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PHYSICS RESEARCH

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THE THERMAL CONDUCTIVITY OF SOME PROJECT MATERIALS

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December 7, 1944

Abstract

An apparatus for measuring the thermal conductivities of materials which are moderately good conductors of heat is described. The conductivities obtained with this apparatus on a number of project materials are given as functions of temperature.

The heat transfer through a pile of thin aluminum discs is also measured, using the same apparatus, and the effects of varying pressures and surface oxidation on the transfer are determined.

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THE THERMAL CONDUCTIVITY OF SOME PROJECT MATERIALS

Introduction

The method used in determining the thermal conductivities of the materials tested is based on the well known equation for heat flow in the steady state,

$$\boxed{Q = \frac{k A \Delta t}{l}}$$

where

Q is the quantity of heat flowing through the specimen,

A is the cross-sectional area of the specimen perpendicular to the lines of heat flow,

l is the length of the specimen parallel to the lines of heat flow,

Δt is the temperature drop across the length l of specimen,

k is a proportionality constant called the thermal conductivity of the material composing the specimen.

In c.g.s. units, k has the dimensions of $\frac{\text{cal.}}{\text{sec.cm.}^{\circ}\text{C.}}$.

If the heat flow equation is solved for the thermal conductivity, the equation

$$\boxed{k = \frac{Ql}{A \Delta t}}$$

is obtained. All the quantities on the right side of this equation except Q may be easily and accurately found. A typical specimen of the material being tested is cylindrical, so that the cross-sectional area A may readily computed. Temperatures are measured at two points along the length of the specimen by thermocouples located sufficiently far from its ends to avoid irregular heat flow due to end effects, thus providing an accurate measurement of Δt. The distance between thermocouples, l, may be easily measured.

The development of a reliable method of measuring thermal conductivity is, therefore, a problem of accurately measuring the amount of heat put into the specimen and of making sure that exactly this amount of heat flows all the way through the specimen, i.e., that heat is neither lost nor gained in a radial direction. The apparatus discussed in the next section is designed to attain that purpose.

Experimental Method

A diagram of the appartus is on the next page (Fig. 1). A close-up photograph of the apparatus is also included (Fig. 1A). A cylindrical specimen (generally 3" long and 1" in diameter) of the material to be tested is prepared. The upper end of this specimen is soldered to a brass cooling chamber through which water circulates in the direction indicated by the arrows in Fig. 1. The lower end of the specimen is threaded for about 1/8" and is screwed thightly into the copper heater holder. Directly below the bottom of the specimen this heater holder contains a coiled heater wound from 1/8" nichrome ribbon, which is insulated from the specimen and heater holder with micanite sheet. Two 1/8" brass rods lead from the heater to the outside of the apparatus, where the external electrical connections are made. As the potential drop along the brass leads is very small, a wattmeter connected across them gives an accurate measure of the power put into the specimen heater.

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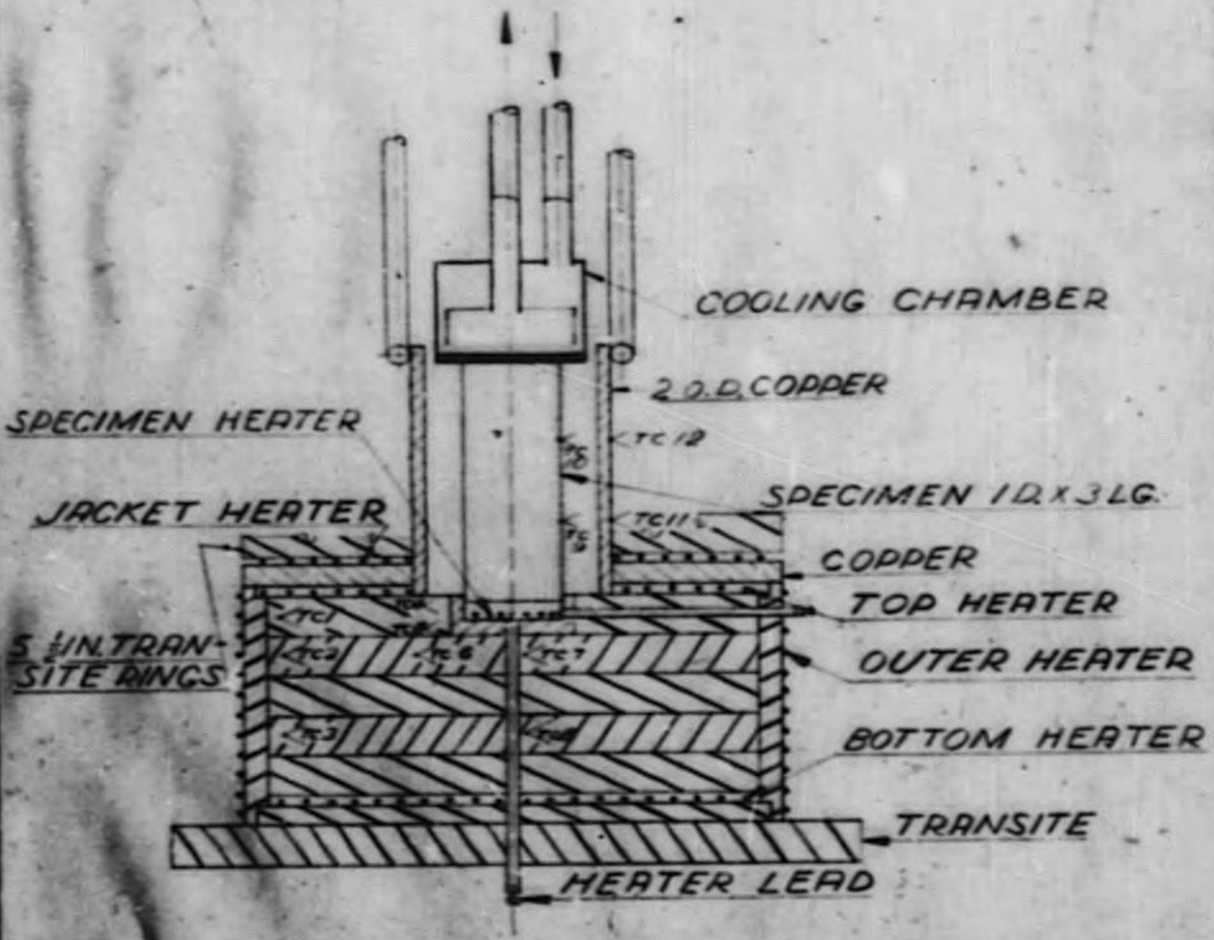

FIG. 1-THERMAL CONDUCTIVITY APPARATUS

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Two chromel-alumel thermocouples (9 and 10 in Fig. 1) are peened into the specimen (or, in the case of graphite, inserted in #60 holes), about one inch apart, each being also about one inch from the end of the specimen nearer to it. A copper guard jacket, 2" in diameter with 1/8" walls, is fitted around the specimen, and the space between specimen and jacket is filled with asbestos paper. This jacket is heated at its base by a nichrome heater wound on a flat micanite ring and is cooled by water flowing through a ring of 3/16" copper tubing at the top. The flat annular copper ring soldered to the bottom of the guard jacket acts as a heat receptor for the jacket heater, and conducts this heat to the jacket. The jacket also has chromel-alumel thermocouples (11 and 12 in Fig. 1) peened into it, and adjusted so that 9 and 11 are in the same horizontal plane, as are 10 and 12. The guard jacket is enclosed by annular rings of ½" transite to cut down heat loss to the outside.

The base of the apparatus contains a number of transite discs and rings fitted within a transite cylinder. Three heaters, called the top, outer, and bottom heaters, are located within the base in positions shown in Fig. 1. The base also contains eight iron-constantan thermocouples, located and numbered as shown. The positions of these couples are so arranged that if they all read the same temperature there can be no heat flow in any direction within the base, and therefore, all power put into the specimen heater must be passing into the specimen.

As can readily be seen from the construction of the apparatus, its operation consists of two steps: (1) adjusting the heaters in the base so as to secure a balance of thermocouples 1 to 8, inclusive, and (2) adjusting the jacket and specimen heaters and the rate of water flow through the specimen cooling chamber and the jacket cooling ring so as to balance thermocouple 9 with 11 and thermocouple 10 with 12. The first step makes it possible to measure accurately the amount of heat passing into the specimen; the second prevents any radial loss or gain of heat as the input heat passes up through the specimen to the cooling chamber. Thus the two problems mentioned in the last paragraph of the introduction are solved and the value of Q to be used in the equation for the thermal conductivity is obtained.

The power input to all heaters is controlled by Variacs operating through constant voltage transformers. The power input to the specimen heater is measured by a precision low range A.C. Wattmeter. In taking a run about one-half hour is allowed to elapse between the attainment of a balance and the actual taking of data, to make sure that steady state conditions are approximated rather closely.

Data and Results

Pure Beryllium

Dimensions of Specimen: $l = 2.553$ cm., $A = 5.047$ cm.^{2}

The top surface of this speciment is plated with .001" of copper and is then soldered to the cooling chamber using coreless soft solder and $ZnCl_2 - NH_4Cl$ Flux.

Run No.	Av. Temperature	t	Q	k
	(°C)	(°C)	(cal/sec)	(cal/sec/cm/°C)
1	55.2	9.37	8.03	.433
2	54.6	9.15	7.91	.437
3	60.1	9.32	7.88	.428
4	46.6	8.95	7.86	.444
5	64.9	10.80	9.15	.425
6	53.7	10.61	9.08	.437
7	41.1	6.89	6.02	.443
8	47.7	6.78	5.95	.443
9	42.9	5.43	4.78	.445
10	39.9	5.39	4.78	.448
11	33.9	3.78	3.37	.451

The results contained in this table are shown in a graph (Fig.2) of the thermal conductivity of this specimen as a function of temperature.

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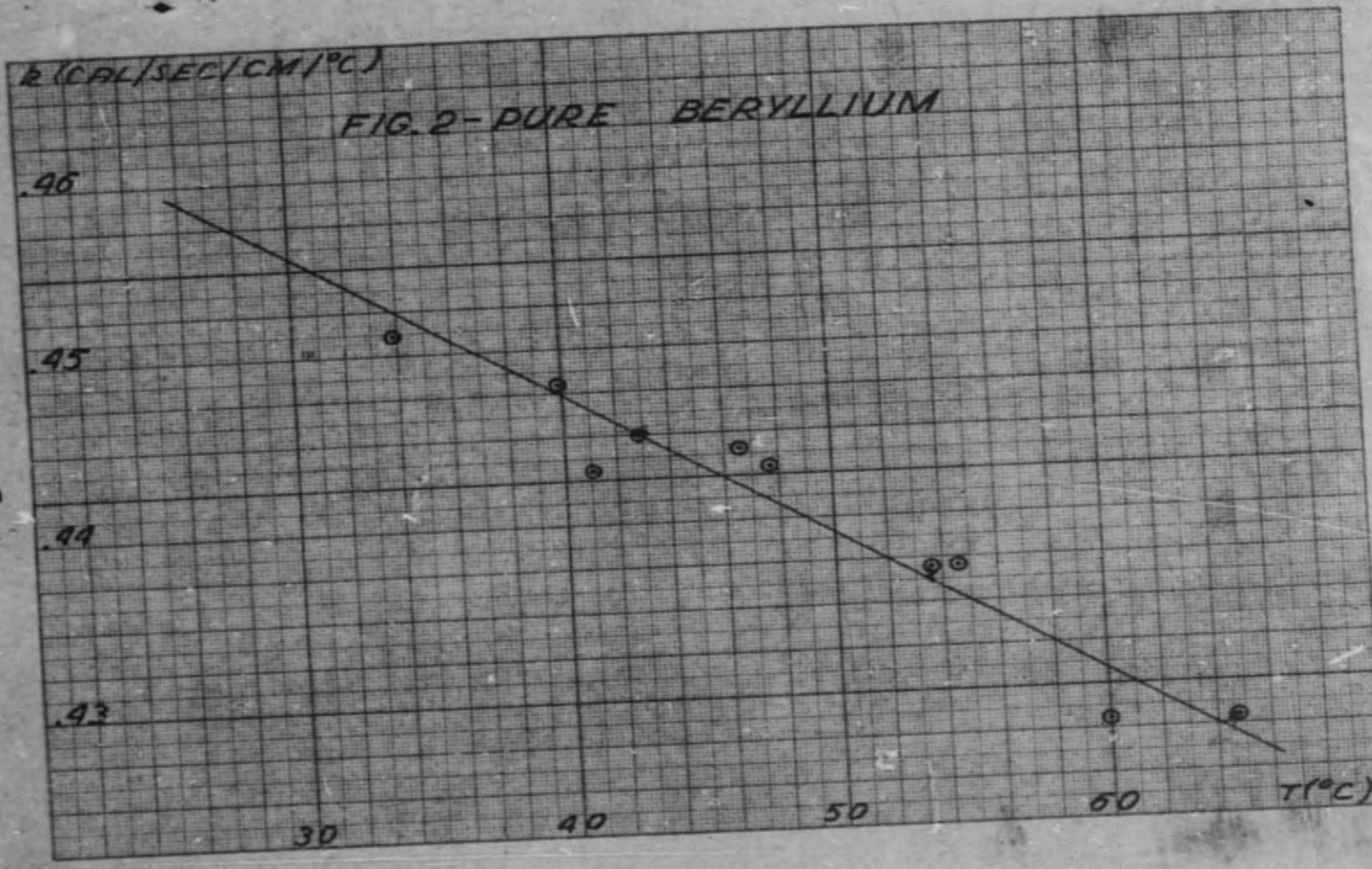

FIG. 2 - PURE BERYLLIUM

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97% Beryllium, 3% Aluminum Alloy

Dimensions of Specimen: l = 2.542 cm., A = 5.070 cm.^{2}

The top surface of this specimen is soldered to the cooling chamber using coreless soft solder and Mogul Flux, the specimen surface being scratched under the flux in order to secure an adherent coating of solder.

Run No.	Av. Temperature (°C)	t (°C)	Q (cal/sec)	k (cal/sec/cm/°C)
1	40.5	9.07	6.70	.370
2	51.5	9.10	6.62	.365
3	29.8	8.81	6.60	.375
4	54.8	9.10	6.57	.362
5	64.4	9.01	6.52	.362
6	45.8	11.85	3.72	.369
7	57.1	11.99	8.72	.364

The results contained in this table are shown in a graph (Fig. 3) of the thermal conductivity of this specimen as a function of temperature.

Pure Thorium

Dimensions of Specimen: l = 1.618 cm., A = 5.042 cm.^{2}

Thorium will not take an adherent copper plate, nor will soft solder adhere to it. Therefore, the top surface of this specimen is sand-blasted and dipped in molten 99% Zn – 1% Al, which forms a "galvanized" coating on it. The cooling chamber is soldered to this coating using coreless soft solder and ZnCl$_2$ –

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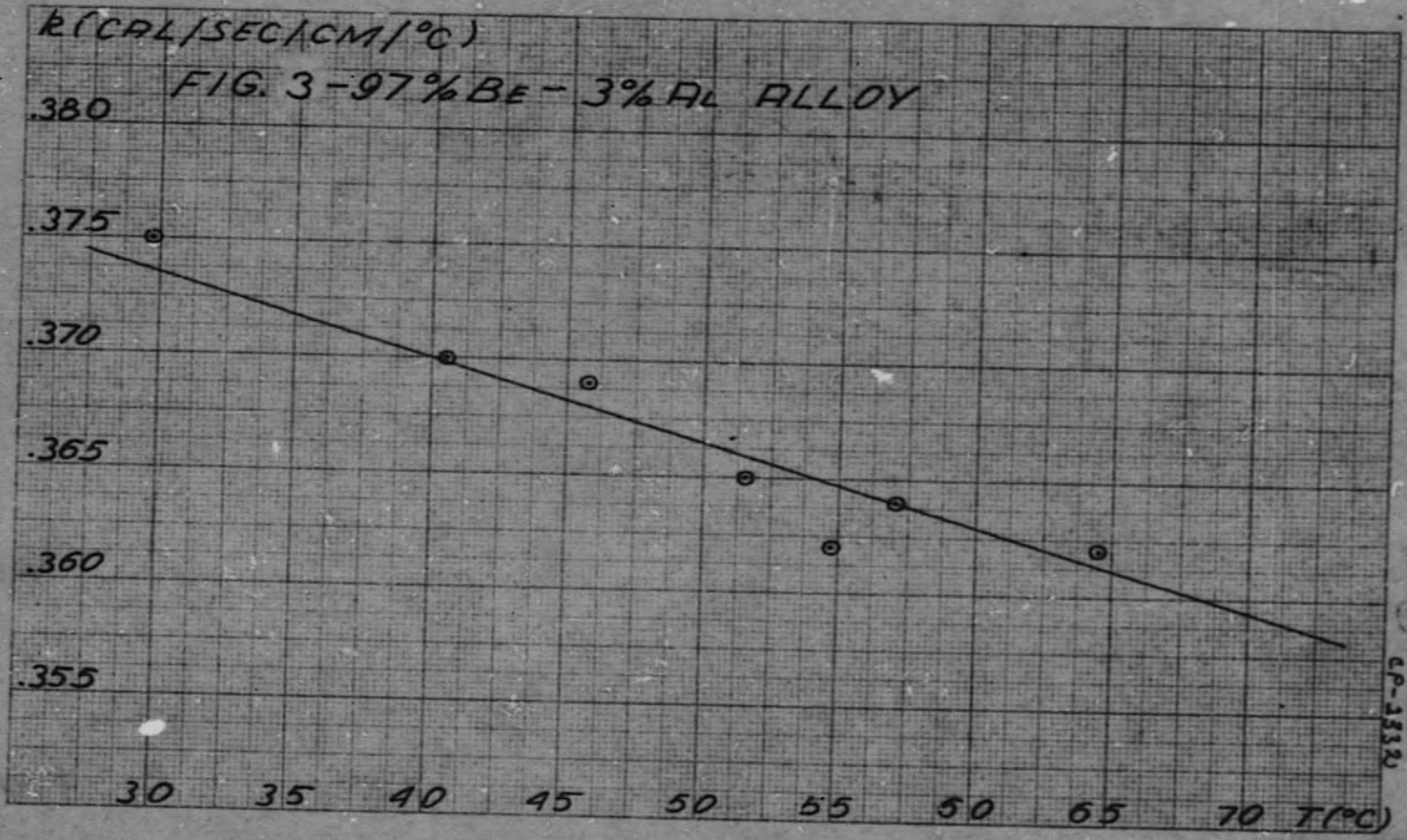
FIG. 3 - 97% Be - 3% Al ALLOY

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NH_4Cl flux.

Because of the relatively low conductivity of thorium, the power input to attain a given temperature gradient is much lower than for the other specimens. As it is difficult to measure such low powers accurately with the wattmeter, D.C. power from a storage battery is used for this specimen only. The power is determined as the product of current through and voltage drop across the specimen heater. The current is measured with a standard resistor and potentiometer; the voltage drop, with a volt box and potentiometer.

Run No.	Av. Temperature (°C)	t (°C)	Q (cal/sec)	K (cal/sec/cm/°c)
1	61.3	6.53	1.49	.0733
2	70.8	7.92	1.84	.0747
3	77.8	9.20	2.13	.0744
4	85.0	10.45	2.47	.0759
5	93.3	11.22	2.65	.0759
6	79.5	9.07	2.11	.0747
7	72.1	7.98	1.83	.0738

The results contained in this table are shown in a graph (Fig.4) of the thermal conductivity of this specimen as a function of temperature.

#1583 Graphite, Lengthwise

Dimensions of Specimen: 1 = 2.607 cm., A = 5.068 cm.^{2}

The top surface of this specimen is plated with .001" of copper and is then soldered to the cooling chamber using coreless soft solder and $ZnCl_2$ - NH_4Cl flux.

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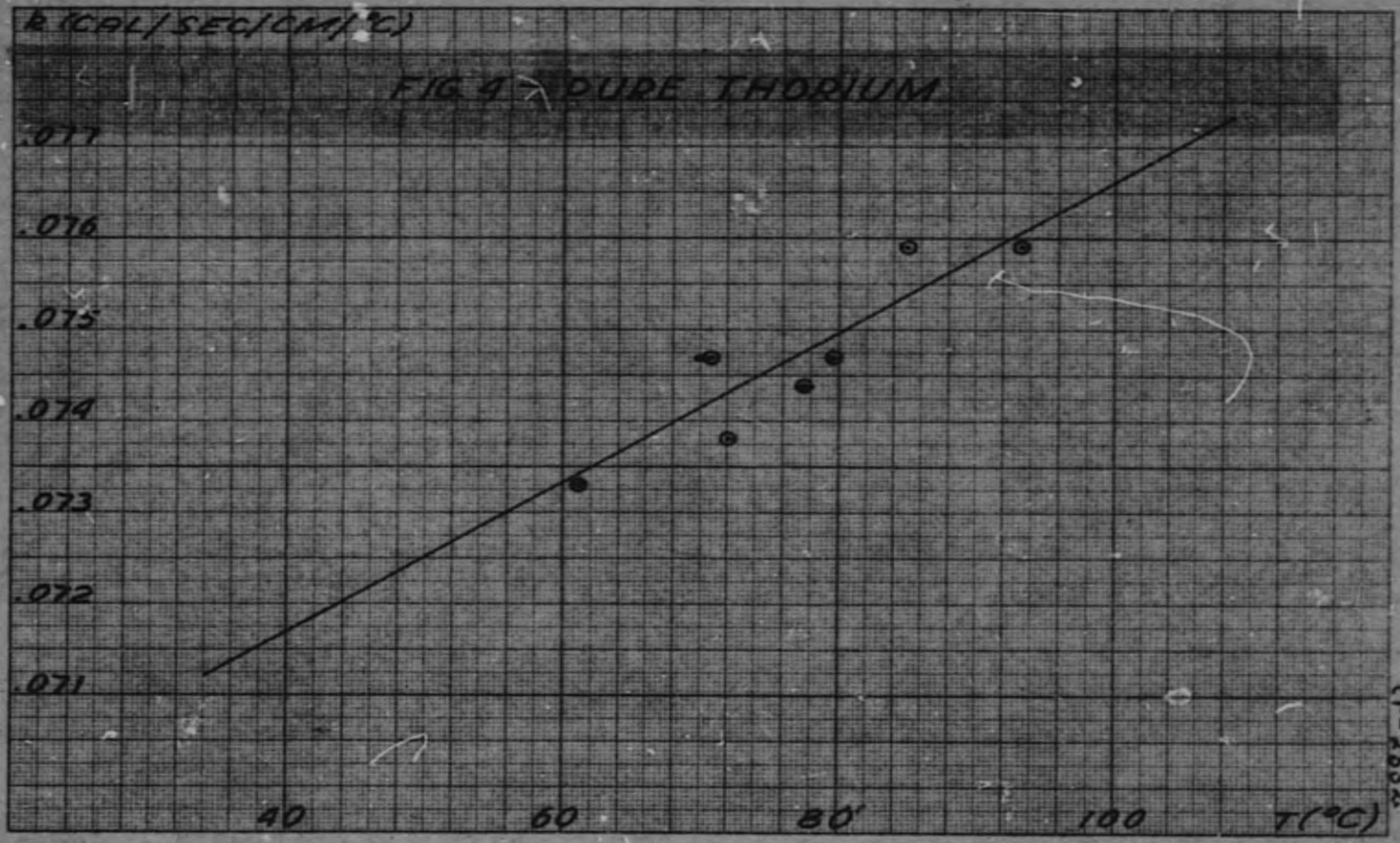

FIG 4 - PURE THORIUM

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Run No.	Av. Temperature (°C)	t (°C)	q (cal/sec)	k (cal/sec/cm/°C)
1	43.6	8.36	7.19	.442
2	52.2	8.42	7.17	.438
3	57.2	10.60	8.96	.435
4	51.4	10.56	8.99	.437
5	56.3	12.79	10.80	.434
6	64.1	12.78	10.72	.432
7	71.9	12.76	10.72	.432

The results contained in this table are shown in a graph (Fig. 5) of the thermal conductivity of this specimen as a function of temperature.

#1583 Graphite, Crosswise

Dimensions of Specimen: 1 = 2.523 cm., A = 5.068 cm.^{2}

The top surface of this specimen is plated with .001" of copper and is then soldered to the cooling chamber using coreless soft solder and $ZnCl_2$ - NH_4Cl flux.

Run No.	Av. Temperature (°C)	t (°C)	q (cal/sec)	k (cal/sec/cm/°C)
1	47.4	9.10	4.73	.259
2	54.7	9.23	4.73	.255
3	60.6	11.77	6.07	.256
4	53.6	11.69	6.07	.258
5	58.9	13.86	7.17	.257
6	66.3	13.96	7.17	.255
7	71.1	14.02	7.17	.254

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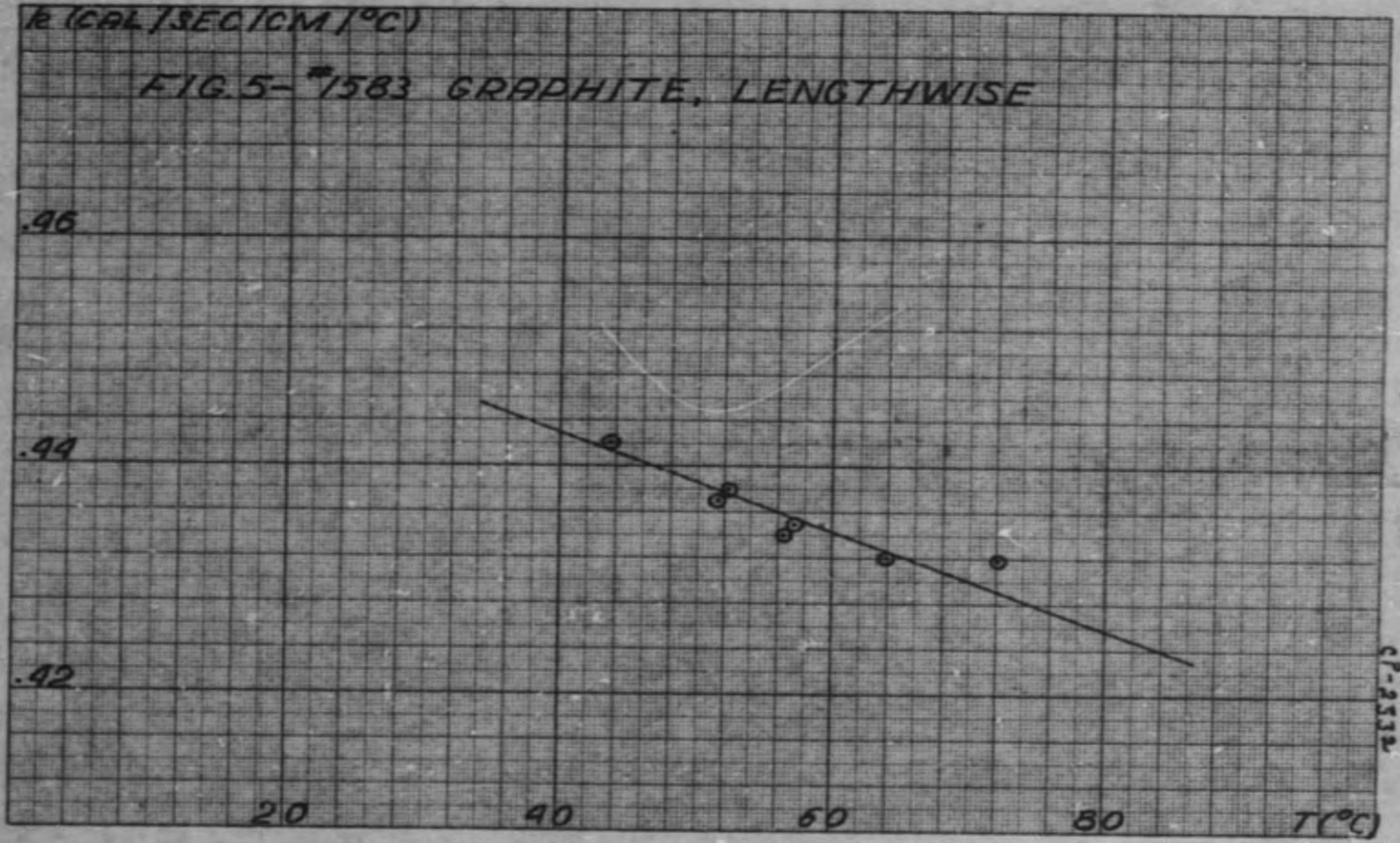

FIG. 5- #1583 GRAPHITE, LENGTHWISE

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FIG. 6 - #1583 GRAPHITE, CROSSWISE

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The results contained in this table are shown in a graph (Fig. 6) of the thermal conductivity of this specimen as a function of temperature.

These results, taken on two specimens from the same bar of extruded graphite, indicate that the thermal conductivity along the length of the bar is about 1.7 as great as the conductivity through the bar.

Brass (From piece tested by Newbergh in Chemistry)

Dimensions of Specimen: $l = 2.565$ cm., $A = 5.017$ cm.^{2}

The top surface of this specimen is soldered to the cooling chamber using coreless soft solder and $ZnCl_2$ - NH_4Cl flux.

Run No.	Av. Temperature (°C)	t (°C)	Q (cal/sec)	k (cal/sec/cm/°C)
1	61.4	13.66	7.17	.268
2	51.6	13.56	6.98	.263
3	43.1	13.63	6.91	.259
4	46.1	9.54	4.92	.263
5	42.6	9.63	4.92	.261
6	33.9	9.88	4.92	.255
7	29.0	7.24	3.53	.250

The results contained in this table are shown in a graph (Fig. 7) of the thermal conductivity of this specimen as a function of temperature.

Brass (From piece for transfer measurements of Christ and Peterson)

Dimensions of Specimen: $l = 2.570$ cm., $A = 5.447$ cm.^{2}

The top surface of this specimen is soldered to the cooling chamber using coreless soft solder and $ZnCl_2$ - NH_4Cl flux.

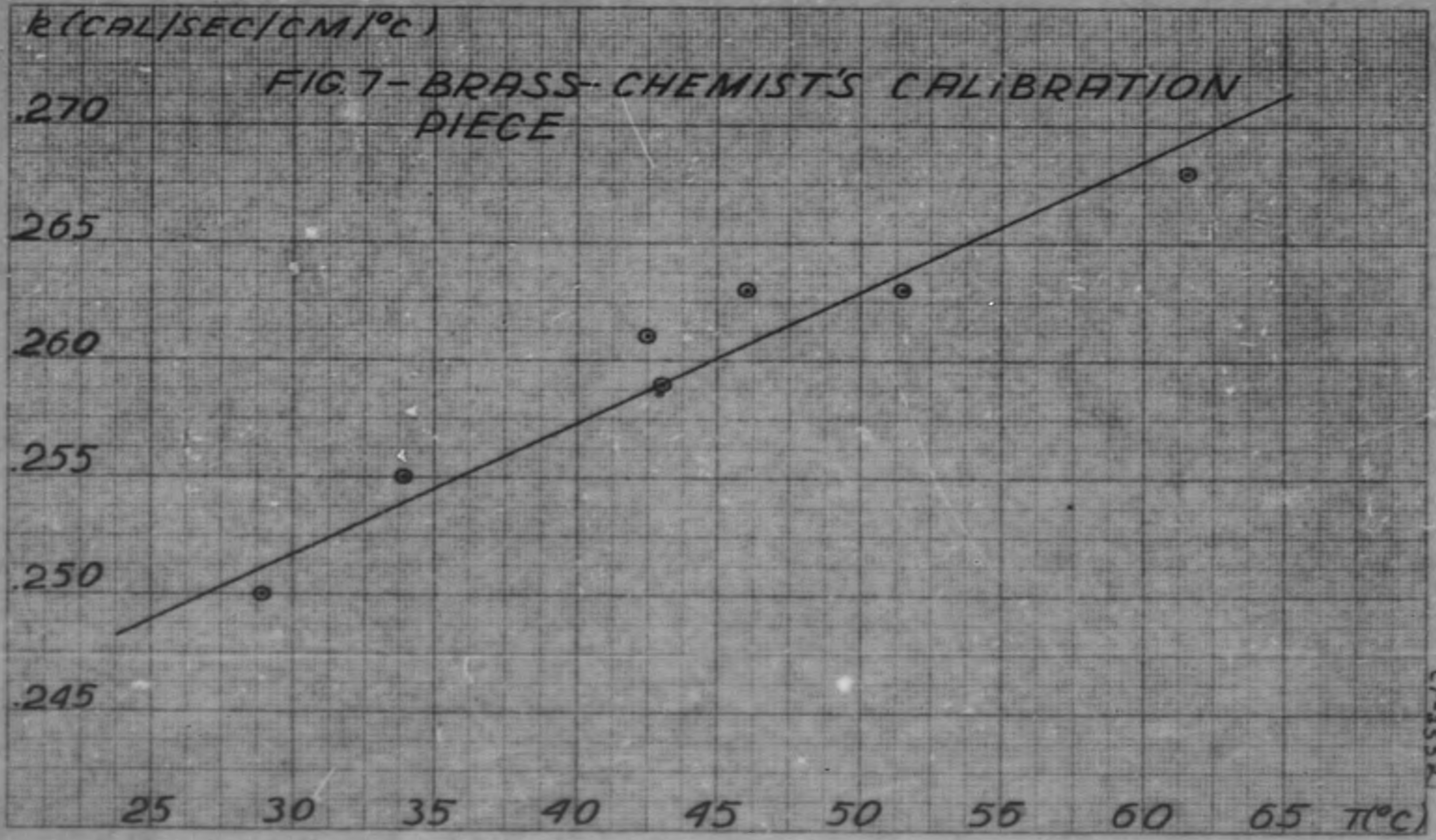

FIG. 7 - BRASS - CHEMIST'S CALIBRATION PIECE

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Run No.	Av. Temperature	t	Q	k
	(°C)	(°C)	(cal/sec)	(cal/sec/cm/°C)
1	52.7	11.55	4.29	.276
2	58.9	11.26	4.19	.277
3	64.6	10.94	4.11	.280
4	44.7	8.56	3.11	.271
5	51.0	8.49	3.11	.273
6	48.3	6.27	2.34	.278
7	40.6	6.37	2.34	.274
8	58.7	13.55	5.16	.282
9	62.1	13.52	5.09	.281
10	70.3	13.38	5.12	.285

The results contained in this table are shown in a graph (Fig. 8) of the thermal conductivity of this specimen as a function of temperature.

Heat Transfer Through a Pile of Thin Aluminum Discs.

This experiment is intended to determine the heat transfer through a pile of .020" thick aluminum discs under various pressures, and thereby the heat transfer h_1 across the air film between two adjacent discs. It is reported along with the foregoing results on thermal conductivity because the same apparatus is used. The specimen consists of a horizontally split brass cylinder between the two parts of which the aluminum discs are compressed by a known pressure, and the power passing through the discs is determined by measuring the temperature gradient in the lower brass piece, the thermal conductivity of which has been measured (see Fig. 7). The unit heat transfer h_1 is then determined as follows. First the overall heat transfer h_{Al} is determined from the defining equation

$$\boxed{h_{Al} = \frac{k_{Al}}{l_{Al}}}$$

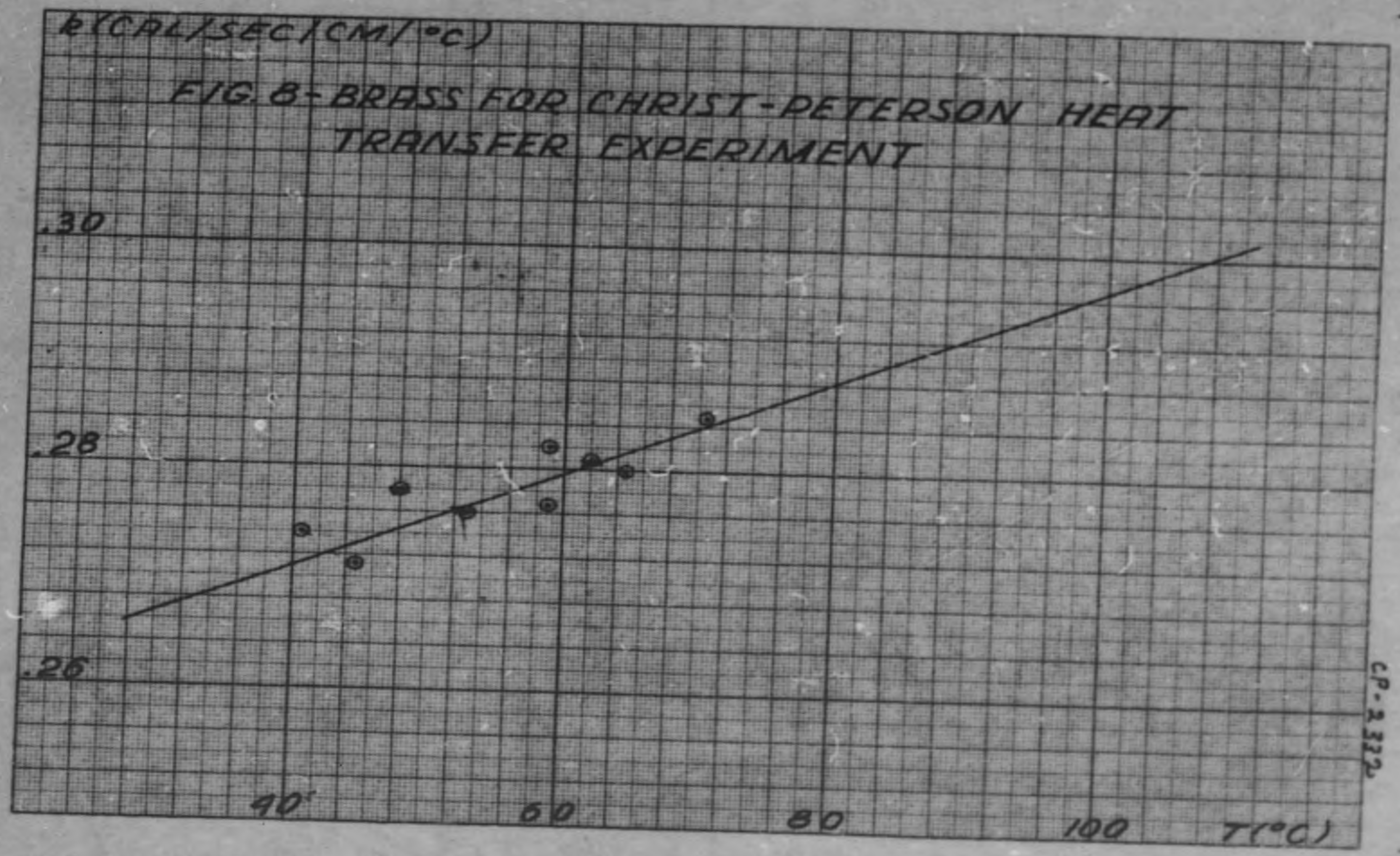
FIG. 8 - BRASS FOR CHRIST-PETERSON HEAT TRANSFER EXPERIMENT

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where k_{Al} is the apparent overall thermal conductivity of the pile of discs and l_{Al} is the thickness of the pile. By substituting the standard equation for k_{Al}, it is found that

$$\boxed{h_{Al} = \frac{Q_{Al}}{A_{Al}\,\Delta t_{Al}}} \quad .$$

Neglecting the thermal resistance of the aluminum discs in comparison with the much greater resistance of the air films between discs, and since

$$\boxed{\frac{1}{h_{total}} = \frac{1}{h_1} + \frac{1}{h_2} + \cdot \cdot \cdot + \frac{1}{h_n}} \quad .$$

it is found that for n air films between discs (assuming an equal resistance to heat flow in each air film),

$$\boxed{h_i = nh_{Al}} \quad .$$

Aluminum Discs with Normally Air-Oxidized Surfaces.

Dimensions: Nine discs, ten air films ($h_i = 10\ h_{Al}$).

l_{Al} = .462 cm., A_{Al} = 5.047 cm.^{2}

Run No.	Pressure	t_{Al}	Q_{Al}	h_{Al}	h_i
	(lbs/in.^{2})	(°C)	(cal/sec)	(cal/sec/cm^2/°C)	(cal/sec/cm^2/°C)
1	41.6	15.11	2.92	.0383	.383
2	41.6	20.06	4.17	.0411	.411
3	41.6	19.16	4.08	.0422	.422
4	20.4	25.04	3.45	.0273	.273
5	20.4	23.71	3.46	.0288	.288
6	41.6	18.89	3.41	.0357	.357

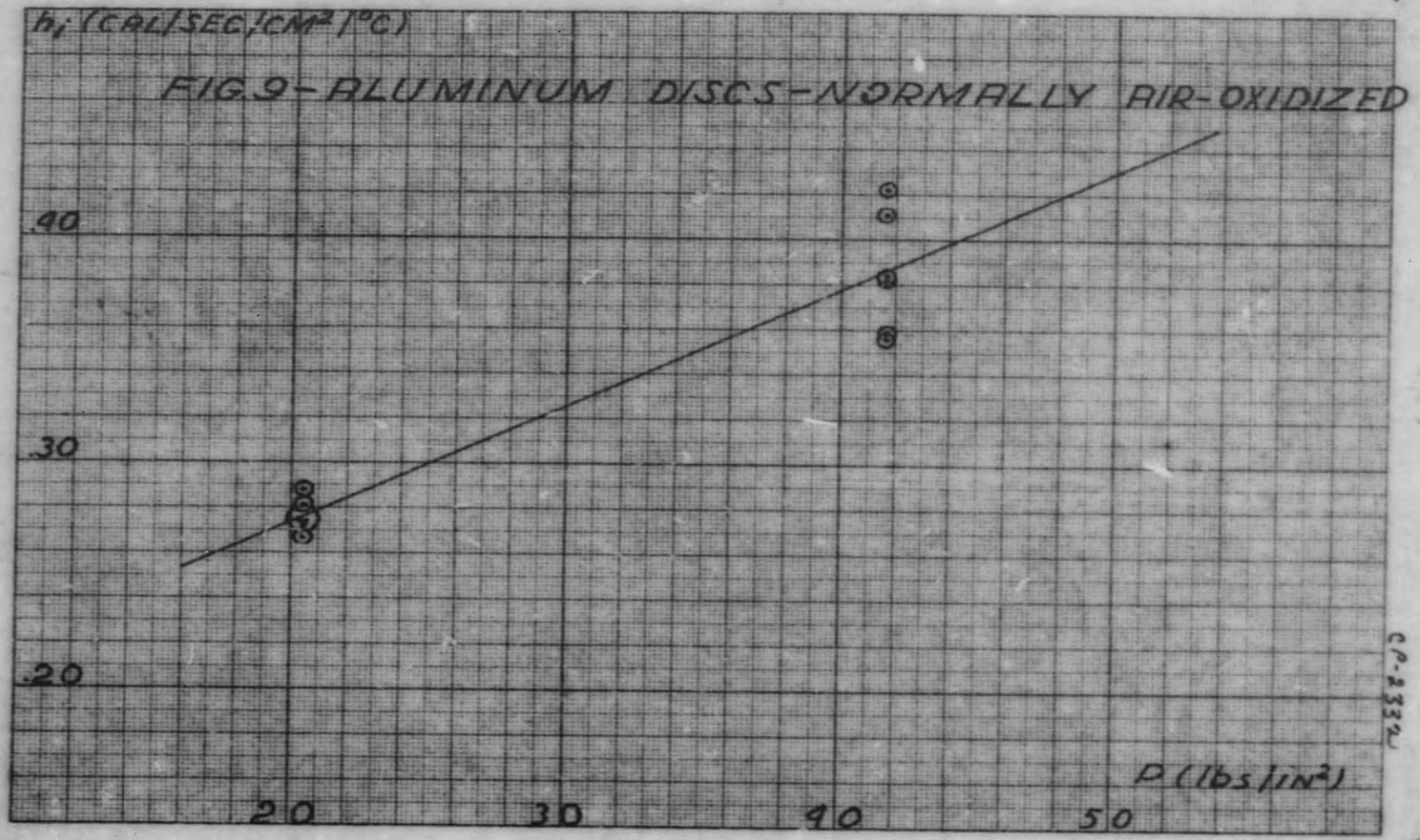

FIG.9-ALUMINUM DISCS-NORMALLY AIR-OXIDIZED

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Dimensions: Six discs, seven air films ($h_1 = 7h_{A1}$).

$l_{A1} = .309$ cm., $A_{A1} = 5.047$ cm.^{2}

Run No.	Pressure	t_{A1}	Q_{A1}	h_{A1}	h_1
	(lbs/in.^{2})	($^\circ$C)	(cal/sec)	(cal/sec/cm^2/$^\circ$C)	(cal/sec/cm^2/$^\circ$C)
1	20.4	16.95	3.26	.0382	.267
2	20.4	16.96	3.43	.0401	.281
3	20.4	17.19	3.40	.0392	.274
4	20.4	17.27	3.36	.0386	.270
5	41.6	12.75	3.29	.0511	.358
6	41.6	15.24	4.22	.0547	.383

The results contained in these two tables are shown in a graph (Fig. 9) of the unit heat transfer coefficient as a function of pressure.

Aluminum Discs Oxidized by Anodizing in Oxalic Acid.

Dimensions: Nine discs, ten air films ($h_1 = 10\ h_{A1}$).

$l_{A1} = .470$ cm., $A_{A1} = 5.047$ cm.^{2}

Run No.	Pressure	t_{A1}	Q_{A1}	h_{A1}	h_1
	(lbs/in.^{2})	($^\circ$C)	(cal/sec)	(cal/sec/cm^2/$^\circ$C)	(cal/sec/cm^2/$^\circ$C)
1	20.4	42.19	3.27	.0154	.154
2	20.4	37.06	2.75	.0147	.147
3	41.6	40.76	3.40	.0165	.165
4	104.4	34.18	3.42	.0198	.198

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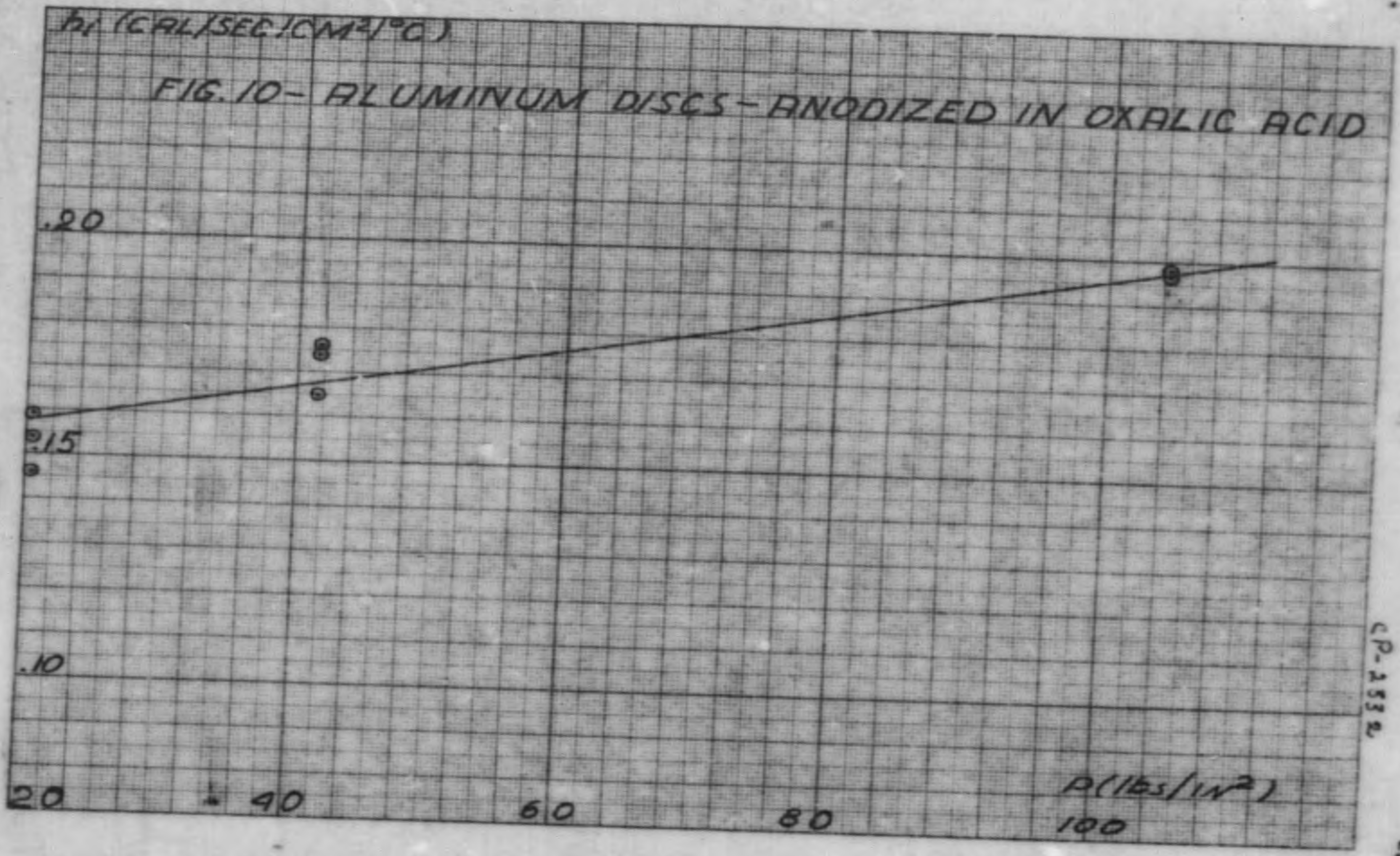

FIG. 10- ALUMINUM DISCS-ANODIZED IN OXALIC ACID

Dimensions: Six discs, seven air films ($h_1 = 7\ h_{Al}$).

$l_{Al} = .311$ cm., $A_{Al} = 5.047$ cm.^{2}

Run No.	Pressure	t_{Al}	Q_{Al}	h_{Al}	h_1
	(lbs/in.^{2})	(°C)	(cal/sec)	(cal/sec/cm^2/°C)	(cal/sec/cm^2/°C)
1	20.4	31.41	3.59	.0227	.159
2	41.6	27.01	3.42	.0251	.176
3	41.6	23.00	2.88	.0249	.174
4	104.4	20.22	2.87	.0281	.197

The results contained in these two tables are shown in a graph (Fig. 10) of the unit heat transfer coefficient as a function of pressure.

These results indicate that the thermal resistance of the air and oxide film between aluminum discs is markedly increased by increasing the Al_2O_3 film on the discs to a thickness of only .0001", the approximate thickness of the film used in the second part of this experiment.

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