WADC TR 59-185

THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING
Department of Chemical Engineering

Final Report

THERMAL CONDUCTIVITY OF LUBRICATING OILS AND HYDRAULIC FLUIDS

D. W. McCready

UMRI Project 2774

under contract with:

UNITED STATES AIR FORCE
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FOREWORD

This report was prepared by The University of Michigan Research Institute under USAF Contract No. AF 33(616)-5745. This contract was initiated under Project No. 7360, "Materials Analysis and Evaluation Techniques," Task No. 73603, "Thermodynamics and Heat Transfer." It was administered under the direction of the Materials Laboratory, Directorate of Laboratories, Wright Air Development Center, with Mr. Hyman Marcus acting as project engineer. The principal investigator was D. W. McCready, Associate Professor of Chemical Engineering, who was assisted by Thomas E. Altenbern.

This report covers work conducted during the contract period from 1 July 1958 to 30 June 1959, and is in effect a continuation of research initiated under USAF Contract No. AF 33(616)-3543. This previous work was reported in December, 1958, in report WADC TR 58-405.

ABSTRACT

An all-metal concentric cylinder type of thermal conductivity cell was used to measure the thermal conductivity of twelve natural and synthetic base lubricating fluids.

Thermal conductivity values in the temperature range of from 70 to 500°F are reported for fluids considered stable to the higher temperature. The maximum temperatures for other fluids were limited by their instabilities under test conditions. Since each fluid has individual characteristics, no correlation of conductivity values appears possible. Values are considered precise and for possible correlation can be compared to those of a fluid chosen as a "standard reference."

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

L. F. Salzberg
Chief, Materials Physics Branch
Materials Laboratory

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I. INTRODUCTION

Under Contract No. AF 33(616)-3543, determinations of the thermal conductivity of ten synthetic base and five mineral base lubricating fluids were initiated. Conductivities over the temperature range of 70-500°F were required. Later twenty-five additional fluids were submitted for evaluation. This research under USAF Contract No. AF 33(616)-5745 is an extension of the above to measure the thermal conductivities of twelve additional fluids, to make a total of fifty-two fluids.

The work was initiated because such data are required for engineering designs of heat-transfer equipment. Such data were not available in the literature or from other sources.

Very few measurements of thermal conductivities of liquids have been made previously at temperatures above about 200°F. Those reported were made on apparatus of doubtful precision. Thus the only references to data in the literature are limited to those of value to this work and they are referred to when used.

II. DESIGN OF THERMAL CONDUCTIVITY CELL

Apparatus for the measurement of thermal conductivities of fluids may be classified into three general types on a basis of the directions of heat flow: (1) direct flow between flat plates; (2) radial flow through an annulus of fluid (between concentric cylinders); and (3) flow from a hot wire. All types were considered for this research.

A concentric cylinder type of cell was chosen. Several such cells have been used by other investigators and have proven as precise means of measuring thermal conductivities. Factors considered in this selection were:

(1) The high temperature (500°F) which limited materials to ceramics or metals except for gaskets where Teflon could be used.
(2) The stability of the fluids to oxidation which required operation in the absence of air.

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(3) The stability of fluids in contact with metals, specifically copper, which accelerate thermal decomposition.
(4) The high temperature which made it unfeasible to use a fluid as the final heat sink.
(5) The desire for flexibility so that heat fluxes and film dimensions could be readily changed.

The metal chosen for the essential parts of the cell was copper because of its high thermal conductivity. Silver was considered too expensive for the initial cell. Corrosion-resistant metals were considered to have too low thermal conductivities, a conclusion drawn after computations of expected temperature differentials.

Copper is the least desirable metal to use from the standpoint of stability of the fluids, and so the copper surfaces were plated with chromium. Means of excluding air were devised, and a procedure, discussed later, was initiated to insure that the fluids were not operated under unstable conditions.

The concentric cylinder type of cell consists of a central cylinder or core, which is the heat source, surrounded by another cylinder, which is heat Sink I. Heat flows from the core to Sink I through the sample contained in the annular space between the cylinders. A second sink (II) surrounds the whole to maintain controlled conditions; in most cases this is a fluid bath, but in this research a large cylinder of aluminum was used.

Thermal conductivity of a fluid may be computed from the known heat input, temperature drop across the annulus, and dimensions of the annulus.

The components and method of assembly of the thermal conductivity cell are shown in Figs. 1 and 2. Figure 1 shows the components, the filling and emptying tubes in the foreground, the central electric heater behind them, and in the rear, the bottom seal, seal gaskets, central core with top seal, and Sink I and Sink II. The central core and Sink I are of electrolytic copper and chromium-plated. Sink II is anodized aluminum. The seals are chromium-plated brass. The core and Sink I are 8 inches long.

The thermocouple holes (8) in the central core are arranged 45° apart. The bottoms of these holes are 1, 2, 3, 4, 4, 5, 6, and 7 inches from the top.

The thermocouple holes in Sink I, at the same levels, are holes drilled to 1/16 of an inch of inner face and with channels leading from the holes to the top, through which the thermocouple wires pass. This sink is tapered to fit a similar taper in the central hole in Sink II.

Figure 2 shows the means of assembling; the heater centered in the central core; the core is centered and bolted by the seals to Sink I, and Sink I is centered in Sink II.

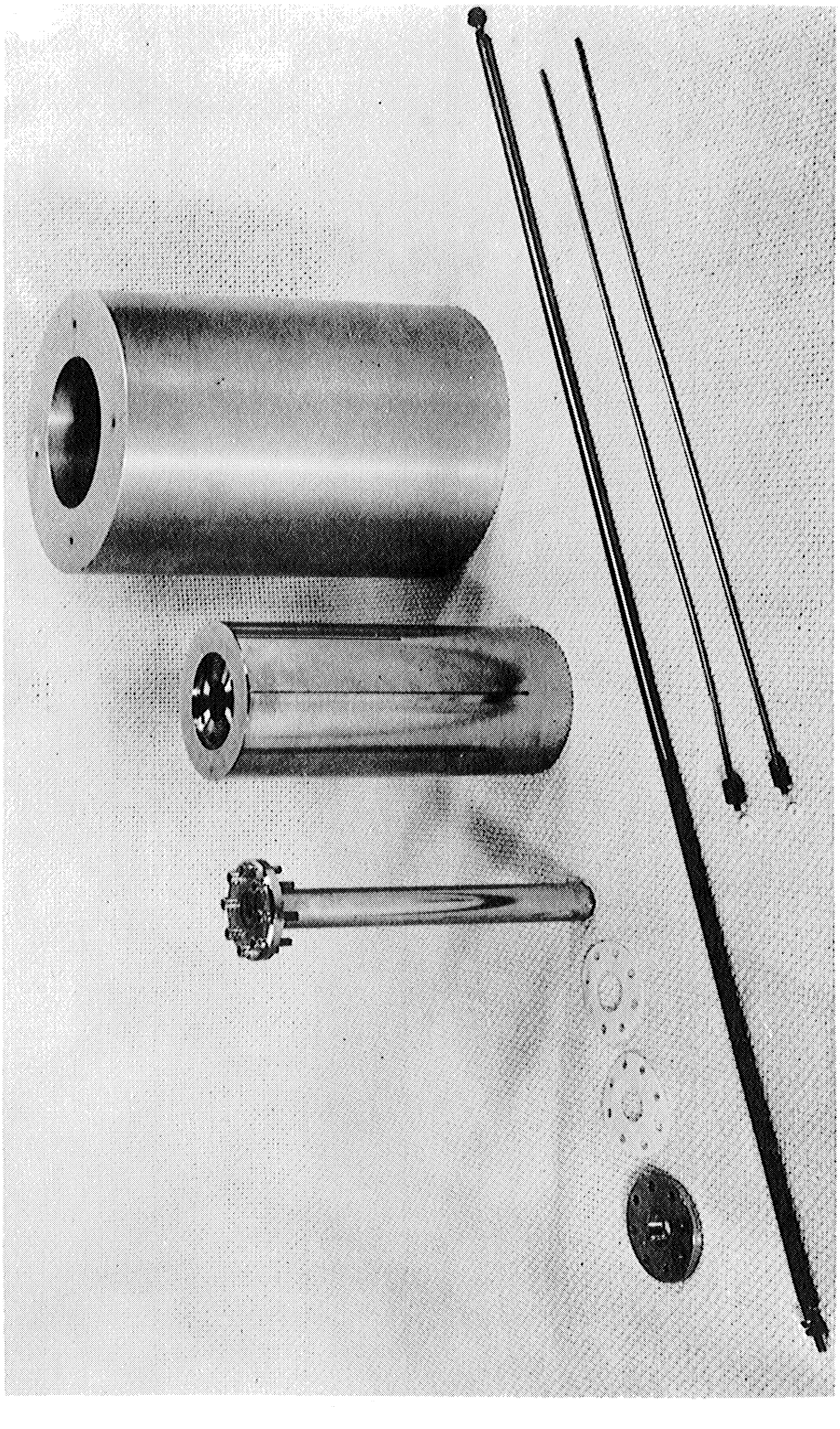

Fig. 1. Components of cell.

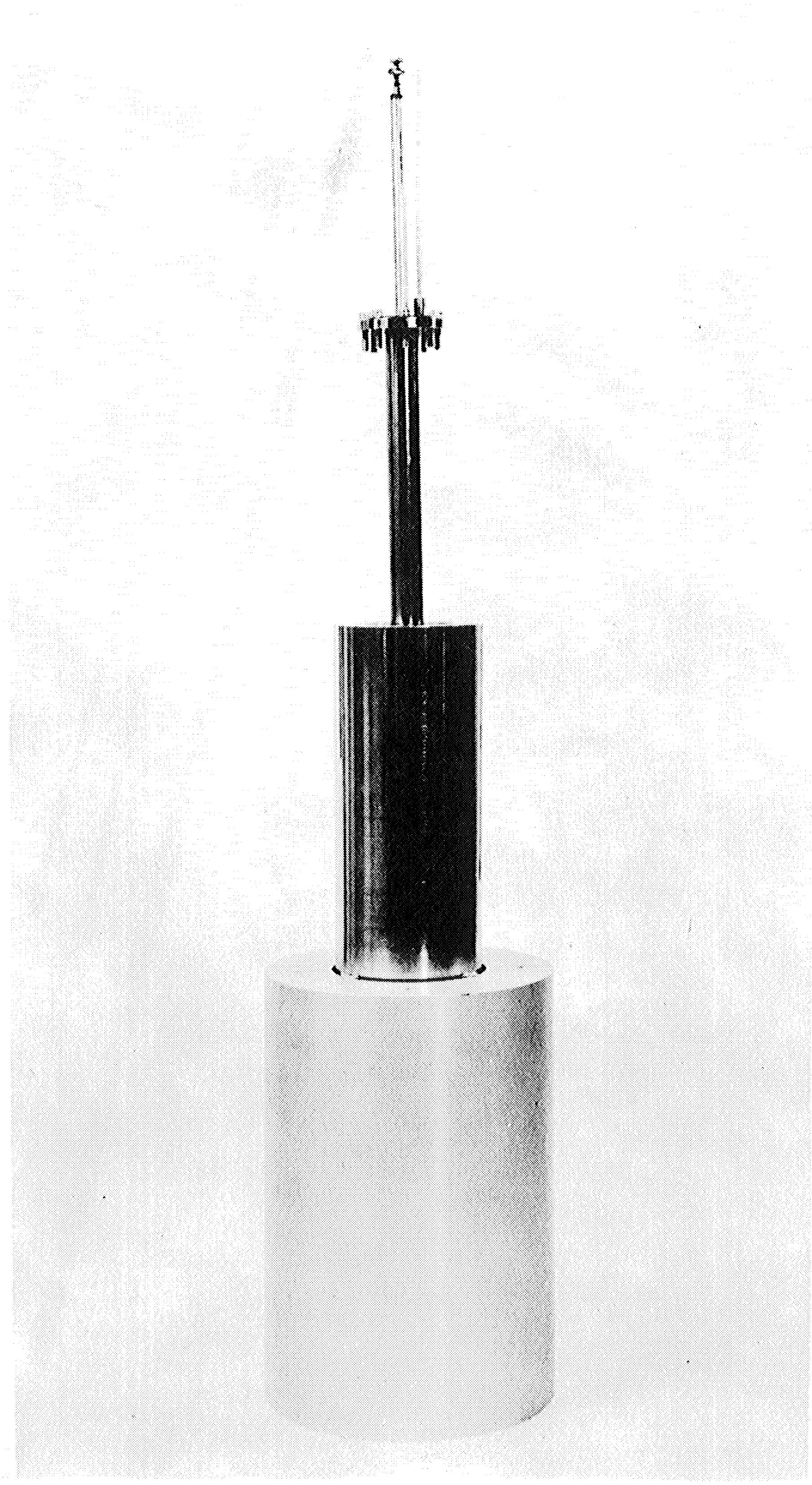

Fig. 2. Assembly of cell.

In operation, the whole apparatus is insulated and heated by electrical tapes wound around Sink II.

The filling and emptying tubes connect to the top and bottom seals as shown with the top seal.

All units are pictured in Figs. 3 and 4. Figure 3 shows almost all the parts; the K-2* potentiometer, galvanometer, standard cell on the left-hand table, and under the table the battery used with the potentiometer. The left side of the instrument panel is the Wheelco Controller** with the temperature-indicating scale near the top and the temperature-controlling cam in the center.

On the right-hand panel below the clock are the thermocouple switches. Further right are switches and ammeters for control of battery discharge and charge circuits. Power for the central core heater is supplied by the batteries on the floor and they are floating on the 110-volt d-c source in the building. In this way these batteries maintain a constant voltage.

Just behind the panel is the volt box for measuring the voltage drop across the central heater. This voltage is measured by the K-2 potentiometer. Next behind is the ice chest which serves as ice storage and thermocouple cold junction. The white unit behind it is the thermal conductivity cell insulated with asbestos winding and blocks.

Figure 4 shows the components behind the panel board: the large ice chest with the cold junction tubes apparent at the further end; the core reactor behind the ice chest; and the standard ohm resistance behind the insulated cell.

The current to the central heater flows through the standard ohm (0.1 Ω) resistance and is evaluated as a potential drop across the standard ohm resistance by the K-2 potentiometer.

III. PROOF OF THE THERMAL CONDUCTIVITY APPARATUS

Thermal conductivity values are acceptable only if obtained with an apparatus of proven precision. Such precision is always difficult to confirm and generally is determined by comparison with accepted results of other investigations. Or the apparatus may be, after thorough study, considered a precision instrument, and the results obtained as absolute or at least comparable with expected results. The latter is the case with this apparatus.

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*Leeds and Northrup.

**Wheelco; Model 72000-5253 Chronotrol, 110 volt, 60 cycle, 0-600°F range for iron-constantan thermocouple, 1 rev in 3 days; and Saturable Core Reactor.

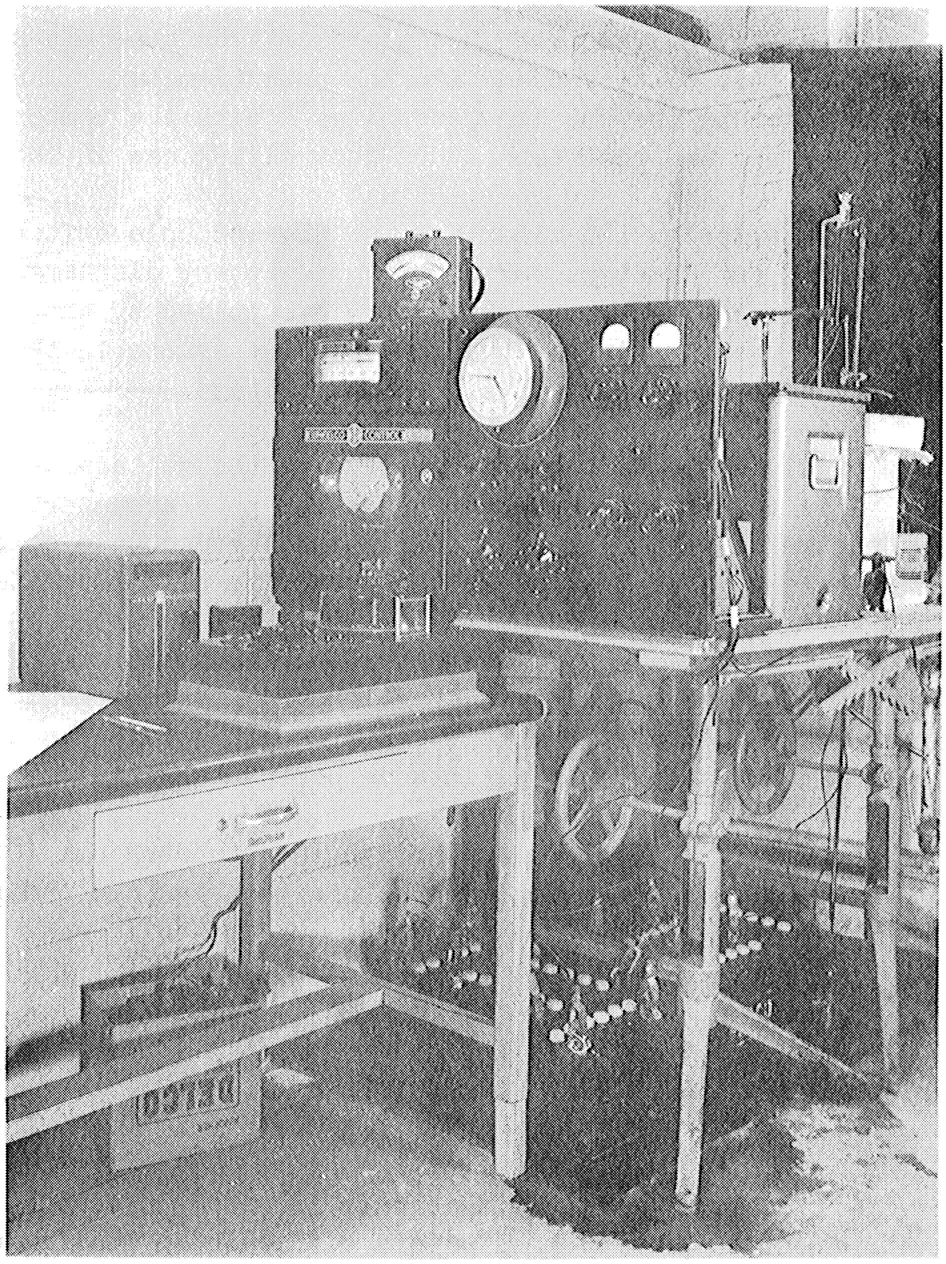

Fig. 3. Front view of apparatus.

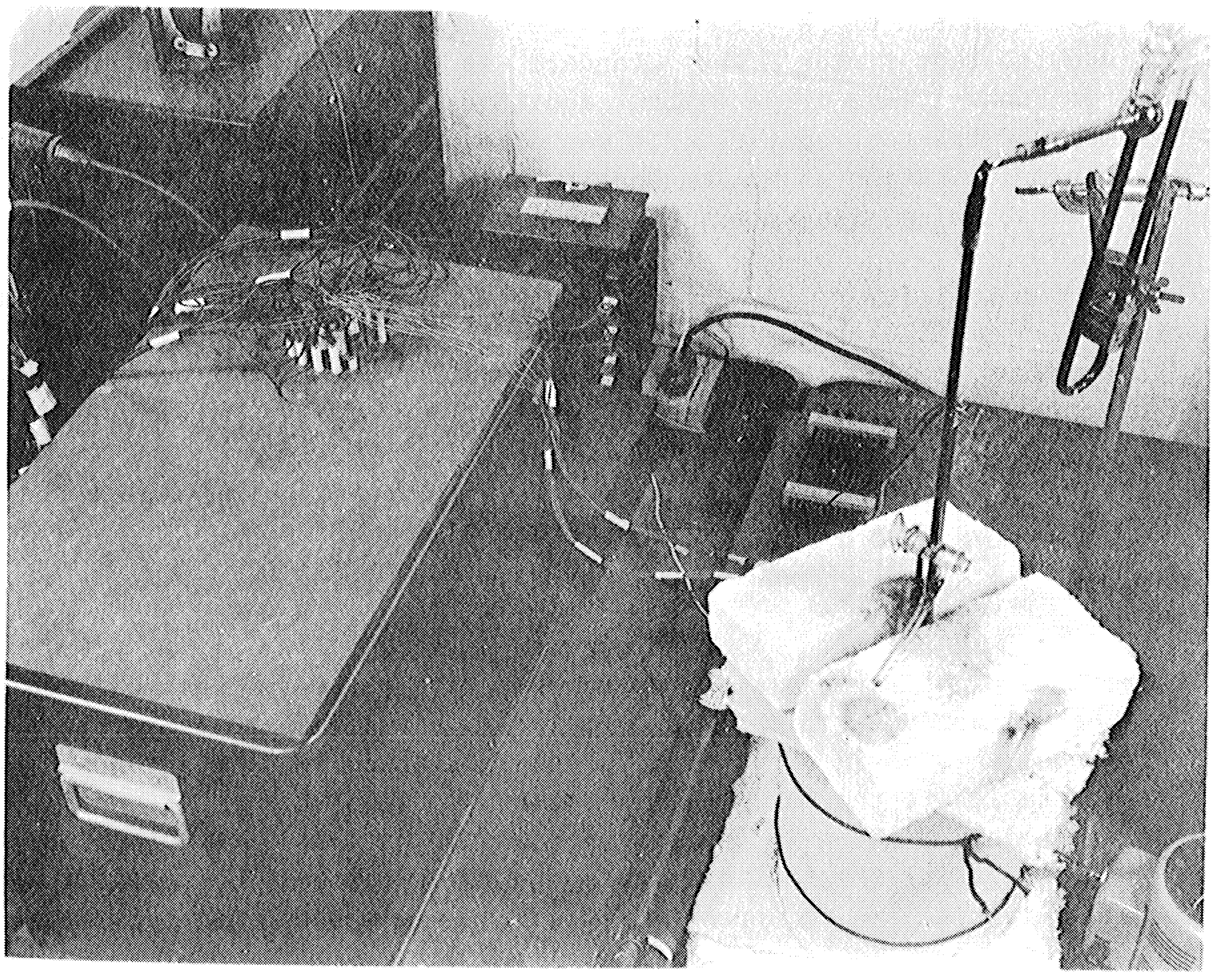

Fig. 4. Top view of apparatus.

The design and proof of the cell is detailed in WADC TR 58-405. Also in that report are the methods of making and calibrating thermocouples, and data on typical set of readings.

The proving of the apparatus resulted in the realization that the apparatus was precise only at temperatures above about 250°F with normal ambient temperatures. A "standard of reference" was therefore established to evaluate the apparatus and the test fluids. The "Standard" is a close-cut lubricating oil fraction from Pennsylvania crude without additives and having about the same viscosity as most of the test samples. It was obtained as a standard oil from the Gulf Research organization at Mellon Institute in 1951. At that time it was placed in glass bottles, deaerated, and sealed.

Thermal conductivity vs. temperature curves on this oil were obtained at the beginning and middle of the research. The results are plotted in Fig. 5 and the consistency of the results confirms the operation of the cell and the choice of the "standard of reference."

IV. VALUES OF THERMAL CONDUCTIVITY OF FLUIDS

The results of this research are most readily reported as the measured values of thermal conductivities of the fluids as a function of temperature. They are plotted as such in Figs. 6 to 9, and tabulated in Table I. Also apparent in the table are the maximum temperatures to which these oils could be heated for at least 20 hours in contact with copper without apparent decomposition. The details of the test are in Appendix I. Typical computations of thermal conductivities are in Appendix III. The high melting point of several fluids is also apparent in the table.

Several attempts were made to see if the curves in Figs. 6-9 could be fitted to a typical curve, but all were unsuccessful. Each fluid has individual characteristics.

Data on stability apply only to the test as made, namely, 20-hr duration. Stabilities under other than test conditions were not measured and are not inferred.

No measurements of decomposition of the fluids were made after thermal conductivity determinations, although acid numbers were requested. Most of the fluids showed no visible change during a determination. As a 100% sample could not be obtained, and as apparent changes in the fluids were negative, acid numbers were not run. The method of determining acid numbers would depend on the chemical characteristics of the fluids, and it was considered that the expected small differences between fresh and used fluids would not be sufficient to warrant conclusions concerning stability. Stabilities were considered measured by tests reported in Appendix I.

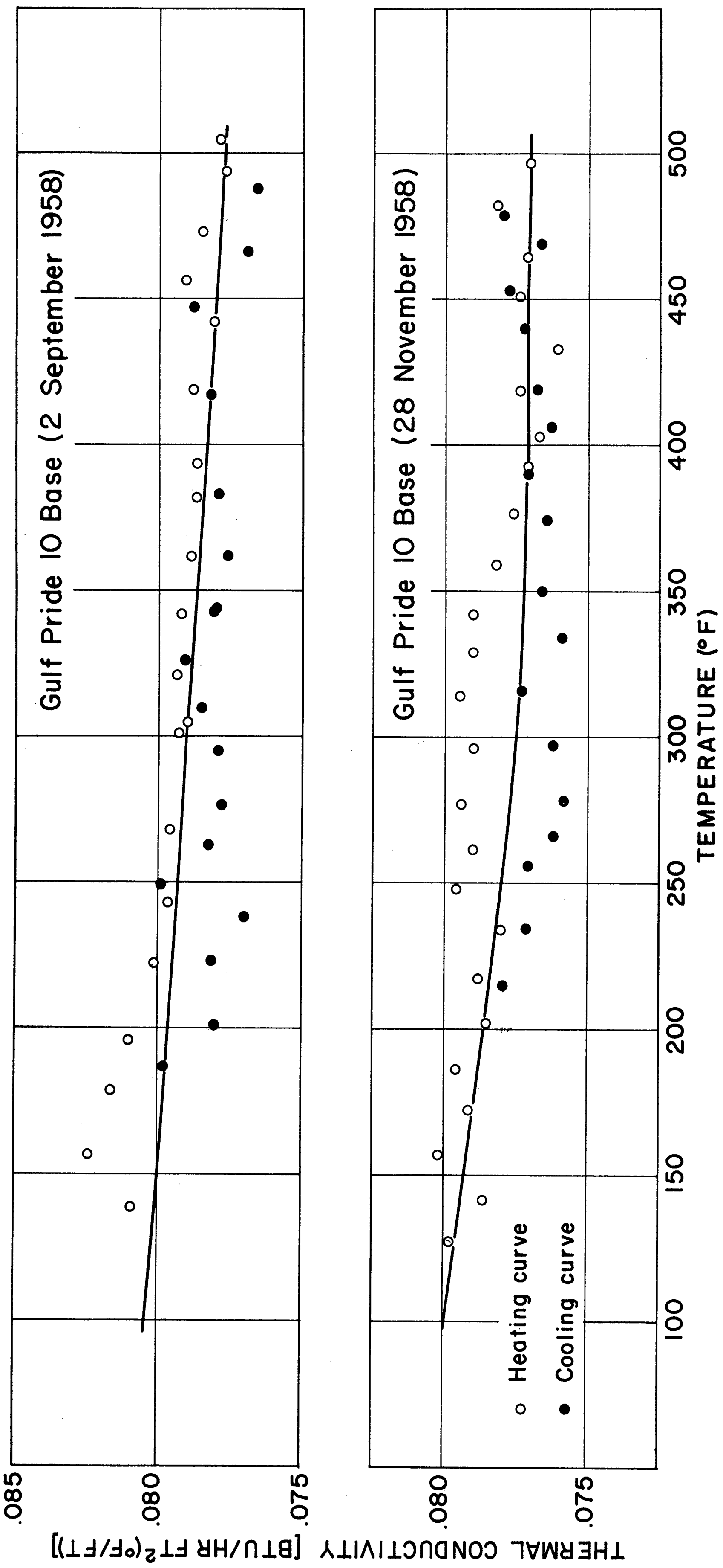

Fig. 5. Thermal conductivity of calibration fluid.

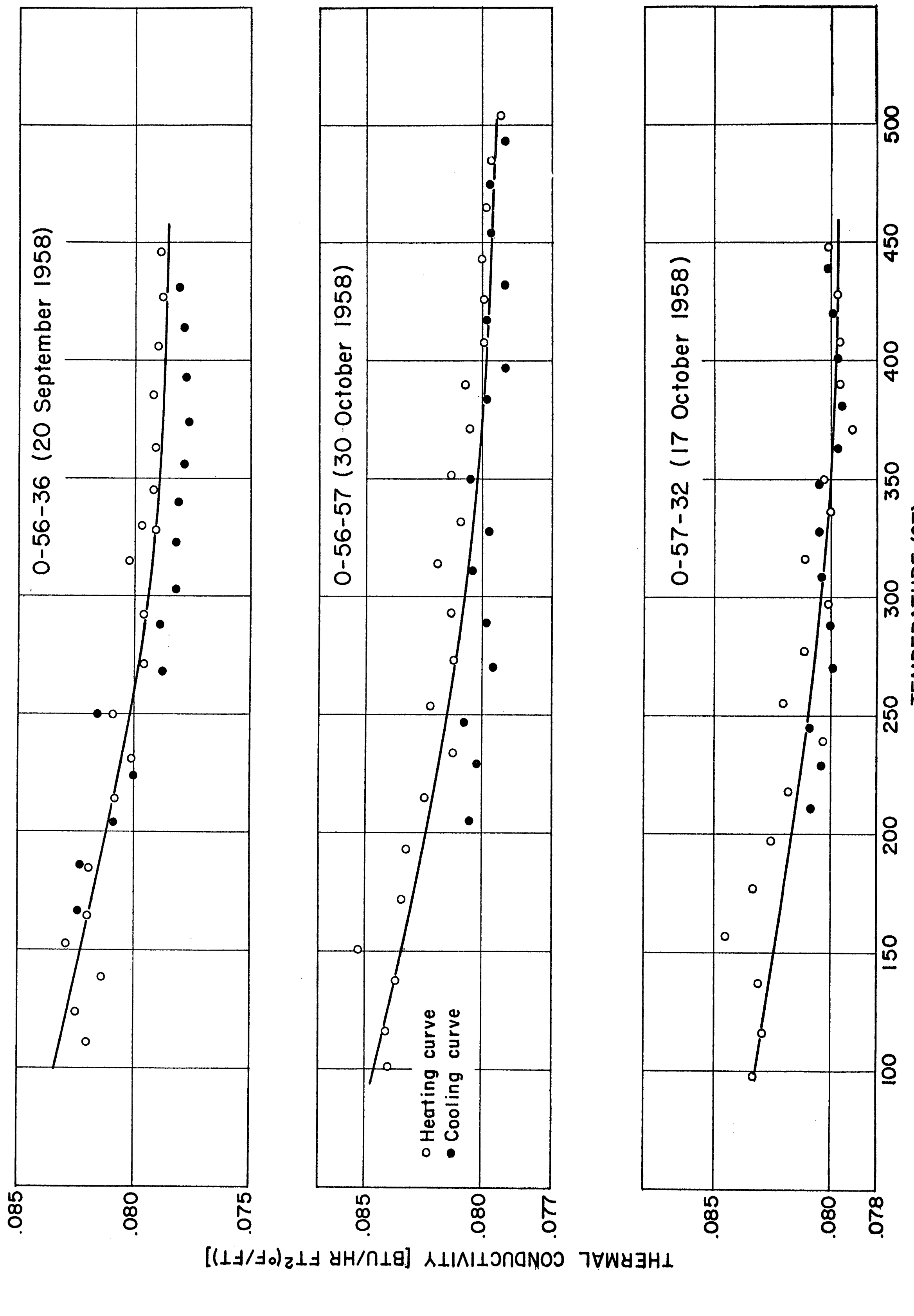

Fig. 6. Thermal conductivity of 0-56-36, 0-56-57, 0-57-32.

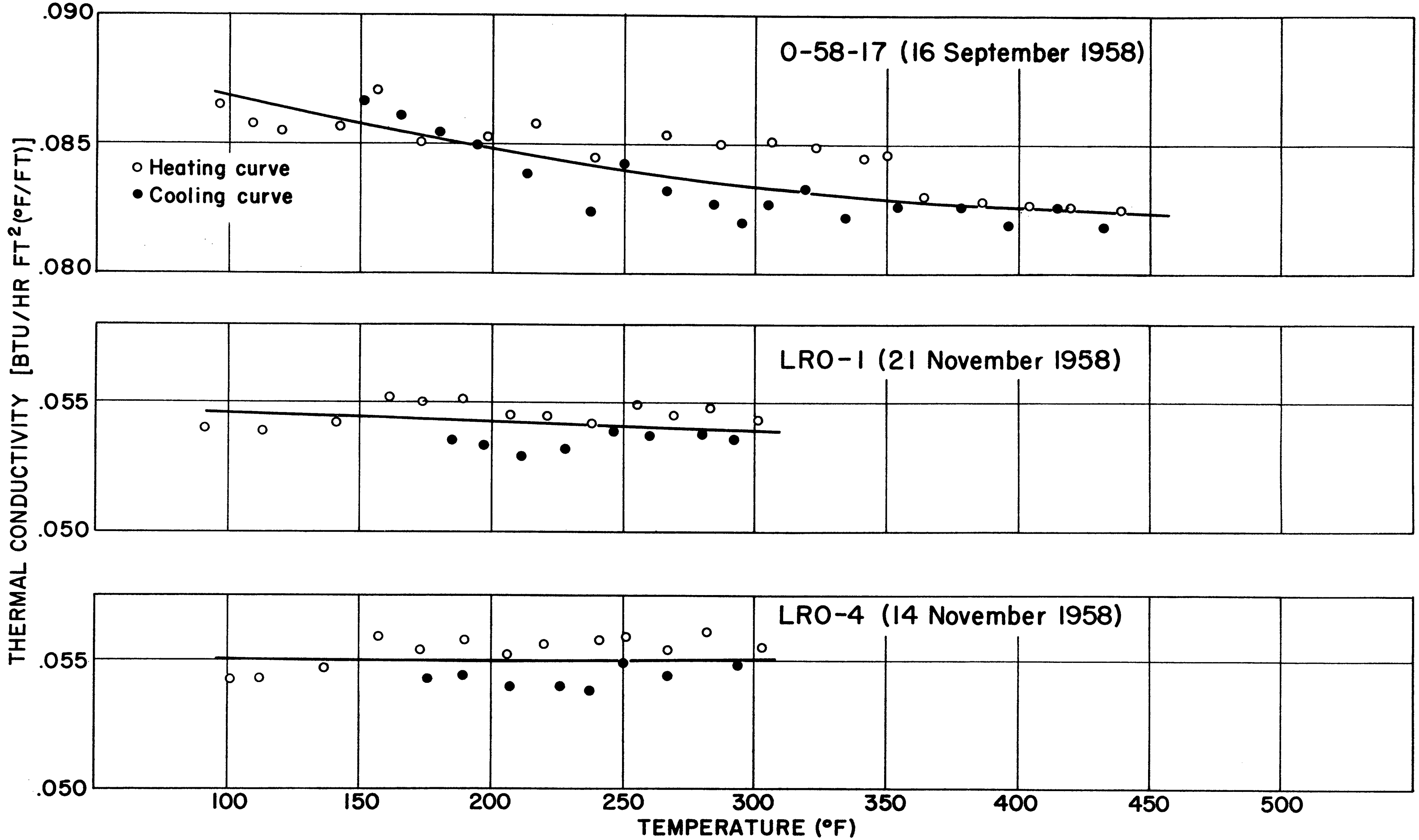

Fig. 7. Thermal conductivity of O-58-17, LRO-1, LRO-4.

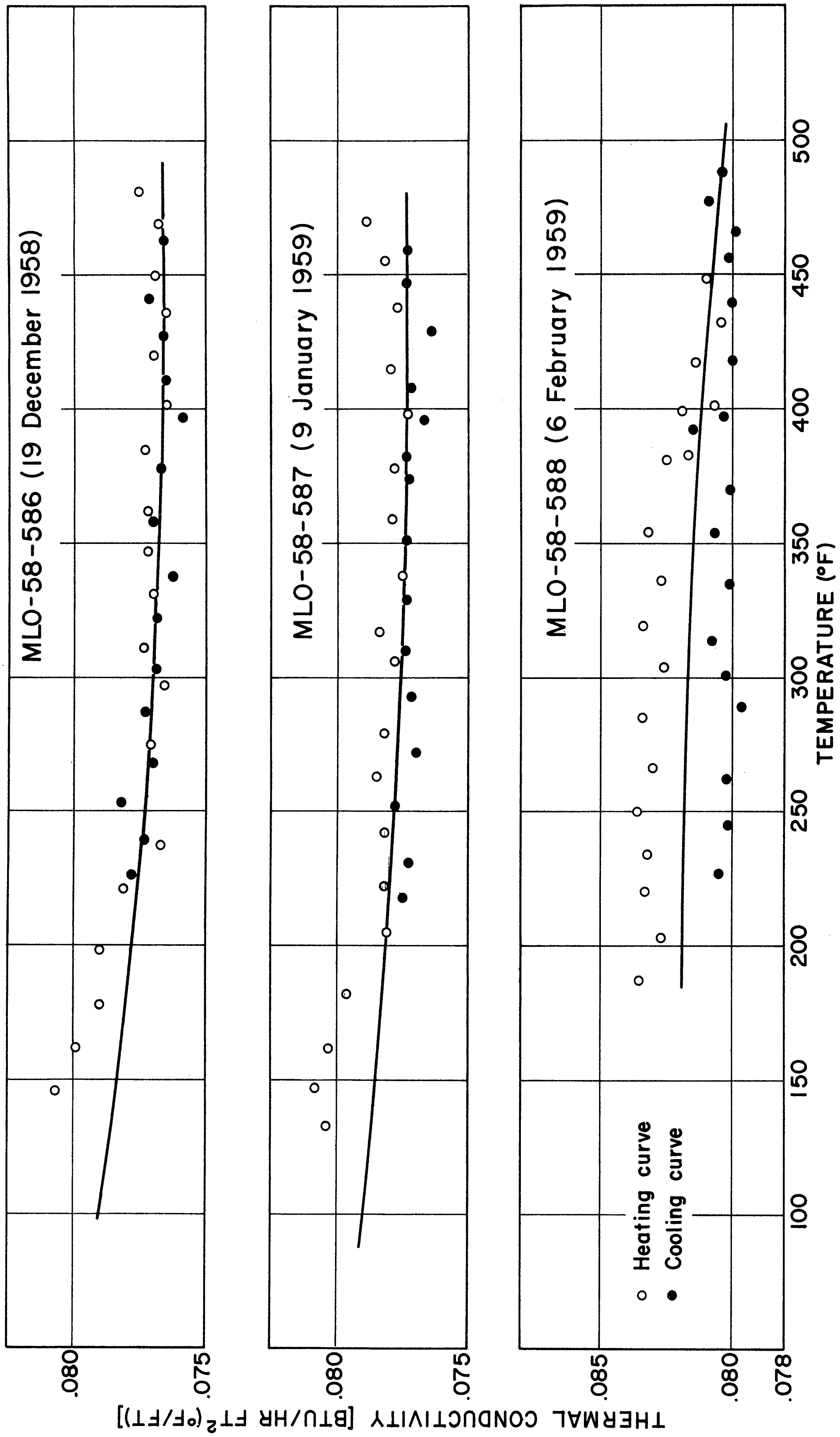

Fig. 8. Thermal conductivity of MLO-58-586, MLO-58-587, MLO-58-588.

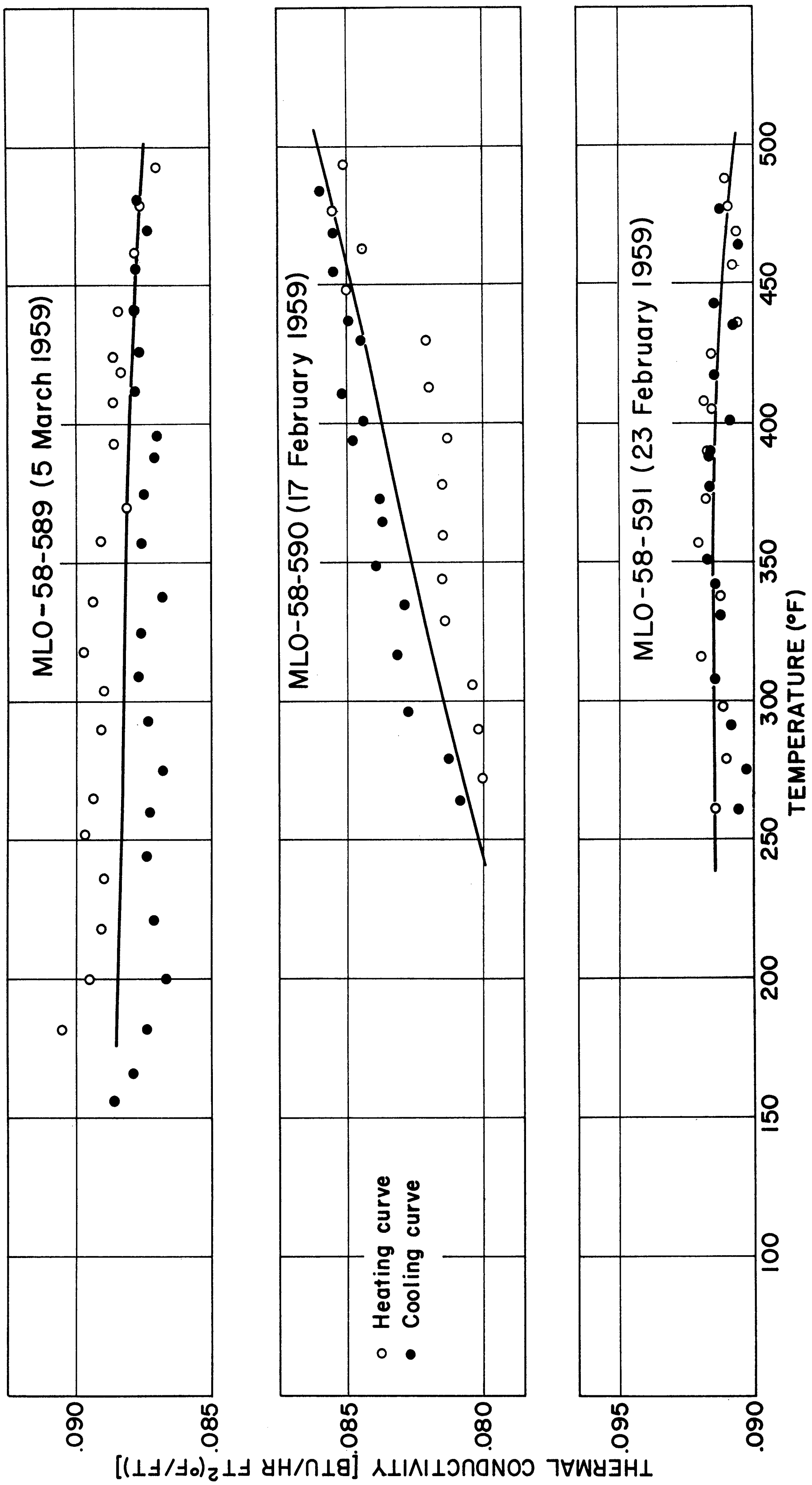

Fig. 9. Thermal conductivity of MLO-58-589, MLO-58-590, MLO-58-591.

TABLE I

THERMAL CONDUCTIVITY AS A FUNCTION OF TEMPERATURE[a]

Fluid	100°F	150°F	200°F	250°F	300°F	350°F	400°F	450°F	500°F
0-56-36	.0834	.0823	.0812	.0802	.0794	.0789	.0787	.0786	---
0-56-57	.0846	.0835	.0824	.0815	.0808	.0802	.0798	.0796	.0794
0-57-32	.0832	.0824	.0817	.0810	.0804	.0800	.0798	.0797	---
0-58-17	.0868	.0858	.0848	.0840	.0834	.0829	.0826	.0824	---
LRO-1	.0546	.0545	.0543	.0541	.0539	---	---	---	---
LRO-4	.0551	.0551	.0550	.0550	.0551	---	---	---	---
MLO-58-586	.0790	.0783	.0778	.0773	.0770	.0768	.0767	.0766	---
MLO-58-587	.0790	.0785	.0781	.0778	.0776	.0774	.0774	.0774	---
MLO-58-588	---	---	.0819	.0818	.0817	.0815	.0812	.0808	.0803
MLO-58-589	---	---	.0885	.0884	.0883	.0882	.0880	.0878	.0875
MLO-58-590	---	---	---	.0801	.0814	.0826	.0837	.0848	.0860
MLO-58-591	---	---	---	.0915	.0915	.0915	.0914	.0912	.0907
Gulfpride[b] 10 Base	.0804	.0800	.0796	.0793	.0790	.0787	.0783	.0780	.0777
Gulfpride[c] 10 Base	.0800	.0793	.0786	.0780	.0775	.0773	.0771	.0771	.0770

(a) Thermal conductivity is reported in [Btu/hr ft² (°F/ft)].
(b) 2 September 1958.
(c) 28 November 1958.

V. CONCLUSIONS

The thermal conductivity apparatus, designed, built, and proven under Contract No. AF 33(616)-3543, was used for measurements on submitted samples of lubricating fluids.

The values of thermal conductivities of the fluids are considered absolute or at least precise in references to a "standard oil."

APPENDIXES

APPENDIX I

STABILITY TEST

The protection of the thermal conductivity cell against corrosive attack of the fluids or vice versa had to be determined. It was proposed that a test be made on all samples by subjecting them to elevated temperatures in contact with copper, the metal of which the cell is constructed. The following test was devised.

A 5/8-in.-ID x 6-in. heavy-walled Pyrex test tube is used. Into it is placed a polished and bent piece of copper sheet about 1 inch square. The test tube is then drawn down to a narrow neck to form an open ampoule about 3 inches long. The fluid sample is carefully pipetted into the ampoule to prevent any oil contacting the glass surface that will be heated in sealing the ampoule. The fluid completely covers the copper; the fluid sample is then deaerated under high vacuum with care being taken to avoid vaporization of the fluid. While under vacuum the ampoule is sealed by fusing the glass at the drawn-down portion. The ampoules are then placed in a controlled temperature oven and observed at intervals. Conditions of this test are considered comparable to the conditions within the calorimeter.

Maximum Temperature to Which the Fluids Are Stable for 20 Hours

0-56-36	450°F	MLO-58-586	500°F
0-56-57	500	MLO-58-587	500
0-57-32	450	MLO-58-588	500
0-58-17	450	MLO-58-589	500
LRO-1	300	MLO-58-590	500
LRO-4	300	MLO-58-591	500
		Gulfpride 10 Base Oil	500

The five fluids which are stable only below 500°F had such doubtful stability that it was felt that they might decompose and do harm to the apparatus if run up to and down from the maximum temperature of 500°F. Permission was granted to limit the determination on the fluids in this group to the maximum temperature determined by the test.

APPENDIX II

OPERATION OF CELL

The thermal conductivity cell is filled by applying a vacuum to the top fill tube, forcing the fluid into the annulus by the pressure of its own vapor from a reservoir at the bottom fill tube. It is felt that this procecure effectively eliminates entrained air.

The cell is regulated by the controller to induce a heating, or cooling, rate of 20°F/hr. (The controller regulates the heating tapes on Sink II.)

There are 16 thermocouples in the cell which are paired across the annulus to measure the temperature differential at 8 locations in the cell. The locations are circularly about the annulus at levels of 1, 2, 3, 4, 5, 6, 7, and 4 inches depth. Only the temperature differentials at levels of 2, 3, 4, 5, 6, and 4 inches are used to calculate the average "k" value for a given set of readings. This is done to prevent errors due to heat losses at the ends of the cell at positions 1 and 7.

An example of the temperature distribution of the thermocouples on a cooling and heating cycle is shown in Table II and Fig. 10. Outside couples are odd-numbered and are located in Sink I; inside couples are even-numbered and are in the central core. Readings are taken at exact one-minute intervals and are repeated approximately every 45 minutes throughout the complete heating and cooling run.

TABLE II

TEMPERATURE DISTRIBUTION OF THERMOCOUPLES

(Gulfpride 10 Base Oil - 28 November 1958)

Thermocouple	Depth (inches)	Heating Cycle emf (millivolts)	Cooling Cycle emf (millivolts)
1*	1	10.5622	9.3653
2*	1	10.8761	9.7095
3	2	10.5738	9.3431
4	2	10.9341	9.7345
5	3	10.5884	9.3288
6	3	10.9544	9.7187
7	4	10.6021	9.3113
8	4	10.9716	9.7043
9	5	10.6221	9.3018
10	5	10.9816	9.6820
11	6	10.6301	9.2815
12	6	11.0040	9.6750
13*	7	10.6260	9.2470
14*	7	11.0010	9.6290
15	4	10.6673	9.2611
16	4	11.0405	9.6611

*Not used in calculations.

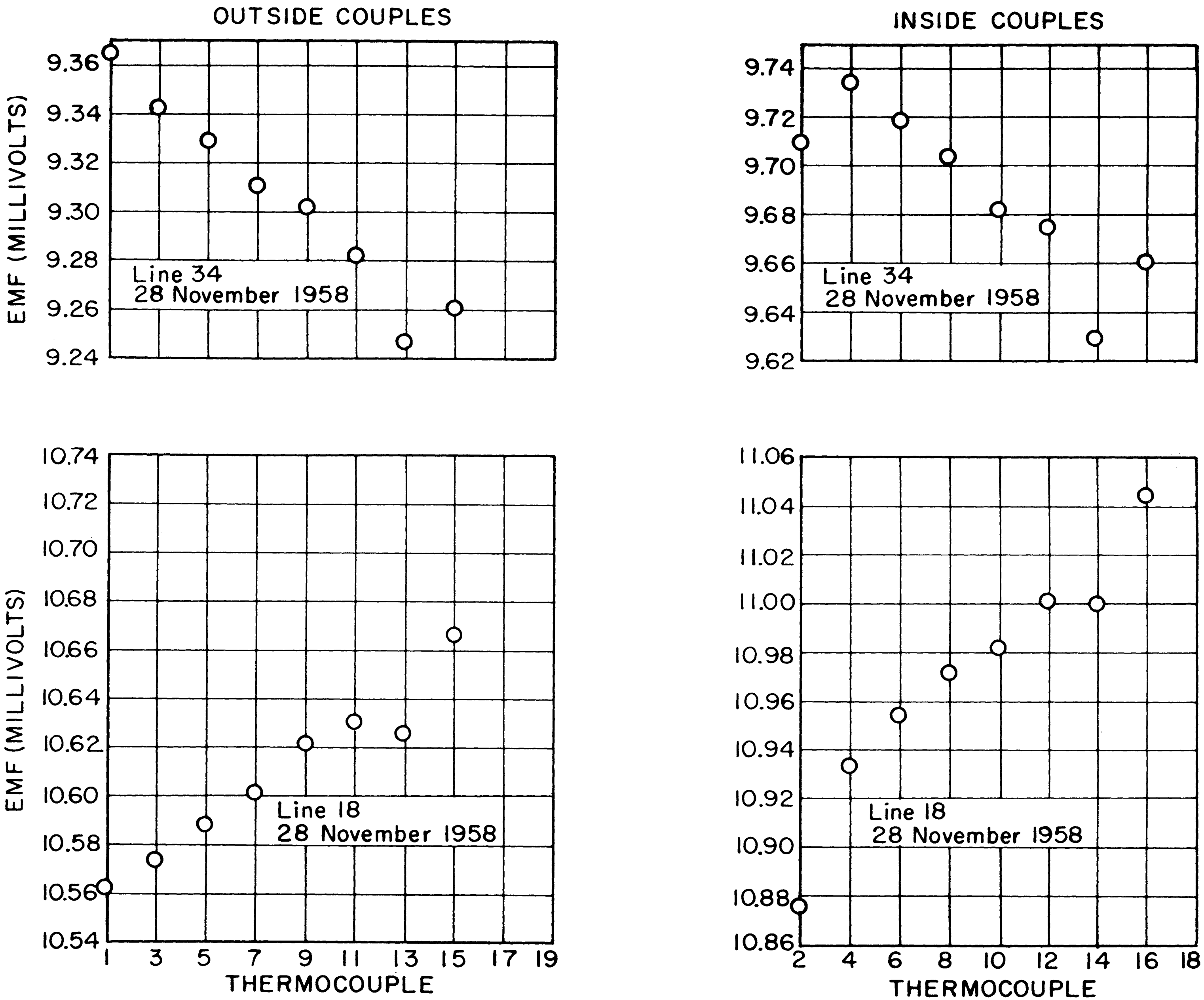

Fig. 10. Temperature distribution in conductivity cell (Gulfpride 10 Base Oil).

APPENDIX III

CALCULATION OF k FROM DATA

NOMENCLATURE

q	=	heat/time, Btu/hr
k	=	heat/time length temp, Btu/hr-ft^2 (°F/ft)
A	=	length^2 normal to flow, ft^2/in.
T	=	temperature, °F
X	=	distance along direction of flow, ft
r_o	=	outside radius of central core, in.
r_1	=	inside radius of Sink I, in.
d_o	=	outside diameter of central core, in.
d_1	=	inside diameter of Sink I, in.
V	=	voltage, volts
I	=	current, amperes
emf	=	emf of thermocouples, millivolts
H.L.	=	heater length, in.

(a) $$q = kA \frac{dT}{dX}$$

Since the annular spacing is only .036 in., ΔX may be used in place of dX. Solving for k, then,

(b) $$k = q \frac{1}{A} \frac{\Delta X}{\Delta T}$$

$$\Delta X = (r_1 - r_o/12)$$

$$A = [\pi(r_1 + r_o)/144]$$

ΔT = [Δemf/.0290 mv/°F] for temperature range* 70°-122°F
[Δemf/.0295 mv/°F] for temperature range 123°-142°F
[Δemf/.0300 mv/°F] for temperature range 143°-239°F
[Δemf/.0305 mv/°F] for temperature range 240°-299°F
[Δemf/.0309 mv/°F] for temperature range 300°-500°F

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*Values approximated from Fig. 11, Δemf/°F vs. temperature for iron-constantan thermocouples. This figure is based on data taken from Ref. 11.

$$q = (VI)\ 3.42\ \frac{Btu/hr}{watt}\ x \left(\frac{1}{H.L.}\right)\ in.^{-1} = VI \left(\frac{3.42}{19.31}\right) \frac{Btu/hr}{in.}$$

$$\therefore k = (VI)\ \frac{3.42}{19.31}\ \frac{144}{\pi}\ \frac{1}{(r_1+r_o)}\ \frac{(r_1-r_o)}{12}\ \frac{1}{\Delta T}$$

noting that:

$$\frac{r_1-r_o}{r_1+r_o} = \frac{d_1-d_o}{d_1+d_o} = \frac{.0362}{1.8072}$$

(c) $$k = \frac{VI}{\Delta T}\ \frac{3.42 \cdot 12 \cdot .0362}{19.31 \cdot \pi \cdot 1.8072} = 1.3551 \cdot 10^{-2} \frac{VI}{\Delta T}$$

The values used for VI are the average values of the beginning and end of a line.

SAMPLE CALCULATION

Data from MLO-58-589 run of 5 March 1959

$$\left.\begin{array}{l} EI \text{ line 13 start} = 66.4890 \\ EI \text{ line 13 end} = 66.3073 \end{array}\right\} EI_{avg} = 66.3982 \text{ watts}$$

Average temperature line 13 = 393°F

Position: 4A line 13

Δemf couples 7 and 8 = 0.3139

$$k = 1.3551 \cdot 10^{-2} \cdot \frac{66.3892}{0.3139} \cdot .0309 = 0.0884\ Btu/hr\text{-}ft^2\ (°F/ft)$$

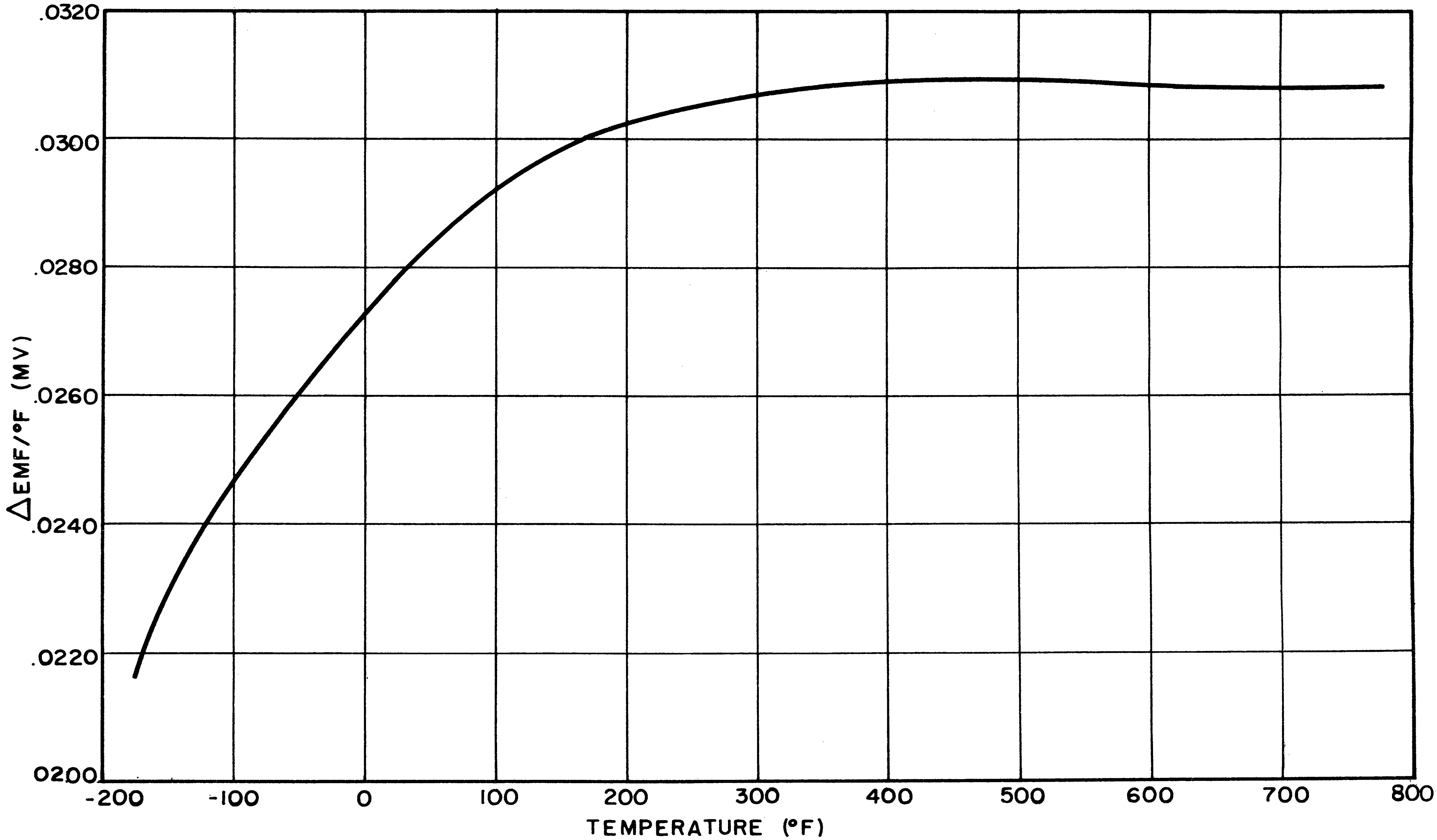

Fig. 11. Δemf/°F vs. temperature for iron-constantan thermocouples.

APPENDIX IV

IDENTIFICATION OF THERMAL CONDUCTIVITY FLUIDS

Sample No.	Identification
0-56-36	Conoco 9372
0-56-57	CRC 156
0-57-32	Richfield L7-52
0-58-17	Shell WRGL 31
LRO-1	Halocarbon 4-11V
LRO-4	Halocarbon A0213
MLO-58-586	Phenyl ether
MLO-58-587	Phenyl ether*
MLO-58-588	1,4 Diphenoxybenzene
MLO-58-589	1,4 Diphenoxybenzene*
MLO-58-590	Bis (ρ-phenoxyphenyl) ether
MLO-58-591	Bis (ρ-phenoxyphenyl) ether*

*Irradiated 10^{11} ergs/gm C.

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The University of Michigan, The University of Michigan Research Institute, Ann Arbor, Michigan. THERMAL CONDUCTIVITY OF LUBRICATING OILS AND HYDRAULIC FLUIDS, by D. W. McCready. May 1959. 26p. incl. illus. tables (UMRI Final Report 2774-1-F; WADC TR 59-185) [Contract AF 33(616)-5745]

Unclassified report

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Thermal conductivity values in the temperature range of from 70 to 500°F are reported for fluids considered stable to the higher temperature. The maximum temperatures for other fluids were limited by their instabilities under test conditions. Since each fluid has individual characteristics, no correlation of conductivity values appears possible. Values are considered precise and for possible correlation can be compared to those of a fluid chosen as a "standard reference."

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