ACCURACY LIFE OF FINE WIRE

CHROMEL-ALUMEL THERMOCOUPLES

by

JAMES PATRICK HARTNETT
B.S., Illinois Institute of Technology
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MASTER OF SCIENCE

at the

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(1948)

Signature of Author..
Department of Mechanical Engineering
May 19, 1948

Certified by...
Thesis Supervisor

....
Chairman, Departmental Committee on Graduate Students

May 21, 1948

Professor Joseph S. Newell
Secretary of the Faculty
Massachusetts Institute of Technology

Dear Sir:

In partial fulfillment of the requirements for the degree of Master of Science from the Massachusetts Institute of Technology, I hereby submit my thesis entitled "Accuracy Life of Fine Wire Chromel-Alumel Thermocouples".

Respectfully yours

Contents

ACKNOWLEDGMENT

The author is greatly indebted to Assistant Professor Warren M. Rohsenow, under whose supervision this thesis was conducted, for the suggestion of the problem, his advice and his criticism.

Object

The object of this research is to correlate the life and accuracy of fine wire Chromel-Alumel thermocouples when subjected to an oxidizing atmosphere at elevated temperatures.

Summary

If a thermocouple is used to measure high gas temperatures it is desirable to use as fine a wire as possible since this reduces the radiation error. Tests were made in an oxidizing atmosphere on three sizes of small diameter Chromel-Alumel thermocouple wire at temperatures ranging from 2000 to 2500 deg. F to determine their useful upper limit. At lower temperatures the fine wire thermocouple comes up to furnace temperature in the manner expected. At higher temperatures an initial deterioration occurs causing the thermocouple to read higher than the furnace temperature which is held constant, and then a further change occurs and the couple indicates a continually decreasing temperature thereby deviating rapidly from the true furnace temperature. If the furnace temperature is increased still further the thermocouple reading at first increases but begins to decrease before it reaches the true furnace temperature.

To correlate life and accuracy of a fine wire thermocouple an "accuracy life" is defined as the length of time the couple indicates the true gas temperature within the limits imposed; for example, a "ten degree F life" is the length of time the couple reads within ten degrees of the true gas temperature. The accuracy life is found to be a function of the wire diameter and the temperature encountered, increasing with increasing diameter and decreasing with increasing temperature.

Introduction

The measurement of high gas temperatures rapidly and accurately is of vital importance in many phases of engineering today. Base metal thermocouples are widely used to measure temperatures up to 2000 deg. F and noble metal thermocouples are used from 2000 to 3000 deg. F. However, when a thermocouple is used to indicate gas stream temperatures, an error is introduced since the measuring junction of the couple "sees" the surrounding walls which are at a temperature different from that of the gas.

If conduction along the thermocouple is neglected the following condition holds at equilibrium for an unshielded thermocouple: the net heat transferred to the thermocouple from the gases by convection and radiation must equal the net heat transferred to the walls by radiation from the couple,

$$Q_{GT} + R_{GT} = R_{TW}$$

where Q is convection heat transfer, R is radiant heat transfer and the subscripts G, T, and W are for gas, thermocouple, and wall, respectively, and where a pair of subscripts reads from -- to; for example, Q_{GT} = convection heat transfer from the gas to the thermocouple.

Neglecting the R_{GT} term since this is negligible as compared with the remaining terms the above equation reduces to

$$h_T (T_G - T_T) = \epsilon_T \sigma (T_T^4 - T_W^4)$$

where the subscripts are as before and,

T = absolute temperature deg. R

h = Film coefficient of heat transfer $\frac{\text{Btu}}{(\text{hr ft}^2 \text{ deg. F})}$

σ = $0.1723 \times 10^{-8} \frac{\text{Btu}}{\text{ft}^2 \text{ hr (deg. R)}^4}$, Stefan-Boltzmann constant

ϵ = emissivity

Since radiation is proportional to the fourth power of the absolute temperature, the radiant heat transfer will be large at high temperatures if the wall temperature differs very much from that of the gas. This can be seen in Fig. 1 in the appendix. An error of 500 deg. F may exist in the reading of an unshielded thermocouple. Methods have been suggested for eliminating this error. A few of these methods will be discussed briefly.

Methods of Eliminating Radiation Error

1) Bare Thermocouple with Calculated Correction

W.M. Rohsenow (1)* has presented a graphical method for finding the correction to be applied to bare thermocouple readings. The evaluation, however, is only approximate and rather tedious.

2) Multishield Thermocouple

Emmons (2) has found theoretically and experimentally that a thermocouple with eight concentric polished metal shields reads within five degrees of the true gas temperature of 1500 deg. F when the pipe wall temperature is 200 deg. F

*Numbers in parentheses refer to the Bibliography in the appendix.

lower than the gas stream.

However, multishielded couples are clumsy to handle and the hazard of mechanical failure exists, thereby endangering any rotating machinery which might be present.

3) Single-Shielded Thermocouple with Calculated Correction

The correction to be applied to a single-shielded couple is smaller than that of a bare thermocouple and this correction has been determined by W.M. Rohsenow and J.P. Hunsaker (3), who present a graphical method for the rapid determination of the error.

4) Rotating Thermocouples

It has been suggested that the use of a thermocouple rapidly rotated by a motor will increase the convection heat transfer, thereby increasing the accuracy of the thermocouple readings. The method, however, is not of much practical value.

5) High Velocity Thermocouple

In the high-velocity thermocouple a flow of gases over the measuring junction is forced by an aspirator pump of some sort. However, high-velocity brings into play another temperature error since the conversion of kinetic energy as the stream is partially stopped by the thermocouple affects the temperature reading. The problem of temperature measurement in high-velocity air streams has been studied by Hottel and Kalitinsky (4).

6) Covering of Low Emissivity

It is possible to cover the hot junction of a thermocouple with a material having a low emissivity which, while not affecting the convection heat transfer to the thermocouple, does decrease the radiation to the wall. Therefore the thermocouple reads closer to the true gas temperature.

7) Small Diameter Thermocouple

The radiation error of a thermocouple decreases as the size of the wire decreases and theoretically a thermocouple wire of zero diameter would give the true gas temperature. The effect of decreasing the thermocouple diameter can be seen in Fig. 1 in the appendix.

A combination of the last two possibilities mentioned might prove very desirable for the measurement of high temperatures. A fine wire thermocouple with a coating of low emissivity might be introduced into the gas stream and the temperature read before the coating and the couple deteriorate, the working life of the combination being very short.

Stability and Life of Base Metal Thermocouples

A.I. Dahl (5) found that Chromel-Alumel and iron-constantan thermocouples, when subjected to ordinary service in an oxidizing atmosphere, experience a change in their thermoelectric properties which renders them inaccurate for high precision work. These changes in the thermoelectric characteristics are gradual and accumulative, and depend upon such factors as the temperature encountered, type and size of the thermocouple, length of time in service, and the atmosphere surrounding the couple.

Dahl worked with No. 8, No. 18 and No. 22 gage Chromel-Alumel wire. Measurements of the thermal emfs of the three gages, as received, were made at various temperatures from 0 to 1600 deg. F in increments of 200 deg. F. The thermocouples were then placed in a furnace at 1600 deg. F for a specified number of hours, then removed and the emfs rechecked at the various temperatures from 0 to 1600 deg. F. He found an increase of emf at each temperature as the length of time the couple was subjected to the 1600 deg. F oven was increased. Therefore long time exposure of a Chromel-Alumel wire to high temperatures causes the emf corresponding to a given temperature to increase.

In tests with No. 8 gage Chromel-Alumel wire Dahl found that failure occurred in 300 hours when the couple was subjected to 2200 deg. F. At 2000 deg. F the thermocouple had oxidized considerably. At test below 1600 deg. F, the wire was relatively unaffected by oxidization.

Description of Apparatus

To obtain the high temperatures desired the furnace was formed of two Kaolin (K-30) insulating bricks. A cavity approximately 2-1/4 inches wide by 4 inches long by 3/4 inches deep was made in the center of the large face of each of the two K-30 insulating bricks. These were then placed together, cavity to cavity, forming a rectangular furnace. Four Glo-Bars were then used in the furnace, running lengthwise through the furnace cavity and protruding about 2 inches through the furnace walls on each side. The holes in the walls through which the Glo-Bars ran were made tight-fitting so that the heat loss would be small. More insulating bricks were placed around the central portion to further reduce the heat loss, thereby decreasing necessary power input. A picture of the furnace assembly can be seen in Fig. 21.

After the furnace assembly had been completed a small hole was made in the center of each side of the furnace so a thermocouple could then be inserted into the heated cavity from either side.

The four Glo-Bar elements were connected in series to a 230 volt source and a hand operated voltage regulator was used to regulate the temperature. An ammeter was also placed in the line.

Materials Tested

Three sizes of Chromel-Alumel wire were tested; 30, 32, and 35 gage. A platinum-platinum 10% rhodium thermocouple was used as the standard against which the Chromel-Alumel couples were checked.

An accurate potentiometer was used to measure the emf output of the various couples.

The Chromel-Alumel thermocouples were welded on a standard arc welder.

Test Methods

Both the standard platinum-platinum 10% rhodium couple and the Chromel-Alumel thermocouple under test were insulated by a 2 hole porcelain insulator and the measuring junction protruded about 1/4 inch beyond the protection tubing. The measuring junction without protection was exposed to the high furnace temperature. The reference junction of all thermocouples were maintained at 32 deg. F during the measurements.

The furnace was turned on and allowed to come to equilibrium at the desired temperature level between 2000 deg. F and 2500 deg. F. The platinum couple was inserted into the chamber through one of the holes provided in the side of the furnace and the measuring junction placed at a point equidistant from each Glo-Bar. Equilibrium was attained when no further change in the emf output of the platinum was observed. When equilibrium was reached the platinum couple was left in place and the Chromel-Alumel wire was placed as near as possible to the measuring junction of the platinum. A timer was started at the instant the Chromel-Alumel thermocouple was inserted in the furnace and a record of emf versus time was taken. Throughout the run checks were also made on the platinum couple to determine any change in the furnace temperature. Runs of twenty minutes were taken.

After each run approximately six inches of Chromel and Alumel wire were removed from the measuring junction of the Chromel-Alumel thermocouple and a new joint welded using an ordinary arc welder. The ends to be welded were twisted together and brought slowly into the region of the arc and removed quickly when a small bead formed, being careful not to burn the thermocouple which would cause the emf temperature relation to change.

This testing procedure was followed for the 30, 32, and 35 gage thermocouples at various temperatures ranging from 2000 deg. F to 2500 deg. F.

The platinum-platinum 10% rhodium thermocouple and the three size Chromel-Alumel thermocouples were checked at the steam point, the sulfur point, and the copper point and a calibration curve drawn plotting deviation from standard emf against observed emf. No other pure metals were obtainable above the sulfur point so a straight line is drawn from the sulfur extending through the copper point. The calibration curves are shown in Figs. 19 and 20.

Results

Figures 6 through 17 show the results of the data that were taken during the test runs. In each of these figures a pair of similar lines represent the temperature as indicated by the Chromel-Alumel couple being tested. These figures indicate a change in the thermoelectric properties as the temperature level changes. At the lower temperatures

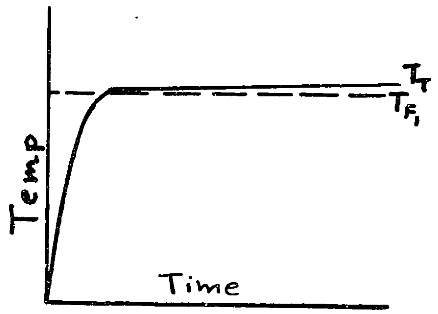


Diagram 1

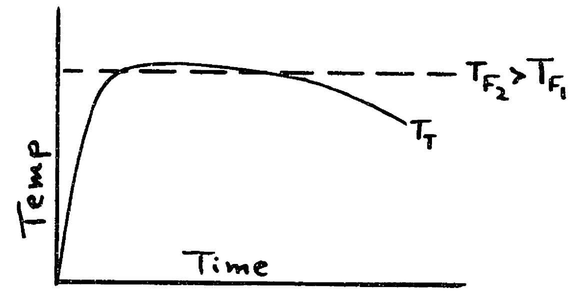


Diagram 2

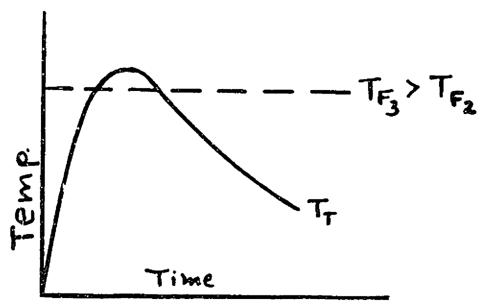


Diagram 3

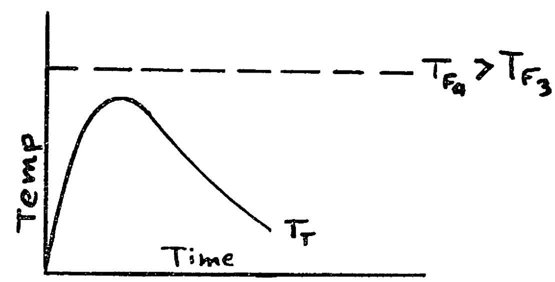


Diagram 4

the thermocouple comes up to temperature in the expected manner, as shown in Diagram 1 above. Dahl (5) found that a gradual increase in emf occurs for this case. As the furnace temperature is increased, Diagram 2 shows the thermocouple reading increasing slightly above furnace temperature and after a short time decreasing below furnace temperature.

At still higher temperatures Diagram 3 shows thermocouple reading rise over the furnace temperature and then suddenly drop. Then finally Diagram 4 shows the effect of still higher furnace temperatures where the thermocouple reading never reaches the actual temperature. Figure 18 shows the results of actual test runs as a 30 gage Chromel-Alumel couple is subjected to various furnace temperatures.

To determine a working useful life for a thermocouple an "accuracy life" may be defined as the length of time a thermocouple reads the true furnace temperature with the required accuracy; for example, a "10 deg. F life" is the length of time a thermocouple reads within ten degrees of the furnace temperature. Similarly a "20 deg. F life" or "30 deg. F life" can be determined. With this definition the 10 deg. F life versus temperature curves of Figs. 1-3 were obtained from Figs. 5-17. In all cases the furnace temperature was taken to be that indicated by the platinum-platinum 10% rhodium couple. From these plots it can be seen that the 10 deg. F life of the thermocouples drops off very rapidly at high temperature. From Fig. 2, the 30 gage Chromel-Alumel couple shows long life at 2100 deg. F and falls off to zero life at 2550 deg. F. The 32 gage couple shows a life of more than 20 minutes at 2000 deg. F and then decreases to zero life at 2440 deg. F as shown in Fig. 3. The little data available on the 35 gage Chromel-Alumel wire (Fig. 4) seems to indicate that long life can be expected only at temperatures below 1900 deg. F and zero life occurs at 2350 deg. F.

Figure 5 shows a composite of Figs. 2-4. From this curve the effect of wire diameter on the accuracy life may be seen. Increasing the wire diameter shifts the curve over to the right so that for a particular temperature a greater 10 deg. F life can be expected.

Discussion of Results

The changes in the thermoelectric characteristics of the Chromel-Alumel thermocouples at the higher temperature levels encountered are probably due to the effect noted by A. I. Dahl (5). Dahl, working with comparatively large Chromel-Alumel wires (Nos. 8, 18, and 22 gage) and fairly low temperatures (a maximum of 1600 deg. F for the 18 and 22 gage and a maximum of 2200 deg. F for the 8 gage wire), in an oxidizing atmosphere found that the emf corresponding to a given temperature increased if the couples were exposed to the above-stated temperatures for a long period of time. The results obtained in the tests for this paper indicate that a decrease in thermocouple diameter and an increase in furnace temperature accelerate this effect, causing it to occur in a matter of minutes or seconds, rather than in hours. However, a further deterioration of a different nature occurs and the emf decreases rapidly. This decrease probably occurs in the larger wires and at lower temperature, but only after a very great period of time.

The problem of determining the accuracy life is a statistical one, and therefore requires that a great many tests be made. Since only a limited amount of data was obtained for this paper the results as given should be taken as qualitative, since further research may modify them. It is believed however that the shape of the curves and their relative positions are correct.

The main sources of inaccuracy are in the placing of the Chromel-Alumel couple in the furnace and in the thermocouple calibration curves. The type of furnace was such that a variation of 15 deg. F existed when the platinum thermocouple was moved 1/2 inch. However care was taken to place the Chromel-Alumel couple as close as possible to the platinum-platinum 10% rhodium couple so that this error is probably small. The error introduced in the calibration curves is probably not too great since one calibration point was obtained in the range where the tests were made.

The runs were made in still air and, therefore, in an oxidizing atmosphere. On removing the Chromel-Alumel couples from the furnace at the conclusion of a run the wires were found to be oxidized completely for quite some distance from the measuring junction. In fact if care were not exercised the measuring junction would drop off while the couple was being removed after a test run. Tapping the end of the thermocouple after it had been exposed for a few minutes at the higher temperatures also caused the measuring junction to drop off. It was necessary therefore to remove a considerable portion of the thermocouple after each run. Other than exercising these precautions the three sizes of Chromel-Alumel wire were very easy to handle.

Modification of Technique

1) To allow accurate and sufficient data to be taken as the Chromel-Alumel thermocouple is placed into the furnace a high speed recording potentiometer should be used. This would allow one man to do the job thoroughly. During the runs for this paper, it was necessary to have two persons present since data were desired at the very beginning of the run.

2) To cut down unwanted temperature gradients an Alundum tube wound with a platinum-rhodium wire resistance type heater could be used.

3) The platinum-platinum 10% rhodium and Chromel-Alumel thermocouples could be welded together thereby insuring their being subjected to the same temperature.

4) Obtain samples of more pure metals with freezing point between 1000 - 2500 deg. F in order that more accurate calibration curves may be determined.

Suggestions for Future Research

1) In addition to the Chromel and Alumel wires used, introduce a third wire, platinum. Weld the three together to form the measuring junction, thereby forming three possible thermocouple combinations, the Chromel-Alumel, Chromel-platinum, and Alumel-platinum so that in addition to finding the thermoelectric changes of the Chromel-Alumel combination, the changes of the individual Chromel and Alumel wires may also be obtained.

2) The atmosphere of the furnace could be changed to a reducing atmosphere, and the effects of such an atmosphere noted on the life and accuracy of the Chromel-Alumel couple.

3) The effect of velocity on the life and accuracy of the Chromel-Alumel couple could also be investigated.

APPENDIX

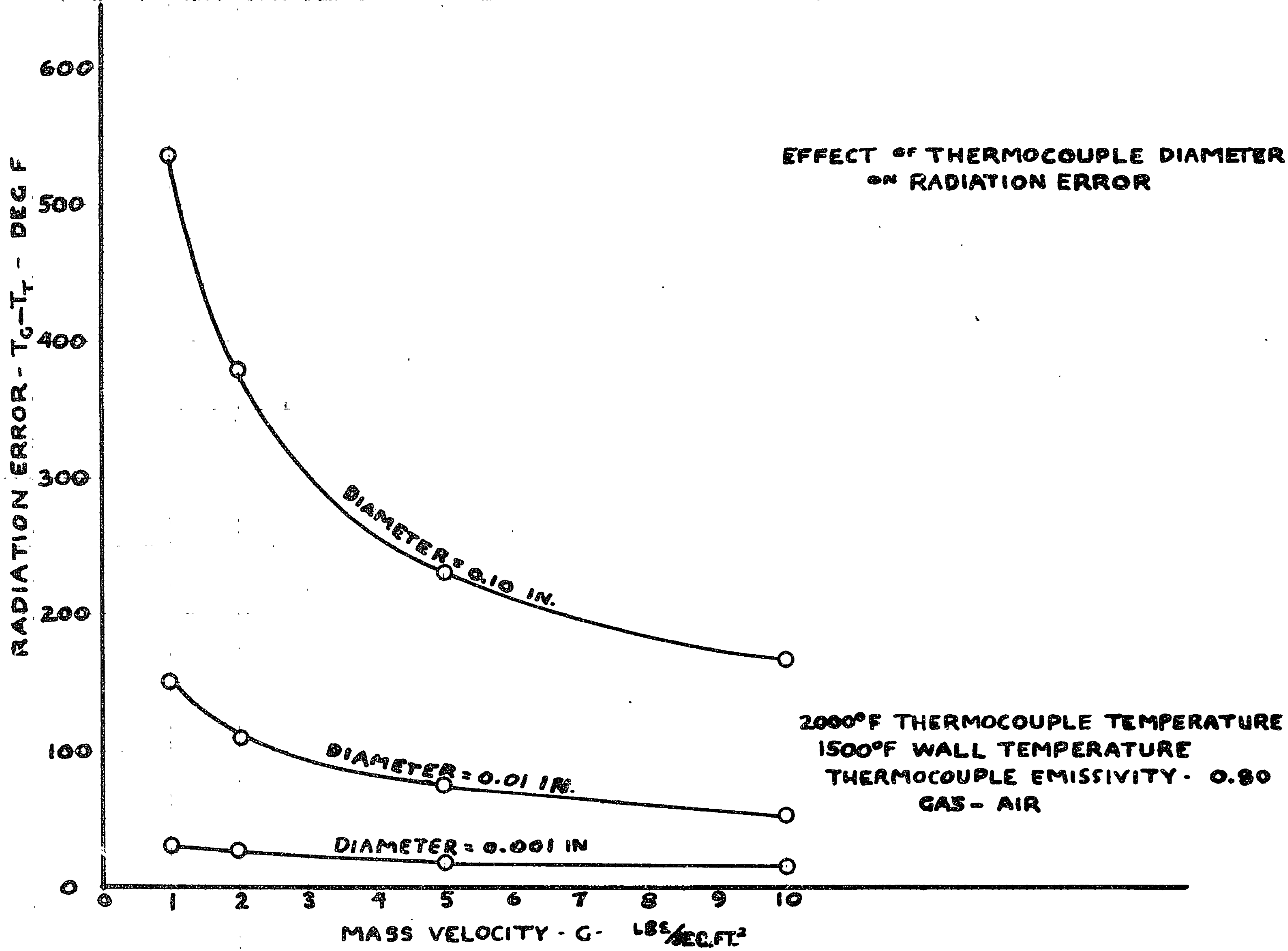

EFFECT OF THERMOCOUPLE DIAMETER
ON RADIATION ERROR
2000°F THERMOCOUPLE TEMPERATURE
1500°F WALL TEMPERATURE
THERMOCOUPLE EMISSIVITY - 0.80
GAS - AIR
RADIATION ERROR - $T_G - T_T$ - DEG F
MASS VELOCITY - G - LBS/SEC.FT.²
DIAMETER = 0.10 IN.
DIAMETER = 0.01 IN.
DIAMETER = 0.001 IN
0
100
200
300
400
500
600
1
2
3
4
5
6
7
8
9
10

FIG. 1

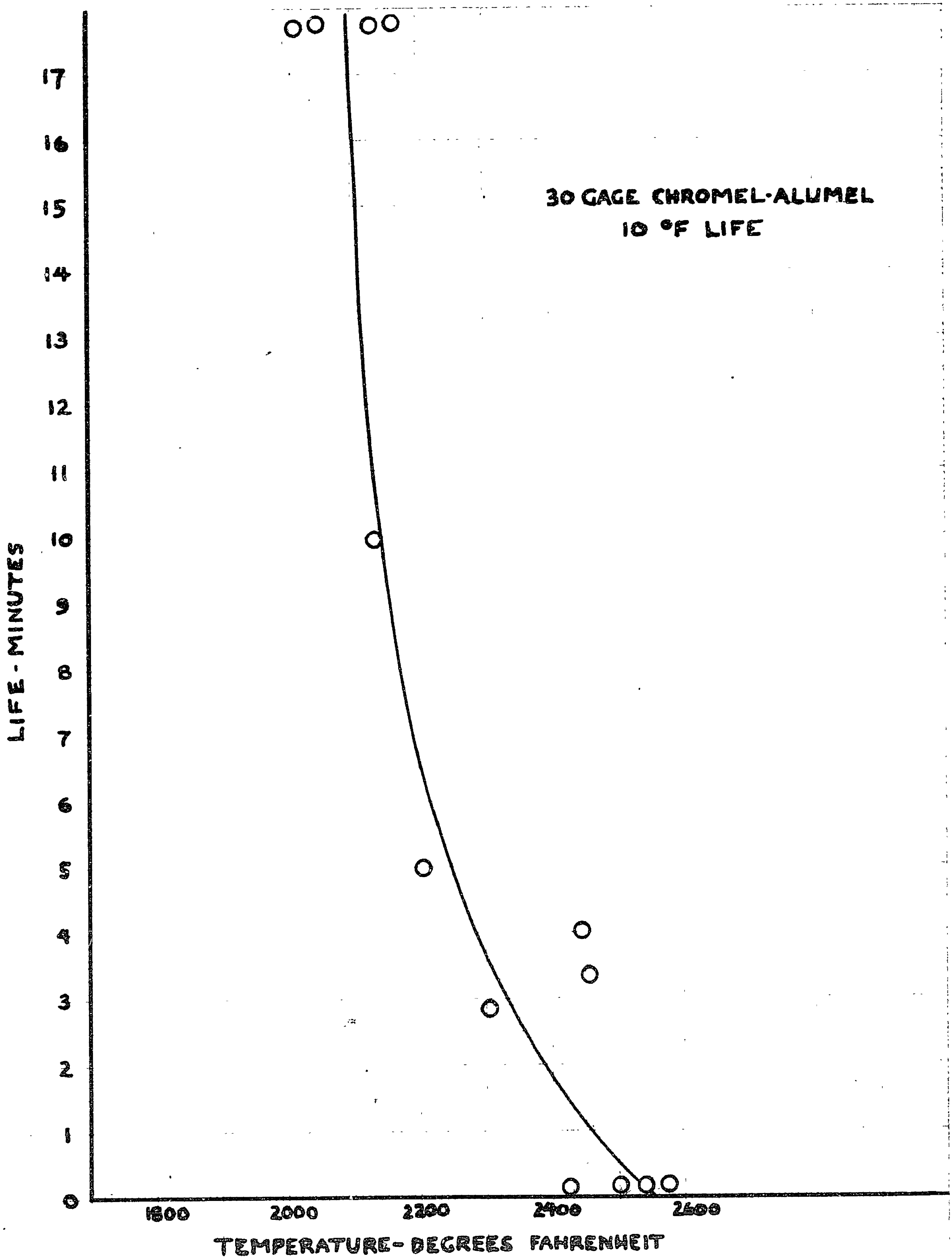
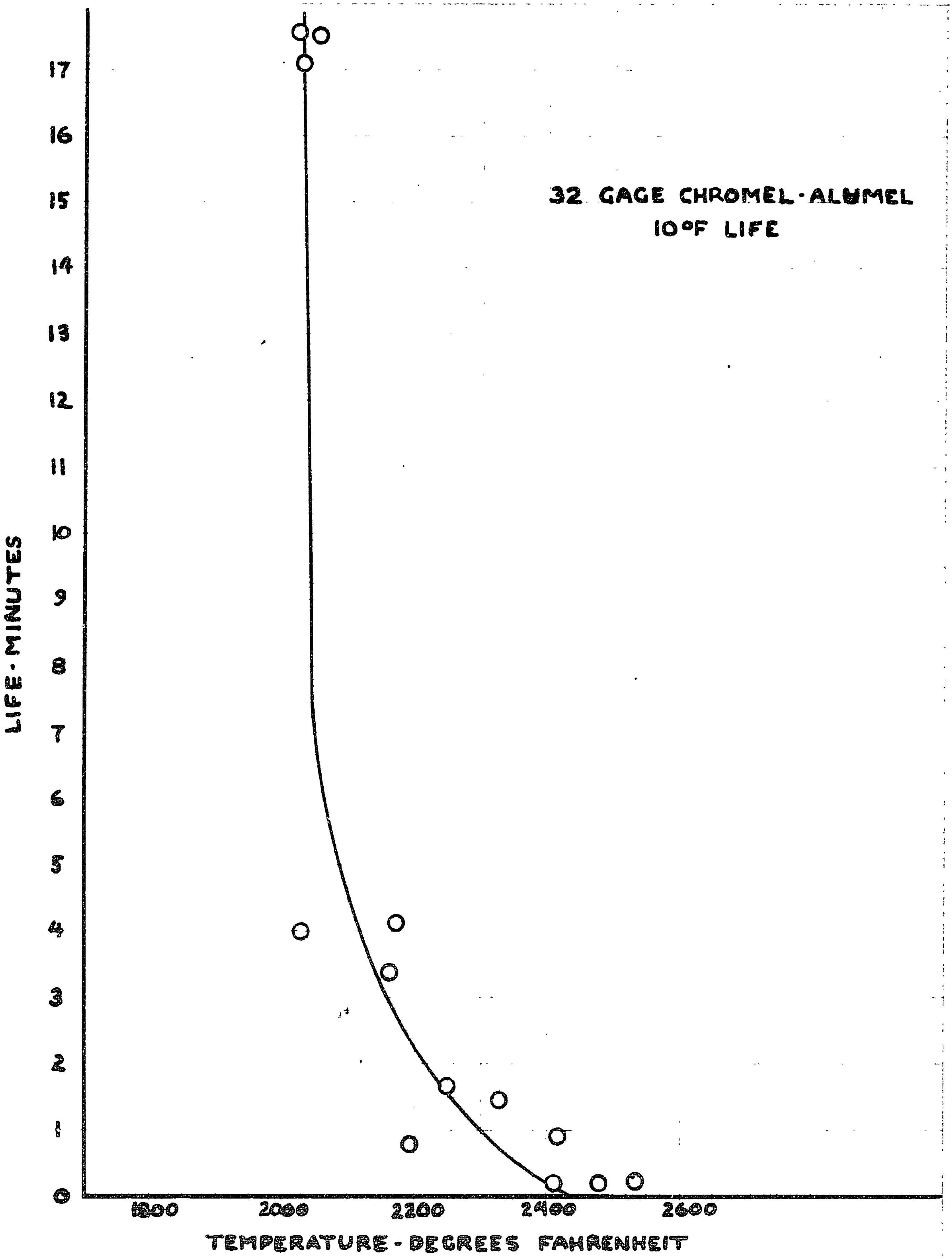

30 GAGE CHROMEL-ALUMEL
10 °F LIFE
LIFE - MINUTES
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
1800
2000
2200
2400
2600
TEMPERATURE - DEGREES FAHRENHEIT

FIG. 2



32 GAGE CHROMEL-ALUMEL
10°F LIFE
LIFE-MINUTES
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
1800
2000
2200
2400
2600
TEMPERATURE-DEGREES FAHRENHEIT

FIG. 3

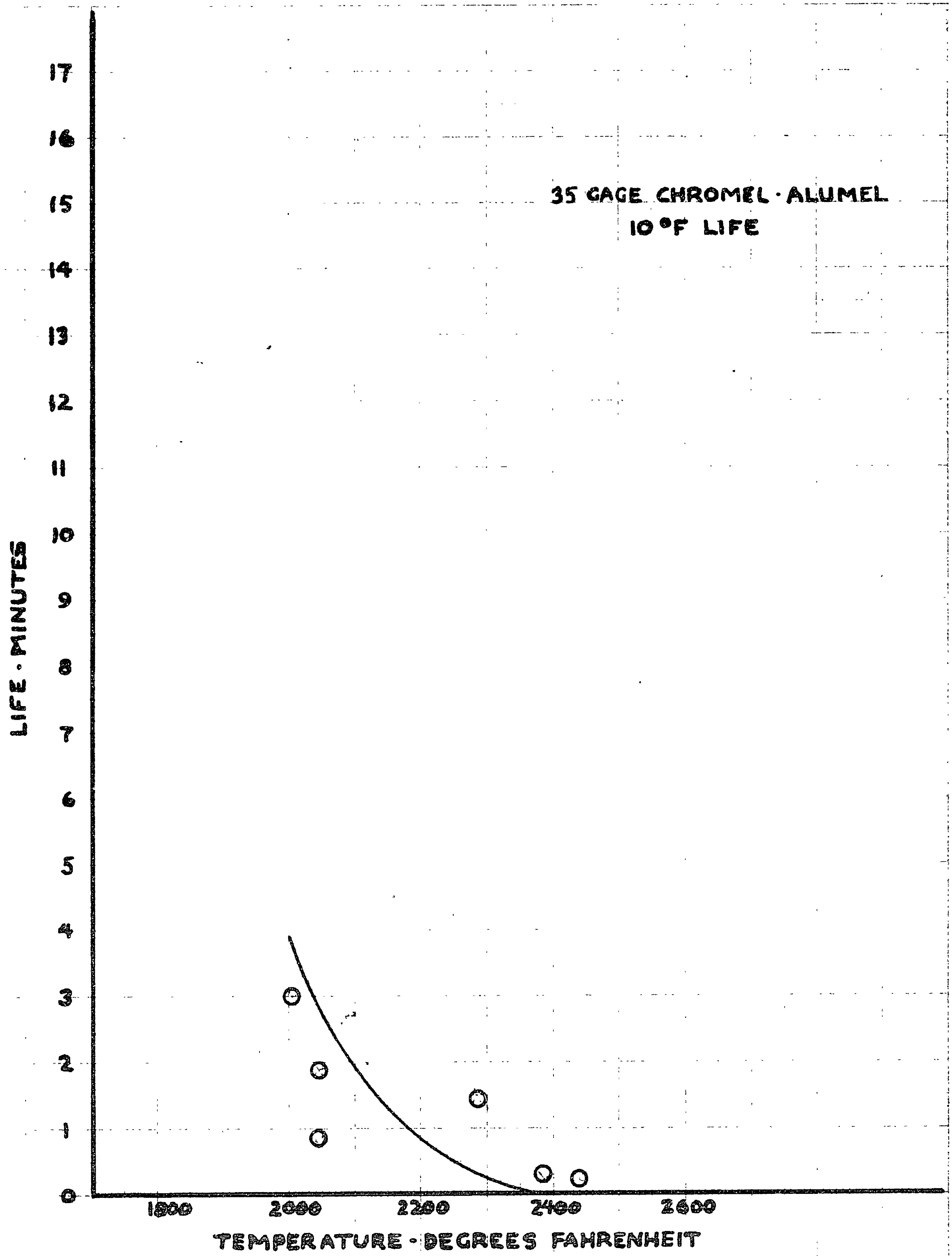

35 GAGE CHROMEL · ALUMEL
10 °F LIFE
LIFE · MINUTES
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
1800
2000
2200
2400
2600
TEMPERATURE · DEGREES FAHRENHEIT

FIG. 4

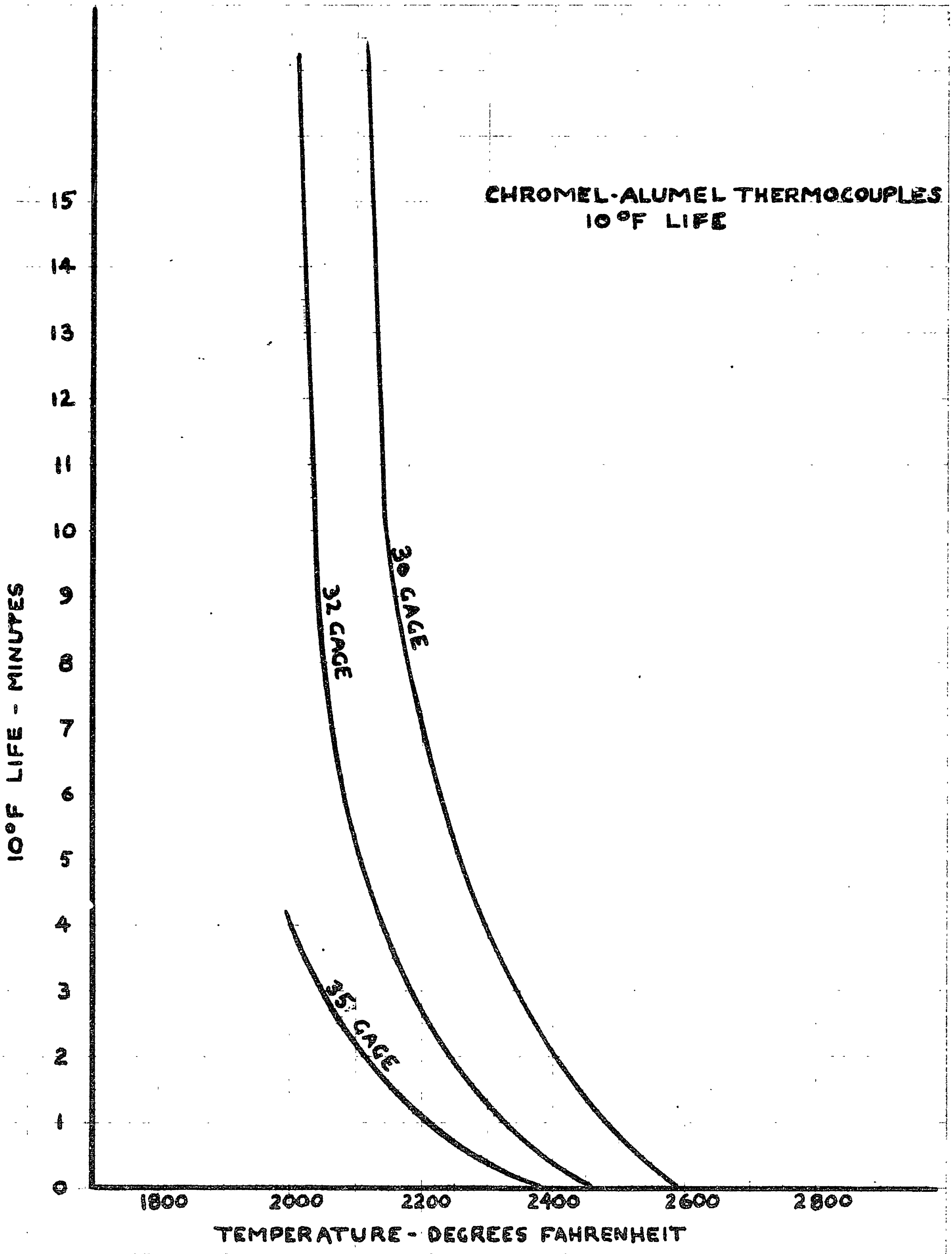

CHROMEL-ALUMEL THERMOCOUPLES
10°F LIFE
10°F LIFE - MINUTES
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
1800
2000
2200
2400
2600
2800
TEMPERATURE - DEGREES FAHRENHEIT
30 GAGE
32 GAGE
35 GAGE

FIG. 5

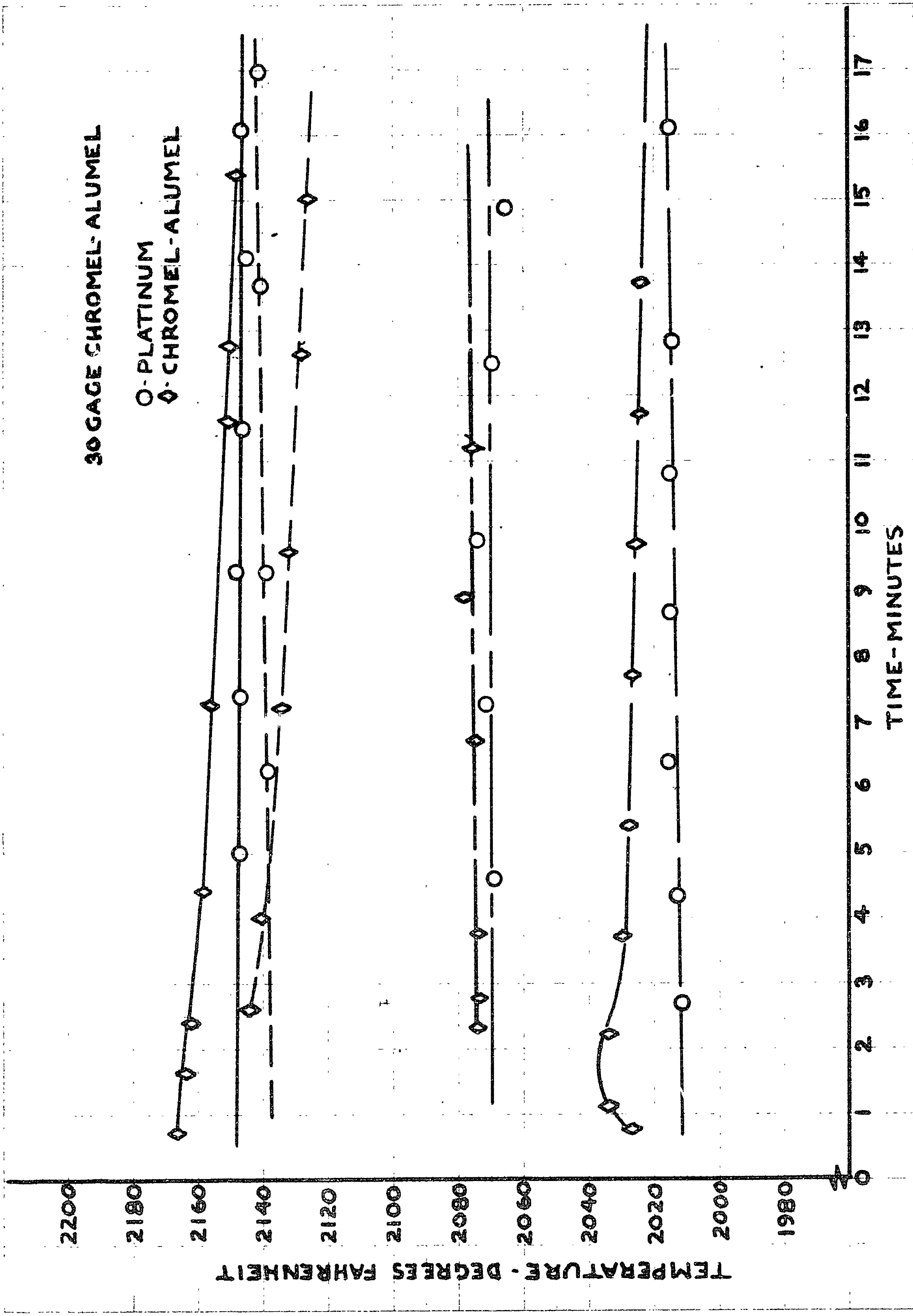

30 GAGE CHROMEL-ALUMEL
O - PLATINUM
◊ - CHROMEL-ALUMEL
TEMPERATURE - DEGREES FAHRENHEIT
2200
2180
2160
2140
2120
2100
2080
2060
2040
2020
2000
1980
TIME-MINUTES
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17

FIG 6

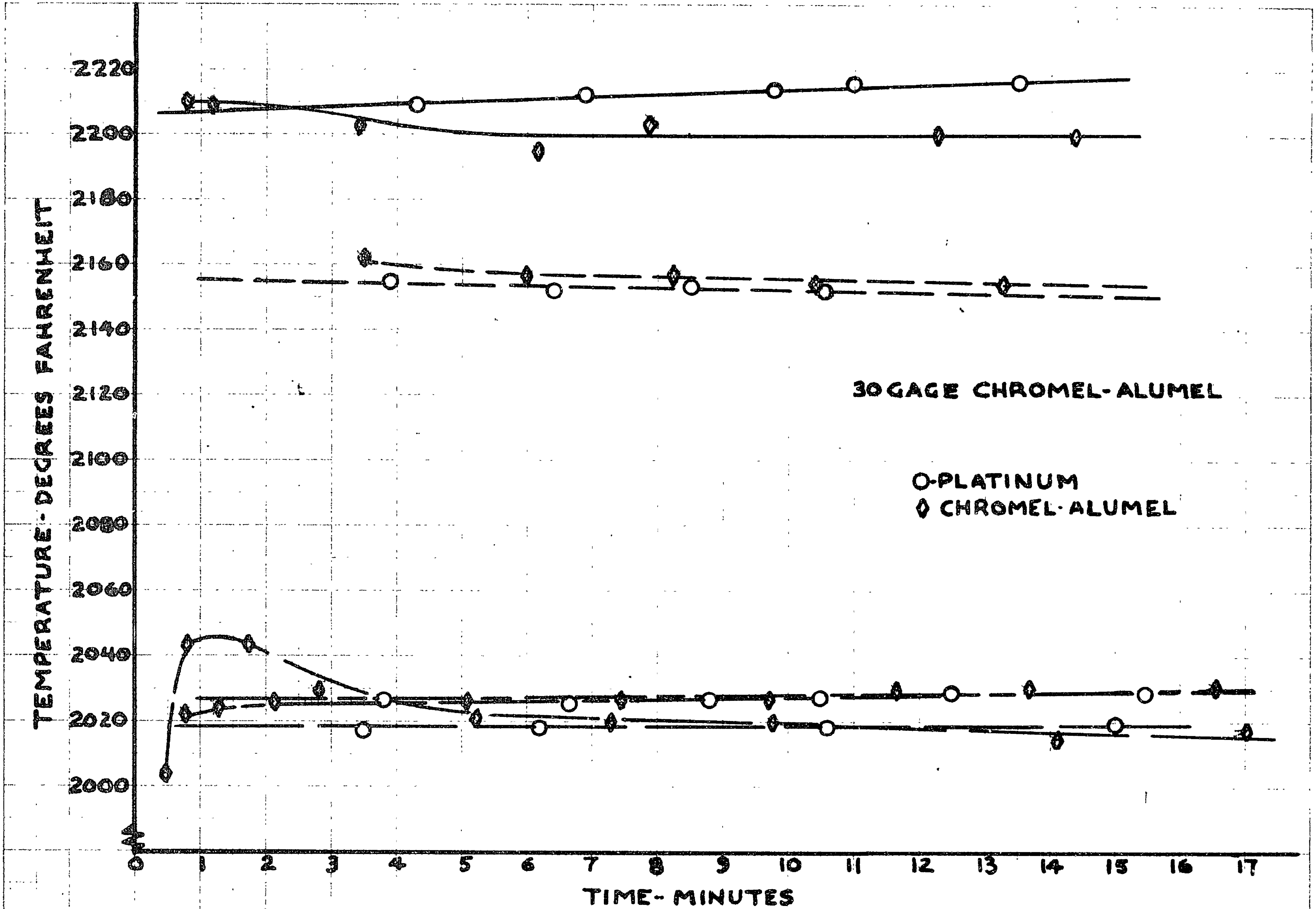

30 GAGE CHROMEL-ALUMEL
O-PLATINUM
◊ CHROMEL-ALUMEL
TEMPERATURE - DEGREES FAHRENHEIT
2220
2200
2180
2160
2140
2120
2100
2080
2060
2040
2020
2000
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
TIME - MINUTES

FIG. 7

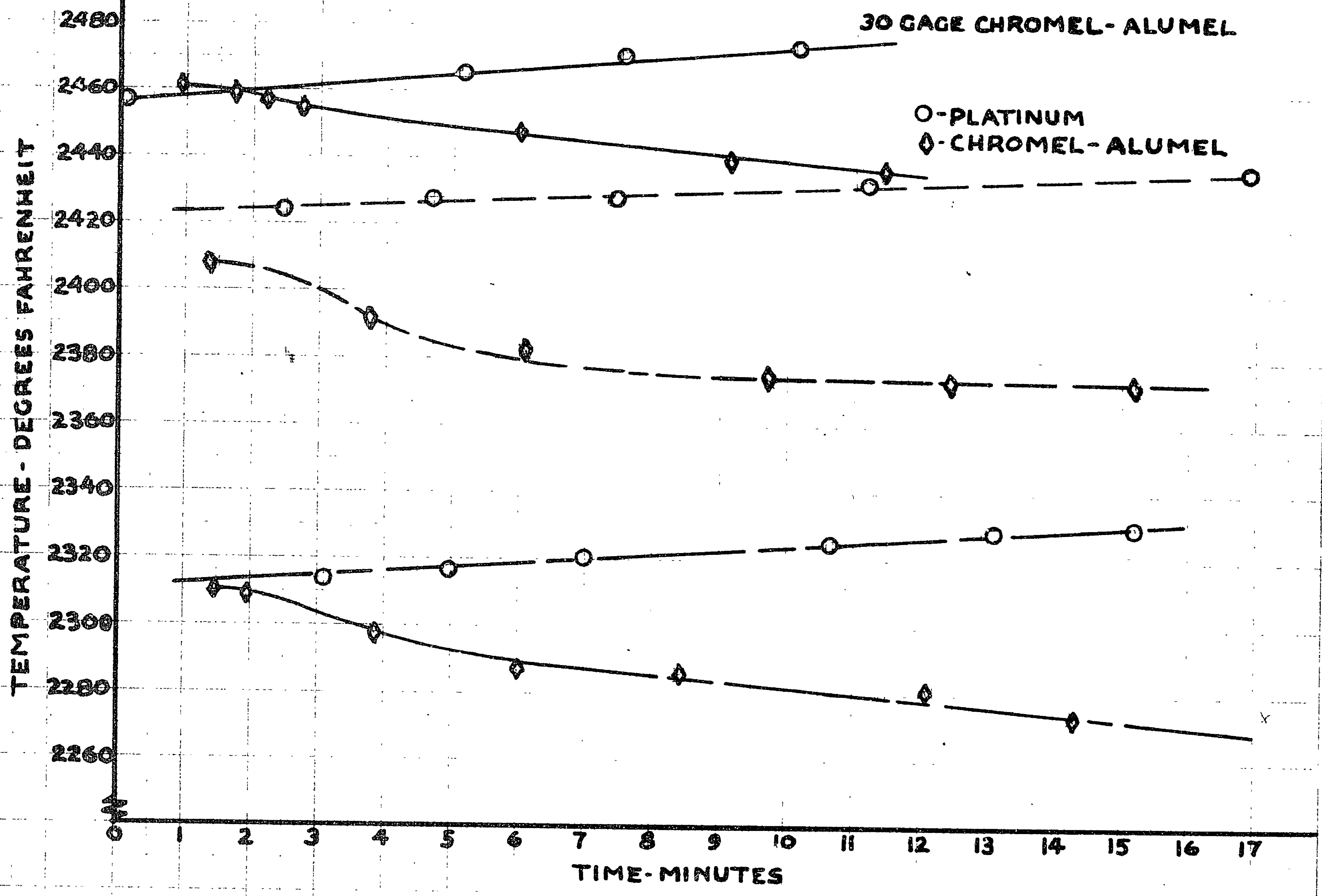

30 GAGE CHROMEL- ALUMEL
O-PLATINUM
◊-CHROMEL-ALUMEL
TEMPERATURE - DEGREES FAHRENHEIT
2480
2460
2440
2420
2400
2380
2360
2340
2320
2300
2280
2260
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
TIME-MINUTES

FIG. 8

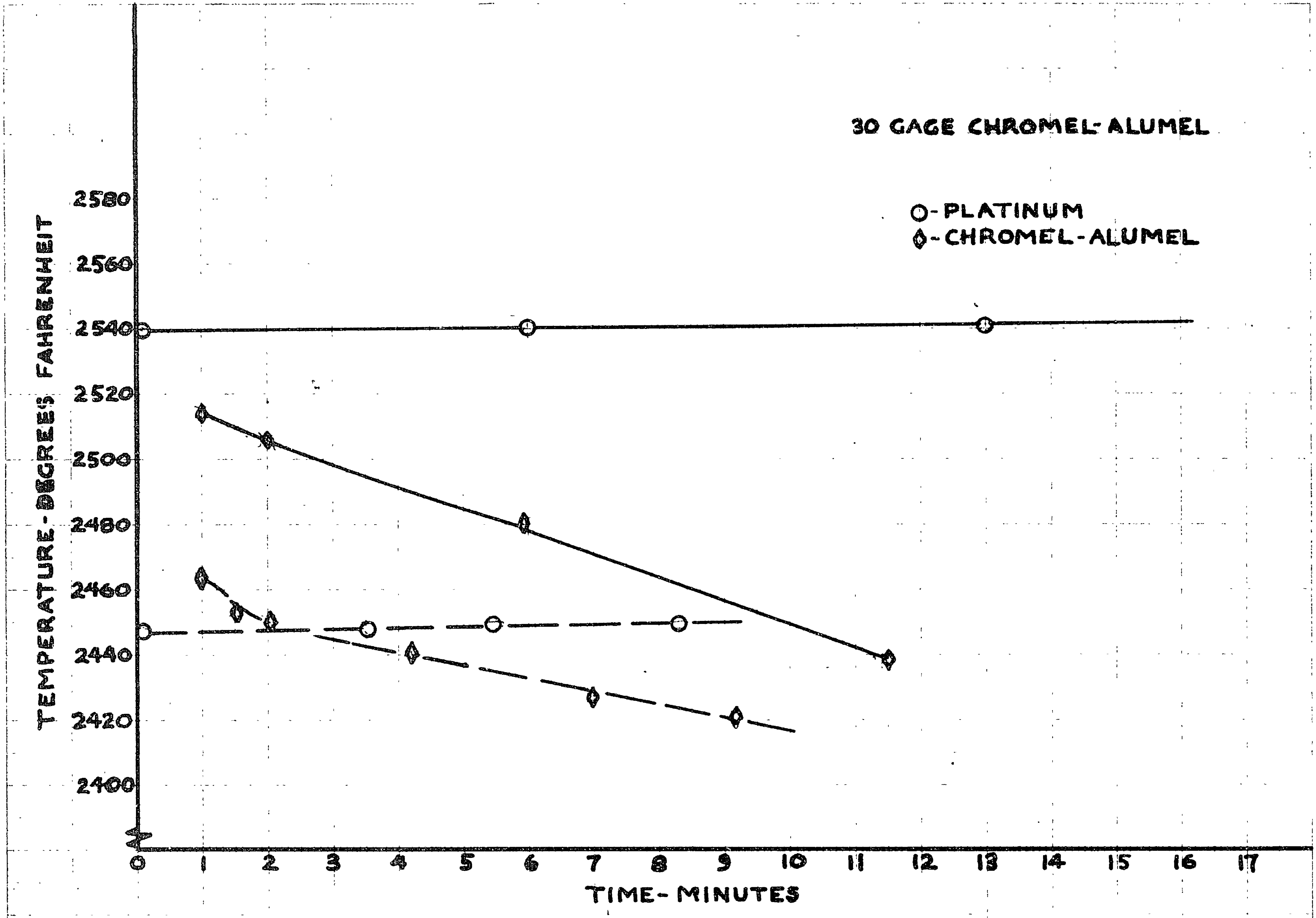

30 GAGE CHROMEL-ALUMEL
O-PLATINUM
◊-CHROMEL-ALUMEL
TEMPERATURE-DEGREES FAHRENHEIT
2580
2560
2540
2520
2500
2480
2460
2440
2420
2400
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
TIME-MINUTES

FIG. 9

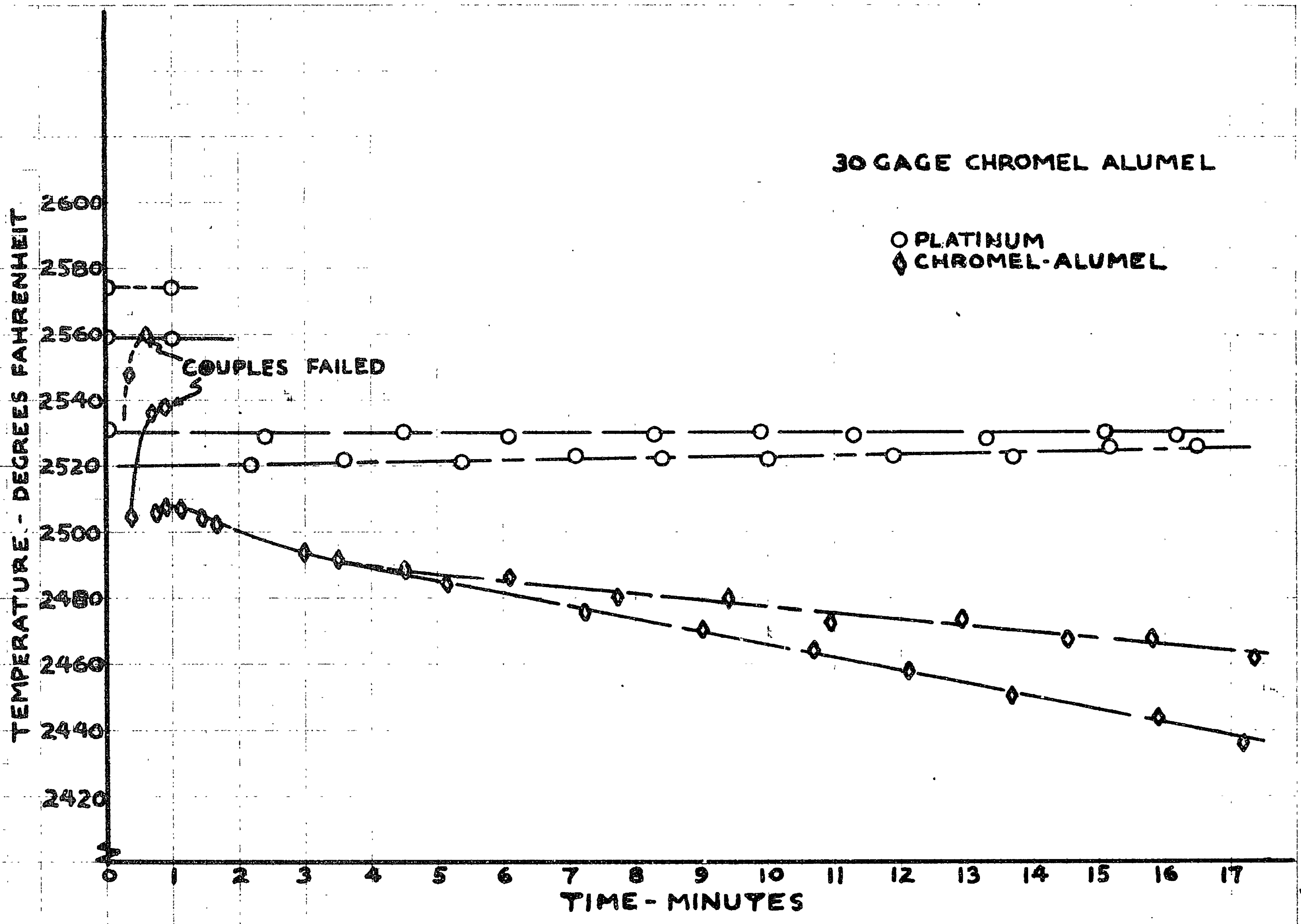

30 GAGE CHROMEL ALUMEL
O PLATINUM
◊ CHROMEL-ALUMEL
COUPLES FAILED
TEMPERATURE - DEGREES FAHRENHEIT
2600
2580
2560
2540
2520
2500
2480
2460
2440
2420
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
TIME - MINUTES

FIG. 10

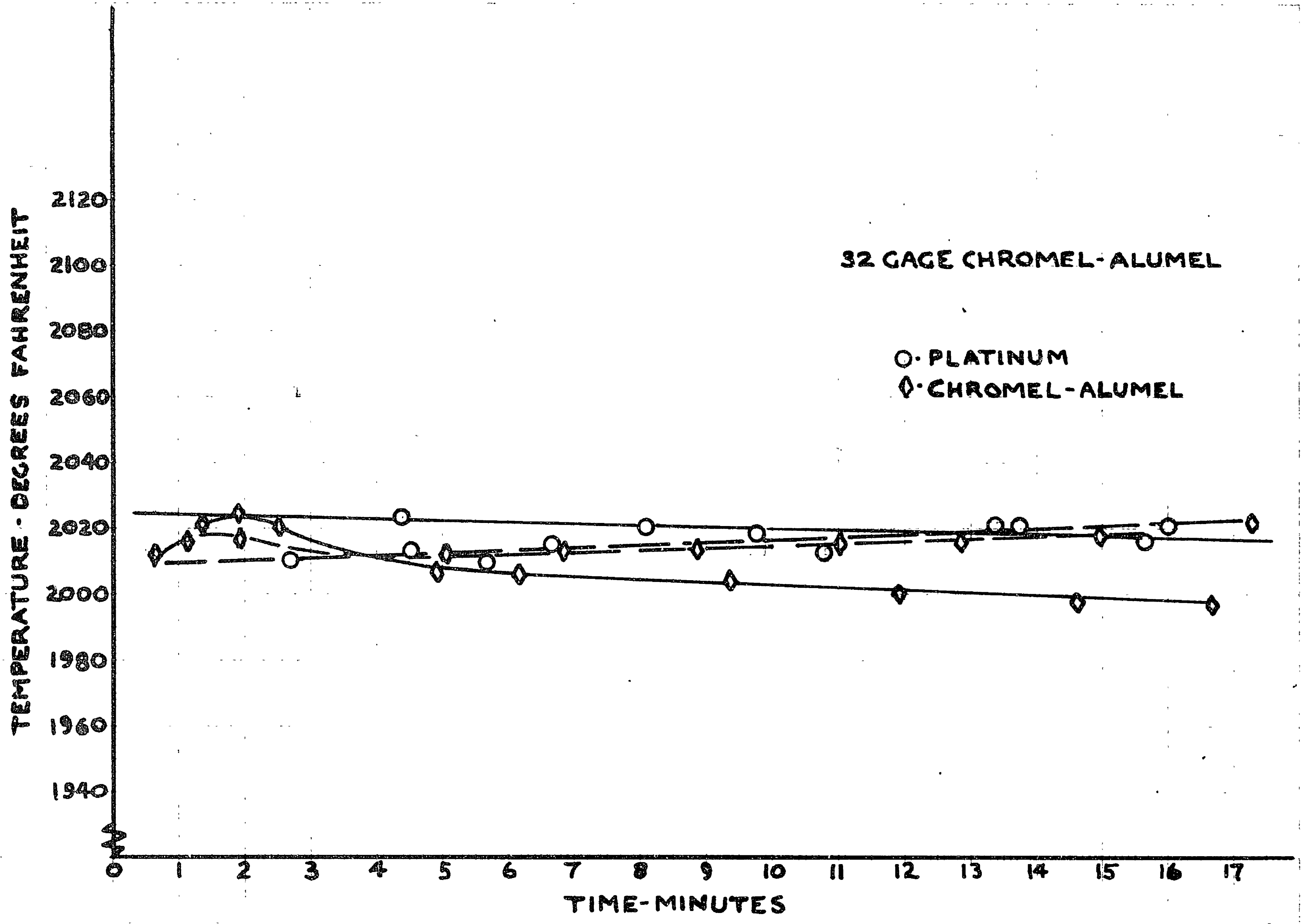

32 GAGE CHROMEL-ALUMEL
O· PLATINUM
◊· CHROMEL-ALUMEL
TEMPERATURE - DEGREES FAHRENHEIT
2120
2100
2080
2060
2040
2020
2000
1980
1960
1940
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
TIME-MINUTES

FIG. 11

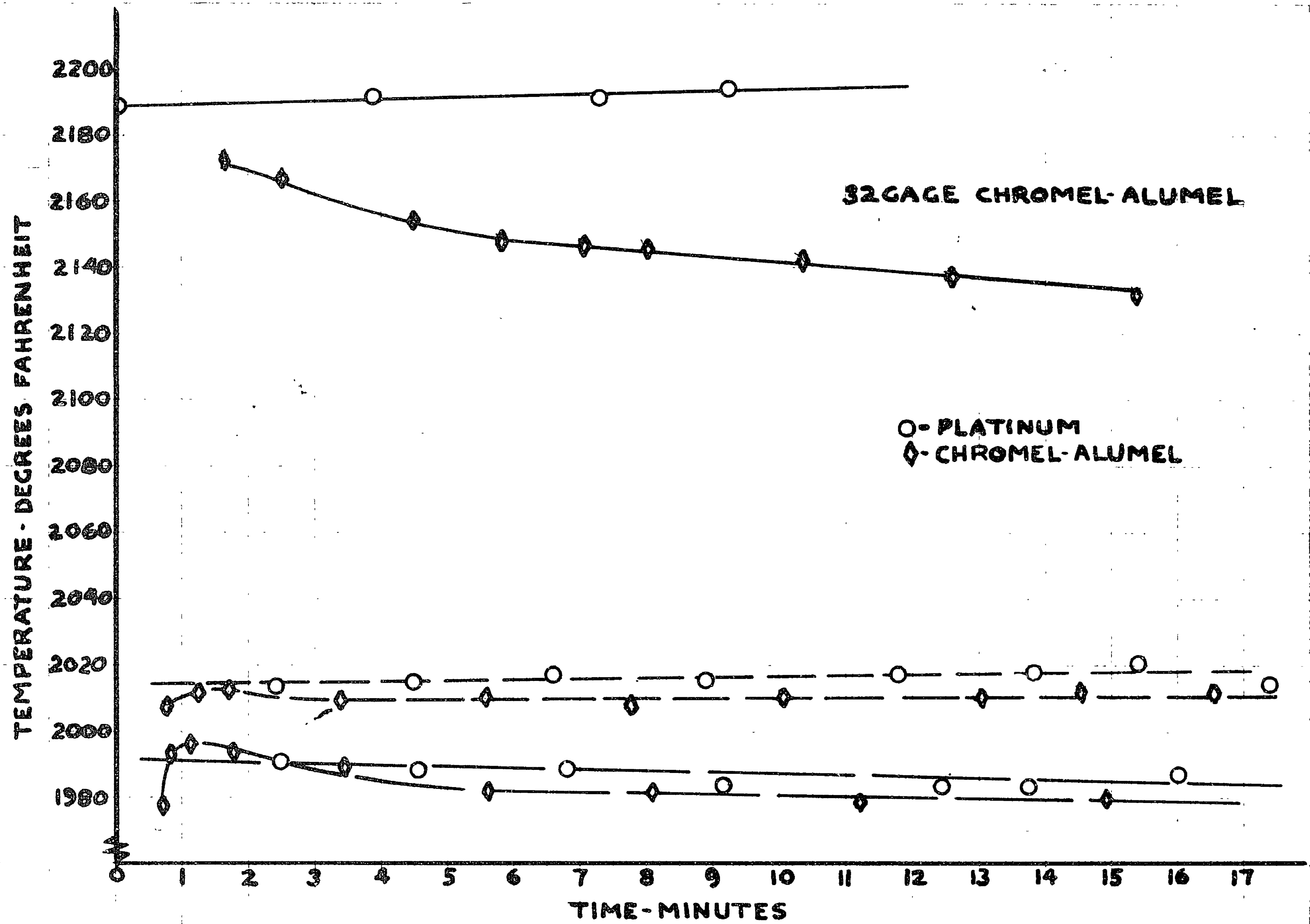

32GAGE CHROMEL-ALUMEL
O- PLATINUM
◊- CHROMEL-ALUMEL
TEMPERATURE - DEGREES FAHRENHEIT
2200
2180
2160
2140
2120
2100
2080
2060
2040
2020
2000
1980
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
TIME-MINUTES

FIG. 12

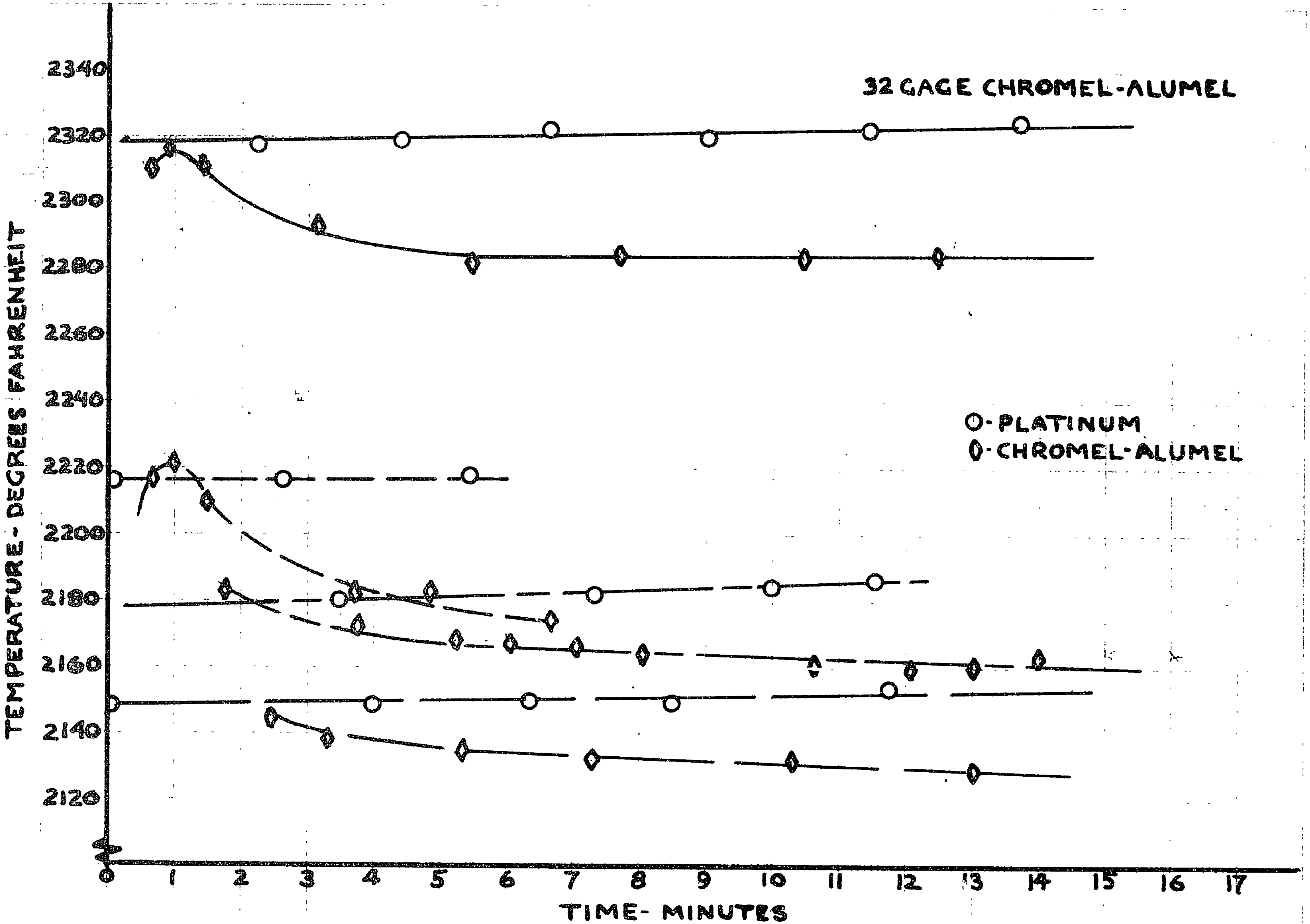

32 GAGE CHROMEL-ALUMEL
O-PLATINUM
◊-CHROMEL-ALUMEL
TEMPERATURE - DEGREES FAHRENHEIT
2340
2320
2300
2280
2260
2240
2220
2200
2180
2160
2140
2120
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
TIME- MINUTES

FIG. 13

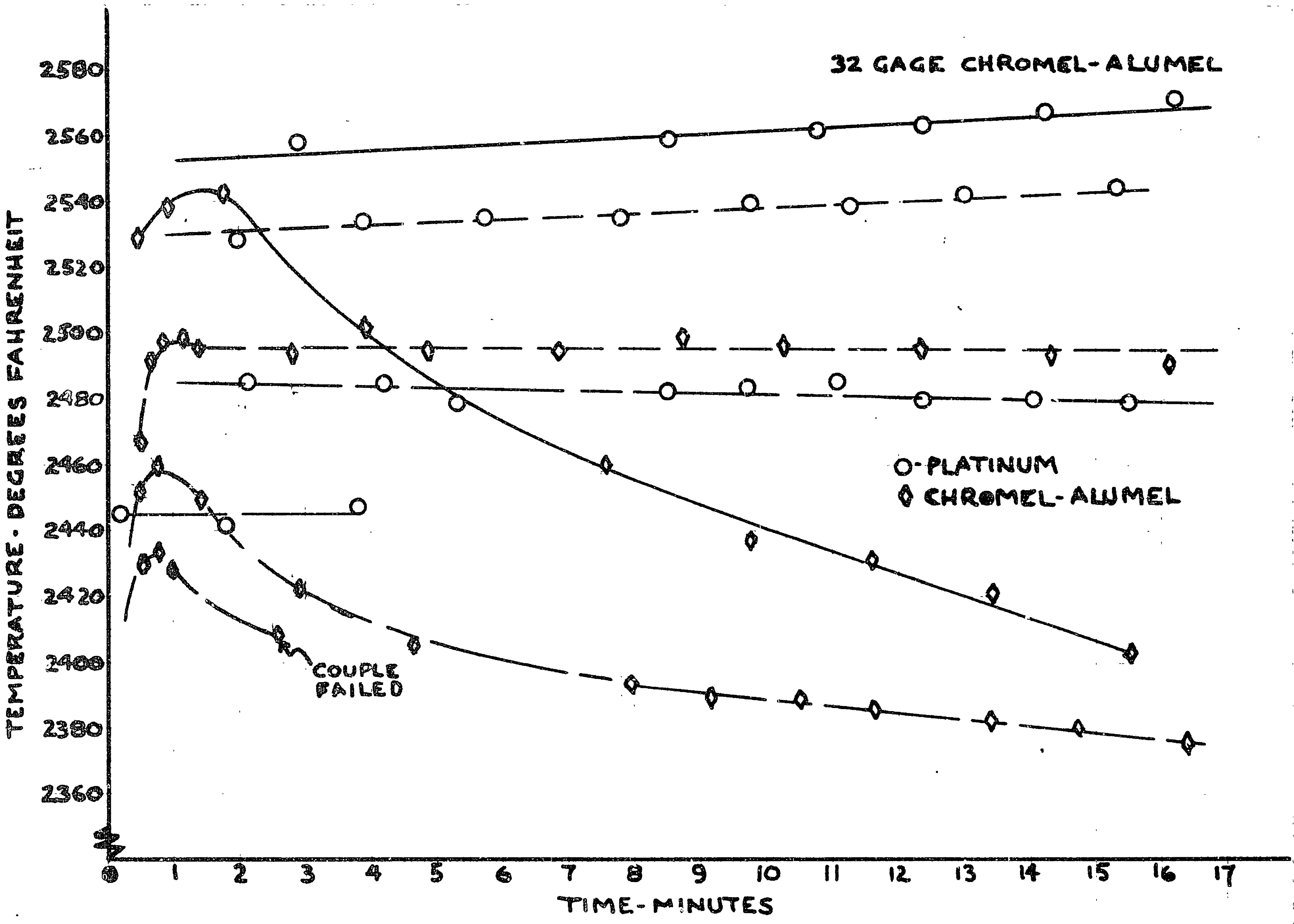

32 GAGE CHROMEL-ALUMEL
O-PLATINUM
◊ CHROMEL-ALUMEL
COUPLE FAILED
TEMPERATURE - DEGREES FAHRENHEIT
2580
2560
2540
2520
2500
2480
2460
2440
2420
2400
2380
2360
TIME-MINUTES
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17

FIG. 14

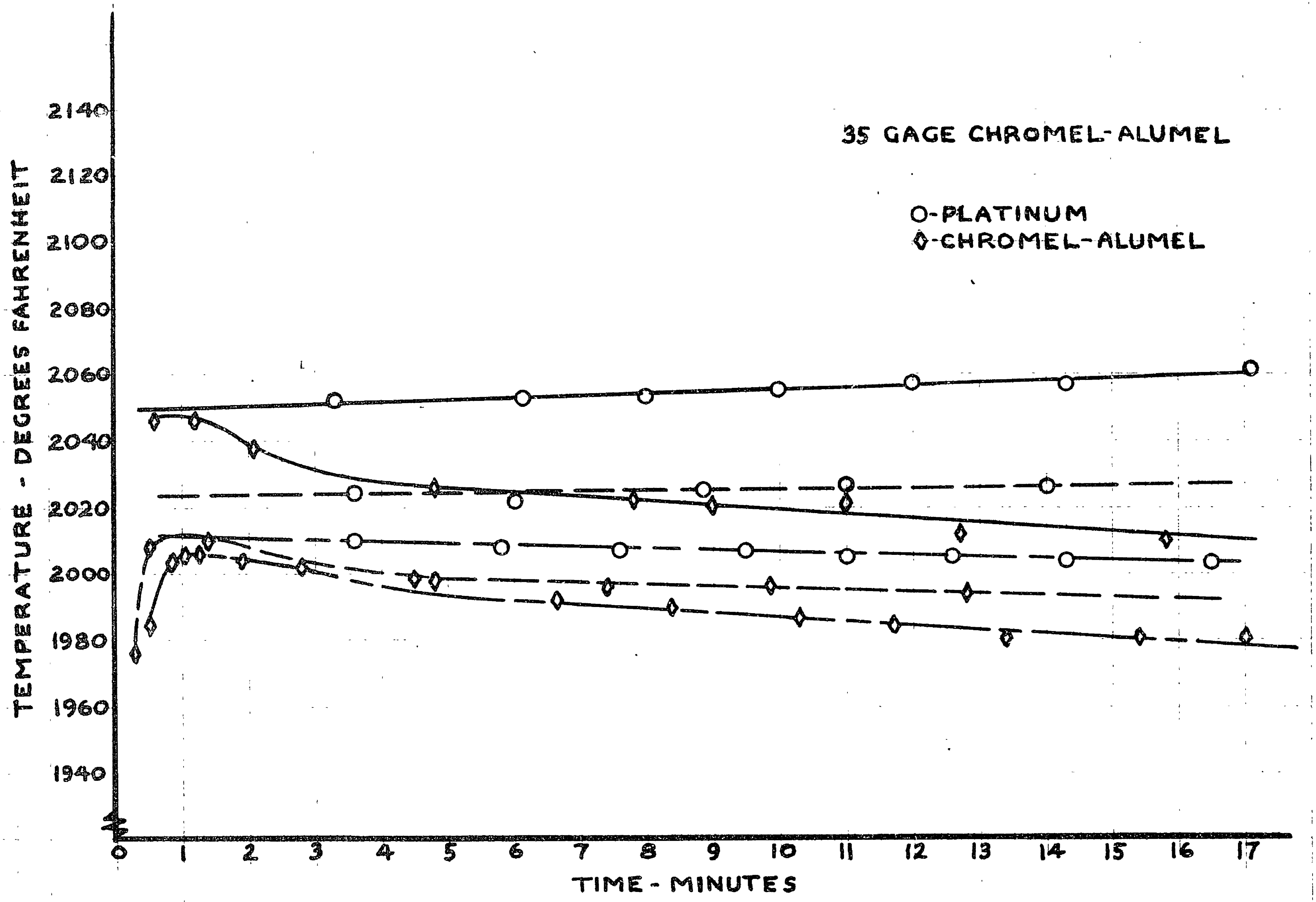

35 GAGE CHROMEL-ALUMEL
O-PLATINUM
◊-CHROMEL-ALUMEL
TEMPERATURE - DEGREES FAHRENHEIT
2140
2120
2100
2080
2060
2040
2020
2000
1980
1960
1940
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
TIME - MINUTES

FIG. 15

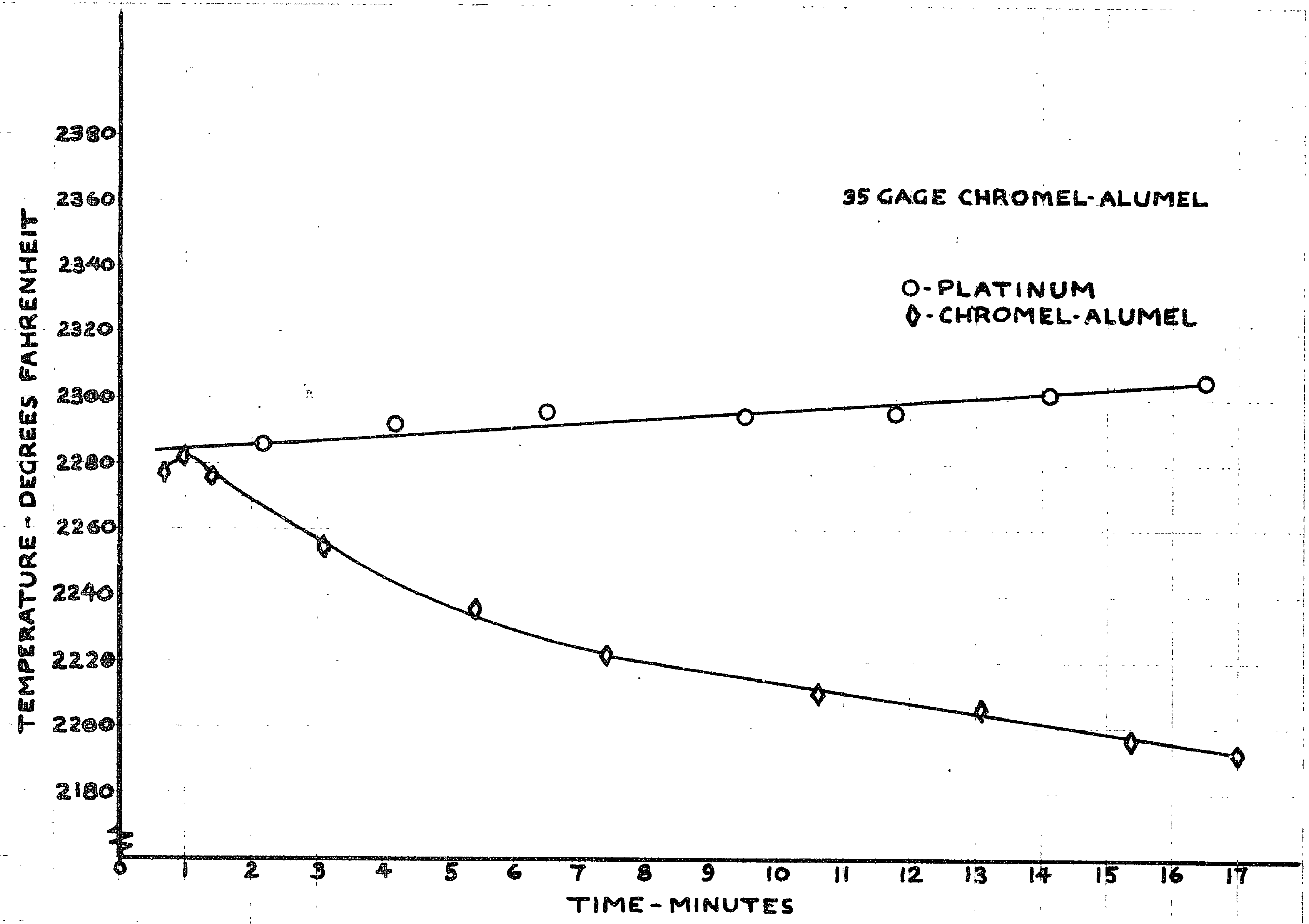

35 GAGE CHROMEL-ALUMEL
O-PLATINUM
◊-CHROMEL-ALUMEL
TEMPERATURE - DEGREES FAHRENHEIT
2380
2360
2340
2320
2300
2280
2260
2240
2220
2200
2180
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
TIME - MINUTES

FIG. 16

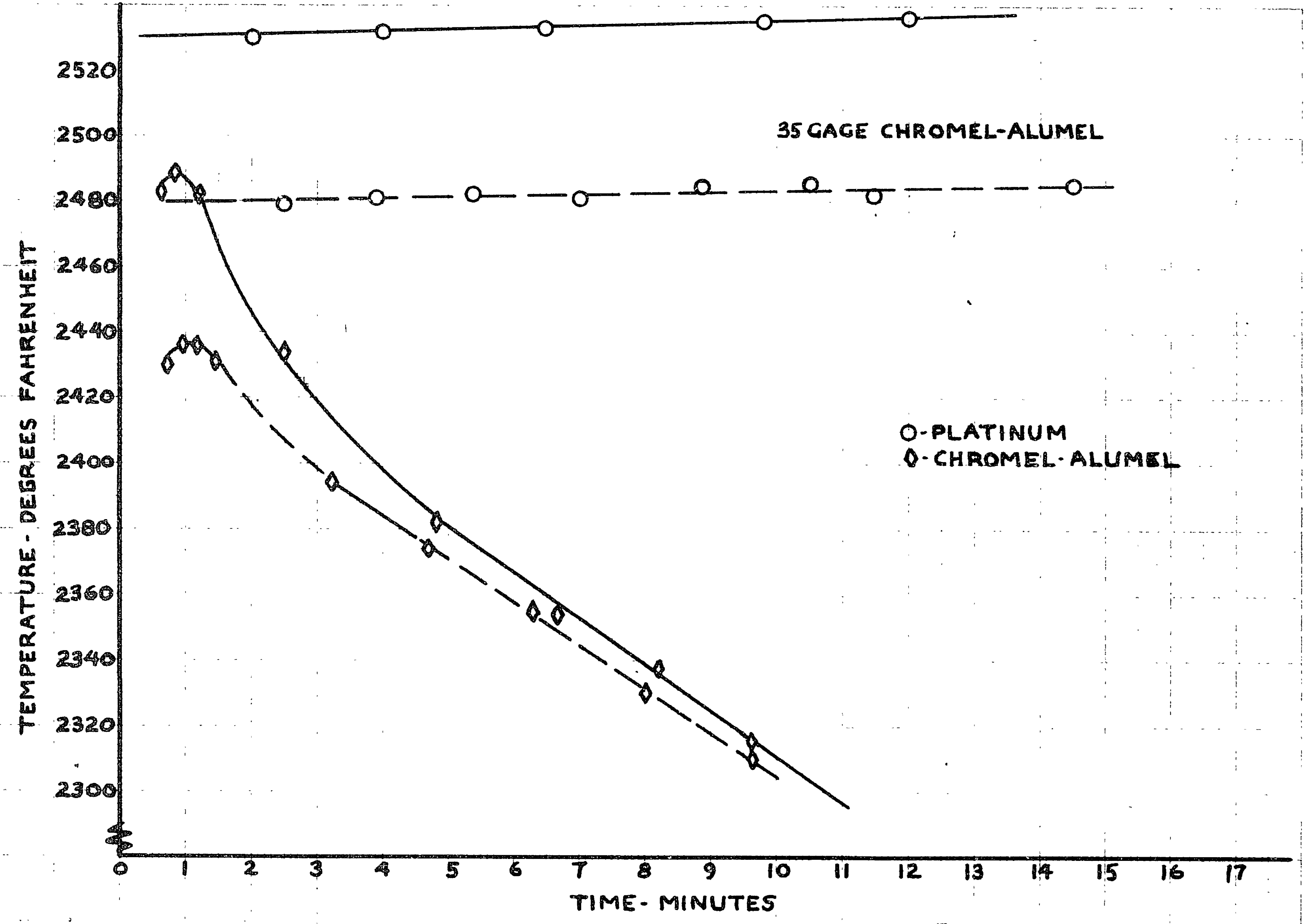

35 GAGE CHROMEL-ALUMEL
O-PLATINUM
◊-CHROMEL-ALUMEL
TEMPERATURE - DEGREES FAHRENHEIT
2520
2500
2480
2460
2440
2420
2400
2380
2360
2340
2320
2300
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
TIME- MINUTES

FIG. 17

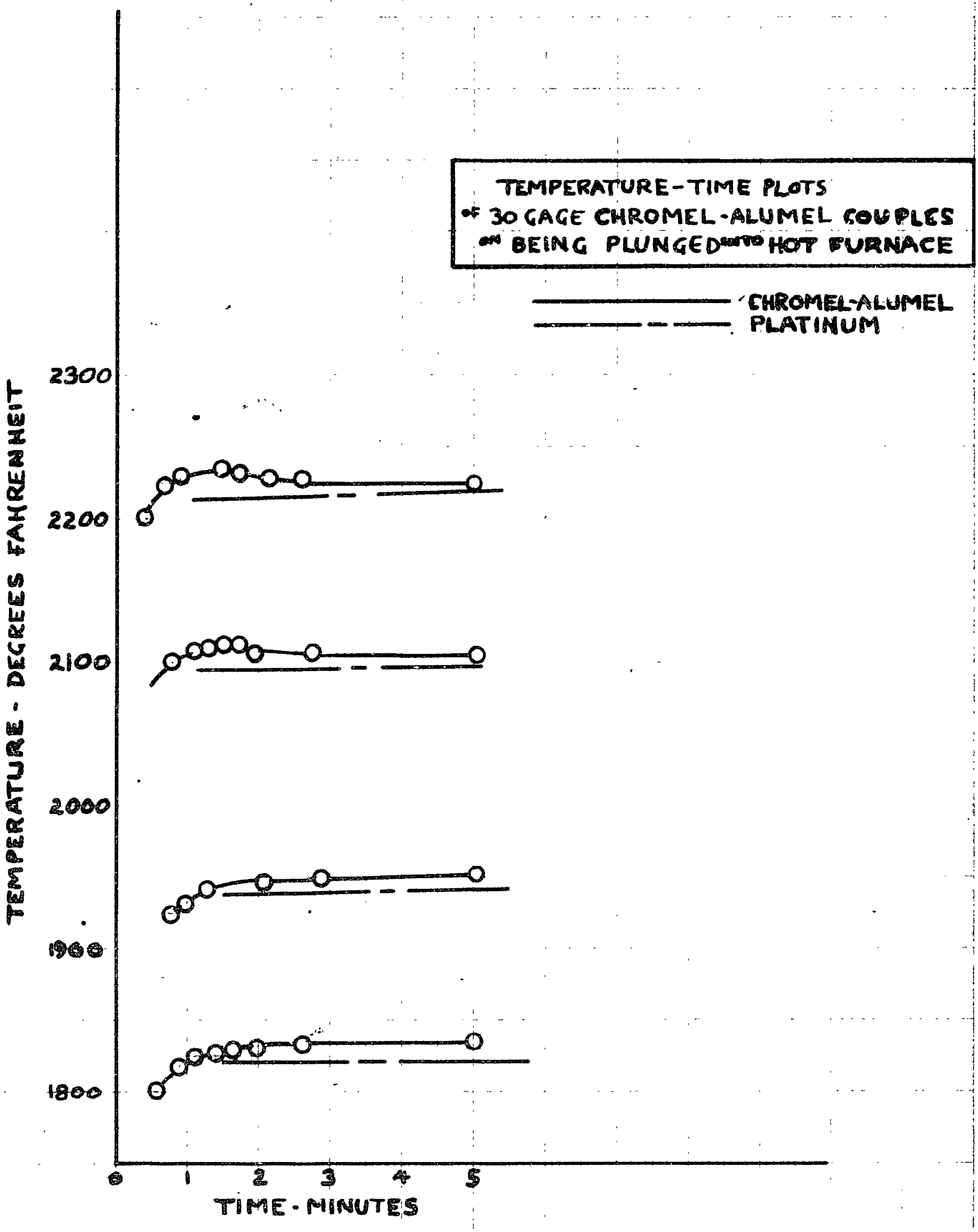

TEMPERATURE-TIME PLOTS
OF 30 GAGE CHROMEL-ALUMEL COUPLES
ON BEING PLUNGED INTO HOT FURNACE
CHROMEL-ALUMEL
PLATINUM
TEMPERATURE - DEGREES FAHRENHEIT
2300
2200
2100
2000
1900
1800
0
1
2
3
4
5
TIME - MINUTES

FIG. 18

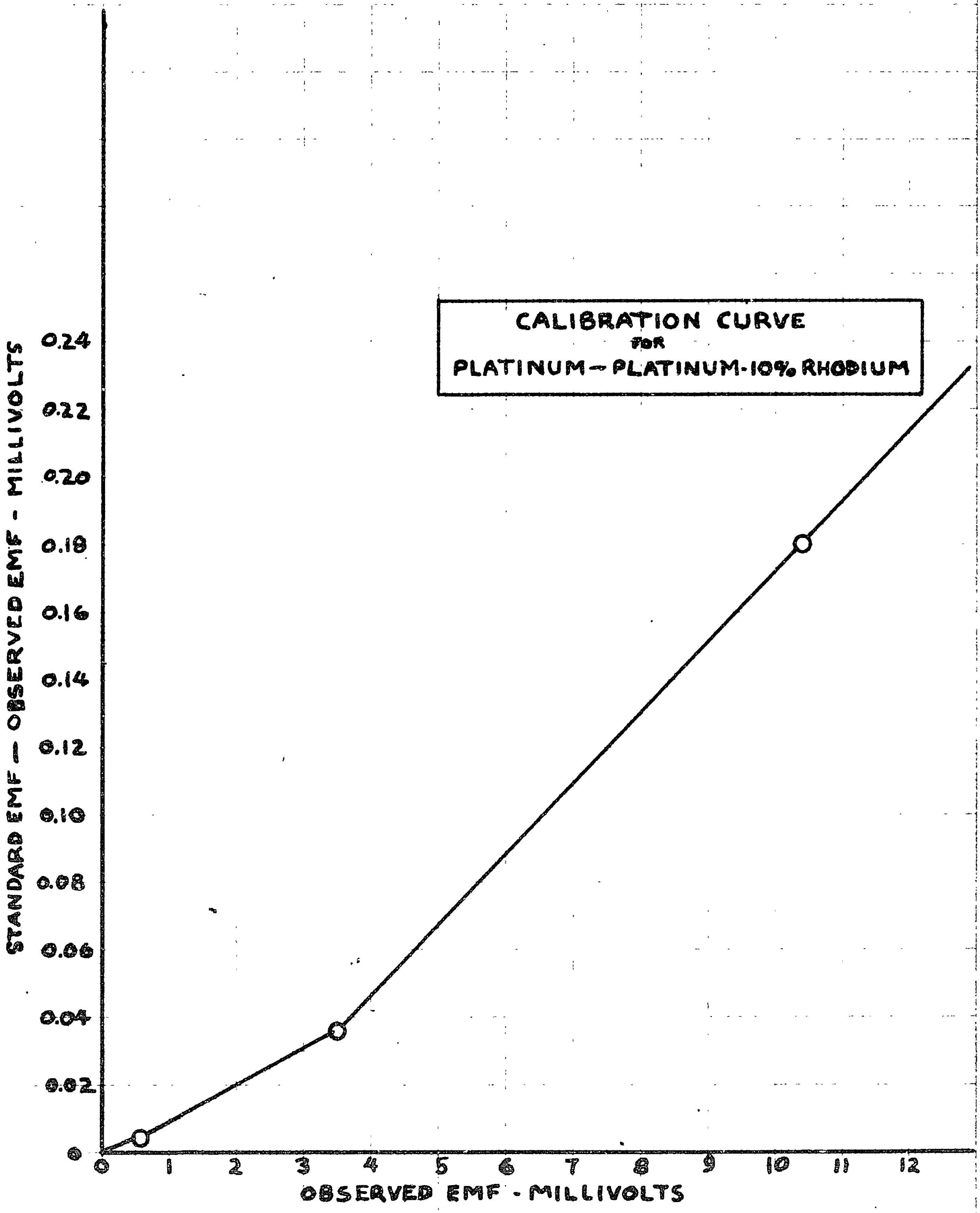

CALIBRATION CURVE
FOR
PLATINUM — PLATINUM-10% RHODIUM
STANDARD EMF — OBSERVED EMF - MILLIVOLTS
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0
0
1
2
3
4
5
6
7
8
9
10
11
12
OBSERVED EMF - MILLIVOLTS

FIG. 19

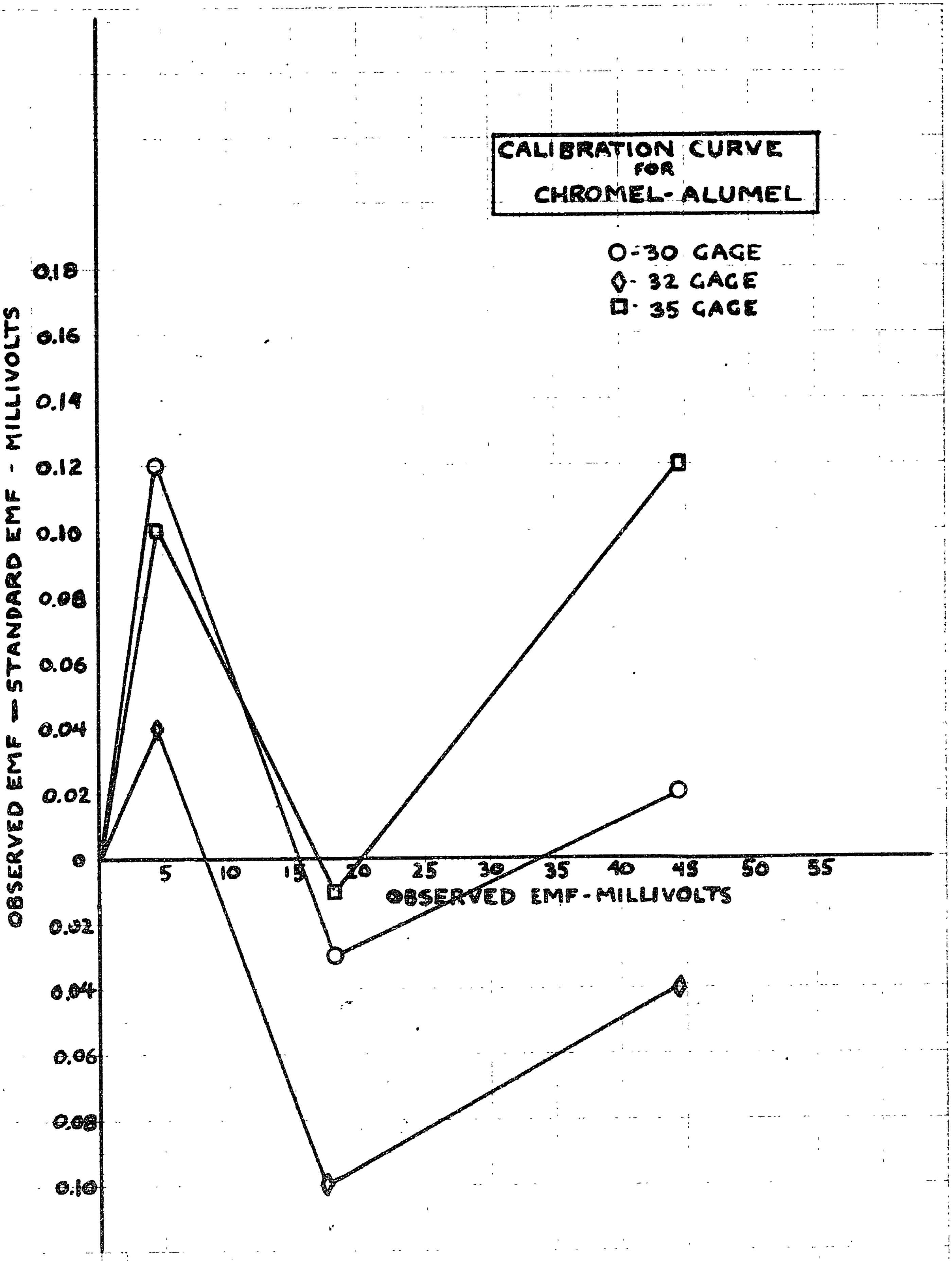
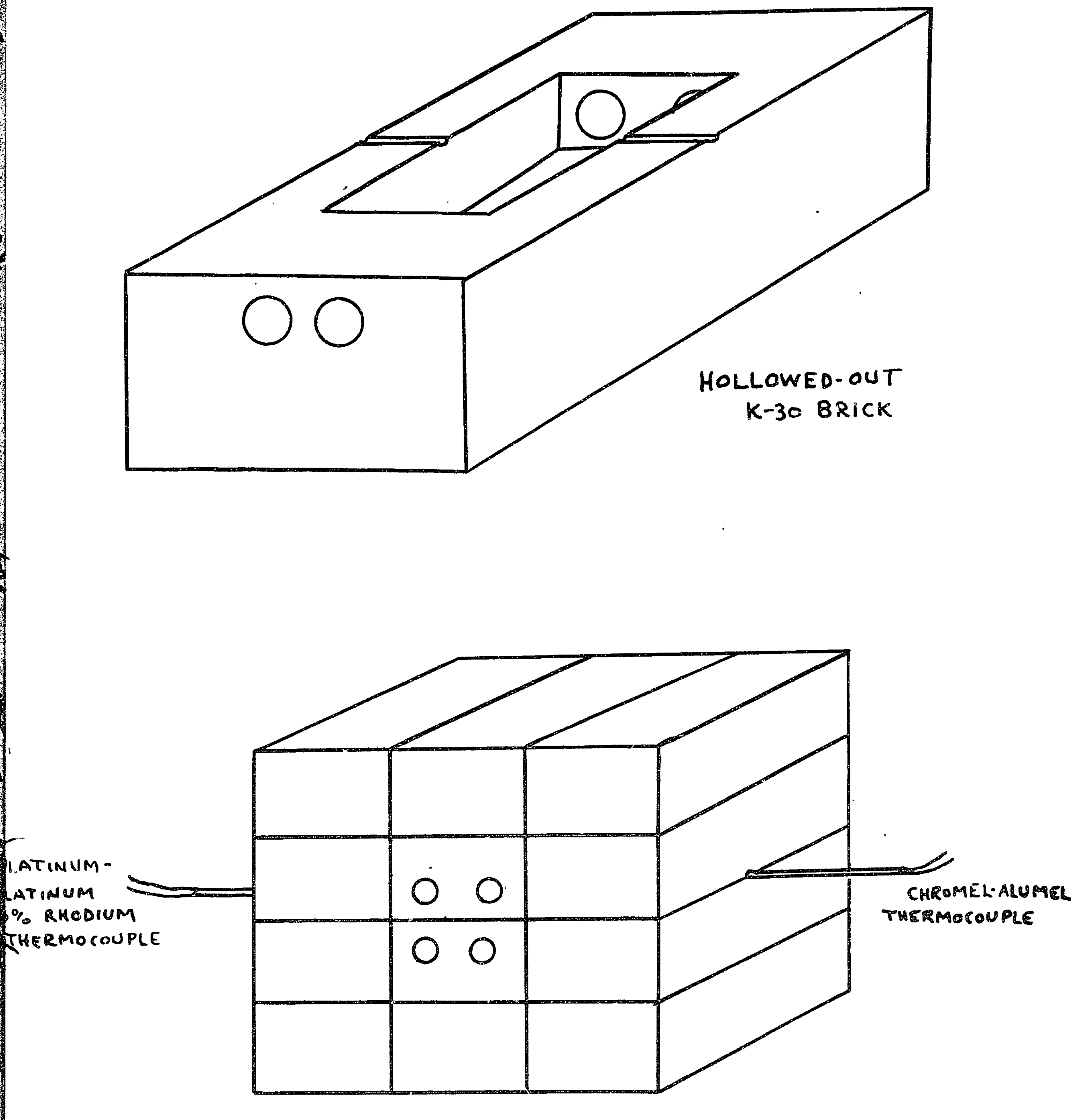

CALIBRATION CURVE
FOR
CHROMEL-ALUMEL
O - 30 GAGE
◊ - 32 GAGE
□ - 35 GAGE
OBSERVED EMF — STANDARD EMF - MILLIVOLTS
OBSERVED EMF - MILLIVOLTS
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0
0.02
0.04
0.06
0.08
0.10
5
10
15
20
25
30
35
40
45
50
55

FIG. 20



FURNACE ASSEMBLY

FIG. 21

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