NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2427

AN INVESTIGATION OF AIRCRAFT HEATERS

XXXV - THERMOCOUPLE CONDUCTION ERROR OBSERVED IN MEASURING SURFACE TEMPERATURES

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Washington
July 1951

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SUMMARY

When thermocouples are used to measure the temperature of surfaces which are exposed to fluids at temperatures different from that of the surface, errors occur because of conduction of heat along the thermocouple wires. These errors have been analyzed and predicted in a previous report; the present report presents experimental results which verify this analysis.

The data also indicate that the electrical insulation of the wires is not effective in reducing the errors involved when the thermocouples are placed normal to the surface and exposed to the ambient fluids. The errors are greatly reduced, however, if the wires are maintained in thermal contact with the plate for about 4 inches before allowing the wires to pass through the fluids.

A welding device utilizing the electrical discharge from a bank of condensers was successfully used to attach thermocouples (No. 28 to No. 40 B. & S. gage) to the metallic surfaces.

INTRODUCTION

This report concerns the experimental and analytical determination of one of the errors involved in the measurement of the temperature of a surface exposed to fluids existing at temperatures different from that of the surface.

The necessity for measuring these surface temperatures arises during thermal tests of aircraft heaters, investigation of heated leading-edge systems for anti-icing, and many other types of thermal analyses. (See reference 1.)

The particular error of measurement discussed herein is caused by conduction of heat along the thermocouple wires used for the determination of the surface temperature.

Consider, for example, a plate at uniform temperature exposed to a hot fluid on one side and a cold fluid on the other side. If thermocouple wires are brought through the hot fluid and attached to the plate in order to measure the plate temperature, heat flows from the hot fluid along the thermocouple wires and thence into the plate. This heat flow increases the temperature of the plate at the point of attachment of the thermocouple (the thermocouple junction) so that the temperature recorded by the thermocouple is too high. Conversely, if the thermocouple is mounted on the cold-fluid side of the plate, heat is transferred away from the point of thermocouple attachment along the wires and then into the cold fluid so that the measured temperature is too low.

The magnitude of the error caused by these "external" heat flow paths is a function of the fluid temperatures and velocities, the thermal conductivities of the thermocouple wires and plate, and the physical dimensions of the wires and plate. A complete analysis of this problem with predictions of the probable error was presented in reference 2.

The present experimental work consisted in using various sizes (No. 8 to No. 37 B. & S. gage) of thermocouple wires to measure the temperature of a 0.037-inch-thick stainless-steel plate exposed to hot air at about 1000° F on one side and to cool air at about 100° F on the other side of the plate. The thermocouples were exposed to the cool air. One series of tests was made using bare (uninsulated) thermocouple wires, and a second series of tests was made using insulated wires in order to determine the effect of the insulation on the magnitude of the error. A third series of tests was made with insulated wires laid along the plate for several inches (attached at 1-in. intervals by means of small wires) in order to reduce the heat flow (temperature gradient) along the wires.

The authors wish to express appreciation to Mr. L. Possner for assistance in taking and analyzing the data and to Messrs. H. Poeland and E. Conway for their help in constructing the test equipment.

The work reported herein was conducted under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics.

SYMBOLS

b	thickness of test plate, feet
C	constant
f_{p_c}	unit thermal convective conductance, cold-air side of test plate, Btu/(hr)(sq ft)(°F)
f_{p_h}	unit thermal convective conductance, hot-air side of test plate, Btu/(hr)(sq ft)(°F)
f_w	average unit thermal convective conductance around each thermocouple wire, Btu/(hr)(sq ft)(°F)
G	cool-air weight rate per unit area, (lb)/(hr)(sq ft)
k_p	thermal conductivity of test plate, 11 Btu/(hr)(sq ft)(°F/ft)
k_w	"effective" thermal conductivity of a pair of thermocouple wires, Btu/(hr)(sq ft)(°F/ft) $\left(\text{e.g.}, \sqrt{k_{Fe\text{-}Con}} = \frac{1}{2}\left(\sqrt{k_{Fe}} + \sqrt{k_{Con}}\right), \text{ where subscripts Fe and Con designate iron and constantan, respectively}\right)$
K_0	modified Bessel function of second kind, zero order
K_1	modified Bessel function of second kind, first order

$$K_R = \frac{K_1\left(\sqrt{\beta}r_s\right)}{K_0\left(\sqrt{\beta}r_s\right)}$$

r	radius of bare thermocouple wire, feet
r_s	"effective" radius of a pair of equal-diameter thermocouple wires, feet $\left(\sqrt{2}r\right)$
t	temperature indicated by thermocouple, °F
t_p	temperature of test plate indicated by one or more embedded reference thermocouple, °F

$\alpha_1 = 2\pi r\sqrt{2f_w k_w r}$, Btu/(hr)(sq ft)

$$\beta = \frac{f_{p_h} + f_{p_c}}{bk_p}$$

τ_c temperature of cold air, °F

DESCRIPTION OF APPARATUS AND TEST PROCEDURE

Plate and Ducts

The stainless-steel test plate used in this experiment formed the separating wall of a single-pass counterflow heat exchanger. The heat exchanger was connected to the heater test stand described in reference 3. Hot air (heated upon passing through a natural-gas furnace) was forced over the lower side of the plate, and cool air, taken directly from the blower, was forced over the top of the test plate.

The ducts on either side of the test plate were 15 inches wide and 3 inches high (a cross-sectional area of 0.312 sq ft). To obtain uniform flow of the gases across the ducts, guide vanes were placed in the diverging section of the hot-air side and a movable 4-inch orifice was placed 10 diameters upstream of the diverging section of the cold-air duct. Uniform flow distribution was checked by means of a pitot-tube traverse.

The test plate consisted of an 18-8 stainless-steel plate 0.037 inch thick, 24 inches long, and 15 inches wide. The plate was screwed down to the exchanger at approximately 2-inch intervals with 6-32 stainless-steel screws.

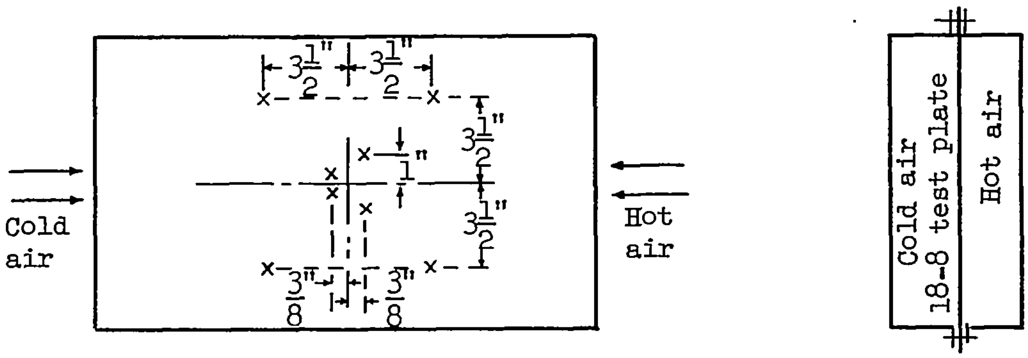
A temperature traverse of both air streams was made by means of shielded Chromel-Alumel thermocouples.

The weight rate of flow of the air streams was measured by means of calibrated orifices.

All of the test thermocouples were mounted on the side of the plate exposed to the cool air.

Reference Thermocouples

The temperature of the test plate was measured by eight embedded thermocouples constructed of No. 37 Brown & Sharpe gage iron-constantan thermocouple wire. (All thermocouples referred to as No. 37 B. & S. gage were constructed from No. 38 iron thermocouple wire and No. 36 constantan wire.) Each wire of the embedded thermocouple was laid in a V groove about 0.015 inch deep and spot-welded with a special condenser-discharge spot welder (described in the appendix) at the points indicated by x in the following sketch. The thermocouple leads were insulated



from the plate by Dow Corning Resin No. 993 - a silicone insulation "enamel" - which was baked on the wires in the grooves by slowly heating the exchanger to approximately 700° F. The grooves for each wire of the couple were about 3/32 inch apart.

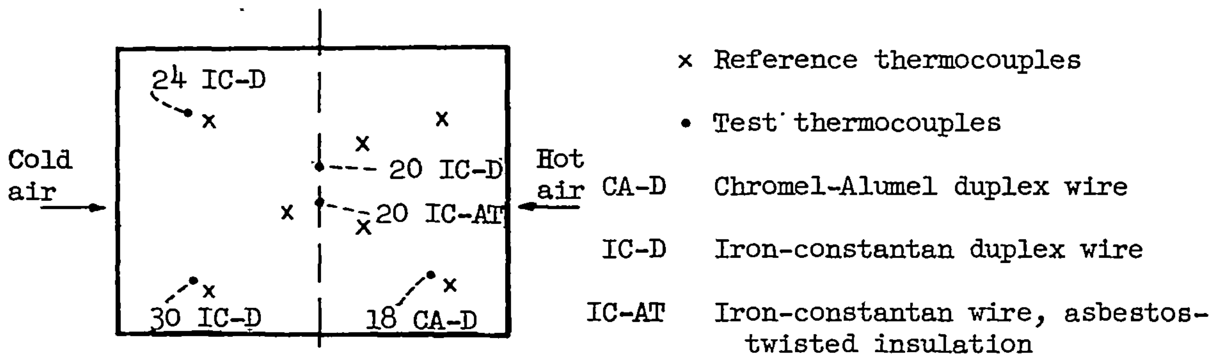
After the resin was baked in the grooves, each wire of the thermocouple was checked for short circuits to the plate by comparing the electrical resistance of the wire with the electrical resistance of the same length of the same size and kind of wire. Only a few shorts were observed in mounting about 25 thermocouples in this manner. To produce a smooth surface over the groove, Dow Corning Silastic (silicone rubber) was used to fill any irregularities. The leads were brought out through the sides of the exchanger between sheets of asbestos. Woven-glass tubing was later slipped over these leads emerging from the exchanger. Outside of the exchanger, the leads were bolted to No. 30 Brown & Sharpe gage duplex thermocouple wire and brought out to the selector switch and ice bath. A "double-wire" cold junction was used, and the electromotive force produced by the thermocouples was measured with a Type 8657 Leeds and Northrup potentiometer.

Test Thermocouples

Nine sizes and kinds of bare thermocouple wires and five sizes and kinds of insulated thermocouples were tested. These are listed in table I.

The first series of tests consisted of nine bare thermocouples which were condenser-discharge spot-welded or soldered (see table I) to the test plate in a position normal to the surface. (See fig. 1.)

The second series of tests consisted of five insulated thermocouples mounted in a manner similar to those in the first series. All wires except the No. 30 gage duplex-insulated wire were silver-soldered to the test plate. The No. 30 gage wire was attached by means of the condenser-discharge welder. The glass-covered duplex wire and the separate-strand asbestos-covered wires were purchased from the Leeds and Northrup Company. The mounting position of the thermocouples is shown in the following sketch:



A third series of tests was performed in which the thermocouples were laid on the plate, and the junctions attached in the same position and manner as in the second series of tests. The insulated leads were held to the plate at 1-inch intervals by means of small tie-down wires for at least 4 inches. (See fig. 2.).

Test Procedure

For each of the three series of tests and for two different plate temperatures (475° and 600° F), five runs were made in which the cool-air weight rate was altered. The weight rate of the hot air was held constant for all runs, but the temperature was varied in order to produce a constant test-plate temperature for each set of runs.

The cool-air weight rates per unit area, G, were 4480, 8350, 11,580, 14,800, and 17,700 pounds per hour per square foot, and the hot-air weight rate per unit area was held constant at 13,000 pounds per hour per square foot.

The data recorded were:

(a) Electromotive force produced by each of the test and reference (embedded) thermocouples

(b) Electromotive force produced by the traversing thermocouples in the hot- and cold-air ducts

(c) Weight rates of hot and cold air

METHODS OF ANALYSIS

All of the predicted curves presented in this report were calculated using equation (21) of reference 2. This equation is, for bare thermocouples of equal-diameter wire,

$$\frac{t_p - t}{t_p - \tau_c} = \frac{1}{1 + \frac{2\pi r_s}{\alpha_1} bk_p\sqrt{\beta} \frac{K_1\left(\sqrt{\beta}r_s\right)}{K_0\left(\sqrt{\beta}r_s\right)}} \tag{1}$$

$$\alpha_1 = 2\pi r\sqrt{2f_w k_w r}$$

$$\beta = \frac{f_{p_h} + f_{p_c}}{bk_p}$$

The "effective" thermal conductivity of Chromel-Alumel thermocouple wire was taken to be 16 Btu/(hr)(sq ft)(°F/ft) while that for iron-constantan wire was taken to be 24 Btu/(hr)(sq ft)(°F/ft) (see reference 2). The thermal conductivity of the 18-8 stainless-steel plate was taken to be 11 Btu/(hr)(sq ft)(°F/ft) at both 475° and 600° F.

Equation (1) may be simplified as follows (equation (30) of reference 2 for bare wire):

$$\frac{t_p - t}{t_p - \tau_c} = \frac{r\sqrt{2f_w k_w r}}{k_p b}\left[-\log_e\left(\frac{\sqrt{\beta}r_s}{2}\right) - 0.577\right] \tag{2}$$

for cases where

$$0 < \sqrt{\beta} r_s < 0.05$$

$$K_1\left(\sqrt{\beta} r_s\right) \approx \frac{1}{\sqrt{\beta} r_s}$$

$$K_0\left(\sqrt{\beta} r_s\right) \approx -\log_e\left(\frac{\sqrt{\beta} r_s}{2}\right) - 0.577$$

The above approximations are given in references 2 and 4.

These equations can be used with small error for values of $\frac{t_p - t}{t_p - \tau_c}$ less than 0.10. For larger values the more exact equation should be used.

To calculate the predicted curves for figure 3, using equation (1), the following procedure was used:

From average values of the test data

$$bk_p = \frac{0.037}{12} \times 11 = 0.034 \text{ Btu/(hr)(}^{\circ}\text{F)}$$

$$f_{p_c} + f_{p_h} = 18 \text{ Btu/(hr)(sq ft)(}^{\circ}\text{F)}$$

(range for all runs was 13.7 to 21.7 Btu/(hr)(sq ft)(°F))

$$\sqrt{\beta} = 23 \text{ ft}^{-1}$$

(range for all runs was 20.1 to 25.3 ft^{-1}).

Substituting these values into equation (1) gives

$$\frac{t_p - t}{t_p - \tau_c} = \frac{1}{1 + \frac{1}{\sqrt{f_w k_w r}} CK_R}$$

where

$$C = bk_p\sqrt{\beta} = 0.034 \times 23 = 0.782$$

$$K_R = \frac{K_1\left(\sqrt{\beta}r_s\right)}{K_0\left(\sqrt{\beta}r_s\right)}$$

So finally

$$\frac{t_p - t}{t_p - \tau_c} = \frac{1}{1 + \frac{0.782}{\sqrt{f_w k_w}} \frac{K_R}{\sqrt{r}}} \tag{3}$$

The ratio $K_R/\sqrt{r}$ is a function of wire diameter only when β is a constant.

DISCUSSION

Reference-Thermocouple Measurements

The temperature of the surface of the test plate is defined in reference 2 as the temperature that the surface would attain at the point of attachment of the thermocouple if the thermocouple were not present. This temperature was experimentally obtained by No. 37 gage iron-constantan thermocouples embedded in the test plate with their junction near the junction of the test thermocouples. (The reference thermocouples were far enough from the test thermocouples to be unaffected by the local temperature distribution at the base of the test thermocouple). Calibration of these embedded thermocouples was impractical, but there was some experimental evidence that these embedded thermocouples indicated the true plate surface temperature.

The following evidence is presented:

(1) For the first series of runs (bare thermocouple wires mounted in the vertical position), the average temperature indicated by the four central embedded thermocouples was used as the test-plate surface temperature. Extrapolating the curves of figures 4 and 5 to the zero-wire-diameter (no-thermocouple) ordinate indicates a "surface" temperature that was close to the observed surface temperature. Also there was a negligible difference in the output (temperatures) of the test and embedded thermocouples when cold air was passed over both sides of the test plate.

(2) For the second series of runs (insulated thermocouple wires mounted in the vertical position), each test thermocouple was near an embedded thermocouple which served to indicate the individual plate surface temperature near each test thermocouple. (Because a thin plate of low thermal conductivity was chosen for these tests to make the magnitude of the thermocouple error as large as possible, and because the distribution of temperature and flow of the air on both sides of the plate was not uniform, temperature distributions existed along the test plate). No checks on the reliability of the embedded thermocouples, such as extrapolating the curves to zero wire diameter, can be made for the second series of runs. However, the same embedded thermocouples were used for the third series of runs where there is evidence of the reliability of the embedded thermocouples in indicating the true surface temperature.

(3) For the third series of runs (insulated thermocouples laid on the plate), there was a negligible difference in the output between embedded and test thermocouples when cold air was passed over both sides of the test plate. (Calibration at the cold temperature was satisfactory.) For another test of the thermocouples mounted on the cold-air side, asbestos sheeting was placed over the plate, thus covering the thermocouples. Hot air was passed over the other side of the test plate and when equilibrium conditions were obtained at plate temperatures of 475° and 600° F the temperatures indicated by the thermocouples were recorded. Differences from 5° to 12° F were observed between the embedded and test (laid-on-plate) thermocouples. Because heat losses from the thermocouple leads by means of free and forced convection and also due to radiation were negligible as a result of the thermal insulation, the only errors that could be present would be due to conduction of heat out of the ends of the leads (4-in. lengths were tied down to the test plate) and due to errors of calibration of the various types and sizes of thermocouples.

Because the order of magnitude of the thermal-conduction error for this series of runs was twice that of observed "end-leakage and calibration" error, this latter error was subtracted from the apparent conduction error. This correction was not made to the first two series of runs because the conduction error was much greater in magnitude than the corresponding correction due to end-leakage and calibration error.

Test Thermocouples

The test thermocouples used in this experiment were attached to the test plate by silver-soldering or condenser-discharge spot-welding methods. The errors recorded in some cases, therefore, include the "fin effects" of solder or weld beads. These errors were minimized in this experiment. Thermocouples attached by the condenser-discharge welding method have little, if any, fillet or bead. The amount of solder under the thermocouple wires was reduced by the use of a careful procedure in soldering the thermocouple to the plate. To reduce any shorting effect of the solder bead, the bead or fillet was cut down to the test plate between the wires of the thermocouple wherever possible. Noticeable effects (see figs. 3 to 5) of increased error were observed for No. 20 Brown & Sharpe gage iron-constantan and No. 22 Brown & Sharpe gage Chromel-Alumel thermocouples where the wires were too close together to cut the bead between them.

Of the two methods of attaching the thermocouples to the test plates, the condenser-discharge spot-welding method (see appendix) had the advantage of being quicker and of eliminating the solder bead at the point of attachment. The disadvantage of this method is that wires larger than No. 28 Brown & Sharpe gage could not be attached.

Discussion of Curves

Thermocouple errors due to thermal conduction along bare thermocouple leads are presented in figure 3. The curves are the graphical representation of equation (1) with given values of bk_p and $f_{p_c} + f_{p_h}$, and were calculated using equation (3). The ordinate $\frac{t_p - t}{t_p - \tau_c}$ is the ratio of the measured thermocouple error to the maximum possible error.

The predicted values of error compare well with the measured values. Evidently the data for the runs of the highest weight rate (farthest to the right for each series of points) were slightly in error because the experimental points are all higher than expected by extrapolating the curve from points recorded at lower weight rates of air.

The experimental values for Chromel-Alumel and iron-constantan thermocouple wires fall equally close to the predicted error curves, an indication that the assumed effective value of thermal conductivity for the thermocouple wires obtained from reference 2 may have been of a correct order of magnitude.

The temperatures recorded by the thermocouples attached to the plate by the condenser-discharge spot-welding method (Nos. 37, 30, and 28 B. & S. gage) are closer to the predicted curve than those recorded by the thermocouples that were soldered to the test plate.

Predicted curves and experimental points for the temperature indicated by bare iron-constantan thermocouple wire in the vertical position are shown in figure 4. (All of these data are also plotted in fig. 3.) The large values of the errors recorded should be noted.

Figure 5 is similar to figure 4, but is for Chromel-Alumel thermocouple wires. (These data are also shown in fig. 3.) The thermocouple of No. 22 Brown & Sharpe gage has a greater error than predicted, probably because of the solder bead at the base of the thermocouple.

Thermocouple-error curves for bare iron-constantan thermocouple wire in the vertical position are shown in figure 6. These points represent the difference between the observed plate temperature (embedded reference thermocouples) and the indicated test-thermocouple temperature and are merely a replot of figure 4. Figure 7 is the same as figure 6 except it is for Chromel-Alumel thermocouple wire, and figure 8 is the same as figure 6 except the plate temperature is approximately 600° F.

Figure 9 is the same as figure 7 except for a plate temperature of approximately 600° F. It may be noted that the spread of error is greater for a given size of iron-constantan wire than for the same size of Chromel-Alumel thermocouple wire.

In figures 10 and 11 experimental points for insulated wires mounted in the vertical position are compared with curves taken from data plotted in figures 6 to 9 for bare wires. (These insulated thermocouple wires were covered with braided glass insulation (duplex wire) or were asbestos-covered twisted wire (each wire insulated separately).) These data points indicate that the electrical insulation has relatively little effect in reducing the heat flow from the thermocouple junctions. A possible explanation of this fact may be obtained from a consideration of the "critical thickness of insulation." If the outside radius of a wire, including the insulation, is less than a critical value r_o, additional insulation increases the heat losses from the wire, while if the radius is greater than r_o, additional insulation serves to decrease the heat flow rates. This critical thickness is given by the equation (see reference 5, page IIb-6)

$$r_o = k/f_o$$

where k is the thermal conductivity of the insulation and f_o is the average unit thermal conductance around the outside of the wire. Because the radii of the thermocouple wires were less than the calculated value of r_o, except for the asbestos-twisted insulated wires (in this case the radius was approximately equal to r_o), one should have expected larger errors than for the bare wires. As stated above, the measured errors were less than for bare wires but in many cases only by a small magnitude.

There are two sets of points on the curves of figure 10 for No. 20 Brown & Sharpe gage wire because there are two different types of insulation on the same size and kind of wire.

The curves in figures 12 and 13 indicate the error observed when the thermocouples were mounted in the best possible manner on the test plate. The errors recorded were due to heat convected and radiated away from the top and side surfaces of the wire. Large thermocouple errors observed with the asbestos-covered No. 20 gage thermocouple wire are probably due to the fact that the wire is twisted and each wire is in contact with the test plate only at a few points.

The data from reference 1 appear to agree with the data presented here for thermocouples mounted along the plate.

CONCLUSIONS

From the results of an investigation of thermocouple conduction errors in measuring surface temperatures, the following conclusions were drawn:

1. Imbedded thermocouples are the most accurate method of measuring a plate surface temperature with fluids of different temperature from that of the plate on each side of the plate. (They have been successfully mounted in 0.037-in.-thick plate and used at temperatures up to 700° F.)

2. A possible means of measuring the plate surface temperature is to lay and tie down on the plate, for a length great compared with diameter (about 50 diam), insulated thermocouple leads.

3. The thermal-conduction error of thermocouples mounted normal to the test plate can be calculated from given equations.

4. The spot-welding technique of attaching thermocouples to a plate is preferable to soldering or welding. If the thermocouple is soldered or welded to the plate the bead should be cut to the plate between the thermocouple wires.

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Berkeley, Calif., February 26, 1946

APPENDIX

CONDENSER-DISCHARGE SPOT WELDER

A method of discharging a bank of condensers through a short length of thermocouple wire to a metallic surface at the point at which a thermocouple is desired has been developed for attaching small-size thermocouples (between No. 40 and No. 28 B. & S. gage) to aluminum alloys and to stainless steel. This method of attachment has been used successfully where other methods have failed.

A wiring diagram of the welder is given in figure 14. This model was designed as an experimental laboratory model and has a larger voltage and a larger capacity range than are required for thermocouple wires of less than No. 28 Brown & Sharpe wire gage. The unit is completely housed in an 11- by 12- by 8-inch cabinet and weighs about 35 pounds. (See fig. 15.)

For a given metallic surface and thermocouple wire, one combination of voltage and capacitance will produce a satisfactory weld. A complete table of satisfactory combinations of voltage and capacitance will not be given because the particular values may vary with such factors as the type of capacitance used in each model.

The optimum welding results are a function of

(1) The condition of the plate and wire surfaces (slightly oxidized surface is preferable to clean surface)

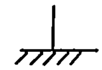
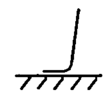
(2) The length of thermocouple wire between the alligator clip and the plate

(3) The type of weld (butt or "bent-over" welds - see sketches in the following table)

(4) The electrical resistance and inductance of the leads within the welder and from the welder to the thermocouple wire

(5) Type of capacitors used in the welder

In the particular application of this experiment, the following optimum conditions were found. All thermocouples were mounted on an 18-8 stainless-steel plate.

Thermocouple		Voltage (volts)	Capacitance (µf)	Type of weld
B. & S. gage	Wire material			
38 36	Iron Constantan	140 140	30 37	Vertical butt weld 
30 30	Iron Constantan	280	50	Bent over 
28 28	Chromel Alumel	350	73	Bent over 

A preliminary investigation of this welding technique indicates that:

(1) Great care should be taken in constructing the welder, in that the resistance and inductance in the discharge circuit should be held to a minimum.

(2) For a given wire material, wire size, and plate material, optimum discharge time and energy are required to obtain a satisfactory weld.

(3) Surfaces of high thermal and electrical conductivity are the most difficult to weld.

(4) Thermocouple wires have been welded at the bottom of holes drilled in a metallic surface. They may be welded at great depths (3 to 6 in.), but the discharge current should not pass through more than 1/2 inch of the fine thermocouple wire.

(5) Extremely small wires such as No. 46 gage are not easily attached because of the high resistance of wire compared with the contact resistance.

(6) The welds produced using No. 24 gage (or larger) wire are very weak and usually break if the wire is bent from its original position.

(7) Butt welds can be made more successfully if the thermocouple wire is bent slightly before making contact (bent-over welds).

(8) Paper-wound condensers give more satisfactory results than electrolytic-type condensers.

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TABLE I.- TEST THERMOCOUPLES

B. & S. gage	Material (1)	Wire diameter (in.)	Insulation	Method of attachment
Series 1 - bare wires mounted in vertical position				
37	Fe-Con	0.005	----------------	Condenser-discharge spot weld
30	Fe-Con	.0100	----------------	Do.
28	Cr-Al	.0126	----------------	Do.
24	Fe-Con	.0201	----------------	Silver solder
22	Cr-Al	.0254	----------------	Do.
20	Fe-Con	.0319	----------------	Do.
18	Cr-Al	.0403	----------------	Do.
14	Fe-Con	.0640	----------------	Do.
8	Cr-Al	.1285	----------------	Do.
Series 2 - insulated wires mounted in vertical position				
30	Fe-Con	------	Glass duplex	Condenser-discharge spot weld
24	Fe-Con	------	-------do-------	Silver solder
20	Fe-Con	------	-------do-------	Do.
20	Fe-Con	------	Asbestos twisted	Do.
18	Cr-Al	------	Glass duplex	Do.
Series 3 - insulated wires laid on plate				
30	Fe-Con	------	Glass duplex	Condenser-discharge spot weld
24	Fe-Con	------	-------do-------	Silver solder
20	Fe-Con	------	-------do-------	Do.
20	Fe-Con	------	Asbestos twisted	Do.
18	Cr-Al	------	Glass duplex	Do.

[1]Fe-Con indicates iron and constantan thermocouple wires; Cr-Al indicates Chromel and Alumel thermocouple wires.

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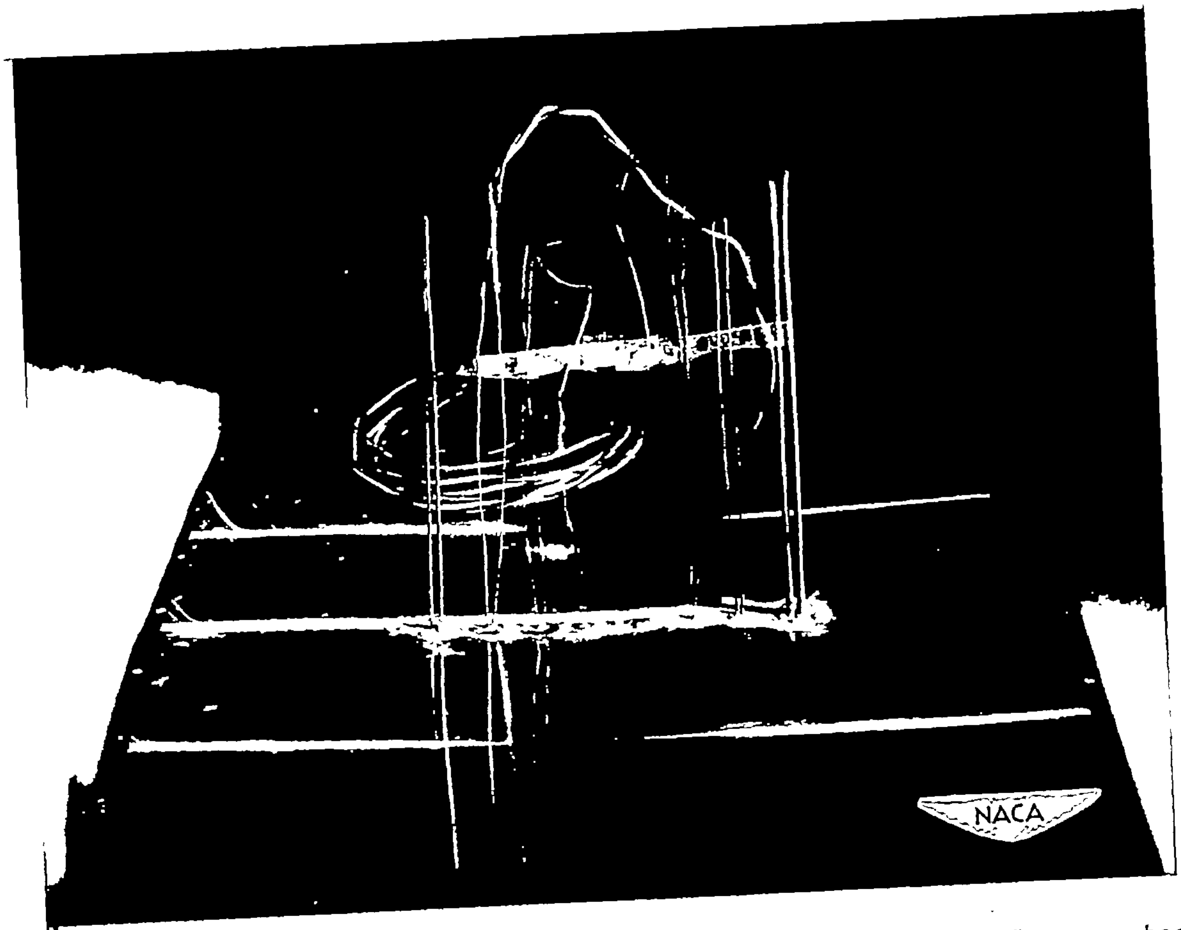


Figure 1.- Bare iron-constantan and Chromel-Alumel thermocouples mounted in vertical position. (Note how the weld beads were cut to test plate wherever possible.) White streaks indicate position of embedded thermocouples. (Three more were added before data were recorded.)

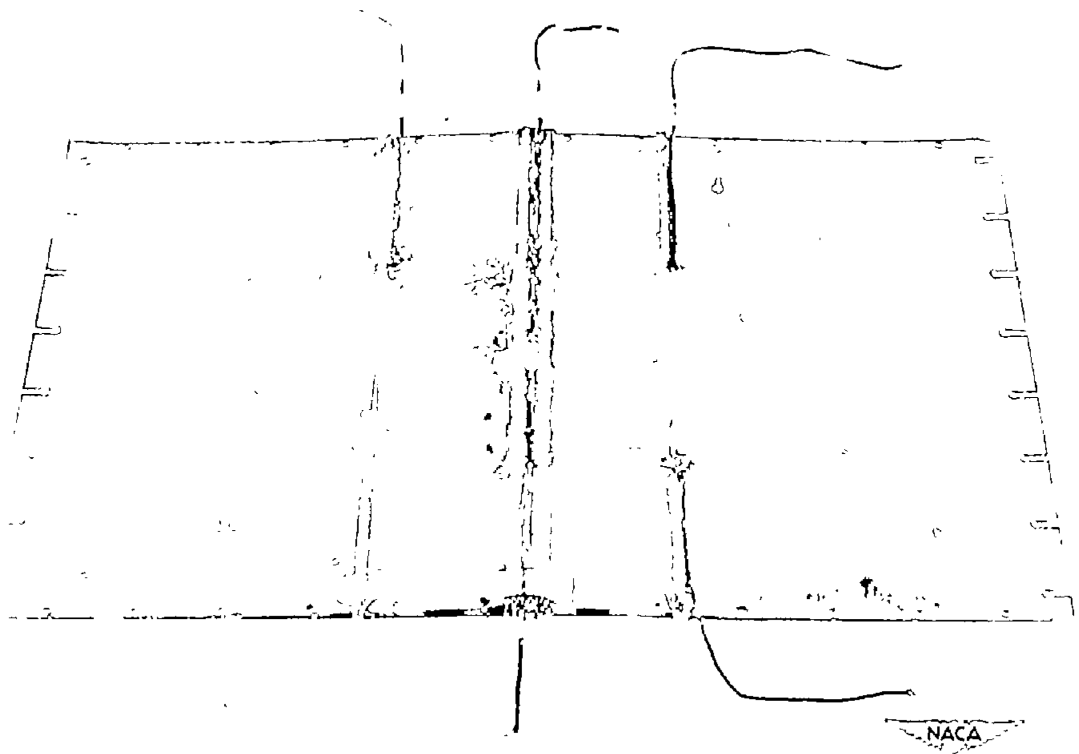


Figure 2.- Insulated iron-constantan and Chromel-Alumel thermocouples mounted in "laid-on-plate" position. Leads were tied down to plate at 1-inch intervals. White streaks indicate position of embedded thermocouples.

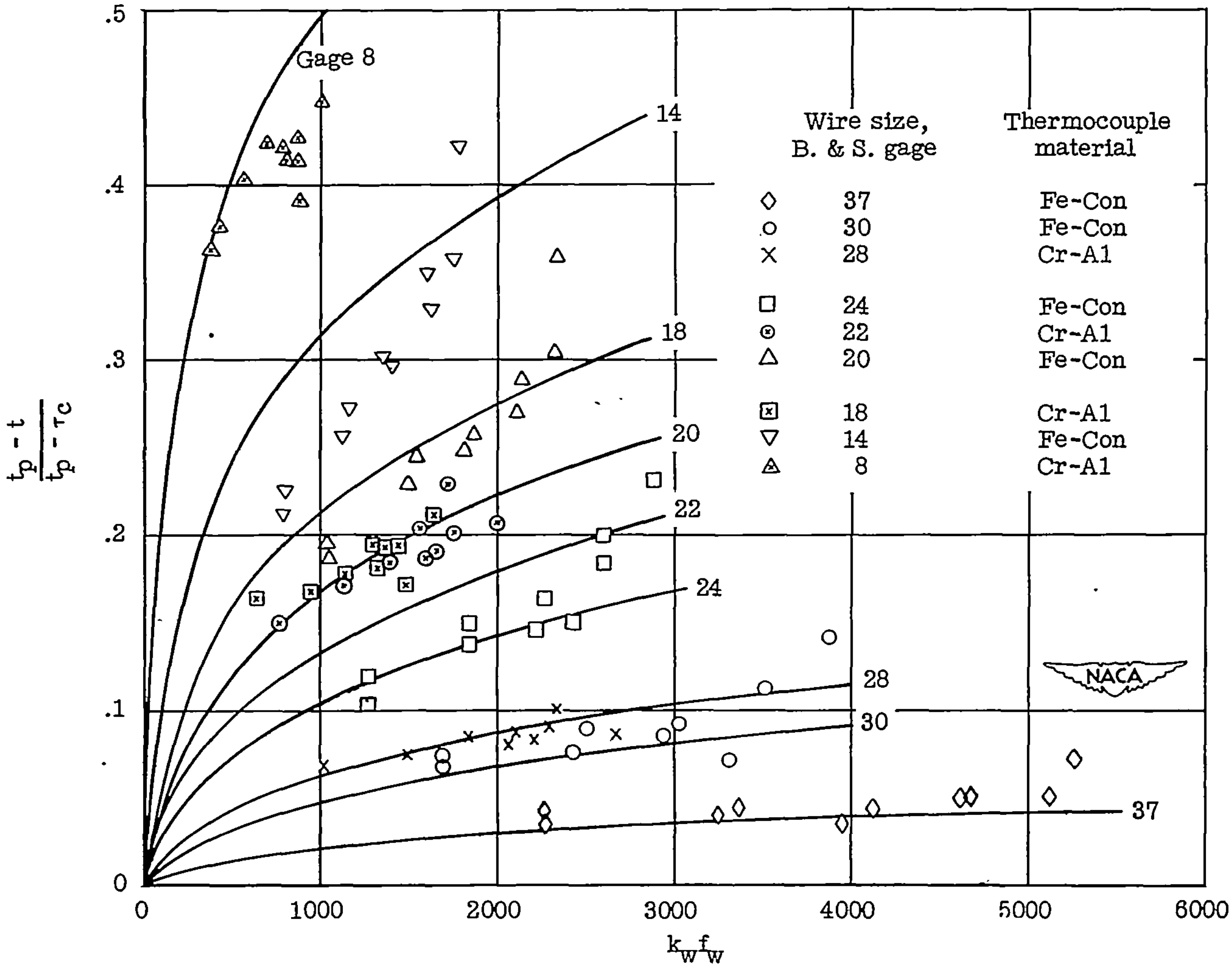


Figure 3.- Measured and predicted thermocouple error due to thermal conduction along bare thermocouple leads. Predicted curves calculated from equation (3).

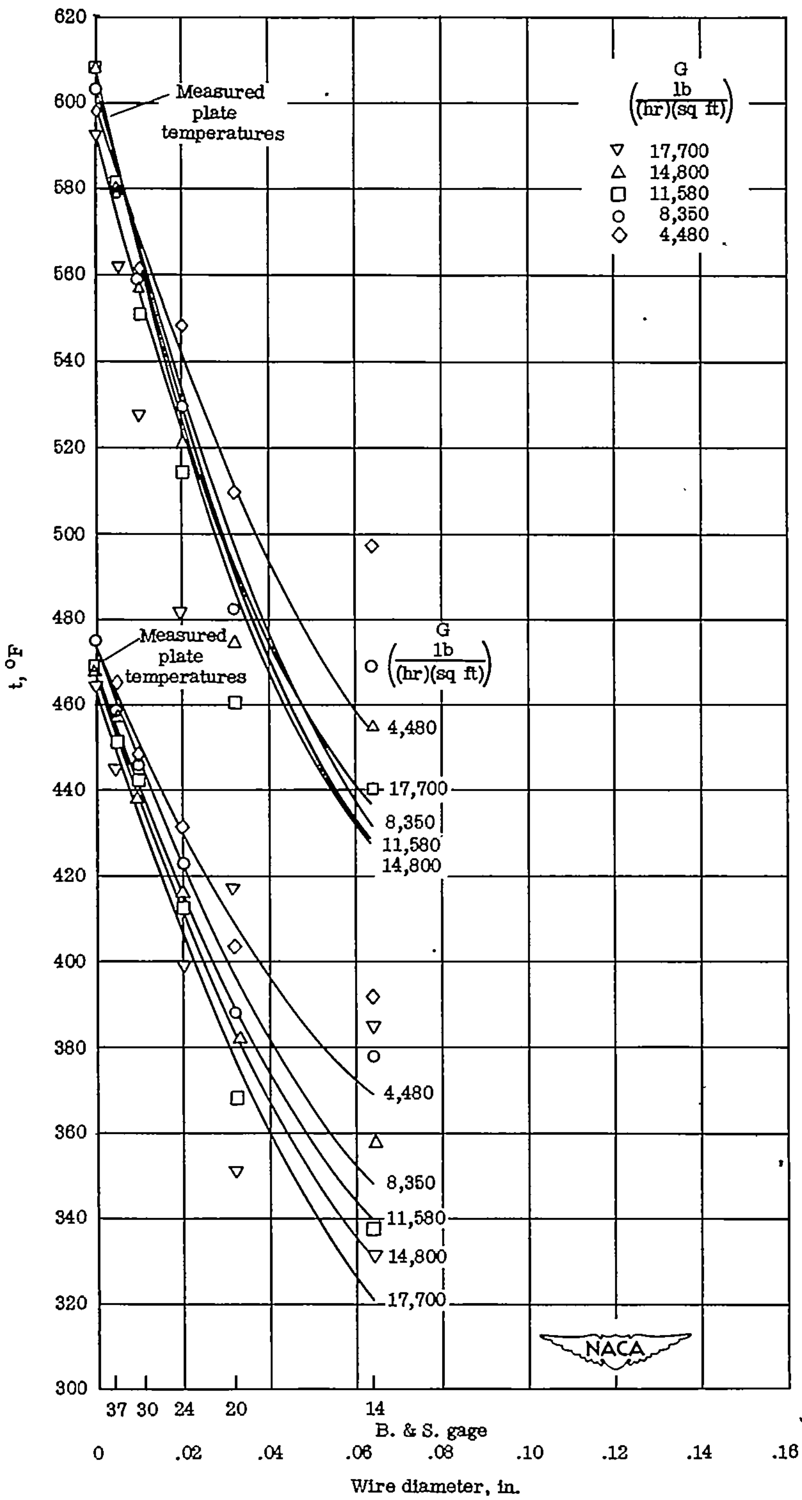


Figure 4.- Predicted curves (calculated from equation (1)) and experimental points for temperature indicated by bare iron-constantan thermocouple wire mounted in vertical position.

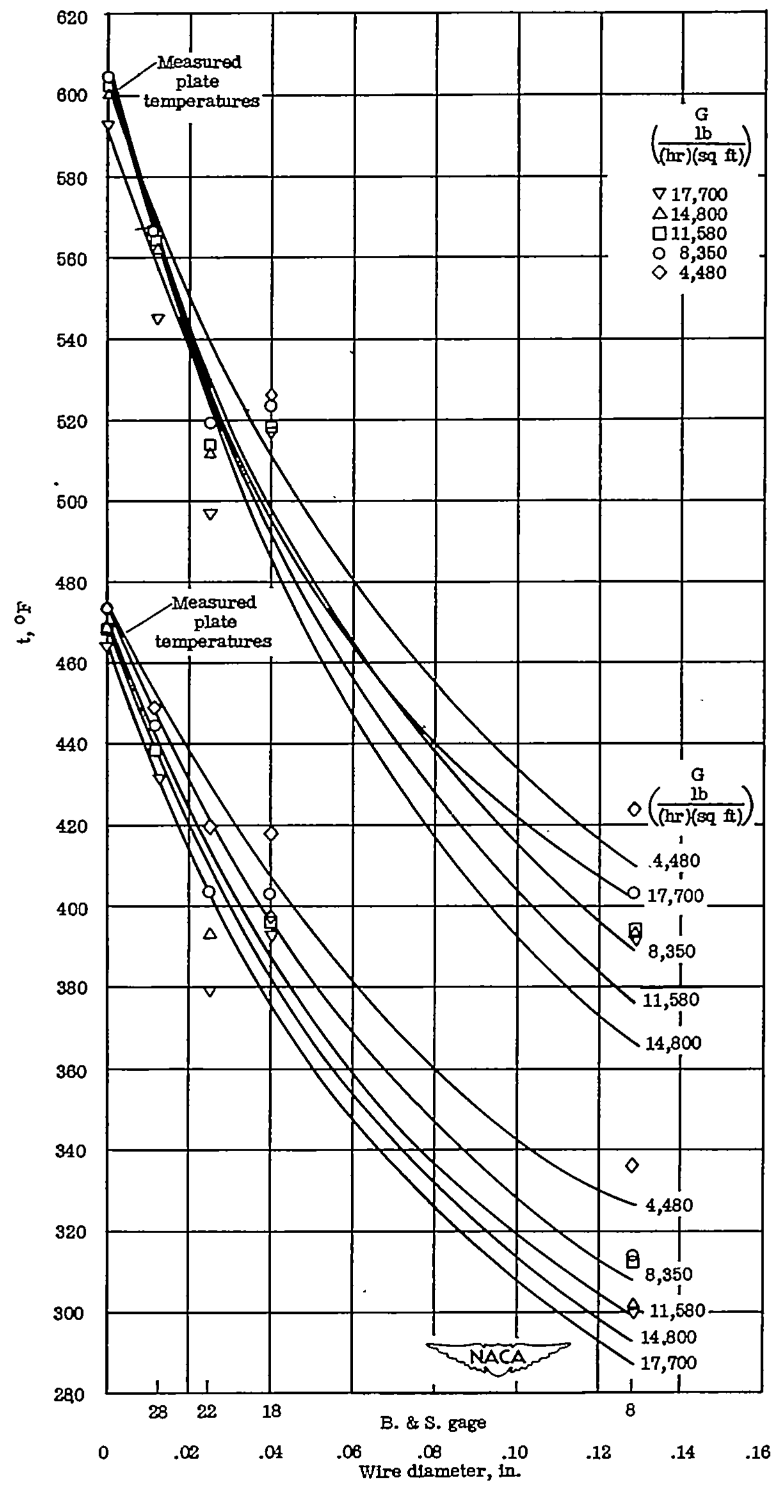


Figure 5.- Predicted curves (calculated from equation (1)) and experimental points for temperature indicated by bare Chromel-Alumel thermocouple wire mounted in vertical position.

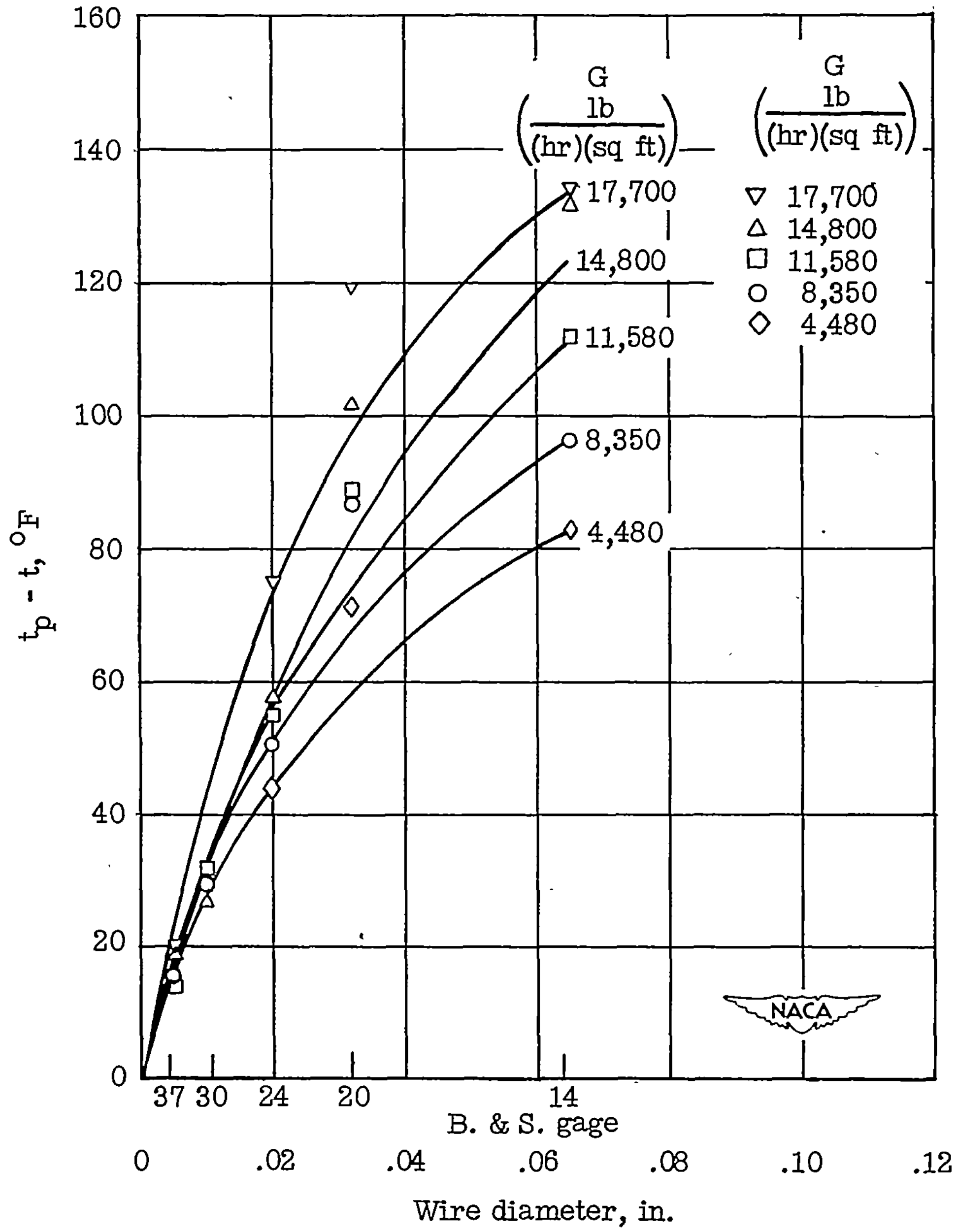


Figure 6.- Thermocouple-error curves for bare iron-constantan thermocouple wire mounted in vertical position. Temperature of test plate t_p, 475° F.

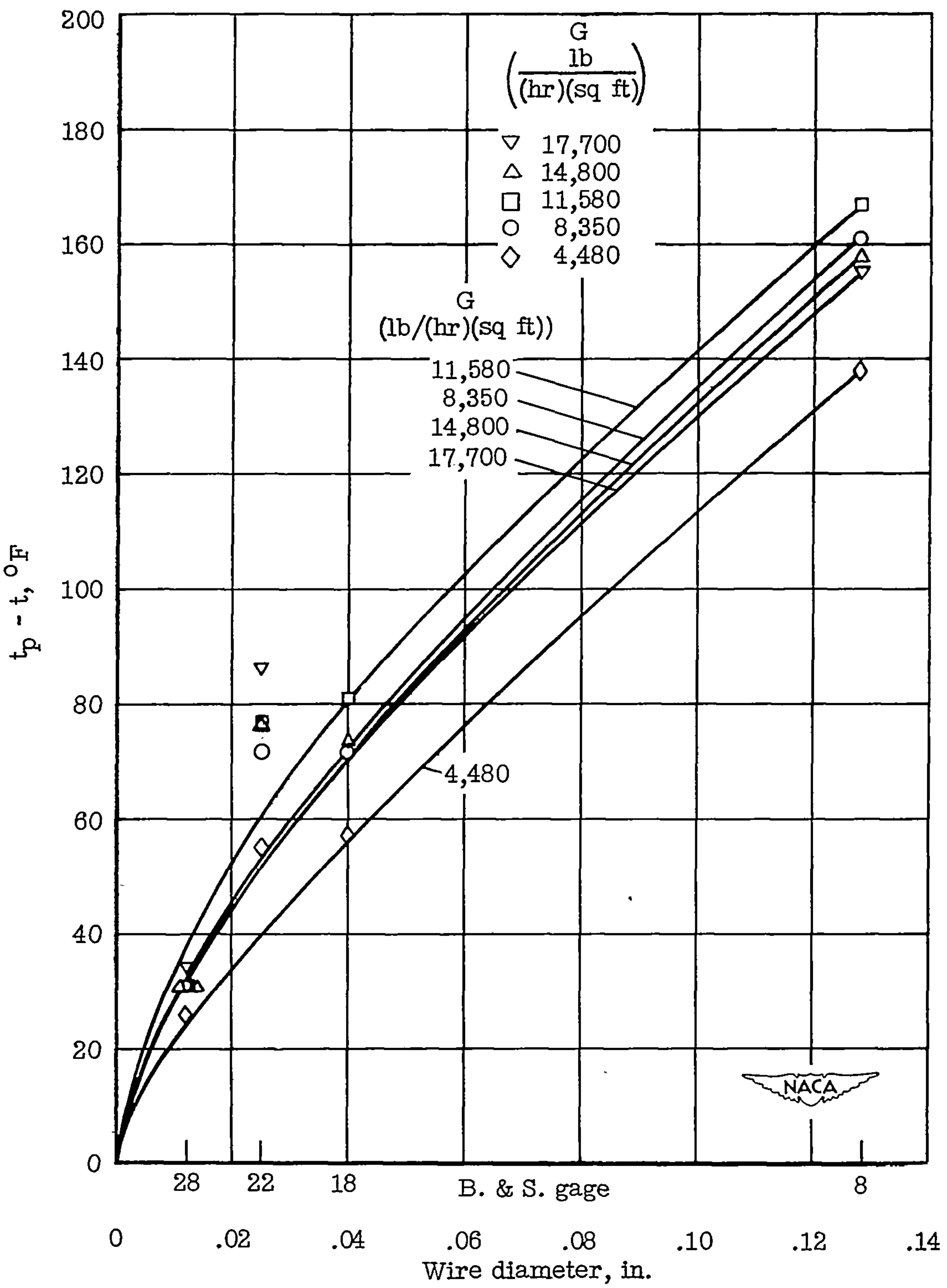


Figure 7.- Thermocouple-error curves for bare Chromel-Alumel thermocouple wire mounted in vertical position. Temperature of test plate t_p, 475° F.

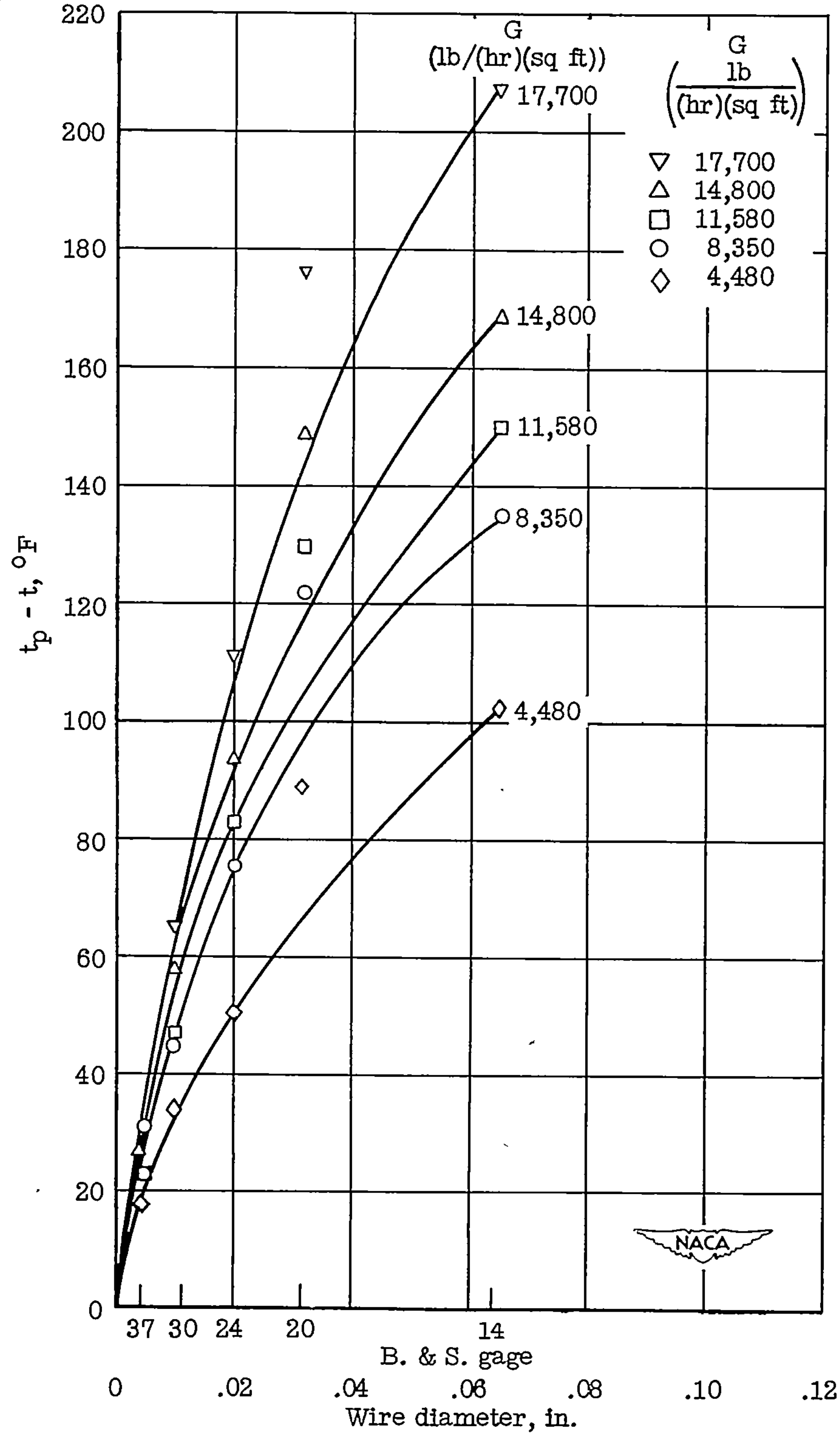


Figure 8.- Thermocouple-error curves for bare iron-constantan thermocouple wire mounted in vertical position. Temperature of test plate t_p, 600° F.

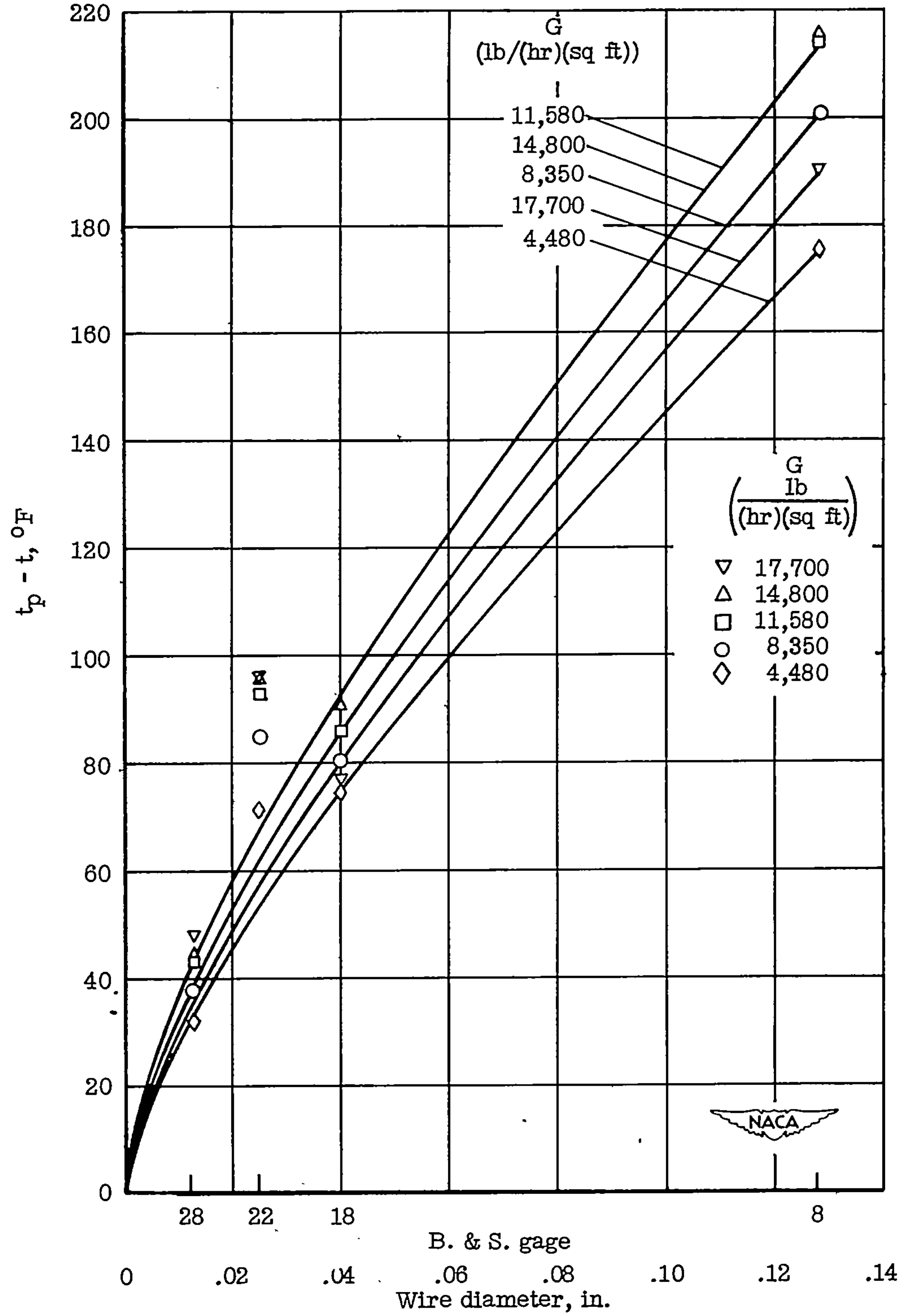
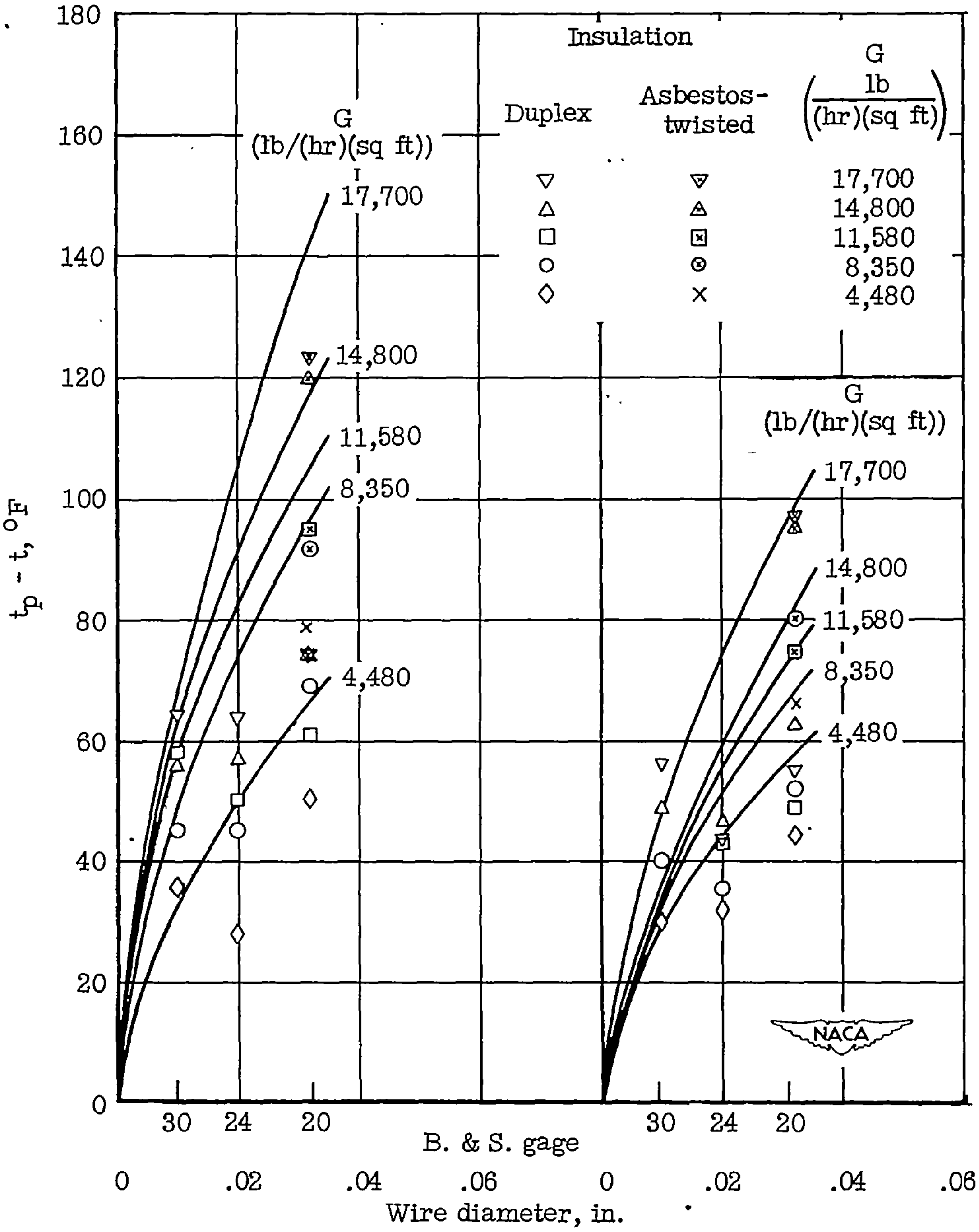


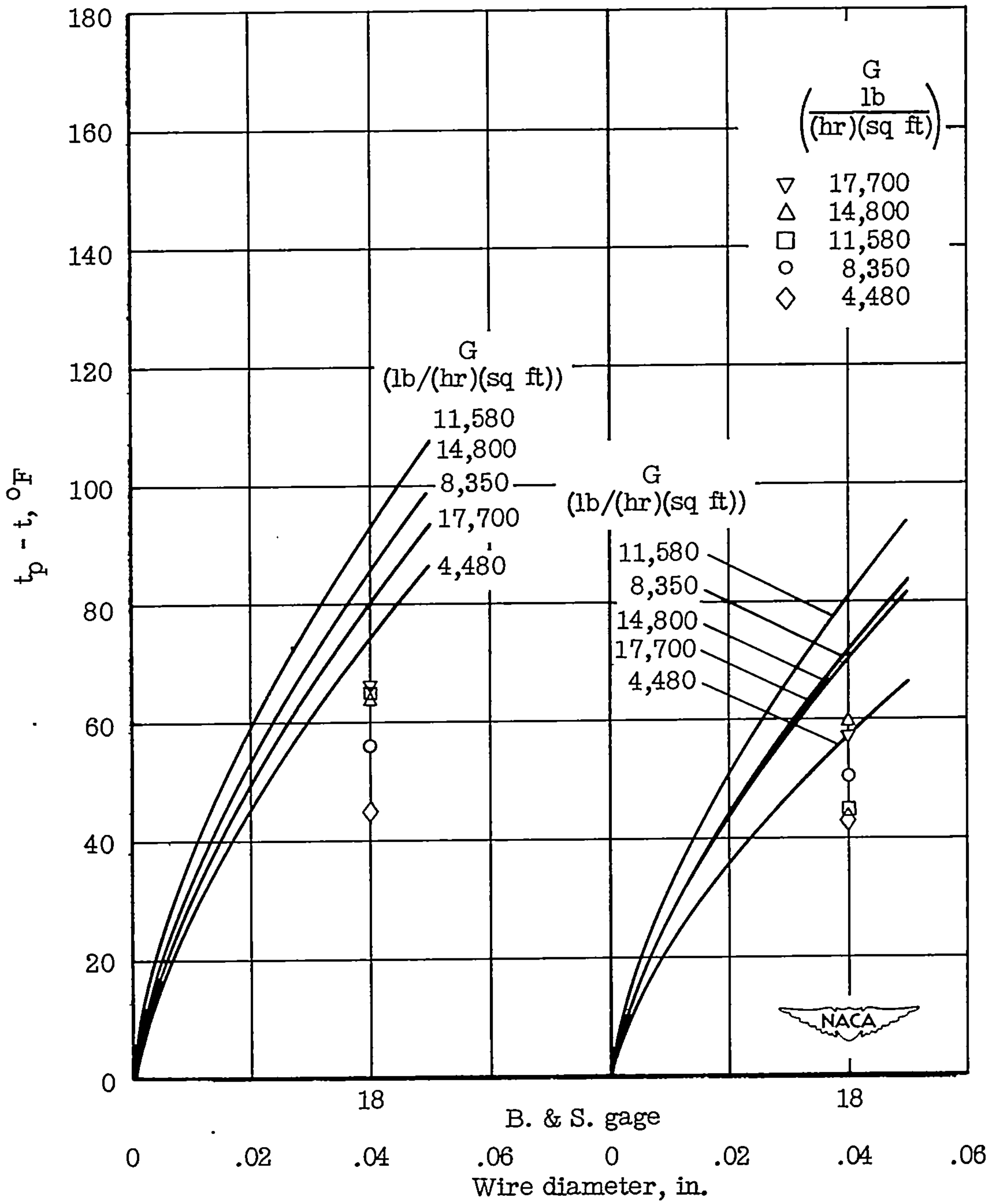
Figure 9.- Thermocouple-error curves for bare Chromel-Alumel thermocouple wire mounted in vertical position. Temperature of test plate t_p, 600° F.



(a) Temperature of test plate t_p, 600° F.

(b) Temperature of test plate t_p, 475° F.

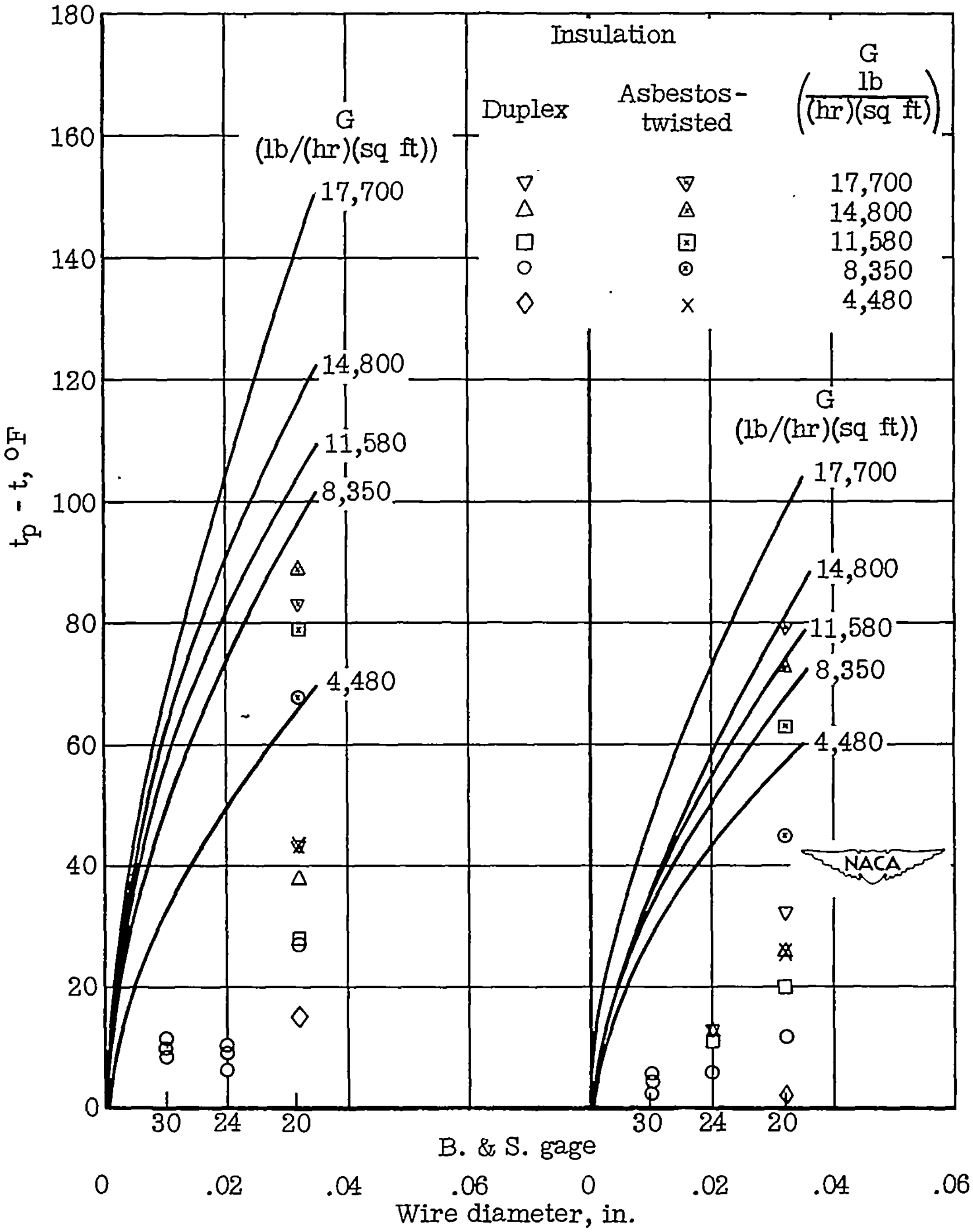
Figure 10.- Experimental points for insulated iron-constantan thermocouple wire mounted in vertical position. Experimental-error curves for bare iron-constantan thermocouple wire mounted in vertical position.



(a) Temperature of test plate t_p, 600° F.

(b) Temperature of test plate t_p, 475° F.

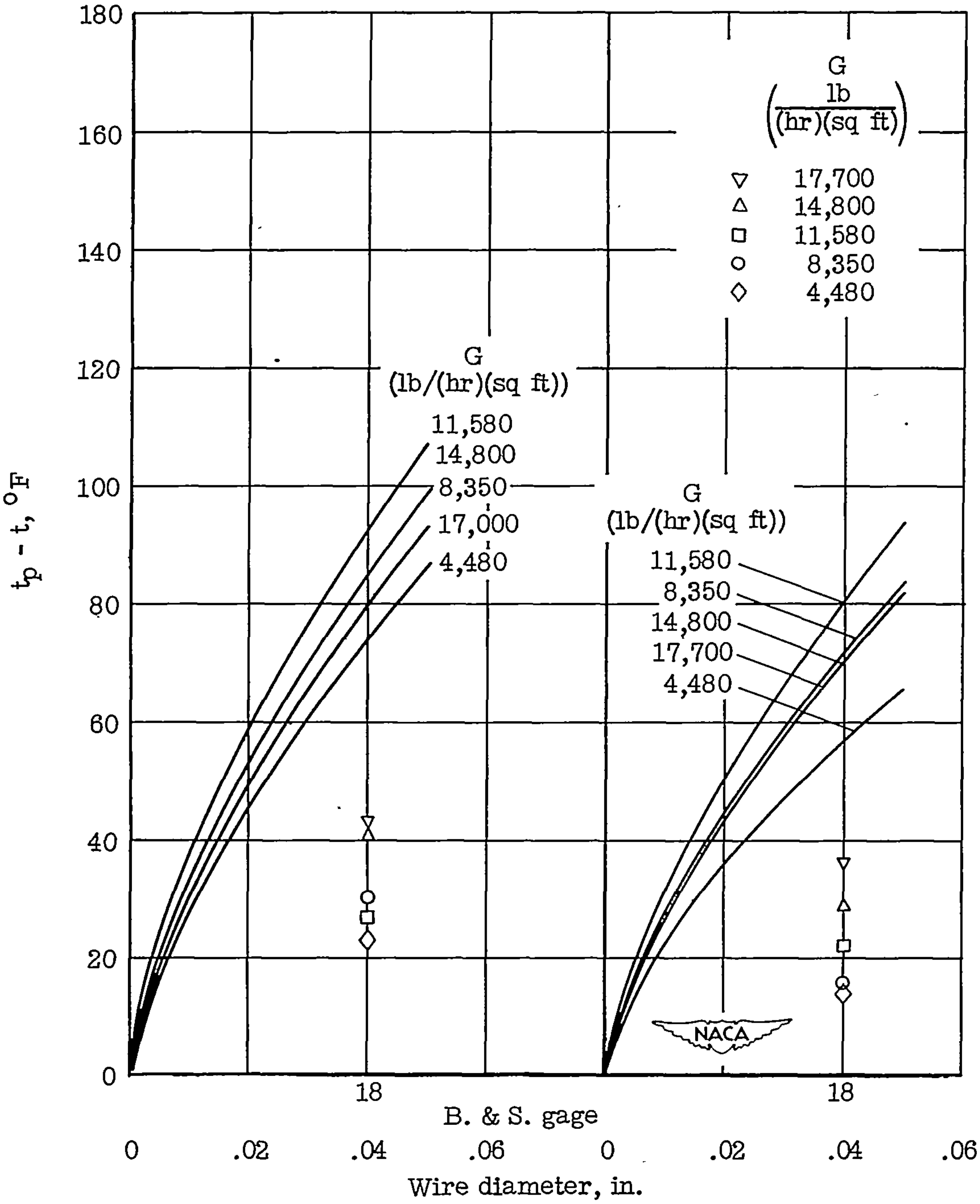
Figure 11.- Experimental points for insulated Chromel-Alumel thermocouple wire (duplex insulation) mounted in vertical position. Experimental-error curves for bare Chromel-Alumel thermocouple wire mounted in vertical position.



(a) Temperature of test plate t_p, 600° F.

(b) Temperature of test plate t_p, 475° F.

Figure 12.- Experimental points for insulated iron-constantan thermocouple wire laid on test plate. Experimental-error curves for bare iron-constantan thermocouple wire mounted in vertical position.



(a) Temperature of test plate t_p, 600° F.

(b) Temperature of test plate t_p, 475° F.

Figure 13.- Experimental points for insulated Chromel-Alumel thermocouple wire (duplex insulation) laid on test plate. Experimental-error curves for bare Chromel-Alumel thermocouple wire mounted in vertical position.

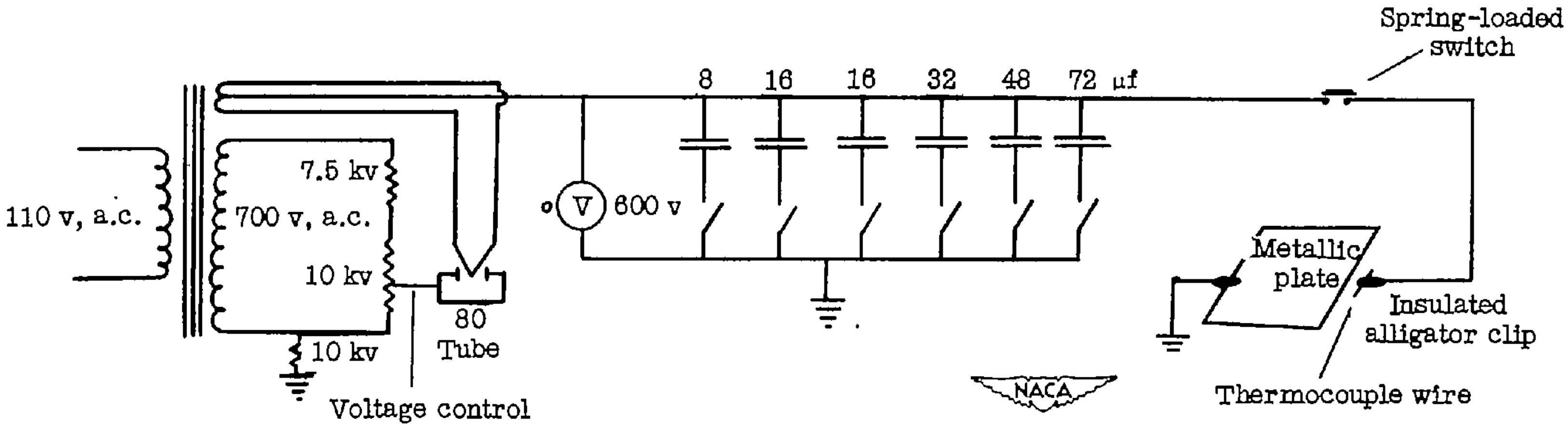


Figure 14.- Wiring diagram of condenser-discharge welder. (Values indicated are name-plate data. Capacities were observed to be 7.3, 15, 15, 30, 43, and 70 μf, respectively.)

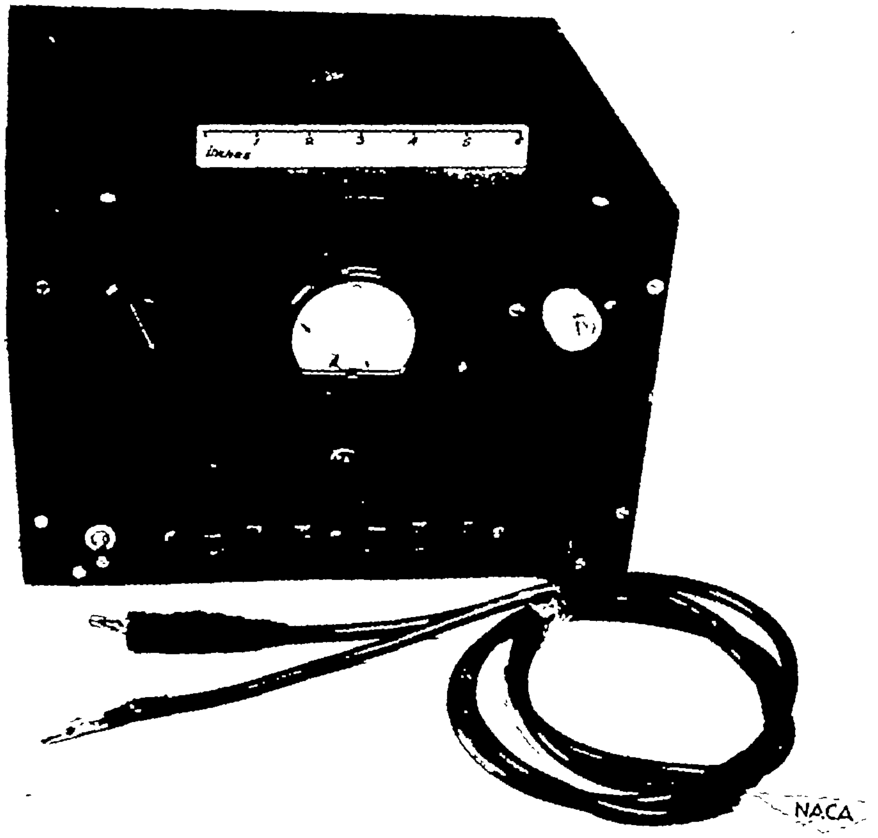


Figure 15.- Condenser-discharge spot welder.