AN ABSTRACT OF THE THESIS OF

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Title: THE DESIGN, CONSTRUCTION AND CALIBRATION OF AN INSTRUMENTED SURFACE FOR CONVECTIVE HEAT TRANSFER STUDIES.

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Abstract approved: ____________
James R. Welty

The purpose of this thesis work has been the design, construction and calibration of an instrumented surface for convective heat transfer studies. The surface is in the form of a flat plate roughly 24 inches wide by 48 inches long. It is made up of 48 individual cells, laminated side-by-side and insulated from each other, which can be individually heated or cooled with water. This results in the ability to impose arbitrary boundary conditions with respect to surface temperature along the plate.

The individual cells were laminated together in three layers. The upper surface facing the fluid stream is a copper strip which incorporates a thermocouple to measure surface temperature. The center section includes a 3/32 inch micarta thermal resistance with

a thermopile wrapped around it and a thermocouple installed on one side to measure temperature. This was then cast into one piece with epoxy resin. The bottom of the sandwich is an aluminum tube which provides a hot or cold water supply to the instrumented plate.

The thermopiles, which are included in 28 of the cells, were then calibrated to indicate heat flux between the aluminum tube and the copper surface. An average value for the thermopile response of 0.0528 mv/Btu/hr-ft^2 was found for all the calibration runs. Included in the body of the thesis are the construction details and calibration data which were obtained during the calibration of the instrument.

The Design, Construction and Calibration of an Instrumented Surface for Convective Heat Transfer Studies

by

Stanley Kent Meyers

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A special kind of thanks is reserved for my wife whose support and good faith have been a source of inspiration throughout my graduate study.

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I. INTRODUCTION

As originally defined, the object of this thesis work was to design and construct an instrument for experimental studies of convective heat transfer under conditions of controlled pressure gradient flow. Later, during the construction of the instrumented surface, the scope of the project was modified to include only the design, construction and calibration of an instrumented surface for convective heat transfer investigations. With this as a starting point the following conditions were established as minimum requirements of any acceptable design:

1. The pressure gradient must be controllable and adjustable.
2. The capacity to measure local values of the convective heat transfer coefficient is required.
3. The turbulence level in the fluid stream must be measurable.
4. Heat transfer both to and from the fluid stream should be possible.
5. Studies should include both the laminar and turbulent flow regimes.

6. Studies are to be made under steady state conditions.

Before design details could be considered, it was necessary to establish the physical quantities that the instrument will have to measure. These will be discussed in the order mentioned in the requirements set forth above.

In considering the free stream with respect to pressure measurements there are two quantitites of interest. The first of these is the static pressure which can be measured with standard pressure tap methods at several points to provide a profile along the plate. The second is the use of pitot tubes to measure the total pressure in the free stream so that the fluid velocity may be determined.

Since the values of the local convective heat transfer coefficient cannot be measured directly this quantity must be obtained indirectly from other measurements. To see what these measurements entail we look at the local convective heat transfer coefficient defined according to:

$$dq_c = dAh_c \Delta T \tag{1}$$

where

dq_c = local rate of heat transfer by convection, Btu/hr-ft^2;

dA = increment of heat transfer area through which dq_c is determined, ft^2;

ΔT = difference between the surface temperature T and a temperature of the fluid at some specified location (usually far away from the surface), °F;

h_c = local convective heat transfer coefficient, Btu/hr-ft^2-°F.

It is apparent that the value of the convective heat transfer coefficient for any particular location can be determined if the rate of heat transfer, the area, the surface temperature, and the free stream temperature can be measured at the same position.

The turbulence level in the free stream can best be measured with a hot-wire anemometer. No discussion of the operation of hot-wire anemometers or of turbulence measurement parameters will be given here. For this the reader is referred to references (1), (2), (5), and (6).

Since it is most convenient to express experimental data in dimensionless form three basic parameters of convection heat transfer and fluid flow will be presently discussed. The first of these is the Reynold's number which is defined as follows:

$$Re = \frac{\rho U L}{\mu} \qquad (2)$$

where

ρ = the density of the fluid in the free stream, lb$_m$/ft^3;

U = the velocity of the free stream, ft/sec;

L = a significant length, ft;

μ = viscosity of the fluid, lb$_m$/sec-ft.

Second is the Nusselt number, given by the expression:

$$Nu = \frac{hL}{k} \tag{3}$$

where

h = convective heat transfer coefficient, Btu/hr-ft^2-°F;

L = a significant length, ft;

k = thermal conductivity of the fluid, Btu/hr-ft^2 (°F/ft).

As can be readily seen the value of the Nusselt modulus is a convenient measure of the convective heat transfer coefficient if it is known. Since we are experimentally determining the convective coefficient we can work in reverse and determine the value of the Nusselt number. This will allow verification of newly developed or previously determined expressions, both theoretical and empirical, for the Nusselt number.

Another valuable parameter is the Stanton number defined as follows:

$$St = \frac{h}{\rho C_p U} = \frac{\dot{q}_0''/\Delta T}{\rho C_p U} \tag{4}$$

where

h = convective heat transfer coefficient, Btu/hr-ft^2-°F;

C_p= specific heat at constant pressure, Btu/lb$_m$-°F;

U = the velocity of the free stream, ft/sec;

q_0'' = heat flux, Btu/hr-ft^2;

ΔT= same as before;

ρ = same as before.

There are, of course, many other parameters that have been developed for use in convective heat transfer work. However, for purposes of heat transfer data measurements the above will be sufficient.

In summary, then, it is apparent that if total and static free stream pressure, local heat transfer rate, area, temperature difference, turbulence, and a significant length can be determined for the desired regions of the instrument it will satisfy the requirements set forth with respect to the needed physical measurements. Other factors such as the laminar and turbulent flow regime requirements are of secondary importance since this type of requirement can be easily controlled by adjustments of the flow channel.

II. DESIGN CONSIDERATIONS

General Considerations

Due to the empirical nature of many convective heat transfer studies there have been many instruments and test procedures developed. In the investigation of forced convection with controlled pressure gradients these are generally flat surfaces which are instrumented to give surface temperature and a method of determining the heat flux being transferred to the adjacent fluid stream.

Methods range from electrically heated surfaces such as used by A. P. Hatton and V. A. Eustace (3) to surfaces that are heated by steam such as used by Kestin, Maeder, and Wang (4). The electrically heated models are a close approximation to the constant heat flux boundary condition while the steam heated surfaces conform closely to the constant surface temperature boundary condition. Methods of determining the heat flux vary from the measurement of the electrical power input in the electrical models to the use of calorimeters.

P. M. Morretti (8) carried out some experimental investigations using a flat heat transfer surface that was constructed in such a manner that the surface temperature of the plate could be arbitrarily varied in the direction of fluid flow. This meant that the plate could be used for investigations involving temperature steps, varying surface temperature profiles, and the common constant surface temperature and constant heat flux boundary contions. The free stream pressure gradient was then controlled by varying the shape of the flow channel cross section along the axis of flow. The construction of this plate was also discussed by P. A. McCuen (7).

Due to the versatility of the flat plate used by Morreti and McCuen it was decided that this approach to the problem would be most suitable. This would allow the maximum use of the instrument for research purposes as it would not be limited by an inability to impose arbitrary surface temperature boundary conditions. This generality was the big advantage in this approach to the design. The disadvantage, which was to become more apparent as construction was undertaken, was the complexity and tremendous number of individual components necessary to make up the completed plate.

At this point the general design of the surface assumed the following form. The surface was to be a flat plate roughly 48 inches long by 24 inches wide. The plate itself would be made up of 48 individual cells, each one insulated from the adjacent cell by a 0.060 inch Micarta strip. Each cell then could be operated essentially isothermally and would be independent of the cell adjacent to it. This would allow adjacent cells to be operated at different temperatures thus allowing arbitrary surface temperature profiles.

The cell was constructed in three parts and then laminated together. The surface of the cell facing the fluid stream is a 1/8 inch by 1 inch by 24 inch copper plate with a thermocouple embedded in it to measure the surface temperature. The embedding was accomplished by milling a shallow groove in the bottom of the copper plate and installing a 28 ga. iron-constantan thermocouple with the measuring junction at the center of the plate. The center section of the cell is a thermal resistance with 28 (all even numbered ones plus numbers 1, 3, 23, and 25) of the center sections incorporating a heat flux transducer or 'heat meter' to determine the heat flux between the surface and an aluminum tube at the bottom of the cell. The aluminum tube is 1/2 inch by 1 inch by 1/8 inch wall with aluminum plugs in each end. The plugs were then drilled and a 1/4 inch O. D. aluminum tube inserted to provide for tubing connections to the rectangular tube. Hot or cold water may then be fed to the aluminum tube on the bottom of each cell to provide either a heat source or sink. The heat meters were then calibrated to measure the energy exchange between the surface of the cell (i. e. the copper plate) and the aluminum tube at the bottom of the cell. Figures 1 and 2 show the conception of the plate at this point.

Along with the instrumented surface the instrumentation and circuitry required to record surface temperature and heat flux was necessary. The instruments used and the circuits necessary for their

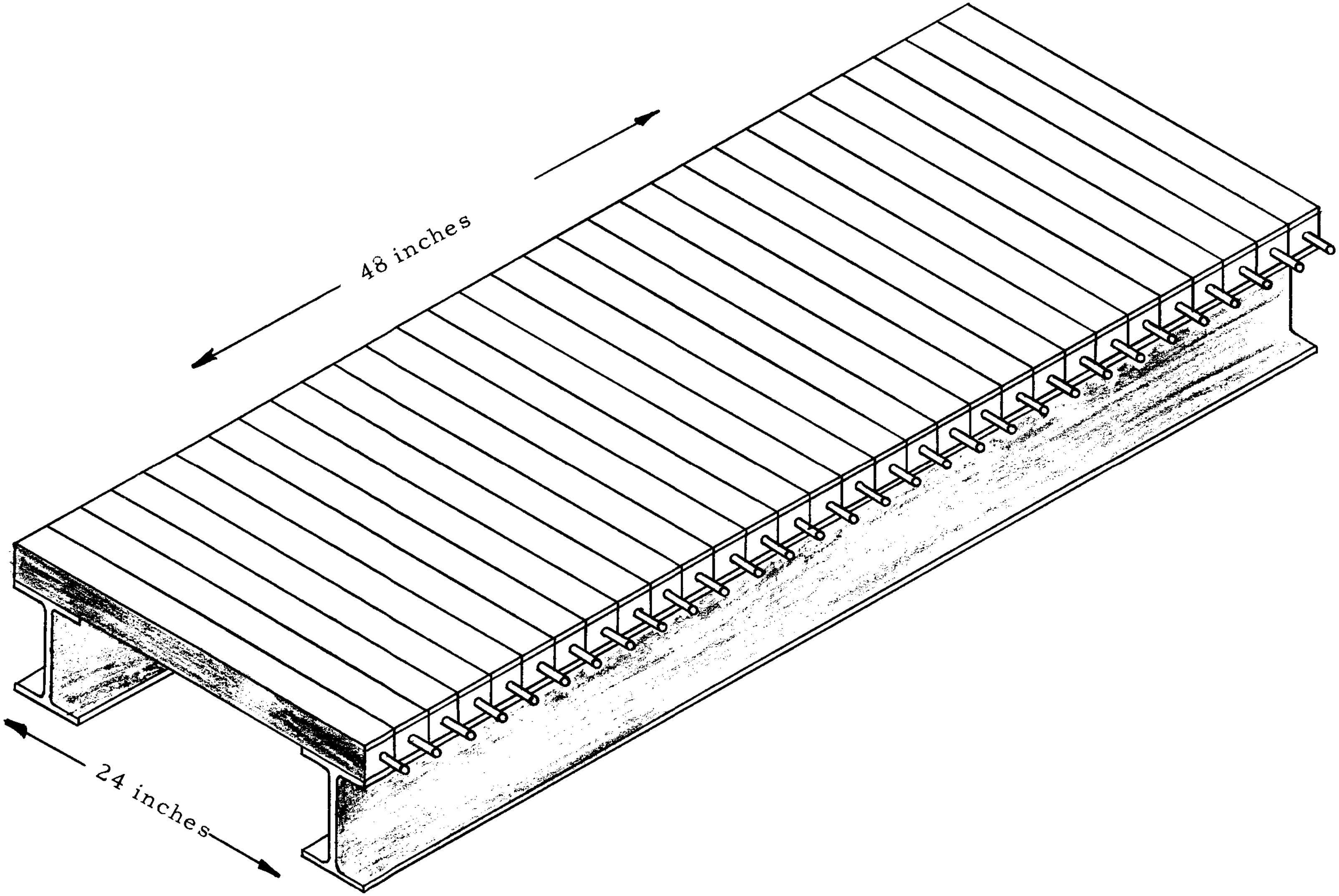

Figure 1. Plate assembly conception.

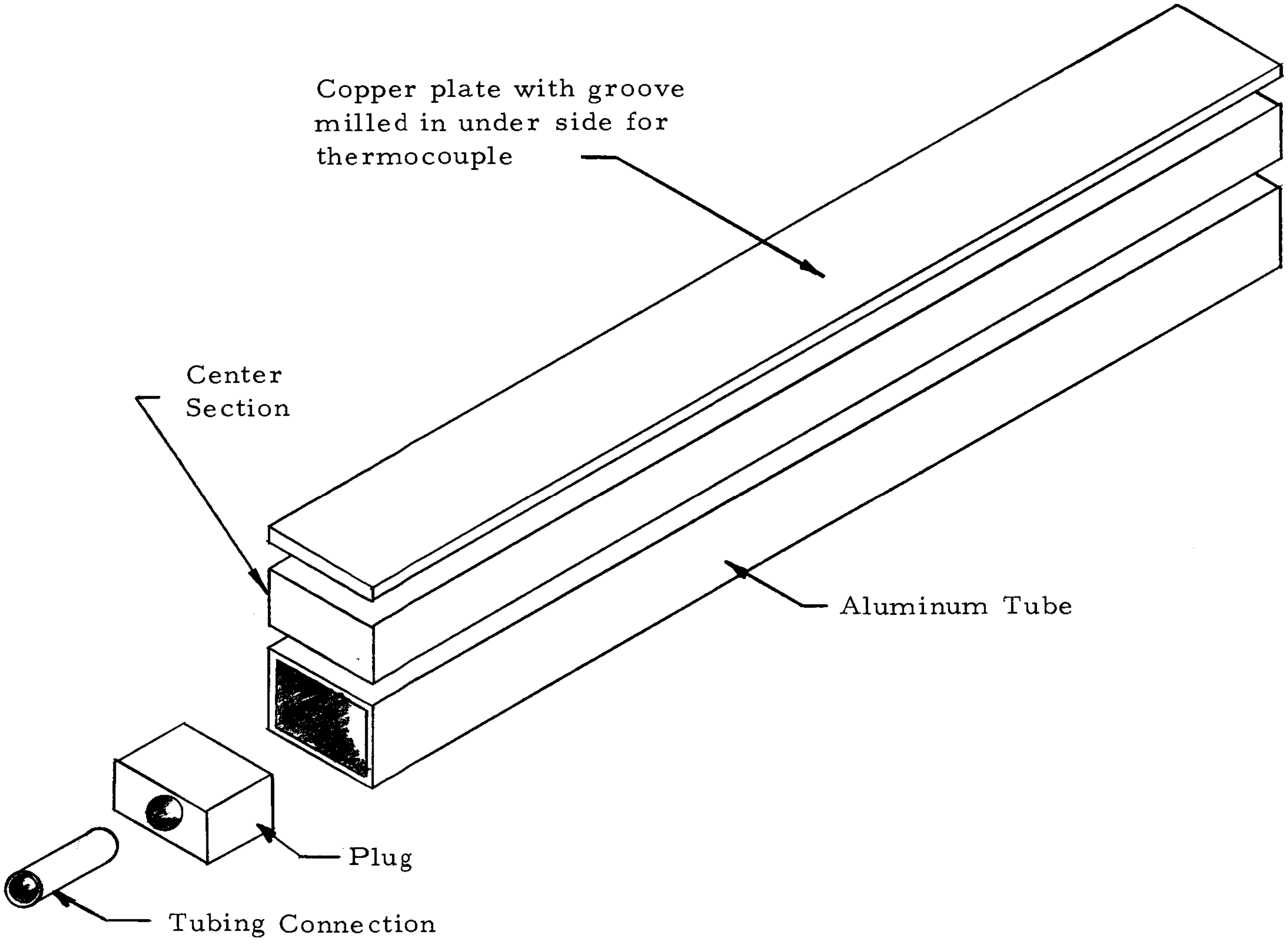

Figure 2. Cell construction conception.

operation are discussed further in the next section.

Detail Considerations

With the form of the plate decided upon, details required to construct a workable project had to be decided. McCuen (7) refers to the use of a Beckman and Whitley (now Packard Bell Space and Systems Division) thermopile heat flux transducer sandwiched in bakelite between the copper plate and the aluminum tube for measurement of heat flux. Correspondence with Beckman and Whitley determined the price of similar transducers at $100.00 each. Subsequent correspondence with other instrument manufacturers was undertaken without favorable results. At this point design and construction of a heat meter to replace the Beckman and Whitley models was undertaken.

The heat meter designed makes use of a thermopile to measure the temperature difference across a thermal resistance placed between the copper plate and aluminum tube. Since the temperature difference across any thermal resistance is directly related to the heat flux, the emf output of the thermopile, when properly calibrated, is an indication of the heat flux passing through the resistance.

As a design criterion the published response of the Beckman and Whitley transducers of 0.0417 Mv/Btu/hr-ft^2 was decided upon. There are two factors that will effect the emf output of the heat meter.

The first of these is the thickness of the thermal resistance since this is directly related to the temperature difference across the resistance for any given heat flux. The second factor is the number of junctions in the thermopile itself. Since the output of the thermopile is a multiple of the number of junction pairs the emf is directly proportional to the number of junction pairs used. The thermopile finally incorporated was made of 24 ga. iron-constantan with the number of junction pairs set at 25. The thermal resistance is a 3/32 of an inch thick linen grade micarta which has a thermal conductivity of approximately 5×10^{-4} cal/sec-cm-°C. Theoretical calculations show that the response of this meter should be 0.0461 Mv/Btu/hr-ft^2 which is well within the limits of the design criteria.

The individual thermopiles were welded with a small hand operated spot welder. After wrapping the thermopiles around the micarta strip and attaching copper lead wires, a thermocouple was installed on the top side of each strip to measure the thermopile temperature. This thermocouple will allow any corrections to be made in the thermopile output in case of temperature dependency of the thermopile emf. The center section of the cell was then finished by casting an epoxy resin around the thermopile, thermocouple, and thermal resistance in order to provide a smooth contact surface for lamination to the copper plate and aluminum tube. The epoxy system used was a CIBA Araldite 502/956 resin-hardener system that was available locally. Photographs of the cells in various stages of construction are shown below.

The 48 individual cells were then laminated together with Devcon "2-ton" epoxy adhesive. Twenty of the cells were made without incorporating the heat meter or the thermopile thermocouple. The micarta strip was used to insure that the thermal resistance between the copper strip and aluminum tube was the same in all cells. All of the cells contain the thermocouple in the copper strip to record surface temperature. The epoxy adhesive used is not recommended for use above 250° F; for this reason this limit should be observed during experimental investigations.

After lamination the 48 cells were machined flat on both sides perpendicular to the copper face. This was accomplished by using a large milling machine with a fly cutter which was made available by Mater Machine Works, Corvallis, Oregon. This insured proper alignment when the cells were laminated side-by-side to form the final 48 inch long instrumented surface.

The 48 cells were then laminated side-by-side with the micarta strips between each of the cells. The lamination was done by clamping the cells together on a plane table, copper face down, to form as smooth a surface as possible in order to minimize the amount of finishing required. After lamination the bottom side of the plate (aluminum tubes) was secured to two six-inch I beams to form a frame

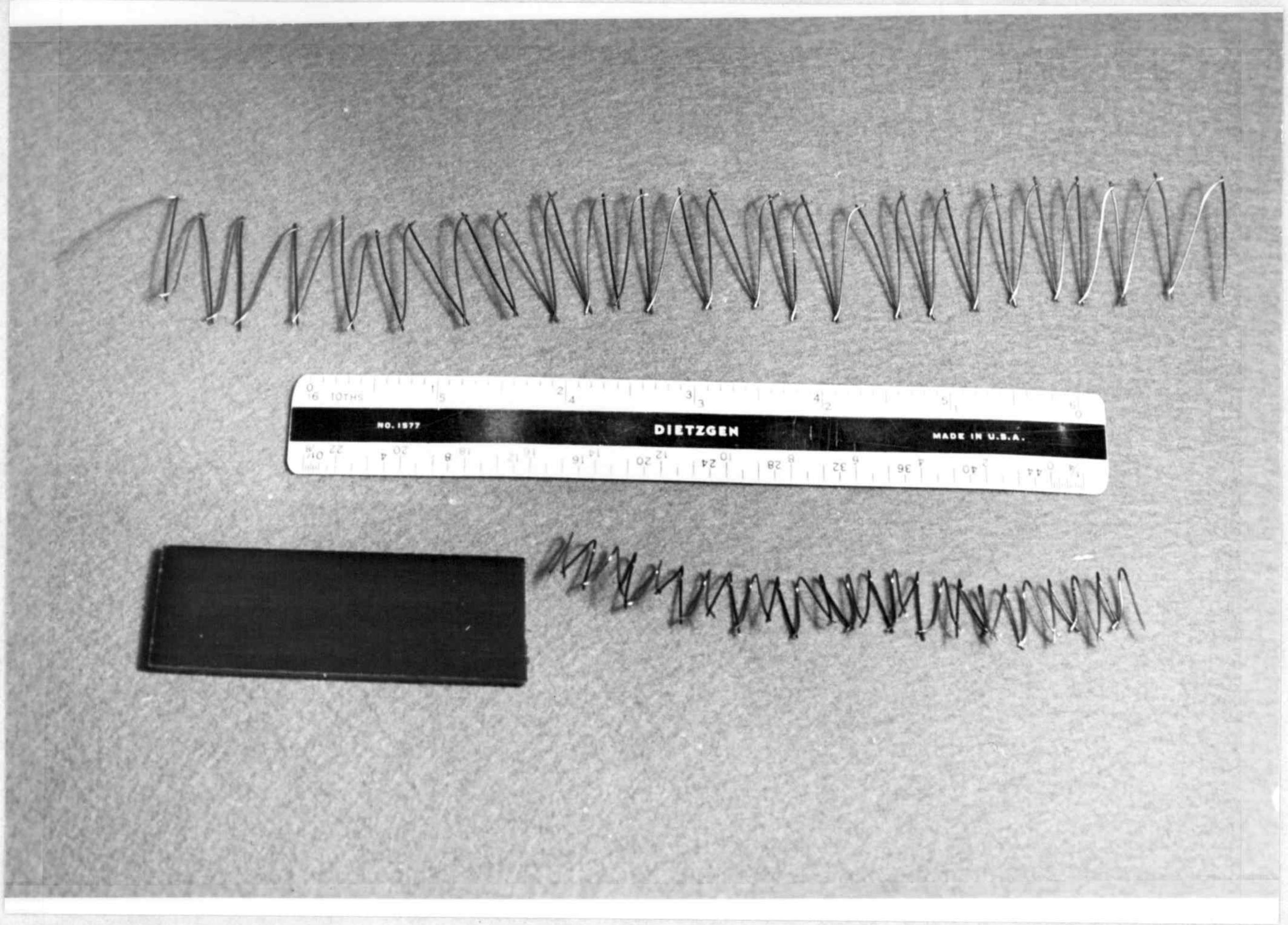

Figure 3. Thermopile, wrapped thermopile, and piece of micarta.

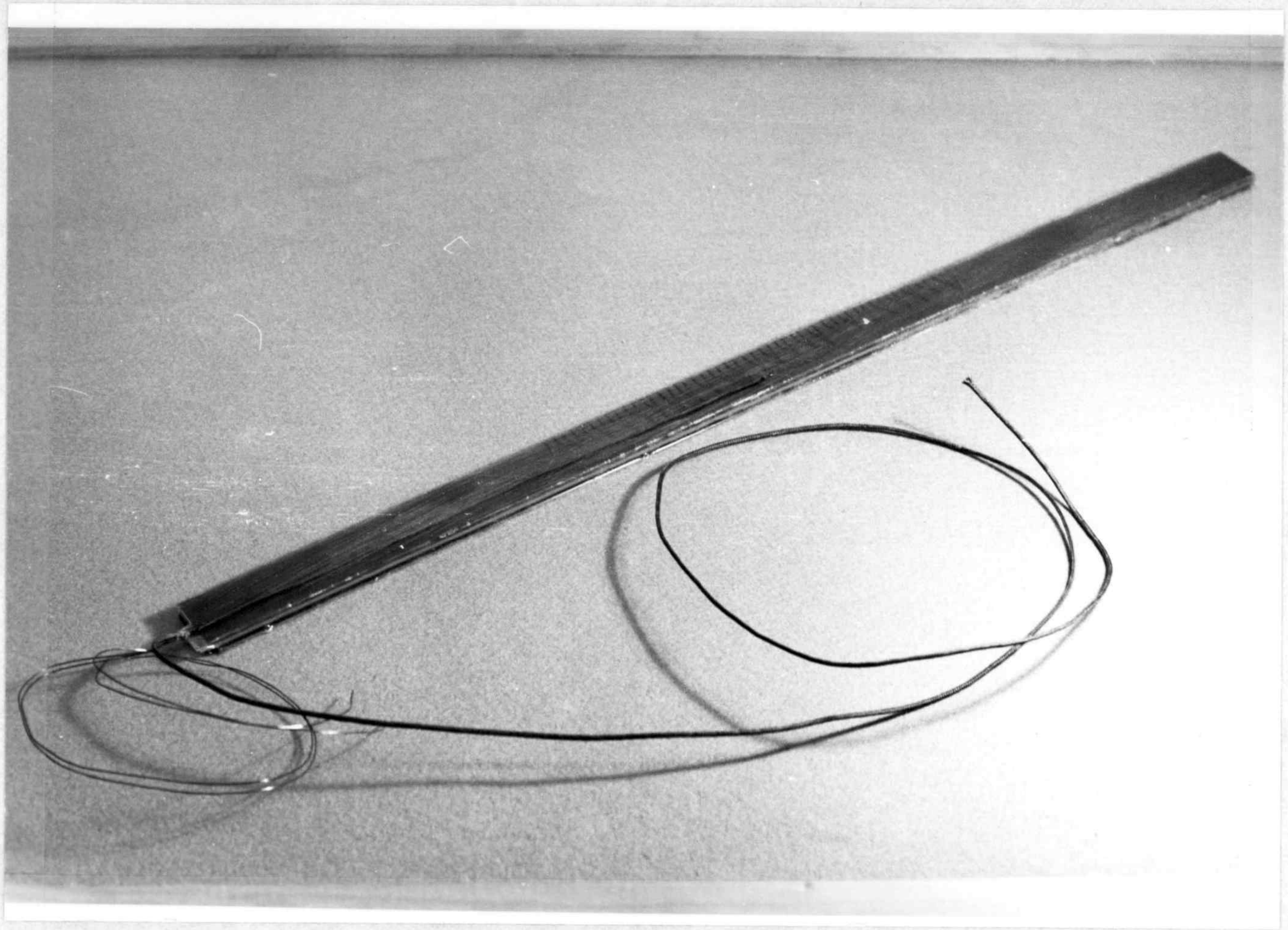

Figure 4. Finished center section with thermocouple and thermopile.

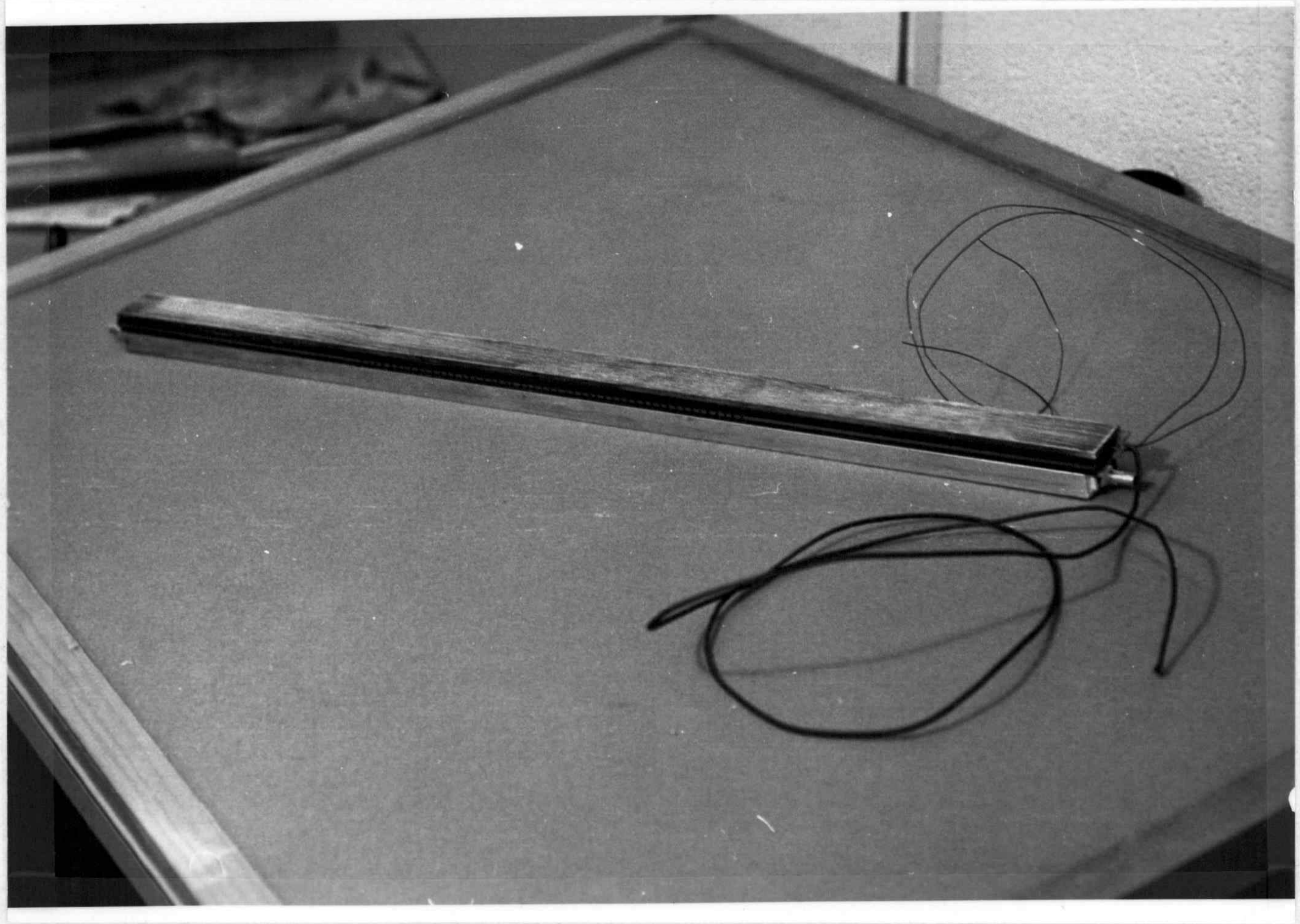

Figure 5. Finished cell.

and provide rigidity. The copper surface was ground on a large surface grinder and then hand polished to a smooth surface. At this point the surface was finished except for the wiring necessary to provide the instrument readouts.

Both the surface temperature and the thermopile temperatures were measured by means of a Leeds and Northrup 8686 millivolt potentiometer. This instrument was used with an ice bath for reference junction temperature. The wiring for the thermocouple measurements is as shown on the circuit diagram, Figure 6. Rotary switches were used to accomplish the necessary thermocouple selection. Pin connectors are used between the thermocouples and the lead wires so that the instrument board can be detached from the instrumented plate for ease of transport. All pin connectors, for both thermocouples and thermopiles, are located in a constant temperature zone box to eliminate any errors in the instrument readings.

The circuit diagram for the thermopile output is shown in Figure 7. It is essentially the same as for the thermocouples with the exception that no reference junction is required as the heat meters record a temperature difference and are not used to determine actual temperatures. In recording the output of the thermopiles a vacuum-tube-voltmeter can be used since it has a high internal resistance which eliminates the requirement to correct for changes in the lead resistance to the thermopiles. However, a VTVM with the required

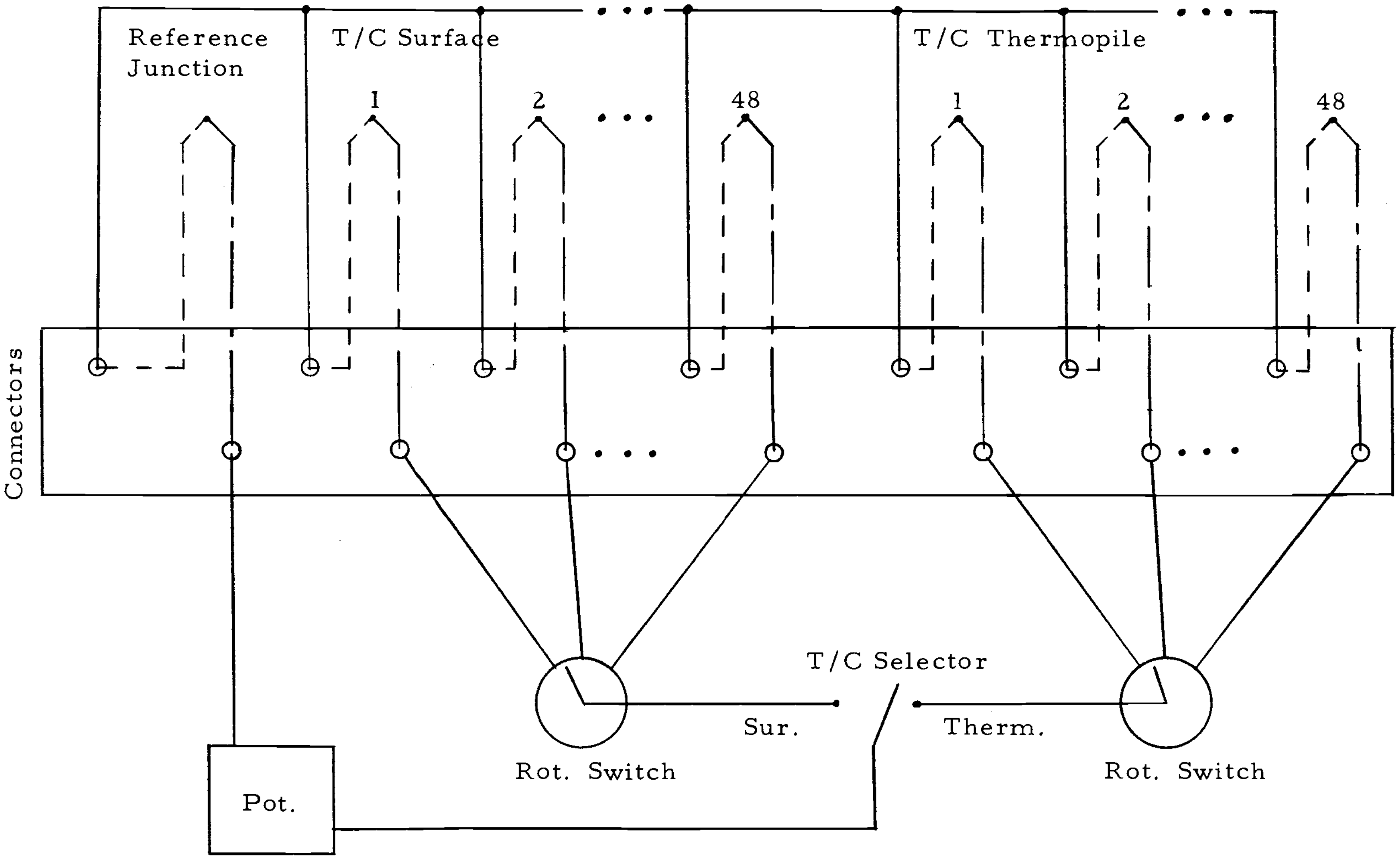

Figure 6. Thermocouple circuit.

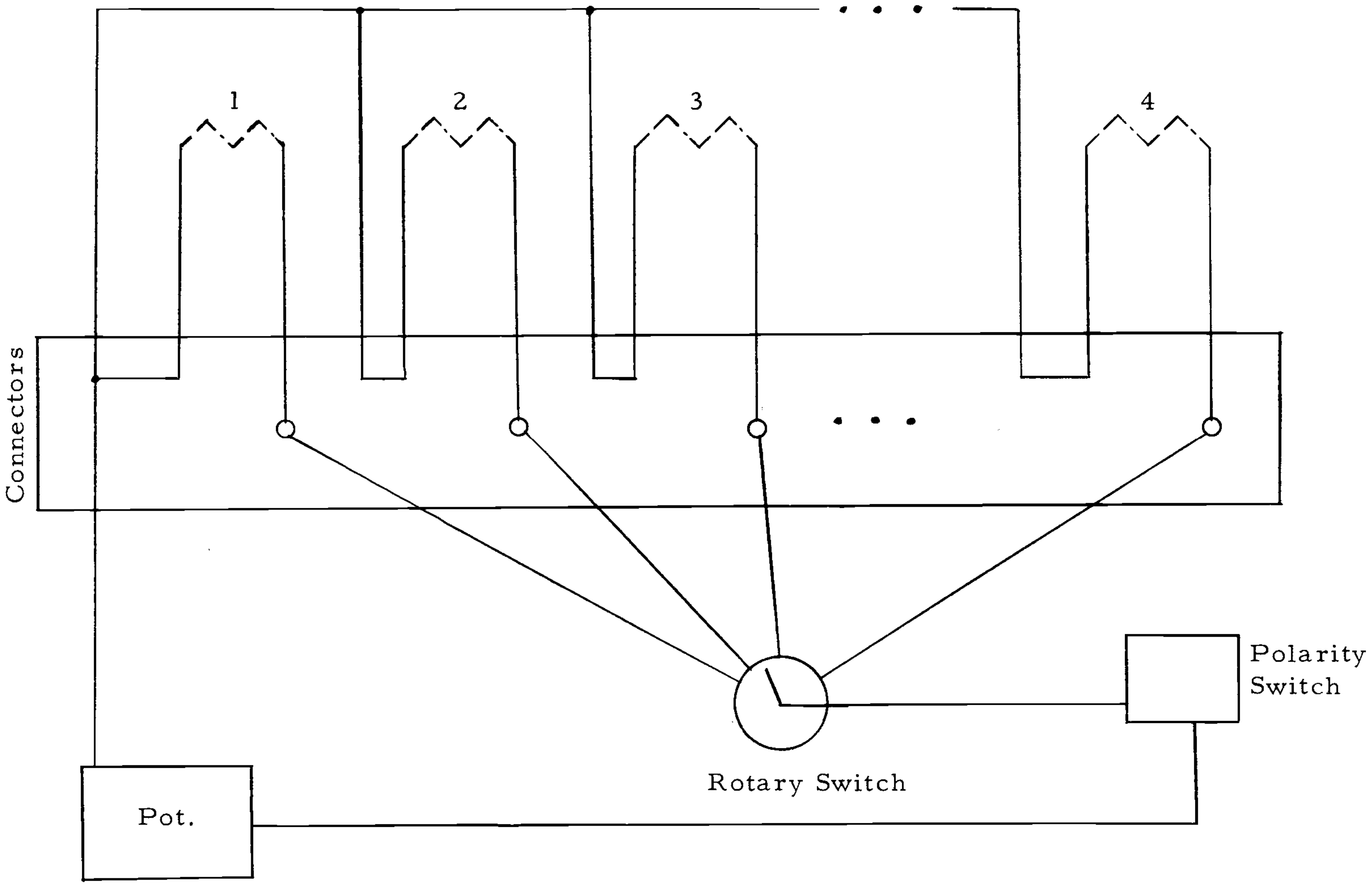

Figure 7. Thermopile circuit.

sensitivity was not available so a second potentiometer was used to record thermopile outputs. Once again, rotary switches were used to make thermopile selection.

A photograph of the finished circuit board is shown in Figure 8. It should be noted that although the surface and thermopile temperature thermocouples make use of a common ice junction the surface temperature selection is made on one set of switches while the thermopile temperature and thermopile emf selection is made simultaneously on the other set of switches. A toggle switch is then used to select either surface or thermopile temperature.

After final assembly the plate had a finished length of 46-1/2 inches with the center-to-center distance of adjacent cells 31/32 of an inch. A photograph of the finished surface with instrumentation is shown on the following page.

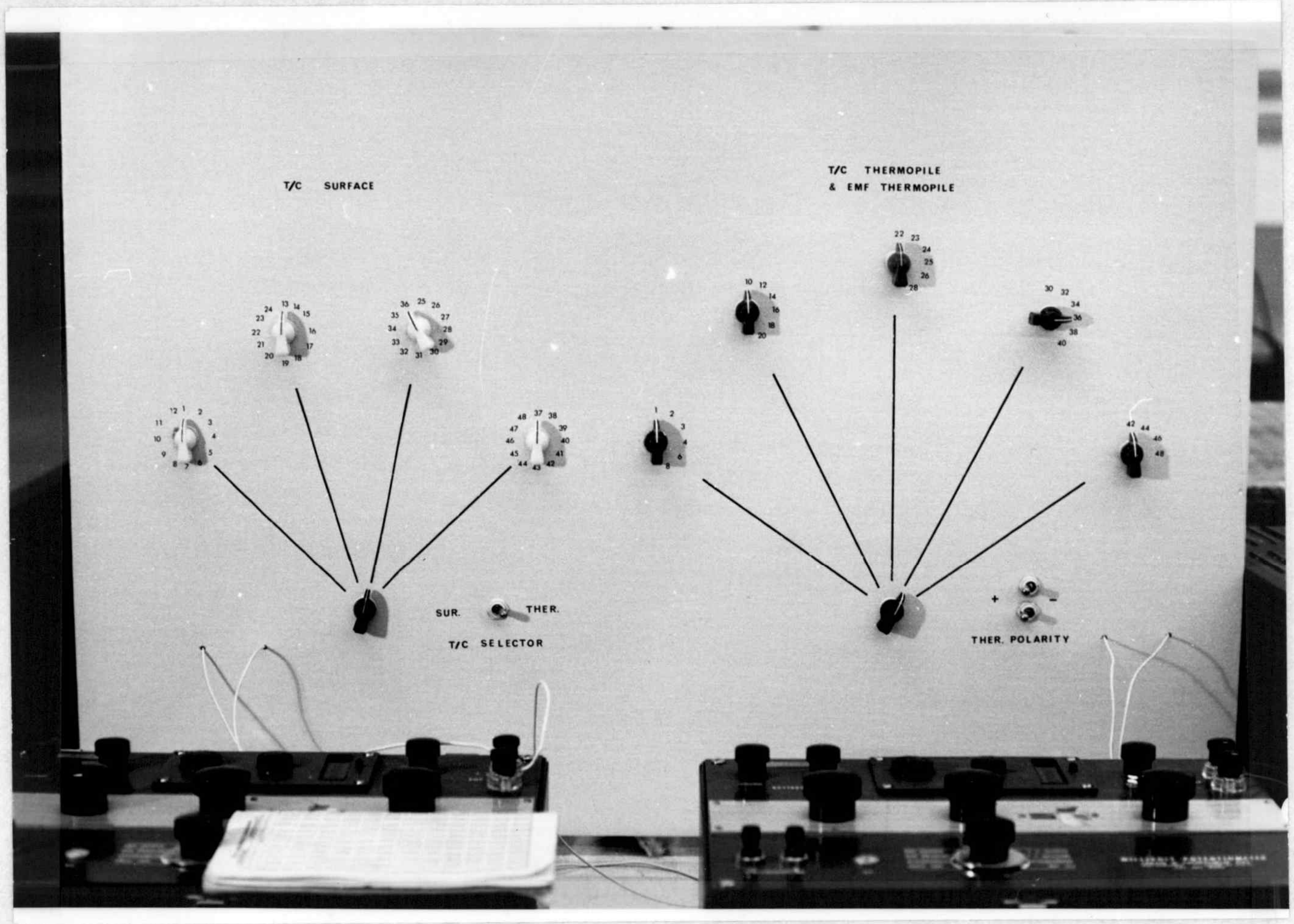

Figure 8. Circuit board.

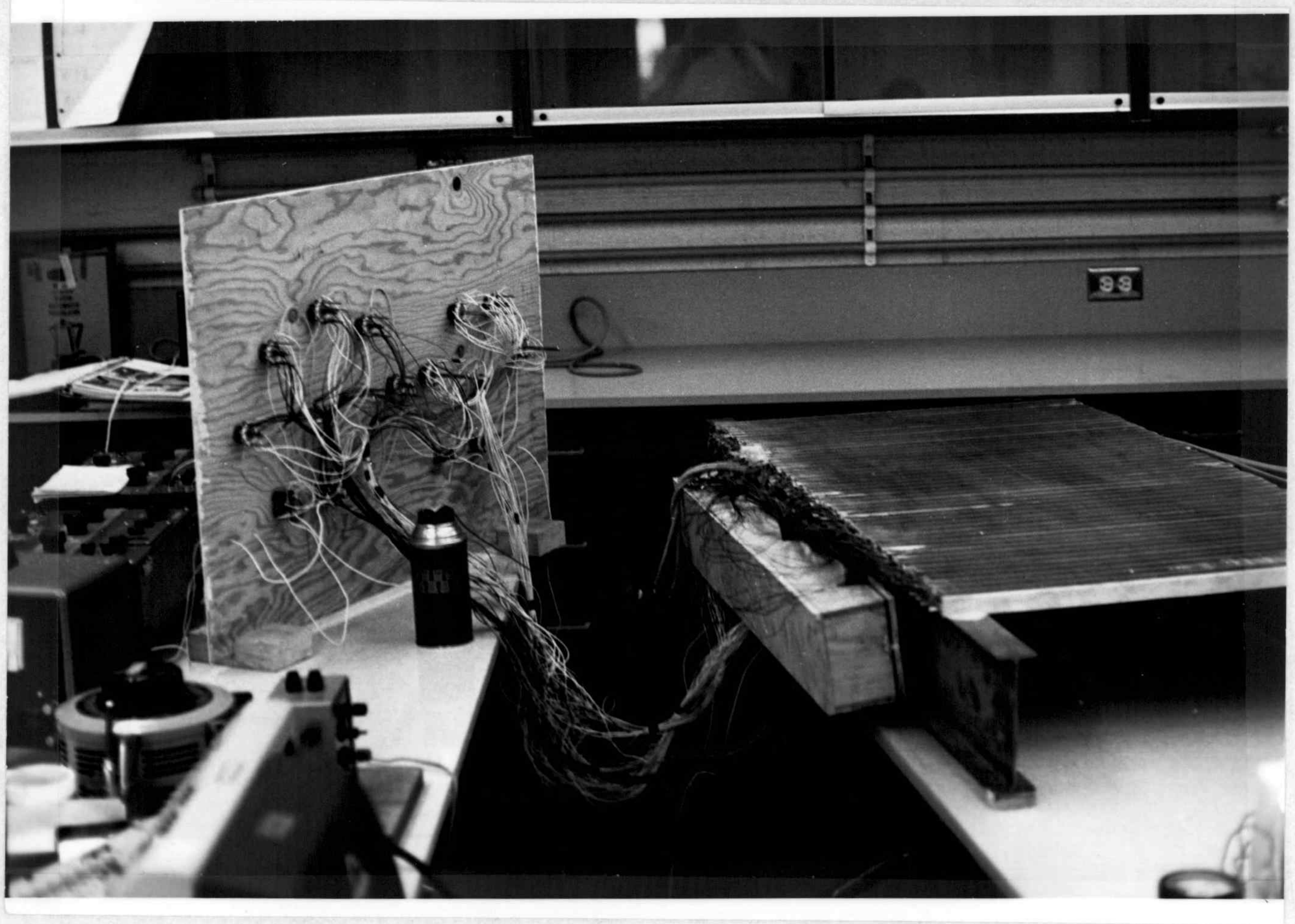

Figure 9. Plate and circuit board.

III. CALIBRATION TECHNIQUES AND RESULTS

After completing the construction of the instrumented surface it was necessary to calibrate the plate in a manner so that the thermopile responses could be translated directly into indications of the heat flux between the copper surface and the aluminum tube on the bottom. In order to do this the emf outputs of the thermopiles for a known heat flux were required.

In order to provide a known heat source three strips of 1/4 inch wide by 0.0015 inch thick Nichrome ribbon were used as strip heaters. The heaters were placed on a 1/4 inch thick asbestos pad, six inches wide and 24 inches long, on the back of which was placed a 4 inch thick pad of sytrofoam to provide further insulation. The three strips were placed with the center-to-center distances corresponding to the center-to-center distances of the cells that make up the instrumented surface.

The two heaters on the outside were connected in series and an AC variable voltage transformer was connected to the leads. The center strip heater was then connected to a Heathkit Model IP-12 battery eliminator which was used as a variable voltage DC power supply. A Raytheon voltage stabilizer was used to stabilize the line voltage input to the two power sources. The DC supply was used since more sensitive instruments were available to monitor DC voltage and current than for the corresponding AC parameters. The resistance of the center strip was then accurately determined by a wheatstone bridge. The value of the resistance, corrected for operating temperature according to the manufacturer's specifications, along with the measurement of the current, allowed the wattage input to the heater to be accurately determined. Figure 10 shows the circuit arrangement used for the calibration set-up.

During the calibration the three strip heaters were placed so that each heater ran the length of one of three adjacent cells in the surface. The heaters were then adjusted so that the temperature of the center cell was the average of the temperature of the cells on each side of it. This eliminated any net lateral heat flux in the center cell. The watt input to the center strip was then calculated from the current reading and the corrected resistance of the heater. During the calibration runs the strip heaters were electrically insulated from the copper surface by a 0.005 inch thick mylar sheet. The power input to the center strip was then converted to an indication of the heat flux through the center cell by the following equation:

$$q = (MF)(W) \tag{5}$$

where

MF = multiplying factor

W = watts = I^2R.

The multiplying factor used contains a conversion factor to

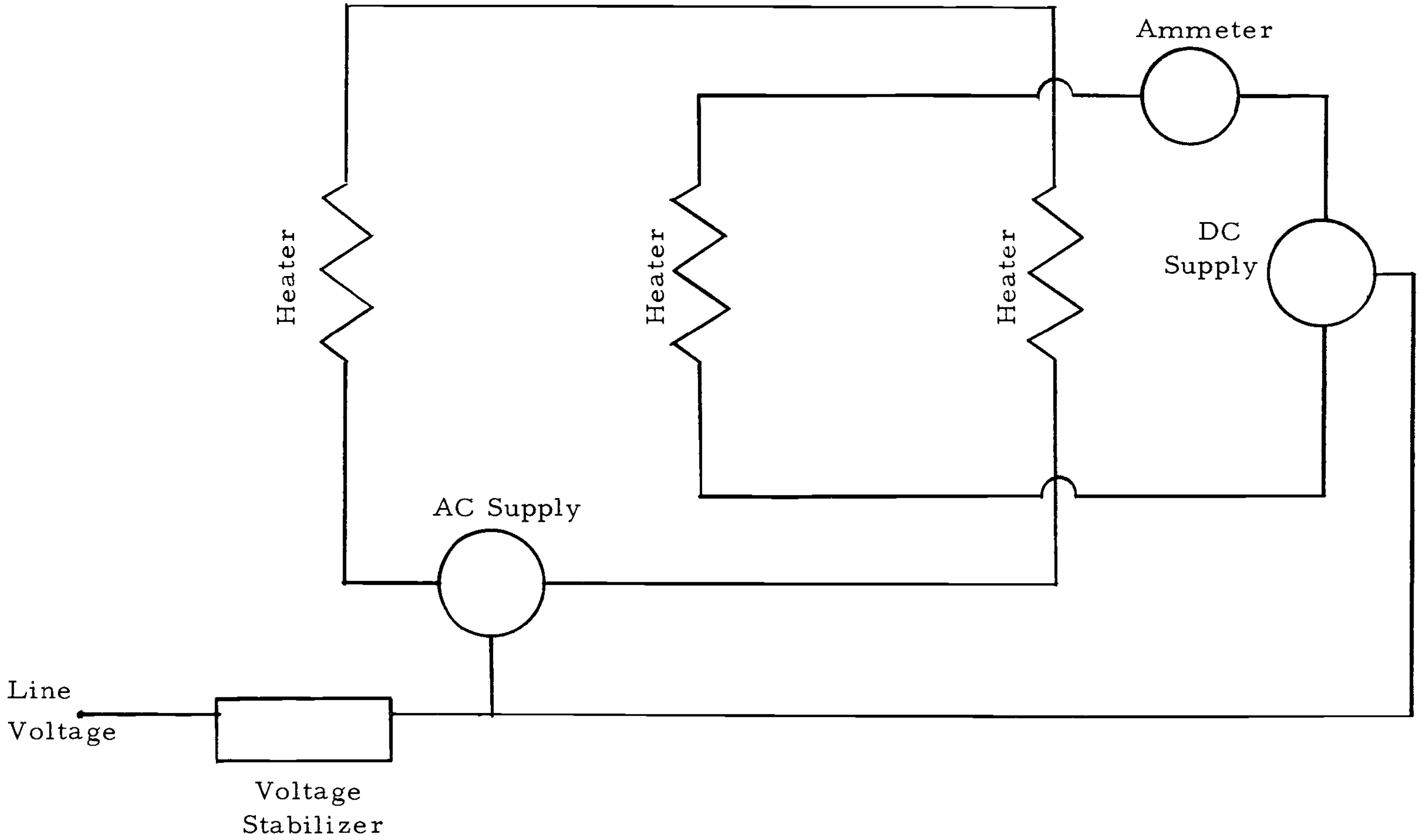

Figure 10. Calibration circuit.

convert the power input to the heater into thermal units of Btu/hr. In addition it contains a factor to relate the power input to the area of each cell. The variance in the multiplying factors is due to the varied length of the copper strips which were not accurately cut to length by the supplier. The factor itself is defined by the following equation:

$$MF = (3.413 \text{ Btu/hr-W})(1/A) \tag{6}$$

where

A = the surface area of the copper strip.

Table A-1 gives the value of the multiplying factors used in this calibration.

During the calibration procedure the cells were protected from end losses by packing glass insulation around the ends of each of the tubes. Due to the high thermal resistance of the center section and the high thermal conductivity of the copper surface the copper strips were assumed to be isothermal during the calibration runs. A calculation of the distribution of the heat flux from the heaters to the cooling water on the one hand and to the asbestos and stryofoam insulation on the other yielded a factor of about 10^4. For this reason no correction for heat loss to this source was made in the calibration figures.

After the initial calibration, several of the cells were operated with widely different temperature values in the adjoining cells. This yielded a leakage along the plate, above the heat meters, of about

13.4 Btu/hr-ft^2 for each side and each degree of temperature difference in the adjoining cells.

During the calibration runs it was found that the response of the heat meters decreased with increasing temperature of the thermopile. The response of the thermopile is defined by the following relation:

$$\text{Response} = \frac{mv}{\dot{q}_0''} \tag{7}$$

where

mv = millivolt output of the thermopile at T, mv;

$\dot{q}_0''$ = calibration heat flux, Btu/hr-ft^2.

Both the millivolt output of the thermopile and the value of $\dot{q}_0''$ are functions of the absolute value of the temperature of the transducer. The heat flux across the thermal resistance is given by

$$\dot{q}_0'' = k(t)(\Delta T) \tag{8}$$

where

$k(t)$ = the thermal conductivity of micarta as a function of temperature, Btu/hr-ft^2 - °F;

ΔT = the temperature difference across the micarta, °F.

The emf of the thermopile is given by the following relation:

$$mv = A(t)(\Delta T) \tag{9}$$

where

$A(t)$ = electrical response of the thermopile element as a function of temperature, mv/°F.

Substituting these two relations into the definition for the response of the heat meter yields

$$\text{Response} = \frac{A(t)}{k(t)} \tag{10}$$

A calculation of the variation of A(t) with temperature for iron-constantan thermocouple wire shows a slight increase with increasing temperature. Data are not available to show the variation of k(t) with temperature for micarta. For this reason it can only be assumed that the increase in thermal conductivity overshadows the increase in A(t). This results in the inverse relation of the heat meters with temperature.

In order to compensate the thermopile output for variations with temperature a correction factor, C_T, has been defined and is plotted on the calibration curves as a function of thermopile temperature. The correction factor is given by the following definition:

$$C_T = \frac{\text{Response at } T_2}{\text{Response at } T_1} \tag{11}$$

where

T_1 = a reference temperature (for each thermopile this was taken as the temperature of the thermopile at the first calibration point and is identifiable on each curve as that temperature for which $C_T = 1.00$);

T_2 = Response of the thermopile at any other calibration point temperature.

An example of the use of the calibration curves and the temperature correction factor is included in the appendix.

The calibration curves in the appendix give plots of $\dot{q}_0''$ vs. thermopile emf and the temperature correction factor, C_T, vs. thermopile temperature. Table A-2, included in the appendix, includes all of the data obtained during the calibration runs.

As a result of the calibration an average value for the thermopile response of 0.0528 mv/Btu/hr-ft^2 was determined. This compares favorably with the original design criterion of 0.0417 mv/Btu/hr-ft^2 that was established.

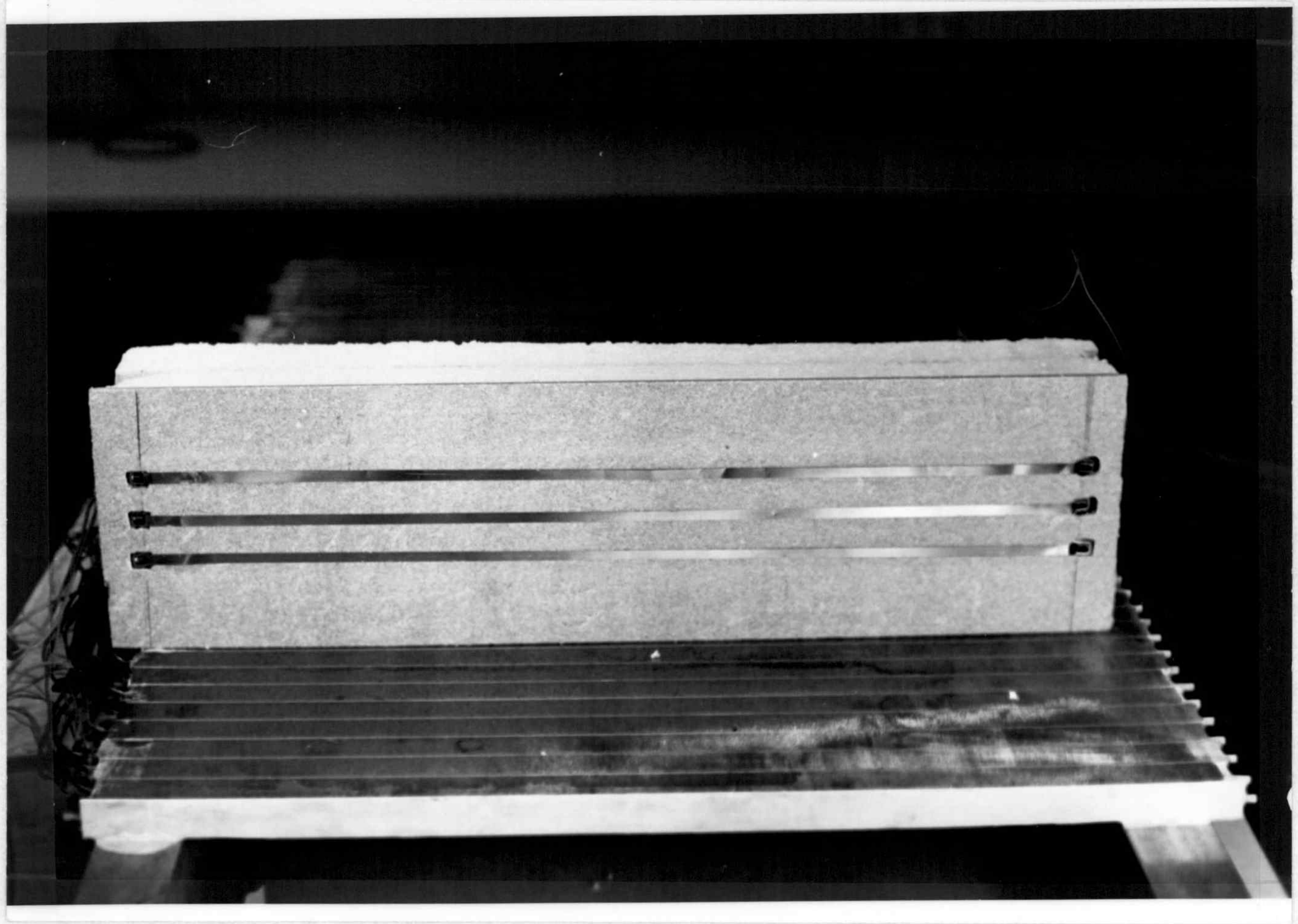

Figure 11. Strip heaters.

Figure 12. Strip heaters in operation.

IV. CONCLUSIONS AND COMMENTS

The result of this thesis work has been the successful completion of an instrumented surface for the study of convective heat transfer. The thermopile heat flux meters have demonstrated the ability to detect changes in heat flux which are within the limits of the calibration accuracy.

During the calibration procedure the sensitivity of the epoxy cement to temperature was noticed. Manufacturer's recommendations suggest a temperature limit of 250 °F, however a slight but detectable effect can be noticed at temperatures exceeding 150 °F. This takes the form of a slightly plastic condition which can be determined by means of a small probe. It is not felt that this phenomenon will impose serious limits on the use of the surface as plate temperatures were repeatedly recorded in the 225 °F temperature range during preliminary work without adverse effects to the structure and smoothness of the plate surface. Until experience has been gained with the instrument it is suggested that reasonable caution be used to prevent possible damage to the plate assembly.

As the plate stands it could be used for natural convection studies with the addition of a manifold to feed water to the aluminum tubes. The manifold could be designed in several ways. The easiest, of course, would be to use a large header with 48 outlets to feed water to the 48 aluminum tubes. At the same time, for the maximum utilization of the plate to be realized a manifold that would independently mix either steam and cold water or hot water and cold water before entering the aluminum tubes would be required. This would enable the temperature of each cell to be altered at will which is necessary if the boundary conditions are to be altered at will. With the addition of a flow tunnel and proper instrumentation for determining flow parameters the surface will be ready for forced convection studies. The shape of the flow tunnel will be dictated by the boundary conditions and therefore is not discussed at this time.

As previously noted it is believed that a surface for convective heat transfer investigations has been constructed that will allow studies in natural and forced convection with complete freedom to establish boundary conditions in each of these regimes. It should also be noted that although additional difficulties would have to be overcome the surface is not strictly limited to the use of atmospheric air for the fluid medium. Any fluid or gas which is compatible with the materials used in construction can be used.

The total cost of the instrument, including machining costs for the surface grinding, was less than $500.00. This, of course, does not include the potentiometers, power supplies, and other measuring instruments. This compares quite favorably with the prospect of commercially available heat meters whose cost would by approximately

$2800.00 in addition to the other materials necessary to complete the project.

In conclusion, it is the belief of this author that a versatile and useful instrument has been constructed for convective heat transfer studies that can be accomplished with the flat surface configuration. It is sincerely hoped that a continuing program of research will be carried out which will utilize the capabilities of the instrumented surface.

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APPENDIX

Table A-1. Multiplying factors.

Cell Number	Multiplying Factor (MF)
1	22.54
2	22.07
3	22.13
4	22.10
6	22.63
8	22.10
10	22.13
12	22.54
14	22.10
16	22.07
18	22.07
20	22.10
22	22.13
23	22.13
24	22.10
25	22.16
26	22.07
28	22.10
30	22.13
32	22.10
34	22.10
36	22.10
38	22.10
40	22.13
42	22.13
44	22.10
46	22.54
48	22.07

Table A-2. Calibration data.

Thermopile No.	Calibration Point No.	Amps	$\dot{q}_0''$ Btu/hr-ft^2	$T_{surface}$ F	$T_{thermopile}$ F	Thermopile emf-mv	Response mv/Btu/hr-ft^2	T_{water} F	C_T
2	1	1.36	101.0	92.3	84.3	5.57	0.0551	70.2	1.00
	2	2.00	218.8	111.7	96.0	10.72	0.0490	79.9	0.889
	3	2.54	353.5	130.7	108	15.79	0.0447	71.2	0.811
	4	3.1	527.8	161.0	132.3	23.50	0.0445	71.1	0.808
3	1	1.26	86.9	89.3	84.3	4.92	0.0566	70.0	1.00
	2	2.03	225.7	110.0	98.3	11.48	0.0509	66.0	0.899
	3	2.46	331.9	129.0	112.7	15.93	0.0480	67.5	0.848
	4	3.03	504.9	159.5	135.3	23.86	0.0472	68.5	0.834
	5	3.54	690.5	193.0	160.0	32.86	0.0475	69.5	0.839
5	1	1.23	82.3	89.3	84.7	4.54	0.0552	69.2	1.00
	2	2.10	241.4	119.5	109.0	11.60	0.0481	69.5	0.871
	3	2.50	342.6	138.7	124.7	16.35	0.0477	68.3	0.864
	4	3.00	494.3	165.0	144.0	22.90	0.0463	68.3	0.839
	5	3.57	702.2	203.0	173.7	32.01	0.0456	68.7	0.826
6	1	1.30	94.5	90.3	82.0	5.05	0.0534	69.0	1.00
	2	2.00	223.6	110.3	91.0	10.65	0.0476	69.0	0.891
	3	2.47	342.9	133.0	103.0	15.91	0.0463	69.1	0.867
	4	3.00	505.7	157.0	115.3	22.55	0.0446	68.2	0.835
	5	3.57	718.2	194.0	134.0	31.86	0.0444	68.7	0.831
8	1	1.30	92.3	94.3	87.5	5.37	0.0582	73.2	1.00
	2	1.93	203.6	114.7	100.7	10.64	0.0525	73.1	0.902
	3	2.47	334.4	140.0	117.0	17.12	0.0512	73.2	0.880
	4	3.07	517.6	170.0	137.0	25.65	0.0496	71.5	0.852
	5	3.50	672.2	198.0	155.7	33.28	0.0495	71.2	0.851

Table A-2. (continued)

Thermopile No.	Calibration Point No.	Amps	$\dot{q}_0''$ Btu/hr-ft^2	$T_{surface}$ F	$T_{thermopile}$ F	Thermopile emf-mv	Response mv/Btu/hr-ft^2	T_{water} F	C_T
10	1	1.30	92.4	89.3	84.0	5.09	0.0551	68.5	1.00
	2	2.07	234.9	117.0	105.7	11.40	0.0485	68.6	0.880
	3	2.50	342.9	134.0	118.0	15.54	0.0453	68.6	0.822
	4	3.04	508.2	162.0	139.3	22.36	0.0440	69.0	0.799
	5	3.56	698.6	194.3	162.7	30.20	0.0432	69.0	0.784
12	1	1.30	94.1	90.3	90.2	5.01	0.0532	68.5	1.00
	2	2.03	229.9	114.7	112.3	11.15	0.0485	69.0	0.912
	3	2.50	357.7	135.3	133.0	16.20	0.0453	69.0	0.852
	4	3.04	517.6	163.0	159.0	23.18	0.0448	69.4	0.842
	5	3.53	699.9	196.0	189.3	31.64	0.0452	69.0	0.850
14	1	1.30	92.3	90.0	84.7	4.87	0.0528	69.0	1.00
	2	2.06	232.1	111.7	99.3	10.75	0.0463	69.1	0.877
	3	2.53	350.7	133.3	113.3	15.42	0.0440	69.1	0.833
	4	3.07	517.6	162.0	132.0	22.53	0.0435	69.0	0.824
	5	3.57	701.6	195.7	155.3	31.12	0.0443	69.5	0.839
16	1	1.33	96.4	90.0	83.7	5.49	0.0570	69.0	1.00
	2	2.03	225.1	111.7	97.7	11.38	0.0502	69.0	0.881
	3	2.50	341.9	131.3	110.7	16.92	0.0495	68.9	0.868
	4	3.03	503.1	158.0	128.3	24.45	0.0486	68.9	0.853
	5	3.53	685.7	189.7	147.7	33.11	0.0483	69.5	0.847
18	1	1.27	87.9	89.4	82.0	4.52	0.0514	69.2	1.00
	2	2.03	225.1	111.3	95.3	9.42	0.0418	69.2	0.813
	3	2.53	350.2	132.0	109.0	14.15	0.0404	70.0	0.786
	4	3.06	513.1	158.0	125.3	20.25	0.0404	70.0	0.786
	5	3.56	696.5	188.0	144.3	27.61	0.0396	70.0	0.770

Table A-2. (continued)

Thermopile No.	Calibration Point No.	Amps.	$\dot{q}''_0$ Btu/hr-ft^2	$T_{surface}$ F	$T_{thermopile}$ F	Thermopile emf-mv	Response mv/Btu/hr-ft^2	T_{water} F	C_T
20	1	1.30	92.3	91.3	86.3	5.62	0.0609	69.2	1.00
	2	2.00	218.8	110.7	102.0	11.27	0.0515	69.2	0.846
	3	2.53	350.7	131.7	118.0	17.39	0.0496	69.0	0.815
	4	3.03	503.8	160.7	140.3	24.57	0.0487	69.0	0.800
	5	3.57	701.6	193.7	165.7	33.67	0.0480	69.0	0.788
22	1	1.33	96.7	90.5	86.3	5.26	0.0544	69.0	1.00
	2	2.00	219.1	111.3	103.3	10.63	0.0485	69.0	0.892
	3	2.50	342.9	133.0	121.0	16.48	0.0481	69.4	0.884
	4	3.03	508.2	160.7	143.0	23.83	0.0469	69.5	0.862
	5	3.53	686.6	186.3	163.0	31.15	0.0454	70.0	0.835
23	1	1.33	96.7	90.7	87.0	4.40	0.0455	70.0	1.00
	2	1.97	212.6	111.7	103.0	8.98	0.0422	70.0	0.927
	3	2.50	342.9	135.0	122.0	14.36	0.0419	70.1	0.921
	4	3.06	514.9	164.3	145.3	21.36	0.0415	70.2	0.912
	5	3.55	695.3	198.3	171.3	29.04	0.0418	70.2	0.919
24	1	1.27	88.0	91.3	86.3	4.78	0.0543	69.8	1.00
	2	1.97	212.1	109.3	100.0	8.87	0.0418	69.5	0.770
	3	2.53	350.5	132.0	117.0	14.20	0.0405	69.5	0.746
	4	3.07	507.9	161.0	139.3	20.93	0.0492	69.5	0.758
	5	3.53	686.0	189.0	160.0	27.45	0.0400	70.0	0.737
25	1	1.30	92.5	92.3	88.3	5.23	0.0565	70.8	1.00
	2	2.00	219.4	113.0	104.7	10.54	0.0480	70.6	0.850
	3	2.47	335.2	132.7	121.0	15.59	0.0465	70.8	0.823
	4	3.03	505.6	160.7	140.0	23.19	0.0459	70.9	0.812
	5	3.53	687.6	191.0	170.0	31.60	0.0460	70.9	0.814

Table A-2. (continued)

Thermopile No.	Calibration Point No.	Amps	$\dot{q}_0''$ Btu/hr-ft^2	$T_{surface}$ F	$T_{thermopile}$ F	Thermopile emf-mv	Response mv/Btu/hr-ft^2	T_{water} F	C_T
26	1	1.30	92.1	91.7	84.3	5.44	0.0591	69.2	1.00
	2	1.94	205.5	108.3	95.3	9.95	0.0484	69.4	0.819
	3	2.50	341.8	130.7	110.3	15.76	0.0461	70.4	0.780
	4	3.07	516.9	159.7	128.7	23.56	0.0456	70.5	0.772
	5	3.53	684.8	188.7	148.0	31.17	0.0455	70.5	0.770
28	1	1.33	96.6	86.3	79.3	4.63	0.0479	66.5	1.00
	2	2.00	218.5	109.3	95.0	9.68	0.0443	68.0	0.925
	3	2.50	342.4	132.7	111.0	15.06	0.0440	68.2	0.919
	4	2.97	484.2	156.3	128.7	21.15	0.0437	69.0	0.912
	5	3.56	697.7	190.3	152.0	29.60	0.0424	69.2	0.885
30	1	1.33	96.7	89.0	84.7	5.09	0.0526	67.0	1.00
	2	2.07	234.5	105.0	96.3	9.96	0.0425	64.0	0.809
	3	2.53	350.9	124.0	111.0	14.61	0.0416	64.5	0.791
	4	3.00	494.3	147.3	130.3	20.40	0.0413	65.8	0.785
	5	3.53	686.1	181.0	157.0	28.84	0.0420	67.0	0.798
32	1	1.33	96.6	88.0	79.3	4.99	0.0517	67.0	1.00
	2	2.05	229.8	108.7	92.0	10.62	0.0462	67.1	0.894
	3	2.50	342.3	129.3	104.7	15.32	0.0448	67.4	0.867
	4	3.07	517.6	160.0	124.0	23.08	0.0446	67.2	0.863
	5	3.57	701.6	191.7	143.7	31.18	0.0444	68.4	0.859
34	1	1.33	96.5	84.0	79.5	4.72	0.0489	64.0	1.00
	2	2.03	225.2	103.0	93.7	9.54	0.0424	63.4	0.867
	3	2.50	342.1	124.0	110.0	14.42	0.0421	64.0	0.861
	4	3.06	513.8	153.3	133.7	21.70	0.0422	65.0	0.863
	5	3.57	701.3	184.7	159.0	29.33	0.0418	67.0	0.855

Table A-2. (continued)

Thermopile No.	Calibration Point No.	Amps.	$\dot{q}_0''$ Btu/hr-ft^2	$T_{surface}$ F	$T_{thermopile}$ F	Thermopile emf-mv	Response mv/Btu/hr-ft^2	T_{water} F	C_T
36	1	1.33	96.6	89.7	84.0	4.81	0.0498	70.0	1.00
	2	2.00	218.7	108.5	98.3	9.48	0.0433	69.8	0.869
	3	2.53	350.5	131.3	115.0	15.24	0.0435	69.8	0.873
	4	3.00	494.1	157.0	134.0	21.30	0.0431	70.1	0.865
	5	3.55	693.8	188.7	157.7	29.68	0.0428	70.8	0.859
38	1	1.33	96.5	85.7	79.3	4.92	0.0510	67.0	1.00
	2	2.06	232.0	106.3	93.0	10.13	0.0437	67.0	0.857
	3	2.53	350.5	126.0	106.5	14.97	0.0427	67.1	0.837
	4	3.07	517.4	155.3	127.7	22.13	0.0428	69.0	0.839
	5	3.57	701.1	183.7	147.3	29.77	0.0425	69.5	0.833
40	1	1.33	96.7	89.7	82.3	4.97	0.0514	69.0	1.00
	2	2.00	219.1	111.3	95.7	10.22	0.0466	69.0	0.907
	3	2.50	342.9	131.7	107.7	15.25	0.0445	69.0	0.866
	4	3.07	518.3	162.0	125.7	22.90	0.0442	69.0	0.860
	5	3.57	702.6	194.7	146.0	31.27	0.0445	70.4	0.866
42	1	1.33	96.7	88.7	82.0	5.04	0.0521	68.9	1.00
	2	2.04	227.8	108.0	95.0	10.35	0.0454	69.0	0.871
	3	2.53	351.0	128.0	107.7	15.77	0.0449	69.1	0.862
	4	3.07	517.9	154.7	125.7	23.27	0.0449	69.3	0.862
	5	3.57	702.6	188.0	145.3	31.82	0.0453	69.7	0.869
44	1	1.33	96.6	89.7	82.7	4.56	0.0472	69.4	1.00
	2	2.07	234.4	111.0	96.0	9.55	0.0408	69.4	0.864
	3	2.50	342.3	129.3	108.0	14.13	0.0413	69.8	0.875
	4	3.04	507.3	157.7	127.0	20.94	0.0413	69.7	0.875
	5	3.56	697.4	185.3	145.0	28.13	0.0403	69.5	0.854

Table A-2. (continued).

Thermopile No.	Calibration Point No.	Amps.	$\dot{q}''_0$ Btu/hr-ft^2	$T_{surface}$ F	$T_{thermopile}$ F	Thermopile emf-mv	Response mv/Btu/hr-ft^2	T_{water} F	C_T
46	1	1.33	98.5	87.7	84.3	4.17	0.0423	68.8	1.00
	2	2.06	236.6	110.3	103.7	9.32	0.0394	69.6	0.931
	3	2.50	349.1	128.7	119.5	13.60	0.0390	69.8	0.922
	4	3.03	514.0	152.7	140.7	19.55	0.0380	70.4	0.898
	5	3.53	699.1	183.0	166.7	26.90	0.0385	70.6	0.910

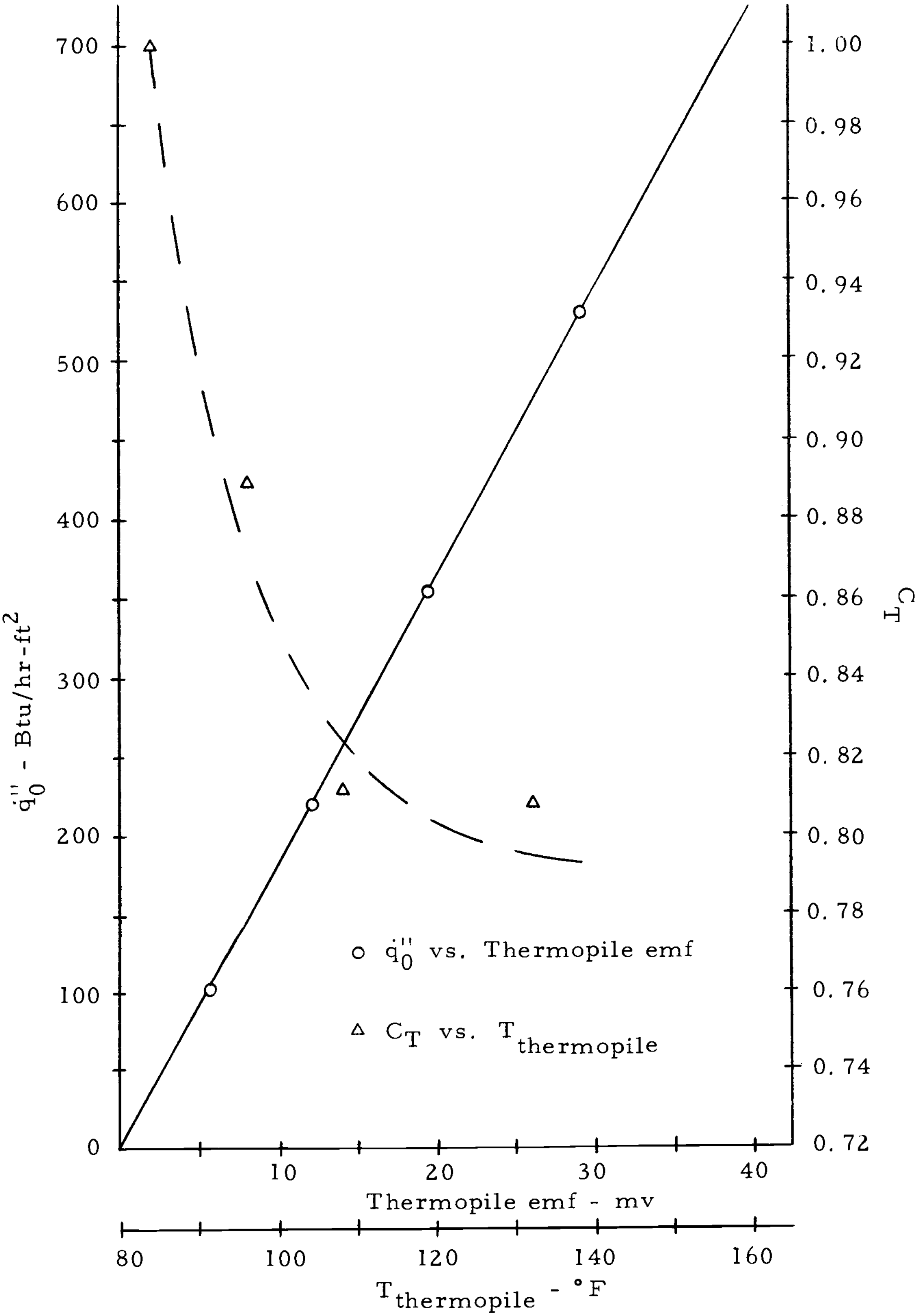


Figure A-1. Calibration curve - Thermopile No. 2

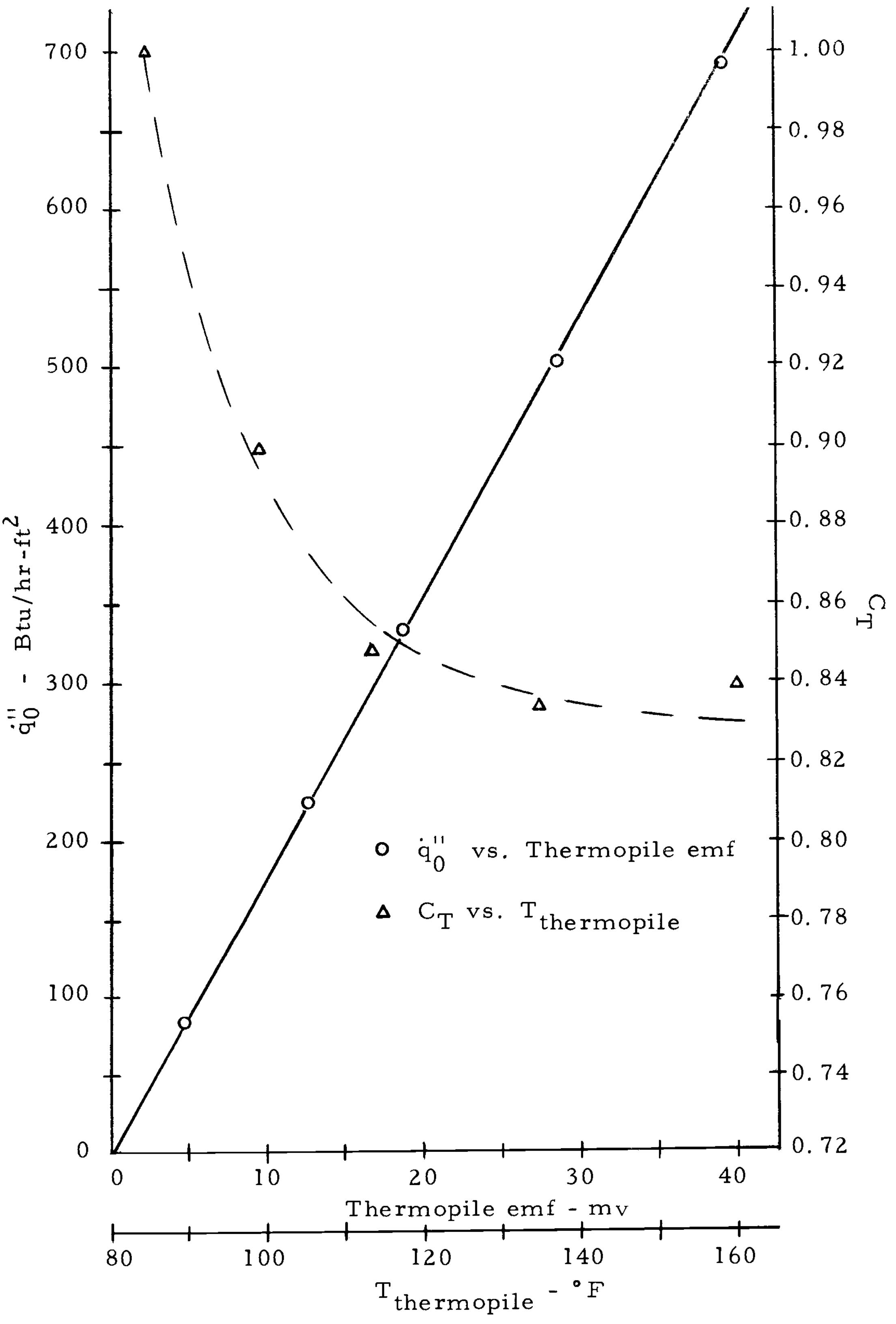


Figure A-2. Calibration curve - Thermopile No. 3.

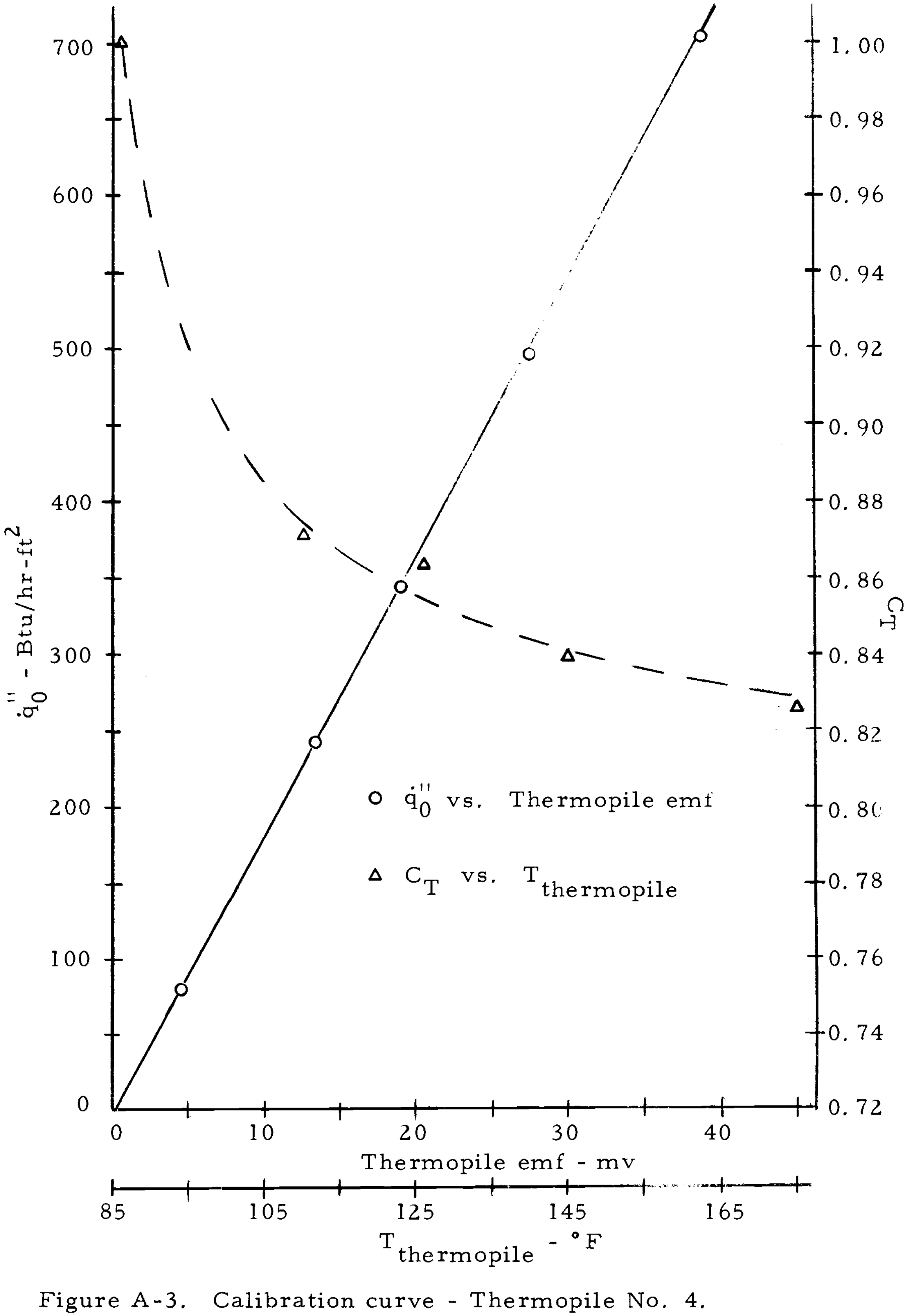


Figure A-3. Calibration curve - Thermopile No. 4.

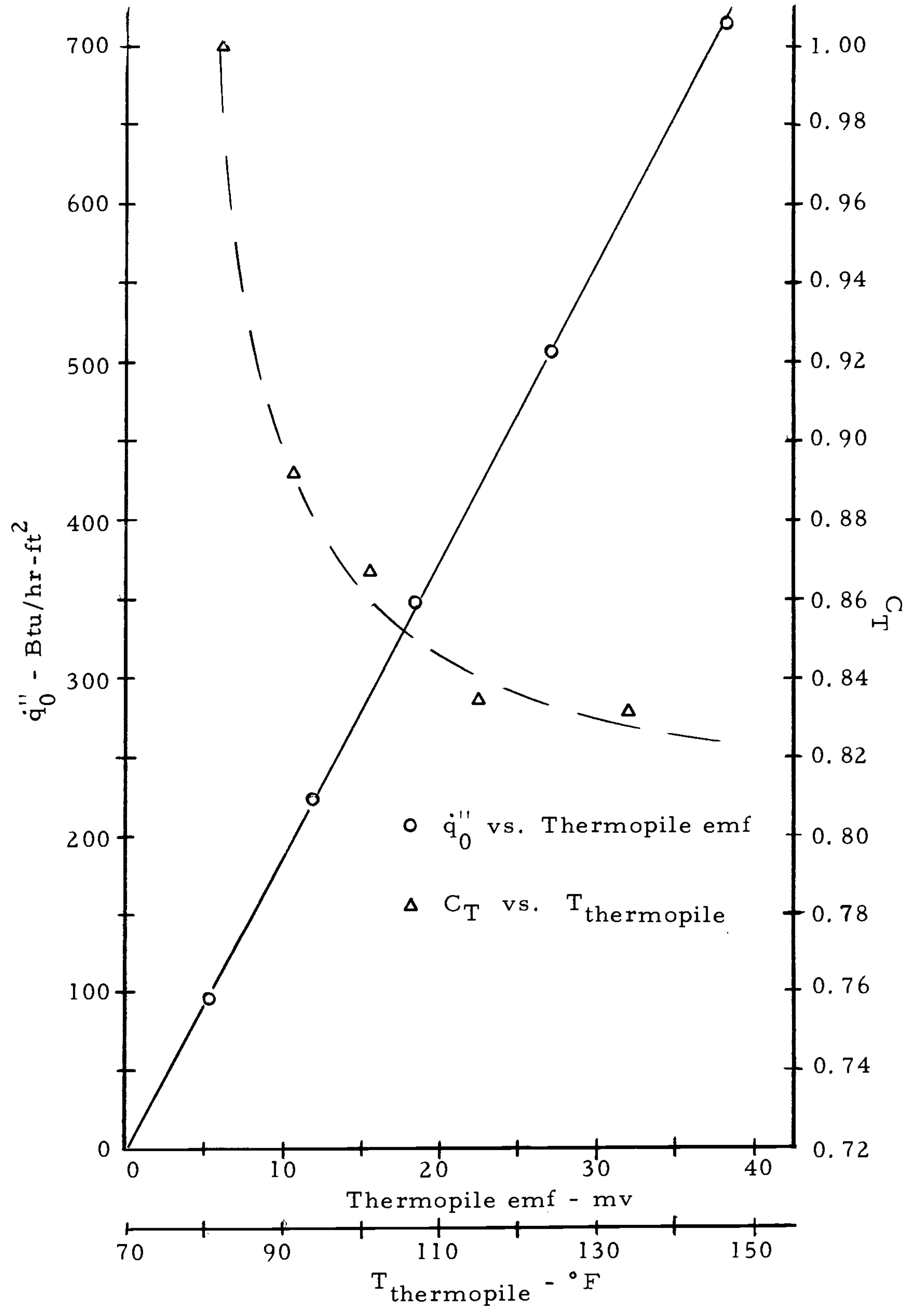


Figure A-4. Calibration curve - Thermopile No. 6.

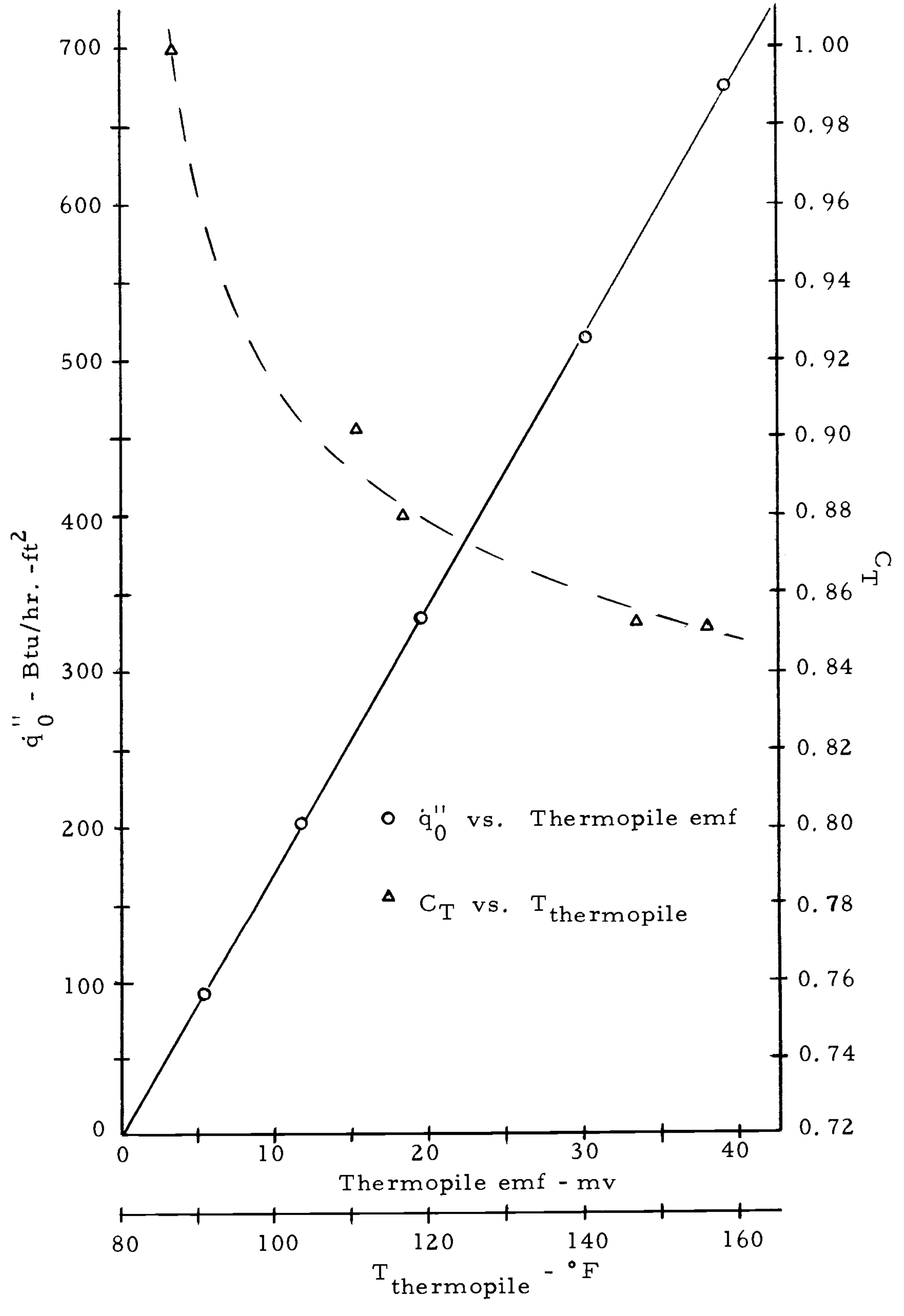


Figure A-5. Calibration curve - Thermopile No. 8.

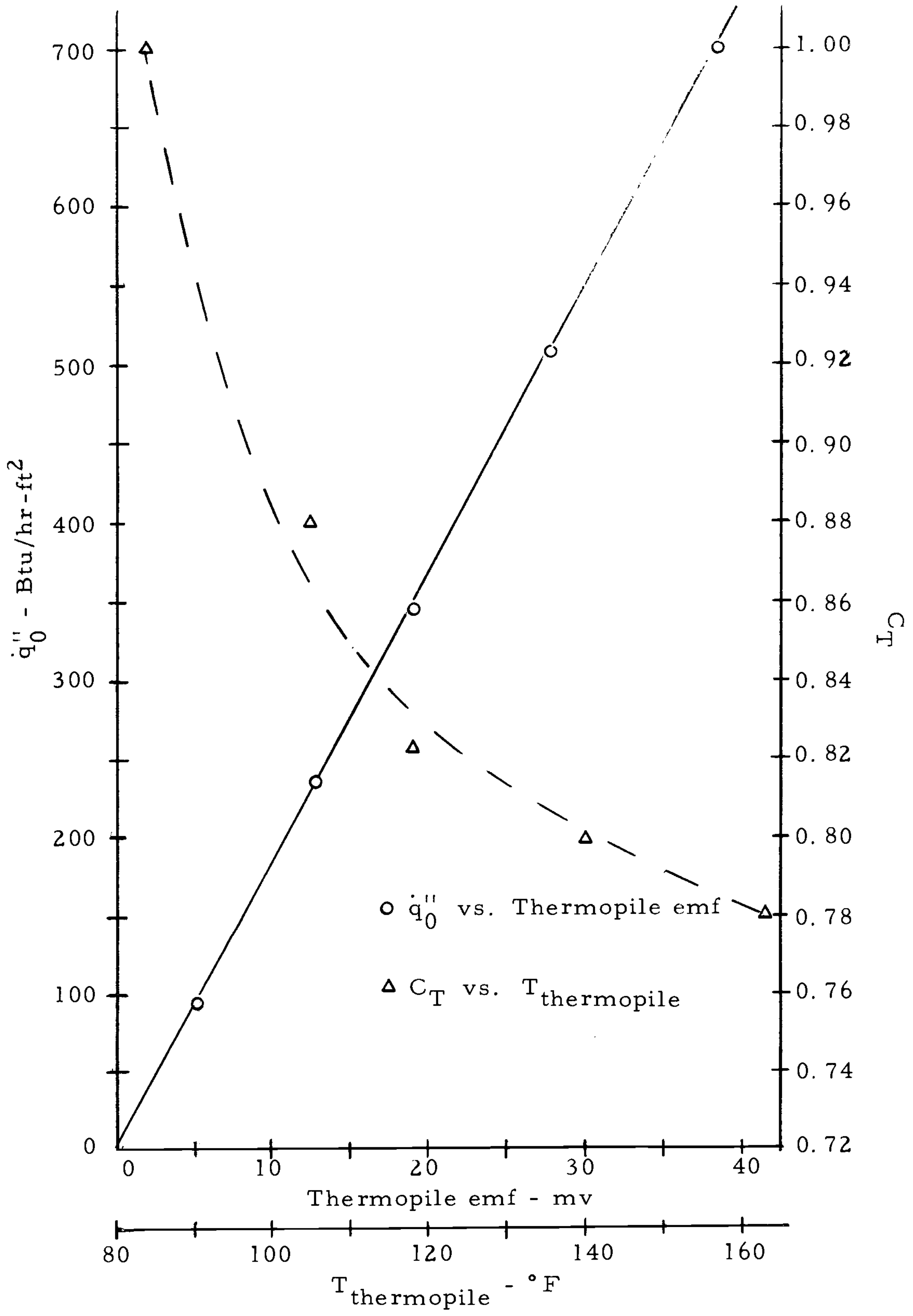


Figure A-6. Calibration curve - Thermopile No. 10.

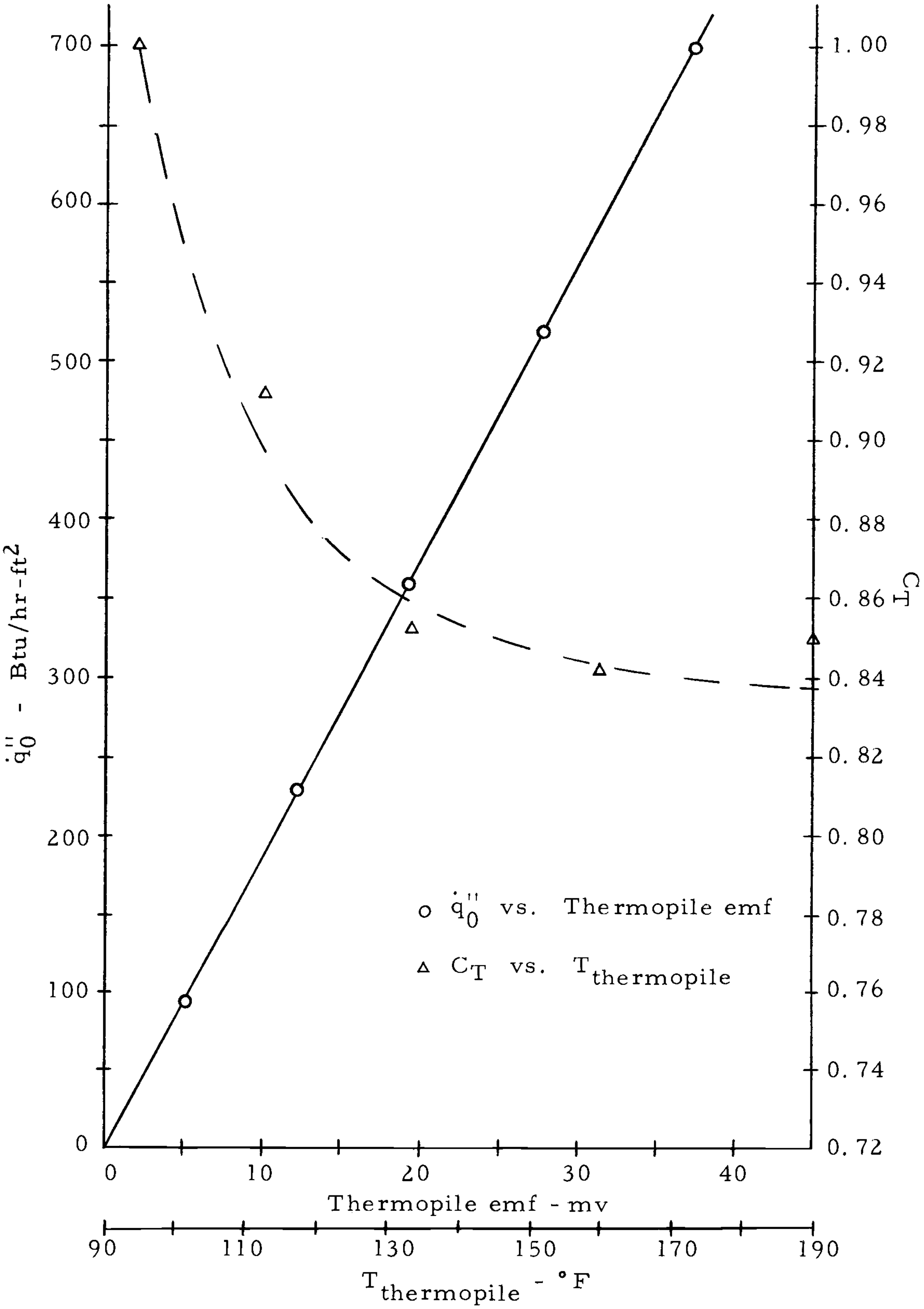


Figure A-7. Calibration curve - Thermopile No. 12.

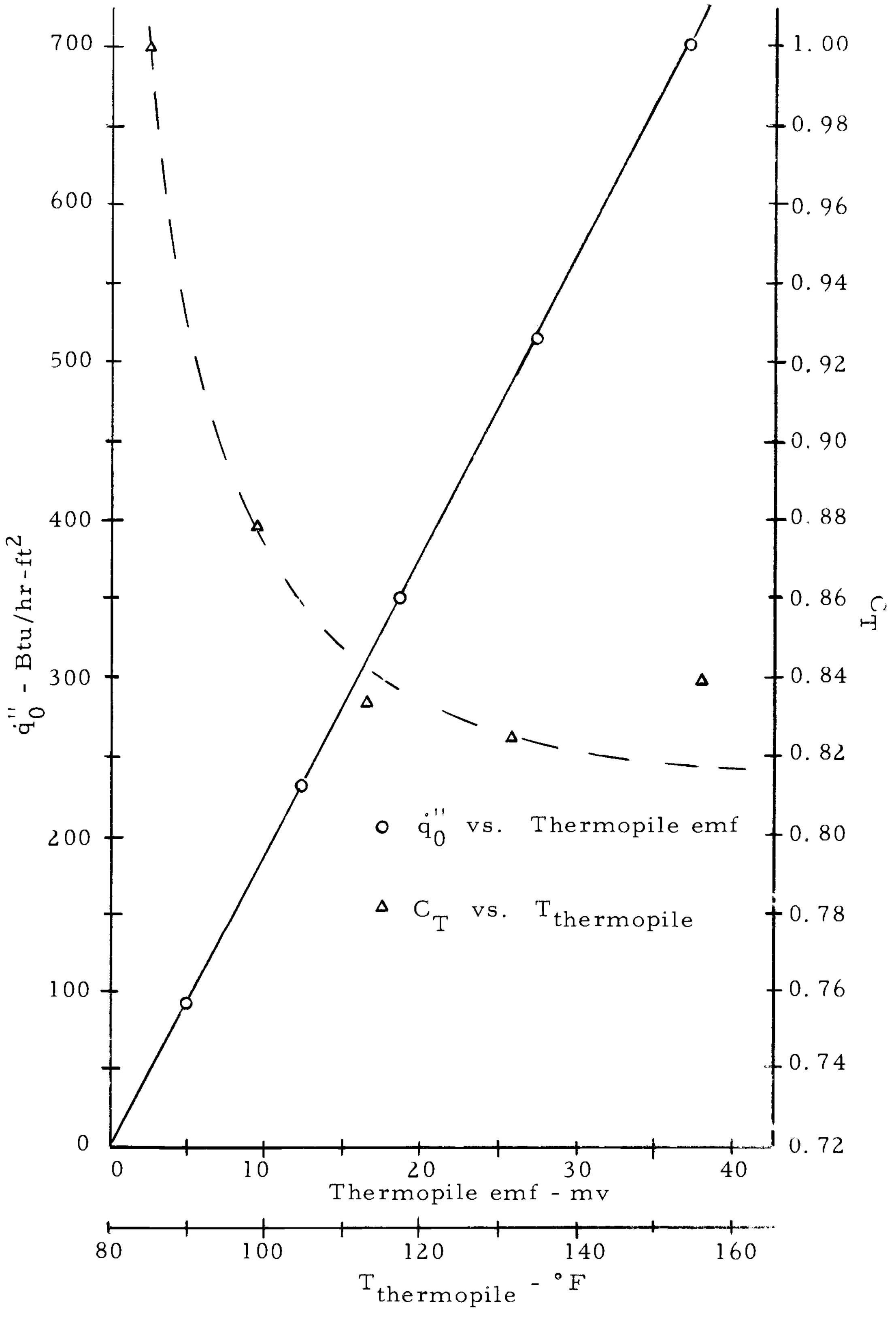


Figure A-8. Calibration curve - Thermopile No. 14.

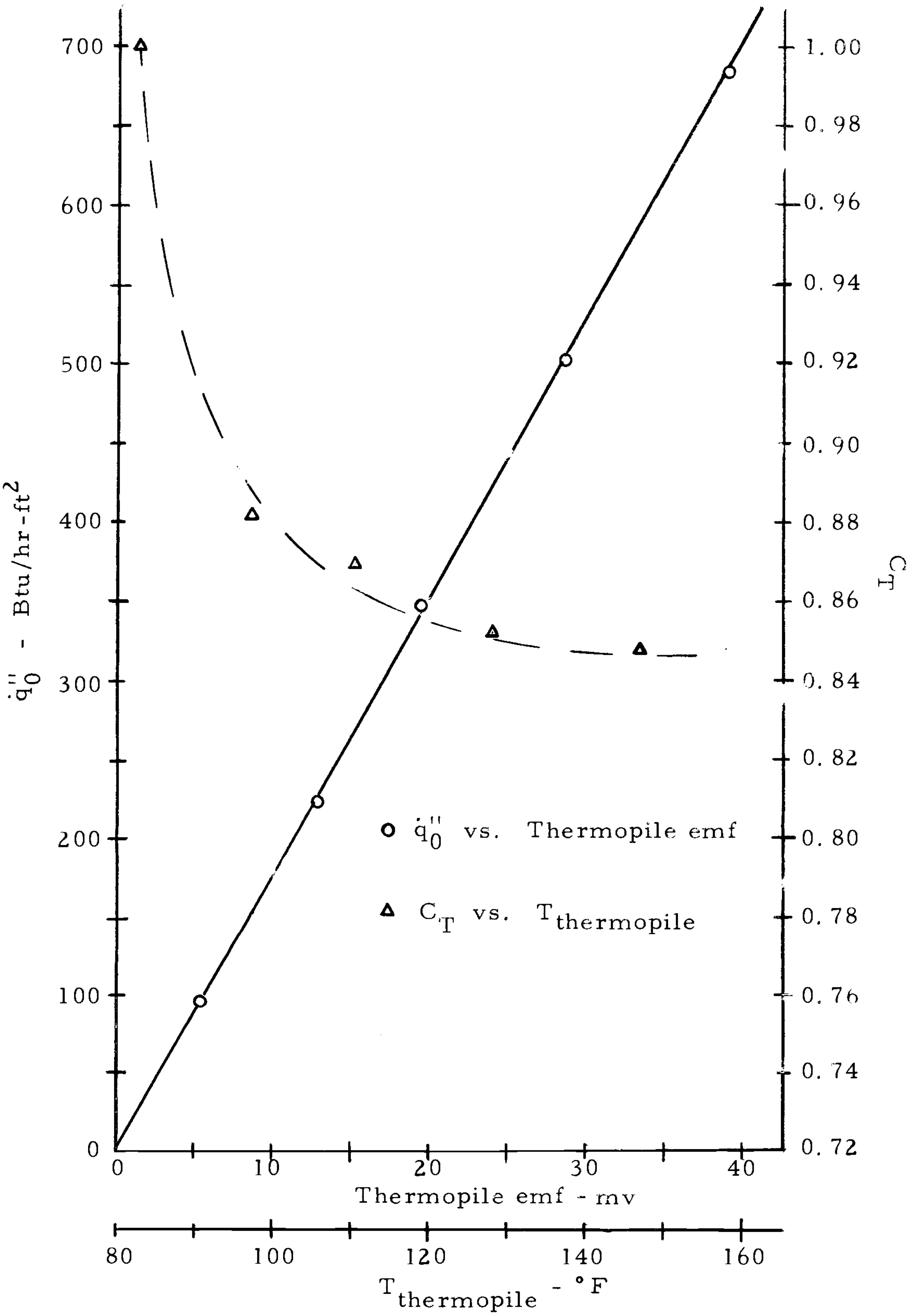


Figure A-9. Calibration curve - Thermopile No. 16.

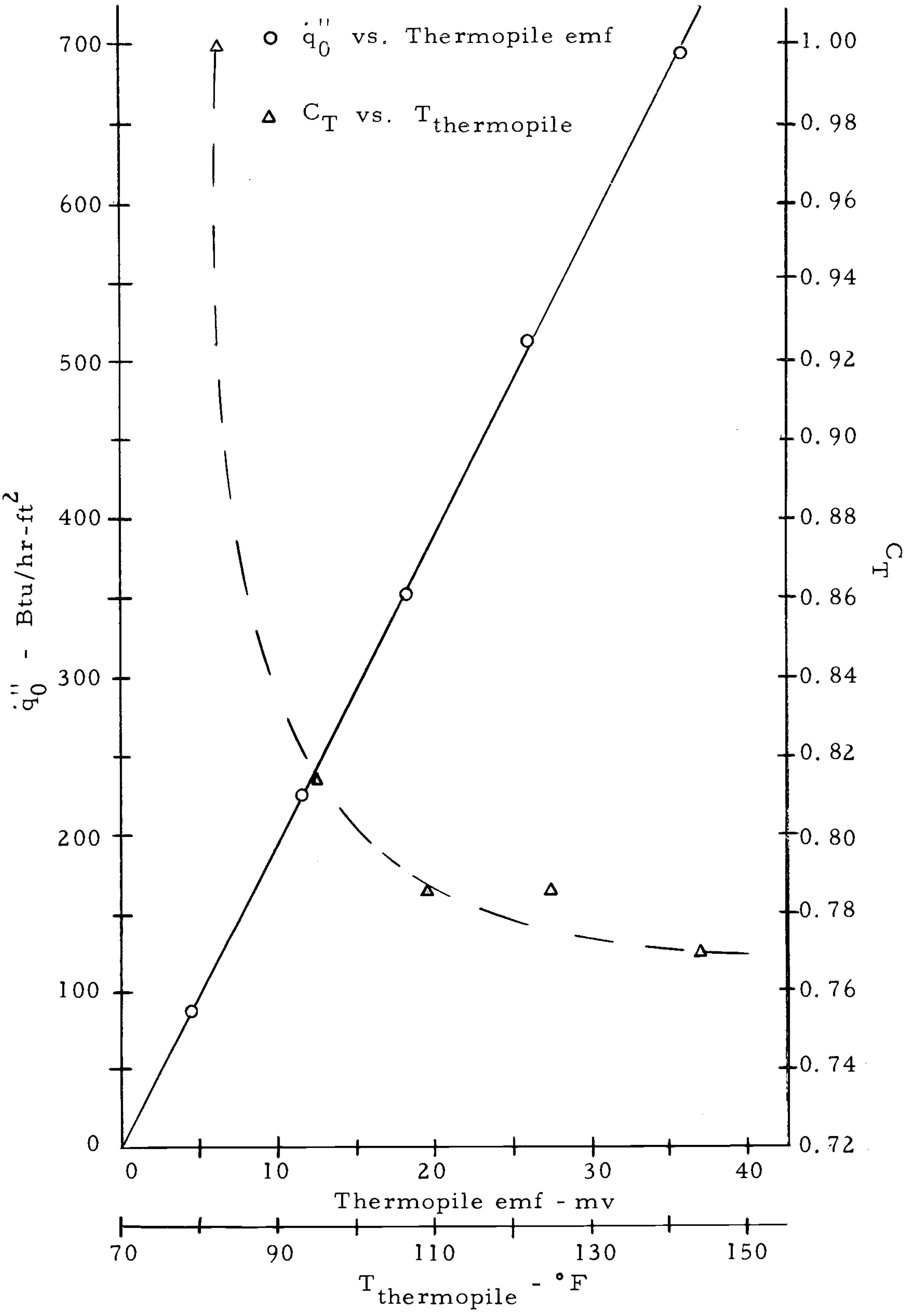


Figure A-10. Calibration curve - Thermopile No. 18.

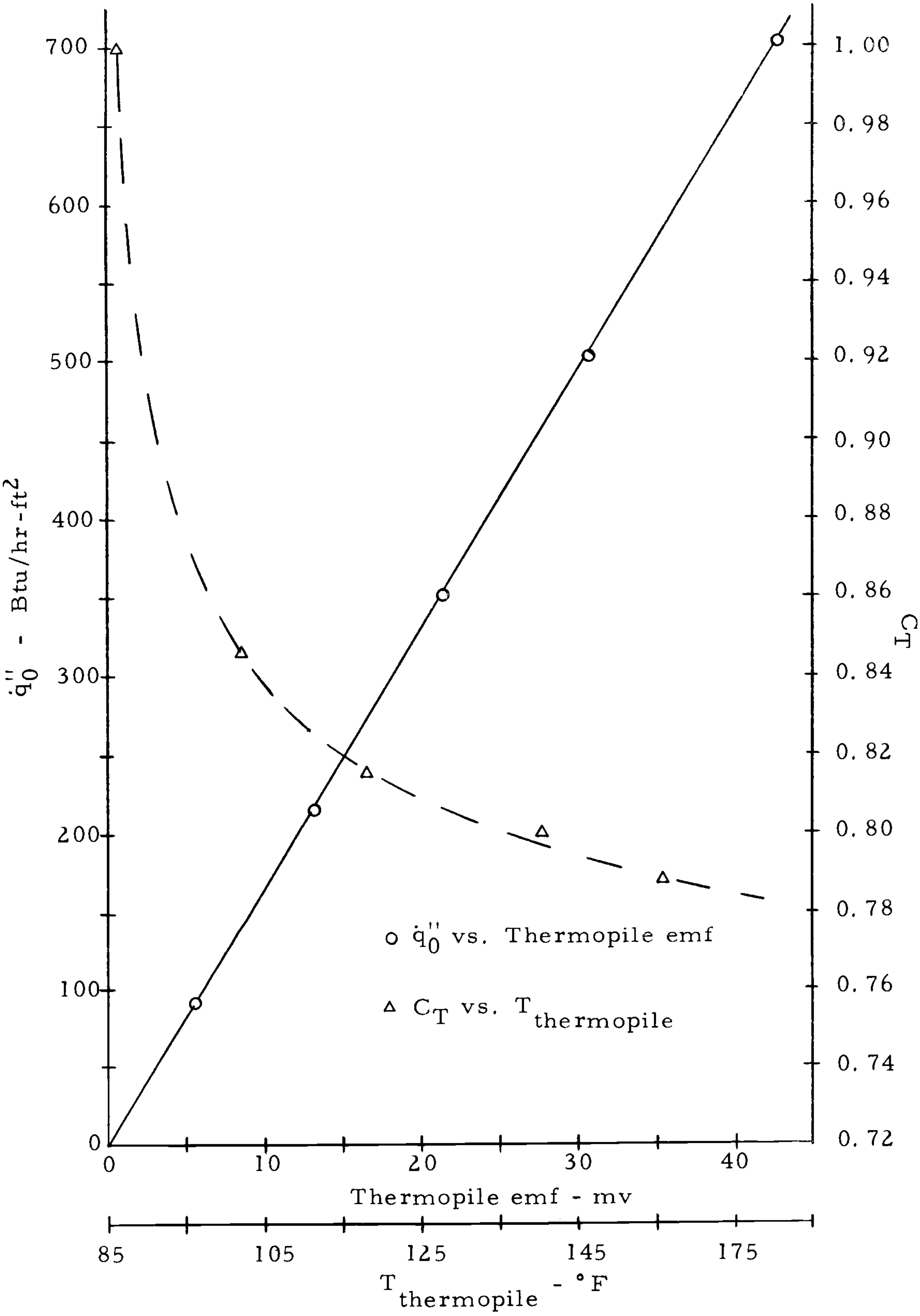


Figure A-11. Calibration curve - Thermopile No. 20.

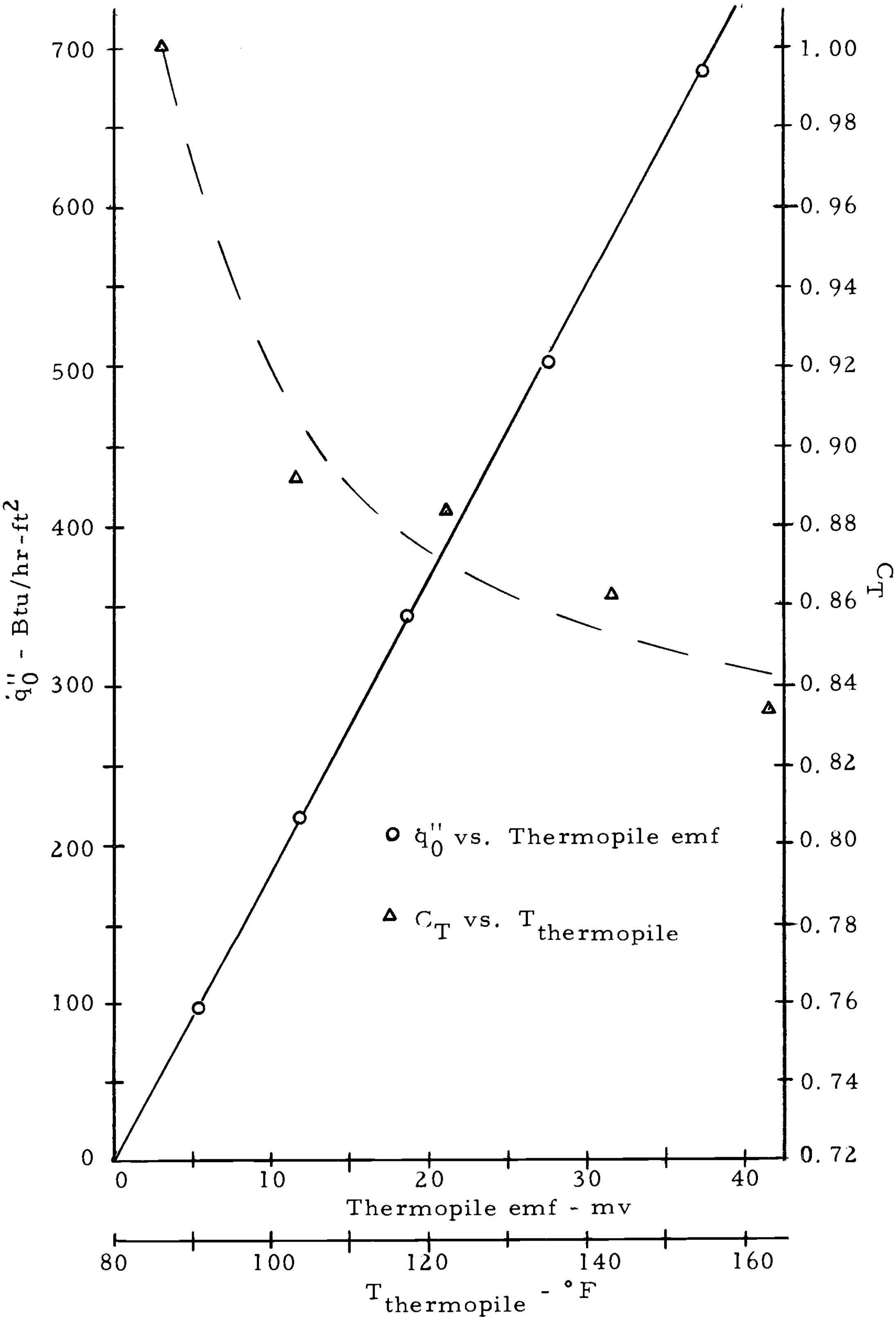


Figure A-12. Calibration curve - Thermopile No. 22.

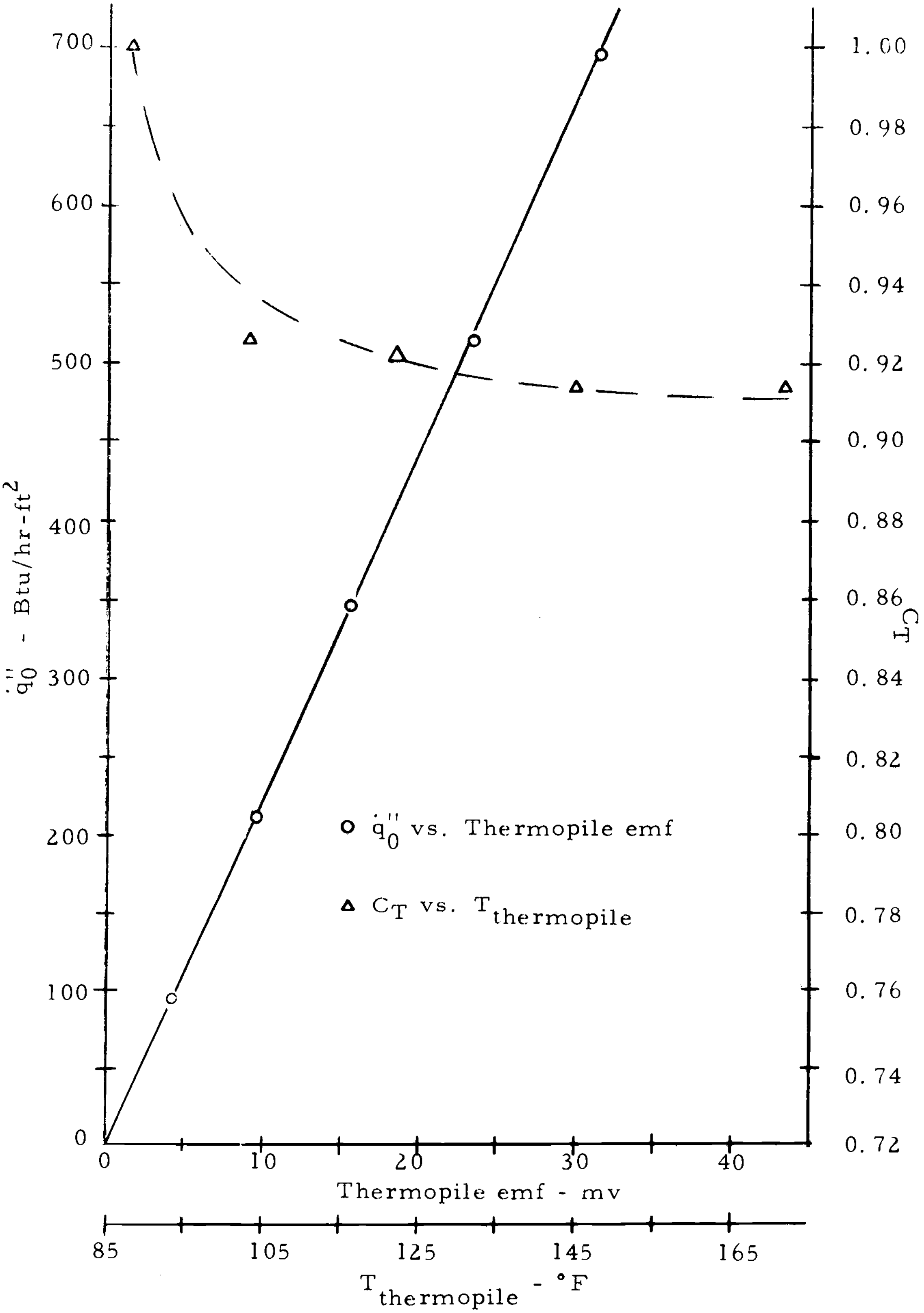


Figure A-13. Calibration curve - Thermopile No. 23.

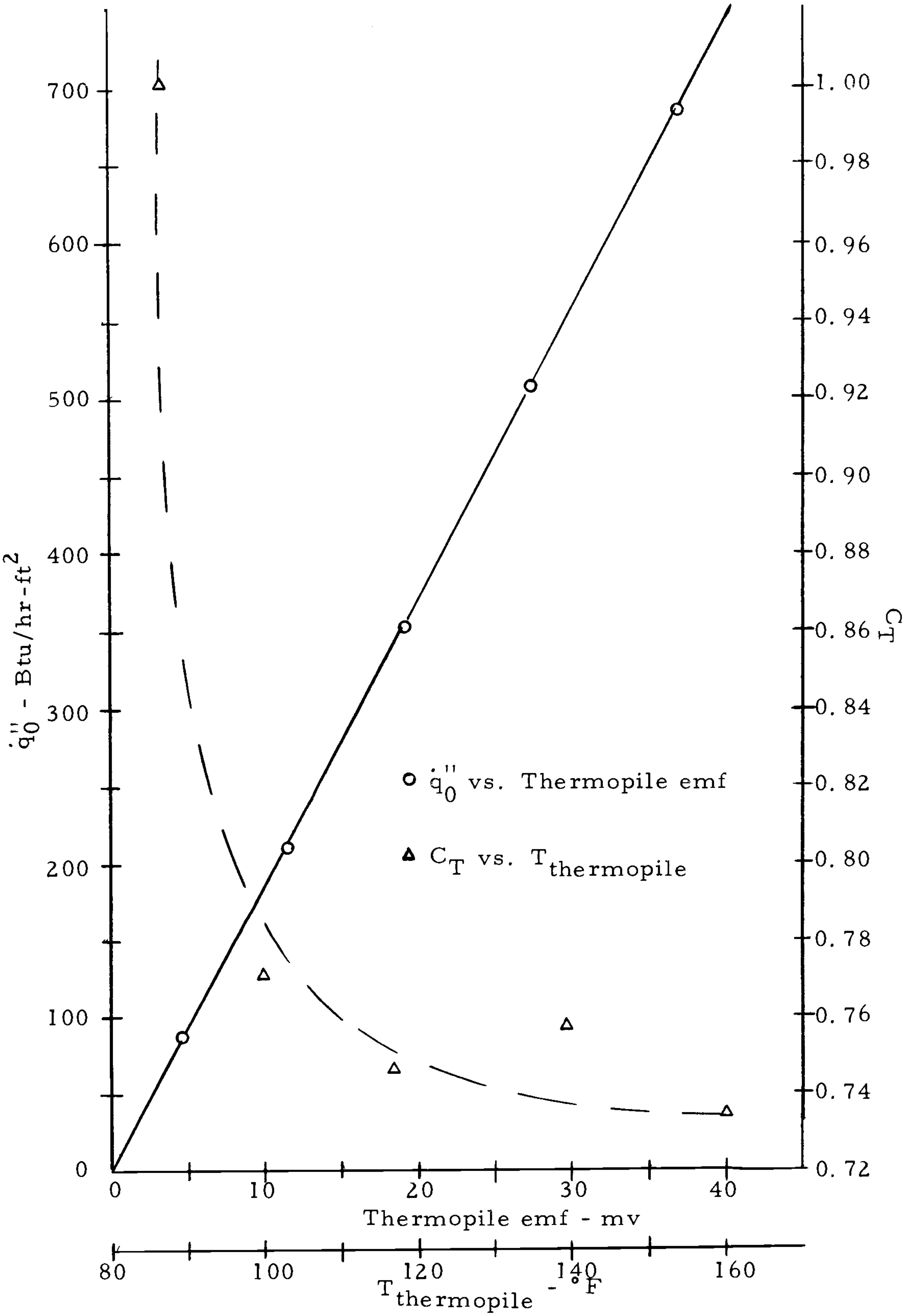


Figure A-14. Calibration curve - Thermopile No. 24.

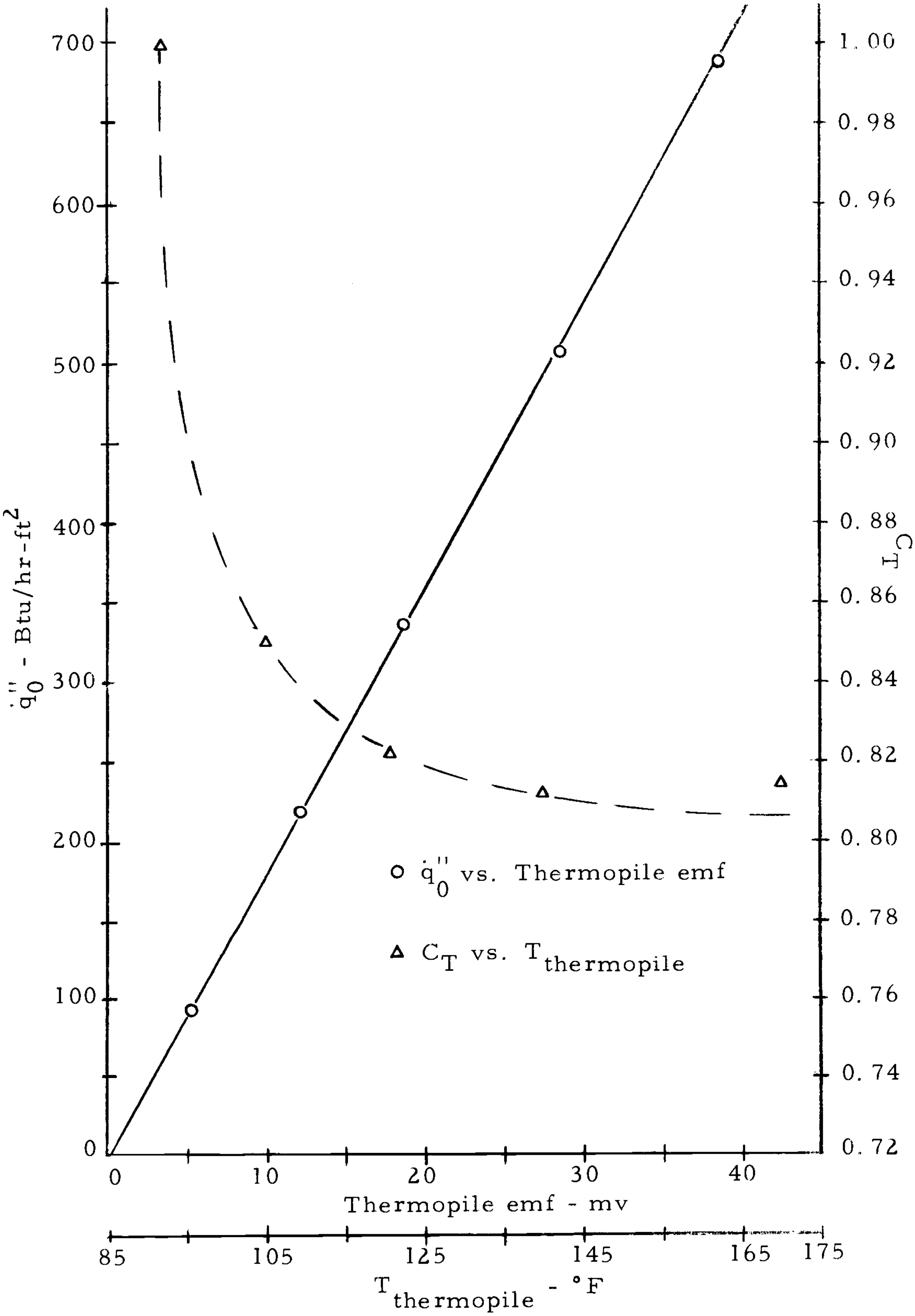


Figure A-15. Calibration curve - Thermopile No. 25.

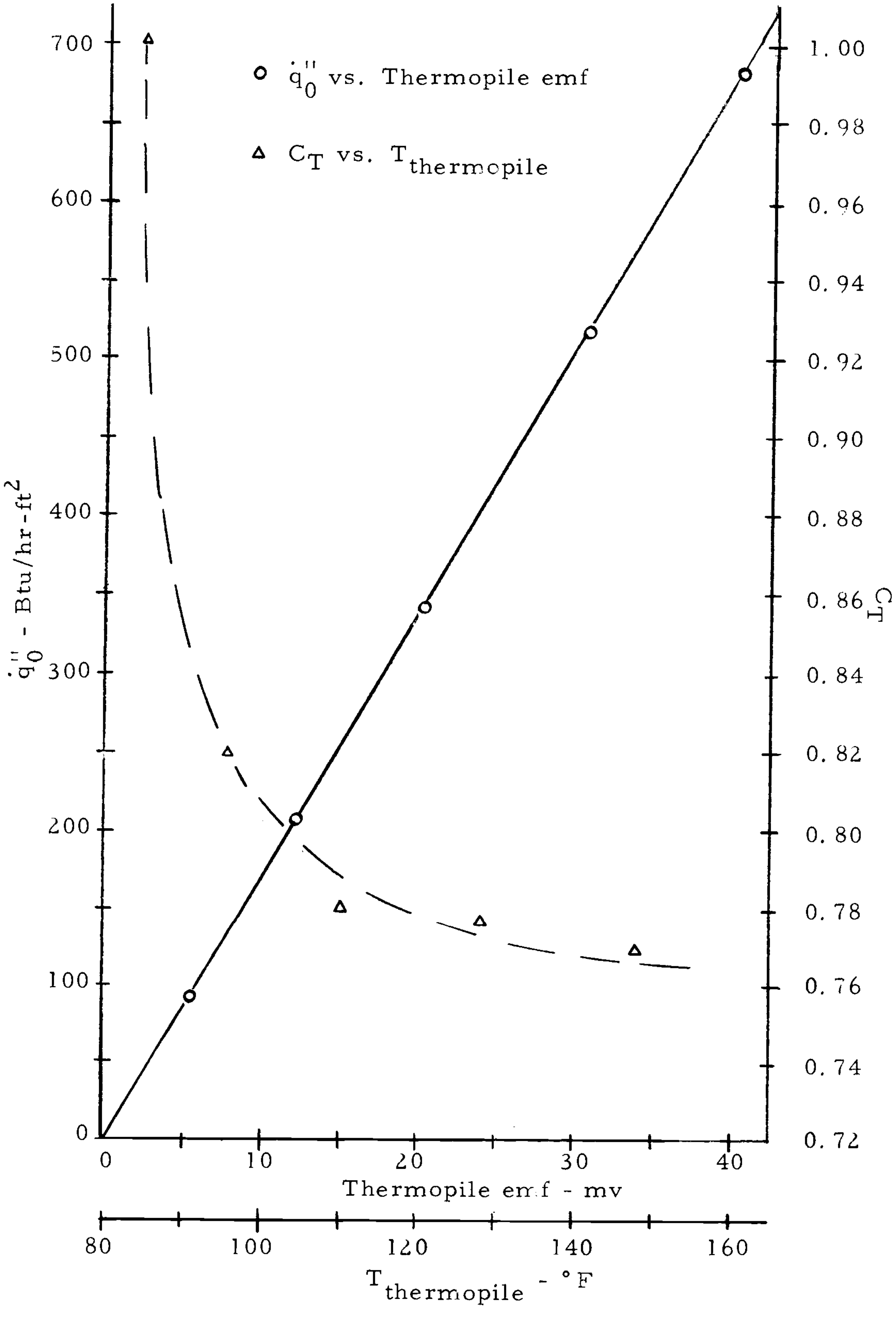


Figure A-16. Calibration curve - Thermopile No. 26.

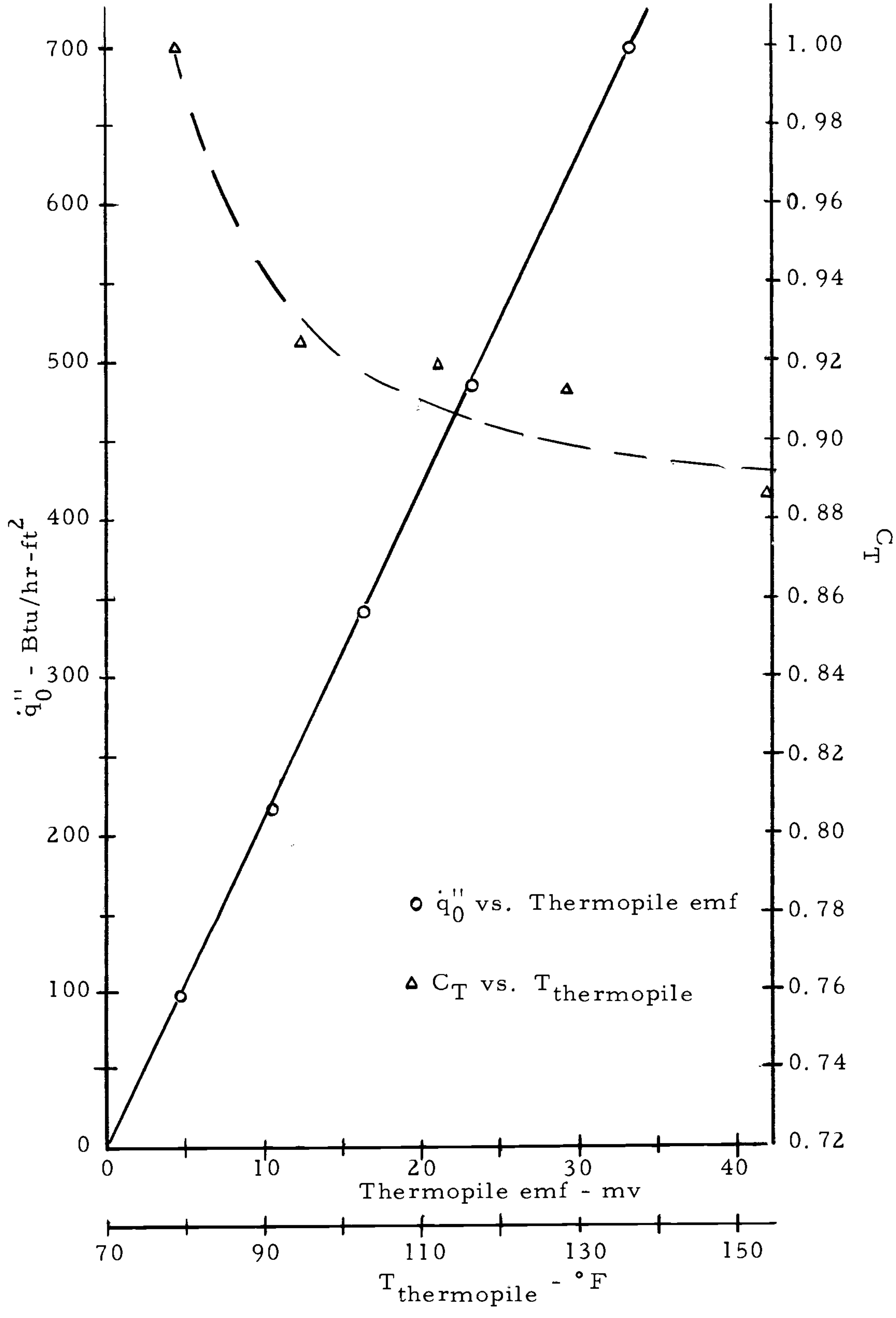


Figure A-17. Calibration curve - Thermopile No. 28.

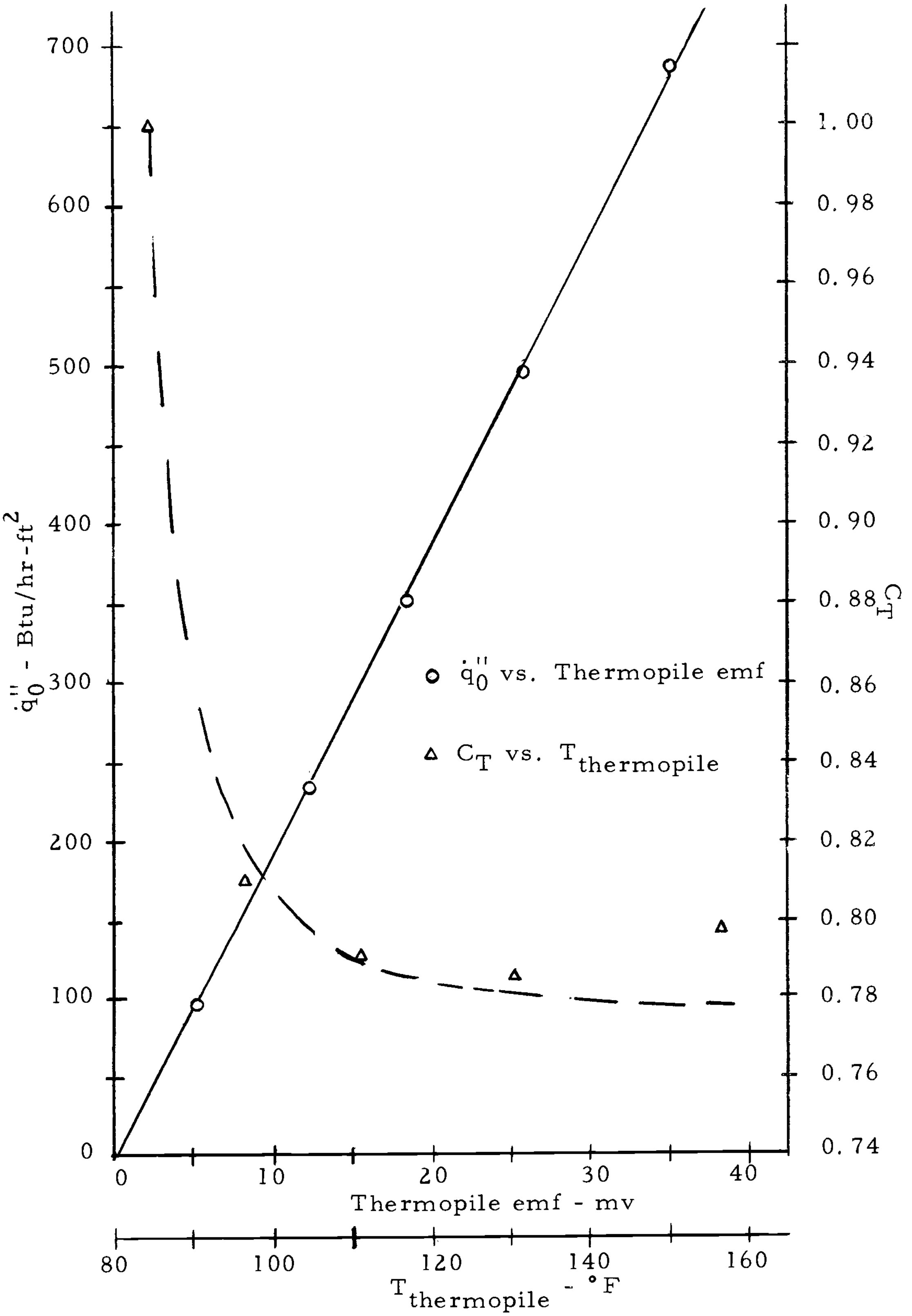


Figure A-18. Calibration curve - Thermopile No. 30.

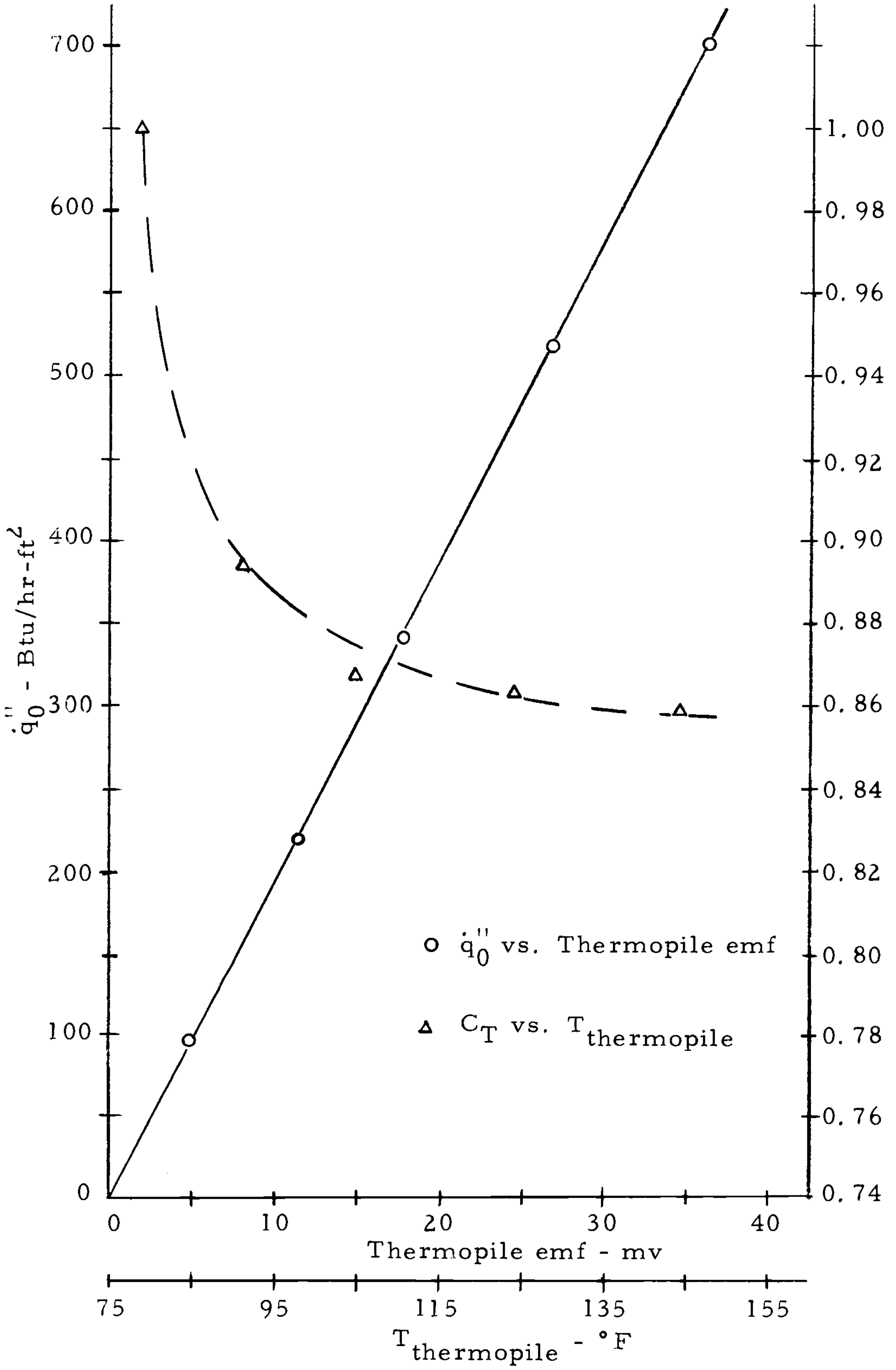


Figure A-19. Calibration curve - Thermopile No. 32.

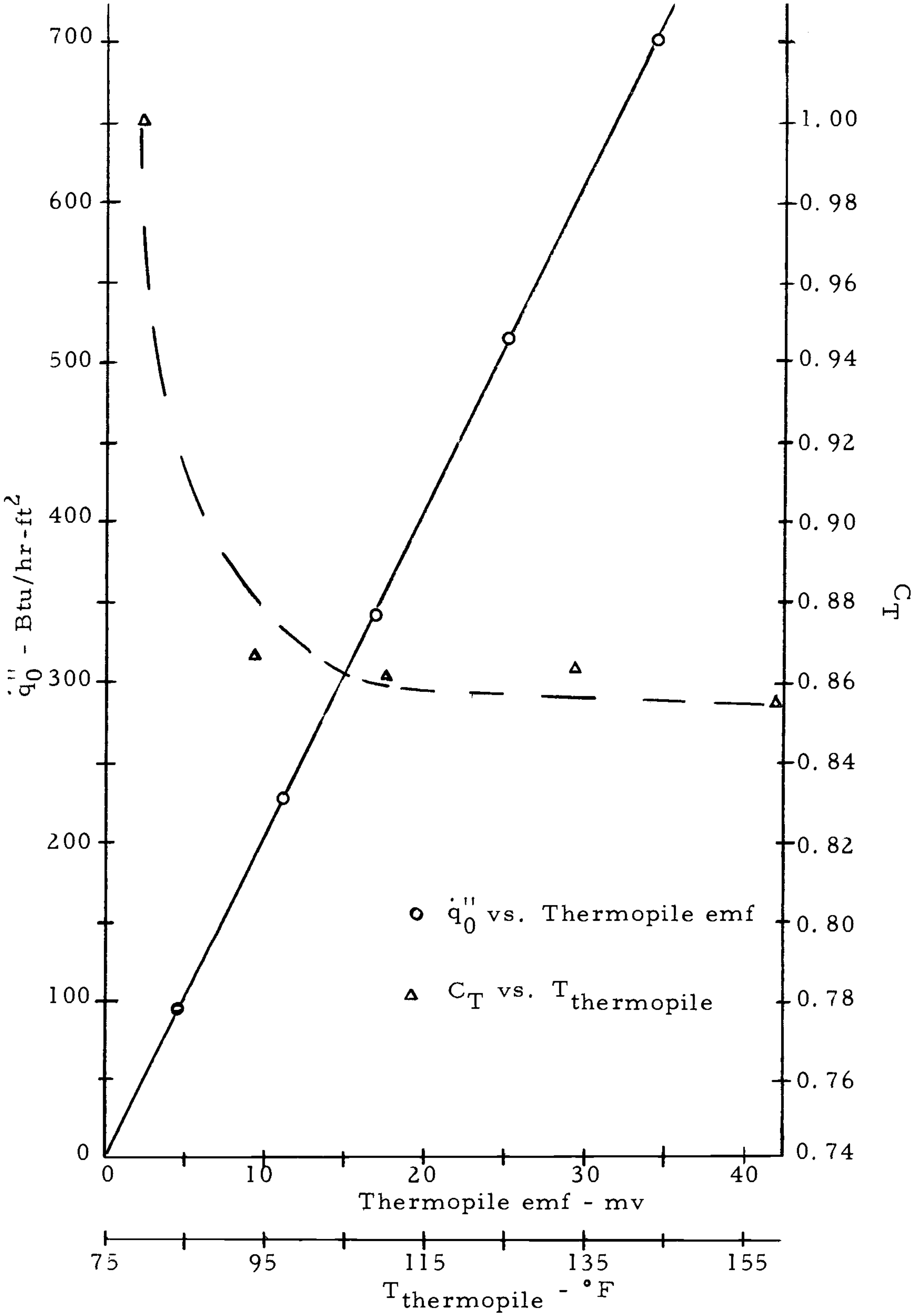


Figure A-20. Calibration curve - Thermopile No. 34.

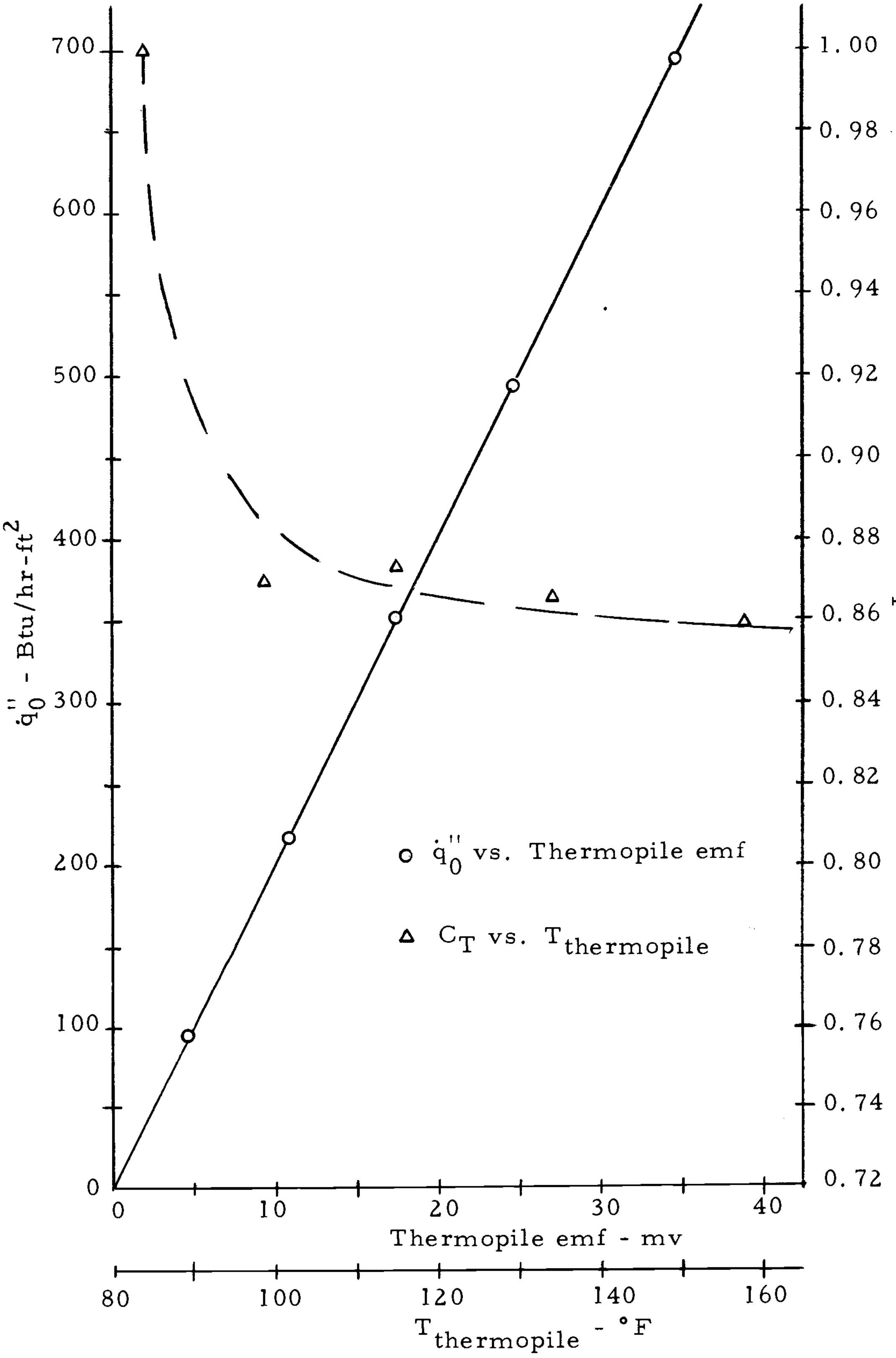


Figure A-21. Calibration curve - Thermopile No. 36.

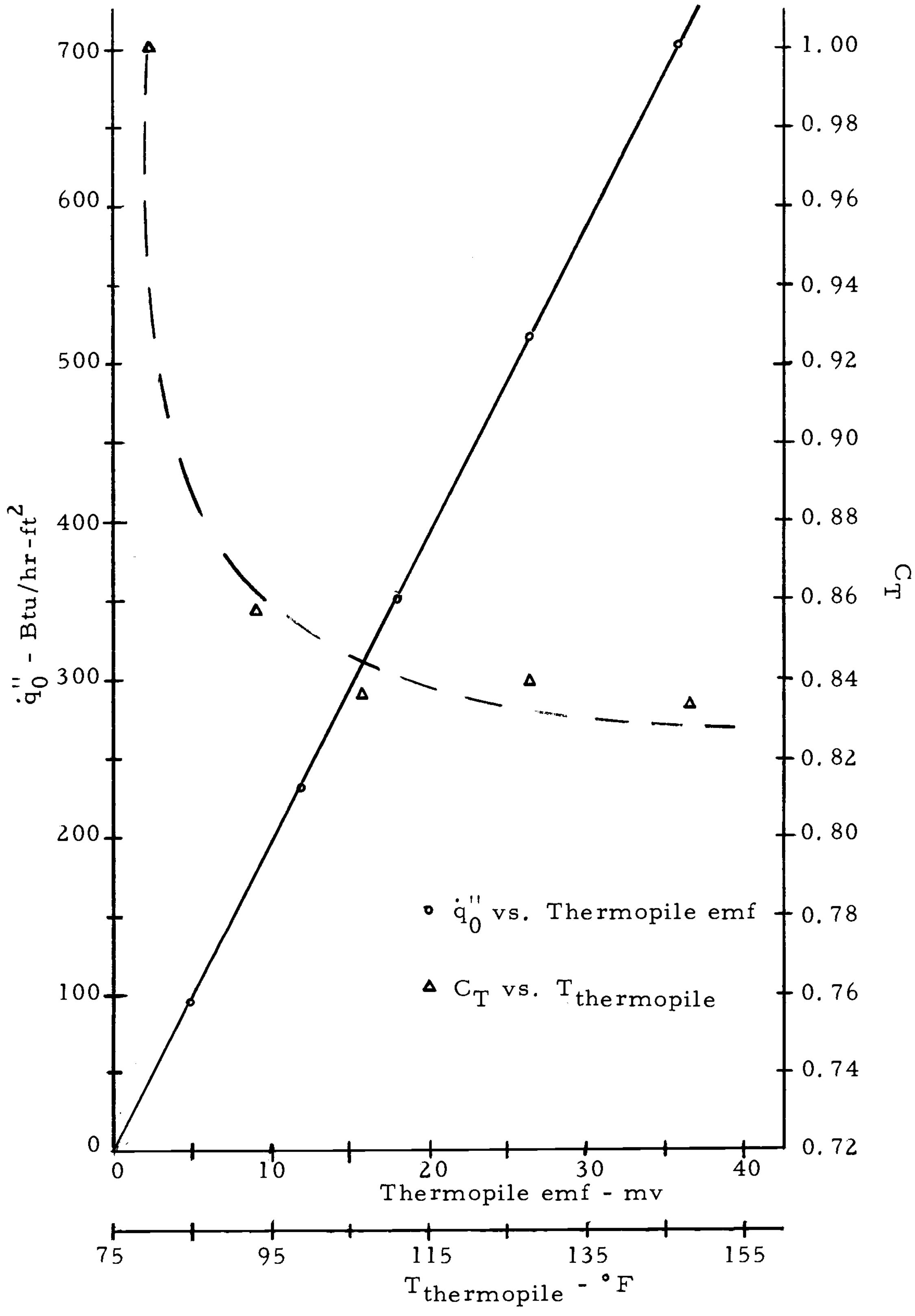


Figure A-22. Calibration curve - Thermopile No. 38.

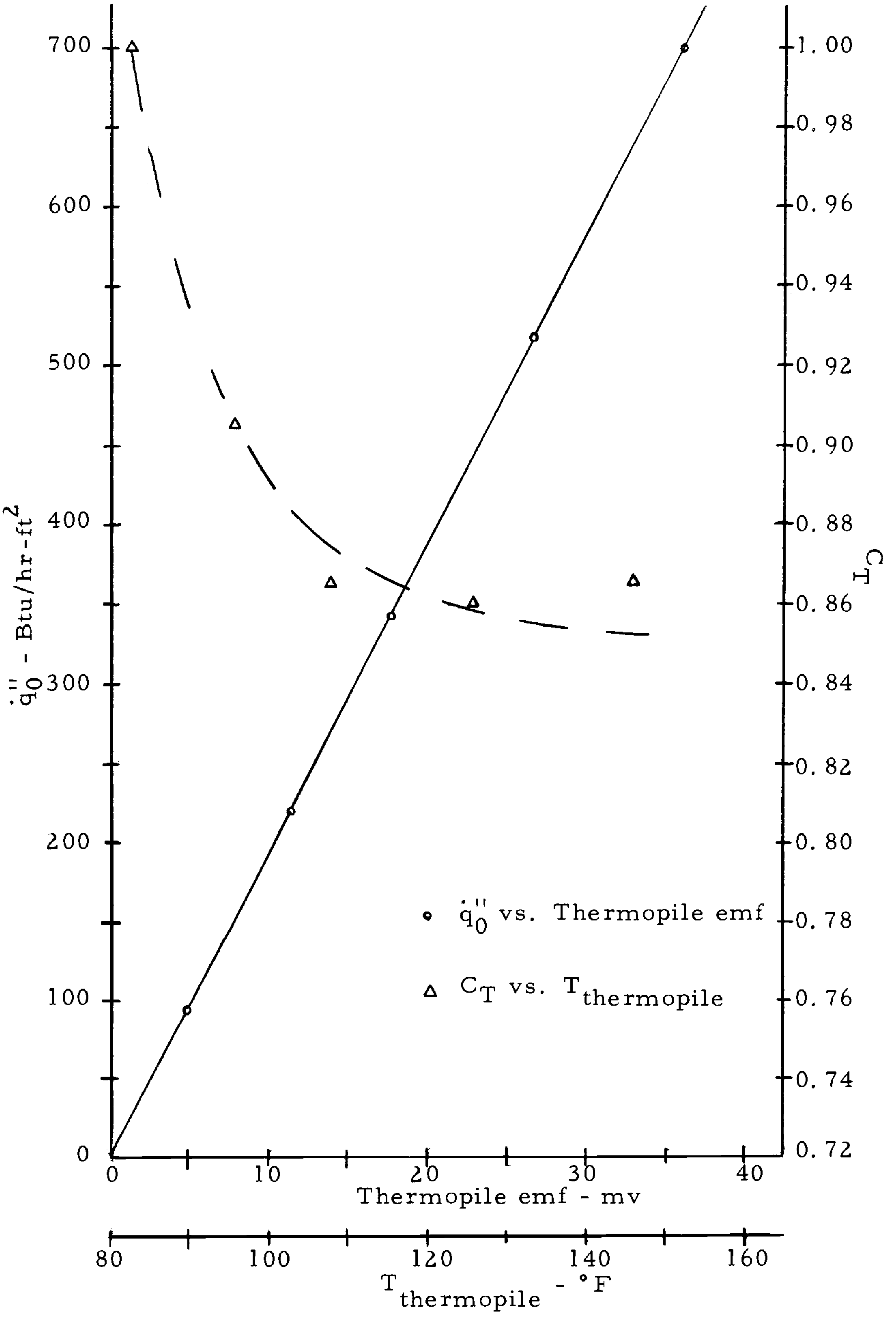


Figure A-23. Calibration curve - Thermopile No. 40.

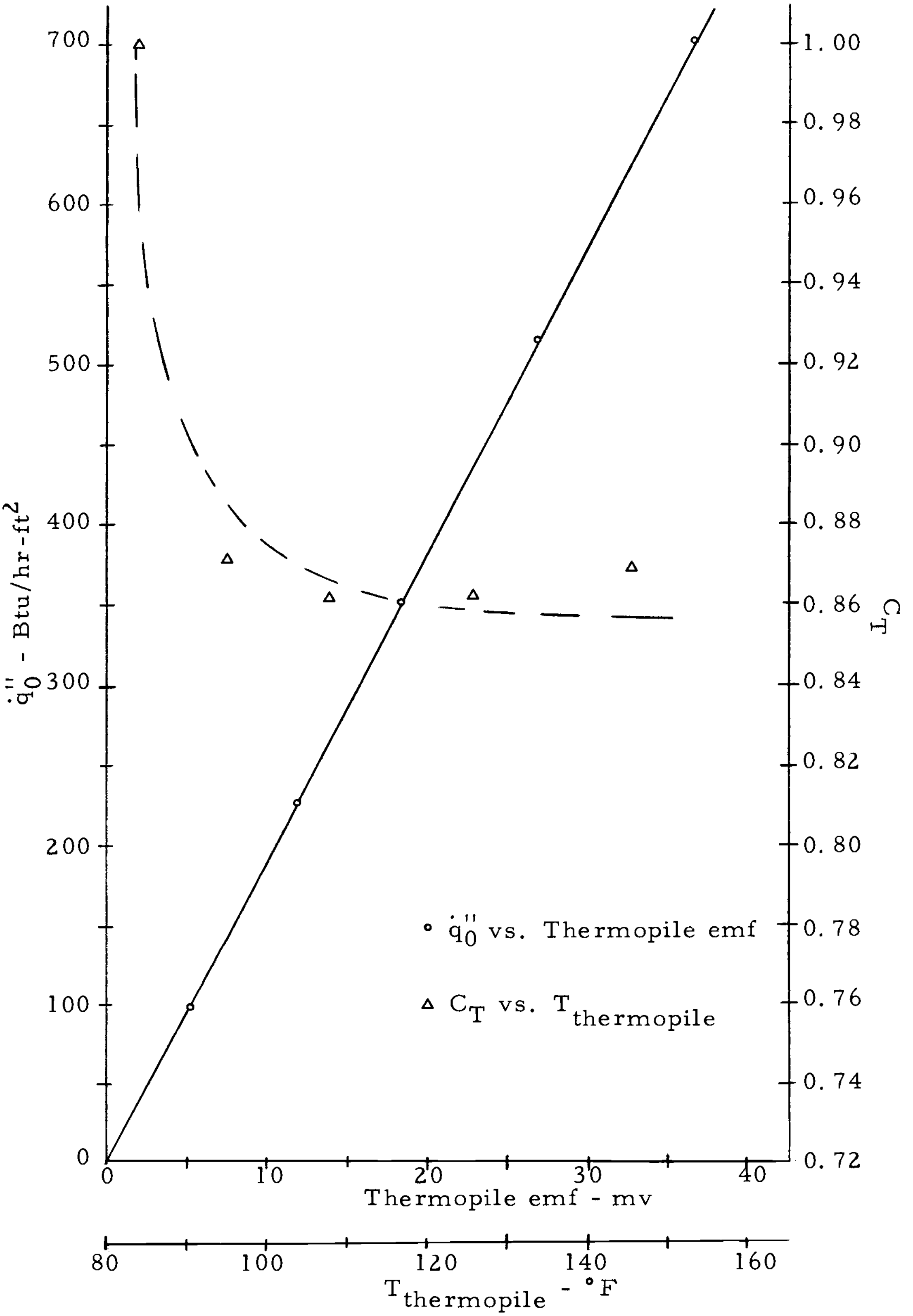


Figure A-24. Calibration curve - Thermopile No. 42.

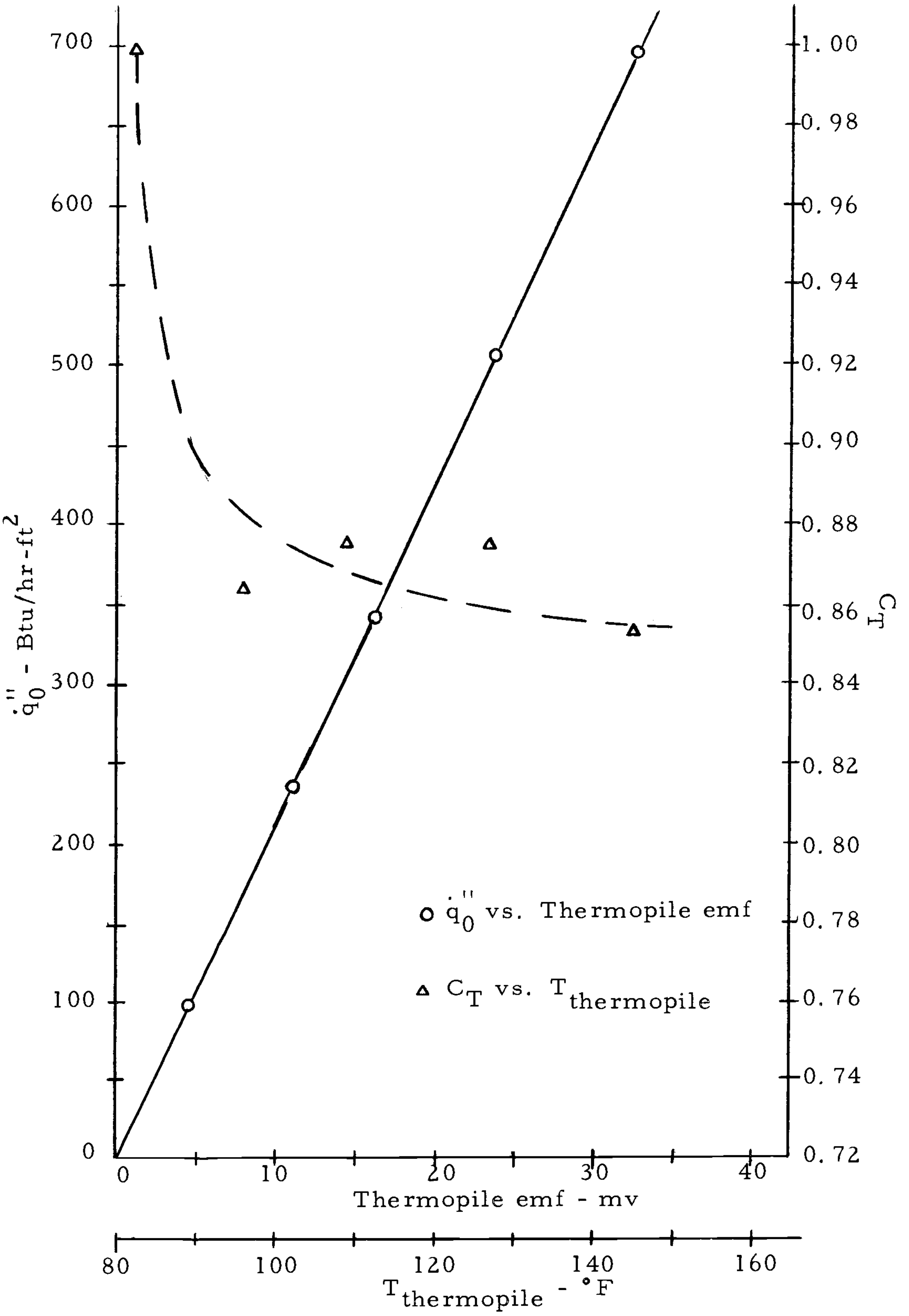


Figure A-25. Calibration curve - Thermopile No. 44.

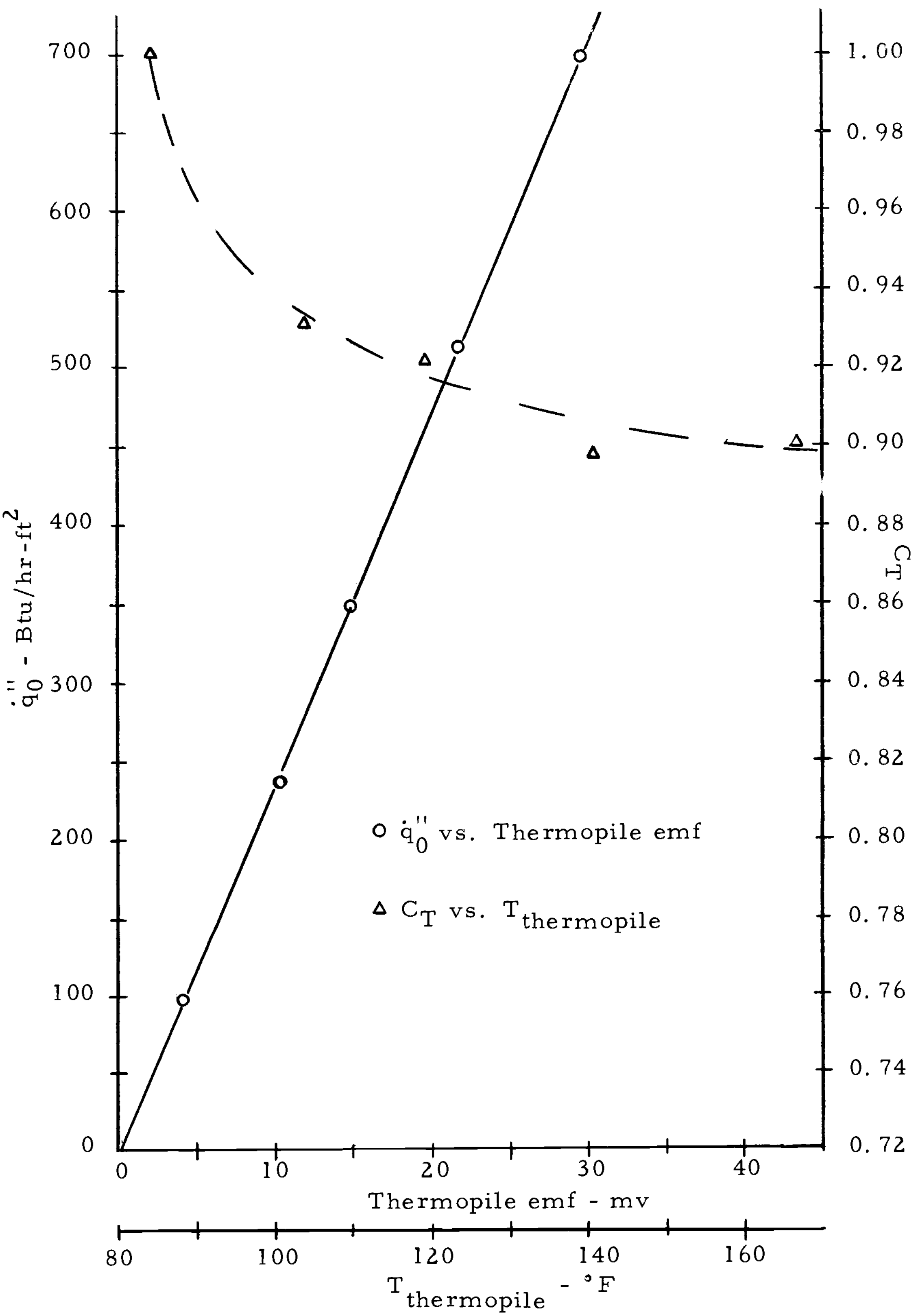
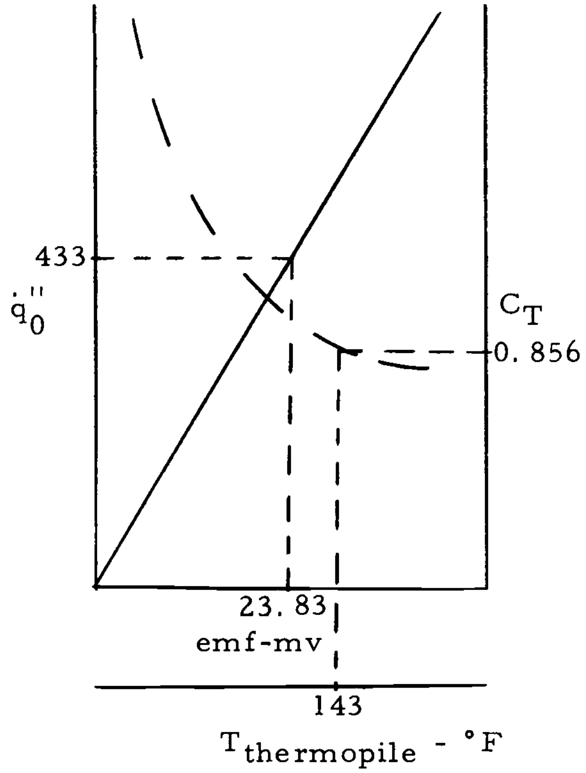


Figure A-26. Calibration curve - Thermopile No. 46.



Sample:

Example Usage of Calibration Curve:

Assume:

Heat meter number 22 reads:

23.83 mv at $T_{\text{thermopile}} = 143°$ F;

For 23.83 mv, $\dot{q}_0'' = 433$ Btu/hr-ft^2
and for $T_{\text{thermopile}} = 143°$ F, $C_T = 0.856$

Then $\dot{q}_0''$ corrected for thermopile temperature is:

$$\dot{q}_0'' \text{ corrected} = \frac{\dot{q}_0''}{C_T} = \frac{433}{0.856} = 506 \text{ Btu/hr-ft}^2$$

Figure A-27. Example usage of calibration curve.

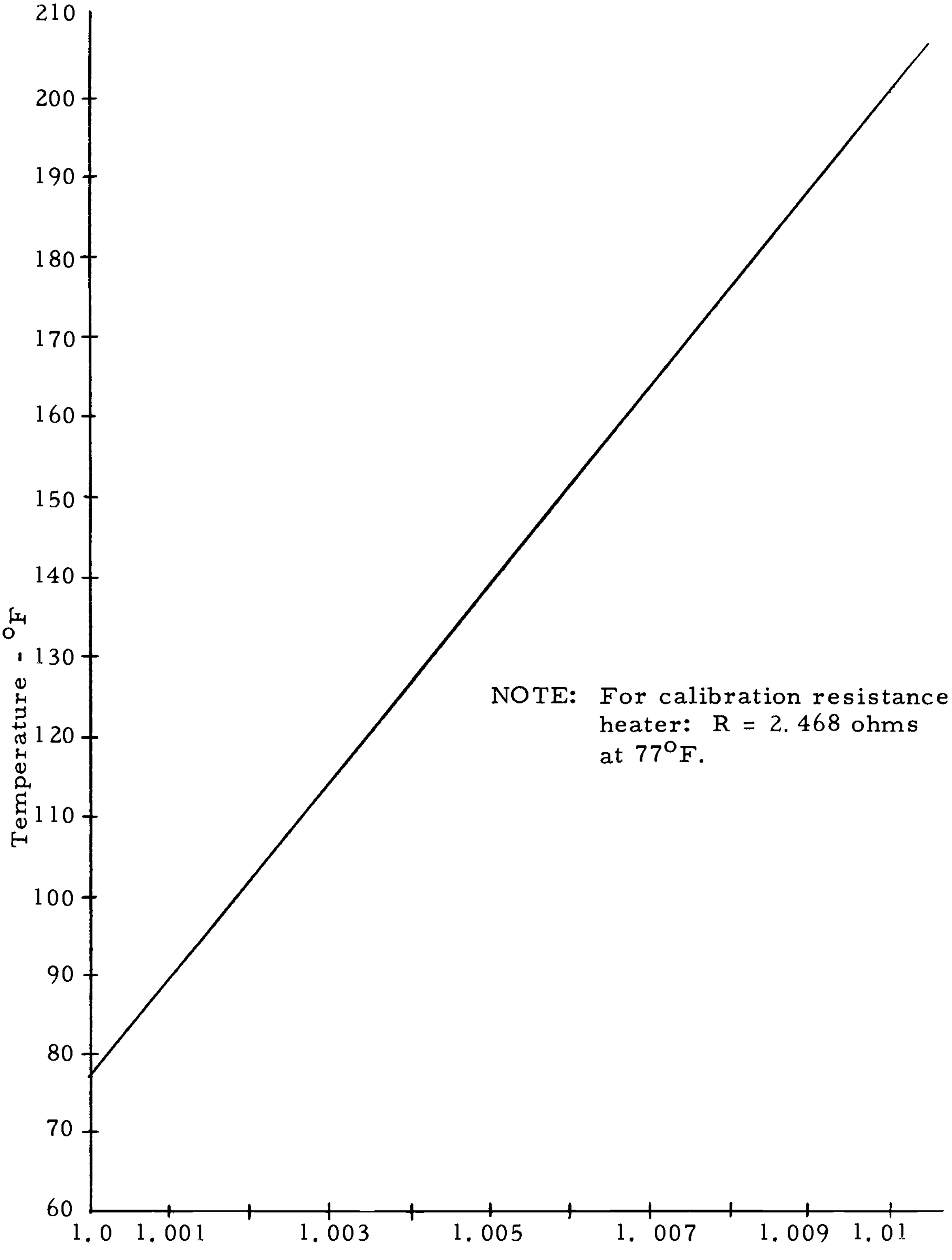


Figure A-28. Temperature vs. resistance multiplying factor for calibration resistance heater.