NATIONAL BUREAU OF STANDARDS REPORT

9337

CALIBRATION OF AIR FORCE CALIBRATION LABORATORY
BLACKBODY FURNACES

By
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Joseph C. Richmond

Contract AF 36(600) 19320

U. S. AIR FORCE 2802D INERTIAL GUIDANCE
AND CONTROL GROUP
NEWARK AIR FORCE STATION
NEWARK, OHIO

NBS

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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Gaithersburg, Md.

Sponsored by U. S. Air Force 2802D Inertial Guidance
and Control Group
Newark Air Force Station
Newark, Ohio

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Abstract

The spectral radiance of two laboratory blackbody furnaces supplied by the Air Force Calibration Laboratory was compared to that of an NBS laboratory blackbody furnace at blackbody furnace temperatures of 500, 800, 1100 and 1400°K, and at 16 wavelengths in the range 1 to 15.5 microns. No statistically significant difference was detected.

Introduction

The National Bureau of Standards was requested by the Air Force, 2802nd Inertial Guidance and Control Group, to compare the spectral radiance of two laboratory blackbody furnaces to that of an NBS reference blackbody furnace.

The effective emissivity of the NBS reference blackbody furnace was computed, from the geometry of the cavity and the known emittance of the cavity lining, to be 0.9997 or better when the cavity is isothermal. Thermal gradients in the cavity do not exceed 3°K except in the area immediately adjacent to the aperture, where the temperature may be as much as 50°K lower than the temperature at the back of the cavity. Preliminary rough computations indicate that these gradients will reduce the effective spectral emissivity of the cavity by no more than 0.005 at 1μ and 500°K, and by less than 0.001 at 15μ and 1400°K. A computer code is being developed to compute more accurately the effect of the thermal gradients on the emissivity of the NBS blackbody.

Temperature Equalization of Blackbodies

Before making any measurements, the power input to each AF blackbody was adjusted to minimize thermal gradients within the cavity. The heater winding on each furnace consists of a coil of platinum-20% rhodium wire, about 5 in. long, with two taps located about one inch from each end, as is indicated in figure 1. The primary power supply is an autotransformer, which is used to vary the input voltage. Three 5-ohm, 500-watt variable resistors are used as shunts across the front, center and rear sections of the heater winding, respectively.

In adjusting the thermal gradients, the three shunt resistors were set at their maximum resistance (zero on the dial), and the input voltage was increased by increments that increased the overall amperage through the furnace (as indicated by ammeter A) in increments of about 2A every 15 minutes, until a temperature near that desired was attained. The furnace was allowed to approach thermal equilibrium for at least one hour, before measuring the temperature profile.

The temperature profile in the cavity was measured by means of a thermocouple probe. A thermocouple made from 10-mil chromel and alumel wires was used at temperatures up to 1100°K, and a thermocouple made from 20-mil platinum and platinum-10% rhodium wires was used at 1400°K. The thermocouple wires were inserted into the holes in a 12-in. length of 2-hole alumina insulator, which served to support the thermocouple in the cavity as well as to insulate the wires from each other electrically. The thermocouple bead extended about 1 cm from the end of the insulator, and the wires were bent at an angle so that the thermocouple bead was in contact with the wall of the cavity when the insulator was positioned along the axis of the cavity. Ten marks, one cm apart, were made on the insulator, starting near the end opposite the thermocouple.

A small ring stand was used to hold an aluminum guide bushing which surrounded the thermocouple insulator with a snug fit. In making a temperature profile measurement, the thermocouple was positioned in the bushing so that the first mark on the thermocouple insulator was aligned with the end of the bushing, and the whole assembly was positioned so that the bushing and thermocouple insulator were aligned with the axis of the cavity, and the thermocouple was in contact with the wall of the cavity at its rear. The emf from the thermocouple was then measured with a portable potentiometer. Successive temperature measurements were made as the thermocouple was withdrawn from the cavity in increments of one centimeter, as determined by aligning successive marks with the end of the stationary bushing.

After a temperature profile measurement was completed, adjustments in the settings of the variable resistors were made to decrease the power to the warmer parts. After allowing 15 to 30 minutes for the cavity to approach thermal equilibrium, the temperature profile was again measured, and additional adjustments made, successively, until the gradients in the cavity were reduced to a minimum. The temperature profiles obtained at this point, together with the control settings, are given in Table 1 for cavity temperatures of 500, 800, 1100 and 1400°K.

Modification and Repair of Air Force Equipment

There were several deficiences in the Air Force equipment as received. The first to be noticed was the result of failure of the thermocouple for the temperature limiting controller. Upon investigation, it was determined that the couple was drastically undersized for a chromel-alumel couple to be used at 1400°K. A platinum versus platinum 10% rhodium couple was selected. The back plates of the furnaces were removed and a 20 mil platinum couple was inserted beside the heater winding. This placement will lead to a discrepancy between the control setting and the actual cavity temperature, but it will provide for maximum cavity temperature stability in temperature limit control usage. It may be possible to use the controller to maintain the appropriate temperature of the comparison furnace rather than use the manual power setting method. The chromel-alumel control units were returned to the manufacturers for credit and platinum control units were ordered, received, and installed. The units will require zeroing as described in the instructions after the appropriate lead wires have been attached.

The first attempt to use the differential controls revealed more deficiencies. Neither of the C.A.T. units was functioning. In order to save time, an NBS unit was substituted therefor and two complete sets of new tubes were ordered. Proceeding on, it was found that the polarity of the recorder input was reversed and as a consequence, as the temperature of the controlled body decreased, the recorder pointer went up scale and the power sent to the furnace was decreased. The recorder input wires were reversed so that the recorder indication was in the same direction as the meter deflections on the microvolt amplifier.

In the absence of the temperature limit controllers, the operation of the furnaces was by manual adjustment of the voltage input after the limit switch leads to the temperature limit control module were shorted. Shortly before the consoles were shipped from NBS, the new controllers arrived and were installed. At this time, it was noticed that the limit switch relay was designed for only five amperes. The furnaces require fifteen amperes, hence a mercury relay was installed in each relay rack to interrupt the furnace power on signal from the limit switch relay as shown in Figure 2.

Adaptation of the Spectroradiometer

The spectroradiometer was modified to accommodate the additional blackbody in the specimen beam by enlargement of the sliding platform that makes possible the insertion of either blackbody accurately into the specimen beam, and the fabrication of furnace cradles and a clamp. The cradles and clamp provided the necessary flexability for positioning the blackbodies in the horizontal plane relative to beam axis and focus.

The NBS blackbody cavities have not yet been modified to permit viewing the entire back wall by inclining the thermocouple port as was done with the AF blackbodies. As a consequence, both the AF and NBS blackbodies had to be aligned so that the same area of the cavities was included in the beam envelope fixed by the spectrometer and that this area did not include the thermocouple port of the NBS blackbodies. This was accomplished by directing a mercury light back through the spectrometer from the detector and by adjusting the position of each cavity until corresponding areas were illuminated.

Exploration for a Comparison Procedure

The differential control thermocouples for the AF blackbodies were too large to be inserted into the NBS blackbodies and consequently the thermocouples normally used for the NBS blackbodies were used for both. This seemed to cause a thermocouple immersion depth sensitivity in the AF blackbodies, meaning that changing the depth of immersion into the cavity changed the measured temperature. The looseness of the fit of the couple to the port may have caused unstable temperature gradients in the couples. The proper immersion depth was therefore determined by comparing the optical pyrometer temperature at 1100°K with the thermocouple temperature, and coincided with the depth beyond which no further change in the thermocouple temperature occurred.

The blackbodies were then switched to automatic control and while the recorder indicated zero temperature difference between the cavities, the temperature difference was checked with the optical pyrometer. This measurement concurred with the recorder indication at 1100 and 1400°K. The optical technique cannot be used at 500 or 800°K, and therefore the proper immersion depth was taken as that beyond which the temperature did not change with immersion depth.

At 500°K, even this technique was questionable because the couple could be pulled practically all of the way out of the port before any temperature change was noted. The effect of a difference in temperatures of the blackbodies was measured. A difference of approximately two degrees K produced a one percent change in the spectrometer reading at a wavelength of two microns. A check of the comparison blackbody stability revealed that the temperature might drift slowly at a rate of several degrees per hour.

An attempt was made to control both the NBS reference blackbody and one of the AF blackbodies at the same temperature as the NBS comparison blackbody, but interaction between the two sets of electronic controls made it impossible to achieve the degree of control desired. The design of the NBS furnaces permitted only one control thermocouple at a time to be used in a furnace, and the one control thermocouple could not be used successfully as a junction for two different differential thermocouples at the same time without interaction of the two sets of controls.

Comparison Procedure

The AF blackbodies were compared to the NBS reference blackbody by the following procedure. The power input to the NBS comparison blackbody was adjusted manually until it achieved an equilibrium temperature near the test temperature, after which no further adjustment was made to the power input controls. The temperature of the furnace remained nearly constant, with a slow drift of not over 5°K per hour. The power input to the NBS reference blackbody was similarly adjusted, to bring it to an equilibrium temperature near the test temperature. The temperature of the AF blackbody being tested was controlled to be the same, as nearly as possible, as that of the NBS reference blackbody by means of the AF control equipment actuated by a differential thermocouple. One junction of the differential thermocouple was located in the cavity of the AF blackbody, and the other was located in the cavity of the NBS reference blackbody. The temperature equality of the two blackbodies was checked with an optical pyrometer at 1100° and 1400°K.

The spectral radiance of the AF blackbody was compared to that of the NBS reference blackbody at the same temperature at 16 different wavelengths between 1 and 15.5 microns by means of a Perkin-Elmer model 13 spectroradiometer having source optics modified to permit direct comparison of two different sources. The NBS comparison blackbody was always used as source for the Io beam of the spectrometer.

In making a comparison the wavelength drum was first adjusted to give the desired wavelength, and then the slit width and amplifier gain were adjusted to give a signal of 10 mv on the "Recorder Range" meter. This meter measures the potential drop across the slidewire on the potentiometer recorder. With the NBS reference blackbody in position to serve as source for the I beam of the spectrometer, the "Fine Gain" control was adjusted to give a reading of about 95 on the chart. The I beam was then blocked with a sheet of aluminum, and the "Ratio Zero" control was adjusted to give a reading of about 2 on the chart.

After the preliminary adjustments had been completed, the comparison measurements were made. With the I beam blocked, the zero signal was recorded for about one minute. The height of this curve is designated Z1. The aluminum plate was then removed, and the signal from the NBS blackbody was recorded for one minute. The height of this curve is designated R1. The AF blackbody was then substituted for the NBS reference blackbody, which could be done in less than one second, and its signal was recorded for one minute. The height of this curve is designated A. The NBS reference blackbody was then substituted for the AF blackbody, and its signal was again recorded for one minute. The height of this curve is designated R2. The I beam was then blocked and the zero curve was recorded for one minute. The height of this curve was designated Z2.

The difference in the spectral radiances of the two blackbodies was computed as

$$\frac{2A-(R1 + R2)}{R1+ R2-(Z1 + Z2)} \tag{1}$$

All five measurements were completed in a total elapsed time of approximately 5 minutes. The order in which the measurements were made and the method of computation effectively compensates for any linear drift of the temperature of the NBS comparison blackbody, or of the zero curve, during the period of measurement.

The procedure outlined above was followed at each of the 16 wavelengths at which comparisons were made. The data obtained are given in Table 2.

DISCUSSION

The two AF blackbody furnaces are obviously quite different. The adjustments required to equalize the temperature of one furnace are reversed for the other. This phenomenon prompted a check of both furnaces to confirm correspondence between shunt controls, shunt current, and temperature of a furnace zone. This was done by turning one control at a time to the extreme position and noting the effects. Eventually, the furnaces may require modification of the heater elements, but at present, there is enough shunt capacity to equalize the temperature. Table 1 shows the results of the final temperature probe and the control settings at the time. Except for T9 and T8 which are probe temperatures measured at the mouth and one centimeter inside the cavity respectively, the maximum temperature difference was in blackbody number one at 1100°K and was less than 3°K.

The emittance comparisons were very good also, and are generally better than one would expect, considering the reproducability of previous emittance measurements. An insensitivity in the recorders discussed later may have resulted in temperature differences between the blackbodies of 1°K or possibly more. This was shown to cause an emittance error of ±0.005 at 1.5 microns and slightly less than ±0.001 at 15 microns for measurements at 800°K. Considering the decreasing scatter in the direction of the higher temperature data and the fact that temperature control is known to be more precise at the higher temperatures, one would have reason to expect that the emittance differences were primarily the result of imprecise temperature control.

The tests indicate that at the temperatures of 1100 and 1400°K, where the temperature control is most precise, the AF blackbodies have effective emissities equal to that of the NBS reference blackbody within the error of measurement, which is considered to be about 0.003 in emittance, expressed as a standard deviation of a single measurement. This figure is based on a large number of measurements, made prior to calibration of the AF blackbodies.

At temperatures of 500° and 800°K, where temperature control is less precise, and where there is less radiant flux available for measurement, the measured differences were somewhat larger than at the higher temperatures. Even here, the measured differences are not large enough to substantiate, on a statistical basis, a real difference in the effective emittance of the AF blackbodies and the NBS reference blackbody.

It should be emphasized that the contribution to the error in computing the spectral radiance of an AF blackbody, at a temperature below the range at which an optical pyrometer can be used, due to error in measuring the temperature of the cavity is likely to be appreciably larger than the error due to deviation of the cavity from a true blackbody emitter.

RECOMMENDATIONS

During the course of the work, a lack of sensitivity in the AF recorders was noticed. Efforts to improve this by replacement of tubes and increasing the gain of the recorder amplifier failed to yield any improvement. A Leeds & Northrup service representative was called in to search for a solution. At this point, it seems best for the AFCL to request assistance from the local representatives.

The system should have a water flow actuated power shut-off in the event the water circulation stops. Any number of things can occur which will stop the circulation of the cooling water which can not be tolerated for very long without melting the soldered joints of the furnace. A small cup, with an orifice slightly smaller than that which will pass the minimum flow required, placed beneath the water return fitting and attached to a microswitch by a rod through the top of the refrigeration unit should work. The very low water pressure excludes the use of all the commercial limit switches known. The microswitch should be in series with the holding coil on the mercury relay. A sketch of the proposed device is given in Figure 3.

All thermocouple connections should be in an isothermal block to insure that the only junction of dissimilar materials to contribute to the emf is the hot junction of the thermocouple. Mounting the connectors on a large copper block shielded from strong air currents may be sufficient. Gold plated connectors produce very low emfs with respect to platinum, but nickel plated banana plugs of the type supplied with the AF equipment may contribute significant spurious emfs when used in a thermocouple circuit.

TABLE 1. FURNACE SETTINGS

BLACKBODY 1

	500°K	800°K	1100°K	1400°K
Front Dial	60	60	40	25
Center Dial	90	80	100	100
Rear Dial	0	0	0	0
Front Current	0.8	1.58	2.13	2.38
Center Current	1.0	1.58	3.37	4.42
Rear Current	0.5	1.02	1.58	2.12
Variac Setting	7	14	23	30
Volts	0.9	17.4	24.8	30.0
Total Amperes	6.3	10.3	13.7	15.7
T0 (°K) (Rear)	502.1	794.7	1105.1	1411.7
T1	502.1	794.7	1105.1	1411.7
T2	502.1	794.7	1105.1	1411.7
T3	502.1	796.6	1108.0	1411.7
T4	503.7	796.6	1108.0	1411.7
T5	503.7	796.6	1108.0	1411.7
T6	503.7	796.6	1108.0	1411.7
T7	503.7	796.6	1108.0	1411.7
T8	502.1	762.4	1105.1	1411.7
T9 (Front)	496.5	754.3	1037.7	1108.3

BLACKBODY 2

	500°K	800°K	1100°K	1400°K
Front Dial	60	48	0	0
Center Dial	70	75	80	80
Rear Dial	0	26	25	60
Front Current	0.8	1.30	1.45	1.88
Center Current	0.7	1.45	2.57	3.60
Rear Current	0.4	1.05	1.70	3.13
Variac Setting	8	16	25	32.3
Volts	0.9	16.8	30.0	44.5
Total Amperes	6.3	10.2	13.0	14.8
T0 (°K) (Rear)	503.6	798.7	1102.1	1394.9
T1	503.6	798.7	1102.1	1394.9
T2	503.6	799.1	1102.1	1394.9
T3	503.6	799.7	1102.1	1394.9
T4	503.6	799.7	1102.1	1394.9
T5	505.1	799.7	1102.1	1394.9
T6	505.1	799.7	1102.1	1394.9
T7	505.1	799.7	1102.1	1394.9
T8	505.1	747.3	1076.6	1394.9
T9 (Front)	493.6	702.0	1036.5	1363.7

TABLE 2. EMITTANCE DIFFERENCES

	500°K								800°K							
	Blackbody 1				Blackbody 2				Blackbody 1				Blackbody 2			
WL(μ)	Run 1	Run 2	Run 3	Avg	Run 1	Run 2	Run 3	Avg	Run 1	Run 2	Run 3	Avg	Run 1	Run 2	Run 3	Avg
1.52	.045	.024	.050	.0397	-.020	-.030	-.050	-.0333	.006	-.015	-.010	-.0063	-.034	-.003	-.003	-.0133
3.45	.009	.009	.010	.0093	.000	.007	.000	.0023	.000	-.001	-.005	-.0020	-.012	-.002	-.001	-.0050
5.27	.002	.002	.002	.0020	-.007	.000	-.001	-.0027	.000	.000	-.005	-.0017	-.004	-.003	-.002	-.0030
6.58	.002	.000	.001	.0010	-.009	-.001	.000	-.0033	.000	.000	-.002	-.0007	-.012	-.002	-.002	-.0053
7.71	.000	.002	.003	.0016	-.015	.000	-.001	-.0053	.000	-.001	-.004	-.0016	-.006	-.002	-.003	-.0037
8.70	.000	.003	.004	.0023	-.014	.001	.000	-.0043	.002	-.001	-.004	-.0023	-.004	-.005	-.002	-.0037
9.55	.000	.002	.003	.0016	-.008	.000	-.001	-.0030	.000	-.002	-.001	-.0010	-.005	-.005	-.001	-.0037
10.34	.003	.002	.001	.0020	-.004	.000	-.001	-.0016	.000	-.002	-.004	-.0020	-.006	-.005	-.002	-.0043
11.08	.004	.000	.000	.0013	-.002	.000	.000	-.0007	.000	-.002	-.004	-.0020	-.005	-.002	-.003	-.0033
11.74	.004	.000	.000	.0013	.000	.000	-.001	-.0003	.000	-.002	-.002	-.0013	-.004	-.006	-.002	-.0040
12.38	.004	.000	.002	.0020	-.001	.000	-.001	-.0007	.000	-.001	.000	-.0003	-.003	-.002	-.002	-.0023
13.00	.002	.002	.001	.0016	-.002	.000	-.001	-.0010	.000	.000	-.003	-.0010	-.004	-.003	-.002	-.0030
13.60	.001	.000	.002	.0010	-.010	.000	-.001	-.0037	.000	-.002	-.006	-.0027	-.003	-.005	-.002	-.0033
14.17	.000	.000	.000	.0000	-.011	-.003	-.006	-.0067	.000	-.002	-.003	-.0017	-.005	-.004	-.003	-.0040
14.71	.000	-.004	.000	-.0013	-.014	-.010	-.001	-.0083	.000	-.006	-.007	-.0043	-.005	-.004	-.005	-.0047
15.25	.000	-.002	.000	-.0007	-.020	-.006	-.010	-.0120	-.005	-.008	-.010	-.0077	-.005	-.004	-.004	-.0043

	1100°K								1400°K							
	Blackbody 1				Blackbody 2				Blackbody 1				Blackbody 2			
WL(μ)	Run 1	Run 2	Run 3	Avg	Run 1	Run 2	Run 3	Avg	Run 1	Run 2	Run 3	Avg	Run 1	Run 2	Run 3	Avg
1.52	.000	-.003	-.003	-.0020	-.001	-.005	-.002	-.0027	.004	.002	.000	.0020	.000	.006	-.002	.0013
3.45	.000	-.003	.000	-.0010	-.002	-.005	-.002	-.0030	.003	.001	.000	.0013	.000	.002	.000	.0007
5.27	.000	-.001	-.002	-.0010	-.007	-.006	.000	-.0043	.000	.000	.000	.0000	.000	.000	.000	.0000
6.58	.000	-.001	.000	-.0003	-.005	-.003	-.004	-.0040	.000	.000	.000	.0000	.000	.000	.000	.0000
7.71	.000	-.001	-.001	-.0007	-.002	-.001	-.001	-.0013	.000	.000	.000	.0000	.000	.001	.000	.0003
8.70	-.001	.000	.000	-.0003	-.005	-.002	-.002	-.0030	.000	.000	.001	.0003	.000	.001	.000	.0003
9.55	-.001	.000	-.001	-.0007	-.003	-.004	-.001	-.0027	.000	.001	.000	.0003	.000	.001	.000	.0003
10.34	.000	.000	.000	.0000	-.001	-.002	-.001	-.0013	.000	.001	.000	.0003	.001	.000	.000	.0003
11.08	.000	.000	.000	.0000	-.002	-.001	-.006	-.0030	.000	.000	.000	.0000	.000	.001	.000	.0003
11.74	.000	.000	.000	.0000	-.004	-.002	-.002	-.0023	.000	.000	.000	.0000	.000	.000	.000	.0000
12.38	.000	-.001	.000	-.0003	-.003	.000	.000	-.0010	.000	.000	.000	.0000	.000	.000	.000	.0000
13.00	.000	-.001	.000	-.0003	-.002	-.004	.000	-.0020	.000	.000	.000	.0000	.001	.000	.000	.0003
13.60	.000	.000	.000	.0000	-.003	-.003	-.004	-.0033	.000	.000	.000	.0000	.000	.001	.000	.0003
14.17	.000	-.001	-.001	-.0007	-.001	-.002	-.005	-.0027	.000	.000	.000	.0000	.000	.000	.000	.0000
14.71	-.001	-.001	.000	-.0007	-.002	-.005	-.003	-.0033	.000	-.001	.000	-.0003	-.001	.000	.000	-.0003
15.25	-.001	-.003	-.001	-.0017	-.001	-.002	-.003	-.0020	.000	.000	.000	.0000	.000	.000	[illegible]	.0000

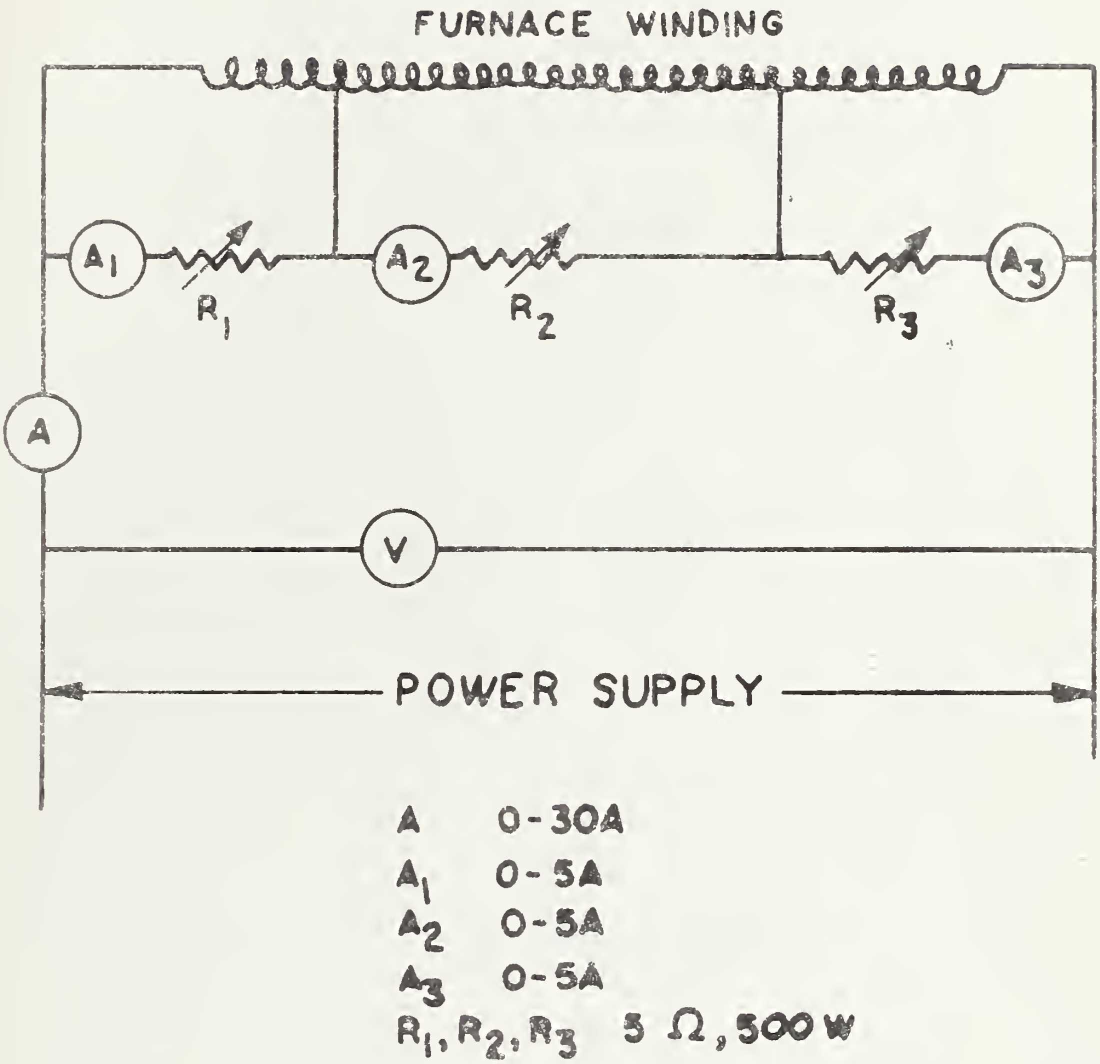

Figure 1. Heater Winding Wiring Diagram

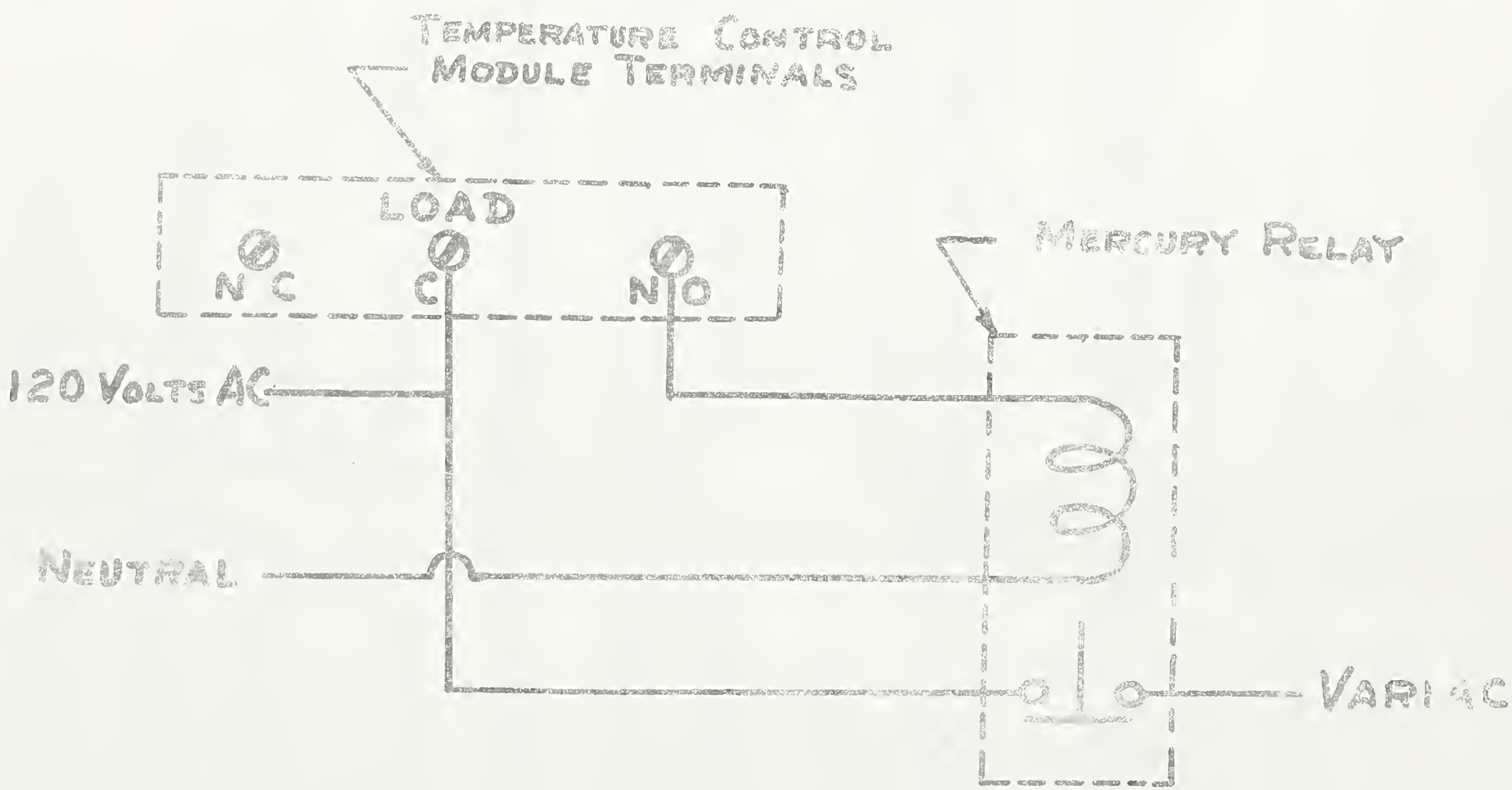

FIGURE 7. MERCURY RELAY WIRING

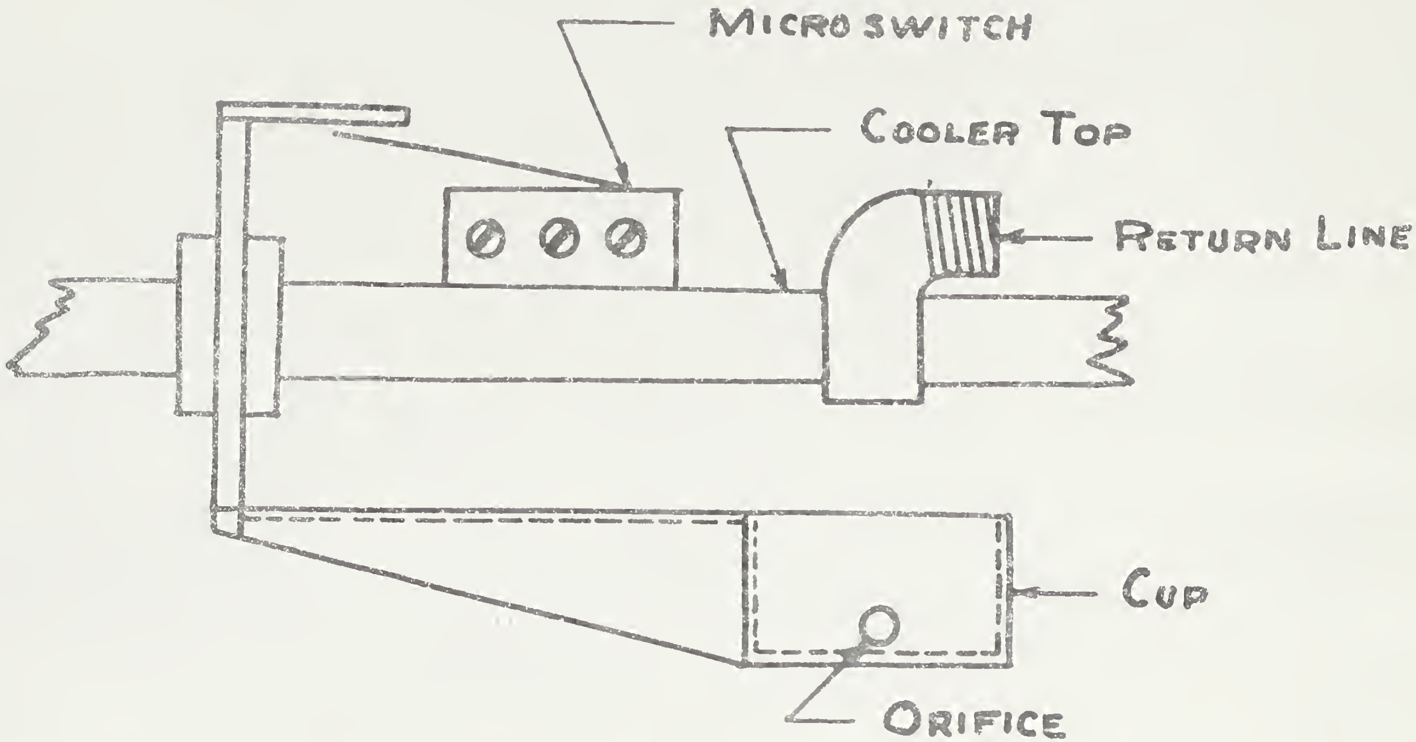

FIGURE 3. WATER FLOW SWITCH

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