DEVELOPMENT AND ANALYSIS OF AN INFRARED RADIOMETER FOR THE REMOTE DETECTION OF TEMPERATURE

By

NORMAN FLOYD WHITSITT

Bachelor of Science in Mechanical Engineering

Arlington State College

Arlington, Texas

1961

Submitted to the faculty of the Graduate School of
the Oklahoma State University
in partial fulfillment of the requirements
for the degree of
MASTER OF SCIENCE
August, 1962

DEVELOPMENT AND ANALYSIS OF AN INFRARED

RADIOMETER FOR THE REMOTE

DETECTION OF TEMPERATURE

Thesis Approved:

R. L. Lowery
Thesis Adviser

R. E. Chapel

Robert MacVicar
Dean of the Graduate School

ACKNOWLEDGMENT

I wish to express my appreciation to Dr. R. L. Lowery for his support and suggestions for this investigation. Without his support, this investigation would have been impossible. The help and advice of Dr. John Wiebelt is also greatly appreciated.

I am also indebted to Alvin Baker and John Leland who were of much help in carrying out this investigation.

Recognition should also be given to John McCandless, L. S. Benjamin, and George Cooper whose help in the construction of a portion of the apparatus made this thesis possible.

I would also like to thank Mrs. Fred Welsh who typed this thesis.

Last, but certainly not least, I want to express my deep appreciation to my wife, Libby, whose patience and encouragement, along with her review of the thesis, have been of untold value to me in this endeavor.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

FOREWORD

This report represents an investigation of methods of utilizing the infrared radiation of a turbine wheel of a J-47 jet engine to measure its temperature. The investigations which are discussed in this report represent a portion of the duties of the author while assigned to the Nondestructive Testing Project as a graduate research assistant. The Nondestructive Testing Project was conducted for the Directorate Materiel Maintenance of the Oklahoma City Air Materiel Command under contract number AF 34(601)-9879.

CHAPTER I

INTRODUCTION

In many applications, rotating systems, such as turbine wheels, operate at temperatures slightly under those at which the centrifugal forces on the system will cause certain components to fail. Therefore, it is desirable to have a means of monitoring the temperature of the rotating system in order that the design limits will not be exceeded.

One particular application for this type of device is in the J-47 turbojet engine. In this engine, the turbine wheel will sometimes overheat when the engine is in a stalled condition. This overheating is due to a combination of increased temperatures caused by an increase in the fuel-air ratio and a decrease in the mass flow rate of cooling air which is supplied by the compressor stages of the engine. If this overheated condition is allowed to persist in the turbine wheel, the stresses caused by centrifugal forces will initiate failure in the wheel. The most serious type of failure caused by this environment is a chunk type failure in which a section of the Timken alloy 16-25-6 outer rim separates from the AISI 4340 steel hub at the point of the weld between the hub and the rim as illustrated in Figure 1. The mechanism of the failure is the yielding of the 29CR-9-NI weld material which attaches the hub to the rim. This weld, whose temperature must be monitored, is located approximately 10.5 inches from the axis of the turbine wheel.

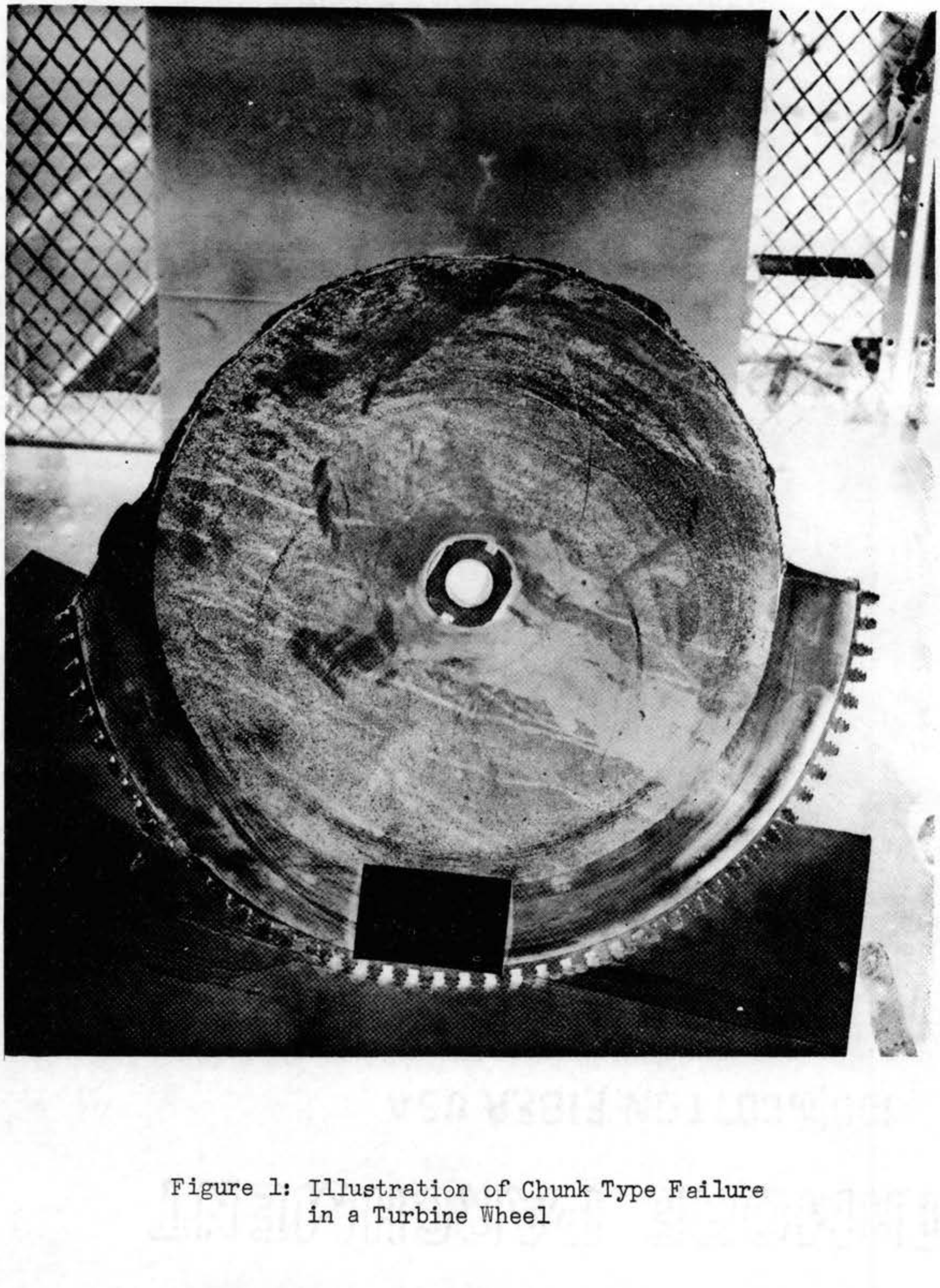


Figure 1: Illustration of Chunk Type Failure
in a Turbine Wheel

Several active and passive methods of temperature detection have been tested and proven unsatisfactory. The passive methods include fuseable plugs and temperature sensitive paints. The paint and plugs were inspected after each flight; however, their indications were erratic and did not exhibit the turbine wheel temperature history clearly. Also, these methods did not provide the pilot with the in-flight temperature monitoring capability needed. Embedding thermocouples in the turbine wheel was tried as an active method of temperature monitoring. Two methods were used to monitor the thermocouple signal from the rotating turbine wheel. One was by the use of slip rings on the turbine wheel shaft, and the other was by mounting a signal transmitter on the shaft. Although this method would provide in-flight temperature monitoring capability, neither of the signal monitoring methods provided the necessary reliability or operating life required.

Previous tests indicated that a simple temperature detection device which did not come into direct contact with the turbine wheel, but which would give in-flight temperature monitoring capability with a high degree of accuracy was desirable.

Since all bodies emit thermal radiation in the infrared range at intensities which are proportional to their temperature, this study investigates the feasibility of using the infrared radiation emitted by the turbine wheel to monitor its temperature. This study encompasses the investigation of the characteristics of a radiation type temperature monitor and temperature transducers. An attempt is also made to describe and optimize parameters of time response, sensitivity, stability, and output scatter for this type of detector. The nature of these parameters will be described and methods of controlling them will be discussed.

Three types of temperature detectors or transducers are investigated in this study to evaluate their common and peculiar characteristics. The types of transducers studied are the thermocouple, the thermistor, and the thermopile. Each of these transducers uses a reflector to concentrate the radiated energy flux of the heated body on the sensing element to, in effect, amplify the flux concentration and thus increase the output of the transducer. Actually, both the reflector and sensing element, as well as their combination, are considered transducers; however, in this discussion only the sensing elements will be referred to as transducers.

It should be stressed that even though there are many commercial radiometers on the market which could be individually evaluated in order to determine their adaptibility to this particular problem, the expense of their aquisition for study would have been prohibitive. Also, it was desired that a study be made of the feasibility of constructing a simple, inexpensive radiometer which could withstand the dynamic and thermal environment present in a turbojet engine.

CHAPTER II

THEORY OF OPERATION

This study is basically an investigation of the feasibility of using the thermal radiation of a body to detect its temperature and the characteristics of a thermal radiation detector. Basically, this is an attempt to design and calibrate a device which will detect the thermally radiated energy of a heated object.

All objects which are above absolute zero temperature radiate thermal energy. This radiated energy flux is proportional to the fourth power of the absolute temperature of the body, or

$$E = eaT^4$$

where E is the radiated energy, e is the emissivity of the body relative to a black body, a is the Stefan-Boltzmann constant of proportionality, and T is the absolute temperature of the radiating body.

The wave length of this radiated energy may or may not lie within the visible range, which is in the region between 0.4 to 0.7 microns. This is commonly called infrared radiation. All of the emitted radiation of a body does not occur at a particular wave length, but is distributed over a range of wave lengths. However, for a black body, there is a wave length at which the monochromic emissive power is a maximum. Also, this maximum point will move to shorter wave lengths as the temperature of the body increases. A relationship between the absolute temperature of a black body and the wave length of maximum emission is given by Wien's displacement law as follows.

$$l_m = 5215.6/T$$

This is also a relatively good approximation of the location of the maximum emission wave length of a gray body.

The above discussion relates to the emission of energy of a body in all directions. Therefore, since the radiometer used in this study will only intercept a portion of the radiation which is emitted by the heated surface, only a small portion of the total radiated energy will be intercepted by the reflector and concentrated on the transducer.

Since the turbine wheel is not a perfect black body, the radiation emitted from its surface will be reduced to some fraction of that of a black body. This fraction is a measure of the emissivity of the wheel.

An investigation of three different transducers was made in order to determine what type of radiation detector would give optimized performance. The three types of transducers were a single thermocouple, a single thermistor, and a thermopile.

In order to optimize the performance of this radiometer, it was found that there were several important parameters which must be controlled. One of these was a stable temperature surrounding the transducer. This is required because the transducer senses both the radiated energy and the temperature of the surrounding media. Therefore, if the temperature of this media increased, the transducer signal would indicate a change even though there was no increase in the radiant energy flux.

The mass, and thus the heat capacity of the transducer, must be made as small as possible without affecting stability. The small heat capacity is required in order to shorten the time required for the transducer to react to a change in the radiant energy incident upon it. Along this line, the lead wires from the transducer must also be made small in order that the heat conducted away from the transducer by them will not affect the transducer's sensitivity.

The rate at which heat is transferred away from the transducer by modes other than radiation must be held as constant as possible and must be a great deal smaller than the rate at which heat is added by the radiant energy flux. In order to accomplish this, the air surrounding the transducer must be kept from being extremely turbulent and must not carry the heat away from the transducer area by mass flow. Therefore, a window had to be used to separate the air around the transducer from the very turbulent air which is used to cool the turbine wheel. This window also served to separate this relatively constant temperature air around the transducer from the turbine wheel cooling air whose temperature varied over a very wide range.

Since normal glass does not pass infrared energy radiated at the long wave lengths, a special type of window material had to be found which would be transparent to the infrared wave lengths at which the turbine wheel was emitting energy.

Also, the transducer must be able to produce an appreciable signal from the radiation impinging upon it. This is due to the fact that this signal must be large enough so that the random electrical noise signals present in the surroundings will not have an appreciable effect on the transducer signal.

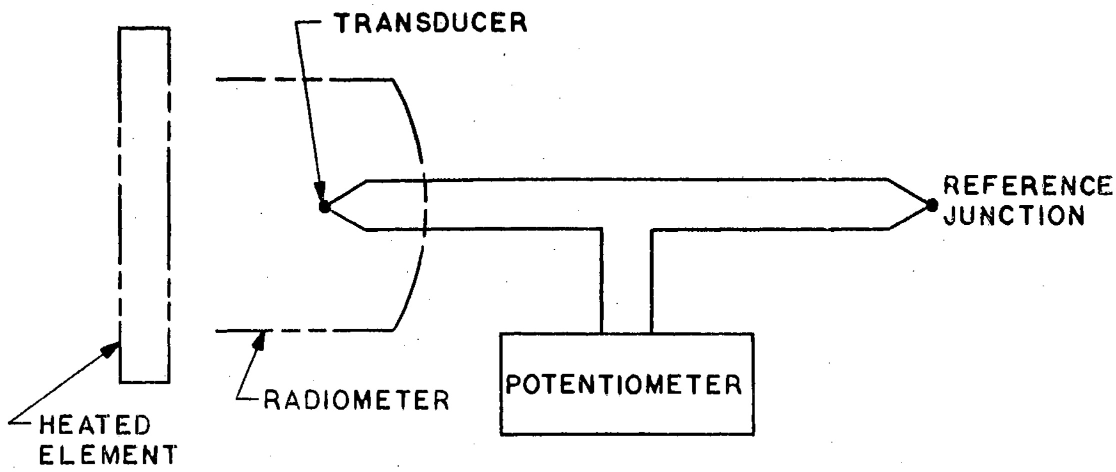
CHAPTER III

EXPERIMENTAL METHODS

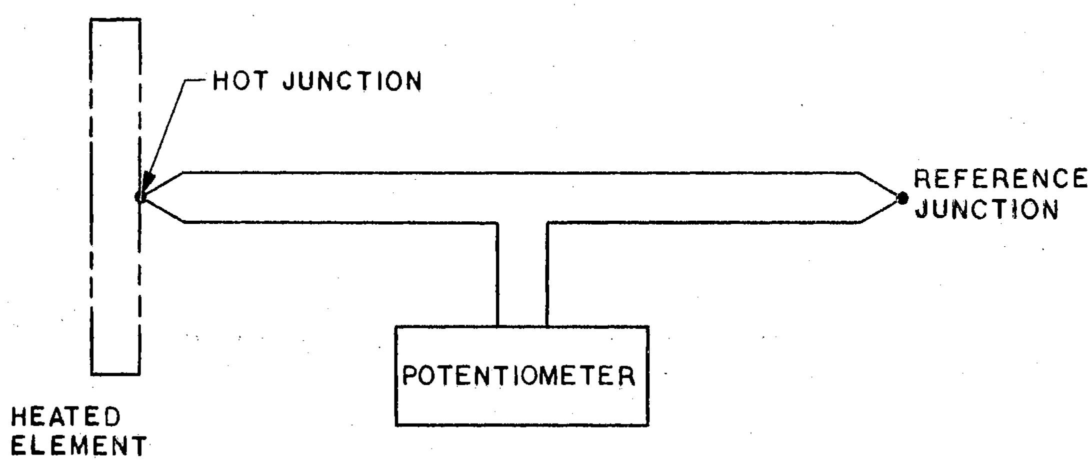
THERMOCOUPLE

One Iron-Constantan thermocouple was used as a radiation sensing element upon which radiation was focused. Another thermocouple was submerged in an ice bath to produce a standard back e.m.f. upon which the data could be based. Figure 2.a illustrates the way in which this transducer was instrumented in order to detect the infrared radiation from the heated element. The reflector was used to focus the radiation from a relatively large area upon the thermocouple, as illustrated in Figure 3. The e.m.f. created by the thermocouple was then indicated by a potentiometer of high sensitivity. The actual temperature of the heated element was detected by a thermocouple fastened to its surface and indicated on another potentiometer as illustrated in Figure 2.b. An ice bath reference junction was also used in this circuit to produce a standard back e.m.f. The equipment used in this analysis is shown in Figure 4.

The calibration and evaluation of the thermocouple transducer was accomplished by using the gas flame of a Bunsen Burner to heat the heated element to a relatively constant temperature. However, it was impossible to hold the heated element used to an exact temperature without some fluctuations. The magnitude of these fluctuations at different temperatures can be seen in Figure 5. This temperature setting was maintained for approximately five minutes to make sure that the trans-



A. THERMOCOUPLE CIRCUITRY



B. HEATED ELEMENT TEMPERATURE SENSOR CIRCUITRY

FIGURE 2: THERMOCOUPLE RADIATION TRANSDUCER CIRCUITRY

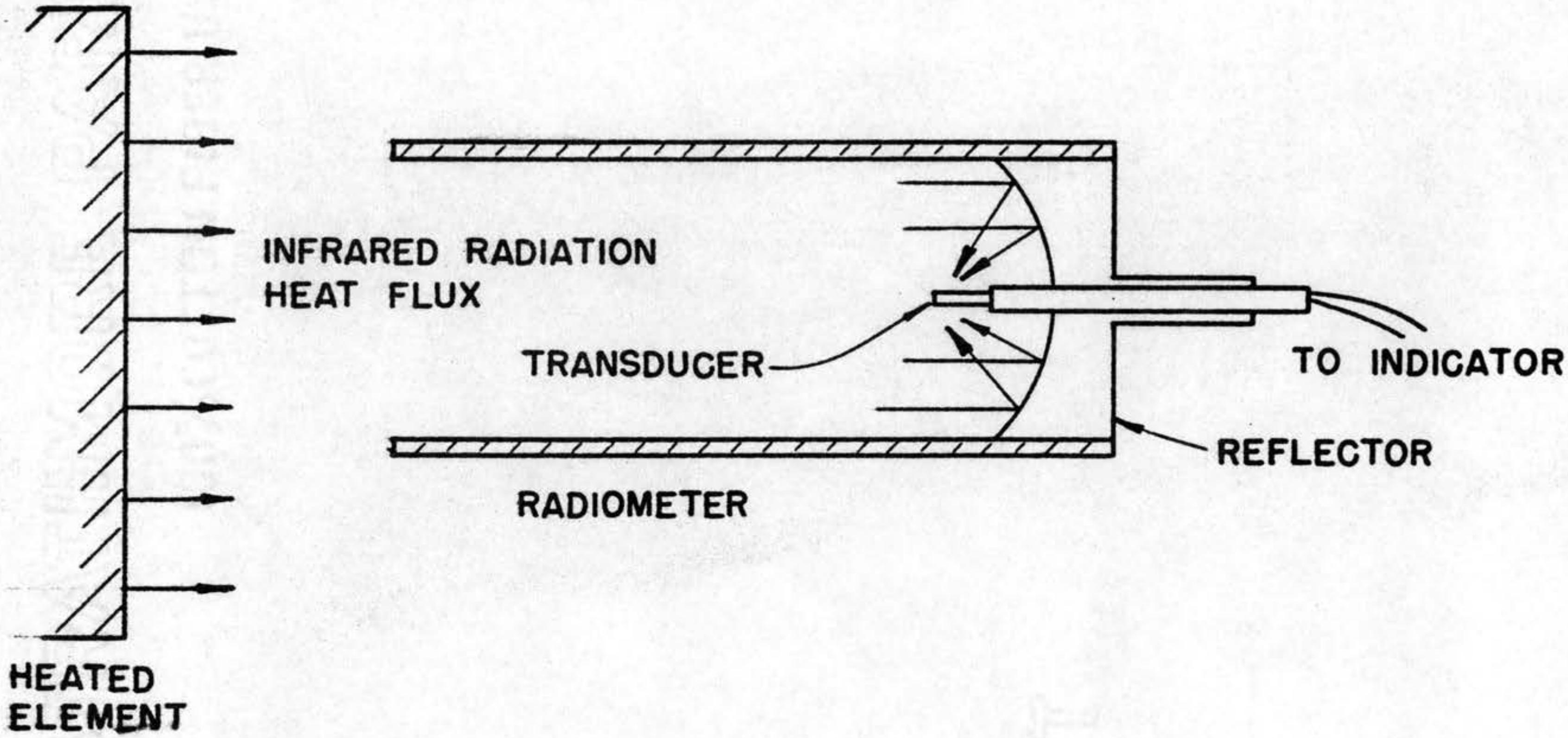


FIGURE 3: ILLUSTRATION OF RADIOMETER DESIGN.

ducer had reached an equilibrium condition and then then output of the radiation transducer and the temperature of the heated element were recorded. This procedure was repeated at many flame settings in order to obtain calibration data points between 500 and 1000 degrees F. These data are given in Table I. Data points for heating element temperatures below 500 degrees F. could not be obtained because of the instability of the temperature of the heated element due to fluctuations in the low flame from the Bunsen Burner. However, data could have been obtained for higher heated element temperatures if they had been desired.

The data from Table I are plotted in Figure 6. This figure shows that these data closely approximate a straight line when plotted on log-log coordinates. On this figure, a straight line calibration curve can be drawn. In Appendix A the equation of this line is found to be,

$$E = aT^{c},$$

where E is the output of the thermocouple transducer in volts, a is a constant which is equal to $4.8(10)^{-12}$, and the exponent c is a constant which is equal to 2.91. The constants given above apply only to the particular case which was tested and are functions of system geometry and characteristics; however, the general equation given should apply for any thermocouple whose output varies linearly with temperature.

The output of the thermocouple varied from approximately 2.50 to 7.75 millivolts. These signals could be read accurately to two decimal places using a precision potentiometer.

In Figure 7 the data are plotted on linear coordinates in order to

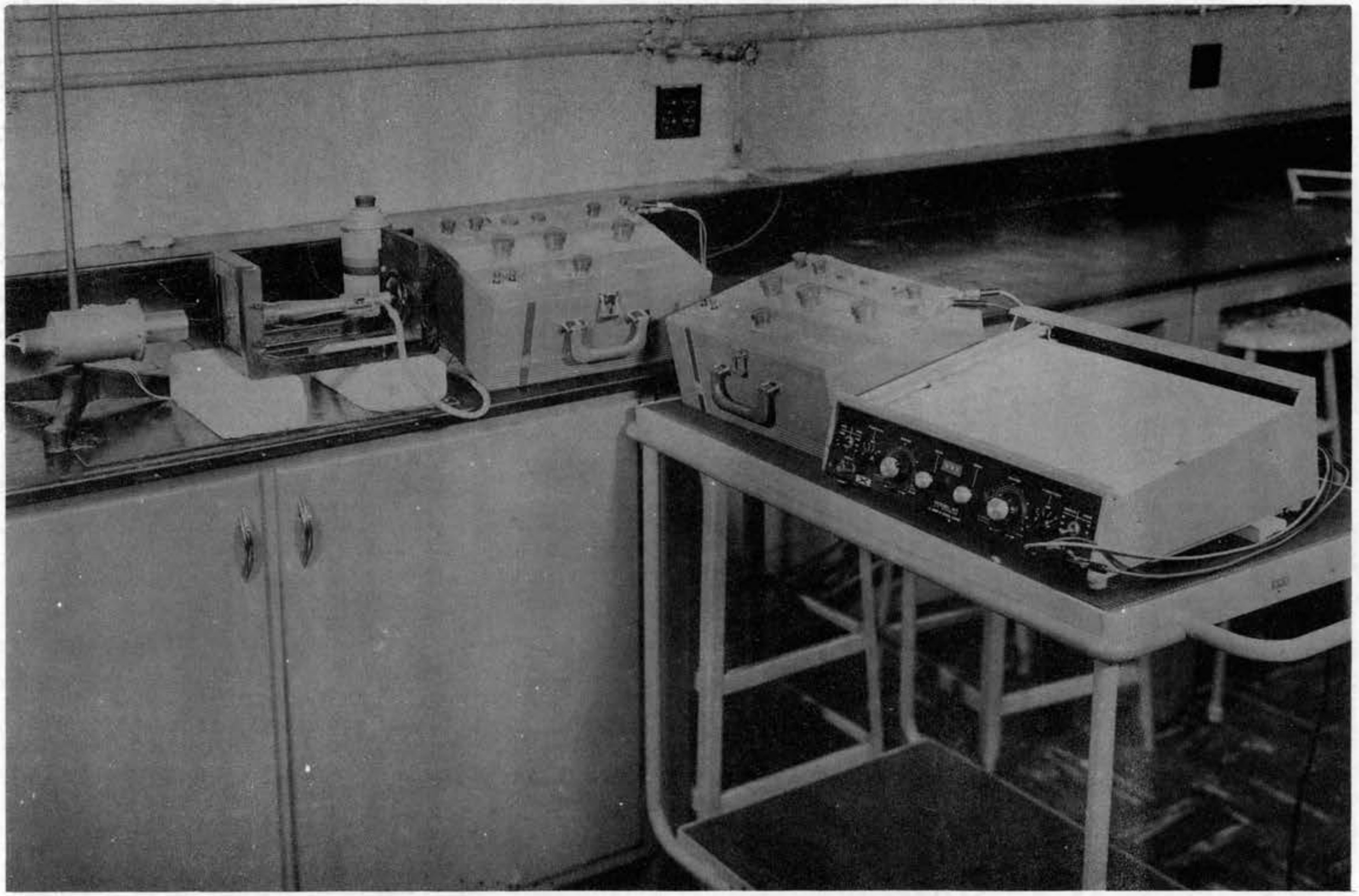


Figure 4: Equipment Used to Analyze the Thermocouple
Transducer

investigate the limits of the data scatter. From this figure it can be seen that the data scatter was no more than 20 degrees overall. Some of this spread is probably due to errors encountered in determining exactly the temperature of the heated element due to the fluctuations inherent in the heating system used. The data scatter over the entire range of measurement is also shown in Figure 7. This indicates a high reliability of measurement and shows that measurements were repeatable with a high degree of accuracy.

The response time of the thermocouple transducer was found by replacing the potentiometer in the thermocouple transducer circuit with an X-Y recorder. The heating element was then allowed to stabilize at a particular temperature. Then, when the transducer had reached an equilibrium condition, the infrared radiation from the heated element was blocked by an insulated body, creating a step drop in the infrared heat flux. The resulting e.m.f. output of the transducer was then plotted by the X-Y recorder. This resulted in a plot of the cooling time response. When the transducer had reached an equilibrium condition with a radiation heat flux impinging upon it, the insulated body was removed, thus creating a step input of radiation heat flux. The response of the transducer to this step function was also recorded with the aid of the X-Y recorder. Time response curves were plotted for heated element temperatures of 914 and 732 degrees F. respectively as shown in Figures 8 and 9. The response time is considered to be the time required for 63.2 percent of the total temperature change to take place. The response times for both heating and cooling step functions are given below in Table II.

The output of the thermocouple transducer was very steady. This was partly due to the relatively large thermal capacity of the transducer and the low intensity of turbulence around the transducer. These conditions coupled to make the transducer hold a relatively constant temperature when a constant heat flux was impinging upon it. The difference in the heating and cooling curve response times is partly due to the failure to completely block the heat flux from the heated element and radiation from the walls of the radiometer housing which had been heated to above room temperature by radiation and convection from the heated element.

TABLE II: THERMOCOUPLE TRANSDUCER RESPONSE TIMES

Heated Element Temperature (degrees F.)	Response Time	
	Heating (sec.)	Cooling (sec.)
914	2.3	4.2
732	5.5	7.7

TABLE I

THERMOCOUPLE TRANSDUCER CALABRATION DATA

No.	Heated Element (°F)	Temperature (°R)	Transducer Output (millivolts)
1	948	1408	7.05 (1)
2	884	1344	6.25
3	868	1328	6.01
4	852	1312	5.85
5	823	1283	5.40
6	770	1230	4.90
7	701	1161	4.16
8	633	1093	3.52
9	493	953	2.60
10	948	1408	7.06
11	942	1402	6.96
12	929	1389	6.80
13	877	1337	6.16
14	959	1419	7.16
15	951	1411	7.06
16	939	1399	6.92
17	921	1381	6.63
18	908	1368	6.38
19	875	1335	5.96
20	802	1262	5.05
21	767	1227	4.68
22	702	1162	4.03
23	606	1066	3.19 (1)
24	502	962	2.45
25	618	1078	3.25
26	712	1172	4.13
27	811	1271	5.23
28	909	1369	6.46
29	1003	1463	7.75
30	984	1444	7.39
31	968	1428	7.13
32	655	1115	3.53 (2)
33	820	1280	5.27
34	904	1364	6.32
35	942	1402	6.89
36	979	1439	7.46
37	998	1458	7.77
38	361	821	1.64
39	592	1052	2.93
40	689	1149	3.75
41	772	1232	4.60
42	886	1346	5.99
43	991	1451	7.42

(1) Transducer output indicated on H-P millivolt meter.

(2) Transducer output indicated on L&N potentiometer.

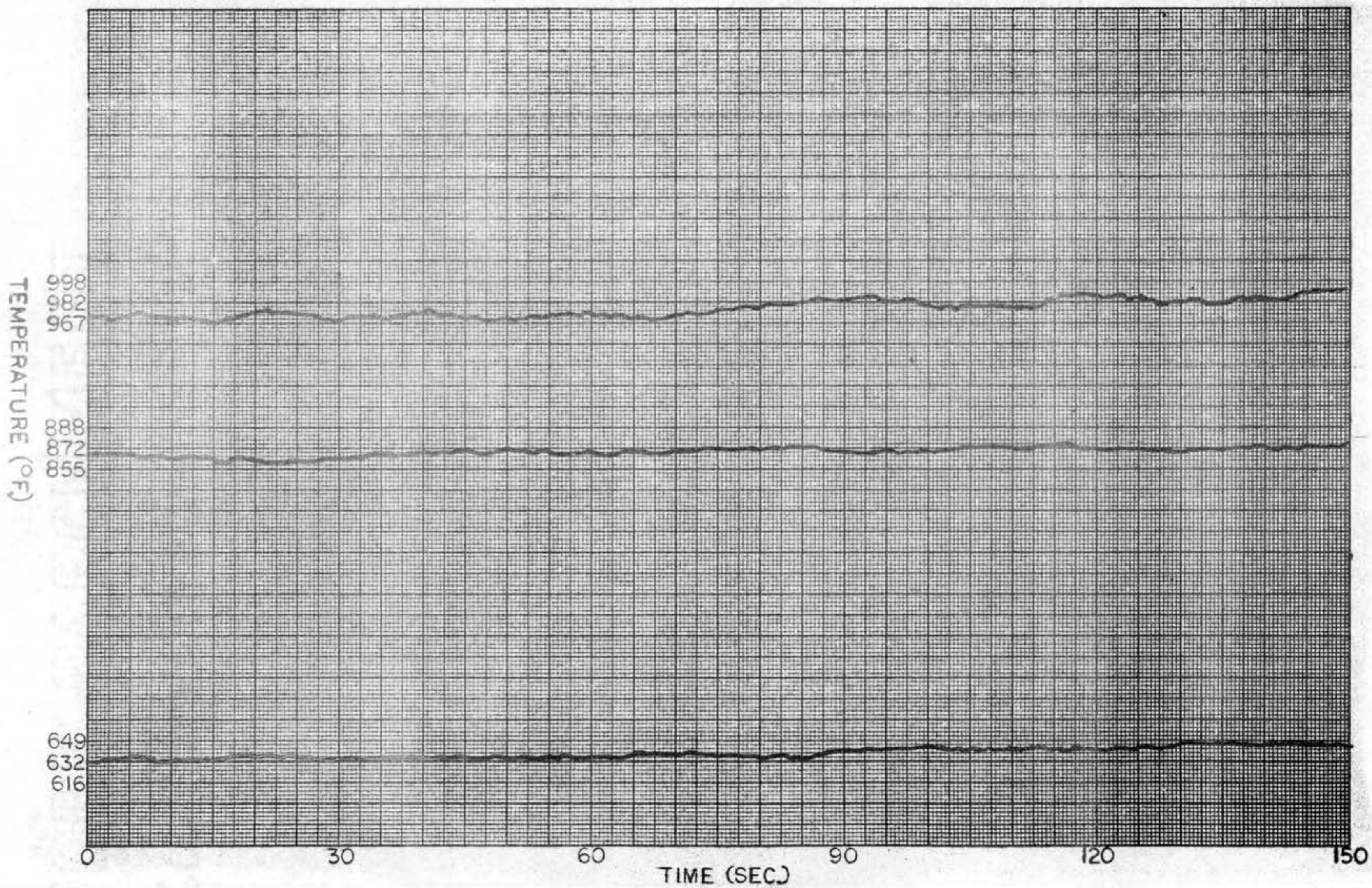


FIGURE 5: FLUCTUATION OF HEATED ELEMENT TEMPERATURE

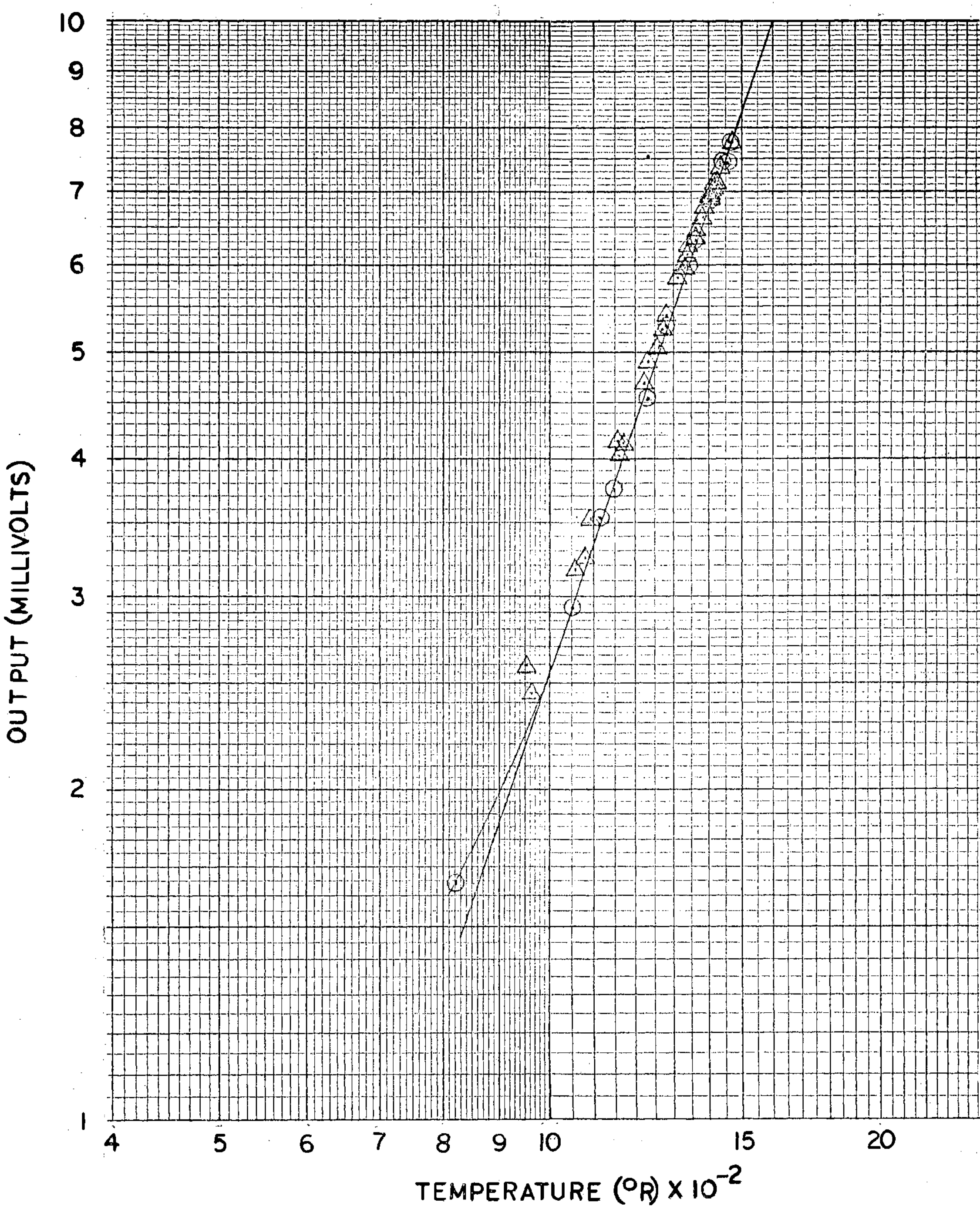


FIGURE 6: THERMOCOUPLE TRANSDUCER CALIBRATION CURVE

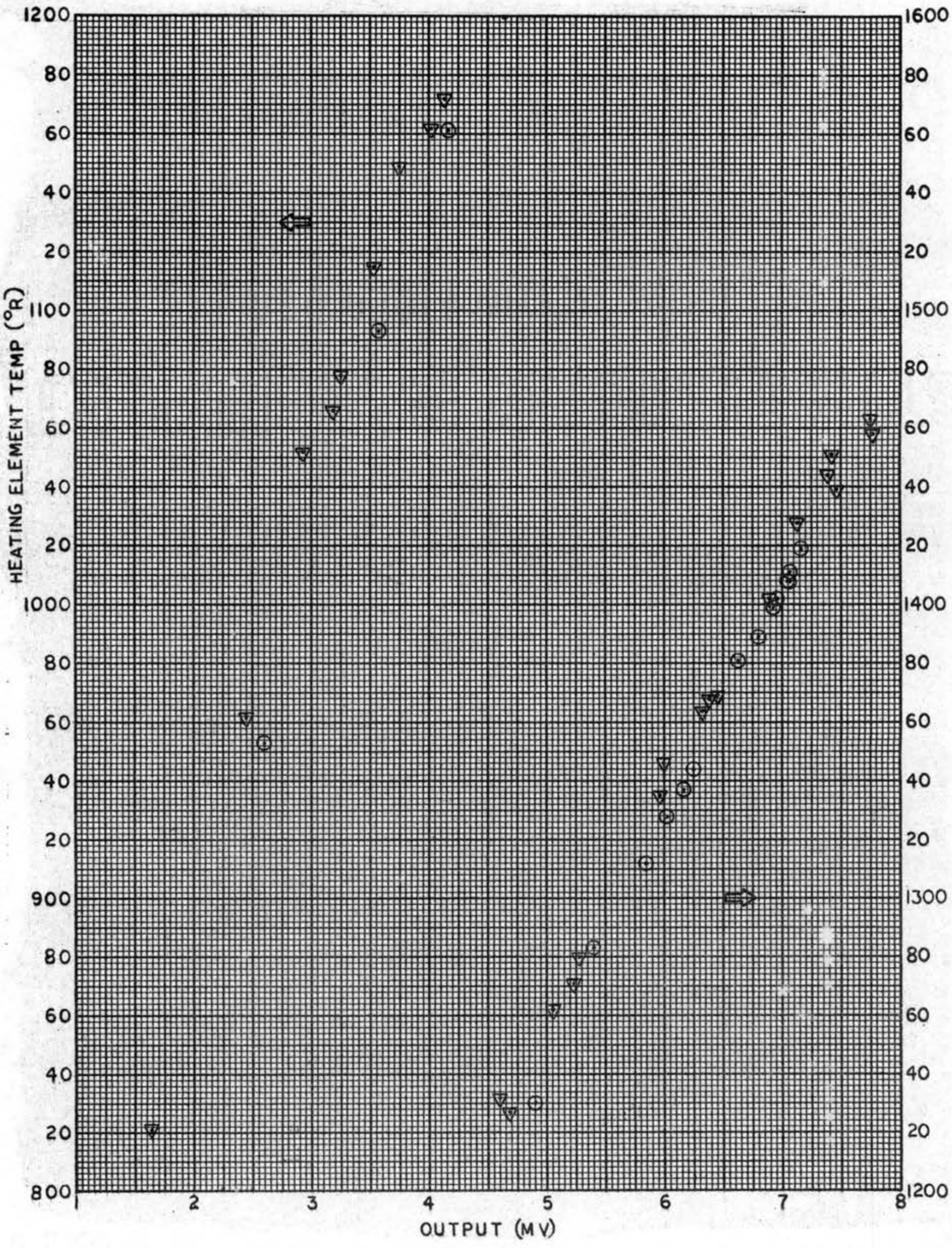


FIGURE 7: THERMOCOUPLE TRANSDUCER DATA SCATTER

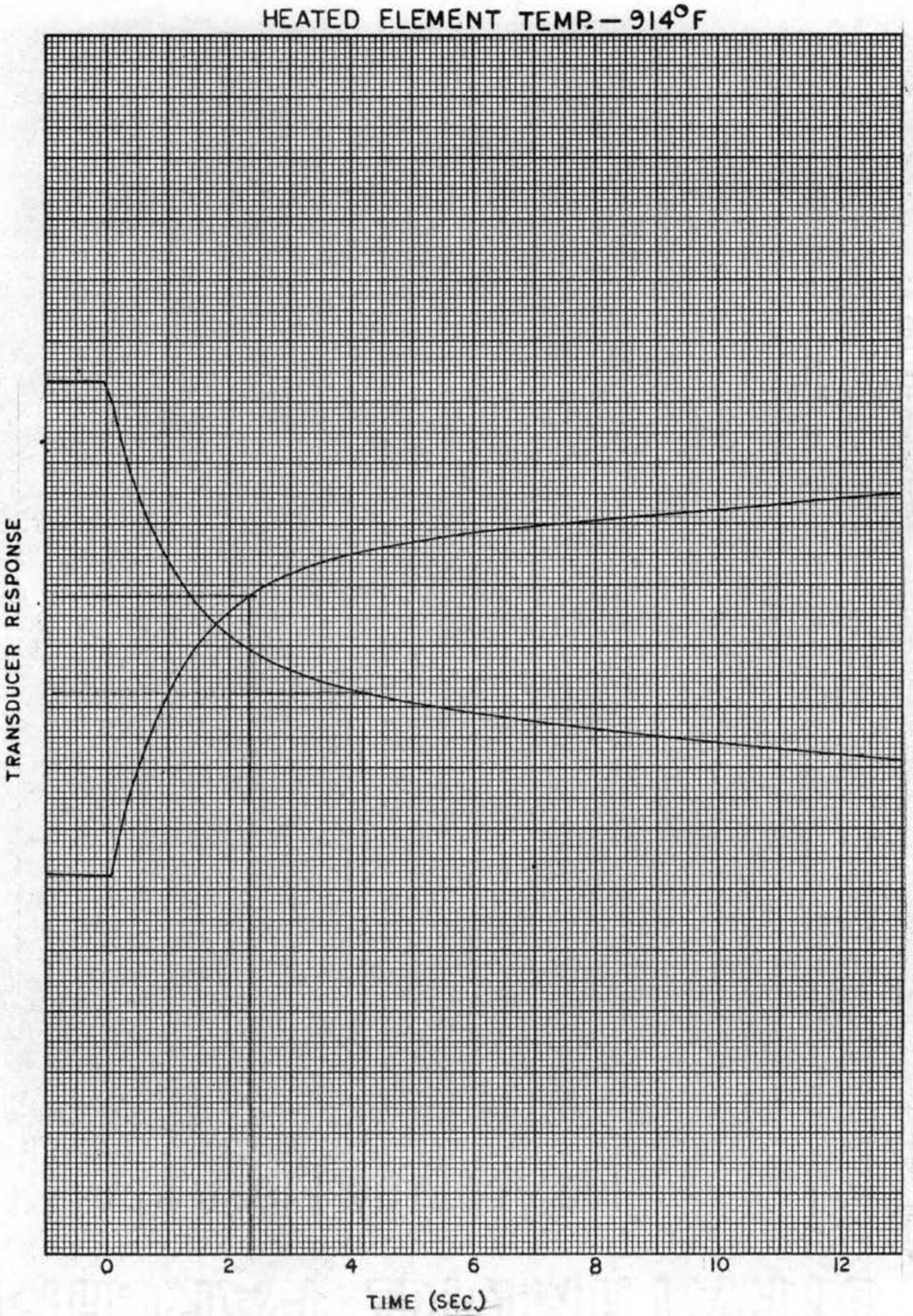


FIGURE 8: THERMOCOUPLE TRANSDUCER TIME RESPONSE CURVE

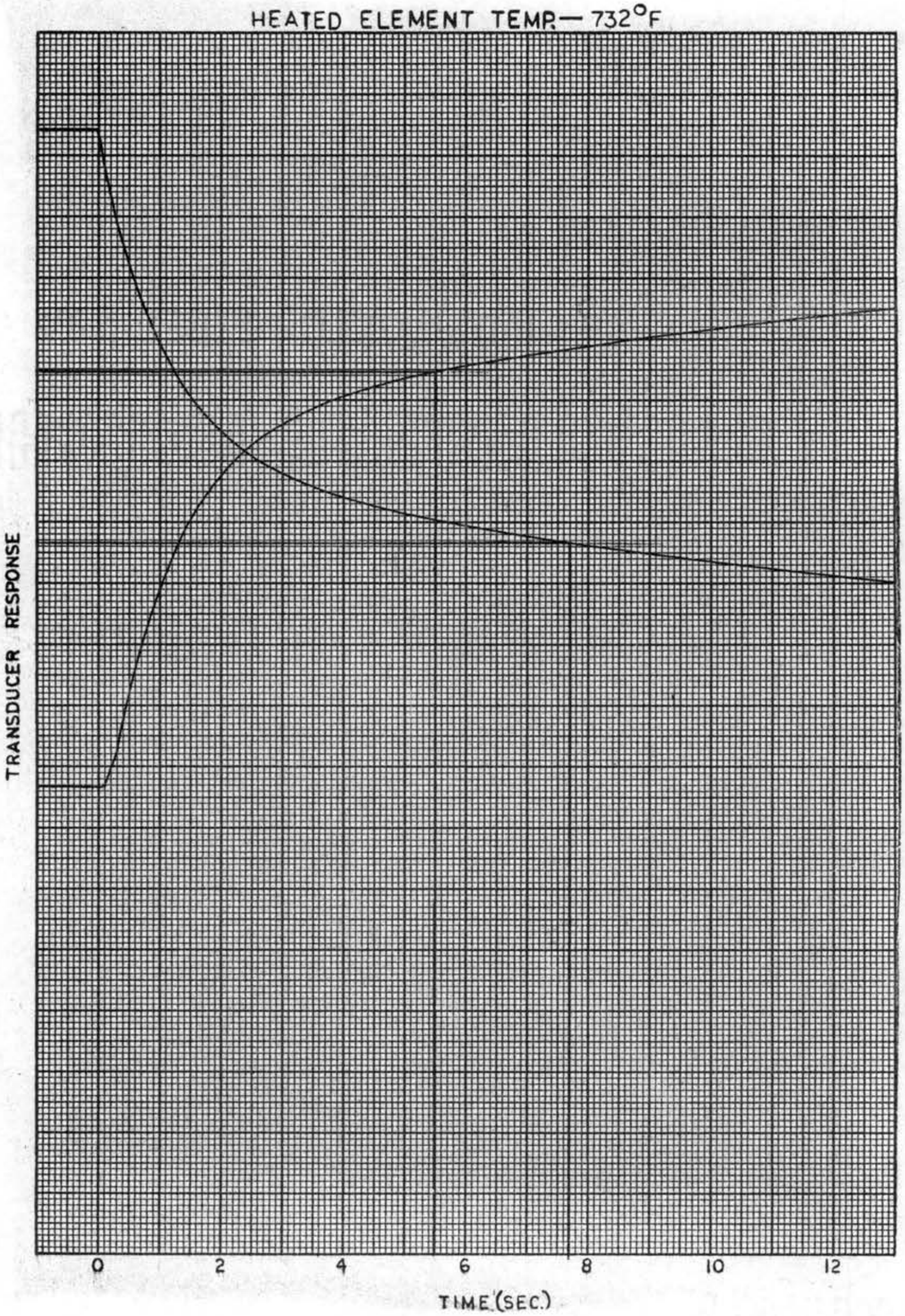


FIGURE 9: THERMOCOUPLE TRANSDUCER TIME RESPONSE CURVE

THERMISTOR

In this series of experiments, one thermistor transducer was used as a sensor of the focused heat flux from the heated body. Since the thermistor is simply a temperature sensitive resistor, it was hooked up as the one active leg of a Wheatstone Bridge as shown in Figure 10. The bridge was balanced to have zero potential across opposite legs when the thermistor was at room temperature with no radiation heat flux impinging upon it. This was accomplished by adjusting the resistance of an adjacent leg until the millivolt meter used to measure unbalance indicated zero voltage across the bridge. The actual temperature of the heating element was found by the same method used in the thermocouple analysis procedure. The equipment used to analyze the thermistor transducer is shown in Figure 11.

The thermistor transducer was calibrated and evaluated by controlling the temperature of the heated element in the same manner used in the thermocouple transducer evaluation. After the temperature of the element had stabilized and ample time had been allowed for the thermistor transducer to reach an equilibrium condition, the voltage across the bridge due to the resistance change of the transducer was recorded. This same procedure was repeated for numerous heated element temperatures, and the data from these measurements are presented in Table III.

It was noted in day to day measurements that the variable resistance settings were not the same and, therefore, the bridge would have to be re-zeroed. To evaluate the effect of the changes in room temperature, which varied up to 5 degrees F. from day to day, the first 21 readings were taken on three different days, with the bridge being re-zeroed each day. For the remaining readings, also taken on several

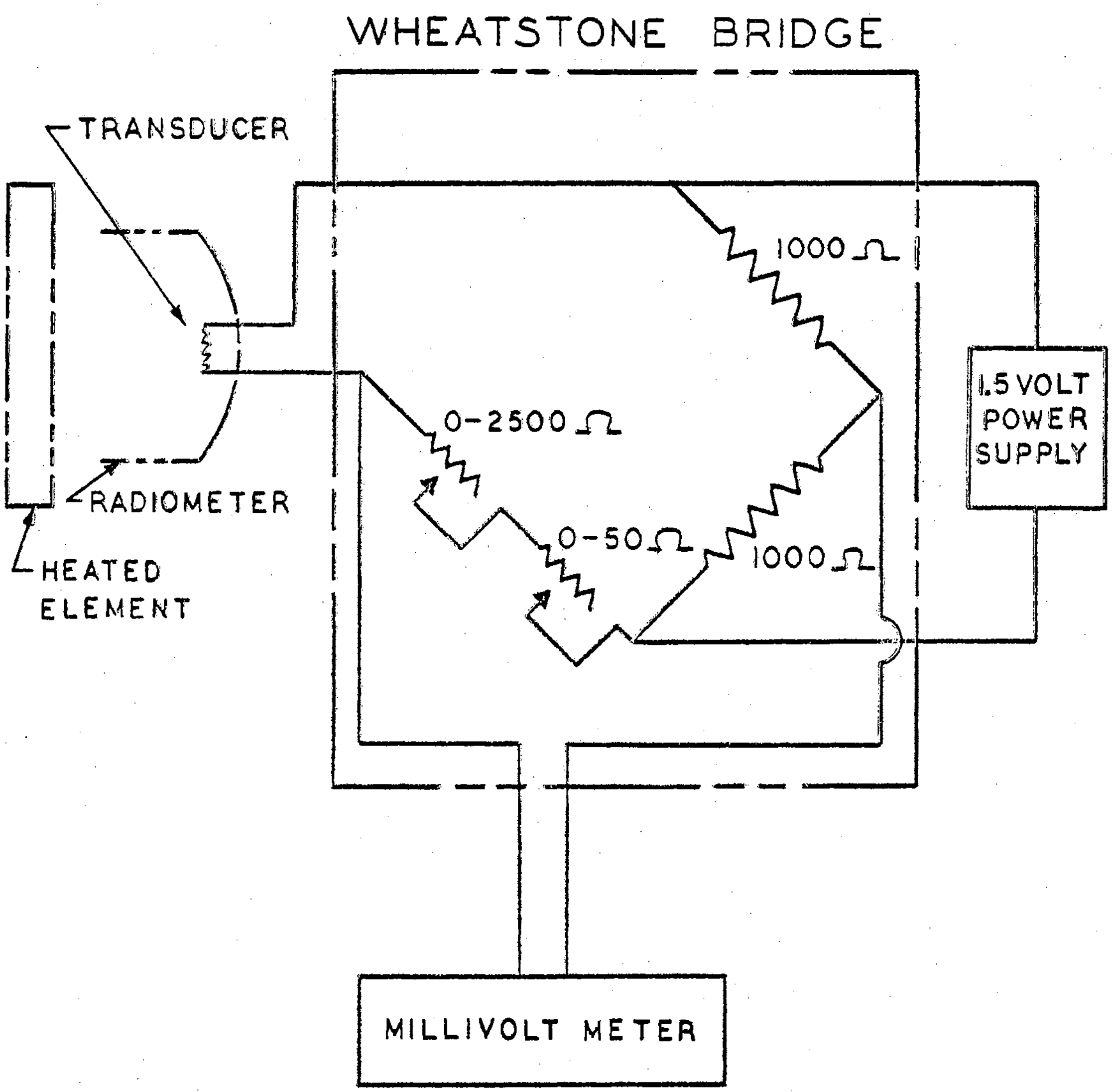


FIGURE 10: THERMISTOR TRANSDUCER CIRCUITRY

different days, the bridge was not re-zeroed to existing room termperature but left at the resistance setting of one of the previous test runs. Upon examining the data presented in Table III and Figure 12, it can be seen that this did not cause any detectable discrepancy in the data points. This could be due to an environmental temperature stabilizing effect of the heating element on its immediate surroundings, the outweighing of the surrounding atmosphere effects by the radiation heat flux, or possibly a combination of both.

In this series of tests, data points were taken for heating element temperature as low as 450 degrees F.; however, due to flame instability on the element, their reliability is somewhat in doubt. In this series of tests, as in the previous series data points were taken up to approximately 1000 degrees F. The same limitations to the heated element temperature range apply to this transducer that applied to the previous transducer evaluation.

A plot of the data from Table III is given in Figure 12. From this plot of data on log-log coordinates, it can be seen that the relationship of the voltage change across the bridge to the temperature of the heated element cannot be approximated by a straight line. This could be anticipated from the fact that the change in the resistance of the thermistor with temperature is not a linear function. Therefore, due to this complication, no attempt was made to establish an empirical relation between the voltage due to bridge unbalance and the temperature of the heated element.

The voltage output of the bridge used in these tests varied from approximately 0.21 to 0.64 volts. It should be noted that the output obtained depends upon the resistances and the supply voltages used in the particular bridge. These components and bridge details are given

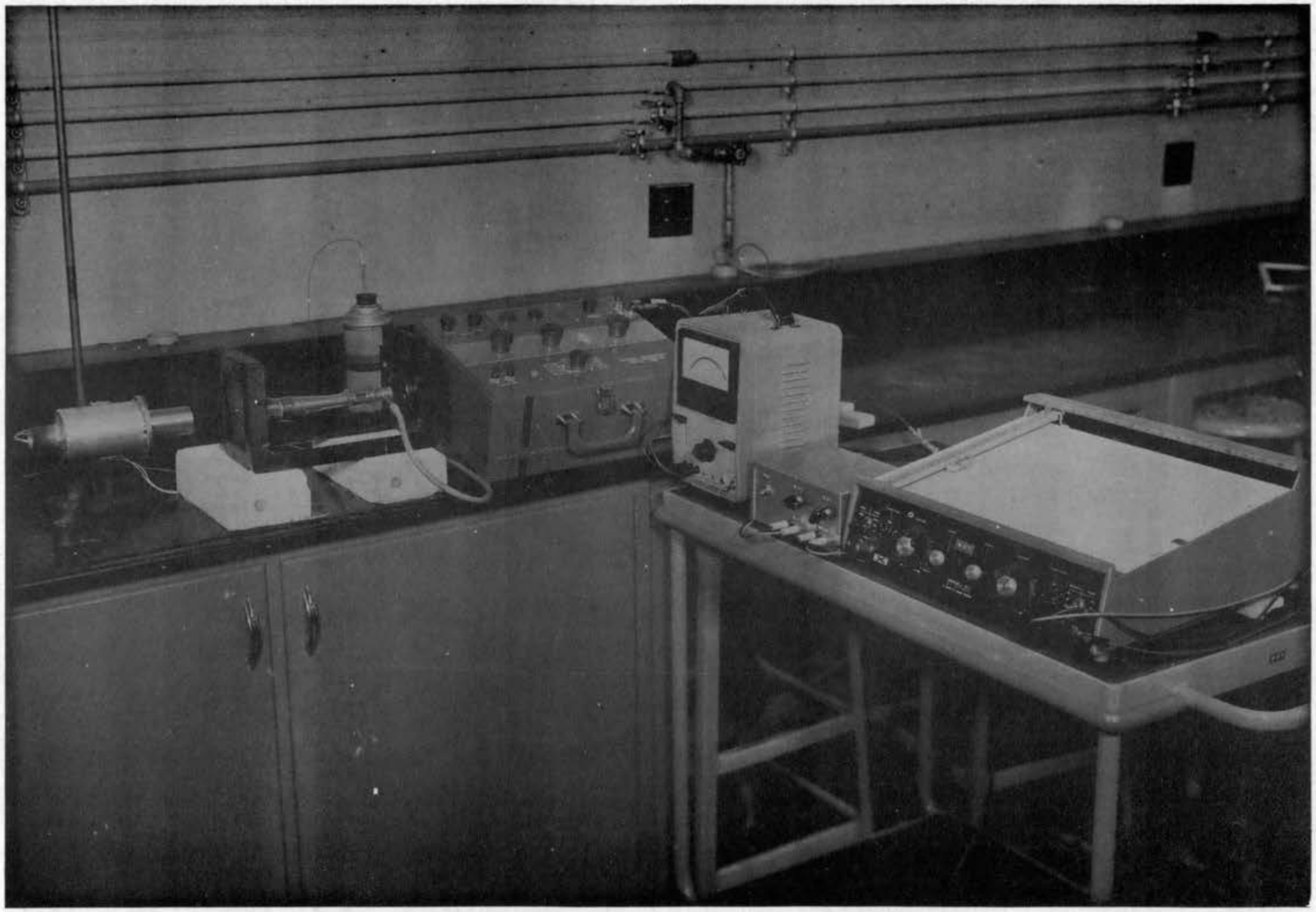


Figure 11: Equipment Used to Analyze the Thermistor Transducer

in Figure 10. The output of the bridge could be read accurately to two significant figures on the millivolt meter, but the third significant figure could be interpolated within the tolerance limitations of the data.

The data are plotted on linear coordinates in Figure 13 to evaluate the scatter of the data points. This figure indicates that there is variation of the data over a range of 40 to 50 degrees. Some of this scatter can be accounted for in errors encountered in the measurement of the temperature of the plate and interpolation errors; however, some of the spread must be charged to the characteristics of the particular transducer itself, such as the size of the element and its lead wires and the possibility of fluctuations in its resistance at a fixed temperature. This points out that the reliability of repeatability of measurements with this transducer lies within a 50 degree temperature range.

To find the response time of the thermistor transducer, the millivolt meter was replaced by an X-Y recorder, and step type heat fluxes were applied to the transducer in the same manner as they were applied to the thermocouple transducer. Plots were made of the time response for both heating and cooling at heating element temperatures of 939 and 760 degrees F. as shown in Figures 14 and 15 respectively. The response times are shown in Table IV.

TABLE IV: THERMISTOR TRANSDUCER RESPONSE TIMES

Heated Element Temperature (degrees F.)	Response Time	
	Heating (sec.)	Cooling (sec.)
939	22.5	75 plus
760	31.3	75 plus

The probable causes of the difference in the heating and cooling response times are the same as those discussed for the thermocouple transducer; however, the increased length of the response time is due to the larger mass and thus heat capacity of the transducer.

TABLE III

THERMISTOR TRANSDUCER CALABRATION DATA

No.	Heated Element (°F)	Temperature (°R)	Transducer Output (volts)	No.	Heated Element (°F)	Temperature (°R)	Transducer Output (volts)
1	820	1281	0.497 (1)	26	697	1157	0.400 (2)
2	674	1134	0.383	27	571	1031	0.290
3	744	1204	0.440	28	630	1090	0.335
4	814	1274	0.498	29	701	1161	0.393
5	913	1373	0.581	30	813	1273	0.494
6	783	1243	0.488	31	1015	1475	0.620
7	728	1188	0.439	32	952	1412	0.600
8	639	1099	0.353	33	880	1340	0.552
9	947	1407	0.580	34	836	1296	0.520
10	798	1238	0.478	35	743	1203	0.447
11	728	1188	0.417	36	523	983	0.253
12	602	1062	0.305	37	685	1115	0.391
13	693	1153	0.410	38	1013	1473	0.642
14	793	1253	0.469	39	958	1418	0.622
15	842	1302	0.520	40	955	1415	0.620
16	852	1312	0.540	41	895	1355	0.585
17	907	1367	0.558	42	994	1454	0 638
18	812	1272	0.498	43	1008	1468	0.633
19	673	1133	0.471	44	958	1418	0.603
20	571	1011	0.292	45	640	1100	0.348
21	692	1152	0.391	46	517	977	0 253
22	960	1420	0.605 (2)	47	557	1017	0.284
23	871	1331	0.546	48	451	911	0.210
24	819	1279	0.508	49	621	1081	0 239
25	800	1260	0.490	50	461	921	0.261

(1) Bridge zeroed to existing room temperature before each series of runs.
(2) Bridge not re-zeroed to existing room temperature for these runs.

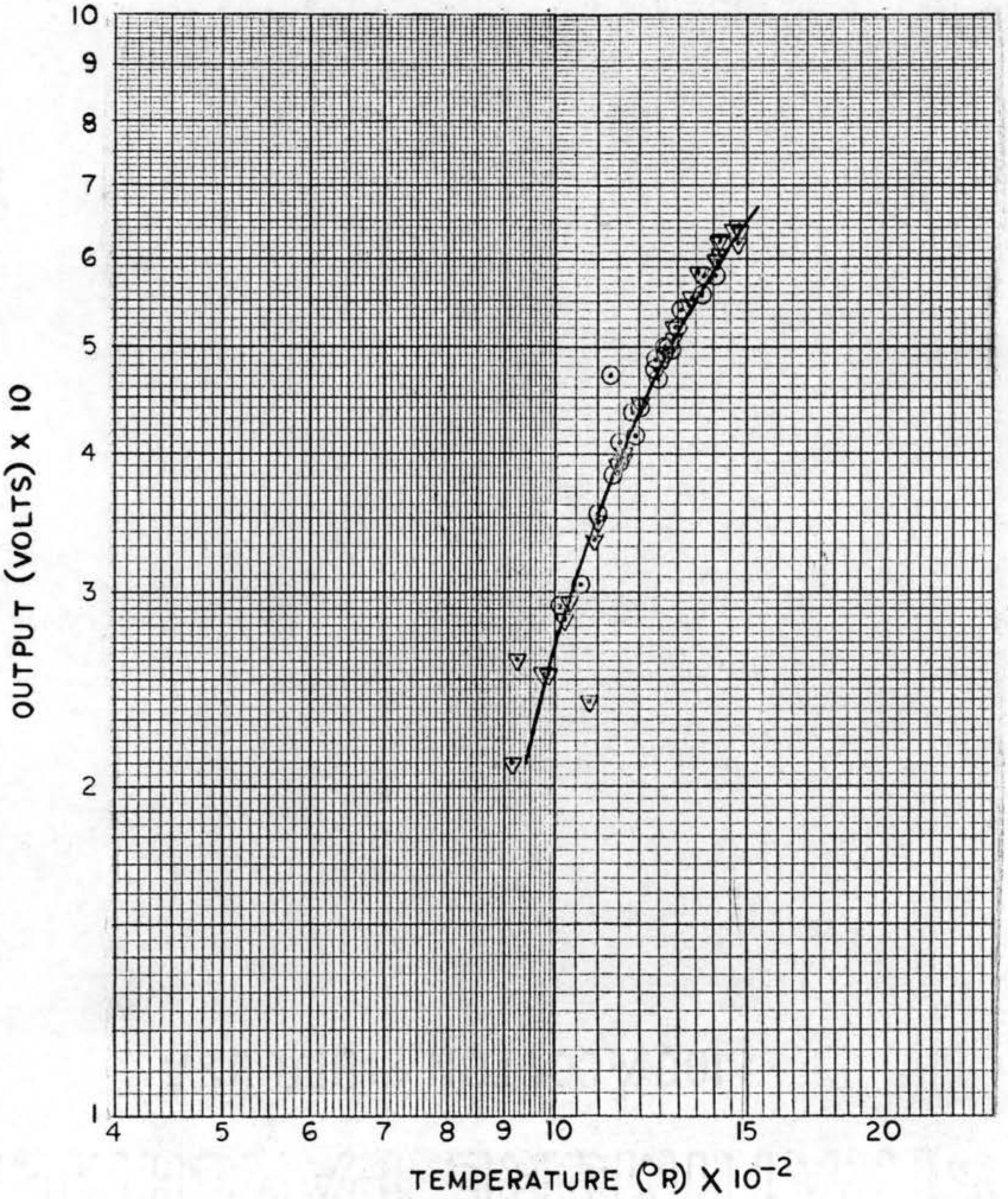


FIGURE 12: THERMISTOR TRANSDUCER CALIBRATION CURVE

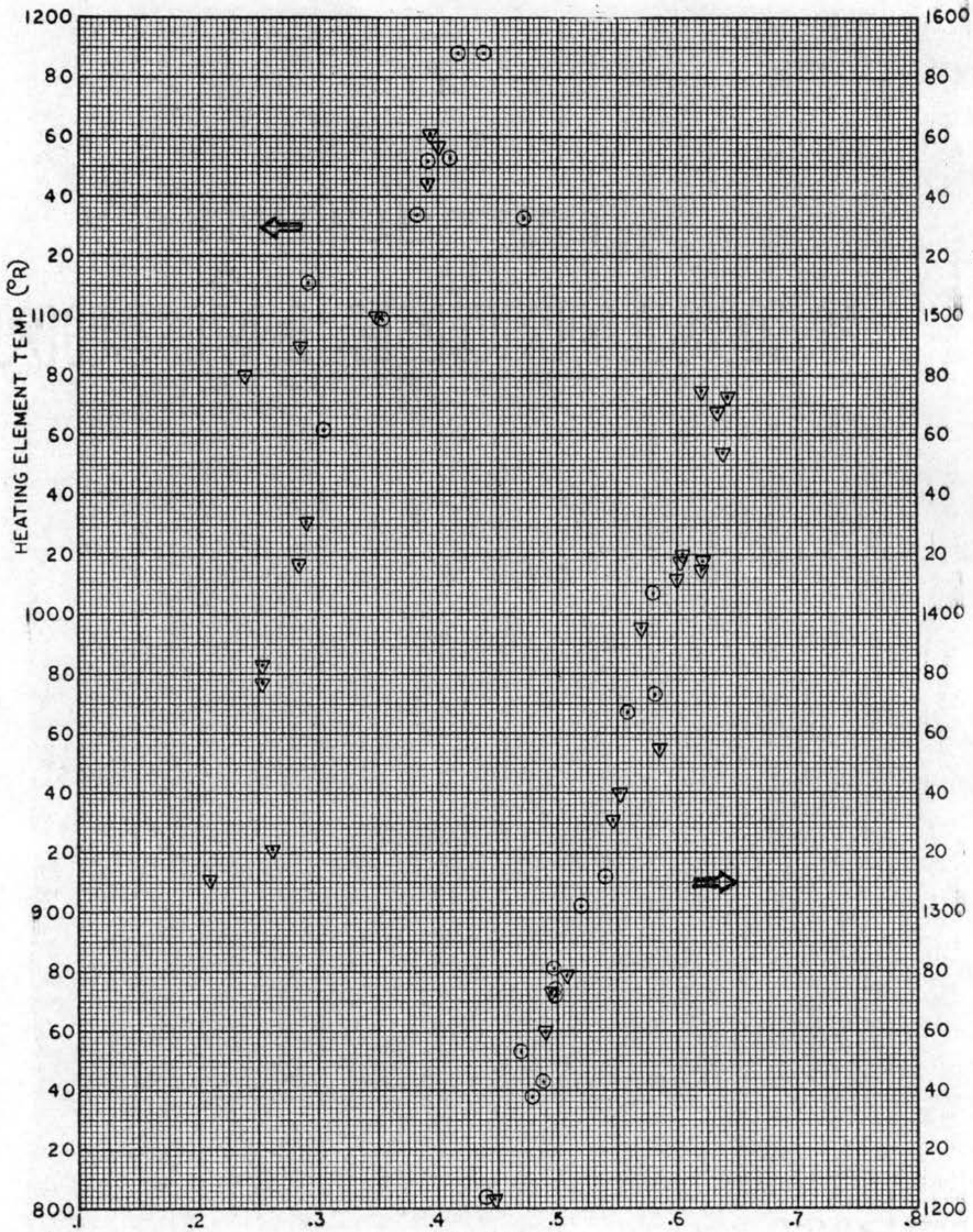


FIGURE 13: THERMISTOR TRANSDUCER DATA SCATTER

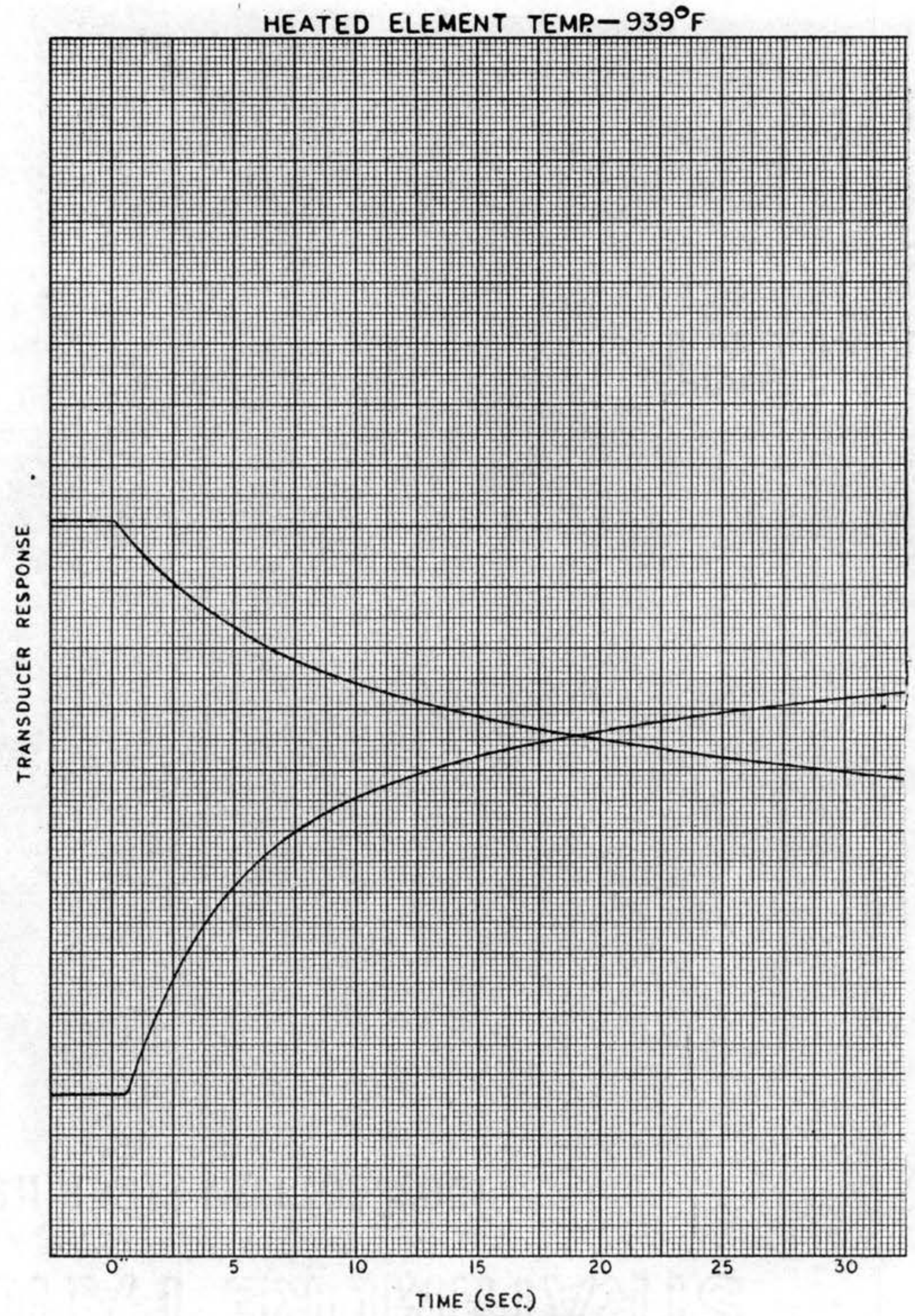


FIGURE 14: THERMISTOR TRANSDUCER TIME RESPONSE CURVE

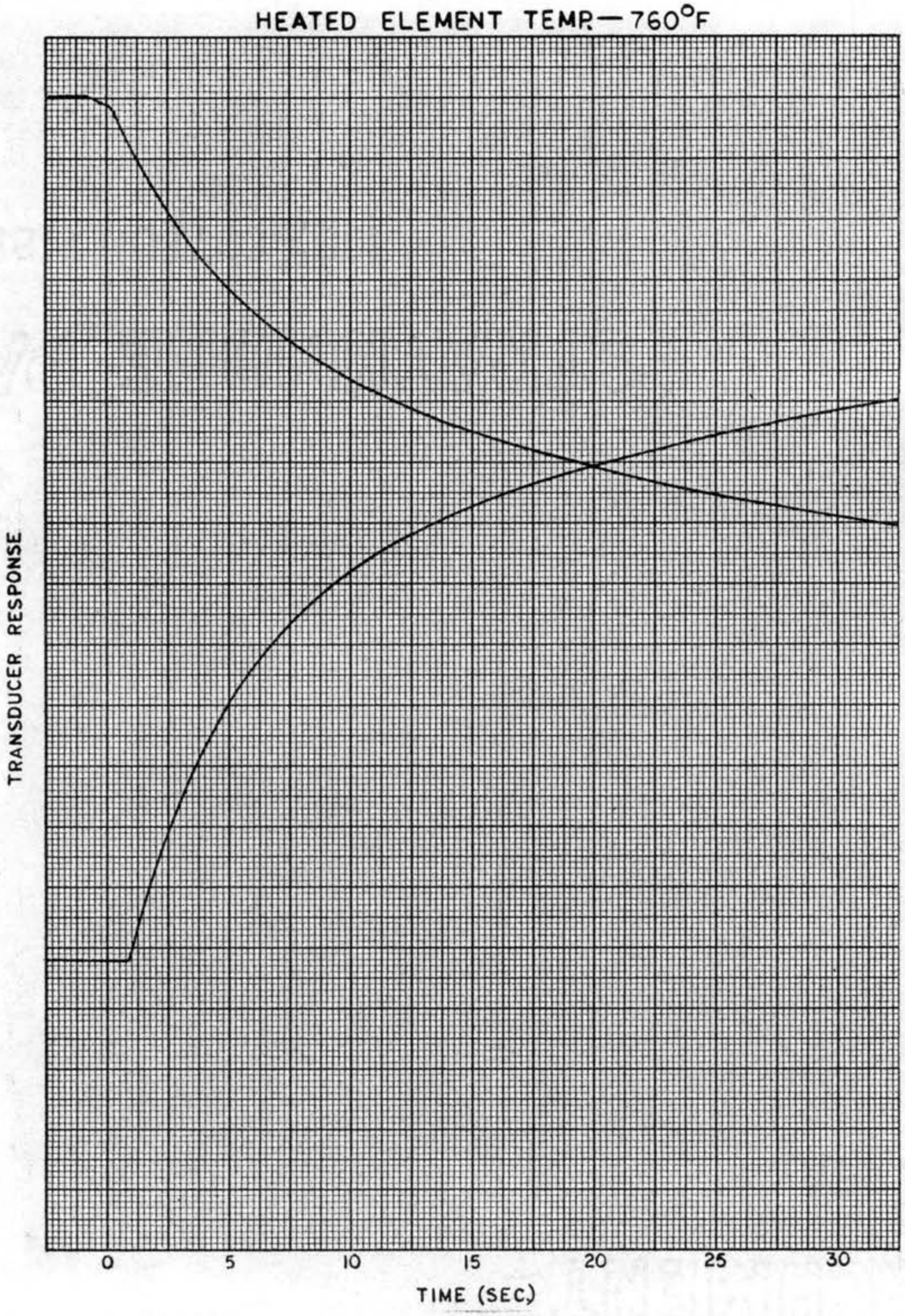


FIGURE 15: THERMISTOR TRANSDUCER TIME RESPONSE CURVE

THERMOPILE

The thermopile used in this analysis consisted of 20 radiation sensing and 20 reference junctions connected in series so that the net e.m.f. generated by the individual thermocouples would be additive. The thermocouples were located inside a reflector housing which focused the radiation heat flux on the radiation sensing junctions of the thermopile. The reference junctions were enclosed within a housing which blocked radiation heat; therefore, they were maintained at the temperature of the surrounding media. This housing could also receive a small amount of heat from the reflector housing by conduction. The signal from the thermopile was indicated on a self-balancing millivolt meter. The temperature of the heated element was monitored by the same method used in the thermocouple analysis procedure.

As in the thermocouple analysis, the heated element was brought to a relatively constant temperature and then, after the thermopile had reached an equilibrium condition, the output of the thermopile and the temperature of the heated element were recorded. This procedure was repeated for numerous heated element temperatures, and these data are given in Table V. The upper and lower values of heated element temperatures were governed by the same limitations that were encountered in the thermocouple analysis given previously.

The output of the thermopile was not completely stable but had relatively high frequency fluctuations about some mean point. A plot of the data from Table V, using the mean value of the thermopile fluctuations, is given in Figure 16. From this plot it can be seen that these data can be closely approximated by a straight line when the data are plotted on log-log coordinates. The general equation of this line is of the same form as the equation given for the thermocouple transducer, namely

$$E = aT^{c};$$

however, the values of the constants are different. The values of these constants, as found in Appendix A, are a equals $4.1(10)^{-12}$, and c equals 3.26. Again, it should be noted that these constants are functions of the geometry and characteristics of the system.

The output of this particular thermopile over the range of temperatures measured varied from approximately 0.020 to 0.080 volts. As mentioned before, since fluctuations of the thermopile output were present, only approximate mean values could be read by averaging the limits of these fluctuations. However, these mean values could be approximated with a relatively good degree of accuracy to two significant figures.

The fluctuations in the thermopile output were probably caused by a coupling of both the natural convective turbulence of the air surrounding the radiation sensing thermocouples and the small mass and, therefore, low thermal capacity of the thermocouples themselves. A plot of these fluctuations in the thermopile output at two different temperatures of the heated element is shown in Figure 17.

A plot of the thermopile transducer data is given on linear coordinates in Figure 18 in order that the scatter of the data could be evaluated. From this figure it can be seen that there is a scatter of data points over an approximate temperature range of 40 degrees. This scatter could have been caused by combinations of several different items. For instance, errors were introduced by fluctuations in the heated element temperature which was discussed previously. Errors in determining the mean value of the thermopile output could be present because of the difficulty in determining a mean value about which the random fluctuations were taking place. Also, some of the data scatter was undoubtedly produced by the fluctuations in the output of the thermopile reference junctions. The room temperature was observed to fluctuate over a range of up to approximately 5 degrees during the data gathering periods.

The response time of the thermopile transducer was found by the same method used to find the response time of the thermocouple transducer. The heating and cooling time response curves are given in Figures 19 and 20 for temperatures of the heated element of 971 and 747 degrees F. respectively. The response times were determined from these curves and are given in Table VI.

TABLE VI: THERMOPILE TRANSDUCER RESPONSE TIMES

Heated Element Temperature (degrees F.)	Response Time	
	Heating (sec.)	Cooling (sec.)
971	1.30	1.43
747	1.36	1.08

Again, the probable cause of the difference in the heating and cooling response curves is the same as that discussed for the thermocouple transducer. It is apparent, however, that the response time can be reduced significantly when the transducer has a small thermal capacity and when the rate of heat removal or addition to the transducer is made relatively large by having a large ratio of surface to cross-sectional area.

TABLE V

THERMOPILE TRANSDUCER CALABRATION DATA

No.	Heated Element (°F)	Temperature (°R)	Transducer Output (volts)	No.	Heated Element (°F)	Temperature (°R)	Transducer Output
1	897	1447	.074	25	809	1269	.051
2	914	1374	.064	26	669	1129	.075
3	837	1297	.051	27	630	1090	.033
4	736	1196	.042	28	719	1179	.043
5	596	1056	.027	29	918	1378	.069
6	734	1194	.041	30	833	1293	.056
7	757	1217	.048	31	692	1152	.043
8	864	1324	.058	32	643	1103	.034
9	992	1452	.079	33	521	981	.022
10	812	1272	.053	34	983	1443	.079
11	704	1164	.043	35	894	1354	.063
12	634	1094	.033	36	809	1269	.051
13	586	1046	.028	37	760	1220	.046
14	523	983	.022	38	651	1111	.033
15	617	1077	.032	39	555	1015	.025
16	701	1161	.040	40	504	964	.022
17	777	1237	.048	41	675	1135	.038
18	837	1297	.055	42	732	1192	.044
19	938	1398	.070	43	767	1227	.048
20	625	1112	.035	44	588	1048	.028
21	714	1174	.041	45	621	1081	.031
22	873	1333	.060	46	964	1424	.078
23	965	1425	.070	47	860	1320	.060
24	1000	1460	.075	48	792	1252	.050

TABLE V (CONTINUED)

No.	Heated Element (°F)	Temperature (°R)	Transducer Output (volts)	No.	Heated Element (°F)	Temperature (°R)	Transducer Output (volts)
49	638	1098	.034	60	771	1231	.051
50	511	971	.022	61	732	1192	.042
51	680	1140	.039	62	664	1124	.035
52	745	1205	.046	63	719	1179	.041
53	799	1259	.053	64	792	1252	.050
54	845	1305	.060	65	826	1286	.054
55	888	1348	.065	66	865	1325	.060
56	945	1405	.069	67	888	1348	.063
57	612	1072	.031	68	848	1308	.056
58	938	1398	.072	69	730	1190	.044
59	875	1335	.061	70	571	1031	.025

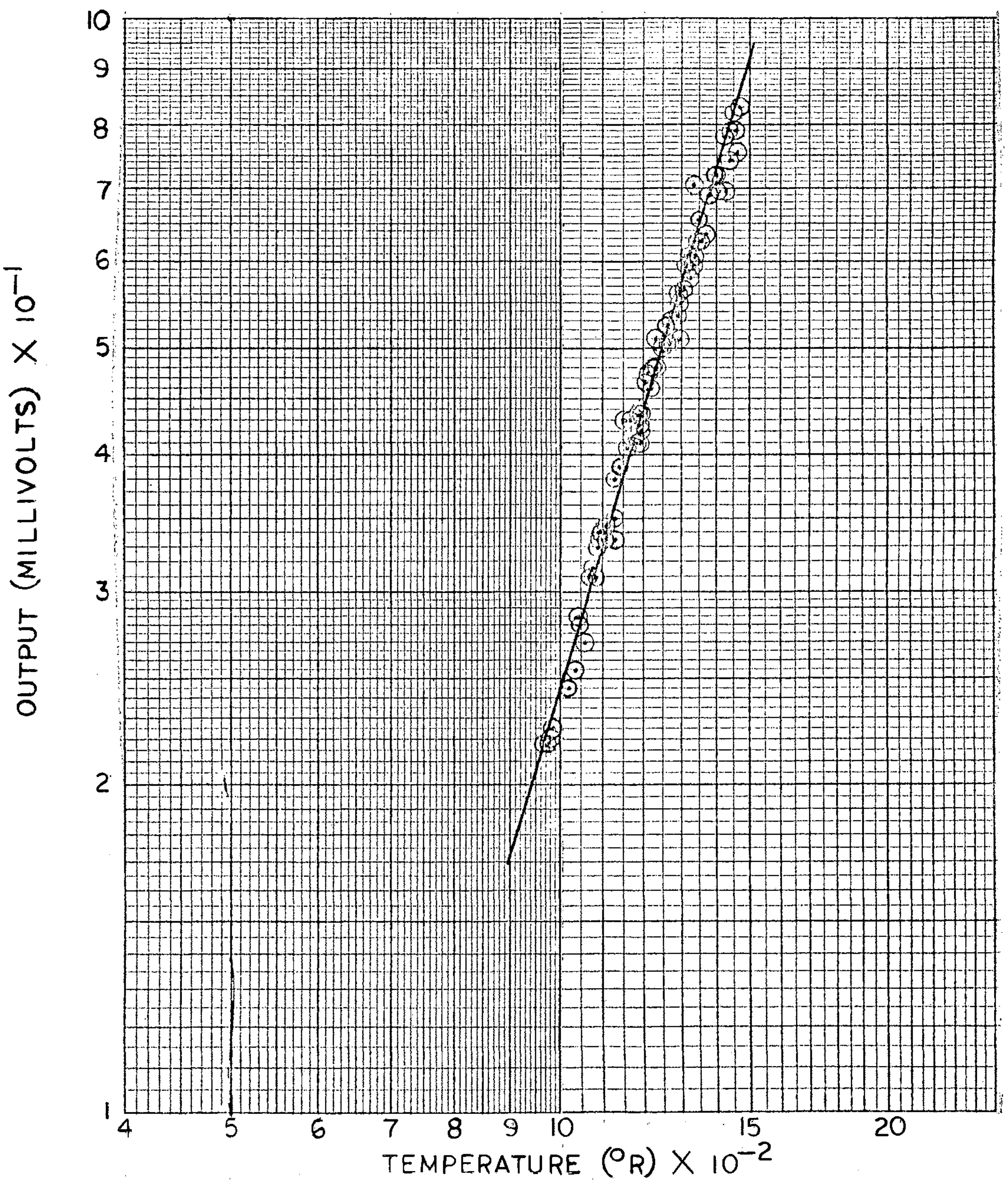


FIGURE 16: THERMOPILE TRANSDUCER CALIBRATION CURVE

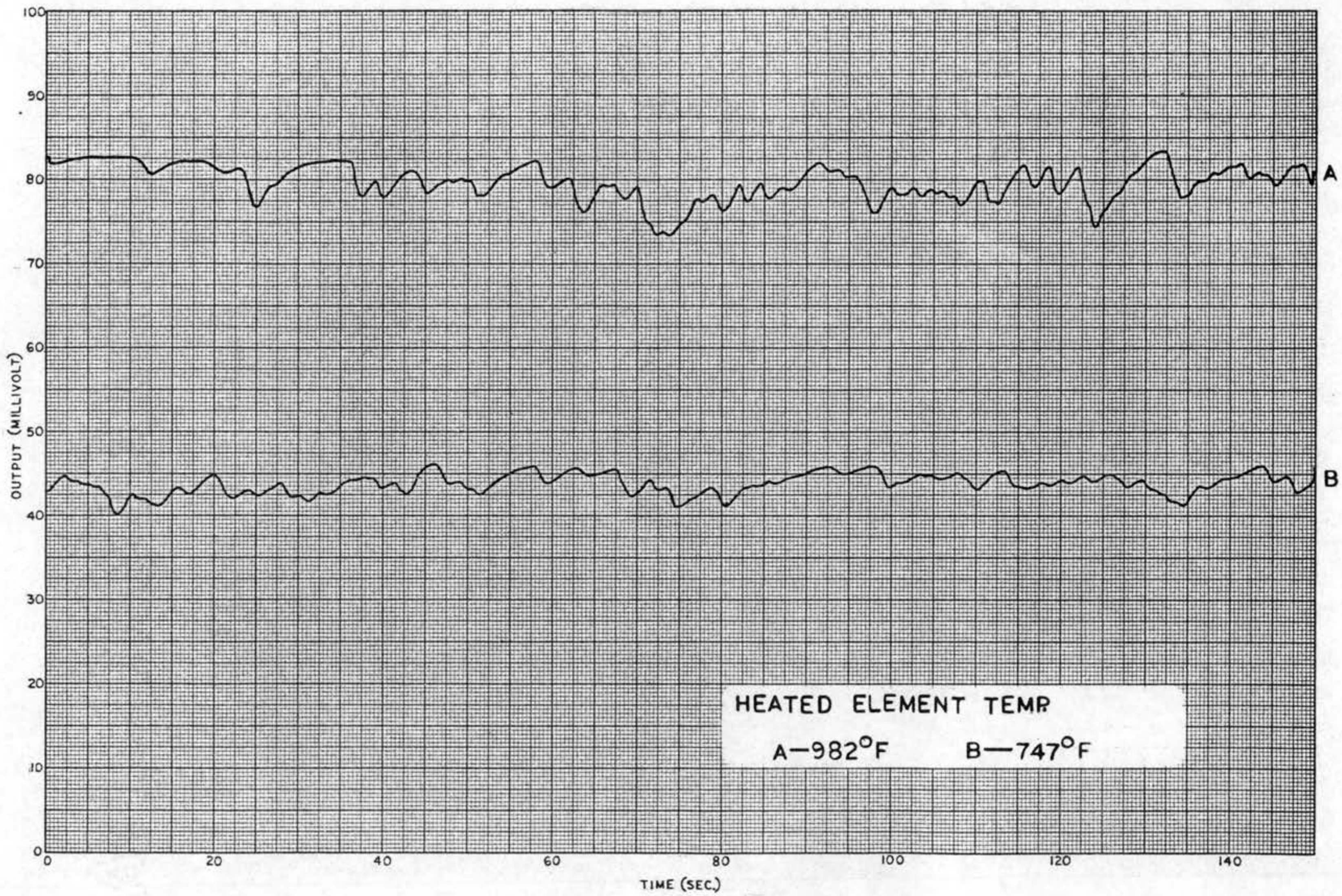


FIGURE 17: FLUCTUATIONS OF THERMOPILE OUTPUT

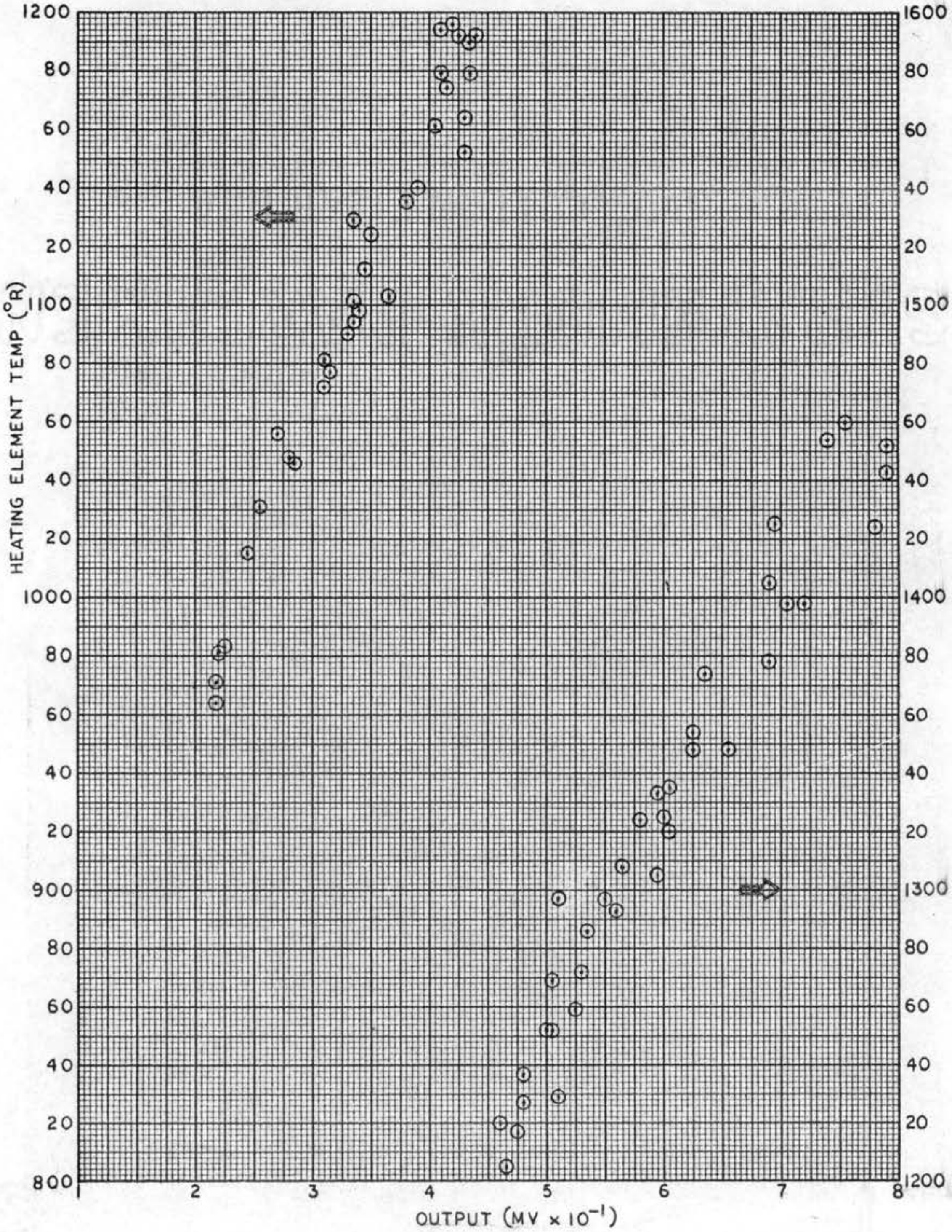


FIGURE 18: THERMOPILE TRANSDUCER DATA SCATTER

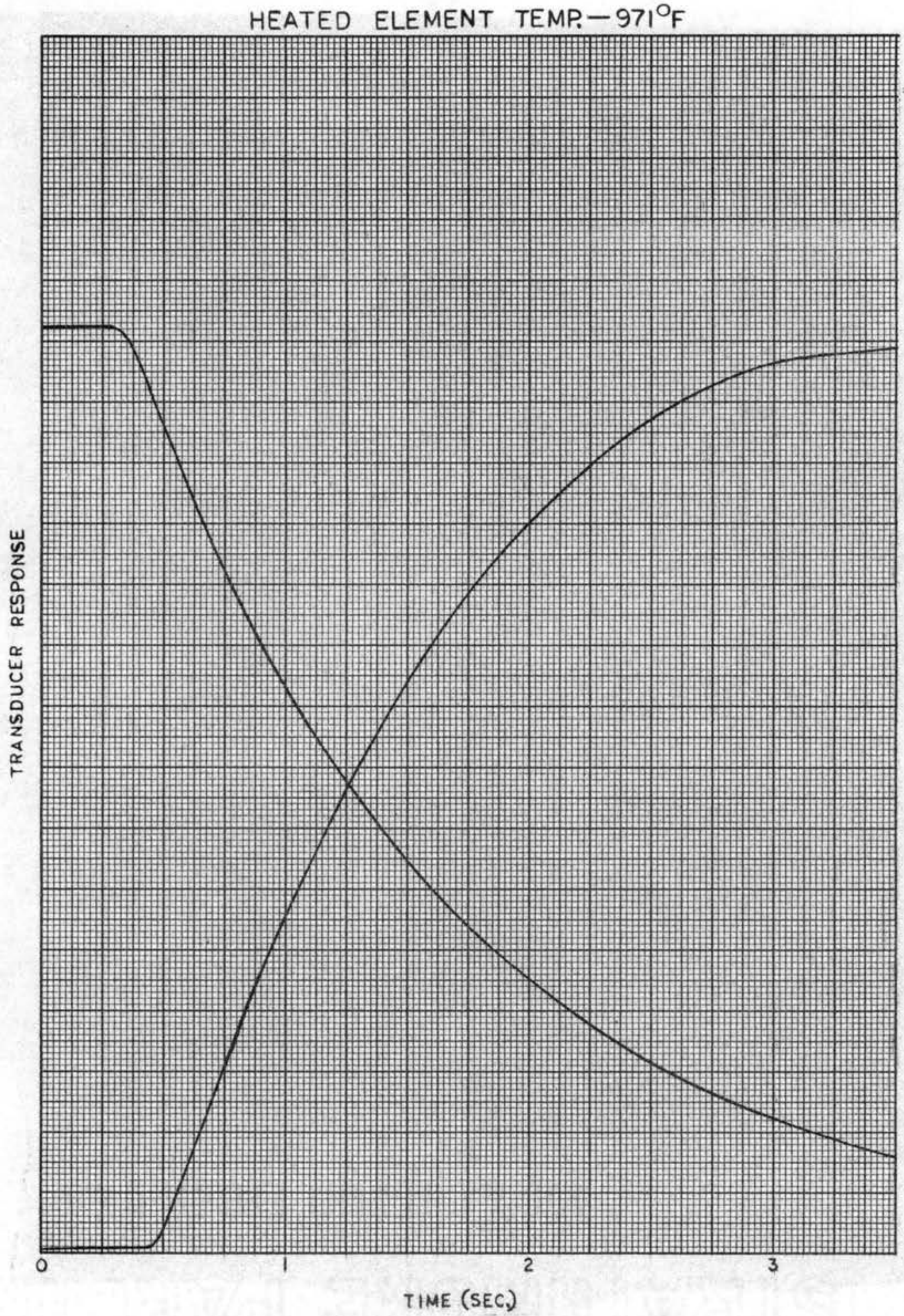


FIGURE 19: THERMOPILE TRANSDUCER TIME RESPONSE CURVE

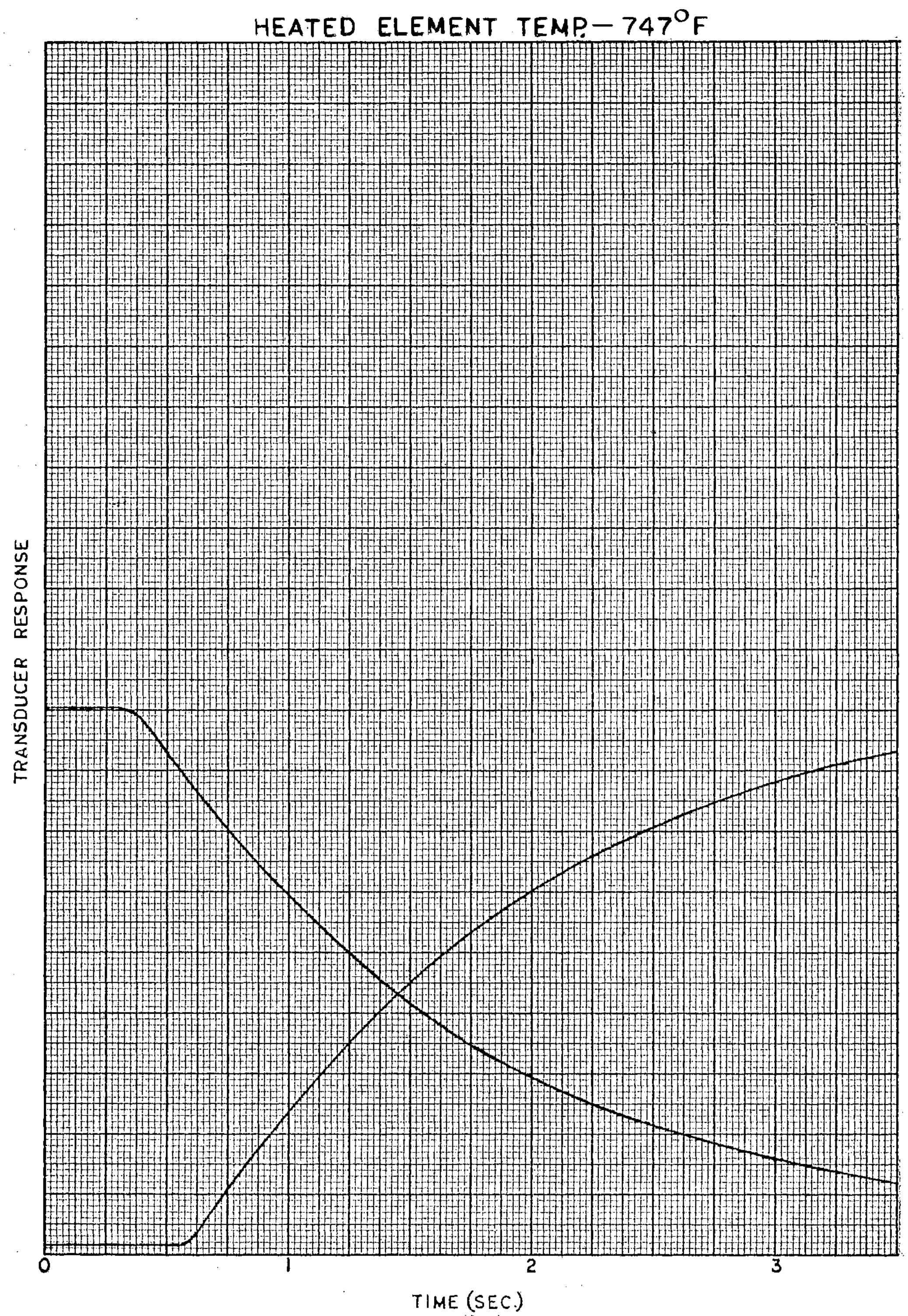


FIGURE 20: THERMOPILE TRANSDUCER TIME RESPONSE CURVE

CHAPTER IV

EVALUATION OF RESULTS

The instrumentation for the study of the thermocouple transducer allowed the reading of the data points to four significant figures where the instrumentation for the study of the thermistor and thermopile permitted the reading of only three significant figures of the output of the transducers.

The sensitivity of the potentiometer used to measure the heated element temperature was actually greater than required since small, random temperature fluctuations were persistent in the element. Therefore, the data were based on a mean temperature of the heated element. This was permissible because the sensitivity and response of the transducers to very small changes in radiated heat flux were very low.

The data scatter of the thermocouple transducer was much less than that for either the thermistor or thermopile transducer. The thermopile data scatter would probably have been much less if it had been possible to have had the reference junctions in a constant temperature surrounding such as an ice bath. Also, if a more constant surface heat transfer coefficient could have been maintained on the sensing junctions of the thermopile, the data scatter would have been reduced. Much of the scatter of the thermistor transducer can probably be attributed to resistance changes in the resistors of the Wheatstone Bridge. This type of change could have been caused by electrical heating of the resistors due to current flow. If this is true, then the use of resistors which are less sensitive to heating would have reduced data scatter. Another possible cause of data scatter could have been changes in the supply voltage, which was supplied by a $1\frac{1}{2}$ volt ignition dry cell battery. Also, some scatter could have been caused by errors in the reading of the transducer outputs and the heated element temperatures. Finally, the random fluctuations in the heated element temperature could have introduced some of the scatter of the data for each of the transducers analyzed.

Upon investigating the calibration curves for each of the transducers, it was found that while the trend of the data for both the thermocouple and thermopile approximated a straight line, the data for the thermistor did not. The straight line trend of the data on log-log coordinates lends itself to the calculation of an empirical relation which will approximately predict the transducer output for a given temperature. Since the calculation of the approximate relationship between the voltage change across the Wheatstone Bridge relative to the heated element temperature is much more involved and since the data scatter was much more than could be allowed, the empirical relation for the thermistor transducer was not found.

From the results of the analysis of these three transducers, it was found that the largest signals could be obtained from the thermistor with the particular bridge used. This type of large signal is desirable because of the background noise which is generally present in the atmosphere and especially near rotating systems. Since the output of the thermistor apparatus was of the order of tenths of volts, it should be well above the background noise level. The output of the thermopile was of the order of tens of millivolts while the thermocouple output was in the order of millivolts. Since the output of these two transducers is probably close to the potential level of the noise, their use would probably entail the use of shielding devices to block out this noise since it could cause inadvertent and false indications to appear in the calibrated temperature indicator system.

The investigation of systems with both large and small response times indicated that the stability and time response of these systems were coupled. Indications were that when the thermal capacity of the transducer was reduced and the convective heat dissipation characteristics were increased, the response time would be greatly reduced, but the stability of the transducer output would be adversely affected. From this analysis it is indicated that an optimized transducer configuration must be found where the response time can be made as short as possible without affecting the stability of the transducer output with fluctuations of an order of magnitude great enough to be detected by the indicating system.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

In evaluating the overall characteristics of the transducers studied with regard to determining the temperature of a turbine wheel, it appeared that the thermopile transducer, if properly designed, would give the best overall performance. This is due to the relative simplicity of the instrumentation required and the relatively large signal generated. This is provided that its stability and response time design characteristics are optimized as previously discussed. However, it is important that the data scatter be reduced to a maximum of plus or minus 10 degrees of a mean signal output which is within the design requirements established for the turbine wheel. The order of magnitude of the thermopile signal is probably great enough that a minimum amount of shielding would be required against the effects of background noise.

In the final design of such a detector for this particular application, it is necessary that either some means of compensation must be provided for changes in ambient temperature around the sensor and reference junctions to cancel its effect on the thermopile's output or the sensor and reference junctions must be maintained in constant temperature surroundings. Also, a window which will pass the infrared wave lengths encountered must be provided to separate the sensor junctions and reflector from the normal turbine wheel cooling air. This is required because of the large fluctuations in the temperature of this air and because of the contaminates present in it. Similarly, a means must also be found to prevent contaminates, which could block radiation heat flux, from depositing on the window.

Further studies should be made to determine the configuration of the thermopile sensor junctions which will best balance response time against signal stability. Investigations also need to be conducted into the development of a means to compensate for changes in the temperature of the media surrounding the detector. Also, studies must be made in order to determine whether or not the emissivity of the turbine wheel will change enough to affect the calibration of the radiometer and, if so, methods must be developed to cancel or compensate for these changes. Methods must also be developed to furnish instantaneous temperature monitoring along with a recording of the temperature history of the turbine wheel.

SELECTED BIBLIOGRAPHY

1. Kreith, Frank. Principles of Heat Transfer. Scranton, Conn.: International Textbook Co., 1958.

2. Locke, A. S. Guidance. Princeton: Van Nostrand Co., 1955.

3. Semat, H. and Katz, R. Physics, Vol. II. New York: Rinehart and Co., 1958.

4. Clark, Walter. Photography by Infrared. New York: John Wiley and Sons, 1946.

5. Bird, R. B., Steward, W. E., and Lightfoot, E. N. Transport Phenomena. New York: John Wiley and Sons, 1960.

6. Wilburn, D. K. "A Survey of Infrared Inspection and Measuring Techniques", ASTM Materials and Research Standards, Vol. I, No. 7, (July 1961).

7. Beckwith, T. G. and Buck, N. L. Mechanical Measurements. Reading, Mass.: Addison Wesley Pub. Co., 1961.

8. Moore, M. B. Theory and Application of Mechanical Engineering Measurements. Princeton: Van Nostrand Co., 1960.

APPENDIX A

The equation of a straight line on log-log coordinates may be expressed as

$$\log E = c \log T + \log a, \qquad (1)$$

where a and c are constants. Therefore, to evaluate the constants for the straight line approximation of the relationship between the thermocouple transducer output and the heated element temperature, proceed as follows.

Pick two points on the line, one at each end of the line to obtain

$$E = 0.0100 \text{ volts at } T = 1600^{\circ}R$$

$$E = 0.00255 \text{ volts at } T = 1000^{\circ}R.$$

Then,

$$\log .0100 = \log 1600 + \log a \qquad (2)$$

$$\log .00255 = \log 1000 + \log a. \qquad (3)$$

Now subtracting equation 3 from equation 2, it is found that

$$\log .0100 - \log .00255 = c(\log 1600 - \log 1000)$$

or

$$\log(.0100/.00255) = c \log(1600/1000).$$

Then,

$$c = \log(3.92)/\log(1.6) = .593/.204;$$

therefore, c is equal to 2.91.

Now noting that equation 1 can be written in the form

$$E = aT^{c}, \tag{4}$$

the following equation is obtained;

$$E = aT^{2.91}. \tag{5}$$

Now, the constant, a, is evaluated by using the values of one of the points on the line as follows,

$$.00255 = a(1000)^{2.91}$$

or

$$a = .00255/5.31(10)^{8};$$

therefore, a is equal to $4.80(10)^{-12}$.

Then equation 4 becomes, for this particular thermocouple transducer and radiometer geometry,

$$E = 4.8(10)^{-12}(T)^{2.91} \tag{6}$$

where E is the thermocouple output in volts and T is the heated element temperature in degrees Rankine.

The approximate relationship between the output of the thermopile transducer and the heated element temperature is found by the same method as that used for the thermocouple transducer. Its calculation is as follows.

Picking two points on the approximating line,

$$E = .0173 \text{ volts at } T = 900^{o}R$$

$$E = .0918 \text{ volts at } T = 1500^{o}R,$$

these values are then put into equation 1 to form two equations as,

$$\log .0918 = c \log 1500 + \log a$$

$$\log .0173 = c \log 900 + \log a.$$

Following the same procedure as before, c is found to equal 3.26.

Then from equation 4 and one of the points given, it is found that a is equal to $4.1(10)^{-12}$. Therefore, for this particular thermopile and system geometry, equation 4 becomes,

$$E = 4.1(10)^{-12}(T)^{3.26}. \qquad (7)$$

APPENDIX B

Apparatus and Equipment

1. Millivolt Potentiometer: Manufacturer, Leeds and Northrup Co.; Model No. 8686.

2. D. C. Vacuum Tube Voltmeter: Manufacturer, Hewlett Packard Co.; Model No. 412A.

3. X-Y Recorder: Manufacturer, F. L. Moseley Co.; Model 2D.

4. Wheatstone Bridge: Manufacturer, Oklahoma State University Mechanical Engineering Laboratory.

5. Heated Element: Manufacturer, Oklahoma State University Mechanical Engineering Laboratory.

6. Thermopile: Manufacturer, Central Scientific Co.; Model No. 81070.

7. Thermistor: Manufacturer, Gulton Industries; Model, Glennite 31TD5.

VITA

Norman Floyd Whitsitt

Candidate for the Degree of

Master of Science

Thesis: DEVELOPMENT AND ANALYSIS OF AN INFRARED RADIOMETER FOR THE REMOTE DETECTION OF TEMPERATURE

Major Field: Mechanical Engineering

Biographical:

Personal Data: Born near Jacksboro, Texas, March 9, 1938, the son of Ira Floyd and Meredith Alexine Whitsitt; married the former Elizabeth Ann Chapin of Graham, Texas on March 22, 1958.

Education: Attended elementary school in Jacksboro, Texas; graduated from Jacksboro High School in 1956; received a Bachelor of Science degree in Mechanical Engineering from the Arlington State College, Arlington, Texas in May, 1961; completed the requirements for a Master of Science degree in Mechanical Engineering at the Oklahoma State University in August, 1962.

Experience: Worked as an engineering coop student from 1957 until 1960 and as a design engineer during the summer of 1961 for General Dynamics/Fort Worth, Texas; served as a research assistant for three semesters while attending the Oklahoma State University.

Honors and Awards: Who's Who in Mechanical Engineering in 1959 and 1961 at Arlington State College; member of college and engineering honor societies at Arlington State College; member of Pi Tau Sigma.

Professional Organizations: Member of the American Society of Mechanical Engineers; American Society for Testing Materials; the Society of Automotive Engineers; the American Rocket Society; Engineer-In-Training, State of Texas.