SELECTION AND TESTING OF PYROMETERS FOR HIGH-TEMPERATURE GAS FLOW

by

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TABLE OF CONTENTS

LIST OF FIGURES

SELECTION AND TESTING OF PYROMETERS FOR HIGH-TEMPERATURE GAS FLOW

INTRODUCTION

With the steadily increasing importance of the gas turbine in the last few years, the problem of measuring the temperature of the combustion gases accurately in order to determine the operating conditions of the unit has become very important. This problem has been quite evident in the Oregon State College gas turbine. This turbine was constructed by a group of students, under the supervision of Professor Arthur D. Hughes, from a war surplus B-31 turbosupercharger with a De Havilland H-1 jet engine combustion chamber. A picture of the second complete unit is shown in Figure 1.

Since this unit was built, it has been evident that the temperatures being measured at the turbine inlet and the turbine exhaust were very much in error. Neither the turbine inlet temperature nor the turbine exhaust temperature was consistent. At times the turbine inlet temperature indicated would be 1400 F to 1500 F, and at other times it would be closer to 1000 F under the same operating conditions. When an attempt was made to plot the temperature as ordinate with various abscissas such as turbine speed, turbine expansion ratio, and air-fuel ratio, there was no correlation at all. The points plotted were widely

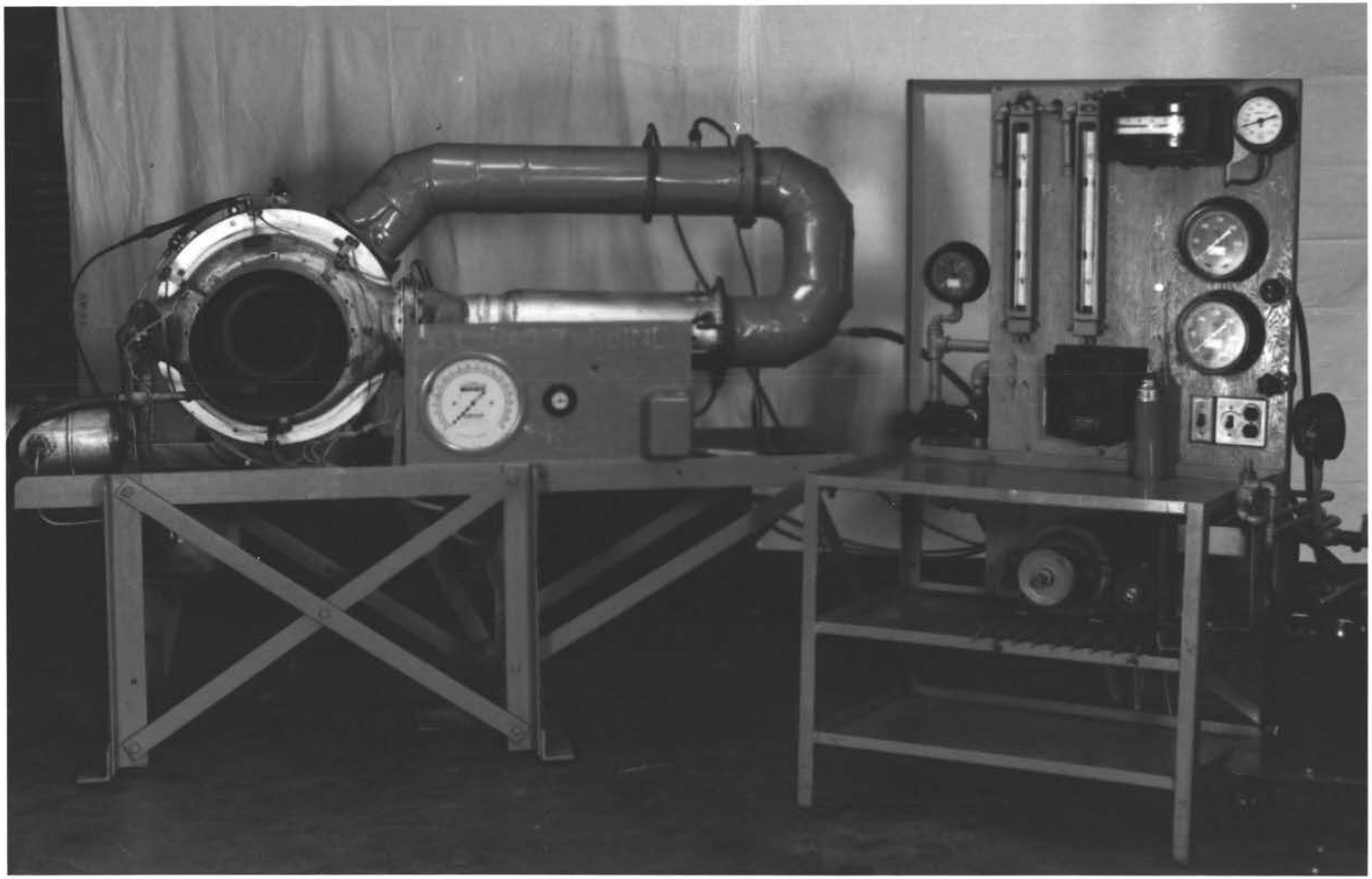


FIGURE 1 THE OREGON STATE COLLEGE GAS TURBINE

scattered and did not indicate a trend through which a curve could be drawn.

Theoretically, in order to do work by passing a gas through a turbine wheel there must be a temperature drop and a pressure drop. The required pressure drop across the turbine is quite easily measured, but to date the measured temperature of the exhaust gases has always been greater than the temperature of the inlet gases. This is another indication that the temperatures have not been accurately measured.

In the second unit the thermocouples measuring the turbine inlet temperature were placed in two locations. The first location was in a hollow stainless steel staybolt, while the second location was about 3 or 4 inches ahead of the hollow staybolt in a removable elliptical steel section. These two locations are shown diagrammatically in Figure 2a. As may be seen from Figure 2b, the elliptical section was made in such a manner that four thermocouples could be placed in the section at once.

The exhaust thermocouples measuring the turbine exhaust temperatures were placed in three positions 120 degrees apart around the exhaust ring. These three thermocouples were approximately 3 inches from the turbine wheel.

When an attempt was made to explain the reasons for the peculiar temperatures measured, it was thought that

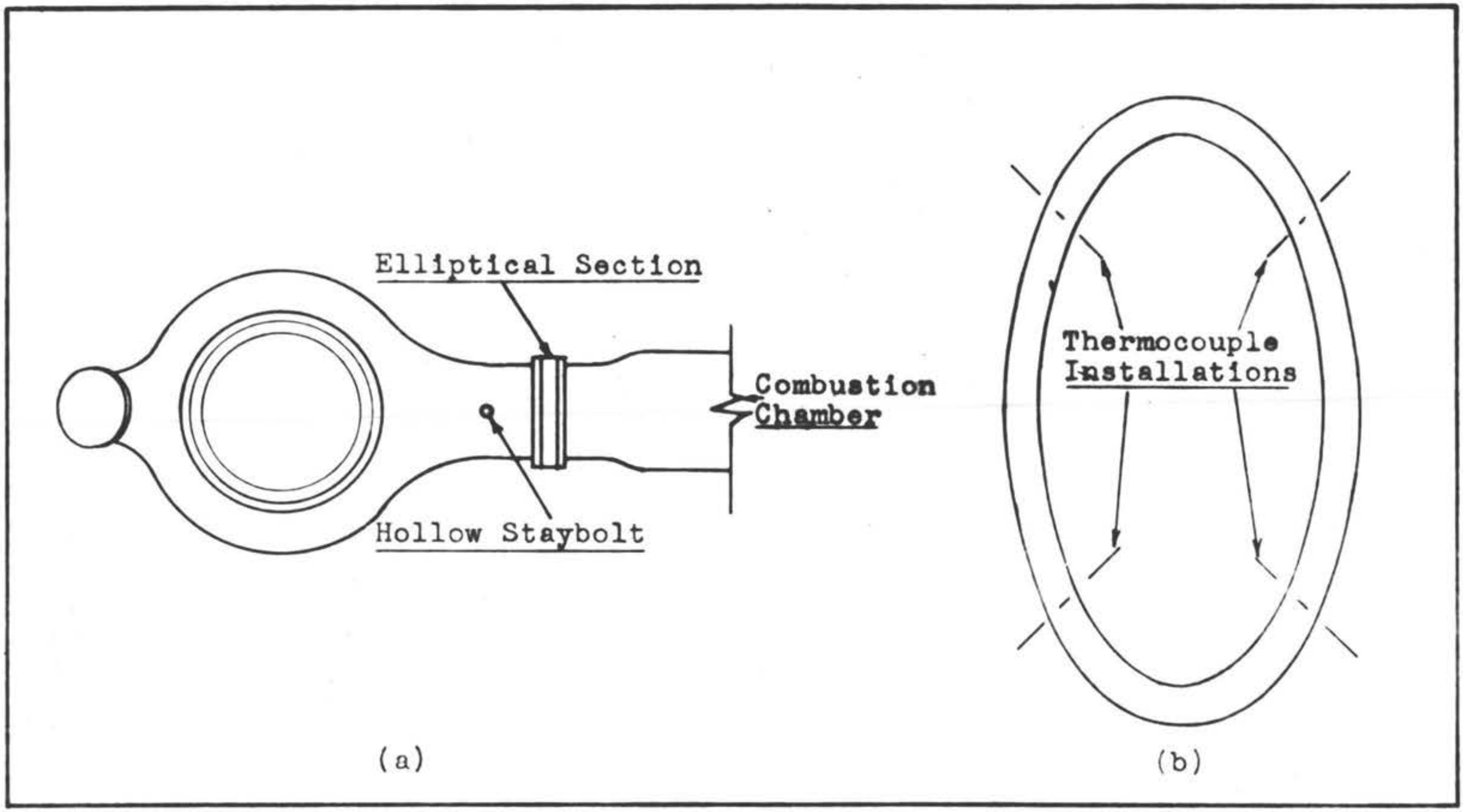


FIGURE 2 (a) DIAGRAMMATICAL SKETCH OF PREVIOUS THERMOCOUPLE INSTALLATIONS
(b) PLAN VIEW OF ELLIPTICAL SECTION

there were several factors causing the inconsistency. Since the thermocouples placed in the elliptical section were actually at the throat of the exhaust of the combustion chamber, the velocity at that section was quite high--in the order of 200 to 500 feet per second. Therefore, the portion of the gas that slows up as it approaches the thermocouple imparts a portion of its kinetic energy to the thermocouple, increasing its temperature above that of the static gas temperature. Also, the location of these thermocouples in the elliptical section made it possible for the thermocouples not only to "see" the flame, but also to "see" the cold walls of the section. This gas radiation to the thermocouple tends to increase the thermocouple's temperature while the thermocouple's radiation to the cold walls tends to reduce its temperature. For a time it was thought that the radiation loss caused by the cold walls would tend to offset the gain in temperature caused by the gas radiation and by the kinetic energy of the gas. Since the temperature measurements were inconsistent, however, this idea was discarded. Various stainless steel shields were tried several times, but they did not correct the situation.

The thermocouple placed in the hollow staybolt actually had a stainless steel shield around it, so some of the radiation loss and gain should have been decreased, but the thermocouple junction measured a temperature several hundred degrees lower than that measured by the thermocouples in the elliptical section. This difference was believed to be caused by the radiation gain by the thermocouples in the elliptical section due to radiation from the flame and by the conduction loss along the hollow stainless steel staybolt.

The exhaust thermocouples have three factors entering into possible causes for errors in their readings. These factors are the kinetic energy change due to slowing up of the gases as they pass the junction and the heat radiated to and from the thermocouple.

Since this gas turbine was built for a dual purpose (demonstration and testing), it is necessary to measure with a certain degree of accuracy the temperature at various critical points in order to conduct a worthwhile test. As has been previously stated, up until this time these temperatures have not been measured accurately. It is the purpose of this thesis, therefore, to select and test several pyrometers which can be used for high-temperature gas stream measurement. If the tests should prove that a pyrometer can measure the required temperatures accurately, it will be used as a permanent temperature-measuring instrument for the turbine.

SELECTION OF THE PYROMETER

A pyrometer must have certain requirements for each individual installation in order to be able to measure the temperature of the gas stream accurately. In this installation it is desired to measure the static temperature rather than the total temperature as is commonly measured in high-temperature gas streams. These two terms are defined as follows:

1. Static temperature is that temperature which would be indicated on a recording instrument if the temperature-measuring device were traveling with zero relative velocity with the gas stream.
2. Total temperature is that temperature which would be indicated on a recording instrument if the temperature-measuring device were stationary, and the measuring device absorbed all of the energy given up by the gases as the gas velocity approached zero.

The static temperature is the temperature desired since it is this temperature along with the static pressure that completely defines the thermodynamic state of the gas (3, p.219). Therefore, the pyrometer selected must measure the static temperature, or it must be possible to correct the measured temperature to give the static temperature. In this installation it is expected that the gas stream's temperature varies across the turbine casing, so the pyrometer either must measure the average temperature, or it must be adaptable for use in a temperature traverse. It is known also that at any one point there is a rapid temperature fluctuation; therefore, the response rate of the pyrometer need not be fast in order to obtain the desired average temperature.

The pyrometer also must reduce the radiation, conduction, and convection losses to a minimum. Other requirements that should be met are simplicity, low cost, reliability, and durability.

There are many different pyrometers for measuring temperatures, but only a few of these methods will meet the above requirements. Some of the most used methods are as follows:

1. Thermocouples, both bare and shielded
2. Sonic pyrometer
3. Pneumatic pyrometer
4. Resistance thermoelement

A brief discussion of each pyrometer is given below.

Thermocouples

Pyrometers employing thermocouples have become quite popular over a period of years due to their simplicity, accuracy, low cost, and ease of production. However, they still are subject to errors such as conduction loss along the wires and along the thermocouple well, radiation loss from the thermocouple junction to the cold walls, radiation gain from the hot gases to the junction, and impact error due to the high-velocity gases striking the thermocouple. Also, they have an inherent property of only being able to measure the temperature at one small point. In order to obtain an average temperature, therefore, it would be necessary to use many thermocouples and average the readings.

Numerous investigators (4, pp.153-160), (11, pp. 421-425), and (16, p.334) have attempted to correct the readings of a thermocouple by incorporating various forms of shielding to reduce the errors due to radiation. It has been reported by A. I. Dahl and E. F. Fiock that if a silver shield were pressed on a thermocouple, the errors due to radiation would be negligible (4, p.156). This same silver-shielded thermocouple gives excellent performance because of its ruggedness, rapid response, and ease of construction.

Another type of radiation shielding consists of two tubes concentrically placed with the thermocouple in the center (16, p.334). Another thermocouple is placed between the two concentric tubes, and a coil of wire is wrapped around the center tube. This coil of wire is connected in series with a voltage source and a current-limiting device. During operation the current is adjusted in the coil until the two thermocouples indicate the same temperature. At this point the center shield is at the same temperature as the main thermocouple, so there can be no heat loss due to radiation from the main thermocouple to the first shield. A sketch of this thermocouple is shown in Figure 3. This thermocouple gives very good results, but due to its construction and elaborate control necessary to maintain the center shield at the required temperature, it is only suitable for installations in which the temperature is relatively constant.

Another shield used by W. J. King (11, p.424) uses a thermocouple with quadruple shields spaced 1/16 inches apart. These shields are 2-1/2 inches long and made of 18-8 stainless steel. The accuracy of this thermocouple is not quite as good as that of the other two, and due to its large outside diameter, 1-1/8 inches, it is limited to use in large-size ducts.

Shielding of various forms and sizes also has been used in trying to obtain the maximum amount of heat transfer from the change in kinetic energy due to stopping the gases by the thermocouple. W. J. King reports on a diffuser-type shield probe (11, p.424), used to avoid velocity errors, which has been quite successful for velocities from 150 to 600 feet per second and at room temperatures.

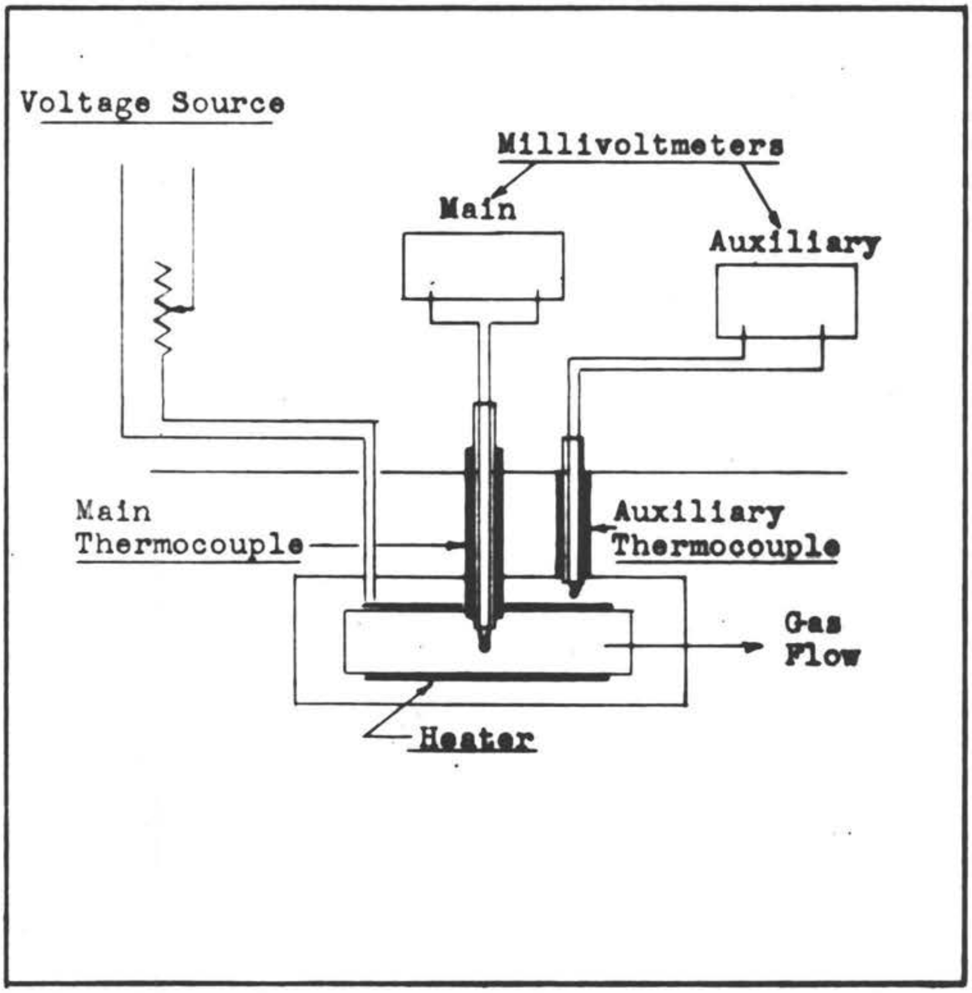


FIGURE 3 DOUBLE-SHIELDED THERMOCOUPLE
CENTER SHIELD ELECTRICALLY HEATED

This probe, however, does not have adequate shielding for radiation, so it is unfit for high-temperature usage.

Another group of investigators (1, pp.338-341) has reported on numerous designs of shielding to be used to recover the maximum amount of kinetic energy in the gas. The shields developed recovered nearly all of the total available energy caused by the change in velocity in the form of heat, and so they measure the total temperature quite accurately. In this case, however, the static temperature is the one desired, so they would not be suitable for this use unless the velocity at the location of the thermocouple were known.

Sonic Pyrometer

The sonic pyrometer (17, pp.851-858) was developed by E. P. Walsh, Sidney Allen, and J. R. Hamm for the express purpose of measuring the total temperature of a high-temperature, low-density gas stream. This type of pyrometer incorporates three essential parts, the thermocouple, the flow nozzle, and the encasing tube; but other parts may be added depending upon the accuracy desired. For instance, in order to decrease radiation, a second tube is placed around the first, and gas is drawn through the annular space raising the inner tube temperature to that of the gas. In order to decrease conduction loss, the high-velocity gas may be allowed to pass over the thermocouple wires for a short distance. A sketch of this type of pyrometer is shown in Figure 4.

The principle upon which this pyrometer operates is that if a gas is allowed to pass through a flow nozzle at such a rate that its velocity approaches the velocity of sound and that if a thermocouple is placed within the flow of this gas stream, then a maximum amount of heat will be transferred to the thermocouple giving the maximum temperature obtainable. This point of operation may be found by varying the gas flow through the nozzle. When the flow reaches such a point that the temperature of the thermocouple does not increase, then sonic velocity is obtained. The true static temperature then may be found by applying the following equation:

$$T_s = 1.02T_j - \frac{V^2}{2gJc_p} \tag{1}$$

where T_s = Static temperature, R
T_j = Junction temperature, R
V = Velocity, ft/sec
g = Acceleration of gravity, ft/sec^2
J = Heat equivalent of work, Btu/ft lb
c_p = Specific heat at constant pressure, Btu/lb R
1.02 = Conversion factor for obtaining the total temperature of the gas stream (17, p.852)

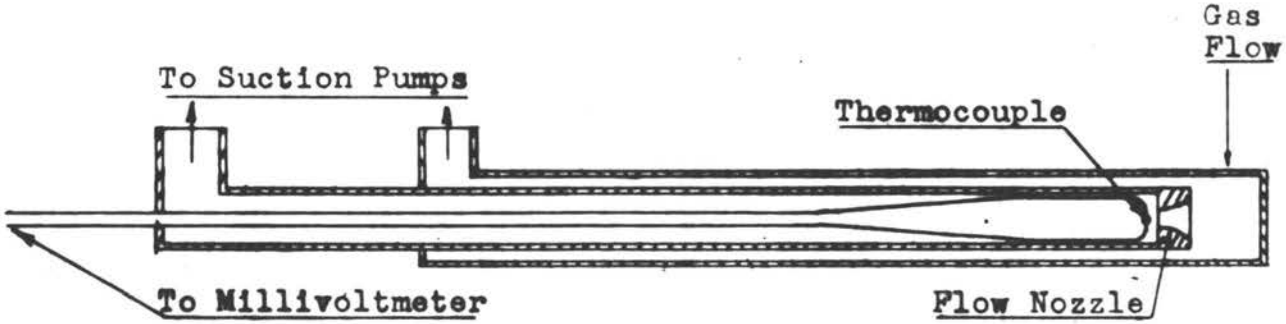


FIGURE 4 SONIC PYROMETER

This type of pyrometer then gives a relatively simple method for measuring the static gas temperature of not only constant-temperature gas streams, but also of rapidly-changing-temperature gas streams due to its rapid response rate.

Certain characteristic features of this instrument, however, make it less desirable for this application. For instance, with a suction pyrometer corrected for radiation two suction pumps must be used, and their cost plus the cost of construction of the pyrometer will give a high total cost. Also, in order to calibrate the pyrometer in the easiest possible manner, it takes quite an elaborate and costly selection of instruments. Walsh, Allen, and Hamm used a gravimetric chemical analysis of the gas stream in order to obtain the true temperature. This gravimetric technique as described by Lloyd (12, pp.335-341) has proved to be quite accurate.

This pyrometer is only capable of obtaining the temperature at one point in the gas stream. In order to obtain a true average temperature, either a time-consuming temperature traverse would have to be taken, or several sonic pyrometers would have to be installed at various positions, which would further increase the cost.

Still another disadvantage is that this pyrometer requires a definite amount of gas to be drawn off through the pyrometer. In this case the amount of gas flow in the unit is critical, and all gas flow should be used in driving the turbine.

Pneumatic Pyrometer

The pneumatic pyrometer as developed by the Fairchild Camera and Instrument Company (15, pp.30-34) is a relatively simple device. It consists of a tube containing two small orifices with a heat exchanger located between these orifices. A sketch of this instrument is shown in Figure 5a.

In order to measure the temperature of the gas stream, a sample of gas is drawn into the tube and passed through the first orifice. The gas is then cooled by the heat exchanger and is passed through the second orifice, after which it is discharged into the atmosphere. It is then only necessary to measure the pressure drop across both orifices and the temperature at the second orifice. These values are then used with the equation,

$$T_{s1} = K\,T_{s2}\left(\frac{P_{s1} - P_{s2}}{P_{s2} - P_{s3}}\right) \tag{2}$$

where T_{s1} = Static temperature before the first orifice, R
T_{s2} = Static temperature before the second orifice, R
P_{s1} = Static pressure before the first orifice, psia
P_{s2} = Static pressure before the second orifice, psia
P_{s3} = Static pressure after the second orifice, psia

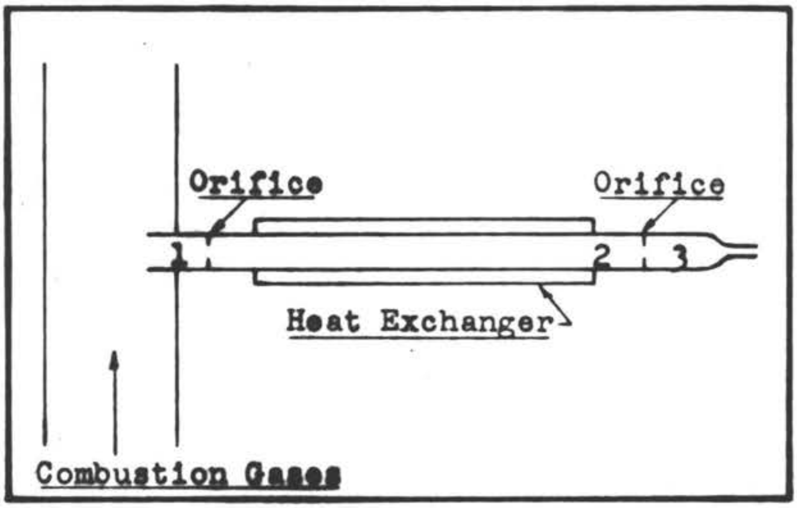


FIGURE 5a FAIRCHILD PNEUMATIC PYROMETER

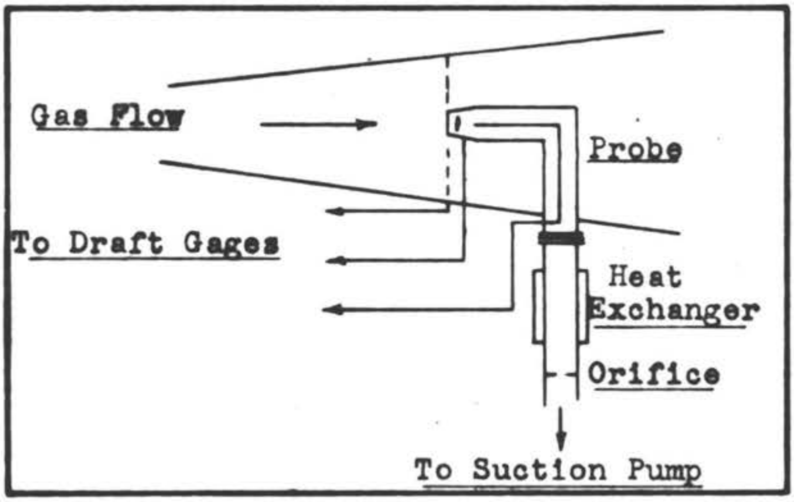


FIGURE 5b PNEUMATIC PYROMETER

K = Constant containing the orifice coefficients and areas

when the difference $(P_{s1} - P_{s2})$ is small.

With this type of instrument it is possible to calculate the temperature of the gas stream very closely. This is due to the fact that the only heat loss will be by radiation from the gas to the walls, which is a very small amount. The response of this instrument is almost instantaneous since the density of the gas stream changes with temperature, and any change in density must immediately affect the pressure drop across the first orifice.

Like the sonic pyrometer, this instrument has the inherent property of only being able to measure the temperature at one point, and while doing so a sample of gas must be by-passed through the instrument, both of which are considered undesirable in this case.

Another type of pneumatic pyrometer (Figure 5b) is that developed by J. A. Clark and W. H. Rohsenow (3, pp.219-227). In this pyrometer a portion of gas is pulled through a tube by a suction pump in a way similar to that used with the sonic pyrometer. Various values of pressure are measured at the inlet to the tube, and the flow is measured by an orifice after the gas has passed through a heat exchanger. These values are then used in Equation 3 to find the static temperature at the inlet to the probe.

$$T_{s1} = \frac{2g_o}{R_1}\left(\frac{P_{s1}}{G_1}\right)^2\left(\frac{k}{k-1}\right)\left[\left(\frac{P_{t1}}{P_{s1}}\right)^{\left(\frac{k-1}{k}\right)} - 1\right] \qquad (3)$$

where T_{s1} = Static temperature, R

g_o = Conversion factor, 32.2 lbm/sec^2 lbf

R_1 = Gas constant, ft lbf/lbm R

P_{s1} = Static pressure, lbf/ft^2

G_1 = Mass flow, lbm/sec ft^2

k = Ratio of specific heats, dimensionless

P_t = Total pressure, lbf/ft^2

It may be noticed in Equation 3 that T_{s1} depends upon the gas composition. However, R_1 (the gas constant) can be assumed to be the same as that for air since the amount of fuel added is very small compared with the amount of air, but the value of k changes materially with varying gas concentrations. J. A. Clark and W. H. Rohsenow have shown that if k is assumed to be 1.250, the calculated temperatures by Equation 2 will not vary more than 2 per cent over that calculated by using the true value of k as determined from the gas composition.

This pyrometer is quite easily calibrated. Since it may be done at room temperature, all effects of heat exchange by conduction, convection, and radiation can be eliminated. The calibration is performed to obtain the required flow necessary for accurate results.

One inherent property of this method that makes it advantageous for this use over that of the thermocouple is that as the temperature and velocity of the gas are increased, the accuracy of the results also increases.

The pyrometer can be constructed to give a simple, cheap, durable instrument. If it is made of stainless steel and is water cooled, it may be used at extreme temperatures without being subject to effects of corrosion.

As with the shielded thermocouples, the sonic pyrometer, and the Fairchild pyrometer, the temperature found by this method is measured at one point. In order to obtain an average temperature, either several pyrometers or a temperature traverse would be necessary.

Resistance Thermoelement

Since 1871 when Siemens suggested using the property of changing resistance with temperature of various materials for measuring temperature, the resistance thermoelement has become quite popular.

The two materials used at present for most temperature measurements by resistance thermoelements are pure nickel and pure platinum. Nickel is used for only low-temperature measurements up to 450 F. This limitation on its useful temperature range is caused by the change in the temperature-resistance curve as the transition point of nickel is approached and by the danger of oxidation. Bare platinum, on the other hand, can be used up to temperatures of 1800 F without difficulty if it is in the presence of an oxidizing atmosphere. Usually, however, the platinum element is placed within a shield. This shield performs two functions; (1) that of a rigid support and protection of the element, and (2) that of radiation correction.

Errors in the readings of resistance thermoelements are subject to the same factors that enter into temperature measurement by thermocouples. Consequently, it is necessary to apply corrections to the readings of a resistance thermoelement similar to those of the thermocouple readings. A resistance thermoelement, however, has another characteristic which must be considered, and that is the current-carrying capacity of the wire. The effects of the current on heating and thus changing the resistance must be watched closely, or incorrect results will be obtained.

Temperature lag of a shielded resistance thermoelement is much greater than that of any of the other types of instruments mentioned previously, but it does not measure the temperature at a point in a gas stream as the other types of instruments do. It measures the average temperature of the gas stream. If this resistance thermoelement is connected to a wheatstone bridge or a similar type of apparatus, the thermoelement is very sensitive to temperature changes.

Now, after examining the various pyrometers, the pyrometer which meets the requirements can be selected. Two pyrometers were selected to be subjected to tests for their suitability for this installation.

The silver-shielded Chromel-Alumel thermocouple was selected because of its accuracy, reduction in radiation losses, availability, low cost, and simplicity. It is true that it does not measure the average temperature, but with several thermocouples the average temperature may be obtained.

The resistance thermoelement was also selected because of its inherent property of measuring the average temperature. It was realized that the cost of a platinum resistance thermoelement was prohibitive and that nickel was out of the question, but it was felt that if another material could be found, this method would be excellent for measuring the temperatures desired. It was also realized that the errors obtained in resistance thermoelements are the same as those for the silver-shielded thermocouple except for radiation, but correction for this error can be made.

It was decided that two trial thermoelements would be made--one from Inconel wire and the other from Chromax wire--to determine their suitability.

THEORY OF TEMPERATURE MEASUREMENT BY THERMOCOUPLES AND RESISTANCE THERMOELEMENTS

The first thermocouple used to measure temperature was devised by Seebeck in 1821. This temperature-measuring device was a direct result of his discovery that when the junction of two dissimilar metals is heated, an electromotive force is generated (18, p.33). This potential was later found to be the algebraic sum of three separate electromotive forces.

These three electromotive forces are due to what is known as the Peltier effect, the Thompson effect, and the Becquerel effect (2, p.109). The potential generated by the Peltier effect is due to heating a junction of two dissimilar metals, whereas the Thompson effect generates an electromotive force when there is a temperature difference along a homogeneous wire. The Becquerel effect generates an electromotive force when there is a physical or chemical inhomogeneity in a single wire. This effect is usually negligible in good thermocouple wire.

The algebraic sum of these three electromotive forces varies with the temperature difference between the two junctions of a thermocouple circuit. A simple circuit is shown in Figure 6.

If Junction 1 is maintained at a definite temperature while Junction 2 is heated, then the electromotive

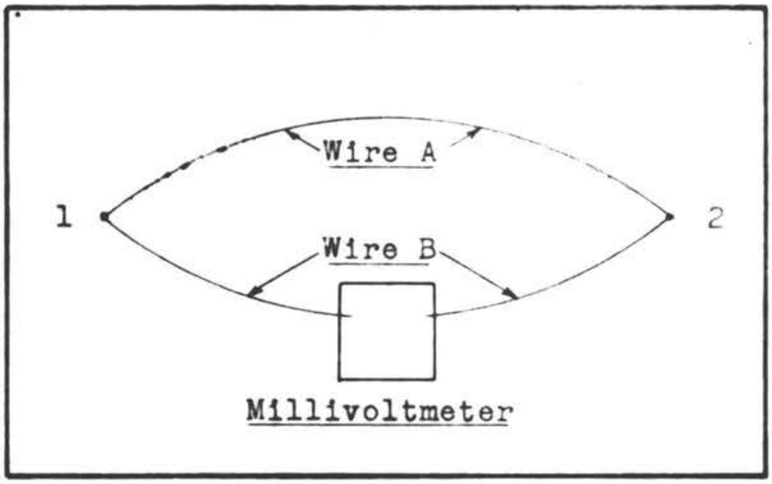


FIGURE 6 SIMPLE THERMOCOUPLE CIRCUIT

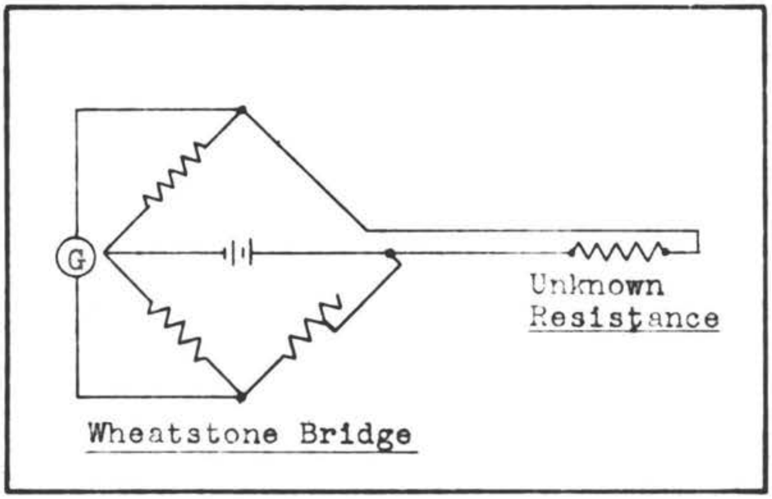


FIGURE 7 WHEATSTONE BRIDGE CIRCUIT

force indicated on the millivoltmeter will be the algebraic sum of the two electromotive forces generated at each junction and will be an indication of the actual temperature at Junction 2. The temperature at which Junction 1 is kept is usually 32 F and is maintained by immersing it in chipped ice and water. Junction 1 is usually called the "cold" junction, while Junction 2 is called the "hot" junction.

Curves and tables of millivolts versus temperature can be obtained from any of the reliable thermocouple manufacturers. A typical table is shown in Appendix B.

The most common combinations of materials used to produce good temperature versus electromotive force curves are given in Table I with their operating temperature range.

Table I

Combination of Materials for Thermocouple Use

Material	Temperature Range F
Copper-Constantan	32 - 650
Iron-Constantan	32 - 1400
Chromel-Alumel	32 - 2200
Platinum-Platinum Rhodium	1000 - 2650
Chromel-Constantan	32 - 1400

The ability of metals to change their electrical resistance with temperature as a means to measure temperature was first suggested by Siemens in 1871. The change in resistance of metals with temperature is due mostly to the activity of the molecules within the metal as the temperature varies.

In order to measure this temperature, it is usually necessary to use a wheatstone bridge circuit. With this circuit the resistance can be measured at any temperature. Then, by use of a temperature versus resistance curve, it is possible to obtain the true temperature. This type of instrument will give good results due to its inherent accuracy and sensitivity. A typical wheatstone bridge circuit is shown in Figure 7.

Metals that are usually used in making resistance thermoelements and their operating temperature ranges are listed in Table II.

Table II

Suitable Metals for Resistance Thermoelements

Metal	Temperature Range F
Pure Nickel	-328 - 482
Pure Platinum	-310 - 2000

One advantage that the resistance temperature-measuring circuit has over the thermocouple circuit is the elimination of a cold junction. This eliminates the chance for error in the measured temperature because of fluctuations in the cold-junction temperature.

With the exception of the error due to the cold junction, the errors obtained in measuring the temperature by a thermocouple are the same as those for a resistance thermoelement. The following discussion, therefore, will be applied only to the thermocouple. It must be understood, however, that the same discussion and mathematical formulas may be used with the resistance thermoelement.

Four major factors tend to produce a difference between the measured thermocouple temperature and the actual temperature of a gas stream. These four factors are:

1. Heat loss due to conduction along the thermocouple wires and well,
2. Heat loss due to radiation from the thermocouple junction to the cold walls,
3. Heat gain due to radiation from the gas to the thermocouple,
4. Heat gain due to a change in kinetic energy as the gas stream approaches the thermocouple.

In this discussion each factor will be discussed individually and then collectively.

Heat Loss Due to Conduction

Since the main purpose of the thermocouple is to measure the temperature of the gas stream accurately, it is necessary to determine whether or not the conduction loss can be made negligible. Jakob and Hawkins (8, p.203) have treated this subject very well. They have found that the error obtained in the temperature indicated by the thermocouple and that of the true temperature, neglecting radiation loss, may be found from the equation,

$$t_s - t_j = \frac{t_s - t_w}{\cosh L\sqrt{\frac{hC}{k'A}}} \qquad (4)$$

where t_s = Static temperature, F

t_j = Junction temperature, F

t_w = Wall temperature, F

L = Depth of immersion, ft

h = Heat transfer coefficient by convection, Btu/ft^2 hr F

C = Circumference of well material, ft

k' = Thermal conductivity of well material, Btu ft/ft^2 hr F

A = Cross-sectional area of well material, ft^2

when the thermocouple wires are small.

From Equation 4 it may be seen that there are five values that can be used to reduce the error caused by conduction. These factors are as follows:

1. Insulate the wall to bring $t_w = t_s$,
2. Make L as long as possible,
3. Reduce the cross-sectional area to a minimum,
4. Use a well material with a low thermal conductivity,
5. Make the heat transfer coefficient as large as possible by increasing the velocity of the gases.

In view of these five factors it was decided that the depth of immersion is the easiest to control. With this in mind, a family of curves was plotted by using Equation 4 with the depth of immersion as the abscissa and the ratio of the temperatures as the ordinate. This family of curves is shown in Figure 8.

From these curves it can be seen that the error in the thermocouple reading will be less than 1 per cent if the thermocouple is immersed into the gas stream at least 0.6 inches. It may be concluded, therefore, that if the thermocouple is immersed into the gas stream a distance of 0.6 inches or more, the error produced will be negligible, and the thermocouple will give the true temperature.

Heat Loss by Radiation

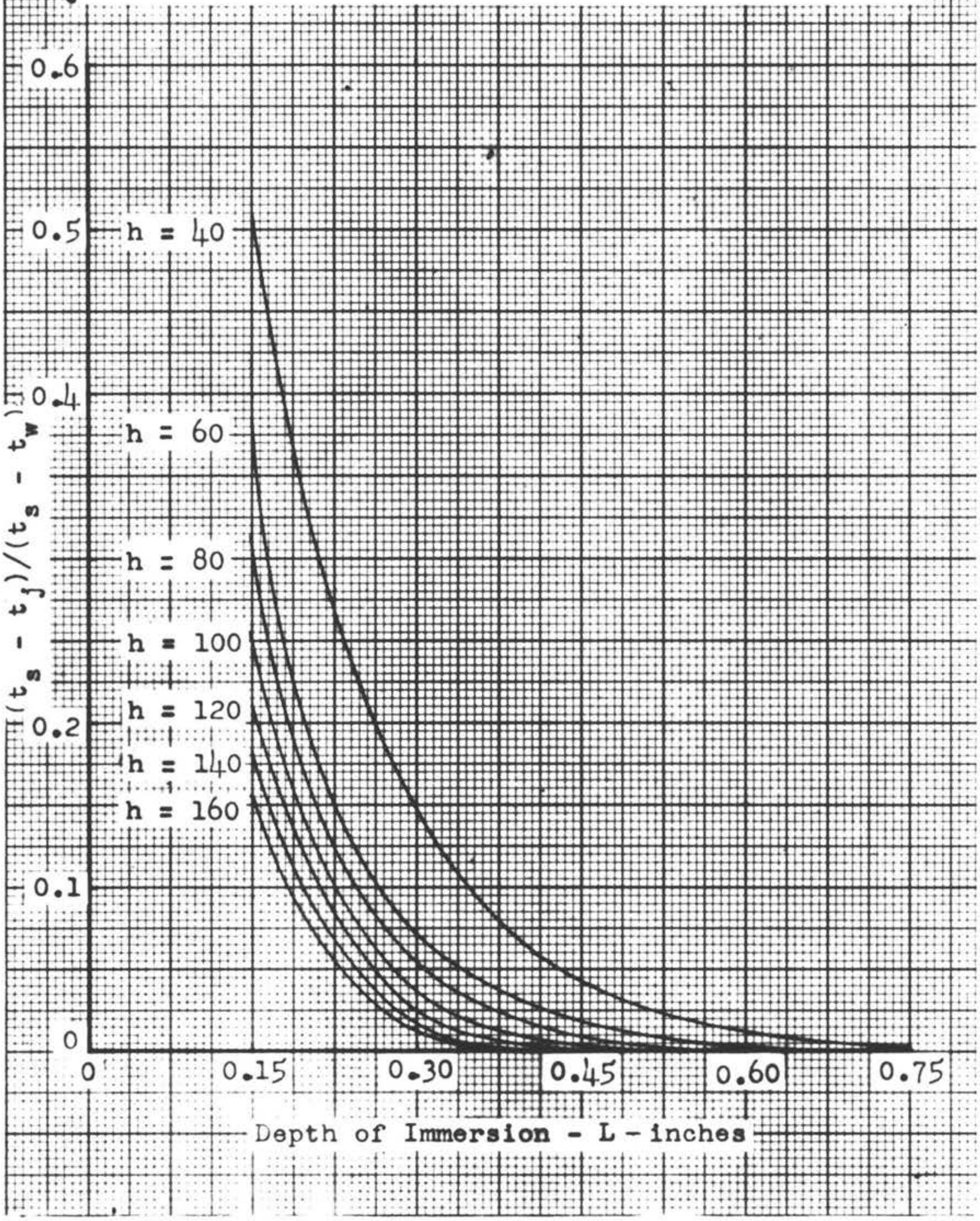
Theoretically, the heat loss due to radiation from a hot body to a cold body is proportional to the difference of the fourth powers of their respective absolute temperatures. If this heat loss is set equal to the heat gain by convection while assuming the conduction and velocity effects as being negligible, there results an equation from which the temperature of the gas can be calculated. This equation is as follows:

$$A_t h(t_s - t_j) = A_t \sigma \epsilon (T_j^4 - T_w^4) \qquad (5)$$

FIGURE 8

EFFECTS OF CONDUCTION ON THE TEMPERATURE MEASURED BY A THERMOCOUPLE

As Calculated from Equation 4b, Appendix A



where A_t = Area of the thermocouple, ft^2

h = Heat transfer coefficient by convection, Btu/ft^2 hr F

t_s = Static temperature, F

t_j = Junction temperature, F

σ = Stefan-Boltzmann's radiation constant, Btu/hr ft^2 R^4

ϵ = Emissivity of the junction, dimensionless

T_j = Junction temperature, R

T_w = Wall temperature, R

It is often quite difficult, however, to measure the effective wall temperature, and it is much more difficult to determine the actual emissivity of the junction (5, p.152). Therefore, the method most commonly used to correct for radiation is by some physical means. This may be accomplished either by shielding the thermocouple from the surrounding cold walls by coaxial shields or by increasing the wall temperature. Since it is often quite difficult to increase the wall temperature, many investigators have devised various forms of shielding for the thermocouple. These shields tend to reduce the ability of the thermocouple to follow fluctuating temperatures, however, and are quite difficult to install.

Another common method for reducing the radiation loss is to use junctions of low emissivity. As can be seen from Equation 5, the heat loss by radiation is directly proportional to the emissivity of the junction. If this emissivity is reduced, the heat loss will be decreased, and the junction temperature will approach the true gas temperature. A. I. Dahl and E. F. Fiock have developed a junction covered with silver in which the emissivity is reduced to 0.05 (4, p.154). This reduced the heat loss to 1/16 of that for a bare oxidized Chromel-Alumel junction. A comparison of Chromel-Alumel thermocouples with different radiation shields is given in Table III.

Table III

Effectiveness of Radiation Shields (5, p.155)
True Gas Temperature 1500 F Wall Temperature 1200 F

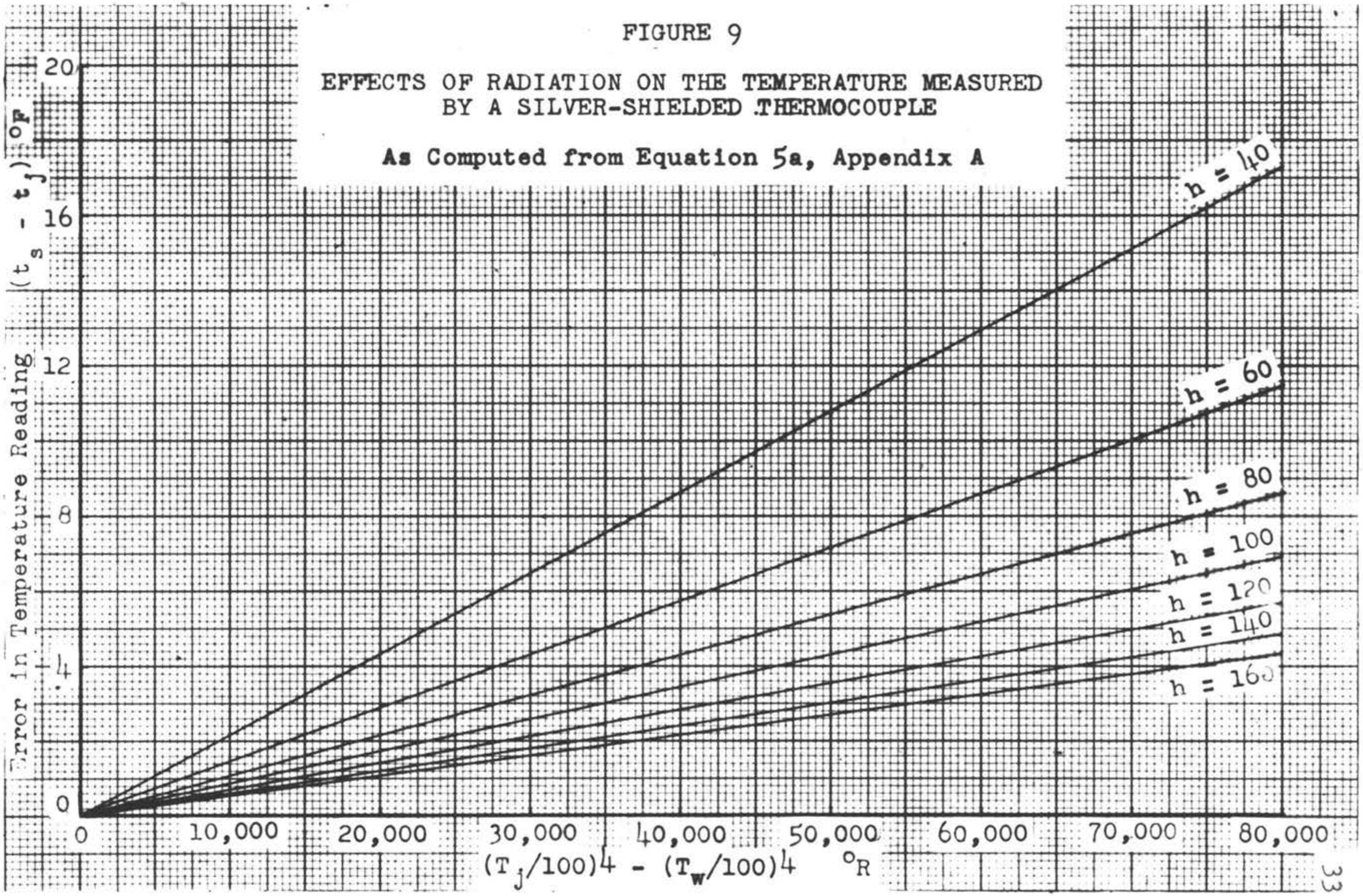
	Shields				
	None	1 Coaxial Tube	3 Coaxial Tubes	Pressed Silver	Pressed Platinum
Indicated Temperature, F	1432	1480	1490	1494	1478
Radiation Correction, F	68	20	10	6	22

From Table III and from the curves shown in Figure 9, it may be seen that the error in the indicated temperature is less than 1 per cent. Therefore, in most cases the indicated temperature may be assumed to be that of the true static gas temperature.

FIGURE 9

EFFECTS OF RADIATION ON THE TEMPERATURE MEASURED BY A SILVER-SHIELDED THERMOCOUPLE

As Computed from Equation 5a, Appendix A



Heat Gain by Radiation

The heat gain by the thermocouple due to radiation from the gas stream is of relatively small value. This is especially true in gas streams in which the air-fuel ratio is quite high. In this installation the air-fuel ratios are in the order of 60 to 85 pounds of air per pound of fuel. This gives a combustion gas composition, assuming complete combustion, as is shown in Table IV.

Table IV

Variation of Combustion Gas Composition

Combustion Gases	Range of Composition, % by Volume
Carbon Dioxide	3.5 - 2.5
Water Vapor	2.9 - 2.0
Oxygen	15.8 - 17.5
Nitrogen	77.8 - 78.0

It can be seen from Table IV that the amounts of nonradiating gases, oxygen and nitrogen, are many times that of the radiating gases, carbon dioxide and water vapor, (13, p.64); therefore, the emissivity of the total gas stream would be extremely small, and the heat gain by radiation from the gases can be assumed to be negligible.

If the thermocouples are placed in such a position that they can see the flame, then there may be a considerable heat gain due to radiation, since during combustion there are higher concentrations of radiating gases and lower concentrations of nonradiating gases.

Heat Gain Due to Kinetic Energy Change

If a thermocouple is immersed in a rapidly-moving gas stream, it will tend to slow up a portion of this gas stream. As a result of this change in velocity, the temperature of the thermocouple will increase. This increase is due to three effects; (1) the transfer of kinetic energy of the random molecular motion by collision, (2) the transfer of kinetic energy by direct impact, and (3) the transfer of heat generated by friction due to the flow of gases around the junction (5, p.157). If the thermocouple were able to absorb all of the kinetic energy, the temperature indicated by the thermocouple would be the total temperature. This may be expressed mathematically, assuming that the process is adiabatic in the following equation:

$$T_t = T_s + \frac{V^2}{2gJc_p} \tag{6}$$

where T_t = Total temperature, R

T_s = Static temperature, R

V = Velocity, ft/sec

g = Acceleration of gravity, ft/sec^2

J = Heat equivalent of work, Btu/ft lb

c_p = Specific heat at constant pressure, Btu/lb R

It is practically impossible, however, for the thermocouple to absorb all of the energy available. This is due to the fact that the process is not entirely adiabatic and that as the temperature of the thermocouple approaches the total temperature, it tends to lose heat to the gas. Therefore, the thermocouple will reach an equilibrium temperature somewhere between the total temperature and the static temperature. This point has been found to be approximately 85 per cent of the theoretical increase for a bare thermocouple. In other words, the junction temperature expressed mathematically is

$$T_j = T_s + 0.85 \frac{V^2}{2gJc_p} \tag{7}$$

where T_j = Junction temperature, R
T_s = Static temperature, R
V = Velocity, ft/sec
g = Acceleration of gravity, ft/sec^2
J = Heat equivalent of work, Btu/ft lb
c_p = Specific heat at constant pressure, Btu/lb R

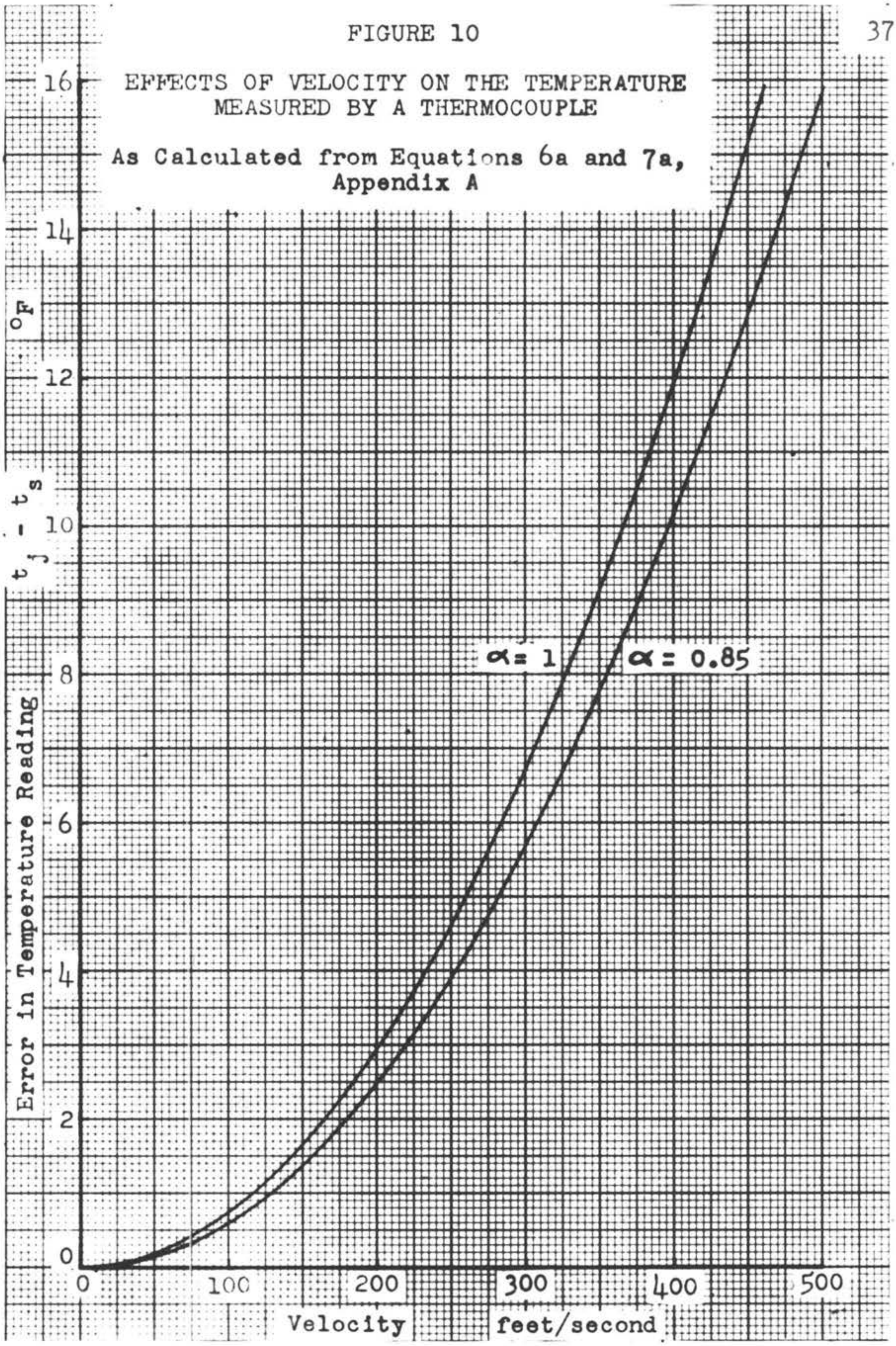
The factor, 0.85, is commonly referred to as the recovery factor, α, for the thermocouple.

A curve for velocity versus temperature difference is shown in Figure 10 for recovery factors of 1.00 and 0.85. It can be seen from this curve that for a recovery factor of 1.00 and a velocity of below 300 feet per second, the error

FIGURE 10

EFFECTS OF VELOCITY ON THE TEMPERATURE MEASURED BY A THERMOCOUPLE

As Calculated from Equations 6a and 7a, Appendix A



in the true static temperature is less than 1 per cent. Therefore, for this velocity and below, the measured temperature may be assumed to be that of the static temperature. Above this velocity the error increases rapidly for a small change in velocity.

In the above discussion each effect was considered separately. Now they will be considered together. If a heat balance is written for a thermocouple in equilibrium, it will be noticed that the heat transferred by convection from the gas stream to the thermocouple plus the heat transferred by radiation from the gas stream to the thermocouple plus the heat transferred by the change in kinetic energy of the gas stream must equal the heat lost by radiation from the thermocouple to the cold walls plus the heat lost by conduction along the thermocouple wires and well. If the heat loss due to conduction and the heat gain due to gas radiation are negligible, then the effect of the kinetic energy change tends to offset the effect of radiation on the thermocouple junction temperature. This is only true, however, for gas velocities below 400 feet per second and for a silver-shielded thermocouple with a recovery factor of 0.85 or less. The temperature indicated on the measuring instrument below this velocity may then be assumed to be essentially the true static temperature.

CONSTRUCTION AND PLACEMENT OF PYROMETERS AND EQUIPMENT

Silver-Shielded Thermocouple

Since the previous thermocouple installation allowed the thermocouples to "see" the flame, and since they were placed in the section of highest velocity, it was decided that it would be better to place the new thermocouples in an area of lower velocity and in a position where they could not "see" the flame. The three thermocouples at the turbine inlet, therefore, were placed 120 degrees apart around the turbine casing with the silver shield of the thermocouple about 1/2 inch upstream from the nozzle ring and directly opposite the nozzle inlets. The three thermocouples at the turbine exhaust were placed directly opposite the thermocouples at the turbine inlet and about 1-1/2 inches downstream from the turbine wheel blades.

The thermocouples were made of No. 20 Chromel-Alumel thermocouple lead wire. A section of the wire was cut off to the desired length, depending upon whether the thermocouple was to be used in the inlet casing or in the exhaust casing. The lengths required are 8 inches for the turbine inlet temperature and 5 inches for the turbine exhaust temperature.

The thermocouple bead was formed by twisting the two wires together for a distance of 1/2 inch. The twisted portion was then heated in a neutral acetylene flame until both wires glowed bright red. The wires were then dipped into bronzing flux until a good coating was formed. The flux-coated ends were immediately placed into the flame until the bead formed. After the wires cooled, the flux was broken off, and the wires and bead were cleaned with a wire brush.

The silver shield was made from a tube 1/8 inch in diameter and with a wall thickness of 0.020 inches. This silver tube was cut into 1/2-inch lengths. Each length was slipped over a thermocouple bead until the bead was halfway into the shield. The shield was then pressed tightly on the thermocouple wires and bead. The tighter the silver is pressed on the bead, the better the heat transfer is between them. After the shields were pressed on the beads, the ceramic insulators were slipped over the thermocouple wires.

The terminal strip and individual connectors were all made of fiberboard. The terminal strip contains enough terminals for twelve thermocouples and was used to join the Chromel-Alumel lead wires to the copper wires of the switch. Each connector contains two brass cylinders into which the thermocouple wires and the lead wires were placed. These wires were then clamped into place by set screws.

Since the thermocouples at the turbine inlet were to be placed in the turbine casing, it was necessary to construct a thermocouple support. These supports were made of 7/16-inch hexagonal head machine bolts (the heads of which were ground to fit the casing). These machine bolts were then drilled with a 7/32-inch drill to provide the necessary opening to facilitate the installation and removal of the thermocouple. Due to the curvature of the casing, it was necessary to grind a spacer to fit closely to the outside of the casing in order to prevent gas leakage around the supporting bolt. A hexagonal head machine nut was used to hold the assembly in place. A bushing drilled out to 0.15 inches for the ceramic insulator was used to hold the thermocouple in its support. An exploded view of the thermocouple and its support is shown in Figure 11, and a typical assembly drawing is shown in Figure 12.

The supports for the exhaust thermocouples were made of 1/4-inch brass machine screws. These screws were held in place by a 1/4-inch hexagonal head machine nut. A 0.152-inch hole was drilled longitudinally through the bolt for the ceramic insulators on the thermocouple.

Resistance Thermoelement

The resistance thermoelement was to be made by coiling the resistance wire in the form of a loop approximately 12 inches in diamter and passing it in front of the entire circumference of the nozzle ring. It was believed that by doing this the actual average temperature of the

FIGURE 11 EXPLODED VIEW OF THERMOCOUPLE AND ITS SUPPORT
1. Support bolt
2. Spacer
3. Connector and connector bracket
4. Spacer
5. Hexagonal head nut
6. Thermocouple bushing
7. Silver-shielded thermocouple

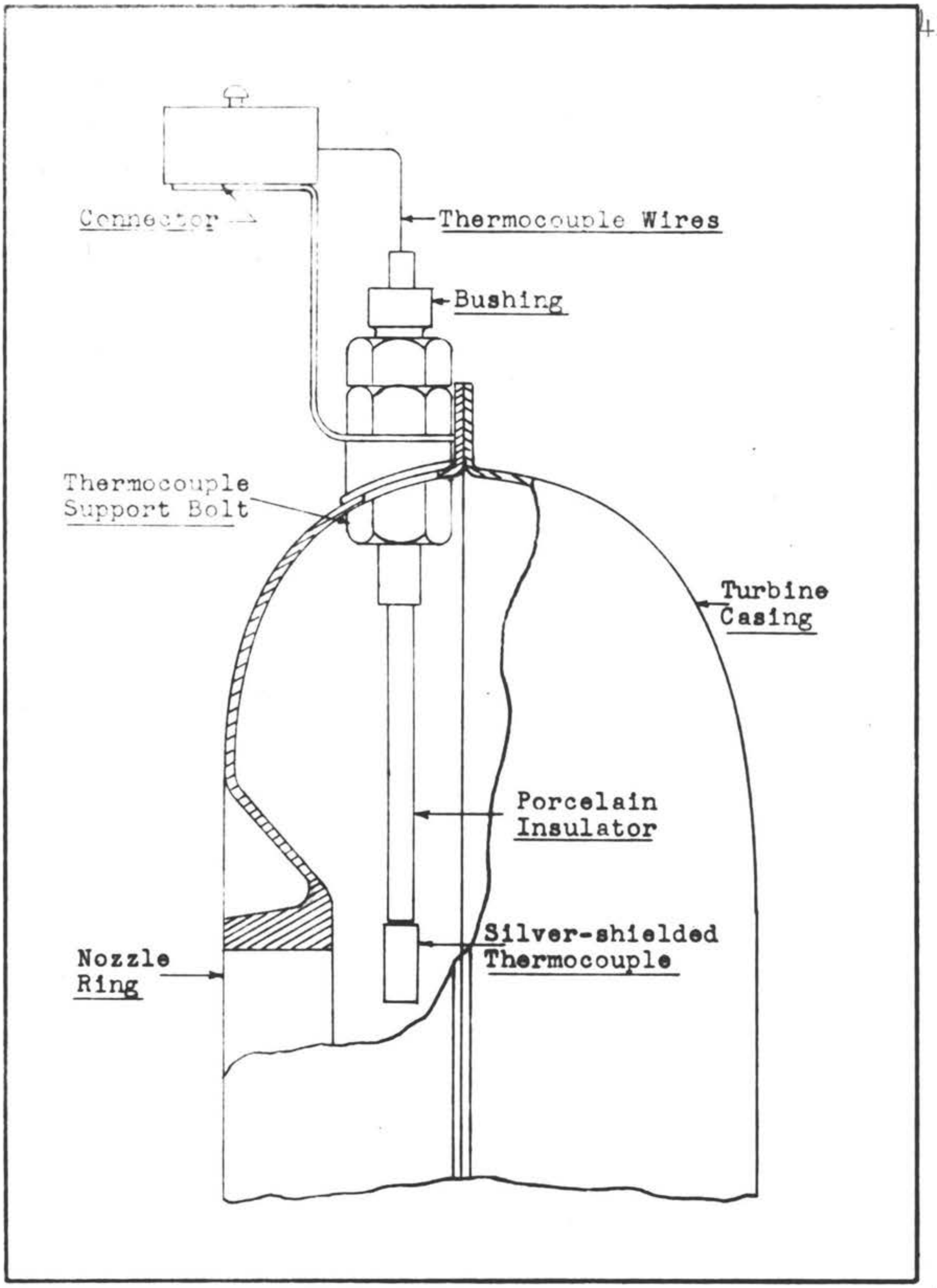


FIGURE 12 TYPICAL ASSEMBLY OF THERMOCOUPLE AND SUPPORT

gases passing through the nozzles could be obtained. This is due to the fact that the variation of the mass flow across the entrance to the nozzle section is at a minimum. In other words, the velocity of the gases entering the nozzle will not vary substantially from the bottom of the nozzle to the top of the nozzle. The materials from which these thermoelements were to be made were No. 20 Chromax wire and No. 22 Inconel wire. The coils were to be supported by insulators fastened to bolts extending down through the thermocouple supports. The exhaust thermoelement was to be constructed and supported in a similar manner.

The support for the thermoelement to be used in the preliminary tests to determine the suitability of the wire to temperature measurement was made from a heater element core similar to that used in the ordinary household electric heater. Three feet of wire was wrapped on this porcelain core, and two copper leads of No. 10 wire were fastened to each end of the thermoelement.

Pressure Probe Section

The pressure probe section was made of 1-inch steel plate with an 8 x 4-5/16-inch elliptical opening. A photograph of this section is shown in Figure 13. The pressure probes were made from No. 321 stainless steel tubing 1/8-inch in diameter with a wall thickness of 0.020 inches.

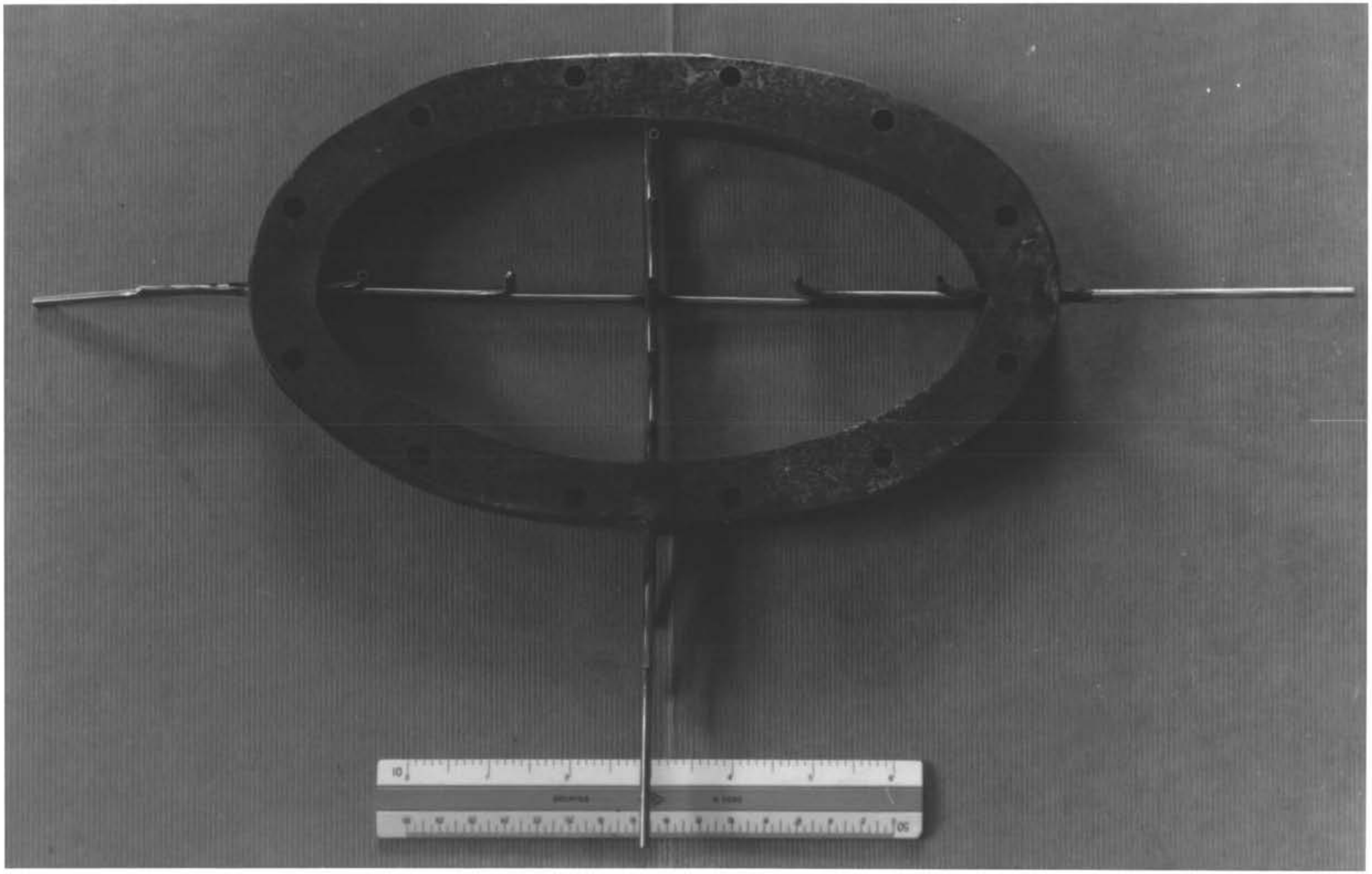


FIGURE 13 PRESSURE PROBE SECTION

There were three total and two static pressure probes across the horizontal and vertical dimensions. Each probe was located in the center of an area equal to one-third of the total area of the opening. The entire unit is located in the transition section between the combustion chamber and the turbine casing.

The purpose of this pressure probe section was to determine the velocity of the gases as they leave the combustion chamber. Since this section has the smallest cross-sectional area and the highest weight flow, the velocity at this point will be higher than at any point in the turbine casing. This is due to the fact that as soon as the gases enter the combustion chamber, a portion of the gas leaves the chamber through the nozzles. This gives a varying weight flow around the entire turbine casing. Therefore, if the velocity at the elliptical section is not appreciable, the velocity at any other point in the casing will be lower, and it will affect the temperature indicated by the thermocouple very little.

TESTS

Apparatus

The apparatus, other than the gas turbine, used in the thermocouple tests can be divided into two groups; (1) the equipment for temperature measurements and (2) the equipment for other measurements. The equipment contained in the first group is as follows:

1. The silver-shielded thermocouple
2. Cold-junction thermocouple
3. Twelve-point switch
4. Englehard millivoltmeter

The other equipment may be listed according to the values measured as follows:

1. Air flow - Ellison draft gage, capacity 6 in. water
2. Fuel rate - Toledo Scales and stop watch
3. Velocity pressure - Meriam water manometer, capacity 60 in. water
4. Static pressure - Meriam mercury manometer, capacity 14 in. mercury

The electrical circuit for the thermocouple is shown in Figure 14. This circuit contains the thermocouples, terminal strip, 12-point switch, and the millivoltmeter. It may be noticed from Figure 14 that the Chromel-Alumel lead wires run only as far as the terminal strip. From that point on, the wires are made of copper. At first glance it may seem that this would cause an error in the readings, but

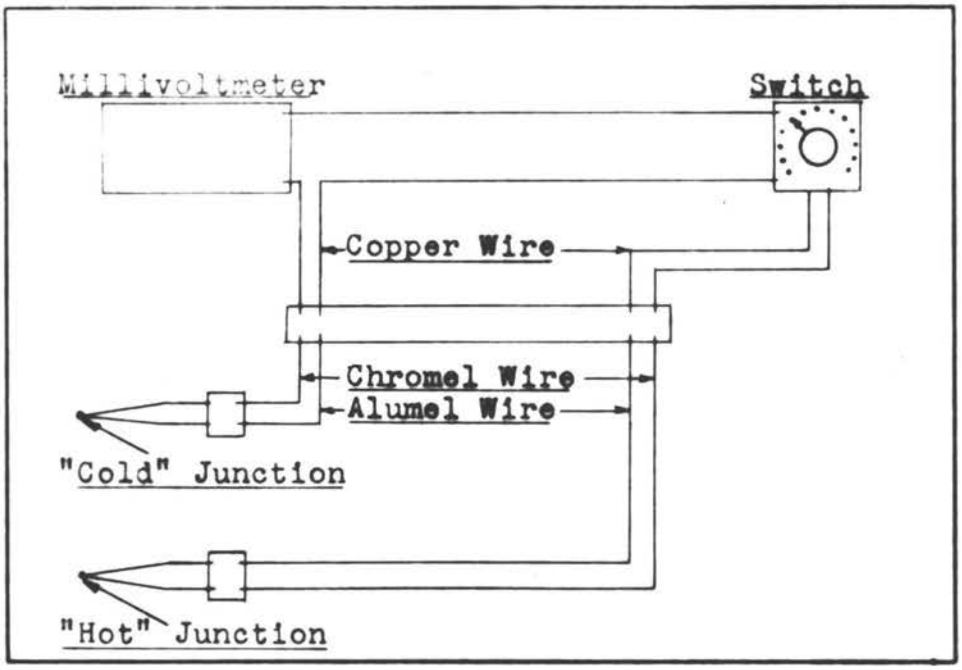


FIGURE 14 ELECTRICAL CIRCUIT FOR THERMOCOUPLES

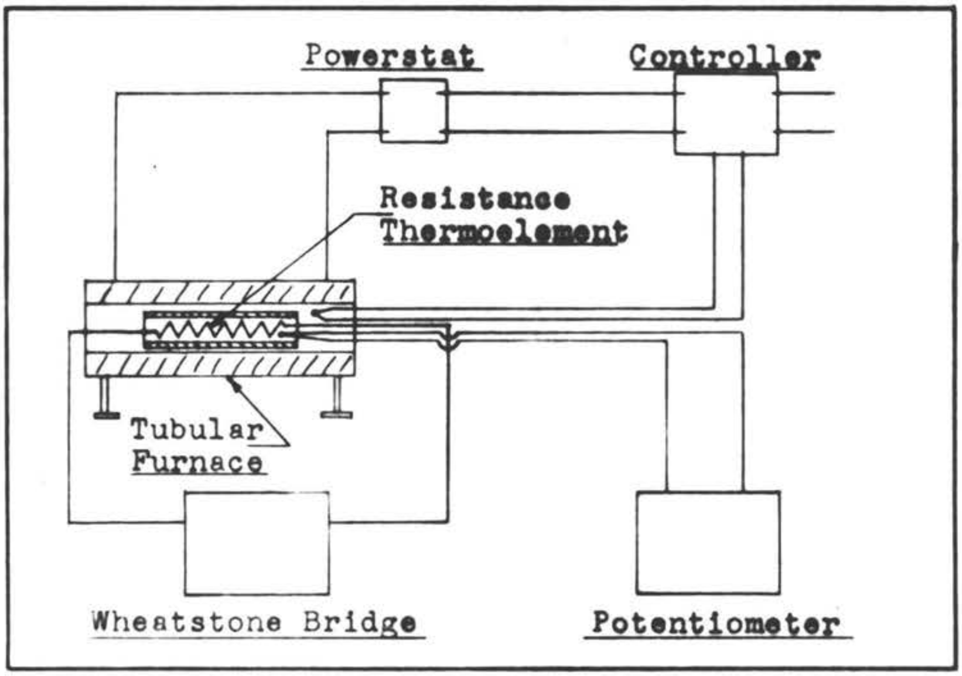


FIGURE 15 ELECTRICAL CIRCUIT FOR RESISTANCE THERMOELEMENT

if the cold-junction wires are connected to the copper wires at the terminal strip; then all copper-Chromel and copper-Alumel junctions will be at the same temperature, and no error will occur (6, p.85).

The apparatus for the tests on the resistance thermoelement can also be divided into two groups; (1) the equipment used in the preliminary tests and (2) the equipment which was to be used in the final tests. The equipment in Group 1 is listed as follows:

1. The resistance thermoelement
2. Leeds and Northrup wheatstone bridge
3. Marshall-Hall tubular furnace
4. Wheelco controller and its thermocouple
5. Comparison Chromel-Alumel thermocouple
6. Leeds and Northrup potentiometer

The electrical connections for this equipment are shown in Figure 15. The equipment contained in Group 2 is the same as the equipment used in the thermocouple tests except that in place of the temperature-measuring equipment, the following equipment was to be used:

1. Resistance thermoelement
2. Leeds and Northrup wheatstone bridge

Procedure

The procedure used in conducting the test on the thermocouples and the procedure which was to be used for the final test on the resistance thermoelement were similar. The original method of conducting the tests consisted of bringing the turbine up to a definite speed and jockeying the fuel control valve to maintain this speed. After the designated speed had been reached, a series of readings of all values were taken. The fuel rate was measured in seconds per half-pound and was measured twice during each run.

The values obtained from this test were quite erratic. Since it was necessary to constantly jockey the fuel control valve to maintain a definite speed, the conditions could never reach a static state. Consequently, it was decided to revise the procedure by adjusting the throttle once and letting the turbine reach its own speed. After this had been stabilized, a series of readings were taken as before. The results obtained by this method were more consistent, so this procedure for controlling the turbine speed was used throughout the test. A series of 8 to 10 readings, each at a different turbine speed, were taken during each test.

The procedure used in the thermocouple calibration was the standard calibration procedure. This procedure consists of immersing the thermocouple into a bath of molten pure metal and then recording the millivoltmeter readings as the metal cools. As the metal begins to solidify, its temperature will tend to remain constant. The temperature indicated by the thermocouple can be compared with the known true freezing temperature of the metal. These thermocouples were calibrated at three points, the freezing point of water, the freezing point of pure lead, and the freezing point of pure aluminum.

The procedure used to determine the suitability of Inconel wire and Nichrome wire for resistance thermoelements was quite simple.[1] The Wheelco temperature controller was set for the desired temperature, ranging from 0 F to 1850 F. When the controller indicated this desired temperature, a series of readings were taken for the resistance of the thermoelement and for the temperature of the comparison thermocouple. These readings were taken every 30 seconds until three readings of constant value were recorded. The controller temperature was then increased approximately 166 F. This temperature interval gave a total of thirteen test points.

[1] The Nichrome wire test was added at the last minute since the Chromax wire did not arrive in time to be tested.

RESULTS

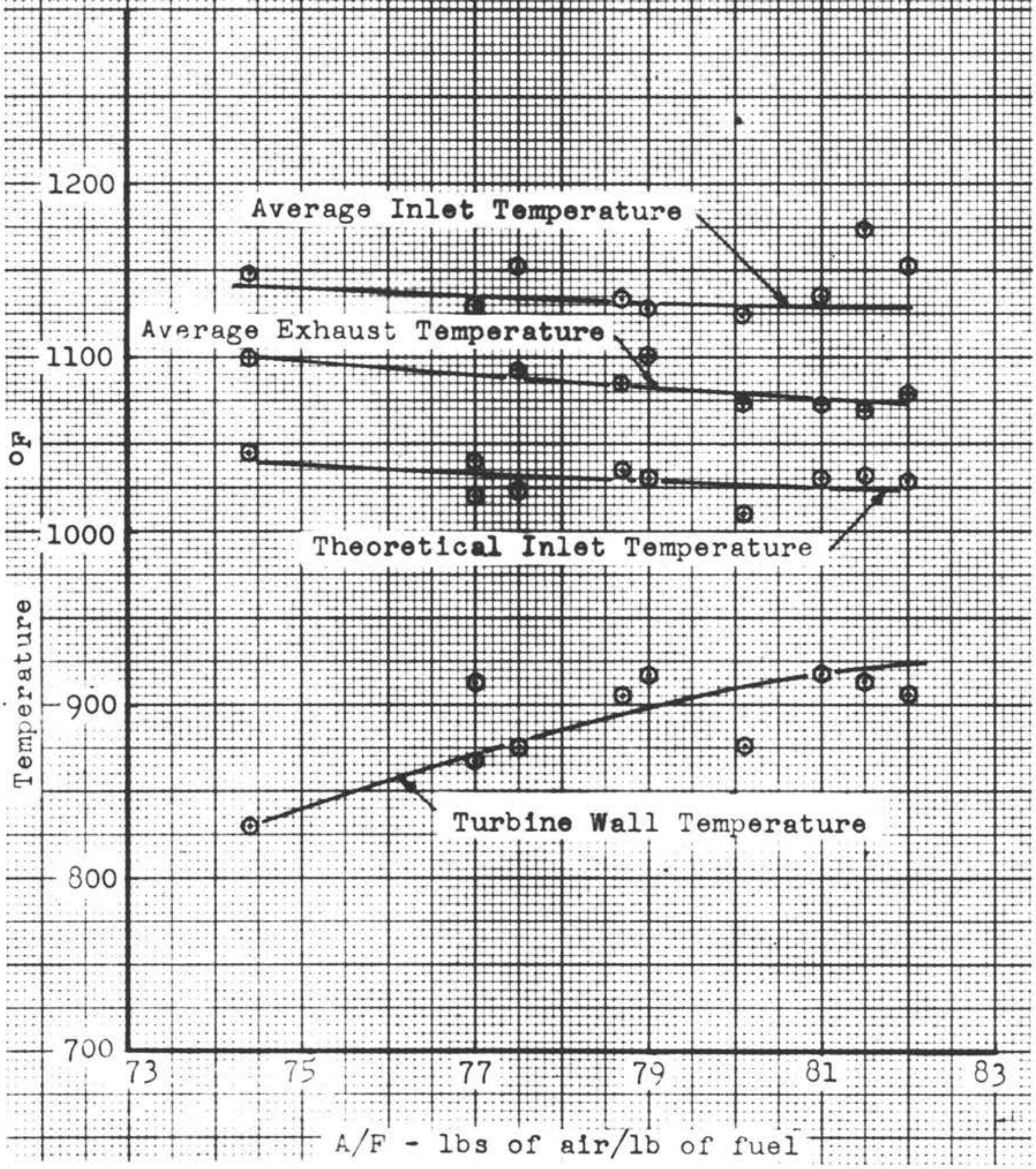
The results of the calibration tests on the silver-shielded and bare thermocouples are shown in Appendix B. A calibration curve was not drawn since the difference between the true temperature and the indicated temperature for both types was quite small--less than 1.5 per cent. Since this difference was so small, the indicated temperature was assumed to be the true temperature. It was also assumed that since the twelve thermocouples calibrated were not in error by more than 1.5 per cent, any other thermocouple made from the same sample of wire and in the same way would not have a greater error. The calibration data also indicates that the silver shield does not have a noticeable effect on the thermocouple reading since both types of thermocouples had the same range of inaccuracy.

It was quite difficult to obtain the calibration for the silver-shielded thermocouples at the freezing point of aluminum since the melting point of silver is only a few hundred degrees higher than that of aluminum. Consequently, extreme care had to be taken to prevent excessive superheating of the aluminum before the silver-shielded thermocouple was immersed in the bath of molten metal.

The results of the tests on the silver-shielded thermocouples are shown in Figure 16. A test using bare thermocouples instead of the silver-shielded thermocouples

FIGURE 16

TEMPERATURES AS MEASURED BY THE SILVER-SHIELDED THERMOCOUPLE



was made in order to draw a comparison between the two. The results from the bare thermocouple test are shown in Figure 17, with a comparison of the average turbine inlet temperatures as measured by these two methods appearing in Figure 18.

The turbine was stopped after four runs were completed in the test on the silver-shielded thermocouples, and each of the silver shields on the turbine inlet thermocouples were inspected for signs of deterioration. The shields on the two top thermocouples, Nos. 1 and 2, did not show any signs of having been subjected to high temperatures. The shield on Thermocouple 3, however, which is located at the bottom of the turbine casing, was burned off. Another silver-shielded thermocouple was substituted for it during the remainder of the test. The exhaust thermocouple shields were found to be without signs of deterioration.

The shields on all of the thermocouples were inspected again at the end of the test, and again the silver shield on Thermocouple 3 was burned off. This meant that at some time during the testing period, the gases were at a temperature greater than the melting point of silver, 1762 F. This period was probably during the first few minutes after the turbine had started and while the air-fuel ratio was still considerably below the normal operating range of 72 to 82 pounds of air per pound of fuel. It was

FIGURE 17

TEMPERATURE AS MEASURED BY THE BARE THERMOCOUPLES

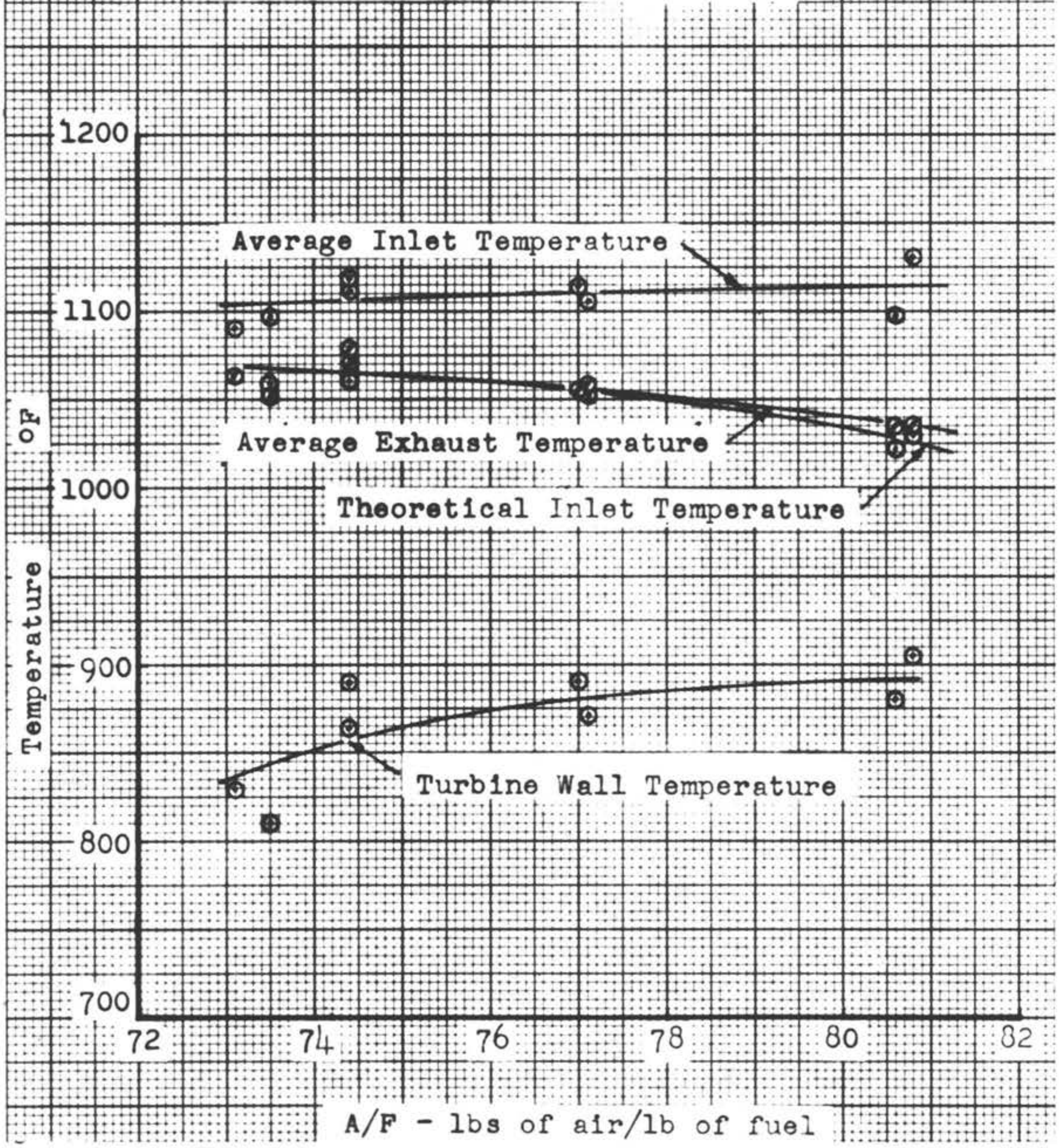
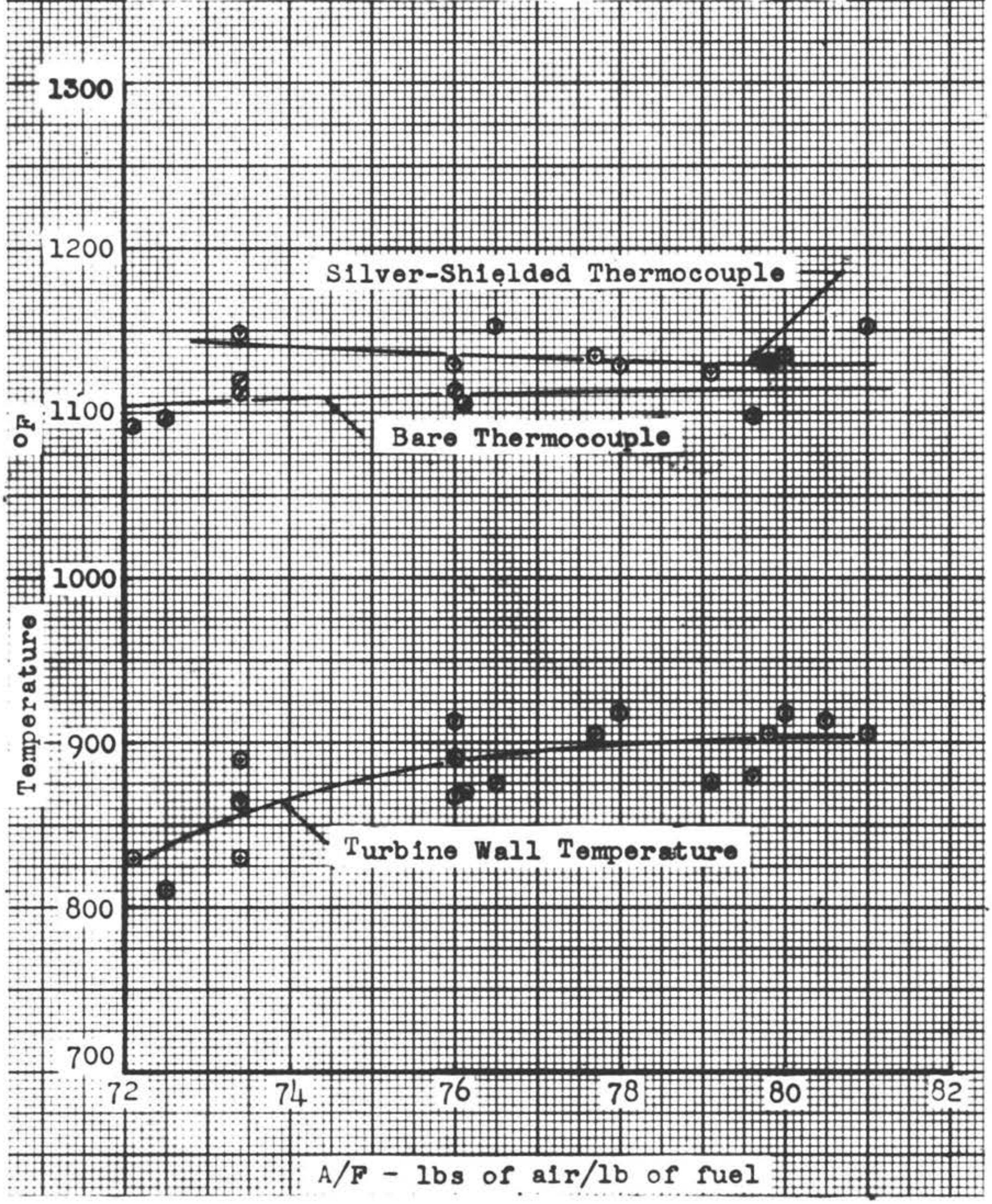


FIGURE 18

COMPARISON OF AVERAGE INLET TEMPERATURES AS MEASURED BY A SILVER-SHIELDED AND A BARE THERMOCOUPLE



apparently impossible to keep a silver shield on Thermocouple 3, so the indicated temperature was used in finding the average turbine inlet temperature used in Figure 16.

The temperature indicated by Thermocouple 3, whether it had a silver shield or not, was always several hundred degrees higher than the temperature indicated by Thermocouples 1 and 2 located in the upper portion of the turbine casing. Thus, the hottest gases pass through the bottom of the turbine casing rather than through the top. This is often illustrated by flame shooting through the turbine wheel blades during either the starting cycle or during rapid acceleration.

A check on the maximum velocity in the turbine was obtained at the elliptical section by computation, and it was found to be not greater than 390 feet per second. It was therefore deemed unnecessary to apply a velocity correction to the thermocouple readings since the velocity was still below 400 feet per second. The actual velocity of the gas around the thermocouples would be less than the velocity at the elliptical section due to the gases leaving the turbine casing through the nozzle ring.

It can be noticed in Figures 16 and 17 that the average turbine exhaust temperature is below that of the average turbine inlet temperature. Up until this time the measured turbine exhaust temperature had always been greater than the measured inlet temperature, a condition which theoretically and physically can not be.

Figures 16 and 17 also show that the average turbine inlet temperature is considerably higher than the theoretical inlet temperature. This might be due to some phenomenon occuring during the combustion of the fuel. It was quite evident during the tests that something was wrong with the combustion since large amounts of blue smoke issued from the exhaust ring. This smoke contained compounds which were irritating to the eyes causing tears to form. During complete combustion these irritating compounds are not noticeable in the exhaust gases.

Figure 18 shows a comparison of the average inlet turbine temperature measured by the silver-shielded and bare thermocouples. It can be noticed that as the wall temperature and air-fuel ratio increase, the difference between the temperatures indicated by the two thermocouples decreases. This is due to the decrease in the radiation loss by the bare thermocouple and an increase in the heat transfer coefficient by convection caused by an increase in velocity of the gases.

The results from the preliminary test on No. 20 Inconel wire are shown in Figure 19. A preliminary test on a sample of Nichrome wire taken from a heater element was also conducted, and the results are shown in Figure 20.

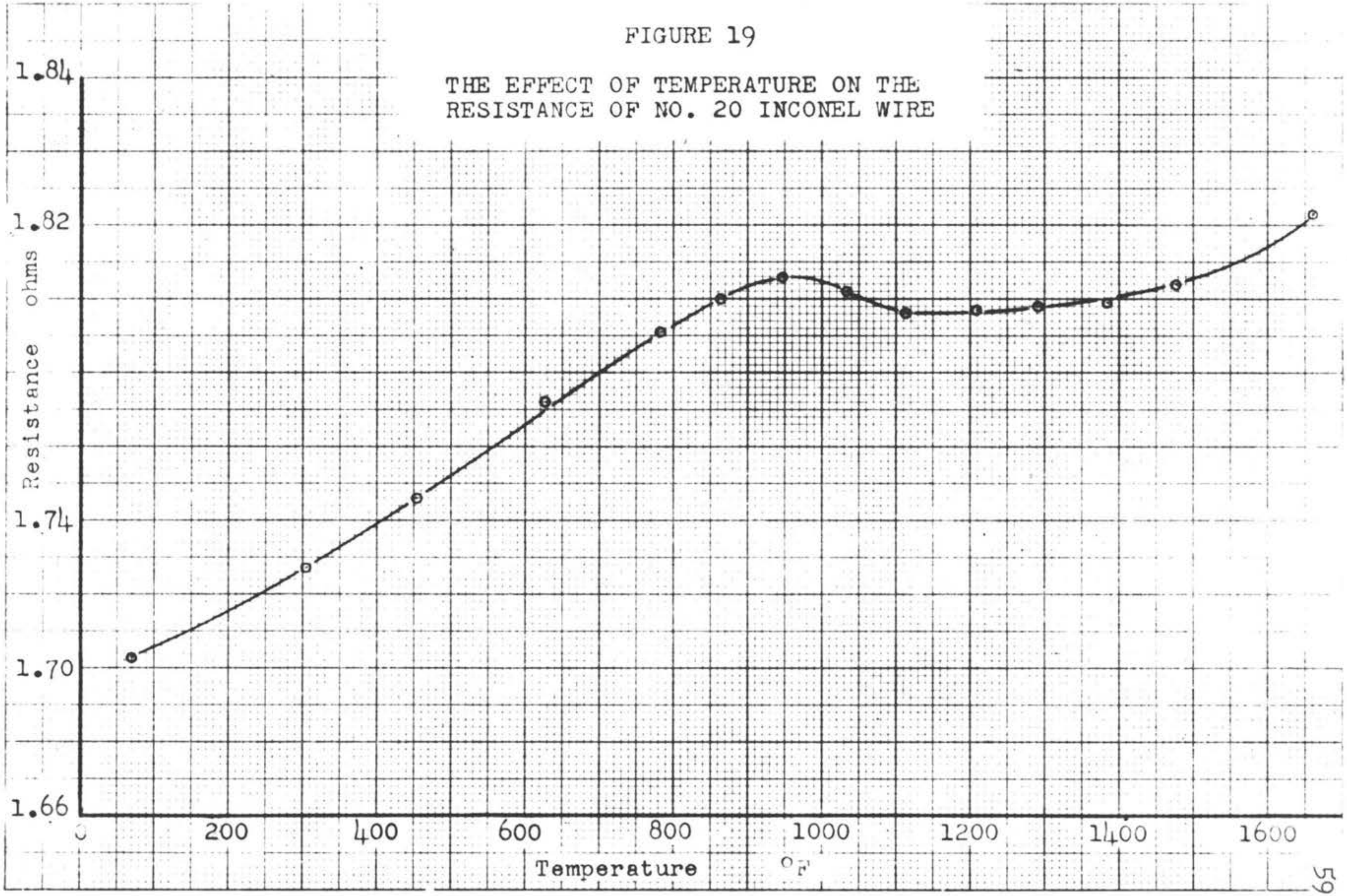


FIGURE 19

THE EFFECT OF TEMPERATURE ON THE RESISTANCE OF NO. 20 INCONEL WIRE

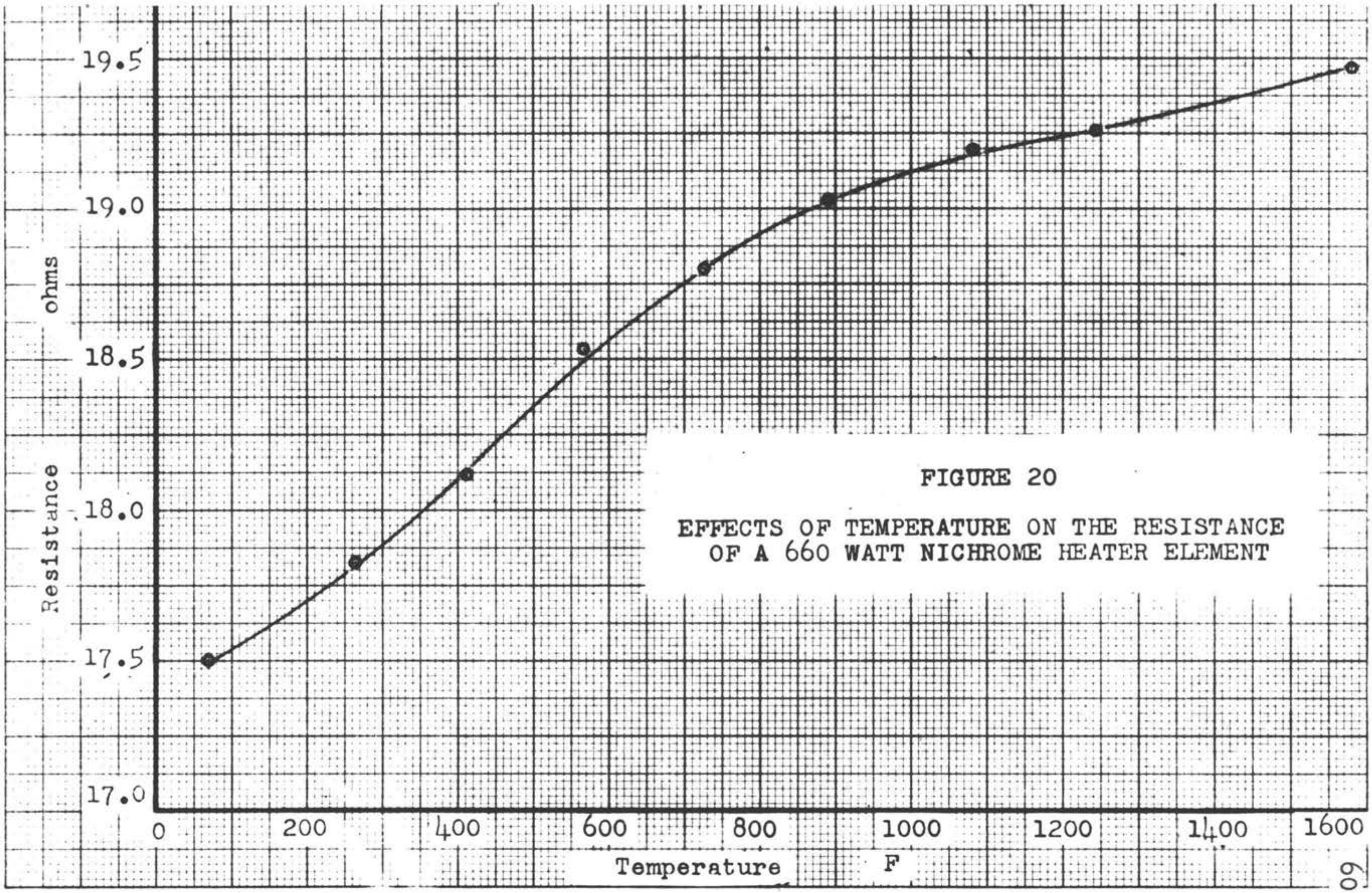


FIGURE 20

EFFECTS OF TEMPERATURE ON THE RESISTANCE OF A 660 WATT NICHROME HEATER ELEMENT

It can be seen in Figure 19 that there is a definite dip in the resistance versus temperature curve. At first it was believed that this dip was caused by the fact that the wire was slightly hardened by cold-working while it was being wrapped on the porcelain core. This hardening would tend to increase its resistance. As the annealing range for Inconel wire was approached, this hardening would be relieved with the result that the resistance decreased slightly. However, after annealing the wire, another test was made, and an identical curve was obtained.

Because of this dip it would make it extremely difficult to measure a temperature between 800 and 1600 F since for any given resistance between 1.795 and 1.806 there are several corresponding temperatures. This fact alone makes the use of Inconel wire unsuitable for a resistance thermoelement above temperatures of 800 F. Due to this characteristic the tests on Inconel wire were discontinued.

It can be seen from Figure 20 that the Nichrome wire's resistance versus temperature curve did not produce a dip in the curve as did the Inconel wire. However, the increase in the resistance with temperature of the wire above 1000 F becomes very small--in the order of 0.00045 ohms/ F. This low value of the thermal coefficient of resistance would then require a very sensitive instrument in order to measure the increase in resistance. In fact, it would be almost impossible to use a manually-balanced wheatstone bridge to measure the resistance of the element if the element were placed in a varying-temperature gas stream. An automatic balancing bridge could probably be used with some degree of accuracy, but since this type of instrument was not available, the use of a Nichrome wire from a heater element as a resistance thermoelement was discontinued.

CONCLUSIONS

From the results of the tests on the silver-shielded thermocouples, it may be concluded that this type of temperature-measuring device does have the qualities for measuring the temperatures of high-temperature gas streams if the gas stream temperature does not fluctuate above the melting point of silver. This is the main factor which would prevent its use in the Oregon State College gas turbine. The constant replacing of the silver shield on just one thermocouple would soon become not only expensive, but also time-consuming. Even if the expense were considered to be negligible, the fact that the shield burns off during the starting cycle and before any test runs can be made defeats the purpose of the shield, and a bare thermocouple might as well be used.

It was interesting to note that a temperature drop was measured across the turbine by both the silver-shielded thermocouples and the bare thermocouples. This was undoubtedly due to better placement of the thermocouples with the result that fewer temperature-measuring errors were involved.

The poor characteristics of resistance versus temperature for Inconel wire in the temperature range of 800 to 1600 F makes it prohibitive for use as a resistance thermoelement material within this temperature range. It might, however, prove to be a good material for measuring temperatures below 800 F.

The Nichrome wire from a heater element is unsuitable for this installation since it has a very low increase in resistance with temperature between 1000 and 1300 F. Between 1100 and 1300 F the thermal coefficient of resistance is 0.00045 ohms/ F. Consequently, any change in the resistance of the lead wires would give a sizable error in the measured resistance.

RECOMMENDATIONS FOR FUTURE INVESTIGATIONS

Since none of the pyrometers selected for testing were suitable for use in the gas turbine installation, the recommendations for future investigations of types of pyrometers to be tested are as follows:

1. Investigate the suitability of either the sonic pyrometer or one of the pneumatic pyrometers with a tube into which a sample of gas may be drawn from several points across the turbine casing. This tube should be of such size that the weight flow within the tube is a small percentage of the total weight flow.
2. Investigate the suitability of Chromax wire as a resistance thermoelement. It is believed that the resistance of the wire increases approximately 4 per cent between 1000 and 1400 F. This increase would be a small quantity, but it could be measured easily enough. This investigation might include whether it can be used in an oxidizing atmosphere, whether it can be accurately reproduced, and whether its resistance versus temperature properties change with use.
3. Investigate the possibilities of using Alumel wire as a resistance thermoelement. This wire is used mostly for thermocouples, but it does

have a high thermal coefficient of resistance and may prove to be a good material for resistance thermoelements.

4. Install three platinum resistance thermoelements in the present turbine inlet thermocouple installations. The cost of one platinum resistance element enclosed in an 18-8 stainless steel tube 6 inches long is approximately $36. It is realized that this is quite expensive, but it is believed that this instrument will give the best results since it has a very high thermal coefficient of resistance.

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APPENDICES

APPENDIX A

SAMPLE CALCULATIONS

The Effect of Conduction on the Temperature Measured by A Thermocouple

Equation 4 (p. 28) may be simplified by substituting

$$\pi D = C^{*}$$

and

$$\frac{\pi D^2}{4} = A$$

where D = Diameter of well material, ft

then Equation 4 is reduced to

$$t_s - t_j = \frac{t_s - t_w}{\cosh 2L\sqrt{\frac{h}{Dk'}}} \qquad (4a)$$

Dividing Equation 4a by $(t_s - t_w)$ will give the dimensionless equation,

$$\frac{t_s - t_j}{t_s - t_w} = \frac{1}{\cosh 2L\sqrt{\frac{h}{Dk'}}} \qquad (4b)$$

In this equation, D and k' are constants and are equal to 0.15 inches and 1.21 Btu in/ft^2 F hr (14, pp.146-147) respectively. The value of the heat transfer coefficient, h, may be found from the equation,

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* Nomenclature for the symbols used in the Appendices is the same as in the text.

$$h = 0.3\left(\frac{k'_g}{D}\right)\left(\frac{G_1 D}{\mu_g}\right)^{0.57}$$

where μ_g = Dynamic viscosity of the gas, lb/ft^2 hr and where k_g and μ_g (10, p.34) are taken as that of air at a temperature corresponding to $\frac{T_s + T_w}{2}$.

Assuming that

$$\frac{T_s + T_w}{2} = 1400 \quad R$$

and that

$$G_1 = 10{,}000 \text{ lb/ft}^2 \text{ hr}$$

the heat transfer coefficient is

$$h = (0.3)\left(\frac{0.0348}{0.0125}\right)\left(\frac{(10{,}000)(0.0125)}{0.871}\right)^{0.57}$$

$$= 52.5 \text{ Btu/ft}^2 \text{ hr} \quad F$$

Then assuming that the heat transfer coefficient, h, is equal to 100 Btu/hr ft^2 F and that the depth of immersion, L, is equal to 0.30 inches, the ratio of $\frac{t_s - t_j}{t_s - t_w}$ may be found from Equation 4b

$$\frac{t_s - t_j}{t_s - t_w} = \frac{1}{\cosh 2(0.025)\sqrt{\frac{100}{(0.0125)(1.21)}}}$$

$$= 0.0345$$

The Effect of Radiation on the Temperature Measured by A Silver-Shielded Thermocouple

Solving Equation 5 (p. 29) for $(t_s - t_j)$ the following equation is formed:

$$t_s - t_j = \frac{\sigma\epsilon\,(T_j^4 - T_w^4)}{h} \tag{5a}$$

In this equation σ is equal to 0.174×10^{-8} Btu/hr ft^2 R^4, and assuming that the silver shield has an effective emissivity of 0.05, then only the heat transfer coefficient, h, and the difference of the absolute temperatures will vary. Then assuming that h = 100 Btu/hr ft^2 F and

$$\left(\frac{T_j}{100}\right)^4 - \left(\frac{T_w}{100}\right)^4 = 50{,}000 \text{ R}$$

the error in the thermocouple reading as calculated from Equation 5a is

$$t_s - t_j = \frac{(0.174)(0.05)(50{,}000)}{100}$$

$$= 4.3 \text{ F}$$

The Effect of Velocity on the Temperature Measured by A Thermocouple

Solving Equations 6 and 7 (pp.35 and 36) for $(T_j - T_s)$ the following equations are formed:

$$T_j - T_s = \frac{V^2}{2gJc_p} \qquad (6a)$$

$$T_j - T_s = 0.85\,\frac{V^2}{2gJc_p} \qquad (7a)$$

Then assuming a mean value for $c_p = 0.267$ (10, p.34) the error in the thermocouple readings for a velocity of 300 feet per second for Equation 6a is

$$t_j - t_s{}^* = \frac{(300)^2}{2(32.2)(778)(0.267)}$$

$$= 6.73 \text{ F}$$

and for Equation 7a is

$$t_j - t_s = \frac{(0.85)(300)^2}{2(32.2)(778)(0.267)}$$

$$= 5.71 \text{ F}$$

---

* Since the difference between the absolute temperatures is equal to the difference between the temperature in F, $t_j - t_s$ can be substituted for $T_j - T_s$.

The Turbine's Theoretical Inlet Temperature

The heat balance for the combustion chamber based on one pound of fuel and assuming complete combustion and no heat loss is as follows:

> lower heating value of the fuel minus latent heat of vaporization plus heat content of the entering air equals heat content of the combustion gases.

The lower heating value of the fuel is found as follows:

HHV = Higher heating value,

$$\text{Btu/lb} = 323.5(\%H_2) + 15{,}410 \quad (7, \text{p.}135) \tag{8}$$

LHV = Lower heating value,

$$\text{Btu/lb} = \text{HHV} - \frac{\%H_2(9)(h_{fg})}{100} \tag{9}$$

where h_{fg} = heat of vaporization of water at 60 F.

The per cent by weight of hydrogen in the fuel may be found by the equation

$$\%H_2 = \left(\frac{24.5}{\text{sp. gr.}_{60/60}}\right) - \left(\frac{19.4}{(\text{sp. gr.}_{60/60})(K)}\right)^3 - 8.6 \tag{10}$$

where sp. $\text{gr.}_{60/60}$ = specific gravity at 60 F

K = characterization factor of the fuel oil (7, p.93)

Then from tests on the fuel oil the require values were found to be as follows:

gravity = 31.9 API at 60 F
specific gravity = 0.866 at 60 F
kinematic viscosity at 100 F = 3.5 centistokes
viscosity = 37.5 SSU at 100 F

Using these values the characterization factor, K, may be found from curves of characterization factor and viscosity at 100 F (7, p.91) for this fuel K = 11.5.

Then using Equation 10 the percentage of hydrogen is

$$\%H_2 = \left(\frac{24.5}{0.866}\right) - \left(\frac{19.4}{(0.866)(11.5)}\right)^3 - 8.6$$

$$= 12.27\%$$

Using this value for hydrogen in Equation 8 the higher heating value is

$$\text{HHV} = 323.5(12.27) + 15{,}410$$

$$= 19{,}370 \text{ Btu/lb}$$

and the lower heating value is

$$\text{LHV} = 19{,}370 - \frac{(12.27)(9)(1060)}{100}$$

$$= 18{,}200 \text{ Btu/lb}$$

The latent heat of vaporization may be found from the equation

$$L = \frac{1}{d}\left[110.9 - 0.09(t)\right] \tag{11}$$

where L = latent heat of vaporization Btu/lb

d = specific gravity 60/60

t = temperature F (9, p.210)

Assuming t = 60 F the latent heat of vaporization is

$$L = \frac{1}{0.866}\left[110.9 - 0.09(60)\right]$$

$$= 122 \text{ Btu/lb}$$

The heat content of the incoming air is

$$\text{Btu/lb} = c_p(f)(t_{cd} - 60) \tag{12}$$

where f = air-fuel ratio, lbs of air/lb of fuel

t_{cd} = compressor discharge temperature, F

Then assuming

$$f = 70 \text{ lbs of air/lb of fuel}$$

and $t_{cd} = 100$ F

$$\text{Btu/lb} = 0.24(70)(100 - 60)$$

$$= 671 \text{ Btu/lb}$$

The heat content of combustion gases is as follows:

Combustion gases assuming f = 70 lbs of air/lb of fuel

Combustion Gas	lb. moles/lb fuel
CO_2	0.073
H_2O	0.061
O_2	0.403
N_2	1.910

The heat content of combustion gas is

$$\sum \text{Btu/lb} = \sum \left[m(h_t - h_{60}) \right] \qquad (13)$$

where m = combustion gas, lb moles/lb fuel

h_t = enthalpy of gas at temperature t, Btu/lb mole

h_{60} = enthalpy of gas at 60 F, Btu/lb mole

Assuming t = 1100 F

$$\text{Btu/lb } (CO_2) = 0.073(15{,}325 - 3{,}880) = 835$$
$$\text{Btu/lb } (H_2O) = 0.061(13{,}115 - 4{,}122) = 548$$
$$\text{Btu/lb } (O_2) = 0.403(11{,}505 - 3{,}606) = 3{,}180$$
$$\text{Btu/lb } (N_2) = 1.910(11{,}104 - 3{,}611) = \underline{14{,}300}$$
$$\text{Total} \quad 18{,}863 \text{ Btu/lb}$$

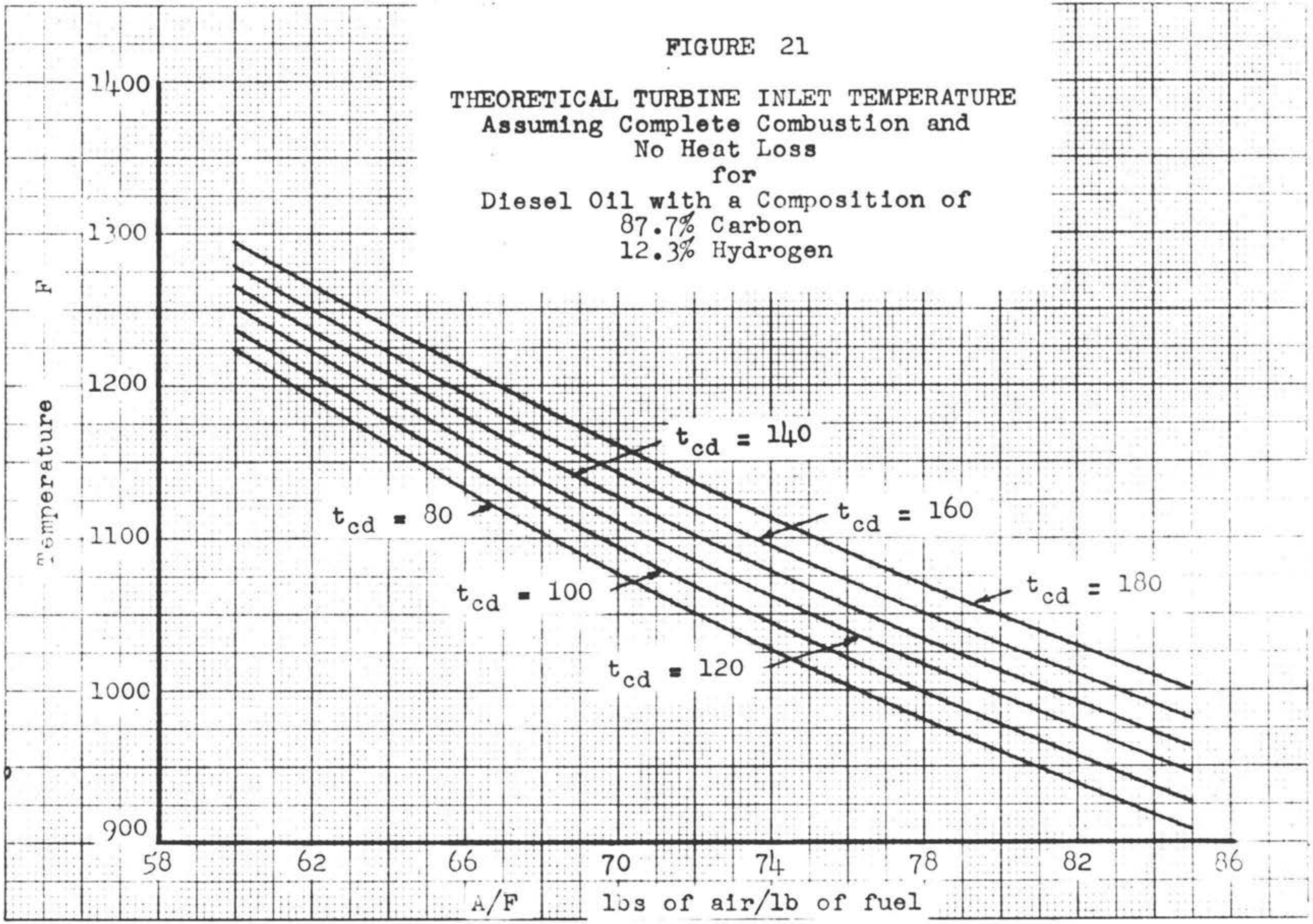
Using the value from Equation 13 with the values from Equations 9, 11, and 12, the heat balance is

$$18{,}200 - 122 + 671 = 18{,}863$$
$$18{,}749 \neq 18{,}863$$

Since this heat balance does not agree, a new temperature, t, in Equation 13 must be assumed and the calculations for heat content in the exhaust gases repeated. When the two values in the heat balance agree, temperature, t, is the turbine's theoretical inlet temperature. A family of curves for the theoretical temperature versus air-fuel ratio is shown in Figure 21.

FIGURE 21

THEORETICAL TURBINE INLET TEMPERATURE
Assuming Complete Combustion and
No Heat Loss
for
Diesel Oil with a Composition of
87.7% Carbon
12.3% Hydrogen



APPENDIX B

DATA FOR

SILVER-SHIELDED THERMOCOUPLES

rpm x 10^{-3}	8	9	10	10.8	11.8	12.0	12.4	13.6	14.2	14.5
Inlet t_1 - F	1065	1099	1086	1099	1070	1099	1082	1099	1099	1091
t_2 - F	998	1018	1010	1032	1002	1023	1015	1023	1040	1032
t_3 - F*	1380	1252	1363	1260	1302	1260	1312	1282	1337	1398
ave t - F	1148	1123	1153	1130	1125	1127	1135	1135	1159	1174
t_w - F	829	867	875	913	875	917	905	917	905	913
Exhaust t_4 - F	1078	1087	1083	1103	1057	1087	1065	1070	1065	1065
t_5 - F	884	888	875	897	863	888	875	875	875	863
t_6 - F	1338	1065**	1320	871**	1299	1329	1299	1277	1299	1277
ave t - F	1100	1013	1093	957	1073	1101	1084	1074	1079	1068
Theoretical t - F	1045	1020	1023	1041	1010	1035	1035	1030	1027	1032
T_{cd} - F	106	112	125	134	136	151	152	170	174	176
P_n - in H_2O	1.05	1.55	1.73	2.03	2.40	2.52	2.75	3.31	3.45	3.73
w_f - sec/lb	55.8	47.6	45.3	41.6	39.8	38.3	36.5	34.3	34.0	32.5
A/F - $\frac{\text{lb of air}}{\text{lb of fuel}}$	74.4	77.0	77.5	77.0	80.1	79.0	78.7	81.0	82.0	81.5
P_v - in H_2O	4.0	3.5	6.2	7.0	8.0	8.5	8.6	10.2	10.7	11.0

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* Silver shields burned off at start of run.

** Values are in error due to switch not being adjusted correctly.

DATA FOR

BARE THERMOCOUPLES

rpm x 10^{-3}	9	9.2	10.6	11.0	11.6	12.6	13.5	14.1
Inlet t_1 - F	1065	1065	1078	1099	1075	1087	1057	1090
t_2 - F	955	917	973	990	968	968	960	994
t_3 - F	1277	1295	1286	1269	1273	1286	1273	1312
ave t - F	1096	1092	1112	1119	1105	1114	1097	1132
t_w - F	810	829	863	890	870	890	870	905
Exhaust t_4 - F	1045	1048	1040	1080	1050	1050	1025	1000
t_5 - F	835	845	850	870	840	845	830	835
t_6 - F	1275	1295	1320	1285	1285	1270	1250	1270
ave t - F	1052	1063	1070	1078	1058	1055	1035	1035
Theoretical t - F	1058	1065	1060	1077	1052	1055	1021	1030
T_{cd} - F	107	108	122	142	149	150	154	164
ΔP_n - in H_2O	1.43	1.63	2.05	2.26	2.46	2.89	3.42	3.70
w_f - sec/lb	47.4	44.2	40.0	38.1	37.8	34.8	33.6	32.3
A/F - $\frac{\text{lb of air}}{\text{lb of fuel}}$	73.5	73.1	74.4	74.4	77.1	77.0	80.6	80.8
P_v - in H_2O	5.5	6.0	7.4	7.6	8.7	9.6	10.6	11.4

DATA FOR CALIBRATION OF CHROMEL-ALUMEL THERMOCOUPLES

LEAD BATH

Thermocouple No.	True Temperature F	Indicated Temperature F	% Error
(Bare)			
1	620	624	0.65
2	620	622	0.38
3	620	615	0.81
4	620	620	0.00
5	620	620	0.00
6	620	611	1.45
(Shielded)			
1	620	623	0.48
2	620	623	0.48
3	620	616	0.65
4	620	621	0.16
5	620	619	0.16
6	620	612	1.29

ALUMINUM BATH

Thermocouple No.	True Temperature F	Indicated Temperature F	% Error
(Bare)			
1	1217	1214	0.25
2	1217	1218	0.08
3	1217	1222	0.41
4	1217	1214	0.25
5	1217	1214	0.25
6	1217	1218	0.08
(Shielded)			
1	1217	1215	0.16
2	1217	1217	0.00
3	1217	1221	0.33
4	1217	1215	0.16
5	1217	1214	0.25
6	1217	1216	0.08

DATA FOR

THE EFFECT OF TEMPERATURE ON THE RESISTANCE OF NO. 20 INCONEL WIRE

Run	Resistance of Element ohms	Temperature	
		Mv	F
1	1.703		70
2a	1.727	6.19	
b	1.727	6.19	
c	1.727	6.19	
ave.	1.727	6.19	305
3a	1.746	9.52	
b	1.746	9.53	
c	1.746	9.52	
ave.	1.746	9.52	454
4a	1.772	13.54	
b	1.772	13.54	
c	1.772	13.54	
ave.	1.772	13.54	629
5a	1.791	17.18	
b	1.791	17.18	
c	1.790	17.09	
ave.	1.790	17.15	784
6a	1.800	19.13	
b	1.800	19.04	
c	1.800	19.04	
ave.	1.800	19.07	866
7a	1.806	21.04	
b	1.806	20.98	
c	1.806	20.98	
ave.	1.806	21.00	948
8a	1.804	23.09	
b	1.801	23.09	
c	1.801	23.07	
ave.	1.802	23.08	1034

Run	Resistance of Element ohms	Temperature	
		Mv	F
9a	1.796	24.98	
b	1.796	24.98	
c	1.796	24.98	
ave.	1.796	24.98	1115
10a	1.797	27.15	
b	1.797	27.20	
c	1.797	27.20	
ave.	1.797	27.18	1210
11a	1.798	29.11	
b	1.798	29.11	
c	1.797	29.11	
ave.	1.798	29.11	1291
12a	1.799	31.32	
b	1.799	31.32	
c	1.799	31.32	
ave.	1.799	31.32	1385
13a	1.804	33.44	
b	1.804	33.44	
c	1.804	33.44	
ave.	1.804	33.44	1479
14a	1.822	37.55	
b	1.823	37.55	
c	1.823	37.55	
ave.	1.823	37.55	1660

DATA FOR

PRELIMINARY TEST ON NICHROME HEATER ELEMENT

Run	Resistance of Element ohms	Temperature	
		Mv	F
1	17.50		70
2a	17.82	5.29	
b	17.82	5.29	
c	17.82	5.29	
ave.	17.82	5.29	265
3a	18.18	8.56	
b	18.18	8.56	
c	18.18	8.56	
ave.	18.18	8.56	411
4a	18.53	12.09	
b	18.53	12.09	
c	18.53	12.09	
ave.	18.53	12.09	567
5a	18.80	15.74	
b	18.80	15.74	
c	18.80	15.73	
ave.	18.80	15.74	724
6a	19.03	19.67	
b	19.04	19.67	
c	19.04	19.74	
ave.	19.04	19.69	892
7a	19.19	24.16	
b	19.19	24.16	
c	19.19	24.16	
ave.	19.19	24.16	1081
8a	19.26	28.08	
b	19.26	28.08	
c	19.26	28.05	
ave.	19.26	28.07	1246
9a	19.46	35.76	
b	19.47	35.70	
c	19.48	35.80	
ave.	19.47	35.75	1580

CHROMEL vs. ALUMEL THERMOCOUPLES

Degrees Fahrenheit **Reference Junction 32° F.**

Deg. F.	0°	100°	200°	300°	400°	500°	600°	700°	800°	900°	1000°	1100°	1200°	1300°
	Millivolts													
0°	-.68	1.52	3.82	6.09	8.31	10.56	12.85	15.18	17.52	19.88	22.25	24.62	26.98	29.33
5°	-.58	1.63	3.93	6.20	8.42	10.67	12.96	15.29	17.63	20.00	22.37	24.74	27.10	29.45
10°	-.47	1.74	4.05	6.31	8.53	10.79	13.08	15.41	17.75	20.12	22.49	24.85	27.21	29.56
15°	-.37	1.85	4.16	6.42	8.64	10.90	13.19	15.52	17.87	20.24	22.60	24.97	27.33	29.68
20°	-.26	1.97	4.28	6.53	8.76	11.02	13.31	15.64	17.99	20.36	22.72	25.09	27.45	29.79
25°	-.15	2.08	4.39	6.64	8.87	11.13	13.43	15.76	18.10	20.47	22.84	25.21	27.57	29.91
30°	-.04	2.20	4.51	6.75	8.98	11.25	13.55	15.88	18.22	20.59	22.96	25.33	27.68	30.02
35°	.07	2.31	4.62	6.86	9.09	11.36	13.67	16.00	18.34	20.71	23.08	25.45	27.80	30.14
40°	.18	2.43	4.74	6.98	9.20	11.47	13.[illegible]	16.11	18.46	20.83	23.20	25.57	27.92	30.26
45°	.29	2.54	4.85	7.09	9.31	11.58	13.89	16.23	18.58	20.95	23.32	25.69	28.04	30.38
50°	.40	2.66	4.97	7.20	9.43	11.70	14.01	16.35	18.70	21.07	23.43	25.80	28.15	30.49
55°	.51	2.77	5.08	7.31	9.55	11.81	14.12	16.47	18.81	21.18	23.55	25.92	28.27	30.61
60°	.62	2.89	5.19	7.42	9.66	11.93	14.24	16.58	18.93	21.30	23.67	26.04	28.39	30.72
65°	.73	3.00	5.30	7.53	9.77	12.04	14.36	16.70	19.05	21.42	23.79	26.16	28.51	30.84
70°	.84	3.12	5.42	7.64	9.88	12.16	14.48	16.82	19.17	21.54	23.91	26.27	28.62	30.[illegible]
75°	.95	3.24	5.53	7.75	9.99	12.27	14.60	16.93	19.29	21.66	24.02	26.39	28.74	31.08
80°	1.06	3.36	5.64	7.87	10.11	12.39	14.71	17.05	19.41	21.78	24.14	26.51	28.86	31.19
85°	1.17	3.48	5.75	7.98	10.22	12.50	14.83	17.17	19.52	21.89	24.26	26.63	28.98	31.31
90°	1.29	3.59	5.87	8.09	10.33	12.62	14.94	17.29	19.64	22.01	24.38	26.74	29.09	31.42
95°	1.40	3.70	5.98	8.20	10.44	12.73	15.06	17.40	19.76	22.13	24.50	26.86	29.21	31.54
100°	1.52	3.82	6.09	8.31	10.56	12.85	15.18	17.52	19.88	22.25	24.62	26.98	29.33	31.[illegible]
M. V. per °F.	.022	.023	.0227	.0222	.0225	.0229	.0233	.0234	.0236	.0237	.0237	.0236	.0235	.0232

Degrees Fahrenheit **Reference Junction 32° F.**

Deg. F.	1400°	1500°	1600°	1700°	1800°	1900°	2000°	2100°	2200°	2300°	2400°
	Millivolts										
0°	31.65	33.94	36.20	38.43	40.62	42.77	44.89	46.97	49.01	51.00	52.95
5°	31.77	34.06	36.31	38.54	40.73	42.88	45.00	47.08	49.11	51.10	53.05
10°	31.88	34.17	36.42	38.65	40.83	42.98	45.10	47.18	49.21	51.20	53.14
15°	32.00	34.29	36.54	38.76	40.94	43.09	45.20	47.28	49.31	51.30	53.24
20°	32.11	34.40	36.65	38.87	41.05	43.20	45.31	47.38	49.41	51.39	53.33
25°	32.23	34.51	36.76	38.98	41.16	43.31	45.41	47.49	49.51	51.49	53.43
30°	32.34	34.62	36.87	39.09	41.27	43.41	45.52	47.59	49.61	51.59	53.52
35°	32.46	34.74	36.99	39.20	41.38	43.52	45.62	47.69	49.71	51.69	53.62
40°	32.57	34.85	37.10	39.31	41.48	43.62	45.73	47.79	49.81	51.78	53.71
45°	32.69	34.97	37.21	39.42	41.59	43.73	45.83	47.89	49.91	51.88	53.81
50°	32.80	35.08	37.32	39.53	41.70	43.83	45.93	47.99	50.01	51.98	53.90
55°	32.92	35.19	37.43	39.64	41.81	43.94	46.04	48.10	50.11	52.08	54.00
60°	33.03	35.30	37.54	39.75	41.91	44.04	46.14	48.20	50.21	52.17	54.09
65°	33.15	35.42	37.65	39.86	42.02	44.15	46.25	48.30	50.31	52.27	54.19
70°	33.26	35.53	37.76	39.96	42.13	44.26	46.35	48.40	50.41	52.37	54.28
75°	33.38	35.64	37.88	40.07	42.24	44.37	46.46	48.51	50.51	52.47	54.38
80°	33.49	35.75	37.99	40.18	42.34	44.47	46.56	48.61	50.61	52.56	54.47
85°	33.60	35.87	38.10	40.29	42.45	44.58	46.66	48.71	50.71	52.66	54.57
90°	33.71	35.98	38.21	40.40	42.56	44.68	46.76	48.81	50.80	52.75	54.66
95°	33.83	36.09	38.32	40.51	42.67	44.79	46.87	48.91	50.90	52.85	54.76
100°	33.94	36.20	38.43	40.62	42.77	44.89	46.97	49.01	51.00	52.95	54.85
M. V. per °F.	.0229	.0226	.0223	.0219	.0215	.0212	.0208	.0204	.0199	.0195	.0190