SAE The Engineering Society For Advancing Mobility Land Sea Air and Space® INTERNATIONAL

400 Commonwealth Drive, Warrendale, PA 15096-0001

AEROSPACE INFORMATION REPORT

Submitted for recognition as an American National Standard

SAE AIR46 REV. A

Issued 1956-03-15
Revised 1990-01-25

THE PREPARATION AND USE OF CHROMEL-ALUMEL THERMOCOUPLES FOR AIRCRAFT GAS TURBINE ENGINES

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

FOREWORD:

This document, originally prepared in 1956, was reviewed by industry and committee members between 1983 and 1988. Those who reviewed it generally agreed that the document, with minor changes, would continue to be a useful industry reference. Changes were limited to updating the list of references as well as to exhibit temperatures in both °F and °C.

1. INTRODUCTION:

This report reviews the precautions which must be taken and the corrections which must be evaluated and applied if the experimental error in measuring the temperature of a hot gas stream with a thermocouple is to be kept to a practicable minimum. Such information is assembled here to assist those concerned with measuring gas temperatures in turbines and those who wish to utilize gas temperature for actuating engine controls. In these applications, the problem of temperature measurement may be considered to consist of two distinct parts; namely, a determination of the actual temperature of the measuring junction and a reliable estimation of the difference in temperature beween this junction and the gas. The former requires that numerous precautions be observed in the construction, installation, and use of the thermocouple; the latter requires proper application of appropriate corrections for such effects as impact and heat exchange by conduction, convection, and radiation.

Discussions will focus on Type K thermocouples. These are defined in NBS Monograph 125 as Nickel-Chromium Alloy vs. Nickel-Aluminum Alloy thermocouples.

2. PROCURING AND CALIBRATING TYPE K (CHROMEL ALUMEL) THERMOELEMENTS:

2.1 Specification of Thermocouple Wire: A reasonable thermoelectric specification for Type K thermocouple wire to be used in making engine thermocouples is as follows: The temperature-emf relation for thermocouples made from the wire shall conform to that given in Tables 7.3.2 and A7.1.1 of National Bureau of Standards Monograph 125.

2.2 Methods of Making Thermocouple Junctions: The methods for forming the measuring junction are as follows: autogenous welding; joining the thermoelements by means of a third material such as solder, brazing spelter or welding rod; and the use of a third element through which the thermocouple circuit is completed, as when the thermoelements are individually peened or welded to a solid conductor or dipped into a molten one.

The most widely used method is autogenous welding, in which the thermoelements are fused together by a torch or by electrical means without using any other metal to form the joint. The noble metals may be welded with a torch in the absence of flux. For base metals, it is advantageous to use a flux to minimize oxidation. Care should always be exercised to limit the heating to the very ends of the thermoelements and to avoid heating them too long or too hot. Oxy-acetylene, oxy-gas or air-gas flames with small, sharply defined inner cones are suitable for making thermocouple junctions. Borax is often used as a flux, and after the weld has been made, all traces of flux should be removed. Immersion in boiling water for several minutes is effective for most fluxes.

2.2 (Continued):

Three methods of electric welding are in common use. An arc between two carbon electrodes may be used to fuse the ends of the thermoelements together, or the thermoelements may be used as one of the electrodes with a carbon rod as the second. Still another method utilizes mercury covered with oil as one electrode and the thermoelements as the other, so that the latter are arc welded together when brought into contact with the mercury. In all electrical methods, current and voltage must be adjusted to meet the specific needs. Resistance welding is well adapted to making butt-welded junctions. The ends of the thermoelements are held in firm contact and a surge of current is passed to effect fusion.

In measuring the surface temperature of a piece of metal, it is often advantageous to attach the thermoelements separately to the metal. This may be done by spot welding or peening the wires to the metal whose temperature is to be measured. To avoid errors, the points of attachment should be close enough together that there is no significant difference in temperature between them.

Twisting the thermoelements at the measuring junction is not recommended, despite the fact that such a junction may have greater mechanical strength than its untwisted counterpart. Twisting leaves the exact location of the first electrical contact between the thermoelements in doubt; it leaves strains in the wires which are particularly difficult if not impossible to remove from the Alumel; and a twisted junction responds less rapidly than its untwisted counterpart to sudden changes in temperature.

2.3 Calibration of Thermocouple Wire: All calibrations must be related directly or indirectly to the International Practical Temperature Scale (see 11.6). In general, the fixed points defined therein are used only for primary calibrations and the devices so calibrated are then used for calibrating others for practical application. More specifically, type K thermocouples are normally calibrated by direct comparison with a standard platinum-platinum rhodium couple. As a result of experience and common practice over the years, reference values of emf as a function of temperature have come into general usage. National Bureau of Standards Monograph 125 Reference Tables for Thermocouples contain identical reference tables for several combinations of thermoelements, shown in Table 1.

2.3 (Continued):

Table 1 - Thermocouple Materials

Type	
B	Platinum - 30% rhodium vs. platinum - 6% rhodium
E	Nickel-chromium alloy vs. copper-nickel alloy
J	Iron versus a copper-nickel alloy
K	Nickel-chromium alloy vs. nickel-aluminum alloy
R	Platinum - 13% rhodium vs. platinum
S	Platinum - 10% rhodium vs. platinum
T	Copper vs. copper-nickel alloy

For any given combination of thermoelements, the reference table serves as the goal toward which performance is directed, and from which unavoidable differences are determined and applied as corrections. Manufacturers and vendors of type K thermoelements need to know the thermoelectric characteristics of each alloy individually, in order that batches of wire may be matched to perform as nearly in accordance with the reference table as the purchaser may specify. This sort of calibration is usually done by determining the emf of individual samples against pure platinum. One alloy being positive and the other negative to Pt, the sum of emfs against Pt is identical with the emf of the type K couple.

Those who use type K in making complete thermocouples, and those who use the finished thermocouples are interested only in the emf of the particular samples of type K employed. In other words, the calibration which the users need is not of the individual thermoelements against Pt, but rather of the type K directly.

A calibration of the latter type is made at NBS by welding the junction of a standard Pt-PtRh couple to that of the Chromel-Alumel couple being tested; by placing this common junction near the center of a Chromel tube furnace which is heated by passing current through the furnace tube itself; and by taking simultaneous readings of the emfs of the two couples over the range of temperature which is of interest. Both are long enough that their reference junctions may be kept at the ice point. Immersion is sufficient to insure against loss of heat by conduction from the junction. By using the comparison method, problems of heat transfer to and from the junction by radiation and convection do not arise.

2.3 (Continued):

It is normally convenient to express and use the results of such a calibration in the form of a table or chart of differences from the reference curve. While samples of the thermoelements currently used in the manufacture of gas turbine thermocouples are calibrated in this or similar fashion originally, and are spot checked at one or more stages in the manufacture of the couples, deviations of the actual production thermocouples from the standard curve are not measured and hence no corrections can be applied for such differences as may exist from the reference curve for Chromel-Alumel. Assuming that the calibration of the type K thermocouple is no farther from the reference curve than the thermoelements were originally, then the maximum errors that can arise from not applying corrections are therefore given by the tolerances in the specifications under which the thermoelements were purchased originally; namely ±2.2°C (±4°F) up to 277°C (530°F) and ±0.42% (±3/4%) of the temperature in °C (°F) above 277°C (530°F).

The calibration of thermocouple wire by direct comparison with a standard Pt-PtRh thermocouple in a tube furnace, other methods for calibrating thermocouples and testing thermocouple materials, and the precautions which must be observed in order to attain various degrees of accuracy are given in detail in a paper by Roeser and Wensel (1). Such calibrations are conducted at the National Bureau of Standards for the public on a fee basis.

3. CIRCUITRY FOR HIGHEST ACCURACY:

3.1 Lead Wires and Terminals: Where highest accuracy is sought, it is preferable that the thermoelements extend without a break from the measuring junction to a reference junction. If this is impracticable, all parts of the thermocouple and lead circuit which contain alloys that differ in thermoelectric properties from the thermoelements proper should be kept at a uniform temperature. This is not possible in thermocouples which have a terminal lead in direct thermal contact with a hot part of an engine. The only alternative here is to match all parts of the thermocouple circuit in thermoelectric characteristics, inasmuch as large temperature gradients are bound to exist through the head. Joints should be made only by autogenous welding, never by use of any brazing or welding spelter.

3.2 The Reference or Cold Junction: A bath at 0°C (32°F) consisting of an intimate mixture of shaved ice and water provides the most convenient and easily reproducible bath for the reference junction. Keeping the reference junction at the ice point is recommended practice for all accurate thermoelectric thermometry, and most standard tables apply directly when the reference junction is at this temperature. As applied to the problem of engine thermocouples, an ice bath should be used in making all calibrations, in determinations of recovery factor, or when reproducibility better than ±1.1°C (±2°F) is required in the temperature of the reference junction.

NOTE: Throughout this document, numbers in parentheses refer to the Bibliography, Section 12.

3.2 (Continued):

A convenient form of ice bath is illustrated in Fig. 1. A large-mouth Dewar (preferably one quart capacity) is first filled with shaved or finely cracked ice, and enough water is added to fill all of the spaces between the pieces of ice, but not enough to float the ice. Any potable water and ice are sufficiently pure for this purpose. When first prepared, there should be ice down to the bottom of the Dewar.

For each junction to be kept at the ice point, a small glass tube, closed at the bottom and flared at the top, is inserted through a hole in the cork for the Dewar. Enough mercury is placed within each tube to fill it for about 2 cm (0.75 in). The cork and tubes are inserted so that the mercury is several cm (inches) below the top surface of the slush.

The actual reference junctions are made by inserting a thermoelement and a copper wire, each polished with a file or sandpaper for about 1.25 cm (1/2 in) but not as much as 2.0 cm (3/4 in), and each insulated in some manner so that electrical contact between them is made only below the mercury. There must be no electrical contact between these wires above the mercury, because no other point is sure to be at the known reference temperature.

Excess water should be poured off, and more ice and water should be added, as indicated above, at regular intervals sufficiently short that the bottoms of the tubes containing mercury are never surrounded by water alone. The temperature of the water below floating ice may be several degrees above the ice point. Just how often such renewal is required will depend upon many factors, including the quality of the Dewar and the rate at which heat is conducted downward along the wires and glass tubes.

Cold junctions may be made by hard soldering the thermoelements to copper lead wires, but the excellent thermal and electrical contact provided by the mercury makes soldering unnecessary.

When an ice bath is used, the circuit from there on should be all copper. The use of other materials in switches, terminals, etc. will cause errors in the presence of temperature gradients.

When it is inconvenient to use an ice bath, a thermally-insulated block of copper, aluminum, or silver, or a stirred liquid bath may be substituted. In such case, the temperature of the reference junction must be measured with an auxiliary instrument and taken into proper account.

3.3 Automatic Cold-Junction Compensation: Some accuracy may be sacrificed for the convenience of eliminating the ice bath, and some indicating and recording instruments have built-in cold junction compensators. When a type K thermocouple is used with a given instrument, its compensator must be for Chromel-Alumel, etc. In effect, the compensator adds to the indication of the measuring instrument a value equal to the emf of a thermocouple with its measuring junction at the temperature of the compensator and its cold junction at the ice point. Rapid variations in temperature at the location of the compensator may lead to errors of several degrees. Controlled application of heat within a potentiometer in the vicinity of the compensator, as for instance by a thermostatically controlled light bulb, will improve the accuracy of compensation.

When a compensator is used, the thermoelements should ideally run without any kind of joint from the measuring junction to the instrument. Problems of installing parallel thermocouples in engines make this difficult, and in some cases virtually impossible to achieve. Then the entire thermocouple circuit between the measuring junctions and the compensator should consist of material with the same thermoelectric properties as the elements constituting the measuring junction.

3.4 The Selector Switch: If a selector switch is used so that several thermocouples can be read on a single instrument, this should come between the reference junction and the instrument. It is thus usually in a copper circuit, and should itself be of all copper for highest accuracy. When a selector switch having copper or brass contacts is used with a compensated instrument, the switch should be enclosed so that it is free from drafts and not subjected to large, sudden changes of temperature.

4. INDICATING AND MEASURING INSTRUMENTS:

The emf of a thermocouple depends upon the temperatures of its measuring and reference junctions, and after appropriate calibration, thermocouple emfs may be translated quantitatively into temperature differences. If the temperature of the reference junction is known, and if the emf is determined, the temperature of the measuring junction also becomes known. Thermocouple emfs can be measured conventionally with appropriate millivoltmeters or potentiometers.

4.1 Analog Millivoltmeters: Analog millivoltmeters are galvanometer-type instruments with pointers and scales which may read in millivolts or directly in degrees. Since the deflection of a galvanometer is a function of the current flowing through it, the reading of a particular millivoltmeter-thermocouple system depends upon the total resistance of the circuit including the instrument. Thus the instrument reads properly only when the total resistance is the same as it was during calibration. This requirement for proper adjustment of the resistances of instrument and circuit is a disadvantage per se, and such a system has the further disadvantages that its calibration may vary as a result of a) unavoidable changes in resistance during use, as from changes in the temperature of the thermocouple, its leads, or the instrument; b) physical or chemical changes in the various metals constituting the circuit; c) contact resistances in connectors and switches; d) changes in the strength of the permanent magnet and of the spring in the millivoltmeter; and e) pivot friction in the instrument. Since the thermal emf of Chromel-Alumel is approximately

4.1 (Continued):

0.04 mV per °C (0.02 mV per °F), and since the emf of such a couple with reference junction at 0°C (32°F) and measuring junction at 1260°C (2300°F) is about 51 mV, it will be obvious that a millivoltmeter without suppressed zero would have to have a very large scale to be readable to better than 5°C (10°F).

Nevertheless the millivoltmeter is in wide use in cockpits where small size and weight are desirable, and where the use of standard cells and batteries is inconvenient or impractical.

In some gas turbine installations, the same thermocouples are connected to a millivoltmeter in the cockpit and to a control system. Movement of the meter parts due to maneuvers of the aircraft can generate emfs within the instrument, which may feed back into and disturb the control system.

4.2 Digital Millivoltmeters: Many modern aircraft use high impedance digital millivoltmeters. The high impedance eliminates the need for controlling input resistance.

4.3 Servo-driven Indicators: This type of indicator is among the most accurate. In basic terms, a servo-motor drives the indicator. It is often expensive relative to other types but is very rugged.

4.4 Potentiometers: The potentiometer is an instrument which provides and measures a controllable emf that can be made equal and opposite to that of the thermocouple. Being a null instrument, readings are made only when the two opposed emfs are so nearly alike that no measurable current is flowing. In such a system, the balancing emf is independent of the resistance of the circuit. However, the sensitivity with which the point of balance can be determined with a given detector decreases as the circuit resistance increases.

Conventional potentiometers contain a standard cell of known, constant emf from which practically no current is ever drawn, and a dry cell which supplies the current that flows through the instrument. The so-called Mallory or mercury cells have been substituted successfully for both the standard cell and the dry cell in potentiometers designed for the battery voltages involved thereby. The mercury cells are more rugged and less sensitive to damage by freezing and by high temperatures than are the cells in common use.

Potentiometers are available commercially in types too numerous to mention, from portable, manual indicators to electronic, self-balancing indicators and recorders. Some read emf directly, and others are calibrated in degrees. In the latter case, the instrument reads correctly only when used with thermoelements of a particular calibration and when the reference junction is at a particular temperature. Some potentiometers have the automatic cold junction compensation discussed in 3.3 of this report.

In general, potentiometers are laboratory instruments, not well suited for installation in the crowded cockpit of an aircraft.

5. CORRECTIONS APPLICABLE TO GAS TURBINE THERMOCOUPLES:

Even when all of the known precautions have been taken as to circuitry and instrumentation, and when the emf is known as a function of temperature, errors are still possible. The only thing that a thermocouple can indicate is the temperature of its own measuring junction. Thus, when a thermocouple is used to determine the temperature of a medium to which its measuring junction is attached or in which it is immersed, the difference in temperature between the junction and the medium must be evaluated, or this difference must be reduced to a negligible amount.

When a thermocouple is used to indicate the temperature of the working medium of a gas turbine engine, major practical problems are involved in trying to determine how much the measuring junction differs in temperature from the gas. Actually, when such a measuring junction attains a steady state, its temperature is the resultant of several simultaneous rates of heat exchange between the junction and its surroundings; namely, a) the rate (Qk) at which heat is transferred to or from the junction by conduction along the thermoelements and other solid parts of the thermocouple, this being normally from the junction to the cooler walls; b) the rate (Qc) at which heat is exchanged by convection between the gas and the junction, this being normally from the gas to the junction; and c) the rate (Qr) at which heat is exchanged by radiation, this being normally from the junction to the cooler walls. If the gas velocity exceeds a few hundred meters/s (ft/s), the junction also receives more or less heat as a result of the conversion of velocity head into heat wherever the measuring device slows down or stops gas which impinges upon it. This latter may be called the impact effect, and may be considered to include effects of friction which are difficult if not impossible to determine separately. Under conditions of rapidly changing gas temperatures, immersed sensing devices always heat or cool at a slower rate than the gas itself, so that under changing conditions this lag may be thought of as still another correction which must be applied to convert indicated temperature into true gas temperature at any instant. The so-called rate of response or characteristic time of a thermocouple is also of importance in another way which may be discussed later.

5.1 Conduction Correction: Engine thermocouples are attached to walls which are cooler than either the measuring junction or the gas. Hence there is always a tendency for heat to flow from the junction toward the wall. As a matter of fact, this rate is normally too slow to be significant, as will now be shown.

For simplicity, consider from Exhibit 1 that a wire of diameter D projects for a distance (a) into gas at temperature T_g from a wall at temperature T_w. Assume that the innermost end of the wire is located where a measuring junction might be, and that the temperature of the wire is T at a distance (x) from its free end. Let h be the coefficient of heat transfer by convection from the gas to the wire, and let k be the thermal conductivity of the wire. For further simplicity, let the constant α represent a group of other constants already defined, so that

$$\alpha^2 = 4h/Dk. \quad (1)$$

5.1 (Continued):

By equating the rates of heat flow into and out of element δx of the wire, the equation representing the steady state can be shown to be

$$d^2T/dx^2 = \alpha^2(T - T_g) \quad (2)$$

The solution to this equation is

$$T - T_g = Ae^{\alpha x} + Be^{-\alpha x} \quad (3)$$

in which the constants A and B may be evaluated from the boundary conditions of $dT/dx = 0$ at $x = 0$; and $T = T_w$ at $x = a$, and in which e is the base of Naperian logarithms. The final result is

$$\frac{T_g - T}{T_g - T_w} = \frac{\cosh 2x\sqrt{h/Dk}}{\cosh 2a\sqrt{h/Dk}} \quad (4)$$

or, if T_j is the temperature of the measuring junction located at $x = 0$,

$$\frac{T_g - T_j}{T_g - T_w} = \frac{1}{\cosh 2a\sqrt{h/Dk}} \quad (5)$$

Only the coefficient (h) of heat transfer by convection is not subject to direct measurement in an apparatus designed primarily for observing temperature. However, if the mass velocity, specific heat, absolute viscosity, and thermal conductivity of the fluid flowing around the wire are known, the value of h can be calculated from empirical equations given by McAdams (2).

Using the methods and equations listed above, numerical values of the conduction correction can be estimated under assumed engine operating conditions. Fig. 2 shows such corrections for bare No. 22 and 14 gage Chromel-Alumel thermocouple wires and for a stainless steel tube 0.635 cm (0.25 in) o.d. x 0.432 cm (0.17 in) i.d. at an assumed $T_g - T_w$ of 55°C (100°F) for mass flows of 0.40 kg/m²-s (2 lb/ft²-s), 0.80 kg/m²-s (4 lb/ft²-s) and 1.20 kg/m²-s (6 lb/ft²-s) gas turbine thermocouples normally consist of thermoelement wires within packed magnesia and outer supporting tubes, and the thermal conductivity of the assembly is somewhat greater than the sum of the conductivities of the wires plus the tubes. Nevertheless the conduction correction is insignificant at immersion of 5 cm (2 in) and more, even at the low flow rates which correspond to gas turbine idling at sea level and to full speed at the flight ceiling. For mass velocities as high as those experienced in turboprop engines in normal operation, immersion of 2.5 cm (1 in) or more seems ample to insure against significant conduction error.

5.2 Heat Gain by Convection: The rate (Q_c) at which heat is gained from the gas by convection is given by the familiar equation

$$Q_c = hA_c(T_g - T_j), \tag{6}$$

in which A_c is the area of the junction through which heat is added by convection, and the other quantities have been defined previously. As pointed out in the previous section, h is strongly dependent upon the mass velocity.

5.3 Radiation Correction: If the conduction correction is negligible, a steady state is attained by the measuring junction when the Rate (Q_c) of heat gain by convection equals the rate (Q_r) of heat loss by radiation, i.e. when

$$Q_c = Q_r. \tag{7}$$

The area of the measuring junction of a thermocouple is small compared to that of all the surroundings which it can "see". Hence, little, if any, of the energy radiated by the junction is ever reflected back to it regardless of the ability of the surroundings to reflect. This means that the surroundings act as a black body, without regard to their surface emissivity.

By integrating Planck's radiation law over all wavelengths from zero to infinity, the rate (W_{bt}) at which energy is radiated over all wavelengths per unit area of a black body surface is

$$W_{bt} = \sigma T^4 \tag{8}$$

in which α is the Stefan-Boltzmann constant and T is the absolute temperature, expressed in Kelvins or degrees Rankine. The ratio of the radiant flux density from an actual junction (W_{jt}) to that of a black body (W_{bt}) at the same temperature is called the emissivity (ε_t) of the actual body. Hence

$$W_{jt} = \sigma \varepsilon_t T_j^4 \tag{9}$$

and the rate at which a junction having an area A_j and temperature T_j loses heat is $\sigma\varepsilon_t A_j T_j^4$. It simultaneously gains heat from surroundings at temperature T_w at the rate of $\sigma\varepsilon_t A_j T_w^4$, and the net rate of heat loss by radiation is thus

$$Q_r = \sigma\varepsilon_t A_j (T_j^4 - T_w^4). \tag{10}$$

Since $Q_c = Q_r$ at a steady state,

$$hA_c(T_g - T_j) = \sigma\varepsilon_t A_j (T_j^4 - T_w^4), \text{ or} \tag{11}$$

5.3 (Continued):

$$T_g - T_j = \frac{\sigma \varepsilon_t}{h} \frac{A_j}{A_c} (T_j^4 - T_w^4). \qquad (12)$$

The difference $T_g - T_j$ is obviously the correction which must be applied for heat loss by radiation. Its value for a junction of given configuration is seen to depend upon the emissivity of the junction, the coefficient of heat transfer by convection which is dependent upon the mass velocity, and upon the difference in the fourth powers of its own absolute temperature and that of the surrounding walls. Thus the correction for radiation can be decreased by decreasing the emissivity of the junction, as by pressing a small shield of silver, gold or platinum around it, by locating it in a region of high mass velocity, or by surrounding it with radiation shields which attain higher temperatures than the walls.

5.4 Impact Effect: In a gas at rest, temperature is a measure of the mean kinetic energy of random motion of the gas molecules. However, in many gas streams which find current application, the directed velocity is appreciable as compared with the mean velocity of random motion. In such cases the two temperatures of interest are the static temperature, T_s, which would be indicated by an error-free instrument moving with the gas, and the total temperature, T_t, which would be indicated by an instrument immersed in the gas after it is brought to rest adiabatically. These two temperatures are related through the familiar equations

$$T_t - T_s = v^2/2gJC_p, \text{ and } T_t/T_s = 1 + M^2 (\gamma - 1)/2, \qquad (13)$$

in which v is directed velocity, g is the gravitational constant, J is the mechanical equivalent of heat, C_p is the heat capacity at constant pressure, M is the Mach number, and γ is the ratio of the specific heat at constant pressure to that at constant volume.

Typical values of the difference $T_t - T_s$ for air with C_p = 0.24 Btu/lb °F (310.148 joules/kg °C), as a function of velocity, are as follows:

Velocity m/s	Velocity ft/s	$T_t - T_s$ °F	$T_t - T_s$ °C
0	0	0.0	0.0
32.8	100	0.8	0.4
65.6	200	3.3	1.8
98.4	300	7.5	4.2
131.2	400	13	7.2
164.0	500	21	11.7
198.9	600	30	16.7
229.7	700	41	22.8
262.5	800	53	29.4
295.3	900	67	37.2
328.1	1000	83	46.1

5.4 (Continued):

A stationary instrument attains neither T_t nor T_s when immersed in flowing gas, but rather some intermediate value, T_j, which depends upon how completely the directed kinetic energy is converted into thermal energy upon impact. The capacity of an instrument for effecting this conversion is its recovery factor, r, defined as

$$r = (T_j - T_s)/(T_t - T_s). \quad (14)$$

5.5 Rate of Response: The rates of response of sensing elements to sudden changes in temperature are of practical concern to those who are interested in observing transient conditions (as during engine acceleration), and to those dealing with control systems actuated by devices sensitive to gas temperature. To the former group, the amount by which the measuring junction lags behind the gas temperature at any instant can be regarded as a correction which might be applied to obtain the temperature at the same instant. To those interested in controls, the absolute value of the indicated temperature may be of less importance than the time between a sudden change in gas temperature and the development of a usable signal from the measuring junction as a result thereof.

When the temperature of a gas is increased instantaneously from T_1 to T_2, the increase (ΔT) in the temperature of an immersed object with time (t) thereafter by forced convection is given by the equation

$$\Delta T = (T_2 - T_1)(1 - e^{-t/\tau}), \quad (15)$$

in which e is the base of Naperian logarithms and τ is a constant. It is apparent that τ must have the dimension of time, and that at time $t = \tau$, $\Delta T/(T_2 - T_1) = 1 - 1/e = 0.632$. Thus τ is the time required for the immersed object to undergo 63.2% of any temperature change to which it is subjected instantaneously, and thus defined is referred to as the characteristic time (time constant) of the object.

Actually τ is not characteristic of the object alone, but of the object and the rate at which heat is transferred to it. The latter varies with the coefficient of heat transfer to the object, so that a numerical value of τ is significant only when the flow rate is specified. The coefficient also varies somewhat with temperature, and there is some difference of opinion as to whether observed values of τ vary significantly with the values of T_1 and T_2 selected for the measurement.

6. LABORATORY EVALUATION OF THERMOCOUPLE PERFORMANCE:

Since the performance to be expected of an individual thermocouple in an engine can, to a large extent, be predicted from laboratory tests, a description of facilities used for this purpose at the National Bureau of Standards (3) may be of interest. These facilities are used for thermocouples already calibrated for conventional service, i.e., for which the emf-temperature relationship is known, but for which additional information is required as to performance in flowing products of combustion.

6. (Continued):

As indicated schematically in Fig. 3, this supplementary facility consists essentially of blowers supplying compressed air to a gas turbine can-type combustor with afterburner, and an exhaust system in which test instruments and standard instruments can be immersed and compared under a variety of controlled operating conditions.

The Inconel test section downstream from the burners has three convenience hatches for installation of the test and reference instruments which, because of the configuration of the exhaust system, receive no direct radiation from the flame. It supports a mechanism, to be described later, for determining response rates. Thermocouples are peened into the walls to indicate the pipe temperature, and external thermal insulation is applied if desired. Similarly constructed test sections 7.6 cm (3 in) and 15.2 cm (6 in) in diameter are available, and temperatures up to 1093°C (2000°F) can be provided at mass velocities up to 3.1 kg/s m^2 (15 lb/s ft^2) in the 15.2 cm (6 in) section and up to approximately twice this figure in the 7.6 cm (3 in) section.

The lower flow channel in Fig. 3 is an air line, used for determining recovery factor, and is described in more detail in 6.2. It is also used for quenching specimens in thermal shock tests.

Fuel and air rates, pressures and velocities are measured by conventional means. Water cooling of valves is accomplished by internal sprays, and the lines downstream of such sprays are sloped to prevent unevaporated water from influencing the temperature of the gas in the test section.

6.1 Correction for Radiation and Conduction: For determining the combined correction for conduction and radiation, it is desirable to have a comparison instrument free from losses by either of these processes. Such a laboratory standard for use in flowing gases is shown in Fig. 4. It consists essentially of a central, bare thermocouple junction surrounded by two coaxial tubular radiation shields. The inner shield is a silver tube 13.97 x 2.54 x 0.10 cm (5.5 in long x 1 in o.d. x 0.04 in) wall thickness. The outer shield is a stainless steel tube 16.51 x 4.44 x 0.08 cm (6.5 in long x 1.75 in o.d. x 0.03 in) wall thickness, wound externally with a tapped heating element and having three thermocouples peened into its inner surface. The assembly is mounted coaxially in the 15.2 cm (6 in) test section from the central hatch shown in Fig. 3.

In operation, the outer shield is heated electrically until its temperature is uniform and equal to that indicated by the thermocouple at the center. Under these conditions, loss from the central junction by conduction and radiation is prevented by the shields. It is apparent that proper operation of such a unit requires considerable time and care, and that it is not convenient for routine calibrations. Hence, it is used only for calibration of more convenient secondary standards, consisting of Chromel-Alumel thermocouples with pressed radiation shields of silver, gold, or platinum.

6.1 (Continued):

For calibration, such secondary standards are installed at equal distances upstream and downstream from the laboratory standard. Under various operating conditions the former are read when the latter is adjusted as already described to read true gas temperature. Gas velocity is kept sufficiently low that impact corrections are small and known. The separate sets of secondary standards, when read differentially, give the axial rate of temperature decrease due to heat loss along the test section. The gas temperatures at the locations of the secondary standards are obtained by applying the corrections for axial gradient to the temperature indicated by the laboratory standard. Wall temperatures are subject to some control by applying more or less thermal insulation, and by dropping the gas temperature suddenly from a high value to that chosen for a particular run.

The corrections applicable to the secondary standards are obtained by subtracting the values which they indicate from the true gas temperature indicated by the laboratory standard, after taking due account of the effects of impact and axial heat loss. Such corrections are determined at various temperature levels, flow rates, and for various values of the temperature difference between the gas and the walls of the test section.

The corrections applicable to gas turbine thermocouples are determined in the same way, the test couples being installed where the laboratory standard was before. True gas temperature is obtained by applying the proper corrections to the indications of the secondary standards. Gas temperatures are currently varied from 538 - 871°C (1000 - 1600°F), wall temperatures from 427 - 760°C (800 - 1400°F), at mass velocities of 0.41, 0.82, 1.23 Kg/s m^2 (2, 4, and 6 lb/s ft^2).

Typical values of the combined correction for conduction and radiation of a bare, loop-type gas turbine thermocouple and of a stagnation-type unit are as follows:

Gas	Wall	Bare, Loop-Type Couple			Stagnation-Type Couple		
		Corrections to be Added to the Indicated Temperatures at Mass Velocities in lb/s ft^2 of					
		2	4	6	2	4	6
		°F					
1500	1400	20	14	11	25	17	14
1500	1300	37	26	21	47	32	26
1500	1200	52	36	30	66	45	37
1500	1100	64	45	37	82	56	45
1500	1000	76	52	43	94	65	53
1400	1300	18	13	11	22	15	12
1400	1000	60	42	34	70	48	39
1300	1200	16	11	9	20	14	11
1300	1000	39	27	22	50	34	28
1200	1100	13	9	8	17	12	10
1200	900	33	23	19	42	29	24
1100	1000	11	8	6	14	10	8
1100	800	27	19	15	36	25	20
1000	900	10	7	6	13	9	7
1000	800	17	12	10	22	16	13

Gas	Wall	Bare, Loop-Type Couple 0.41	Bare, Loop-Type Couple 0.82	Bare, Loop-Type Couple 1.23	Stagnation-Type Couple 0.41	Stagnation-Type Couple 0.82	Stagnation-Type Couple 1.23
		Corrections to be Added to the Indicated Temperatures at Mass Velocities in kg/s m²					
		°C					
815.6	760	11.1	7.8	6.1	13.9	9.4	7.8
815.6	704.4	20.6	14.4	11.7	26.1	17.8	14.4
815.6	648.9	28.9	20	16.7	36.7	25	20.5
815.6	593.3	35.6	25	20.6	45.6	31.1	25
815.6	537.8	42.2	28.9	23.9	52.2	36.1	29.4
760	704.4	10	7.2	6.1	12.2	8.3	6.7
760	537.8	33.3	23.3	18.9	38.9	26.7	21.7
704.4	648.9	8.9	6.1	5	11.1	7.8	6.1
704.4	537.8	21.7	15	12.2	27.8	18.9	15.6
648.9	593.3	7.2	5	4.4	9.4	6.7	5.6
648.9	482.2	18.3	12.8	10.6	23.3	16.1	13.3
593.3	537.8	6.1	4.4	3.3	7.8	5.6	4.4
593.3	426.7	15	10.6	8.3	20	13.9	11.1
537.8	482.2	5.6	3.9	3.3	7.2	5	3.9
537.8	426.7	9.4	6.7	5.6	12.2	8.9	7.2

6.1 (Continued):

These values show that the radiation correction is important, and that it depends strongly on the mass velocity, the temperature level, and the difference in temperature between the junction and its surroundings. While it might at first be thought that the correction for a stagnation probe should be less than for a bare junction because the stagnation chamber is in effect a radiation shield, the above values show that the decreased flow rate over the junction in the stagnation chamber has a greater effect than does the radiation shield.

6.2 Determination of Recovery Factor: The lower flow channel in Fig. 3 is a 30.5 cm (12 in) pipe terminating in a calibrated 10.2 cm (4 in) nozzle which discharges air from the compressor directly into the atmosphere. A heavy aluminum spool at the nozzle exit is used for mounting instruments for determinations of recovery factor. A heating coil on this spool can be used to bring its temperature to equality with that of the test instrument, thus preventing heat loss by conduction along solid parts of the instrument.

In the 30.5 cm (12 in) pipe, the velocity is low and the temperature T_t and T_s are nearly alike and directly measurable. The test instrument indicates a temperature T_j at the discharge of the nozzle. The thermal properties of the air are known, and the velocity past the test instrument is known from the calibration of the nozzle and the measured pressure drop across it. The expansion is nearly adiabatic, and the value of T_t measured just upstream of the nozzle applies also at the test instrument. Thus the value of T_s can be calculated from eq 13, and all the quantities needed to calculate the recovery factor from eq 14 are known. Measurements of this type must be made with considerable care, because the differences among T_t, T_s, and T_j are not great.

Recovery factors for gas turbine thermocouples, as determined in air at approximately room temperature, are normally within the range 0.7 - 0.8 for bare, loop-type, V-type and twisted junctions, and from 0.9 - 0.99 for stagnation types.

Fig. 5 illustrates the combined effect of radiation and impact upon the temperature attained by a typical, bare Chromel-Alumel thermocouple ($r = 0.65$) in flowing gas at a pressure of one atmosphere when the surrounding walls are at a temperature (T_w) of 537.8°C (1000°F). One curve in each rectangle gives T_t for the gas, one its T_s, and the third shows the temperature (T_j) attained and indicated by the measuring junction. The upper set of curves applies when T_s is constant at 815.6°C (1500°F) and the lower when T_t = 815.6°C (1500°F), the latter being the more realistic case. In both cases, the effect of radiation decreases and that of impact increases with velocity, causing the thermocouple in the present example to indicate exactly the static temperature of the gas when the velocity is approximately 243.8 m/s (800 ft/s). This figure is presented primarily to indicate the magnitude of the error that can arise from radiation and impact unless proper corrections are applied.

The desirability of attempting to determine an average stagnation temperature by having several upstream openings in a stagnation probe is open to serious question.

6.3 Determination of Characteristic Time: Apparatus which has proved suitable for determining characteristic times under conditions simulating those prevailing in engines is shown in Fig. 6. An Inconel tube, held in position around the test instrument by a release plate, provides a flow channel for cold air. Upon removing the release plate, the Inconel tube is removed suddenly by a spring, thus exposing the instrument to the stream of hot exhaust gas which had already been established in the test section. During the downward movement of the tube, which requires only about 0.01 s, the supply of cold air is stopped automatically. In this way, a test instrument at a known, moderate temperature (controlled by the rate of air flow through the Inconel tube) can be exposed to exhaust gas at any chosen temperature and mass velocity within the capability of the test system.

The rate of response of a thermocouple is recorded with a direct-inking oscillograph. Since an ac amplifier is used with the oscillograph, it is necessary to first chop the thermocouple emf. The amplified emf determines the amplitude of the record, the envelope of which represents emf as a function of time. For thermocouples in which emf varies nearly linearly with temperature, it is not necessary to know the amplification factor, and although the initial and final temperatures are usually measured with other instruments, these need not be known.

Typical curves showing the variation of the characteristic time of bare thermocouples with the size of the wire and with flow rate are shown in Fig. 7. More detailed discussions of the response characteristics of temperature-sensing elements for use in gas turbine engines will be found in references (4) and (5).

7. LOCATING THE MEASURING JUNCTION:

The measuring junction should be immersed as far as is practicable, to reduce the heat loss by conduction along the thermoelements, insulation, and supporting tube. Locating the measuring junction in a region of high mass velocity is advantageous because the rate of heat transfer from the gas to the junction by convection increases approximately as the square root of this rate. An exception is in regions of transonic flow, as mentioned in the following paragraph. For a given rate of loss from the junction by radiation and conduction, the temperature of the junction approaches that of the gas in which it is immersed more closely as the mass velocity is increased.

It is undesirable to locate a measuring junction in a region where the gas velocity may vary in either magnitude or direction. Location in regions where the Mach number is between 0.7 and 1.0 should be avoided, because unstable, local shock waves may cause undesirable changes in the rates of energy exchange between the gas and the junction.

It is better not to locate a measuring junction so that it can "see" the flame. Observing this precaution is more important for flames having a high emissivity for total radiation, such as those containing free carbon, than for more common flames which radiate only a few percent of the total energy that would be emitted by a blackbody at the same temperature.

7. (Continued):

The measuring junction should never be located in a region where it can be struck by liquid fuel. A junction so placed will read low whenever it is wet.

In ground tests under simulated altitude conditions, it is essential to have a pressure-tight seal around the thermoelements, so that no ambient air can leak along these. Leaks there can greatly increase the heat loss from the junction by conduction and possibly cool it by direct impingement.

It is highly inadvisable to attempt to measure temperature by locating the measuring junction of a thermocouple in a region of continuing chemical reaction, such as in the primary combustion zone. While gaseous reactions are believed not to be catalyzed by Chromel-Alumel, or their oxides, the mere fact that the reactions are continuing indicates incomplete mixing and the absence of equilibrium distribution of energy among the translational, vibrational, and rotational states of some of the gas molecules. Very large gradients are to be expected in reacting gases, so that, for all these reasons, no single translational temperature characterizes such gases. Also, a probe in such a location may act as a flameholder, and thereby give erroneous temperatures.

8. PARALLEL THERMOCOUPLE NETWORKS:

The temperature distribution over any given cross section of the gas stream in a gas turbine engine is not uniform. Some of this nonuniformity is unavoidable, and it is not uncommon to purposely make the gas hotter at the tips than at the roots of the turbine blades. Since the gas temperature is not uniform, measuring it at several locations in an attempt to obtain a representative, average value is highly desirable. This can be done by connecting in parallel a number of thermocouples distributed across the section in some definite pattern. However, the direct measurement of a meaningful average temperature from a single observation of the net emf of thermocouples in parallel requires certain specific precautions (6). If these are observed and if proper corrections are applied for radiation and impact, the average temperature of the junctions will approximate the gas temperature more or less closely, depending primarily upon the magnitudes of the gradients in temperature and velocity within the gas stream and upon the relative locations of the junctions with respect to these gradients.

In addition to this averaging feature, another marked advantage of connecting thermocouples in parallel is that all but one may fail without rendering the system inoperative. This is particularly desirable in control systems for gas turbine engines, since reliability is essential under operating conditions so severe that the possibility of mechanical failures during service must be anticipated.

The two distinct types of network currently in use on turbojet engines are the common-terminal and the ladder-type systems.

8.1 Common-Terminal Systems: In this arrangement, all thermocouples are connected directly to a pair of terminals at which the network signal is measured, as shown schematically in Fig. 8. By employing Kirchhoff's laws, it can be shown that the emf of such a network is

$$E = \frac{e_1(r_2r_3 \ldots r_n) + e_2(r_1r_3r_4 \ldots r_n) + -- + e_n(r_1r_2 \ldots r_{n-1})}{r_2r_3 \ldots r_n + r_1r_3r_4 \ldots r_n + r_1r_2 \ldots r_{n-1}} \qquad (16)$$

where E is the output of the network and e_1, e_2 ... e_n and r_1, r_2, ... r_n are the emfs and resistances, respectively, of the individual thermocouples. From the above equation, it is apparent that when

$$r_1 = r_2 = r_3 --- r_n \qquad (17)$$

the equation reduces to

$$E = \frac{e_1 + e_2 + e_3 + --- + e_n}{n} \qquad (18)$$

Thus when the resistances of all branches between the common terminals are equal, the network will indicate the true arithmetic average of the emfs of the individual thermocouples.

If the resistances of the thermocouples are not equal, a weighted average emf will be indicated. The relative weights of the individual thermocouple emfs are then inversely proportional to the resistances of the thermocouples. For example, consider a four-junction network in which $r_1 = 1.0$, $r_2 = 1.1$, $r_3 = 1.2$ and $r_4 = 1.3$. The output of the network will be

$$E = \frac{e_1 + \frac{e_2}{1.1} + \frac{e_3}{1.2} + \frac{e_4}{1.3}}{1 + \frac{1}{1.1} + \frac{1}{1.2} + \frac{1}{1.3}} \qquad (19)$$

In engine thermocouple networks employing the common-terminal system, the thermocouple resistances are generally made equal by adjusting the physical dimensions (wire length or diameter), or by inserting resistances in the individual thermocouple circuits. Should any of the thermocouples become open circuited, the network will continue to indicate the true average emf of those which continue to function.

The practical difficulty of running lead wires from a pair of common terminals to each of many thermocouples distributed over the periphery of a gas turbine engine is obvious. Thus, difficulties of constructing a harness having multiple leads may outweigh the disadvantages inherent in circuits which require only a single pair of leads, as is the case of ladder-type systems.

8.2 Ladder-Type Systems: The inherent simplicity of using a single pair of leads to which individual thermocouples are attached at intervals along the leads has led to the ladder-type network shown schematically in Fig. 9. The electrical characteristics of such a system may be summarized as follows (7):

Only when the resistances between the branch points are zero and when all thermocouple resistances are equal do the individual junctions exert equal weight on the net emf. If the thermocouple resistances and those between the branch points are all equal, the two junctions adjacent to the measuring terminals have the most weight, and their relative weight increases with the number of junctions. The greater the resistance of the thermocouples as compared with the resistance between branch points, the more closely will the emf of the network approach the average of the individual emfs. The emf of a ladder-type network depends upon the relative position of the measuring terminals with respect to the junctions and of the junctions with respect to the temperature gradients, even if the average of the temperatures of the individual junctions is always identical with the average gas temperature. It is advantageous, in ladder-type networks, to keep the resistances between branch points small compared with the resistances of the individual thermocouples.

Because so many factors influence the weight which an individual junction may exert on the net emf, it is very laborious to solve the general equations applicable to such networks, and more useful to work out expressions for specific cases in which certain simplifying conditions are assumed. This method has been followed in the detailed analysis of ladder-type systems given in reference (7).

It is possible, by varying the resistances of the individual thermocouples in a ladder-type system, to weight the output of each according to its distance from the measuring terminals and thus give equal weight to each. More specifically, let

n = number of junctions to the left of the measuring terminals;

n' = number of junctions to the right of the measuring terminals;

Ra_m = resistance of any harness section to the left of the measuring terminals;

$Ra'_{m'}$ = resistance of any harness section to the right of the measuring terminals;

Rt_m = resistance of any thermocouple to the left of the measuring terminals; and

$Rt'_{m'}$ = resistance of any thermocouple to the right of the measuring terminals.

8.2 (Continued):

If the junctions are to have equal weights, the following relations must exist among the thermocouple and harness-section resistances:

$$Rt_m = Rt_{(m-1)} + (m-1)Ra_{(m-1)}; \tag{20}$$

$$Rt'_{m'} = Rt'_{(m'-1)} + (m'-1)Ra'_{(m'-1)}; \text{ and} \tag{21}$$

$$\frac{Rt_n}{nn'} + \frac{Ra_n}{n'} = \frac{Rt'_{n'}}{nn'} + \frac{Ra'_{n'}}{n} \tag{22}$$

The above equations may be applied as follows:

Decide on the number of thermocouples, their spacing, and the location of the lead wires. Based on wire diameter and length, assign values to all harness-section resistances except Ra_n and $Ra'_{n'}$. Depending upon whether it is desirable to assign a value to the sum $(Ra_n + Ra'_{n'})$, or to the individual resistances Ra_n and $Ra'_{n'}$, two cases may be recognized, namely:

a) Assign a value to the sum $(Ra_n + Ra'_{n'})$.

1. Assume values of Rt_1 and $Rt'_{1'}$.

2. Working from the outside in, calculate the resistances of the other thermocouples and Ra_n and $Ra'_{n'}$, using eqs 20, 21, and 22.

b) Assign values to Ra_n and $Ra'_{n'}$.

1. Letting Rt_m be used on the side of the network having the most thermocouples and $Rt'_{m'}$ be used on the side having the lesser number of thermocouples, assign a value to Rt_1.

2. Determine all values on the side of Rt_1.

3. Determine the value of $\frac{Rt_n}{nn'} + \frac{Ra_n}{n'}$.

4. Calculate $Rt'_{n'}$, using eq 22.

5. Calculate $Rt'_{(n'-1)}$; $Rt'_{(n'-2)}$; etc. down to $Rt'_{1'}$, using eq 21.

Although this method for correcting the averaging characteristics of a ladder-type thermocouple and harness system can give accurate averaging for any value of the ratio of thermocouple resistance to harness-section resistance so long as all the thermocouples are functioning, it is still advantageous to keep this ratio high for the sake of the accuracy of the averaging process when one or more of the couples have failed.

8.2 (Continued):

Mathematical computation of the circuitry errors of parallel-thermocouple networks is cumbersome, and it is often convenient to use instead an electrical analog for this purpose.

8.3 Electrical Analog for Parallel-Thermocouple Networks: A schematic diagram of such an analog is shown in Fig. 10.

The thermocouples, represented between points a_1 and b_1, a_2 and b_2, etc. have resistances $r_{1,1} + r_{4,1}$, $r_{1,2} + r_{4,2}$, etc., the value of r_4 being kept at one percent or less of r_1. The emf of the thermocouple is simulated by the potential drop across r_4, which is applied to each thermocouple by a separate 45-volt dry battery through a high, variable resistor. The resistances $r_{2,1}$, $r_{3,1}$, $r_{2,2}$, etc. simulate the lead resistances of a ladder-type network.

For any particular network, assumed resistances, and assumed temperatures, the analog provides a convenient means for determining the net output of the system from which the circuitry error can be derived simply. The analog is also convenient for determining the net resistance of the circuit, which is laborious to compute for ladder-type systems with many junctions.

8.4 Connections Between Thermocouples and Harness: In most current engine thermocouple systems, the couples may be attached to and detached from the harness as desired. It is important that the attaching means do not become sources of variable resistance or of spurious emfs. The connections must also be removable after extended periods of service at relatively high temperatures.

Since the thermocouple terminals are normally subject to gradients in temperature during engine operation, it is particularly important that no metals differing significantly in thermoelectric properties from the thermoelements themselves should form part of the electrical circuit at the thermocouple head. All parts of the Chromel circuit should be of thermocouple grade Chromel, etc. It is desirable that the Chromel terminal be welded to the Chromel thermoelement and the Alumel terminal to the Alumel thermoelement. If hard soldering or brazing must be used, the quantity of solder or spelter in each joint should be kept to an absolute minimum. It is preferable that contact between each lug and its terminal be made at a shoulder on the terminal rather than through threads. Oxide coatings should be removed to leave bright metal surfaces where primary electrical contact is made. All flux should be removed to preclude galvanic action and corrosion.

Where connections are made by threaded studs and nuts, Chromel nuts for the Chromel terminal, etc., would be preferable except for the well-known tendency of like metals to seize when heated for long periods. If the terminal nuts must be removable, it is probably necessary to make them of materials other than Chromel and Alumel until means of preventing seizure are developed.

9. POSSIBLE EFFECTS OF FABRICATION ON GAS TURBINE THERMOCOUPLE PERFORMANCE:

9.1 Mechanical Working: In the development of turbine engines, it was logical that conventional thermocouples using two-hole porcelain tubes for insulation should be tried first. In this type of couple, the thermoelements have some freedom of movement within the insulator and the latter can move within the supporting tube. When these couples were used in operating gas turbine engines, the mechanical vibrations often proved great enough to produce a rapid grinding away of the thermoelements, particularly at the end or at a break in the porcelain insulator. The necessity of supporting the thermoelements over their entire lengths soon became apparent, and the type of construction long used in sheathed electrical heaters for cookstoves was suggested.

Such heaters, and more recently most production-type gas turbine thermocouples, are made by surrounding the wires first with packed magnesia (MgO) and then with a relatively thick-walled tube of Inconel or stainless steel. The packing of the MgO between the wires and the outer sheath is done by various proprietary processes, all of which yield stock which can be cut into the desired lengths for thermocouples.

Good MgO has a specific resistance of about 10^8 ohm/cm at 1000°C. This is approximately halved for each 100°C additional temperature rise. Fused and heat-treated MgO, with only traces of such undesirable elements as sulfur and iron, is available commercially. Crystals of MgO are cubic, and this shape is maintained in the crushed material. Because of this shape, the particles can be packed tightly and the packed material will stay in place where the outer sheath ends.

Regardless of the method used to pack the MgO, the purpose is always to compact it so that the stock may be cut at will without losing the insulation from any open end, even under conditions of extreme mechanical vibration such as are experienced in engines. This requires firm packing indeed, with hydrostatic pressures that may approximate 7031 kg/cm^2 (100 000 psi) needed to reduce porosity to about 15%.

In packing to the desired density, the thermoelements may be subjected to considerable mechanical working, as would be the case if the diameter of the sheath were decreased and the total length of the stock were increased substantially by drawing through dies.

It is well known that the temperature-emf relation of a Chromel-Alumel thermocouple can be changed by mechanical working and thereafter by heat treatment. If the thermoelements are work-hardened in the production of the packed MgO stock, subsequent heat treatment may be required to restore the performance to within the limits given in 2.1. It is a routine matter to determine whether or not this has been achieved, because appropriate lengths of the stock may be calibrated accurately by conventional methods (1). However, the only test which seems to be available for determining the density of the packed MgO is direct weighing of a section before it is opened and of the same metal parts after the MgO has been removed.

9.1 (Continued):

Because gas turbine thermocouples are normally short, and because their heads may be subjected to uncontrolled temperature gradients during calibration and in service, evaluation of the performance of complete units is a problem which is discussed separately in Section 10.

Since MgO cannot be made impermeable by packing, there is considerable interest in the possible effects upon thermocouple performance of moisture, salt spray, fuel and products of combustion that may be absorbed through the exposed end of the insulation.

9.2 <u>Moisture, Fuel, and Sulfur in the Magnesia</u>: Foreign substances in the MgO may have an adverse effect on the insulation resistance and in some cases on the thermoelements themselves. If moisture, or particularly salt spray, penetrates the MgO, the resistance between thermoelements and to ground may be low during warm-up and thereafter return to a satisfactorily high value. Obviously some kind of seal to prevent such absorption would be highly desirable.

If fuel enters the MgO while the couple is cold, it will exert a harmful effect only if it breaks down subsequently by thermal cracking to leave carbon in the pores of the MgO. Carbon so deposited in the insulation of thermocouples in operating engines and in the laboratory can virtually short out the measuring junction and render the couple useless. Carbon has seldom, if ever, been found within about 0.3 cm (1/8 in) of the exposed end of the MgO, even when the insulation is completely black farther along. This indicates that the fuel can escape as vapor from this region before it cracks. Based on this evidence, a "fix" for the carbon problem is to bore small holes through the sheath on approximately 0.64 cm (1/4 in) centers. This treatment, while undesirable from the standpoint of mechanical strength of the thermocouple, has been found effective in preventing carbon formation by letting absorbed fuel escape as vapor before it can crack. Such a remedy may not be successful if fuel penetrates as far as the head of the thermocouple.

In laboratory tests, it has been possible to maintain a continuous flow of fuel under pressure through a heated specimen of packed MgO stock without depositing any carbon. It is surmised that the porosity of the MgO was abnormally high in such samples. In similar tests, other samples did form carbon and still others appeared to have the MgO packed to a degree which completely prevented fuel penetration under the moderate driving pressures used. These exploratory results point up the need for a nondestructive test which will yield quantitative data on the porosity of the MgO in the packed stock and in complete engine thermocouples.

9.2 (Continued):

It is well known that Alumel is subject to intergranular corrosion at elevated temperatures, and that such action is accelerated in the presence of sulfur. The changes which occur in the physical structure of the alloy cause it to become weak mechanically, but they are virtually without effect upon the thermoelectric behavior so long as the electrical circuit is not broken. Other foreign elements such as lead and vanadium have been suspected of producing a similar effect on Alumel, but this is not fully verified.

If a bare Chromel-Alumel thermocouple is exposed to products of combustion of a fuel containing sulfur, the exposed Alumel will break in a relatively short time, its actual life depending upon the concentration of sulfur, the temperature and the accelerations to which it is subjected. There is not enough sulfur in present day jet fuels to make this a problem in aircraft engines; it is a real problem today in other types of turbines which burn oil containing much more sulfur than is allowed in JP fuels.

If sulfur by accident contaminates the MgO used in making packed thermocouple stock, a small amount will cause the Alumel to fail in the manner already mentioned at points within the packed stock. Such failures will not occur in a short time unless the stock is heat treated. The failures are areas of incipient separation, without mechanical strength, but difficult to detect by measuring electrical resistance. The obvious solution of this problem is to use MgO containing not more than a few parts per million of total sulfur (such material being available at reasonable cost) and to guard against sulfur contamination during the fabrication of the packed MgO stock.

9.3 Terminal Connectors for Thermocouples: As mentioned previously, in an ideal circuit the Chromel and Alumel wires would be continuous from the measuring junction to the reference junction. In practice, however, it is more convenient and economical to make a separate unit including the measuring junction, so that it may be installed and replaced easily on an engine. Several distinct types of terminal connectors in current use may be described as follows:

a) One of these has the Chromel and Alumel thermoelements extending through a braided pig tail to Chromel and Alumel lugs, respectively. Usually these lugs are attached to the wires by silver brazing, in which case care should be used that the flux does not flow into the insulation; that all flux is removed after brazing; that the amount of silver used be kept to a minimum and that it not be allowed to run along the wires or beyond the joint on each lug. In using such terminals, it is important that all lugs be clean and bright when they are bolted together, and that the temperature gradient across the brazed joint be kept to a practical minimum.

9.3 (Continued):

b) In a less familiar type, the lugs are attached directly at the thermocouple head, and temperature gradients across the joints between the wires and the lugs are more difficult to keep down. Welding is therefore preferable to brazing, and care should be exerted to avoid overheating either thermoelement; against getting a "cold weld" because of possible differences in the mass of wire and lug at the point of attachment; and against getting too much metal melted during the welding operation. As before, any flux which might be used must be removed completely, and all lugs should be clean when they are bolted together.

c) The most common type involves threaded studs of Chromel and Alumel, welded to the corresponding thermoelements, and firmly attached to the insulation used in making the head. Because large temperature gradients through this type of head are normal in service, all welds should be autogenous. It is believed that the following precautions are worthwhile: the threaded studs should include a shoulder against which the mating lug can be pressed by the nut; the thermoelements may, to advantage, be run through central holes in the studs and the welds can then be made in a region where the temperature gradient is likely to be a minimum; rolling the threads, instead of die-cutting them in the conventional way, is currently believed to decrease the probability of seizure during service. Obviously the shoulders on the studs should be clean and bright when the thermocouples are installed.

d) Pin connectors have also been used. The use of metals other than Chromel and Alumel in such connections may cause errors in the presence of temperature gradients. Plating to prevent oxidation may be necessary to maintain good electrical contact but is undesirable from the thermoelectric standpoint. However, by making the coatings very thin the temperature gradients across them can be kept down. The need for an acceptable method for evaluating the performance of pin-type connectors of all types is recognized.

e) Pressure-type contacts between buttons of thermoelement material, one having a flat and the other a curved surface, with the pressure applied by the nuts which hold down both the thermocouple and the leads to it, are a recent development in this field.

10. <u>TESTING GAS TURBINE THERMOCOUPLES</u>:

10.1 <u>For Initial Calibration and Stability After Use</u>: As mentioned in 9.1, where adequate lengths of material are available, the packed MgO stock can be calibrated in exactly the same way as the thermocouple wire itself (1). After the material has been fabricated into thermocouples for engines, the problem becomes more difficult for two primary reasons, namely that such couples are normally short and that most types have some kind of a head which may embody in the electric circuit materials not identical thermoelectrically with the thermoelements themselves. To complicate the picture further, the temperature gradients within the heads vary widely with operating conditions and therefore cannot be reproduced in a laboratory test.

10.1 (Continued):

Since the engine couples are so short, heat loss by conduction could cause an appreciable error during calibration in a furnace. The most promising solution of the problem of losses by both conduction and radiation is to weld the measuring junction of a calibrated couple to that of the engine couple under test. When both are inserted in a furnace, or preferably in a metal comparator block that is heated in a furnace, both measuring junctions attain the same temperature which can be determined by reading the calibrated couple with its reference junction in ice.

If the thermoelements of the engine couple could be run to ice, a direct comparison could be made with the calibrated couple. Actually it is not to be expected that the thermoelectric behavior of the Chromel and Alumel used for making terminal posts, or of that available for lead wires, will be identical with that of the wire used in making the measuring junction. Hence, it is not possible to make a rigorously exact calibration of the engine couple. It, therefore, becomes a matter of finding an acceptable, approximate solution of the problem in the form of a test method that will determine whether or not a couple is suitable for use in an engine.

As a beginning, the apparatus shown schematically in Fig. 11 has been tried at the National Bureau of Standards.

Calibrated Chromel-Alumel thermocouples A_1C_1, A_2C_2 and A_3C_3 are attached, either by spot welding or mechanically, to the measuring junction, to the Alumel terminal, and to the Chromel terminal, respectively, of the engine couple under test. The latter is mounted on a metal tempering plate (copper in the present equipment) which is drilled to permit circulation of water or air throughout its interior. The assembly is then lowered through a central hole in a copper block within a vertical tube furnace until the underside of the tempered plate rests on the top of the furnace through thin insulators. Means for protecting the copper comparator from oxidation and for supporting it vertically are not indicated in Fig. 11.

Each of the six leads goes to an ice bath, where it connects with a copper wire. The latter go through appropriate switches to a Brown-Rubicon Electronik potentiometer indicator on which the smallest division is two microvolts. A manual switch is connected so that the following leads run to the potentiometer:

1. A_1-C_1 for the temperature of the measuring junction
2. A_2-C_3 for the engine couple, using as leads NBS Chromel and Alumel
3. A_2-C_2 for the temperature of the Alumel terminal
4. A_3-C_3 for the temperature of the Chromel terminal
5. A_1-A_2 for spurious emfs in the all-Alumel circuit
6. A_1-C_3 for spurious emfs in the all-Chromel circuit

10.1 (Continued):

Switch points 5 and 6 are desirable but not necessary. Their readings show to what extent each circuit is responsible for errors. Taking proper account of polarity, the difference between readings 5 and 6 is within a few microvolts of the difference between readings 1 and 2. However, the latter differences alone tell nothing of the source of the errors.

A typical run can be made as follows. Heat the furnace until a previously selected, steady temperature is indicated by A_1C_1 with water flowing through the tempering plate, and take readings with the switch on positions 1 through 6 successively. Shut off the water, turn on the air full blast and repeat. After each change in the amount of cooling supplied to the tempering plate, the current to the furnace must be reset and sufficient time must be allowed for the thermocouple head to reach a steady state. Repeat this process at as many different air flow rates as may be desired, ending with a head temperature as high as the limiting zone temperature which the test couple must withstand on an engine.

In the test runs made to date, readings with the switch at points 1-2-3-4-5-6-5-4-3-2-1 have been made in the order stated at 10 s intervals and the averages of each pair of such readings have been used in making the final computations. This greatly reduces any errors which might otherwise be caused by a steady drift in the furnace temperature.

The temperature of common measuring junction of couple A_1C_1 and of the test couple is obtained by applying the calibration correction to A_1C_1. Rates of heat gain and loss by this junction due to conduction and radiation are immaterial, so long as a steady state prevails during the readings. In other words, the corrected temperature obtained with couple A_1C_1 is also the temperature of the measuring junction of the engine couple regardless of the process of heat exchange by which this steady-state temperature was reached.

When the tempering plate is water cooled, the output of couple A_2C_3 approaches the emf of the engine couple between the ice point and the known temperature of its measuring junction. The only error that can be included here involves the difference in thermal emf of the Chromel and Alumel in the engine couple and that in the calibrated couples over the temperature interval from the ice point to the lowest attainable head temperature. Where good materials are used, this uncertainty is normally much less than 0.55°C (1°F), and therefore completely negligible for present purposes. Nevertheless, the wire used in making couples A_2C_2 and A_3C_3 should have a calibration which is as close as possible to the standard curve. For these couples, a tolerance much smaller than the usual $\pm 3/4\%$ of the temperature is desirable. Wire used in the present tests does not deviate from the standard curve by more than 30 microvolts.

In order that they could be transferred conveniently from one test couple to another, couple A_2C_2 was spot welded to an appropriate Alumel washer and A_3C_3 to a Chromel one. It is not necessary to apply calibration corrections to either of these, as the head temperature need not be known accurately.

10.1 (Continued):

In the evaluation to date of the test equipment, runs have been made for each test couple with the measuring junction at several temperatures in the range 482 - 843°C (900 - 1550°F), and at each measuring junction the head temperature was varied from about 93°C (200°F) up to as high as 538°C (1000°F), the latter being as hot as the head would get without any cooling in the tempering plate and with the copper comparator at 815°C (1500°F).

The results can best be shown by plotting the difference (A_1C_1 (corrected) - A_2C_3 (uncorrected)) vs the average head temperature (avg. of A_2C_2 and A_3C_3), as is done in Fig. 12 for two of the couples tested. For all couples tested to date, curves of this kind are sensibly independent of the furnace temperature, as can be seen in Fig. 12.

Of the two couples whose behavior is shown in Fig. 12, the one which gave the upper set of data deviates from the standard curve by more than the tolerance of ±3/4% allowed for the wire itself. The lower set of data under no conditions deviates from the standard curve by more than half the aforementioned tolerance. It could therefore be reasoned with logic that the former couple is unacceptable and that the latter highly satisfactory for all limiting zone temperatures up to 538°C (1000°F). The satisfactory couple was run at 815°C (1500°F) on three different days.

The test method and apparatus can be readily reproduced by any one who wishes to use it. Experience with it to date indicates that engine-type couples in general are precision devices in which considerable confidence may be placed. It has been difficult to find one couple (namely, that shown in the upper part of Fig. 12) whose performance seems unacceptable.

In several instances, a few degrees of permanent change were experienced upon first heating the head to about 538°C (1000°F). There has not yet been any evidence that similar permanent changes occur in subsequent tests, although no couple has been cycled more than four times. Errors greater than any of those shown in Fig. 12 may be introduced during periods of rapidly changing head temperatures.

For bare gas turbine couples, the method could be applied without spot welding the test couple to A_1C_1. If the readings on the all-Alumel and all-Chromel circuits are dispensed with, then the two measuring junctions might be brought into good thermal contact by placing them together within a short length of copper or silver tubing and flattening the latter in a press. Even when spot welding is used, couple A_1C_1 can be filed or ground off, leaving the test couple essentially unharmed.

The method seems applicable equally to new and to used couples. For couples of the total temperature type, the stagnation chamber must be cut away to permit attaching the calibrated couple.

No precise control is required on the water or air flowing through the tempering plate. A Variac and ammeter provide adequate control on the furnace. On the other hand, the method requires about a day to set up and test one couple, which means that it is appropriate for evaluating selected samples but not for production testing.

10.1 (Continued):

In the equipment used to date, the tempering plate is of copper. If high thermal conductivity is essential in this plate, silver should be used to avoid oxidation. It seems probable that stainless steel or Inconel might also be used despite their poorer conductivity. It is obvious that a separate plate will have to be provided for each type of thermocouple mounting. Only off-center, flange mounted couples with threaded terminal posts have been tried thus far.

All parts of the present copper comparator block except the bottom face are surrounded by Inconel and this latter should be similarly protected against oxidation. Copper oxide is likely to be harmful to the furnace tube and to the thermoelements.

10.2 With Commercially-Available Equipment: The reliability of thermocouple systems for gas turbine engines involves, among other things, maintaining the necessary agreement as to thermoelectric behavior with a standard curve, circuits without breaks, high resistance to ground, and proper performance by the indicating instrument. The instruments needed to check each of these are more or less conventional, and they may be combined in various ways for convenience. Typical combinations capable of making some or all of the aforementioned checks are available under the trade names Jetcal and Veritherm.

By proper use, single thermocouples or groups of couples connected in parallel may be tested, in some instances without being removed from the engine. A key part of such systems is an electrically heated comparator block for each thermocouple. The comparator may be made portable, in which case it must have a built-in heating element and a standard thermocouple or resistance thermometer. The comparator is designed so that the measuring junction of a thermocouple to be tested attains the temperature indicated by the standard sensing element. If the latter is a thermocouple, as many of the standards as desired may be connected in parallel if equal resistances are maintained between branch points.

11. REFERENCE DATA ON CHROMEL AND ALUMEL AND ON THE TEMPERATURE SCALE:

11.1 Composition: Chromel and Alumel are nickel-base alloys that were manufactured by the Hoskins Manufacturing Company since their invention in 1906 by the late A. L. Marsh, upon whose many patents the Company was founded.

Chromel is nominally 90% Ni + 10% Cr, and Alumel is 94% Ni + 3% Mn + 2% Al + 1% Si, but both, like most other alloys, also contain many minor and trace elements. Because the thermoelectric properties of any alloy are very sensitive to composition changes, each element must be very closely controlled in the manufacturing process. This is done by the use of virgin metals of known composition, careful control of melting practices in induction furnaces, and the supervision of only the most experienced melters. Even then, sizeable quantities of the metal are not suitable for processing into wire which will meet the close limits of the thermocouple guarantee.

11.1 (Continued):

A few minor changes have been made in the alloys to improve their service performance, and a few others to compensate for changes in raw material compositions, but essentially the alloys have been changed very little from what they were originally. Nor can they be changed to any great extent and still meet the thermoelectric requirements.

11.2 Processing: The alloys are cast into iron molds, hot-rolled and then cold-drawn to wire sizes. Each stage of processing has its effect on thermal emf. The final anneal is, of course, designed to yield the best combination of uniformity and stability. The wire may be supplied either with an oxide or a bright finish, and in many applications either could be used with identical results. However, there are special conditions under which one or the other may be preferred. Originally only an oxide finish was used because of its dielectric properties, and perhaps some degree of protection from certain atmospheres. However, with new applications the bright finish has found more and more usage, particularly because of recent findings for Chromel of reactions between the oxide and metal in closely confined spaces.

11.3 Physical Properties: Some of the physical properties of the thermoelements are as follows:

	Chromel	Alumel
Melting Point	1427°C; 2600°F	1399°C; 2550°F
Coefficient of thermal expansion, 68°-212°F, parts per million per °F	7.3	6.7
Heat capacity, calories per gm °C or Btu per lb °F	0.107	0.125
Specific gravity	8.73	8.60
Tensile strength, annealed, lb per in^2 kg per cm^2	95 000 6 679	85 000 5 976
Tensile strength, work hardened, lb per in^2 kg per cm^2	165 000 11 600	170 000 11 951
Curie temperature	-120°C; -184°F	+170°C; +338°F
Magnetic at room temperature	No	Yes

Coefficient of Resistivity

Temperature °F	Temperature °C	Chromel Microhm-cm	Chromel Ohms/cmf*	Alumel Microhm-cm	Alumel Ohms/cmf*
68	20	70.6	425	29.4	177
200	93	72.6	437	34.4	207
400	204	75.6	455	40.9	246
600	316	78.5	472	44.4	267
800	427	80.6	485	47.0	283
1000	538	84.1	506	49.7	299
1200	649	85.4	514	52.4	315
1400	760	87.6	527	55.0	331
1600	871	90.4	544	58.0	349
1800	982	92.6	557	60.8	336
2000	1093	94.8	570	63.5	382

*cmf = circular mil ft

Thermal Conductivity

Temperature °C	Temperature °F	Chromel watts/cm °C	Chromel Btu/ft hr °F	Alumel watts/cm °C	Alumel Btu/ft hr °F
100	212	0.190	10.98	0.296	17.10
200	392	0.209	12.08	0.318	18.38
300	572	0.228	13.18	0.350	20.23
400	752	0.247	14.27	0.381	22.02
500	932	0.266	15.37	0.412	23.81

11.4 Stability in Service: Chromel and Alumel thermoelements may be used from -184°C (-300°F) to about 1260°C (2300°F) in oxidizing atmospheres. High-temperature life is short in reducing and in alternately oxidizing and reducing atmospheres. Regardless of the nature of the surrounding atmosphere, Alumel undergoes changes in crystal structure when maintained at high temperatures for extended periods of time. These changes have a minor influence upon the thermoelectric properties of the alloy, but render it considerably weaker mechanically. Sulfur is known to accelerate intergranular corrosion in Alumel considerably, but even this process does not change its thermoelectric behavior significantly.

Atmospheres that are oxidizing to chromium and aluminum but reducing to oxides of nickel can cause rapid corrosion. This is particularly true for Chromel and this process can cause the emf at a given temperature to be much lower than the reference value.

The stability of Chromel-Alumel thermocouples in an oxidizing atmosphere is discussed in the Bureau of Standards Research Paper RP 1278 (8). For example, from Fig. 9 of that report, an 8 gauge Chromel-Alumel thermocouple operating at 871°C (1600°F) would be in error by about 1.67°C (3°F) after 1000 h service at that temperature. An 18 gauge Chromel-Alumel thermocouple would be in error by about 1.67°C (3°F) after 400 h and about 3.33°C (6°F) after 1000 h, and a 22 gauge Chromel-Alumel thermocouple would be in error by about 1.67°C (3°F) after 100 h and by about 3.89°C (7°F) after 1000 h at 871°C (1600°F).

11.4 (Continued):

These conditions, oxidizing in clean air, are ideal for Chromel-Alumel service. However, there is no limit to how bad a thermocouple can be under severe corrosive conditions. One of the most common corrosive agents is sulfur, particularly in a reducing atmosphere as hydrogen sulfide gas. It will corrode both Chromel and Alumel, and will cause rapid breakage of the Alumel by localized penetration. Atmospheres that are marginally oxidizing, that is oxidizing to the chromium or aluminum but reducing to the oxides of nickel, can cause rapid corrosion in the approximate temperature range of 815 - 1038°C (1500 - 1900°F). This is particularly true of the Chromel, and it can cause large negative errors in this alloy, giving a low emf reading. Marginal atmospheres can actually be produced from air by partial consumption of the oxygen by oxidation in a restricted space.

These corrosive conditions have characteristically been combatted in the past by thermocouple protection tubes. When the tubes have been clean and free from sulfur-bearing oils, refractories, etc., in their interiors, and have been of the proper diameter-to-length ratios to permit adequate ventilation of the interior by outside air, they have served adequately. Applications where response is of prime importance preclude the use of large protection tubes.

11.5 Thermocouple Lead Wire: Chromel and Alumel lead wires are of the same nominal composition as Chromel and Alumel thermocouple wires. They will conform to the standard curve for thermocouple wire within 2.2°C (±4°F) up to 204°C (400°F).

11.6 The International Practical Temperature Scale: To measure any temperature, it is first necessary to have a temperature scale, and for this purpose the International Practical Temperature Scale of 1968 (9) is in almost universal use. This scale is based upon a number of fixed and reproducible equilibrium temperatures (fixed points) to which numerical values are assigned, and upon specified formulas for the relationships between temperature and the indications of certain instruments calibrated at these fixed points. Within the range of interest in gas turbine engines, the following fixed points are of importance:

Fixed Point	Temperature °C	Temperature °F
Ice Point	0	32
Normal boiling point of water	100	212
Normal boiling point of sulfur	444.600	832.28
Freezing point of silver	960.8	1761.4
Freezing point of gold	1063.0	1945.4

11.6 (Continued):

For interpolating between the ice point and the freezing point of antimony (630.3-630.7°C), temperature t is defined by the formula

$$R_t = R_o(1 + At + Bt^2) \quad (23)$$

in which R_t and R_o are the resistances of the platinum resistance thermometer at t and at 0°C, respectively, and A and B are constants determined from measurements of resistance at the steam and sulfur points. In addition, other characteristics of the resistance thermometer are specified, but these need not be detailed here.

From the freezing point of antimony to the gold point, the temperature t is defined by the formula

$$E = a + bt + ct^2 \quad (24)$$

in which E is the emf of a standard Pt-PtRh thermocouple with reference junction at 0°C and measuring junction at temperature t°C. The constants a, b, and c are calculated from measured values of emf at the antimony, silver, and gold points. Again, the standard thermocouple is further stipulated, but other characteristics need not be reviewed here.

The International Practical Temperature Scale of 1968 above the gold point is based upon the temperature of this point, upon Planck's radiation law, and upon an accepted value of 1.438 cm deg for the constant c_2 in that law. The optical pyrometer is used for purposes of extrapolation above the gold point.

12. BIBLIOGRAPHY:

(1) W. F. Roeser and H. T. Wensel, Methods of Testing Thermocouples and Thermocouple Materials. J. Research Nat. Bur. Standards 14, 247 (1935).

(2) W. H. McAdams, Heat Transmission, 3rd ed. McGraw-Hill, New York (1954).

(3) E. F. Fiock and A. I. Dahl, Temperature Measurements in High-Velocity Streams of Hot Gas. Proc. Iowa Thermodynamics Symposium, p. 190. State Univ. Iowa, Iowa City (April 1953). Also NBS Report 3164 (April 1953).

(4) A. I. Dahl and E. F. Fiock, Response Characteristics of Temperature-Sensing Elements for Use in the Control of Jet Engines. J. Research Nat. Bur. Standards 45, 292 (1950).

(5) M. W. Carbon, H. J. Kutsch and G. A. Hawkins, The Response of Thermocouples to Rapid Gas-Temperature Changes. Trans. Am. Soc. Mech. Engrs. 72, 655 (1950).

(6) A. I. Dahl and E. F. Fiock, Use of Parallel Thermocouples in Turbojet Engines. USAF Technical Report No. 6546 (July 1951).

12. (Continued):

(7) A. I. Dahl and E. F. Fiock, Circuitry Errors of Ladder-Type Thermocouple-Harness Assemblies. WADC Tech. Report 53-4 (Dec. 1952).

(8) A. I. Dahl, Stability of Base-Metal Thermocouples in Air from 800 to 2200°F. J. Research Nat. Bur. Standards 24, 205 (1940).

(9) International Practical Temperature Scale of 1968, National Bureau of Standards.

(10) National Bureau of Standards Monograph 125.

(11) "Manual on the Use of Thermocouples in Temperature Measurement" ASTM Special Technical Publication 470B, July 1981.

(12) "Temperature, Its Measurement and Control in Science and Industry" ISA, Vol. 3 (1962) and Vol. 4 (1972).

13. FIGURE LEGEND:

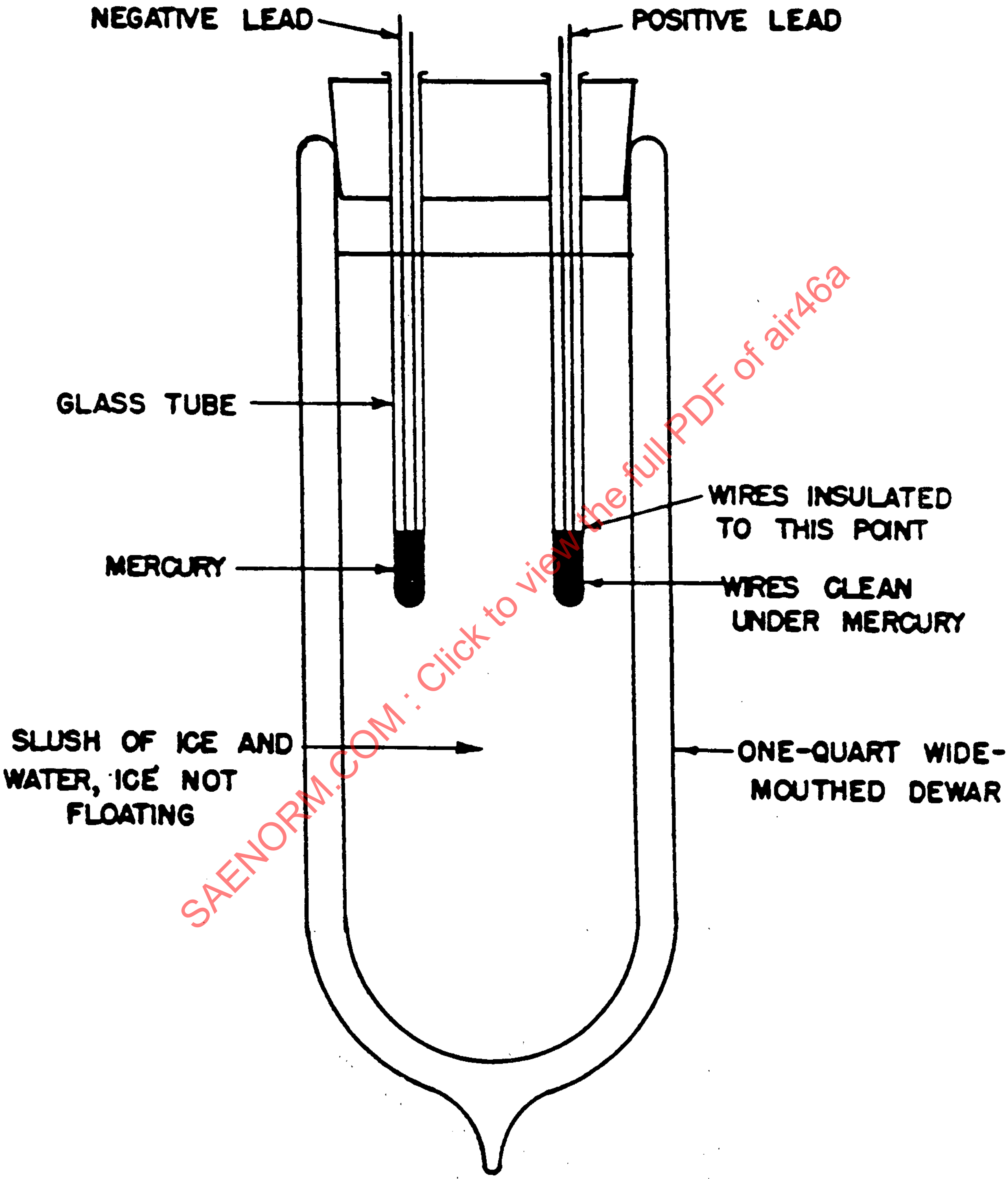

FIGURE 1 - Recommended Reference Junction at Ice Point

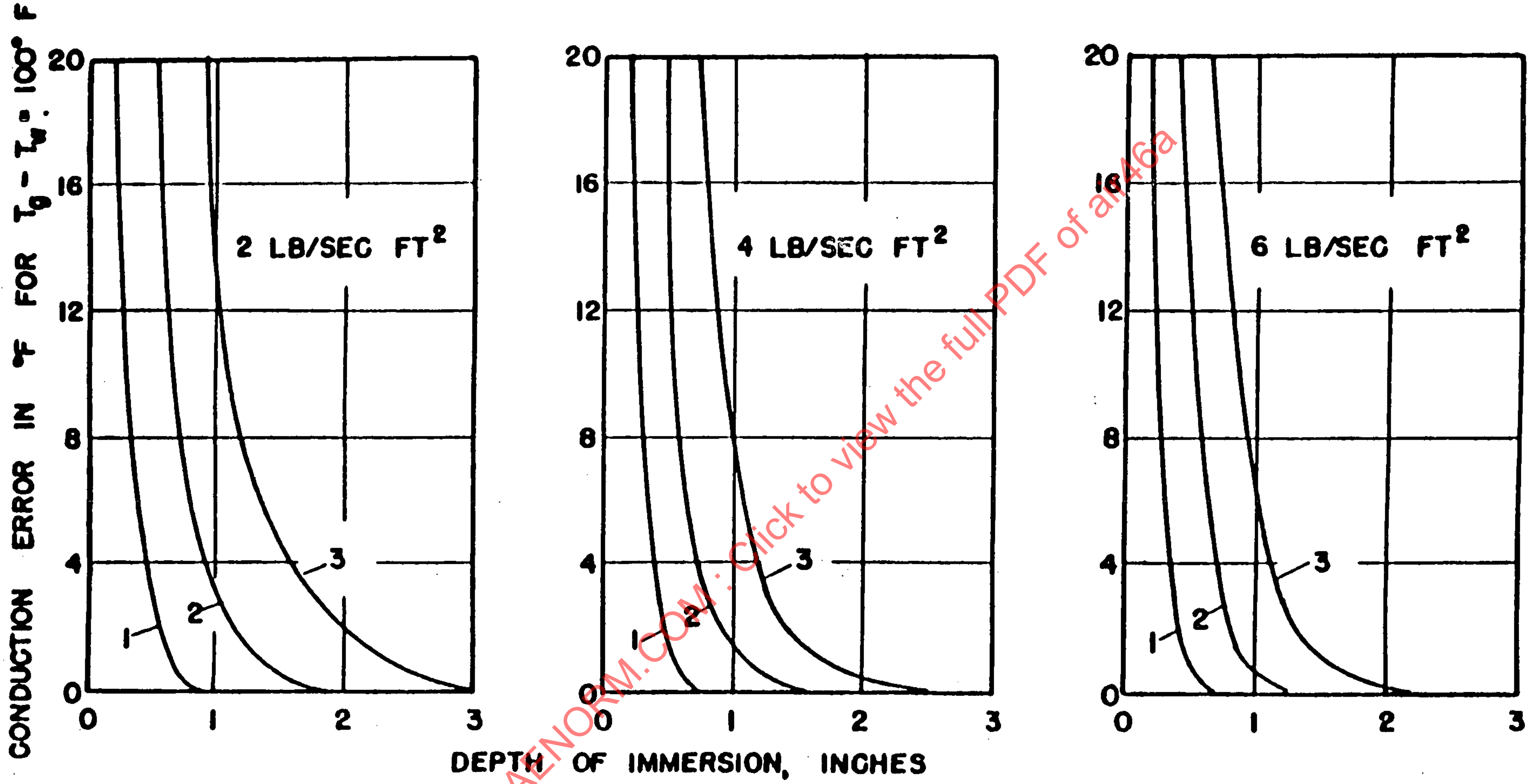

FIGURE 2 - Effect of Immersion on Conduction Error. Curves 1 and 2 Apply for Bare No. 22 and No. 14 Chromel-Alumel Thermocouples, Respectively; Curve 3 is for a 0.25 in O.D. x 0.17 in I.D. Stainless Steel Tube

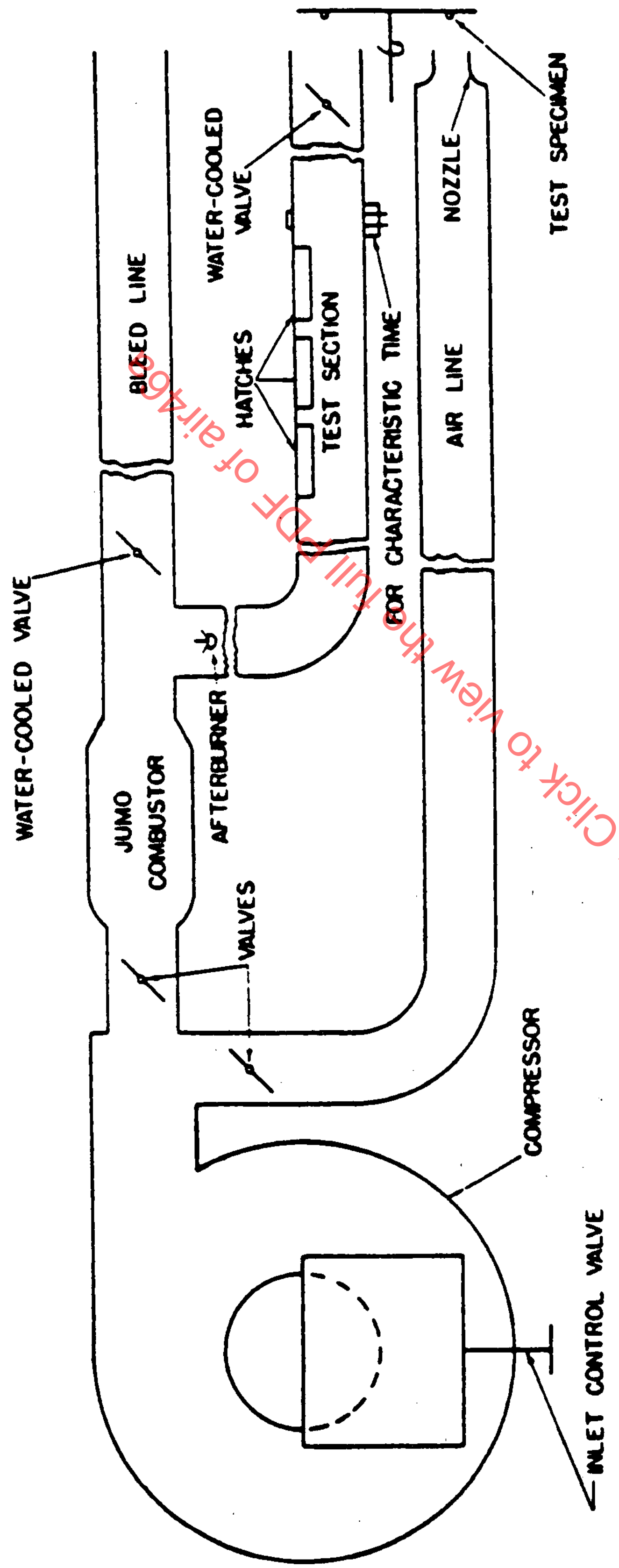

FIGURE 3 - Composite Diagram of Supplementary Test Facilities

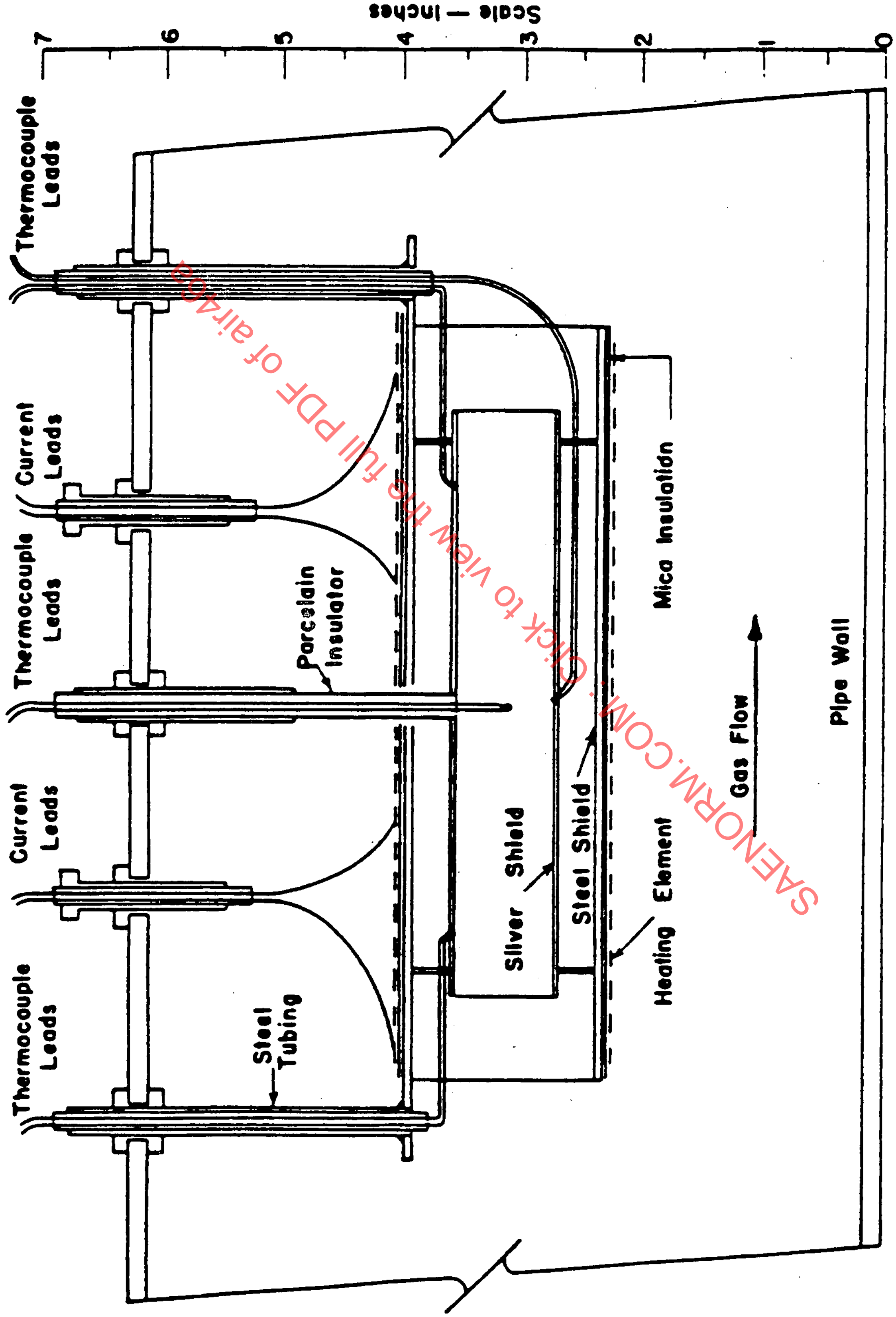

FIGURE 4 - NBS Laboratory Standard for Determining the Combined Correction for Conduction and Radiation