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MINIATURE SHEATHED THERMOCOUPLES FOR TURBINE BLADE TEMPERATURE MEASUREMENT

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16. Abstract

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SUMMARY

An investigation was made of sheathed thermocouples for turbine blade temperature measurements. Tests were performed on Chromel-Alumel sheathed thermocouples with both two-wire and single-wire configurations. Sheath diameters ranged from 0.25 to 0.76 millimeter, and temperatures ranged from 1080 to 1250 K. Both steady-state and thermal cycling tests were performed for times up to 450 hours. Special-order and commercial-grade thermocouples were tested. The tests showed that special-order single-wire sheathed thermocouples can be obtained that are reliable and accurate with diameters as small as 0.25 millimeter. However, all samples of 0.25 millimeter-diameter sheathed commercial-grade two-wire and single-wire thermocouples that were tested showed unacceptable drift rates for long-duration engine testing programs. The drift rates were about 1 percent in 10 hours. A thermocouple drift test is recommended in addition to the normal acceptance tests in order to select reliable miniature sheathed thermocouples for turbine blade applications.

INTRODUCTION

The purpose of this investigation was to evaluate the performance of miniature sheathed Chromel-Alumel thermocouples for turbine blade temperature measurement. An historical review of the literature concerning turbine blade temperature measurements shows a definite trend to smaller thermocouple size requirements. This is so because air-cooled turbine blade configurations are becoming smaller with more intricate cooling schemes. The blades often have thinner walls, which require a corresponding reduction in thermocouple size. As the size of sheathed thermocouples is reduced, the associated failure rates increase substantially.

A list of thermocouple terminology is presented in table I. The ASTM designations are obtained from reference 1. ASTM does not present a term to describe a thermocouple formed from two dissimilar individually sheathed thermoelements. Therefore, for the purpose of this report this type of thermocouple is referred to as a single-wire sheathed thermocouple. For ease of distinction, the standard sheathed thermocouple (which has both thermoelements in the same sheath) is referred to in this report as a two-wire sheathed thermocouple.

Some preliminary tests were performed with commercial-grade two-wire sheathed thermocouples with diameters from 0.76 to 0.51 millimeter. In the final testing program, special-order single-wire sheathed thermocouples from 0.51 to 0.25 millimeter in diameter and commercial-grade single-wire sheathed thermocouples 0.25 millimeter in diameter were tested. Previous experience had indicated that the single-wire configuration might be more reliable in these smaller sizes. In addition, commercial-grade two-wire sheathed thermocouples 0.25 millimeter in diameter were tested in order to compare thermocouples of the same size in different configurations.

The thermocouple tests were performed primarily on simulated turbine blades. They included steady-state and cycling tests to simulate engine testing programs and were performed for times up to 450 hours. In addition, some 0.25-millimeter-diameter special-order single-wire thermocouples were tested on an actual turbine blade in a test engine for 30 hours. The temperature range of the tests was from 1080 to 1250 K. The problem of thermocouple drift was considered.

This report covers part of a continuing effort at the Lewis Research Center in the development and testing of thermocouples.

HISTORICAL REVIEW

The standard method of installing thermocouples for turbine blade temperature measurement has been embedding the thermocouple in the blade. This method has been in use since about 1947 at the Lewis Research Center. A groove is cut into the turbine blade, the thermocouple is secured in the groove in some manner, and the groove is filled or covered to return the blade to its original aerodynamic profile. However, strength and heat-transfer characteristics are affected by the grooving process, and therefore the size and number of grooves made in a given blade are limited.

The thermocouple configuration used in these applications has been the two-wire sheathed thermocouple, in which the thermocouple is placed in a two-hole ceramic insulator, which is, in turn, placed in a protective metallic sheath, usually stainless steel or Inconel. Originally a solid ceramic was used, and the assembly was fitted together with close tolerances, but later a crushable ceramic was used in conjunction with a swaging operation to obtain a compact assembly with firm wire support and a smaller outside diameter for a given wire size.

One of the first investigations to confront the problem of thermocouple miniaturization is described in reference 2. The problem was to fit a thermocouple in a 0.25-millimeter-deep groove for measuring temperatures of thin-walled, air-cooled turbine blades. The possibility of swaging was considered, but attempts to swage from a 1.00-millimeter diameter (the diameter of the smallest sheathed assembly then available) down to a 0.25-millimeter diameter failed. Attempts were also made to swage the assembly into an oval shape with the minor diameter equal to 0.25 millimeter, but again the reduction was too great. The possibility of a single wire in each sheath was considered. The smallest wire size that was practical for this application was determined to be 0.13 millimeter and the smallest sheath diameter 0.25 millimeter. However, the appropriate single-hole ceramic to go with this assembly was not available to the technology of that time, and the idea was abandoned. In order to achieve the goal, the arrangement shown in figure 1 was used. The sheathed assembly was terminated at the point in the blade where the wall thickness could no longer accommodate it, and only the bare wires were extended into the 0.20- by 0.25-millimeter grooves. The grooves were first insulated with a thin coating of ceramic cement and then filled with the same material. Both single-wire and double-wire grooves were used. Failure rates were reported to be about 15 percent in times ranging from 2 to 30 hours in actual engine tests for blade temperatures from 640 to 1050 K. Most of these failures were traced to erosion of the cement. In this installation the cement, serving as the outer protective coating as well as the insulator, was not as durable as a metallic sheath.

Reference 3 proposes coaxial construction with one of the thermoelements as the sheath. The main disadvantage of this arrangement in a turbine blade application is that the protective function of a durable metallic sheath to both the thermoelements is lost when one of the elements is itself the sheath.

Reference 4 reports a study of a thermocouple for a gas turbine engine application, a coaxial Chromel-Alumel thermocouple in which one of the thermoelements (Alumel) was chosen as the protective sheath. The Alumel thermoelement was chosen because it was the least susceptible to oxidation, but it could not withstand the conditions, even though protective coatings were tried.

Reference 5 reports that Colclough used a single-thermoelement thermocouple in which the Stellite blade was used as the other thermoelement. Easier installation and smaller grooves with consequently smaller stresses are advantages when single wires are used. The main disadvantage of this arrangement is that the output of the pair is not standard, so that a special calibration is required.

The main advantage of a single-wire sheathed thermocouple over the conventional two-wire sheathed thermocouple is cited by reference 3: "The insulation layer between thermocouple components would be increased by a factor of about 3 for a given sheath diameter." This is illustrated in figure 2 for a typical 0.25-millimeter-diameter sheath. Based on the nominal values for wire size and wall thickness given in reference 1, the ratio of interelement insulation for single-wire sheathed thermocouples to that for two-wire sheathed thermocouples is approximately 2.5. Thus, an increase in reliability should be expected for the same sheath diameter, because the greater amount of insulation will decrease the likelihood of a physical shunting between the elements. Also, it provides a greater barrier to high-temperature chemical degradation between the elements. Both physical shunting and chemical degradation may result in a gradual drift in the electromotive-force (emf) output of the thermocouple with time.

With smaller sheath diameters, the exact location of the thermocouple junction in a blade is determined with greater accuracy. In situations where the temperature gradient across a cooled blade wall can be several hundred degrees, the exact depth of this junction is important to know for heat-transfer calculations.

The main disadvantage of making a thermocouple from two sheathed thermoelements is the increase in mass of the resulting thermocouple. However, with thin-walled blades, the increased mass and the broader groove can be tolerated in order to decrease the depth of the groove.

TEST PROGRAM

Preliminary Investigation

A preliminary testing program was conducted on commercial-grade two-wire sheathed thermocouples to determine at which point problems due to miniaturization developed. The results determined the starting point for a final testing program for the evaluation of single-wire sheathed thermocouples. Five 0.76- and nine 0.51-millimeter-diameter thermocouples were tested on five different simulated turbine blades. All the thermocouples were tested for 75 to 100 hours at a steady-state temperature of 1140 K. In addition, the thermocouples were exposed to thermal cycling up to 12 hours. No problems of drifting or adverse effects due to thermal cycling were observed on the 0.76-millimeter-diameter thermocouples. Of the nine 0.51-millimeter-diameter thermocouples, one exhibited a degree of drift which caused the thermocouple to exceed the manufacturer's accuracy specifications, and another exhibited erroneous readings during thermal cycling.

Final Test Program Selection

From the results of the preliminary investigation with simulated turbine blades and from the experience of others at this laboratory with actual turbine blade testing programs, it was determined that problems of reliability begin to develop in two-wire sheathed thermocouples at diameters of about 0.51 millimeter. Since an increase in reliability was expected from single-wire sheathed thermocouples compared to two-wire sheathed thermocouples for the same outside diameter, the performance evaluation of single-wire thermocouples began with 0.51-millimeter diameters and continued down to the smallest size obtainable, which was 0.25 millimeter in diameter. Initially single-wire sheathed thermocouples were not available commercially, so it was necessary to obtain these in small quantities on special order. Later, both single-wire and two-wire 0.25-millimeter-diameter sheathed thermocouples were available commercially. The testing program was extended to include these thermocouples. Test results for special-order and commercial-grade thermocouples were compared. The next section pertains to the final test program.

APPARATUS AND TEST PROCEDURE

Simulated Turbine Test Blade

The front of a typical simulated turbine test blade assembly is shown in figure 3. This surface contained three rectangular grooves down the center of the span in which three sheathed thermocouples were installed. The thermocouple junctions were located $2\frac{1}{2}$ centimeters from the right end of the blade. A test flame was applied to the front of the blade. The back of the blade had a bare-wire reference thermocouple spot-welded to the surface opposite the center test thermocouple junction. Platinum foil radiation shields (not shown) were placed over the area of the reference thermocouple junction to equalize the indicated temperature on the two sides of the blade. Holes were drilled in the blade to inhibit chordwise heat flow and thus provide a more uniform temperature in the junction region. The blade was about $1\frac{1}{2}$ millimeters thick.

Thermocouples

The thermocouples used in these experiments were Chromel-Alumel and had magnesium oxide insulation and Inconel sheaths. Two-wire and single-wire special-order and commercial-grade sheathed thermocouples were tested. The special-order thermocouples were purchased in small quantity from nonproduction runs with specifications corresponding to those used for standard commercial two-wire sheathed thermocouples, including a ±3/4 percent limit of error. The diameters were 0.51, 0.38, and 0.25 millimeter. Table II gives the number of simulated turbine test blades tested, the blade material, the number of thermocouples and their size, and the description of the thermoelement.

Installation technique. - The installation technique for two-wire sheathed thermocouples is essentially that described in reference 6. A cross-sectional sketch of a single-wire sheathed thermocouple away from the junction is shown in figure 4(a). The two sheathed thermoelements are laid side by side in the rectangular groove after a small amount of insulation has been removed from the open ends of each assembly. This allows the single wires from each assembly to be placed in closer proximity to each other prior to end closure. A contoured peening tool is then applied to flatten the tubes at the junction region. The flattened end (fig. 4(b)) is then laser- or spot-welded to form a seal and also to secure the thermocouple to the bottom of the groove. This multipurpose operation forms the thermocouple junction, seals the ends of the thermoelements, and thermally and mechanically attaches the junction region to the blade. The groove void above the junction region is filled in with a contoured metal slug. Then a thin cover plate (fig. 4(a)), whose top surface is approximately flush with the blade surface, is spot-welded along the surface edges of the remainder of the groove. This cover plate retains and protects the swaged thermocouple sheath and maintains the aerodynamic blade surface, but still allows free expansion of the assembly. In the simulated blades, the three test junctions were located on the same chord $2\frac{1}{2}$ centimeters from the end of the blade. On an actual blade, the cover plate and metal filled regions would all be dressed down to form a smooth aerodynamic surface. Another installation technique with several similar features is described in reference 7.

Acceptance tests. - The thermocouple acceptance checking procedures are described in detail in reference 6. They include a sheath integrity test, an insulation resistance test, a thermocouple homogeneity or spurious emf test, and a junction integrity test. The acceptance testing procedure was modified for the spurious emf tests for the single-wire thermocouples. Here, the two ends of the same wire formed the circuit, and deviations from zero output were observed as a flame is passed over the length of the sheathed wire assembly. All the thermocouples used in these tests were subjected to the same rigid acceptance checks and were installed by the same person in the most repeatable manner possible.

Burner Test Apparatus

The simulated blade assembly was cantilever mounted with the span and chord planes in a horizontal position (U channel facing up) over a Meker burner. This natural gas and air burner produced a flame which was $2\frac{1}{2}$ centimeters in diameter and whose temperature ranged to 1350 K. The burner was always centered at the midchord position during heating. However, the blade mounting support could be moved in a spanwise direction to relocate the blade over the burner at various span positions.

For cyclic heating the burner was pneumatically actuated to and from the blade in a chordwise direction. An automated timing system cycled the burner every 6 minutes. This cycle time was long enough to allow the blade to reach and maintain the desired temperature but short enough to allow life cycling data to be obtained. Self-balancing strip-chart potentiometers were used to record the test and reference thermocouple outputs continuously.

Test Procedures

The testing program consisted of the following parts:

(1) Three separate simulated blades (1, 2, and 3 of table II) were tested with three 0.51-, three 0.38-, and three 0.25-millimeter-outside-diameter single-wire special-order thermocouple pairs, respectively. The tests consisted of the following steps:

(a) One hundred hours of steady exposure at 1140 K with the flame applied to the junction

(b) Four hours of thermal cycling consisting of 6 minutes of heating with the flame applied to the junction and 6 minutes of cooling with the flame removed for a total of 20 cycles, to simulate thermal cycling in engine testing

(c) Same as step (b), except with the flame 3.8 centimeters from the junction during the heating cycle, to simulate thermal cycling in engine testing with the hottest part of the blade away from the junction

(d) Repetition of step (b) until failure occurs

(2) Six special-order single-wire thermocouples of 0.25 millimeter diameter were mounted on a turbine blade in a J-75 test engine. The test ran for 30 hours at blade temperatures up to 1140 K.

(3) Tests were performed on commercial-grade single-wire and two-wire thermocouples of 0.25-millimeter diameter in simulated turbine blades. Three blades were run, two with single-wire thermocouples from different manufacturers and one with two-wire thermocouples (blades 4, 5, and 6 of table II). All these blades were tested for 100 hours at a steady-state temperature of 1140 K. In addition, one of the blades (4) was subjected to an additional 350 hours of thermal cycling to investigate long-term drift characteristics.

(4) A further test used to investigate the drift characteristics was to apply the 1140 K flame at various points along the blade span while measuring the output of the test and reference thermocouples. The test was performed over a 5-centimeter length of a blade from the thermocouple junction towards the connector. This test will indicate if secondary junctions have formed along the wire.

RESULTS AND DISCUSSION

Preliminary Investigation

The preliminary testing of commercial-grade two-wire sheathed thermocouples to determine at which point problems developed because of miniaturization revealed the following: No problems of drifting or adverse affects of thermal cycling were observed on the five 0.76-millimeter-diameter thermocouples. Of the nine 0.51-millimeter-diameter thermocouples tested, one exhibited a degree of drift which caused the thermocouple to exceed the manufacturer's accuracy specifications and another exihibited erroneous readings during thermal cycling. Efforts were therefore concentrated on thermocouples 0.51 millimeter in diameter and smaller.

Special-Order Thermocouples

Simulated blade tests. - The results of the special-order thermocouple tests (blades 1, 2, and 3) are shown in figure 5. The ordinate is a temperature difference, taken with respect to the average temperature of the three test thermocouples on each blade T_{av}. This temperature was chosen because the reference thermocouple exhibited more drift than the test thermocouples in all three tests. At the start of each test, the reference thermocouple agreed with the test thermocouples to within 1 percent. At the end of the tests on the 0.25-millimeter-diameter thermocouple (blade 3), the original reference was removed and a new one installed. Values from this new reference thermocouple agreed with final values from the test thermocouples to within less than 1 percent which verified that the drift was being correctly attributed to the reference thermocouple. It should be noted that the reference thermocouples were attached to the surface without any cover protection. Physical inspection of them after the tests revealed severe structural degradation.

Although the data were taken continuously, only periodic points are given in figure 5. The data for the cycling period were taken for the part of the cycle when the thermocouples were in the flame at their final equilibrium temperatures. For blades 1 and 2 (figs. 5(a) and (b)), the tests were terminated after about 250 hours of testing because of the stainless-steel blade buckled because of thermal creep. For the remainder of the tests of this report, simulated turbine test blades of Hastelloy were used to eliminate this problem. Fifty hours of the 0.25-millimeter-diameter thermocouple test (blade 3) were run at 1240 K (steady state) because this temperature was of interest for future turbine blade applications. No degradation effects were observed on the test thermocouples. The results of the special-order thermocouple tests were zero failures in all nine thermocouples, no noticeable drifting in times up to 425 hours, and maximum deviation between thermocouples of each group of ±6 K (±1/2 percent).

J-75 engine test. - It should be noted that gas stream velocity, vibration, and gravitational loading of thermocouples were not simulated in the foregoing testing procedures. To introduce these variables, six of the 0.25-millimeter-diameter thermocouples from the special order of material were installed in an actual turbine blade on a J-75 test engine involved in turbine blade cooling studies. The acceptance checking and installation techniques were the same as those used in this program. The tests were run with gas temperatures ranging from 1220 to 1640 K and cooled blade temperatures up to 1140 K. Total test time was 30 hours at 9000 rpm. Five of six thermocouples performed satisfactorily, with the one failure being due to faulty installation.

Commercial-Grade Thermocouples

The results of the steady-state tests on commercial-grade thermocouples (blades 4, 5, and 6) are presented in figures 6 and 7 and show the drift of the temperatures of the test thermocouples compared to that of the reference thermocouple T_{ref}. For these shorter duration tests the reference thermocouples were stable. In these experiments, all the test thermocouples experienced considerable drift. The single-wire thermocouples drifted 75 to 125 K in 100 hours (fig. 6), and the two-wire thermocouples drifted 135 to 140 K in 100 hours (fig. 7). A possible quality difference between the products of the two manufacturers may be responsible for the slightly different drift rates of figures 6(a) and (b). The time it took for these thermocouples to drift 1 percent of their original value was 10±2 hours.

Figure 8 shows the results of further testing with the blade used to obtain the data of figure 6(b) (test blade 4). The first 100 hours of testing are those shown in figure 6(b). For the next 350 hours the blade was subjected to thermal cycling (a total of 1750 cycles). The data show further drift before finally reaching a stable value. Such drift patterns have previously been noted (ref. 8).

Drift Characteristic

The test used to investigate the drift characteristic was to apply the 1140 K flame at various points along the blade span while monitoring the output of the test and reference thermocouples. The results of such a test are shown in figure 9. Figure 9(a) shows the thermocouple output on a typical blade whose thermocouples experienced no degradation. The farther the flame is moved from the junction, the lower the temperature indicated by the thermocouple; this is what would be expected since with the flame at a distance the junctions receive their heat by conduction. But when this same test was applied to a blade (test blade 4) whose thermocouples had experienced a considerable amount of drift, the output of the thermocouples was as shown in figure 9(b). The point of maximum temperature indication of the test thermocouples was between 1 and $2\frac{1}{2}$ centimeters from the original junction. This was the area of the blade which experienced the greatest temperature gradient during the previous high-temperature tests. It appears as if a broad band of secondary junctions had formed in this region and caused the point of maximum temperature indication to occur when the flame was applied in this region and the temperature at the original junctions to be depressed when the flame was applied at these junctions. Note that in this figure the reference thermocouple, which experienced no drift, has the same curve as all the thermocouples in figure 9(a).

Discussion of Drift

A type of failure which occurred in the testing program was thermocouple drift. Drift was previously defined in a general way as a gradual change in the emf output of the thermocouple with time due to physical or chemical degradation. This occurred in one out of nine of the 0.51-millimeter-diameter commercial-grade samples in the preliminary testing and in all nine of the 0.25-millimeter-diameter commercial-grade samples in the final phase of the testing program, as well as in several of the unprotected reference thermocouples. The nine 0.25-millimeter-diameter commercial-grade thermocouples had passed the acceptance checking tests and suffered no failures due to installation procedures. None of the special-order thermocouples exhibited drift over ±1/2 percent during steady-state and cyclic testing of up to 425 hours.

According to reference 9, "thermocouple drift may be associated with change in the composition or structure of the thermocouple materials when exposed to a thermal gradient. Chemical composition changes occur by exchange of material between the wires and also between the wires and the surrounding media. Some of the mechanisms involved are diffusion, chemical action, selective evaporation of an alloy constituent, . . . Among the factors affecting drift are insulator and sheath materials, assembly geometry, fabrication method, gas environment, rate of thermal cycling, . . ." There are other factors including wire diameter. The smaller the wire, the bigger the drift for the same conditions, because the surface-to-volume ratio is greater.

Reference 8 reports that the preferential oxidation of the chromium in the positive type K thermoelement is an important factor in the drift mechanism. References 10 and 11 cite contaminants and preferential oxidation of the positive element as causes of drift in type K thermocouples. Reference 12 attributes lack of stability to selective oxidation in the Chromel wire. Reference 6 mentions voids in the insulation and dielectric breakdown in the insulation as factors affecting the secondary junctions which contribute to the drift mechanism. Related to this, reference 13 attributes lack of proper insulation compaction to thermocouple failure rates and recommends additional in-house swaging when necessary to increase insulation density.

Reference 8 reports that improved oxidation-resistant alloys can be developed to provide resistance to preferential oxidation. This provides a more stable thermocouple with a longer total service life. Such a thermocouple in finer diameter may be used to achieve an equivalent or better stability than conventional type K thermocouples of larger diameter. In addition, reference 8 speculates that an even more stable thermocouple could be built if it did not have to match type K emf tables. The use of this special material has solved the problem of how to obtain long life at high temperature in a jet engine application (ref. 4).

It is apparent that different levels of material quality and/or fabrication quality controls were involved in the special-order and commercial-grade 0.25-millimeter-diameter single-wire thermocouples. This was indicated by the variation in drift rates. No other explanation for these differences was uncovered in this investigation. An unacceptable drift rate was not revealed by the present acceptance checking tests. A long-duration, steady-state high-temperature acceptance test would serve to check this aspect of thermocouple reliability.

SUMMARY OF RESULTS

The performance of miniature Chromel-Alumel thermocouples for turbine blade temperature measurement was evaluated as part of a continuing program at the Lewis Research Center in the development and testing of thermocouples for various applications. Tests were performed on both single-wire and two-wire sheathed thermocouples with wire diameters from 0.76 to 0.25 millimeter at temperatures up to 1250 K for times up to 450 hours.

Preliminary investigations with 0.76- and 0.51-millimeter-diameter commercial-grade two-wire sheathed thermocouples showed that problems of reliability developed with this configuration at diameters of about 0.51 millimeter. As a result, the final test program was set up to evaluate special-order single-wire sheathed thermocouples from 0.51 to 0.25 millimeter in diameter and to compare commercial-grade single-wire and two-wire sheathed thermocouples 0.25 millimeter in diameter.

The 0.51-, 0.38-, and 0.25-millimeter-diameter single-wire thermocouples obtained from a small-quantity nonproduction run (before such thermocouples were commercially available in quantity) had negligible drift (within ±1/2 percent) for times up to 425 hours when tested in simulated turbine blades. Five out of six such thermocouples (0.25-mm diam) installed in a cooled turbine blade on a jet engine test of 30 hours total time performed satisfactorily at blade temperatures up to 1140 K.

Commercial grade 0.25-millimeter-diameter sheathed thermocouples of both two-wire and single-wire geometries (now commercially available in quantity) exhibited considerable drift with time. The single-wire thermocouples drifted 75 to 125 K in 100 hours, and the two-wire thermocouples drifted 135 to 140 K in 100 hours. Further tests revealed that these thermocouples performed as if a band of secondary thermocouple junctions had formed in the zone of greatest temperature gradient.

Stringent thermocouple acceptance tests (i.e., for sheath integrity, insulation resistance, thermoelement homogeneity, and junction integrity) and fabrication techniques have reduced failure rates to a negligible level. However, the drift associated with miniature (0.25-mm diam) commercial-grade sheathed thermocouples used for turbine blade measurements is beyond acceptable limits for long-duration testing programs. The drift rate was about 1 percent in 10 hours. Special-order thermocouples and previous work dealing with thermocouple stability indicate that long-term drift may be considerably reduced by using high-purity materials of construction and a higher degree of fabrication quality control. A long-duration, steady-state temperature acceptance test would serve to check this aspect.

Lewis Research Center,
National Aeronautics and Space Administration,
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TABLE I. - TERMINOLOGY

Definition	ASTM designation	Designation in this report
A thermocouple having its thermoelements embedded in ceramic insulation compacted within a metal protecting tube	Sheathed thermocouple	Two-wire sheathed thermocouple
A thermoelement embedded in ceramic insulation compacted within a metal protecting tube	Sheathed thermoelement	Single-wire sheathed thermoelement
Two sheathed thermoelements (of dissimilar wire material) joined together to form a junction	---------------------	Single-wire sheathed thermocouple
A thermocouple element consisting of a thermoelement in wire form, within a thermoelement in tube form, and insulated from the tube except at the measuring junction	Coaxial thermocouple element	Coaxial thermocouple

TABLE II. - DESCRIPTION OF SIMULATED TURBINE TEST BLADES

[Type K thermocouples; three thermocouples on each blade.]

Test blade	Blade material	Thermocouple sheath diameter, mm	Thermocouple configuration	Production method	Company
1	304 Stainless steel	0.51	Single-wire	Special order	A
2	304 Stainless steel	.38	Single-wire	Special order	A
3	Hastelloy	.25	Single-wire	Special order	A
4	Hastelloy	.25	Single-wire	Commercial grade	A
5	Hastelloy	.25	Single-wire	Commercial grade	B
6	Hastelloy	.25	Two-wire	Commercial grade	B

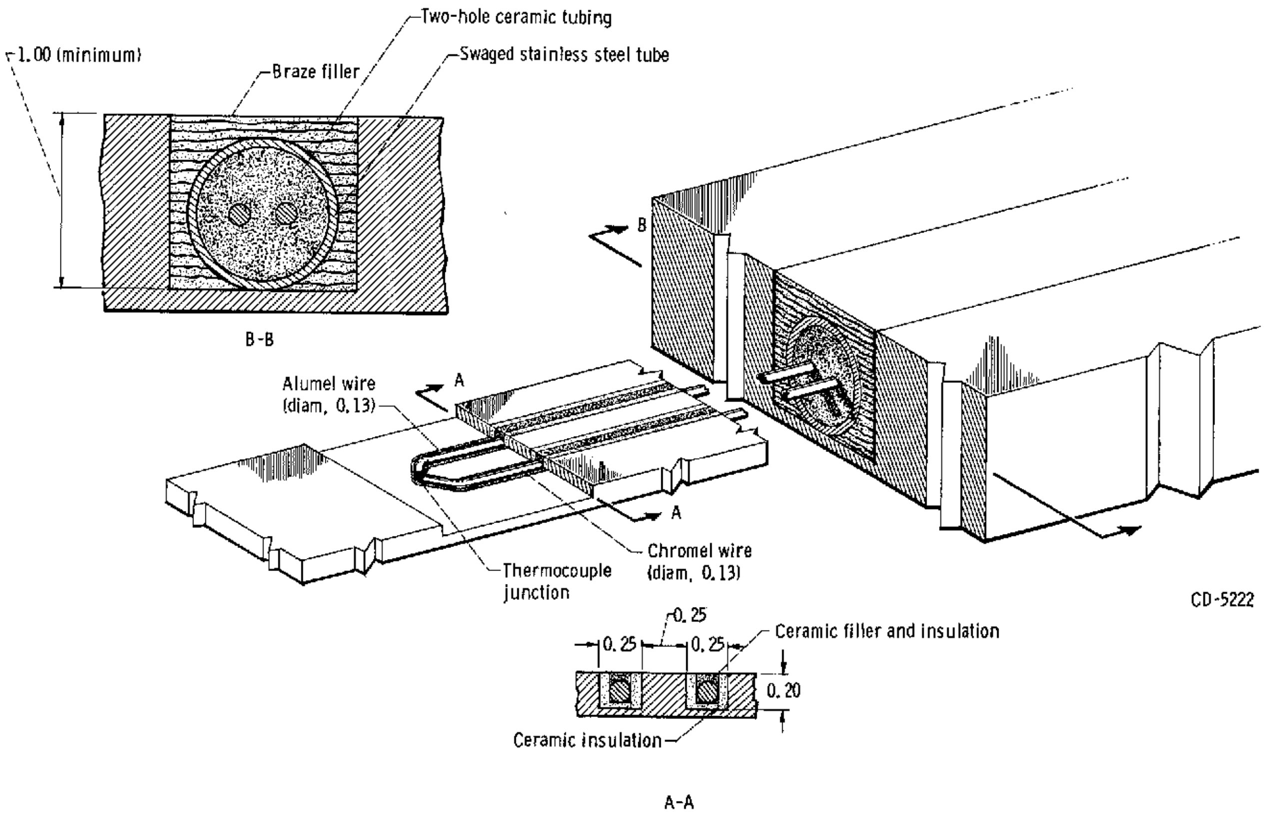
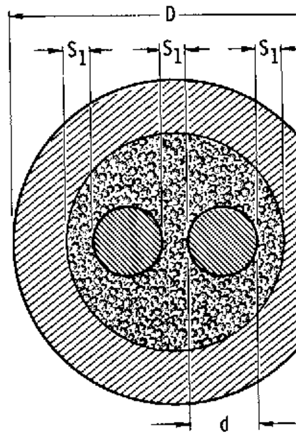
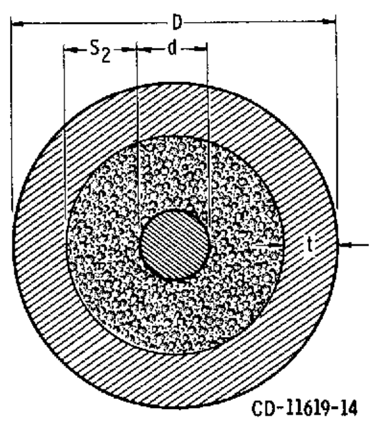


Figure 1. - Thermocouple installed in thin wall by method of reference 2. (Dimensions in millimeters.)



(a) Two-wire sheathed thermocouple.



(b) Single-wire sheathed thermoelement.

Figure 2. - Comparison of geometry of a two-wire sheathed thermocouple and a single-wire sheathed thermoelement. Nominal values (from ref. 1): $t = 0.16$ D and $d = 0.19$ D; example: for $D = 0.25$ millimeter, $d = 0.05$, $t = 0.04$, $S_1 = 0.025$, and $S_2 = 0.06$ millimeter.

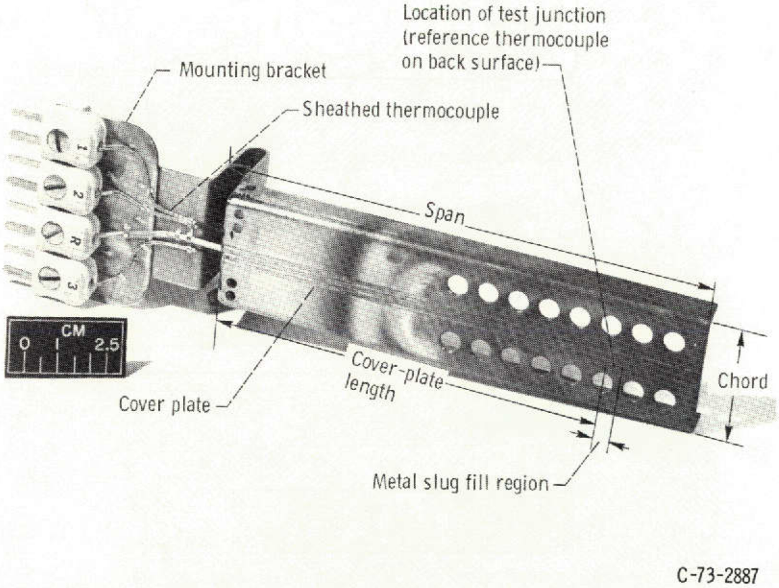
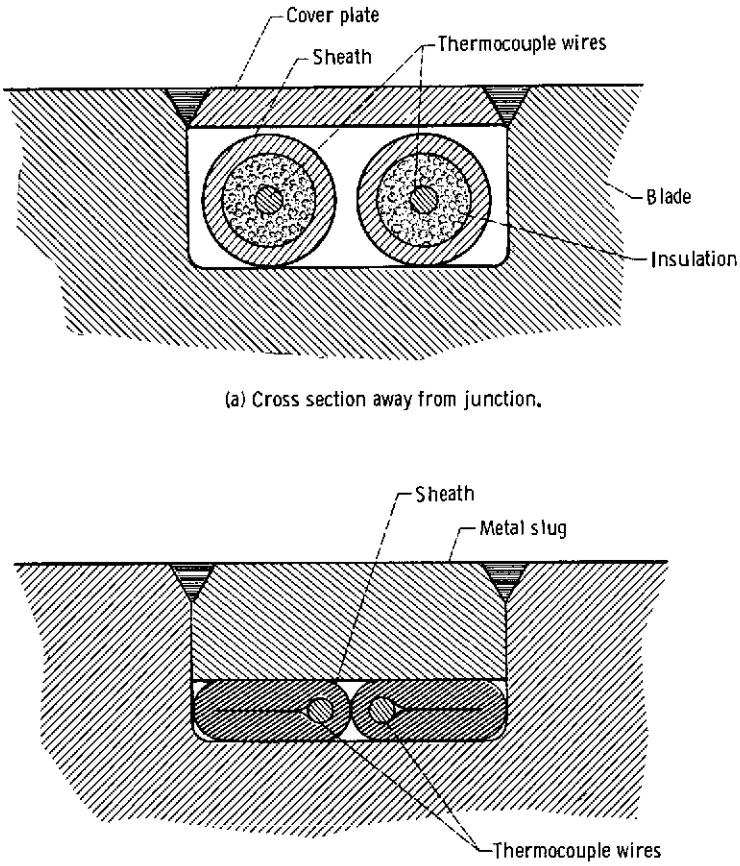


Figure 3. - Instrumented simulated turbine test blade.



(a) Cross section away from junction.

(b) Cross section at sheath end closure.

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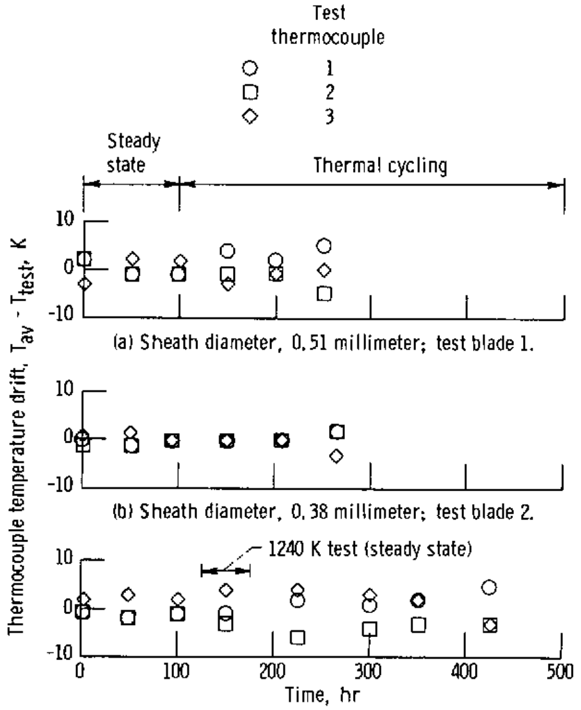
Figure 4. - Thermocouple formed with two sheathed thermoelements in blade groove. Single-wire sheathed thermocouple.

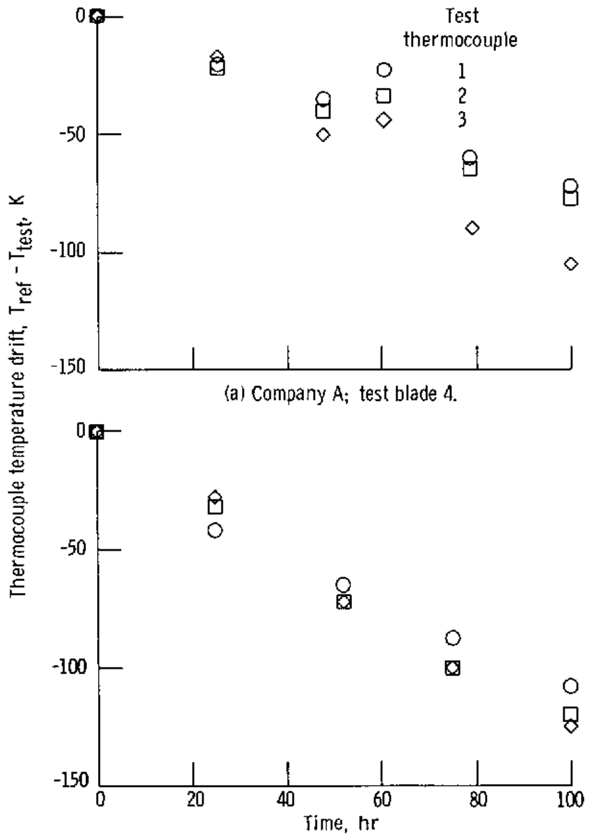


(a) Sheath diameter, 0.51 millimeter; test blade 1.

(b) Sheath diameter, 0.38 millimeter; test blade 2.

(c) Sheath diameter, 0.25 millimeter; test blade 3.

Figure 5. - Drift of single-wire Chromel-Alumel sheathed thermocouples. Special limited-quantity order; temperature of reference thermocouple, 1140 K.



(a) Company A; test blade 4.

(b) Company B; test blade 5.

Figure 6. - Drift of single-wire Chromel-Alumel sheathed thermocouples. Commercial grade; sheath diameter, 0.25 millimeter; temperature of reference thermocouple, 1140 K; steady state.

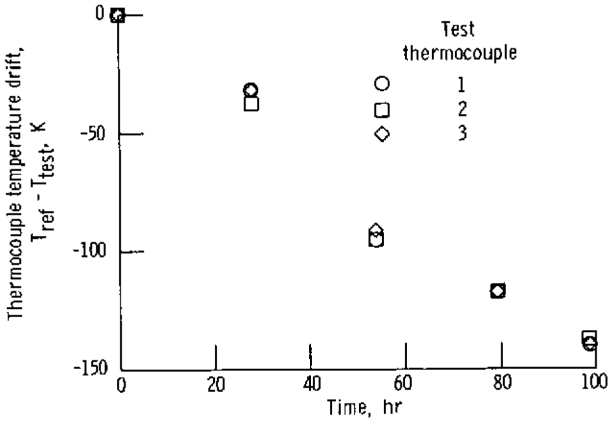


Figure 7. - Drift of two-wire Chromel-Alumel sheathed thermocouples. Commercial grade; sheath diameter, 0.25 millimeter; temperature of reference thermocouple, 1140 K; steady state; test blade 6.

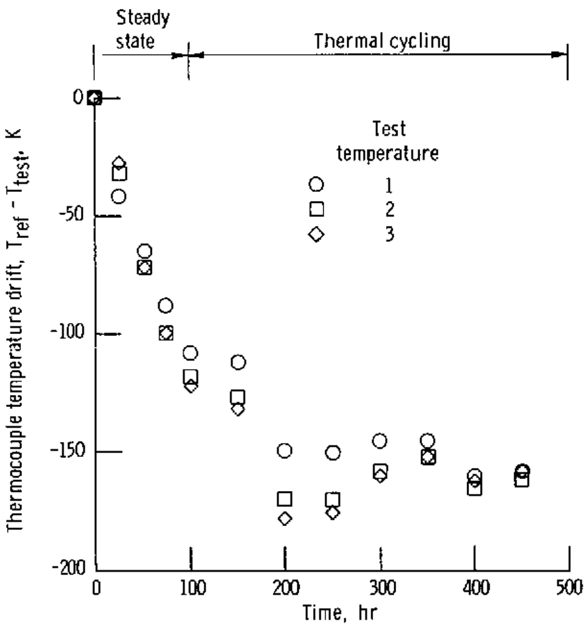
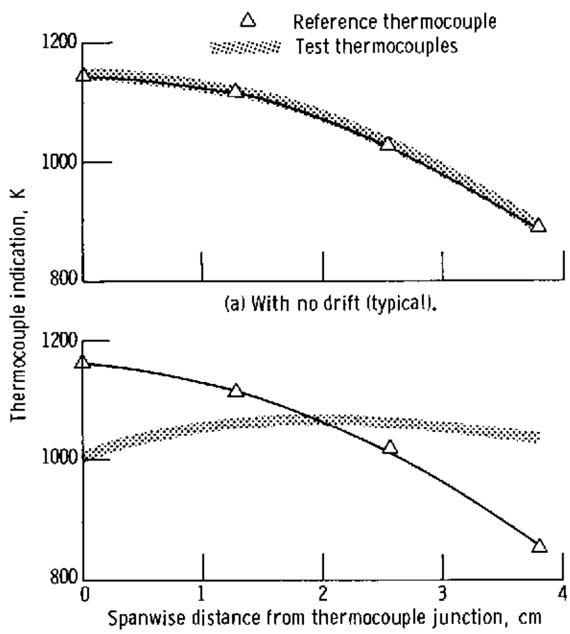


Figure 8. - Drift of single-wire Chromel-Alumel sheathed thermocouples. Commercial grade; sheath diameter, 0.25 millimeter; temperature of reference thermocouple, 1140 K; test blade 4.



(b) With considerable drift (test blade 4).

Figure 9. - Test blade thermocouple outputs obtained by moving flame away from thermocouple junctions.