NACA

RESEARCH MEMORANDUM

METHODS FOR MEASURING TEMPERATURES OF THIN-WALLED GAS-TURBINE BLADES

By Francis S. Stepka and Robert O. Hickel

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON

November 2, 1956

NACA RM E56G17

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

METHODS FOR MEASURING TEMPERATURES OF THIN-WALLED GAS-TURBINE BLADES

By Francis S. Stepka and Robert O. Hickel

SUMMARY

The accuracy and durability of two means for measuring metal temperatures of thin walls of air-cooled turbine blades in a turbojet engine were investigated. One method employed thermocouples which were cemented in small grooves, about 0.008 inch deep by 0.020 inch wide, in the surface of the blades. The second method consisted of applying commercial temperature-indicating paints to the blade surfaces. The majority of the investigations were conducted at maximum rated engine conditions, a turbine-inlet gas temperature of about 1650° F and an engine speed of 11,500 rpm. At rated engine speed, the thermocouple junctions were subjected to a force equivalent to about 42,000 times gravity.

The accuracy of the cemented thermocouples as compared to reference thermocouple installations that have been used in the past by the NACA to obtain temperatures of blades with shells which were about 0.040 inch or thicker was good; the agreement between the two types of thermocouples was about ±5° F with the maximum deviation being about ±15° F over most of the speed range. The temperature distributions indicated by the paints were in reasonable agreement with those indicated by the reference thermocouples and were in general about 50° F below those obtained with the reference thermocouples.

The durability of the cemented thermocouples was also good; 47 of 55 cemented thermocouples were operated in the engine without failure for times ranging from 2 to 30 hours. The average operating time for all cemented thermocouples was 12 hours. Eight thermocouples failed mechanically at operating times ranging from 1 to 22 hours with the average time to failure being about 10 hours. The durability of the temperature-indicating paints was satisfactory for evaluation of the blade temperature distribution, providing the paint was not subjected to more than 15 minutes of engine operation.

INTRODUCTION

Thermocouples installed in the walls of rotating turbine blades have been used by the NACA Lewis laboratory since about 1947 to determine the metal temperature of various cooled and uncooled turbine blades used in gas-turbine aircraft engines. A thermocouple installation that is typical of those used in turbine cooling research is described in detail in reference 1. Briefly, this installation consists of 36-gage chromel and alumel wire installed in two-hole ceramic tubing, which is in turn enclosed in a stainless steel tube having an outside diameter of 0.040 inch. The turbine blades in which temperatures are to be measured have their outer surfaces grooved so that the thermocouple assembly can be buried and brazed in the blade metal. When the blades with thermocouples are installed in a turbine rotor, the leads are strapped to the rotor face and connected to junction posts near the rotor hub. From the junction posts, chromel and alumel wires are led through an axial hole in the turbine and compressor shafts to a slipring thermocouple pickup which transmits the thermocouple electromotive force to a suitable potentiometer for indicating or recording or both.

When a blade thermocouple system such as that just described is installed in blades that have a wall thickness less than 0.040 inch, a portion of the thermocouple assembly protrudes into the combustion gas stream or into the coolant passages within the blade. When the thermocouple assembly extends through the outer surface of the blade, the combustion gas flow around the blade is disrupted and the aerodynamic characteristics of the blade are altered. If the assembly extends into the coolant passages (which on some blades may be triangular passages having a height of 0.025 to 0.050 inch and a width of 0.050 to 0.070 inch), a relatively large portion of the flow area available to the coolant can be blocked. Such blockage would cause the blade temperature in the vicinity of the thermocouple to be higher than if the thermocouple were not present. Furthermore, when portions of the thermocouple assembly near the thermocouple junction extend into the combustion gas or coolant streams, erroneous readings of the thermocouple are likely because of thermal conduction effects along the thermocouple assembly.

In the past, blade walls have been thick enough to allow the thermocouple assembly to be completely buried. Recently, however, certain cooled turbine blade configurations for turbojet engines having blade shell thicknesses of the order of 0.020 to 0.040 inch have been investigated at the Lewis laboratory. For cooled turbine blades in turboprop engines, configurations having wall thicknesses as small as 0.010 inch are being investigated. Consequently, thermocouple assemblies having outside diameters much smaller than 0.040 inch are required. A thermocouple installation has been developed that can be buried in blade walls having thicknesses as small as 0.010 inch. This report presents the method of installing thermocouples for use on very thin walled blades and presents information relative to the reliability of such thermocouple installations in turbojet engines. In addition, a commercially available temperature-indicating paint was investigated to determine whether such a product is suitable for temperature measurement of gas-turbine blades.

These investigations were made on a production turbojet engine that was modified to accomodate several air-cooled turbine blades. The engine was operated at turbine-inlet temperatures up to about 1650° F and at turbine tip speeds up to 1300 feet per second.

TEMPERATURE MEASUREMENT METHODS CONSIDERED

Thermocouples

Thought was first given to the possibility of employing a thermocouple assembly similar to that described previously, except that a smaller diameter assembly would be used. Inasmuch as it was desired to measure temperatures in blades with walls as thin as 0.010 inch, an assembly no thicker than 0.010 inch would be required. Past experience has shown that for practical reasons (ease of handling, resistance to breaking, and reliability of calibration) the thermocouple wire should not be less than 0.005 inch in diameter for application to turbine blades. Thus, the encasement of both chromel and alumel wires in a single stainless steel tube having a 0.010-inch outside diameter was impossible. An alternate solution might have been to put only a single wire in each of two stainless steel tubes with a 0.010-inch outside diameter. This was considered impractical because such an assembly would require single-hole ceramic tubing having an inside diameter slightly greater than 0.005 inch and an outside diameter of about 0.007 inch. Ceramic tubing of this size is not readily available and probably would be difficult to handle because of its smallness and fragility. Swaging the 0.040-inch-diameter thermocouple assembly was attempted, but sufficient reduction in the assembly diameter could not be attained in this manner. The possibility of swaging the thermocouple assembly to an oval shape (with the minor axis being 0.010 inch) was also attempted, but again the desired reduction could not be realized.

Inasmuch as a method of encasing thermocouple wire in ceramic and stainless steel tubes having an outside diameter of 0.010 inch seemed undesirable for physical and practical reasons, an entirely different approach regarding the thermocouple installation was considered. In general, the method consisted of placing and cementing the thermocouple wires in shallow grooves that were machined, ground, or electrolytically etched in the surface of the blade shell. The latter method was performed by having a blade completely coated, except for the region to be grooved, by a plating stop-off lacquer and then immersing the blade in a phosphoric hydrochloric solution until a groove of the desired depth was etched.

Hereinafter, thermocouples installed by this method are referred to as cemented thermocouples. Several variations of this method of installation were employed and they are discussed in detail in the following paragraphs. Thermocouples were installed in sheet metal as thin as 0.010 inch and in test blades which had walls that were from 0.015 to 0.70 inch thick.

Single-groove cemented thermocouple. - One thermocouple installation evaluated is shown schematically in figure 1. The first step in the installation of the thermocouple was to machine or otherwise provide a groove in a thin piece of sheet metal. This groove was about 0.008 inch deep and about 0.020 inch wide. The length of the groove depended upon the location of the thermocouple junction in the sheet metal. The surface of the groove was brush painted with a ceramic cement (a mixture of equal volumes of two commercial cements: Quigley 1925 and Allen P-1). The ceramic coating was dried in an electric oven for 1 hour at a temperature of 160° F. This coating process provided an electrical insulating layer on the grooved surfaces that was about 0.001 inch thick. Chromel and alumel thermocouple wires having a diameter of 0.005 inch were then placed in the groove (fig. 1). The wires in the early installations were bare. In the later installations, the wires were individually given a thin (about 0.001 inch thick) insulating coating of either the same cement used to paint the bottoms of the grooves or of a National Bureau of Standards coating, NBS-A-417. Care was taken so that the wires, especially the bare wires, did not touch each other in the groove except at the point where the thermocouple junction was made. In some installations the thermocouple junction was placed over the insulation on the bottom of the groove and in some installations the junction was resistance welded to a bared metal surface at the bottom of the groove. After the thermocouple wires were located in the groove, the groove was filled with the same ceramic cement used to insulate the surfaces of the groove initially. The thermocouple assembly was again dried in an electric oven at 160° F for 1 hour. If after drying there was excess cement that extended above the metal surface, the cement was hand sanded until the ceramic surface was level with the metal surface. A cross section of the completed installation is shown in section A-A of figure 1. In a blade installation, in order to keep the length of thermocouple wire supported in the ceramic-filled groove to a minimum, the wires were inserted in two-hole ceramic tubing and encased in stainless steel tubing as soon as a region of the blade became thick enough (about 0.040 inch) to contain such an installation. A view of this installation is shown in section B-B of figure 1. The stainless steel tube originally had a 0.050-inch outside diameter and 0.005-inch walls. The two-hole ceramic tube had an outside diameter of about 0.036 inch. After the thermocouple wires and ceramic tubing were installed in the stainless steel tube, the tube was swaged to an outside diameter of about 0.040 inch. The purpose of the swaging operation was to bind the wires, ceramic tubing, and stainless steel tubing into an assembly that provided firm support and insulation for the thermocouple wires.

Double-groove cemented thermocouple. - An alternate method of installing the cemented thermocouple was developed. It was believed that the two thermocouple wires might shift slightly in the single thermocouple groove during fabrication or operation, touch, and become shorted. To avoid this possibility, an installation procedure wherein each thermocouple wire was installed in a separate groove as shown in figure 2 was employed. The basic principle of installation was the same as that described previously except that two grooves were cut in the surface to accomodate a pair of thermocouple lead wires. The grooves were 0.008 inch deep and 0.010 inch wide. The space between the grooves was 0.010 inch. The procedure for insulating and cementing the thermocouple wires was the same as that described for the single-groove cemented thermocouple discussed previously. The leads of the double-groove thermocouple were encased in two-hole ceramic tubing and in a swaged 0.040-inch-outside-diameter stainless steel tube when the blade metal thickness was large enough to accomodate such an assembly. This portion of the assembly is shown in section B-B of figure 2.

Temperature-Indicating Paints

The use of temperature-indicating paints for temperature measurement on thin-walled blades was also considered. These paints are composed of metallic salts that liberate water, carbon dioxide, ammonia, and other substances (ref. 2) at definite temperature levels and simultaneously change color. Generally, the reaction is irreversible and the color change remains upon cooling. Such paints are available commercially and have been used successfully in a variety of applications. These paints have not, however, been used in the past at the Lewis laboratory for metal temperature indication of either cooled or uncooled turbine blades in engine operation. The paints investigated herein were applied to air-cooled blades only and were applied according to the general recommendations supplied by the manufacturer.

APPARATUS

Test Engine

The test engine was a commercial turbojet with the same alterations as those described in reference 1 except that provision was made for cooling as many as four turbine rotor blades (90° apart) rather than only two blades (180° apart). The engine was capable of being operated over a range of engine speeds from 4000 to 11,500 rpm and at turbine-inlet gas temperatures up to about 1670° F.

Blades

Evaluation of the cemented thermocouple was made using a total of 13 turbine blades. Two of the blades were solid and eleven were hollow (for cooling). The temperature-indicating paints were evaluated on a total of 32 air-cooled turbine blades.

Although the cemented thermocouple was developed primarily for use on cooled blades having wall thicknesses of the order of 0.010 inch, blades having such thin walls were not available when this investigation was made. The blades on which cemented thermocouples were installed had wall thicknesses of the order of 0.015 to 0.070 inch.

Reference Thermocouple

In order to compare the blade metal temperatures indicated by cemented thermocouples and temperature-indicating paints with a known temperature, reference thermocouples of known reliability were installed on the test blades. The reference thermocouples used were the same type thermocouples described in the INTRODUCTION. As indicated previously, this thermocouple installation has been used extensively for turbine cooling research at the Lewis laboratory. A sketch of the reference thermocouple is shown in figure 3.

Thermocouple System

After blades with thermocouples were installed in the turbine rotor, the leads from the thermocouples were fastened to the rear face of the turbine rotor by resistance-welded straps (fig. 4). The ends of the leads were fastened to junction posts at the rotor hub. From the junction posts, the thermocouple leads were brought to the front of the engine through an axial hole drilled through the turbine and compressor shafts. The thermocouples were then connected to a slipring pickup (fig. 5) which had 24 sliprings, 2 rings being used for each thermocouple. To minimize wear, the pickup brushes were in contact with the sliprings only while temperature readings were being taken. In order to reduce the amount of chromel-alumel lead wire required and also to reduce errors that might be caused by temperature differentials between sliprings and components of the switching system, an electrical system for the thermocouples such as that shown schematically in figure 6 was employed. In this system, the thermocouple leads from the rear of the engine are connected to copper leads in a steam box. The copper wires lead to the sliprings and then run to a selector switch located in the control room. Copper wires are run from the selector switch back to the steam box where a junction is made with chromel-alumel wires, which then lead to a calibrated potentiometer used for indication of the thermocouple electromotive force. The steam box is an integral part of the slipring pickup and is shown in figure 5. Steam at a pressure slightly above atmospheric was supplied to the steam box so that all parts of the box were essentially at a constant and uniform temperature. With this arrangement, temperature differences between junction points of the system where copper wire is used do not affect the electromotive force developed by the thermocouple. Reference 3 indicates that the errors incurred by the use of a thermocouple slipring pickup system such as that described herein is less than ±0.045 millivolts or ±1.9° F when chromel-alumel thermocouples are used.

PROCEDURE

Cemented Thermocouples

Accuracy investigation. - The accuracy of the cemented thermocouple was indicated by comparing its potentiometer reading with that produced by a reference thermocouple. For such comparisons both types of thermocouples were located at similar positions on the test blades. Six thermocouples (three cemented and three reference) were installed according to the methods discussed previously and were arbitrarily located in two hollow test blades as indicated in figure 7(a). No cooling air was supplied to the blades. The blades were investigated simultaneously and temperature readings for each type of thermocouple were obtained within a few seconds of each other when steady engine operating conditions had been attained. The agreement between the two types of thermocouples was evaluated over a wide range of engine operating conditions that resulted in the blade metal temperature at the thermocouple locations ranging from about 765° F to about 1430° F.

Durability investigation. - In order to investigate the durability of the cemented thermocouple under conditions of high temperature and high centrifugal force, 13 turbine blades were instrumented with cemented thermocouples and operated either one or two at a time in a turbojet engine. In some instances, the test blades were operated cooled and in others uncooled. Most of the testing was done at maximum rated engine conditions, an engine speed of 11,500 rpm and a turbine-inlet temperature of 1650° F. The junction of the cemented thermocouples was subjected to a centrifugal force equivalent to about 42,000 times gravity. The engine was shut down periodically to permit inspection of the thermocouple installations.

Temperature-Indicating Paints

The temperature-indicating paints were investigated for accuracy and durability at maximum rated engine conditions. During normal starting and acceleration of a turbojet engine, instantaneous values of turbine-inlet gas temperature that are considerably above the time-averaged temperature values occur. Such high temperature, though present for only a relatively short period of time, may effect a color change in temperature-indicating paints, and an erroneous indication of the blade metal temperature under steady operating conditions results. In order to minimize the possibility of such color changes, several precautions were taken. The temperature-indicating paint was applied to air-cooled turbine blades only. Inasmuch as the cooling air was supplied from a source external to the engine, large quantities of air could be supplied to the blades prior to starting the engine. A large cooling-air flow rate was maintained during starting and acceleration of the engine up to the desired engine speed. In this manner, blade metal temperatures below the temperature values for color change of the paint were maintained during transient engine operation. When the desired engine speed was attained, the blade coolant flow was reduced to a nominal value so that the blade metal temperature increased and a color change in the paint was effected. Another precaution that was taken was starting the engine with extreme care and accelerating slowly so as to reduce the possibility of producing instantaneous values of combustion-gas temperature that were much above the time-averaged temperature.

Accuracy investigation. - The accuracy of temperature-indicating paints when applied to gas-turbine blades was determined by applying the paints to a group of four air-cooled turbine blades which were operated in the engine for two test runs. For each of the runs, each of the four blades was completely coated with a paint that exhibits a color change at a different temperature level. The initial color, final color, and temperature at which the color change occurs for each of four paints used are given in table I. Six reference thermocouples were installed in one of the blades on which temperature-indicating paints were applied. The location of the thermocouples is shown in figure 7(b). The blade metal temperature distributions as obtained by the temperature-indicating paints were compared to the temperature distributions indicated by the reference thermocouples. This procedure assumes an equal cooling-air distribution to the four air-cooled blades. This assumption is justified by unpublished data which indicate that the cooling air is distributed uniformly when a cooling-air system such as that employed herein and discussed in detail in reference 1 is used. Furthermore, in order to eliminate fabrication variations that are likely to occur when rather complex internal heat-transfer configurations are used, only plain hollow air-cooled blades were employed. It is believed, therefore, that temperature variations that are likely to occur from blade to blade were reduced to a minimum for this investigation.

Durability investigation. - The durability of the paints was evaluated on a total of 32 painted air-cooled blades. The procedure was to subject four paints (each on a different blade) simultaneously to maximum engine conditions. Each set of four blades was subjected to these conditions for a different length of time. Inspection of the paints was then made and the durability evaluated.

RESULTS AND DISCUSSION

Cemented Thermocouples

Accuracy. - The results of the investigation to determine the accuracy of the cemented thermocouples indicated good agreement of the temperatures measured by the cemented and reference thermocouples. A comparison of the blade temperatures of two uncooled hollow blades measured by the two types of thermocouples at three locations is shown in figure 8. Generally, the agreement between the two types of thermocouples is very good as shown by the fact that the line of exact agreement of the readings provides a good average curve for the data. The best agreement was obtained for temperatures between about 1000° and 1400° F. In this temperature range, most of the cemented-thermocouple temperatures were within ±5° F of those indicated by the reference thermocouple; the maximum variation was about ±15° F. For the blade metal temperature range between about 800° and 1000° F, the agreement between the two types of thermocouples was not as good, the variation between thermocouple types being of the order of ±35° F. It is not believed that the lesser agreement between the cemented and reference thermocouples that occurred below 1000° F indicates that the thermocouples themselves are inaccurate at lower temperatures. The lower blade metal temperatures were obtained by operating the test engine at engine speeds considerably below rated engine speed. When the engine operates at these lower speeds, the angle of incidence of the combustion gas with respect to the turbine blades is "off design". This can result in erratic gas flow around the blades which in turn affects the blade outside heat-transfer coefficients. Thus, a greater variation in temperature from blade to blade in the turbine might be expected at lower engine speeds and consequently in the lower blade metal temperature range of this investigation. In any event, the turbine blade metal temperatures that generally occur in either cooled or uncooled gas-turbine engines for aircraft are of the order of 1000° F or higher, and in this temperature range the cemented thermocouples agreed well with the reference thermocouples.

Durability. - The results of the thermocouple durability investigations indicated that in general the cemented thermocouple performed satisfactorily. Of the 55 cemented thermocouples installed in the blades, 47 operated in the engine without failure for times ranging from 2 to 30 hours; the average operating time for all cemented thermocouples tested was 12 hours. Eight of the thermocouples failed at times ranging from 1 to 22 hours of engine operation with the average time to failure being 10 hours. This experience with the cemented thermocouples compares favorably with past experience accumulated with reference-type thermocouples.

Five of the failures that occurred with the cemented thermocouples were in the leading-edge regions of the blades. Inspections indicated that generally failure of a leading-edge cemented thermocouple was preceded by erosion of the ceramic cement from the grooved slot in the blade. These erosive effects were noticeable after about 5 hours of operation. As erosion of the cement progressed the thermocouple wires became loosened and finally failed by breaking. The erosive action of the high-temperature, high-velocity combustion gases would be expected to be most severe at the leading-edge regions of the blades. Although ceramic cements other than those mentioned previously were not investigated, it is believed that a cement offering greater erosion resistance might result in fewer leading-edge thermocouple failures.

One cemented thermocouple failed in the midchord region and two thermocouples failed in the trailing-edge region. Although these failures resulted from broken thermocouple wires, the failures were not preceded by severe erosion of the cement from the grooves in the blade surface. The erosion of the cement in the midchord and trailing-edge regions of the blades was very slight.

The electrical reliability of the cemented thermocouples was satisfactory. Throughout the durability tests, blade metal temperatures indicated by cemented thermocouples were compared to the temperatures indicated by reference thermocouples. The degree of agreement observed was within the spread of the data shown in figure 8.

Evaluation of installation methods. - The investigation indicated that no one method of installing the cemented thermocouples, such as using an electrically grounded thermocouple junction rather than an electrically insulated junction, coated thermocouple wires rather than bare wires, a single groove instead of a double groove, or combinations of these methods, offered any particular advantage.

Temperature-Indicating Paints

Accuracy. - A color photograph showing the suction surfaces of three painted blades after about 15 minutes of engine operation is shown in figure 9. A black and white photograph of the same painted blades with dashed lines drawn to emphasize the boundaries of the color changes is also shown in figure 9. The initial and final colors of the paints and the temperatures at which the color changes occur are given in table I. The black areas on the blades in the color photograph are regions where the paint was eroded by the combustion gases. It can be noted that for paint B brown areas are apparent at the leading- and trailing-edge regions of the blade. These brown areas are not part of the normal color change of the paint associated with a definite temperature but are discolorations due to a scorching effect of the combustion gases upon the paint. A discolored area in paint C at the midchord region of the blade is also apparent.

From visual data such as those shown in figure 9, blade metal temperature distributions can be obtained. In order to obtain a similar distribution with reference thermocouples, a large number of thermocouples would be required. Therefore, to minimize the number of thermocouples needed to check the accuracy of the temperatures indicated by the paints, comparison is made of the peripheral temperature distributions obtained with the paints and with six reference thermocouples at only one arbitrarily selected spanwise location. Temperature distributions at a spanwise position 1.5 inches from the blade base obtained by the two measuring methods are shown in figure 10. The two plots (figs. 10(a) and (b)) were obtained from separate runs that were made at slightly different temperature levels. The general temperature trends indicated by the paints agree reasonably well with those indicated by the thermocouples. The actual temperature levels indicated by the paints, however, are in general about 50° F below those shown by the reference thermocouples. The paints indicated temperatures that were a maximum of 50° F above and 120° F below those indicated by the reference thermocouples.

Although the level of the temperatures shown in the plots of figure 10 is assumed fixed within the accuracy of $\pm 9.0^{\circ}$ F indicated by the paint manufacturer, the curves could be slightly altered by interpretation of the locations of the boundaries of the color changes. The amount of uncertainty in interpreting these boundaries, due to blending of the two colors and to erosion of some of the paint, is about 0.06 inch. The temperature data from temperature-indicating paints for the trailing-edge portions of the pressure surfaces (fig. 10) could not be obtained because of complete erosion of the paint in this region of the blades.

Durability. - The results indicated that in order to obtain a satisfactory evaluation of the blade temperature distribution the paints should not be subjected to the hot gases for more than 15 minutes. This 15-minute limit is probably satisfactory for many studies of the metal temperature distribution in cooled turbine blades. Generally, turbine blades reach their equilibrium temperature shortly after steady engine operating conditions have been established. If care is exercised, a given engine condition can probably be set and maintained so that suitable temperature data can be obtained within 15 minutes after starting the engine. The paints which were operated for this period of time started to erode in the leading- and trailing-edge regions. The erosion was especially severe at the trailing edge of the pressure surface where in most cases, even after 15 minutes of operation, the paint was so eroded that no temperature data could be obtained. Although progressively larger areas of the paint eroded as the test time was increased, enough of the paint had remained at the midchord region on some blades after 3 hours of operation to permit an estimate of the blade temperature in this region.

Applicability of Methods

In order to use temperature-indicating paints to obtain a complete survey of the variation of blade metal temperature for a range of engine operating conditions such as engine speed, turbine-inlet temperature, and cooling-air flow, a large number of engine starts, shutdowns, and inspections of blades would be required. Such a testing procedure might be extremely time consuming or impractical for certain test installations and thus preclude the use of temperature-indicating paints. The accuracy that is desired may also rule out the use of temperature-indicating paints.

The use of thermocouples requires considerable time for installation of the thermocouples in the blades by skilled technicians. Also, equipment such as a thermocouple pickup and a potentiometer is needed. Furthermore, a large number of thermocouples are required to obtain a complete survey of the chordwise and spanwise blade temperature variations. Whether the use of thermocouples or of temperature-indicating paints is preferable for a given application would depend upon the accuracy desired, the time available, the equipment available, and the ease with which blade inspections can be made.

SUMMARY OF RESULTS

The results of an investigation of two methods capable of measuring temperatures of thin walls of air-cooled turbine blades by using thermocouples cemented in grooves in the blade surfaces and temperature-indicating paints are as follows:

1. Agreement between the blade metal temperatures indicated by the cemented thermocouples and reference thermocouples was good. Over most of the temperature range investigated agreement was $\pm 5^\circ$ F, with the maximum deviation being $\pm 15^\circ$ F.

2. The temperature distributions given by the temperature-indicating paints agreed reasonably well with those indicated by the reference thermocouples. The actual temperature levels indicated by the paints, however, are in general about 50° F below those measured by reference thermocouples.

3. The durability of the cemented thermocouple compared favorably with past experience obtained with reference-type thermocouples. Of the 55 cemented thermocouples investigated, 47 were operated in the engine without failure for times ranging from 2 to 30 hours; the average operating time for all the cemented thermocouples tested was 12 hours. Eight thermocouples failed because of mechanical breakage at times ranging from 1 to 22 hours with the average time to failure being 10 hours.

4. In order to obtain a satisfactory evaluation of the blade metal temperature distribution, the paint could not be subjected to more than 15 minutes of engine operation.

5. Of the various methods of installing the cemented thermocouple investigated, no one method was better than any other.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, July 18, 1956

REFERENCES

1. Ellerbrock, Herman, H., Jr., and Stepka, Francis S.: Experimental Investigation of Air-Cooled Turbine Blades in Turbojet Engine. I - Rotor Blades with 10 Tubes in Cooling-Air Passages. NACA RM E50I04, 1950.

2. Penzig, F.: Temperature-Indicating Paints. NACA TM 905, 1939.

3. Tarr, Philip R.: Methods for Connection to Revolving Thermocouples. NACA RM E50J23a, 1951.

TABLE I. - TEMPERATURE-INDICATING PAINTS

APPLIED TO TURBINE BLADES

Paint	Initial color	Final color	Temperature at color change, °F (a)
A	Green	White	824
B	Red-orange	Yellow	1040
C	Yellow	Green	1184
D	Yellow	Olive	1319

[a] Accuracy reported to be ±9° F by paint manufacturer.

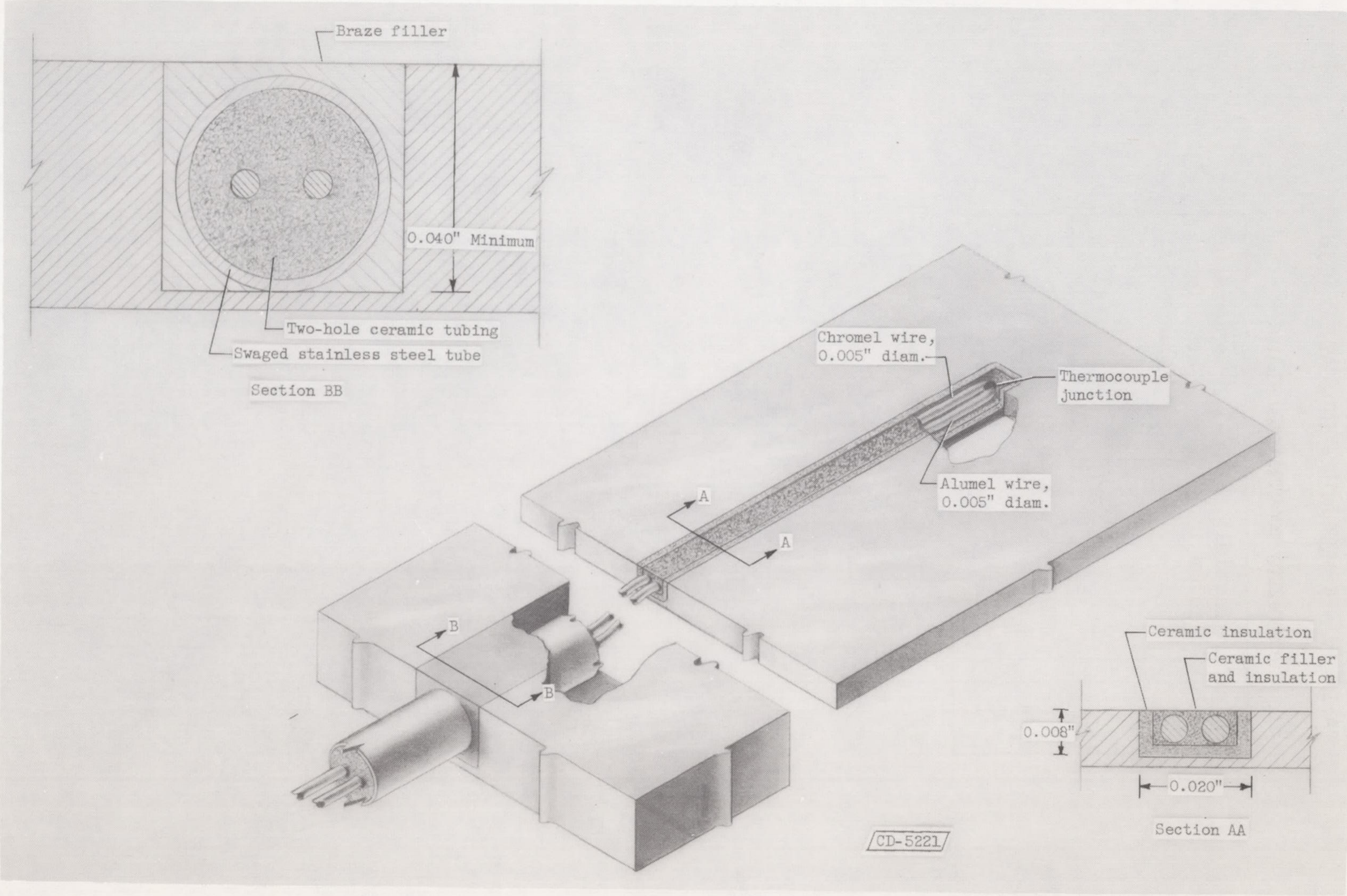


Figure 1. - Schematic drawing of thermocouple installed in single groove in thin wall.

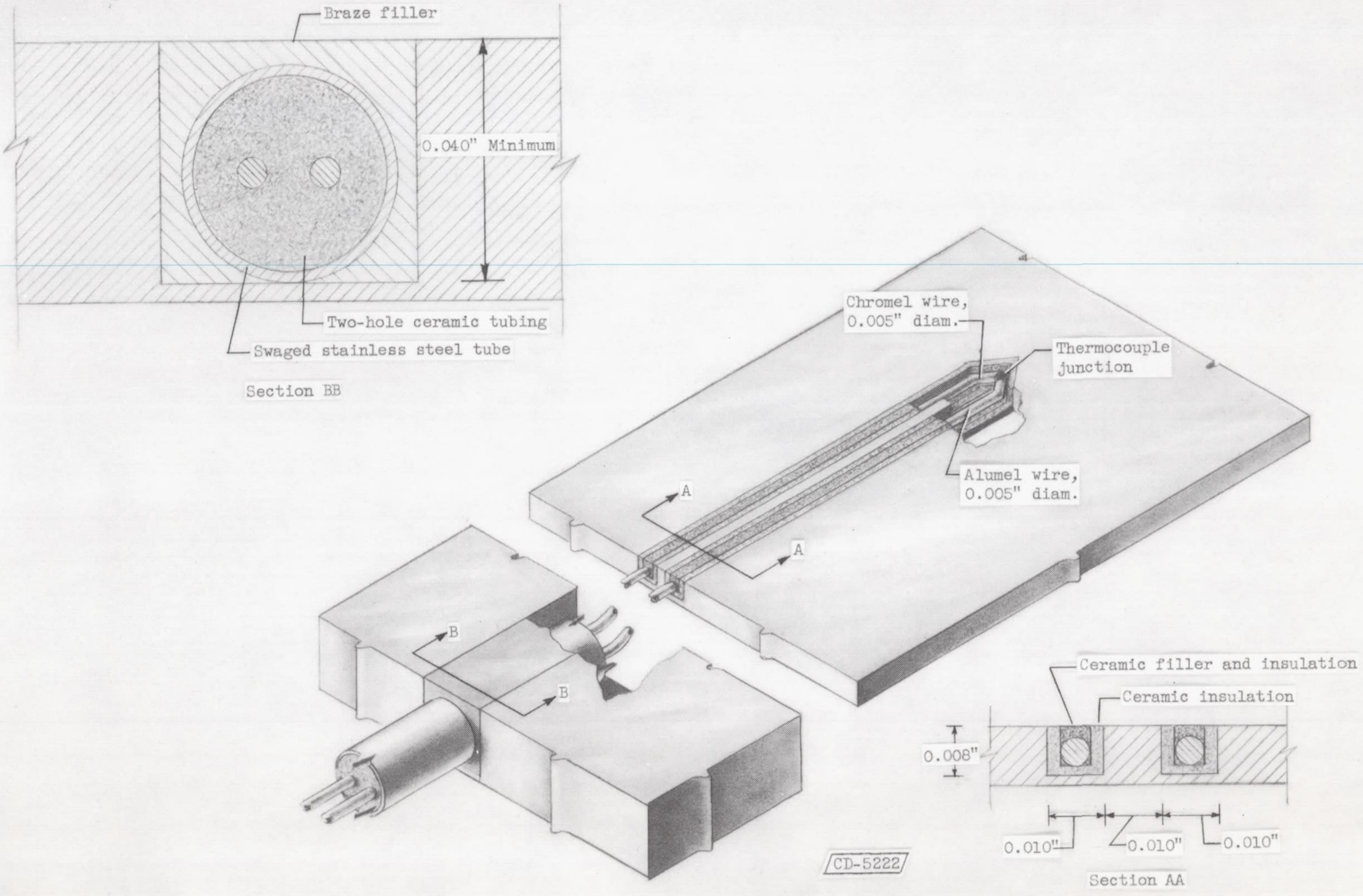


Figure 2. - Schematic drawing of thermocouple installed in double groove in thin wall.

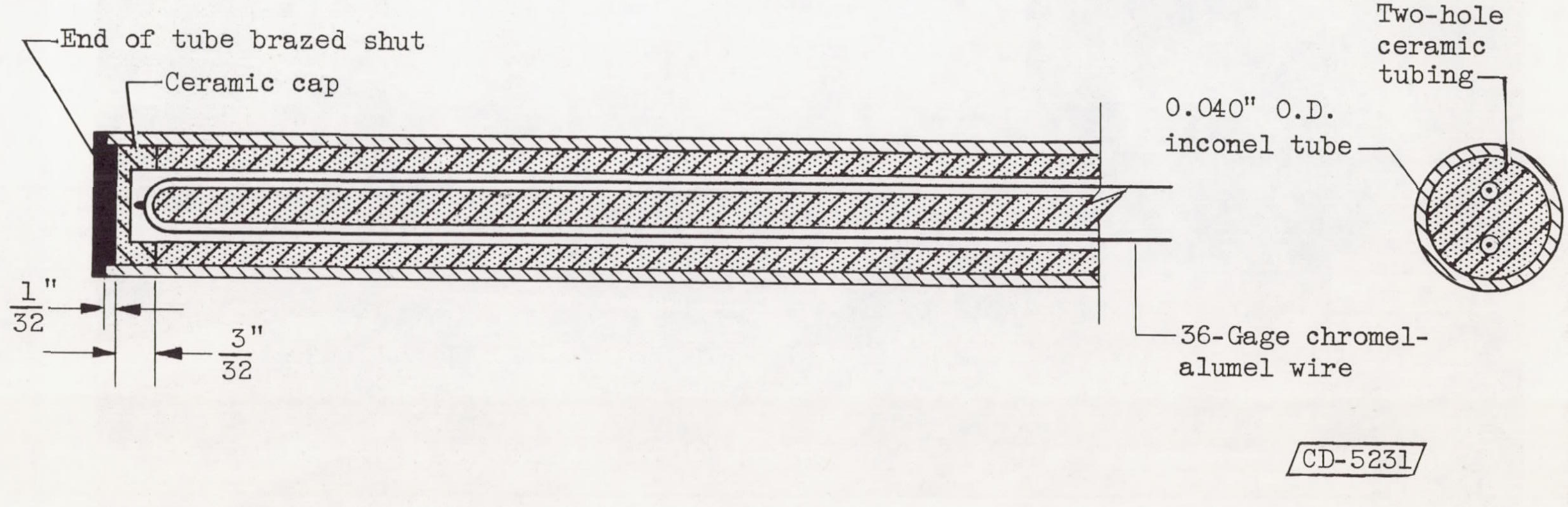


Figure 3. - Sketch of reference thermocouple.

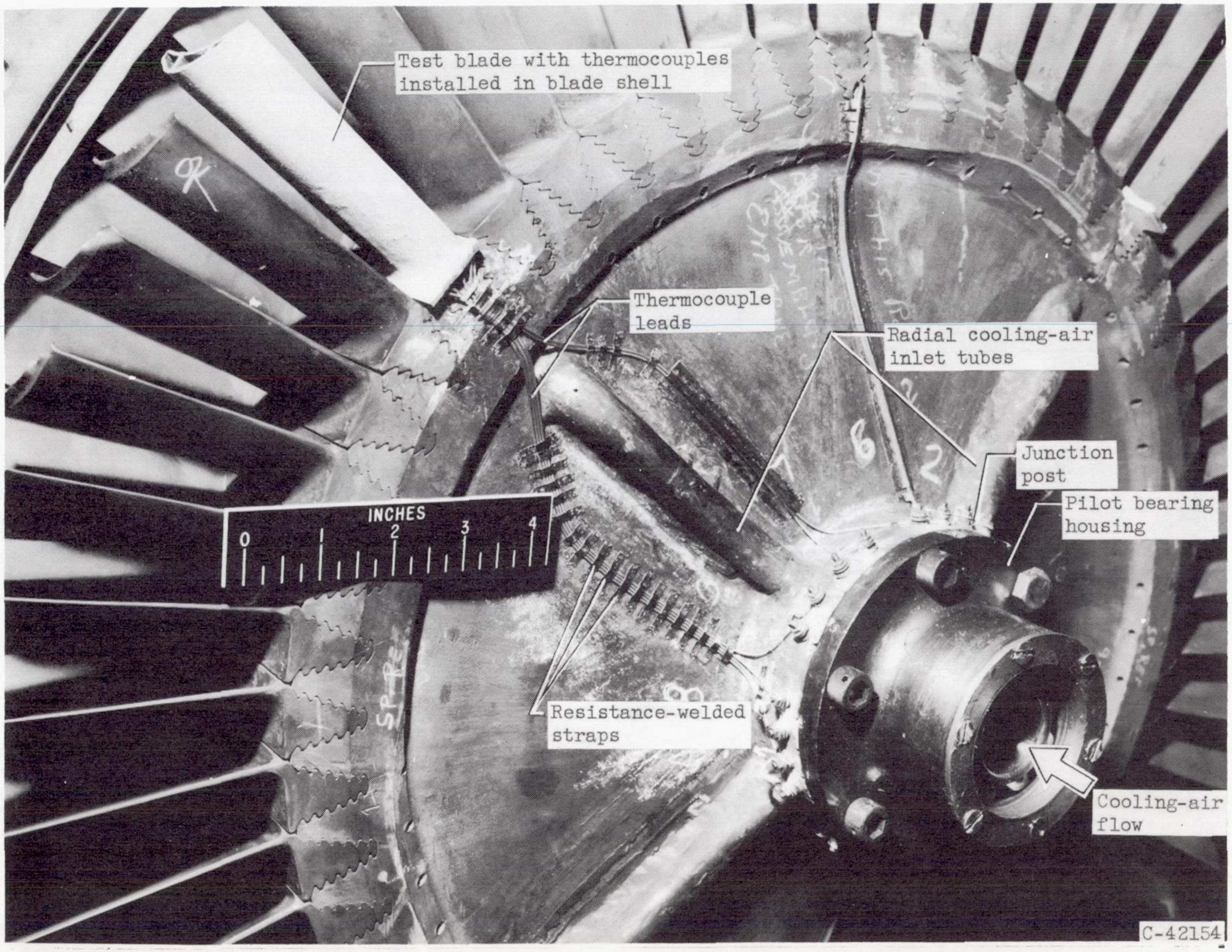


Figure 4. - Installation of instrumented blades in turbine rotor.

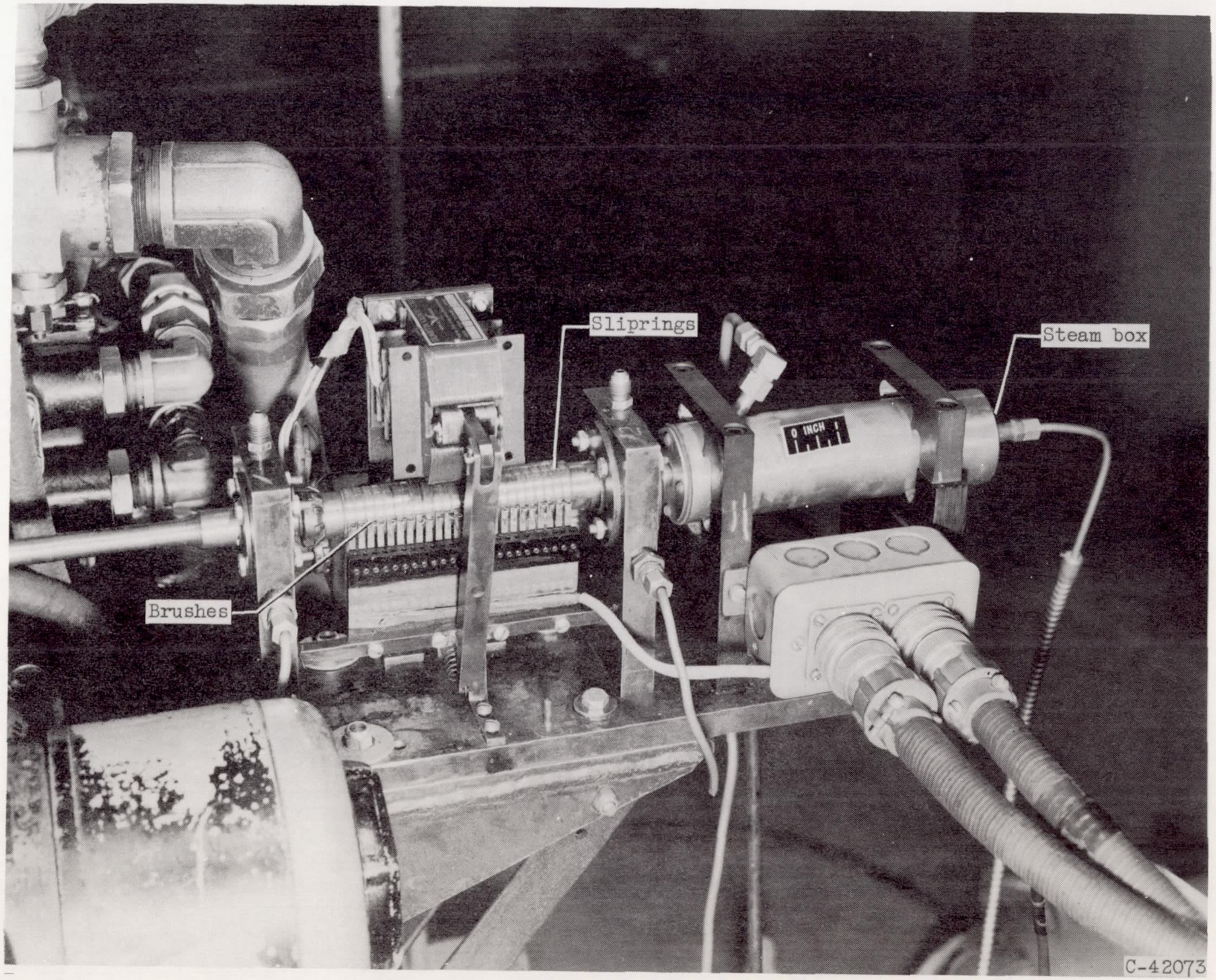


Figure 5. - Slipring thermocouple pickup.

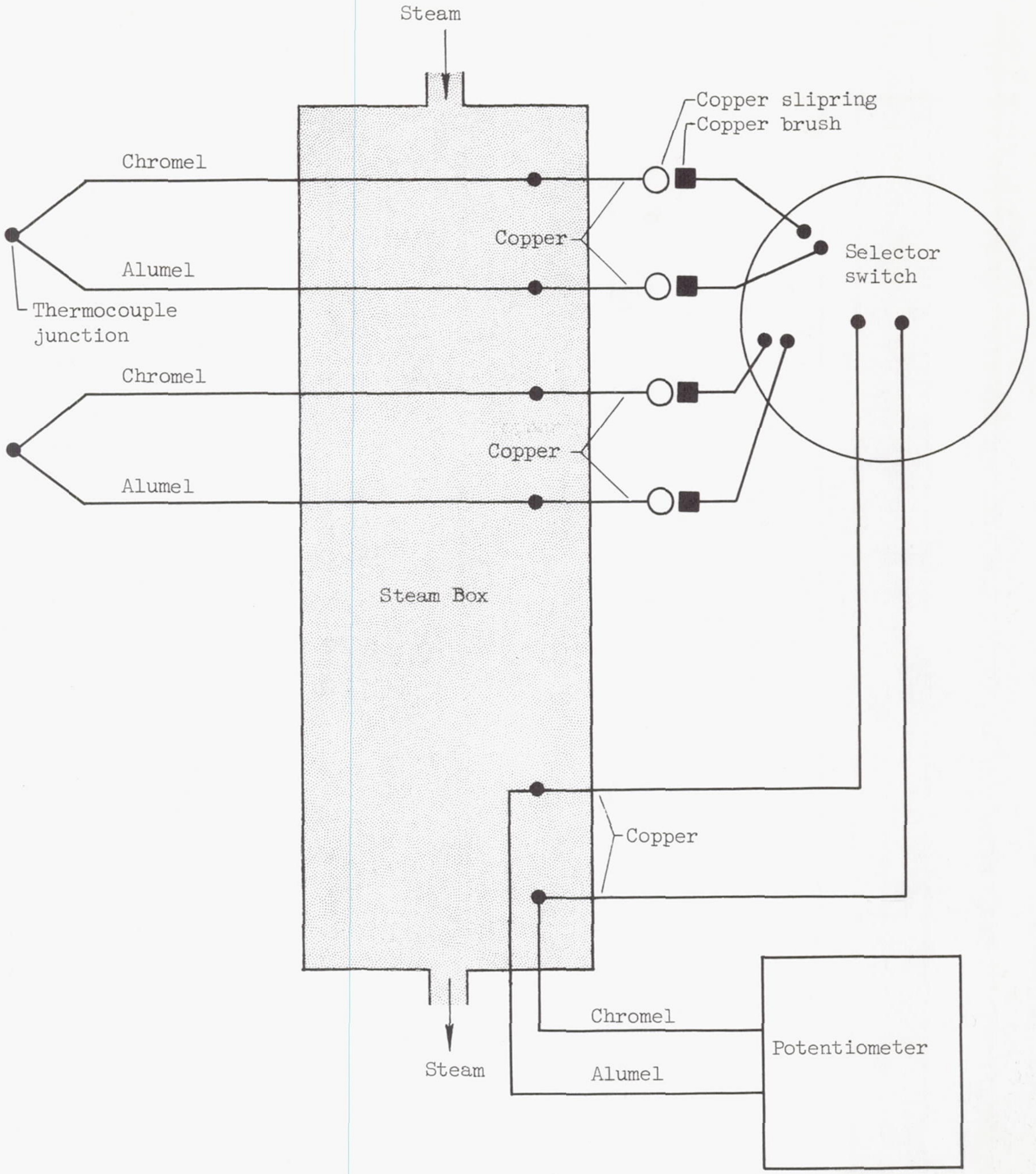
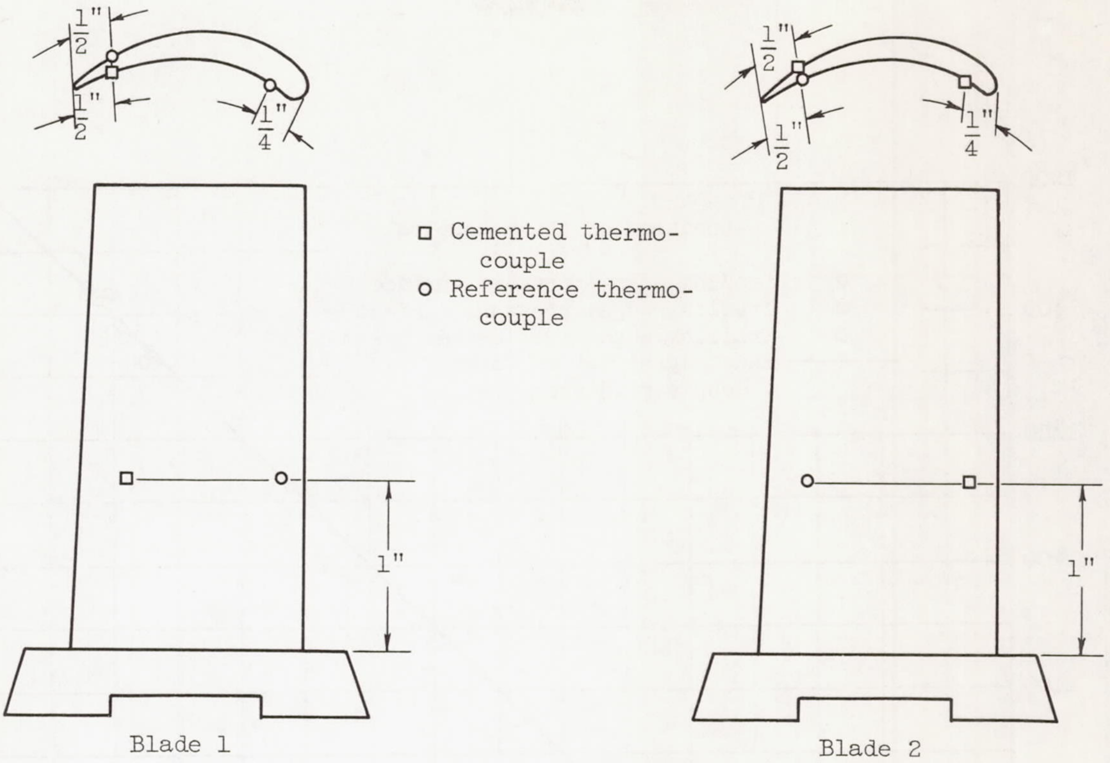
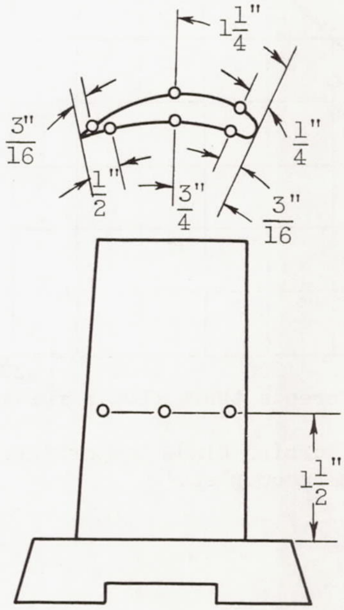


Figure 6. - Schematic diagram of thermocouple system for measuring turbine blade temperatures.



(a) For evaluating accuracy of cemented thermocouples.



(b) For evaluating accuracy of temperature-indicating paints.

Figure 7. - Location of thermocouples on turbine blades used for accuracy test.

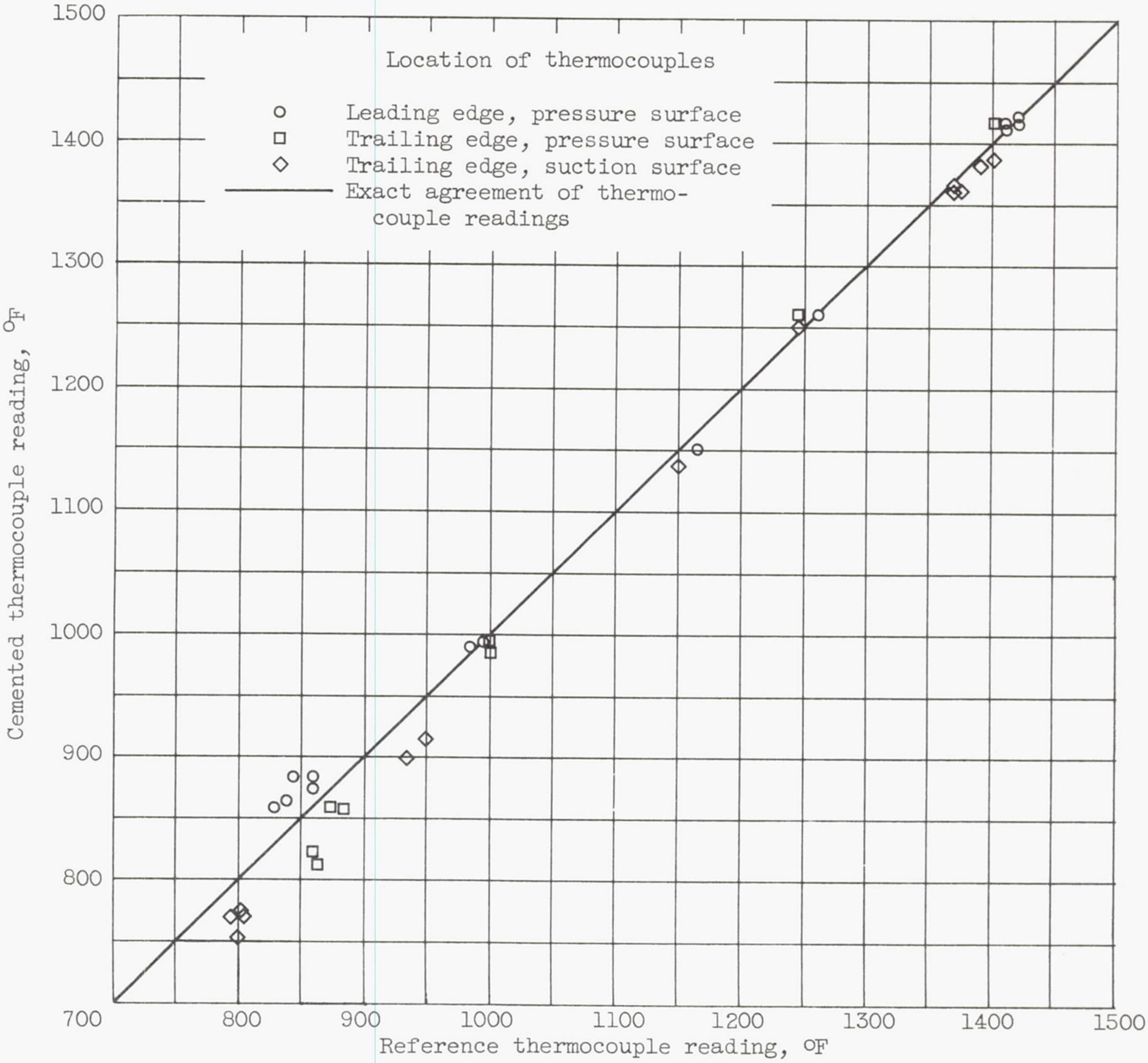


Figure 8. - Comparison of turbine blade temperatures measured by cemented thermocouples and reference thermocouples.

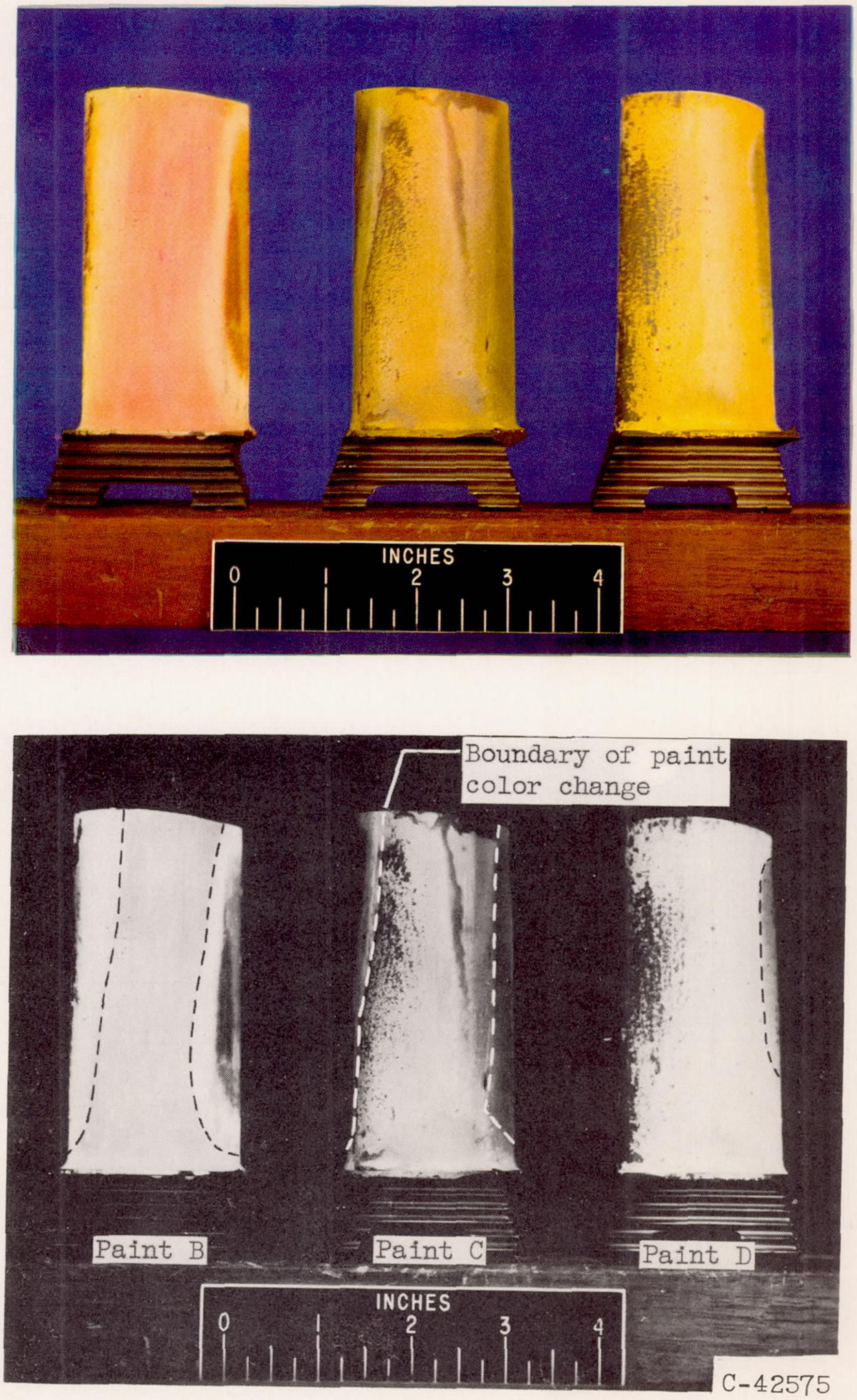
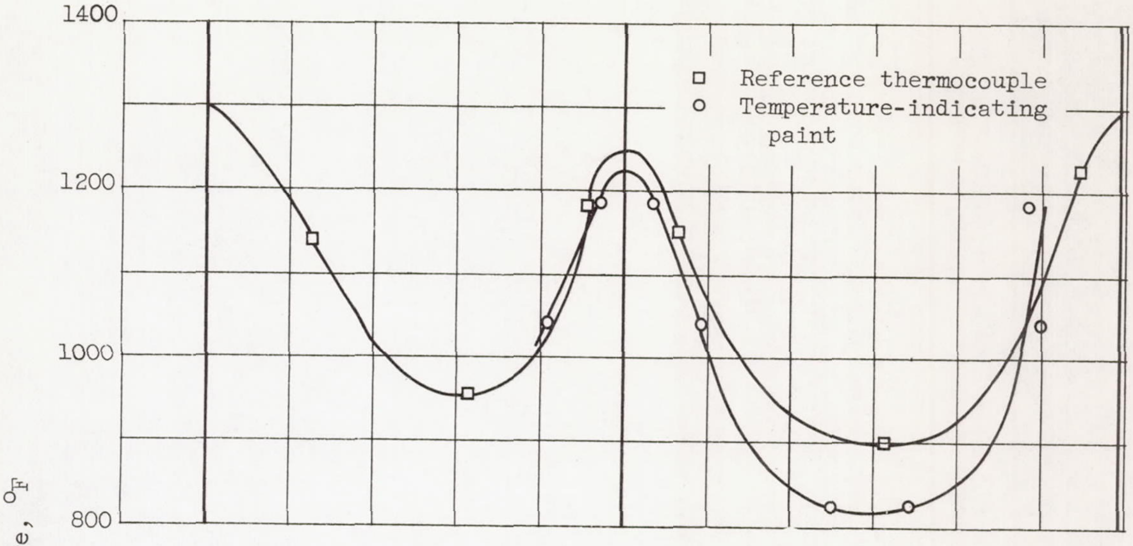
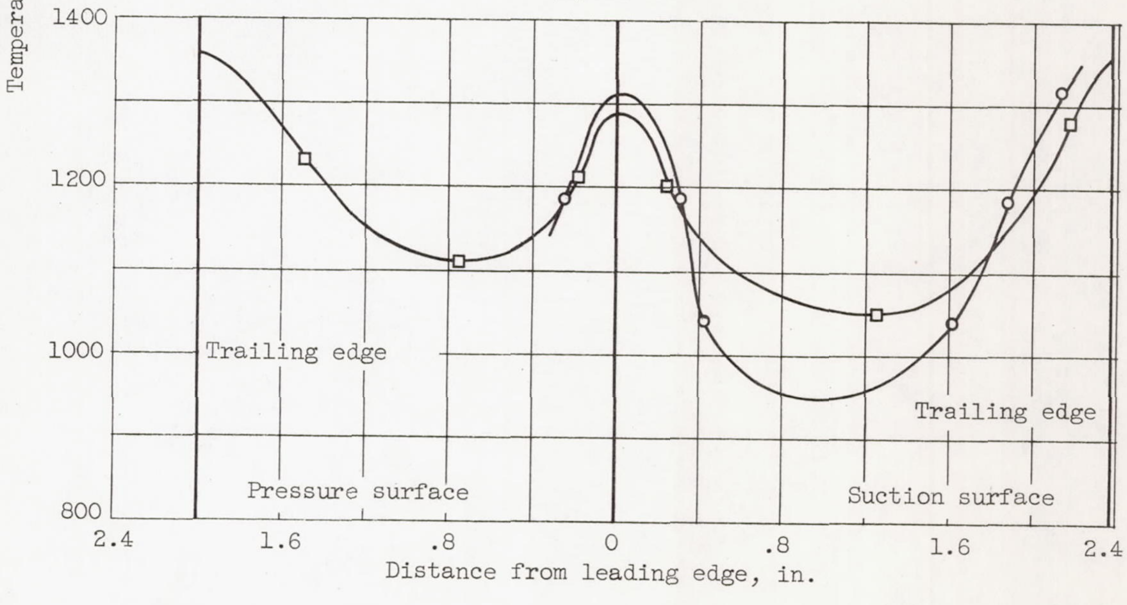


Figure 9. - Air-cooled blades with temperature-indicating paints after 15 minutes of engine operation (see table 1).



(a) Run 1.



(b) Run 2.

Figure 10. - Comparison of blade temperatures measured by temperature-indicating paints and reference thermocouples $1\frac{1}{2}$ inches from the blade base.