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# RESEARCH MEMORANDUM

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## EXPERIMENTAL INVESTIGATION OF AIR-COOLED TURBINE BLADES IN TURBOJET ENGINE

## X - ENDURANCE EVALUATION OF SEVERAL TUBE-FILLED ROTOR BLADES

By Jack B. Esgar and John L. Clure

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON
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RESEARCH MEMORANDUM

# EXPERIMENTAL INVESTIGATION OF AIR-COOLED TURBINE BLADES IN TURBOJET ENGINE

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## SUMMARY

In an investigation to develop air-cooled gas turbine blades made of noncritical materials that are capable of sustained operation in turbojet engines at minimum coolant-flow rates, several tube-filled rotor-blade configurations were fabricated and tested in order to develop an improved type of blade configuration. The improved type of blade configuration was nontwisted and designed for use with twisted stator blades. The blade had a thinner profile and thinner blade walls than any of the air-cooled blades previously investigated. The blade was formed from low-alloy steel tubing and the blade shell was attached to the base by brazing.

From the results of tests on the improved type of blade configuration and other similar configurations it was found that the attachment of an air-cooled turbine-blade shell to the blade base by means of Nicrobrazing provided a sound root structure if the clearance between the shell and base was less than 0.003 inch before brazing and if a fillet was provided at the junction of the shell and base. For a formed-shell blade, where the coolant passage extended far into the leading- and trailing-edge regions, the leading- and trailing-edge temperatures could be substantially reduced below the temperatures obtained from cast-shell blades. At an engine speed of 10,000 rpm and a coolant-flow ratio of 0.029, the reduction in trailing-edge temperature was about 200° F. Cyclic and constant-speed endurance tests at reduced coolant-flow rates showed that the noncritical blades that were investigated were capable of operation for at least 25 hours at rated speed for a turbine-inlet temperature of 1670° F and a coolant-flow ratio of 0.03. One blade was operated for over 55 hours at coolant-flow ratios ranging from 0.048 to 0.03 at rated-speed endurance conditions and was in reasonably good condition at the completion of the investigation. Blade life was found to be limited by oxidation and erosion at the blade leading edge even though a coating of nickel was applied to the blades to provide oxidation resistance. Nickel coatings applied to the blade by a chemical-deposition

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process were found to provide reasonable oxidation resistance except at the blade leading edge up to approximately 25 hours of rated-speed endurance. Improvements in the coatings are probably possible. Ceramic coatings that were tested in this investigation were found to be unsatisfactory for providing oxidation resistance for low-alloy steel turbine blades because of poor adherence between the coating and the blade shell.

A stress-ratio factor that was based on blade-temperature, blade-stress, and stress-rupture data provided an improved method of comparing and evaluating the cooling effectiveness of air-cooled turbine blades of different configurations and different materials.

## INTRODUCTION

One of the objectives of the research on turbine-blade cooling is to produce blades made of noncritical materials capable of sustained operation in gas turbine engines at minimum coolant-flow rates. The blade-cooling effectiveness of a variety of air-cooled blade configurations was investigated in a production turbojet engine that was modified to accommodate two air-cooled turbine blades (references 1 to 7). Endurance investigations of the more promising of these blade configurations are reported in reference 8 for the case where the ratio of coolant flow to gas flow per blade, hereinafter called coolant-flow ratio, was 0.05.

With respect to the engine performance the minimization of the quantity of air used for blade cooling is desirable. Additional research was therefore required both to improve the cooling effectiveness of air-cooled turbine-rotor blades and to determine the durability of blades at decreased coolant-flow rates. In order to provide a sound basis for determining minimum allowable coolant-flow rates that will permit adequate blade life, a relation between air-cooled turbine-blade temperature distribution, blade-material strength properties, and estimated blade life would be desirable. The fabrication of air-cooled turbine blades should be by methods that are as simple as possible consistent with good cooling performance in order to facilitate production. It was demonstrated in reference 8 that the provision of slots in the leading edges of blades to improve the cooling effectiveness in this area resulted in very poor blade durability. Means of providing high blade-cooling effectiveness while at the same time providing a sound structure and maintaining simplicity in blade fabrication is therefore desirable.

In order to obtain a method that could be used for predicting minimum allowable coolant-flow rates that would provide adequate blade life and to obtain durable air-cooled blades that are relatively easy to fabricate and yet have a high cooling effectiveness, an investigation was conducted on tube-filled turbine blades at the NACA Lewis laboratory in order to develop and evaluate improved fabrication techniques and to provide a very preliminary basis for a method of analytically establishing a blade durability criterion.

In this report are presented the results of tests that were conducted on air-cooled turbine blades (1) to investigate an improved shell-to-base attachment method, (2) to provide a preliminary investigation on oxidation-resistant coatings on the blade shells, (3) to investigate the durability of blades under cyclic endurance conditions at reduced coolant-flow ratios, (4) to investigate the durability of the improved type of turbine blade at coolant-flow ratios from 0.048 to 0.03, and (5) to determine the blade-temperature distributions for an improved type of tube-filled turbine-rotor blade. The improved type of air-cooled turbine blade was nontwisted and was designed for use with twisted stator blades. The blade profile and walls were thinner than any of the blades previously tested in references 1 to 8. These factors made the blade lighter, but also resulted in a blade with less resistance to gas bending forces. In order to provide high strength at the blade root, to provide a smooth coolant passage, and to simplify construction the blade shell was extended through the blade base and a strong attachment provided by brazing. The improved blades of the final design were coated with nickel to reduce oxidation.

The constant-speed endurance tests made during this investigation were conducted at rated engine speed at coolant-flow ratios from 0.03 to 0.048. Cyclic-endurance tests that were conducted consisted of alternate periods of 15 minutes at rated speed with a coolant-flow ratio of 0.03 and periods of 5 minutes at idle. Heat-transfer tests on the improved type of turbine blade were conducted to determine the blade-cooling effectiveness at engine speeds from 6000 rpm to 11,500 rpm (rated speed) at coolant-flow ratios ranging from 0.023 to 0.094 at 6000 rpm and from 0.019 to 0.052 at rated speed.

## SYMBOLS

The following symbols are used in this report:

| | |
|---|---|
| $T_{a,e,h}$ | effective cooling-air temperature at root of blade (°F) |
| $T_B$ | local blade temperature (°F) |
| $T_{g,e}$ | effective gas temperature (°F) |
| $w_a$ | cooling-air flow per blade (lb/sec) |

$w_g$ combustion-gas flow per blade (lb/sec)

$\varphi$ temperature-difference ratio, $(T_{g,e} - T_B)/(T_{g,e} - T_{a,e,h})$

## APPARATUS, BLADE-FABRICATION PROCEDURE, AND INSTRUMENTATION

### Engine

The modified turbojet engine used in this investigation was similar to that described in detail in references 1 and 2 except for different configurations of air-cooled blades. Throughout the investigation standard twisted rotor blades were used adjacent to the air-cooled blade as well as at all other locations on the turbine rotor. The standard blades were installed next to the cooled blades because the durability of the standard blades was better than that of the uncooled, nontwisted blades used in most previous investigations. Tests conducted using twisted blades next to the cooled blades are reported in references 7 and 8. The results obtained showed that the effect on blade-temperature distribution was small.

The instrumentation used on the engine was the same as that discussed in references 1 and 2 with the exception of the location and number of thermocouples on the cooled blade.

### Blade Descriptions and Fabrication Methods

In this investigation 14 air-cooled, tube-filled turbine blades were investigated in order to (1) develop an improved shell-to-base attachment method, (2) investigate oxidation-resistant coatings, and (3) evaluate the endurance life of blades at reduced coolant-flow rates. The blades used in the investigation were of two different aerodynamic profiles. Those blades designated as having profile A were of the same profile as the formed blades investigated in references 8 and 9. A photograph of blade profile A is shown in figure 1(a). The blades contained no twist and the profile was essentially the same as the root section of the conventional solid blades for the engine used in the investigation. The blades designated as having profile B were also nontwisted blades, but the blades were designed to be used with twisted stator blades. The blade cross section was thinner than the blades reported in references 1 to 9. A photograph of blade profile B is shown in figure 1(b). A summary of the construction features of each of the 14 blades used in this investigation is given in table I. Details of the construction of the blades are given in the following paragraphs.

*Blades 1 and 2.* - The blade shells were formed from SAE 4130 steel tubing as described in reference 9. A taper was first machined in the tube wall and blade profile A formed by contour pressing. The wall thickness of the blade shell tapered from 0.070 inch at the base to 0.035 inch at the blade tip. The blade base was precision cast of SAE 4130 steel. The blade shell was extended through the hole in the blade base as illustrated for a typical blade in figure 2. The extension of the blade shell through the base provides a smooth uniform path for the cooling air and should improve the blade-cooling effectiveness because of better air distribution. The use of formed shells extends the coolant passage farther into the leading and trailing edges than is possible for a cast blade as can be seen by comparing figures 1(a) and 1(b) with figure 1(c). On blades 1 and 2 the clearance between the shell and the base varied from 0 to 0.020 inch before brazing. It was realized that such large clearances result in low braze strengths, but it was deemed necessary to determine if the strength of the braze with a poor fit between the base and the shell would be sufficient for use on turbine-rotor blades, where in some cases the casting tolerances of the base might result in clearances of the order of 0.020 inch.

After insertion of the shell into the base, the blade shell was packed with twelve 0.156-inch outside diameter by 0.015-inch wall mild-steel tubes as shown in figure 1(a). Copper wire was laced through the blade shell between adjacent tubes and a paste of Nicrobraze powder and Acryloid B-7 volatile plastic cement was packed around the shell at the blade base. The assembled blade was then inserted in a dry-hydrogen-atmosphere furance and the component parts of the blade were brazed together at a temperature of 2100° F. The blades were heat-treated immediately on removal from the furnace by an isothermal quench in a 1000° F salt bath for 15 minutes and then air cooled. It was found that even though excess brazing material was placed around the shell at the blade base, no fillet was formed in this area during the brazing operation.

Finishing operations, such as cutting the blade to length and grinding the base serrations, were the same as discussed in reference 9. The aerodynamic profile of the completed blade was held within ±0.006 inch of the design value.

*Blades 3 and 4.* - The fabrication method for blades 3 and 4 was essentially the same as for blades 1 and 2, although the blade profile, wall thicknesses, and tube sizes were different. The wall thickness of the blade shell tapered from 0.060 inch at the base to 0.020 inch at the blade tip, and the blade was contour pressed into profile B, which is thinner than profile A. The clearance between the base and the portion of the shell that extended through the hole was held between 0 and 0.003 inch. Ten mild-steel tubes of 0.125-inch outside diameter by 0.0125-inch wall thickness were inserted in the coolant cavity. Brazing and heat-treating of the blades were accomplished in the same manner as for blades 1 and 2. There were no fillets at the junction of the blade shell and the base.

Blade 5. - The fabrication of blade 5 was identical to blades 3 and 4 except that copper was used for brazing the blade shell to the base and a fillet was provided at the junction between the shell and the base (fig. 2) by building up this area with Eutectic 16 brazing alloy. Care was taken so that the blade did not become overheated while the Eutectic 16 was being applied in order that the blade heat-treatment would not be changed in the critical section of the blade that is, at about 1/3 span. A fillet cast integrally with the base would be more satisfactory than the built-up fillet used for this blade with respect to fabrication and blade durability. The built-up fillets used in this investigation were used as a matter of expediency.

Blade 6. - Blade 6 was the same as blades 1 and 2 except that a fillet was provided at the junction of the shell and the base as explained for blade 5 and the clearance between the shell and the base was held to 0 to 0.003 inch before brazing. After fabrication, a coating of nickel from 0.001 to 0.003 inch thick was applied to the blade by the deposition process described in reference 10. The nickel was deposited on the blades without the use of an electric current by a chemical action at a temperature of approximately 194° F. The nickel coating was to provide a resistance to oxidation on the low-alloy steel used for the blade.

Blade 7. - This blade was used primarily to determine the durability of a ceramic coating and not to investigate improved blade fabrication techniques. The blade was integrally cast from SAE 4130 steel as described in reference 9 and the blade had profile A. The blade was coated with ceramic by a ceramic manufacturer in order to provide oxidation resistance. Some development was required by the manufacturer in order to obtain a coating that could be applied satisfactorily to the SAE 4130 steel. The coating was similar to the National Bureau of Standards coating A-19. The coating thickness was about 0.003 to 0.005 inch. The blade was not heat-treated after coating for fear of ruining the coating.

Blade 8. - The fabrication of this blade was similar to that for blades 1 and 2 except the clearance space between the shell and the base was from 0 to 0.010 inch before brazing and a fillet was provided at the junction of the blade base and the shell. This blade was coated with ceramic by a different manufacturer than the one that coated blade 7. The coating thickness was approximately the same and this coating was also similar to National Bureau of Standards coating A-19. No heat-treatment was given to the blade after coating.

*Blades 9 to 11.* - These three blades were fabricated by the same method as the butt welded blades that were investigated in reference 8 and by a process described in reference 9. The blade shells were formed into profile A and the shell was butt welded onto a lip on the blade base after installation of the tubes in the shell, which extended through the base. After the shell has welded to the base, the tubes were copper brazed to the shell and base. The blades contained eleven or twelve 0.156-inch outside diameter by 0.015-inch wall tubes. The number of tubes was dependent on the pack so that all tubes were wedged tightly into the coolant cavity. A smaller tube was sometimes used at some location in the tube pack so that the tubes would be wedged properly. The shell for blade 9 was made from Timken alloy 17-22A(S) steel (containing about 97 percent iron), and the shells for blades 10 and 11 were made from SAE 4130 steel (also containing about 97 percent iron). The bases for all blades were made from cast SAE 4130 steel. Blade 11 was heat-treated by isothermal quenching during fabrication as described for blades 1 and 2. Blade 10 was not heat-treated for comparison purposes. Blade 9 was heat-treated by isothermal quenching shortly after the endurance investigation was started. The blades were coated with nickel as described for blade 6.

*Blades 12 to 14.* - The fabrication of these blades was the same as for blades 3 and 4 except that a Eutectic 16 fillet was provided between the blade shell and the base. After fabrication a coating of nickel was applied to the blades by the deposition process described for blade 6. Blades 12 and 13 were coated immediately after fabrication and were coated a second time in the middle of the endurance investigation. Blade 14 was nickel coated after 21 hours of the endurance investigation were completed.

The quality of the braze between the tubes and the blade shell was checked on these blades by the following method: A temperature-indicating paint, Tempilaq, which melts at about 200° F was applied to the blade shell. Air at a temperature of approximately 1000° F was passed through each individual tube while the outside of the blade was cooled by air blowing over it. In the areas where there was a good thermal bond between the tube and the shell, the Tempilaq melted and caused a dark area (fig. 3). In the areas where there was a poor thermal bond between the tube and the shell, the paint was unaffected. In all blades tested there was poor bonding in some areas of the blade, particularly on the pressure surface. More research is required in the brazing technique for this type of blade construction.

## Blade Instrumentation

Seven chromel-alumel thermocouples were installed in blade 12 (fig. 4) at the completion of the endurance test. The thermocouples were installed as described in reference 1 except that grooves were not cut in the base of the blade for the thermocouple leads in order to keep from setting up excess stresses in this area. The leads were run along the base of the blade and then held in place by Eutectic 16 brazing alloy. The thermocouple junctions were at approximately 1/3 span, which is usually the critical section on gas-turbine rotor blades. Two solid blades were thermocoupled near the leading edge at the same radial location as the thermocouples on the cooled blade (fig. 4), for measuring the effective gas temperature in the same manner as described in references 1 to 8. The cooling-air temperature was measured by a thermocouple placed in the cooling-air-inlet passage near the blade root.

The locations of the thermocouples relative to the areas of the blade where good thermal bond was obtained between the tubes and the shell is shown in figure 3. In the areas where the thermocouples were located on the pressure surface of the blade, there was very poor thermal bond between the tubes and the shell.

## PROPOSED CRITERION FOR EVALUATING AIR-COOLED TURBINE BLADES

In past practice the comparison between the cooling effectiveness of various air-cooled blade configurations has been based on blade temperatures only. The significance of the effects of chordwise temperature gradients has been extremely difficult to evaluate and the effect on the over-all stress-carrying capacity has yet to be determined. The results of the endurance investigation, which was conducted at an arbitrary coolant-flow ratio of 0.05 and is reported in reference 8, have indicated that the presence of chordwise temperature gradients can be tolerated in air-cooled turbine blades but the degree to which the gradients will affect the blade strength is unknown. The actual stresses encountered in air-cooled turbine blades will vary according to the blade configuration and the fabrication method; the stress-carrying capacity of the blade will be a function of the design, the blade material, and the blade temperatures. It would be desirable, therefore, to determine a method of blade evaluation that will consider the combined effects of temperature gradients, blade material, and blade stress. As a first approach the blade evaluation method presented in the following paragraphs is proposed:

Based on stress-rupture data, a given metal temperature determines the maximum allowable constant stress that the metal can withstand for a specified life. When stress-rupture curves and the temperature distribution obtained for a turbine blade either by experimental measurements or by correlations of experimental measurements are used, the allowable stress at any chordwise position for a given life can be determined. For the types of air-cooled blades that have been investigated, the allowable stresses are much higher in the midchord region of the blade than at the leading and trailing edges because the midchord region of the blade operates at a cooler temperature.

The actual operating stresses in the turbine-rotor blade are difficult to determine; however, for most designs the most significant stress is probably due to centrifugal loading. For a blade that has a uniform taper at all locations on the blade, the blade-shell stress due to centrifugal loading will be uniform around the blade periphery. Thermal stresses and gas bending stresses will cause the local combined stresses around the blade periphery to vary, but the average stress level over the blade cross-section at a given radial station will remain constant. In other words, the effect of thermal and gas bending stresses is to partly shift the tensile stresses due to centrifugal loading to different portions of the blade. If vibratory stresses are neglected and if the stress redistribution is complete, the stress-carrying capacity of the blade is a function of the centrifugal loads only. When the elastic limit is exceeded at some location on a blade made from a ductile material, plastic flow will occur and a portion of the load will be transferred to a location of the blade that is still in the elastic range. If the allowable stress levels at the leading and trailing edges of the turbine blade are less than the stress due to centrifugal loading, then a portion of the load at the leading and trailing edges can be transferred by plastic flow to the cooler midchord region of the blade where higher stress levels are permissible. At zero turbine speed, the residual stresses caused by plastic flow in such a blade would cause the leading and trailing edges of the blade to be in compression and the midchord to be in tension.

Based on the assumption that loads in the various portions of the blade can be transferred as explained, it would indicate that the blade could operate safely if the following conditions were obtained; namely, if the area under a plot of allowable stress level (based on blade temperatures and stress-rupture data) against blade periphery was equal to or greater than the area under a plot of actual centrifugal stress (assumed to be uniform around the blade periphery) against blade periphery. Safe operation of air-cooled turbine blades at conditions indicating that the leading and trailing edges were far overstressed indicates that stress redistribution actually does occur in the blades.

The stress redistribution from the overstressed leading and trailing edges probably will not be complete and vibratory stresses will have some effect on blade strength. In order to provide a criterion for safe operating conditions, a factor should be determined that will relate allowable stresses, based on temperature and stress-rupture data, with the major stresses actually occurring in the turbine blade shell. As a first approximation a stress ratio factor, defined as

$$\text{stress-ratio factor} = \frac{\text{area under allowable stress curve}}{\text{area under actual centrifugal stress curve}}$$

can be used for this purpose.

Systematic endurance investigations must be conducted in order to determine the stress-ratio factor that will be necessary so that the blade life will be equal to the stress-rupture life of the blade material. When the required stress-ratio factor has been determined, a design procedure for estimating blade life from temperature and stress-rupture data will be available. Of additional value is the fact that blade configurations can be compared for a constant stress-ratio factor in order to evaluate more fully the combined effects of blade stress, blade-temperature distribution, and blade material. Finally, the stress-ratio factor serves to compare the coolant flows required for a given blade configuration that might be fabricated from several different metal alloys. The stress-ratio factor is used herein to determine the relative quantities of coolant required for blades made of two different steel alloys and to show the approximate stress-ratio factor encountered in the constant endurance investigation of an improved type of air-cooled gas-turbine rotor blade,

## TEST PROCEDURE

The primary purposes of this investigation were to obtain information on air-cooled blade durability at reduced cooling-air flow rates and to evaluate an improved blade design. Investigations were also conducted to evaluate the brazed shell-to-base attachment method and to obtain information concerning the effectiveness of oxidation-resistant coatings that were available at that time.

### Shell-to-Base Attachment Investigation

The suitability of the brazed shell-to-base attachment method for gas-turbine blades was investigated for a number of blades utilizing slightly different configurations at the blade base. The first blades that were fabricated using this type of construction were blades 1 and 2. Constant-speed endurance tests at rated engine speed with an effective gas temperature of 1450° F (approximately 1670° F turbine-inlet temperature), with a cooling-air temperature of approximately 180° F at the blade root, and with a coolant-flow ratio of 0.048 were conducted in order to determine the durability of this attachment method. The coolant-flow ratio was set at a nominal value of 0.05, but corrections for coolant leakage resulted in the value of 0.048.

Blades 3 and 4 were used for further investigation of the brazed shell-to-base attachment method utilizing the improved type of blade design that had blade profile B.

Constant-speed endurance tests similar to those described previously were conducted both to investigate the durability of the brazed joint and to determine if fillets were required at the junction of the blade shell and base. The endurance runs were first conducted at a coolant flow of 0.048 and then reduced to 0.03 in order to determine the durability at reduced coolant-flow rates.

Constant-speed endurance tests were conducted on blade 5 at a coolant-flow ratio of 0.03 in order to determine the suitability of using copper instead of Nicrobraze for brazing in attaching the shell to the base for blades having profile A.

In order to obtain further information on the durability of the brazed structure on blades of profile A, which were heavier than blades with profile B, blade 6 was endurance tested at cyclic conditions. The cyclic-endurance conditions consisted of alternate periods of 15 minutes at rated engine speed, with an effective gas temperature of 1450° F, and a coolant flow ratio of 0.03 with 5-minute periods at idle. The blade was run at cyclic-endurance conditions rather than constant speed to expedite the investigation because the blade was tested concurrently with other blades that were being cyclic-endurance tested.

## Oxidation-Resistant Coating Investigations

The durability of ceramic and nickel coatings for the purpose of reducing or eliminating oxidation of the low-alloy steel-blade shells was investigated in both constant-speed and cyclic-endurance investigations. Ceramic-coated blade 7 was endurance tested at cyclic conditions for 20 cycles at a coolant-flow ratio of 0.048 in order to determine the effect of heat shock on the coating, and then a constant-speed endurance test at a coolant-flow ratio of 0.048 was run until the coating failed.

Ceramic-coated blade 8 was run at constant-speed endurance conditions at a coolant-flow ratio of 0.048 until the coating failed. A constant-speed endurance test was run because of less difficulty in conducting a constant-speed test and because no effect of cycling was observed on blade 7.

The durability of nickel coatings was determined at the same time the structural durability of blades 6 and 9 to 14 was being obtained. The endurance tests on these blades were conducted under a variety of conditions. Blades 6 and 9 to 11 were cyclic-endurance tested at a coolant-flow ratio of 0.03. Blades 12 to 14 were endurance tested at constant speed over a range of coolant-flow ratios from 0.048 to 0.03. The reasons for running part of the endurance tests to determine blade durability under cyclic conditions and part under constant-speed conditions will be discussed in the following sections.

## Cyclic-Endurance Investigation on Blades with Profile A

In reference 8 the blades that were found to be the most durable in cyclic-endurance investigations at a coolant-flow ratio of 0.05 were blades that were fabricated from formed sheet-metal shells and were attached to the blade base by butt welding. Under the conditions of the test, a Timken 17-22A(S) blade was capable of withstanding at least 200 cycles (50 hr at rated-speed conditions). A SAE 4130 blade fabricated by the same method failed because of oxidation after 154 cycles ($38\frac{1}{2}$ hr at rated speed conditions).

The purpose of the cyclic-endurance investigation reported herein was to determine the reliability of blades similar to those investigated in reference 8 at reduced coolant-flow conditions. In an attempt to reduce the possibilities of blade failure due to oxidation, the blades were coated with nickel. Because little or no previous experience had been obtained on this type of coating on gas-turbine blades, the endurance test on the blade structures at reduced coolant flow also constituted a durability test on the nickel coatings.

The endurance tests were conducted on a turbine rotor with provision for two air-cooled blades. A total of four blades were tested. One blade, the Timken 17-22A(S) blade (blade 9), was in the rotor for the entire test. The SAE 4130 blades were installed in the following order: blades 10, 11, and 6. Each SAE 4130 blade was installed after the failure of the previous one.

## Investigations on Improved Blade Configuration

Constant-speed endurance investigation. - The configuration of blades 12 to 14, which had blade profile B, required an endurance investigation in order to determine if this configuration, which had a thinner profile and thinner shell walls so that there would be less resistance to bending, would be satisfactory for operation in gas-turbine engines. Previous endurance investigations had been conducted at cyclic conditions, but in order to expedite the endurance investigations on this blade configuration a constant-speed endurance test was run for the following reasons:

(1) There was no evidence from previous cyclic investigations that the cycling of the engine was a factor in any of the blade failures.

(2) On the best blade designs of previous investigations the endurance life was limited by oxidation and not by blade structure, and the rate of oxidation was not expected to be any more affected by cyclic operation than by constant-speed operation.

(3) The endurance tests could be conducted faster at constant speed because more time was spent at rated-speed conditions and because the engine gave less operational trouble at constant-speed conditions.

The endurance tests were conducted over a range of coolant-flow ratios starting at 0.048 and gradually reduced to 0.03. The tests were started at a high coolant-flow rate to insure that the blade would be satisfactory under conditions that might affect blade life that were not related to high blade-shell temperatures. The coolant-flow rate was then reduced in two steps in order to obtain endurance time at reduced coolant-flow rates. The blades in this investigation were coated with nickel in order to provide oxidation resistance and these blades served to obtain additional information on the durability of nickel coatings.

Blade temperature and allowable stress distribution. - After completion of the constant-speed endurance investigation, blade 12 was instrumented with seven thermocouples in order to obtain the actual temperature distribution during the endurance investigation and to provide information on the stress-ratio factor obtained on these blades at rated-speed conditions. The heat-transfer tests were conducted at nominal engine speeds of 6000, 8000, 10,000, and 11,500 rpm (rated speed) at coolant-flow ratios ranging from 0.023 to 0.094 at 6000 rpm and from 0.019 to 0.052 at rated speed. Heat-transfer tests at rated speed were run for the tail pipe open and also for the tail-pipe nozzle sufficiently closed to raise the effective gas temperature to 1450° F, which was the temperature at which the endurance investigations were conducted. These data were then used to obtain the temperature distributions around the blade, and from stress-rupture data for SAE 4130 and Timken 17-22A(S), the stress-ratio factors were determined for a series of coolant flows for blades of this configuration that would be made from either of the two materials.

The heat-transfer data obtained from blade 12 are presented as the temperature-difference ratio $\varphi$ as was done in references 1 to 7. The effective gas temperature used for calculating $\varphi$ was the measured solid-blade temperature near the leading edge. Actually the solid-blade temperature, or effective gas temperature $T_{g,e}$, varied along the blade chord because of the variations in the local Mach number along the blade. This effect has been measured in turbojet engines and can be calculated using a local recovery factor of 0.89 as specified for gas-turbine blades in reference 11. This effect is indicated in some of the data plots presented herein, but because the variation is small and was not actually measured at the same time the cooled-blade temperatures were measured, the variation in effective gas temperature with blade chord was not included in the calculation of $\varphi$.

## RESULTS AND DISCUSSION

The results of this investigation are summarized in tables II to V. The details of the results are given in the following paragraphs.

### Shell-to-Base Attachment Investigation

The results of the shell-to-base attachment investigation are summarized in table II. Blades 1 and 2, which had a poor fit (0 to 0.020 in. clearance before Nicrobrazing) between the base cavity and the blade shell, were found to be very weak in the brazed section of the blade. Blade 1 failed during the initial acceleration before reaching rated speed and blade 2 failed almost immediately after reaching rated speed. The calculated braze shear stress for these blades was 5500 pounds per square inch at rated speed. This stress is not too high for a good brazed joint where the clearances are low before brazing. The failure of blades 1 and 2 was therefore attributed to the poor fit between the shell and base prior to brazing.

Blades 3 and 4 had a satisfactory fit between the blade shell and the base prior to Nicrobrazing (0 to 0.003 in. clearance) and the shear stress was only 3500 pounds per square inch at rated speed because of lighter blade construction. The primary purpose of the endurance tests on these blades was to determine if a fillet was necessary at the junction between the blade shell and the base. These blades were endurance tested in a modified turbojet engine at the rated engine speed of 11,500 rpm, an effective gas temperature of 1450° F (which corresponds to 1670° F turbine-inlet temperature), and a cooling-air temperature of approximately 180° F at the blade root. After a total of only 3 hours of endurance, 2 hours were at 4.8 percent coolant-flow ratio and 1 hour was at 3 percent coolant-flow ratio, the engine was shut down for a periodic blade check and cracks were found to have developed at the root of each of the blades tested, as shown in figure 5. The cracks were on the suction surface of the blade and were presumably vibratory failures. The short endurance life of these blades gave sufficient evidence that this type of blade construction without fillets at the blade root was unsatisfactory.

Blade 5 was investigated in order to determine if copper brazing would be satisfactory at the blade base. The clearance between shell and base prior to brazing ranged from 0 to 0.003 inch and a fillet at the junction of the shell and base was provided. Temperatures in the base were measured at coolant-flow ratios of 0.02 and 0.03, and 5 hours of rated-speed endurance were completed satisfactorily at a coolant-flow ratio of 0.03. The base temperatures of the cooled blade varied from about 650° to 690° F for both coolant-flow ratios. This

5-hour endurance test was considered sufficient for determining whether the yield strength of the copper braze would be satisfactory at the temperatures that would be encountered in engine operation of air-cooled blades of this type. Further investigations on several varieties of copper-brazed blades will probably be required before it can be determined if this method of attaching the shell to the base is completely satisfactory. The shear stress on the brazed joint of the blade tested was 3500 pounds per square inch at rated engine speed.

Data from the investigation of blade 6 provided information on the strength of the brazed shell-to-base structure for a blade that had a satisfactory clearance between the shell and base prior to Nicrobrazing (0 to 0.003 in.) and had a braze shear stress of 5500 pounds per square inch at rated speed. A fillet was provided at the junction of the blade shell and the base. This blade was operated at cyclic-endurance conditions consisting of alternate periods of 15 minutes at rated speed with an effective gas temperature of 1450° F and a coolant-flow ratio of 0.03 and periods of 5 minutes at idle. The shell-to-base attachment method was found to be satisfactory for at least 46 cycles of the endurance test $\left(11\frac{1}{2}\right.$ hr at rated-speed conditions$\left.\right)$. The test on this blade was stopped arbitrarily by failure of another blade in the turbine rotor being used for a test on blade durability.

Subsequent tests for determining the durability of blades 11 to 14 showed no evidence of weakness in the brazed root structure. The results of all the investigations for determining the suitability of a brazed structure for attaching the shell to the base have indicated, therefore, that the Nicrobrazed shell-to-base attachment is satisfactory for shear stresses up to 5500 pounds per square inch as long as the clearance between the blade and the shell is held to less than 0.003 inch before brazing. For the type of air-cooled turbine blades tested a fillet is required at the junction of the blade shell and the base. Tests of a blade where copper braze was used for attaching the shell to the base was apparently satisfactory for shear stresses up to 3500 pounds per square inch; however, additional experience should be gained before definite conclusions can be drawn concerning the durability and upper operating-temperature limit for copper-brazed shell-to-base attachment.

## Oxidation-Resistant Coating Investigations

Two types of coatings, ceramic and nickel, were investigated in order to determine the durability under engine-operating conditions. The results obtained are summarized as follows:

Ceramic coatings. - As discussed under the section of blade descriptions, the ceramic coatings that were investigated were applied to the blades by two different manufacturers and both the composition and exact method of application were not disclosed by manufacturer. Neither of the two coatings investigated was satisfactory. Ceramic-coated blade 7 completed a total of 20 cycles of the cyclic-endurance test plus $2\frac{1}{4}$ hours of constant-speed endurance for a total of $7\frac{1}{4}$ hours of endurance at rated speed at a coolant-flow ratio of 0.048. At the end of that time the coating was blistered and chipped, particularly at the leading edge, (fig. 6(a)). Ceramic-coated blade 8 was run at constant speed at 11,500 rpm at a coolant-flow ratio of 0.048 for $4\frac{3}{4}$ hours when inspection of the blade showed that the coating material had flowed off at the leading and trailing edges (fig. 6(b)).

Although the ceramic coatings that have been investigated have been unsatisfactory, these results are preliminary and further research may yield satisfactory coatings.

Nickel coating. - During most of the endurance investigations on blades 6 and 9 to 13 in order to determine blade durability at reduced coolant-flow rates, nickel coatings were applied to the blades to reduce blade oxidation. The results obtained from the nickel-coated blades are summarized in tables III and IV. These results are only preliminary and probably indicate poorer coating performance than can be obtained after more experience is gained in the application of the nickel coating. The coatings for this investigation were applied on a laboratory scale and do not necessarily represent the quality that could be obtained by more refined methods.

During the cyclic-endurance investigation of blades that were nickel coated (see table III), the nickel coating came off the leading and trailing edges in about 11 to 15 hours of running at rated speed. At the leading edge erosion apparently played a strong part in removal of the coating, but in addition the temperature level of the blade metal seemed to be a determining factor because the coating also blistered and wore off of the trailing edge of the blade. In the midchord region of the blade, which may be about 300° F cooler than the leading and trailing edges, the coating durability was satisfactory in the tests conducted. The ultimate failure of blade 9 was probably primarily due to oxidation at the leading edge. This oxidation was a result of the nickel coating wearing away in that region. Even though the coating apparently failed at the trailing edges of the blades investigated, oxidation in this region was minor and did not constitute an immediate limitation on blade life.

At the beginning of the constant-speed endurance investigation (see table IV) both of the endurance blades 12 and 13 were coated with nickel. At the end of 4 hours of endurance at 11,500 rpm and an effective gas temperature of 1450° F blade 13 had to be removed because of faulty brazing between the tubes and the shell on the pressure surface of the blade, consequently an evaluation of the coating durability on this blade was impossible. Blade 14, which was used to replace blade 13, was not coated. After completing approximately 25 hours of endurance on the coated blade and 21 hours on the uncoated blade, both blades were removed from the turbine wheel for zyglo inspection. At that time the nickel had started to wear away from the leading edge and near the tip of the blade on the pressure surface of blade 12. Blade 14, which was not coated, was oxidized quite badly particularly at the leading edge. It was necessary to clean the blades thoroughly for the zyglo inspection. This cleaning by vapor blast removed the nickel coating. Both blades were then nickel coated and the endurance test was continued. After approximately 10 hours of the endurance test on the new coatings, blisters began to appear under the coating with some scaling present. These second coatings apparently were not as durable as the first coating on blade 12. The deterioration of the coatings continued until at the completion of the endurance test all the coating was gone from the blade leading edges and part of the coating was missing from other portions of the blades. Some of the areas where the coating failed are shown in figures 7 and 8.

From the endurance investigation on nickel coatings, which were applied by the process described in reference 10, it appears that if proper care and control are exercised in the application of nickel to noncritical turbine blades, the coating will probably provide reasonable protection from oxidation for periods of at least 25 hours for all locations on the blade except at the leading edge. A harder, and possibly thicker, material will be required at the leading edge to prevent a combination of erosion and oxidation. A coating of Nicrobraze, which would be applied at the same time that component parts of the air-cooled blade are being brazed together in the furnace, or hard chrome probably could be applied to the blade leading edge for resisting erosion and then the rest of the blade could be nickel coated.

Other coatings also offer possibilities for use on gas-turbine blades although as yet very little or no operating experience has been gained. Two methods that appear promising are aluminizing of low-alloy steels and using nickel or stainless-steel clad low-alloy steel. At the present time the use of a metal coating is apparently superior to a ceramic coating as a means of providing suitable oxidation resistance for steel turbine blades.

## Cyclic-Endurance Investigation on Blades with Profile A

Cyclic-endurance tests were conducted on both SAE 4130 steel blades and Timken 17-22A(S) blades at a coolant-flow ratio of 0.03. The results of the tests are summarized in table III. The cyclic-endurance tests were the same type as those reported in reference 8 except that the coolant flow was reduced.

The results obtained from this investigation are as follows:

SAE 4130 blade 10 without heat-treatment. - After only two cycles the SAE 4130 blade 10 without heat-treatment elongated until it rubbed on the tail-cone casing. The rubbing caused the blade to bend and the test was terminated.

Heat-treated SAE 4130 blades 11 and 6. - SAE 4130 blade 11 heat-treated by 1000° F isothermal quench from 2100° F completed 59 cycles $\left(14\frac{3}{4}\text{ hr at rated speed}\right)$ when the cooling air was inadvertently cut off so that the blade failed. Up until the time that the air was cut off the blade was in excellent condition with no signs of elongation. SAE 4130 blade 6, which was also heat-treated by 1000° F isothermal quench from 2100° F was installed and run until the completion of the endurance test, which amounted to another 46 cycles $\left(11\frac{1}{2}\text{ hr at rated speed}\right)$. At the end of the test this blade was still in excellent condition.

Timken alloy 17-22A(S) blade 9. - The Timken 17-22A(S) blade 9 was operated for two cycles without being heat-treated with no sign of elongation, but after the nonheat-treated SAE 4130 blade 10 elongated the 17-22A(S) blade was heat-treated. The blade then completed a total of 107 cycles $\left(26\frac{3}{4}\text{ hr at rated speed}\right)$ of which 5 cycles were run at a turbine-inlet temperature of approximately 1800° F, because of malfunctioning instrumentation; and the blade also withstood a few minutes of running with little or no cooling air at the same time the SAE 4130 blade 11 failed because of the air being cut off. The high-temperature running and the running with no cooling air apparently did not harm the blade. The blade probably was not completely uncooled at the time of the cooling-air failure. Cool air was still being supplied at the hub of the rotor and unpublished results obtained on other blades have indicated that enough air will be pumped through the cooling-air tubes on the turbine rotor by the turbine rotation to provide some cooling. This small amount of cooling evidently was sufficient to permit the blade to operate safely for the short period of time that it was run with the normal supply of cooling air cut off. It was not sufficient, however, to permit safe operation of blade 11, which was made of SAE 4130 steel. After 107 cycles the outer third of the pressure surface of blade 9 failed (fig. 9). This failure apparently was due to severe oxidation at the leading edge and a poor bond between the blade shell and the tubes in the coolant cavity. After failure at the leading edge due to oxidation, the shell apparently started vibrating and eventually a large portion of the shell broke off.

From the results of this cyclic test it can be concluded that (1) oxidation of noncritical blades is a serious problem and probably provides a limitation on blade life at the present time; (2) Timken 17-22A(S) steel is far superior to SAE 4130 steel for noncritical turbine blades as evidenced by the lack of elongation in the nonheat-treated state whereas the nonheat-treated SAE 4130 blade elongated, by the fact that there was no damage when the cooling air failed and resulted in the failure of SAE 4130 blade 11, and by previously published results in reference 8 which also showed superior performance of blades made of Timken 17-22A(S) steel; and (3) although inconclusive, formed tube-filled blades apparently can operate satisfactorily at rated speed and a coolant-flow ratio of 0.03 for a cooling-air temperature of 180° F if a means can be provided for eliminating oxidation.

## Investigations on Improved Blade Configuration

Constant-speed endurance investigation. - After the completion of preliminary investigations to determine the durability of a brazed shell-to-base structure on improved type of gas-turbine blades having profile B, constant-speed endurance tests were conducted in order to determine the durability of this type of blade using blades 12 to 14. A summary of the results of the constant-speed endurance investigation is given in table IV.

At the beginning of the endurance investigation the blades were run for 3 hours at a coolant-flow ratio of 0.048 to determine whether cracks would appear at the root as was the case with the unfilleted blades. No cracks were evident; therefore, an additional hour was run at a coolant-flow ratio of 0.03 in order to duplicate the running at low coolant-flow ratio on the unfilleted blades. The blade structure at the blade root was still satisfactory after the additional running at low coolant-flow ratio. At this time one of the two blades installed (blade 13) was found to have the tubes in the coolant passage separated from the blade shell on the pressure surface of the blade. The brazing was poor at the beginning of the test and deteriorated rapidly with running. Blade 13 was therefore replaced by another blade, blade 14.

Endurance testing at rated-speed conditions was continued on the blades at a coolant-flow ratio of 0.048 until 24 hours were completed on blade 12 plus 1 hour at a coolant-flow ratio of 0.03 (21 hr total on blade 14). This portion of the test was run at a high coolant-flow ratio in order to determine whether vibratory stresses would provide a limitation in the blade life for blades having a thin profile and a thin blade shell. After vibratory stresses appeared not to be serious in this type of blade construction, the coolant-flow ratio was reduced to 0.038 for 5 hours to provide a gradual reduction in the flow rate. The coolant-flow ratio was then reduced to 0.03 for the remainder of the test. After

$26\frac{1}{4}$ hours at a coolant-flow ratio of 0.03 and a total of $55\frac{1}{4}$ hours at rated speed on blade 12 $\left(25\frac{1}{4}\right.$ hr at 0.03 and $51\frac{1}{4}$ hr total on blade $\left.14\right)$ a portion of the suction surface of blade 14 broke away near the blade tip as shown in figure 7. As discussed previously, blade 14 was not protected from oxidation by the nickel coating for the first 21 hours of the endurance investigation; therefore, rather severe oxidation and erosion at the leading edge occurred. In the area of the failure, the leading edge had oxidized until the metal thickness was almost zero and, in addition, in the same area there was no mechanical bond between the shell and the tubes in the coolant passage because of poor brazing. The piece of the blade broke off because of vibration. The endurance program was terminated at this point in order to instrument the remaining endurance blade (blade 12) and to determine the blade temperatures and stress-ratio factors that were encountered on this blade during the endurance investigation. Blade 12 was still in relatively good condition except for some oxidation at the leading edge of the blade (fig. 8). The dents that are evident near the blade tip on the suction surface and directly at the tip of the blade were the result of one of the standard uncooled-blade failures during the endurance test.

The results of the constant-speed endurance tests on blades 12 to 14 and the cyclic-endurance tests on blades 6 and 9 to 11 indicate that for properly heat-treated low-alloy steel blades no difficulty was encountered in the structural strengths of formed tube-filled blades with shells brazed into cast-steel bases for coolant-flow ratios as low as 0.03 and a cooling-air temperature of 180° F. In these tests, blade life was limited by oxidation and erosion, particularly at the blade leading edges. This oxidation has lead to vibratory failures in the shell near the blade tip in two cases. These results further indicated the necessity for additional research on methods of increasing oxidation resistance.

Blade temperature and allowable stress distribution. - At the completion of the constant-speed endurance tests on the improved type of blades, blade 12, which had successfully completed $55\frac{1}{4}$ hours at rated speed, was instrumented with seven thermocouples in order to obtain blade-temperature data and to determine stress-ratio factors for the same blade that had been used in the endurance investigation. The blade-temperature data obtained, presented as the temperature-difference ratio $\varphi$, are given in table V for various engine speeds from 6000 to 11,500 rpm.

The temperature distributions of formed blade 12, utilizing a brazed shell-to-base type of construction, and the original cast tube-filled blade (reference 1) are shown in figure 10 for a coolant-flow ratio of 0.029. The gas flow through the engine was 60.6 pounds per second. This flow was obtained at an engine speed of approximately 10,000 rpm. In the tests that were conducted on the cast 10-tube blade of reference 1, there was some cooling-air leakage so that less air was actually going through the blade than was indicated by the data. For the comparison of temperature distributions in figure 10 the coolant flow was corrected to account for the leakage. The formed-blade temperature distribution indicates a reduction in leading- and trailing-edge temperatures relative to the leading- and trailing-edge temperatures of the cast blade. The largest reduction occurred at the trailing edge where the formed-blade temperature was more than 200° F below that of the cast blade for equivalent engine conditions. The temperatures in the midchord region of the formed blade were slightly higher than the temperatures for the cast blade. This increased temperature may be due to the increased cooling at the leading and trailing edges or may be due to poor brazing between the tubes and the blade shell, or possibly a combination of both.

By noting the location of thermocouples on the blade relative to the areas on the blade where good thermal bonds were obtained between the tubes and the shell (fig. 3) it can be seen that thermocouple 3 at the 50-percent chord position on the suction surface and both thermocouples on the pressure surface of the blade are not in areas having a good thermal bond; the blade-shell temperatures would therefore be high. After developing better brazing techniques for the fabrication of tube-filled blades, the blades would be expected to cool more effectively on both the suction and pressure surfaces. Even with good brazing there would probably be small temperature gradients in the blade shell between adjacent tubes; however, these small gradients should have no significant effect on blade strength.

The solid-blade temperature, or effective gas temperature $T_{g,e}$ varies along the blade chord as shown in figure 10 because of the variations in the local Mach number along the blade as discussed in the TEST PROCEDURE section.

The blade temperatures at rated engine speed for coolant-flow ratios of 0.02, 0.03, and 0.05 are shown in figure 11. These curves were obtained from cross plots of temperature data shown in table V. The fact that it was possible to run a blade containing seven thermocouples at these engine conditions and at a coolant-flow ratio as low as 0.02 is a good indication of the high blade-cooling effectiveness.

In figure 12 are shown 100-hour stress-rupture curves for SAE 4130 and Timken 17-22A(S) low-alloy steels. The Timken 17-22A(S) curve was obtained from unpublished data for samples that were normalized at 1725° and drawn for 6 hours at 1200° F and then air cooled. The portion of the SAE 4130 curve represented by the solid line with the three data points indicated by squares was estimated from data obtained from Timken DM-2 alloy, which has a similar composition. No data were available on SAE 4130 and so this estimated curve represents the best knowledge that was currently available. However, a single check point that was obtained from a 100-hour life test at a temperature of 1000° F indicated that the data are probably in the right range. The check point was obtained for SAE 4130 steel that was heat-treated in exactly the same manner as the air-cooled blades that were tested. The dashed extension to the SAE 4130 curve was drawn arbitrarily to an estimated yield-strength point based on limited unpublished data. For temperatures below 900° F the yield point is the limiting strength criterion rather than stress rupture for low-alloy steels.

The allowable stress-distribution curves for blade 12 operating at an effective gas temperature of 1450° F and rated engine speed with a cooling-air temperature of 180° F are shown in figure 13 for coolant-flow ratios of 0.02, 0.03, and 0.05. Figure 13 was obtained from the temperature distributions in figure 11 and the SAE 4130 stress-rupture curve in figure 12. When the ratio of the area under the allowable stress curve to the area under the nominal centrifugal stress curve is taken, stress-ratio factors of 1.29, 2.16, and 2.37 result for coolant-flow ratios of 0.02, 0.03, and 0.05, respectively. These stress-ratio factors were obtained for one of the blades that was endurance tested. Based on the SAE 4130 stress-rupture curve (fig. 12) the tube-filled rotor blades of the type investigated are capable of safe operation at stress-ratio factors of 2.16 or less. The minimum stress-ratio factor will have to be determined by further experimentation; however, an indication of the safety of lower stress ratio factors can be obtained from the fact that blade 12 was able to operate at a coolant-flow ratio of 0.02, which resulted in a stress-ratio factor of 1.29 even though seven thermocouples were buried in the blade shell.

The stress-ratio factor also provides a better comparison of blades that may operate at different stress levels because of variations in the blade configuration than just a comparison of blade temperatures. Such a comparison between the cast and formed 10-tube blades, which are compared on a temperature basis in figure 10, was not possible because the cast blade was never operated at rated speed. At a speed of 10,000 rpm where the temperature comparison was necessary, the blade-temperature level was so low that variations in blade-temperature level were of little or no significance. When the blade temperatures are in the range from 900° to 1200° F, however, variations in temperature level have a very marked effect on the strength of noncritical metals used for cooled turbine-blade fabrication.

The effect of blade material on coolant-flow requirements can be illustrated very effectively by the use of the stress-ratio factor. In figure 14 the blade-temperature distributions that could be expected for the improved type of formed blade (blade 12) for the case where the cooling air was bled from the compressor are shown. This curve was obtained from the data in table V using a cooling-air temperature of 450° F. From figure 14 and the stress-rupture curves in figure 12 the stress-ratio factors for blades made of Timken alloy 17-22A(S) and SAE 4130 can be obtained as explained in the section PROPOSED CRITERION FOR EVALUATING AIR-COOLED TURBINE BLADES in order to obtain a plot of stress-ratio factor against coolant-flow ratio as shown in figure 15. The great reduction in coolant flow required for the Timken 17-22A(S) steel blade is obvious. For a stress-ratio factor of 2.0, the quantity of cooling air required for the Timken 17-22A(S) blade is about 55 percent of that required for the SAE 4130 blade. The difference in critical alloy content in the two metals is insignificant. Figure 15 illustrates the very great gains that can be obtained by use of proper selection of blade materials and, in addition, sheds additional light on the superior performance of Timken 17-22A(S) blade 9 over SAE 4130 blades 10 and 11 in the cyclic-endurance investigation.

## SUMMARY OF RESULTS

The results of the investigation on several tube-filled turbine-rotor blades are summarized as follows:

1. Attachment of air-cooled turbine blade shells to the base by means of Nicrobrazing provided a sound root structure if the clearance between shell and base before brazing was less than 0.003 inch and if a fillet was provided at the junction between the shell and base.

2. Ceramic coatings that were tested in this investigation were found to be unsatisfactory for providing oxidation resistance to low-alloy-steel turbine blades because of poor adherence between the coating and the blade shell.

3. Nickel coatings applied to low-alloy-steel turbine blades by a chemical-deposition process provided reasonable oxidation resistance up to about 25 hours of rated-speed endurance except at the blade leading edge where the coatings wore away rapidly. Improvements in the coatings probably are possible.

4. Cyclic-endurance tests of air-cooled turbine blades at a coolant-flow ratio of 0.03 indicated that at the present time oxidation of noncritical blades is a serious problem and probably provides a limitation on blade life. The tests also indicated that Timken 17-22A(S) steel was far superior to SAE 4130 steel for noncritical turbine blades.

5. Rotor blades having a thinner blade profile and thinner walls than those previously investigated had a satisfactory endurance life with respect to structure. From the limited endurance tests made, the blades were apparently capable of operating satisfactorily at coolant-flow ratios of 0.03 for at least 26 hours at rated engine speed and a turbine-inlet gas temperature of 1670° F. The total endurance time at rated speed on one blade was $55\frac{1}{4}$ hours and the blade was still in relatively good condition at the completion of the test.

6. At an engine speed of 10,000 rpm and a coolant-flow ratio of 0.029 for a formed-shell blade where the coolant passage extended far into the leading- and trailing-edge regions, the leading- and trailing-edge temperatures were substantially reduced below the temperatures obtained from cast-shell blades. The reduction in trailing-edge temperature was about 200° F.

7. The stress-ratio factor provides an improved method of comparing and evaluating the cooling effectiveness of air-cooled turbine blades of different configurations and different materials.

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TABLE I - AIR-COOLED TURBINE-ROTOR BLADE CONFIGURATIONS INVESTIGATED

| Blade number | Blade profile | Blade material (a) | Shell-to-base attachment method (b) | Heat-treatment | Coating | Remarks |
|---|---|---|---|---|---|---|
| 1,2 | A | SAE 4130 | Nicrobrazed with 0 to 0.020 in. clearance, no fillet | Isothermal quench | None | Blades used for preliminary tests to investigate this type of shell-to-base attachment. |
| 3,4 | B | SAE 4130 | Nicrobrazed with 0 to 0.003 in. clearance, no fillet | Isothermal quench | None | Blades used for constant-speed endurance to determine if fillets were necessary at junction of shell and base. |
| 5 | B | SAE 4130 | Copper brazed with 0 to 0.003 in. clearance | Isothermal quench | None | Blade used to determine the suitability of copper brazing in attaching shell to base. |
| 6 | A | SAE 4130 | Nicrobrazed with 0 to 0.003 in. clearance | Isothermal quench | Nickel | Blade used to investigate shell-to-base attachment method and also for cyclic-endurance tests at coolant-flow ratio of 0.03. |
| 7 | A | Cast SAE 4130 | Integrally cast | None | Ceramic 1 | Blades used to investigate oxidation-resistant coatings. |
| 8 | A | SAE 4130 | Nicrobrazed with 0 to 0.010 in. clearance | None | Ceramic 2 | |
| 9 | A | Timken 17-22A(S) | Butt welded | Isothermal quench after three endurance cycles | Nickel | Blades used for cyclic-endurance tests at coolant-flow ratio of 0.03. |
| 10 | A | SAE 4130 | Butt welded | None | Nickel | |
| 11 | A | SAE 4130 | Butt welded | Isothermal quench | Nickel | |
| 12 to 14 | B | SAE 4130 | Nicrobrazed with 0 to 0.003 in. clearance | Isothermal quench | Nickel | Blades were used for constant-speed endurance at coolant-flow ratios from 0.05 to 0.03 to determine blade and coating durability. Blade 14 was uncoated for first 21 hr of endurance. |

[a] Blade shells were formed from seamless steel tubing unless noted otherwise.

[b] Except where noted all blades had fillets at junction of shell and base.

[redacted]

TABLE II - SUMMARY OF RESULTS FROM SHELL-TO-BASE ATTACHMENT

INVESTIGATIONS

| Blade | Total time at 11,500 rpm and effective gas temperature of 1450° F | | | | Remarks |
|---|---|---|---|---|---|
| | Coolant-flow ratio $w_a/w_g$ | | | | |
| | 0.048 | | 0.03 | | |
| | (hr) | (min) | (hr) | (min) | |
| 1,2 | -- | --- | -- | --- | Blade 1 failed on initial acceleration before reaching rated speed and blade 2 failed almost immediately after reaching rated speed. Failure was caused by large clearance between shell and base before brazing. No endurance time was counted. Braze shear stress, 5500 lb/sq in. |
| 3,4 | 2 | 0 | 1 | 0 | After 3 hr of constant-speed endurance cracks developed at root of each blade on suction surface as shown in fig. 5. Failures caused by lack of fillet at junction of shell and base. Braze shear stress, 3500 lb/sq in. |
| 5 | -- | --- | 5 | 0 | Temperatures were measured in area of copper braze used to attach shell to base at coolant-flow ratios of 0.02 and 0.03. Copper braze in satisfactory condition at completion of 5 hr constant-speed endurance test. Braze shear stress, 3500 lb/sq in. |
| 6 | -- | --- | 11 | 30 | Cyclic-endurance test. After 46 cycles blade was still in excellent condition. Nicrobrazed base with a clearance of 0 to 0.003 in. before brazing was found to be satisfactory. Braze shear stress, 5500 lb/sq in. |

## TABLE III - SUMMARY OF CYCLIC-ENDURANCE INVESTIGATION ON BLADES WITH PROFILE A AT COOLANT-FLOW RATIO OF 0.03

| Blade (a) | Number of cycles | Total time at rated speed | | Remarks |
|---|---|---|---|---|
| | | (hr) | (min) | |
| 9, 10 | 2 | -- | 30 | Blade 10 was not heat-treated; blade elongated and was damaged by rubbing on tail cone. Blade 10 was replaced by blade 11. Blade 9 not heat-treated but there was no indication of elongation. Blade 9 was removed from engine, heat-treated, and reinstalled. |
| 9<br>11 | 61<br>59 | 15<br>14 | 15<br>45 | Cooling air inadvertently cut off. Blade 11 (SAE 4130 steel) failed at about 1/3 span. Blade 11 replaced by blade 6. Blade 9 (Timken 17-22A(S) steel) apparently unharmed by cooling-air failure. Nickel coating was wearing away from leading and trailing edges of blade 9. |
| 9<br>6 | 76<br>15 | 19<br>3 | 0<br>45 | Nickel coating gone from leading and trailing edges of blade 9. Oxide scale was forming in these areas. Coating on blade 6 was in good condition. |
| 9<br>6 | 88<br>27 | 22<br>6 | 0<br>45 | Failure of a solid blade caused slight damage to tip of blade 9. Damage repaired by grinding away a small amount of metal. |
| 9<br>6 | 107<br>46 | 26<br>11 | 45<br>30 | Outer third of pressure surface failed on blade 9 (fig. 7) because of oxidation and erosion of blade leading edge, poor bond between tubes and shell, and vibration. Test terminated. Blade 6 was in excellent condition except that the nickel coating was gone from leading and trailing edges and oxidation was starting. |

[a] All blades were nickel coated.

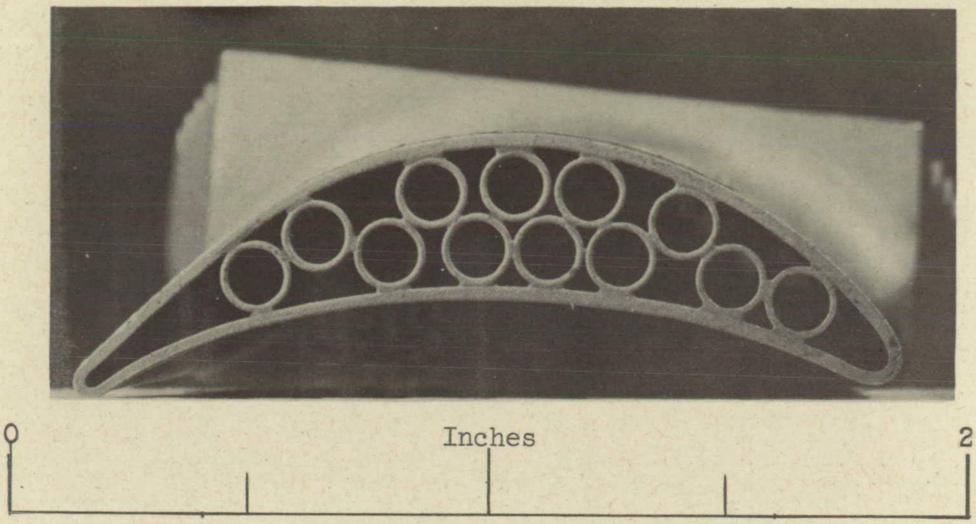
TABLE IV - SUMMARY OF CONSTANT-SPEED ENDURANCE INVESTIGATION ON IMPROVED BLADE CONFIGURATION

| Blade | Total time at 11,500 rpm and effective gas temperature of 1450° F | | | | | | Remarks |
|---|---|---|---|---|---|---|---|
| | Coolant-flow ratio, $w_a/w_g$ | | | | | | |
| | 0.048 | | 0.038 | | 0.03 | | |
| | (hr) | (min) | (hr) | (min) | (hr) | (min) | |
| 12<br>13 | 3<br>3 | 0<br>0 | -<br>- | -<br>- | 1<br>1 | 0<br>0 | Blades 12 and 13 were nickel coated at beginning of test. Blade 13 removed after 4 hr of endurance test because tubes pulled away from shell on pressure surface. Blade 14 installed, blade was not coated. |
| 12<br>14 | 14<br>11 | 10<br>10 | -<br>- | -<br>- | 1<br>- | 0<br>- | Nickel-coated blade 12 was in good condition. Oxide coating had formed on the leading and trailing edges of blade 14. |
| 12<br>14 | 23<br>20 | 55<br>55 | -<br>- | -<br>- | 1<br>- | 0<br>- | Oxide scales were found on the leading edge of blade 14, the entire blade was covered with a brown oxide. Nickel coating on blade 12 was in good condition except as leading edge where some oxidation was observed. Both blades were cleaned by vapor blast, zyglo inspected, and coated with nickel. |
| 12<br>14 | 23<br>20 | 55<br>55 | 5<br>5 | 0<br>0 | 5<br>4 | 3<br>3 | Separation of shell from tubes at trailing edge tip on pressure surface due to poor brazing was observed. The nickel coating on blade 12 began to blister and scale on the pressure surface. |
| 12<br>14 | 24<br>21 | 0<br>0 | 5<br>5 | 0<br>0 | 10<br>9 | 27<br>27 | Blade 14 oxidized badly at leading edge. Blade 12 showed more scaling of coating on pressure surface and oxidation started on leading edge. |
| 12<br>14 | 24<br>21 | 0<br>0 | 5<br>5 | 0<br>0 | 26<br>25 | 15<br>15 | A portion of blade 14 extending approximately 3/4 in. from the tip and 3/4 in. from the leading edge broke away from the pressure surface. Blade 12 was in good condition except for some oxidation at leading edge and the coating had scaled off in some areas. |

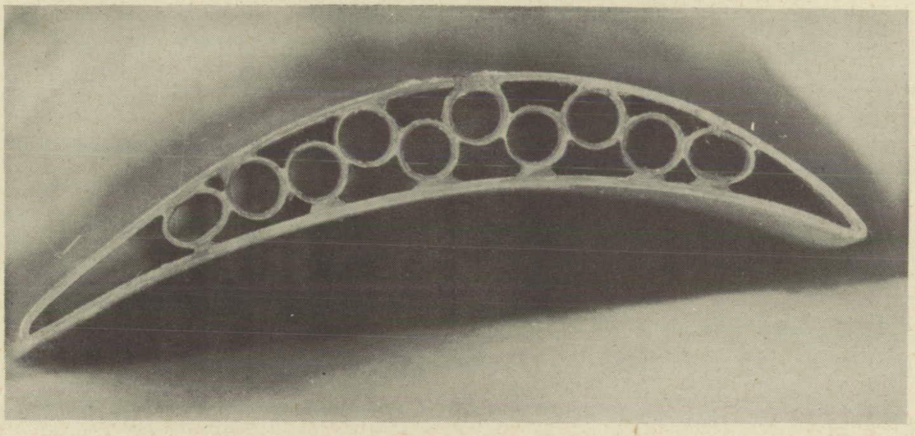
TABLE V - SUMMARY OF ENGINE OPERATING CONDITIONS AND TEMPERATURE-DIFFERENCE RATIOS FOR BLADE 12 AT ENGINE SPEEDS OF 6000, 8000, 10,000, and 11,500 RPM

| Series | Engine speed (rpm) | Average conditions at compressor inlet | | Fuel flow (lb/hr) | Cooling-air flow per blade (lb/sec) | Coolant-flow ratio $\frac{w_a}{w_g}$ | Temperature-difference ratio $\varphi$ | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Total pressure (in. Hg abs.) | Total temperature (°F) | | | | Thermocouple | | | | | | |
| | | | | | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 1 | 6,200 | 29.20 | 60 | 1595 | 0.0575 | 0.094 | 0.454 | 0.671 | 0.652 | 0.731 | 0.600 | 0.665 | 0.612 |
| | | | | | .0492 | .080 | .433 | .655 | .628 | .708 | .573 | .642 | .595 |
| | 6,193 | | | | .0411 | .067 | .407 | .611 | .597 | .679 | .544 | .609 | .566 |
| | 6,197 | | | | .0330 | .054 | .386 | .581 | .567 | .645 | .513 | .581 | .543 |
| | 5,998 | | | | .0237 | .039 | .340 | .526 | .514 | .591 | .463 | .536 | .478 |
| | 5,996 | | | | .0192 | .031 | .307 | .481 | .473 | .544 | .426 | .494 | .437 |
| | 6,003 | | | | .0162 | .026 | .267 | .428 | .430 | .494 | --- | .450 | .383 |
| | 5,993 | | | | .0143 | .023 | .236 | .379 | .395 | .448 | .356 | .408 | .341 |
| 2 | 8,022 | 29.20 | 58 | ---- | 0.0203 | 0.023 | 0.304 | 0.410 | 0.434 | 0.489 | 0.387 | 0.428 | 0.363 |
| 3 | 9,998 | 29.20 | 65 | 2980 | 0.0605 | 0.054 | 0.355 | 0.547 | 0.556 | 0.630 | 0.517 | 0.543 | 0.483 |
| | 9,996 | | | | .0500 | .045 | .321 | .510 | .520 | .594 | .484 | .510 | .449 |
| | 10,001 | | | | .0325 | .029 | .280 | .442 | .461 | .526 | .426 | .447 | .378 |
| | 10,001 | | | | .0286 | .026 | .260 | .408 | .436 | .499 | .404 | .424 | .354 |
| | 9,996 | | | | .0250 | .022 | .241 | .381 | .411 | .469 | .383 | .399 | .322 |
| 4 | 11,498 | 29.20 | 67 | 4320 | 0.0680 | 0.052 | 0.358 | 0.529 | 0.532 | 0.608 | 0.500 | 0.519 | 0.467 |
| | 11,505 | | | | .0427 | .032 | .289 | .443 | .452 | .527 | .422 | .443 | .381 |
| | 11,496 | | | | .0302 | .023 | .230 | .358 | .395 | .449 | .373 | .379 | .306 |
| | 11,505 | | | | .0250 | .019 | .199 | .304 | .338 | .375 | .327 | .318 | .244 |
| [a]5 | 11,498 | 29.20 | 70 | 4790 | 0.0372 | 0.030 | 0.287 | 0.421 | 0.422 | 0.516 | 0.395 | 0.421 | 0.358 |
| | 11,496 | | | | .0300 | .024 | .253 | .371 | .390 | .454 | .366 | .386 | .313 |
| | 11,501 | | | | .0253 | .020 | .222 | .332 | .351 | .437 | .334 | .343 | .272 |

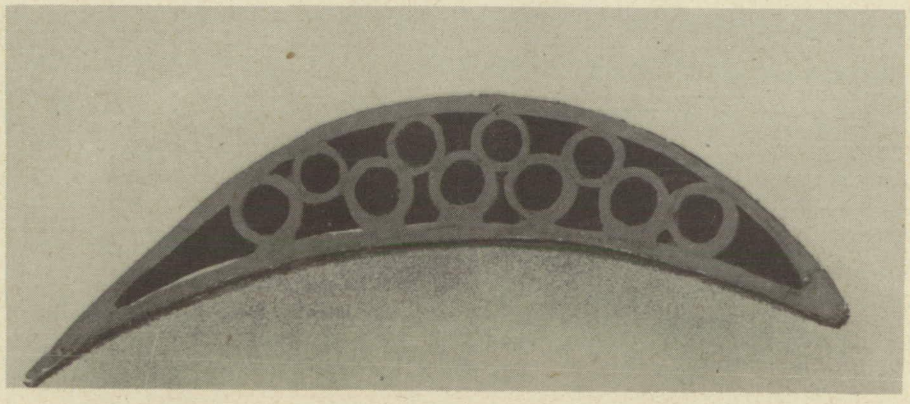
[a] Tail-pipe nozzle was partly closed.



(a) Formed-shell blade with profile A.



(b) Formed-shell blade with profile B.



(c) Cast-shell blade.

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Figure 1. - Comparison of cross-sections of tube-filled blades with formed and cast shells.

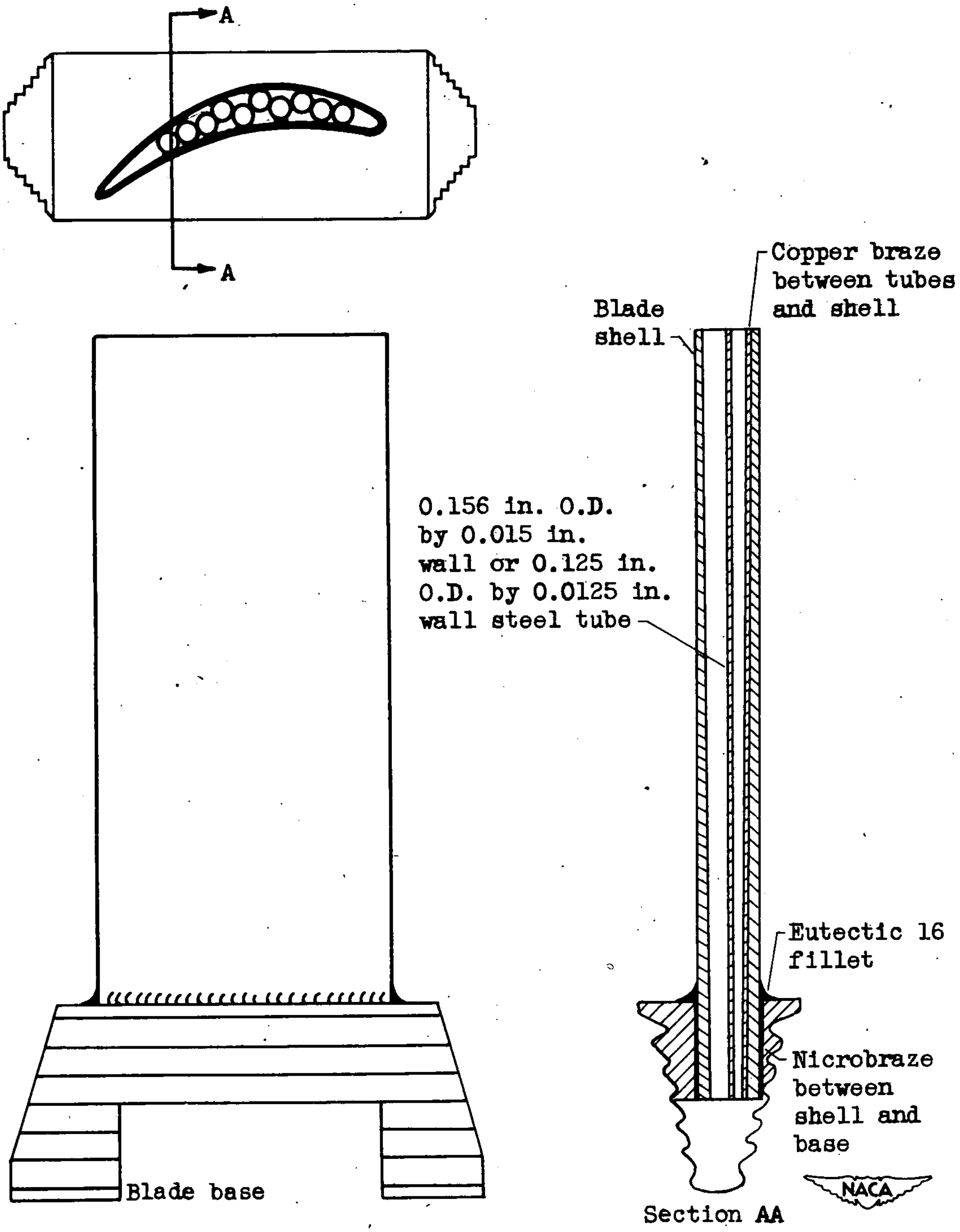
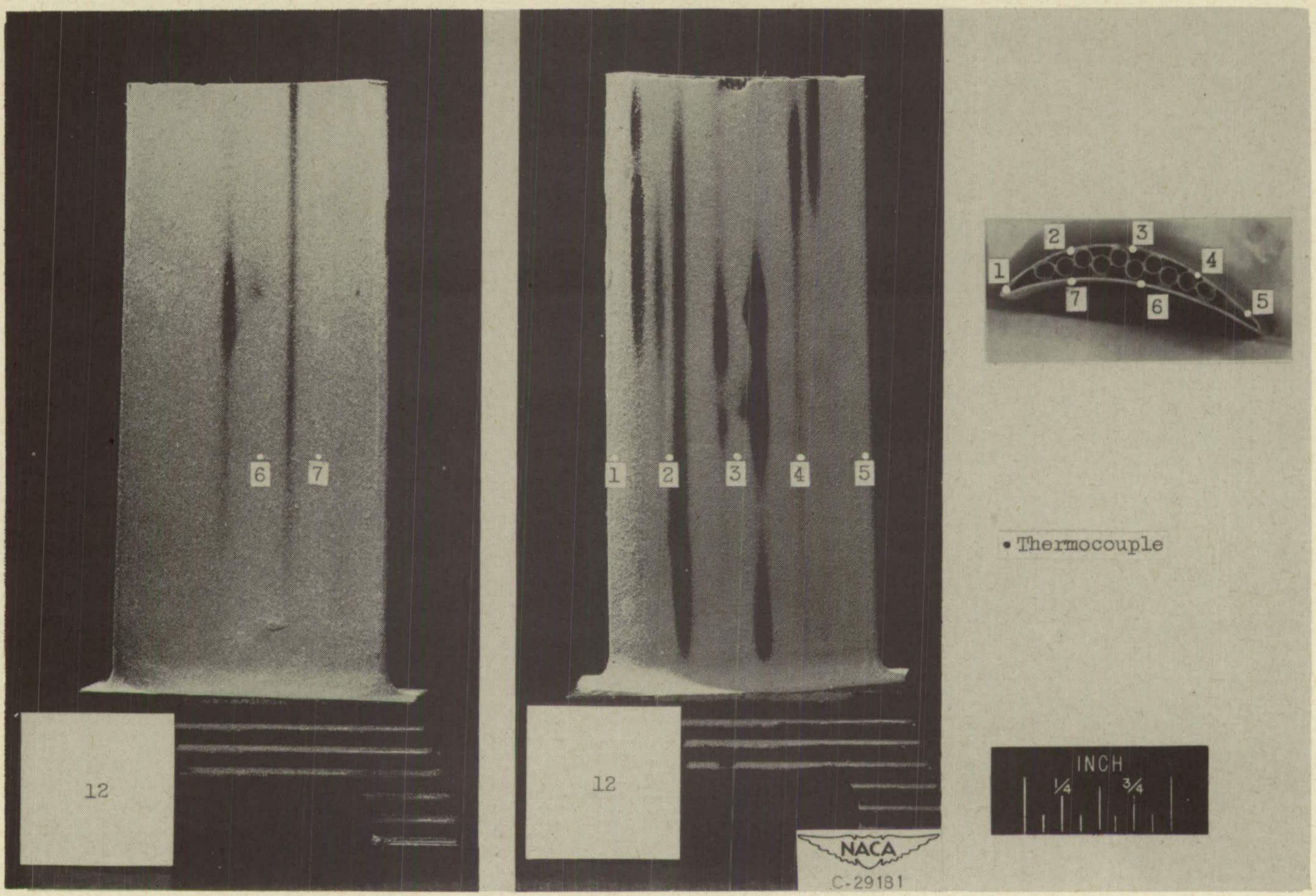


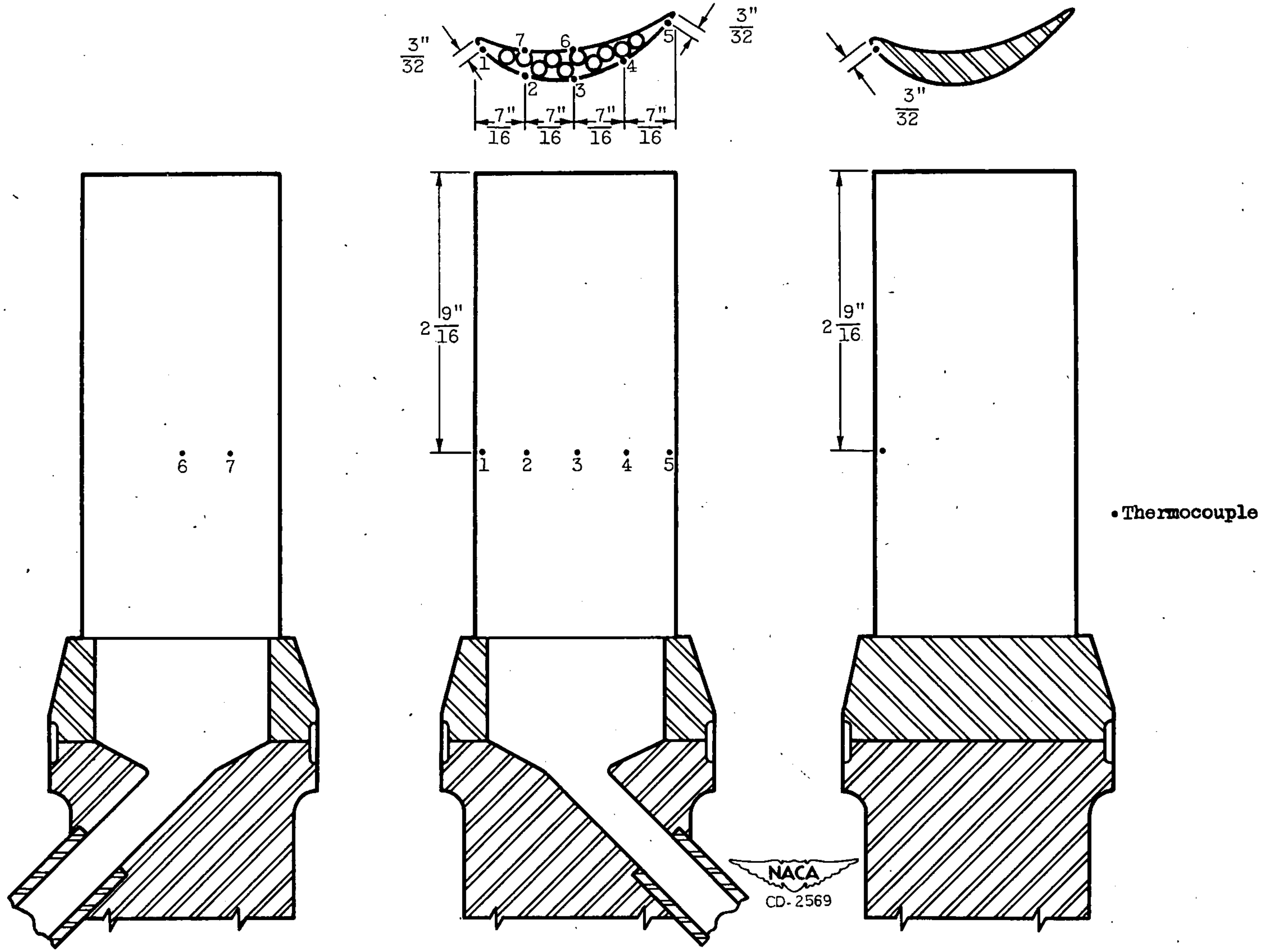
Figure 2. - Construction details of typical formed-shell blade utilizing brazed shell-to-base attachment.



(a) Pressure surface.

(b) Suction surface.

Figure 3. - Location of thermocouples relative to areas showing good brazing between tubes and shell on blade 12.



(a) Pressure surface of blade 12.  (b) Suction surface of blade 12.  (c) Uncooled reference blades.

Figure 4. - Thermocouple locations on cooled blade 12 and on uncooled reference blades.

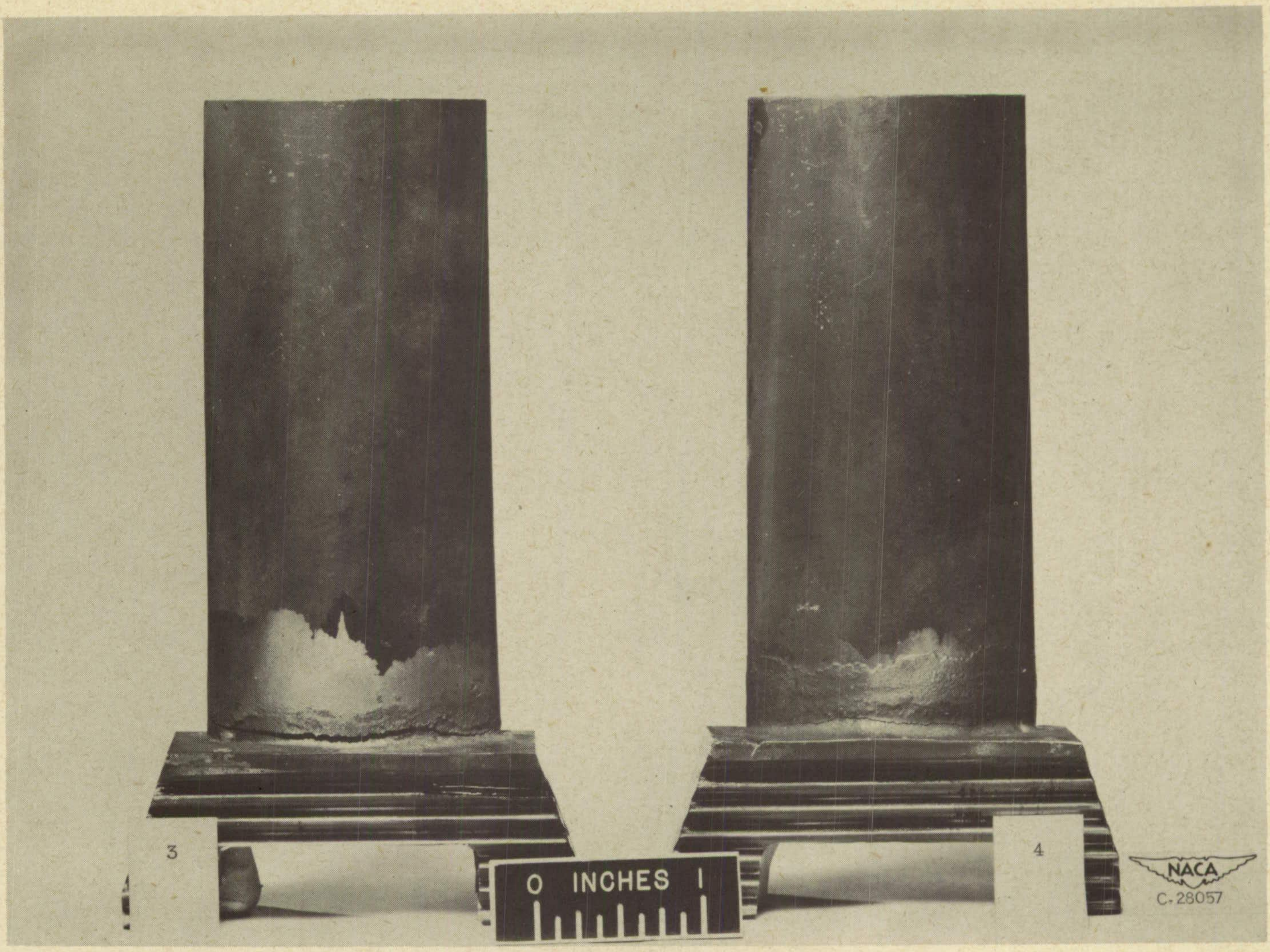
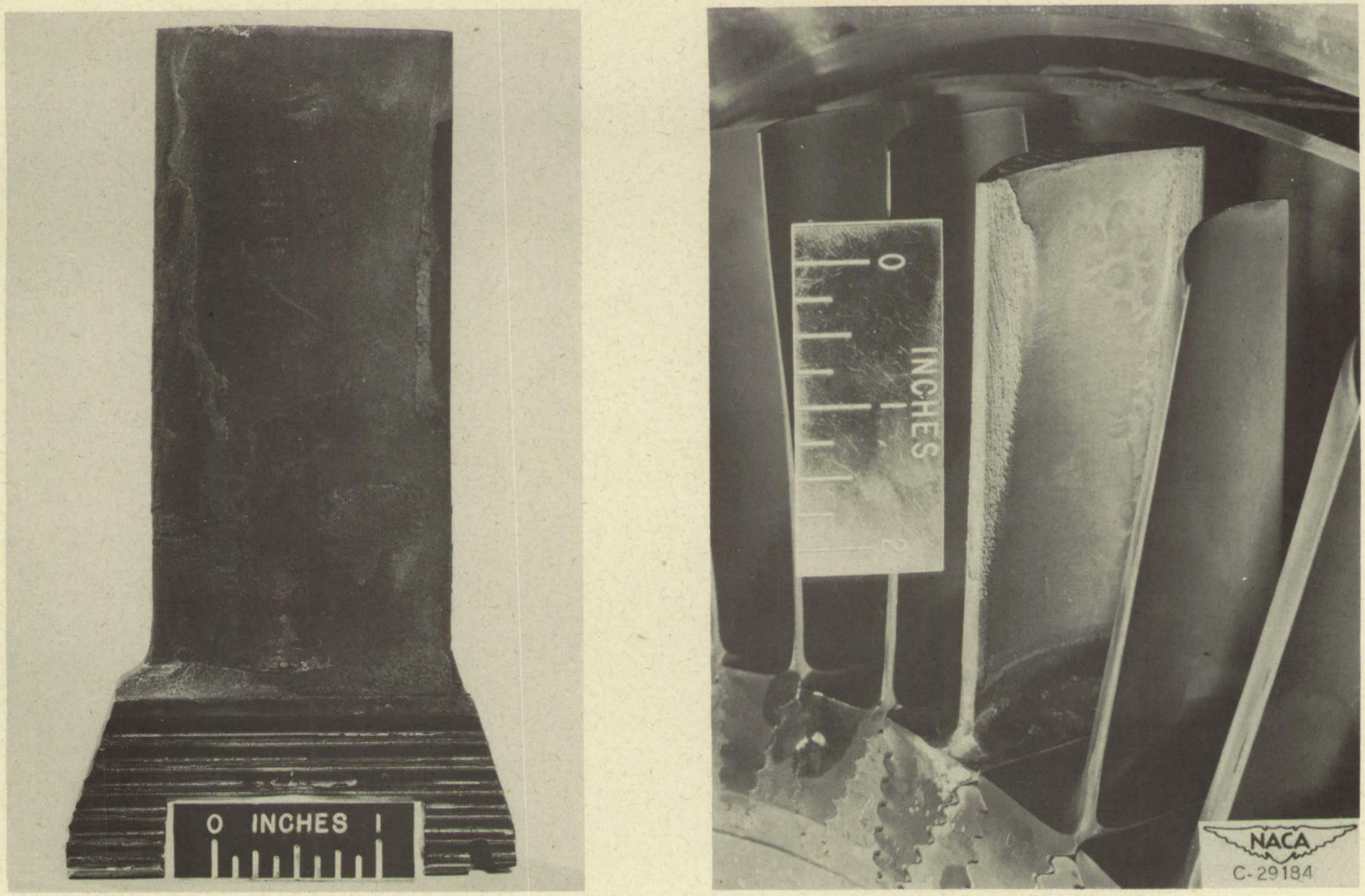


Figure 5. - Blades 3 and 4 without fillet at junction of shell and base after 3 hours of rated-speed endurance test.



(a) Blade 7. Coating chipped, particularly at leading and trailing edges, after $7\frac{1}{4}$ hours of rated-speed endurance test.

(b) Blade 8. Coating softened and flowed off of leading and trailing edges after $4\frac{3}{4}$ hours of rated-speed enduran test.

Figure 6. - Ceramic-coated blades after rated-speed endurance tests.

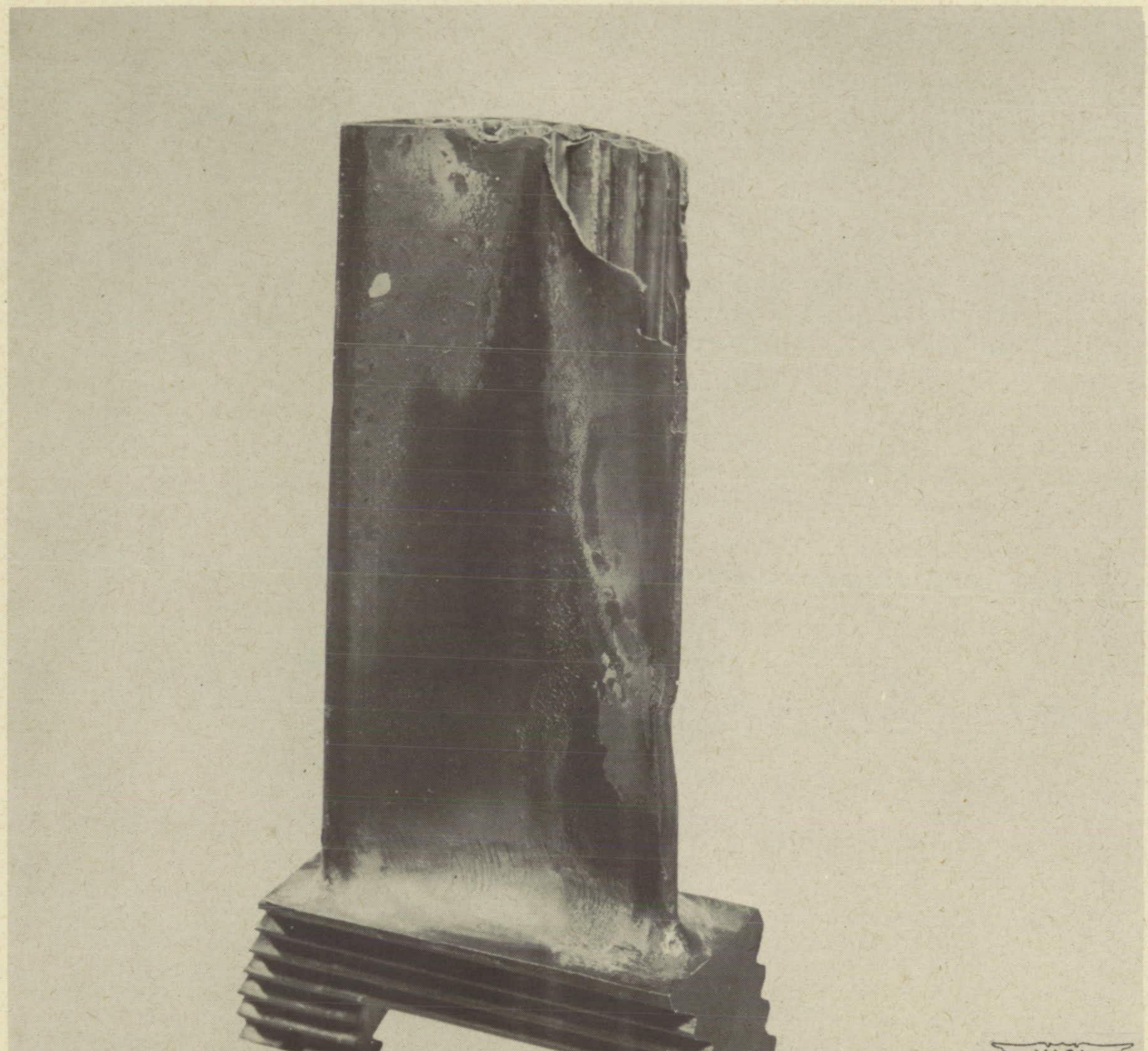


Figure 7. - Blade 14 after a total of $51\frac{1}{4}$ hours of rated-speed endurance test. Failure caused by vibration and erosion in area where there was poor brazing between tubes and shell.

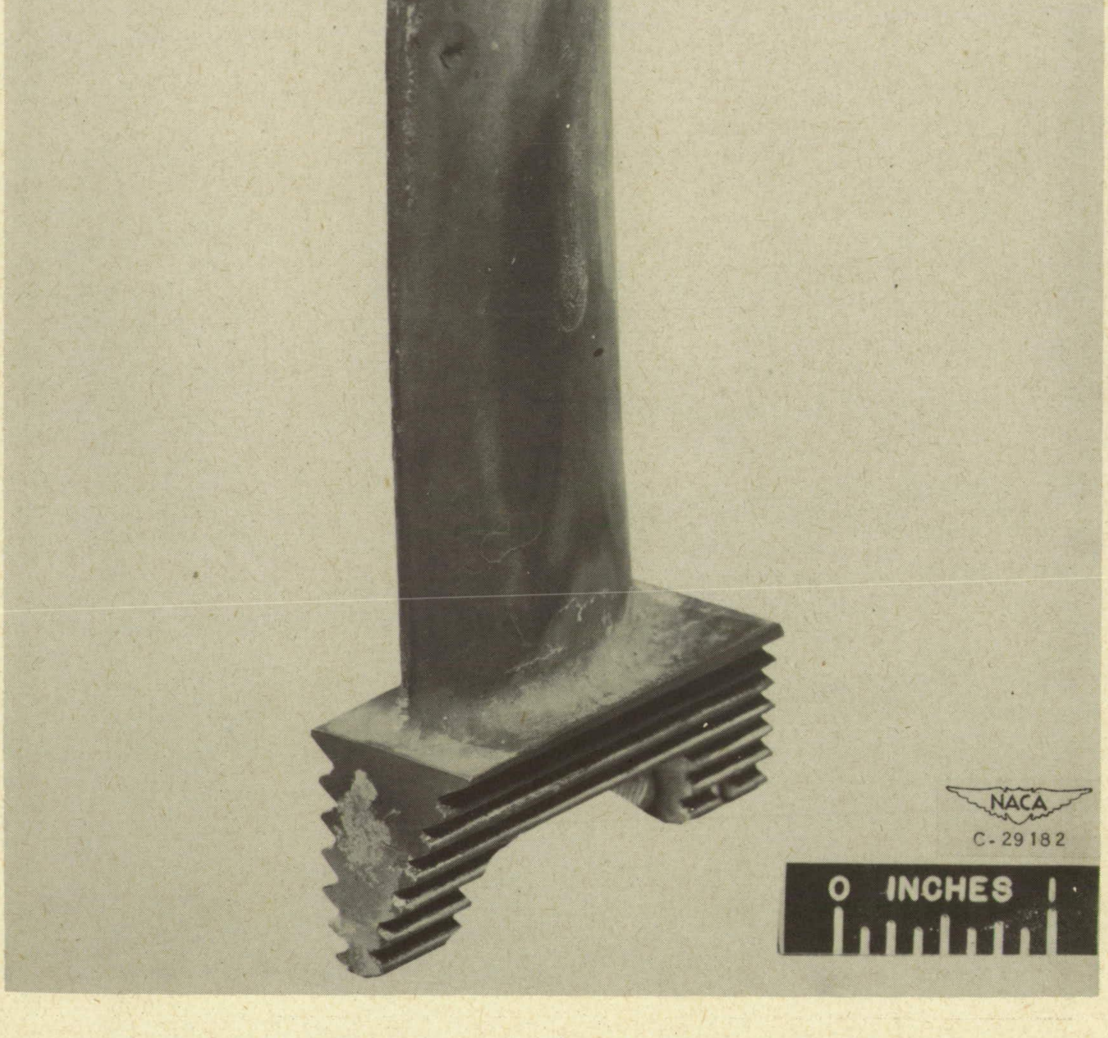


Figure 8. - Blade 12 after total of $55\frac{1}{4}$ hours of rated-speed endurance test.

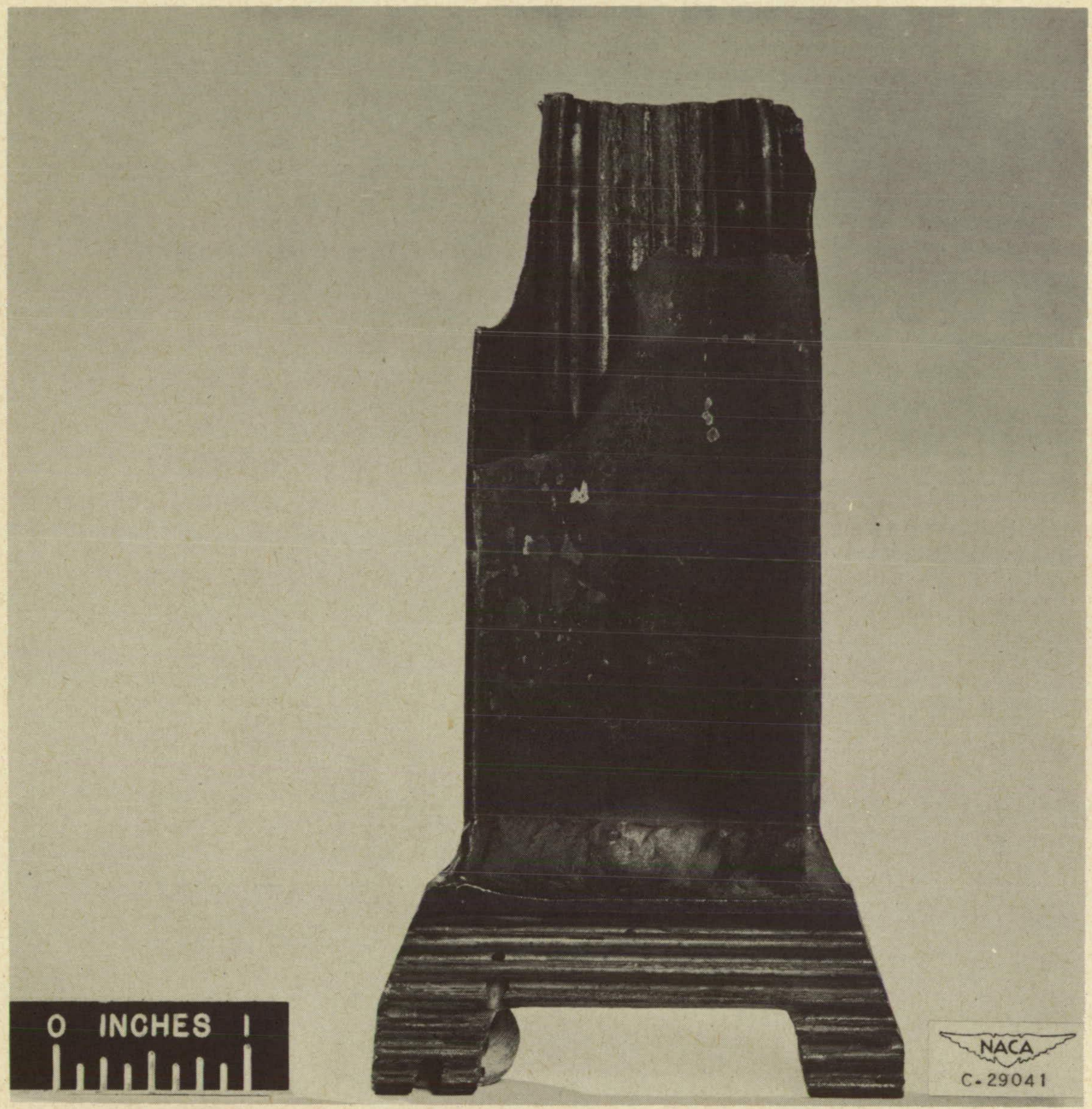


Figure 9. - Blade 9 after 107 cycles ($26\frac{3}{4}$ hours at rated speed) of cyclic-endurance test at coolant-flow ratio of 0.03. Failure was caused by vibration, erosion, and poor braze betweem tubes and shell.

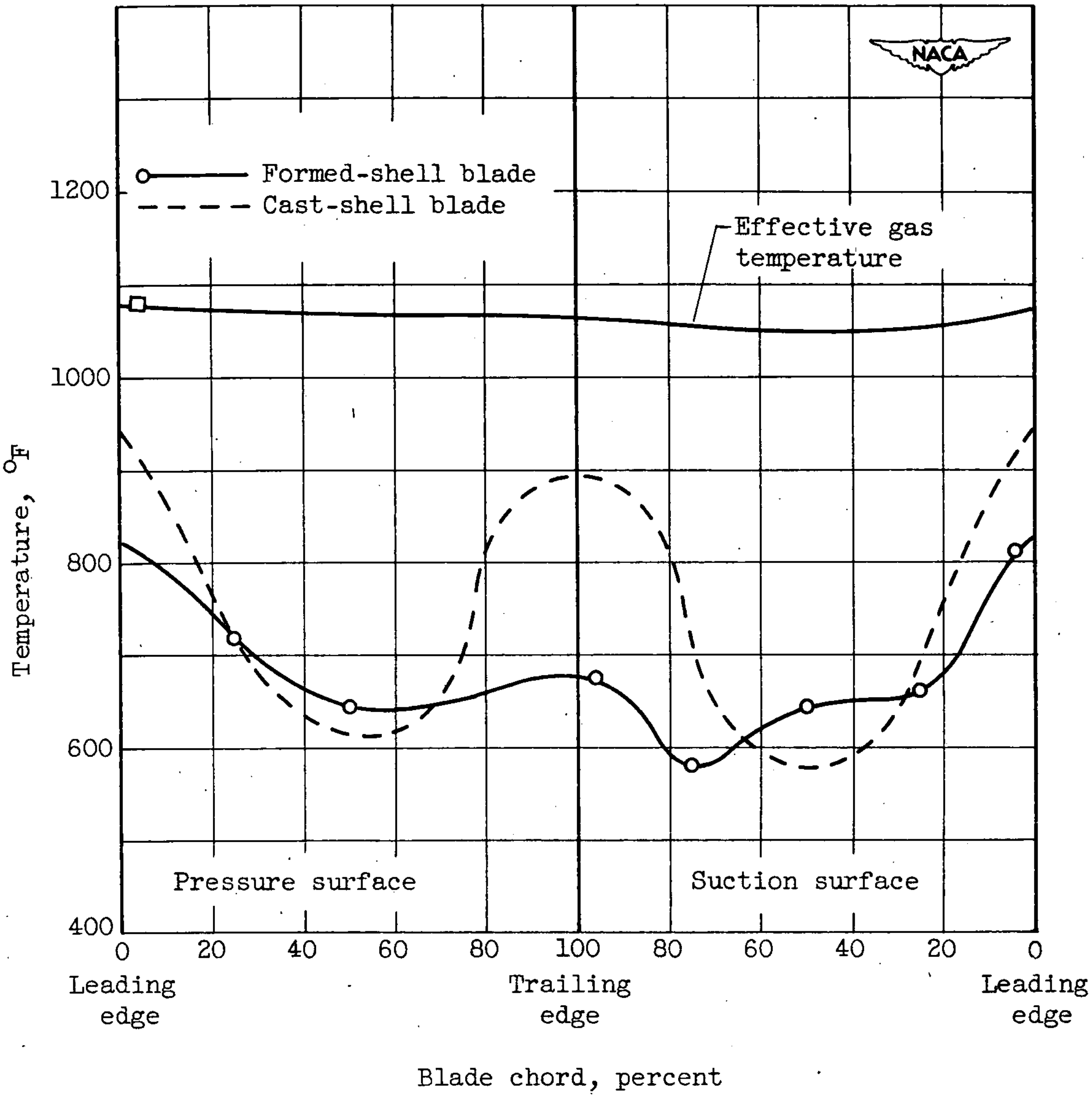


Figure 10. - Comparison of chordwise temperature distribution for cast-shell blade (reference 1) and formed-shell blade 12. Gas flow, 60.6 pounds per second (engine speed approximately 10,000 rpm); coolant-flow ratio, 0.029; cooling-air temperature at blade root, 133° F.

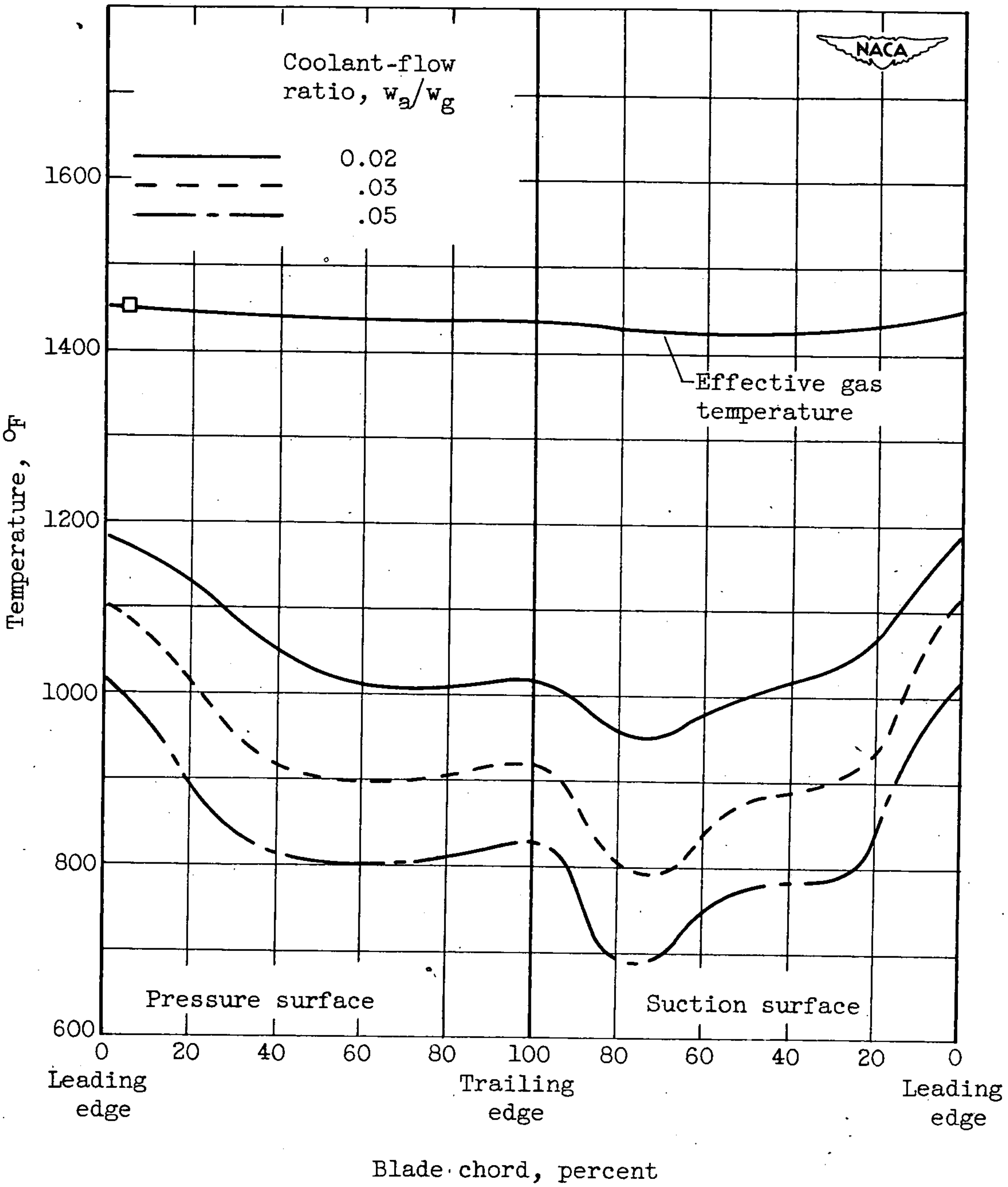


Figure 11. - Blade 12 temperature distributions for three coolant-flow ratios at rated engine speed of 11,500 rpm. Cooling-air temperature, 180° F.

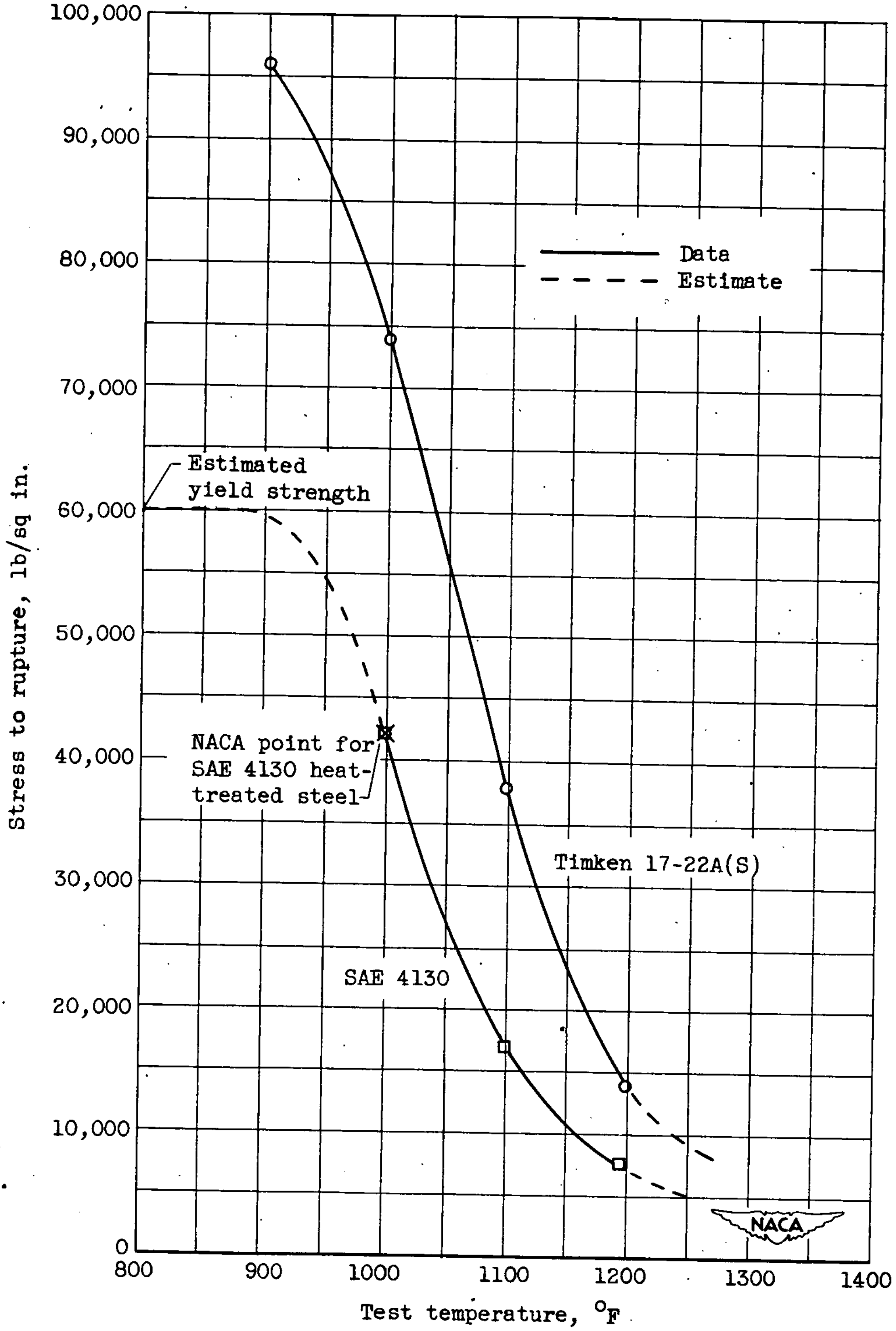


Figure 12. - Stress-rupture curves of 100 hours for heat-treated SAE 4130 and Timken 17-22A(S) low-alloy steels. Curve for SAE 4130 estimated from data obtained from a metal of similar composition.

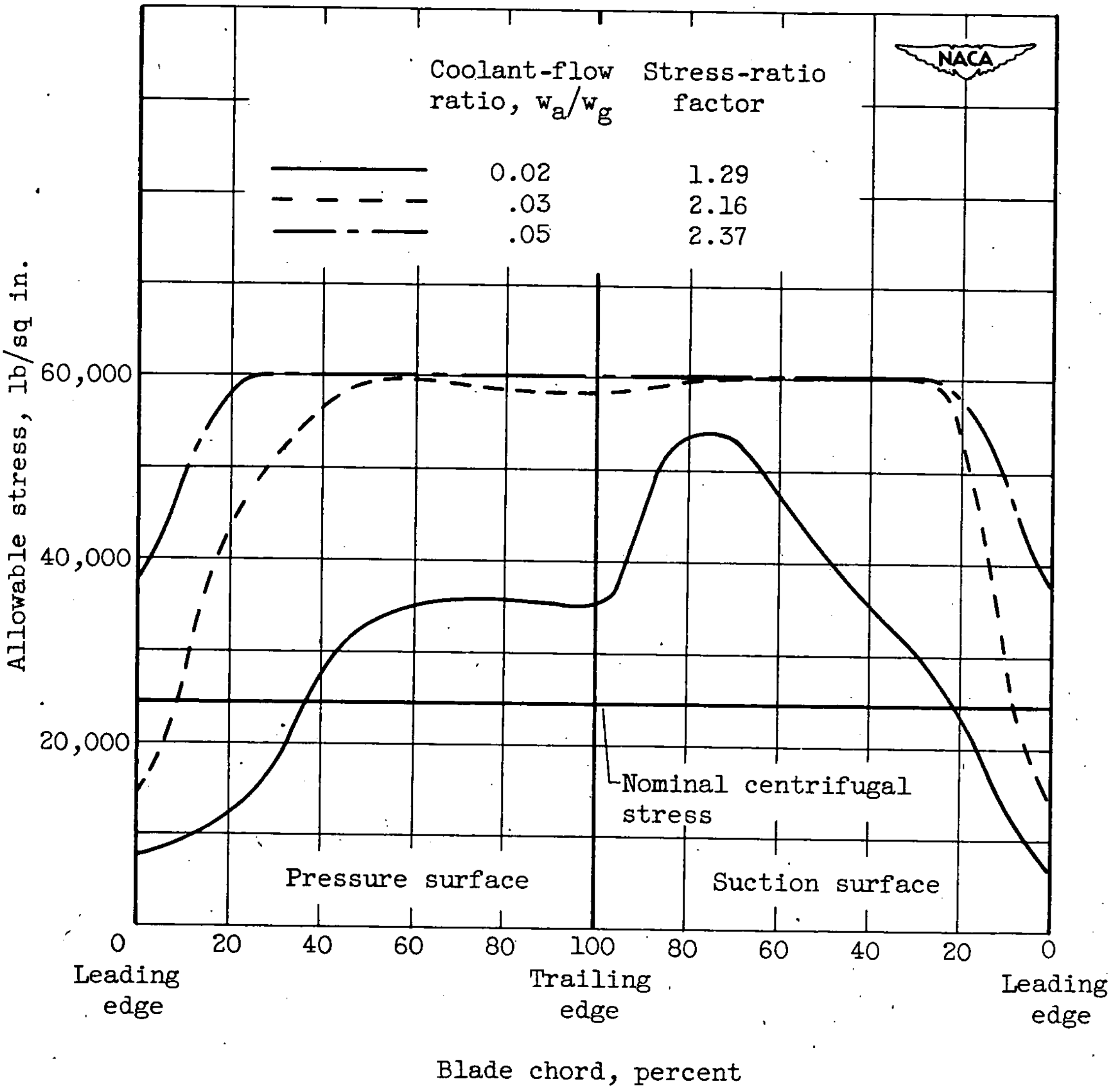


Figure 13. - Allowable stress distributions for blade 12 for three coolant-flow ratios at rated engine speed. Effective gas temperature, 1450° F; cooling-air temperature, 180° F; blade material, SAE 4130 steel.

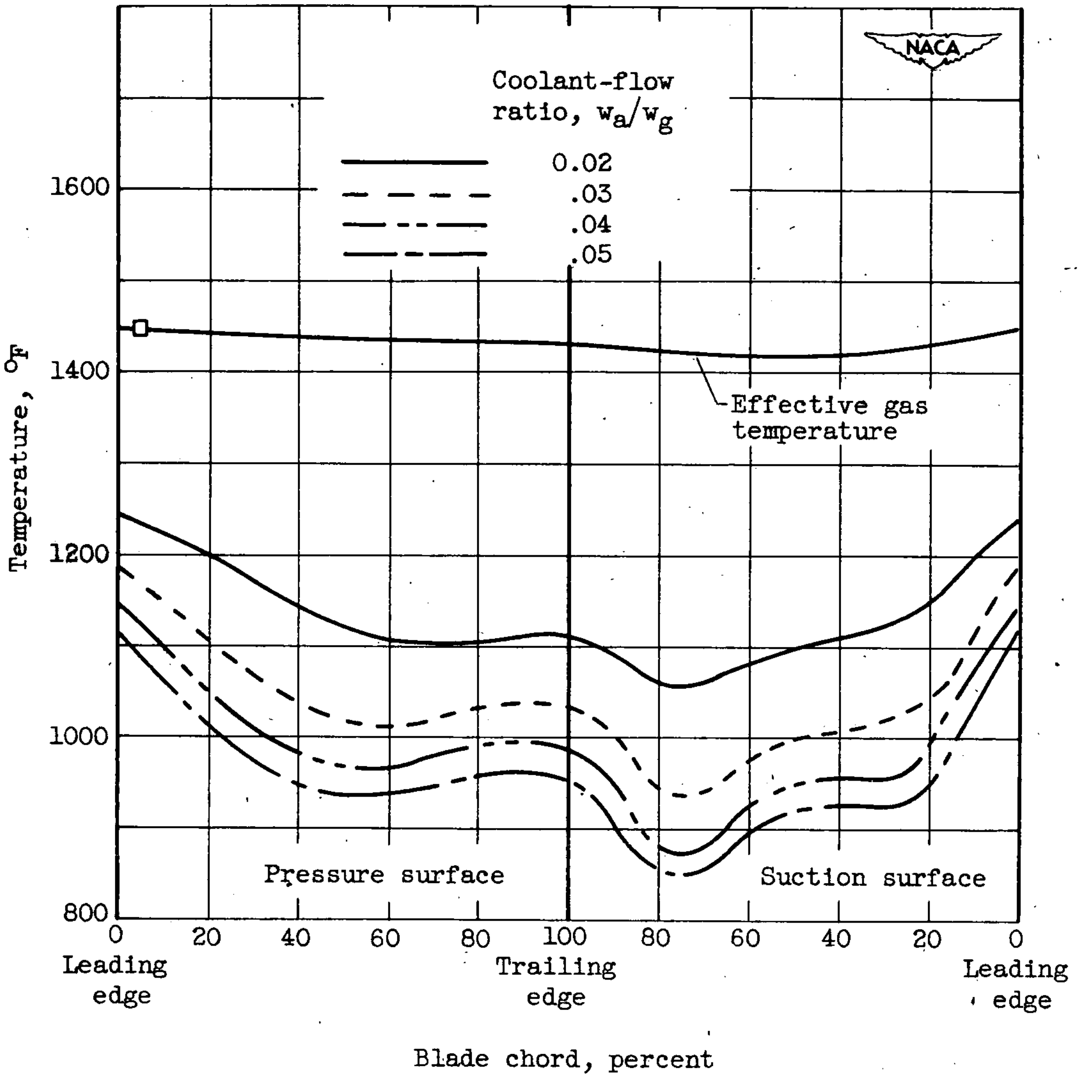


Figure 14. - Predicted temperature distributions for blade 12 with cooling air bled from compressor at rated engine speed. Cooling-air temperature, 450° F.

[redacted]

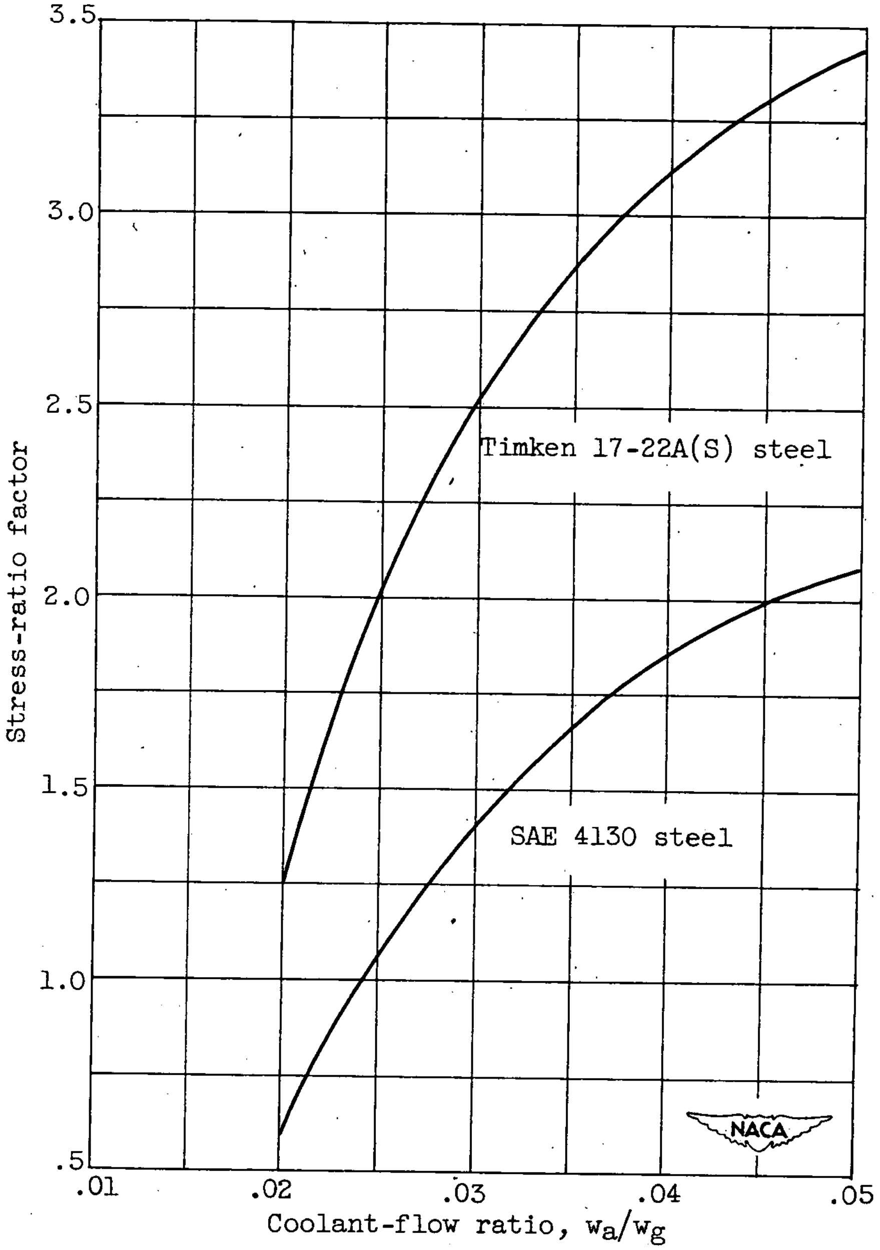


Figure 15. - Comparison of cooling-air requirements for blades made of SAE 4130 and Timken 17-22A(S) steels. Temperature and stress distributions for blade 12 with air bled from compressor at rated engine speed; effective gas temperature, 1450° F; cooling-air temperature, 450° F.

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