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RESEARCH MEMORANDUM

for the

Bureau of Aeronautics, Department of the Navy

EXPERIMENTAL PERMEABILITY MEASUREMENTS ON A STRUT-

SUPPORTED TRANSPIRATION-COOLED TURBINE BLADE WITH

STAINLESS-STEEL SHELL MADE BY THE FEDERAL-

MOGUL CORPORATION UNDER BUREAU OF

AERONAUTICS CONTRACT NOas 51613-C

By Hadley T. Richards

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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EXPERIMENTAL PERMEABILITY MEASUREMENTS ON A STRUT-SUPPORTED

TRANSPIRATION-COOLED TURBINE BLADE WITH STAINLESS-STEEL

SHELL MADE BY THE FEDERAL-MOGUL CORPORATION UNDER

BUREAU OF AERONAUTICS CONTRACT NOas 51613-C

By Hadley T. Richards

SUMMARY

A previous investigation of two strut-supported porous bronze blades, fabricated by the Federal-Mogul Corporation under contract from the Bureau of Aeronautics, Department of the Navy, indicated that the blade average apparent permeabilities were about 25 to 60 percent below those specified by the NACA. The uniformity of permeability was good when metering orifices were employed. The permeability specified was considered suitable for application to blades for a particular turbojet engine that will be used as a test vehicle in the future. These blades were made primarily to investigate fabrication techniques and to determine the degree of permeability control that could be achieved, and were not intended for use in an operating gas-turbine engine.

A blade with a porous stainless-steel shell (a material which is suitable for engine applications) attached to a modified supporting strut has since been fabricated and its permeability investigated. The results are given in this report. Visual examination of this blade indicates that both the internal and external porous surfaces are satisfactorily smooth and free from defects. Use of the modified strut provides improved cooling-air passages at the leading- and trailing-edge regions of the blade. The apparent permeability of this blade, on the average, more nearly approaches the values specified by the NACA. For example, the apparent permeability desired at the leading edge is 14.2×10^{-9} inch; the average value for the present blade is about 13.3×10^{-9} inch, while for the bronze blades the average was about 5.0×10^{-9} inch. In general, similar improvements in the average permeability were obtained for the

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suction and pressure surfaces. The random variations of permeability in the present blade are substantially greater than those of the bronze blades, being as far as ± 30 percent from the specified values, which is considered excessive. These variations apparently can be reduced by improvements in certain phases of the fabrication process.

INTRODUCTION

At present, transpiration cooling is the most effective air-cooling method known for maintaining low blade-metal temperature in a gas-turbine engine. Previous studies (ref. 1) have shown that efficient utilization of the transpiration-cooling process requires certain blade features in addition to a porous shell. It was demonstrated that the effects of altitude on required coolant were minimized if the porous blade shell was attached to a supporting strut that incorporated orifices at the base of the strut. These orifices metered air to the individual compartments formed by the strut body and fins and the porous shell attached to the fins. The use of a strut and a series of metered cooling-air compartments also permits use of a shell that has constant chordwise permeability, which simplifies the shell-fabrication procedures. In addition, the strut principle provides a means of making rotor blades with sintered shells, which by themselves could not withstand the centrifugal stresses imposed by actual engine operation.

Air-cooled turbine blades employing these principles, that is, porous shells bonded to internal supporting struts and having orifices at the base, have been fabricated under Bureau of Aeronautics contract NOas 51613-C by the Federal-Mogul Corporation (Detroit, Mich.). The first two blades fabricated (ref. 2) were made primarily as a basis for study of fabrication methods and techniques of permeability control and were not intended for operation in an engine. These blades had a porous bronze shell sintered to a series of ribs or fins on a supporting strut. The channels between the fins formed 31 passages which distributed the cooling air to the porous shell. The values of permeability around the blades were specified by the NACA (ref. 2). In order to simplify fabrication, an accurate chordwise permeability variation was not prescribed; instead, permeabilities were given for the leading-edge area and the suction and pressure surfaces of the blade. These permeabilities were considered suitable for the engine that will be used when rotation experiments are conducted in the future.

Reference 2 indicated that there was considerable chordwise variation in the actual permeability of the bronze blades. The use of orifices to meter the air flow to the various cooling-air compartments permitted control of this variation within a useful range. The resulting apparent permeabilities, however, were below the values specified by the NACA, particularly in the leading- and trailing-edge regions of the blade.

The design of the strut at the leading and trailing edges precluded the possibility of cooling these portions of the blade adequately, because the coolant supply passages were too small.

On the basis of the foregoing results, another blade of the strut type was fabricated by the Federal-Mogul Corporation. The purposes of fabricating and investigating this blade were to determine whether a satisfactory blade could be made from a material suitable for engine operation, and whether such a blade would have acceptable permeability characteristics. This blade differs primarily from the previous blades investigated (ref. 2) in that the porous shell is made from spherical stainless-steel powder instead of bronze powder, and the supporting strut has been redesigned to divide the interior of the blade into only 15 cooling-air compartments as compared with 31 for the blades of reference 2.

This report summarizes the results of a static experimental investigation made with the modified blade to determine its permeability and to compare the results with the permeabilities specified by the NACA. The apparent permeabilities obtained on the stainless-steel blade are compared with the apparent permeabilities of the bronze blades of reference 2. The tests were made at sea-level, ambient conditions with a pressure drop across the blade of 10 pounds per square inch corrected to standard conditions.

APPARATUS AND EXPERIMENTAL PROCEDURE

An end view of the sintered porous blade and the orifice plate are shown in figure 1. The blade was nontwisted and had a chord of about 2 inches and a span of 5 inches. The porous shell was 0.040 inch thick and was made from AISI type 302 (modified) spherical stainless-steel powder. The strut was SAE 1020 steel and had a constant spanwise cross section. Reference 2 indicated that, with respect to cooling, the porous bronze blades could have had fewer fins on the supporting strut; it was further indicated that improvement of the cooling-air supply to the leading and trailing edges could be achieved by enlarging the flow channels in these regions. A strut configuration that would be an improvement with respect to cooling was proposed in reference 2, and the strut employed in the present stainless-steel blade was essentially the same as that sketched in figure 9(b) of the reference. The diameters of the metering orifices in the orifice plate for the channels that supplied cooling air to the leading edge, trailing edge, suction surface, and pressure surface were 0.125, 0.080, 0.070, and 0.080 inch, respectively.

The "apparent permeabilities" specified for the bronze blades (ref. 2) were also specified for the stainless-steel blades. The term "apparent permeability" is used because the effects of both the orifices

and the porous shell in series are included in the permeability measurements when the orifice plate is attached to the blade. The specified apparent permeabilities were as follows:

Position	Apparent permeability, $(12K'/\tau)_{ap}$ in.
Leading edge	14.2×10^{-9}
Suction surface	8.7
Pressure surface	10.4

Reference 3 indicates that, if blade temperature variations less than $\pm 100^\circ$ F are to be obtained at present-day turbine-inlet temperatures, a blade permeability variation of not over ± 10 percent from that specified is required.

The blade was installed in a holder as shown in figure 2, which permitted air to be supplied from the cooling-air tube to the various passages in the strut. The air was then discharged through the shell to atmospheric conditions. Probes of approximately 0.30-inch diameter (the leading-edge probe had an elliptical cross section) and contoured to fit certain chordwise portions of the blade surface were used to measure individual local flow rates. The method of making local flow-rate measurements is discussed in detail in reference 4.

Permeability measurements were first made without the orifice plate at the blade base in order to determine the actual local permeability. Apparent permeability values were then obtained with the orifice plate installed. Both actual and apparent permeabilities were determined for nine locations around the blade periphery at each of three spanwise positions; namely, at the blade midspan and in planes $1/2$ inch from the blade tip and $1/2$ inch from the blade base. Hereinafter, the latter two positions will be referred to as tip and root. Measurements were not made at the trailing edge, because the necessary configuration of the probe would produce results of questionable accuracy.

The static pressure at the inlet to the blade was measured by a pressure tap, as indicated in figure 2. Before testing, the value of this pressure must first be calculated as outlined in reference 2, so that the resulting air flow will correspond to that for a pressure drop of 10 pounds per square inch discharging to a standard sea-level barometric pressure and 60° F. When the static pressure so calculated is set at the inlet to the blade, the measured local flow rates may then be converted to values of apparent permeability as outlined in reference 2. Permeability is expressed as $12K'/\tau$, where K' is the permeability coefficient in square feet and τ is the porous-metal thickness in feet.

RESULTS AND DISCUSSION

Visual examination of the blade used in the experimental investigation reported herein showed that, with respect to surface finish, the change from a porous bronze shell (ref. 2) to a porous stainless-steel shell was successfully accomplished by the Federal-Mogul Corporation. The outer surface of the stainless-steel blade was relatively smooth and free from undesirable surface blemishes. The internal cooling-air passages formed by the strut and blade shell also appeared to be smooth and free from blockage of the air flow. The modified design of the supporting strut of the present blade results in a decreased number of cooling-air passages within the blade, as compared with the blades of reference 2, and also provides larger air passages at the leading and trailing edges.

The results of the experimental actual and apparent permeability investigations made with the stainless-steel blade are presented in figure 3, along with the apparent permeability results of reference 2.

Actual Permeability

Figure 3(a) shows the variation of actual permeability (orifice plate not used) with blade chord for three spanwise locations on the stainless-steel blade - root, midspan, and tip. In order to obtain a check on the value of permeability, two separate sets of data were obtained for each surface location shown in figure 3(a). The appearance of only one data point for a given location indicates exact agreement of the two sets of data. In general, the reproducibility of the data is considered good.

The variation of actual permeability in a chordwise and spanwise direction, as shown in figure 3(a) for the stainless-steel blade, is greater than that for the bronze blades of reference 2. Chordwise variations in permeability are not generally serious, as they can be corrected to a large extent by the use of metering orifices. Of greater significance is the variation in spanwise permeability at a given chordwise location, because such variations cannot be controlled by orifices at the blade base. The variations of actual spanwise permeability in the stainless-steel blade were considerably greater than those for the bronze blades. For example, the maximum variation of spanwise permeability for a given chordwise location on the stainless-steel blade had a value in terms of $12K'/\tau$ of about 19×10^{-9} and 13.5×10^{-9} inch for the suction and pressure surfaces, respectively. Values of maximum spanwise variation in permeability for the bronze blades of reference 2 were about 8×10^{-9} and 8.5×10^{-9} inch for the suction and pressure surfaces.

The Federal-Mogul Corporation has indicated that the decrease in permeability control in the stainless-steel blade as compared with the bronze blades is due to the increased difficulty encountered when sintering stainless-steel powder. Specifically, the ceramic filler used to close the passages in the strut while sintering the shell-strut combination contained a small percentage of carbon in its volatile binder. The release of this carbon in contact with the steel powder during sintering of the blade caused local decreases in the liquidus temperature of the steel, which in turn caused the shell permeability to vary excessively. The Federal-Mogul Corporation believes it can overcome this difficulty by obtaining a suitable carbon-free filler.

Apparent Permeability

The variation of apparent permeability (orifice plate in base of blades) around the periphery of the stainless-steel blade for the three spanwise locations is shown in figure 3(b). Comparison of the actual permeability distribution of figure 3(a) with the apparent permeability distribution of figure 3(b) shows that the orifices reduce the permeability variations considerably. The variations in apparent permeability for the stainless-steel blade are appreciably greater than for the bronze blades of reference 2, as evidenced by comparing figures 3(b) and (c). It should be noted that the improved strut design in the leading edge of the stainless-steel blade produced apparent permeabilities in this region that more nearly approach the specified values. Similar improvements would also be expected in the trailing-edge region. The average apparent permeabilities of the stainless-steel blade (fig. 3(b)) are within the general range of permeabilities specified previously. For example, while the apparent permeability specified at the leading edge is 14.2×10^{-9} inch, the average value for the present blade is about 13.3×10^{-9} inch and for the bronze blades was about 5.0×10^{-9} inch. However, the variations of apparent permeabilities are on the order of ± 20 to ± 30 percent of the specified values rather than within ± 10 percent as desired. The variations in apparent permeability are caused by the large variations in actual permeability (fig. 3(a)) and cannot be completely resolved by the use of orifices.

In general, the trends of actual permeability with respect to spanwise location should be repeated for the apparent permeability. For example, in figure 3(a) at the 30-percent-chord position on the suction surface the greatest actual permeability is indicated for the tip position, while a relatively low permeability is shown for the midspan position, and an intermediate value for the root region. For the apparent permeability, the same relation would be expected to continue for the 30-percent-chord position. It can be seen, however, that in figure 3(b) the root region has the lowest permeability at this position on the suction surface. Examination of the behavior of the apparent permeability for the root region of other chordwise locations on the suction

and pressure surfaces indicated that often the apparent permeability was lower than would be expected from inspection of figure 3(a). In two instances, on the suction surface at about 70- and 80-percent-chord locations, the flow through the blade was so low that no permeability measurement was possible, thus indicating a very low apparent permeability. It is believed that these low values of apparent permeability are caused by high cooling-air jet velocities from the orifices in the base. These high jet velocities will result in low static pressure near the root region of the cooling-air passages within the blade. Exploratory calculations indicated that the cooling-air Mach number at some of the orifices may be on the order of 0.6 or greater. Calculations also indicated that the effects of the jet may possibly affect the static pressure at the plane in which the root permeability measurements were made (about 1/2 in. downstream of the orifices). If the cooling-air Mach number is sufficiently high, the static pressure in the root region of the blade cooling-air passages may be so low that gases on the outside of the blade would actually flow into the blade. Such an occurrence would be extremely undesirable in engine operation. In a blade designed for operation in an engine, the effects of the cooling-air jet within the cooling-air passages should be considered and precautions taken to avoid low static pressures of the cooling air near the root of the blade.

Calculations of the temperature distributions that would result for the permeability distribution exhibited by the stainless-steel blade were not made because of the undesirably large permeability variations that were evident.

SUMMARY OF RESULTS

The experimental permeability results obtained from investigation of a porous stainless-steel blade fabricated by Federal-Mogul Corporation are summarized below:

1. The blade had a satisfactorily smooth surface both externally and within the various passages of the internal strut. The redesigned strut provided increased leading- and trailing-edge coolant supply volumes as compared with blades investigated previously.
2. The average apparent permeability of the stainless-steel blade more nearly approached the values specified by the NACA than did the bronze blades investigated previously. For example, the apparent permeability prescribed by the NACA for the leading edge is 14.2×10^{-9} inch; the average value for the present blade is about 13.3×10^{-9} inch, while for the bronze blades the average permeability was about 5.0×10^{-9} inch. In general, similar improvements in the average permeability were obtained for the suction and pressure surfaces.

3. The random variation of permeability in the stainless-steel blade was greater than that exhibited by the bronze blades. Variations on the order of ± 20 to ± 30 percent from the specified permeability were observed, whereas for the application of porous blades in present-day engines a variation of permeability on the order of ± 10 percent is considered tolerable.

4. The apparent permeability in the base region of the blade may have been reduced by low static pressures caused by relatively high jet velocities from the orifices.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, April 23, 1954

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4. Bartoo, Edward R., Schafer, Louis J., Jr., and Richards, Hadley T.: Experimental Investigation of Coolant-Flow Characteristics of a Sintered Porous Turbine Blade. NACA RM E51K02, 1952.

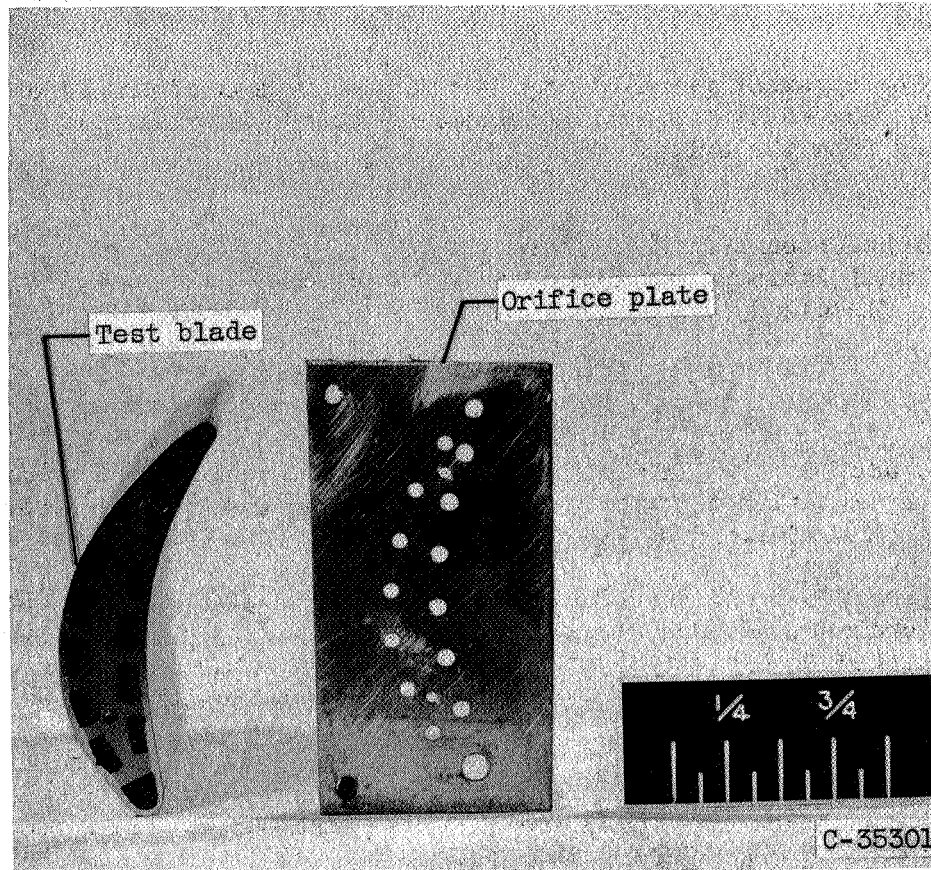


Figure 1. - End view of test blade and orifice plate.

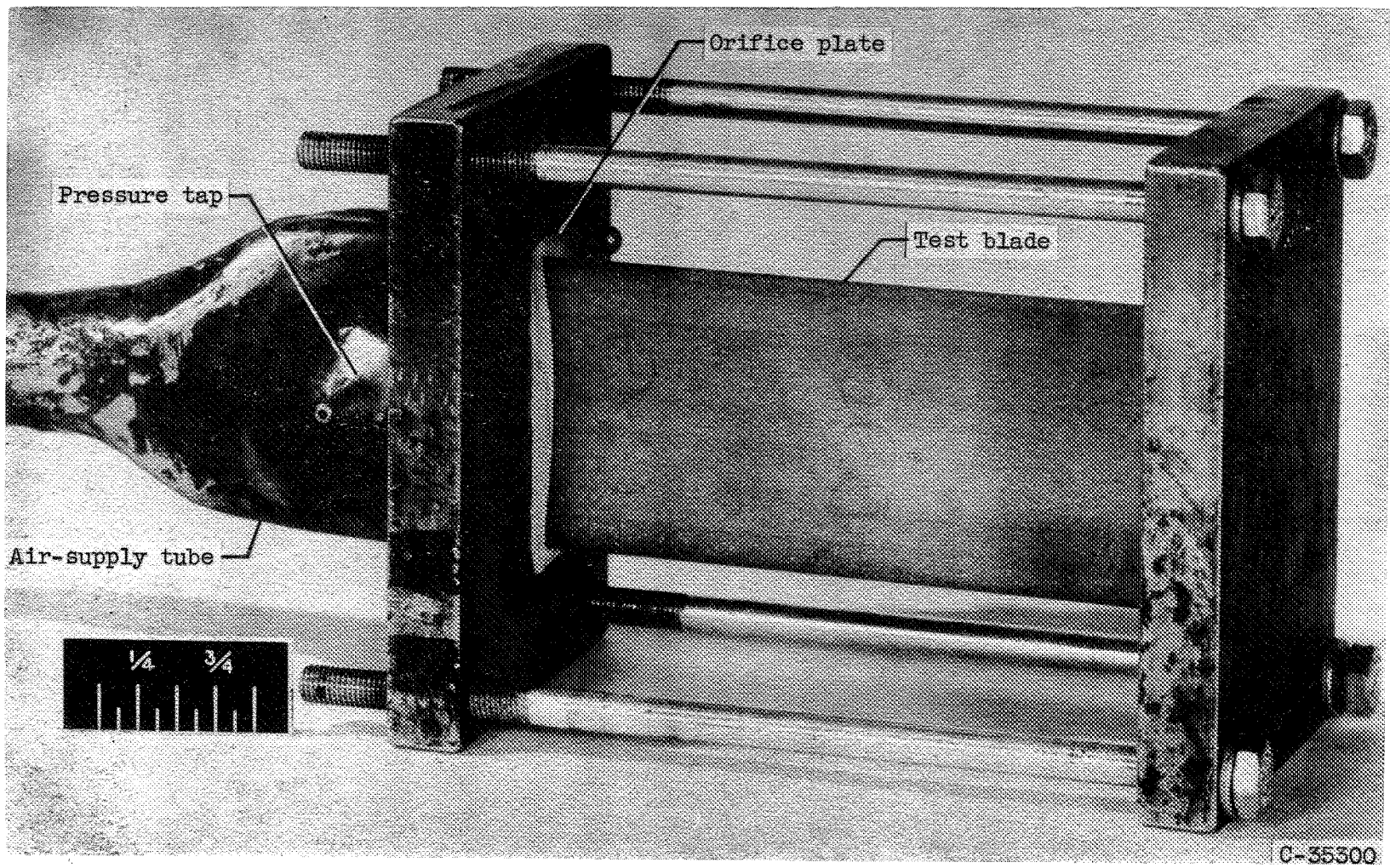


Figure 2. - Test blade mounted in flow-testing apparatus.

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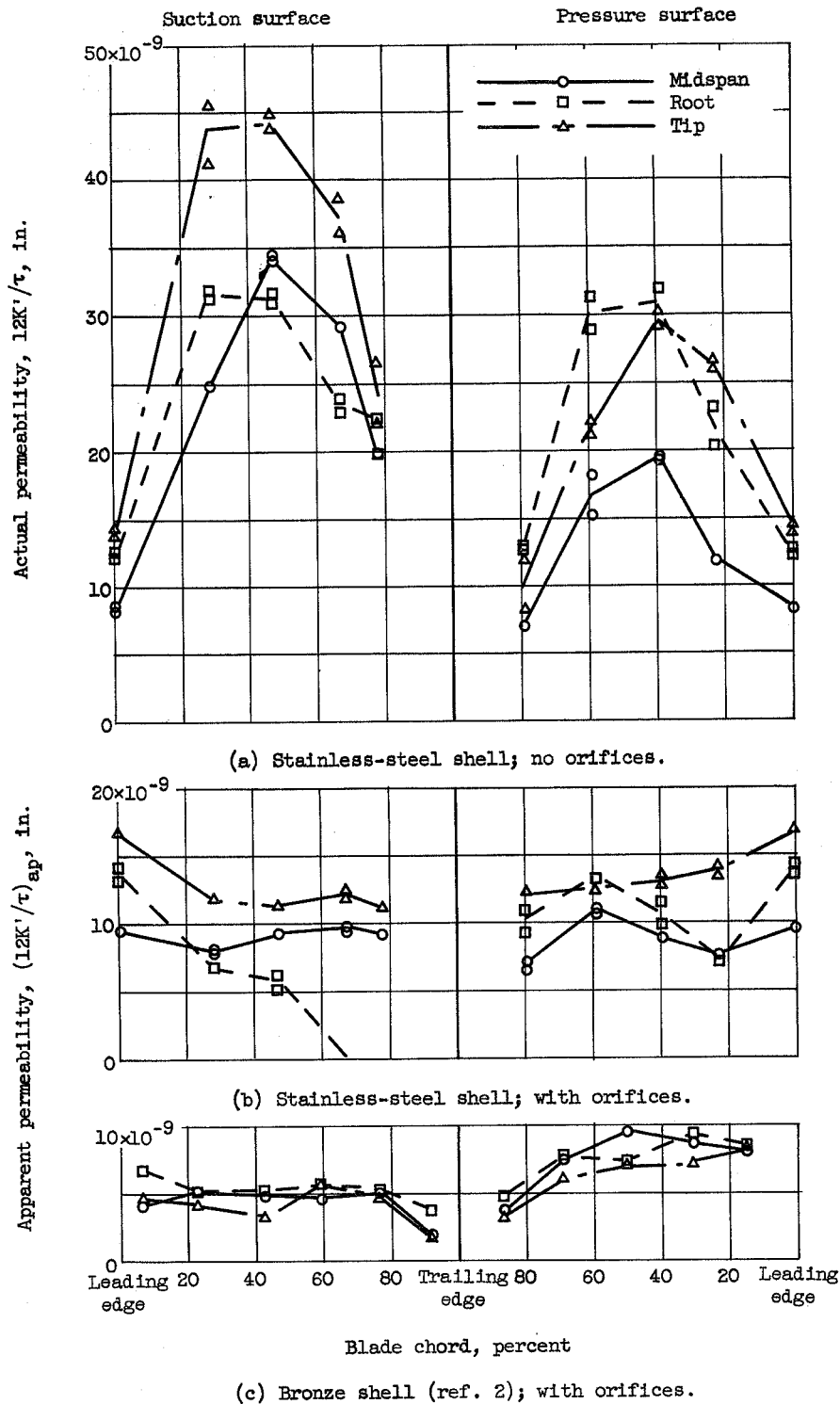


Figure 3. - Experimentally determined permeability distributions around periphery of experimental blades with and without orifices at blade base for three spanwise positions.

EXPERIMENTAL PERMEABILITY MEASUREMENTS ON A STRUT-SUPPORTED
TRANSPIRATION-COOLED TURBINE BLADE WITH STAINLESS-STEEL
SHELL MADE BY THE FEDERAL-MOGUL CORPORATION UNDER
BUREAU OF AERONAUTICS CONTRACT NO. 351613-C

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Turbine Cooling	3.7.2
Heat-Transfer Theory and Experiment	3.9.1
Cooling - Gas-Turbine Systems	3.10.2

Richards, Hadley T.

Abstract

A turbine blade with a porous stainless-steel shell sintered to a supporting steel strut has been fabricated for tests at the NACA by Federal-Mogul Corporation under contract from the Bureau of Aeronautics, Department of the Navy. The apparent permeability of this blade, on the average, more nearly approaches the values specified by the NACA than did two strut-supported bronze blades in a previous investigation. Random variations of permeability in the present blade are substantially greater than those of the bronze blades, but projected improvements in certain phases of the fabrication process are expected to reduce these variations.