NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

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INVESTIGATION OF EFFECTIVENESS OF AIR-HEATING A HOLLOW

STEEL PROPELLER FOR PROTECTION AGAINST ICING

II - 50-PERCENT PARTITIONED BLADES

By Porter J. Perkins and Donald R. Mulholland

Flight Propulsion Research Laboratory
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SUMMARY

The icing protection afforded an internal air-heated propeller
blade by radial partitioning at 50-percent chord to confine the
heated air to the forward half of the blade was determined in the
NACA Cleveland icing research tunnel. A modified production-model
hollow steel propeller was used for the investigation. Temperatures
of the blade surfaces for several heating rates were measured under
various tunnel icing conditions. Photographic observations of ice
formations on blade surfaces and blade heat-exchanger effectiveness
were obtained.

With 50-percent partitioning of the blades, adequate icing pro-
tection at 1050 rpm was obtained with a heating rate of 26,000 Btu
per hour per blade at the blade shank using an air temperature of
400° F with a flow rate of 280 pounds per hour per blade, which is
one-third less heat than was found necessary for similar ice pro-
tection with unpartitioned blades. The chordwise distribution of
the applied heat, as determined by surface temperature measurements,
was considered unsatisfactory with much of the heat dissipated well
back of the leading edge. Heat-exchanger effectiveness of approxi-
mately 56 percent also indicated poor utilization of available heat.
This effectiveness was, however, 9 percent greater than that obtained
from unpartitioned blades.

INTRODUCTION

The protection of propeller blades from icing by the internal
passage of heated air has been previously investigated in flight and
in the laboratory. These investigations are reported in references 1
and 2 (unpartitioned blades) and the results of a theoretical analysis
are given in reference 3 (50-percent radially partitioned blades).

Unpartitioned blades were found by experiment to require large quantities of heat for icing protection and afforded an uneconomical chordwise distribution of the heat.

In an effort to develop propeller blades requiring less total heat for icing protection, an investigation was conducted in the NACA Cleveland icing research tunnel using a modified air-heated hollow steel propeller with blades partitioned radially at 50-percent chord to confine the flow of heated air to approximately the forward one-half of the blade cavity.

Data were obtained to determine the effectiveness of the blade heating system, blade-surface temperatures, and heat requirements. Observations were made of the icing protection attained by the heating system.

APPARATUS AND INSTRUMENTATION

The icing investigation was conducted in a return-type tunnel in which icing conditions were simulated by means of water sprays and the use of refrigerated air. The propeller was driven by a liquid-cooled engine mounted in an airplane fuselage located in the diffuser of the tunnel (fig. 1). A modified production model four-bladed hollow steel propeller 10 feet, 2 inches in diameter was used. Heated air was distributed to the propeller blades, as shown in figure 2.

The instrumentation provided for measurement of tunnel and propeller operating conditions, propeller heated-air temperature and mass flow, and blade-surface temperatures. Chordwise blade-surface temperatures were measured at 40- and 70-percent blade radii on two of the four blades using iron-constantan ribbon-type thermocouples spotwelded to the blade metal. The locations of blade-surface thermocouples at 40- and 70-percent radii are shown in figure 3. In addition, leading-edge surface temperatures were measured at 30- and 55-percent radii. Further details concerning apparatus and instrumentation used for the propeller-icing research are given in reference 1.

Blade partitioning. - The partition installed within the blade cavity was of semiregid fiber-glass construction. It was anchored and sealed at the blade shank and was held in position radially along the blade by means of rivets through the blade walls. A semi-circular construction was used (fig. 3), which held the partition

firmly against the inner walls of the cavity between rivets to prevent air leakage to the rear portion of the blade cavity. The partition terminated approximately 6 inches from the blade tip to allow the heated air to pass to the rear of the blade and escape through a tip orifice on the camber face.

Propeller-blade heating system. - For the 50-percent partitioned blades, the air flow through the blades and the arrangement of seals were unchanged from those described in reference 1 for the unpartitioned blades, except that the air was confined to the forward half of the blade. The tip orifices used for the 50-percent partitioned blades were approximately two-thirds the cross-sectional area of those used for the unpartitioned blades. Construction details and photographs of the blade-shank inlets and tip orifice are shown in figure 4.

Heated air was supplied to the propeller through electric heaters outside the tunnel. The supply of heated air was manually controlled and the blade air flow was calculated by adding or subtracting the leakage past the graphite seals, depending on the seal differential pressure, from the measured manifold air flow. The calibration curve used to determine leakage values is given in reference 1.

CONDITIONS AND PROCEDURE

Tunnel conditions. - The propeller was subjected to icing conditions at tunnel-air temperatures between -4° and 23° F. The tunnel-air velocity averaged approximately 200 feet per second measured at 75 percent of the propeller radius. During the icing period, the velocity decreased because of pressure losses resulting from tunnel ice formations. Liquid-water concentrations were approximately 0.1 gram per cubic meter at 3° F and 0.9 gram per cubic meter at 19° F. The effective droplet diameter based on the volume maximum averaged approximately 55 microns for all tunnel conditions. This value is larger than average droplet diameters usually found in the atmosphere. The icing of propeller blades, however, is not greatly reduced unless relatively small droplet diameters are encountered, because the collection efficiency of small bodies is approximately 100 percent. For the conditions used, the heating values required in this investigation are considered conservative.

Range of propeller variables. - The propeller was operated at two blade angles, 28° and 35°, measured at 75-percent radius with corresponding rotational speeds of 1050 and 850 rpm, at which

advance ratios of 1.1 and 1.4, respectively, were established to
approximate the advance ratio of peak efficiency. Under tunnel
operating conditions, the heated-air flow per blade was adjusted
to range between 250 and 330 pounds per hour at 1050 rpm and
between 165 and 185 pounds per hour at 850 rpm with an air tem-
perature at the shank between 300° and 400° F.

Typical procedure. - Data were obtained during 10-minute
periods of simulated icing conditions. Prior to each icing period,
data were recorded for 2 minutes with all operating conditions
stabilized and heated air flowing through the blades. Blade-
surface temperatures were recorded at approximately 1-minute
intervals throughout the preicing and icing period. Following
each icing condition residual icing photographs were obtained.

RESULTS AND DISCUSSION

Blade Heating System

The blade heat-exchanger effectiveness, as defined in ref-
erence 1, is the ratio of the heat dissipated from the blade sur-
face to the heat applied, including the heat from adiabatic com-
pression of the internal air due to rotation. The values of heat-
exchanger effectiveness shown in figure 5 for both the 50-percent
partitioned and the unpartitioned blades are for the same range of
air temperatures entering the shanks (300° to 400° F). With no
sprays in the tunnel and at a propeller speed of 1050 rpm, the
effectiveness for 50-percent partitioned blades averaged 56 percent
or 9 percent higher than that for the unpartitioned blades (fig. 5).
The partition guided the heated air through the forward section
of the blade, where external heat-transfer coefficients are highest,
and, in addition, a heat sink was provided behind the partition
causing much conduction to take place rearward through the blade
metal as indicated by high surface temperatures aft of the partition.

The effect on the blade heat-exchanger effectiveness of the primer
coating used to hold the surface thermocouples to the blade is also
indicated in figure 5. The effectiveness of the painted blade was
6 to 7 percent lower than that of the bare blade.

Blade-Surface Temperatures

The temperatures measured by the thermocouples located on the
blade surfaces are plotted as a rise in temperature above the ambient
tunnel temperature (figs. 6 to 10). Because values of heating rate

surface temperature, and tunnel temperature varied during an icing period when surface temperature data were taken, all the distribution curves were constructed from plots of average values of surface temperature rise above tunnel ambient temperature. In developing these average curves, all the temperature data for a given location were plotted against heating rate. By assuming a linear relation between the two variables, a straight line was drawn as an average of the data. From these plots the faired distribution curves were constructed for various heating rates. For the range of data investigated the relation of surface temperature rise to heating rate was considered to independent of tunnel-air temperature.

The distribution of this temperature rise is shown in figure 6, where the blade chordwise surface is laid out in plan form with the leading edge as the center and the surface distance over the thrust and camber faces extending along the axis on either side. Data are presented for a propeller speed of 1050 rpm and heating rates of 18,000 and 22,000 Btu per hour per blade with no water spray in the tunnel and heating rates of 22,000 and 28,000 Btu per hour per blade under icing conditions.

It is significant that partitioning the blade at 50-percent chord failed to concentrate most of the heat at the leading edge where it was most needed for icing protection. The high temperature rises aft of the leading edge and near the partition, especially at the 40-percent radius, indicated the dissipation of large quantities of heat in areas not subject to severe ice formations.

Increasing the heating rate from 18,000 to 22,000 Btu per hour per blade with no sprays in the tunnel resulted in practically uniform chordwise surface-temperature increases at both the 40- and 70-percent radii (figs. 6(a) and 6(c)). Under icing conditions, an increase in the heating rate from 22,000 to 28,000 Btu per hour per blade considerably increased the surface temperatures at 40-percent radius except near the leading edge (fig. 6(b)) but did not appreciably increase the temperatures at the 70-percent radius. The increased heating rate did, however, materially increase the temperature gradient aft of the leading edge on the inboard blade sections as shown in figure 6(b). The steeper gradient narrowed the potential icing area and thus afforded greater icing protection for the blade.

The temperature rises at the 40- and 70-percent radii under no-spray and icing conditions at a heating rate of 22,000 Btu per hour per blade and a propeller speed of 1050 rpm are compared in figure 7. With no sprays, temperatures at the 40-percent radius leading edge were considerably higher than those at the 70-percent radius.

The effect of water impingment was to lower all blade-surface temperatures. Under icing conditions, the temperatures near the leading edge for the two radii were approximately equal. Aside from the effects of throw-off due to centrifugal forces, it can therefore be seen that the two radii will be about equally susceptible to icing at the leading edge.

Data taken at a propeller speed of 850 rpm with a heating rate of 14,000 Btu per hour per blade are shown in figure 8 for the chordwise temperature distributions at the 40- and 70-percent radii under icing conditions. Although the heating rate had been reduced from 22,000 to 14,000 Btu per hour per blade and the propeller speed from 1050 to 850 rpm, a comparison of figures 7 and 8 shows that the leading-edge temperature rises at the 40-percent radius were approximately equal. The temperature gradients for the two conditions were also similar. At the 70-percent radius, however, the leading-edge temperatures were lower than the 40-percent radius temperatures and were also lower than the corresponding 70-percent radius temperatures on the high-speed blade with the higher heating rate. Aside from throw-off effects, these results show that at 850 rpm with 14,000 Btu per hour per blade, the 70-percent radius would ice over the entire chord at higher ambient temperatures than the 40-percent radius.

Surface temperatures obtained on the leading edge at the 30-, 40-, and 55-percent radii for a propeller speed of 1050 rpm are presented as temperature rise above tunnel ambinet temperature in figure 9. The decrease in surface temperature rise with increasing radius results from the drop in internal gas temperature with increasing radius and the increase in external heat-transfer coefficient with increasing peripheral velocity. The increase in kinetic heating with peripheral velocity tends to counteract the two effects. These considerations together with results given in reference 2 indicate that with a higher propeller speed the temperature rise for the icing condition may begin to increase beyond the 55-percent radius. This temperature rise increase is corborated by the data of figure 7 where the leading-edge temperatures at the 40- and 70-percent radii under icing conditions differ by only 2° F. The opposite result may be observed in figure 8 where at a lower propeller speed of 850 rpm the 70-percent radius leading-edge temperature is 4° F lower than the corresponding 40-percent radius temperature.

A comparison of the surface temperature distributions obtained with 50-percent partitioned blades at a heating rate of 28,000 Btu per hour per blade and temperature distributions obtained with unpartioned blades at a heating rate of 40,000 Btu per hour per blade is shown in figure 10. These data were obtained at a propeller speed of 1050 rpm under icing conditions. Some improvement in heat

distribution and economy is found with the 50-percent partitioned
blade. Temperatures at the leading edge for the 40- and 70-percent
radii on the 50-percent partitioned blade are both equal to the
leading-edge temperature at 70-percent radius on the unpartitioned
blade, although only three-fourths of the heating rate used in the
unpartitioned blade was used in the partitioned blade.

The high surface temperatures and, hence, ice protection aft
of the partition in the 50-percent partitioned blades indicate that
the back surfaces of the blade would be adequately protected from
ice if the partition were moved even farther forward. By such a
partitioning, ice protection might be afforded the entire blade
with the use of a lower heating rate.

Icing Observations

Comparative photographs of residual ice formations for different
heating rates are shown in figure 11. The heating rate was increased
from 20,000 to 26,000 Btu per hour per blade at a propeller speed
of 1050 rpm and a tunnel ambient-air temperature of 11° F. Increas-
ing the heating rate to 26,000 Btu per hour per blade, corresponding
to approximately 280 pounds of air per hour at a shank temperature
of 400° F, did not completely prevent ice formation on the leading
edge of all the blades, as would be expected. The temperature dis-
tributions shown in figures 6(b) and 6(d) show little increase near
the leading edge when the heating rate was increased from 22,000 to
28,000 Btu per hour per blade. Less ice was to be found on the
blades with the higher heating rate, however, because of the greater
throw-off made possible by the steeper temperature gradients pre-
viously discussed. The residual ice formations shown for the higher
heating rate are not considered sufficient to impair the aerodynamic
performance of the propeller. It had been established in reference 1
that in the tunnel, icing conditions were most severe at an ambient-
air temperature of 11° F, and inasmuch as the blades were adequately
protected for this condition by a heating rate of 26,000 Btu per hour
per blade, this value is believed to be adequate for all other icing
conditions. This heating rate is approximately two-thirds that
required for similar protection using unpartitioned blades.

SUMMARY OF RESULTS

From an investigation conducted in the icing research tunnel,
the following results of the icing protection afforded a propeller
blade by the internal passage of heated air through the forward half
of the blade were obtained:

1. Adequate icing protection existed at 1050 rpm with a heating rate of 26,000 Btu per hour per blade at a shank air temperature of 400° F, and a flow rate of 280 pounds per hour per blade, which was about two-thirds the heating rate required for an unpartitioned blade. Small ice accretions at the leading edge on the inboard blade sections were not considered significant with respect to aerodynamic performance of the propeller.

2. The chordwise distribution of the heat, although better than that of the unpartitioned blade, was still unsatisfactory because too much of the heat was dissipated on the rear sections of the blade and too little on the leading edge.

3. The heat-exchanger effectiveness of the 50-percent partitioned blade averaged 56 percent, which is approximately 9 percent more than that for the unpartitioned blade.

Flight Propulsion Research Laboratory,
        National Advisory Committee for Aeronautics,
                Cleveland, Ohio, January 19, 1948.

REFERENCES

1. Mulholland, Donald R., and Perkins, Porter J.: Investigation of the Effectiveness of Air-Heating a Hollow Steel Propeller for Protection Against Icing. I - Unpartitioned Blades. NACA TN No. 1586, 1948.

2. Darsow, John F., and Selna, James: A Flight Investigation of the Thermal Performance of an Air-Heated Propeller. NACA TN No. 1178, 1947.

3. Gray, V. H., and Campbell, R. G.: A Method for Estimating Heat Requirements for Ice Prevention on Gas-Heated Propeller Blades. NACA TN No. 1494, 1947.

Figure 1. - Tunnel installation of air-heated hollow steel propeller for icing investigation.

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Circumferential seal

Shank seal

Revolving bulkhead

Stationary bulkhead

Stationary manifold

Heated-air duct

NACA

Tip orifice

Blade partition

Hollow steel propeller blade

Shank inlet

Shank duct

Control unit for rotating thermocouples
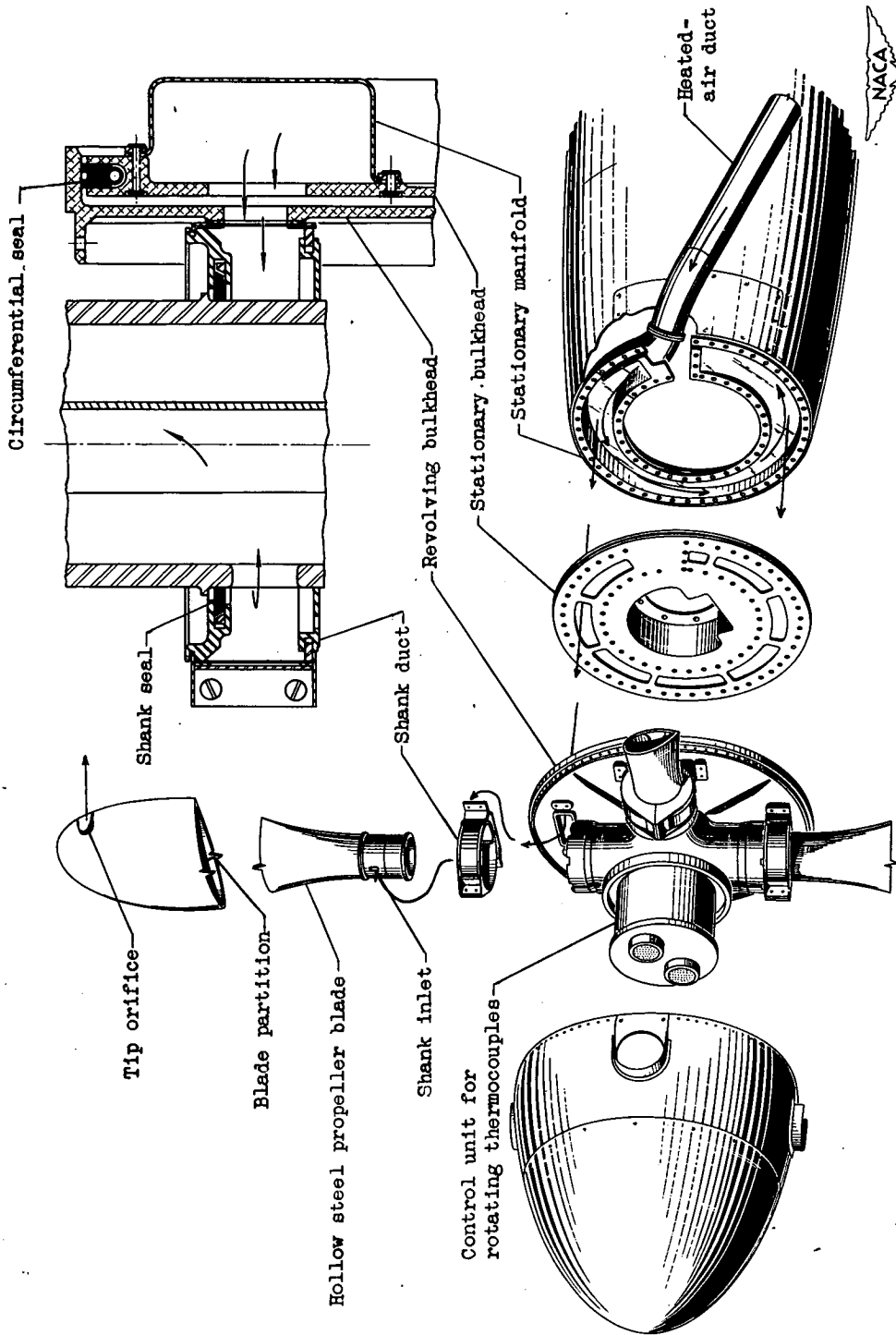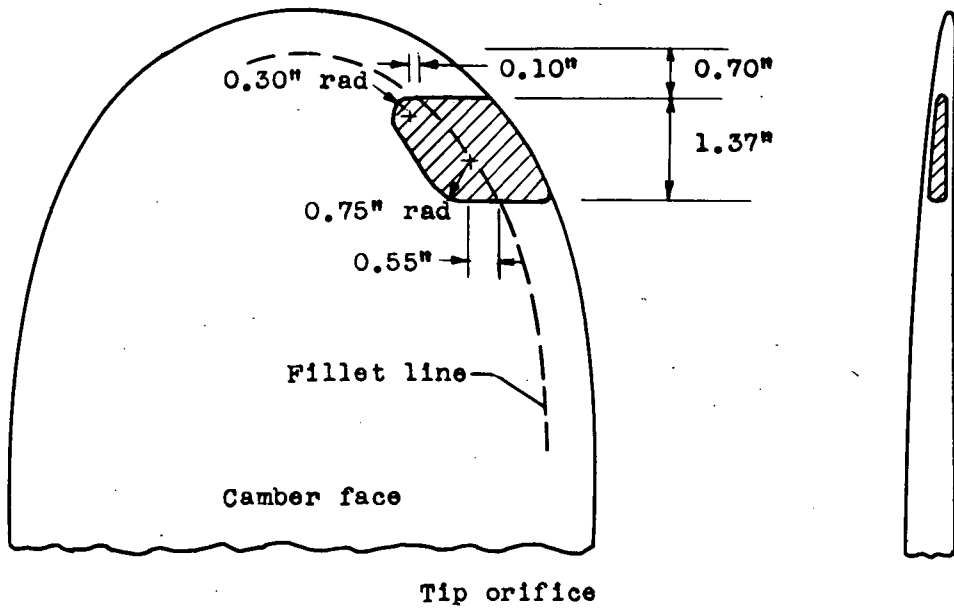
Figure 2. - Details of air-heated propeller installation.

Inches
(Chordwise surface distance)

Fillet

NACA

Partition

(a) 40-percent radius.

(b) 70-percent radius.

Thermocouples

Leading
edge
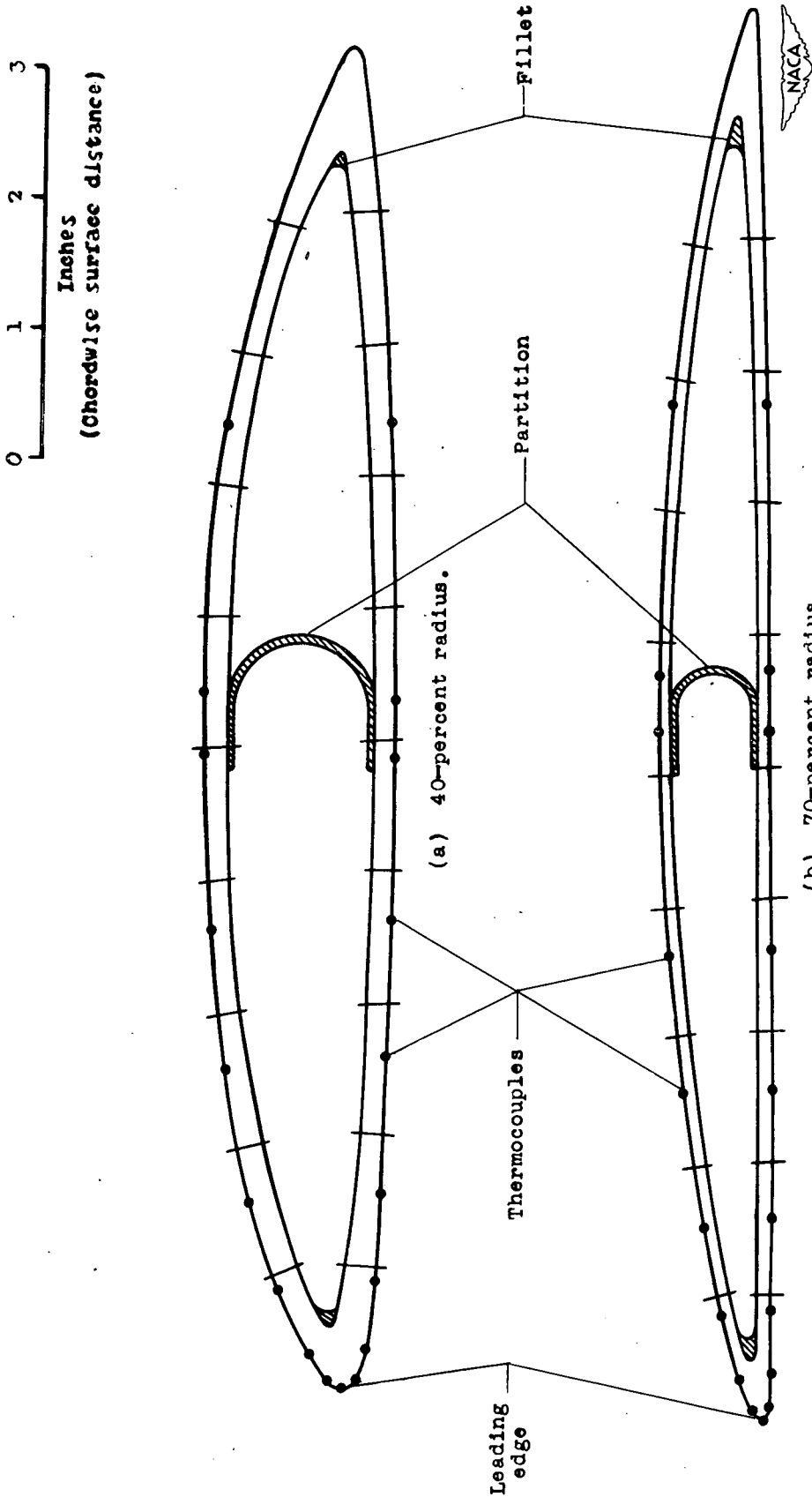
Figure 3.- Chordwise thermocouple locations.

0.30" rad

0.10"   0.70"

1.37"

0.75" rad

0.55"

Fillet line

Camber face

Tip orifice

0.79"

0.38"

Tip

Total area,
0.58 sq in.

90°

102°

0.37"

Blade mark
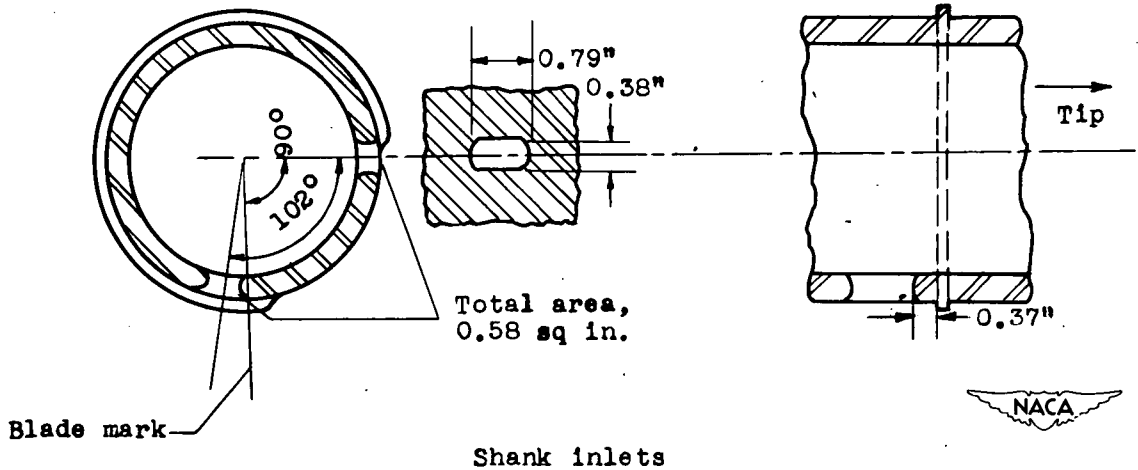
Shank inlets

(a)   Construction details.

Figure 4.- Shank inlets and tip orifice for 50-percent partitioned
air-heated propeller blades.

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(b) Photographs of tip and shank openings in blade.

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Figure 4. - Concluded. Shank inlets and tip orifice for 50-percent partitioned air-heated propeller blades.

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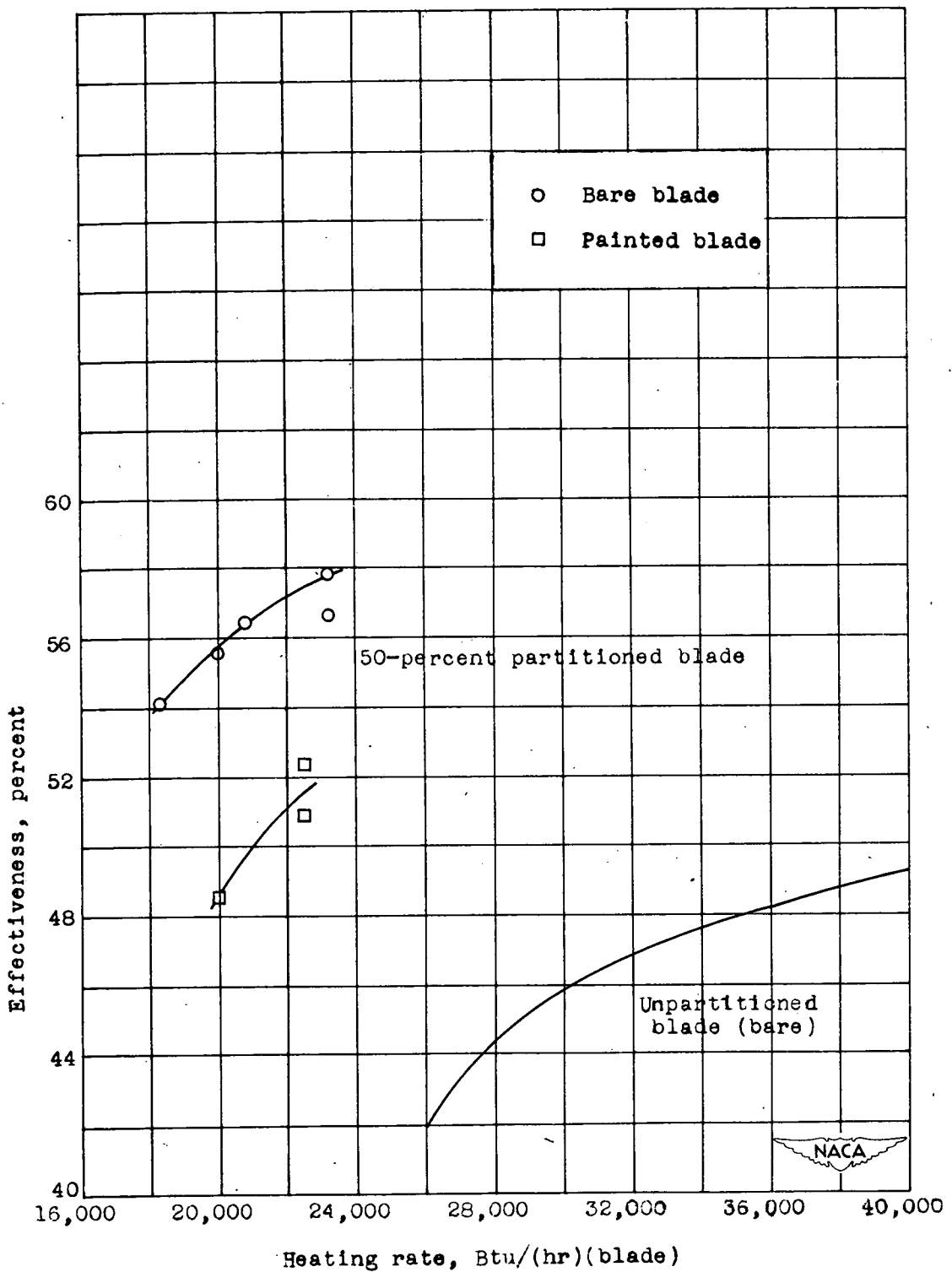
Figure 5.— Comparison of heat-exchanger effectiveness for unpar-
titioned and 50-percent-chord partitioned air-heated propeller
blades. No sprays; propeller speed, 1050 rpm; tunnel air
temperature, −3° to 15° F.
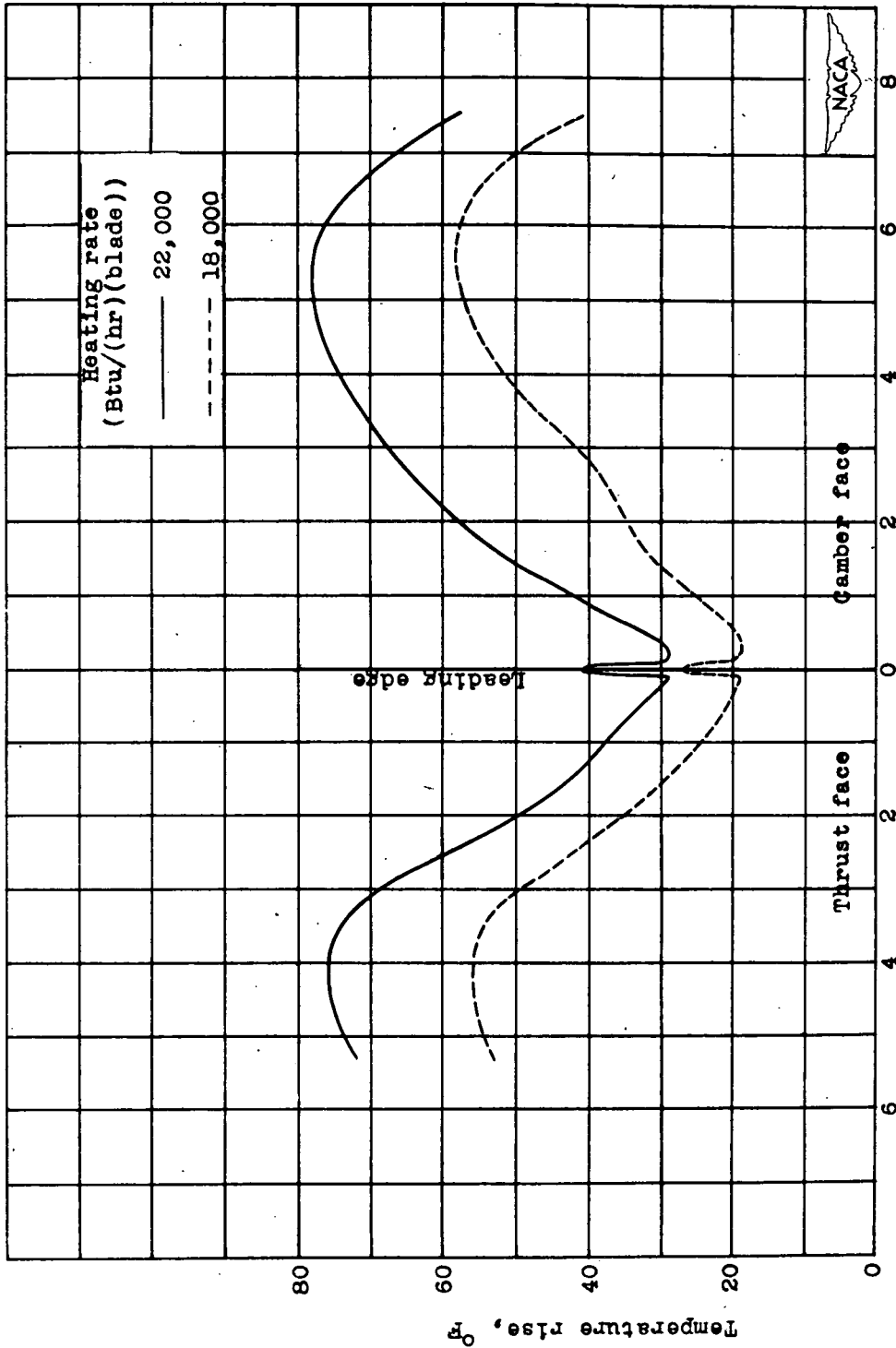
Figure 6.— Effect of increased heating rate on blade—surface—temperature distribution.

(a) No sprays, 40-percent radius.
Propeller speed, 1050 rpm.

Figure 6.- Continued. Effect of increased heating rate on blade-surface-temperature distribution. Propeller speed, 1050 rpm.

(b) Icing, 40-percent radius.
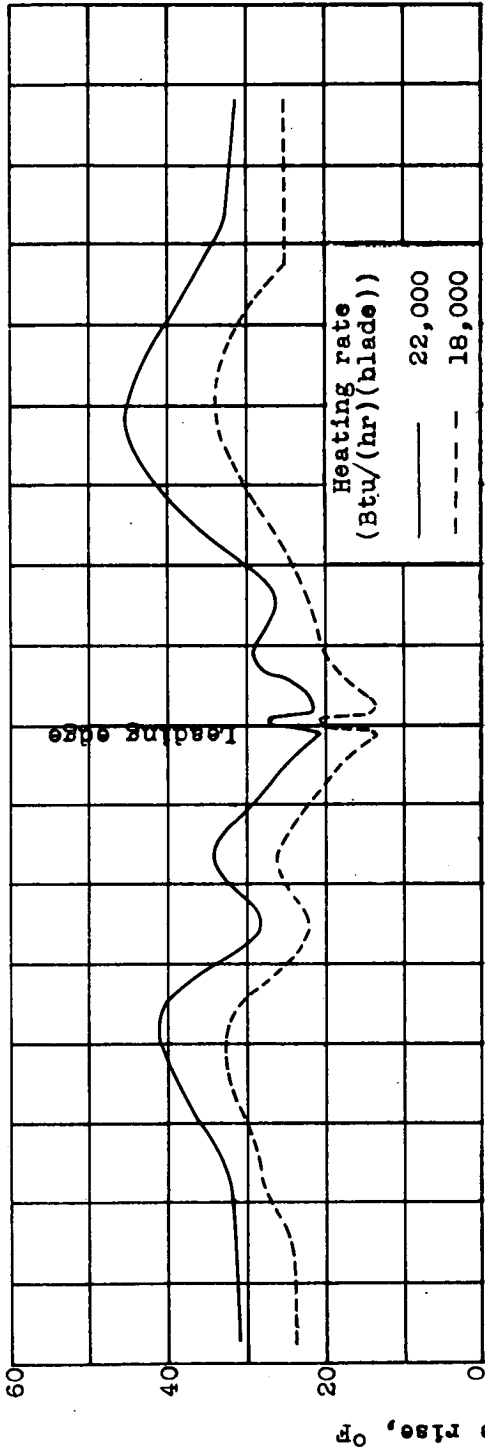
(c) No sprays, 70-percent radius.

Chordwise surface distance, in.
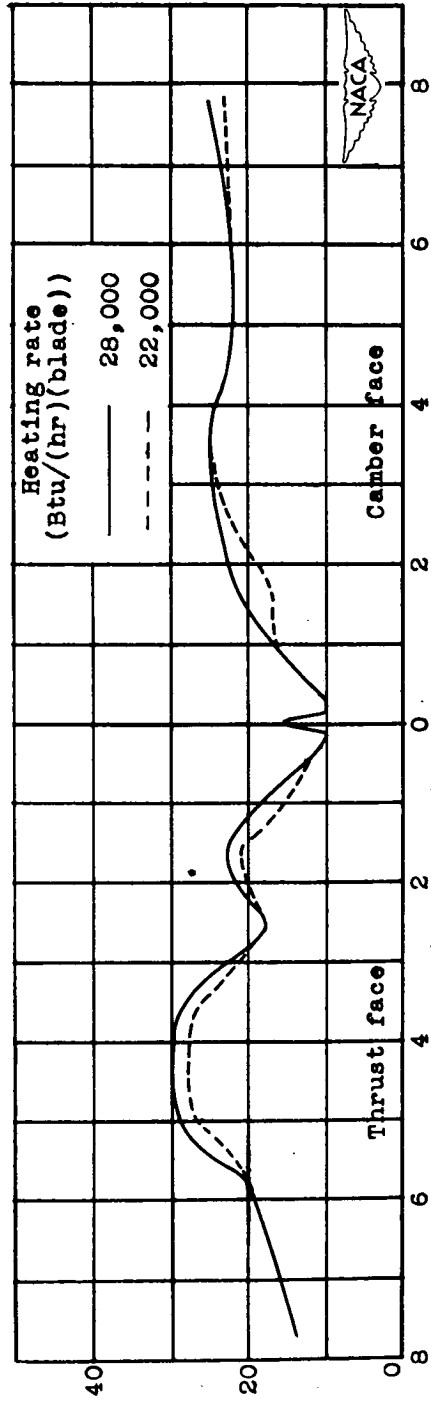
(d) Icing, 70-percent radius.

Figure 6.- Concluded. Effect of increased heating rate on blade-surface-temperature
distribution. Propeller speed, 1050 rpm.
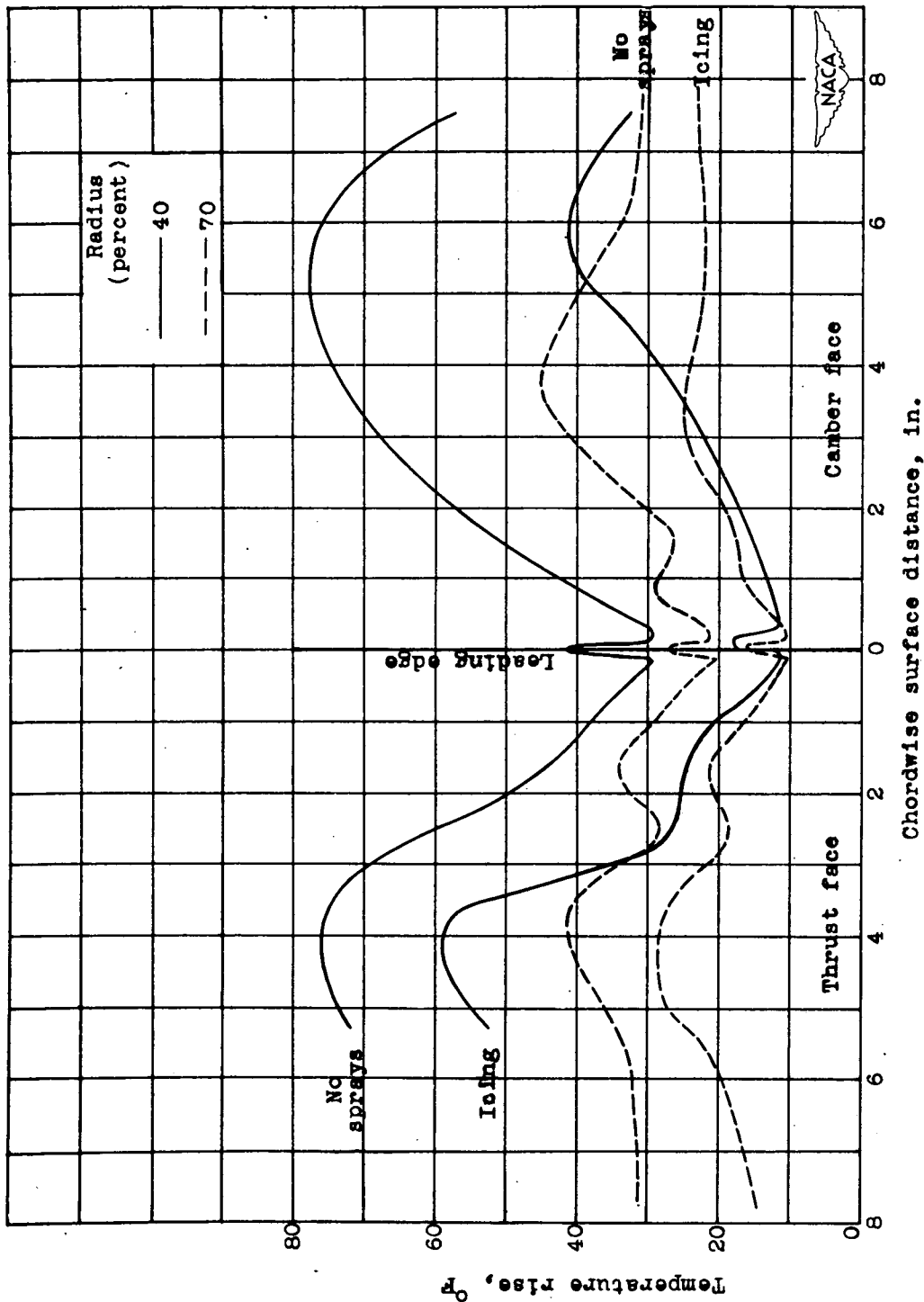
Figure 7.- Comparison of blade-surface-temperature distributions at 40- and 70-percent radii under icing conditions and with no sprays. Heating rate, 22,000 Btu per hour per blade; propeller speed, 1050 rpm.
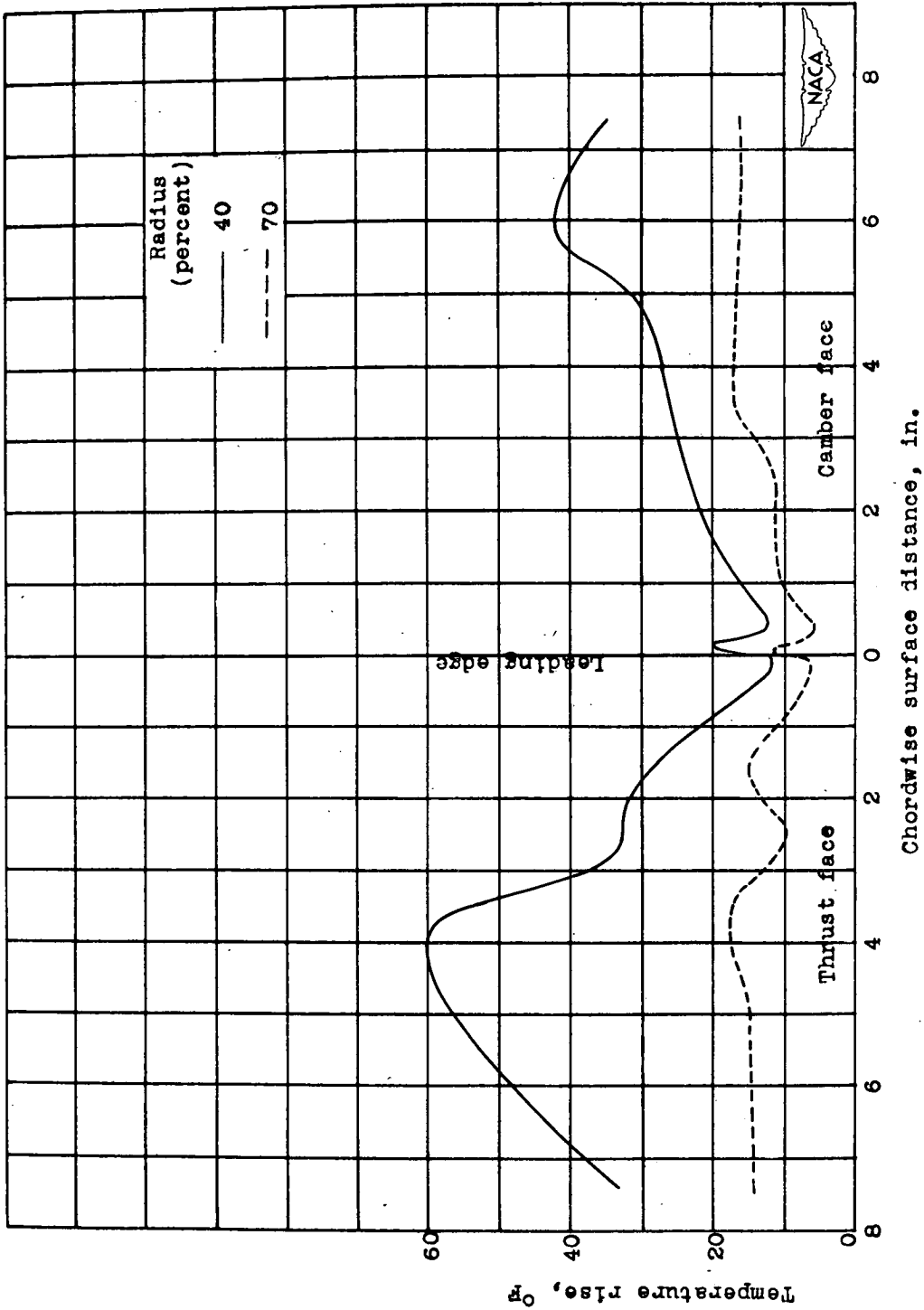
Figure 8.— Chordwise blade—surface—temperature distribution at 40— and 70—percent radii. Icing condition; heating rate, 14,000 Btu per hour per blade; propeller speed, 850 rpm.
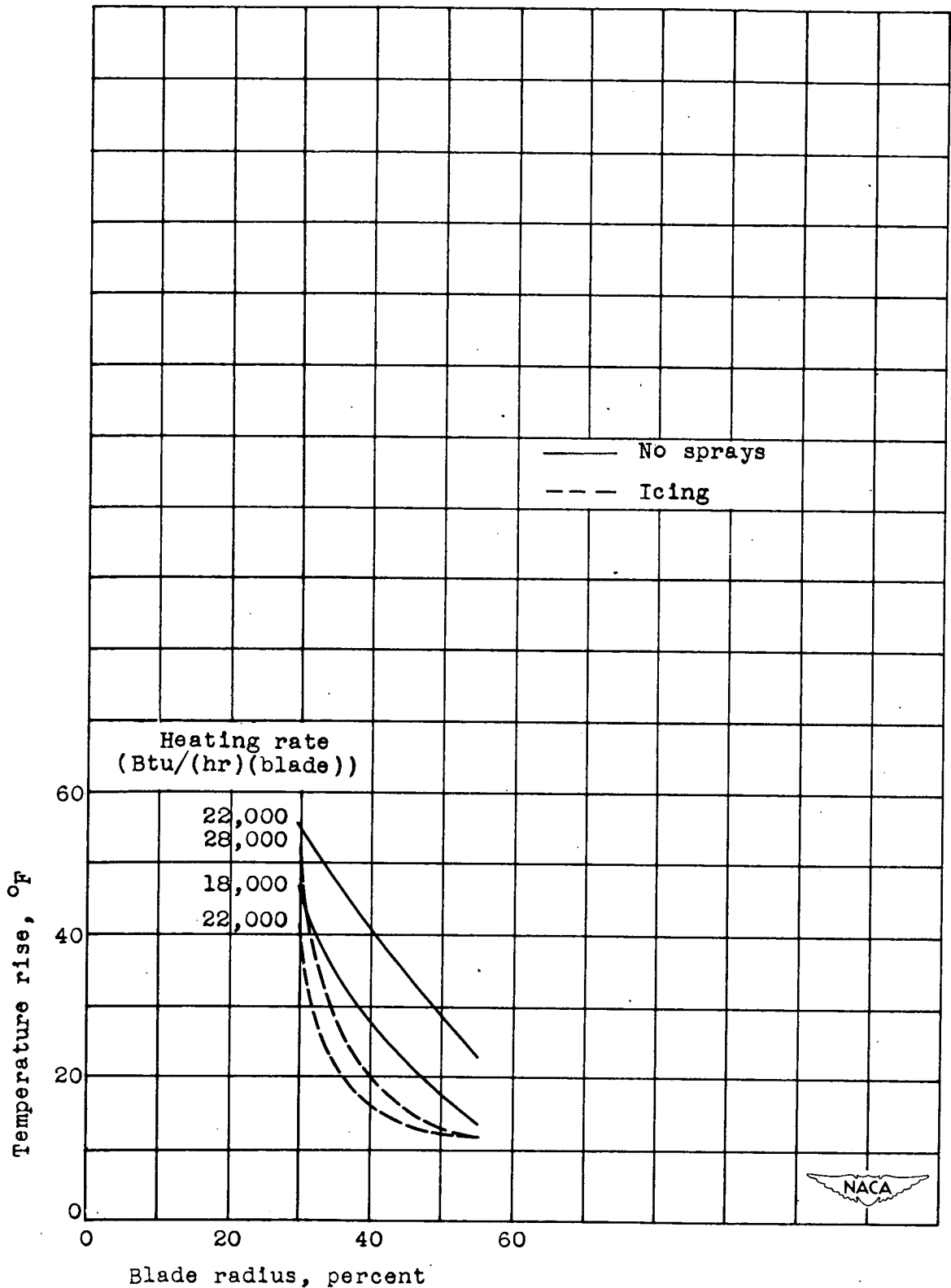
Figure 9.- Radial surface-temperature distribution at blade
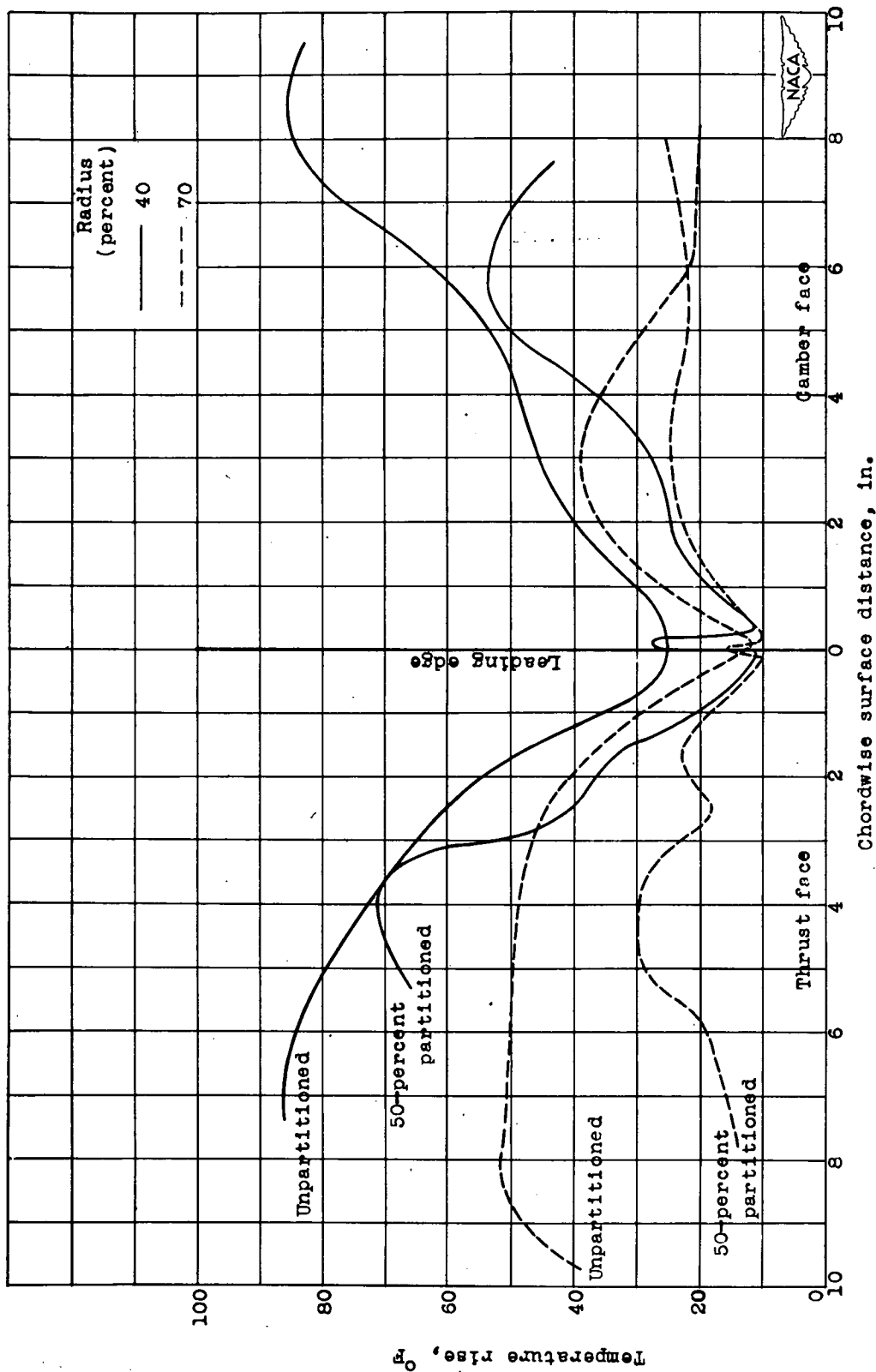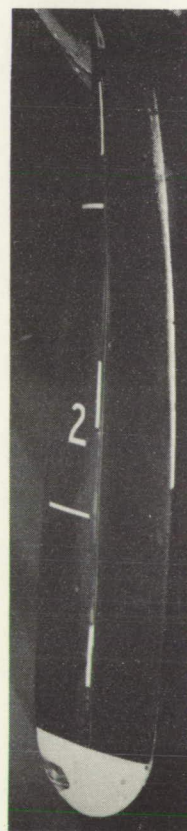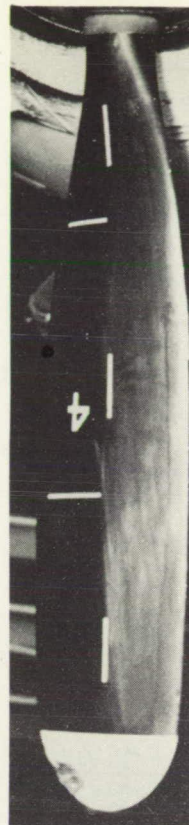leading edge. Propeller speed, 1050 rpm.

Figure 10.— Comparison of blade—surface—temperature distribution for 50—percent partitioned and un—
partitioned blades at 40— and 70—percent radii under icing conditions. 50—percent partitioned
blade, 28,000 Btu per hour per blade; unpartitioned blade, 40,000 Btu per hour per blade; pro—
peller speed, 1050 rpm.

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(a) Heating rate, 20,000 Btu per hour per blade.

(b) Heating rate, 26,000 Btu per hour per blade.

Figure 11.- Effect of increased heating rate on icing. Propeller speed, 1050 rpm; blade angle, 28°; indicated tunnel ambient air temperature, 11° F.