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THE EFFECTS OF AERODYNAMIC HEATING ON ICE

FORMATIONS ON AIRPLANE PROPELLERS

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SUMMARY

An investigation has been made of the effect of aerodynamic heating on propeller-blade temperatures. The blade temperature rise resulting from aerodynamic heating was measured and the relation between the resulting blade temperatures and the outer limit of the iced-over region was examined. It was found that the outermost station at which ice formed on a propeller blade was determined by the blade temperature rise resulting from the aerodynamic heating at that point.

INTRODUCTION

The National Advisory Committee for Aeronautics has conducted an investigation of aerodynamic heating of propeller blades to determine if a relation exists between the resulting blade temperatures and the outermost blade station on which ice will form.

Such data, it is believed, will permit a satisfactorily accurate definition of the region over which ice forms on the propeller blade and facilitate the development of dependable ice-prevention equipment for the airplane propeller.

Pilots have reported that the formation of ice may be minimized on propellers by operating the engine at maximum speed. It has been anticipated that the results of the present investigation would determine whether this method of obtaining partial ice protection depended upon the effect of centrifugal force or aerodynamic heating.

The temperature rise of an airfoil was measured by Brun (reference 1) but, owing to the velocity gradient along the propeller blade and the dissimilarity of the shape and size of blade sections along the radius, calculations of the temperature rise of a propeller from the

airfoil data are laborious and probably not dependable.
The temperature gradient along the radius results in a
heat flow in the same direction, the prediction of which
is highly involved. An attempt was made in the present
investigation to establish a comparatively simple rela-
tion between the atmospheric conditions and the velocity
of the outermost propeller blade station on which ice will
form. Attention is directed to the formula

$$\Delta T = \frac{V^2}{2Jgc_p} \tag{1}$$

which can be developed for the region of zero velocity or
stagnation pressure region from reference 1. In this
equation, ΔT is the temperature rise in $^\circ F$, V the
velocity in feet per second, J the mechanical equivalent
of heat, g the acceleration of gravity, and c_p the
specific heat at constant pressure. When the constants
are put in numerical form, equation (1) becomes

$$\Delta T = \left(\frac{V}{109.5} \right)^2 \tag{2}$$

At the leading edge of an airfoil the aerodynamic
heating is due solely to adiabatic compression, while
rearward from this point friction heating becomes the
major contributing factor. The investigation reported in
reference 1 shows that the temperature rise of the air-
foil rearward from the leading edge will be less than the
quantity given by equation (1). It was anticipated,
therefore, that since the tests of the present investiga-
tion were to be conducted on a solid aluminum blade, the
measured blade temperature rise at the leading edge would
be less than the calculated adiabatic rise, due not only
to the flow of heat along the radius, referred to above,
but also to a chordwise heat transmission.

It was acknowledged that still another factor might
influence the propeller-blade temperature rise. Inasmuch
as the blades are known to be subject to vibrational
stresses and the absorption of the vibrational energy by
internal friction produces heating, some temperature rise
from this cause at model points might be observed. The
internal friction heating, although probably small in
metal propellers, might be considerable where plastic com-
positions or wood are employed.

In order to obtain data on the regions over which
ice forms on propeller blades, an icing investigation was
made in conjunction with the blade temperature measure-
ment tests.

PROCEDURE

The preliminary icing tests were conducted on the
Lockheed 12A airplane, which is shown during a test in
figure 1. The airplane was equipped with constant-speed,
hydraulic, two-blade, 8-foot 10-inch propellers. The ice
tests were made with the airplane on the ground. The ic-
ing conditions were simulated by discharging very small
water drops from a number of spray nozzles located in
front of the rotating propeller. Satisfactory ice forma-
tions were obtained when the air temperature was between
15° and 22° F and when the relative humidity was high.
With these conditions a rime type of ice was obtained, as
is seen in figure 2. Data were recorded on propeller
speed, outermost radius station at which ice formed, and
the ambient air temperature. Observations were made on
the nature of the outer end of the ice formation in order
to determine whether the extent of ice in the radial di-
rection was limited by centrifugal force or by aerodynamic
heating.

The blade temperature measurements were also made on
the ground but with the use of the engine propeller test
stand, which is shown in figure 3. The propeller which
was employed is identified as having a fixed pitch, 10-
foot 6-inch diameter, and employing an R.A.F. 6 section.
Thermocouples constructed from No. 40 B.&S. copper and
constantin wire were used in making the temperature-rise
measurements. The propeller blade on which the measure-
ments were made is shown in figure 4(a). The thermocouple
mounting at which the adiabatic temperature rise of the
air was observed was located at the 60-inch radius station
and is shown in figure 4(b). The junction of the thermo-
couple shown in figure 4(b) was suspended in air by the
thermocouple wires at the open end of a small balsa-wood
box. Blade-temperature-rise measurements were made at
the 60-, 48-, 36-, and 24-inch stations.

The cold junctions for the thermocouples were located
on a balsa-wood block which extended forward about 6 inches
from the propeller hub. A view of the cold-junction block

and the propeller hub are shown in figure 5(a). Because
the cold junctions rotated with the thermocouples, all
the collector circuits could be of the same metal. Inas-
much as copper-constantin thermocouples were employed,
the collector rings were copper and the brushes were a
copper-carbon compound, the thermoelectric power of which
is similar to copper. The circuit was shown to be accu-
rate to within ±0.1° F.

RESULTS AND DISCUSSION

The results of the icing tests are given in table I.
The end of the ice formations at the outermost station
was a smooth, clear glaze. When ice was thrown off the
blade at more centrally located radial stations, the end
of the remaining formation was a rough, granular rime ice.
The presence of glaze ice at the outermost end of the for-
mation indicates that the temperature there had been
raised and that at points radially beyond this point ice
was probably prevented by the effect of aerodynamic heat-
ing.

Because the outer limit of the ice formation appears
to have been determined by aerodynamic heating, the as-
sumption has been made that the temperature of the outer-
most station on which ice formed was 32° F. In this way
a comparison was possible between the blade temperature
and the calculated air temperature based on the adiabatic
temperature rise as given by equation (2). It is noted
that the difference between the blade temperature and the
calculated temperature was between 8° and 13° F during
icing tests. These results indicate that the outermost
point at which ice will form on a propeller blade is de-
termined by the aerodynamic heating, but that the point
cannot be determined precisely on a basis of the adiabatic
equation.

The results from the temperature rise measurements
are shown in table II. In figure 6 the blade temperature
rise of the various points along the blade is plotted
against propeller speed. The temperature rise as calcu-
lated from equation (2) and the measured air temperature
rise at the 60-inch blade station were also plotted in
figure 6.

The data indicate that the aerodynamic heating re-

sults in a temperature rise which is about 10° F less than the rise given by

$$\Delta T = \frac{V^2}{2Jgc_p}$$

The similarity between the results obtained in the icing tests and in the temperature measurements is noted, and it is concluded that the observed effects will be manifest on other propellers when operated in flight. Inasmuch as internal friction apparently did not contribute in a measurable degree to the blade heating, it has been concluded that the temperature of blades which are made from steel or other metals having low internal friction losses and high thermal conductivity will have about the same temperature rise as that which was observed on the aluminum blade.

The empirical equation

$$V = \sqrt{2Jgc_p (42 - T)} \tag{3}$$

expresses the relation between the maximum velocity in feet per second of a propeller-blade element on which ice will form and the temperature in °F of the ambient air. The blade-element velocity to be used in equation (3) is the vector sum of the propeller element rotational speed and the airplane air speed.

It is believed that the results of the present investigation will be useful in designing ice-protection equipment more accurately than is now possible. It will be noted, furthermore, that the numerous reports of pilots having removed or prevented ice on the propeller blade by increasing the propeller speed have been given a fundamental basis.

CONCLUSIONS

1. The temperature rise of airplane-propeller blades resulting from aerodynamic heating has a direct effect upon the extent to which ice will form on the blade.

2. The outermost blade element at which ice will form

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at an air temperature T (^oF) will have a velocity of

$$V = \sqrt{2Jgc_p\ (42 - T)} \quad \text{fps}$$

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., July 29, 1940.

REFERENCE

1. Brun, Edmond: Distribution of Temperatures over an
      Airplane Wing with Reference to the Phenomena of
      Ice Formation. T.M. No. 883, NACA, 1938.

TABLE I.- OBSERVATIONS OF THE FORMATION OF ICE ON PROPELLER BLADES

Air temperature (°F)	Propeller speed (rpm)	Outermost blade station at which ice formed (in.)	Velocity of blade radius station of (3) (fps)	Calculated adiabatic temperature rise, ΔT (°F)	T_A (a) (°F)	$T_A - 32$ (b) (°F)
18	1400	42.0	514	21.9	39.9	7.9
18	1500	41.4	541	24.2	42.2	10.2
18	1600	37.5	523	22.7	40.7	8.7
17.5	1600	38.5	537	23.9	41.4	9.4
17.5	1700	38.8	575	27.4	44.9	12.9
15.0	1400	48.0	586	28.5	43.5	11.5
15.5	1600	42.0	586	28.5	44.0	12.0

(a) T_A is the observed air temperature + ΔT, and represents the calculated air temperature at the leading edge of the propeller blade.

(b) Difference between calculated air temperature at the leading edge and the freezing point of water.

TABLE II.- DATA RELATED TO THE TEMPERATURE RISE OF PROPELLER BLADES DUE TO AERODYNAMIC HEATING

Propeller rotation N (rpm)	Velocity of 60-inch radius blade station in V (fps)	Calculated adiabatic temperature rise of air at 60-inch radius blade station ΔT_A (°F)	Observed temperature rise of air due to adiabatic heating (°F)	Observed temperature rise of blade at station (°F)			
				R = 60 in.	R = 48 in.	R = 36 in.	R = 24 in.
1044	547	24.8	24.0	20.0	13.5	-----	-----
1208	633	33.2	31.5	26.5	17.8	-----	-----
1423	745	46.0	45.5	37.8	24.5	-----	-----
1604	840	58.5	58.5	50.2	31.0	-----	-----
1785	935	72.5	72.3	63.5	39.7	-----	-----
1069	560	26.0	23.0	17.2	-----	5.5	1.5
1227	642	34.2	31.5	26.3	-----	7.5	3.0
1422	745	46.0	44.0	36.0	-----	11.0	4.5
1640	859	61.2	58.5	50.3	-----	15.2	6.5
1804	944	74.0	70.0	63.0	-----	18.5	7.7
1966	1030	88.0	86.0	78.8	-----	20.5	8.5

Figure 1.- Two views of Lockheed 12A airplane. Ice was formed on the rotating propellers of the airplane while on the ground.
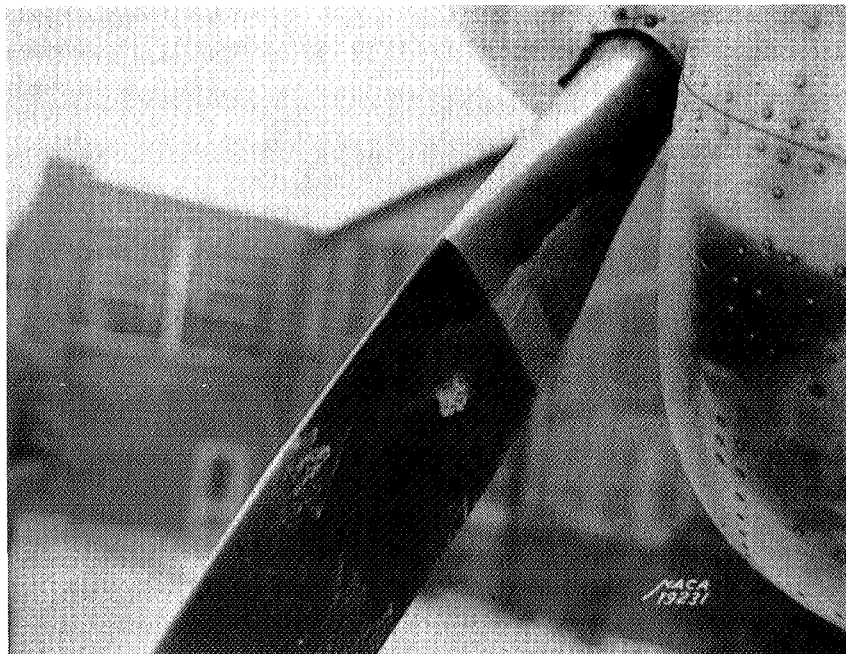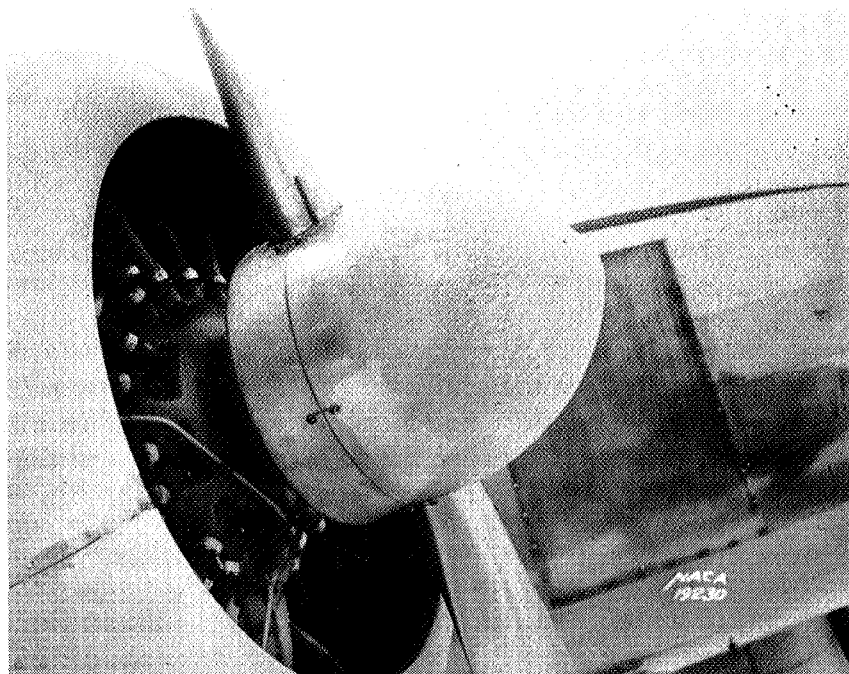
Figure 2.- Two views of ice formation during ground run. The rime type
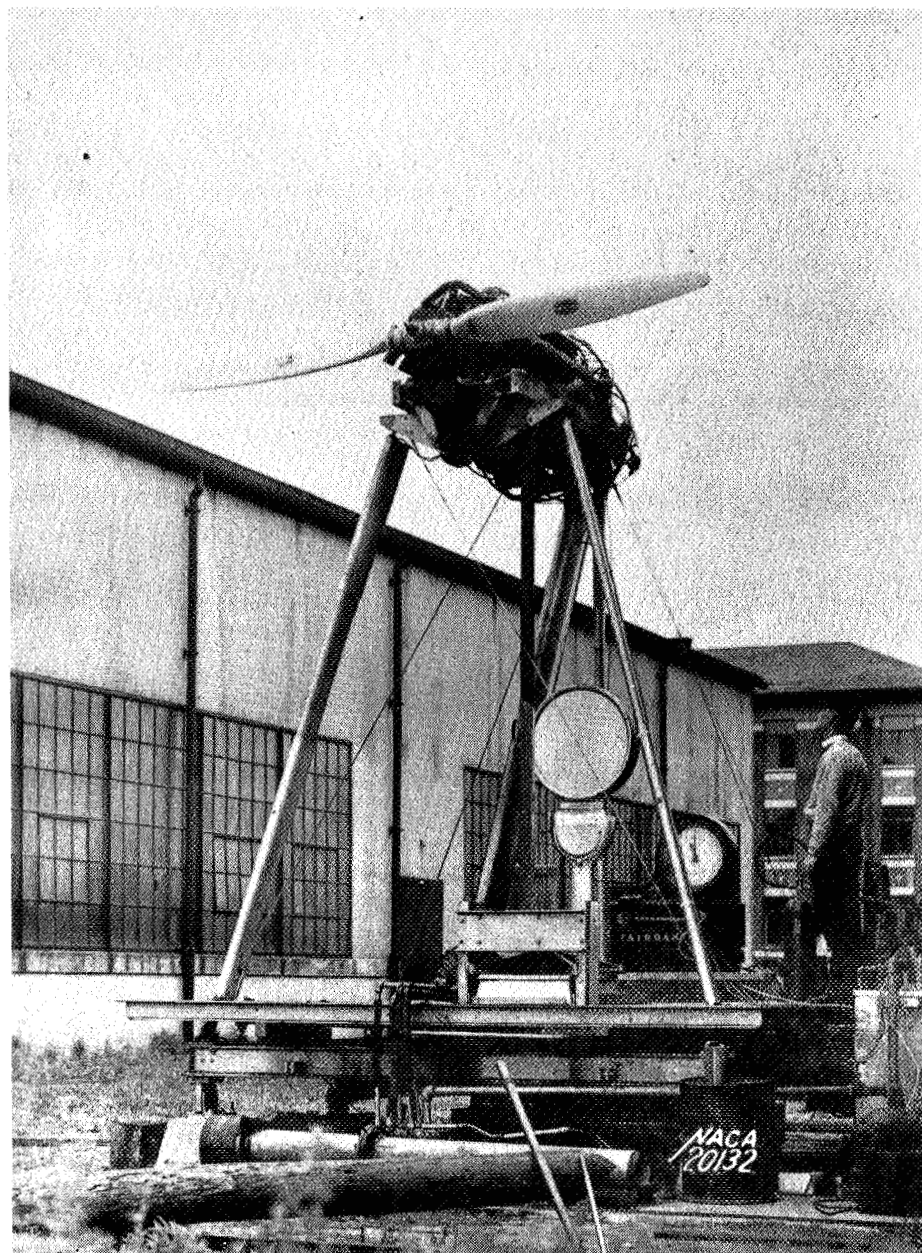ice may be seen on the propeller spinner.

Figure 3.- Propeller test stand. (The temperature of the blade and air
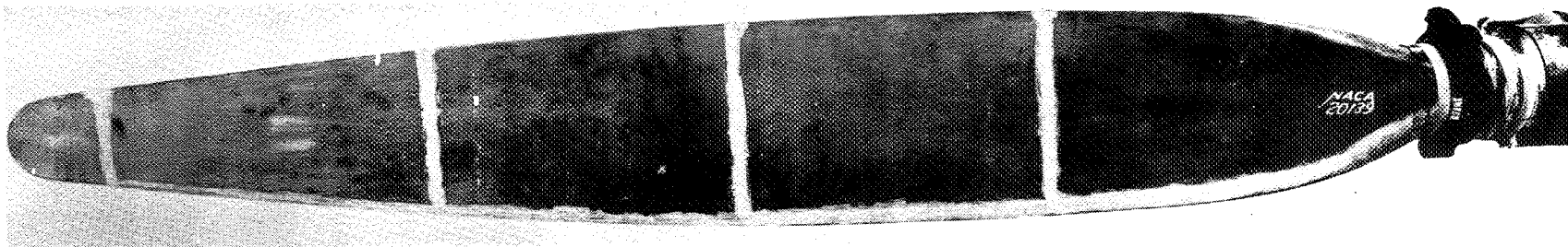   at the blade leading edge were measured with this equipment.

Figure 4a.- Propeller blade on which blade temperatures were measured. The light strips
are insulating and binding material for the thermocouple wires.
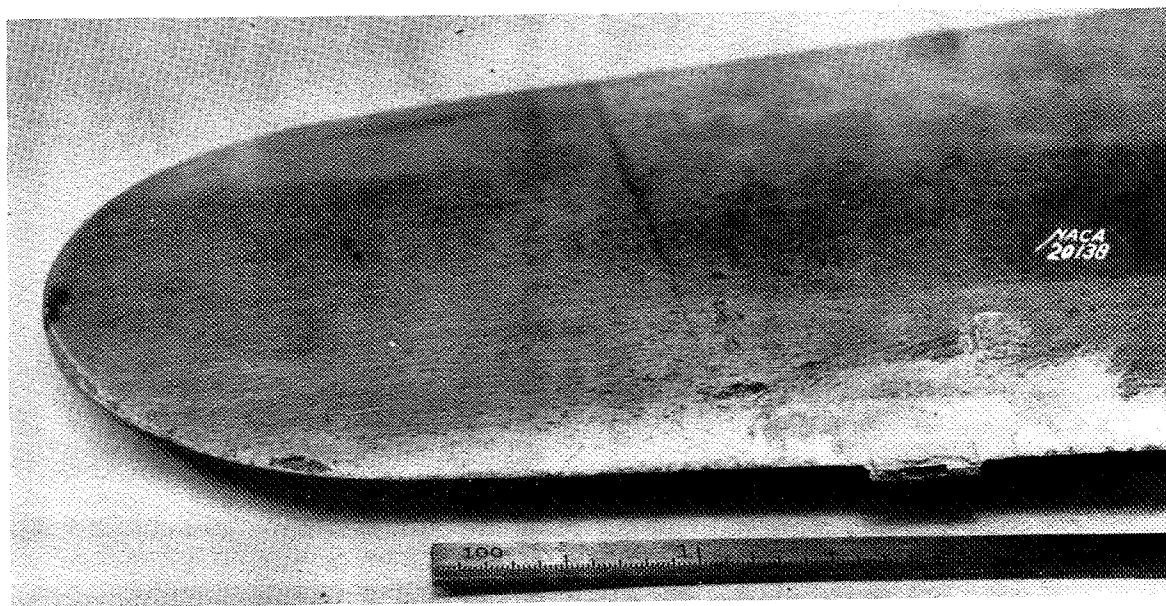
Figure 4b.- The thermocouple mounting at the 60-inch radius station by which the air
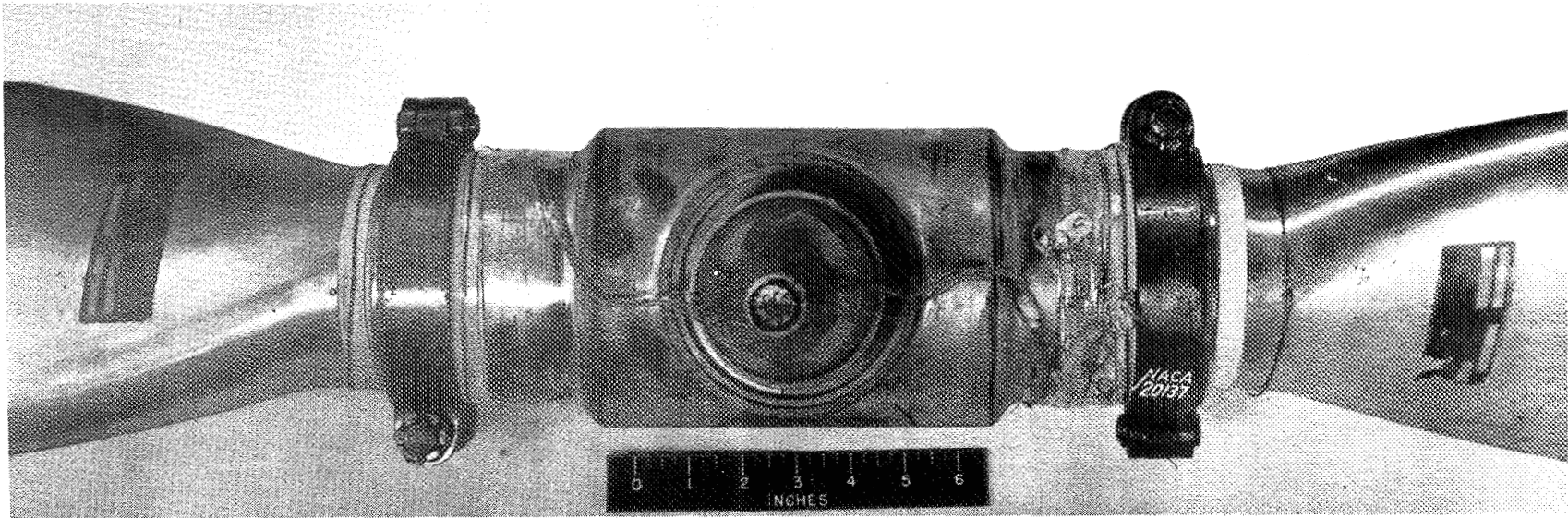temperature rise was measured. The box-like mounting was made of balsa.

Fig. 4

Figure 5a.- The hub of the propeller on which the temperatures were measured, showing the thermocouple cold junctions at the center.
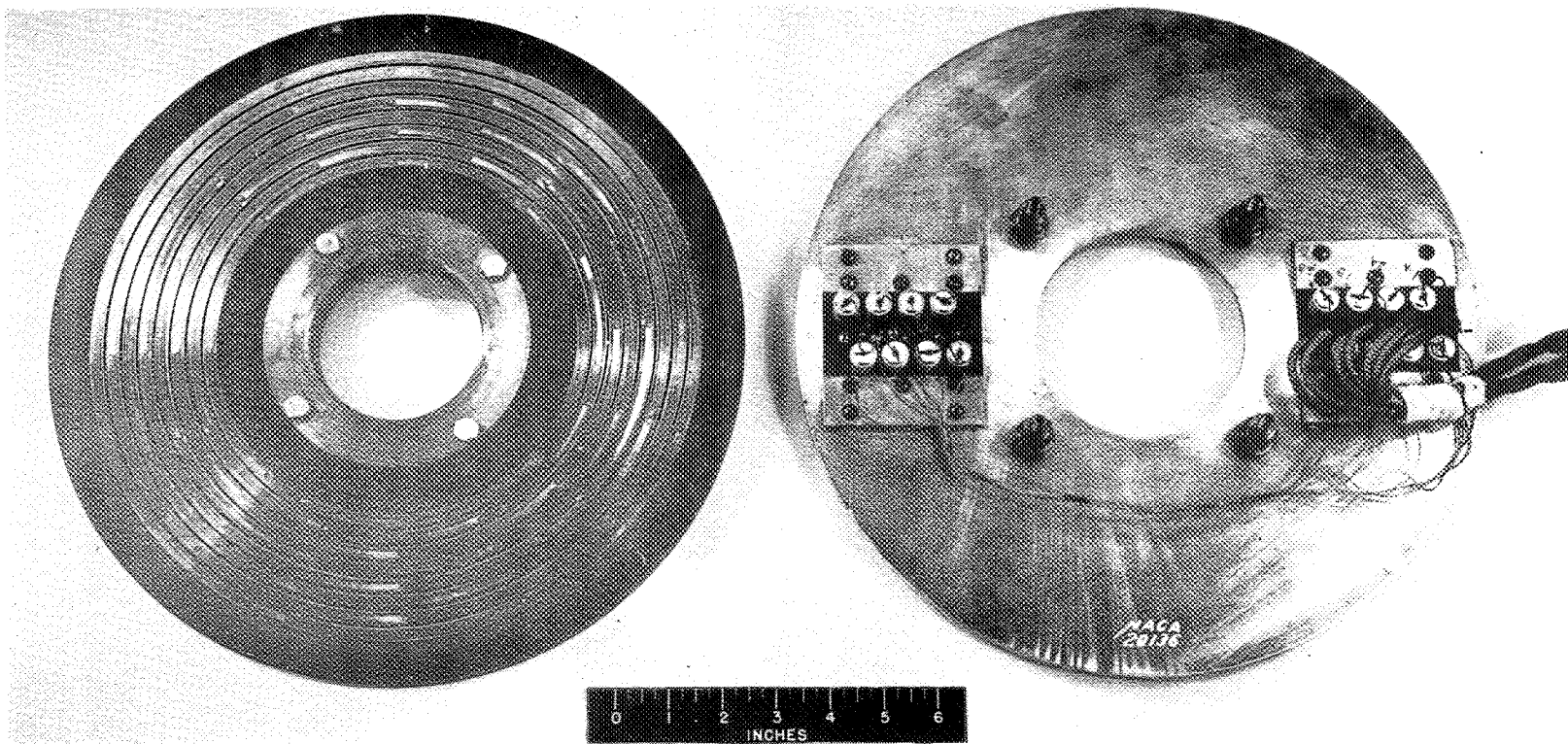
Figure 5b.- The thermocouple commutator rings and brush assembly. Two brushes
were used on each collector ring.

(1) Calculated air temperature rise R = 60 inches
(2) Observed air temperature rise R = 60 "
(3) Observed blade temperature rise R = 60 "
(4)   "   "   "   "   R = 48 "
(5)   "   "   "   "   R = 36 "
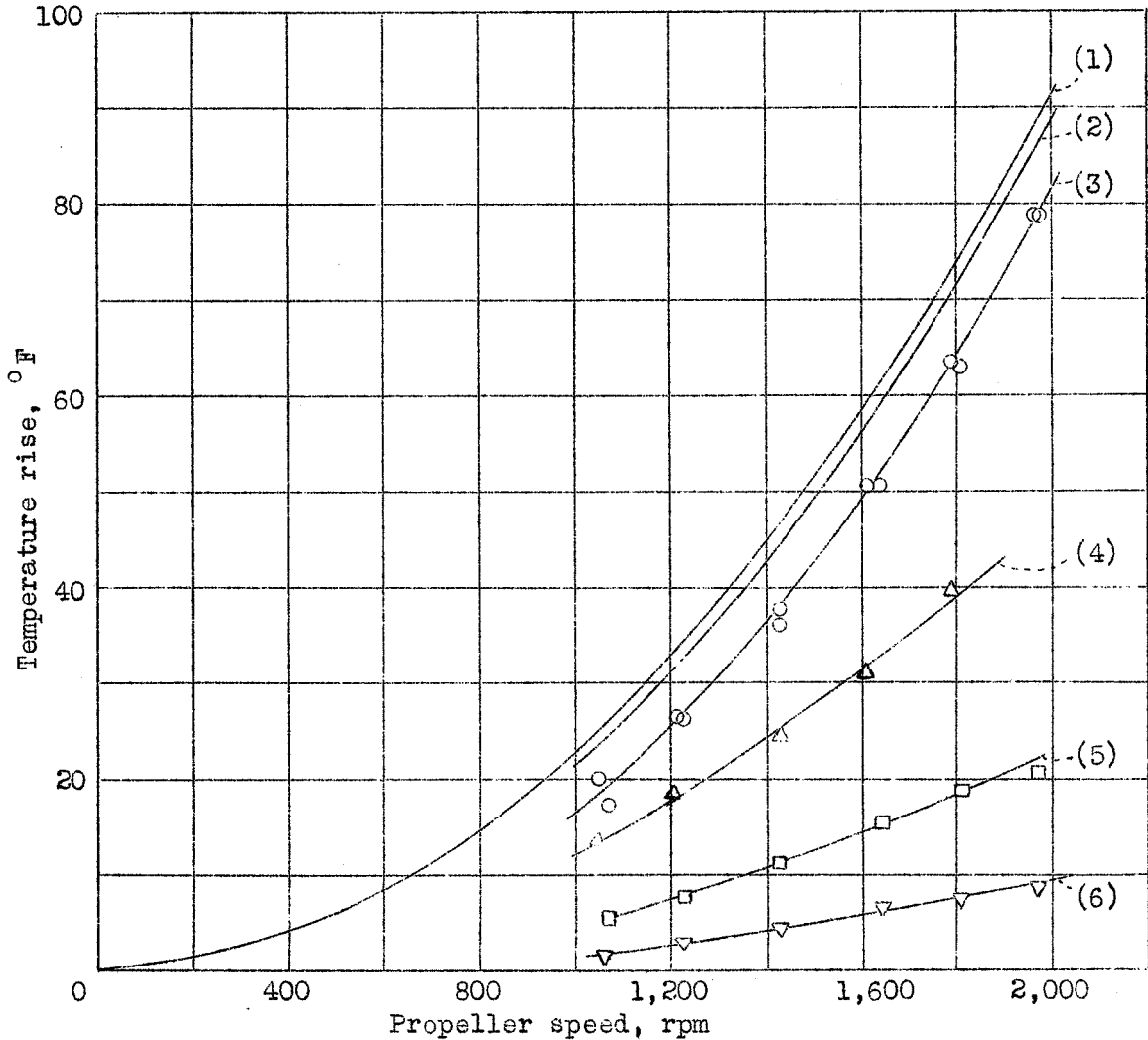(6)   "   "   "   "   R = 24 "

Figure 6.- The relation of propeller-blade temperature rise to propel-
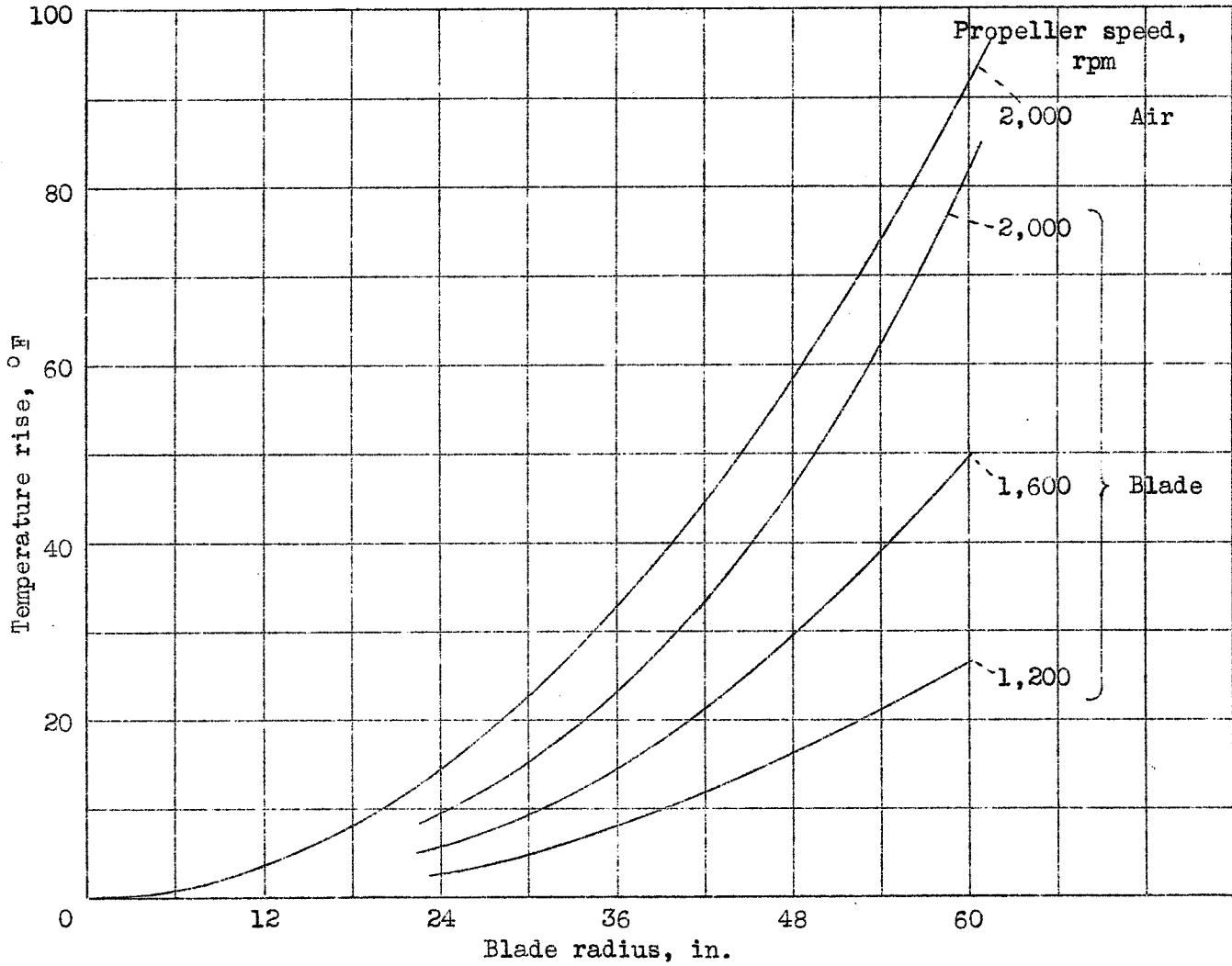   ler speed for a 10-feet 6-inch aluminum R.A.F. 6 section
propeller.

Figure 7.– The relation between propeller-blade temperature rise and blade radius station for several rotation speeds. The adiabatic temperature rise of the air is also shown for 2,000 rpm

Fig. 7