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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 799

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 and its relation to propeller icing. 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. The test results have indicated 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. An empirical analytical relation between the blade-element velocity and the air temperature at which ice would form was established by the data.

INTRODUCTION

The problem of ice prevention on airplane propellers has created an interest in the temperature rise of the propeller blade due to aerodynamic heating. The heating effect of the flow of air over a propeller is of particular interest in the study of the application of thermal means of ice prevention.

Aerodynamic heating results from adiabatic compression of the air at the region of stagnation pressure and from friction in the regions of viscous flow. According to reference 1, the temperature rise at the leading edge is slightly greater than that over the rear portion of the airfoil, the difference depending on the shape of the airfoil and the angle of attack. According to tests at present unreported, the temperature rise over the rear part of an airfoil due to aerodynamic heating is within about 85 percent of that at the leading edge.

Although only the temperature rise of the air at the leading edge can be precisely expressed by the adiabatic equation, an approximation for the entire airfoil section can be made that will be satisfactorily accurate for the intended application of this expression.

Owing to the temperature gradient along the propeller blade and to the dissimilarity of the shape and the 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 opposite direction, the prediction of which is highly involved. An attempt was made in the present investigation to establish a comparatively simple relation between the atmospheric conditions and the velocity of the outermost propeller blade station on which ice will form. Attention is directed to the adiabatic equation

$$\Delta T = \frac{V^2}{2Jgc_p} \qquad (1)$$

that can be developed for the region of zero velocity or for the region of stagnation pressure from reference 1. In this equation ΔT is the temperature rise in degrees Fahrenheit; 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

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

It was anticipated that, inasmuch as the tests of the present investigation 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, owing not only to the referred flow of heat along the radius but also to a chordwise heat transmission.

It was acknowledged that still another factor might influence the propeller-blade temperature rise. Because the blades are known to be subject to vibrational stresses and because the absorption of the vibrational energy by internal friction produces heating, some temperature rise from this cause at nodal points might be observed. The internal friction heating, although probably small in metal propellers, might be considerable where plastic compositions or wood are employed. The transfer of heat through the propeller hub from the engine is believed to be of small importance.

The National Advisory Committee for Aeronautics has conducted the present investigation of aerodynamic heating of propeller blades to determine whether 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 will 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 upon aerodynamic heating.

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 measurement tests.

PROCEDURE

The preliminary icing tests were conducted on the Lockheed 12A airplane, which is shown in figure 1 as it appeared during a test. The airplane was equipped with constant-speed, hydraulic, two-blade, aluminum 8-foot 10-inch propellers. The ice tests were made with the airplane on the ground. The icing conditions were simulated by discharging very small water drops from a number of spray nozzles located in front of the rotating propeller. Satisfactory ice formations 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 ambient-air temperature. Observations were made of the nature of the outer end of the ice formation to determine whether the extent of ice in the radial direction was limited by centrifugal force or by aerodynamic heating.

The blade temperature determinations were also made on the ground, the propeller and an engine being mounted on the propeller test stand, which is shown in figure 3. The aluminum propeller used for the tests is identified as having a fixed pitch, 10-foot 6-inch diameter, and an R.A.F. 6 section. Thermocouples constructed from No. 40 B.& S. copper and constantan wire were used in making the temperature-rise measurements. The propeller blade on which the measurements were made is shown in figure 4. 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 5. The junction of the thermocouple shown in figure 5 was suspended in air by the thermocouple wires at the open end of a small balsa box. Blade temperature-rise measurements were made at the 60-, the 48-, the 36-, and the 24-inch stations.

The cold junctions for the thermocouples were located on a balsa block that extended forward about 6 inches from the propeller hub. A view of the cold-junction block and the propeller hub is shown in figure 6. Because the cold junctions rotated with the thermocouples, all the collector circuits could be of the same metal. Inasmuch as copper-constantan thermocouples were employed, the collector rings shown in figure 7 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 accurate to within ±0.1° F.

RESULTS AND DICUSSION

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 formation 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 heating.

Because the outer limit of the ice formation appears to have been determined by aerodynamic heating, the assumption has been made that the temperature of the outermost 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 determined by the aerodynamic heating but that the point cannot be precisely determined on a basis of the adiabatic equation.

The results from the temperature-rise measurements are shown in table II. In figure 8 the blade temperature rise of the various points along the blade is plotted against propeller speed. The temperature rise as calculated from equation (2) and the measured air temperature rise at the 60-inch blade station are also plotted in figure 8. The same data are plotted in figure 9 in another form that may be more conveniently applied.

The data indicate that the aerodynamic heating results in a temperature rise 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 blades which are made of steel or other metals having low internal friction losses and high thermal conductivity will have about the same temperature rise as that observed on the aluminum blade.

The empirical equation

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

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 degrees Fahrenheit 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 who have 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. It was found that the outermost blade element at which ice will form at an air temperature T (°F) will have a velocity of

$$V \text{ (fps)} = \sqrt{2c_p gJ}\,\sqrt{42 - T}$$

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., September 6, 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 A PROPELLER

Air temperature (°F)	Propeller speed (rpm)	Outermost blade station at which ice formed (in.)	Velocity at blade station at which ice formed (fps)	Calculated adiabatic temperature rise, ΔT (°F)	T_A (°F) (a)	$T_A - 32$ (°F) (b)
18.0	1400	42.0	514	21.9	39.9	7.9
18.0	1500	41.4	541	24.2	42.2	10.2
18.0	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 plus 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 A PROPELLER DUE TO AERODYNAMIC HEATING

Propeller rotation N (rpm)	Circular velocity of 60-inch radius blade station (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 different stations (°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	-	18.8	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.

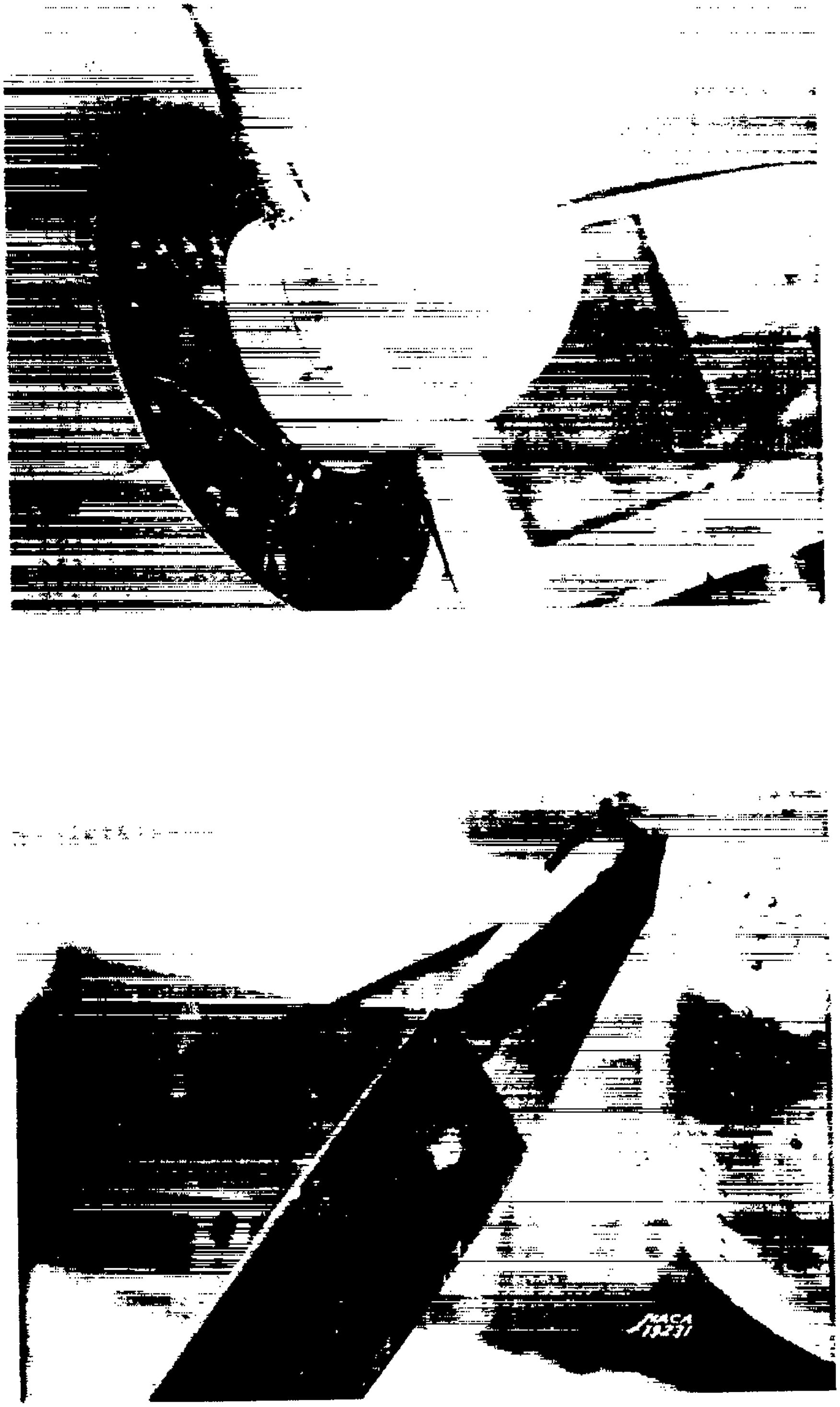

Figure 2.- Two views of ice formations obtained during ground run.
The rime type of ice may be seen on the propeller spinner.

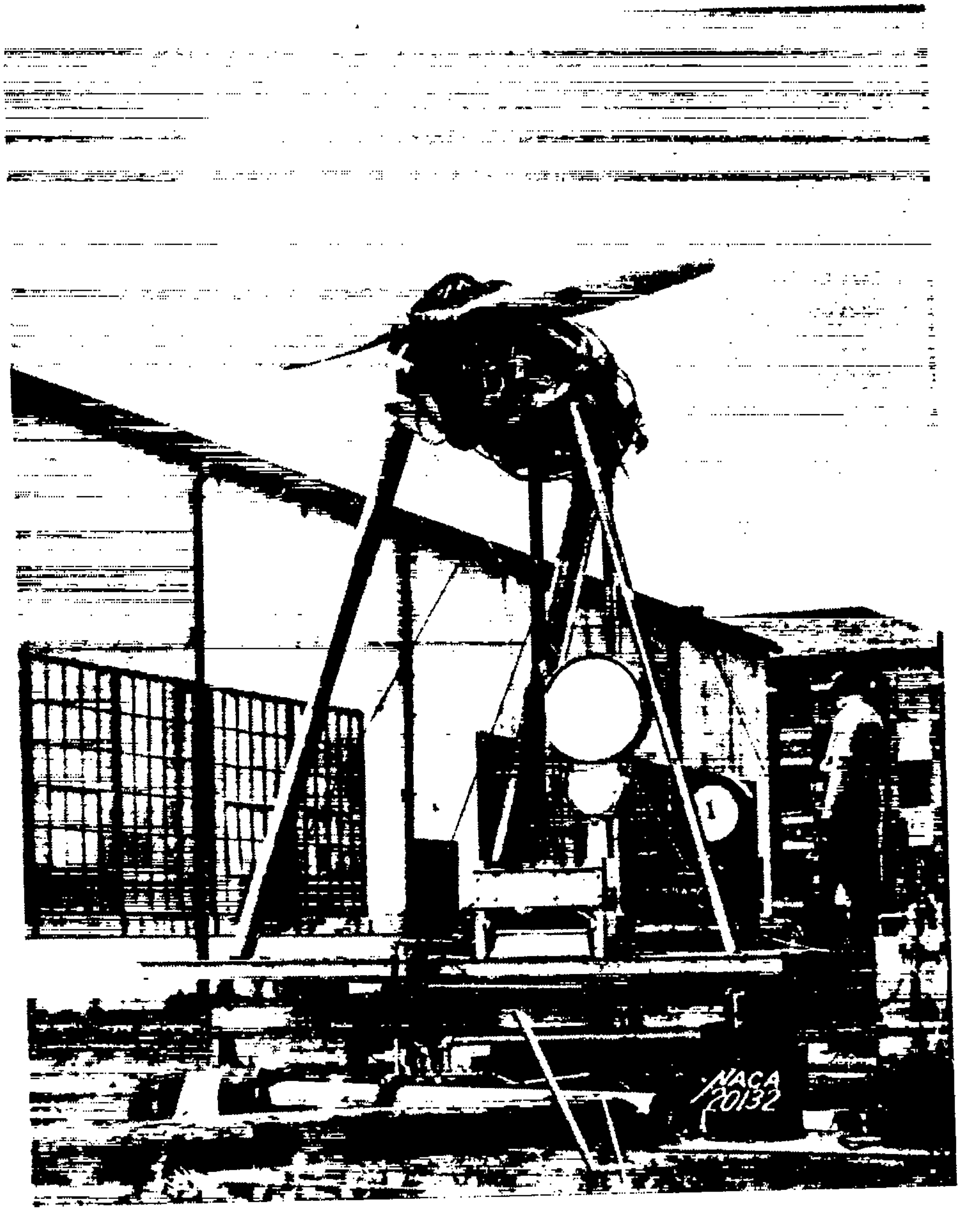

Figure 3.- Propeller test stand. The temperatures of the blade and the air at the blade leading edge were measured with this equipment.

Figure 4.- Propeller blade on which blade temperatures were measured. The light strips are insulating and binding material for the thermocouple wires.

Figure 5.- 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.

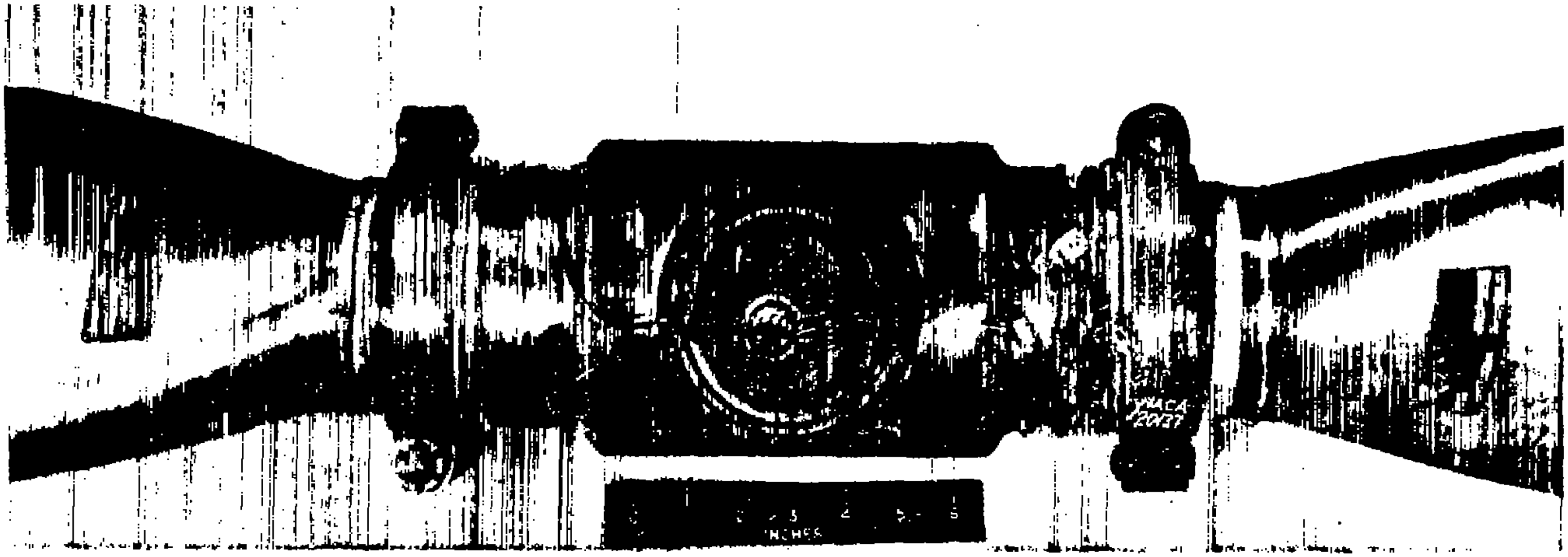

Figure 6.- The hub of the propeller on which the temperatures were measured, showing the thermocouple cold junctions at the center.

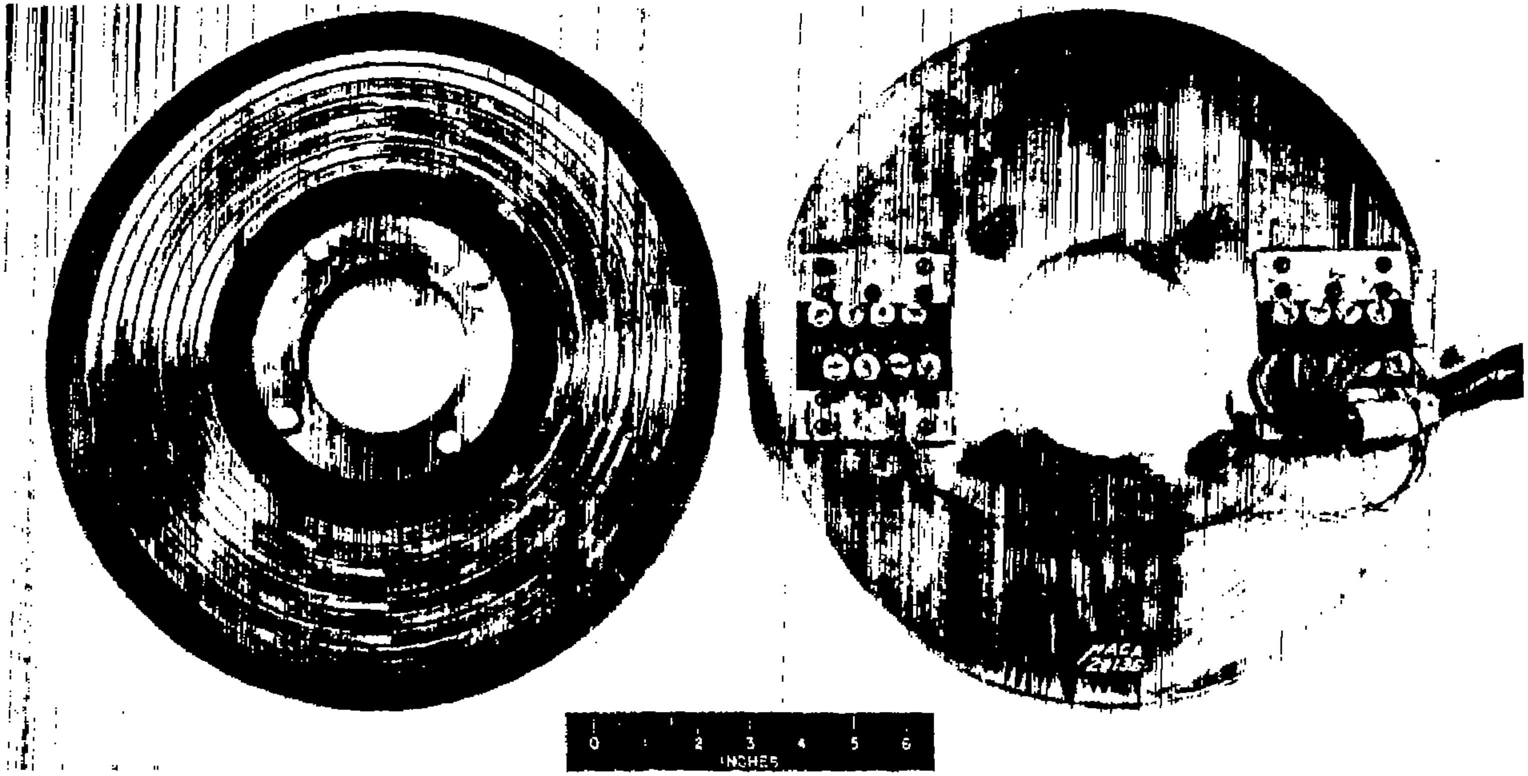

Figure 7.- The thermocouple commutator rings and brush assembly. Two brushes were used on each collector ring.

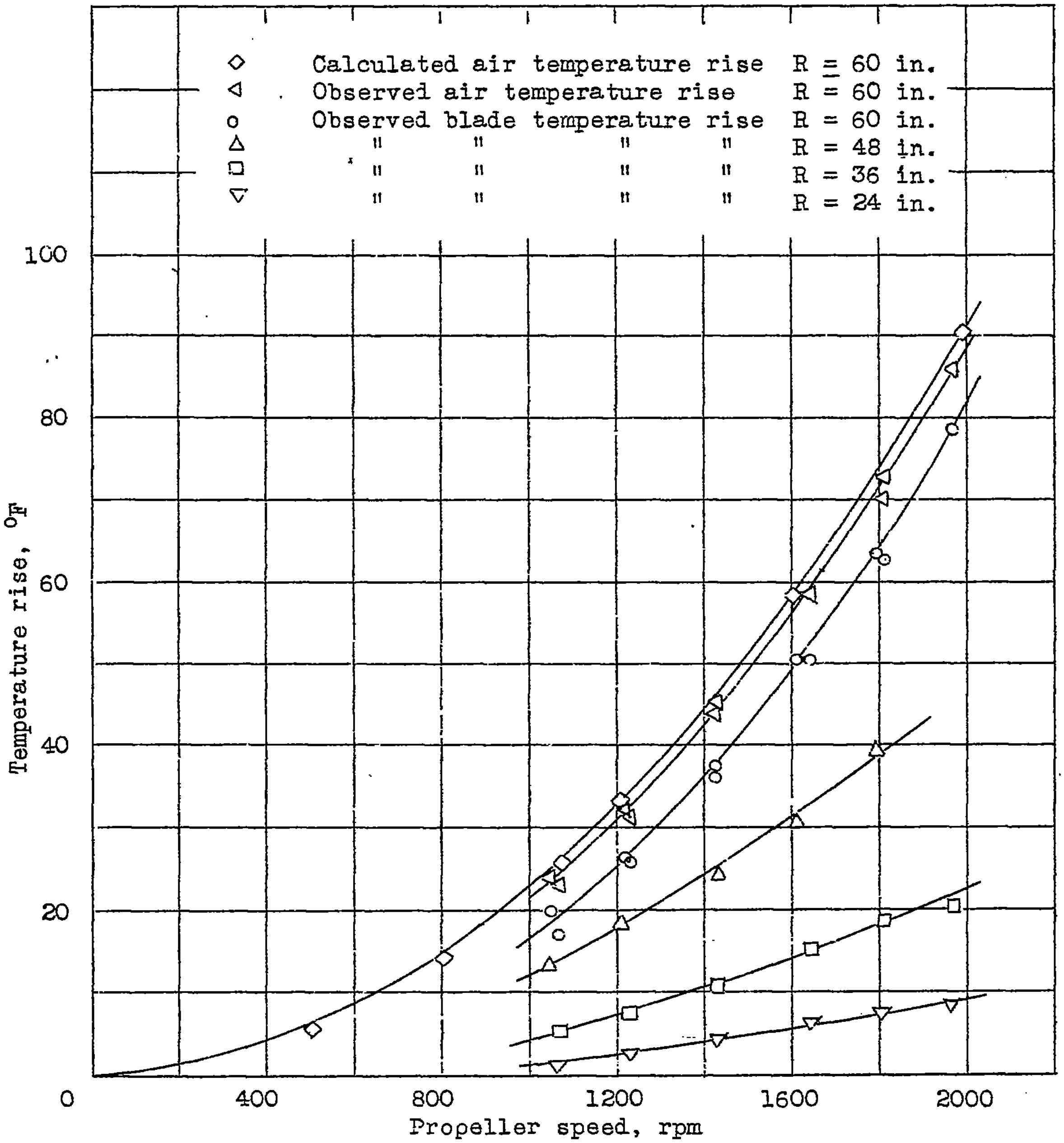

Figure 8.- The relation of propeller-blade temperature rise to propeller speed, for a 10-foot 6-inch aluminum R.A.F. 6 section propeller.

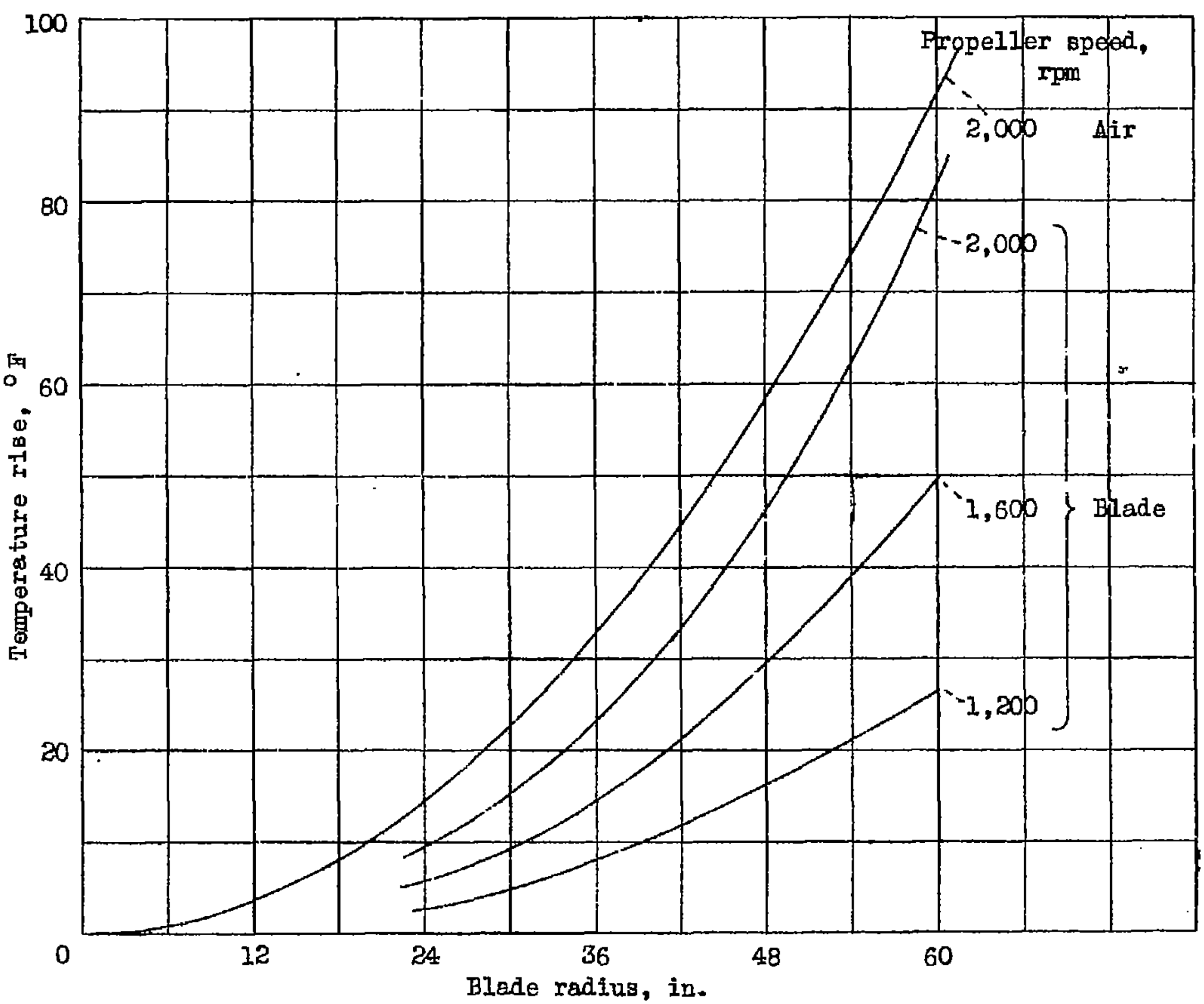

Figure 9.- The relation between propeller-blade temperature rise and blade radius-station for several rotation speeds. The adiabatic temperature rise of the air is also shown for 2,000 rpm