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FLIGHT INVESTIGATION OF BOUNDARY-LAYER TRANSITION AND PROFILE DRAG OF AN EXPERIMENTAL LOW-DRAG WING INSTALLED ON A FIGHTER-TYPE AIRPLANE

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FLIGHT INVESTIGATION OF BOUNDARY-LAYER TRANSITION AND PROFILE DRAG OF AN EXPERIMENTAL LOW-DRAG WING INSTALLED ON A FIGHTER-TYPE AIRPLANE

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SUMMARY

A boundary-layer-transition and profile-drag investigation was conducted in flight by the National Advisory Committee for Aeronautics on an experimental low-drag wing installed on a P-47 airplane designated the XP-47F and supplied by the Army Air Forces. The wing incorporates airfoil sections that vary from an NACA 66(215)-1(16.5), a = 1.0 at the plane of symmetry to an NACA 67(115)-213, a = 0.7 at the tip. The surface of the wing as constructed was found to have such a degree of waviness that it had to be refinished in order to obtain the performance generally expected of low-drag airfoils. Measurements were made at a section outside the propeller slipstream with smooth and with standard camouflage surfaces and on the upper surface of a section in the propeller slipstream with the surface smoothed.

Tests were made in normal flight - that is, in level flight and in shallow dives - at indicated airspeeds ranging from about 150 to 300 miles per hour and in steady turns at 300 miles per hour with normal accelerations from 2g to 4g. These speed and acceleration limits were imposed by structural considerations. The tests in normal flight covered a range of section lift coefficient from about 0.58 to 0.15, of Reynolds number from about 9×10^6 to 18×10^6, and of Mach number from about 0.27 to 0.53. In the tests in turns at 300 miles per hour, the range of section lift coefficient was extended to 0.63.

The results for the section with smooth surface outside the slipstream were in reasonable accord with the performance expected of low-drag airfoils and indicated a minimum profile-drag coefficient of 0.0045, which corresponded to the most rearward position of transition observed at about 50 percent of the chord on the upper

surface. With a standard finish, a minimum profile-drag coefficient of 0.0063 was obtained. The results obtained in turns with the smooth surface showed an increase of about 6 to 14 percent in the profile-drag coefficient above that obtained in normal flight at lower Mach numbers and corresponding lift coefficients; whereas, with the standard finish, no increase was observed.

The results on the smooth upper surface of the wing section in the slipstream indicated that, with normal engine operation, the most rearward position of transition was between 20 and 25 percent chord. The attempt to measure the profile drag of the smooth upper surface by means of a half-wake trailing-edge rake was not successful because a large lateral component of boundary-layer flow existed at the trailing edge of this section.

INTRODUCTION

An investigation of boundary-layer transition and profile drag of an experimental low-drag wing installed on a P-47 airplane designated the XP-47F and supplied by the Army Air Forces is reported herein. This wing incorporates airfoil sections that vary from an NACA 66(215)-1(16.5), a = 1.0 at the plane of symmetry to an NACA 67(115)-213, a = 0.7 at the tip and is the type used on several current airplane designs.

An investigation of the aerodynamic performance of the complete airplane was not undertaken because the surface of the wing, as constructed, was found to have such a degree of waviness that extensive laminar boundary layers could not be expected. The results of performance tests of the complete airplane, therefore, would have had no particular significance in evaluating the merits of low-drag wings having surfaces that conform closely to the requirements for extensive laminar boundary layers. The investigation was consequently limited to the study of boundary-layer transition and profile drag of sections of the wing with the surfaces in the original wavy condition and also with the surfaces refinished to reduce the waviness to tolerable limits.

Previous flight investigations of low-drag airfoils have been concerned entirely with the determination of boundary-layer and profile-drag characteristics of sections located outside the propeller slipstream; hence, no information is available on the characteristics of such airfoils located in the propeller slipstream, which may cover 20 percent or more of the wing area depending on the type of airplane. Boundary-layer-transition and profile-drag tests were consequently made at two spanwise stations of the low-drag wing of the XP-47F airplane - one outside the propeller slipstream and one behind the propeller - to determine the extent to which low-drag airfoil characteristics may be obtained in these two regimes of air flow with the surfaces of the wing carefully finished. Measurements on the wing section in the propeller slipstream were limited to the smoothed upper surface because irregularities on the lower surface due to the landing-gear cover could not be faired. Tests were also made of the section outside the slipstream on the production surfaces with a standard camouflage finish.

Measurements on the section behind the propeller were made in level flight and in shallow dives over a range of indicated airspeed from about 155 to 310 miles per hour. Measurements on the section outside the propeller slipstream were made in level flight and in shallow dives over a range of indicated airspeed from about 150 to 300 miles per hour and in steady turns at 300 miles per hour with normal accelerations from 2g to 4g to obtain high wing loadings. Some measurements were made on both of these sections in glides with the engine throttled. The speed and acceleration limits observed in the tests were imposed by structural considerations of the airplane.

SYMBOLS

c section chord

x distance along chord from leading edge

s distance along surface from leading edge

d deflection of curvature gage

q_{c_1} impact pressure in boundary layer at 0.006 inch above surface

q_{c_2} impact pressure outside boundary layer

c_l section lift coefficient

c_{d_o} section profile-drag coefficient

P pressure coefficient

V_{i_s} correct service indicated airspeed; that is, the correct reading of an airspeed indicator calibrated in accordance with Army and Navy standards

R section Reynolds number

M Mach number

M_{cr} critical Mach number

g acceleration of gravity

Subscript:

t transition

APPARATUS

The XP-47F airplane tested is a low-wing, single-engine monoplane with a Pratt & Whitney R-2800-21 engine and a four-blade Curtiss electric propeller (fig. 1). It is equipped with a low-drag wing, the master airfoil sections of which are NACA 66(215)-1(16.5), a = 1.0 at the plane of symmetry and NACA 67(115)-213, a = 0.7 at the wing tip. The airplane has a gross weight of about 11,600 pounds, a wing span of 42 feet, and a wing area of 322 square feet.

Two sections of the low-drag wing were tested - one on the right wing located 21 inches outboard of the flap and the other on the left wing located 12 inches within the edge of the propeller disk (fig. 2). The right wing section had a chord of 88.3 inches and a maximum thickness of 14.7 percent at 45 percent of the chord. The ordinates of the right wing section measured relative to an arbitrary chord are given in table I. The left wing section behind the propeller had a chord of

108.3 inches and a maximum thickness of 15.8 percent at 45 percent of the chord.

Two surface conditions of the right wing section and one of the left wing section were tested - the right wing section with the surfaces having smooth and standard camouflage finishes; the upper surface of the left wing section with only the smooth finish.

The smoothed and faired surfaces were obtained by building up with glazing putty the base provided by the refinishing done on the wing at the Air Technical Service Command, Wright Field, and then sanding to reduce the surface waviness. These surfaces were then sprayed with four coats of white lacquer as a protective coating and sanded lightly. Surface waviness was measured by a curvature gage (fig. 3) with legs spaced 4 percent of the chord. The waviness condition of the final smoothed surfaces is indicated in figures 4 and 5 by the plot of the waviness index d/c against s/c. The values of d/c include the curvature of airfoil surfaces free of waviness as well as the departure of the actual surfaces from the waviness-free contour.

After completion of the tests of the smooth right wing section, the paint and glazing putty on this section were removed to the metal skin with acetone and a standard camouflage finish was then applied. The standard camouflage finish consisted of one coat of zinc chromate primer, one coat of gray surfacer, and two coats of olive-drab camouflage. The surface with this standard camouflage finish is hereinafter designated "standard surface." The surface-waviness index for this surface condition is shown in figure 6.

Boundary-layer racks, each consisting of a total-pressure and a static-pressure tube, were used in measuring boundary-layer transition. The tubes were made of $\frac{1}{8}$-inch brass tubing with a $\frac{1}{32}$-inch wall thickness. The upstream end of the total-pressure tube was filed and flattened leaving an opening 0.003 inch deep and $\frac{1}{8}$ inch wide and a 0.003-inch wall thickness. The static-pressure tube had six orifices 0.02 inch in diameter equally spaced around the periphery at $1\frac{1}{4}$ inches downstream from the hemispherical end. The effective pressure center of the total-pressure tube in contact with a surface was at approximately 0.006 inch from the surface. The total-pressure tube was connected to an NACA recording manometer and referenced to the static pressure obtained from the static-pressure tube set about $\frac{1}{4}$ inch from the surface to measure the impact pressure next to the surface. The static pressure measured by the static-pressure tube was referenced to free-stream total pressure giving the impact pressure outside the boundary layer.

Wake surveys were made on the right wing section by the rake shown in figure 7 mounted 18.1 percent of the chord behind the trailing edge. The rake consisted of 24 total-pressure tubes spaced 0.3 inch and five static-pressure tubes spaced equally across the rake. The total-pressure tubes were connected to an NACA recording manometer and referenced to free-stream total pressure in order that the total-pressure loss at each point in the wake could be obtained. The static pressure in the wake was measured with the central static-pressure tube, which was connected to the manometer, and referenced to the static pressure obtained by means of a swiveling static-pressure head mounted on a boom 1 chord ahead of the leading edge of the right wing tip.

A half-wake trailing-edge rake (fig. 8) was used in an attempt to measure the profile drag of the upper surface of the left wing section. A full-wake rake, such as described in the preceding paragraph, was not used because surface irregularities on the lower surface due to the landing-gear cover could not be faired. The trailing-edge rake consisted of 21 total-pressure tubes spaced about $\frac{1}{4}$ inch and three static-pressure tubes. The total-pressure tubes were connected to an NACA recording manometer and referenced to slipstream total pressure as measured by the rake total-pressure tube 5 inches above the surface. The slipstream total pressure was referenced to free-stream total pressure giving the total-pressure component due to thrust in the survey plane. The static pressure in the wake was measured by a static-pressure tube $\frac{3}{4}$ inch above the surface; this tube was connected to the manometer and referenced to the static pressure measured by the swiveling static-pressure head.

Wool tufts were used on the upper surfaces of the right and left wing sections over the trailing-edge area to determine whether any cross flow that would invalidate the wake surveys existed in the boundary layer. Chalk lines indicating angular deviation from the thrust axis of 0°, ±10°, ±20°, and ±30° were marked off in the region of each of two tufts located 3 and 4 feet, respectively, on each side of the fuselage and about 10 inches from the trailing edge (fig. 2) to enable the pilot to judge the angularity of the tufts at those points.

All pressures were recorded on NACA recording instruments. The position of the ailerons during the tests was recorded on an NACA control-position recorder. An indicating accelerometer was used to indicate normal accelerations.

METHOD

In order to obtain free-stream static pressure, corrections determined from an airspeed calibration were made to the static pressure measured by the swiveling static-pressure head mounted on a boom ahead of the right wing tip. These corrections were applied to all measurements for which reference to free-stream static pressure was required.

The section lift coefficient at which transition occurred at a given chordwise position was determined from the boundary-layer measurements of impact pressure q_{c_1} at 0.006 inch above the surface and the impact pressure q_{c_2} outside the boundary layer. The ratio $\frac{q_{c_1}}{q_{c_2}}$ was plotted against section lift coefficient as determined from airplane lift coefficient and theoretical spanwise lift distribution by the method of reference 1. The section lift coefficient corresponding to transition was chosen at the elbow of the curve as the ratio $\frac{q_{c_1}}{q_{c_2}}$ suddenly increased from its laminar level to its turbulent level. In the transition measurements on the wing section in the propeller slipstream, the measured q_{c_2} was corrected to slipstream conditions by adding to it the increment of total pressure due to propeller thrust in the survey plane.

The profile-drag coefficients were determined by the integrating method of reference 2; that is, the total-pressure loss was integrated across the wake and then multiplied by factors depending on free-stream impact pressure, maximum total-pressure loss, static pressure in the wake, and flight Mach number. For the wake surveys on the section in the slipstream, the field of flow was assumed to consist of free-stream static pressure and of total pressure increased by the increment of total pressure due to thrust of the propeller in the survey plane.

TESTS

Transition measurements were made at 20, 30, 40, and 48 percent of the chord on the smooth upper surface of the right wing section and at 5, 10, 15, 20, and 25 percent on the smooth upper surface of the left wing section. Wake surveys were made on the smooth right wing section and on the smooth upper surface of the left wing section. Wake surveys were also made on the right wing section with standard surfaces.

Transition tests of the smooth upper surface of the right wing section were made in normal flight; that is, in level flight and in shallow dives, when necessary to attain the higher speeds, over an indicated-airspeed range from about 180 to 300 miles per hour. Some of the tests were made with power off, that is, with engine throttled; others, in steady turns at an indicated airspeed of 300 miles per hour and normal accelerations of 2g and 4g.

Transition tests of the smooth upper surface of the left wing section in the slipstream were made in normal flight over a range of indicated airspeed from about 155 to 310 miles per hour. A few test runs were also made with power off.

Wake surveys on the right wing section with smooth and standard finishes were made in normal flight within a range of indicated airspeed from about 150 to 310 miles per hour and in steady turns at an indicated airspeed of about 300 miles per hour and normal accelerations from 2g to 4g. Some of the test runs on the smooth wing section were made with power off.

Wake surveys on the smooth upper surface of the left wing section were made in normal flight over an indicated-airspeed range from about 185 to 310 miles per hour. A few test runs were made with power off.

PRESENTATION OF RESULTS

The results of the investigation are presented in figures 9 to 15. The pressure distribution over the smooth right wing section is given in figure 9. The theoretical pressure distribution was calculated from the ordinates given in table I by the method of reference 3.

Transition results obtained on the smooth upper surface of the right wing section are shown in figures 10 and 11. In figure 10, the section lift coefficient chosen as corresponding to transition at a given chordwise position is indicated by an arrow at the elbow of each $\frac{q_{c_1}}{q_{c_2}}$-curve. The Reynolds numbers corresponding to the section lift coefficients of the $\frac{q_{c_1}}{q_{c_2}}$-curves are plotted above the $\frac{q_{c_1}}{q_{c_2}}$-curves. The variation of the position of transition with section lift coefficient is shown in figure 11; the Reynolds numbers corresponding to the section lift coefficients are plotted above the transition curve.

The variation of profile-drag coefficient with section lift coefficient for the right wing section with smooth and standard finishes is presented for normal flight in figure 12 and for high-speed turns in figure 13.

Transition results obtained on the smooth upper surface of the left wing section in the slipstream are presented in figures 14 and 15.

During the tests of the right wing section, it was found that the right aileron trimmed up from $\frac{1}{2}^{\circ}$ to 1° in normal flight and from 1° to 2° in high-speed turns. Corrections for these aileron deflections have been made to the section lift coefficient for the right wing section computed by the method of reference 1.

DISCUSSION OF RESULTS

Right Wing Section outside Slipstream

Pressure distribution.- In figure 9 the theoretical pressure distribution for the right wing section is shown with a few experimental points determined from the static-pressure measurements in the boundary-layer-transition tests. The theoretical pressure distribution for incompressible flow was computed for a section lift coefficient which the right wing section would experience in incompressible flow if it retained the angle of attack it had in compressible flow for a section lift coefficient of 0.200 at a Mach number of 0.46. The section lift coefficient for incompressible flow was taken as $c_l\sqrt{1 - M^2}$ or 0.177. The theoretical pressure distribution for compressible flow, as determined by dividing the pressures for incompressible flow by $\sqrt{1 - M^2}$ or 0.887, agreed closely with the few experimental points obtained.

An analysis of the theoretical pressure-distribution characteristics, computed by the method of reference 3 with use of the measured ordinates of the right wing section (table I), indicates that the characteristics of this section may be best approximated by the NACA 66,2-2(14.7) airfoil section. The mean camber line as determined from the measured ordinates of the right wing section cannot be specified by the usual a-designation.

Boundary-layer transition.- Transition from laminar to turbulent flow in the boundary layer as occurring on the smooth upper surface of the right wing section and as affected by engine operation and high wing loading is indicated in figure 10. As the section lift coefficient decreased, the point of transition moved progressively rearward up to and beyond $x/c = 0.48$, which is about 7 percent forward of the calculated minimum pressure point. With further decrease in section lift coefficient, the point of transition appeared to move forward as is indicated by the occurrence of transition from laminar to turbulent flow at $x/c = 0.48$ at $c_l = 0.16$. The forward movement of transition is attributed to the increased Reynolds number which accompanies increasing airplane speeds and decreasing section lift coefficients.

It is possible that, although a considerable improvement was made in the surface waviness by the very careful refinishing of the wing section (figs. 4 and 6), a still further reduction in waviness may have resulted in the movement of the point of transition at least up to the minimum pressure point.

The transition results obtained with power off - that is, with engine throttled - indicate that, allowing for experimental error, the extent of the laminar boundary layer was no greater than with normal operation of the engine. (Two values of $\frac{q_{c_1}}{q_{c_2}}$ at a given lift coefficient (fig. 10) indicate an unsteady boundary-layer condition in which the total pressure next to the surface varied from one level to the other.) In the high wing-loading condition, as obtained in a steady turn at an indicated airspeed of 300 miles per hour and a normal acceleration of 2g, transition appeared to be as far back on the upper surface as in normal flight for the same lift coefficients. (The value of $\frac{q_{c_1}}{q_{c_2}}$ at $x/c = 0.40$ for the 2g turn is off-scale; that is, $\frac{q_{c_1}}{q_{c_2}} = 0.5$.)

The variation of the point of transition with section lift coefficient is given in figure 11. Transition appeared to reach the most rearward position at $x/c = 0.50$ or about 5 percent of the chord forward of the calculated minimum pressure point.

Profile drag in normal flight.- The profile-drag coefficients obtained in normal flight on the right wing section with smooth and standard surfaces are shown in figure 12. Because tuft surveys over the upper surface near the trailing edge of this section indicated no cross flow in the boundary layer, the wake surveys are valid. For the smooth surfaces, the profile-drag coefficient decreased with decreasing lift coefficient and increasing speed until a minimum of 0.0045 was obtained at $c_l = 0.185$, $R = 16 \times 10^6$, and $V_{i_s} = 275$ miles per hour; with a further decrease in lift coefficient, there was an increase in the profile-drag coefficient that corresponded to the increment in profile-drag coefficient estimated, according to the method of reference 4, from the noted forward movement of the point of transition. As may be expected from the transition results, no favorable effect on profile drag was observed due to airplane operation with power off. With the standard surface finish, a minimum profile-drag coefficient of 0.0063 was obtained at about $c_l = 0.22$, $R = 14.7 \times 10^6$, and $V_{i_s} = 250$ miles per hour. At the higher lift coefficients, the profile-drag coefficients of the surface with the standard finish tended to approach the values obtained on the smooth surfaces.

Profile drag at high wing loadings.- The profile-drag coefficients of the right wing section with smooth and standard surface finishes, as measured in steady turns at an indicated airspeed of about 300 miles per hour, are shown in figure 13. Faired curves representing the results obtained in normal flight are included for comparison. The comparison of the results for the standard surfaces in turns and in normal flight is limited to lift coefficients corresponding to 2g and 2.5g turns, because the tests in turns and in normal flight were conducted over different ranges of lift coefficient that overlapped from $c_l = 0.32$ to $c_l = 0.40$. At $c_l = 0.32$ and $c_l = 0.34$, for which a direct comparison was possible, the profile-drag coefficients for the standard surfaces in turns and in normal flight were about the same. At $c_l > 0.45$, the profile-drag coefficients of the standard surfaces in turns were about the same as the profile-drag coefficients of the smooth surfaces in normal flight.

The profile-drag coefficients of the smooth surfaces in turns were higher than the profile-drag coefficients in normal flight throughout the range of lift coefficient tested; the increase amounted to about 6 percent at $c_l = 0.30$ and to about 14 percent at $c_l = 0.58$. The profile-drag coefficients for the smooth surfaces in turns were lower at lift coefficients less than 0.40 and greater at lift coefficients greater than 0.40 than the profile-drag coefficients of the standard surfaces in turns; no satisfactory explanation of this result, which is contrary to general expectations, has been found.

In order to determine how closely the critical Mach number of the right wing section was approached in the high-speed turns, the critical Mach number M_{cr} was estimated from pressure distributions calculated for section lift coefficients of $c_l \sqrt{1 - M^2}$ by the method of reference 3, in which the measured ordinates of the right wing section are used, and from the von Kármán-Tsien relation (reference 5) between M_{cr} and static pressure for incompressible flow. The ratios of the flight Mach number M to the estimated critical Mach number M_{cr} for the various normal accelerations experienced in the tests are as follows:

Normal acceleration (g)	M/M_{cr}	
	For standard surfaces	For smooth surfaces
2	0.74	0.70
2.5	.80	.75
3	.85	.81
3.5	.89	.88
4	.99	.91

The results obtained in high-speed turns therefore indicated that, for the range of values of M/M_{cr} experienced in the tests, no increase occurred in the profile-drag coefficient of the standard surfaces above that obtained in normal flight at lower Mach numbers and corresponding section lift coefficients (from 0.32 to 0.63); whereas, for the smooth surfaces, increases of about 6 percent at $c_l = 0.30$ and about 14 percent at $c_l = 0.58$ were obtained.

Left Wing Section in Propeller Slipstream

Boundary-layer transition.- The variation with section lift coefficient of the point of transition on the smooth upper surface of the left wing section in the slipstream and the effect of engine operation on transition are shown in figures 14 and 15. With normal engine operation, the point of transition moved rearward from $x/c = 0.05$ to $x/c = 0.20$ as the section lift coefficient was decreased from about 0.44 to 0.24. The most rearward position of transition for the range of lift coefficient tested lay between $x/c = 0.20$ and $x/c = 0.25$; however, it is highly probable that, if the test with the boundary-layer rack located at $x/c = 0.25$ were extended to slightly lower lift coefficients such as were experienced in the tests for other chordwise locations of the racks, transition might have occurred at $x/c = 0.25$. With the engine throttled, transition at a given lift coefficient occurred approximately 4 percent of the chord farther rearward than with power on.

Profile drag.- After the wake surveys on the upper surface of the left wing section in the slipstream were completed, tuft surveys were made at positions a, b, c, and d. (See fig. 2.) These surveys have shown that cross flow in the boundary layer existed and was directed toward the fuselage with angular deviations (in deg) from the thrust axis as follows:

V_{i_s} (mph) \ Tuft position	a	b	c	d
Power on				
185	28	20	5	10
255	20	15	5	10
310	20	15	5	10
Power off				
185	18	15	5	10
255	18	12	8	10

Because of the cross flow, the wake surveys on the upper surface of the left wing section in the slipstream cannot be used to determine the profile-drag coefficient of the upper surface of this section. If the presence of cross flow is ignored, however, as it would be if the tuft surveys were not made and there were no reason to suspect the measurements, the evaluation of the wake surveys by the usual methods would give an apparent profile-drag coefficient of 0.0045 with normal engine operation and 0.0040 with engine throttled at a section lift coefficient of about 0.20 and a Reynolds number of about 19×10^6. This difference in the apparent profile-drag coefficients as obtained with normal engine operation and with engine throttled would be expected from the transition results, which showed a more rearward position of transition with engine throttled.

In order to obtain some idea of the magnitude of the profile-drag coefficient to be expected on the upper surface of the left wing section, the profile-drag coefficient was computed for a section lift coefficient of 0.20 and a Reynolds number of 19×10^6 by the method of reference 4 and by using the position of transition as measured on the upper surface of this section with normal engine operation. Profile-drag coefficients computed in this manner have been found in other investigations to agree rather well with profile-drag coefficients measured in absence of cross flow. The results of the computations indicated a value of profile-drag coefficient of 0.0035 for the upper surface as compared with the apparent value of the measured profile-drag coefficient of 0.0045 for the upper surface. It should be mentioned that the profile-drag coefficients computed from the observed transition points were based on slipstream dynamic pressure and that the profile-drag coefficient based on free-stream dynamic pressure may be obtained by multiplying the computed profile-drag coefficients by the ratio of slipstream dynamic pressure to free-stream dynamic pressure.

CONCLUSIONS

The results of the flight investigation of boundary-layer transition and profile drag on the low-drag wing of an experimental fighter-type airplane, the XP-47F, have shown that:

For the specially finished right wing section, which was aerodynamically smooth but had measurable residual waviness,

1. The drag characteristics realized were in reasonable accord with expectations for the type of section tested.

2. The point of transition on the upper surface moved rearward with decreasing lift coefficient to about 50 percent of the chord and then moved forward again with a further decrease in lift coefficient. This forward movement of the point of transition was attributed to the increasing Reynolds number that accompanies decreasing lift coefficient in flight. The section lift coefficient and Reynolds number corresponding to transition at 50 percent of the chord were 0.18 and 15.7×10^6, respectively.

3. The profile-drag coefficient decreased with decreasing lift coefficient until a minimum of 0.0045 was obtained at a section lift coefficient of about 0.19 and a Reynolds number of about 15.9×10^6. With further decrease in lift coefficient, the profile-drag coefficient began to increase again by an amount corresponding to the forward movement of transition on the upper surface.

4. No difference in the point of transition on the upper surface or in the profile-drag coefficient was observed when the airplane was flown with normal engine operation and with engine throttled.

5. An increase in profile-drag coefficient of 6 to 14 percent, at lift coefficients of 0.30 to 0.58, respectively, above that obtained in normal flight at lower Mach numbers and corresponding lift coefficients was measured in steady turns at an indicated airspeed of 300 miles per hour with normal accelerations from 2g to 4g.

For the standard right wing section with camouflage paint and normal construction waviness

6. A minimum profile-drag coefficient of 0.0063 was obtained at a section lift coefficient of 0.22 and a Reynolds number of 14.7×10^6.

7. No increase in profile-drag coefficient above that obtained in normal flight at lower Mach numbers and corresponding lift coefficients was measured in steady turns at an indicated airspeed of 300 miles per hour.

For the specially finished upper surface of the left wing section in the propeller slipstream

8. The most rearward position of transition measured with normal engine operation was between 20 and 25 percent chord at a section lift coefficient between 0.24 and 0.18 and at a Reynolds number between 18.7×10^6 and 21.3×10^6, respectively. With the engine throttled, the position of transition was 4 percent of the chord farther rearward from the leading edge than that obtained with normal engine operation.

9. The attempt to measure the profile drag of the upper surface by a half-wake trailing-edge rake was not successful because a large lateral component of boundary-layer flow existed at the trailing edge of this section.

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REFERENCES

1. Anderson, Raymond F.: Determination of the Characteristics of Tapered Wings. NACA Rep. No. 572, 1936.

2. Silverstein, A., and Katzoff, S.: A Simplified Method for Determining Wing Profile Drag in Flight. Jour. Aero. Sci., vol. 7, no. 7, May 1940, pp. 295-301.

3. Theodorsen, T., and Garrick, I. E.: General Potential Theory of Arbitrary Wing Sections. NACA Rep. No. 452, 1933.

4. Squire, H. B., and Young, A. D.: The Calculation of the Profile Drag of Aerofoils. R. & M. No. 1838, British A.R.C., 1938.

5. von Kármán, Th.: Compressibility Effects in Aerodynamics. Jour. Aero. Sci., vol. 8, no. 9, July 1941, pp. 337-356.

TABLE I

ORDINATES OF RIGHT WING SECTION OF XP-47F AIRPLANE

[All values are given in fractions of chord. Ordinates were measured relative to an arbitrary chord and with inboard T.E. of aileron in line with T.E. of flap.]

Station	Ordinate	
	Upper surface	Lower surface
0	0	0
.0125	.0189	-.0163
.025	.0249	-.0213
.050	.0341	-.0273
.075	.0415	-.0333
.10	.0480	-.0379
.15	.0585	-.0453
.20	.0662	-.0501
.25	.0725	-.0546
.30	.0770	-.0581
.35	.0804	-.0605
.40	.0829	-.0620
.45	.0841	-.0629
.50	.0840	-.0629
.60	.0796	-.0600
.70	.0671	-.0506
.80	.0462	-.0344
.90	.0196	-.0129
1.000	0	0

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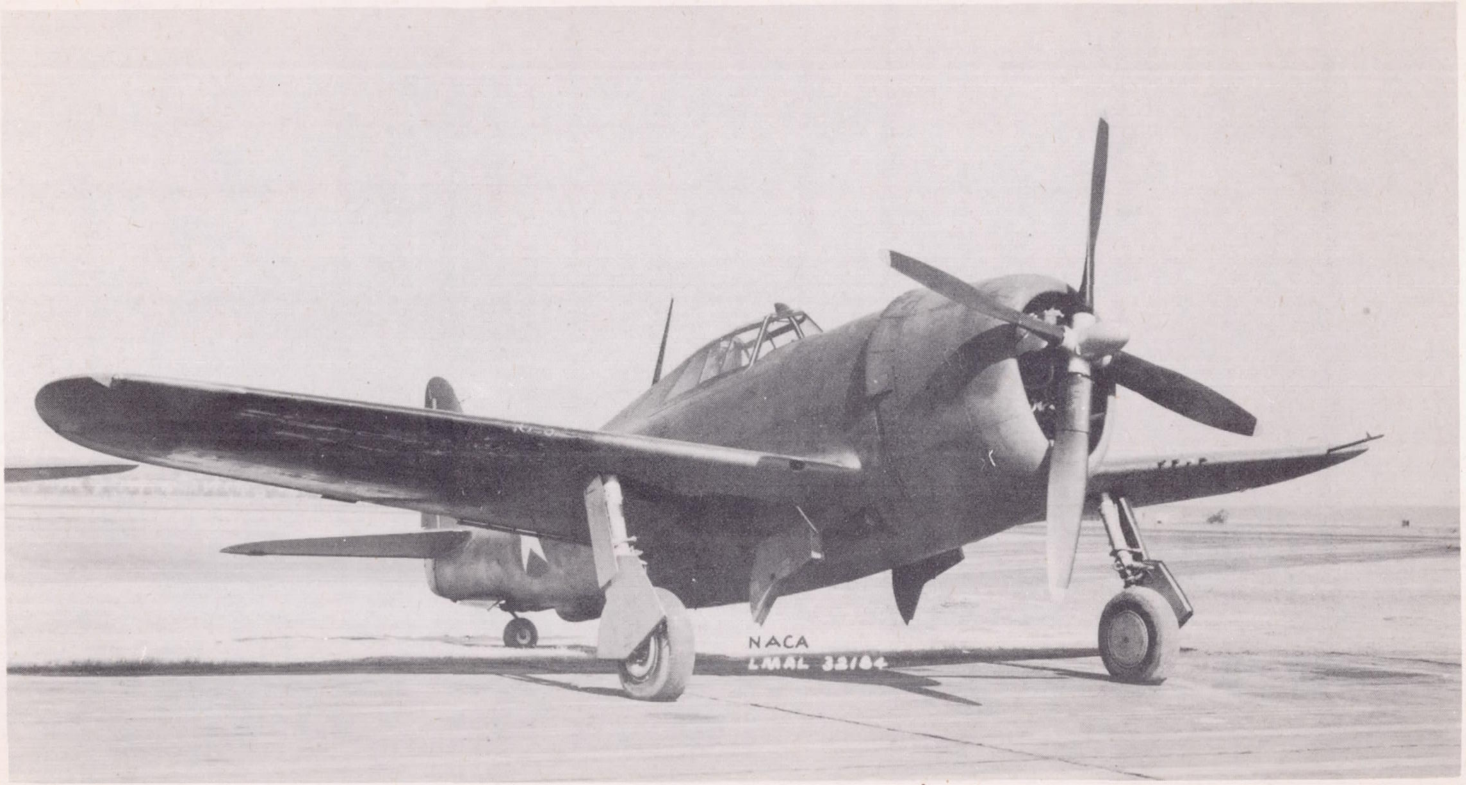


Figure 1.- The XP-47F airplane tested.

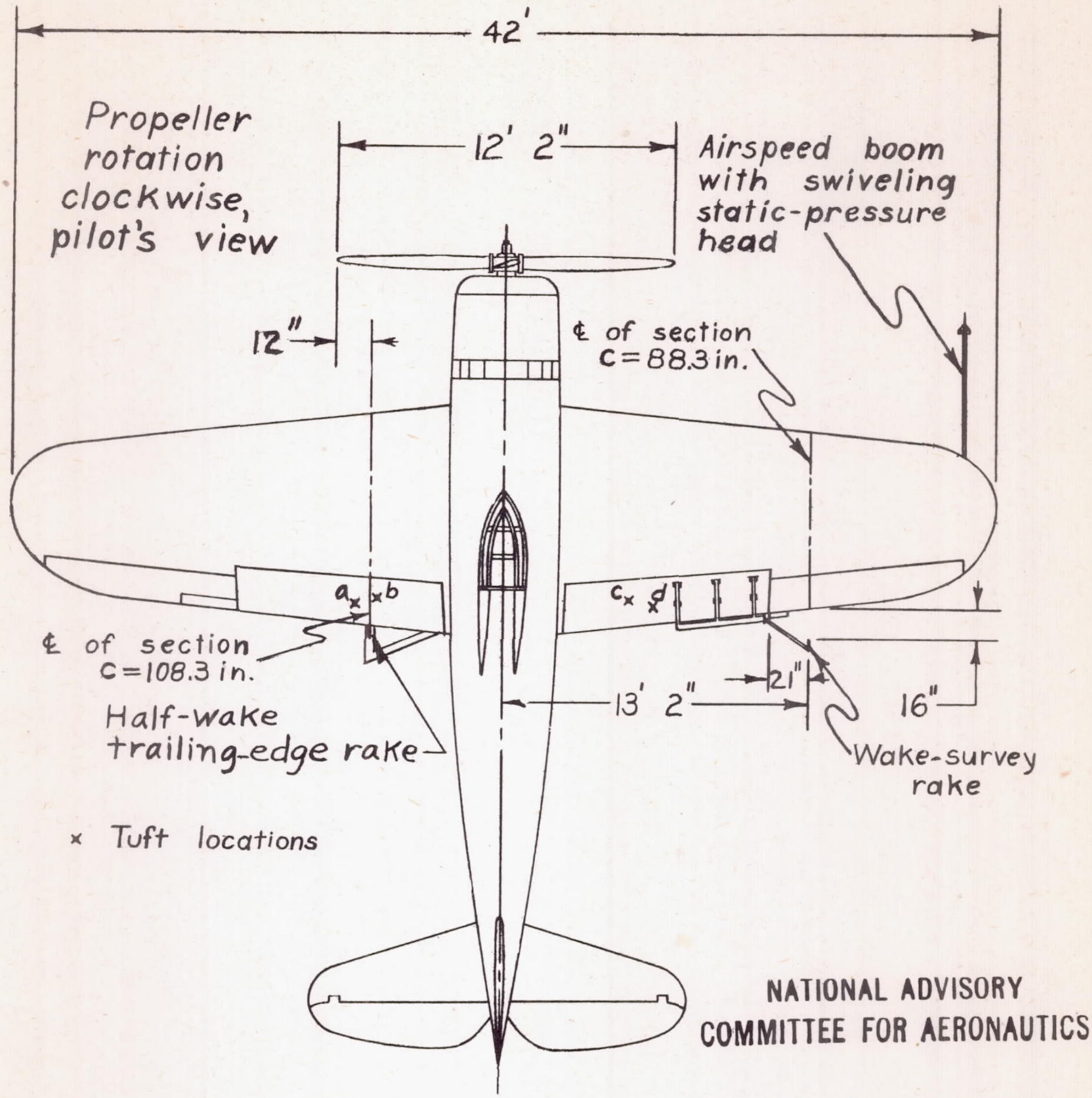


Figure 2.- Sketch of XP-47F airplane showing location of wing test sections.

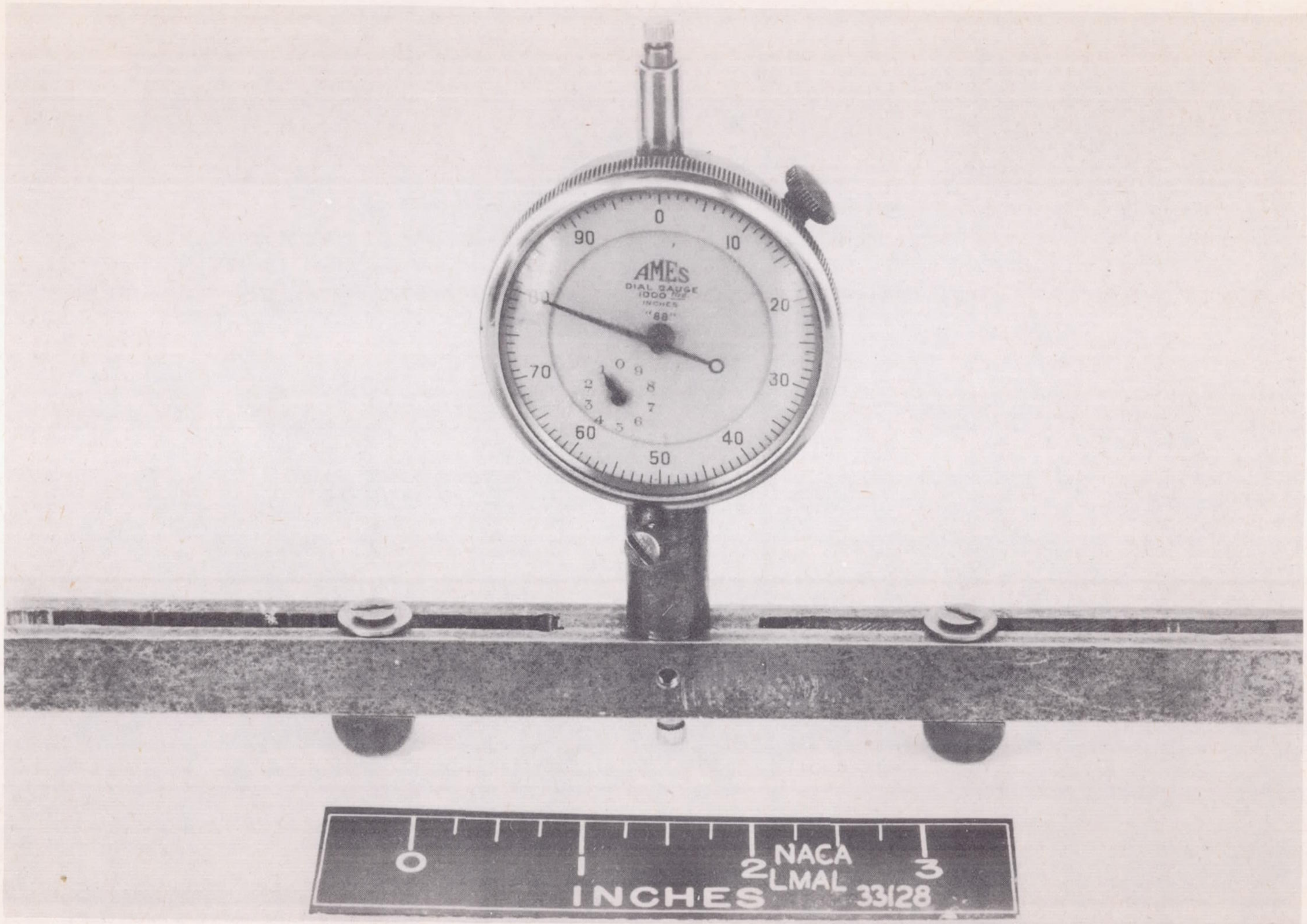
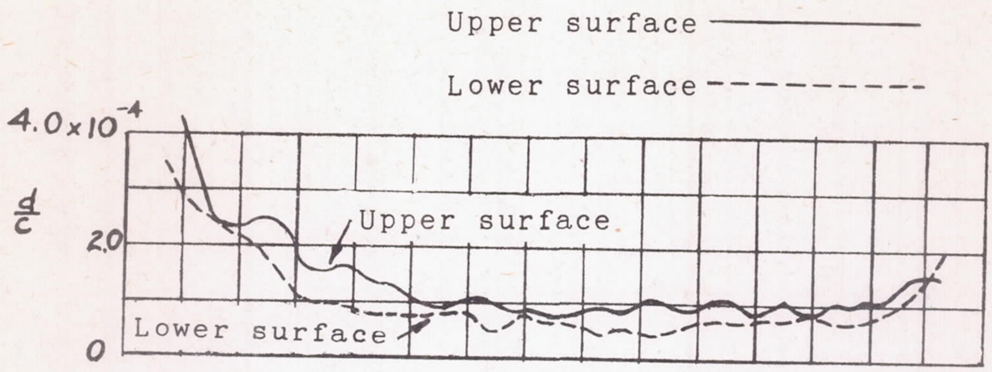
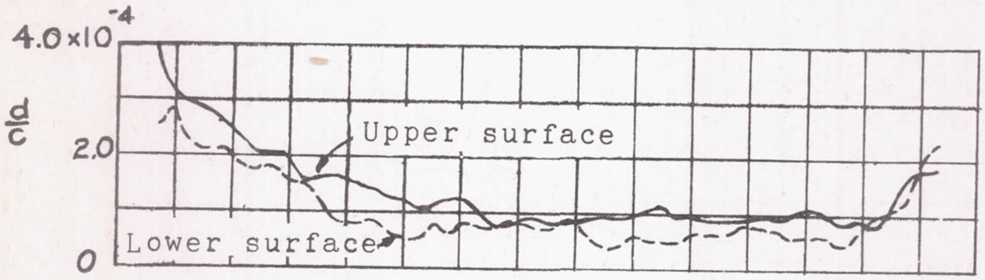


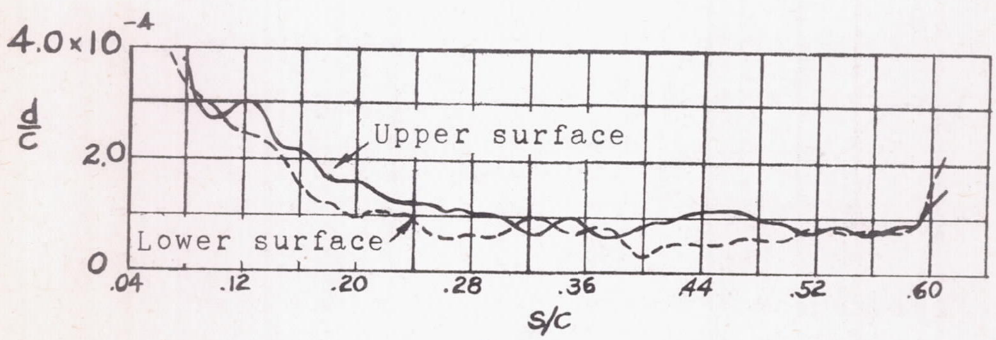
Figure 3.- Curvature gage used in measuring surface waviness.



(a) Measurements 6 inches outboard of section center line.

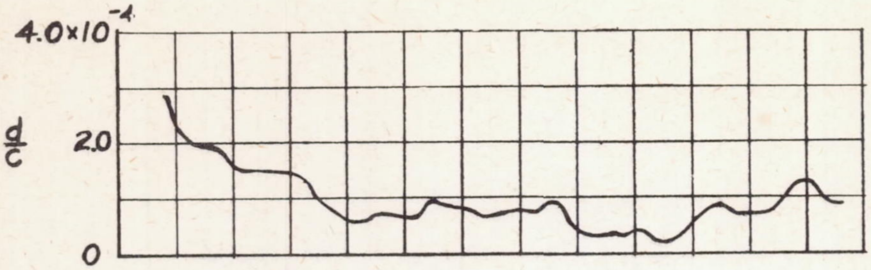


(b) Measurements at section center line.



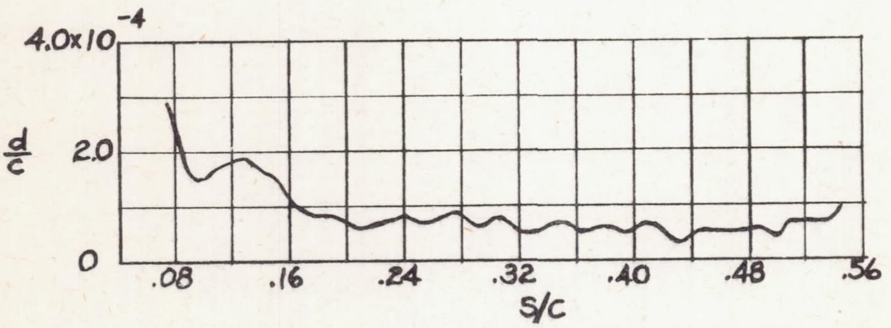
(c) Measurements 6 inches inboard of section center line.

Figure 4.- Surface-waviness index of smooth surfaces of right wing section. XP-47F airplane.



(a) Measurements 6 inches outboard of section center line.

(b) Measurements at section center line.



(c) Measurements 6 inches inboard of section center line.

Figure 5.- Surface-waviness index of smooth upper surface of left wing section in slipstream. XP-47F airplane.

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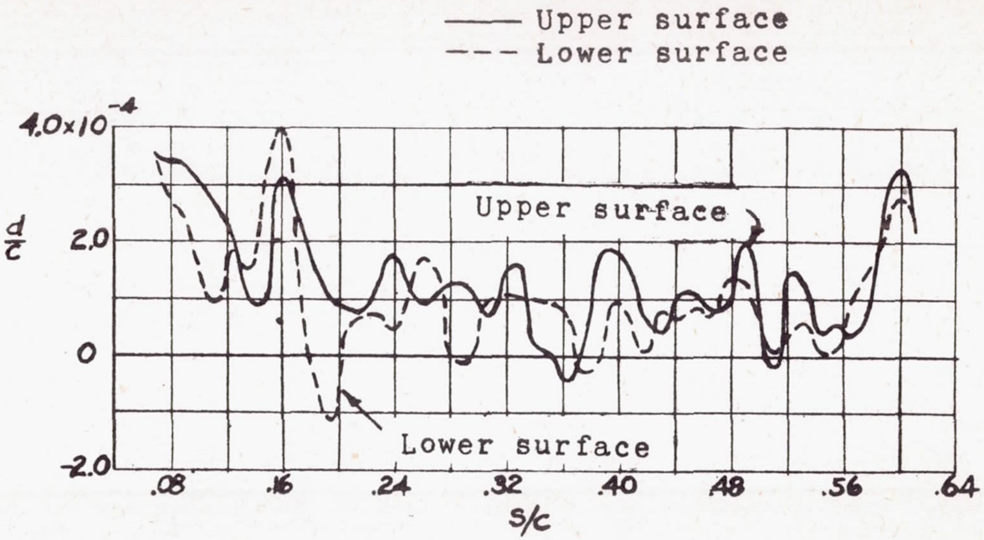

Figure 6.- Surface-waviness index along center line of right wing section with standard surface finish. XP-47F airplane.

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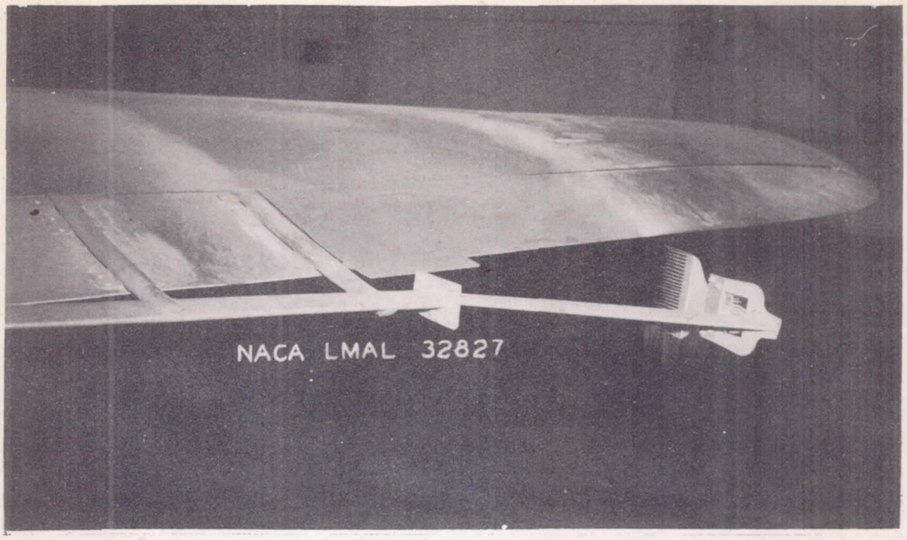

Figure 7.- Rake installation for wake surveys on right wing section. XP-47F airplane.

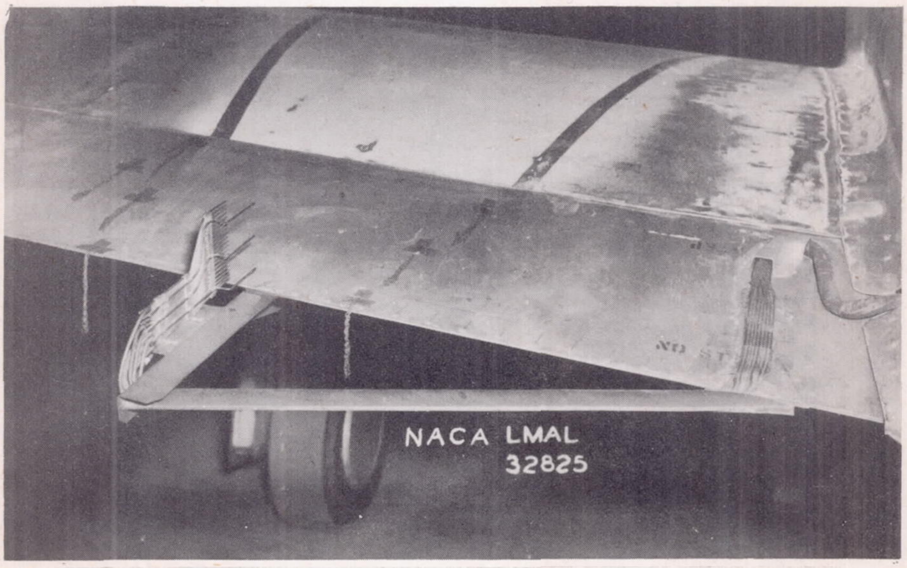

Figure 8.- Half-wake trailing-edge rake used for wake survey on upper surface of left wing section in propeller slipstream. XP-47F airplane.

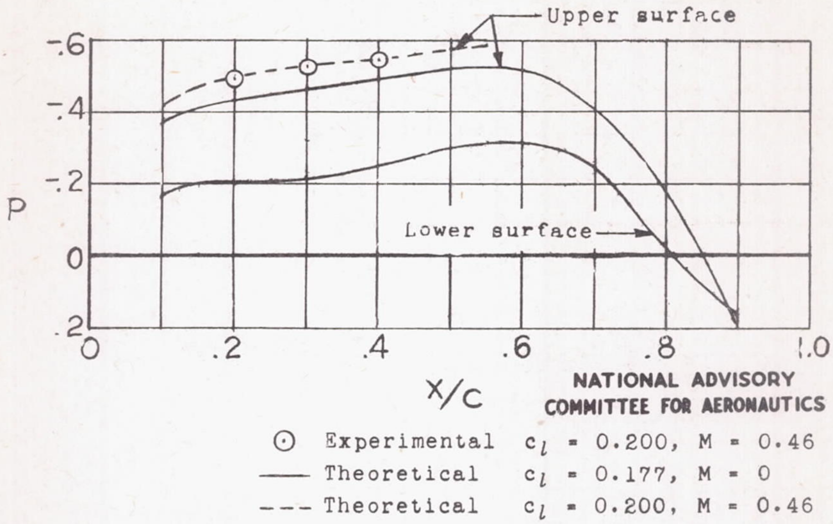

Figure 9.- Pressure distribution over smooth right wing section. XP-47F airplane.

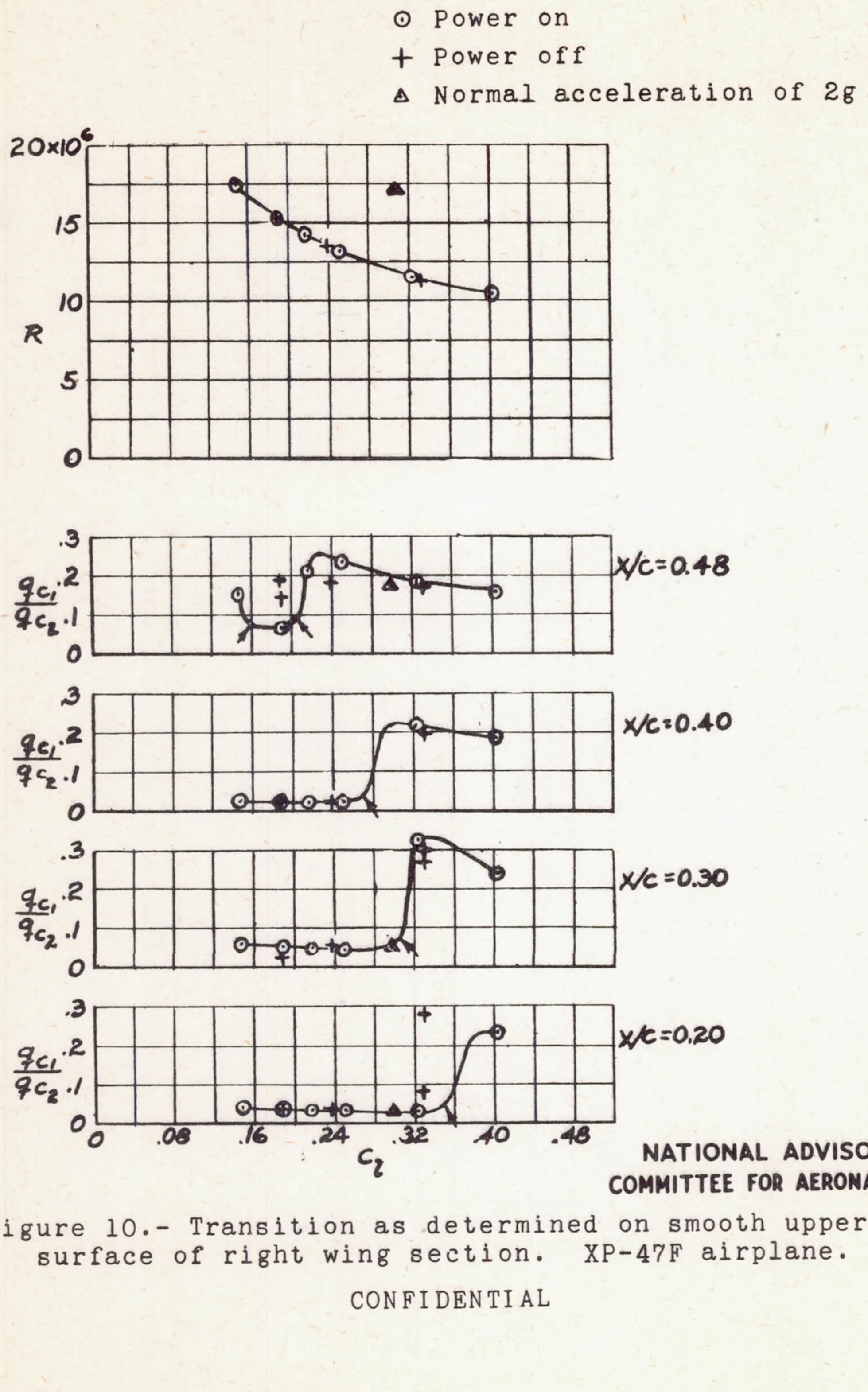

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Figure 10.- Transition as determined on smooth upper surface of right wing section. XP-47F airplane.

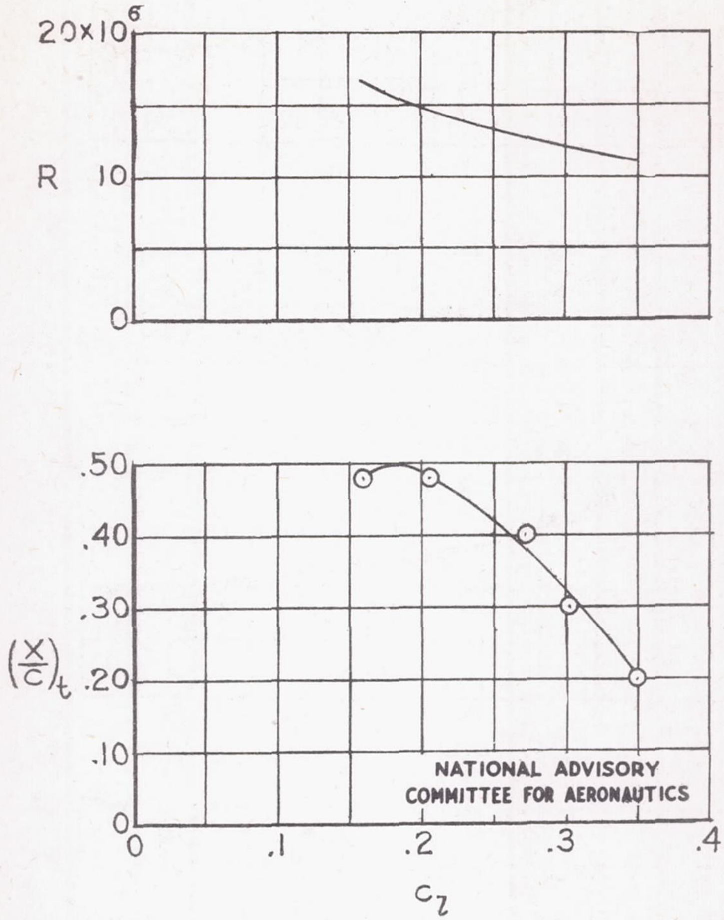

Figure 11.- Point of transition on smooth upper surface of right wing section as function of section lift coefficient. Reynolds numbers for corresponding section lift coefficients plotted above. XP-47F airplane.

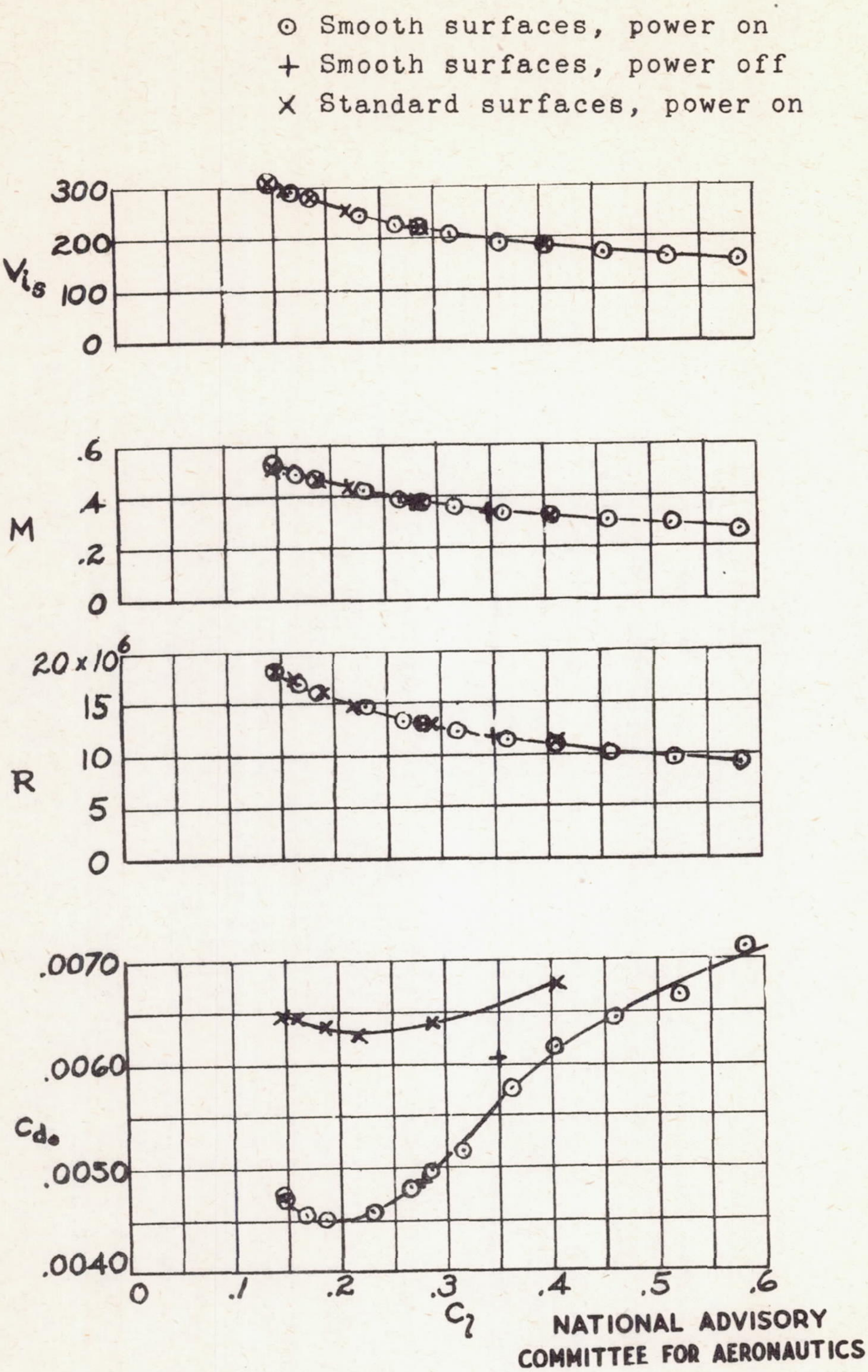

Figure 12.- Profile-drag coefficient of right wing section with smooth and standard surface finishes, in normal flight. XP-47F airplane.

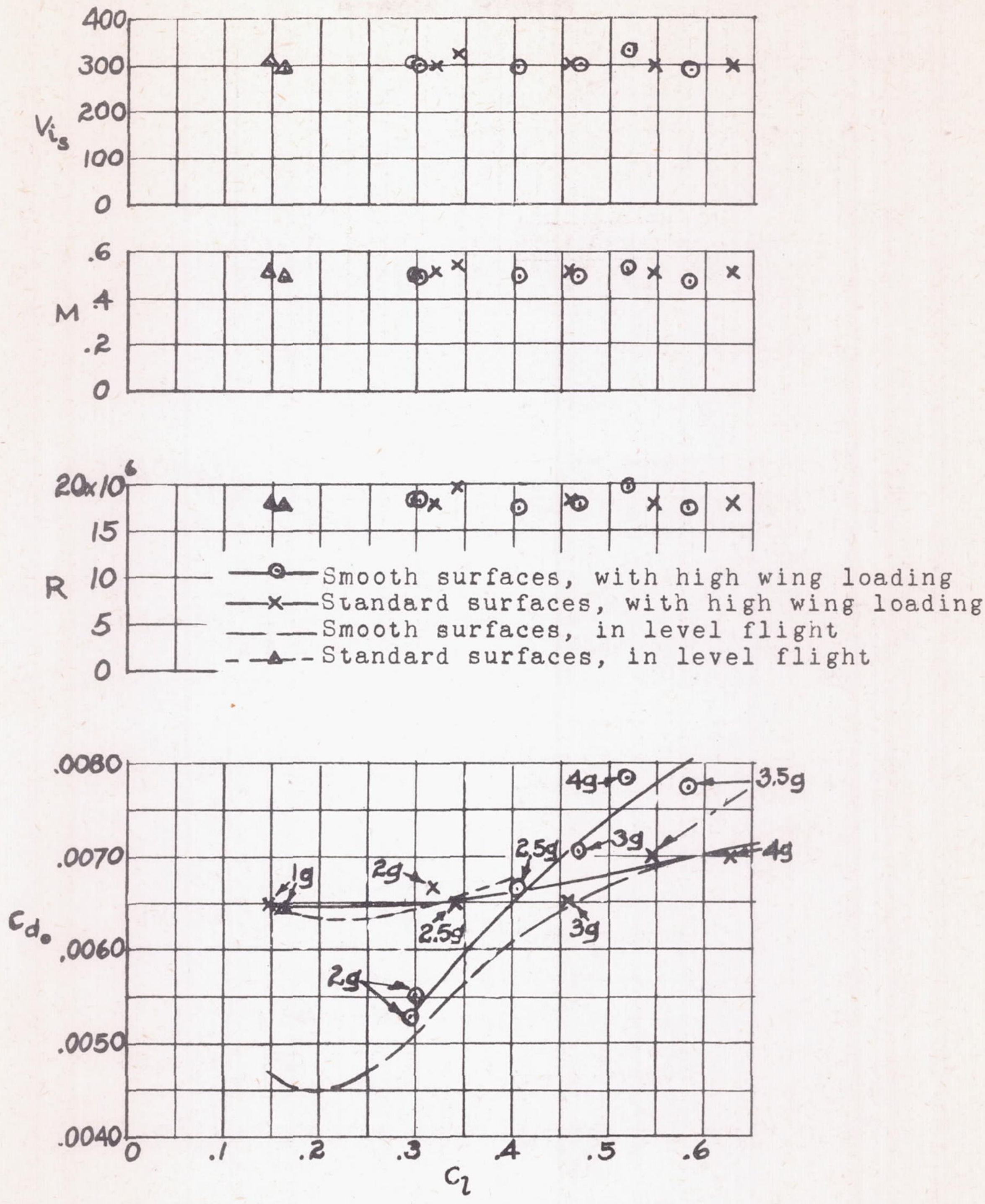

Figure 13.- Profile-drag coefficient of right wing section with smooth and standard surface finishes in the high wing-loading conditions. XP-47F airplane.

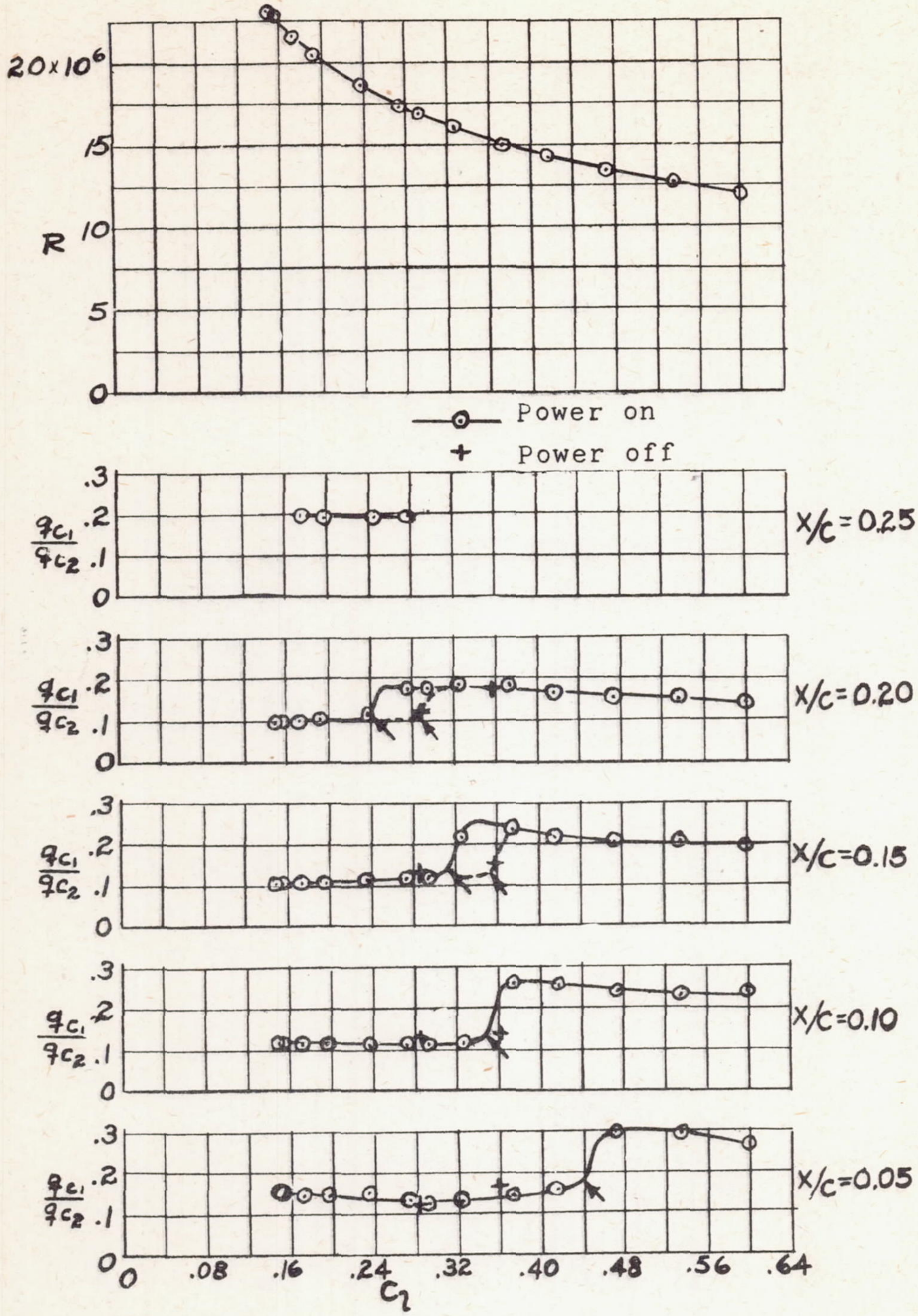

Figure 14.- Transition as determined on smooth upper surface of left wing section in slipstream. XP-47F airplane.

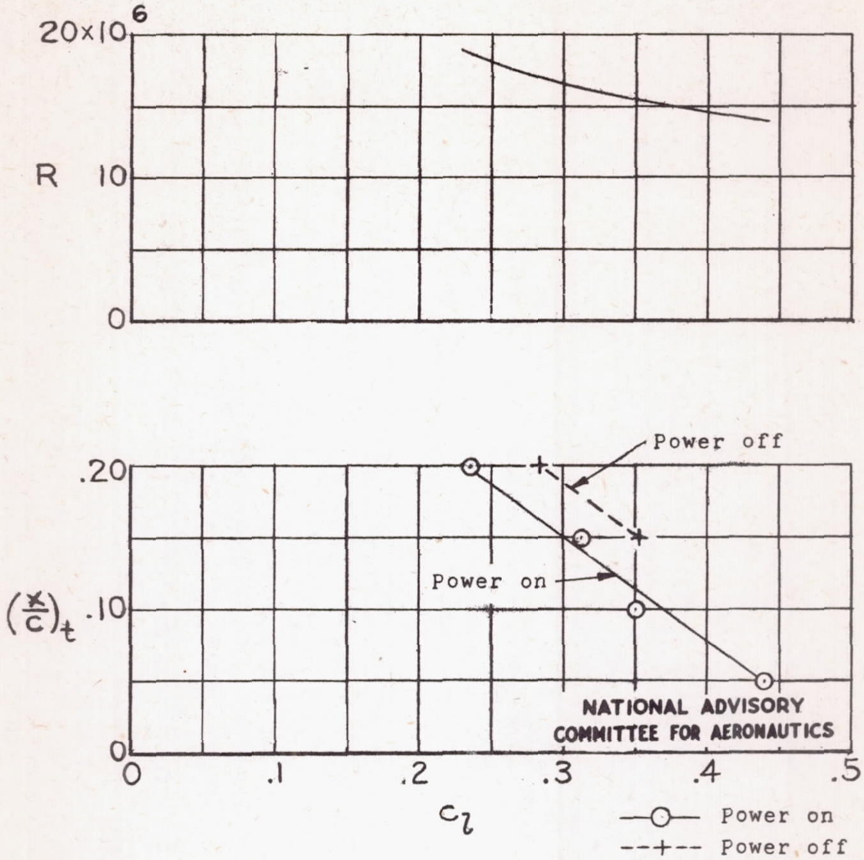

Figure 15.- Point of transition on smooth upper surface of left wing section in slipstream as function of section lift coefficient. Reynolds numbers for corresponding section lift coefficients plotted above. XP-47F airplane.