To: Mr. Chas. J. McCarthy
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WIND-TUNNEL TESTS OF SEVERAL MODEL TRACTOR-PROPELLER AND PUSHER-PROPELLER WING EXTENSION-SHAFT ARRANGEMENTS

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SUMMARY

Tests were made in the 20-foot propeller-research tunnel to investigate the possibility of obtaining increased net efficiencies of propeller-nacelle units by enclosing the engines in the wings and by using extension shafts. A wing of 5-foot chord was fitted with a propeller-drive assembly providing for several axial locations of tractor propellers and pusher propellers. A three-blade 4-foot propeller and a three-blade $3\frac{1}{2}$-foot propeller of special design were tested on this wing with spinners and fairings ranging in diameter from 6 to 16 inches. A 16-inch NACA cowling was tested for comparative purposes. Two types of cuffs were also employed.

It was found that the net efficiency of a conventional round-shank propeller mounted on an extension shaft in front of or behind a wing increased with an increase in the diameter of the spinner and the shaft housing within the scope of the tests. The largest spinner used had a diameter that might favorably compare with that of a radial engine cowling.

The efficiencies for the pusher position appeared to be more critically affected by spinner size than those for the tractor position. The spinners with large diameters for the pusher position resulted in a higher efficiency than those for the corresponding tractor arrangements; the reverse was true for the small spinners.

The use of propeller cuffs in combination with a spinner of small diameter generally resulted in net efficiencies that were comparable with those found for the large-spinner combinations.

INTRODUCTION

The drag of engine nacelles on multiengine airplanes is often from 15 to 30 percent of the total drag. This fact suggests that the engines should be entirely enclosed within the wing and the propellers should be driven through extension shafts.

The problems that arise in the consideration of the extension-shaft arrangement are:

1. The gain attained by the elimination of nacelles if the drag of the optimum size of extension shaft is considered

2. The best location of the propeller

3. The relative merits of the tractor-propeller and the pusher-propeller arrangements

4. The optimum diameter of the shaft fairing and the spinner

5. The relative merits of cuffs and large spinners for covering the cylindrical portions of present-day propeller blades.

The investigation herein reported was made for the purpose of obtaining the information that would help to answer these questions. The tests were made as a continuation of the investigation of the wing-nacelle-propeller combination in the 20-foot tunnel (references 1, 2, and 3), which included tests of several model wings combined with various combinations of cowled and uncowled engines.

APPARATUS

The tests were made in the NACA 20-foot wind tunnel. (See reference 4.) The return passages of the tunnel have been slightly altered and a new six-element balance has been installed since reference 4 was written. The set-up for these tests consisted essentially of a segment of a wing to which a propeller-drive assembly, a propeller, a shaft fairing, and a spinner could be fitted. A pusher-propeller wing extension-shaft arrangement mounted for test is shown in figure 1.

Wing.- An NACA 23018 wing with a 5-foot chord and a 15-foot span and with a wood covering of 1/2 inch was used for the first tests in this series. During the tests the wing was covered with sheet aluminum 1/16 inch thick; this additional covering increased the chord to 5.052 feet and increased the area from 75 to 75.8 square feet.

Propeller drive.- A motor extension-shaft assembly was fitted into the wing, as shown in figure 2. Three shafts of different lengths were used to obtain different axial locations of the propeller. The motor used to drive the propeller, the alternator, and other equipment to supply the proper current are described in reference 2.

Propellers.- A three-blade, 4-foot model of a Hamilton Standard 6101 propeller was used for most of the tests. The blade-form curves for this propeller are presented in reference 2. The NACA 7099 three-blade, $3\frac{1}{2}$-foot propeller was also used. This propeller is of a special design incorporating the NACA 16-series airfoils with low thickness ratios extended inward almost to the hub. It has a basic pitch angle of 39.5° at the 0.75 radius. The blade-form curves of the NACA 7099 propeller are shown in figure 3.

Fairings, spinners, and cowling.- A number of sheet-aluminum fairings and spinners were made to provide spinner diameters of 6 and 10.7 inches for the 6101 propeller in the pusher position and diametersof 6.0, 8.0, 10.7, and 16.0 inches for the same propeller in the tractor position. Four lengths of spinners of 6-inch diameter were made for the pusher-propeller position: three lengths with an elliptical longitudinal section and one length with a sharp-pointed section. An 8-inch diameter spinner and fairing were used for the NACA 7099 propeller. A 16-inch NACA cowling described in reference 3 was also tested. Figure 2 is made up of sketches of these fairings and spinners in all the arrangements tested. Figure 4 is a sketch of the NACA cowling. Photographs of the tractor-propeller and the pusher-propeller extension-shaft arrangements are shown in figures 5 and 6, respectively.

Cuffs.- Two types of cuffs were designed and built for the 6101 propeller. (See fig. 7.) Figure 8 is a photograph of the set-up showing cuff I.

METHODS

The propeller speed was measured by an electric tachometer; a magneto type of tachometer was used for the first part of the program and a condenser type was used for the last part. The torque was obtained from a calibration involving the power input to the motor, the motor speed, and the alternator field current. (See reference 2.)

Wind-tunnel tests were of three types: measurement of lift and drag of the wing, with and without nacelles, for a range of angle of attack at a constant air speed of about 80 miles per hour; measurement of lift and drag of the wing, with and without nacelles, for an angle of attack of 3° at air speeds varying from 30 to 100 miles per hour; and measurement of lift and resultant horizontal force on the wing, with propeller operating, for an angle of attack of 3°. For these propeller tests, the air speed and the propeller revolution speed were varied to obtain values of the advance-diameter ratio V/nD from zero to the values for zero thrust. In every case peak efficiency occurred at the highest air speed - about 100 miles per hour.

SYMBOLS AND COMPUTATIONS

q dynamic pressure of air ($1/2\ \rho V^2$)

ρ mass density of air

V velocity of air stream

n propeller revolution speed

R balance reaction (excess of thrust of propeller over drag of body)

T propulsive thrust (R + drag of body without propeller)

D diameter of propeller

S area of wing

C_D wing drag coefficient $\left(\frac{\text{drag}}{qS}\right)$

C_L wing lift coefficient $\left(\frac{\text{lift}}{qS}\right)$

C_T propulsive thrust coefficient $\left(\frac{T}{\rho n^2 D^4}\right)$

C_P power coefficient $\left(\frac{\text{power}}{\rho n^3 D^5}\right)$

$\frac{V}{nD}$ advance-diameter ratio of propeller

η propulsive efficiency $\left(\frac{C_T}{C_P} \frac{V}{nD}\right)$

η_o net efficiency $(\eta - \text{N.D.F.})$

C_s speed-power coefficient $\left(\frac{V}{nD} C_P^{-1/5}\right)$

N.D.F. nacelle drag factor $\left[\frac{\text{nacelle drag}}{2qD\ C_P}\left(\frac{V}{nD}\right)^3\right]$

Power coefficients C_P, propulsive thrust coefficients C_T, and propulsive efficiency η were computed and plotted against the advance-diameter ratio V/nD for all the propeller tests. A set of typical curves and test points is shown in figure 9. Values of the speed-power coefficient C_s were calculated from faired values from these curves. The drag at a dynamic pressure of 26 pounds per square foot (an air speed of approx. 100 mph) of each extension-shaft combination was determined from faired curves obtained from the 3° angle-of-attack measurements. These drag increments were used to compute the drag coefficient increments and the nacelle drag factors. Net efficiencies were determined and were plotted against C_s. The faired envelopes of these curves are given in this report.

RESULTS

The results of these tests are shown in terms of lift, drag, net efficiencies, and speed-power coefficients.

Lift and drag characteristics of the wing alone are shown in figure 10. Figure 11 shows the lift and drag characteristics of the wing with extension shafts and fairings for tractor propellers, and figure 12 gives similar information for the pusher-propeller arrangements. In figure 13 extreme limits of the curves of the lift and drag characteristics for the wing alone are compared with the limits for the wing with the extension-shaft arrangements. The increments of drag coefficient due to the various nacelles are shown in figure 14.

The envelopes of the net efficiency of the 6101 propeller in the tractor-propeller arrangements are shown in figure 15; the envelopes for the pusher-propeller arrangements are shown in figure 16. In figure 17 the efficiency of the NACA 7099 propeller in tractor and pusher arrangements is compared with that of the 6101 propeller. The tractor-propeller and the pusher-propeller arrangements are compared in figure 18.

DISCUSSION

The discussion is divided into four parts: the lift and drag characteristics of all arrangements, the net-efficiency results of the tractor-propeller arrangements, the net-efficiency results of pusher-propeller arrangements, and a comparison of the tractor-propeller and the pusher-propeller arrangements.

Lift and Drag Characteristics of All Arrangements

The curves of C_D plotted against C_L for the wing alone (fig. 10), obtained from tests made at different times at an air speed about 80 miles per hour, do not coincide; but they do agree at lift coefficients near 0.2, corresponding to the angle at which all propeller tests were run. For the extension-shaft arrangements there is a spread in the curves of C_L plotted against C_D for the different conditions (figs. 10, 11, 12), particularly at high lift coefficients, but the variation does not correlate with the spinner size.

In figure 14 are shown the extension-shaft drag increments to the wing drag coefficient. The group of points plotted for the tractor-propeller nacelles lies above that for the pusher-propeller nacelles, which indicates a higher drag for the tractor-propeller nacelles; the scattering of these points is large, however, and the two groups overlap. The curve from reference 5 indicates increasing drag with increasing nacelle diameter, and the test points of the nacelles in the tractor position 1 and pusher position 4 have a similar tendency. The greatest increment of drag represented is about 2 pounds. Because the balance error may be as large as 0.4 or 0.5 pound and because the various extension-shaft nacelles are not all geometrically similar, the scattering of points seems not unduly large.

Net Efficiency of Tractor-Propeller Arrangements

Before these curves are discussed, it may be well to note that the use of model propellers resulted in low Reynolds numbers and, consequently, in relatively low accuracy. The precision of these efficiency results is believed to be, for the most part, about ±3 percent. Unless otherwise stated, only the 6101 propeller is included in the following discussion.

Spinner size.- As shown in figure 15, the net efficiency of the tractor-propeller extension-shaft combination increased fairly consistently with increases in spinner size within the scope of the tests, particularly for the high values of C_s that correspond to high forward speeds. This trend can be accounted for by the fact that larger spinners cover up more of the poor sections of the propellers, which is particularly important for the high-speed-flight conditions. This effect is in agreement with results given in reference 6.

Comparison of tractor-propeller extension-shaft arrangements and NACA cowling arrangements.- The net efficiency found for the 6101 propeller with the 16-inch NACA cowling (fig. 15) is 0 to 8 percent lower than that found for the 16-inch spinner, the best of the extension-shaft arrangements. (The NACA cowling tests from reference 3 were corrected for cooling air flow according to the relation

$$\text{Increase in drag coefficient} = \text{Conductivity}\left(\frac{\text{pressure drop across the engine}}{\text{dynamic pressure}}\right)^{\frac{3}{2}}$$

which takes into account only the losses through the engine baffles.) It should be noted that the extension-shaft arrangement resulting in the highest net efficiency is about as large as a radial engine that might be used with this propeller. This fact suggests that, if the drag of the radial engine cowling could be reduced to that of an extension shaft having the same diameter, there would be no advantage in burying the engine in the wing.

Another method for reducing the drag of the blade shanks is by the use of cuffs. Cuff I was tested in combination with a 6-inch spinner; the resulting efficiency was equal to that of the propeller with the 8-inch and 10-inch spinners. Lack of time prevented further experiment with cuffs for the tractor propeller.

Distance of the propeller in front of the wing.- Of the three axial positions of the tractor propeller, the intermediate position (about 30 percent of the chord forward of the leading edge) was the best, the difference in efficiency between positions 2, 1, and 3 varying from 0 to 4 percent (fig. 15). There was little difference for positions 1 and 3.

Net Efficiency of Pusher-Propeller Arrangements

Spinner size.- The pusher propeller with the larger spinner had the higher net efficiency, as was the case with the tractor-propeller arrangements. (See fig. 16.) With the 10.7-inch spinner the net efficiency was 6 to 15 percent higher than with the 6-inch spinners. This difference in efficiency due to spinner size for both positions 4 and 5 suggests that the resulting wake is critically affected by the spinner size for this round-shank propeller mounted in the pusher position. The flow over the smaller spinner may be completely separated, whereas it may not be separated for the larger one.

Two cuffs, I and II, were used with the 6-inch-diameter, 12-inch-long spinner. The use of cuff I resulted in about 8 and 7 percent increase in efficiency for positions 4 and 5, respectively (fig. 16). This increase did not, however, raise the efficiency up to that of the 10.7-inch spinner in position 5. This increase did, however, raise the efficiency up to that of the 10.7-inch spinner in position 4, and this is the only case in which the efficiency of the propeller with the 10.7-inch spinner was less than that for the propeller with the 6-inch spinner and a cuff.

The propeller with cuff II in position 5 was about 5 to 7 percent more efficient than without cuffs for the two-blade angles tested. The efficiency in position 4, however, was only about 1/2 percent higher than that without cuffs. The propeller with the 10.7-inch spinner was about 5 or 6 percent more efficient than the 6-inch spinner with this cuff.

In general, the propeller with the 6-inch spinner and cuff had a higher net efficiency than the 6-inch-diameter spinner without cuffs, but the propeller with the largest spinner had, with one exception, a higher net efficiency than the 6-inch spinner with cuffs.

<u>Distance of the propeller behind the wing</u>.- Of the two axial locations of the propeller, the one nearer the trailing edge had a slightly higher net efficiency, with the exception of the 10.7-inch spinner in the lower range of C_s.

<u>Comparison of the 6101 and NACA 7099 propellers</u>.- The NACA 7099 propeller having 16-series airfoil sections throughout also has much better shank sections than the 6101 propeller. The pitch distribution was nearly constant for a blade setting of 40° as compared with 15° for the 6101 propeller; this difference would also favor the NACA 7099 propeller for the high blade angles investigated. With the 16-inch NACA cowling, this propeller resulted in a net efficiency 3 to 4 percent higher than did the 6101 propeller. (See fig. 17.) Likewise, the net efficiency of the NACA 7099 propeller in the tractor position with the 8-inch spinner and the extension shaft was 5 to 14 percent higher than that of the 6101 propeller.

These two propellers were not tested with the same size of spinner in the pusher position, but figure 16 indicates that there would have been little difference in efficiency for the same spinner size. The net efficiency of the 6101 propeller in position 5 with the 10.7-inch spinner was 2 or 3 percent higher than that of the NACA 7099 propeller with the 8-inch spinner. Even with cuffs, the 6101 propeller with the 6-inch spinner did not have quite so high an efficiency as the NACA 7099 propeller with the 8-inch spinner.

Comparison of Tractor-Propeller and Pusher-Propeller Arrangements

The net efficiency of the 6101 propeller in the pusher arrangement with the 10.7-inch spinner was definitely higher than that of the tractor arrangement with the 10.7-inch spinner. With the 6-inch spinner, the pusher arrangement resulted in a somewhat lower efficiency than did the tractor arrangement. It was pointed out in a previous discussion that the flow over the pusher spinner was critically affected by the size of the spinner. Although the spinner size affects the tractor results, there seems to be nothing critical regarding it. The fact that the pusher position is critical may account for the superiority of the pusher position for the 10.7-inch-spinner arrangement and the inferiority for the 6-inch-spinner arrangement.

The NACA 7099 propeller with an 8-inch spinner in the tractor arrangement had a somewhat higher net efficiency than with the 8-inch spinner in the pusher arrangement. This propeller was designed with wide-shank sections and a large amount of twist that would cause high rotational losses if the rotation were not removed. With this propeller in the tractor position, the wing would tend to reduce the rotation and to prevent separation. In the pusher position, however, the wing would have no effect in preventing rotation; it is possible that separation might result, which would be apparent in a low net efficiency.

It is also likely that the 8-inch spinner was below the critical-diameter range for the pusher position, even for a propeller with good shank sections operating at low lift coefficients.

CONCLUDING REMARKS

In view of the fact that the present tests were made at low Reynolds numbers, the accuracy of the results was relatively low and consequently no clear-cut conclusions should be drawn. Certain generalizations may be worth mentioning, however. Of particular importance is the fact that only a few of the determinations of the drag of the extension-shaft fairings indicated negligible drag.

The net efficiency of a conventional round-shank propeller mounted on an extension shaft in front of a wing increased with an increase in the diameter of the spinner and the shaft housing within the scope of the tests. The largest spinner used had a diameter that might compare favorably with that of a radial engine cowling; this fact suggests that tractor extension shafts might not have any aerodynamic advantages over normal nacelle-propeller arrangements having cooling systems of equal drag.

The efficiencies for the pusher positions appeared to be more critically affected by spinner size than those for the tractor position. The spinners with large diameters for the pusher position resulted in a higher efficiency than those for the corresponding tractor arrangement; the reverse was true for the small spinners.

The use of a combination of propeller cuffs and a spinner of small diameter increased the values of the net efficiency in some instances to values that were comparable with those recorded for the large-spinner combinations.

An NACA propeller designed with low-drag sections throughout and having a large amount of twist was generally better than the conventional propeller tested.

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Langley Field, Va.

REFERENCES

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   II - Thick Wing - Various Radial-Engine Cowlings - Tractor Propeller, by Donald H. Wood. Rep. No. 436, NACA, 1932.
   III - Clark Y Wing - Various Radial-Engine Cowlings - Tractor Propeller, by Donald H. Wood. Rep. No. 462, NACA, 1933.
   IV - Thick Wing - Various Radial-Engine Cowlings - Tandem Propellers, by James G. McHugh. Rep. No. 505, NACA, 1934.
   V - Clark Y Biplane Cellule - N.A.C.A. Cowled Nacelle - Tractor Propeller, by E. Floyd Valentine. Rep. No. 506, NACA, 1934.
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6. Biermann, David, Hartman, Edwin P., and Pepper, Edward: Full-Scale Tests of Several Propellers Equipped with Spinners, Cuffs, Airfoil and Round Shanks, and NACA 16-Series Sections. NACA confidential report, 1940.

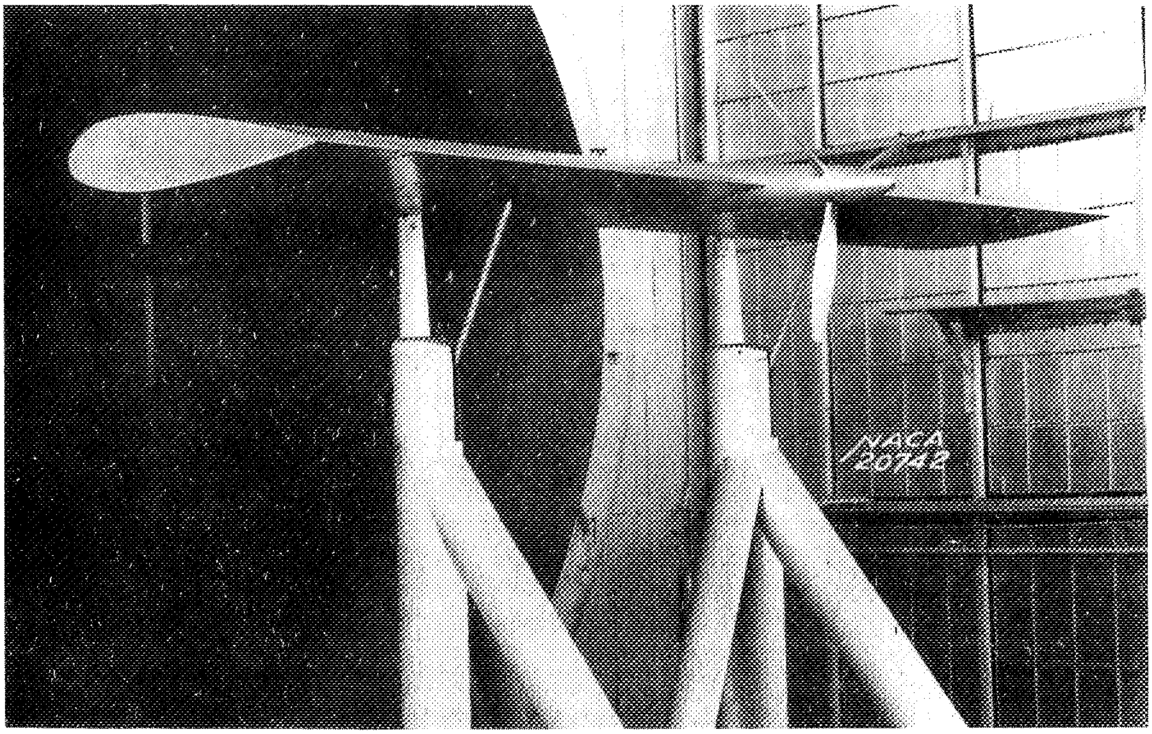


Figure 1.- Photograph of the pusher-propeller wing extension shaft arrangement tested. The 6-inch spinner, 12.0 inches long; propeller 6101; position 5.

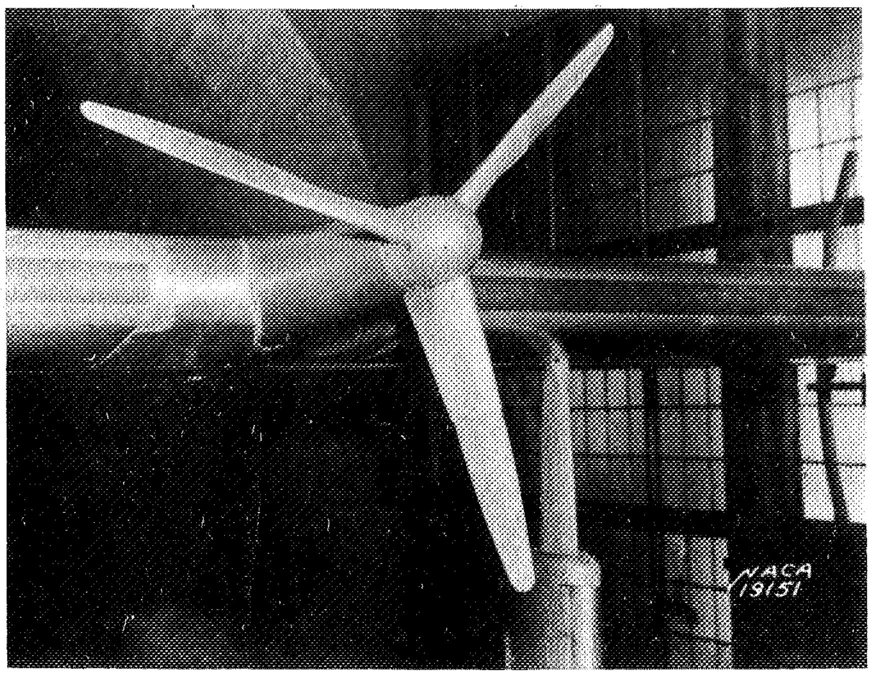
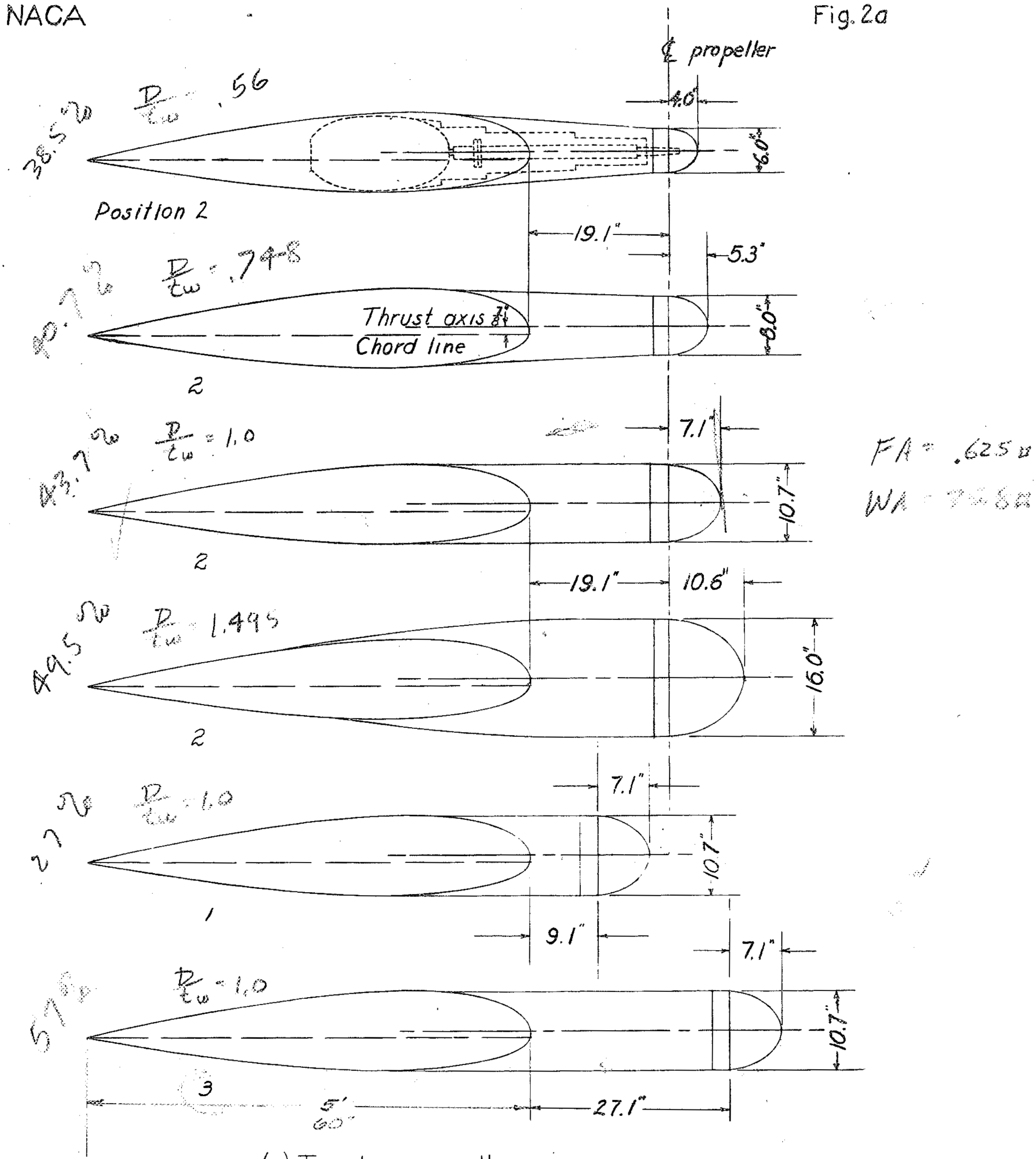
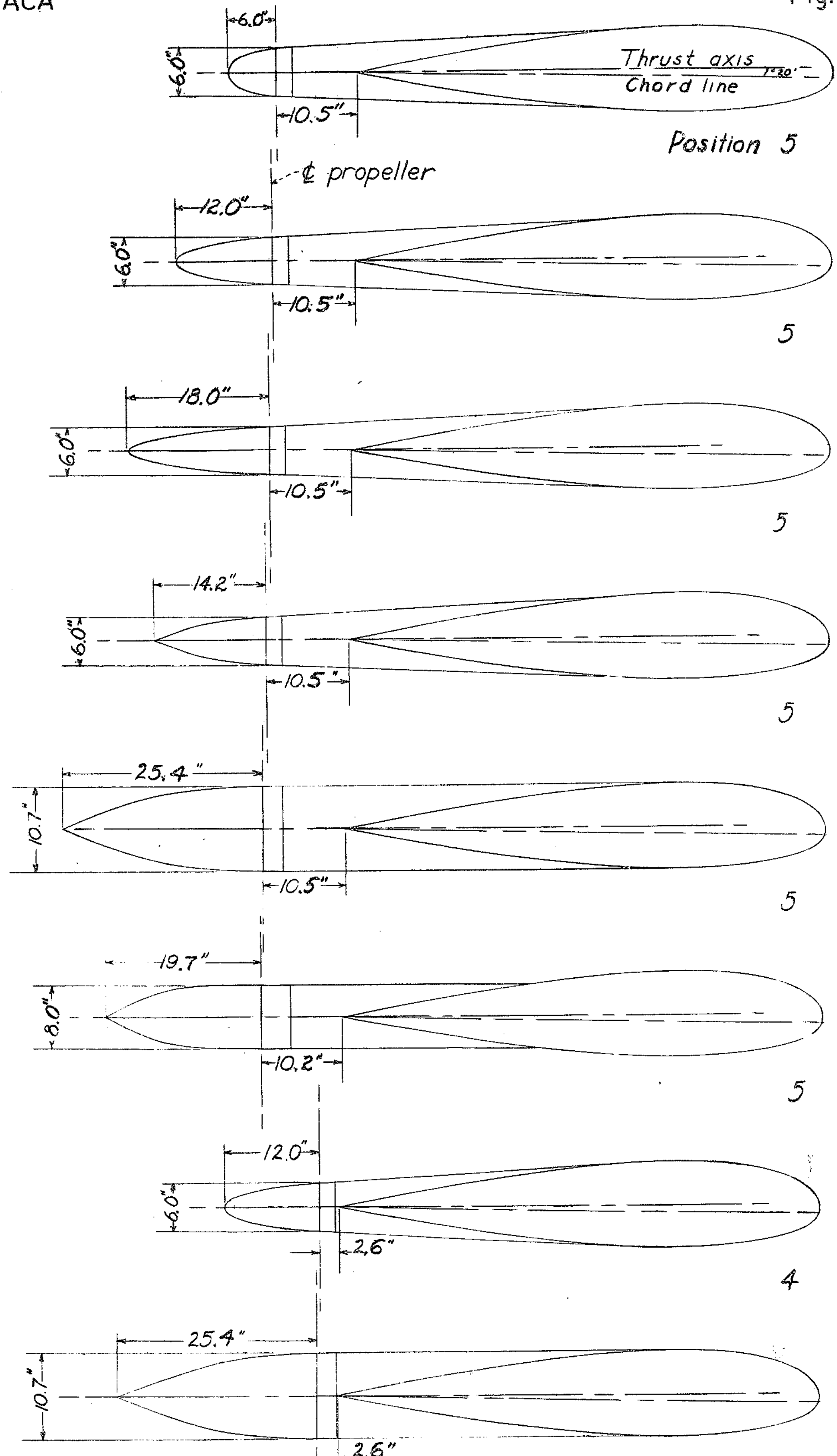


Figure 8.- Photograph of the tractor-propeller wing extension shaft arrangement tested. The 6-inch spinner; propeller 6101 with cuffs; position 2.



(a) Tractor propeller

Figure 2.- Wing extension-shaft arrangements tested.



(b) Pusher propeller Figure 2.- Concluded.

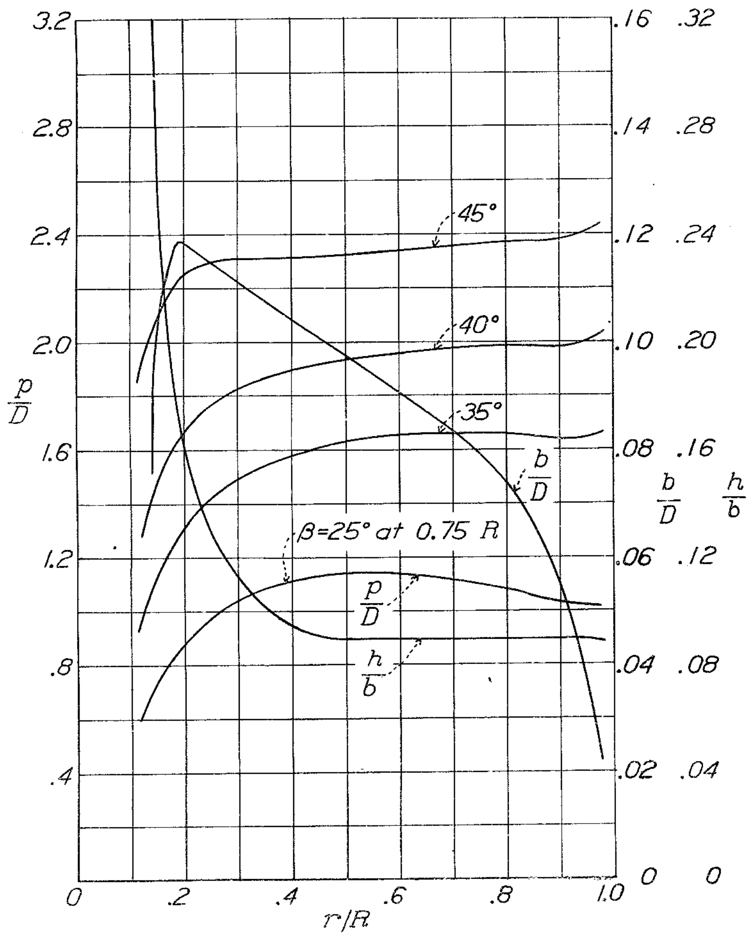


Figure 3.- Blade-form curves for the NACA 7099 propeller. D, diameter; R, radius to the tip; r, station radius; b, section chord; h, section thickness; p, geometric pitch; β, blade angle.

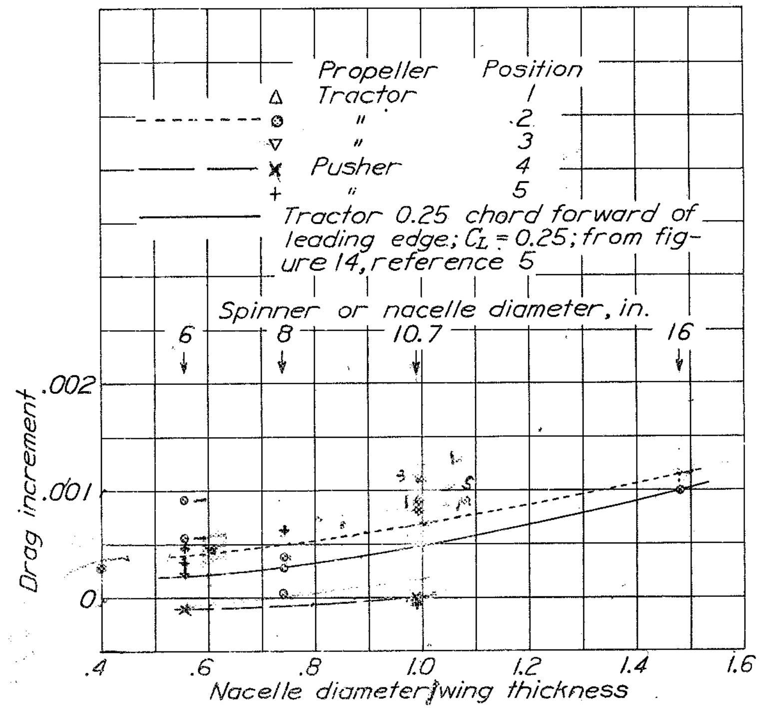


Figure 14.- Extension-shaft and nacelle drag increments.

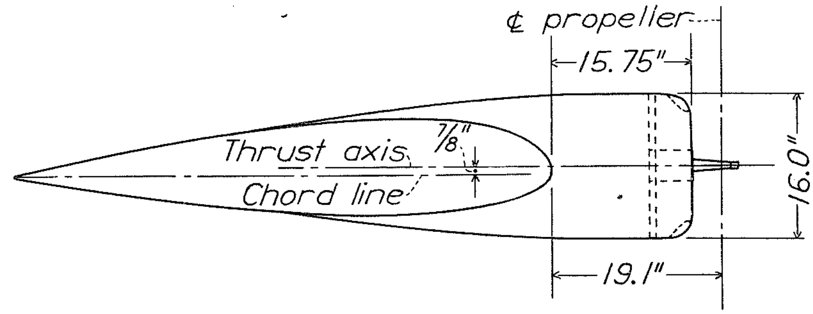
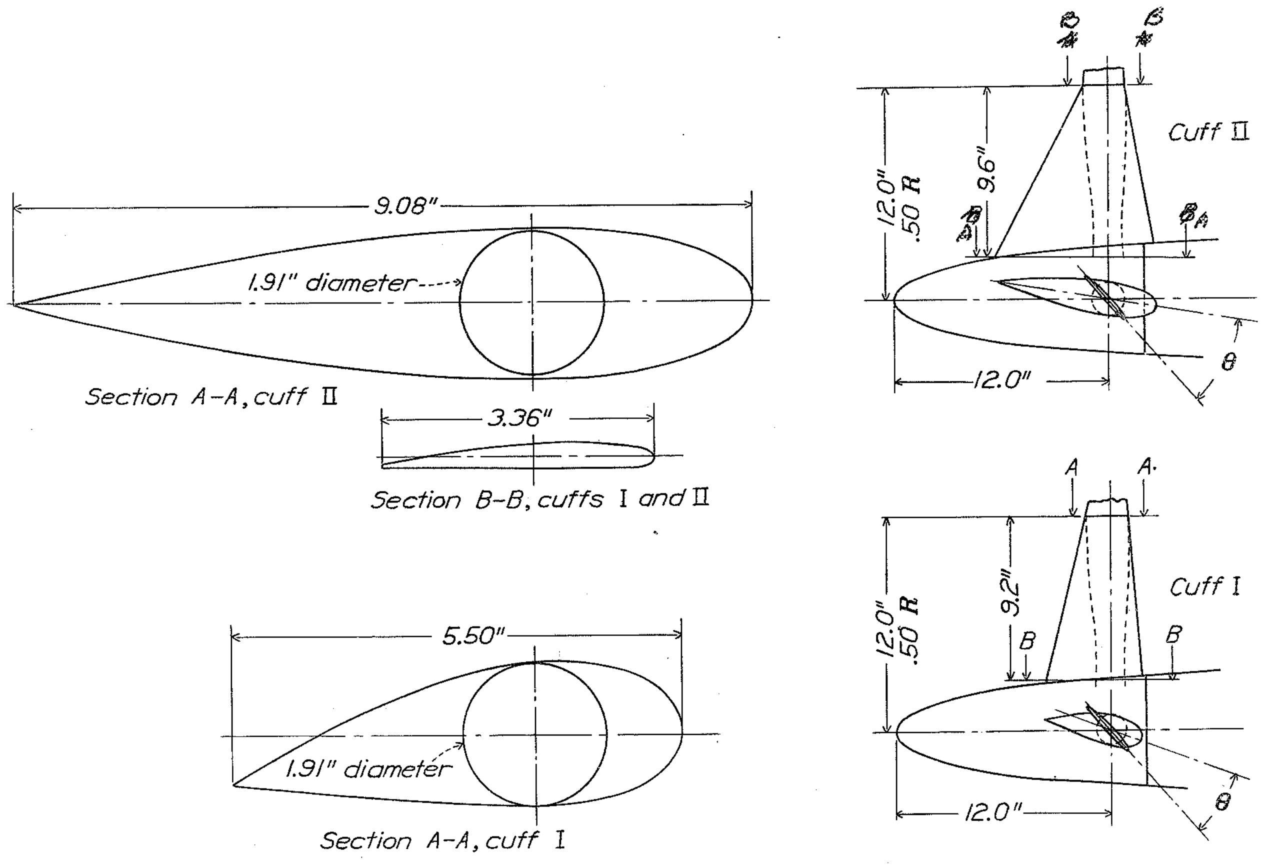
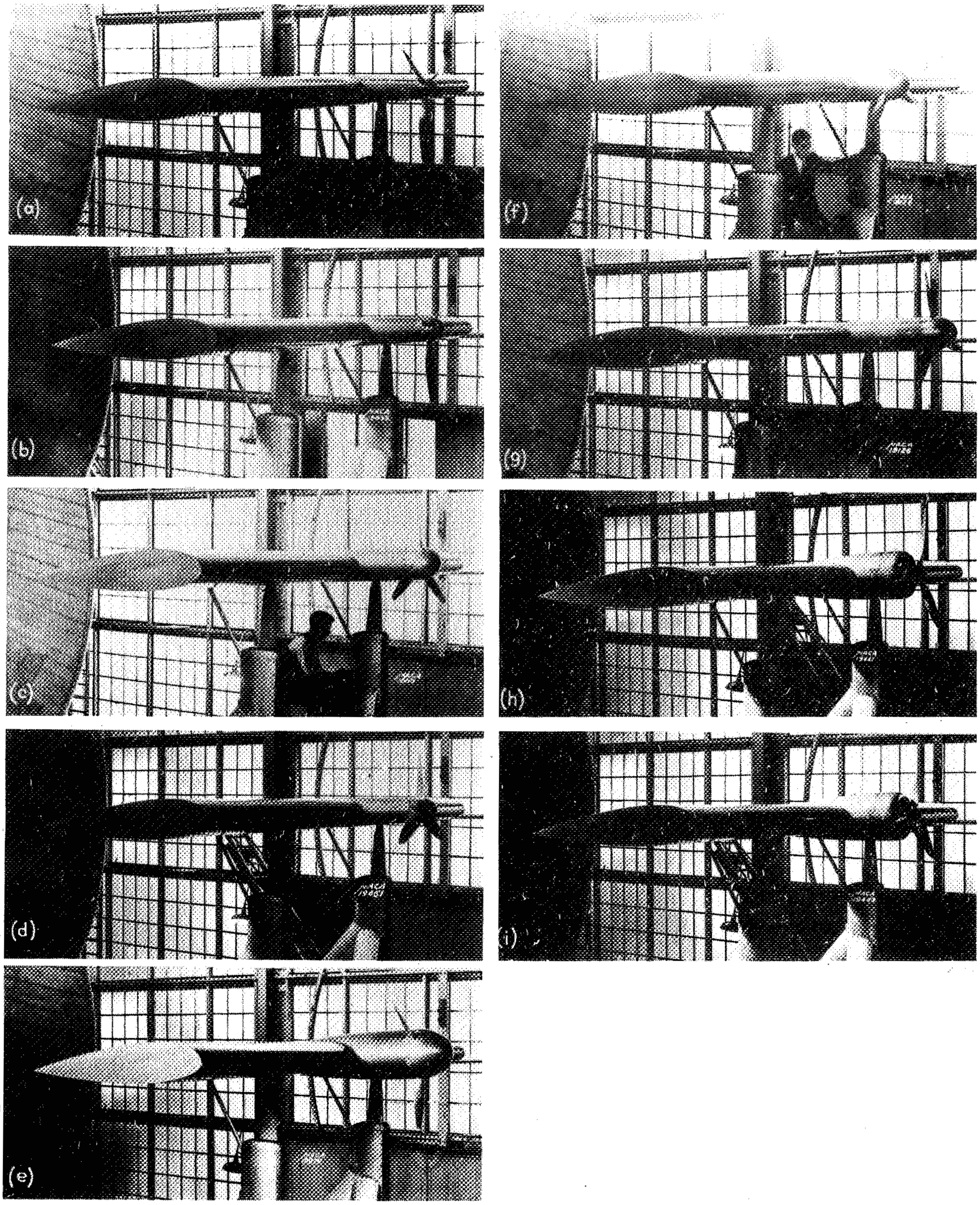


Figure 4.- Sketch of the NACA cowling tested.



Cuff	Blade angle at 0.75R,deg	Angle between sections A and B, θ,deg
I	35	28.7
II	35	40.1
II	45	32.7

Figure 7.- Cuffs I and II as used with the 6101 pusher propeller with an elliptical spinner of 6-inch diameter and 12-inch length.



(a) The 6-inch spinner; propeller 6101; position 2.
(b) The 8-inch spinner; propeller 6101; position 2.
(c) The 10.7-inch spinner; propeller 6101; position 2.
(d) The 8-inch spinner; N A C A 7099 propeller; position 2.
(e) The 16-inch spinner; propeller 6101; position 2.
(f) The 10.7-inch spinner; propeller 6101; position 1.
(g) The 10.7-inch spinner; propeller 6101; position 3.
(h) The 16-inch N A C A cowling; propeller 6101; position 2.
(i) The 16-inch N A C A cowling; N A C A 7099 propeller; position 2.

Figure 5. Photographs of the tractor-propeller wing extension-shaft arrangements tested.

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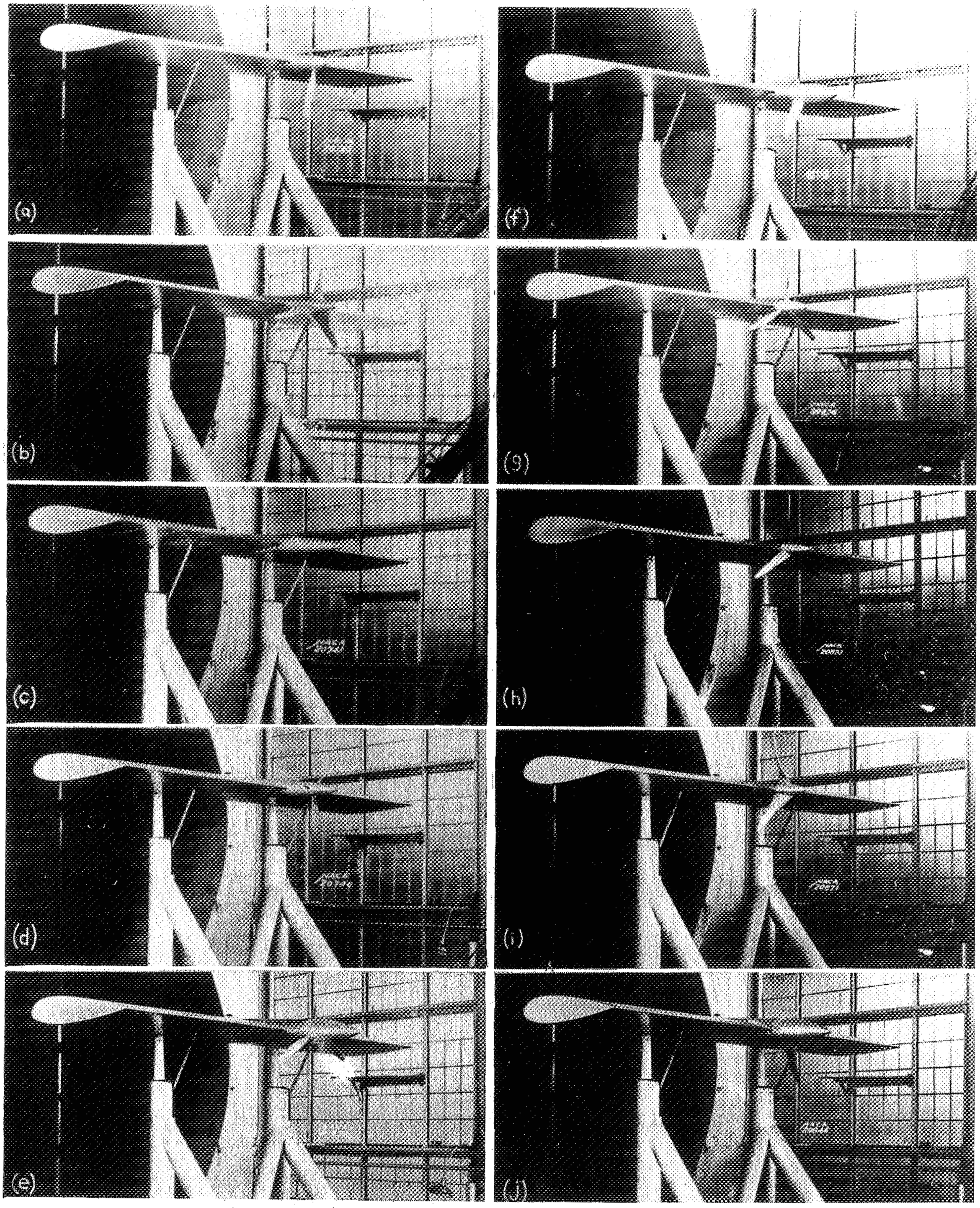


(a) The 6-inch spinner, 6 inches long; propeller 6101; position 5.

(b) The 6-inch spinner, 12 inches long; propeller 6101 with cuffs; position 5.

(c) The 6-inch spinner, 18 inches long; for propeller 6101; position 5.

(d) The 6-inch spinner, 14-18 inches long; propeller 6101; position 5.

(e) The 10.7-inch spinner; propeller 6101; position 5.

(f) The 8-inch spinner; N A C A 7099 propeller; position 5.

(g) The 6-inch spinner, 12 inches long; propeller 6101; position 4.

(h) The 6-inch spinner, 12 inches long; propeller 6101 with cuffs; position 4.

(i) The 6-inch spinner, 12 inches long; propeller 6101 with cuffs; position 4.

(j) The 10.7-inch spinner; propeller 6101; position 4.

Figure 6. Photographs of the pusher-propeller wing extension-shaft arrangements tested.

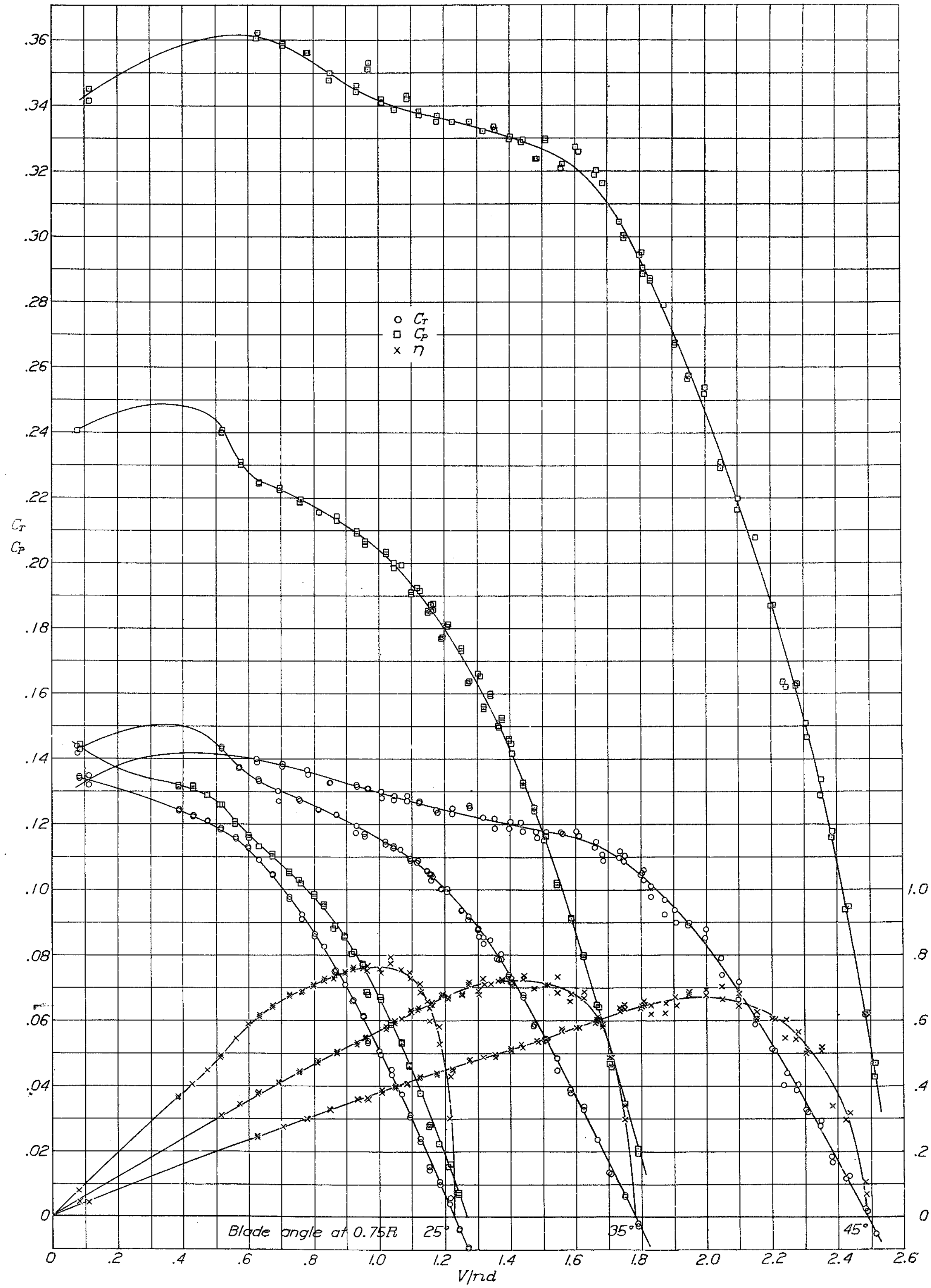


Figure 9.- Typical propeller-test results. The 6101 pusher-propeller extension-shaft combination with the 6.0-inch spinner, 12.0 inches long.

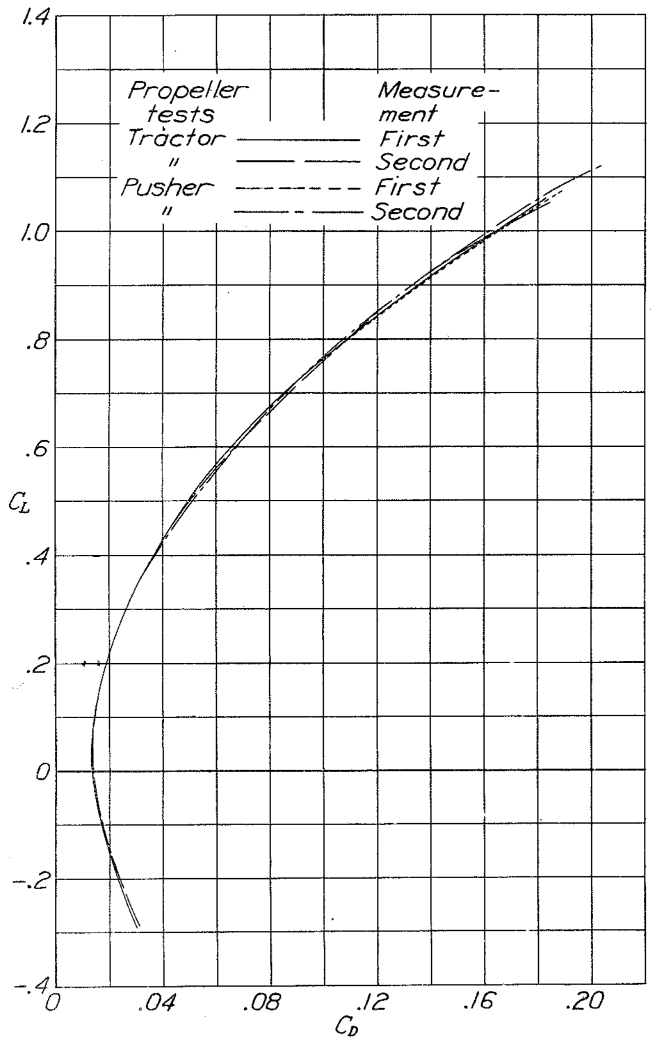


Figure 10.- Lift and drag characteristics of the wing alone, as indicated by the four measurements made during the extension-shaft tests.

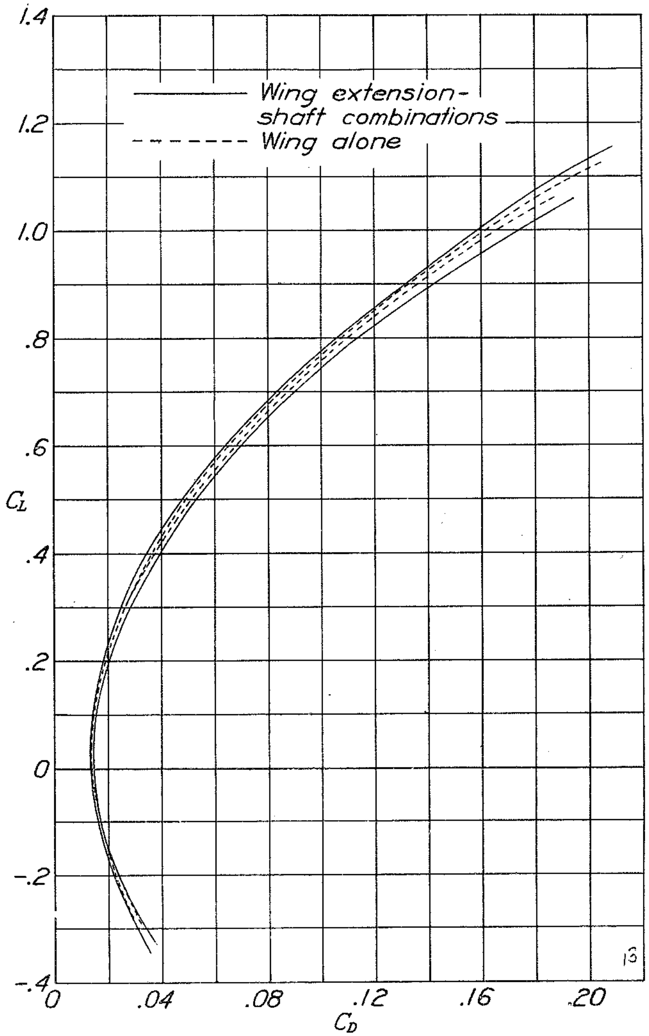
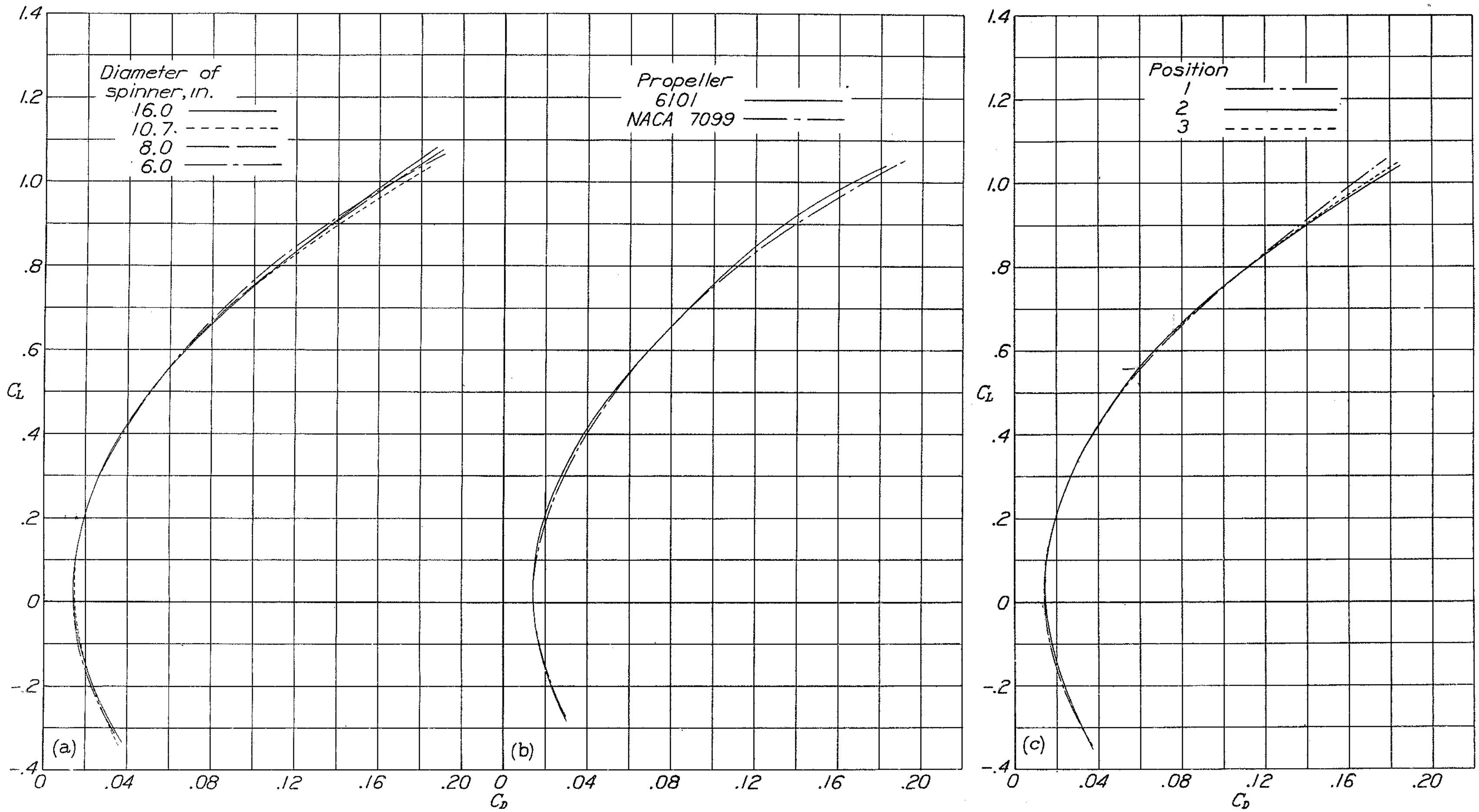


Figure 13.- Extreme limits of curves of lift and drag characteristics for the wing extension-shaft combinations compared with extreme limits of the tests made with the wing alone.

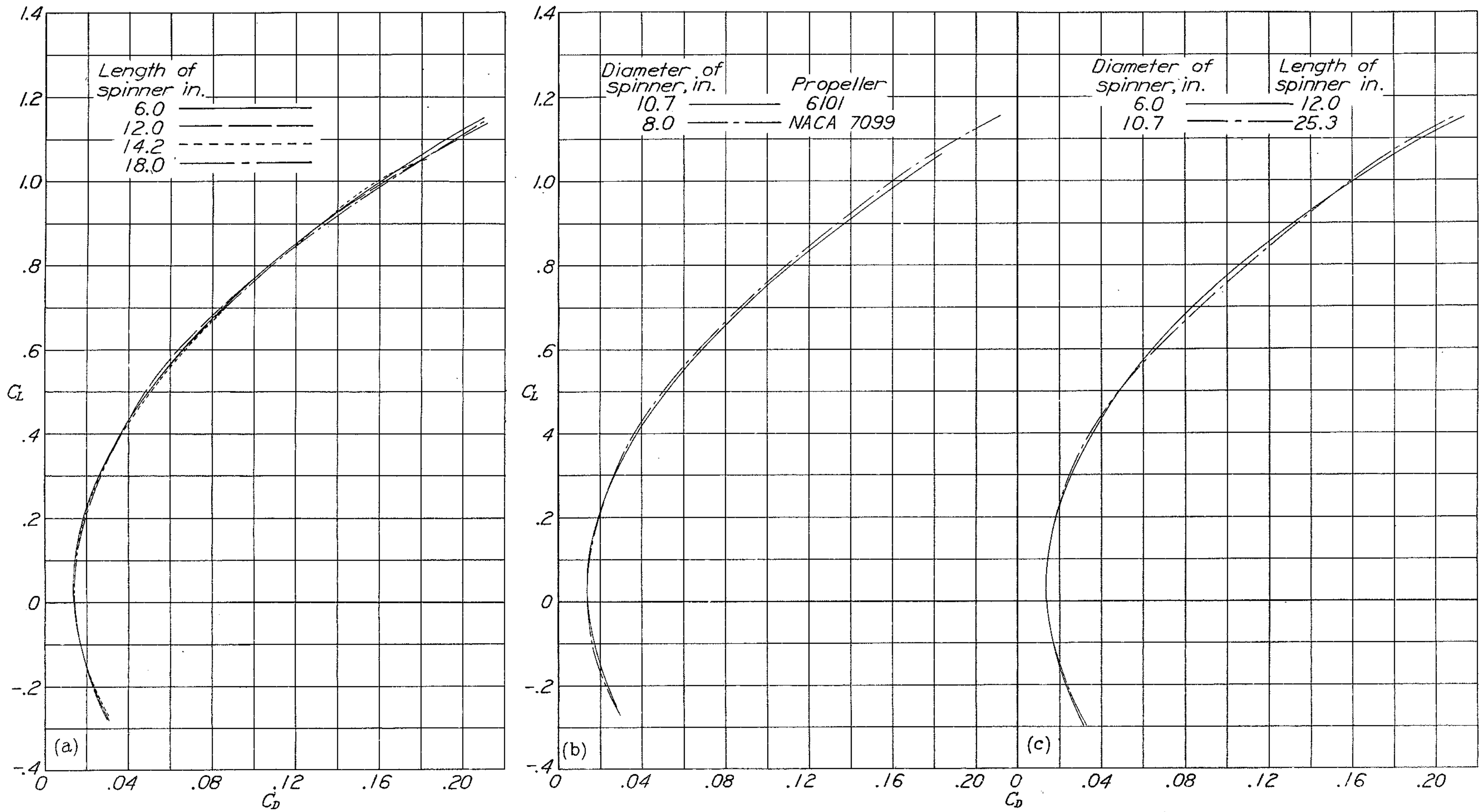


(a) Fairings and spinners of 6.0-, 8.0-, 10.7-, and 16.0-inch diameter in position 2 for propeller 6101.

(b) Fairings and spinners of 8.0-inch diameter in position 2 for the NACA 7099 and the 6101 propellers.

(c) Fairings and spinners of 10.7-inch diameter in positions 1, 2, and 3 for propeller 6101.

Figure 11.- Comparison of lift and drag characteristics of various wing extension-shaft combinations for tractor propellers.



(a) Fairings and spinners of 6.0-inch diameter and 6.0-, 12.0-, 14.2-, and 18.0-inch lengths in position 5 for propeller 6101.

(b) Fairings and spinners of 8.0-and 10.7-inch diameter in position 5 for the NACA 7099 and the 6101 propellers, respectively.

(c) Fairings and spinners of 6.0-and 10.7-inch diameters in position 4 for propeller 6101.

Figure 12.- Comparison of lift and drag characteristics of various wing extension-shaft combinations for pusher propellers.

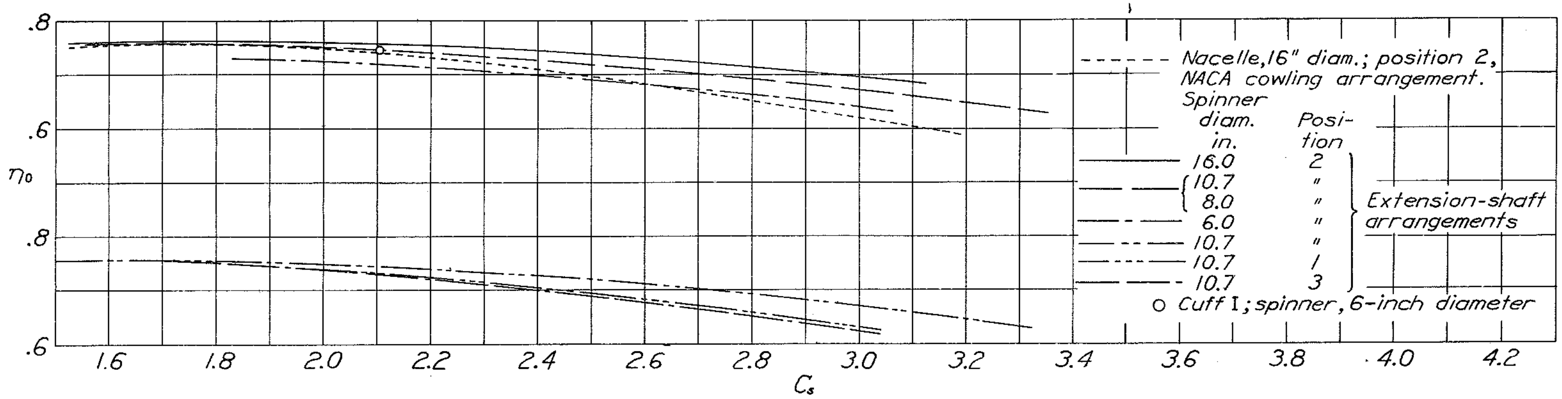


Figure 15.- Comparison of tractor-propeller extension-shaft arrangements for 6101 propeller.

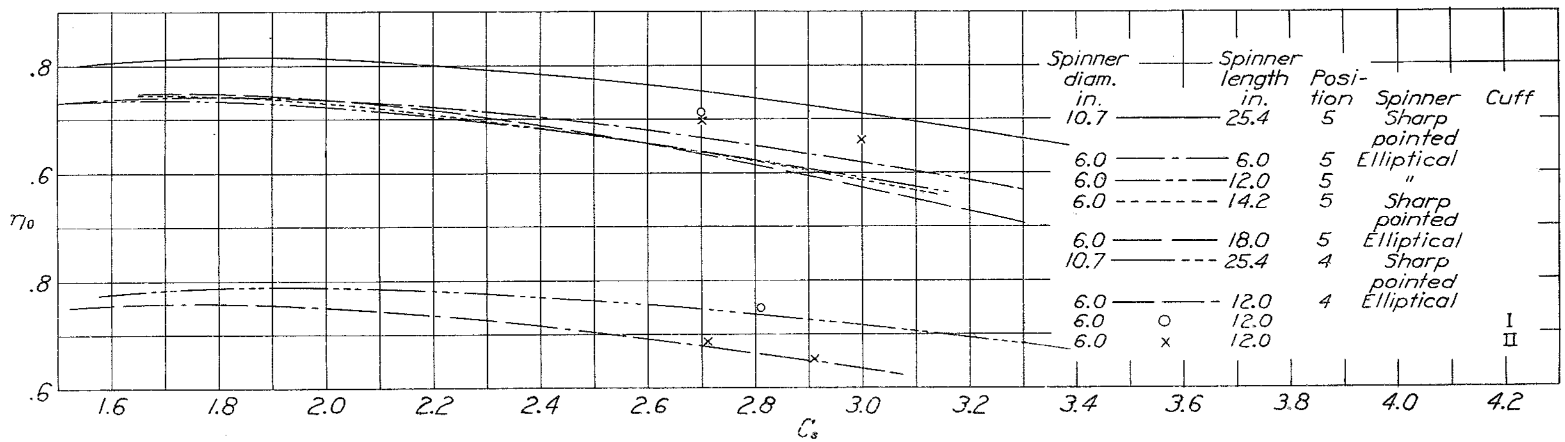


Figure 16.- Comparison of pusher-propeller extension-shaft arrangements for 6101 propeller.

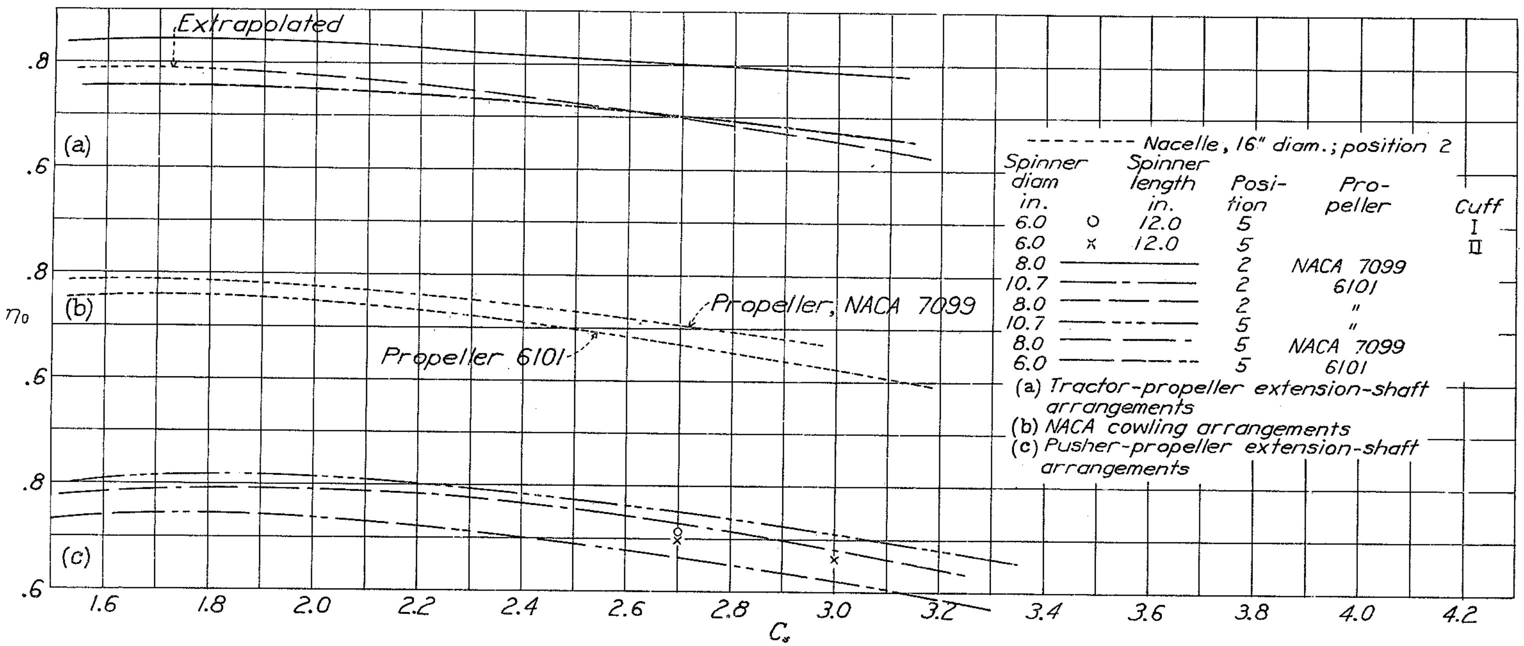


Figure 17.- Comparison of 6101 and NACA 7099 propellers in tractor and pusher arrangements.

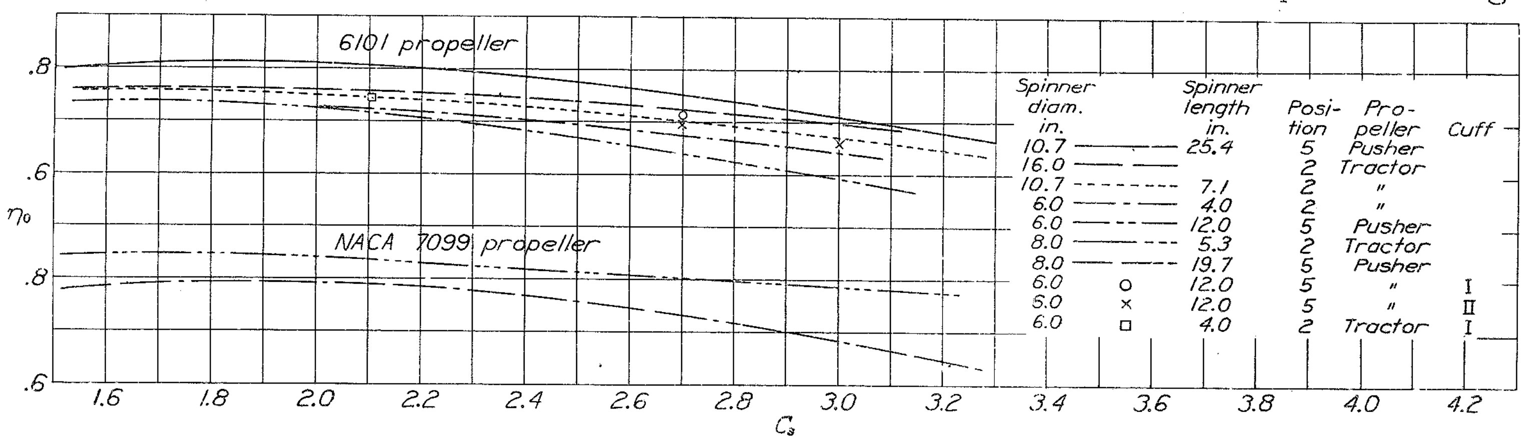


Figure 18.- Comparison of tractor-and pusher-propeller extension shaft arrangements.