REPORT No. 350

WORKING CHARTS FOR THE SELECTION OF ALUMINUM ALLOY PROPELLERS OF A STANDARD FORM TO OPERATE WITH VARIOUS AIRCRAFT ENGINES AND BODIES

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By Fred E. Weick

SUMMARY

Working charts are given for the convenient selection of aluminum alloy propellers of a standard form, to operate in connection with six different engine-fuselage combinations. The charts have been prepared from full-scale test data obtained in the 20-foot propeller research tunnel of the National Advisory Committee for Aeronautics. An example is also given showing the use of the charts.

INTRODUCTION

Several aerodynamic tests on a standard form of detachable blade metal propeller have been made in the N. A. C. A. Propeller Research Tunnel at Langley Field, Virginia. The tests have been made with various odd pitch settings and with various engine-fuselage combinations. In this report a set of faired and cross-faired curves, with the blade angles at three-fourths of the tip radius reduced to even values, is given for each propeller-engine-fuselage combination. The curves may be used for the selection of geometrically similar propellers for aircraft. The final adjusted coefficients are also given in tabular form.

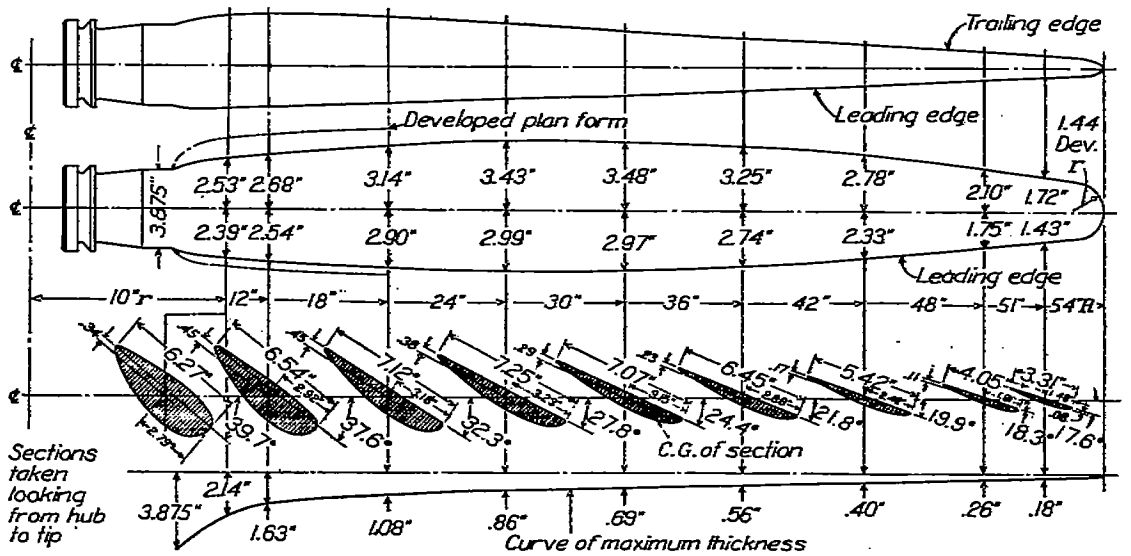

FIGURE 1.—Metal blade 9.0-foot diameter propeller. Right-hand No. 4412

ORDINATES OF SECTIONS AT VARIOUS RADII FOR EXPERIMENTAL METAL PROPELLER BLADE

9.0 FEET DIAMETER, RIGHT-HAND (FIG. 1)

S	10″ r		12″ r		18″ r	24″ r	30″ r	36″ r	42″ r	48″ r	51″ r
	Upper	Lower	Upper	Lower	Upper	Upper	Upper	Upper	Upper	Upper	Upper
	Inches	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*
2.5	0.61	0.25	0.56	0.11	0.44	0.35	0.28	0.23	0.16	0.11	0.07
5	.87	.39	.80	.16	.64	.51	.41	.33	.24	.15	.11
10	1.17	.52	1.07	.21	.85	.68	.55	.44	.32	.21	.14
20	1.41	.63	1.29	.26	1.03	.82	.66	.53	.38	.25	.17
30	1.48	.66	1.36	.27	1.08	.86	.69	.56	.40	.26	.18
40	1.47	.65	1.35	.27	1.07	.85	.68	.56	.40	.26	.18
50	1.41	.63	1.29	.26	1.03	.82	.66	.53	.38	.25	.17
60	1.29	.57	1.18	.24	.94	.75	.60	.49	.35	.23	.16
70	1.10	.49	1.01	.20	.80	.64	.51	.42	.30	.19	.13
80	.83	.37	.76	.15	.61	.48	.39	.31	.22	.15	.10
90	.52	.23	.48	.09	.38	.30	.24	.20	.14	.09	.06
Rad. T. E.	0.18		0.14		.08	.07	.05	.04	.03	.02	.02
Rad. L. E.	0.64		0.30		.11	.09	.07	.06	.04	.03	.02
Chord	6.27		6.54		7.12	7.25	7.07	6.45	5.42	4.05	3.31

The chord is divided into 10 equal parts, or stations, with the one at the leading edge subdivided into halves and quarters. S equals stations in per cent of chord from the leading edge.

PROPELLERS AND BODIES

A standard form of metal propeller 9 feet in diameter was used, having detachable aluminum alloy blades which could be adjusted to any desired angle in a steel split-type hub. A drawing showing the blade dimensions (Navy design No. 4412) is given in Figure 1, and the blade form is also given by the curves in Figure 2. The propeller has standard propeller airfoil sections based on the R. A. F. 6. The pitch is notable in that it is very nearly uniform when the blades are set to pitch ratios around .5, and increases toward the tip for all higher pitch ratios. This is shown in Figure 2, in which the pitch distribution is given for several blade angle settings. (The settings are given in terms of the blade angle at 75 per cent of the tip radius, R, the various pitches having been obtained by merely turning the blades in the hub.)

No. 4. Cabin fuselage with monoplane wing and J–5 engine. (Fig. 6.) No cowling over cylinders or crank case. Maximum cross-sectional area of fuselage alone, 21.3 square feet.

No. 5. Cabin fuselage without wing, with J–5 engine. (Fig. 7.) Large amount of conventional cowling, leaving only the top portions of the cylinder heads and valve gear exposed. Maximum cross-sectional area, 21.3 square feet.

No. 6. Cabin fuselage with J–5 engine and N. A. C. A. type complete cowling. (Fig. 8, References 1 and 2.) Maximum cross-sectional area, 21.3 square feet.

As shown by the photographs, the VE–7 landing gear was used with each of the fuselages. In each case also, the engine was mounted on a special torque dynamometer which was inclosed within the fuselage, so

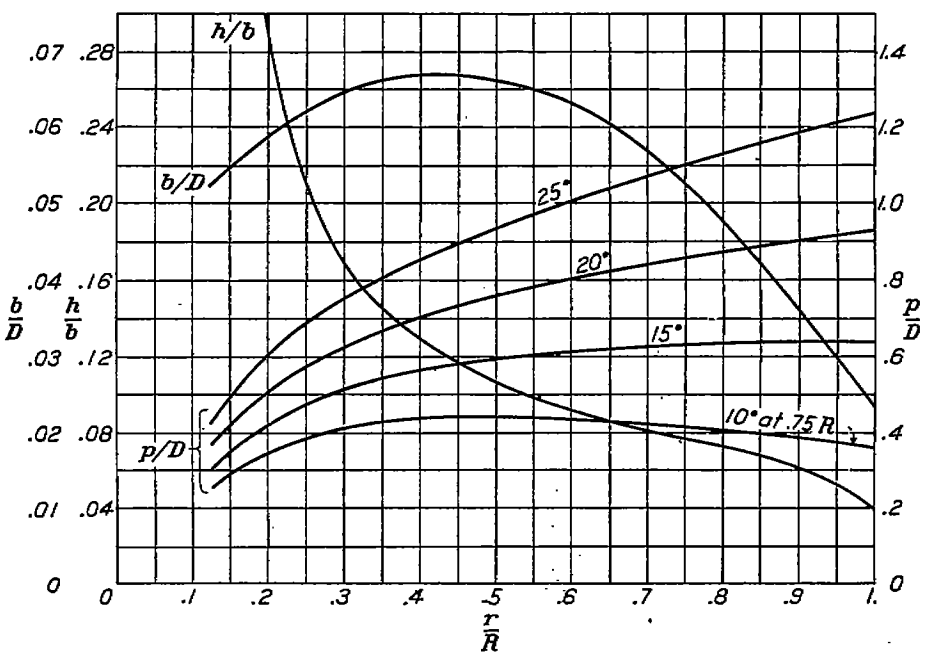

FIGURE 2.—Propeller blade form curves. D=diameter; b=blade width; h=blade thickness; p=pitch; R=tip radius=$\frac{D}{2}$; r=radius

The fuselage-engine combinations upon which the propellers were tested may be listed as follows:

No. 1. Open cockpit fuselage with 400-horsepower Curtiss D–12 engine. (Fig. 3.) No radiator (corresponds to case with wing radiators). Smoothly faired nose. Maximum cross-sectional area, 11.6 square feet.

No. 2. Complete VE–7 airplane with wings and tail surfaces. (Fig. 4.) Open cockpit fuselage with 180-horsepower Wright E–2 water-cooled engine and nose radiator. Maximum cross-sectional area of fuselage, 9.6 square feet.

No. 3. Open cockpit fuselage with Wright "Whirlwind" J–5 9-cylinder 200-horsepower air-cooled radial engine. (Fig. 5.) Medium amount of conventional cowling. Maximum cross-sectional area, 11 square feet.

that the engine torque and power could be determined directly.

The Propeller Research Tunnel is an open throat wind tunnel having an airstream 20 feet in diameter in which velocities up to 110 miles per hour can be obtained. It is described in detail, along with the balances and measuring devices, in Reference 3.

METHODS

The measured engine torque, in the cases with the air-cooled engine, included a torque on the cylinders due to the twist of the slip stream. Special tests were made (References 1, 4, 5, and 6) to determine the magnitude of this slip-stream torque under the various operating conditions, and the results were applied as a correction, which amounted to as much as 3 per cent in some cases, to the measured engine torque.

FIGURE 3.—No. 1. Open cockpit fuselage with D-12 engine. No radiator

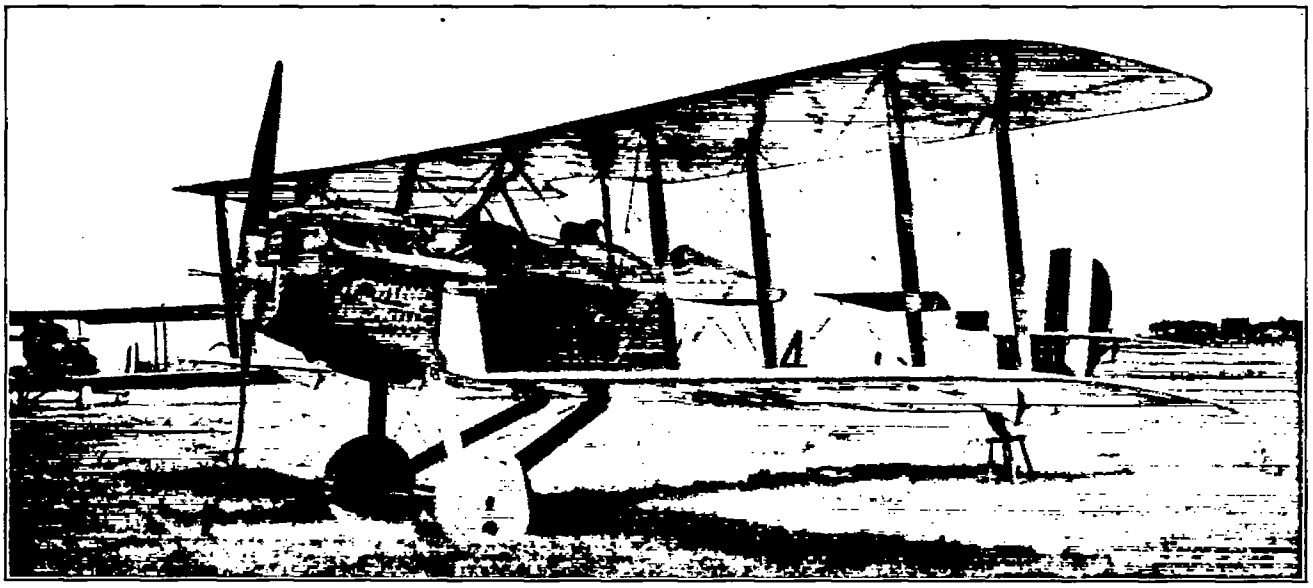

FIGURE 4.—No. 2. VE-7 airplane. (Propeller shown not used)

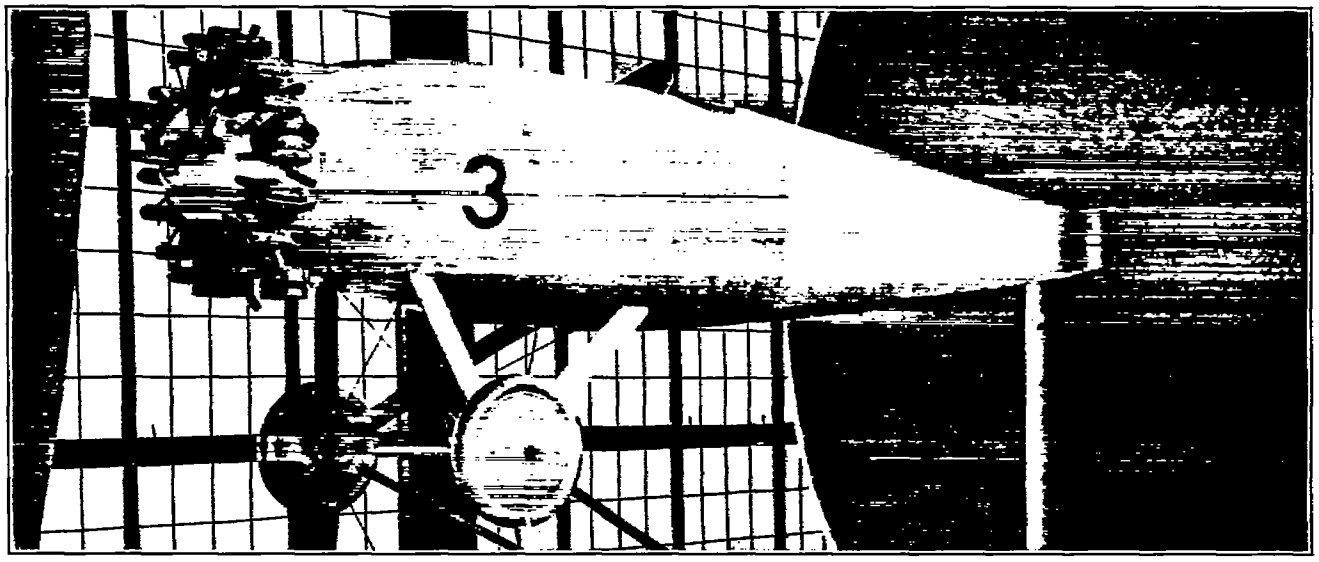

FIGURE 5.—No. 3. Open cockpit fuselage with J-5 engine

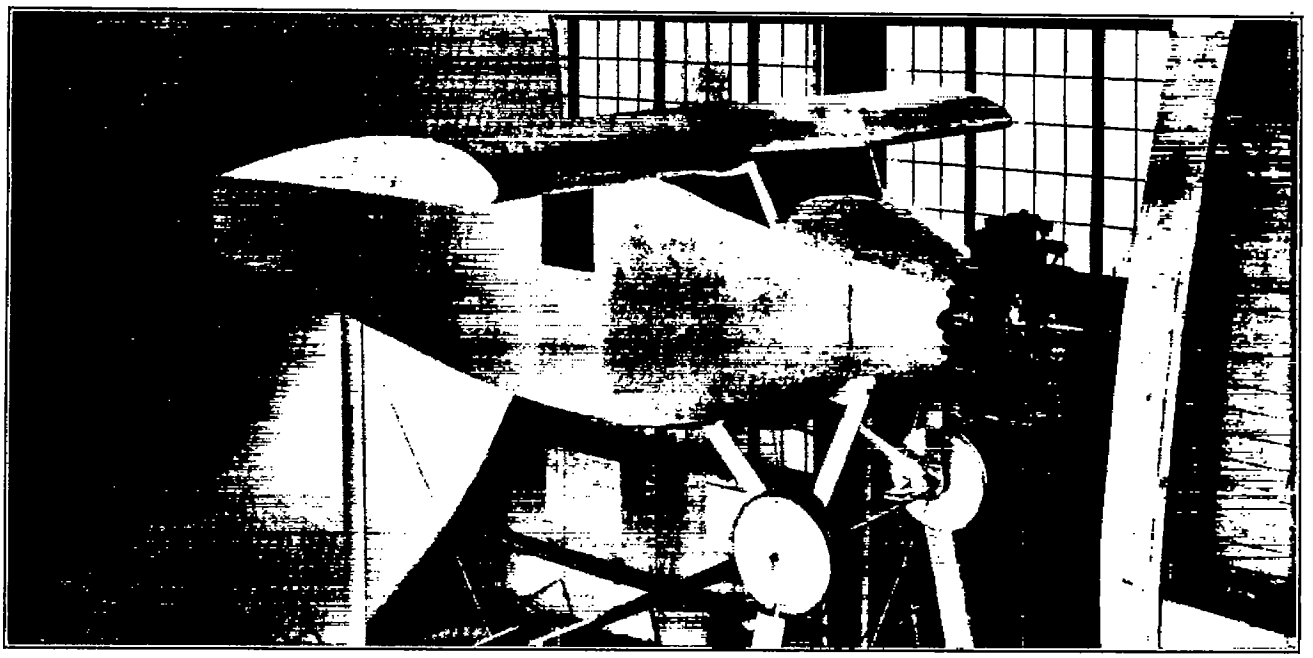

FIGURE 6.—No. 4. Cabin monoplane with J-5 engine

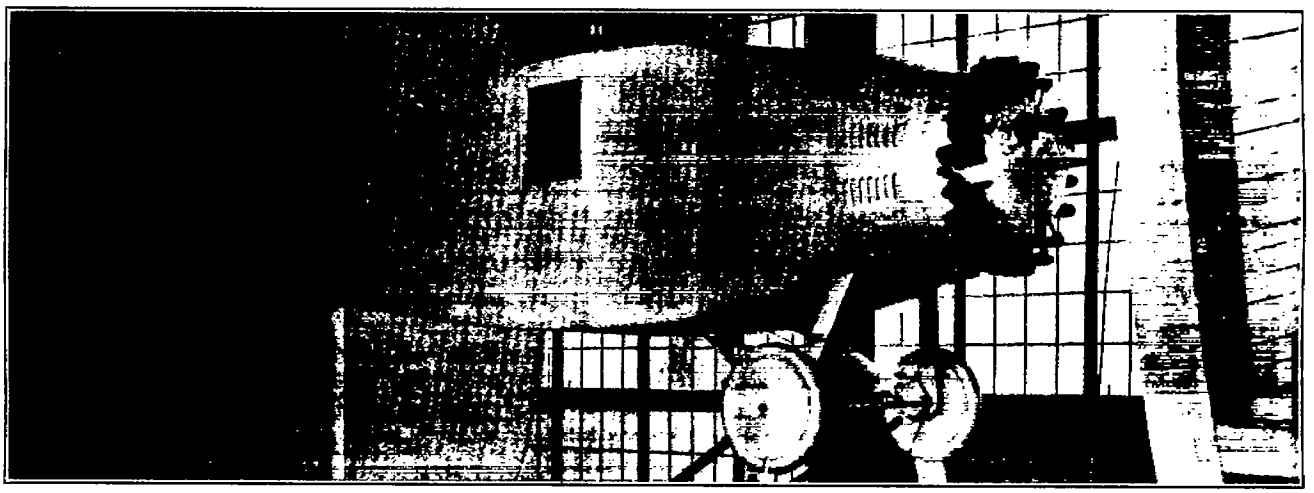

FIGURE 7.—No. 5. Cabin fuselage with J-5 engine

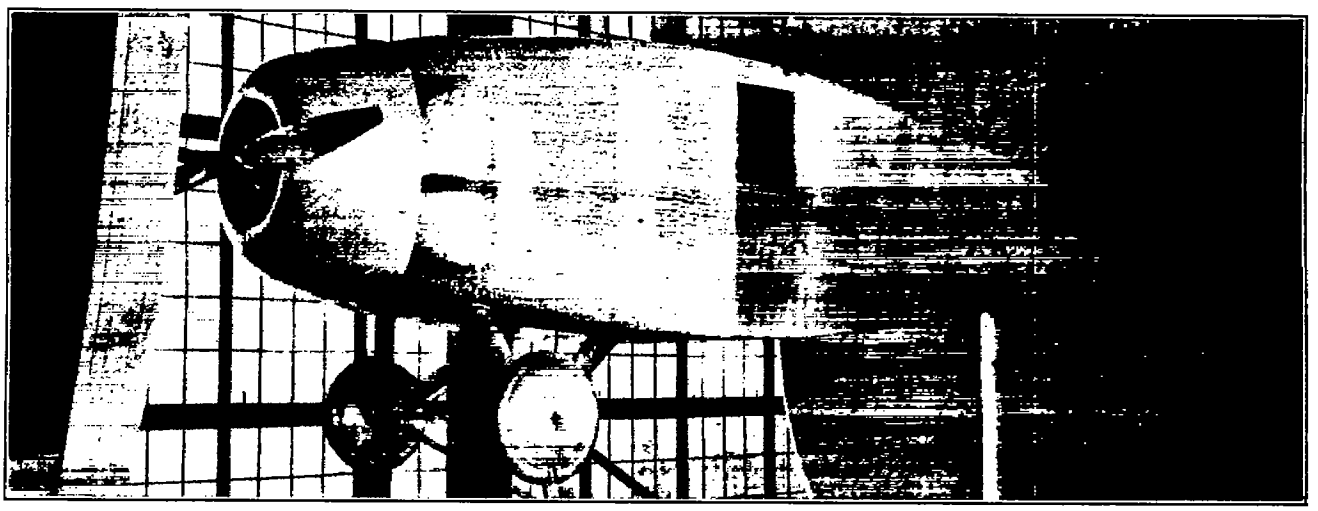

FIGURE 8.—No. 6. Cabin fuselage with completely cowled J-5 engine

The resultant horizontal force of the propeller-body combination, which may be either a thrust or a drag, was measured on the regular thrust balance. (Reference 3.) This resultant horizontal force, R, may be thought of as composed of three horizontal components, such that

$$R=T-D-\Delta D,$$

where

T = the thrust of the propeller while operating in front of the body (the tension in the propeller shaft).

D = the drag of the airplane alone (without propeller) at the same air velocity and density.

ΔD = the increase in drag of the airplane with propeller, due to the slip stream.

In order to obtain the propulsive efficiency, which includes the propeller-body interference, an effective thrust is used which is defined as

$$\text{Effective thrust}=T-\Delta D=R+D.$$

The propulsive efficiency, then, is the ratio of the useful power to the input power, or

$$\text{Propulsive efficiency}=\frac{\text{effective thrust}\times\text{velocity of advance}}{\text{input power}}$$

This propulsive efficiency includes the increase in drag of all parts of the airplane affected by the slipstream, and also the effect of the body interference on the propeller thrust and power.

RESULTS

The observed test data have been faired and cross-faired, the final adjusted coefficients being given for even blade angle settings in Tables I to VI. They are given in terms of the power coefficient C_P, the propulsive efficiency η, and the speed-power coefficient C_S, which are defined by the following equations:

$$C_P=\frac{P}{\rho n^3 D^5},$$

$$\eta=\frac{(T-\Delta D)V}{P},$$

$$C_S=\sqrt[5]{\frac{\rho V^5}{P n^2}},$$

where

P = input power.
n = revolutions per unit time.
V = velocity of advance.
D = propeller diameter,
ρ = mass density of the air.

The coefficients are all dimensionlees, so that any consistent system of units may be employed.

TORSIONAL DEFLECTION OF BLADES

Propellers deflect and twist under load, so that the pitch of an operating propeller is often quite different from the pitch of the same propeller in the static condition where there is no load. It was noticed in the tests with the 400-horsepower D–12 engine that if the same value of $\frac{V}{nD}$ was obtained with different throttle settings and, therefore, different values of power input, the propeller power coefficients were not always the same. The power coefficients seemed to be greater when the propeller absorbed higher power at the same $\frac{V}{nD}$. In order to investigate this variation of the propeller coefficients, the tests with the propeller set at 15.0° at the 42-inch radius were repeated with the D–12 engine at various throttle settings, the corresponding values of horsepower being from about 25 to 400. The results of these tests are shown in Figure 16, which shows that the power coefficients are higher at the higher powers for all values of $\frac{V}{nD}$. At the values of $\frac{V}{nD}$ representing the operating conditions in flight (the values from .4 to .6), the power coefficients are practically constant up to 200 horsepower, but they increase quite markedly from 200 horsepower to 400 horsepower.

In order to make the results of all of the tests comparable, the tests from which the working chart data were taken were run with the D–12 engine throttled to 200 horsepower, which was approximately the power of the other engines.

Two possible causes for the increase in power coefficient with increase of power input, which in these tests was accompanied by an increase in revolutions, are (1) tip speed effect, and (2) deflection in blade angle, tending to increase the pitch due to higher air loading at the higher powers. The tip speeds reached in these tests were all below the values where the compressibility effect due to high velocity would be in evidence. (Reference 7.) On the other hand, it seems quite reasonable that the increase of power coefficient may be due to deflection, and this is substantiated by the fact that the thrust and efficiency coefficients obtained with the high powers are about the same as those obtained with lower powers, but at slightly higher pitch settings. Also, deflection measurements which were taken during the tests show that the blade angles increased with increase of power, but the measurements were unfortunately not sufficiently accurate to use as a basis for showing the exact variation.

If the variation of power coefficient with power input is, as seems reasonable, actually due entirely to

deflection, the working charts can be satisfactorily used for engines of all powers if only the deflection in operation is known. It is only necessary to consider the blade angles as those existing under operating instead of static conditions.

Although deflection data covering a large range of powers, bodies, and propellers are not available, a useful approximate rule for direct drive propellers similar to the design used in these tests can be based on the data obtained with the D–12 engine, shown in Figure 16. This rule is that the working charts may be used without considering deflection in operation for powers up to 200 horsepower, but above 200 horsepower the average blade angle increases at the rate of .5° for each increase of 100 horsepower. This would make an increase of .5° for an engine of 300 horsepower, 1.0° for 400 horsepower, and 1.5° for 500 horsepower, the last being, of course, in the nature of an extrapolation. While there may be a question whether this rule applies to other diameters, it appears to work in practice as mentioned later.

WORKING CHARTS

Figures 9 to 14 are working charts which are arranged for the convenient and accurate selection of metal propellers of the form used in these tests for aircraft having bodies similar to those tested. A separate chart is given for each propeller-body combination, in which curves of propulsive efficiency and $\frac{V}{nD}$ are given, for even blade angle settings, against the speed-power coefficient C_s.

In order to find the diameter and pitch of a propeller of this form for any particular set of operating conditions, it is merely necessary to

(1) Calculate the value of C_s from the power, revolutions, forward speed, and altitude, at which the propeller is to operate;

(2) Choose the pitch setting for the propeller operating at the desired portion of the efficiency curve (depending on the airplane performance desired) and the above C_s;

(3) Find the $\frac{V}{nD}$ for the above C_s and pitch setting from the lower curves;

(4) Knowing $\frac{V}{nD}$, n, and V, calculate D.

If the diameter of the propeller is fixed to start with $\frac{V}{nD}$ is also fixed, and the pitch setting can be found directly from the curves of $\frac{V}{nD}$ versus C_s.

Example:

A propeller is to be selected for a cabin airplane similar in form to that in Figure 6. With an uncowled radial engine developing 250 horsepower at 1,700 revolutions per minute, the maximum horizontal speed is expected to be 130 miles per hour.

$$C_s=\sqrt[5]{\frac{\rho V^3}{Pn^2}} \tag{1}$$

which for sea level and with engineering units may be written

$$C_s=\frac{.638\times \text{m. p. h.}}{\text{hp}^{1/5}\times \text{r. p. m.}^{2/5}}$$

$$=\frac{.638\times 130}{3.02\times 19.6}=1.40$$

The values of hp $^{1/5}$ and r. p. m. $^{2/5}$ can be easily obtained from scales provided for the purpose in Figure 15.

(2) It will be assumed that it is desired to have the propeller operate at its maximum efficiency at the high speed of the airplane. Then from the upper or efficiency curves of Figure 12, it will be seen that a setting of 19.0° at .75 R satisfies this condition (i. e., the efficiency for a setting of 19.0° is maximum at C_s = approximately 1.40).

(3) From the lower set of curves in Figure 12, for $C_s=1.40$ and a blade angle of 19.0°, $\frac{V}{nD}=.723$.

$$D=\frac{88\times \text{m. p. h.}}{\text{r. p. m.}\times\left(\frac{V}{nD}\right)} \tag{4}$$

$$=\frac{88\times 130}{1700\times .723}$$

$$=9.31 \text{ ft.}$$

The propulsive efficiency, from the upper curves, is .798.

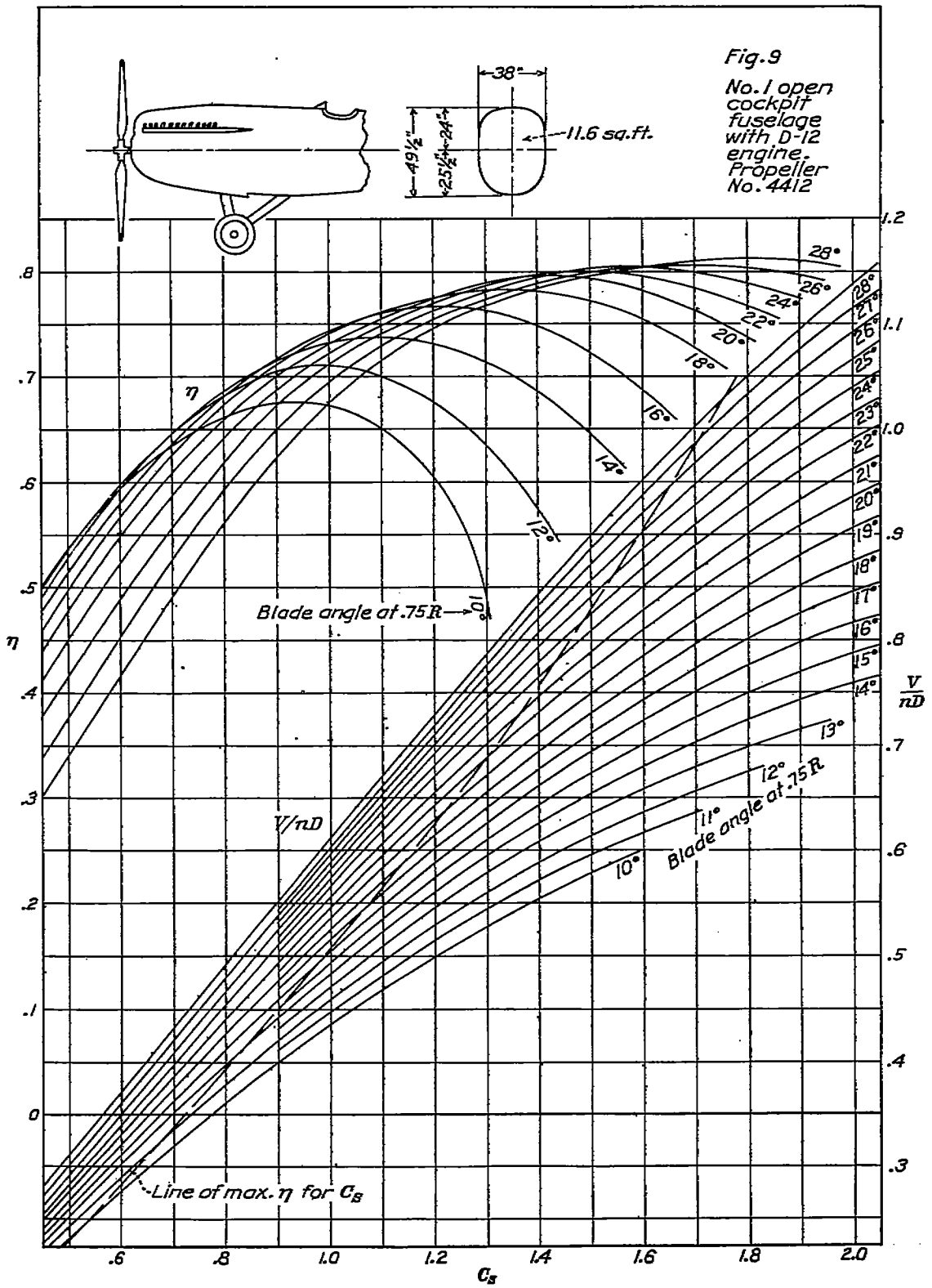
Fig. 9
No. 1 open cockpit fuselage with D-12 engine. Propeller No. 4412
38"
49½"
25½"
24"
11.6 sq. ft.
η
V/nD
Blade angle at .75R
Line of max. η for C_s
C_s
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
0
.1
.2
.3
.4
.5
.6
.7
.8
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3

FIGURE 9

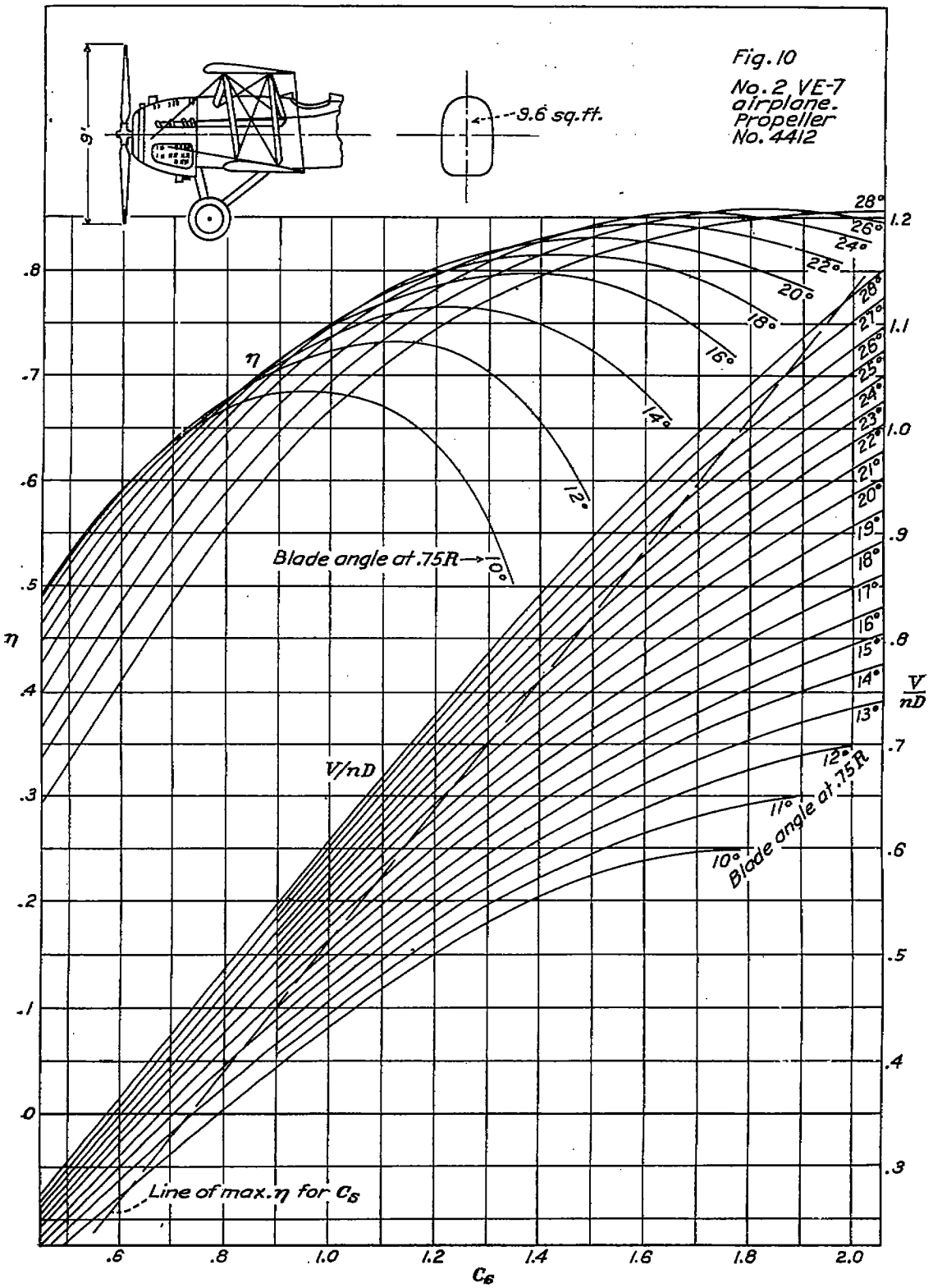
Fig. 10
No. 2 VE-7 airplane. Propeller No. 4412
9'
9.6 sq. ft.
η
V/nD
Blade angle at .75R
Line of max. η for C_S
C_S
$\frac{V}{nD}$

FIGURE 10

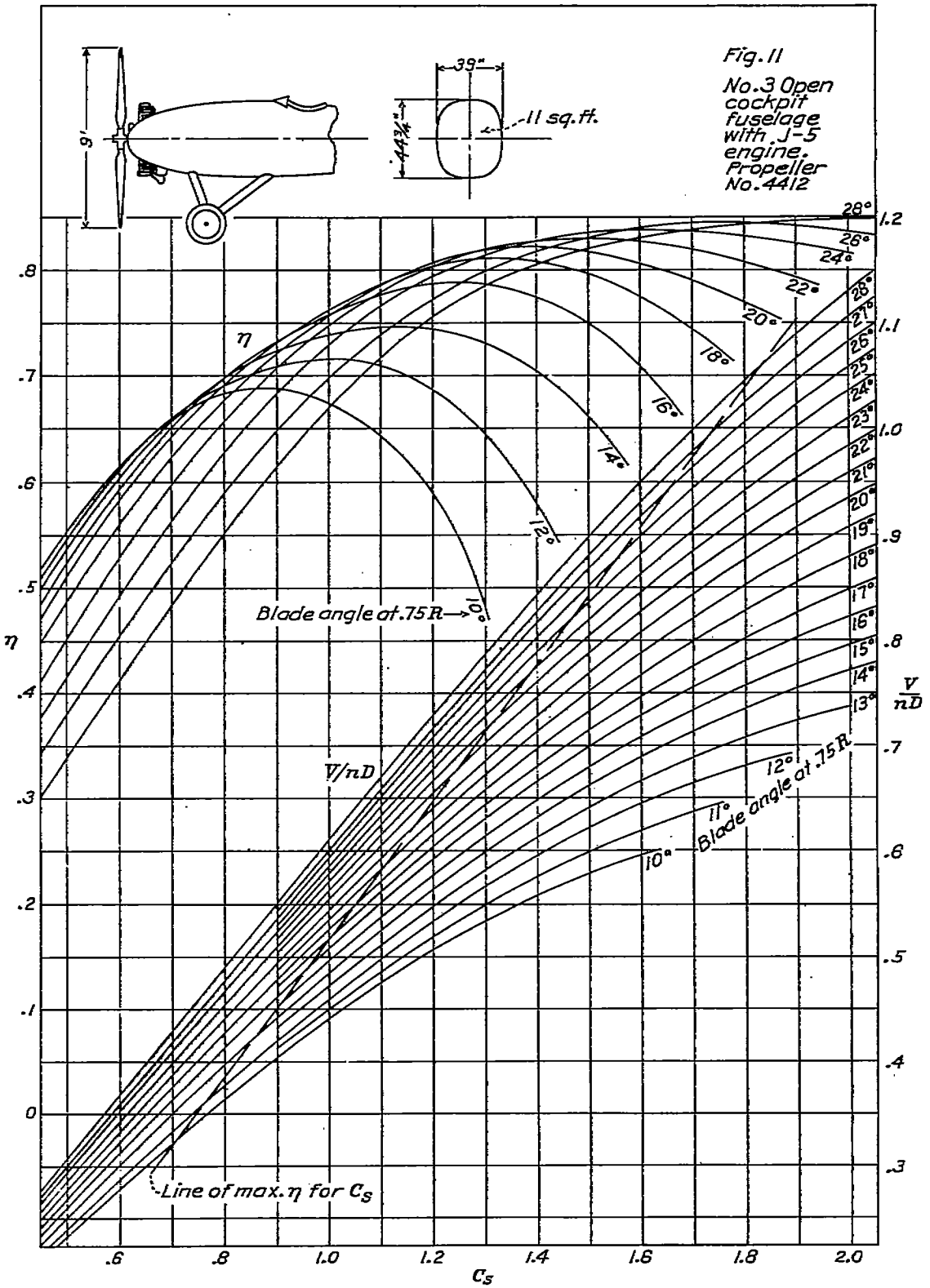
Fig. 11
No. 3 Open cockpit fuselage with J-5 engine. Propeller No. 4412
9'
39"
44¾"
11 sq. ft.
η
V/nD
Blade angle at .75R
Line of max. η for C_s
C_s
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2

FIGURE 11

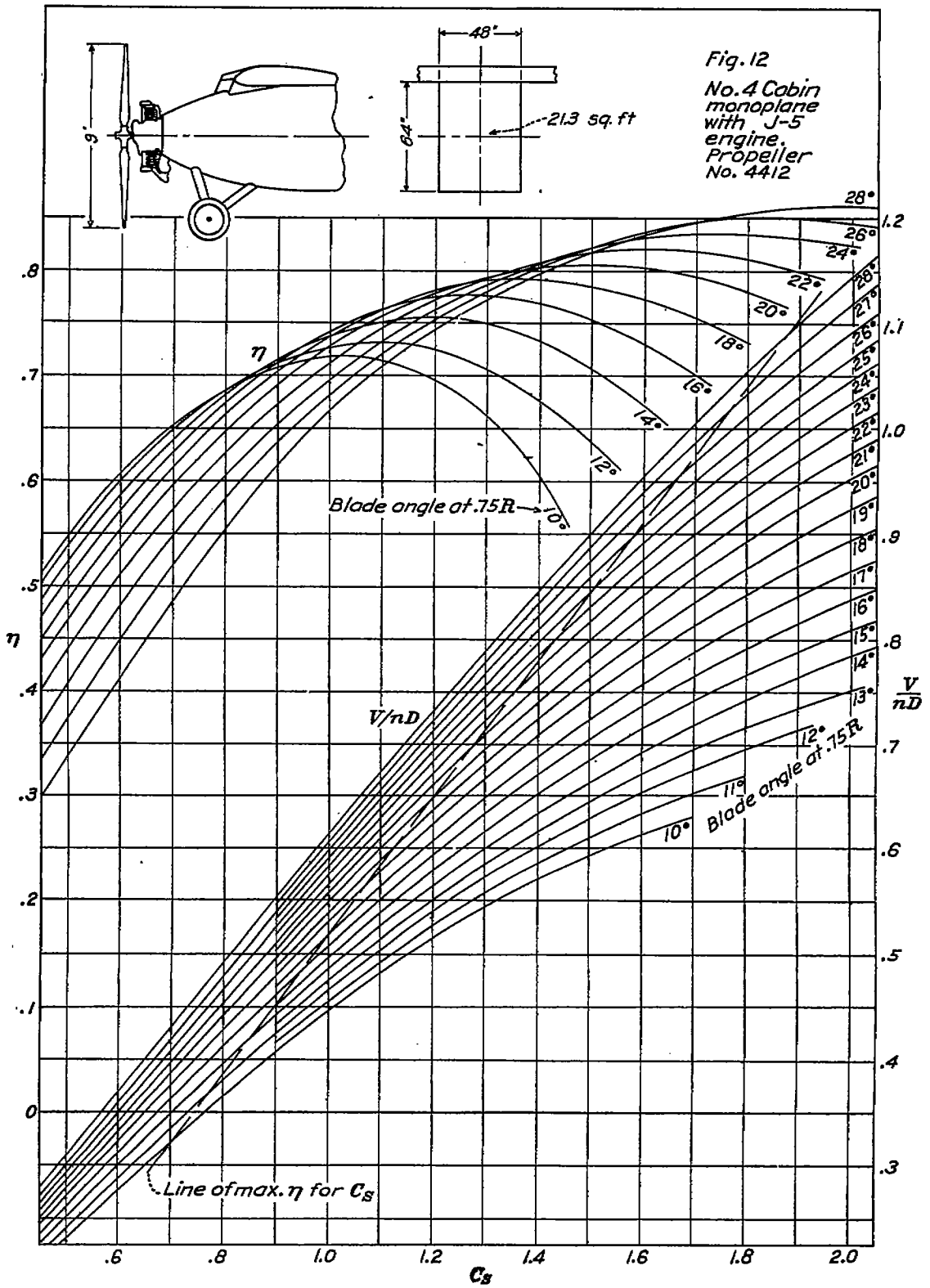
Fig. 12
No. 4 Cabin monoplane with J-5 engine. Propeller No. 4412
48"
64"
9'
21.3 sq. ft
η
V/nD
Blade angle at .75R
Line of max. η for C_s
C_s
$\frac{V}{nD}$

FIGURE 12

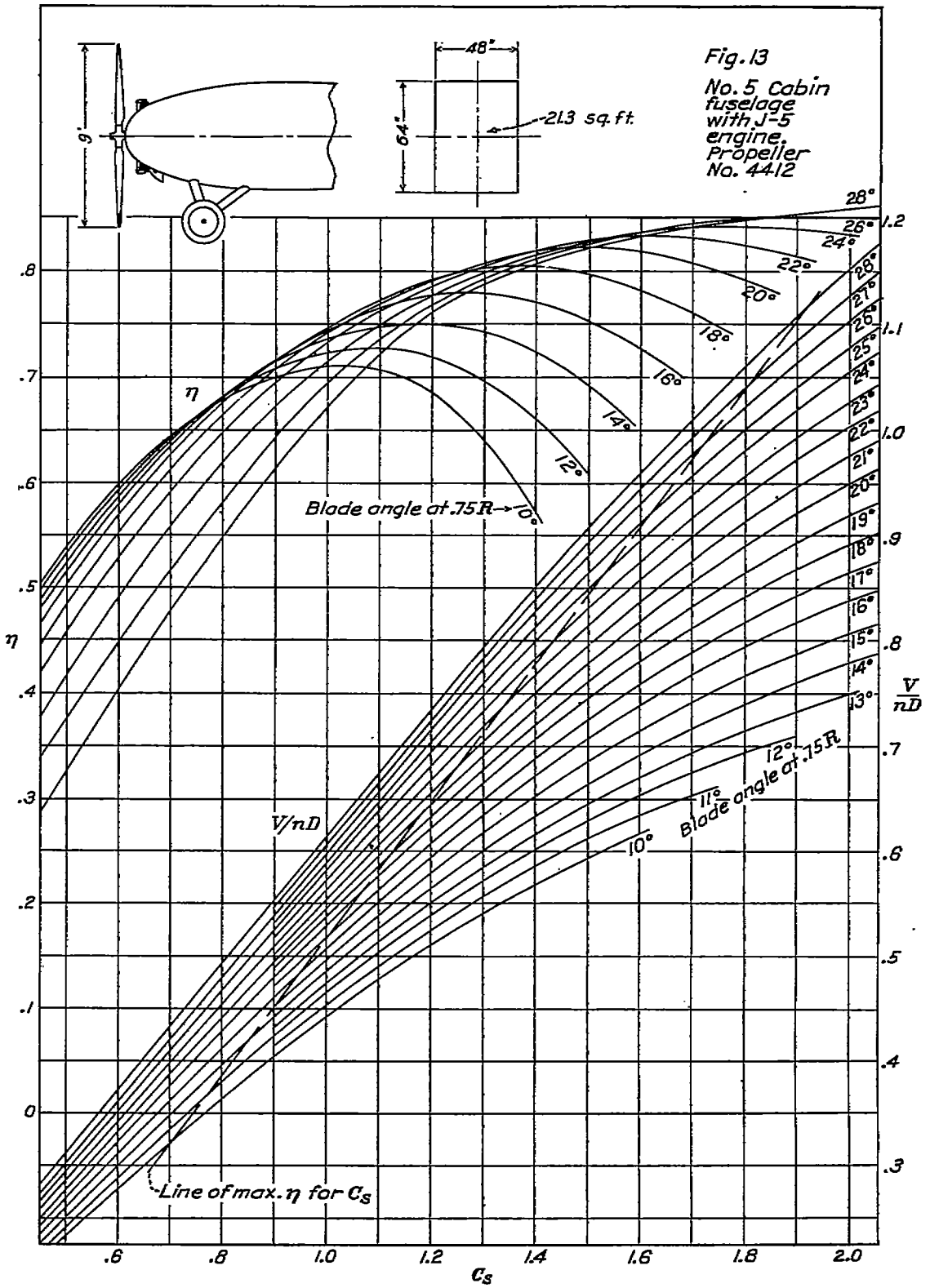
Fig. 13
No. 5 Cabin fuselage with J-5 engine. Propeller No. 4412
48"
64"
21.3 sq. ft.
9'
η
V/nD
Blade angle at .75R
Blade angle at .15R
Line of max. η for C_s
C_s
$\frac{V}{nD}$

FIGURE 13

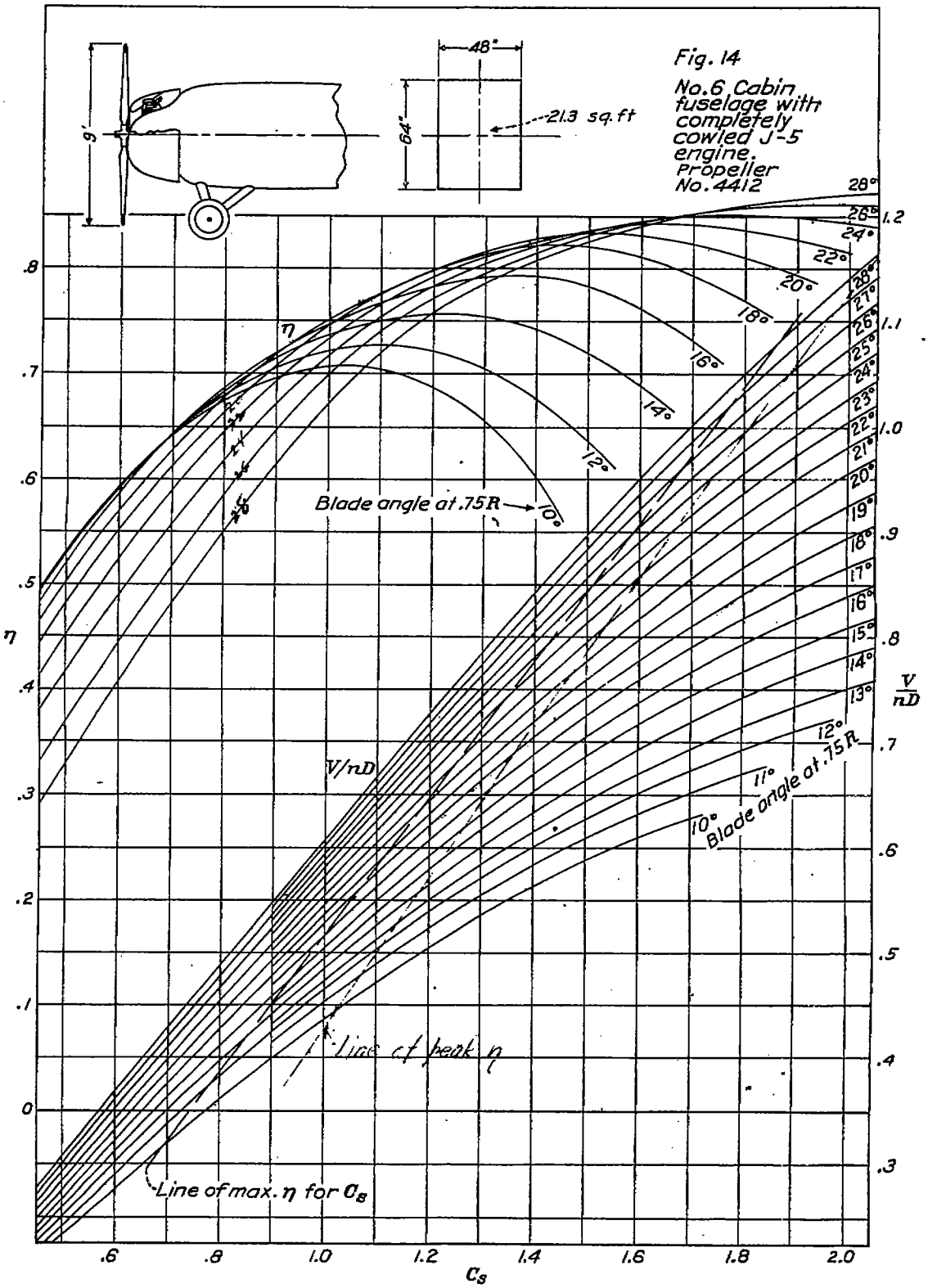
Fig. 14
No. 6 Cabin fuselage with completely cowled J-5 engine. Propeller No. 4412
48"
64"
9'
21.3 sq. ft
η
Blade angle at .75R
V/nD
Line of max. η for C_s
Line of peak η
C_s
$\frac{V}{nD}$

FIGURE 14

The above blade angle of 19.0° at .75 R is the angle in operation and includes the deflection. According to the approximate rule given previously, this deflection would be one-fourth degree for 250 horsepower, so that the setting under static conditions would be

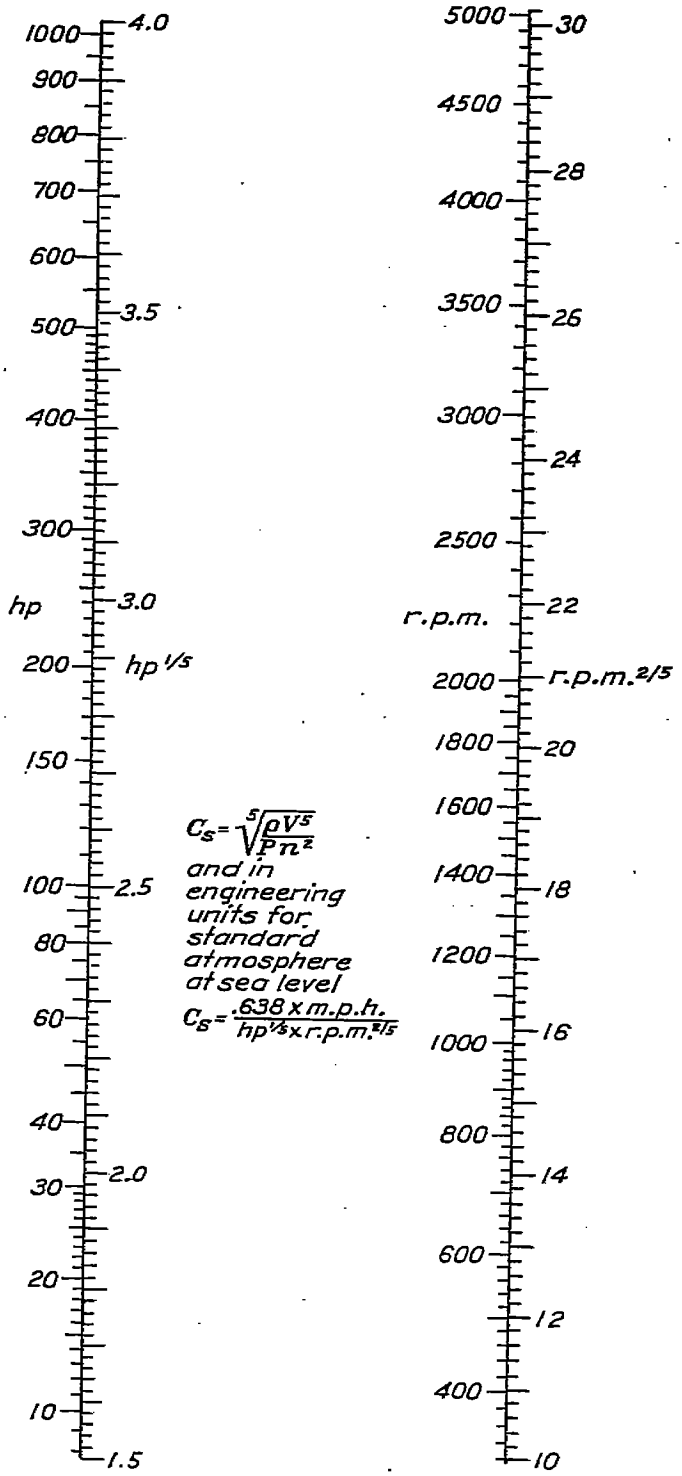

FIGURE 15

18.75°, or, within the usual limit of one-tenth degree, 18.8°.

In case the diameter were fixed at the start at say 9.0 feet, the high speed $\frac{V}{nD}$ would be fixed at

$$\frac{V}{nD} = \frac{88 \times \text{m. p. h.}}{\text{r. p. m.} \times D}$$

$$= \frac{88 \times 130}{1700 \times 9}$$

$$= .748.$$

Then from the lower curves in Figure 12, for $C_s = 1.40$ and $\frac{V}{nD} = .748$, the blade angle should be 20.5° at .75 R., which, considering deflection, makes the actual setting 20.3°. The propulsive efficiency would then be .805.

It will be noticed that the efficiency of the 9.0-foot propeller is greater than that of the 9.31-foot propeller which operates at the peak of its efficiency curve. A still higher efficiency could be obtained at the same value of C_s, with a still smaller diameter and higher pitch. A dashed line has been drawn through the lower set of curves which shows the angle setting giving the maximum possible efficiency with the particular forms of propeller and body used, for any value of C_s or $\frac{V}{nD}$. For the example, in which the value of C_s was 1.40, the maximum possible efficiency would be obtained with a blade angle of 22.5° at 0.75 R (actual setting, considering deflection, 22.3°), and at a $\frac{V}{nD}$ of .777. The corresponding diameter would be 8.66 feet and the propulsive efficiency would be .808.

EFFECT OF WINGS AND TAIL SURFACES

Of the six body forms represented in the working charts, one was equipped with biplane wings and tail surfaces, one with a monoplane wing, and the others with neither wings nor tails. Several series of tests have been made with and without these same wings and tail surfaces, leading to the following conclusions which may be useful in applying the results to other conditions (References 8 and 9):

(1) The monoplane and biplane wings tested with cabin and open cockpit fuselages caused a reduction in propulsive efficiency of from 1 to 3 per cent.

(2) The loss in efficiency was slightly greater for the high than for the low pitch settings.

(3) About the same loss was caused by the monoplane as by the biplane wings.

(4) The effect of the tail surfaces on the propeller characteristics is negligible.

ACCURACY

The charts given in this report have been used to calculate the engine power delivered to propellers in more than 100 full-throttle flight tests made with many different makes of airplanes and engines, the maximum speeds having been obtained over a measured course. The airplanes and engines were taken

from ordinary service and were not specially adjusted for the tests.

The calculated powers averaged very close to (just a trifle above) the rated or guaranteed powers. They were slightly lower, however, than the powers obtained with dynamometer tests of the same type engines, probably due to the fact that the dynamometer tests were made under more ideal conditions.

The powers as calculated from the full-flight propeller tests varied in a very few cases as much as 20 per cent from the mean for any particular type of engine, but most of them came within 5 per cent of the mean. This, considering that ordinary engines and commercial tachometers of various ages and in various conditions were used, is thought to be an excellent check on the general accuracy and usefulness of the full-scale wind-tunnel data.

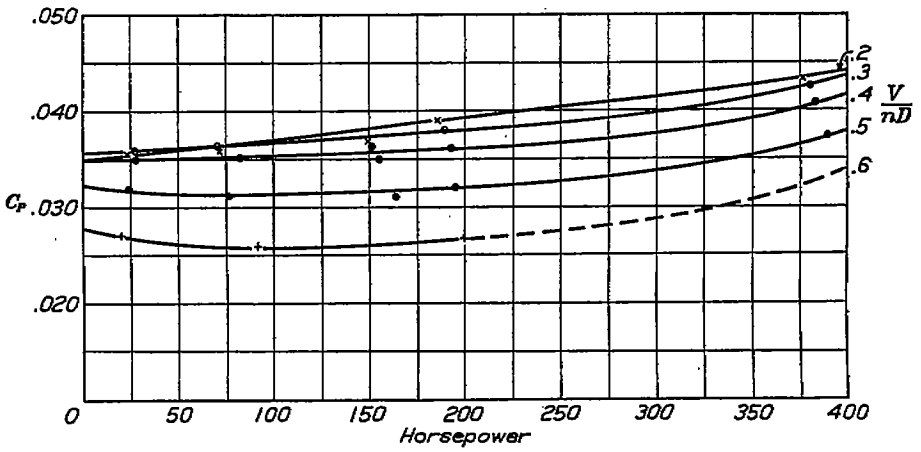

FIGURE 16.—Propeller No. 4412 (15° at 42"), D-12 engine

LANGLEY MEMORIAL AERONAUTICAL LABORATORY,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY, VA., *March 25, 1929.*

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