To: Mr. Chas. J. McCarthy

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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WING-NACELLE-PROPELLER TESTS - COMPARATIVE TESTS OF LIQUID-COOLED AND AIR-COOLED ENGINE NACELLES

By Donald H. Wood
Langley Memorial Aeronautical Laboratory

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WING-NACELLE-PROPELLER TESTS - COMPARATIVE TESTS OF LIQUID-COOLED AND AIR-COOLED ENGINE NACELLES

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SUMMARY

This report gives the results of measurements of the lift, drag, and propeller characteristics of several wing and nacelle combinations with a tractor propeller. The nacelles were so located that the propeller was about 31 percent of the wing chord directly ahead of the leading edge of the wing, a position which earlier tests (N.A.C.A. Report No. 415) had shown to be efficient. The nacelles were scale models of an N.A.C.A. cowled nacelle for a radial air-cooled engine, a nacelle with external radiators for a V-type liquid-cooled engine, a circular nacelle with the V-type engine located inside and the radiator for the cooling liquid located in a cowling hood of the N.A.C.A. type, and a nacelle shape simulating the housing which would be used for an extension shaft if the engine were located entirely within the wing. The propeller used in all cases was a 4-foot model of Navy No. 4412 adjustable metal propeller.

The results of the tests indicate that, at the angles of attack corresponding to high speeds of flight, there is no marked advantage of one type of nacelle over the others as far as low drag is concerned, since the drag added by any of the nacelles in the particular location ahead of the wing is very small. The completely cowled nacelle for a radial air-cooled engine appears to have the highest drag, the liquid-cooled engine nacelle with external radiator slightly less drag. The liquid-cooled engine nacelle with radiator in the cowling hood has about half the drag of the cowled radial air-cooled engine nacelle. The extension-shaft housing shows practically no increase in drag over that of the wing alone. A large part of the drag of the liquid-cooled engine nacelle appears to be due to the external radiator. The maximum propulsive efficiency for a given propeller pitch setting is about 2 percent

higher for the liquid-cooled engine nacelle with the radiator in the cowling hood than that for the other cowling arrangements.

INTRODUCTION

A rather extensive research program for the purpose of determining the relative merit of wing-nacelle-propeller combinations has included a large number of tests with different locations and different cowlings for radial air-cooled engine nacelles. Numerous locations and types of nacelles on monoplane and biplane wings, as well as nacelle arrangements with pusher, tandem, and tractor propellers, have been studied. The reports so far published have dealt with tractor propellers in combination with monoplane wings (references 1, 2, and 3). Reports giving the results of the remaining tests are now being prepared.

There is, of course, no reason why tests of engine nacelles and cowlings should be confined to those for air-cooled engines. There is a well-supported opinion that liquid-cooled engines may be just as successfully used in multi-engine airplanes and it has been realized from the start of the investigation that some attention should be given to the liquid-cooled engine and its possible application in nacelles. The fact that many airplanes have been constructed using liquid-cooled engines in nacelles makes it advisable to determine more accurately the possible advantages of this arrangement, particularly because some airplanes so equipped have apparently had poorer performance than otherwise similar airplanes equipped with radial air-cooled engines.

The shape of the engine nacelle that can be applied to a liquid-cooled engine is subject to wide variations because of the irregular contours of these engines. With the air-cooled radial engine, on the other hand, there does not seem to be any valid reason for departing from circular cross sections in the nacelle. The nacelle shape selected for the liquid-cooled engine in these tests was determined after a study of several layouts of nacelles furnished by the Army Air Corps and an examination of photographs and drawings previously published in aeronautical literature.

The nacelle for the radial air-cooled engine, which is shown in figure 1, was of normal type for a J-5 or Wasp Junior engine of 45-inch over-all diameter, the model representing the engine and nacelle to 4/9 (1/2.25) full scale. The shape and arrangement of the liquid-cooled engine nacelle with an external radiator are shown in figure 2, which represents a nacelle for a geared Conqueror engine to a scale of 4/11.5 (1/3.48).

A study of the dimensions of the Conqueror engine showed that it could be enclosed in a circular nacelle of the same shape and size as that required for a 45-inch radial air-cooled engine by slightly increasing the diameter at the forward end (inside the cowling hood) and placing the required radiators within the hood. The arrangement for this cowling is shown in figure 3, which represents the nacelle for a geared Conqueror engine to 4/9 scale. The decision to try an engine cowling of this type was based on the fact that the completely cowled radial air-cooled engine has a very low drag and interference, and on the fact that the external radiator of the type normally applied to liquid-cooled engines has a high drag. The arrangement of the radiator inside the hood gave some promise of improving the drag characteristics of liquid-cooled engine nacelles, and it was therefore included in this investigation.

There has been considerable discussion of the possibilities of mounting airplane engines entirely within the wing and driving the propeller through an extension shaft carried forward of the leading edge of the wing. The electric motors available for the tests were so designed that they could simulate this arrangement with some degree of accuracy and the opportunity was used to mount one of these motors ahead of the wing, the resulting shape (shown in fig. 4) representing a possible arrangement of the extension shaft.

The location of the engine nacelle at 31 percent of the chord of the wing from the propeller to the leading edge was based on the tests of reference 1, which had shown this location to be more efficient than others. In all the tests discussed herein, the nacelle was placed in this one location. It should be understood, however, that the location is not very critical and any location from 25 to 35 percent of the chord is quite satisfactory.

APPARATUS AND METHODS

The testing facilities of the 20-foot propeller-research tunnel are fully described in reference 4, and the particular alterations for the nacelle tests are discussed in reference 1. The wing is the same as used in previous tests (5-foot chord, 15-foot span, and 20 percent maximum thickness) (reference 1). The propeller is driven by an electric motor supplied with current from control equipment located on the floor of the test chamber. The motor is a specially built alternating-current induction motor, of small dimensions so that its lines do not interfere with the proper simulation of the nacelle shapes exposed to the air stream. The lift of the wing-nacelle combination, the thrust (or drag), and the power consumed can be measured simultaneously.

Figure 5 shows the arrangement of the nacelle types just discussed as they were mounted in the wind tunnel during the tests. No photograph of the cowling arrangement of liquid-cooled engine with radiator in the cowling hood is shown, since in outward appearance it is the same as the N.A.C.A. cowling. The radiators used were pieces cut from full-size honeycomb radiators rather than scaled-down core sections. It was decided that this arrangement would give the most comparable results, considering the large scale effect on radiators with small air passages that would result from scaled-down core sections. The sizes of the cores were based on the assumption of ethylene-glycol as the cooling liquid.

The first test with each nacelle arrangement consisted of measurements of the lift and drag at several angles of attack and air speeds between 50 and 100 miles per hour with the propeller removed. A second test was then made with the propeller in place and operated at various values of V/nD by altering the propeller revolution speed and the wind-tunnel air speed, so that at each angle of attack a set of curves of propeller characteristics could be plotted. Tests were made at -5°, 0°, 5°, and 10° angle of attack.

RESULTS

The results of the tests were reduced to the usual nondimensional coefficients, lift coefficient C_L, drag coefficient C_D, thrust coefficient C_T, power coefficient C_P, and propulsive efficiency η, which are defined by the following equations:

$$C_L = \frac{\text{lift}}{q\ S}$$

$$C_D = \frac{\text{drag}}{q\ S}$$

$$C_T = \frac{T - \Delta D}{\rho\ n^2\ D^4}$$

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

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

where

q, dynamic pressure $(1/2\ \rho\ V^2)$.

ρ, mass density of the air.

V, velocity.

T, thrust of the propeller (tension in the crankshaft).

ΔD, increase in drag of the body due to the presence of the slipstream.

P, power input to the propeller.

n, revolutions per unit of time.

D, the diameter of the propeller.

S, wing area (75 sq.ft. in these tests).

As it is desirable to compare different nacelles for engines of the same horsepower, it is necessary to correct the observed data for the difference in the scale of the various models. The standard for comparison is taken as an engine of 600 horsepower (Conqueror). The corrected coefficients have been plotted in figure 6. The wing-alone coefficients C_L against C_D, have been plotted as computed. For the liquid-cooled engine nacelle with external radiator the observed increases in drag coefficients have been multiplied by the square of the ratio of the scale of the model of this engine to the scale for the air-cooled engine; that is, $(11.5/9)^2$. Similarly, since the model is 4/9 the scale of a 300-horsepower engine, 45 inches in diameter, and since a 600-horsepower single-row radial engine would be about 56 inches in diameter, the observed increases in drag for the cowled air-cooled engine nacelle have been multiplied by $(56/45)^2$. No correction is made to the results of the liquid-cooled engine with radiator in the cowling, since this model is 4/9 the size of a 600-horsepower engine nacelle. Neither has a correction been made to the model representing the extension shaft, since it is presumed that a housing of this size scaled up in the ratio of 9:4 would house the shaft supports for a 600-horsepower engine. The drag values plotted in figure 6, therefore, represent relatively the drag of the wing with the various types of nacelles for engines of 600-horsepower to 4/9 scale. The difference between the drag coefficient of the wing and the drag coefficient of any wing-nacelle combination at a given lift coefficient represents the drag and interference of the engine nacelle.

In figure 7 are shown the curves for the wing alone, the liquid-cooled engine nacelle with external radiator and wing combination, and the same combination with the radiator removed. The same corrections to the measured increase in drag have been made as in the previous figure.

The large amount of propeller data obtained for these wing-nacelle combinations at the several angles of attack would consume considerable space and, since the most interesting comparisons are at high-speed condition, the curves of figure 8 give only the thrust, power, and efficiency characteristics for an angle of attack of 0° and with the propeller set 17° at 0.75 R, which setting was used throughout these tests. In figure 9 are shown the variations in these same characteristics with angle of attack for two values of V/nD. The value of V/nD = 0.65 corresponds to the high-speed condition and the value V/nD = 0.42 to the climbing condition. These values of V/nD have been used in comparisons of results in the previous reports of reference.

DISCUSSION

Examination of the curves in figures 6 and 7 indicates that for a given nacelle arrangement the drag and interference of the nacelle is nearly constant for all angles of attack. Since the principal performance characteristic of interest is usually the high speed and also because the drag of the nacelle is but a small part of the total airplane drag at higher angles of attack, it is usually sufficient to compare the results at an angle of attack corresponding to the high-speed condition. It has been found in another series of unpublished tests recently made in the full-scale wind tunnel that the drag added by the nacelle is practically the same for wings of different aspect ratios. It may therefore be said that the drag added at a given lift coefficient as shown by the present tests can be applied to wings of other aspect ratios at the same lift coefficient. Since the wing used in these tests was of aspect ratio 3, an angle of attack of 0° for the present wing corresponds to one of about -2° for a wing of aspect ratio 6. If the drag and interference of the nacelle is taken at 0° from the present results and applied to wings of normal aspect ratio the angle of attack will be about -2°. This angle is considered sufficiently close to the high-speed condition, particularly in view of the fact that actual wings will probably be tapered and the whole airfoil will have a somewhat smaller average thickness, consequently a higher angle of attack at the high-speed condition. The angle 0° has been used in previous comparisons for this reason.

For the present purposes, a lift coefficient of 0.4, which is very close to that at 0° angle of attack, has been used for comparing the drags and interferences of the various nacelles. In the table (page 12) are listed the drag coefficients corresponding to the nacelle drag and interference of the various nacelle arrangements as obtained by deducting the drag of the wing alone at a lift coefficient of 0.4 from the drag of the wing-nacelle combination at the same lift coefficient. It is to be noted that these coefficients are based on the wing area rather than on the nacelle cross-sectional area. If the coefficient is multiplied by the model wing area and by the dynamic pressure, the drag at any new speed is obtained. If this value is then multiplied by the square of the scale the drag of the full-sized nacelle will be obtained; that is, the nacelle drag equals $C_{D_n} \times 75 \times q \times (9/4)^2$. The result of this operation for the various nacelles at an assumed speed of 200 miles an hour is indicated in the second column of the table. The third column indicates the horsepower corresponding to this drag, obtained by multiplying the drag by velocity in miles per hour and dividing by 375. The fourth column, the power used by this nacelle drag and interference, is column 3 divided by 600, the assumed power of the various engines, in order to obtain the fraction or the percentage of the engine power that is used in nacelle drag and interference at 200 miles an hour.

The table includes values for a 2-row radial engine of the same horsepower, based on the assumption that the 2-row radial is 45 inches in diameter and will have proportionally the same drag $(45/56)^2$, as the single-row radial engine with cowling. These values are of interest because of the recent development of such engines in this country; the figures are included to show the possibilities of drag reduction in the fact that the frontal area of a 600-horsepower engine, 2-row radial type, will be only about 65 percent of that of a single-row of the same power. It may be mentioned in passing that this condition is not likely to be realized at the present time, owing to the fact that cowling modification has been required to insure proper cooling of 2-row radial engines, with the result that the drag of the nacelle is likely to be somewhat greater than that indicated here.

Two other factors influence the complete comparison of the relative merits of nacelle-wing combinations. The propulsive efficiency as indicated in figure 8 for the various combinations does not apply at the speed assumed in the table, since propeller pitch at a speed of 200 miles an hour would be about 28° instead of the 17° used. Other tests have shown that at the high pitches there is no great variation of propulsive efficiency between one nacelle location and another, so that the variation of propulsive efficiency at high speed can be neglected in the first approximation of the merits of the various nacelle combinations. Also, although the additional lift produced by the action of the propeller becomes quite large at high angles of attack, at angles of attack corresponding to high speed it is very small and can be neglected. For this reason the values of the lift with propeller operating are not given here, and are not used in comparing the nacelle arrangements.

The order of merit of the nacelle arrangements, as shown in the fourth column of the table, indicates that the extension-shaft arrangement with engine in the wing is the best, followed in order by the liquid-cooled engine with radiator in the cowling, the liquid-cooled engine with external radiator, the 2-row radial engine with complete cowling, and the single-row radial engine with complete cowling. Direct comparison of the figures given would indicate that the drag of the extension-shaft arrangement consumes less than half as much power as the liquid-cooled engine with radiator in the cowling and less than one fifth as much as the single-row radial engine with complete cowling. It must be remembered, however, that the power required in the high-speed range varies almost as the cube of the speed, so that the total advantage gained from installing an engine in the wing with extension shaft over the arrangement of a single-row radial engine in a cowling ahead of the wing would actually be only about 8 miles per hour at a speed of 200 miles per hour, and the use of the extension shaft in preference to a liquid-cooled engine with the radiator in the cowling would result in only about 2-1/2 miles per hour gain in speed at 200 miles per hour. The figures indicate also that even if the drag of the extension shaft could be entirely eliminated the speed would be increased only about 1-1/2 miles per hour, so that as far as nacelle locations and types are concerned the present arrangements are very near the limit of possibility.

In connection with the extension-shaft scheme it may also be mentioned that as illustrated here no provision is made for cooling the engine, the assumption being that a skin-type radiator is used. The general dissatisfaction with the skin-type radiator would probably mean that in an actual application some other type of radiator would be employed, so that the extension-shaft arrangement in practice would not be as efficient as indicated.

It may be well to mention, in case comparisons are made between the results here given and those of reference

1, that an apparent discrepancy arises between the percentage of 7 shown here for the power used in nacelle drag (for 45-inch-diameter engine) and the 1 percent given in the other report. This difference is due to the fact that an engine of different power was assumed in reference 1 and the speed corresponds to about 120 miles per hour instead of the 200 miles per hour assumed here. In fact, the percentage of the power used in the nacelle drag varies with changes in power, size of nacelle, and speed, and is not by any means a single-valued factor.

The surprising fact that over half the drag of the liquid-cooled engine nacelle with external radiator is due to the radiator is worth noting in figure 7. The scheme just discussed, of placing the radiator in the cowling hood, is one way of partly eliminating this high radiator drag. It also appears from figure 8 that the arrangement of the radiator in the hood would increase the propulsive efficiency slightly so that this nacelle arrangement promises to be somewhat better than indicated in the comparative table. Of course, there may be some difficulties in making the arrangement a practical success but these do not appear to be insurmountable.

The general conclusion to be drawn from these results is that there is no inherent inferiority of the liquid-cooled engine with respect to the air-cooled engine so far as nacelle applications are concerned; in fact, there appears to be an advantage in favor of the liquid-cooled engine, especially when improved means of cowling the radiator are adopted.

CONCLUSIONS

1. The liquid-cooled engine installed in the nacelle appears to be more efficient aerodynamically than a carefully cowled radial air-cooled engine. If special methods of cowling the radiator are adopted the liquid-cooled-engine arrangement can be still further improved.

2. More than half of the drag of liquid-cooled-engine nacelles of ordinary type is due to the external cooling radiator.

3. Further improvement in the aerodynamic efficiency of arrangements of power plants lies in the direction of

placing the engine in the wing and driving the propeller through an extension shaft, provided that the cooling of the engine can be secured without additional drag.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., December 19, 1933.

REFERENCES

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3. Wood, Donald H.: Tests of Nacelle-Propeller Combinations in Various Positions with Reference to Wings. Part III - Clark Y Wing - Various Radial-Engine Cowlings - Tractor Propeller. T.R. No. 462, N.A.C.A., 1933.

4. Weick, Fred E., and Wood, Donald H.: The Twenty-Foot Propeller Research Tunnel of the National Advisory Committee for Aeronautics. T.R. No. 300, N.A.C.A., 1928.

COMPARISON OF WING-NACELLE COMBINATIONS

	C_{D_n}	Full-size nacelle drag at 200 m.p.h.	Full-size nacelle hp. at 200 m.p.h.	Percentage of hp. used by nacelle
	$\frac{D_c - D_w}{q \times 75}$	$C_{D_n} \times 75 \times 102.3 \times (9/4)^2$ lb.	$\frac{\text{drag} \times 200}{375}$	$\frac{\text{hp.(col.3)}}{600} \times 100$
Single-row radial engine with N.A.C.A. cowling (fig. 1)	0.0032	124	66	11
Liquid-cooled engine, external radiator (fig. 2)	.0020	78	42	7
Liquid-cooled engine, radiator in N.A.C.A. hood (fig. 3)	.0015	58	31	5
Engine in wing extension shaft (fig. 4)	.0006	23	12	2
Two-row radial engine with N.A.C.A. cowling (like fig. 1)	.0021	82	44	7

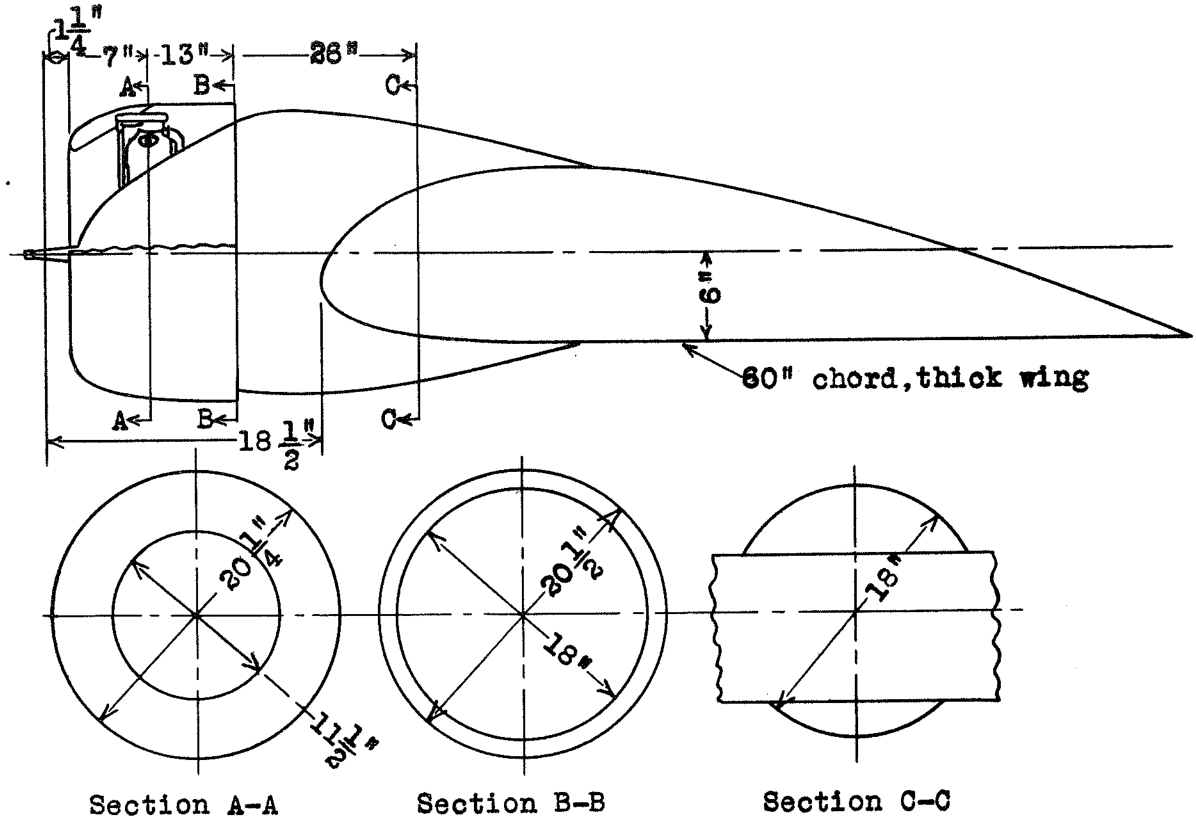


Figure 1.- Wing and air-cooled engine nacelle with N.A.C.A. cowling.

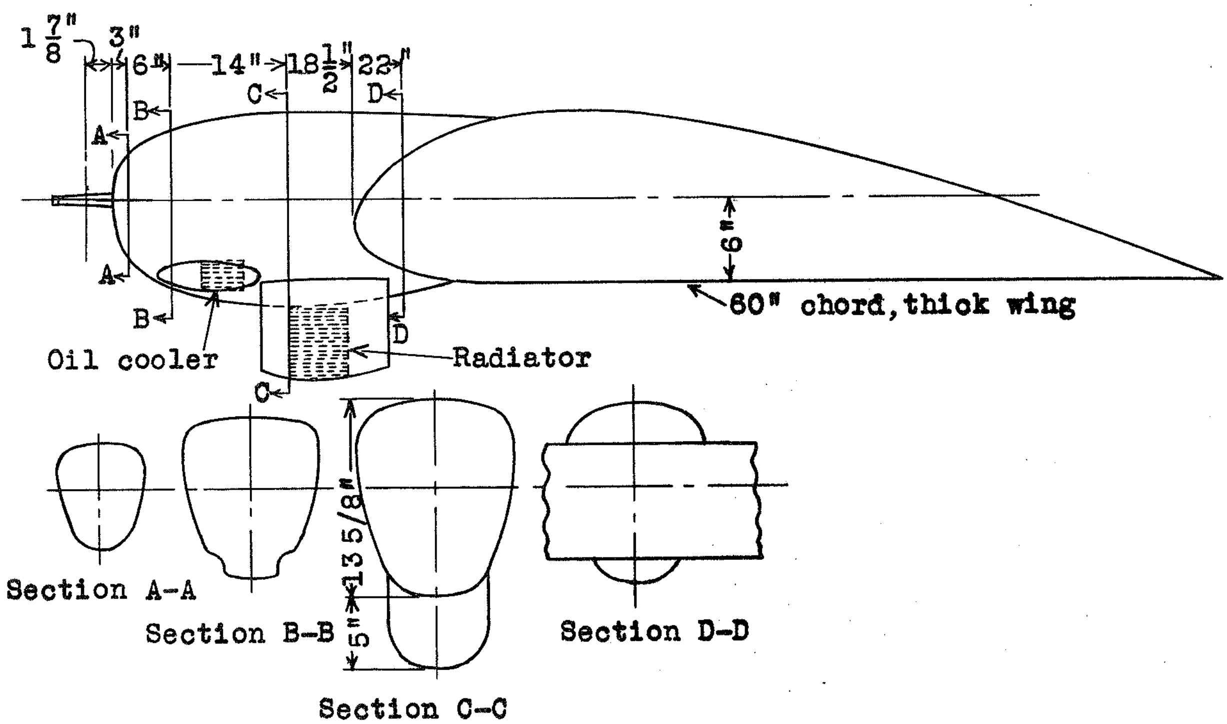


Figure 2.- Wing and liquid-cooled engine nacelle with external radiator.

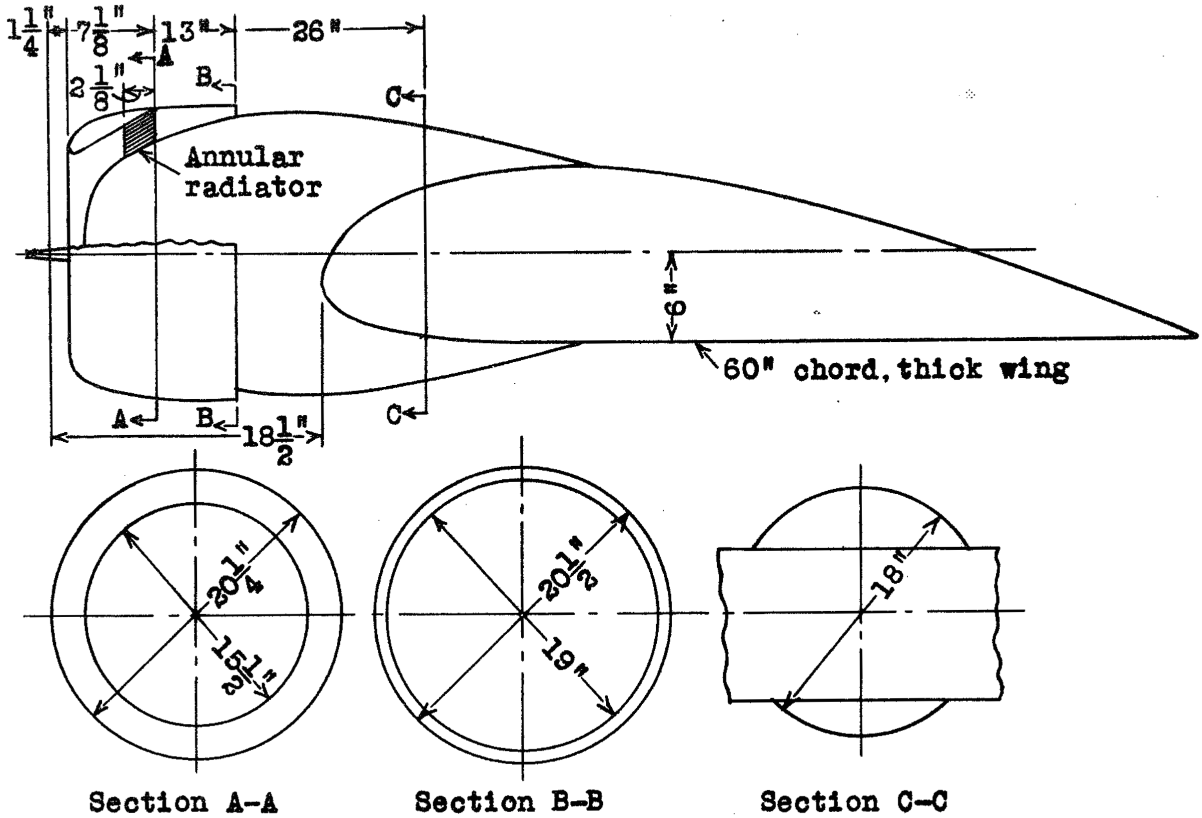


Figure 3.- Wing and liquid-cooled engine nacelle with radiator in N.A.C.A. cowling.

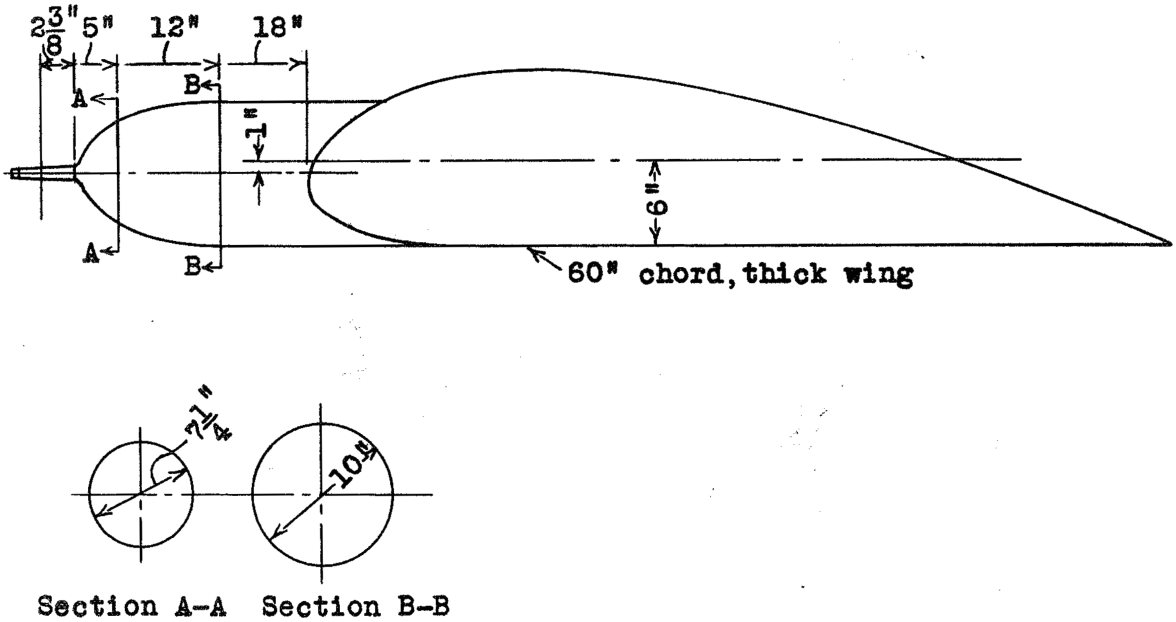
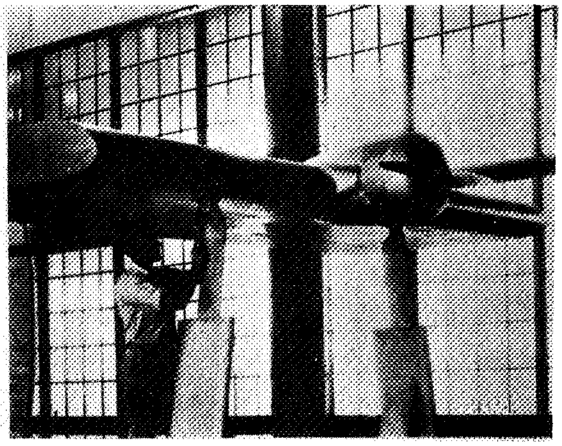
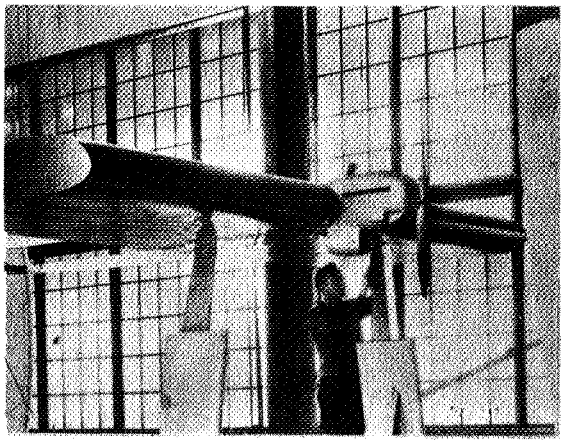


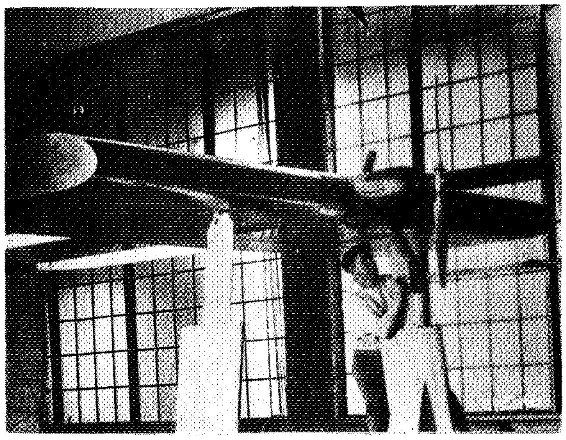
Figure 4.- Engine enclosed in wing with extension propeller shaft.



N.A.C.A. cowling



Liquid-cooled engine nacelle



Engine in wing, extension shaft

Figure 5. - Wing-nacelle combinations mounted for tests

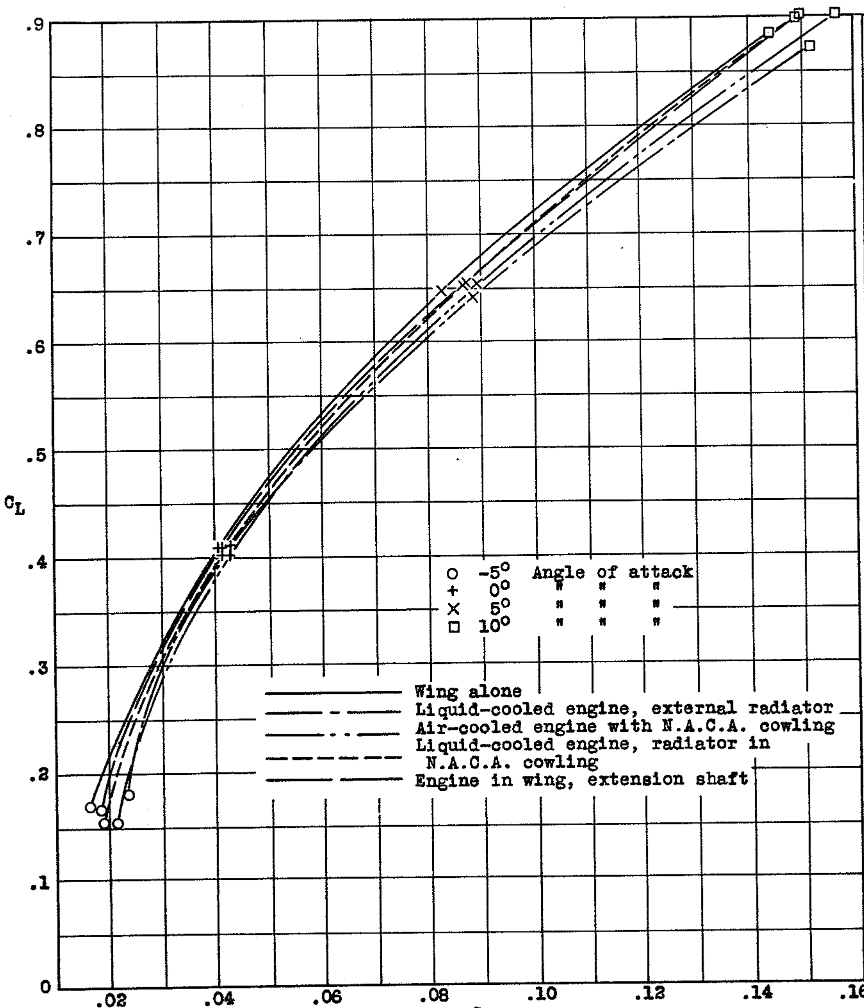


Figure 6.- Comparison of lift and drag characteristics of wing alone and in combination with various nacelles.

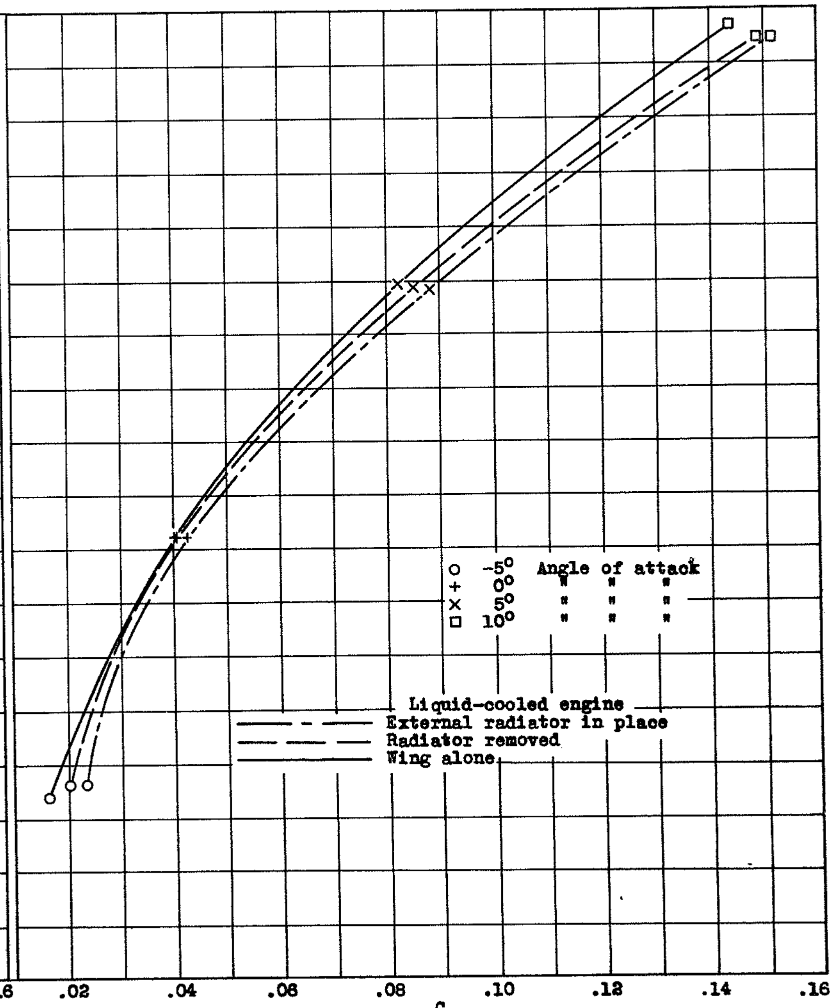
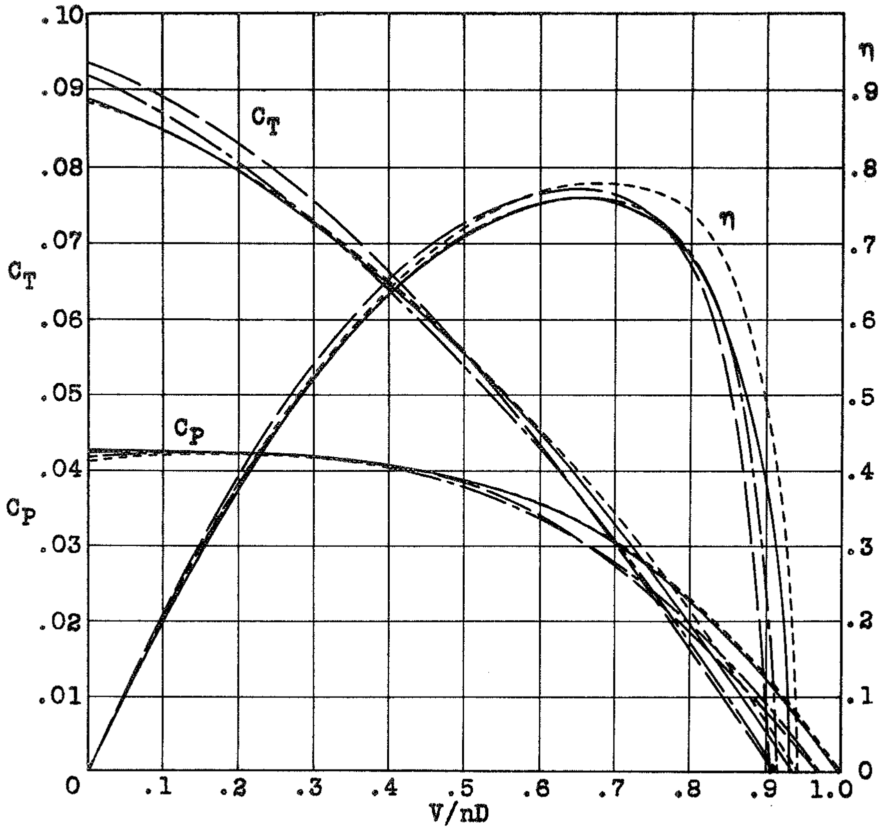


Figure 7.- Effect of external radiator on lift and drag of wing and liquid-cooled engine-nacelle combinations.



Propeller 4412, diameter 4 ft., set 17° at 0.75R, angle of attack = 0°.

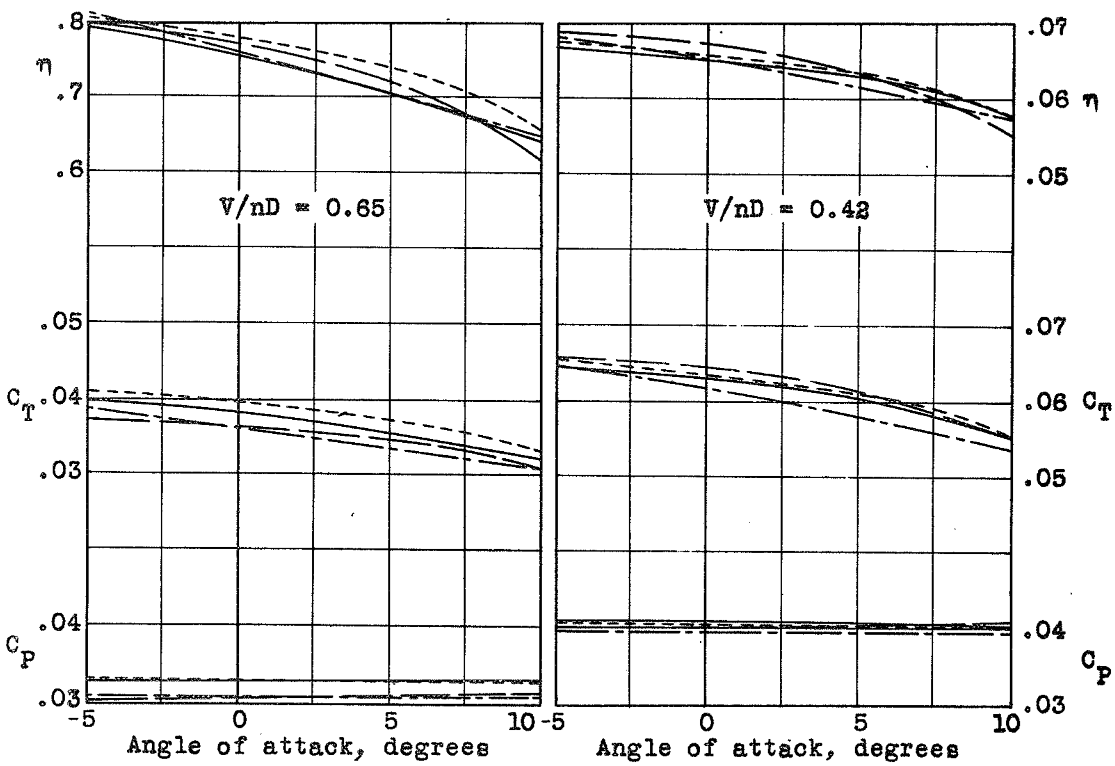
Figure 8.- Propeller characteristics of various nacelle-wing combinations.

- - - - - - - - Liquid-cooled engine, external radiator.

———— Air-cooled engine with N.A.C.A. cowling.

- - - - - - - - Liquid-cooled engine, radiator in N.A.C.A. cowling.

— — — — Engine in wing, extension shaft.



Propeller No. 4412, 4 ft. diameter, set 17° at 0.75R.
Figure 9.- Effect of angle of attack on propeller characteristics of various nacelle-wing combinations.