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THE EFFECT OF SURFACE IRREGULARITIES ON WING DRAG

I. RIVETS AND SPOT WELDS

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SUMMARY

Tests have been conducted in the N.A.C.A. 8-foot high-speed wind tunnel to determine the effect of exposed rivet heads and spot welds on wing drag. Most of the tests were made with an airfoil of 5-foot chord. The air speed was varied from 80 to 500 miles per hour and the lift coefficient from 0 to 0.30.

The increases in the drag of the 5-foot airfoil varied from 6 percent, due to countersunk rivets, to 27 percent, due to 3/32-inch brazier-head rivets, with the rivets in a representative arrangement. The drag increases caused by protruding rivet heads were roughly proportional to the height of the heads. With the front row of rivets well forward, changes in spanwise pitch had negligible effects on drag unless the pitch was more than 2.5 percent of the chord. Data are presented for evaluating the drag reduction attained by removing rivets from the forward part of the wing surface; for example, it is shown that over 70 percent of the rivet drag is caused by the rivets on the forward 30 percent of the airfoil in a typical case.

INTRODUCTION

The streamlining of airplanes has advanced to such an extent that in many cases skin friction constitutes a major portion of the total drag. It has, therefore, become increasingly important that skin friction be reduced. An obvious method of reducing skin friction is the elimination of rivet heads, sheet-metal laps, and other protuberances, and roughness from the surfaces exposed to the air flow. Before the designer can make rational decisions as to the extent to which it is economical to eliminate protuberances and roughness from the surfaces of airplanes, it is essential that he have data showing the magnitude of the drag reductions thereby attainable.

Previous tests have shown that rivet heads (reference 1), certain arbitrary protuberances (references 2 and 3), and roughness (references 4 and 5) greatly increase the drag of wings.

The tests described in this paper were conducted in the N.A.C.A. 8-foot high-speed wind tunnel over a wide range of scale and speed to provide data on the effect upon the wing drag of a variety of rivet types, sizes, and arrangements. The tests showed the effects on the drag of an airfoil of N.A.C.A. 23012 section with a 5-foot chord of 3/32- and 1/16-inch brazier-head rivets, 3/32-inch thin brazier-head rivets, 3/32-inch countersunk rivets, and spot welds. The rivets and spot welds were arranged in spanwise rows at pitches of 3/4, 1-1/2, and 3 inches. Drag reduction attained by eliminating rivets on only the forward portions of wings was also determined. The tests were made at lift coefficients of 0, 0.15, and 0.30 and at speeds from 80 to 500 miles per hour, corresponding to Reynolds Numbers R, from 3,000,000 to 18,500,000.

The proper method of applying the results of the tests on the airfoil of 5-foot chord to wings of various chords was investigated by making tests of an N.A.C.A. 23012 airfoil of 2-foot chord; the size and arrangement of the rivets were in the same relationship to the airfoil chord as they were for the 3/32-inch brazier-head rivets on the 5-foot airfoil.

The effects on wing drag of four types of lap joint alone and with rivets, and of five degrees of roughness were also investigated. The results of the tests to determine the effects of laps and roughness will be presented in subsequent papers, as will also the results of tests of a wing representing average present-day workmanship to show the effect on drag of discrepancies between this wing and the accurate model used for the tests herein reported.

APPARATUS

The N.A.C.A. 8-foot high-speed wind tunnel was used for this investigation. The air flow in the closed circular test section of this wind tunnel is quite uniform. The turbulence of the air flow is so small that sphere tests have shown virtually the same critical Reynolds Number in the tunnel as in free air (reference 6).

Both airfoils used for the tests were of N.A.C.A. 23012 section and had active spans of 6 feet. The airfoil of 5-foot chord consisted of a wooden frame covered with

1/8-inch sheet aluminum except the forward 1-5/8 inches, which was covered with steel to reduce erosion. The airfoil of 2-foot chord was constructed of solid wood and completely covered with sheet steel. All screws in the covering of both airfoils were countersunk below the surface and the countersinks were filled flush. The narrower airfoil and the steel nose of the wider airfoil were polished and left bare but the aluminum-covered part of the wider airfoil was painted, sandpapered, polished, and waxed. The tests of the effect of roughness showed that these polished steel and polished paint surfaces were aerodynamically smooth; that is, further polishing would bring about no further reduction in drag.

The airfoils were mounted horizontally across the center of the test section as shown in figures 1 and 2. The tunnel-wall interference was reduced by enclosing the ends of the airfoils in shields that did not touch the airfoils or their supports but were supported by the test section. The clearance between the airfoils and shields was about 1/8 inch. The 2-foot airfoil projected through the shields and openings in the walls of the test section to the balance ring, but the 5-foot airfoil extended only 1 inch into each shield and was supported at the ends by brackets that projected through the openings in the walls of the test section from the balance ring. The span of each shield was 10 inches. Parallel flat surfaces were built into the sides of the test section and the end shields were arranged to rotate on an axis concentric with that of the airfoils to permit angle-of-attack changes. Motor-driven gear reducers on the balance ring served to change the angle of attack.

On the 5-foot airfoil, actual rivets were used for the tests of protruding rivets, the shanks of the rivets being pressed into holes drilled in the airfoil. Holes not in use were plugged and finished flush. Countersunk rivets and spot welds were simulated by cutting the surface of the airfoil. The details of the rivets and the simulations of the countersunk rivets and spot welds used on the 5-foot airfoil are shown in figure 3. The simulations of countersunk rivets were intended to represent the type of riveting in which the countersinks are punched in the sheet metal rather than being cut, thereby producing slight indentations around the rivet heads.

On the 2-foot airfoil, rivet heads were simulated by lead punchings cemented to the surface with airplane dope.

These punchings were 2/5 as large as the heads of the 3/32-inch brazier-head rivets used on the 5-foot airfoil (fig. 3).

METHOD

For each arrangement of rivets tested, the lift, the drag, and the pitching moment were determined at -1.25°, -0.15°, and 0.95° angle of attack, corresponding to lift coefficients of approximately 0, 0.15, and 0.30, respectively. The tests at lift coefficients of 0.15 and 0.30 were made at air speeds varying from 80 to 370 and 80 to 270 miles per hour, respectively, the upper limit in each case producing a wing loading of approximately 50 pounds per square foot. For the tests at zero lift the speed was varied from 80 miles per hour up to the speed at which compressibility effects caused a rapid increase in drag coefficient, about 500 miles per hour under the conditions of these tests.

Rivets were added to the 5-foot airfoil at 3/4-inch pitch in one or more rows at a time starting with the rear row and working forward as the tests proceeded. The chord positions at which rows of rivets were placed are shown in figure 4. The effects of the 3/32-inch brazier-head rivets on either the upper or the lower surface were determined by first adding one or more rows only to the upper surface and, after testing, adding the same number of rows only to the lower surface. The rivet pitch was varied by removing alternate rivets in each row, after tests with rivets at 3/4-inch pitch were completed, and then, after testing, again removing alternate rows. The rivet holes were plugged and finished flush as the rivets were removed. After tests of each type of rivet were completed, all the rivets were removed, the holes were plugged and finished flush, and the drag of the smooth airfoil was redetermined.

After an initial determination of the drag of the 2-foot airfoil with smooth surface, the lead punchings, simulating rivet heads 2/5 as large as the heads of 3/32-inch brazier-head rivets, were cemented to the airfoil in 13 spanwise rows on each surface at the same relative chord positions used on the 5-foot airfoil (fig. 4). The spanwise pitch of the rivets was 0.3 inch, the same percentage of the airfoil chord as the 3/4-inch pitch used on the 5-foot airfoil. After testing, the three forward rows of rivet heads were removed and the tests were repeated. All the remaining rivet heads were then removed and the drag of the smooth airfoil was redetermined.

Because of the high test speeds employed, the method used for determining dynamic pressure, air speed, and Reynolds Number in the N.A.C.A. 8-foot high-speed wind tunnel must allow for compressibility effects. Bernoulli's equation for a compressible fluid, in a form given in reference 7, is

$$P_a = P_s + \frac{1}{2}\rho_s V_s^2 \left[1 + \frac{1}{4}M^2 + \frac{1}{40}M^4 + \frac{1}{1600}M^6 \; .....\right]$$

where P_a is the atmospheric pressure which, in the case discussed in reference 7, is virtually equal to the total head in the test section.

P_s, static pressure in test section.

ρ_s, density of air in test section.

V_s, air speed in test section.

M, Mach number (the ratio of the air speed to the speed of sound in the air).

The quantity within the brackets is the factor by which the impact pressure (q_c) shown by a pitot-static tube can be divided to give true dynamic pressure $(q = \frac{1}{2}\rho V^2)$. This factor is called the "compressibility factor" and is often designated by $(1 + \eta)$. Accordingly,

$$(1 + \eta) = 1 + \frac{1}{4}M^2 + \frac{1}{40}M^4 + \frac{1}{1600}M^6 \; .....$$

Substituting first $\sqrt{1.4\frac{P_s}{\rho_s}}$ for the speed of sound, then $2q$ for $\rho_s V_s^2$, and finally $\frac{q_c}{(1+\eta)}$ for q gives

$$(1+\eta) = 1 + 0.357\frac{q_c}{P_s(1+\eta)} + 0.051\left(\frac{q_c}{P_s(1+\eta)}\right)^2 + 0.0018\left(\frac{q_c}{P_s(1+\eta)}\right)^3 \ldots$$

From this relation the compressibility factor $(1 + \eta)$ is computed in terms of q_c/P_s and plotted for use in computing test results.

During tests, measurements are made of the pressure difference $P_1 - P_s$ where P_1 is the static pressure in the slow-speed part of the return passage. From this pressure difference, q_c for the model position is computed in accordance with a relation previously determined by pitot-static surveys of the air flow in the test section. The absolute value of P_s is computed from the barometric pressure, a previously determined value of $P_a - P_1$ and the measured pressure difference $P_1 - P_s$. The ratio q_c/P_s is then computed and, from this ratio and the curve described in the preceding paragraph, $(1 + \eta)$ is determined. The true dynamic pressure on which force and moment coefficients are based is then computed from the relation

$$q = \frac{q_c}{(1 + \eta)}$$

The air temperature in the slow-speed part of the return passage T_1, is measured with remote-indicating thermometers. From T_1, P_1, and P_s the temperature and density of the air in the test section T_s and ρ_s, are computed on the assumption that the flow is adiabatic. The air speed in the test section is then easily computed from ρ_s and q. The speed of sound in the air in the test section in miles per hour is $33.5 \sqrt{T_s}$ where T_s is the absolute temperature in Fahrenheit degrees. The viscosity of the air follows from T_s and, since ρ_s has already been determined, the Reynolds Number can be computed.

The assumption that the flow is adiabatic between the slow-speed part of the return passage and the test section is supported by tests which have shown that, except in the boundary layer near the tunnel walls, there is no appreciable difference between the total heads at these two sections.

When the air in the wind tunnel is cool and its relative humidity is even moderately high, fog condenses in the test section when the tunnel is operated at high speeds. Such condensation has appreciable effects on the thermodynamics of the air flow. When this condition is encountered, the tunnel is operated until the air becomes warm enough to dissipate the fog before test data are taken.

Aside from this precaution, no allowance is made for the effects of humidity.

Air-flow measurements ahead of the model have indicated that blocking effects are unimportant under the conditions of these tests.

RESULTS

The tunnel effects on the characteristics of airfoils that are as large relative to the tunnel diameter as the two tested are quite appreciable but, as these effects have not yet been completely determined for this wind tunnel, no corrections have been applied. The results are therefore not presented as absolute drag coefficients but are, instead, presented in terms of increases in drag coefficient, which should be little altered by tunnel effects.

Even though the drag results should usually be applied on the basis of Reynolds Number R, they are, for expediency, shown relative to Mach number M (the ratio of the air speed to the speed of sound in the air) because, at the higher speeds employed in these tests, compressibility effects cause the drag coefficients to vary so rapidly that comparisons are preferably made at equal values of this parameter. The air speeds quoted are not actual test air speeds at the reduced densities existing in the wind tunnel but are speeds that at sea level in a standard atmosphere would produce values of M equal to the test values. The Reynolds Numbers are the averages of the actual Reynolds Numbers for the various test runs. None of the Reynolds Numbers depart from these averages enough to affect the results appreciably.

Increases in the drag coefficient C_D, of the 5-foot airfoil due to the different types and sizes of rivets and the spot welds at 3/4-inch pitch in 13 rows on each surface are plotted against M in figure 5. In order to aid in visualizing the magnitude of these drag increases, the approximate percentage increases at one Reynolds Number are spotted on the curves for a few representative points using as base values full-scale wind-tunnel results from reference 8 extrapolated and corrected for tip effects.

The variation of the drag increases caused by rivets, hereinafter called "rivet drag," with the height of the protruding rivet heads is shown in figure 6.

The fact that rivets on the forward part of a wing increase the drag more than those farther back is illustrated in figures 7 to 9. Figure 7 shows the drag increase due to the different types and sizes of rivets and the spot welds on both surfaces of the airfoil plotted against chord position of the forward rows. Figure 8 is a similar presentation for the 3/32-inch brazier-head rivets with the effects on the upper and lower surfaces separated. Figures 7 and 8 show the drag increases only at 230 miles per hour and $C_L = 0.15$, but the same phenomenon is illustrated in figure 9 in a form that is applicable at all speeds and lift coefficients within the range of the tests and is more convenient for some uses. The percentages shown in figure 9 can be applied to the drag increases shown in figure 5. Figures 7 to 9 correspond to the practical condition in which rivet drag is reduced by removing rivets from only the forward part of a wing.

From the curves in figure 9, which show the effects of rivets on the upper and lower surfaces separately, it is possible to derive the optimum rivet arrangement to attain a maximum reduction in drag by eliminating a given number of rivets. Figure 10 illustrates such optimum arrangements.

The variation of rivet drag with the spanwise pitch of the rivets is shown in figure 11. This figure shows the variation only at 230 miles per hour and at a lift coefficient of 0.15 because the variation for all speeds and lift coefficients within the range of the tests was quite similar to that shown. In this figure the scale of abscissas is linear with respect to the number of rivets per unit span, or the reciprocal of the rivet pitch. This scale was chosen so that the curves could be extended to the condition where no rivets remained on the wing and so that straight lines through the origin would result if the rivet drag were proportional to the number of rivets on the wing.

Drag increases caused by geometrically similar arrangements of rivets on the 5-foot and 2-foot airfoils are compared at equal Reynolds Numbers in figure 12.

As the effects of the rivets and spot welds on lift and pitching moment at the angles of attack included in the tests were not large enough to be of any importance, the results are not shown. No attempt was made to determine the maximum lift coefficients because of the large size of the airfoils in relation to the tunnel diameter. The tests reported in reference 1, however, showed that nine rows of 1/8-inch brazier-head rivets on each surface of a Clark Y airfoil of 6-foot chord reduced the maximum lift coefficient only 1 percent.

PRECISION

The principal errors in the drag increases herein reported are probably random errors due to variations in the condition of the airfoil surface, friction in the drag balance, and similar causes. Errors in the results are, therefore, probably no greater than variations in the drag coefficients determined at various times for the smooth airfoil. Most of the 14 separate determinations of the drag coefficient of the smooth airfoil agreed within ±0.0001, corresponding to ±1.4 percent of the smooth airfoil drag, except at speeds below 100 and above 400 miles per hour where the variations were about twice this large. Systematic errors are thought to be small enough so that their effect on the results is not important.

DISCUSSION

Mechanism of Rivet Drag

Rivet heads increase the drag of a wing in two ways: First, each rivet head, being exposed to the air flow, has some drag in itself that adds to the wing drag; and second, and more important, the rivets disturb the flow in the boundary layer and thereby increase the drag of the wing at all points behind the most forward rivets. That this second factor is responsible for most of the drag increase is indicated by data as yet unpublished, which show that a small spanwise ridge on the forward part of an airfoil causes a drag increase many times as large as the direct drag of the ridge itself.

The fact that increasing the rivet pitch from 3/4 to 1-1/2 inches reduced the drag only slightly (fig. 11), even though half of the rivets were removed in the process, gives further evidence that the direct drag of the rivet heads was quite small, disturbances caused by the individual rivet heads apparently spreading spanwise so as to disturb the entire boundary layer nearly as much when the rivets were at 1-1/2 inch pitch as when they were at 3/4-inch pitch.

Several reasons exist for the relatively large effect of rivets on the forward part of a wing. These rivets are in a thin boundary layer and in a region of high local velocity so that they produce large disturbances in the flow. These disturbances, being on the forward part of the wing, affect the flow over most of the wing surface. Any disturbance forward of the point of transition from laminar to turbulent boundary-layer flow will cause this point to move forward and thereby further increase the drag.

Application of Results

In order to apply the results reported herein to design problems, it is necessary to allow for the differences between the application and the test conditions in respect to Reynolds Number, rivet size, and the chordwise and spanwise arrangement of the rivets.

The variation of rivet drag with speed and Reynolds Number is shown in figure 5 for the 5-foot airfoil. The interpretation of these results is complicated by the fact that Mach number and Reynolds Number were not varied independently of each other; therefore, the effects of compressibility and scale were not separated. At the lower speeds, compressibility effects are negligible so the results shown in figure 5 can be applied directly as a function only of Reynolds Number as long as speed and Reynolds Number are below, say, 250 miles per hour and 12,000,000, respectively. At speeds above about 250 miles per hour the compressibility effect on the drag of the airfoil, either smooth or with rivets, becomes greater than the scale effect and, consequently, the variation of rivet drag at the higher speeds is not necessarily due entirely to scale effect.

Figure 12 shows that rivets having the same size and arrangement relative to wing chord increased the drag coefficients of the 2-foot and 5-foot airfoils by substantially equal amounts at equal Reynolds Numbers. This agreement is, of course, in concurrence with Reynolds' principles of similitude. In the estimation of rivet drag from the results of tests, the size and arrangement of the rivets should therefore be considered in terms of wing chord. At Reynolds Numbers above about 5,000,000, the test speeds for the 2-foot airfoil were so high that compressibility effects on wing drag were large. The agreement with the results for the 5-foot airfoil at equal Reynolds Numbers and lower speeds therefore indicates that compressibility has no marked effect on rivet drag.

From figure 6 it is seen that rivet drag is roughly proportional to the height of the rivet heads except at the lower speeds and higher lift coefficients. The application of the data to wings of different size is facilitated by showing the height of the rivet heads in percentage chord as well as in inches. There is no assurance that the drag increases will continue to be even roughly proportional to the height of the rivet heads for rivet sizes outside the range of those tested. Most applications necessitating extrapolation, however, will involve rivets smaller than those tested so the drag increases will be smaller and inaccuracies introduced by assuming this proportionality should not be important. It is apparent that rivets having the thinnest practicable heads should be used.

The variation of rivet drag with position of the forward rows of rivets can be estimated directly from figure 7, 8, or 9. These figures show that removing rivets from the airfoil starting with the forward rows and progressing rearward reduces the drag quite rapidly at first but the reduction becomes approximately linear 30 percent of the chord back of the leading edge. It is evident from figure 9 that more than 70 percent of the rivet drag is due to the rivets on the forward 30 percent of the airfoil. The results shown on these three figures would probably be somewhat different for airfoils of different profile.

When rivet drag is to be reduced by eliminating only part of the rivets from a wing, it is generally more effective to eliminate more rivets from one surface than from the other, as illustrated in figure 10. For any particular design the optimum arrangement can be determined approximately from figure 10 but the final determination of the drag reduction attained by any particular arrangement can best be made from the curves of figure 9.

The investigation reported herein included no tests that would show the effect of varying the number of spanwise rows of rivets without changing the position of the forward row. The results reported in reference 1, however, show that the drag increase due to a single row of rivets at the 5-percent-chord position is about 90 percent of the drag increase due to nine rows when the forward row is at the same chord position.

The effect of varying the spanwise pitch of the rivets in the 13 rows is shown in figure 11. It is notable that the rivet drag decreased only slightly as the rivet pitch was increased from 3/4 to 1-1/2 inches by removing alternate rivets. As the pitch was further increased, the rivet drag decreased almost proportionately, but the pitch was not varied in small enough increments to determine accurately the shape of the curve. Rivet pitch should be considered in terms of wing chord in applying the results for the same reasons that rivet size should be so considered. It appears that only a negligible reduction in drag can be attained by increasing rivet pitch unless it is made greater than 2.5 percent of the chord. Changes in pitch might, however, affect the drag differently if the most forward row were farther back on the wing so that the effect of the rivets on the transition point would be responsible for a smaller part of the total rivet drag.

It must be remembered that the drag reductions indicated by these tests will not be completely attained by removing rivets from a wing unless the wing is entirely free of other protuberances or roughnesses, especially on the forward part.

The data presented in figure 5 indicate that, except at the lower Reynolds Numbers, the countersunk rivets and spot welds increased the drag roughly one-half as much as the 1/16-inch brazier-head rivets. The simulations of spot welds may have been larger than will be found necessary in actual construction but, in any event, the results show the importance of keeping countersunk rivets and spot welds as nearly flush and smooth as possible.

Comparison with Other Tests

The following shows a comparison of the results reported herein with the full-scale wind-tunnel tests reported in reference 1:

	N.A.C.A. full-scale wind tunnel	N.A.C.A. 8-foot high-speed wind tunnel
Airfoil section	Clark Y	N.A.C.A. 23012
Airfoil chord, ft.	6	5
Rivet size, in.	1/8	3/32
Rivet-head height, percent chord	0.087	0.082
Rivet pitch, in.	1	3/4
Number of rows on each surface	9	13
Position of forward rows, percent chord	5	4
Effective Reynolds Number	7,300,000	7,300,000
Increase in C_D	[1]0.0016	[2]0.0018
Percentage of total increase in C_D due to upper surface	68	62

[1] From figure 5 of reference 1 at $C_{D_{min}}$.

[2] From figure 5 at $C_L = 0$.

The differences in rivet pitch and in the number of rows of rivets would make little difference in drag increase. Allowance for the fact that the forward rows were at different chord positions would be opposite and approximately equal to allowance for the difference in rivet size; hence, the tabulated increases in drag coefficient can be directly compared. The parts of the total drag increases due to the rivets on the upper surface can also be directly compared as tabulated. The close agreement indicates that rivets have approximately equal effects on the drag of the Clark Y and the N.A.C.A. 23012 airfoils.

It is interesting to note that the 0.0018 increase in the drag coefficient of the N.A.C.A. 23012 airfoil is approximately 26 percent of the drag of the smooth airfoil, whereas the 0.0016 increase in the drag coefficient of the Clark Y airfoil is only 18 percent of the drag of that smooth airfoil because of the higher drag of the Clark Y airfoil.

Example

The following example will illustrate the application of the test results to design problems and show the importance of the drag caused by rivets.

Assume a transport airplane having the following characteristics:

Gross weight - - - - - - - - - -	25,000 pounds.
Wing area - - - - - - - - - -	1,000 square feet.
Wing span - - - - - - - - - -	100 feet.
Cruising speed - - - - - - - -	200 miles per hour.
Cruising altitude - - - - - -	8,000 feet.
Cruising power - - - - - - - -	1,200 horsepower.
Propeller efficiency - - - - -	85 percent.
Wing rivets - - - - - - - - - -	1/8-inch brazier head.
Position of forward rows of rivets - - - - - - - - - -	4 percent chord.
Spanwise pitch - - - - - - - -	less than 3 inches.

Wing otherwise smooth and clean.

From these assumed characteristics the following values can be computed:

Average chord - - - - - - - - -	10 feet.
Cruising Reynolds Number - -	14,400,000.
Cruising C_D - - - - - - - - -	0.0238.
Cruising C_L - - - - - - - - -	0.31.

The 1/8-inch brazier-head rivets should have the same effect on the drag of the wing of 10-foot chord as the 1/16-inch brazier-head rivets on the airfoil of 5-foot chord used for the tests. Figure 5 shows that, at a lift coefficient of 0.30 and a Reynolds Number of 12,000,000, the 1/16-inch brazier-head rivets increased the drag coefficient by 0.0010. The curve indicates considerable scale effect so the increase would be less at the cruising Reynolds Number of the assumed airplane but 0.0008 should be a conservative estimate.

Removing all the rivets from the wing would then reduce the drag coefficient of the airplane by 0.0008 and its cruising speed with the same power as before would be increased to 202.2 miles per hour. The original cruising speed of 200 miles per hour could be maintained with a saving of 40 horsepower.

In the foregoing example only the gains due to eliminating the rivets from the wing have been estimated. Additional gains could be made by eliminating the rivets from the fuselage, tail surfaces, and nacelles. Also, the gains would be larger for airplanes cleaner than the one assumed in the example.

A method of estimating to what extent it is economical to increase the cost of an airplane to attain a given increase in speed has been provided by Kendall Perkins in reference 9. In this reference it is estimated that the sales value of a transport airplane having a gross weight of 25,000 pounds is increased $1,000 for every mile-per-hour increase in speed attained without increase in power. On the basis of this estimate and the example cited, approximately $2,200 per airplane could be economically expended in eliminating the rivets from the wing.

On small airplanes the rivets are usually larger with respect to chord than on large airplanes and would therefore have a larger detrimental effect on high-speed performance.

CONCLUSIONS

The most important conclusions drawn from the tests described in this paper can be summarized as follows:

1. Rivets in a representative arrangement on an

airfoil of 5-foot chord increased the profile drag from 6 percent for countersunk rivets to 27 percent for 3/32-inch brazier-head rivets.

2. The increases in drag due to protruding rivet heads were roughly proportional to the height of the heads.

3. Removing the rivets from the forward 30 percent of the airfoil reduced the rivet drag 70 percent.

4. Changes in spanwise pitch of the rivets when the front row was well forward had a negligible effect on the drag as long as the pitch was not more than 2.5 percent of the chord.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., November 22, 1937.

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FIGURE LEGENDS

Figure 1.- The airfoil of 5-foot chord with eight rows of rivets mounted in wind tunnel. The airfoil is set at a large negative angle merely to show the rivets.

Figure 2.- The airfoil of 2-foot chord with 10 rows of rivets mounted in wind tunnel.

Figure 3.- Details of brazier-head rivets and simulations of countersunk rivets and spot welds tested on airfoil of 5-foot chord. All dimensions are in inches.

Figure 4.- Positions of rows of rivets used in tests.

Figure 5.- Increase in drag caused by rivets and spot welds at 3/4-inch pitch in 13 rows on upper and lower surfaces of airfoil of 5-foot chord.

Figure 6.- Variation of rivet drag with height of rivet head. Rivets at 3/4-inch pitch in 13 rows on upper and lower surfaces of airfoil of 5-foot chord.

Figure 7.- Rivet drag with forward rows of rivets at various chord positions. Rivets at 3/4-inch pitch in equal number of rows on upper and lower surfaces of airfoil. Chord 5 ft.; C_L, 0.15; V, 230 m.p.h.; average R, 10,200,000.

Figure 8.- Rivet drag due to rivets on upper surface alone, lower surface alone, and on both surfaces with forward rows at various chord positions. Chord, 5 ft.; 3/32-inch brazier-head rivets at 3/4-inch pitch; C_L, 0.15; V, 230 m.p.h.; average R, 10,200,000.

Figure 9.- Percentage of rivet drag eliminated by removing rivets to various chord positions. Rivets at 3/4-inch pitch in 13 rows on upper and lower surfaces of airfoil of 5-foot chord with forward rows at 4 percent chord before starting removal.

Figure 10.- Maximum reduction of drag by removal of minimum number of rivets with forward rivets at 4 percent chord before starting removal. The 3/32-inch brazier-head rivets at 3/4-inch pitch on airfoil of 5-foot chord.

Figure 11.- Variation of rivet drag with rivet pitch. Rivets in 13 rows on upper and lower surfaces of airfoil. Chord, 5 ft.; C_L, 0.15; V, 230 m.p.h.; average R, 10,200,000.

Figure 12.- Variation with Reynolds Number of drag increase caused by rivet heads.

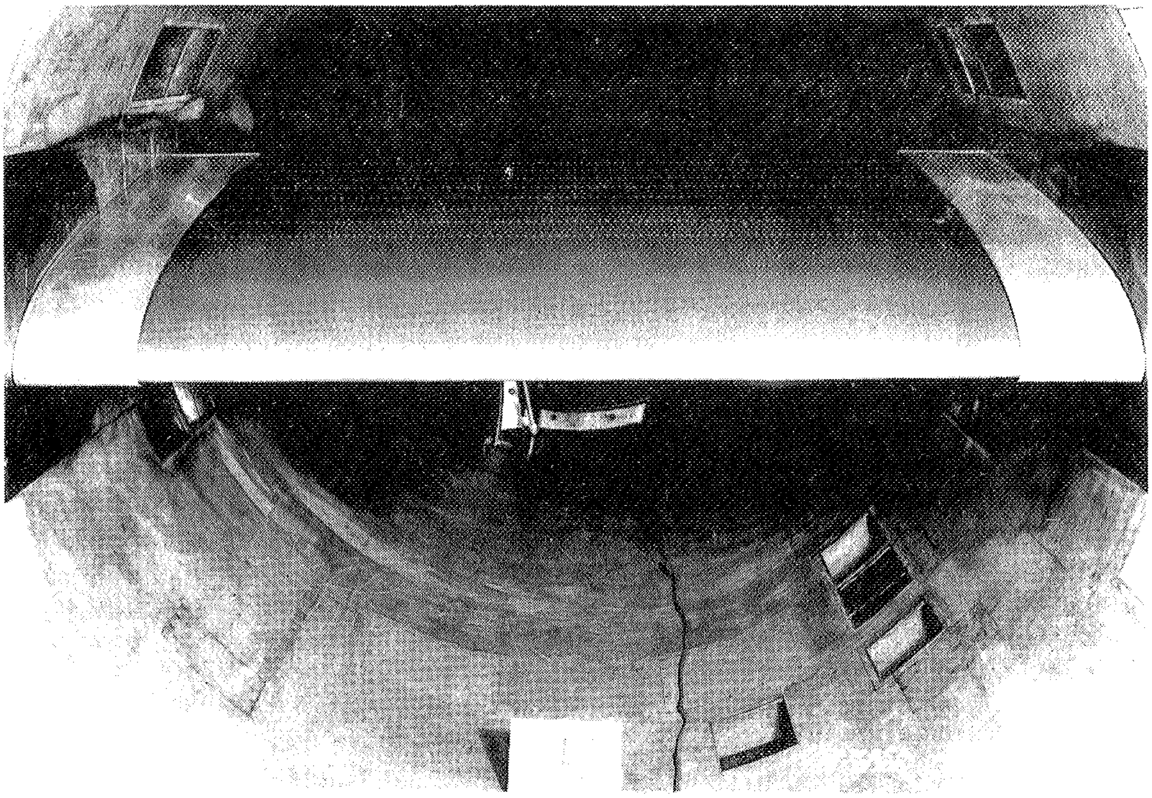


Figure 1.- The airfoil of 5-foot chord with eight rows of rivets mounted in wind tunnel. The airfoil is set at a large negative angle merely to show the rivets.

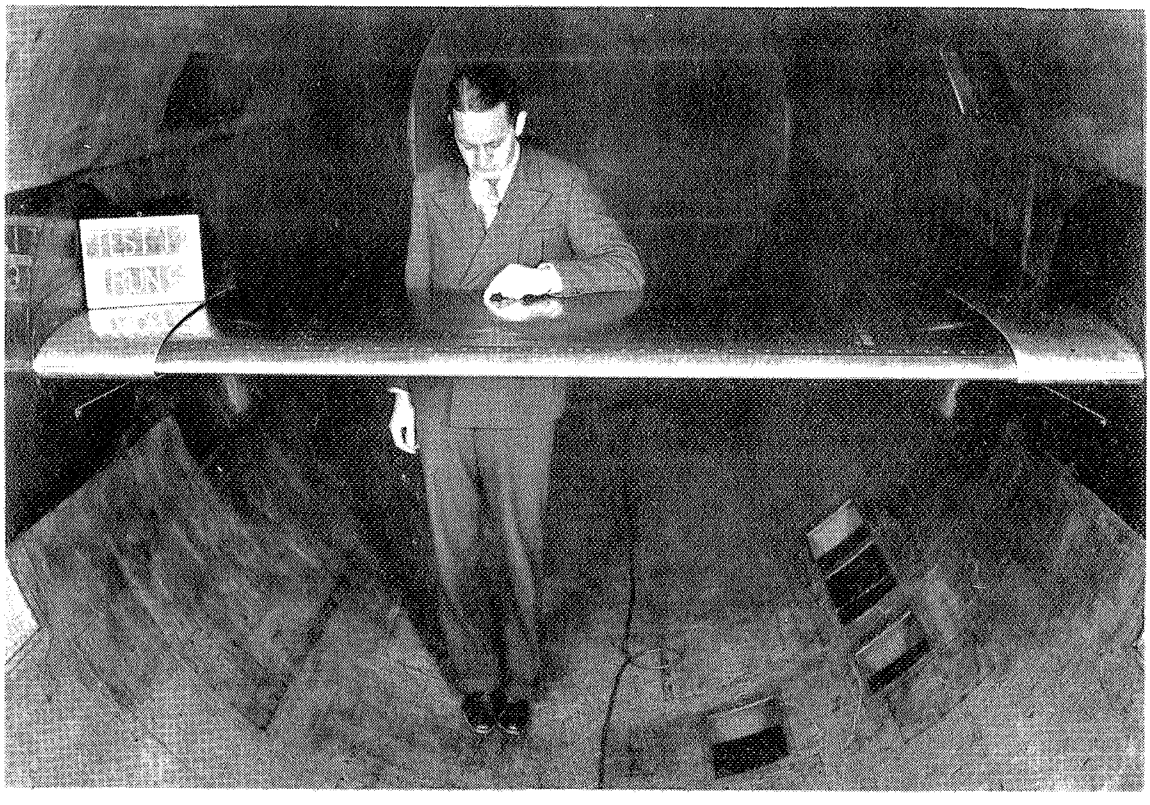
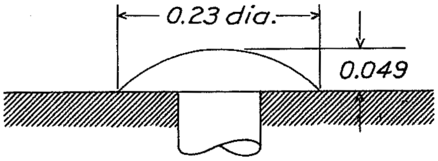
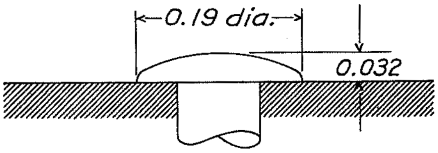


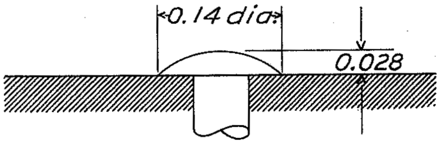
Figure 2.- The airfoil of 2-foot chord with 10 rows of rivets mounted in wind tunnel.



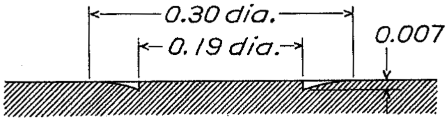
3/32" brazier-head rivet



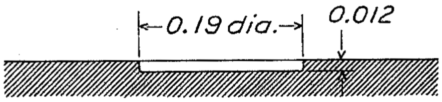
3/32" thin brazier-head rivet



1/16" brazier-head rivet



Simulation of 3/32" countersunk rivet



Simulation of spot weld

Figure 3.

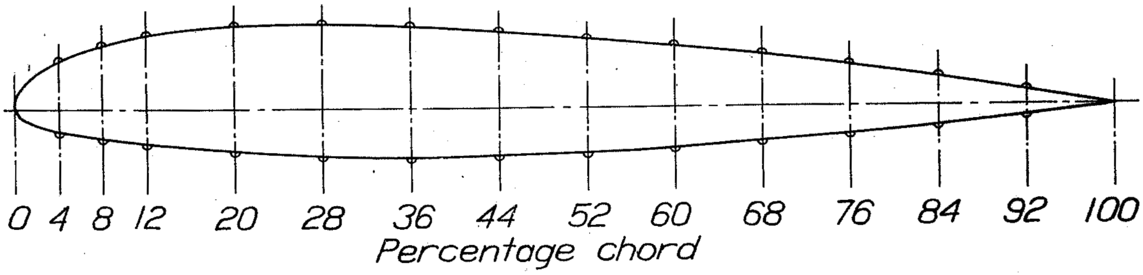
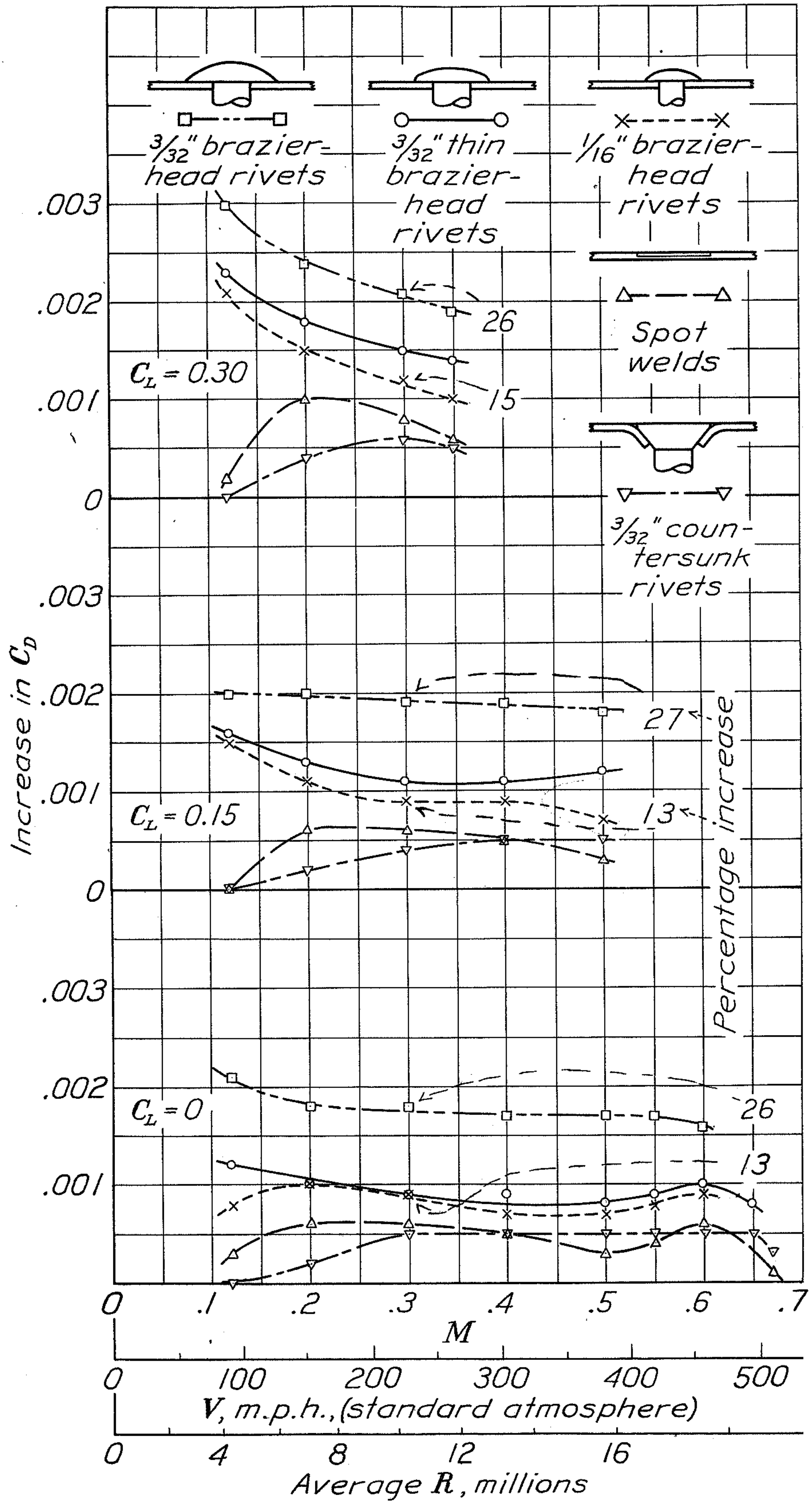
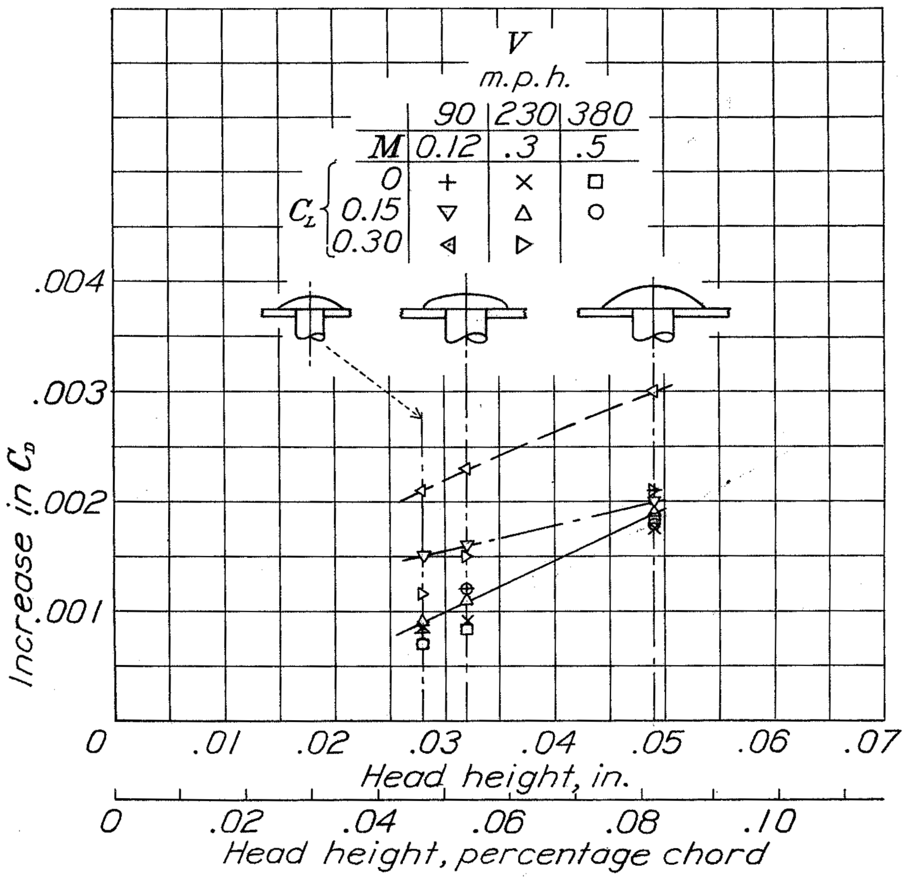


Figure 4.



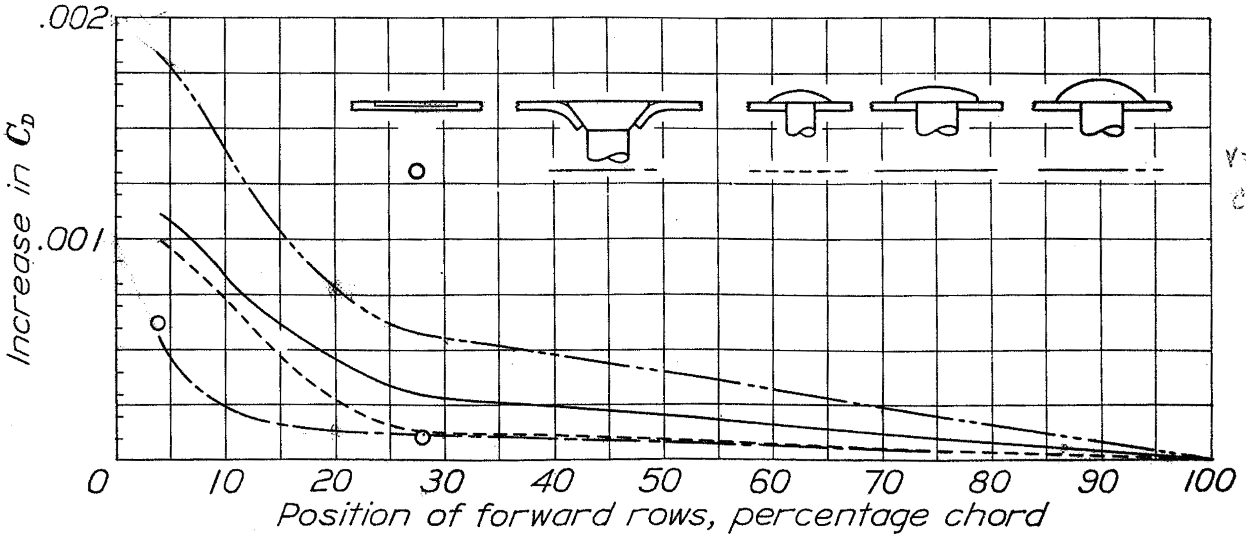
3/4" PITCH
13 ROWS.

Figure 5



$\frac{3}{4}$" pitch
13 rows.

Figure 6



V=230 m
C_L=.15

Figure 7

3/4" pitch on 5-foot chord.

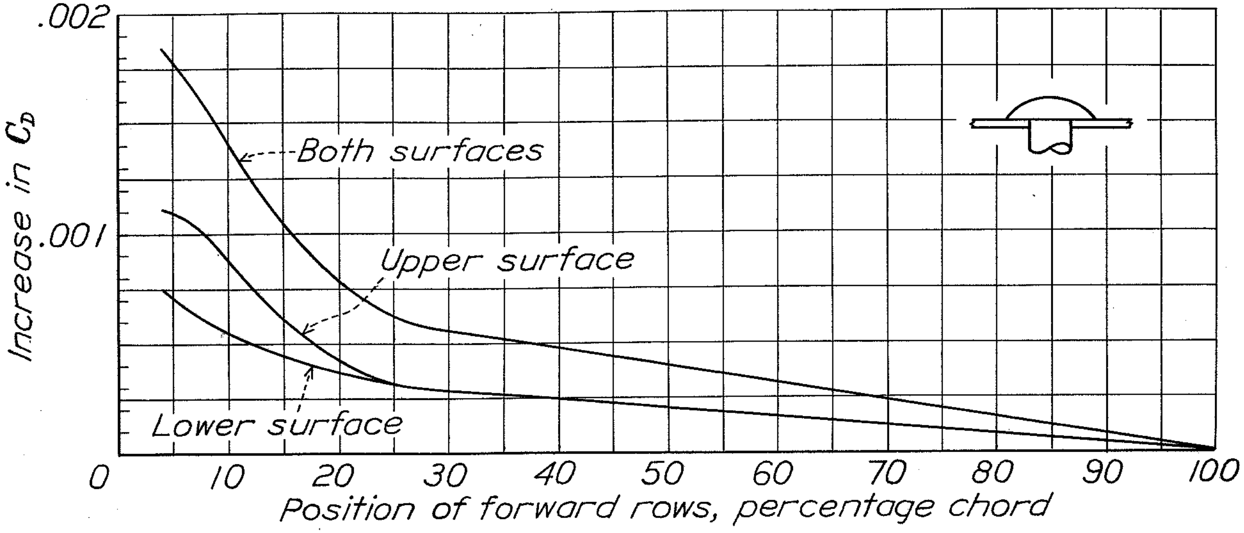


Figure 8

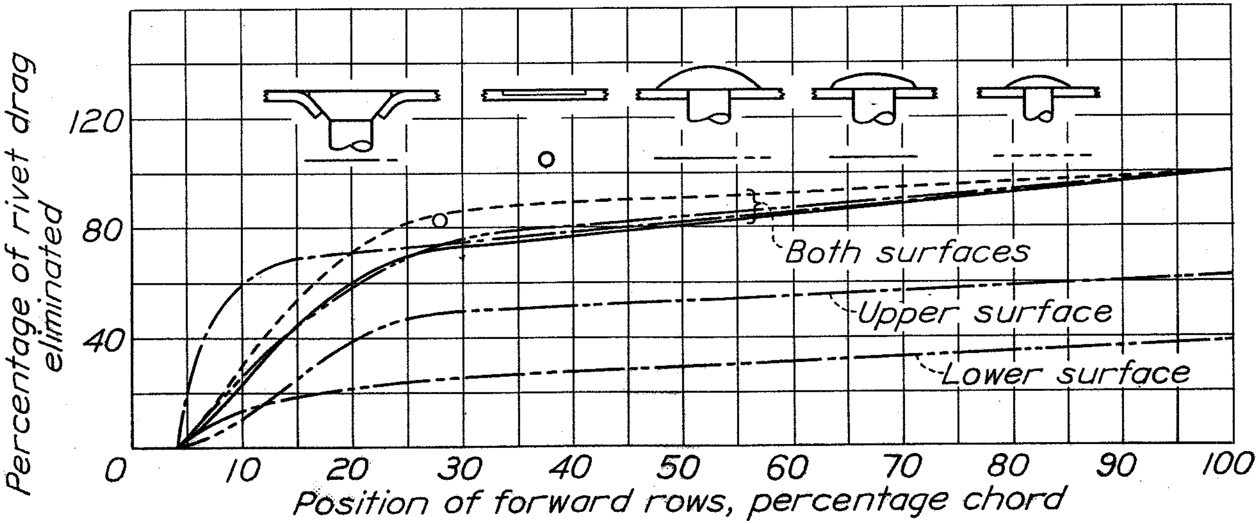


Figure 9

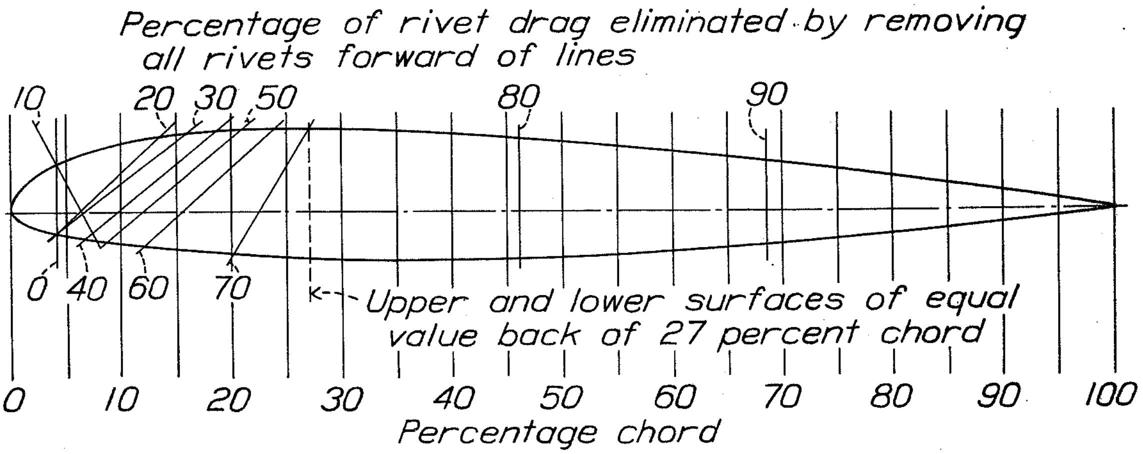
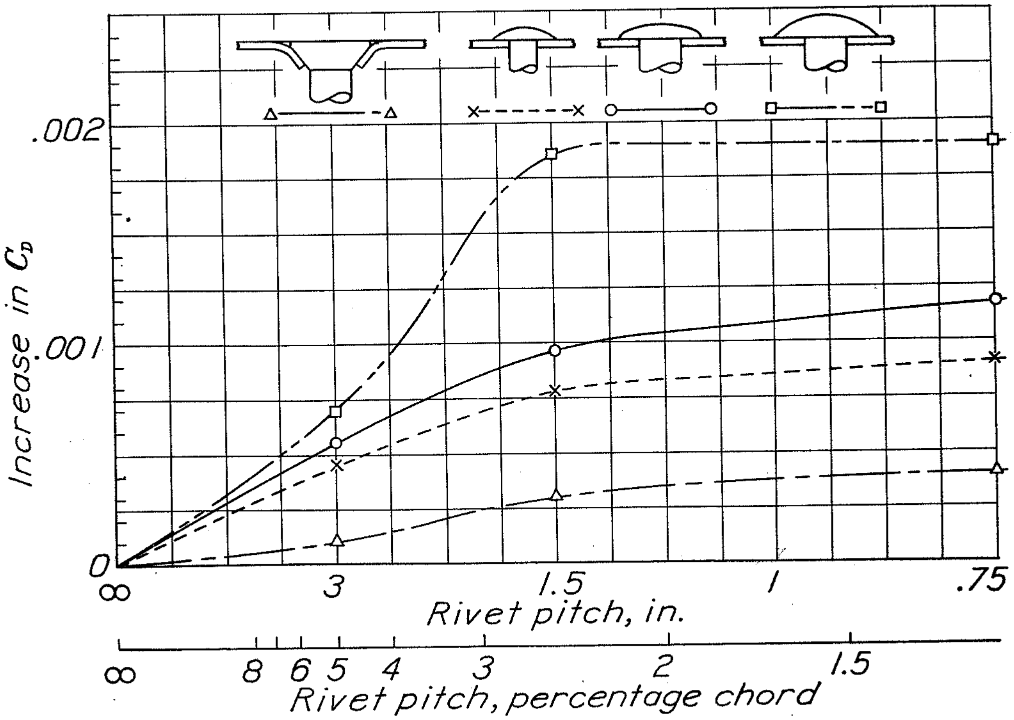


Figure 10.



V = 230 mph
C_L = .15

Figure 11.

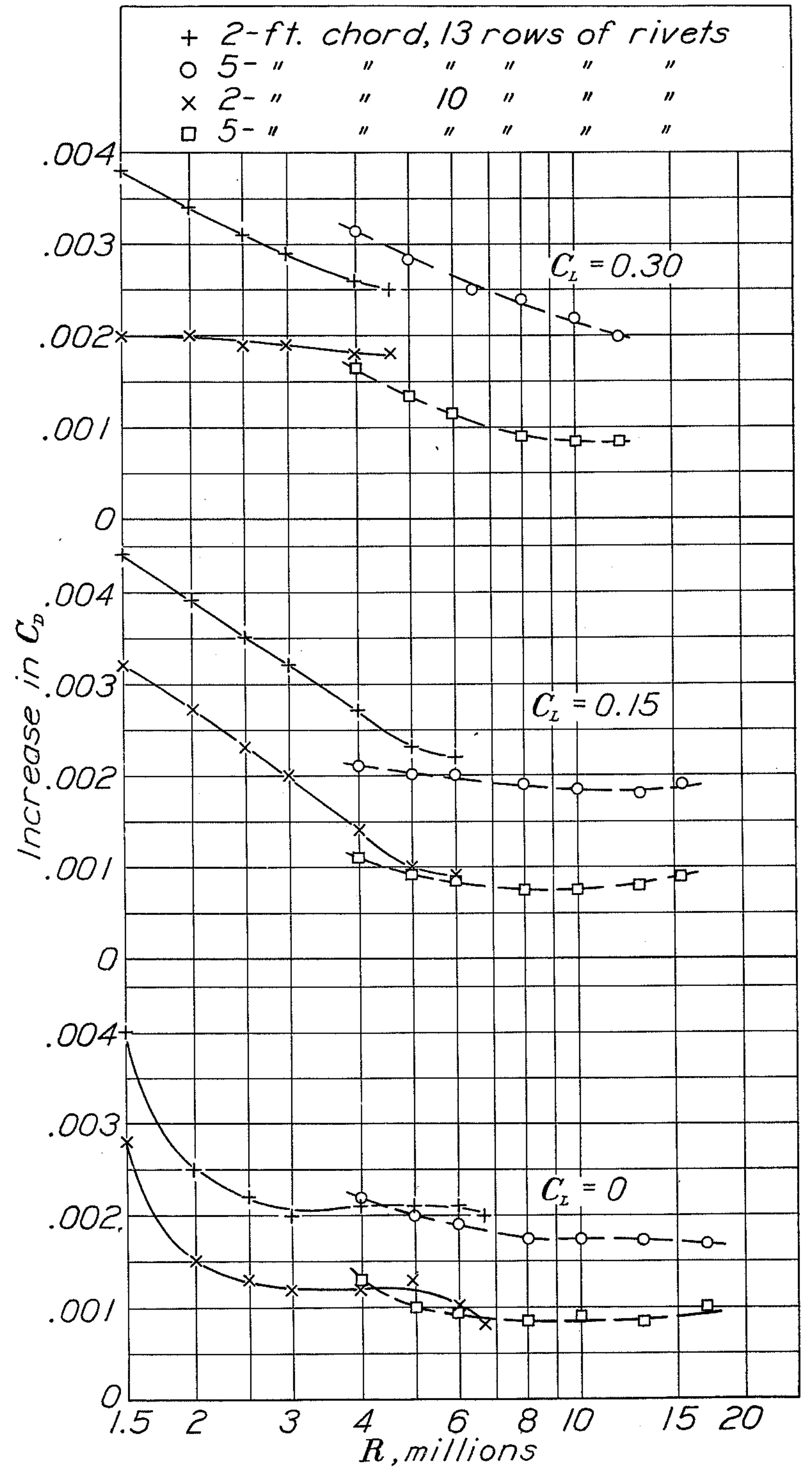

+ 2-ft. chord, 13 rows of rivets
○ 5- " " " " " "
× 2- " " 10 " " "
□ 5- " " " " " "
$C_L = 0.30$
$C_L = 0.15$
$C_L = 0$
Increase in C_D
.004
.003
.002
.001
0
1.5
2
3
4
6
8
10
15
20
R, millions

Figure 12