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No. 695

THE EFFECTS OF SOME COMMON SURFACE IRREGULARITIES

ON WING DRAG

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SUMMARY

The N.A.C.A. has conducted tests to provide more com-
plete data than were previously available for estimating
the effects of common surface irregularities on wing drag.
The irregularities investigated included: brazier-head
and countersunk rivets, spot welds, several types of sheet-
metal joints, and surface roughness. Tests were also con-
ducted to determine the over-all effect of manufacturing
irregularities incidental to riveted aluminum alloy and to
spot-welded stainless-steel construction. The tests were
made in the 8-foot high-speed wind tunnel at Reynolds Num-
bers up to 18,000,000.

The results show that any of the surface irregulari-
ties investigated may increase wing drag enough to have
important adverse effects on high-speed performance and -
economy.

A method of estimating increases in wing drag caused
by brazier-head rivets and lapped joints under conditions
outside the range of the tests is suggested. Estimated
drag increases due to rivets and lapped joints on a wing
of 20-foot chord flying at 250 miles per hour are shown.

INTRODUCTION

Improved streamlining has reduced form drag so much
that on modern airplanes skin friction often constitutes
more than half of the total drag. It is therefore impor-
tant that skin friction be made as small as possible. It
is obvious that protruding rivet heads, roughness, and
other surface irregularities will increase skin friction.
A knowledge of the magnitude of the drag increases is nec-
essary before the designer can decide to what extent it is

economical to eliminate these irregularities from the sur-
faces exposed to air flow.

Previous tests have shown that rivet heads (reference
1), certain arbitrary protuberances (references 2 and 3),
and roughness (references 4 and 5) increase the drag of
wings by important amounts. The N.A.C.A. has conducted
additional tests to provide more complete data on the drag
caused by irregularities of types commonly occurring on
airplane wings so that their effects may be more accurate-
ly estimated. Some of the results of these tests are pre-
sented in this report. The irregularities for which data
are presented include protruding rivet heads, spot welds,
several types of lapped joints, imperfections in butted
joints, surface roughness, and manufacturing irregulari-
ties. Most of the irregularities were tested in various
systematic arrangements over different portions of the
surface of an airfoil of N.A.C.A. 23012 section and 5-foot
chord. The tests were made at lift coefficients of 0 to
0.30 and at Reynolds Numbers up to 18,000,000.

A method of applying the results to predict the drag
increases due to rivet heads and lapped joints on airplane
wings under conditions outside of the range of these tests
is presented.

APPARATUS

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

The airfoils used for the tests were of N.A.C.A.
23012 section and, except for a few supplementary tests
of a 2-foot airfoil, they were of 5-foot chord. The noses
of the airfoils were bare steel to reduce erosion; the
rest of the surface was bare steel in some instances and
painted in others. Except for the irregularities being
tested, the surfaces were aerodynamically smooth; that is,
further polishing would not reduce the drag.

The airfoils were mounted horizontally across the
center of the test section as shown in figure 1. The tun-
nel-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 independently of the balance. The span of each shield was 10 inches and the active span of the airfoils between the shields was 6 feet.

Actual rivets with their shanks pressed into holes drilled in the airfoil were used for most of the tests of protruding rivet heads but for some of the tests it was found more convenient to simulate the rivet heads with properly shaped lead punchings cemented to the surface with airplane dope. Countersunk rivets were simulated by annular cuts in the surface of the airfoil to represent the indentations around rivet heads that result from making countersinks by forming the sheet metal with punches instead of by cutting. Details of the rivets and the simulations are shown in figure 2. The rivet-head simulations tested on the 2-foot airfoil were two-fifths as large as the heads of the 3/32-inch brazier-head rivets.

Spot welds were simulated on the otherwise smooth model by depressions of the dimensions shown on figure 3. The cylindrical simulations were cut in the surface and the spherical simulations were formed by filling the cylindrical simulations with plasticine and forming the depressions with tools having spherical ends.

Most of the lapped joints were represented by cuts made in the surface of the airfoil but, in addition to this method, the plain lap facing aft was also simulated by a ridge built up on top of the normal airfoil surface with paper and lacquer-base glazing putty. Gaps such as occur between the edges of sheets in butt-jointed construction were simulated by square-edge grooves cut spanwise in the surface of the airfoil. Adjoining edges of the gaps were of equal height, representing construction in which the butted sheets are of exactly equal thickness. The dimensions of the simulations of lapped and butted joints are shown in figure 4. All the simulations represented sheets 0.018 inch (0.0003 chord) thick.

The chord positions at which sheet-metal joints and spanwise rows of rivets and spot welds were tested are shown in figure 5. The spanwise pitch of the rivets and spot welds was 3/4 inch (0.0125 chord) except where otherwise noted.

Photomicrographs of samples of the different surface roughnesses tested, all to the same magnification, are

shown in figure 6. The carborundum-covered surfaces were
produced by spraying carborundum grains mixed with thin
shellac onto the smooth airfoils. The common designations
of the grain sizes are:

Average grain size k(in.)	Carborundum Company's designation
0.0037	180
.0013	FF
.0005	800-RA

From figure 6 it is apparent that the 0.0005-inch grains
were piled on top of each other in such a manner that the
degree of roughness was not equivalent to the grain size,
as was the case with the larger grains. The photomicro-
graphs also indicate that the shellac used to hold the
grains was sufficiently thin that the effective size and
shape of the grains were not appreciably changed. The
sizes of the grains were determined from measurements made
with a microscope and from measurements of the photomicro-
graphs. The density (spacing) of the grains varied some-
what over the airfoils but the photomicrographs represent
average conditions. The spray-painted surface was produced
by spraying a lacquer-base primer surfacer onto the air-
foil, probably a little rougher than is common practice.
The sandpapering was done with No. 400 sandpaper lubri-
cated with water. No attempt was made to limit the sand-
papering strokes to any one direction but chordwise strokes
predominated. The surface was polished by rubbing with a
polish of the type used in polishing automobiles, waxing,
and rubbing with a soft cloth.

Two airfoils, one of riveted aluminum-alloy construc-
tion and the other of spot-welded stainless steel, were
tested to obtain a measure of the over-all effect of man-
ufacturing irregularities incidental to conventional metal-
wing construction. These "service wings" were both made
by manufacturers accustomed to the respective types of
construction involved. The manufacturers were instructed
to employ conventional design, tolerances, and workmanship
in order to make the models as nearly as possible repre-
sentative of actual wings being produced at that time
(1936). The riveted model employed the same rivet size
and arrangement and the same lapped-joint positions as
were tested in one instance on the more accurate wind-
tunnel model but the thickness of the lapped sheets was
0.032 inch. The skin of the stainless steel model was

0.015 inch thick on the forward 45 percent and 0.0008 inch thick on the rear 55 percent. The average dimensions of the spot welds are shown in figure 3. The arrangement of spot welds and lapped joints on the stainless-steel model is shown in figure 7. Except for the discrepancy in the profile of the riveted service wing shown in figure 8, there were no departures from true profile large enough to have important effects. Figures 9 and 10 are photographs of the service wings arranged to reflect the image of a lattice so as to show the irregularities of the surfaces. The riveted service wing was furnished by the Bureau of Aeronautics, Navy Department, and the stainless-steel wing was furnished by the U. S. Army Air Corps.

METHOD

For each arrangement of surface irregularities tested, the lift, the drag, and the pitching moment were determined at 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 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 to about 430, and in some instances 500, miles per hour. At the highest speed compressibility effects were so large that the drag coefficient increased very rapidly as the speed was increased. The drag of the smooth airfoil was checked frequently during the tests.

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

$$P_a = P_s + \frac{1}{2} \rho_s V_s^2 \left(1 + \frac{1}{4} M^2 + \frac{1}{40} M^4 + \frac{1}{1600} M^6 \ldots \right)$$

where P_a is the atmospheric pressure which, in the case discussed in reference 7, was virtually equal to the total pressure 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 parentheses 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,

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

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

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

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

During tests, measurements are made of the pressure difference $P_1 - P_s$, where P_1 is the static pressure in the low-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 the 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 pressures at these two sections.

When the air in the wind tunnel is cool and its relative humidity is 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.

PRECISION

The only known systematic errors affecting the results herein presented are due to errors in the dynamic pressure resulting from constriction by the model of the flow through the test section. No correction for constriction has been applied because its magnitude is not yet accurately known. Preliminary tests have indicated, however, that it is not more than 6 percent at speeds up to 270 miles per hour or 9 percent up to 500 miles per hour. The drag increases herein presented may, therefore, be too high by

6 percent at the lower speeds and 9 percent at the higher
speeds. Since most of the increases are small relative
to the smooth-wing drag, these errors are generally unim-
portant.

The scatter of experimental points for separate de-
terminations of the smooth-wing drag indicates that ran-
dom errors in drag coefficients generally do not exceed
±0.0001, corresponding to ±1.4 percent of the smooth-wing
drag; however, at speeds below 100 and above 400 miles
per hour and at all speeds at a lift coefficient of 0.30,
the variations are about twice this large.

RESULTS AND DISCUSSION

Method of Presentation

All results are presented in terms of increases in
drag coefficient C_D, the amount by which the drag coef-
ficient for any condition exceeded the drag coefficient
of the smooth airfoil at the same speed and angle of at-
tack. No corrections for tunnel-wall effects have been
applied because this method of presentation makes correc-
tions unnecessary except those due to constriction effects,
which have been discussed under Precision.

Because of the rapid variation of drag coefficient
with Mach number at the high test speeds, it was necessary
to compute the drag differences at equal values of the
Mach number. Equal Mach numbers correspond approximately,
but not exactly, to equal Reynolds Numbers for a given
size model. This variation from test to test of the
Reynolds Number corresponding to a given Mach number is,
however, small enough to be of little consequence and the
results are therefore presented in terms of Reynolds Num-
bers representing the averages for the various tests. For
the 5-foot airfoils, an average Reynolds Number of
10,300,000 corresponded to a Mach number of 0.3 and an av-
erage Reynolds Number of 17,600,000 to a Mach number of
0.6.

That the effect of compressibility on the drag incre-
ments herein presented may be neglected is indicated by
figure 11, which shows that rivets of geometrically simi-
lar size and arrangement increased the drag coefficients

of the 2-foot and the 5-foot airfoils by substantially equal amounts at equal Reynolds Numbers even though the Mach numbers differed widely. The results may therefore be applied solely on the basis of Reynolds Number. In accordance with Reynolds' law, rivet size and arrangement must be considered in terms of wing chord when the results are used directly to predict the drag of rivets on wings of different chord.

Rivets

Figure 12 shows the drag increments due to the various types and sizes of rivets in 13 spanwise rows on each surface. The spanwise pitch in each row was 3/4 inch (0.0125 chord) and the most forward row on each surface was 4 percent of the chord behind the leading edge. The approximate percentage increments are spotted on the curves for a few representative points to aid in visualizing the magnitude of these drag increments. It is obvious that the drag increments are large enough to have important adverse effects on performance, being as much as 27 percent of the smooth-wing drag for the 3/32-inch brazier-head rivets. Even countersunk rivets may increase wing drag by amounts too large to be neglected.

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; and, second, rivets on the forward part of a wing cause the transition point to move forward and thereby cause an increase in skin friction. That this second factor may be responsible for a large part of the drag increase is indicated by figure 13. This figure shows that, when the front row of rivets was 4 percent of the chord from the leading edge, the rivet drag was reduced only slightly by increasing the spanwise pitch from 3/4 inch to 1-1/2 inches, although half of the rivets were removed in the process. Most of the drag increase in this case must have been due to disturbance of the boundary layer, which was not importantly reduced by increasing the pitch from 3/4 inch to 1-1/2 inches. When the forward rows of rivets were 28 percent of the chord from the leading edge, they were behind the transition point and, as the pitch was varied, the rivet drag varied in proportion to the number of rivets on the wing.

Figures 14 and 15 show the variation of rivet drag with position of the forward rows. The position of the forward rows was varied by adding or removing rows at the

front, rows behind the most forward ones always remaining
in place at the chord position shown in figure 5. These
figures illustrate again the importance of the shift of
the transition point caused by rivets. As rows of rivets
are added, starting at the back and progressing forward,
the drag increases slowly until the region where transi-
tion occurs on the smooth wing (fig. 15) is reached, after
which the drag increases much more rapidly. The shaded
area in figure 15 indicates the excess of the rivet drag
over what it would be if the original rate of increase
were maintained forward of the transition point. This ex-
cess drag is plotted in figure 16 along with the computed
difference between turbulent and laminar flat-plate skin
friction for the Reynolds Numbers involved. The agreement
of the computed and the experimental curves indicates that
the rapid rise of the curves of figures 14 and 15 forward
of the 25-percent-chord position is largely due to forward
movement of the transition point.

From the test results shown in figures 12 to 15, it
can be concluded that the following measures are most ef-
fective in keeping rivet drag small:

(a) Rivets should be as far back on the wing surface
as possible. It is especially important that there be no
rivets forward of the point at which transition occurs on
the smooth wing. With the rivet arrangement shown in fig-
ure 5, for example, 70 percent of the rivet drag was caused
by the rivets on the forward 30 percent of the airfoil.

(b) Rivet heads should be as small as possible.

(c) There should be as few exposed rivet heads as
possible; reducing the number by increasing the pitch in
spanwise rows forward of the transition point, however,
has little effect unless the pitch is larger than 0.025
chord.

Spot Welds

The drag increases caused by the three sizes of spot
welds are shown in figure 17. These increases are smaller
than those caused by any of the protruding rivet heads but
are large enough so that an effort should be made to keep
the depressions at spot welds as shallow as possible. The
two points shown for the 0.012-inch-deep spot welds in
figure 14 indicate that spot welds, as well as rivets,
should be avoided especially forward of the smooth-wing
transition point.

Sheet-Metal Joints

Increases in drag due to the presence of sheet-metal joints are shown in figure 18 for lapped joints and in figure 19 for butted joints with gaps between the edges of the sheets. The conventional plain laps facing aft are only slightly superior to the same type facing forward. Joggled laps cause only about one-half as much drag as either type of plain lap. It is important that the laps be accurately formed to lie inside the true airfoil profile because, if they rise outside the true profile (see fig. 4), appreciably more drag may be created.

Rounding the exposed edges of the sheets to a radius equal to the sheet thickness reduced the drag of the forward-facing laps to about the same magnitude as that of the square-edge laps facing aft. Rounding the edges of the plain laps facing aft to this radius reduced the drag very slightly but fairing the edges back to a width equal to three times the sheet thickness reduced the drag caused by this type of lap to about two-thirds of its previous magnitude.

The variation of lapped-joint drag with chord position of the forward laps was similar to that shown for rivets in figure 14.

From figure 18, it is seen that the drag increments caused by rivets and laps are not additive. Presumably, this condition is due to the fact that the rivets caused transition to take place at the most forward row. Adding laps back of this point therefore had no further effect on the transition point, and the additional drag due to the presence of the laps was only the direct drag of these laps in the turbulent boundary layer.

The 0.024-inch square-edge grooves caused only small increases in drag (fig. 19), indicating that only reasonably small tolerances need be maintained on the permissible gap between the edges of butted sheets.

Roughness

From figure 20, it is evident that even a small degree of surface roughness increases wing drag sufficiently to have serious adverse effects on high-speed performance and economy. Even the roughness due to spray painting may in-

crease wing drag 10 to 14 percent in the high-speed and
cruising range. Except at the lowest speeds, the 0.0013-
inch roughness increased the drag considerably more than
3/32-inch brazier-head rivets. As in the case of other
surface irregularities, it is especially important to keep
the forward portions of wings smooth, but roughness may
cause important increases in wing drag even when entirely
behind the smooth-wing transition point. (See fig. 21.)

In the range of these tests, the drag increases caused
by surface roughness vary considerably with scale (fig. 20).
At the lower speeds, the drag due to roughness decreases
rapidly as speed is reduced and the curves indicate that,
for each degree of roughness, there is a speed or Reynolds
Number below which that roughness has no effect on drag.
Conversely, it is indicated that for every speed or
Reynolds Number there is a limiting "permissible roughness,"
which will cause no increase in drag. The existence of
such a permissible roughness has been shown by other tests
and by the theory that roughness wholly submerged in the
laminar sublayer will not increase the drag (references 8
and 9). Estimating permissible roughness from the results
herein reported involves questionable extrapolations, but
nevertheless the results do indicate the same order of
magnitude of permissible roughness as is tabulated for a
flat plate with a wholly turbulent boundary layer in refer-
ence 8; even though, in the case of the airfoil, part of
the boundary layer is laminar. This agreement suggests the
conclusion that neither the 0.0005-inch grains nor the
roughness due to spray painting had any great effect on
the transition point. This conclusion is supported by
figure 21 because the curves for the two smaller degrees
of roughness do not rise so rapidly forward of the 25-
percent-chord position as they would if the transition
point moved forward with the roughness. There is need for
further investigation of the degree of roughness a wing
surface may have before premature transition is induced.
The permissible roughness in the laminar boundary layer
probably varies widely with dynamic scale, airfoil pres-
sure gradient, and initial air-stream turbulence, so the
indicated conclusion should not be applied where conditions
differ from those of the present tests.

It is of practical interest to note that, within the
limits of accuracy of the tests, the drag of the sandpapered
airfoil was the same as that of the highly polished airfoil.
For airplanes to have the smallest possible skin friction
the surfaces must be smooth but need not be highly polished.

Because of the large scale effect on the drag of rough surfaces (fig. 20), it is essential that experimental investigations of the effects of surface roughness be made at large scale. Degrees of roughness large enough to have serious adverse effects under flight conditions may have no effect whatsoever under conditions of small-scale tests.

The effects of roughness on airplane wings can be estimated only approximately from the results of these tests because the effects depend on grain shape and grain spacing as well as grain size. The variation of drag with grain spacing is especially large (reference 10).

Manufacturing Irregularities

Figure 22, showing the results of tests of the two service wings (figs. 9 and 10), indicates that manufacturing irregularities may cause important drag increases over and above those due to the rivets and the lapped joints. For example, the drag of the riveted service wing was 42 percent greater than that of a smooth accurate wing (at a lift coefficient of 0.15 and a Reynolds Number of 10,300,000), whereas the same arrangement of rivets and lapped joints caused only 29 percent excess drag on the more accurate wind-tunnel model. The rivets on the two models were identical but the lapped sheets were 0.032 inch thick on the service wing compared with 0.018 inch on the wind-tunnel model. It is estimated, by a method hereinafter explained, that the extra sheet thickness on the service wing was responsible for a difference in drag coefficient of about 0.0004, or 5 percent of the smooth-wing drag. There remains a difference of 8 percent of the smooth-wing drag to be attributed to manufacturing irregularities such as sheet waviness, departures from true profile, and imperfections in the lapped joints. In the absence of protruding rivet heads on the forward part of the wing, equivalent manufacturing irregularities would probably have a much larger effect.

The drag of the riveted service wing at zero lift increased rapidly at Reynolds Numbers above 14,000,000, corresponding to a Mach number of 0.43 or a speed of 330 miles per hour at 60° F. It is believed that this rapid rise in drag was due to a shock wave prematurely induced by a bulge in the lower portion of the nose of this model (fig. 8). The importance of making wings for high-speed airplanes accurately to true profile is evident.

The drag of the spot-welded stainless-steel service
wing averaged about 20 percent greater than the drag of a
smooth accurate wing. It is difficult to say how much of
the excess drag of this model was due to the lapped joints
because of uncertainty as to whether the spot welds and the
sheet waviness would induce premature transition in the ab-
sence of the lapped joints.

<div align="center">APPLICATION OF RESULTS</div>

It has been shown that the increase in wing drag
caused by rivet heads can be divided into two parts: the
increase in skin friction due to the fact that the rivets
cause transition from laminar to turbulent boundary layer
to occur abnormally far forward on the wing, and the di-
rect drag of the rivet heads themselves. The separation
of the drag increments into these two parts affords a
basis for estimating the drag due to rivet heads and lapped
joints under conditions of scale and of rivet and lap size
and arrangement outside the range of these tests. The in-
crease due to a forward shift of the transition point can
be approximated by estimating the distance through which
the transition point is moved and then applying the known
difference between laminar and turbulent skin friction for
the Reynolds Numbers involved. The direct drag of the
rivet heads can then be estimated from computed local ve-
locities at the rivet heads and suitable rivet-drag coeffi-
cients.

In order to estimate the drag increase resulting from
a forward shift of the transition point, it is necessary
first to know where the transition point would be if there
were no rivets on the wing. The results of recent tests
by Becker, as yet unpublished, have indicated that, on
smooth conventional airfoils, the transition point approach-
es the point of peak minimum pressure as the Reynolds Num-
ber increases. When there is more than one peak of mini-
mum pressure on a surface of the airfoil, transition will
generally occur at the farthest forward peak even though
it may be smaller than later peaks. Until a more complete
understanding is available, transition at large Reynolds
Numbers may be assumed to occur at the farthest forward
peak of minimum pressure on each side of the wing. It ap-
pears safe to assume that any protruding rivet heads large
enough to be practicable will, if forward of the smooth-
wing transition point, cause transition to occur at the

rivets. Dust patterns on models in the 8-foot high-speed wind tunnel have indicated that the wake of turbulent boundary layer behind individual rivet heads in an otherwise laminar boundary layer spreads laterally with a total included angle of about 15°. This angle may be used in estimating the area over which premature transition is created by individual rivet heads.

Calculated skin friction based on free-stream dynamic pressure and flat-plate coefficients agreed with experimentally determined values on an N.A.C.A. 0012 airfoil. In the absence of further evidence, the increase in skin friction resulting from the estimated shift of the transition point can be estimated as the product of the area affected, the free-stream dynamic pressure, and the difference between the laminar and the turbulent skin-friction coefficients. The difference between local flat-plate skin-friction coefficients for turbulent and laminar boundary layers (reference 8) varies only slowly with Reynolds Number. A constant value of 0.0026 is correct within 10 percent for Reynolds Numbers between 1,000,000 and 10,000,000. This value of the coefficient is based on the total area involved instead of the wing area as usually defined, and the Reynolds Number is based on the distance from the leading edge to the center of the area affected.

From the test results herein reported, a coefficient for the drag of brazier rivet heads in the turbulent boundary layer has been computed. This coefficient, based on the local dynamic pressure in the boundary layer at a distance from the surface equal to the height of the rivet heads and on the frontal area of the rivet heads, has the value of 0.32. A more convenient form of this coefficient for use with standard brazier-head rivets is that based on the square of the shank diameter in inches instead of on the frontal area of the head in square feet. In this form, the coefficient becomes 0.0020.

A coefficient computed in the same manner for plain lapped joints facing aft has the value 0.20 based on the frontal area in square feet but may be as high as 0.30 if the laps lie outside the true airfoil profile:

Since transition will occur at the most forward rivets, all the rest of the rivets will be in a turbulent boundary layer and may be treated as outlined in the preceding paragraph. The most forward rivets, if forward of the smooth-wing transition point, will be in a laminar boundary layer

and this boundary layer will generally be thinner than the height of the rivet heads. These rivets, therefore, have a higher drag coefficient than those wholly submerged in the turbulent boundary layer. The coefficient expressing the drag of 3/32-inch brazier-head rivets in a laminar boundary layer about 0.004 inch thick was computed from the test results to be 1.3, based as before on the dynamic pressure at the top of the rivet head and the frontal area of the head. Based on the square of the shank diameter in inches, this coefficient becomes 0.0079.

In the application of these drag coefficients, the airfoil pressure distribution may be computed by Theodorsen's method (reference 11) and the boundary-layer thickness by the method of Dryden and Kuethe (reference 12). On the assumption that the one-seventh power law applies to the distribution of velocity in the boundary layer, the velocities and the dynamic pressures at the tops of the laps and the rivet heads can be computed for the different positions. The drags of the different laps and rivets can then be computed as the products of these dynamic pressures, the corresponding areas, and the applicable coefficients and be summed up along with the drag increment resulting from the shift of the transition point to obtain the total drag caused by the rivets and lapped joints on the wing.

This method of estimating rivet and lapped-joint drag has been applied to most of the arrangements of lapped joints and 1/16-inch and 3/32-inch brazier-head rivets tested and has yielded results in good agreement with the experimental values.

EXAMPLE

The magnitude of drag increments resulting from the presence of rivet heads and lapped joints on small airplane wings can be judged directly from the test results. As an example to illustrate the magnitude of the increments on large wings, the drag due to rivets and lapped joints on a wing having an average chord of 20 feet has been estimated. The chord positions of the spanwise rows of rivets and lapped joints assumed for this example are shown at the top of figure 23. It was assumed that the rivets were standard 3/32-inch brazier-head rivets, that the spanwise pitch was 1-1/2 inches, and that the thick-

ness of the lapped sheets was 0.040 inch. The flight
speed was taken as 250 miles per hour at sea level, the
corresponding Reynolds Number being 45,000,000.

One set of ordinates in figure 23 shows the drag
caused by the rivets and the lapped joints remaining on
the wing when all the irregularities forward of the chord
positions indicated by the abscissas have been eliminated.
For example, it is estimated that all the rivets and the
lapped joints shown on the wing would increase the drag
coefficient by 0.00115 but that, if the rivets and the
lapped joints on the forward 30 percent of the wing were
eliminated, the excess drag would be reduced to 0.00035.

The excess power required just to overcome the drag
caused by the rivets and the lapped joints is shown by
the second set of ordinates in figure 23. The additional
assumptions that the wing area is 3,600 square feet and
that the propulsive efficiency is 85 percent, have been
used in computing this power. With all the rivets and the
lapped joints shown on the wing, more than 500 horsepower
would be required just to overcome their drag. If the
forward 30 percent of the wing were made smooth, about 160
horsepower would be required to overcome the drag caused
by the remaining rivets and lapped joints.

CONCLUSIONS

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

1. Rivets at 3/4-inch pitch in 13 spanwise rows on
each surface of an airfoil of 5-foot chord increased the
drag from 6 percent for countersunk rivets to 27 percent
for 3/32-inch brazier-head rivets. About 70 percent of
these drag increments were due to the rivets on the for-
ward 30 percent of the airfoil.

2. Lapped joints, arranged six on each surface, in-
creased the drag of the airfoil from 4 percent for joggled
laps to 9 percent for conventional laps.

3. Surface roughness may cause serious increases in
drag; for example, the roughness due to spray painting
increased the drag 14 percent and roughness of 0.0013-
inch grain size increased the drag 42 percent.

4.   Manufacturing irregularities increased the drag
of a typical wing 8 percent of the smooth-wing drag over
and above the increments due to the rivets and lapped
joints.

Langley Memorial Aeronautical Laboratory,
      National Advisory Committee for Aeronautics,
            Langley Field, Va., March 7, 1939.

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Figure 1.- 5-foot airfoil mounted in wind tunnel.
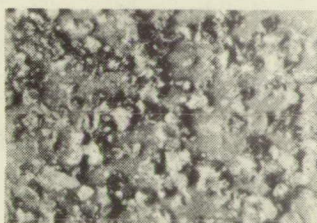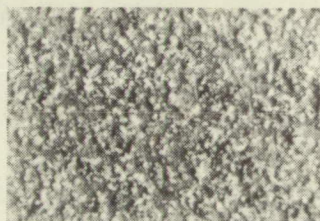
0.0037-INCH GRAINS   0.0013-INCH GRAINS   0.0005-INCH GRAINS
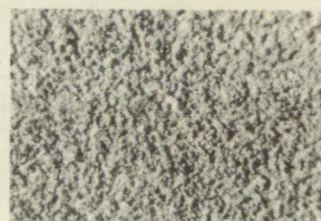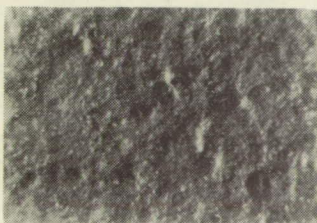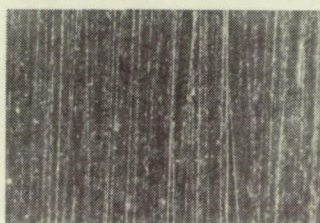
SPRAY PAINTED   SANDPAPERED   POLISHED AND WAXED

0   .05   .10

SCALE, IN.
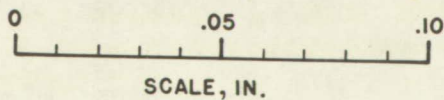
Figure 6.- Photomicrographs of surface roughness.

0.23 dia.

0.049
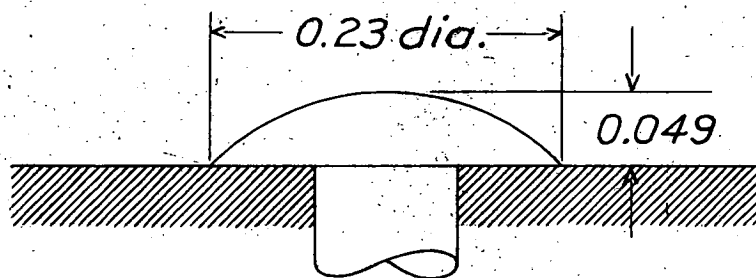
3/32" brazier-head rivet

0.19 dia.

0.032
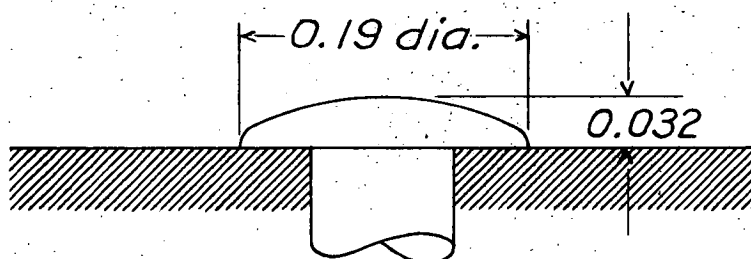
3/32" thin brazier-head rivet

0.14 dia.

0.028
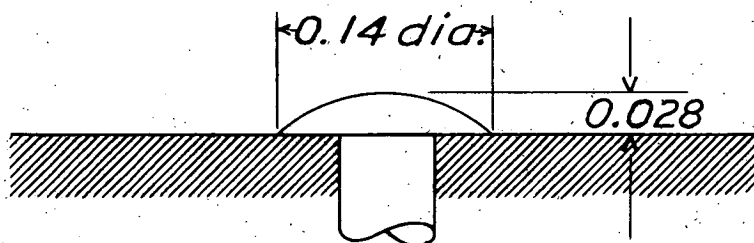
1/16" brazier-head rivet

0.30 dia.

0.19 dia.

0.007
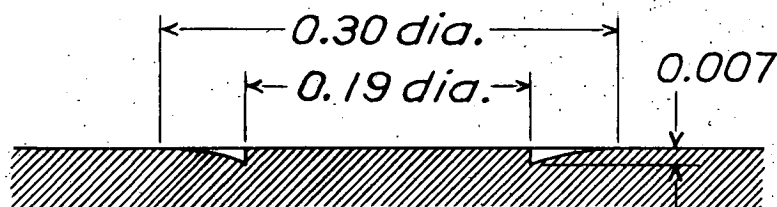
Simulation of 3/32" countersunk rivet

Figure 2.- Details of brazier-head rivets and simulations
of countersunk rivets. All dimensions are
in inches.
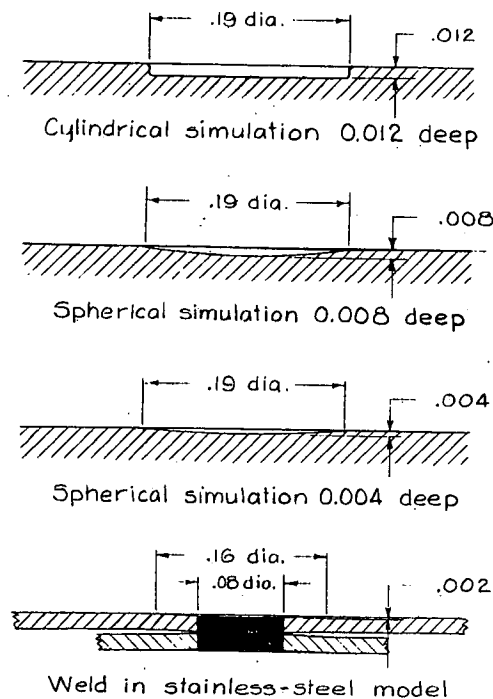
Figure 3.— Dimensions of spot welds and simulations. All dimensions are in inches.

Cylindrical simulation 0.012 deep

Spherical simulation 0.008 deep

Spherical simulation 0.004 deep

Weld in stainless-steel model

Air flow

Joggled lap facing aft

Plain lap facing aft inside   true profile

Plain lap facing aft inside   true profile
with 3/32-inch brazier-head rivets

Plain lap facing aft outside   true profile

Plain lap facing forward inside   true profile

Gap at butt joint

Figure 4.— Details of simulations of lapped and butted sheet-metal joints. All dimensions are in inches.
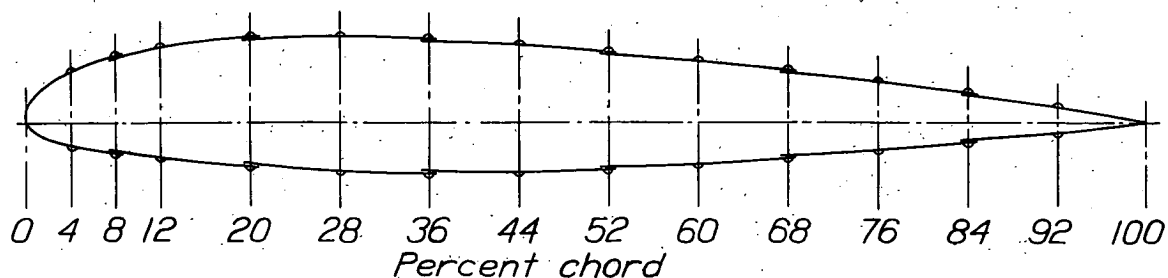
Figure 5.- Positions of rows of rivets and sheet-metal joints used in tests.
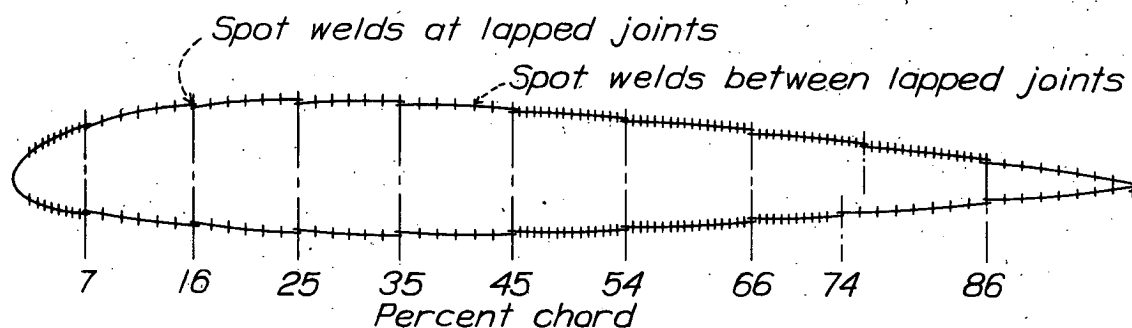
Figure 7.- Arrangement of spot welds and lapped joints on stainless- steel service wing. Spanwise pitch, 1/2 inch (0.0083 chord).
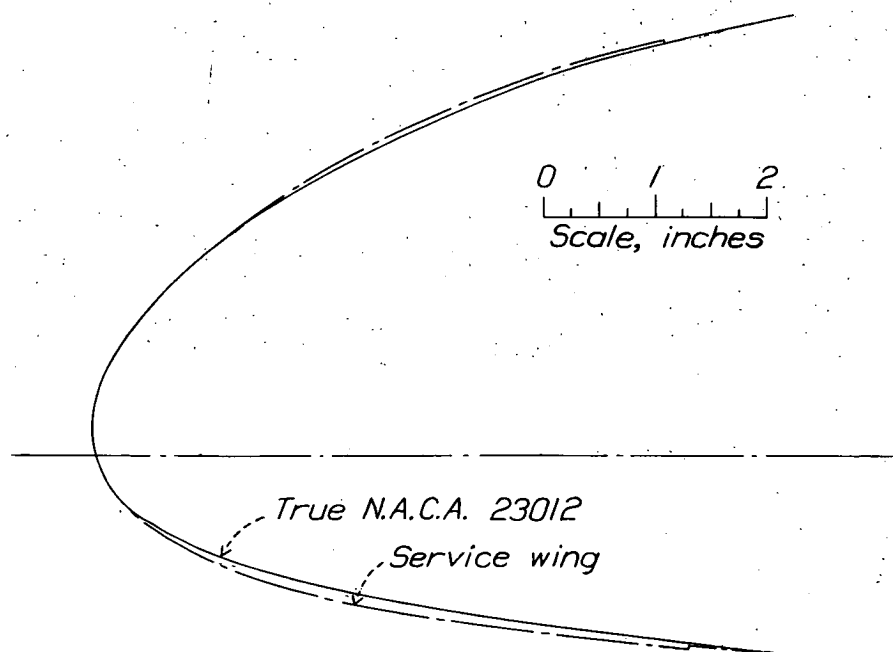
Figure 8.- Profile of riveted service wing compared with true N.A.C.A. 23012
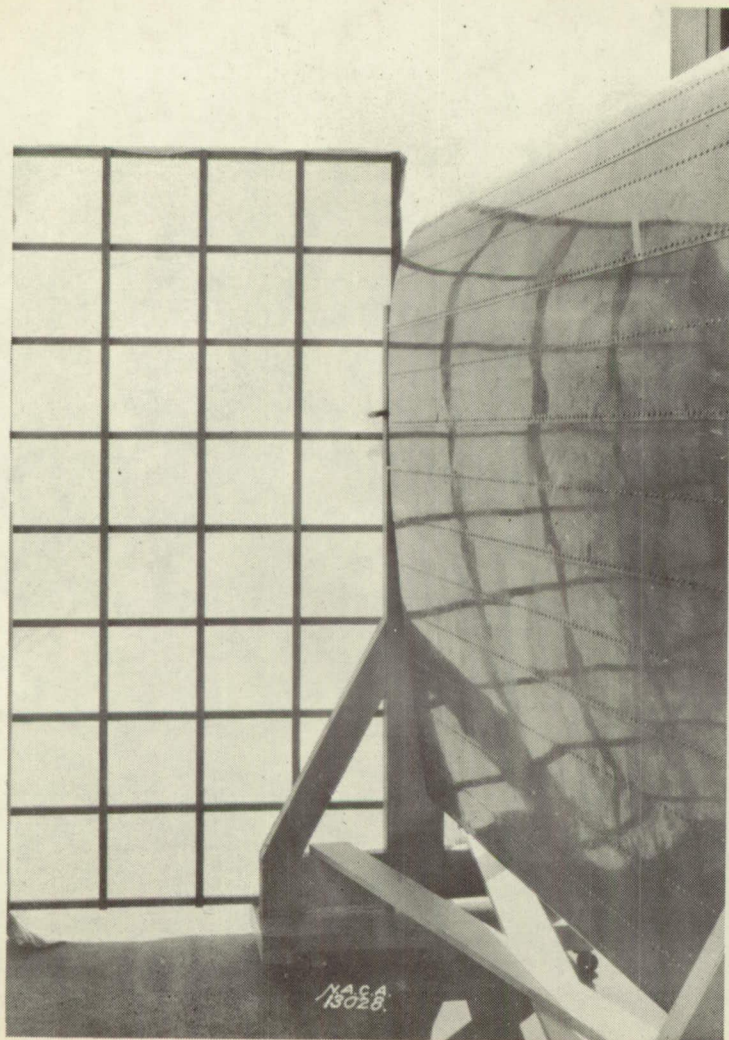
Figure 9.- Service wing of riveted aluminum alloy construction.
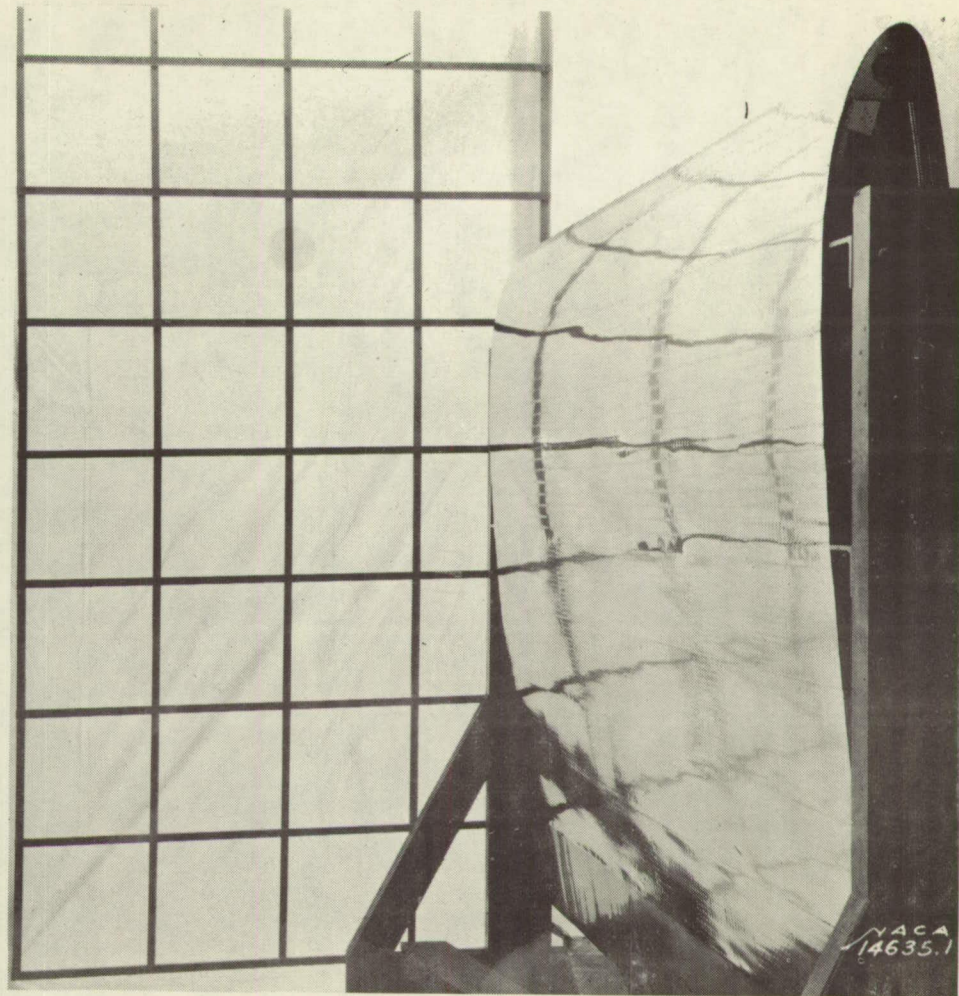
Figure 10.- Service wing of spot-welded stainless-steel construction.
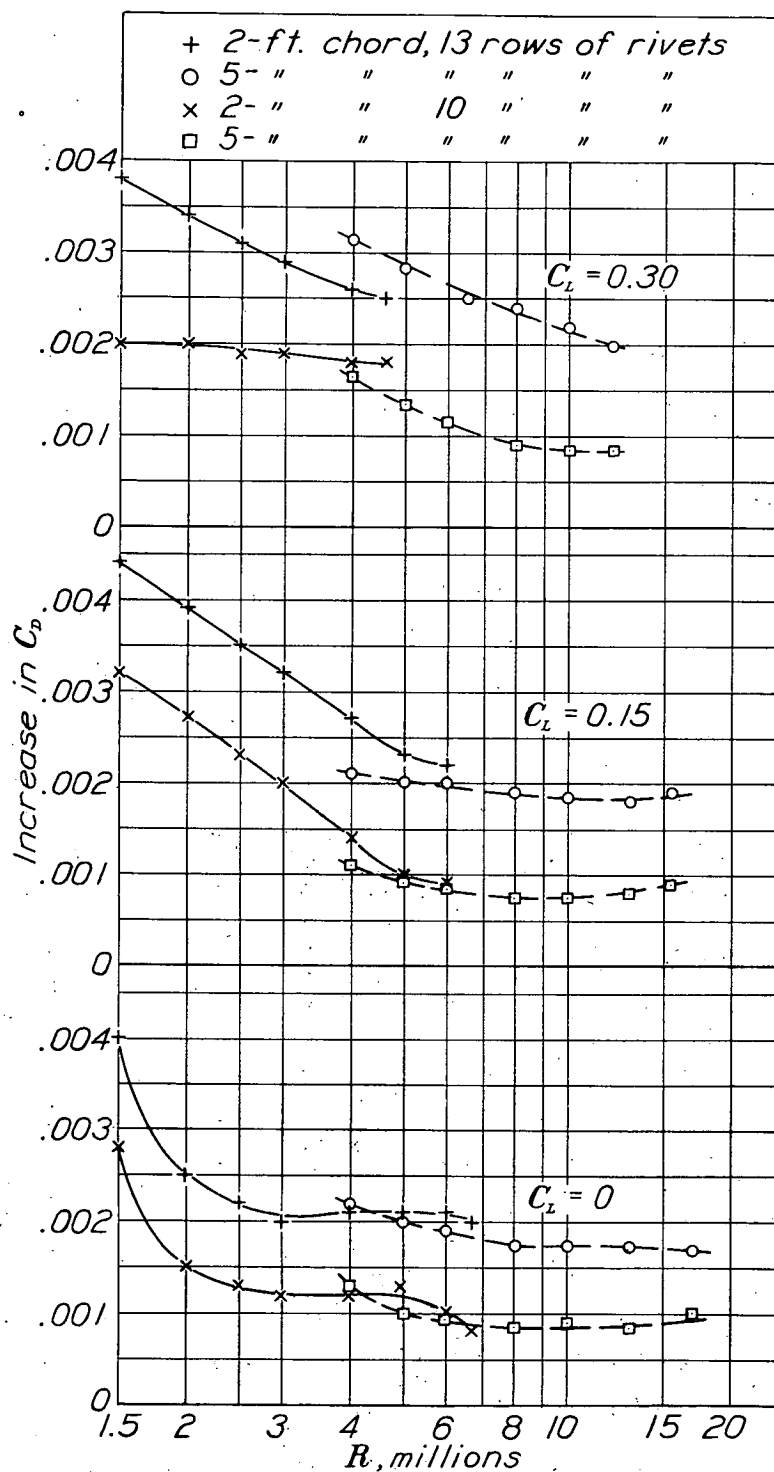
Figure 11. Drag due to geometrically similar arrangements of rivets on 2-foot and 5-foot airfoils.
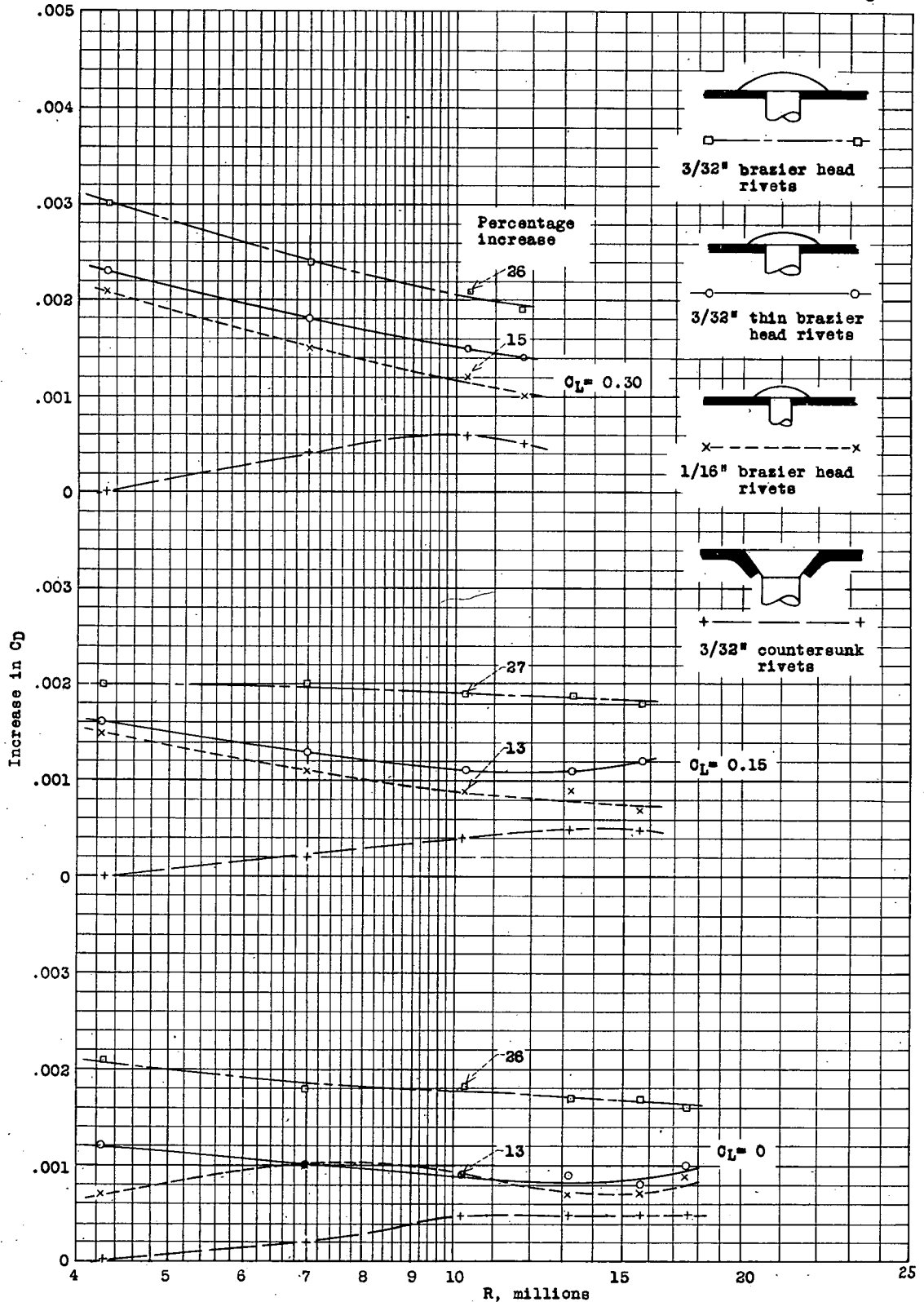
Figure 12.- Drag due to rivets at 3/4-in. pitch in 13 rows on each surface of 5-foot airfoil. Forward rows, 4 percent of the chord from the leading edge.
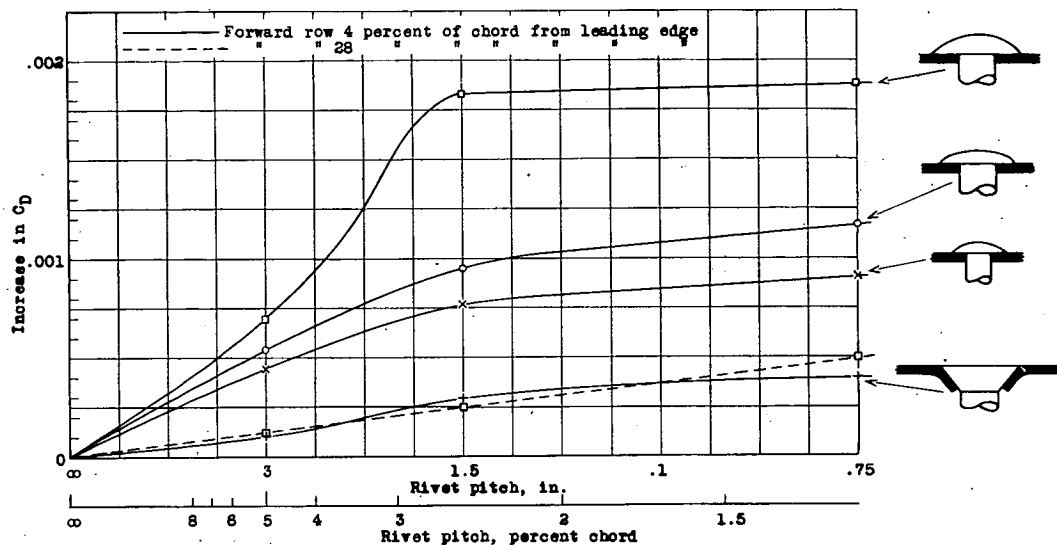
Figure 13.- Variation of rivet drag with spanwise pitch of the rivets. Rivets on both surfaces of airfoil. Chord, 5 feet; C_L, 0.15; R, 10,300,000.
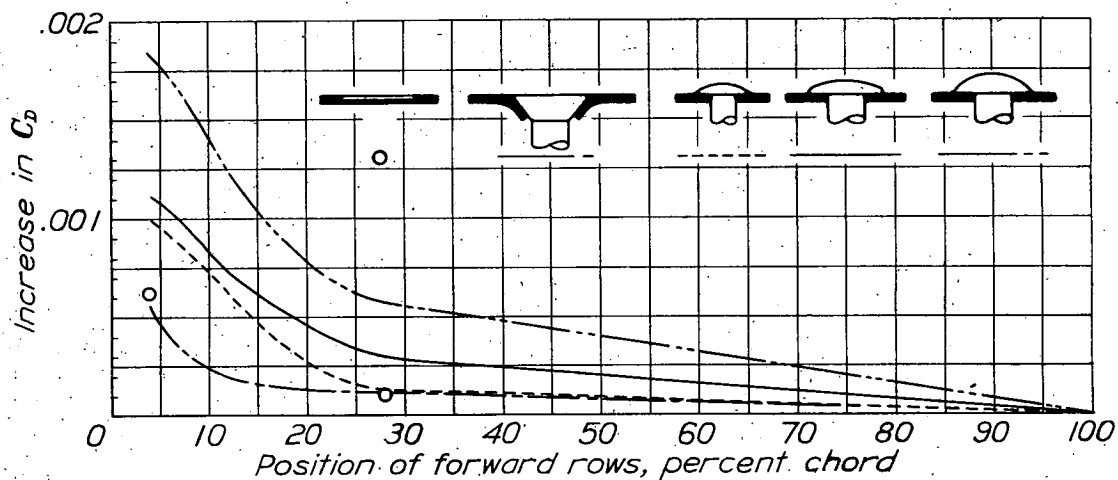
Figure 14.- Variation of rivet drag with position of forward rows. Rivets at 3/4-inch pitch in equal number of rows on upper and lower surfaces. Chord, 5 feet; C_L, 0.15; R, 10,300,000.
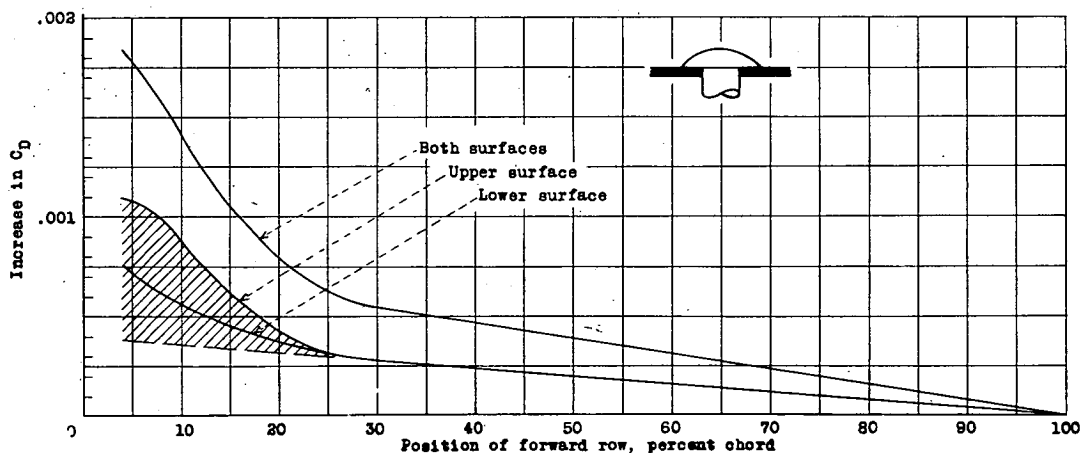
Figure 15.- Variation of rivet drag with position of forward rows on upper and lower surfaces separately. 3/32-inch brazier-head rivets at 3/4-inch pitch in spanwise rows. Chord, 5 feet; C_L, 0.15; R, 10,300,000.
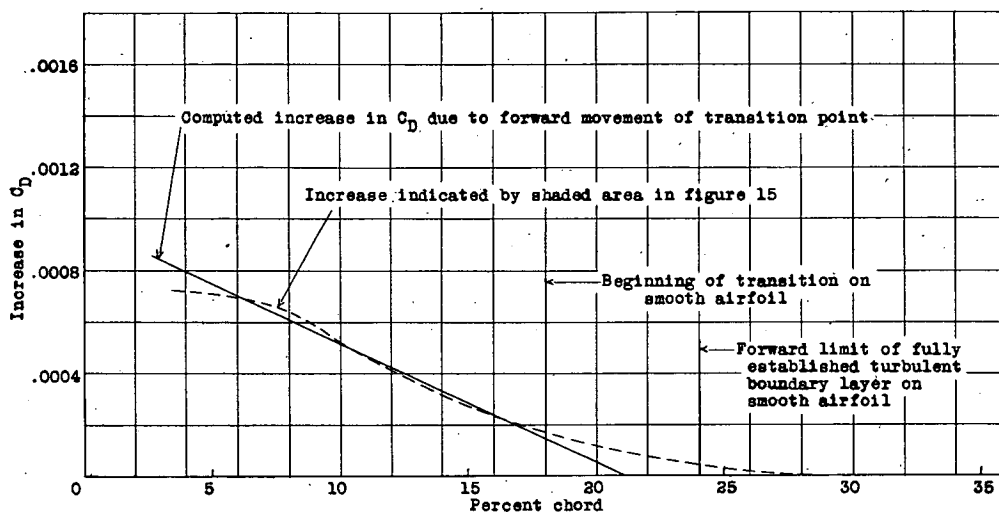
Figure 16. - Increase in drag due to forward movement of the transition point. Chord, 5 feet; C_L, 0.15; R, 10,300,000.
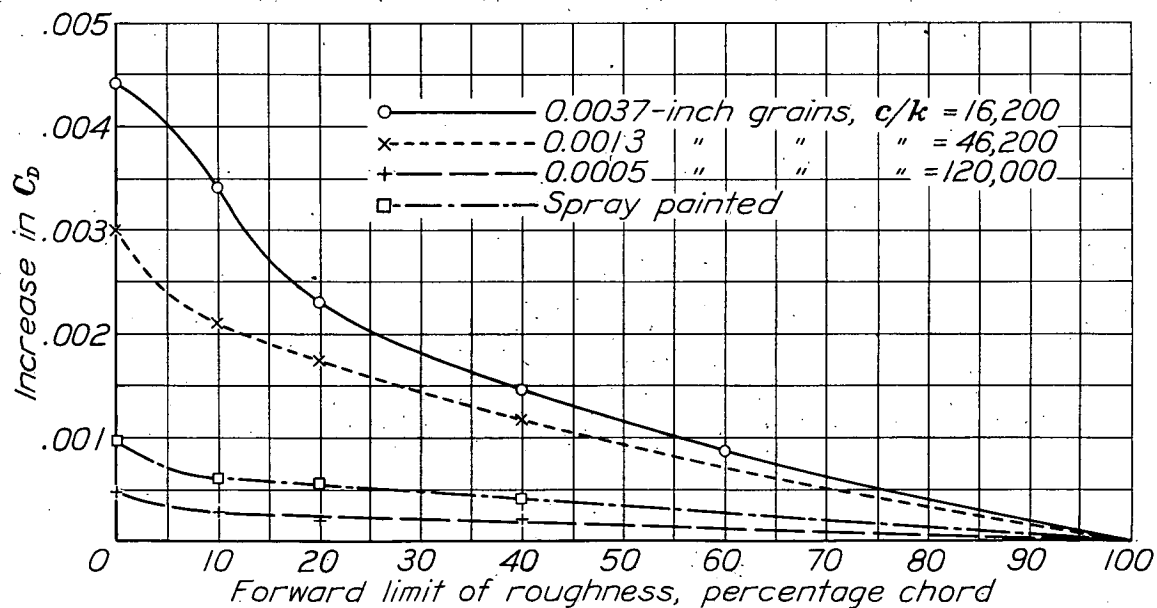
Figure 21. - Variation of drag due to roughness with forward limit of roughened portion. Chord, 5 feet; C_L, 0.15; R, 10,300,000; c, chord; k, grain size.
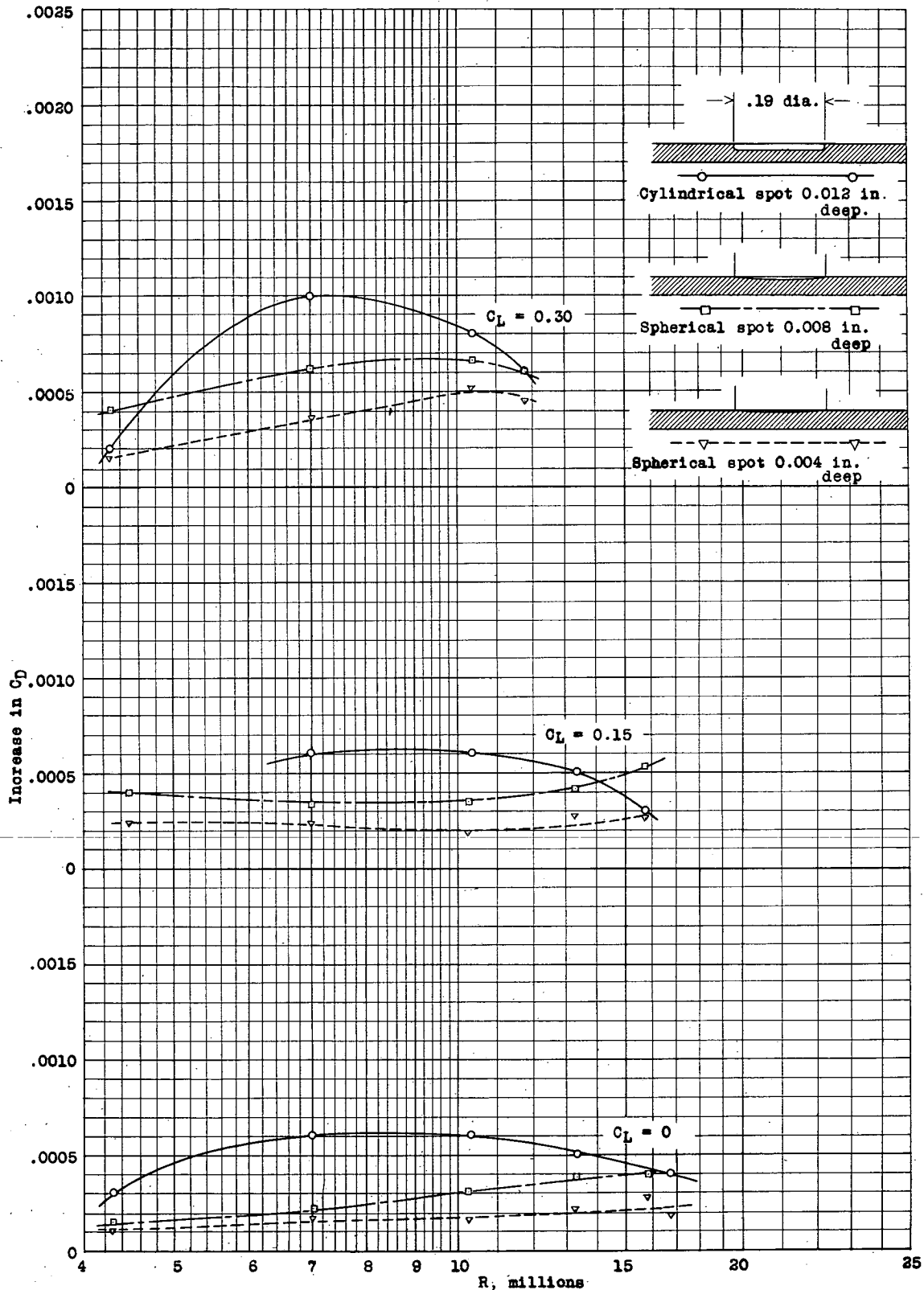
Figure 17.- Increase in drag due to spot welds at 3/4-in. pitch in 13 rows on each surface of 5-foot airfoil. Forward rows, 4 percent of the chord from the leading edge.
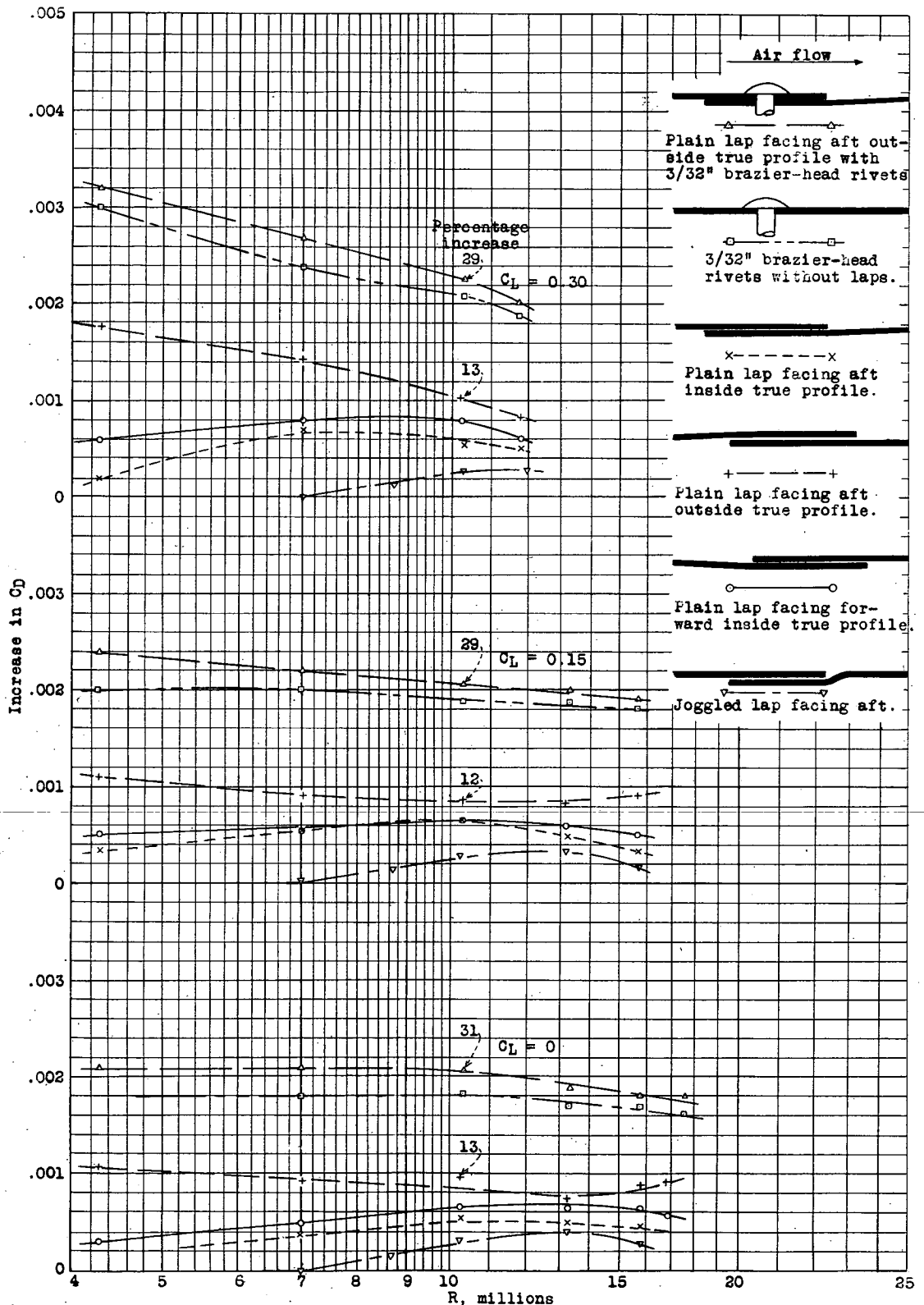
Figure 18.- Increase in drag due to six laps on each surface of airfoil. Forward laps, 8 percent of the chord from leading edge; sheet thickness, 0.018 inch; chord, 5 feet.
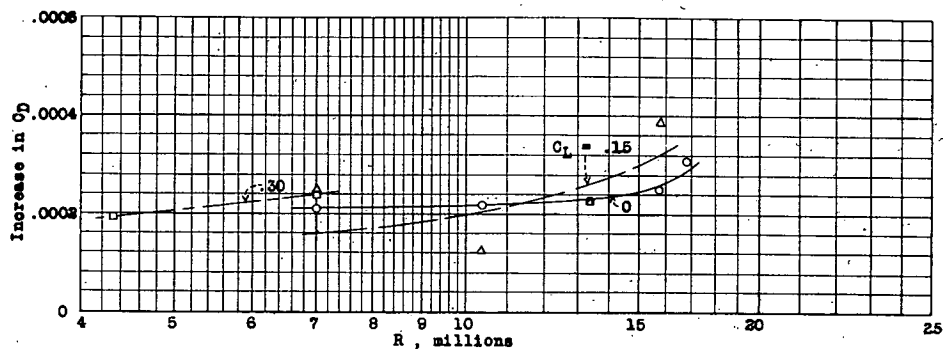
Figure 19.- Increase in drag due to gaps between butted sheets. Width of gaps, 0.024 inch (0.0004 chord); six gaps on each surface; forward gaps, 8 percent of the chord from the leading edge; chord, 5 feet.
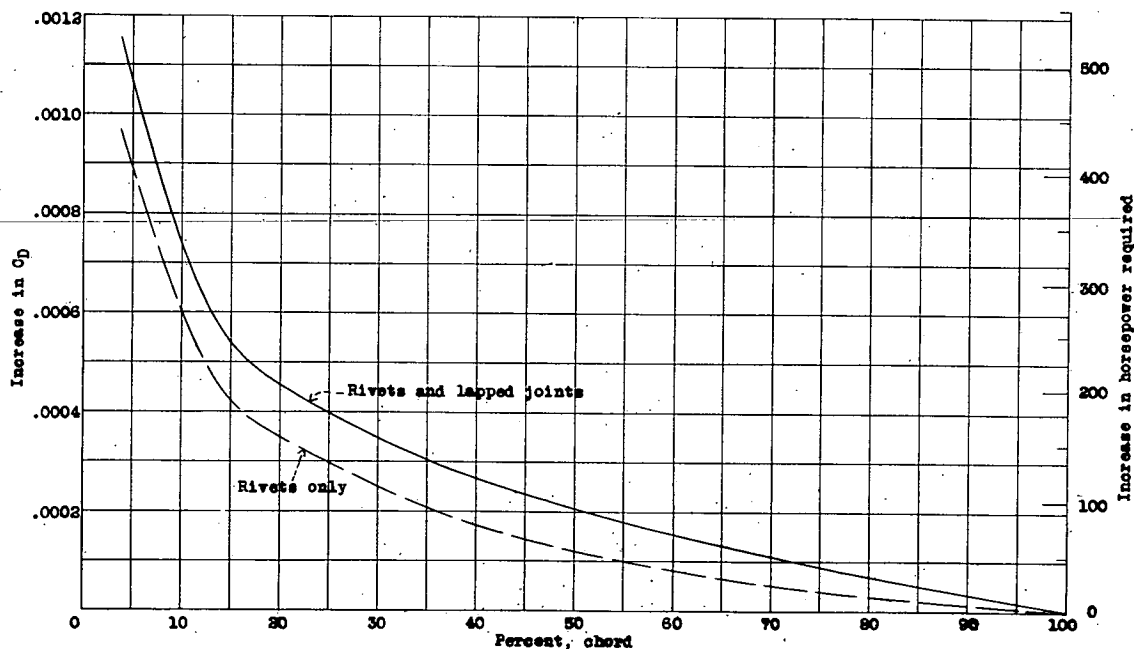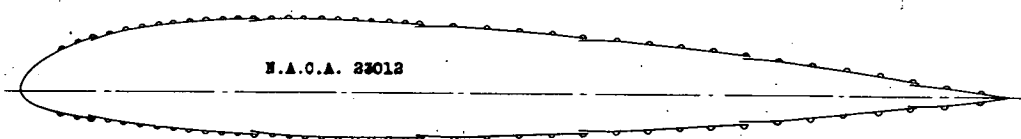

N.A.C.A. 23012

Figure 23.- Estimated effect of rivets and lapped joints on the drag of a large wing. The curves indicate for each chord position the total effect of all rivets and lapped joints back of that position. Average chord, 20 feet; wing area, 3,600 square feet; rivets, 1/8 inch brazier head at 1 1/2 inch spanwise pitch; thickness of lapped sheets, 0.040 inch; V, 250 m.p.h.; C_L, 0.20, propulsive efficiency, 85 percent.
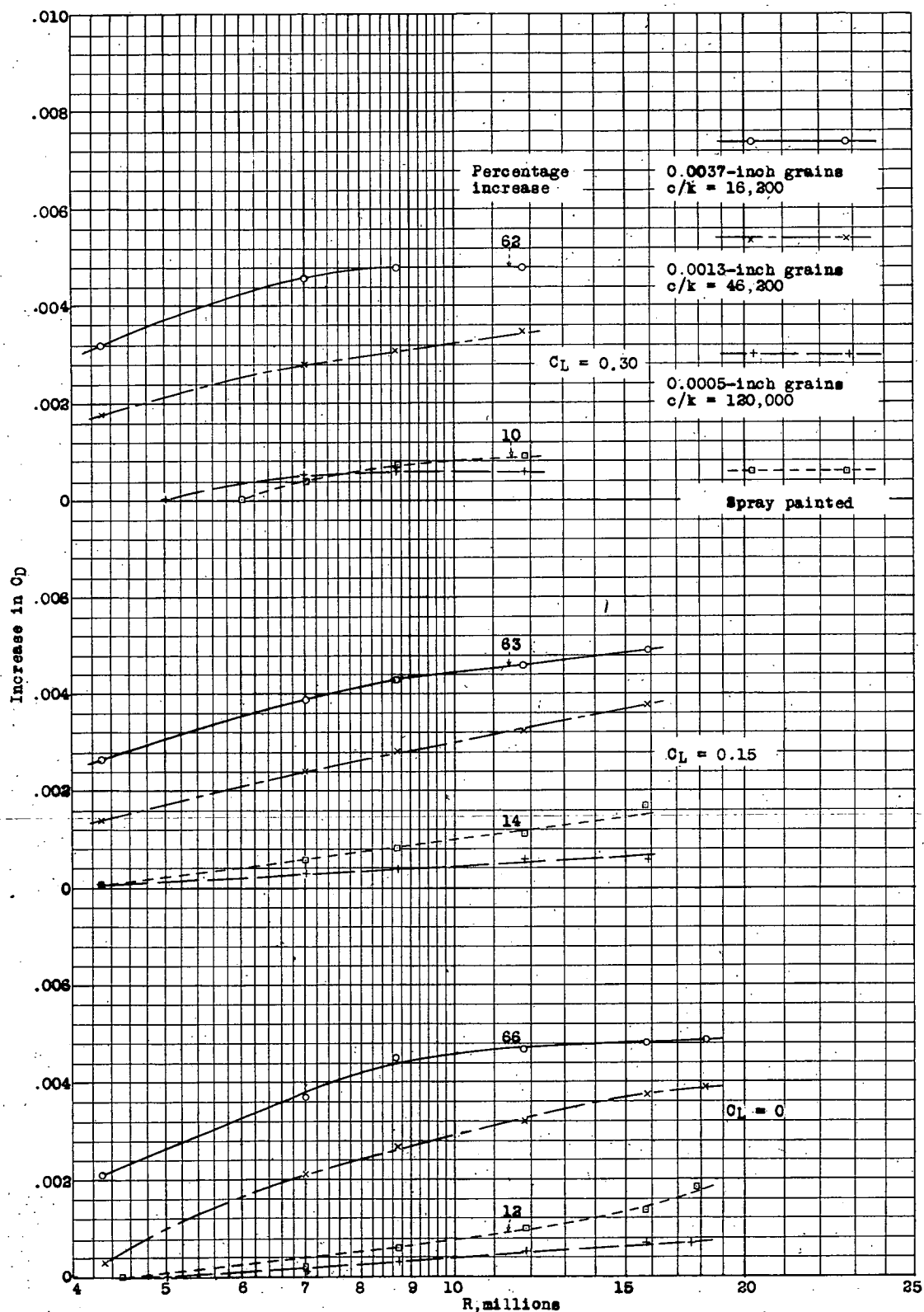
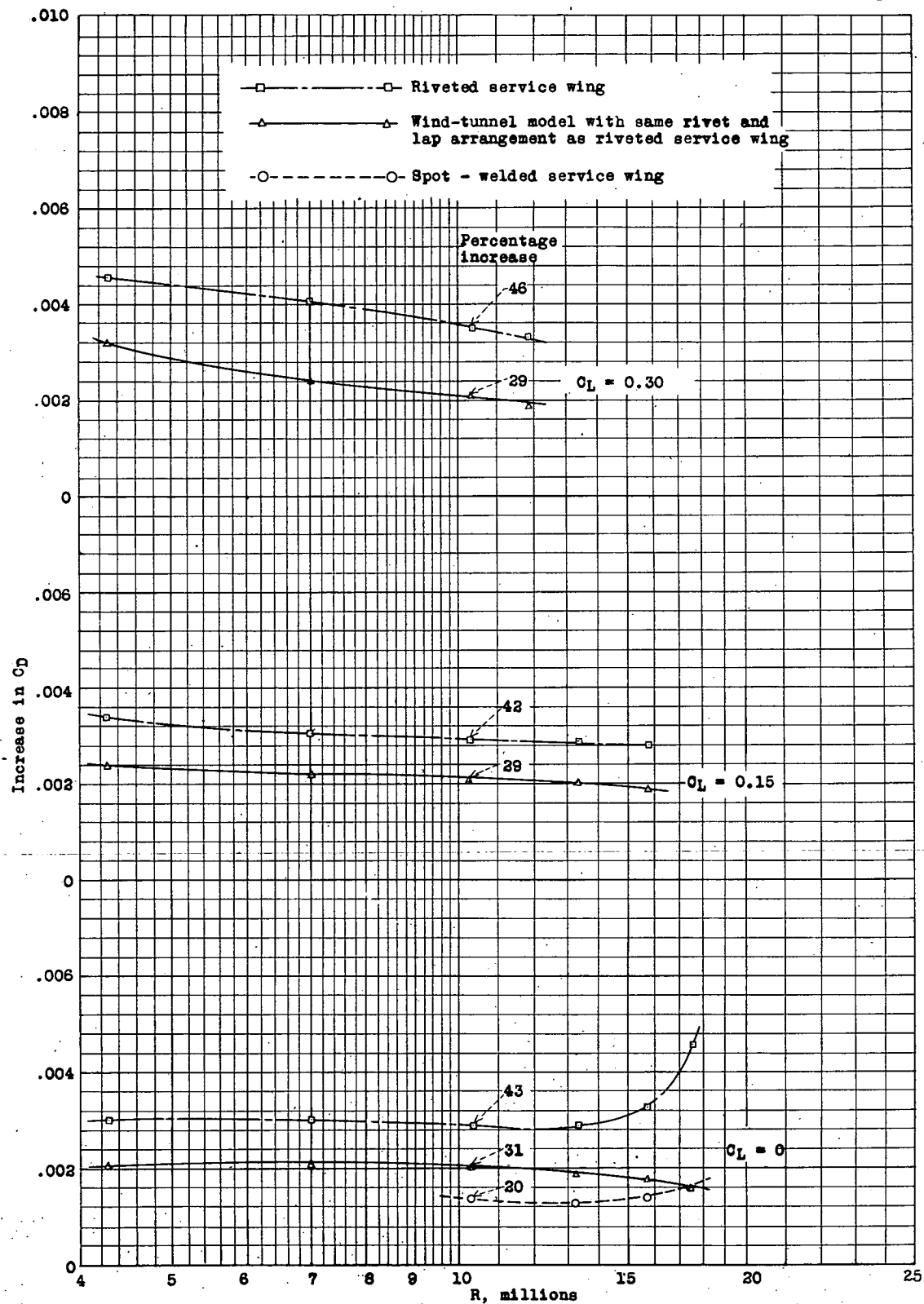Figure 20 - Increase in drag due to roughness over the entire surface.
c, chord; k, grain size.

Figure 22.- Increase in drag of service wings over drag of smooth airfoil.