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RESEARCH MEMORANDUM

MEASUREMENTS OF THE EFFECTS OF THICKNESS RATIO AND ASPECT RATIO ON THE DRAG OF RECTANGULAR-PLAN-FORM AIRFOILS AT TRANSONIC SPEEDS

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MEASUREMENTS OF THE EFFECTS OF THICKNESS RATIO AND ASPECT RATIO ON THE DRAG OF RECTANGULAR-PLAN-FORM AIRFOILS AT TRANSONIC SPEEDS

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SUMMARY

As part of an investigation to determine the effect of variation of the basic airfoil parameters on airfoil drag characteristics at transonic and supersonic speeds, a series of rectangular-plan-form airfoils having aspect ratios of 7.6 and 5.1 and having NACA 65-006, 65-009, and 65-012 sections have been tested by the free-fall method. In the present paper results are presented for two airfoils of the series (those having NACA 65-012 sections and aspect ratios of 7.6 and 5.1) and are compared with results for other airfoils of the series which were reported previously.

The results showed that for the airfoils of thickness ratio 0.12 the effect of reduction of aspect ratio was the same as that previously determined for the airfoils of thickness ratio 0.09; reduction of aspect ratio delayed the occurrence of the drag rise by about 0.02 Mach number and reduced the drag at speeds above the drag rise.

Comparison of results so far obtained indicated that reduction of airfoil-thickness ratio from 0.12 to 0.09 or from 0.09 to 0.06 delayed the occurrence of the drag rise by about 0.02 Mach number; this delay was about one-half the concomitant increase in the theoretical critical Mach number of the airfoil section.

At sonic and low supersonic speeds the pressure-drag coefficient was found to vary in proportion to the square of the thickness ratio between values of thickness ratio of 0.09 and 0.12 but between values of thickness ratio of 0.06 and 0.09 the exponent was somewhat less than 2.

INTRODUCTION

One of the problems encountered in the design of a transonic or supersonic airplane of any fixed configuration is that of selecting the thickness of the wing section so that adequate structural strength and a safe landing speed may be obtained without penalizing the airplane in high-speed flight by excessive wing drag. It is well known that the best combination of strength and landing speed is obtained by use of relatively thick wings; however, thin-airfoil theory for supersonic speeds (reference 1 and many other papers) predicts that for unswept wings of infinite aspect ratio the wing drag is proportional to the square of the airfoil-thickness ratio. Thus a small reduction in wing thickness would result in a considerable saving in supersonic wing drag if the theory was directly applicable.

In order to provide information on this and other basic problems encountered in the design of transonic and supersonic airplanes, the National Advisory Committee for Aeronautics has instituted a general research program on the drag characteristics of airfoil sections, wing plan forms, body shapes, and wing-body configurations at transonic and supersonic speeds. As part of this program, measurements have been made of the drag of NACA 65-006, 65-009, and 65-012 airfoils having rectangular plan forms of two different aspect ratios. Results obtained for the 6- and 9-percent-thick airfoils are reported in references 2 to 4 and results for the 12-percent-thick airfoils are presented in this paper.

Drag results for the airfoils having NACA 65-012 sections are presented as curves showing the variation of drag coefficient with Mach number in the transonic speed range. These results are compared with the results of references 2 to 4 to determine the effects of thickness and aspect ratio on the airfoil drag. Although supersonic thin-airfoil theory does not directly apply to the test results presented because of the rounded airfoil nose (resulting in mixed subsonic-supersonic flows occurring on the airfoil), finite thickness and aspect ratio, possibility of separation effects, and so forth, the test results are compared with the theory to provide some information on the importance of these differences.

The tests were performed by the Flight Research Division of the Langley laboratory by means of the freely-falling-body method described in references 2 to 4.

APPARATUS AND METHOD

Test body and airfoils.- The general arrangement of the test configuration is shown by the photograph (fig. 1) and the details and dimensions are shown on the line drawing (fig. 2). The two test airfoils had rectangular plan forms and NACA 65-012 sections of 8-inch chord; the over-all span of the front airfoil was $60\frac{3}{4}$ inches and that of the rear airfoil was $40\frac{3}{4}$ inches. The aspect ratios for the test airfoils (including that part of the airfoils within the body) were 7.6 and 5.1. The test airfoils entered the body through rectangular slots $9\frac{1}{2}$ inches long and 1 inch wide as did the airfoils of references 2 to 4. The body on which the airfoils were mounted had a flat base and was identical with the body used for the test of reference 4. The body differed from those used in the tests of references 2 and 3 only in that the short tail fairing used on the previous test bodies was replaced by the flat base.

Measurements.- Measurement of the desired quantities was accomplished as in previous tests (references 2 to 4) through use of the NACA radio-telemetering system and radar and phototheodolite equipment. The following quantities were recorded at two separate ground stations by the telemetering system:

(1) Force exerted on body by each test airfoil as measured by a spring balance

(2) Total retardation of body and airfoils as measured by a sensitive accelerometer alined with longitudinal axis of body

A time history of the position of the body with respect to ground axes during free fall was recorded by radar and phototheodolite equipment, and a survey of atmospheric conditions applying to the test was obtained from synchronized records of atmospheric pressure, temperature, and geometric altitude taken during the descent of the airplane from which the test body was dropped. The direction and speed of the horizontal component of the wind in the range of altitude for which data are presented were obtained from radar and phototheodolite records of the path of the ascension of a free balloon.

Reduction of data.- As in the previous tests, the velocity of the body with respect to ground axes, hereinafter referred to as ground velocity, was obtained both by differentiation of the flight path

determined by radar and phototheodolite equipment and by integration of the vector sums of gravitational acceleration and the directed retardation measured by the longitudinal accelerometer. The true airspeed was obtained by vectorially adding the ground velocity and the horizontal wind velocity measured at the appropriate altitude.

The drag D of each airfoil was obtained from the relation

$$D = R + W_T a_e$$

where

R measured reaction between airfoil and body, pounds

W_T weight of airfoil assembly supported on spring balance, pounds

a_e reading of accelerometer (retardation), g

The atmospheric pressure p, the temperature T, and the airfoil frontal area F were combined with simultaneous values of true airspeed and airfoil drag D to obtain Mach number M and the ratio D/Fp. Values of conventional drag coefficient C_{D_F} were obtained from the relation

$$C_{D_F} = \frac{D/Fp}{\frac{\gamma}{2} M^2}$$

where the ratio of specific heats γ was taken as 1.4. Drag coefficients based on plan area C_D were obtained by multiplying the values of C_{D_F} by the ratio of frontal area to plan area. Areas used did not include that area enclosed within the body.

RESULTS AND DISCUSSION

A time history of important quantities obtained in the present test is presented as figure 3.

The ground-velocity data obtained from each of the two independent methods of measurement are presented in figure 3; the data obtained from the accelerometer are shown as a dashed line and the data obtained from the radar and phototheodolite equipment, by the test points. The radar and phototheodolite data are evenly distributed about the accelerometer data but contain a scatter somewhat larger than usual for this equipment. This scatter results from partial failure of equipment during the test, which necessitated use of a less precise auxiliary recording device. Velocity data from the radar and phototheodolite equipment are not presented for the last 6 seconds of the free fall as the photographs, which normally allow corrections to be made for small tracking errors, were not obtained during this period. The true airspeed was obtained from the ground velocity by use of the wind data and is shown on the time history by a solid line. The Mach number was calculated from the true airspeed and temperature data and is believed accurate within ±0.01.

The results of the airfoil drag measurements are summarized in figure 4 where curves are presented which show the measured variations of D/Fp, C_{D_F}, and C_D for the airfoils having NACA 65-012 sections and aspect ratios of 7.6 and 5.1.

Inasmuch as the spring balances with which the airfoil drag forces are measured must withstand the high drag forces occurring at supersonic Mach numbers and high pressures (low altitudes), they are necessarily relatively insensitive to the small drag forces occurring at subcritical Mach numbers and low pressures (high altitudes). The drag parameters are therefore less accurate at the lowest Mach numbers for which data are presented than at supersonic speeds where the drag is high. The values of the ratio D/Fp are believed to be accurate within about ±0.012 at $M = 0.8$ and to within ±0.007 at $M = 1.14$. Corresponding values of C_D are within ±0.003 at $M = 0.8$ and within ±0.0025 at $M = 1.14$. These values correspond to an error in drag measurement of about 1 percent of the full-scale-balance range for values of D/Fp; however, the values of C_D include an additional increment (which is appreciable only when C_D is large) due to the possible uncertainty in Mach number of ±0.01.

The drag of the front airfoil exceeded the range of the drag balance about 6 seconds before impact (see fig. 3). No significant data were lost, however, as the Mach number did not increase appreciably after this time.

The $\frac{D}{Fp}$-curves of figure 4 show that for the front airfoil (aspect ratio 7.6) the drag rose from 0.02 of atmospheric pressure

per unit of frontal area at $M = 0.82$ to 0.50 at $M = 0.97$ and then increased at a slower rate to 0.68 at $M = 1.14$. The drag of the rear airfoil (aspect ratio 5.1) rose from 0.02 of atmospheric pressure per unit of frontal area at $M = 0.84$ to 0.45 at $M = 1.00$ and then increased to 0.67 at $M = 1.15$.

The $\frac{D}{Fp}$-data of figure 4 are compared in figure 5 with results obtained in previous free-fall tests of airfoils having NACA 65-006 and 65-009 sections. The aspect ratio, airfoil section, and reference from which these data were taken are given in tabular form in the figure. Examination of this figure reveals that the curves are similar in shape and are nearly parallel during the abrupt rise which characterized the curves at Mach numbers just below 1.00. In this paper, the difference in Mach number between these parallel portions of the drag curves is defined as the drag-rise delay. It is apparent that reduction in aspect ratio or thickness ratio is effective in delaying the drag rise to slightly higher Mach numbers; reduction in aspect ratio from 7.6 to 5.1 delays the drag rise by about 0.02 Mach number, and reduction of the airfoil-thickness ratio from 0.12 to 0.09 or from 0.09 to 0.06 delays the drag rise a similar amount. The drag-rise delay resulting from reduction in airfoil thickness is about one-half the concomitant increase in the theoretical critical Mach number for the airfoil section.

The drag-rise delays resulting from reduction of aspect ratio and thickness ratio are relatively small with respect to the over-all accuracy of Mach number measurement (within ± 0.01). The results presented herein show, however, that the magnitude of the drag-rise delay due to reduction of aspect ratio reported in reference 3 for airfoils having NACA 65-009 sections is about the same (within the limit of accuracy of the tests) for wings having NACA 65-012 sections.

For application to practical airplane configurations, the magnitude of the drag-rise effects presented herein may require some modification to account for the effect of the open slots through which the airfoils entered the body. The effect of these slots is not known but is believed to be small. In addition, for the airfoils having NACA 65-012 sections, a small effect on the drag of the airfoil of aspect ratio 5.1 results from its location to the rear and at a right angle to the airfoil of aspect ratio 7.6 tested on the same body. Previous tests (references 2 and 3) where identical airfoils were tested in the two positions showed maximum discrepancies in the region of the drag rise of the order of 0.01 Mach number, the order of accuracy of the Mach number measurement.

The variation of airfoil total-drag coefficient C_D with thickness ratio t/c is shown in figure 6. For the airfoils of aspect ratio 7.6, an increase in thickness ratio from 0.06 to 0.09 resulted in an increase in drag coefficient from 0.032 to about 0.055 for Mach numbers in the range from 1.00 to 1.15. In the same Mach number range, an increase in thickness ratio from 0.09 to 0.12 resulted in an increase in drag coefficient from about 0.055 to 0.090. Similarly, for the airfoil of aspect ratio 5.1, an increase in thickness ratio from 0.09 to 0.12 resulted in an increase in drag coefficient from about 0.050 to 0.085.

The variation of airfoil pressure-drag coefficient C_{D_p} with thickness ratio t/c is shown plotted in logarithmic form in figure 7 for NACA 65-series airfoils at sonic and low supersonic speeds. Separate plots (figs. 7(a) and 7(b)) are presented for the two aspect ratios for which measurements have been made. Airfoils tested in the front position on the body are used in figure 7(a) but airfoils tested in the rear position are used in figure 7(b) because of the limited amount of test data available. An estimated friction-drag coefficient of 0.006 has been subtracted from the data to obtain pressure-drag coefficients.

Thin-airfoil theory for supersonic speeds, as presented in reference 1 and in numerous other papers, leads to the conclusion that for a given Mach number and airfoil section the pressure-drag coefficient is proportional to the square of the airfoil-thickness ratio. This relation, which may be represented in figure 7 as a straight line of slope 2, is arbitrarily placed on the figure so that it passes through the test points for a thickness ratio of 0.09. Examination of figure 7(a) shows that the test points for a thickness ratio of 0.12 lie on the line of slope 2 through the points of thickness ratio 0.09, but the test points of thickness ratio 0.06 lie somewhat above the line. Thus, in the range of 0.09 to 0.12, the drag coefficient varies with thickness ratio about as the square of the thickness ratio; whereas in the range from 0.06 to 0.09 the exponent is somewhat smaller.

Similar results are obtained for the lower aspect ratio (fig. 7(b)) although the points at thickness ratio 0.06 are not directly comparable with the other data. These points, which are taken from reference 5, apply to airfoils having an aspect ratio of 4.9, NACA 16-006 sections, and used as stabilizing tail surfaces for a body of revolution. As this airfoil section is not appreciably different from the NACA 65-006 section and as in the test of reference 5 the effect of the location of the airfoils partly in the wake of the body may be presumed to be limited to a slight reduction

in the drag of the airfoils, the location of the test points from reference 5 above the line of slope 2 in figure 7(b) provides additional confirmation of the result observed in figure 7(a).

Thus, if the assumption of a constant friction-drag coefficient is valid, the experimental results show the same variation of pressure-drag coefficient with thickness ratio for the thicker airfoils as that indicated by thin-airfoil theory. The theory is not strictly applicable in this case, however, because of the rounded airfoil nose (resulting in mixed subsonic-supersonic flows occurring on the airfoil), finite thickness and aspect ratios, and so forth. As preliminary consideration of the problem indicates that an additional variation of pressure-drag coefficient with thickness ratio might result from other sources of pressure drag not considered in the theory (separation, for example), no conclusion can be reached concerning the applicability of the theory.

It is considered desirable that further research be performed to determine whether the variation of drag coefficient with thickness ratio here obtained is valid at Mach numbers beyond the low supersonic range, for thickness ratios smaller than those already tested, and for other airfoil sections and plan forms (particularly the so-called "supersonic" airfoil sections). If the trend here indicated at low thickness ratios is found to be generally applicable, the large savings in wing drag which are estimated by means of supersonic thin-airfoil theory to result from reducing the airfoil-thickness ratio would be considerably reduced and the design considerations in regard to use of extremely thin wings on supersonic aircraft could be modified.

CONCLUDING REMARKS

Measurements have been made by the freely falling body method of the drag of airfoils having NACA 65-012 sections and rectangular plan forms of aspect ratio 7.6 and 5.1. Comparison of the results presented herein with results of similar measurements of the drag of airfoils which had NACA 65-009 sections and identical aspect ratios and of an airfoil which had NACA 65-006 sections and an aspect ratio of 7.6 shows that:

1. Reduction of aspect ratio from 7.6 to 5.1 delayed the occurrence of the drag rise for the airfoils having NACA 65-012 sections by about 0.02 Mach number and reduced the drag throughout the explored Mach number range. These results are in agreement with previously reported results for airfoils having NACA 65-009 sections.

2. Reduction of the thickness ratio of NACA 65-series airfoils from 0.12 to 0.09 and from 0.09 to 0.06 also delayed the occurrence of drag rise by about 0.02 Mach number. The drag-rise delay which resulted from reduction in airfoil-thickness ratio was about one-half the concomitant increase in the theoretical critical Mach number for the airfoil section.

3. At Mach numbers from 1.00 to 1.15 the pressure-drag coefficient increased in proportion to the square of the thickness ratio between thickness ratios of 0.09 and 0.12 but increased in proportion to a somewhat smaller power of the thickness ratio between thickness ratios of 0.06 and 0.09. Further research should be performed to determine whether the variation of drag coefficient with thickness ratio herein presented is valid for other airfoil sections and at higher Mach numbers and whether the trend is continued at thickness ratios lower than those so far tested.

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2. Mathews, Charles W., and Thompson, Jim Rogers: Comparative Drag Measurements at Transonic Speeds of Rectangular and Swept-Back NACA 65_1-009 Airfoils Mounted on a Freely Falling Body. NACA ACR. No. L5G30, 1945.

3. Mathews, Charles W., and Thompson, Jim Rogers: Drag Measurements at Transonic Speeds of NACA 65-009 Airfoils Mounted on a Freely Falling Body to Determine the Effects of Sweepback and Aspect Ratio. NACA RM No. L6K08c, 1947.

4. Thompson, Jim Rogers, and Marchner, Bernard W.: Comparative Drag Measurements at Transonic Speeds of an NACA 65-006 Airfoil and a Symmetrical Circular-arc Airfoil. NACA RM No. L6J30, 1946.

5. Bailey, F. J., Jr., Mathews, Charles W., and Thompson, Jim Rogers: Drag Measurements at Transonic Speeds on a Freely Falling Body. NACA ACR No. L5E03, 1945.

Figure 1.- Three-quarter front view of airfoil test body.

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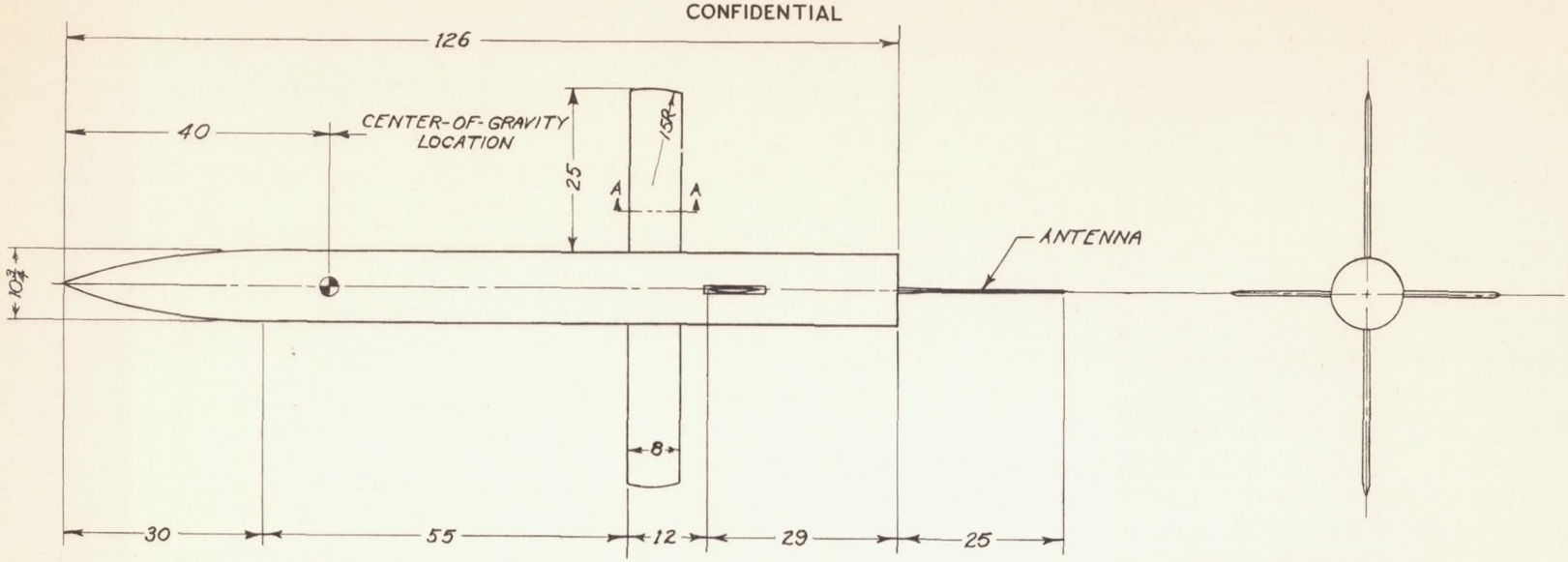

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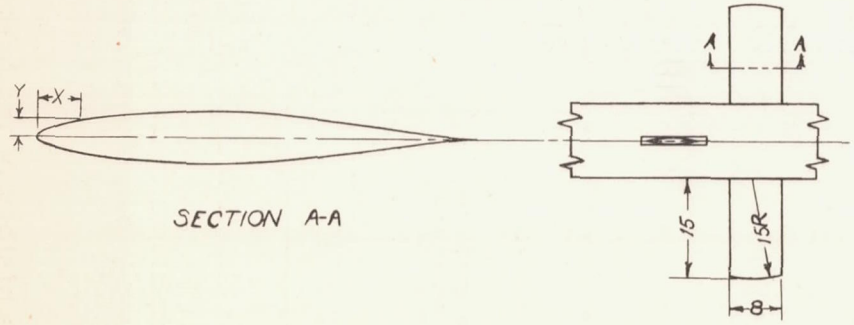

AIRFOIL - SECTION COORDINATES (NACA 65-012 SECTION)					
X	Y	X	Y	X	Y
.000	.000	1.600	.398	5.200	.352
.040	.074	2.000	.432	5.600	.299
.060	.089	2.400	.457	6.000	.244
.100	.111	2.800	.473	6.400	.188
.200	.150	3.200	.480	6.800	.131
.400	.208	3.600	.476	7.200	.076
.600	.254	4.000	.461	7.600	.029
.800	.292	4.400	.433	8.000	.000
1.200	.352	4.800	.396		
L.E. RADIUS: 0.080					

Figure 2.– General arrangement and dimensions of airfoil test body. All dimensions are in inches.

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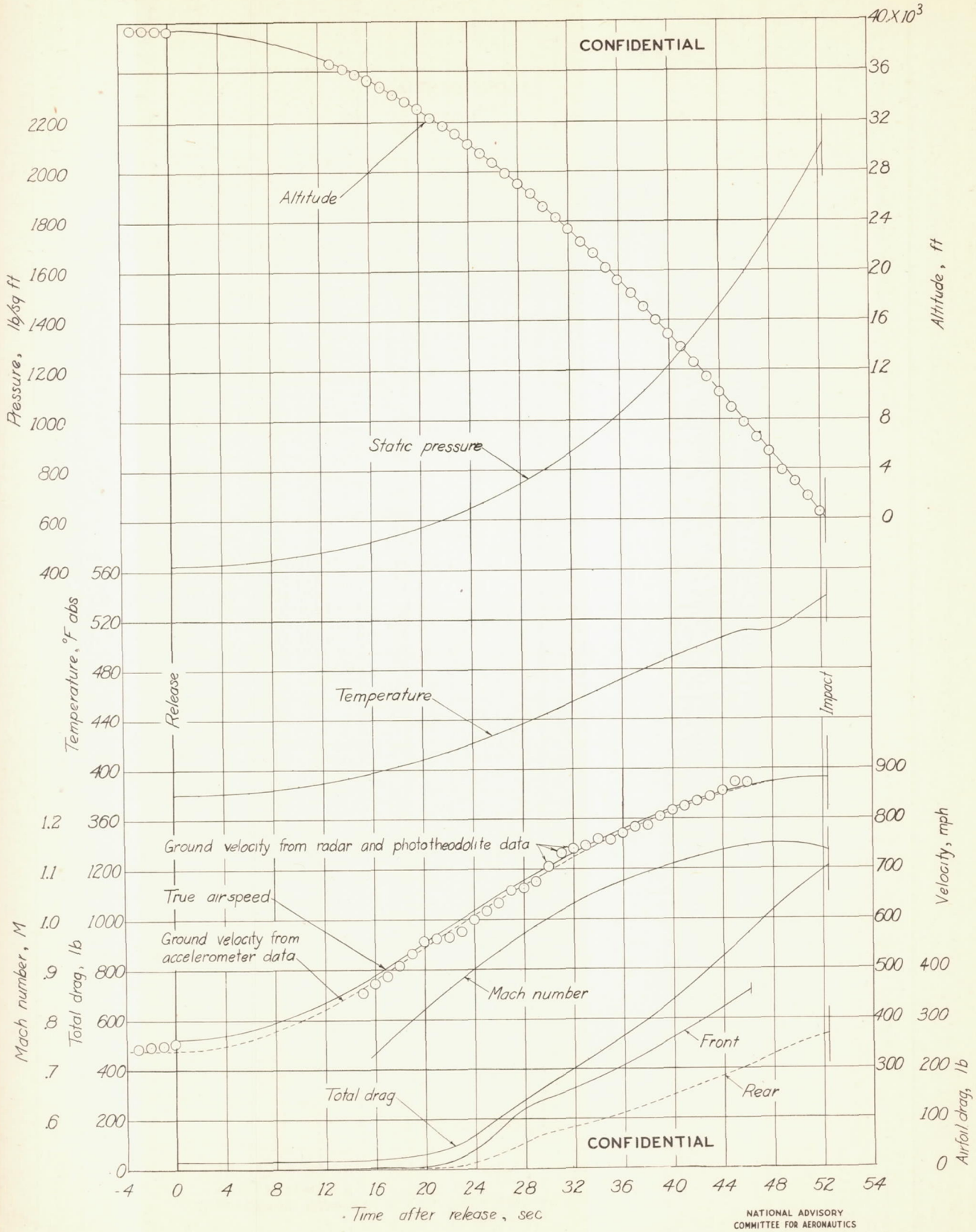

Figure 3.- Time history of important quantities obtained during the free fall of the airfoil test body.

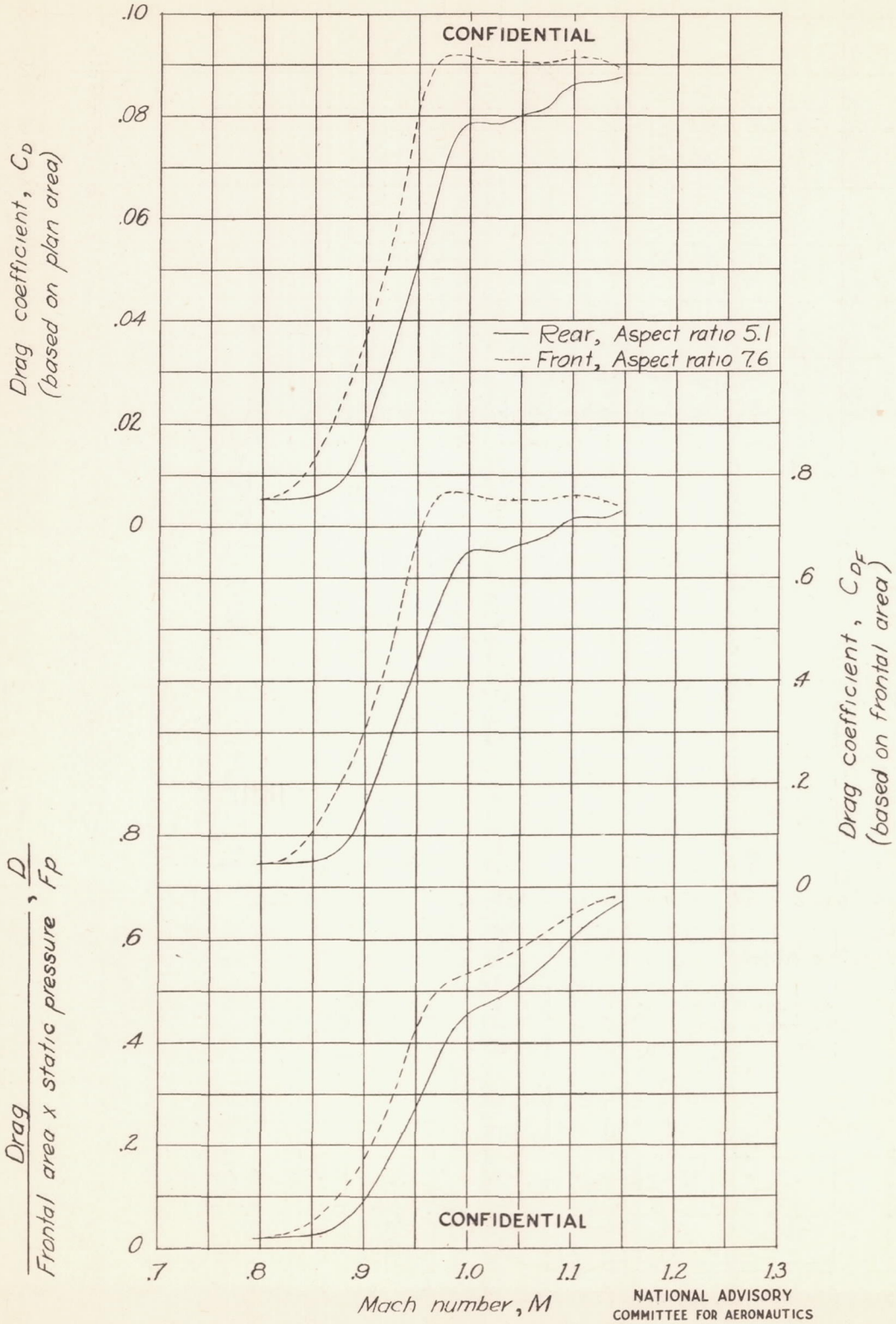

Figure 4.- The measured variation with Mach number of drag coefficients and D/Fp for airfoils having NACA 65-012 sections and aspect ratios of 7.6 and 5.1.

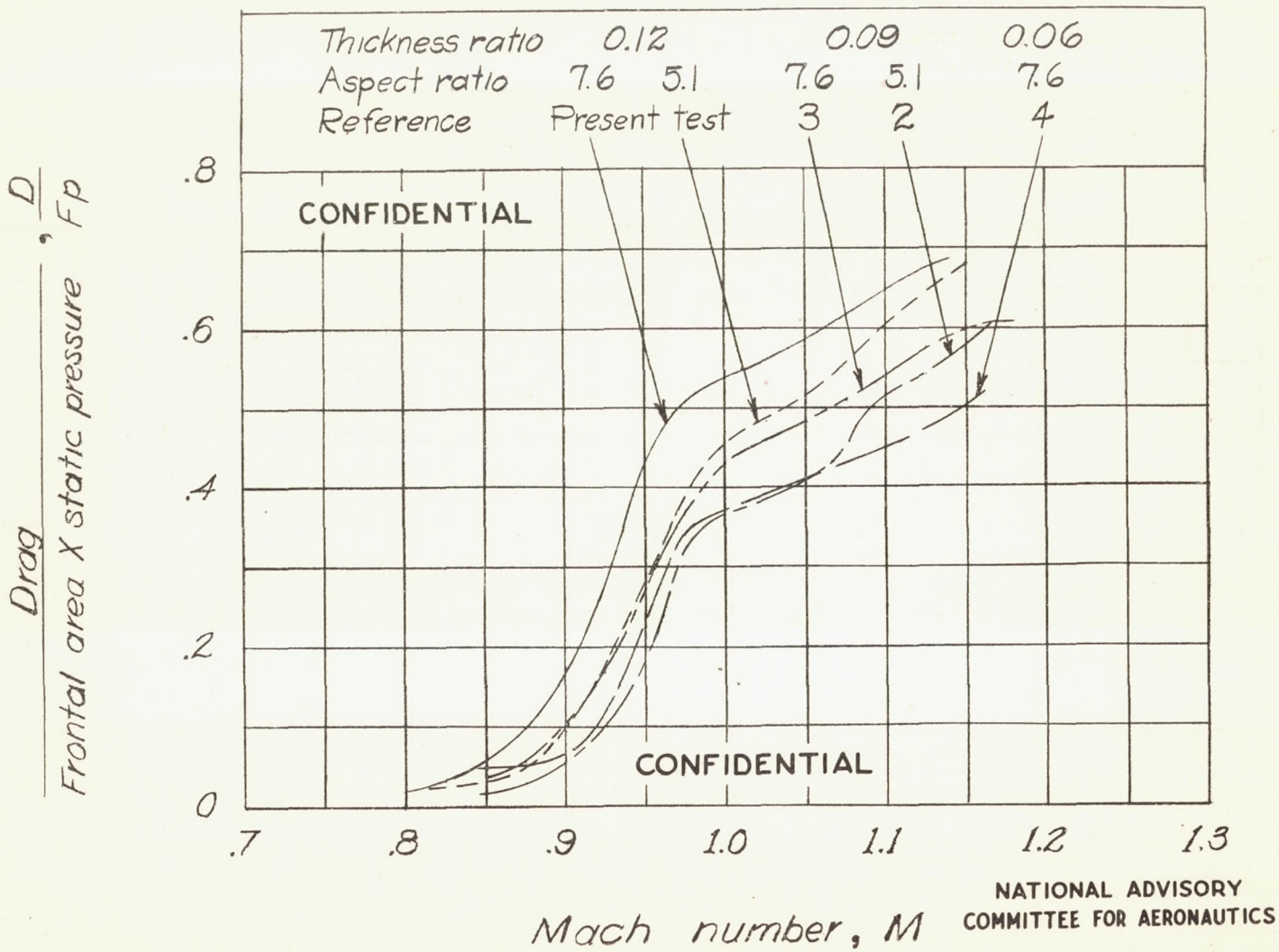

Figure 5.- Comparison of free-fall-test results for NACA 65-series airfoil sections.

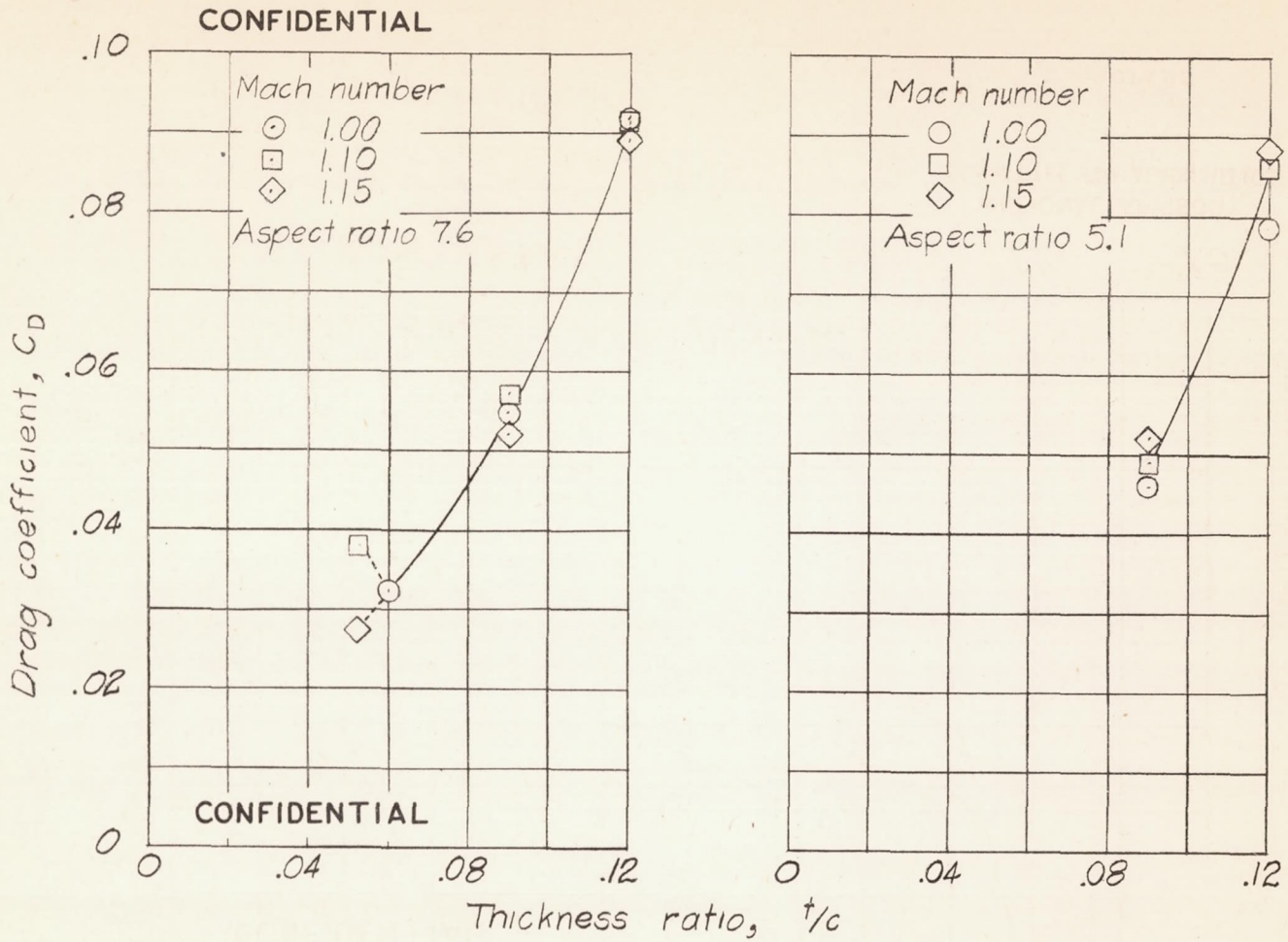

Figure 6.- Variation of drag coefficient with thickness ratio for NACA 65-series airfoils at low supersonic Mach numbers.

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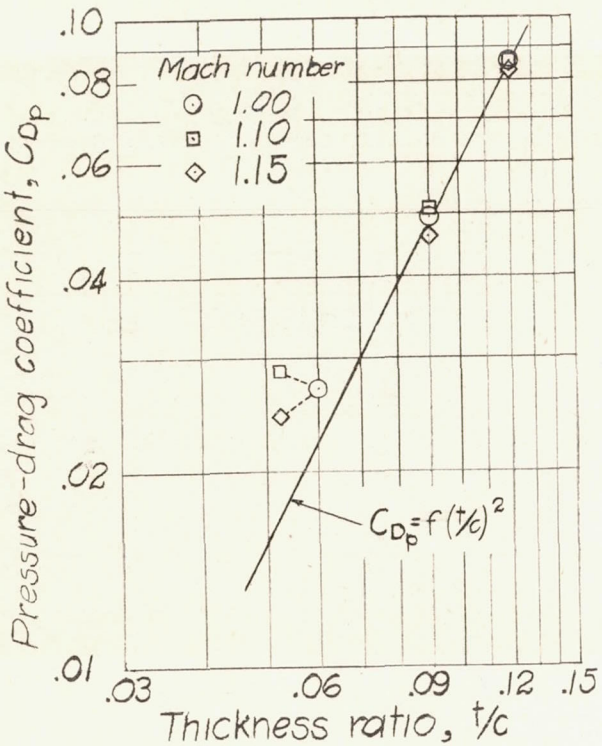
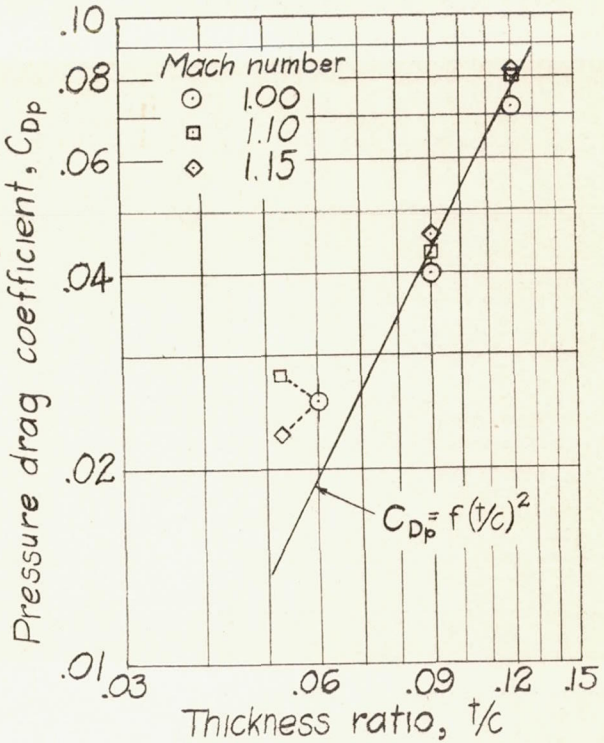


(a) Symmetrical NACA 65-series airfoils of aspect ratio 7.6.



(b) Symmetrical NACA 65-series airfoils of aspect ratio 5.1 except for t/c=0.06 which has NACA 16-006 section and aspect ratio of 4.9.

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Figure 7.- Variation of pressure-drag coefficient with airfoil-thickness ratio at low supersonic Mach numbers. Data are taken from references 2 to 5 and from the present test.

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