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NATIONAL ADVISORY COMMITTEE
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THE EFFECTS OF REYNOLDS NUMBER ON THE APPLICATION OF

NACA 16-SERIES AIRFOIL CHARACTERISTICS

TO PROPELLER DESIGN

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THE EFFECTS OF REYNOLDS NUMBER ON THE APPLICATION OF

NACA 16-SERIES AIRFOIL CHARACTERISTICS

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SUMMARY

An analysis has been made of airfoil data taken on several NACA
16-series propeller airfoils from tests of 5-inch-chord models in the
Langley 24-inch high-speed tunnel and 12-inch-chord models in the
Langley 8-foot high-speed tunnel.

This analysis has shown that the combined effects of Reynolds num-
ber changes and variations in airfoil characteristics resulting from
differences in models and tunnels are such that, when 5-inch-chord and
12-inch-chord data are applied to full-scale propeller design at or near
the design condition, differences of less than 1 percent in efficiency
are involved.

INTRODUCTION

The design of present-day propellers is usually based upon data
obtained under conditions of scale which differ from those of operation.
These propellers are made up to a great degree of high-speed airfoil
sections for which data are obtained from tests of models of 2- to
5-inch chord. In addition, most of the tests of model propellers using
NACA 16-series airfoil sections have been conducted on blades of this
same width. The question therefore has arisen as to the validity of
applying these test data directly to larger scale designs.

In order to provide at least a qualitative answer to these questions,
an analysis has been made of some data available on several NACA 16-series
airfoils of both 5- and 12-inch chord. A comparison of data from 5- and
12-inch-chord airfoils has additional significance because a 12-inch chord
is representative of blade widths commonly used on full-scale propellers.

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[1]Supersedes the recently declassified NACA RM L7H12, "The Effects of
Reynolds Number on the Application of NACA 16-Series Airfoil Characteristics
to Propeller Design" by Harold E. Cleary, 1947.

SYMBOLS

M	Mach number
R	Reynolds number
α	angle of attack, degrees
c_l	section lift coefficient
$c_{m_{c/4}}$	section quarter-chord pitching-moment coefficient
$dc_l/d\alpha$	lift-curve slope
c_d	section drag coefficient

$$\phi_O = \tan^{-1}\frac{V}{nD\pi x}$$

V	forward velocity
n	rotational speed
D	propeller diameter
x	radius ratio

$$\phi = \phi_O + \alpha_i$$

α_i	induced angle of attack

$$\gamma = \tan^{-1}\frac{c_d}{c_l}$$

η'	elemental propeller efficiency

APPARATUS AND METHODS

The tests were made in the Langley 8-foot high-speed tunnel and in the Langley 24-inch high-speed tunnel. At the time of these tests the Langley 8-foot high-speed tunnel was a closed-throat single-return tunnel and the speed was continuously controllable up to a Mach number of approximately 0.70. The Langley 24-inch high-speed tunnel was a nonreturn

induction type of tunnel with the speed continuously controllable to a
Mach number of approximately 0.80 for a 5-inch, 15-percent-thick air-
foil. Both tunnels have degrees of turbulence which are small though
slightly higher than that of free air. In both tunnels the models
completely spanned the jet; thus, the results are essentially two-
dimensional.

The chord of the models tested in the Langley 8-foot high-speed
tunnel was 12 inches; that of the models tested in the Langley 24-inch
high-speed tunnel was 5 inches. The airfoils tested were the following
NACA 16-series sections: 16-209, 16-215, 16-509, 16-515, 16-709, and
16-715, that is, sections having thickness ratios of 0.09 and 0.15 and
design lift coefficients of 0.2, 0.5, and 0.7.

The data obtained were lift, drag, and pitching moment. The data
on the 5-inch-chord airfoils were obtained by means of force measure-
ments in the Langley 24-inch tunnel. In the 8-foot tunnel, for the
12-inch-chord airfoils the lift and moment data were obtained from
pressure-distribution measurements and the drag data were obtained
by means of wake surveys. The average variation of Reynolds number
with Mach number for the airfoils as tested is shown in figure 1.

RESULTS AND DISCUSSION

The changes which occur in airfoil characteristics such as drag and
maximum lift coefficient with changes in the value of Reynolds number
are directly connected with the action of the boundary layer on the flow
over the airfoil. A discussion of the mechanics of these flow changes
is contained in reference 1.

The variations of lift coefficient with angle of attack for the air-
foils tested are compared in figure 2. Because the tests were made with
different-size models of the same airfoil sections and the models were
tested in different tunnels, variations in the data are to be expected
as a result of individual model irregularities, failure to duplicate
model alinement exactly, and slightly different wall effects. For these
reasons, only the shape and character of the curves in figure 2 should
be compared.

The most noticeable effects of difference in Reynolds number are
slight changes in lift-curve slope and differences in the character of
the break in the lift curve corresponding to the end of the low-drag
region. These effects are more marked for the thicker airfoils.

The variation with Mach number of the lift-curve slope, taken in
the design lift range, for the airfoils of different size is presented

in figure 3. The differences in slope are generally small although marked differences occur for the NACA 16-209 and 16-715 airfoils above a Mach number of 0.60.

If the moment coefficients of two airfoils are compared at a given value of lift coefficient, an indication of differences in load distribution is obtained. When this procedure is applied to data for two geometrically similar airfoils tested under different conditions of scale, an indication of fundamental-flow changes is obtained. The variation of pitching-moment coefficient with lift coefficient for several airfoils is therefore presented in figure 4. Analysis of these data indicates that the fundamental-flow changes, which may be due to scale effects or model irregularities, are small. The most noticeable differences occur at lift coefficients corresponding to the end of the region of low drag. These differences indicate that the lift coefficient at which transition occurs decreases as the Reynolds number is increased, as has been pointed out in reference 1. This effect is apparent for the thicker airfoils. The differences between the data for the 5- and 12-inch NACA 16-509 and 16-515 airfoils suggest individual model irregularities.

Because boundary-layer changes are involved, it is to be expected that with changes in Reynolds number the drag characteristics will be affected to a greater degree than the lift and moment characteristics. The variations of drag coefficient with lift coefficient for four airfoils, the NACA 16-209, 16-215, 16-709, and 16-715, at two values of Mach number are shown in figure 5.

In figure 6, curves of the variations of skin-friction drag coefficient with Reynolds number for a flat plate are presented. These curves are based on the laminar and turbulent laws for skin-friction drag (reference 2) and show how the drag coefficient decreases as the Reynolds number is increased. For the combined drag coefficient of both surfaces, the laminar law is

$$c_d = \frac{2.654}{\sqrt{R}}$$

and the turbulent law is

$$c_d = \frac{0.148}{R^{1/5}}$$

The points plotted in figure 6 are the values of minimum drag coefficient taken from figure 5. These data are generally within the limits of the laminar and turbulent curves. Reference 1 shows that rough

airfoil surfaces give drag coefficients well above the turbulent skin-
friction curve. The relative position of the data for a given airfoil
between the laminar and turbulent curves depends on scale effects and
factors such as pressure gradients and surface roughness which affect
boundary-layer transition.

Included in figure 6 is the variation of minimum drag coefficient
for the NACA 16-209 airfoil as reported in reference 3. These data were
obtained in one tunnel under conditions of low turbulence. The simi-
larity between the trends of the drag variation with Reynolds number
shown by the data taken from reference 3 and those reported herein
indicates that the rather large difference in the drag as obtained in the
Langley 8-foot high-speed tunnel and the Langley 24-inch high-speed
tunnel is actually a scale effect and is not caused by differences in
tunnel test techniques or model surface condition.

The differences in slope of the variation of drag coefficient with
Reynolds number for the 5-inch-chord airfoils as compared with the NACA
16-209 data from reference 3 are ascribed to compressibility effects
which result in the steepening of the pressure-recovery gradients over
the airfoils. These effects are expected to be more pronounced for thick
airfoils as is illustrated by the relatively slight variation of drag
coefficient with Reynolds number for the NACA 16-215 and 16-715 airfoils.
The adverse effects of increased recovery gradients in critical Reynolds
number ranges are further illustrated by the increases in value of drag
coefficient as the thickness and camber are increased.

In considering the application of these data to propeller design,
it should be pointed out that changes in drag coefficient of the order
of those found in figure 6 will have only a small effect on propeller
performance at design conditions because at these conditions the lift-
drag ratio is high and, since the elemental efficiency (see, for example,
reference 4) is

$$\eta' = \frac{\tan \phi_0}{\tan (\phi + \gamma)}$$

the changes in efficiency will be of small order.

Wind-tunnel models are carefully prepared and maintained; whereas
in actual operation manufacturing irregularities and surface roughness
will probably produce values of drag coefficient closer to those obtained
on the 5-inch-chord models. Therefore, although the 5-inch-chord data
do not represent true conditions of scale, they may be safely used to
estimate propeller performance. For example, the differences in effi-
ciency computed by the relation just given based upon the differences
in drag coefficient for the 5- and 12-inch-chord airfoils will be of the

order of 0.6 percent if it is assumed that for a typical propeller the
representative sections over the important area of the blade have thick-
ness ratios of 0.09 or less and are cambered to give a design lift
coefficient of 0.5. This difference of efficiency will hold for a range
of lift coefficient ±0.1 from design at values of Mach number up to 0.50.
If thicker or lower cambered sections are used or if the blade is
operated away from the design condition, differences greater than 1 per-
cent may be expected. If, however, operational drag coefficients are
higher than those presented for the 12-inch-chord airfoils, the dif-
ferences in efficiency will be smaller. Moreover, use of the 5-inch-
chord data gives a more conservative estimate of efficiency.

CONCLUSION

Differences of less than 1 percent in propeller efficiency at or
near the design condition will be involved in applying data from 5-inch-
chord and 12-inch-chord airfoil tests to full-scale propeller design.

Langley Aeronautical Laboratory
        National Advisory Committee for Aeronautics
                Langley Field, Va., August 21, 1947

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   ed., McGraw-Hill Book Co., Inc., 1937, pp. 322-325.

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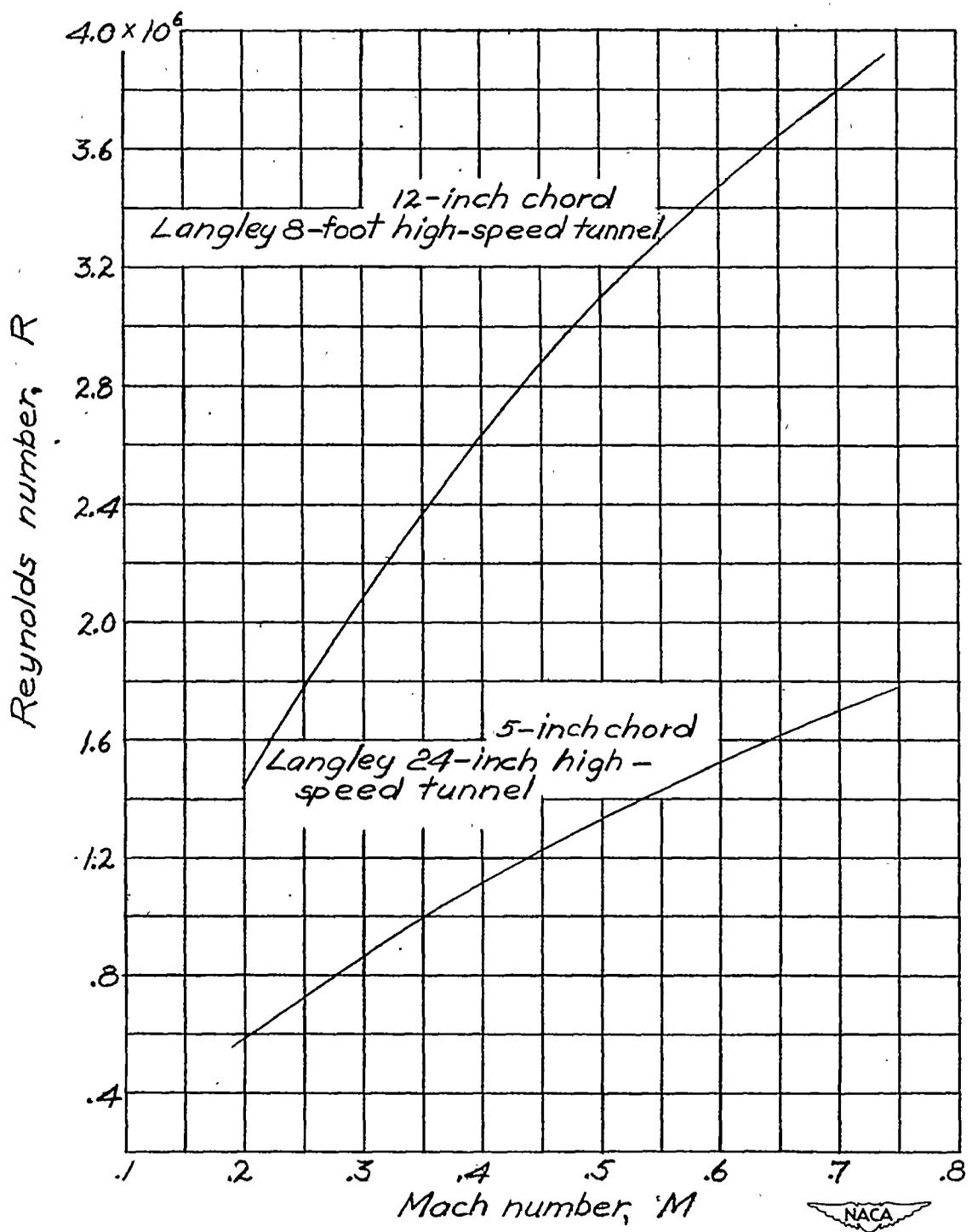   1930, p. 68.

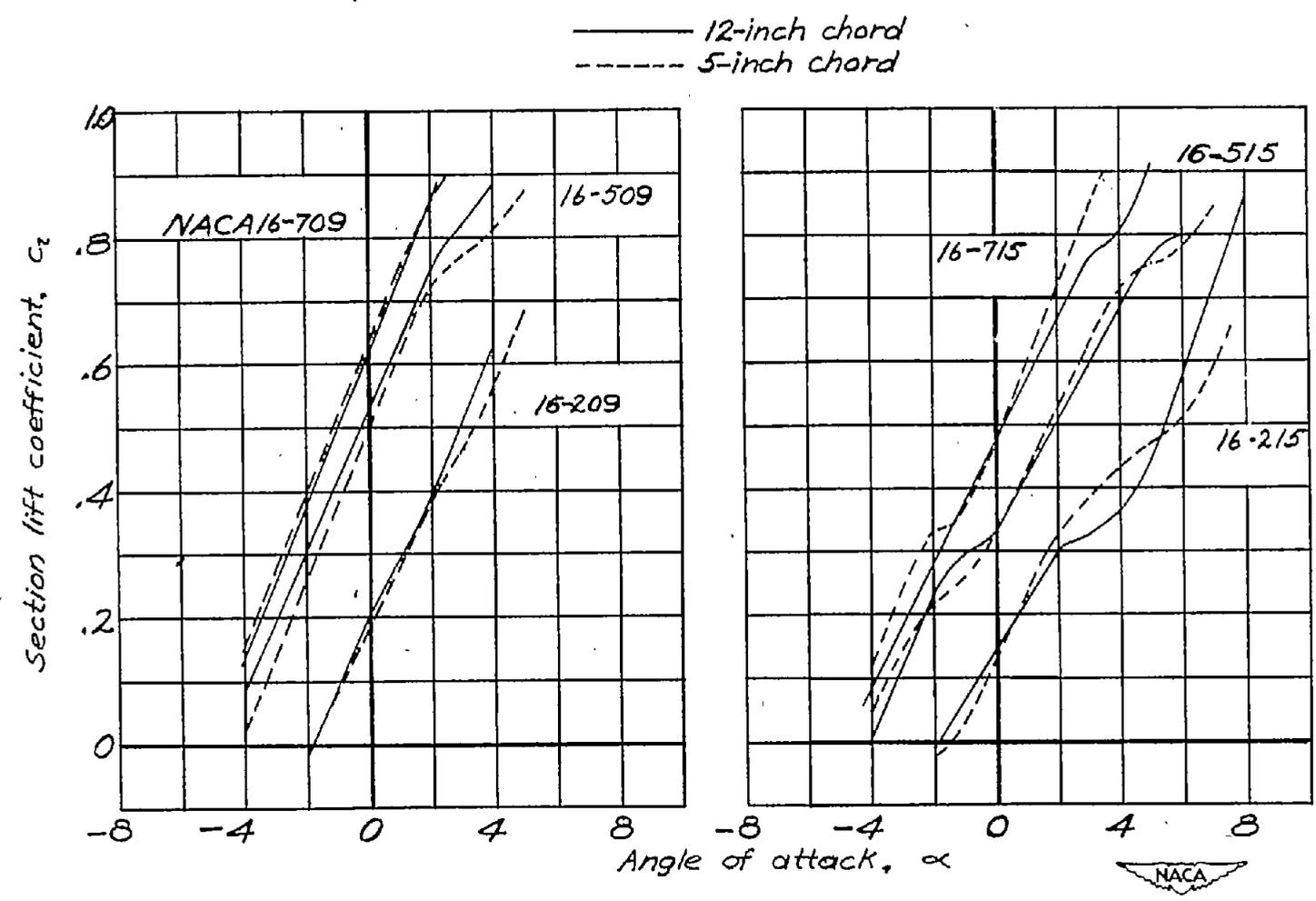Figure 1.- Variation of average Reynolds number with Mach number.

Figure 2.- Variation of lift coefficient with angle of attack for six
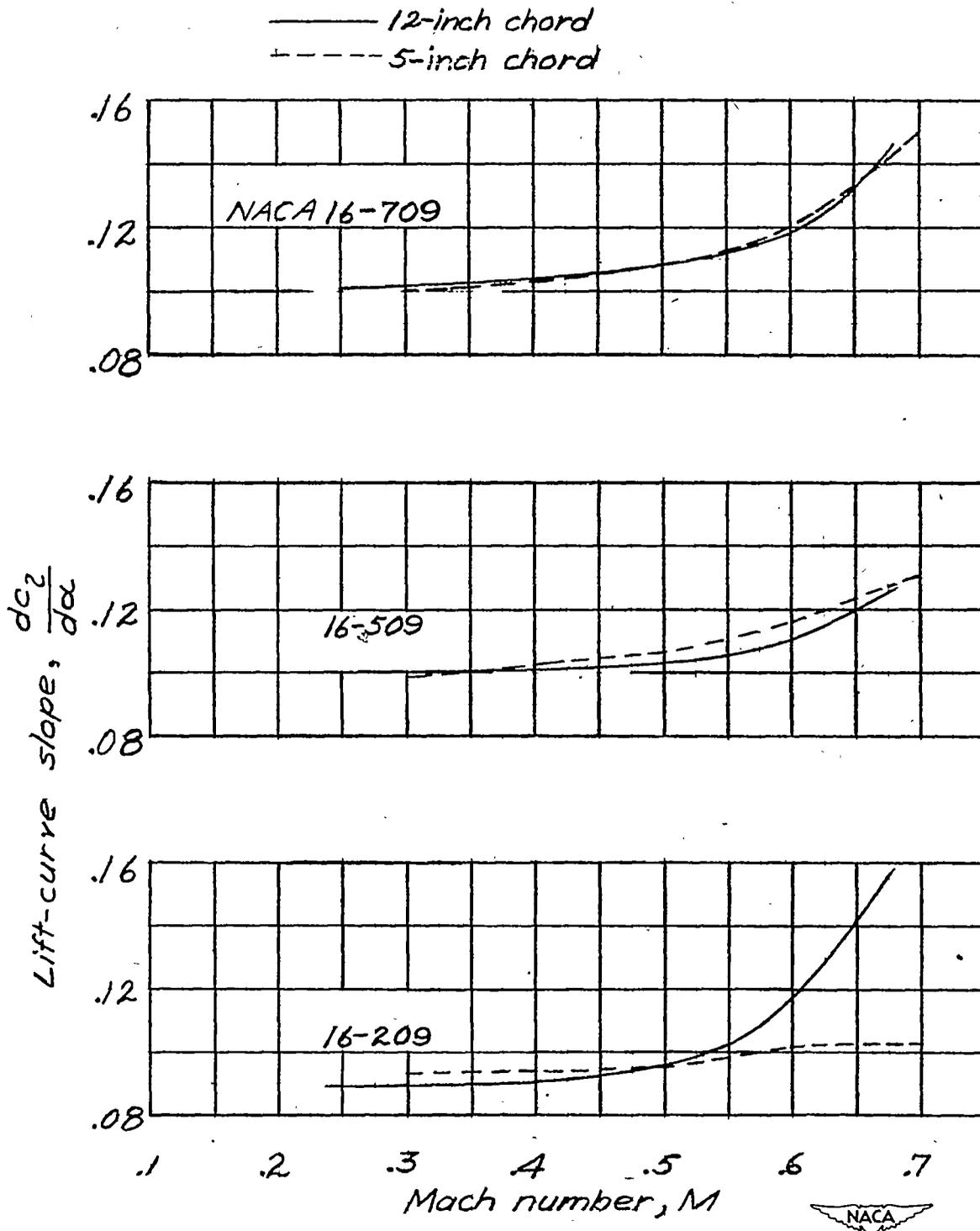NACA 16-series airfoils of two different chord lengths at M = 0.60.

—————— 12-inch chord
- - - - - 5-inch chord

Figure 3.- Variation of lift-curve slope with Mach number for six
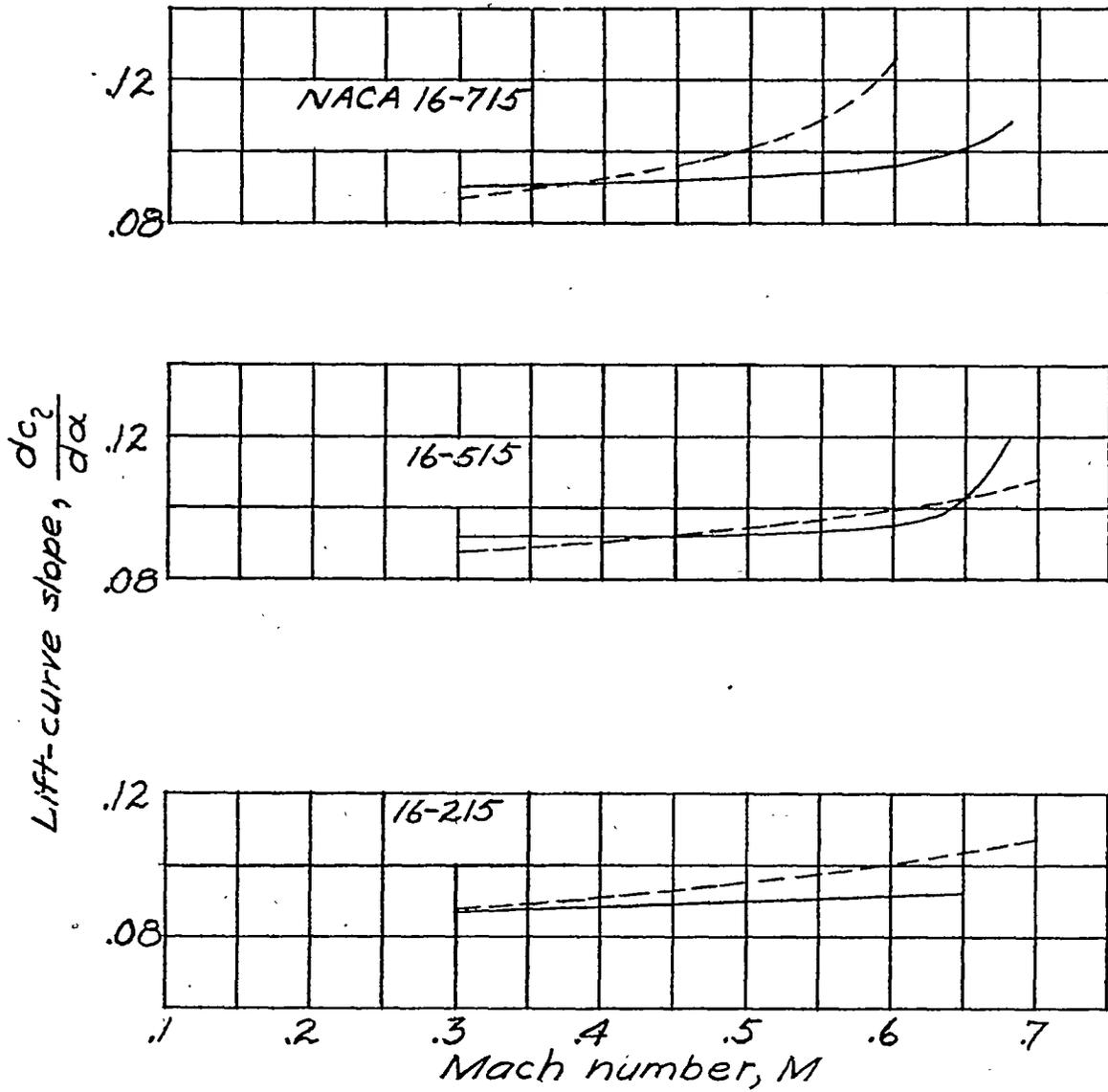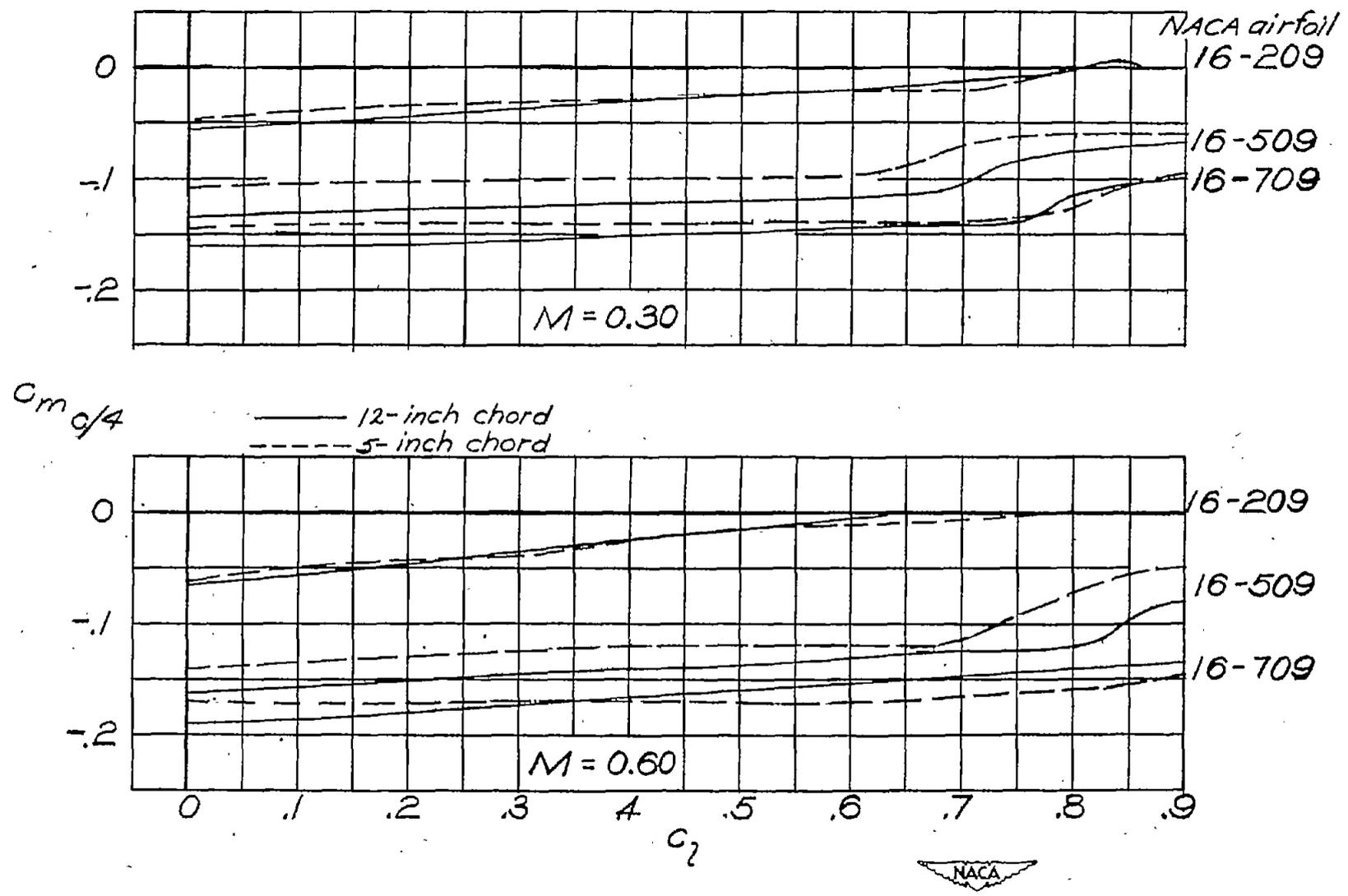NACA 16-series airfoils of two different chord lengths.

Figure 3.- Concluded.

Figure 4.- Variation of moment coefficient with lift coefficient for six NACA 16-series airfoils of two different chord lengths.
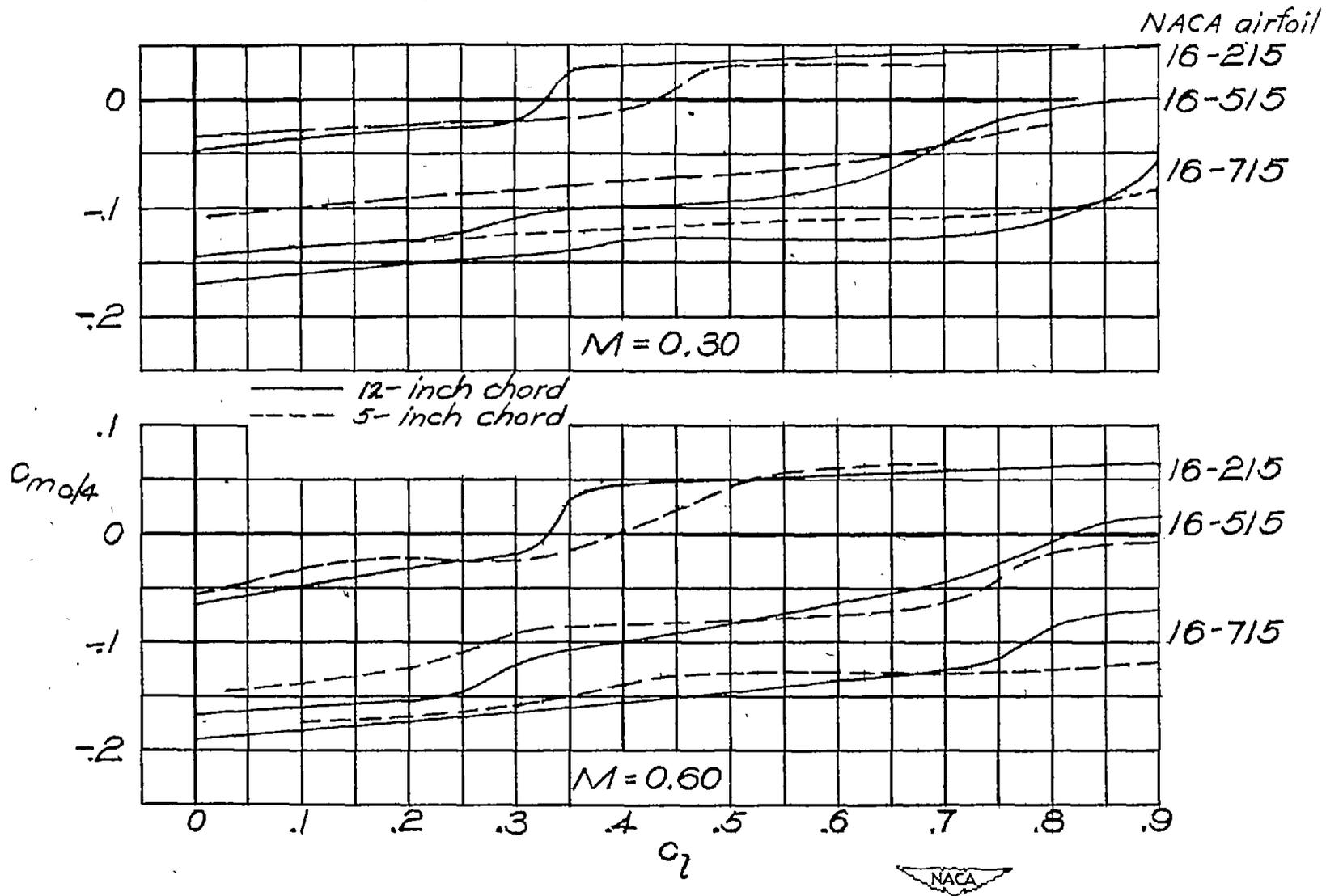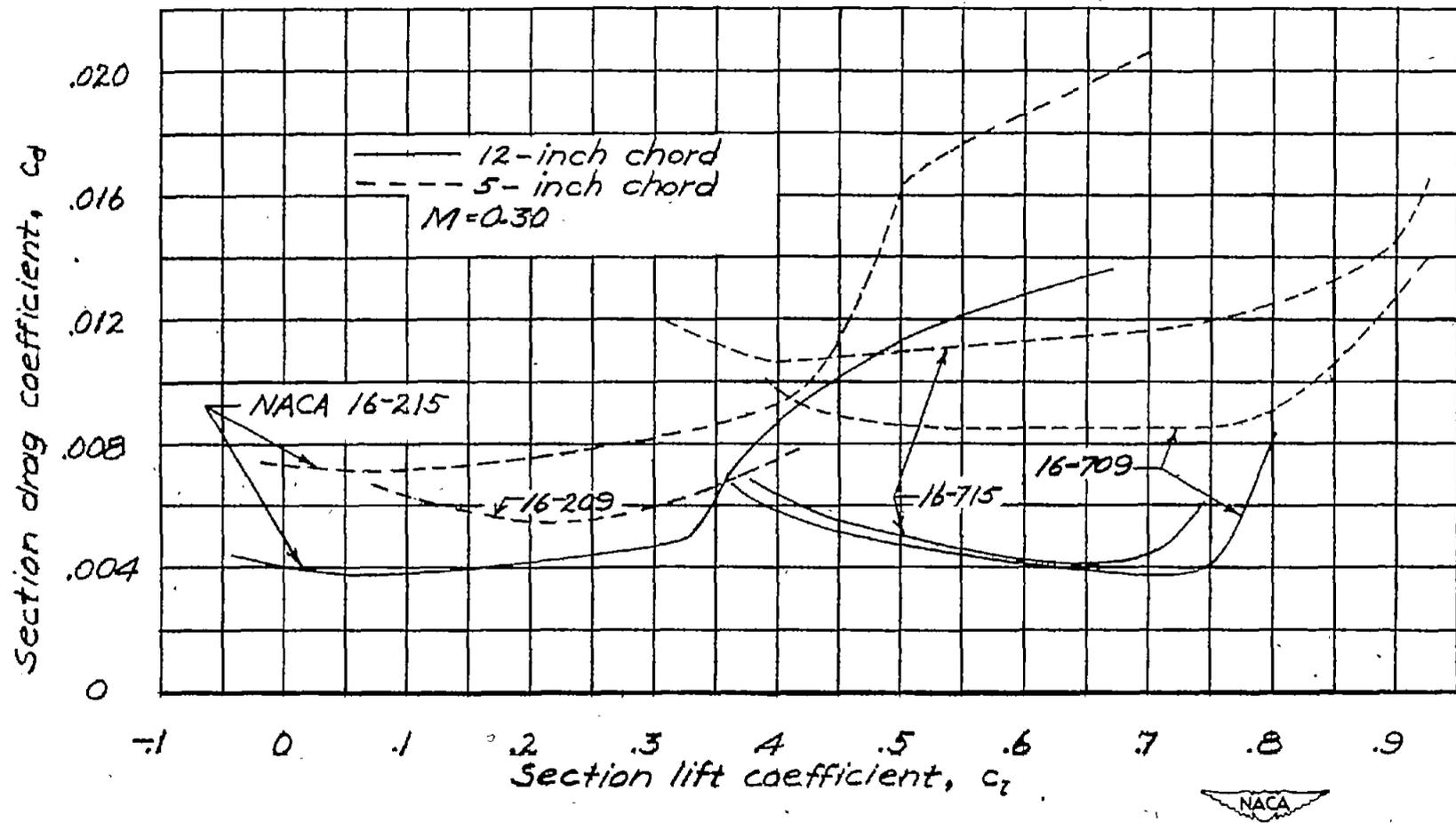
Figure 4.- Concluded.

Figure 5.- Variation of drag coefficient with lift coefficient for four
NACA 16-series airfoils of two different chord lengths.