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NAVY DEPARTMENT

THE DAVID W. TAYLOR MODEL BASIN

AERODYNAMICS LABORATORY

WASHINGTON 7, D.C.

WIND-TUNNEL INVESTIGATION OF THE USE OF WING-TIP BLOWING TO REDUCE DRAG FOR TAKE-OFF AND LANDING

by

Herbert E. White

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January 1963

SYMBOLS

b	span in feet
$\bar{c}$	mean chord in feet
C_μ	blowing momentum coefficient $C_\mu = wV_j/gqS$
g	acceleration due to gravity in feet per second-squared
q	dynamic pressure $(\rho V^2/2)$ in pounds per square foot
R	Reynolds number $(\rho V\bar{c}/\mu)$
S	area in square feet
V	airspeed in feet per second
V_j	jet exit velocity in feet per second, assuming isentropic expansion to atmospheric conditions
w	quantity of air in pounds per second
x	chordwise distance from $\bar{c}/4$ to center of pressure
y	spanwise distance from wing root to center of lift
μ	absolute coefficient of viscosity of air in pound-seconds per square foot
ρ	mass density of air in slugs per cubic foot

Angular Settings

α	angle of attack in degrees (angle between wing chord line and relative wind vector)
δ	flap deflection in degrees, measured in a plane perpendicular to the hinge line
θ_J	angle of inclination of the jet sheet from the chordal plane, in degrees (measured about a chordwise line in the spanwise-blowing case and a spanwise line in the chordwise-blowing case; positive downward)

TABLE OF CONTENTS

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SUMMARY

A wind-tunnel investigation was undertaken to determine the potential value of wing-tip blowing as a means of reducing drag of low-aspect-ratio wings during take-off. Both spanwise and chordwise blowing, parallel to, and inclined to the chordal plane, were investigated. The results indicate that the improvement in lift and drag characteristics for take-off by blowing is small at best, and does not justify the expenditure of power that is required. It is possible that the increase in lift from blowing, available with some configurations, might be useful for landing, where power considerations would not be prohibitive.

INTRODUCTION

One of the possible methods of reducing the magnitude of induced drag of a low-aspect-ratio surface is the application of a jet of air at the tip. There are, of course, a great number of possible configurations that the tip jet could take. The present test was undertaken to investigate the potential value of the principle, to determine which are the more promising of several configurations, and to compare this method of drag reduction with others.

The tests were authorized by the Bureau of Naval Weapons (Reference 1) and were conducted in September 1960.

MODEL AND EQUIPMENT

The model was a half-span wing panel constructed of mahogany over a steel frame. The general arrangement of the model is shown in Figure 1. A plenum chamber was provided at the tip. This was supplied with compressed air at pressures up to 100 psig, brought through the wind-tunnel strut and through tubes in the model. Two basic nozzles were constructed to attach to the plenum chamber. The first of these (the spanwise-blowing nozzle) consisted of a narrow slot which was arranged parallel to the chord of the wing and expelled air in a spanwise direction. The second nozzle (the chordwise-blowing nozzle) consisted of a spanwise extension of the basic wing, with a long, thin opening on the trailing edge parallel to the span. This nozzle expelled air aft and parallel to the chord. Sketches of the nozzles are shown in Figure 2.

To deflect the jets from the chordal plane, blocks were fitted which utilized the Coanda principle. The blocks were cut to geometric angles of 45° and 90°. The actual angles of jet deflection obtained were determined by analysis of the reaction force components.

The model was mounted in the wind tunnel with the chordal plane vertical. The reflection plane was provided by a "false floor" above, and faired into, the tunnel floor. A seal of carpet material was installed between the root rib of the model and the reflection plane. This seal was adjusted by shims to rest lightly against the reflection plane. Details of the model are shown in Figures 2 through 6.

TESTS

The tests were conducted in the Aerodynamics Laboratory Wind Tunnel 2, which is a subsonic atmospheric tunnel having an 8- by 10-foot test section.

Lift, drag, and pitching moment variation with angle of attack were measured for various combinations of jet distribution, jet direction, momentum coefficient, and flap deflection. At some jet directions, a full range of momentum coefficients could not be obtained because of the breakdown of Coanda effect at higher values. Increasing the turning radius of the deflection blocks for the chordwise-blowing nozzle partially alleviated this problem. In order to cover the desired range of C_μ's, it was necessary to use several different dynamic pressures: 4, 6, 9, 18, and 50 pounds per square foot, which correspond to Reynolds numbers of 0.959×10^6, 1.175×10^6, 1.439×10^6, 2.035×10^6, and 3.392×10^6, respectively.

RESULTS

The reduction of the data to coefficient form was based on the following full-span model constants:

$$S = 16.666 \text{ square feet}$$

$$b = 6.666 \text{ feet}$$

$$\bar{c} = 2.593 \text{ feet}$$

The data were corrected for tunnel wall effects by the following equations:

$$\Delta\alpha = 0.94\ C_L$$

$$\Delta C_D = 0.0136\ C_L^2$$

The direct effects of the jet thrust on the load components have been subtracted out, so that the data presented show only the effects of aerodynamic changes on the wing brought about by the presence of the jet.

The results are shown in Figures 7 through 11. In addition to the lift, drag, and pitching moment, two other aerodynamic characteristics are presented. These are the chordwise location of the center of pressure and the spanwise center of lift. While the chordwise center of pressure is a generally understood term, the spanwise center of lift may require some definition. For this report, the spanwise center of lift has been defined as M_r/F_L where M_r is the moment at the root of the wing about an axis parallel to the wind and F_L is the wing lift.

The Reynolds number effect on the coefficients is shown in Figure 11.

DISCUSSION

Spanwise blowing parallel to the wing chordal plane results in an increase in C_L at each α, up to C_μ values of about 0.5 (Figure 9a).

Higher values of C_μ result in practically no change in C_L, and a slight increase in C_D. Evidently, then, a C_μ of 0.5 is approximately the practical limit for increasing C_L by blowing with this configuration. Deflecting the spanwise-blowing jet downward (Figure 9) decreases the increment of C_L obtained by blowing. This decrease is progressive through the range of deflection angles investigated. The lift-curve slope is increased by blowing. However, for a given C_μ, the largest percentage increase in C_L is obtained at the lower C_L's.

In the spanwise-blowing configuration, with $\theta_J = 0°$, the $C_{L_{max}}$ increases approximately linearly with C_μ up to a C_μ of about 0.5. At this C_μ the $C_{L_{max}}$ is increased about forty percent above the no-blowing value. Increasing C_μ from 0.5 to 1.0, the maximum value tested, yields no further increase in $C_{L_{max}}$.

Chordwise blowing at $\theta_J = 0$ has practically no effect on the wing drag (Figure 10a). Nor is the wing lift affected to any significant extent. For θ_J values other than 0, the wing drag increases without a compensating increase of lift.

Since pitching moment considerations are of secondary interest in this drag-reduction study, they will not be discussed except to state that in the chordwise-blowing configuration with $\theta_J = 37°$, C_μ has much more effect on pitching moment than it has in any of the other configurations.

The chordwise center of pressure and spanwise center of lift data presented give an indication of the distribution of lift on the wing. However, this indication is very rough and probably can at best only give a hint as to the direction of changes in the lift distribution.

A striking feature of spanwise blowing, although it is not important from the present point of view, is the discontinuity in the lift curve near $\alpha = 0°$, when $\theta_J = 0°$. This discontinuity disappears at the other values of θ_J investigated. The tuft-mattress studies (Figures 7 and 8) show the change in circulation clearly.

CONCLUDING REMARKS

Since chordwise blowing seems to be at best ineffective, only spanwise blowing will be discussed further. Spanwise blowing at $\theta_J = 0°$

appears to be the most effective of the configurations investigated in improving the characteristics of the wing, but the energy of the jet is totally lost so far as the direct production of thrust (either along the horizontal or the vertical axis) is concerned. Deflecting the spanwise jet downward, while it reduces the beneficial effects on the wing aerodynamic characteristics, does make it possible to recover at least some of the jet thrust as lift. But this downward-deflected jet configuration also has this disadvantage: when the wing is at a positive angle of attack, the jet thrust produces a component of force in the drag direction.

Actually, the relative merits of the various tip-blowing configurations as drag-reduction devices are of small significance. A consideration of the power requirements for even the best of the configurations indicates that this power could better be used for the direct production of thrust at the tail pipe or the propeller.

Up to this point, the discussion has been confined to the merit of tip blowing for the purpose of drag reduction during take-off. We have seen that the improvement in wing aerodynamics does not justify the power expenditure from the standpoint of take-off improvement. However, the higher maximum C_L's obtainable with blowing indicate the blowing might be desirable for the reduction of landing speed, in which case the expenditure of energy might not be a problem. It should be borne in mind, however, that the mechanical problems associated with the tip blowing may be so complex as to render it impractical.

Aerodynamics Laboratory
David Taylor Model Basin
Washington, D. C.
December 1962

REFERENCE

1. BUWEPSINST 3920.1 R-12 of 2 Sep 1960

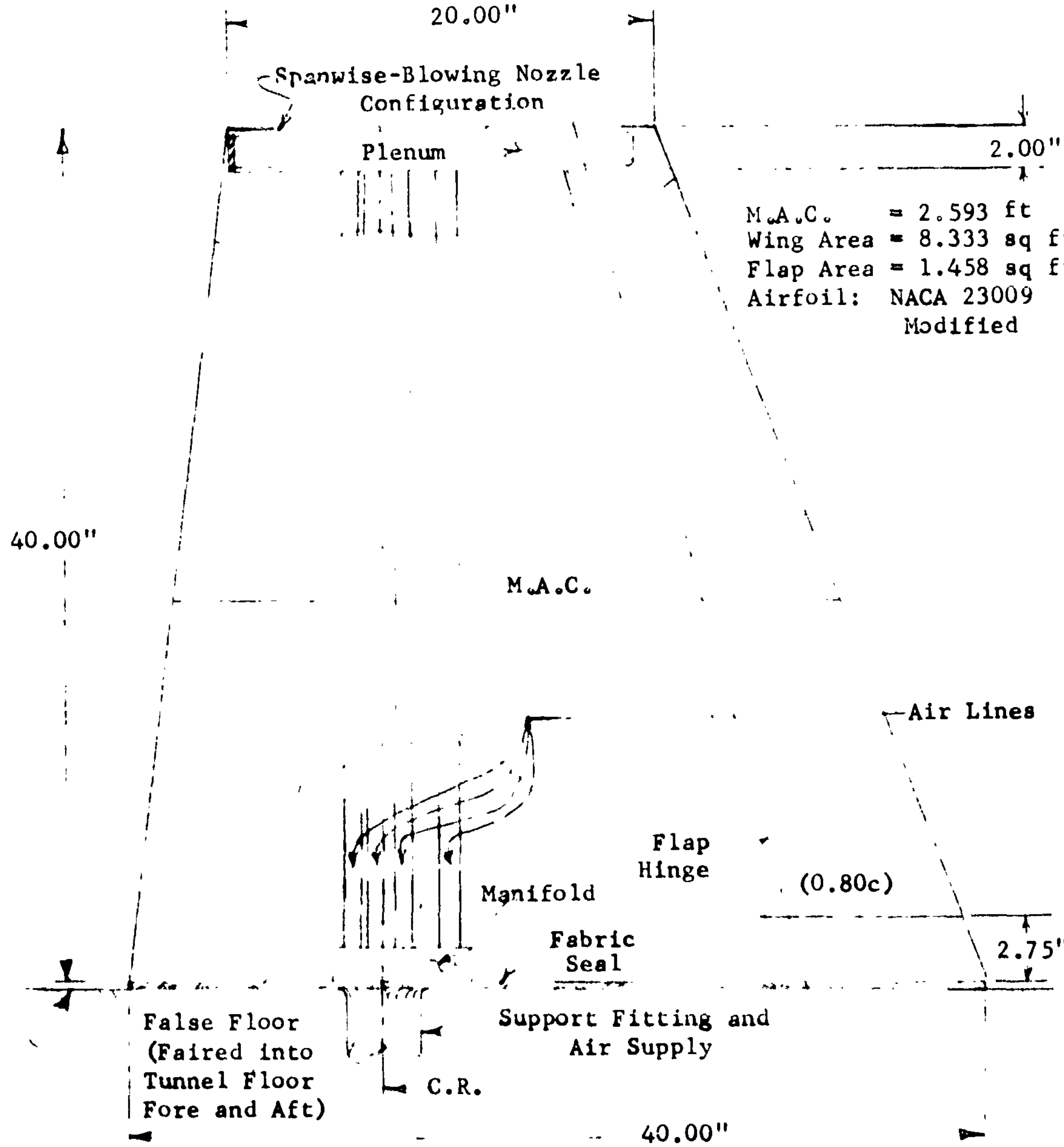


Figure 1 - General Arrangement and Principal Dimensions of the Wing Semispan Model, Including Schematic of the Air Supply System

FIGURE 1

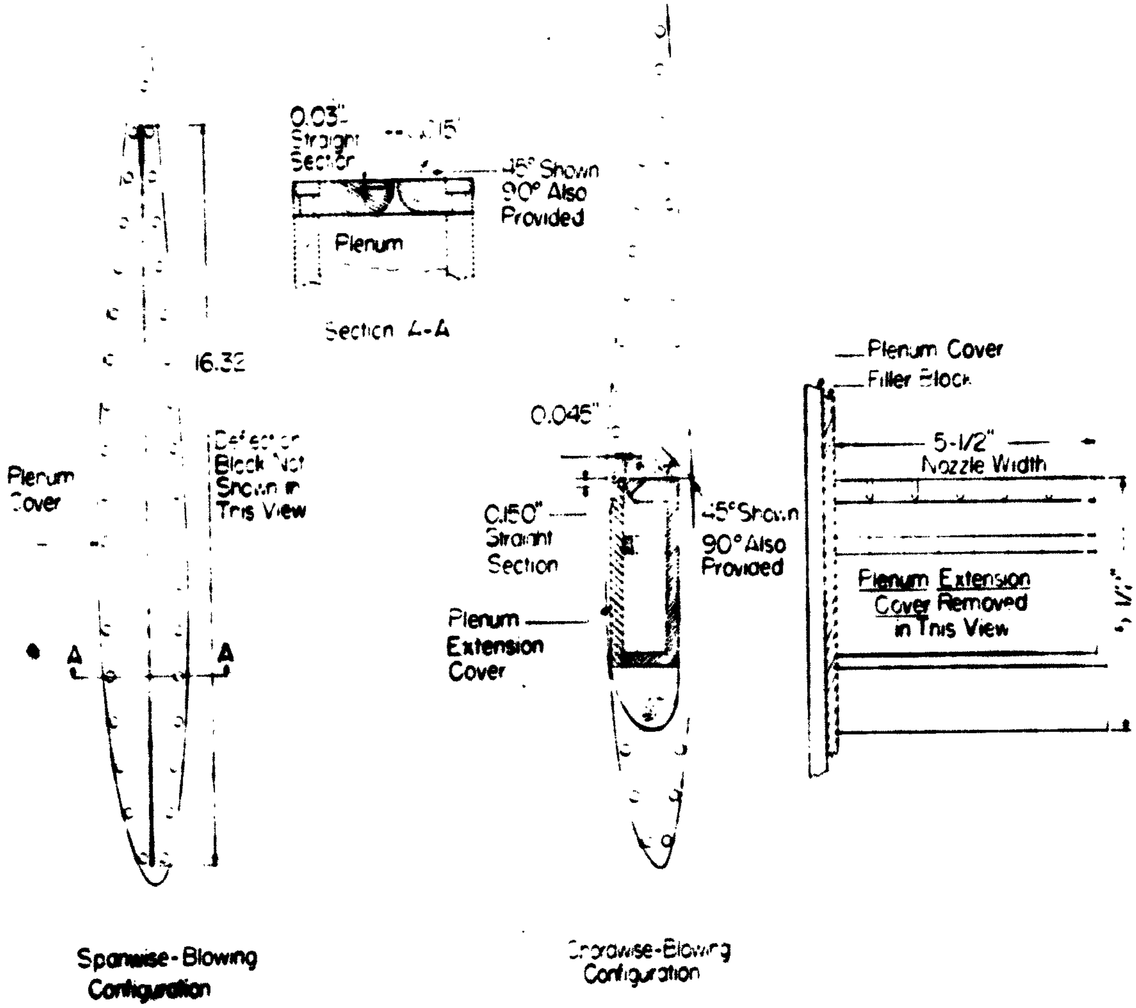
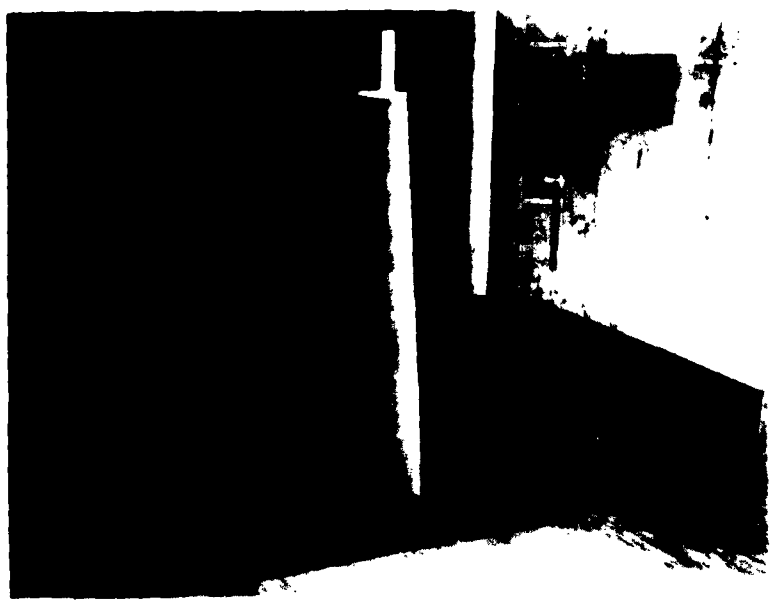


Figure 2 - Details of the Spanwise-Blowing and Chordwise-Blowing Nozzle Configurations

PSD-300,826

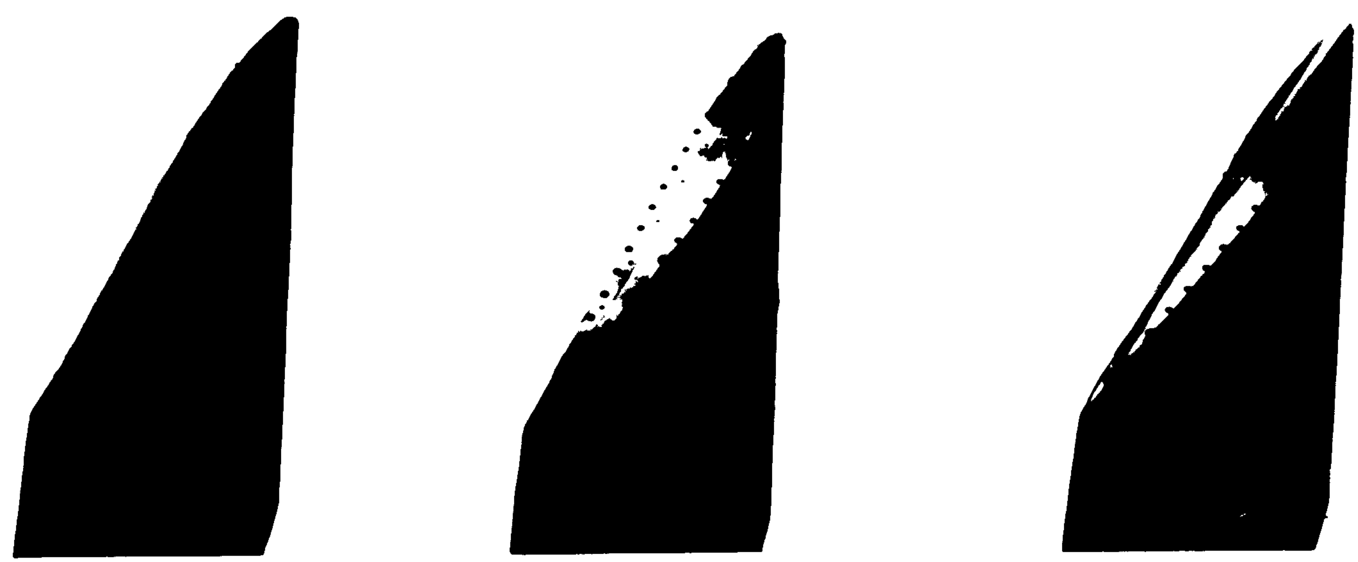
(a) General View Showing False Floor



PSD-300,825

(b) Close-up

Figure 3 - Two Three-Quarter Front Views of the Model Installed in the Wind Tunnel

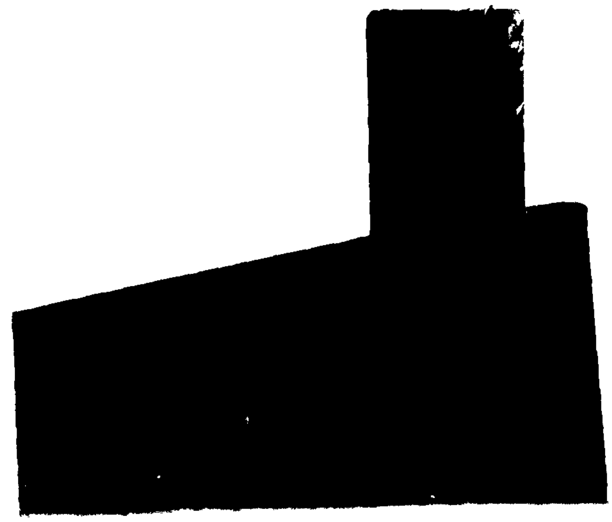


PSD-300,821 — (a) Nozzles Removed

PSD-300,822 — (b) Spanwise-Blowing Nozzle Installed

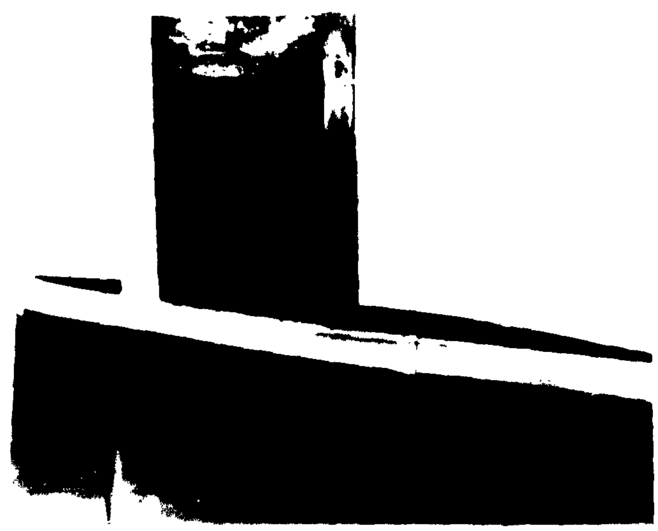
PSD-300,820 — (c) Spanwise-Blowing Nozzle With Deflection Block Installed

Figure 4 - Views of the Wing Tip With and Without Spanwise-Blowing Nozzle Installed



PSD-300,819

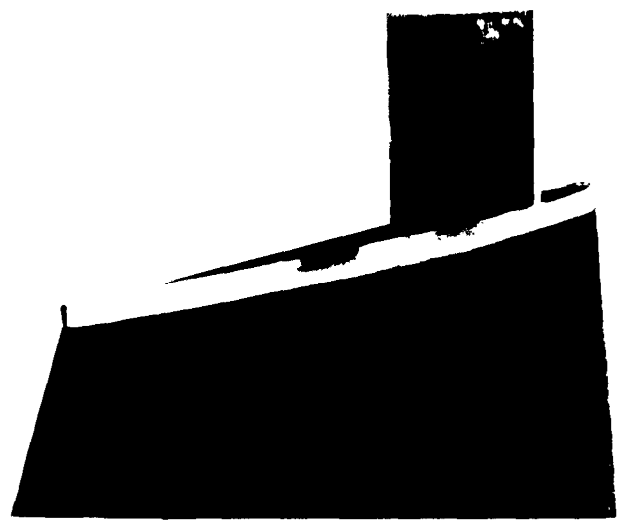
(a) Top View - Cover Removed



PSD-300,823

(b) Bottom View - Cover On

Figure 5 - Two Views of the Chordwise-Blowing Nozzle



PSD-300,824

Figure 6 - Three-Quarter Rear View of the Chordwise-Blowing Nozzle Installed, With Deflection Block Attached

September 20, 1960

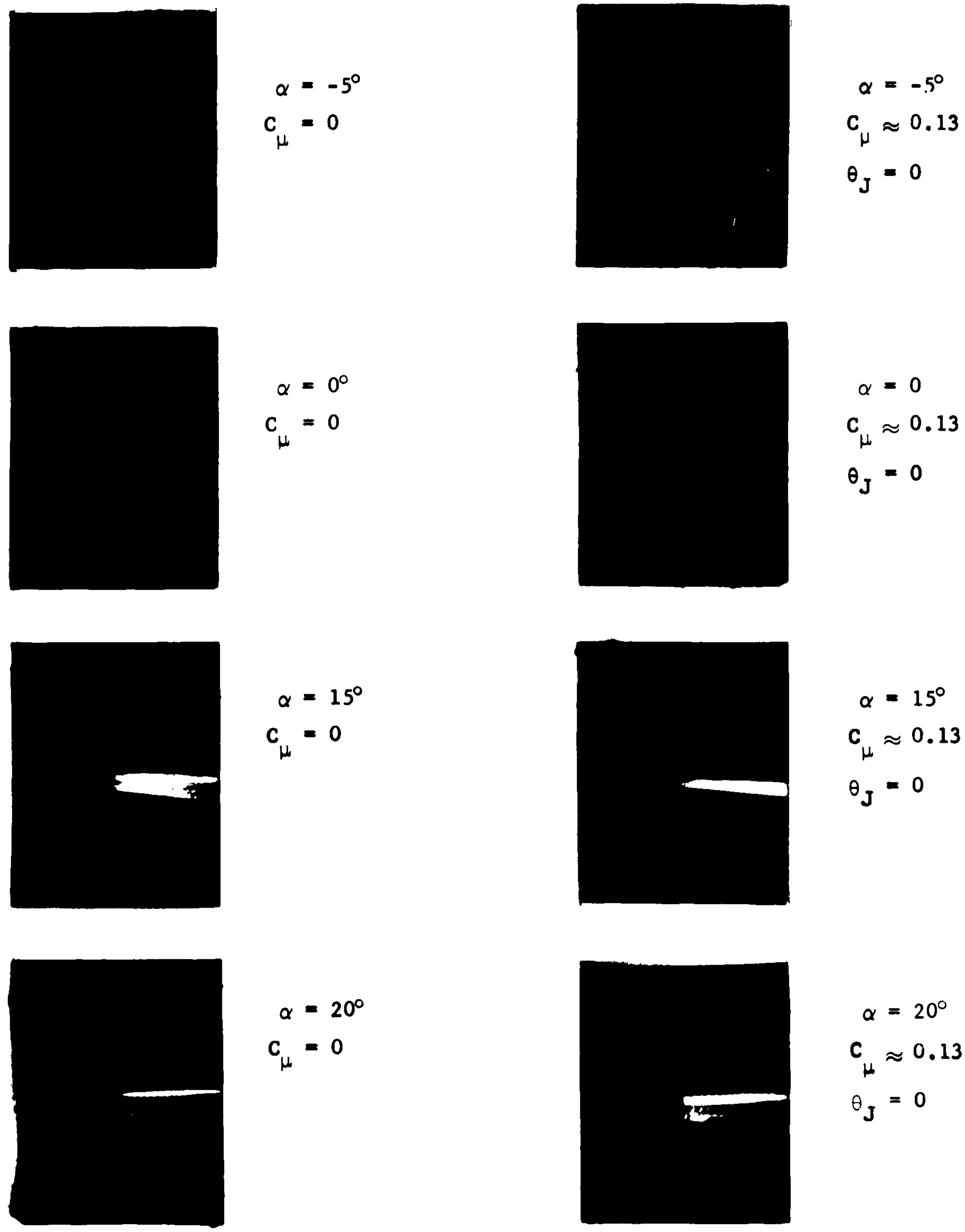


Figure 7 - Tuft-Mattress Study of the Effect of Spanwise Blowing on Tip-Vortex Position

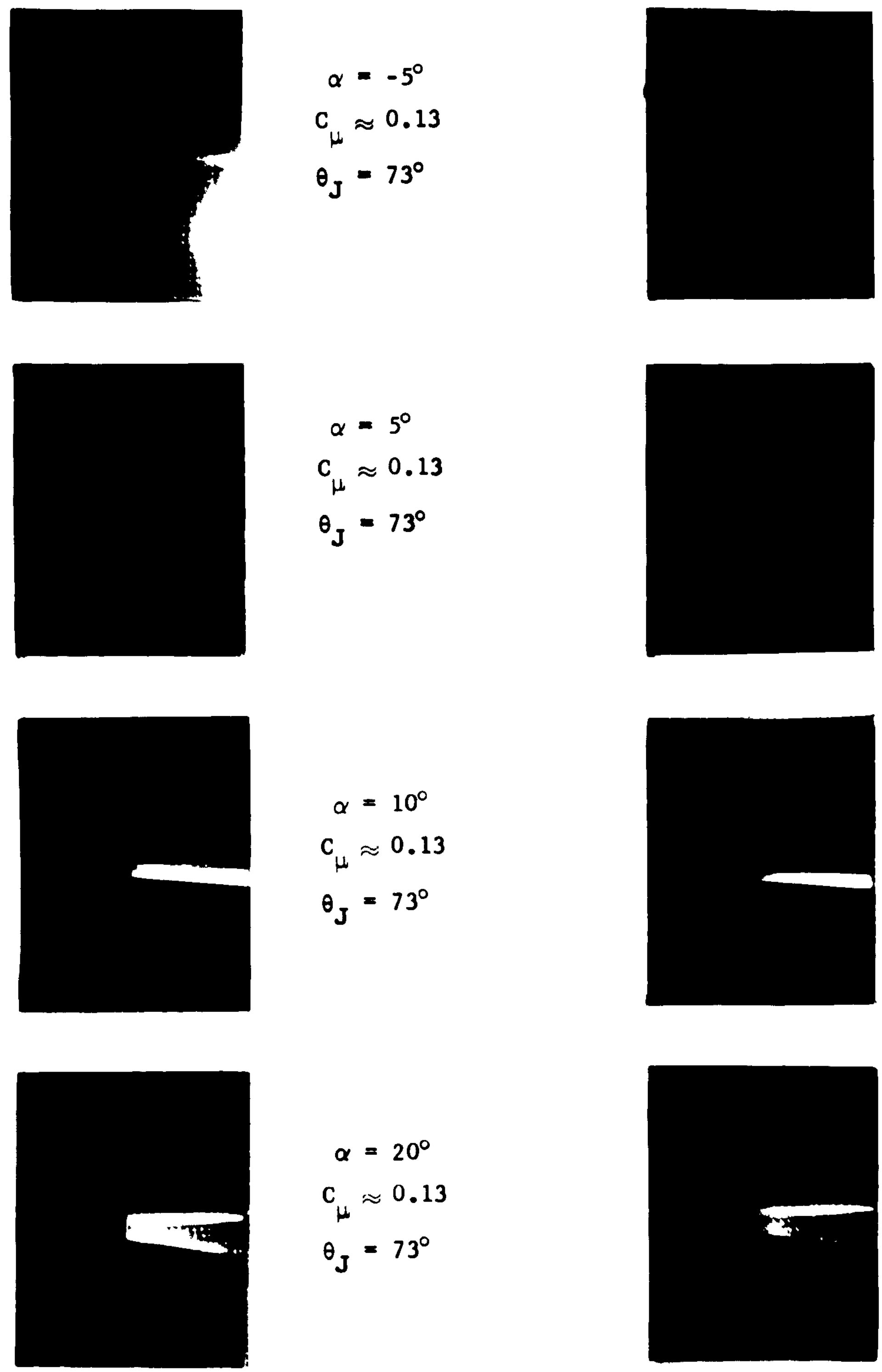


Figure 7 (Concluded)

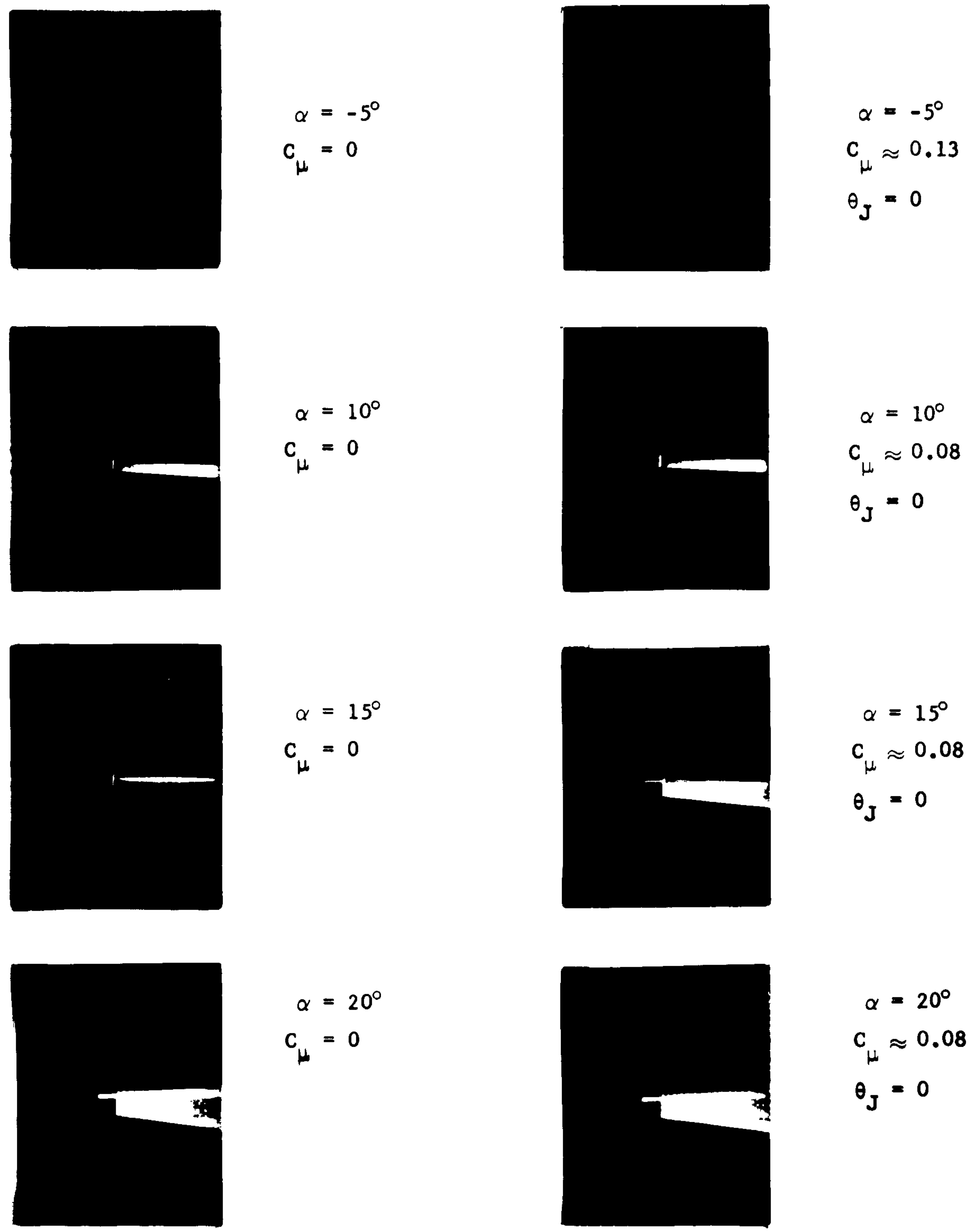
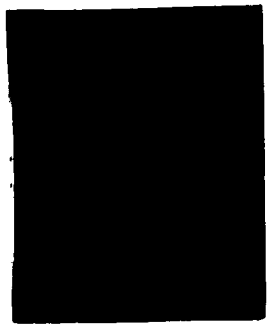
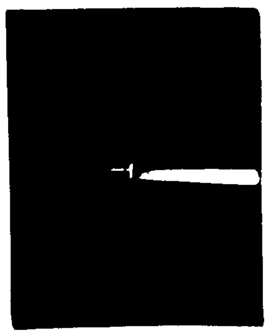


Figure 8 - Tuft-Mattress Study of the Effect of Chordwise Blowing on Tip-Vortex Position



$\alpha = -5^\circ$
$C_\mu \approx 0.06$
$\theta_J = 37^\circ$



$\alpha = 10^\circ$
$C_\mu \approx 0.06$
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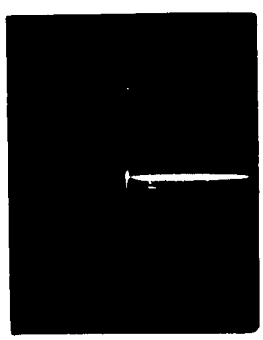

$\alpha = 15^\circ$
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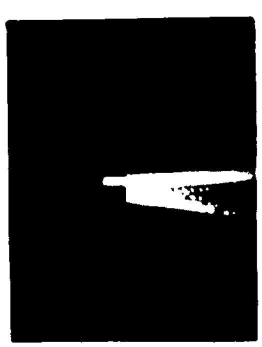

$\alpha = 20^\circ$
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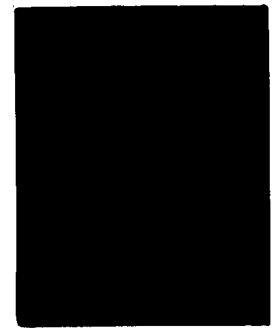
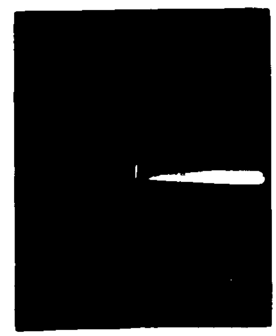
$\theta_J = 37^\circ$

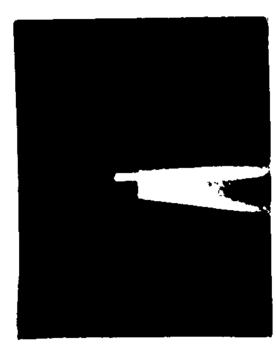


$\alpha = -5^\circ$
$C_\mu \approx 0.07$
$\theta_J = 64^\circ$



$\alpha = 10^\circ$
$C_\mu \approx 0.07$
$\theta_J = 64^\circ$

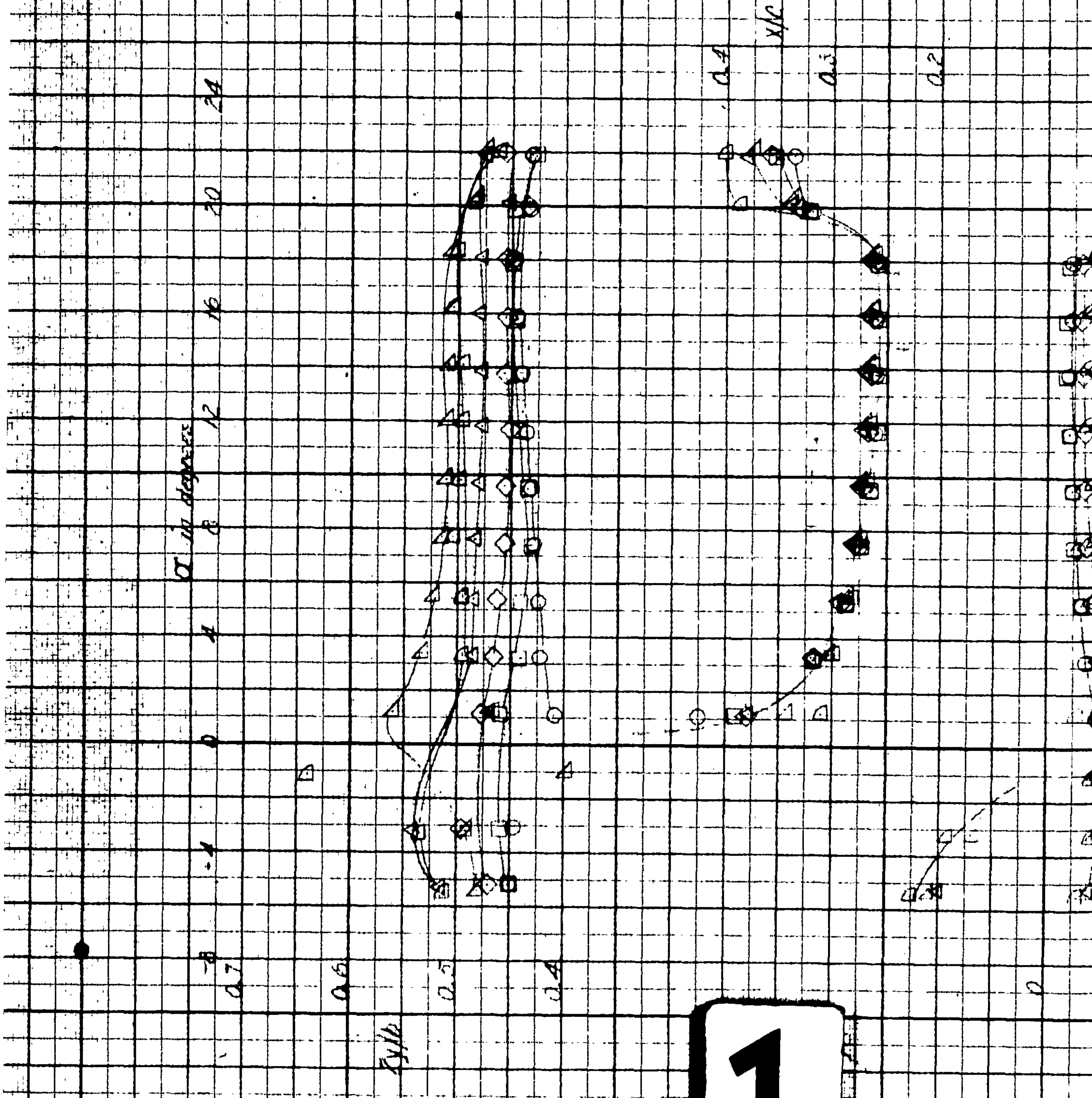
$\alpha = 15^\circ$
$C_\mu \approx 0.07$
$\theta_J = 64^\circ$



$\alpha = 20^\circ$
$C_\mu \approx 0.07$
$\theta_J = 64^\circ$

Figure 8 (Concluded)

AERO 1043



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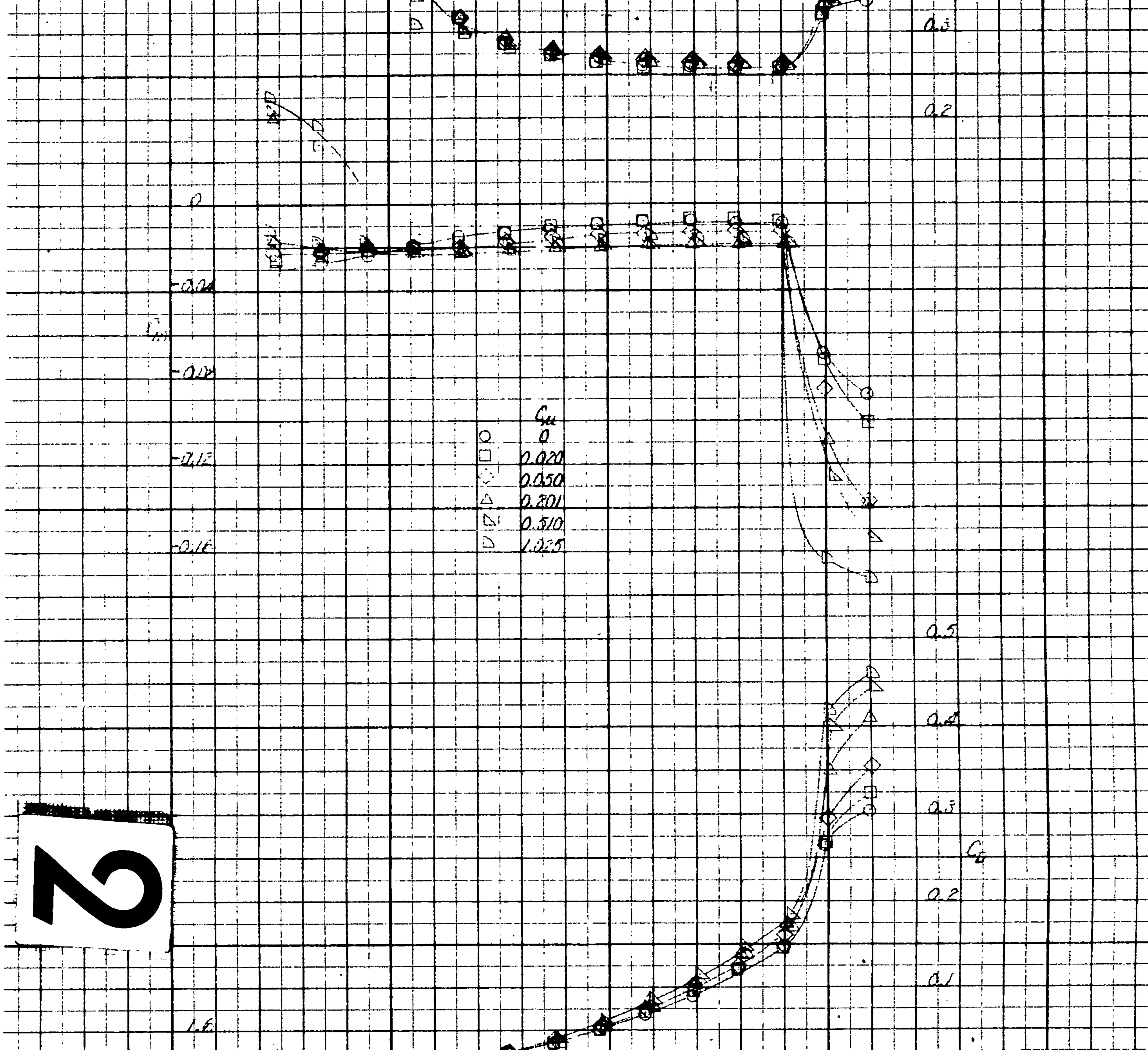

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Cm
-0.08
-0.12
-0.16
Cμ
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0.510
1.025
0.5
0.4
0.3
C_L
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0.1
1.6
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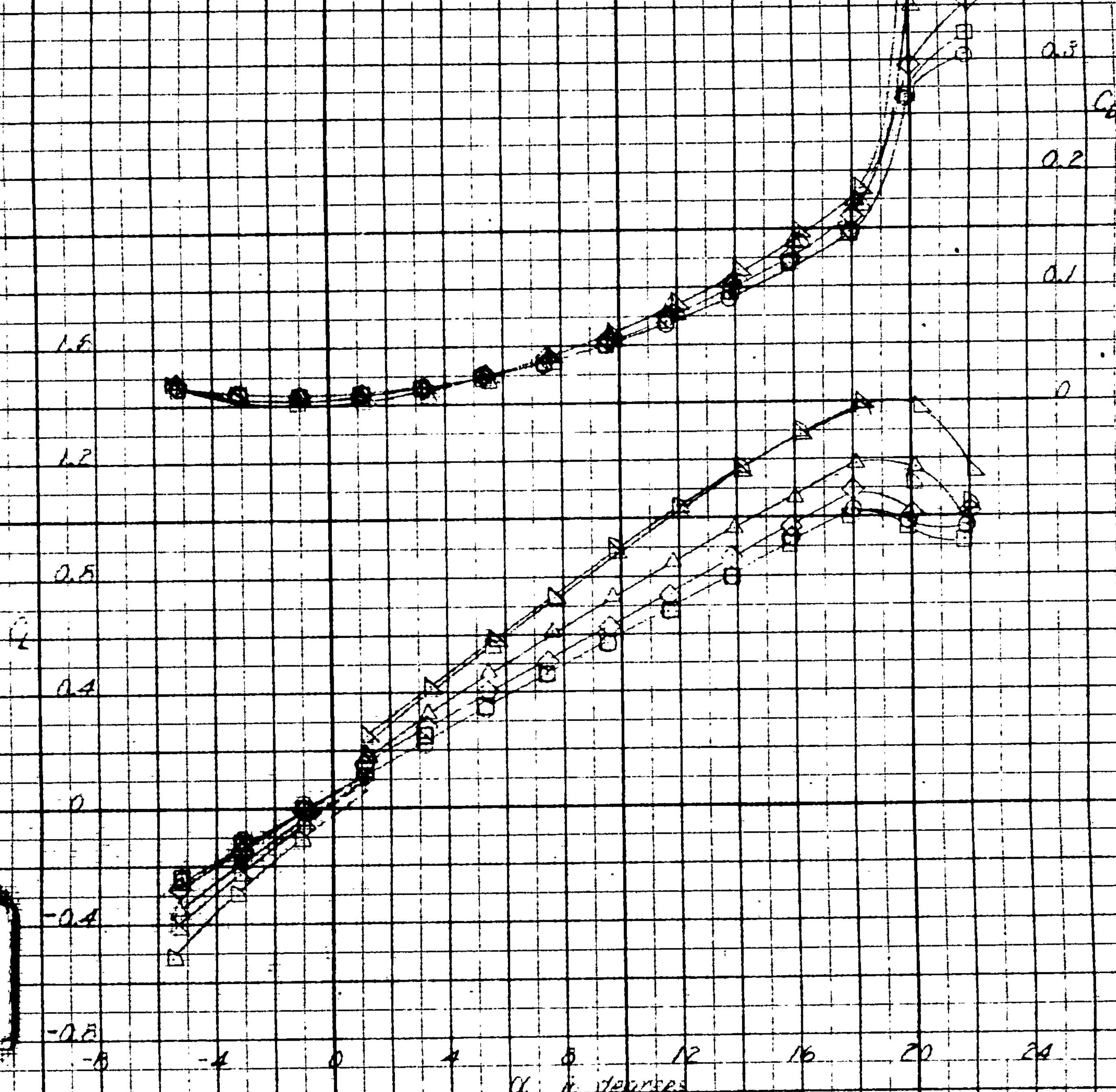
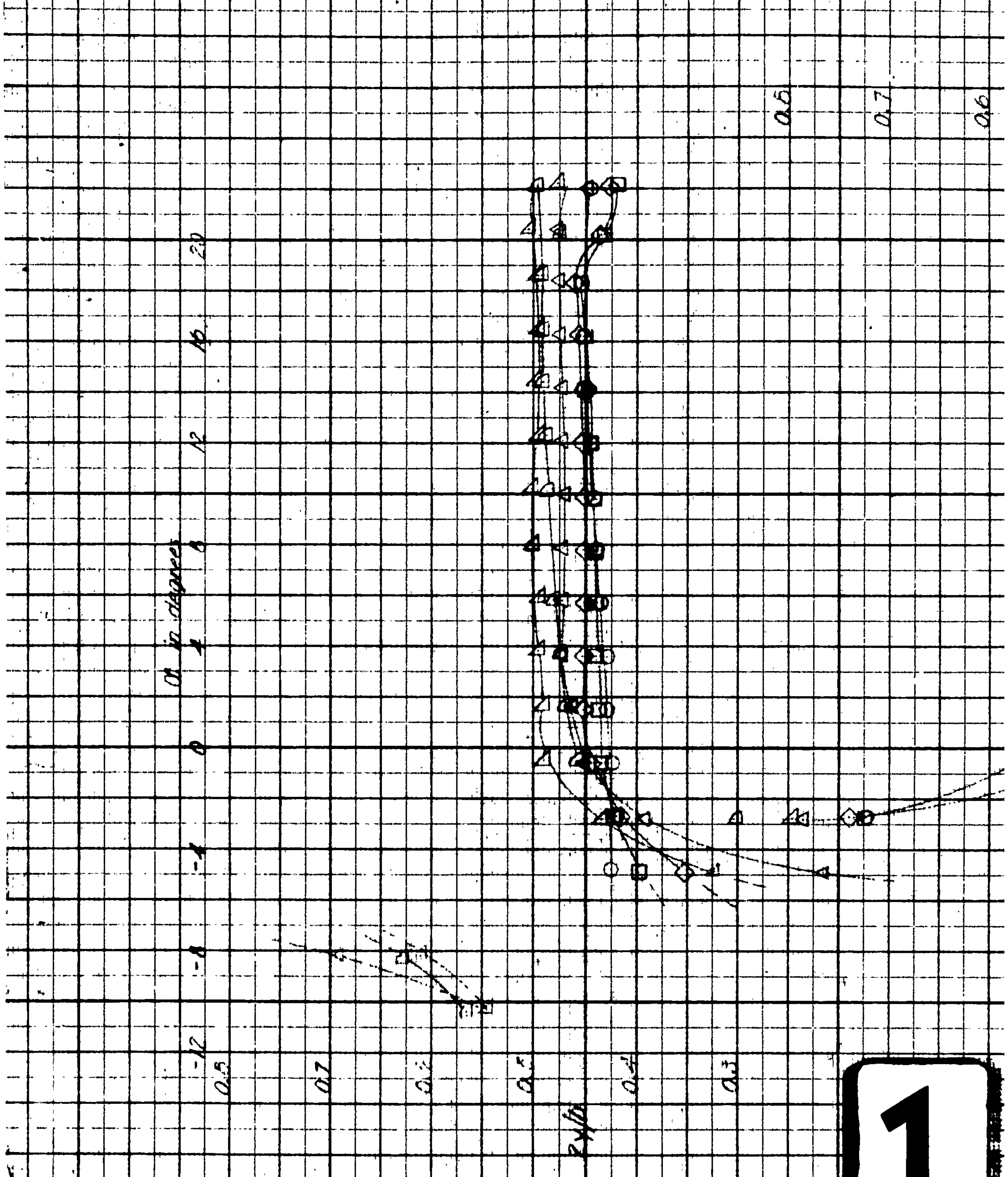


Figure 9 - Effect of Spanwise Blowing on the Aerodynamic Characteristics of the Wing

(a) $\theta_j = 0°$; $\delta_f = 0°$

FIGURE 9 a

AERO 1043



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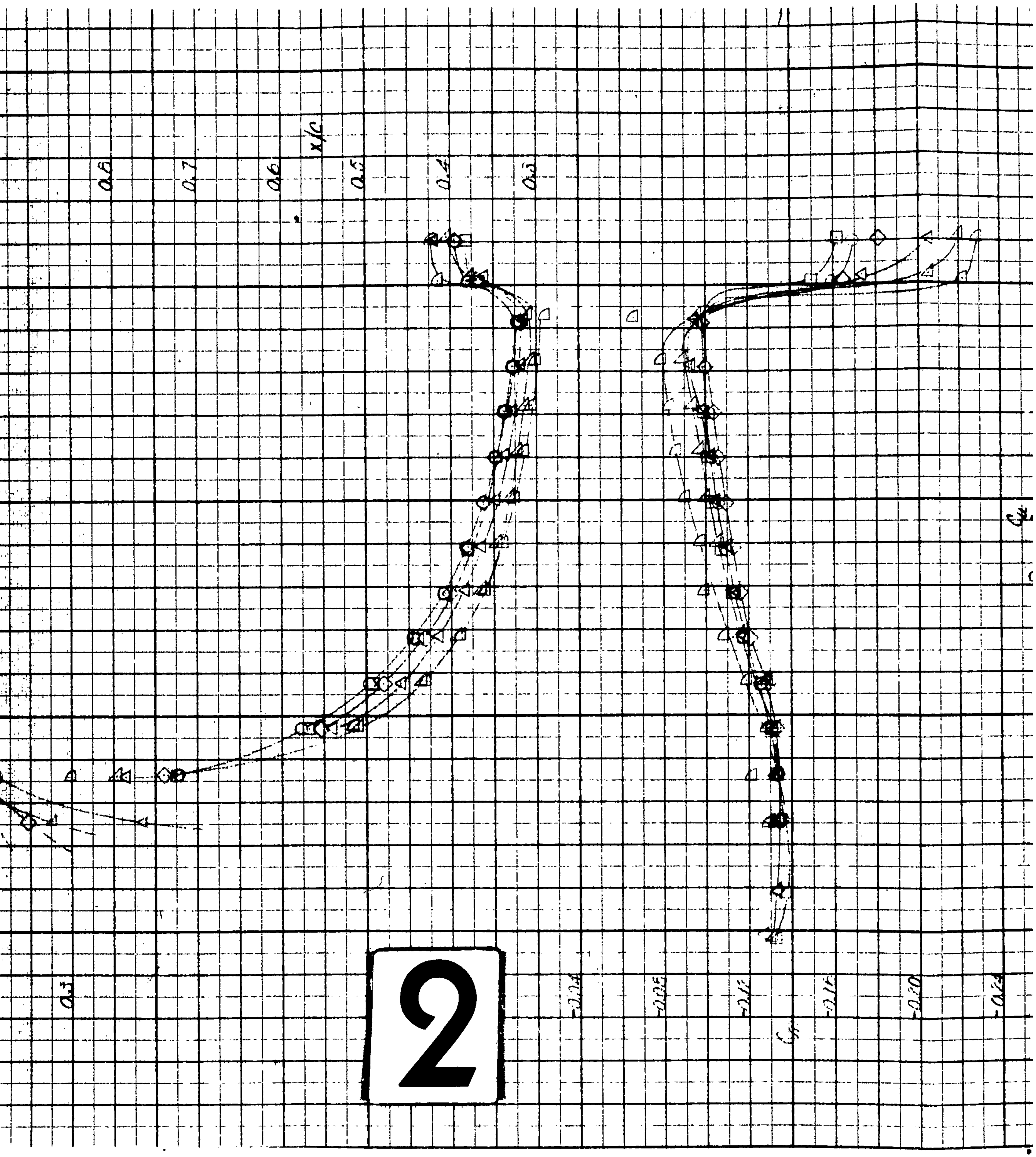

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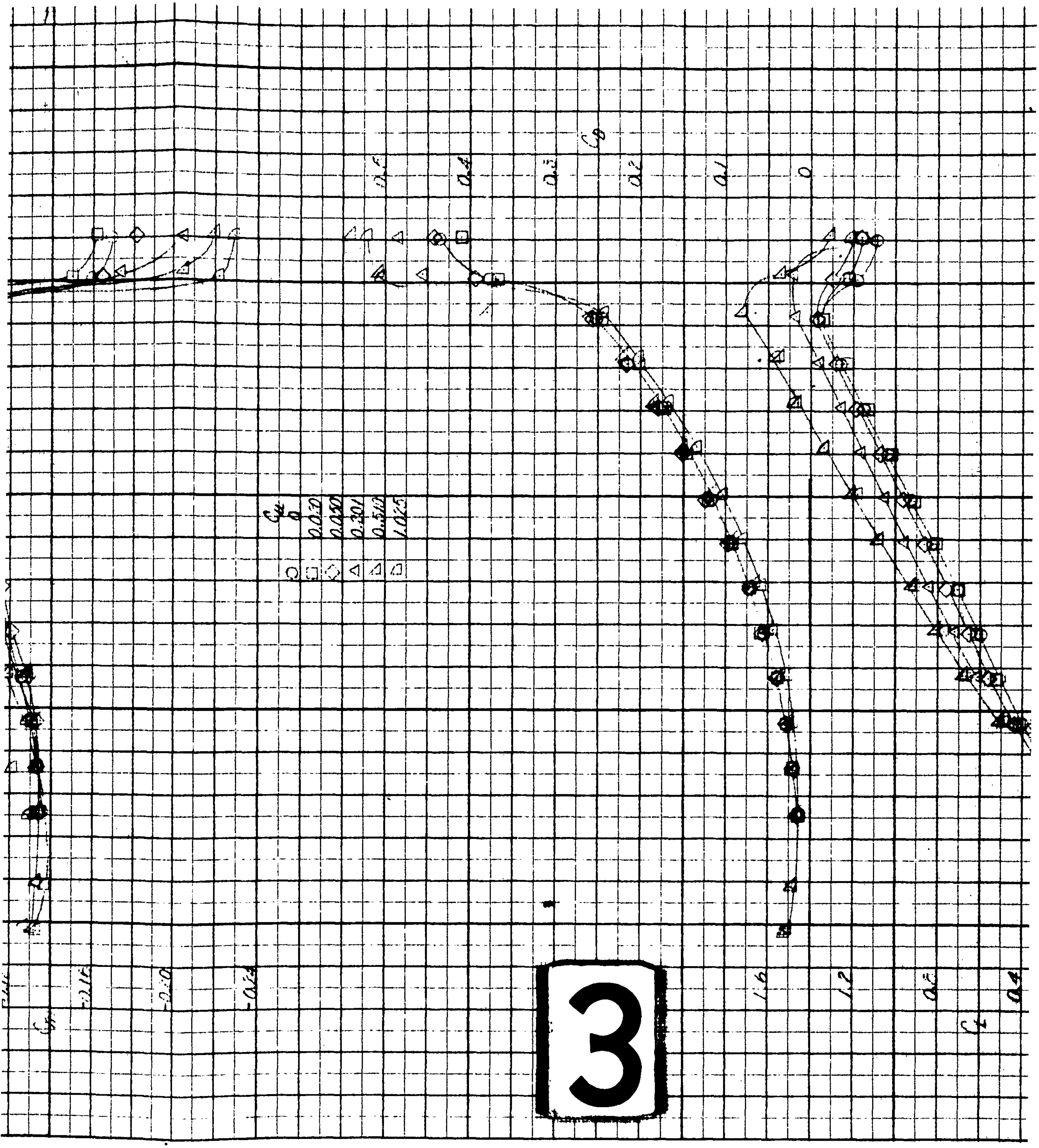

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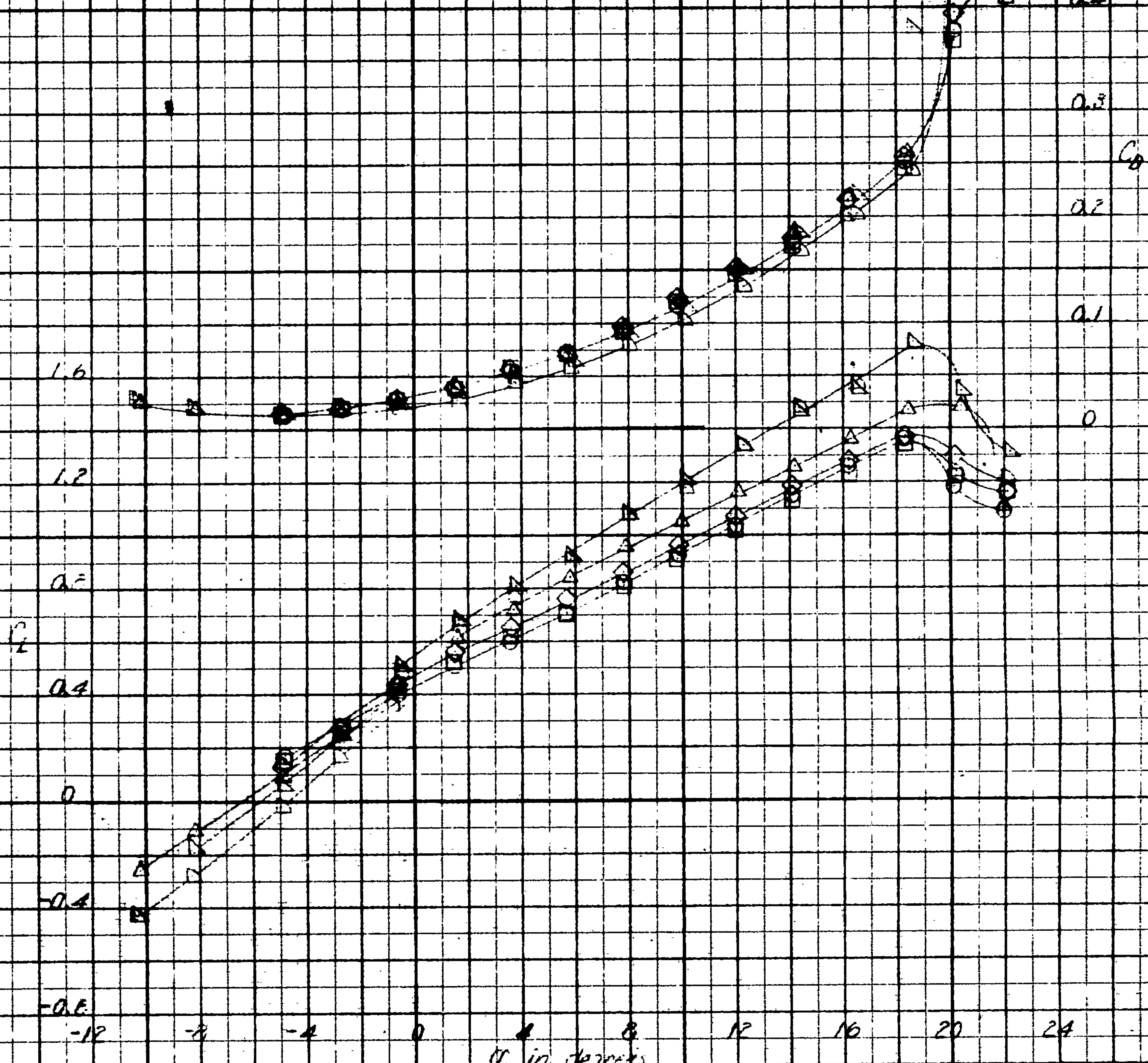


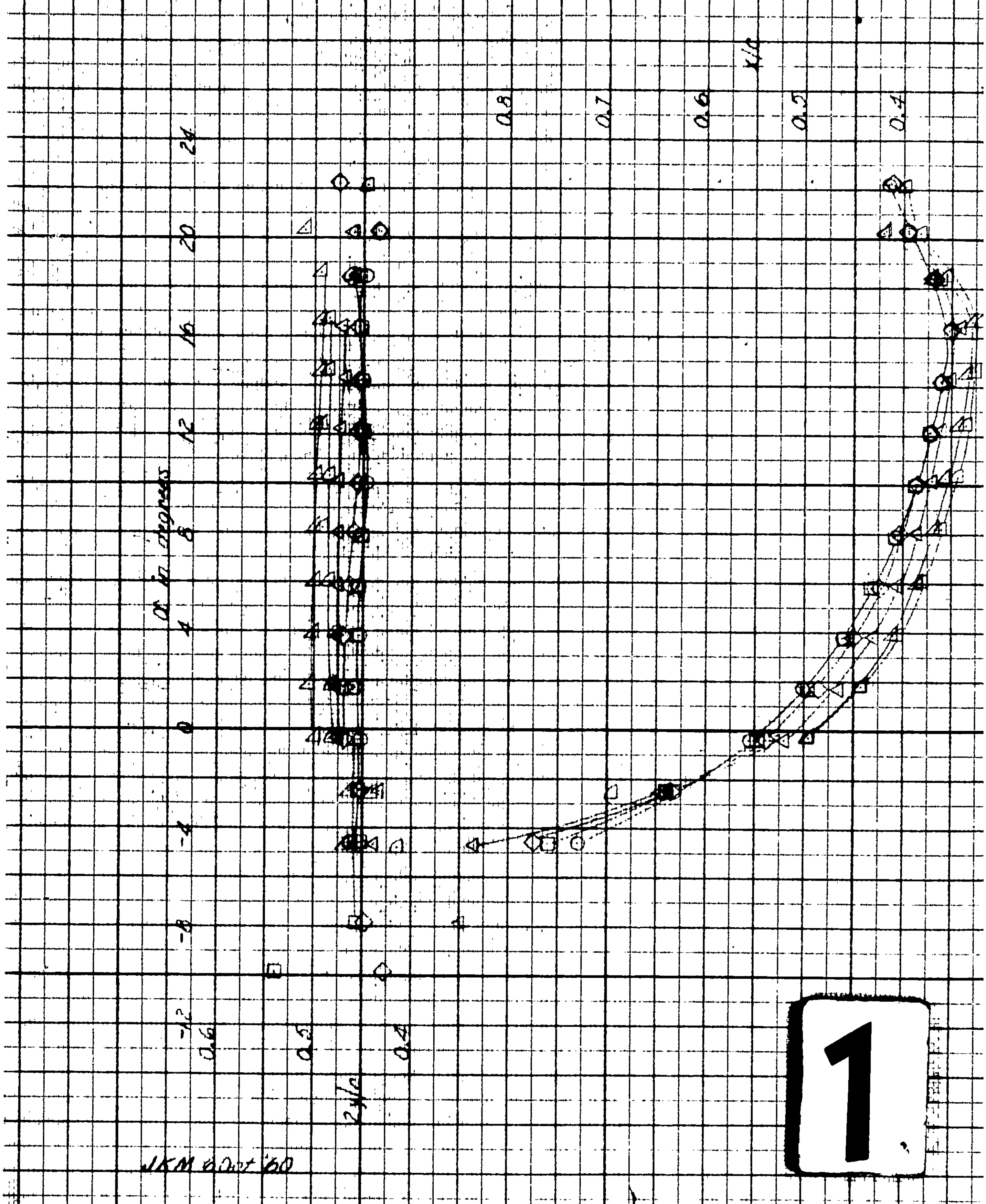
Figure 9 (Continued)

(b) $\theta_J = 0°$; $\delta_f = 15°$

4

FIGURE 9 b

AERO 1043



x/c
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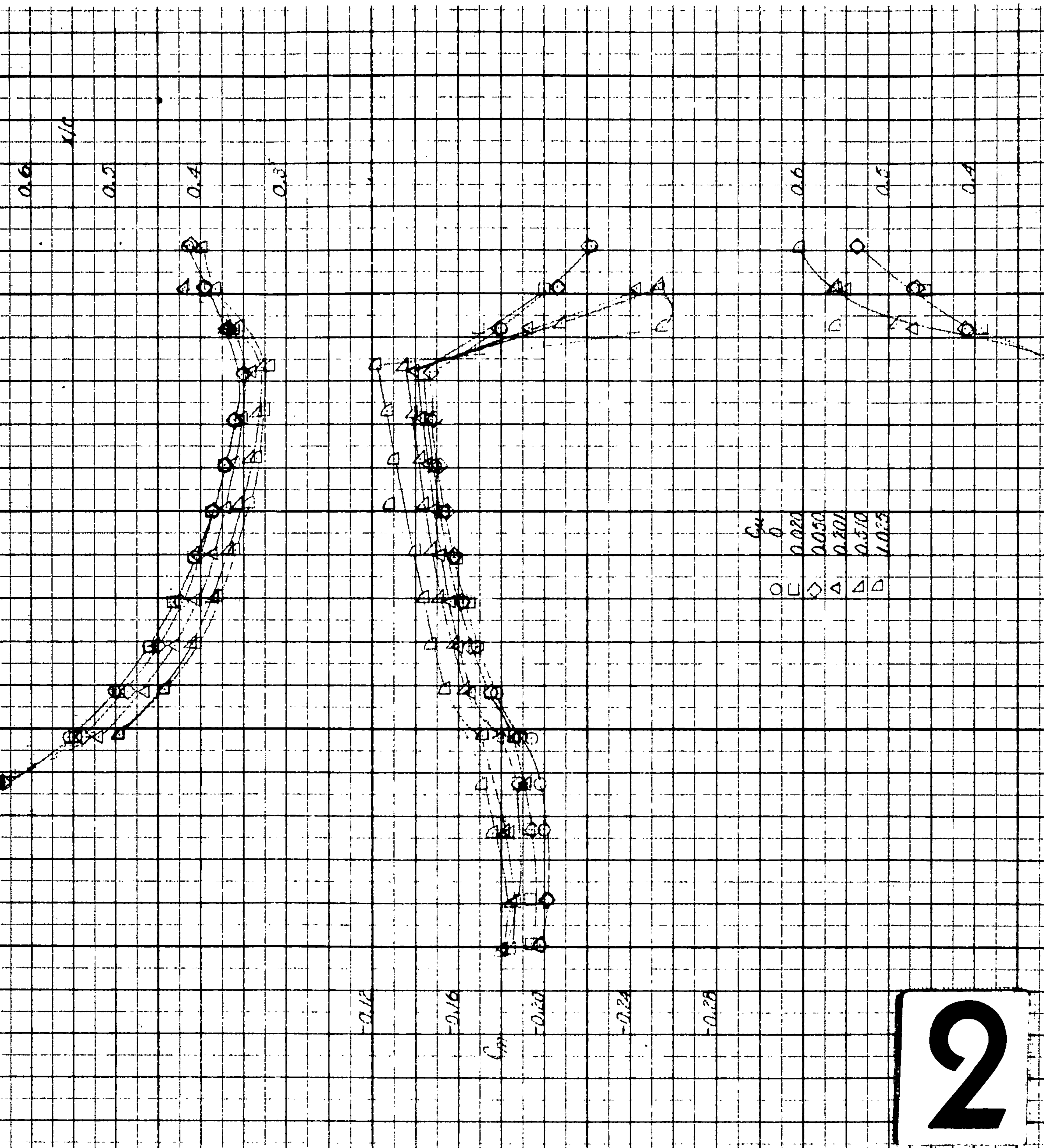
0.7
0.6
0.5
0.4
α in degrees
24
20
16
12
8
4
0
-4
-8
-12
0.6
0.5
0.4
z/c
JKM 6 Oct '60
1



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0.5
0.4
0.3
0.6
0.5
0.4
Cμ
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0.510
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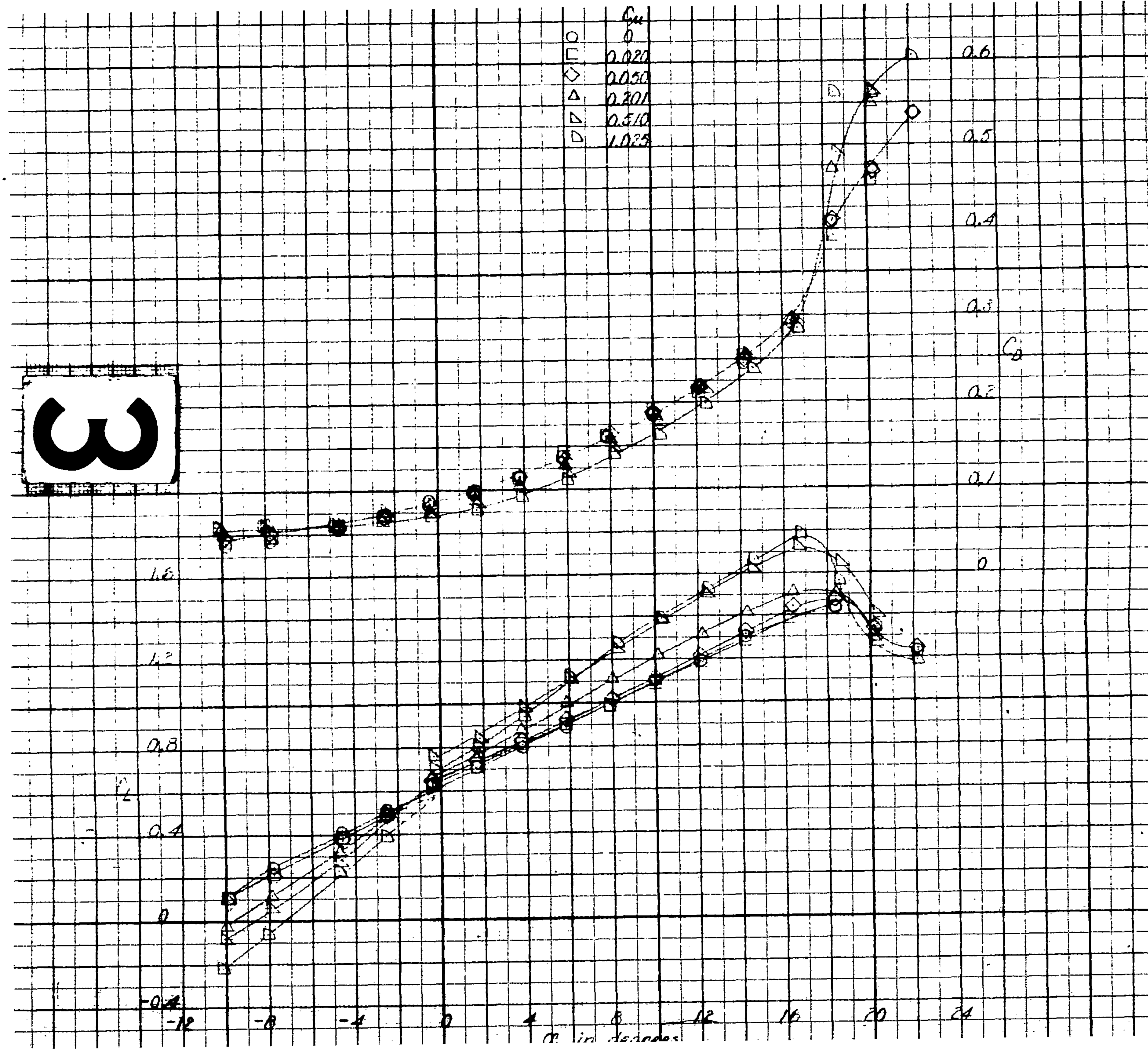
-0.20
-0.24
-0.28
Cm

2

3



C_μ
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0.050
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0
C_D
1.6
1.2
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α in degrees

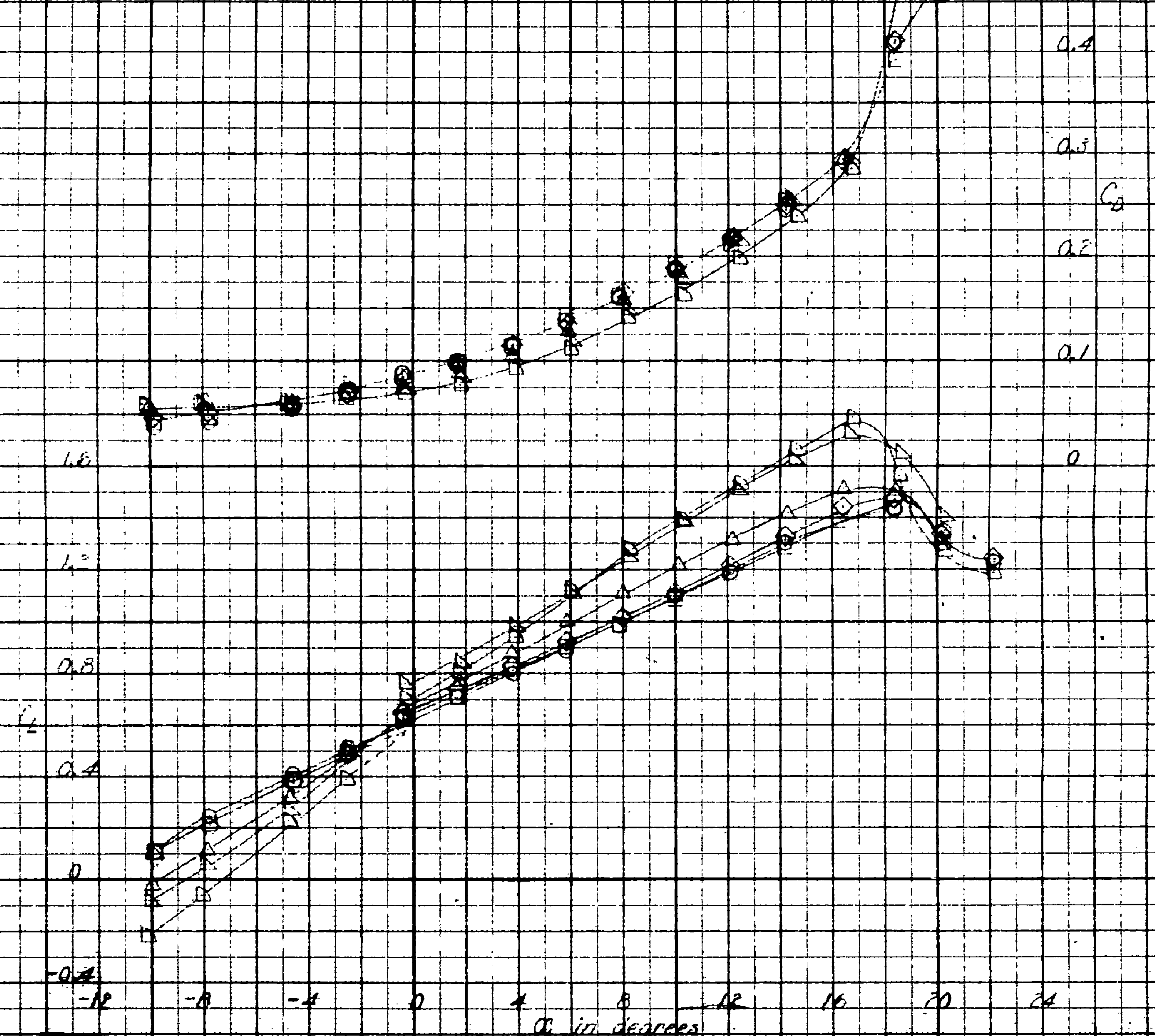
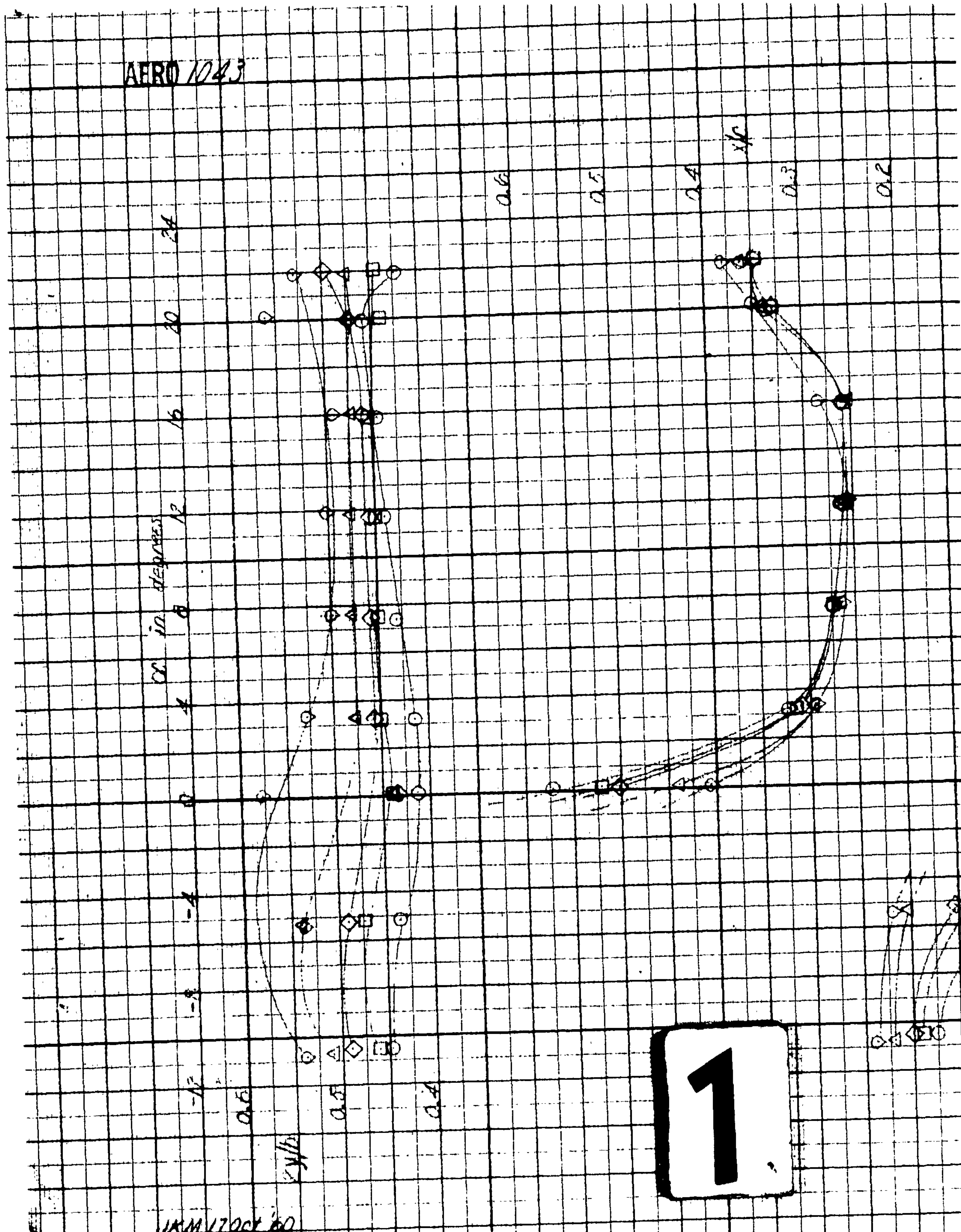


Figure 9 (Continued)

(c) $\theta_j = 0°$; $\delta_f = 30°$

4

FIGURE 9 c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α in degrees
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0.5
0.4
y/b
JKM 17 Oct 60
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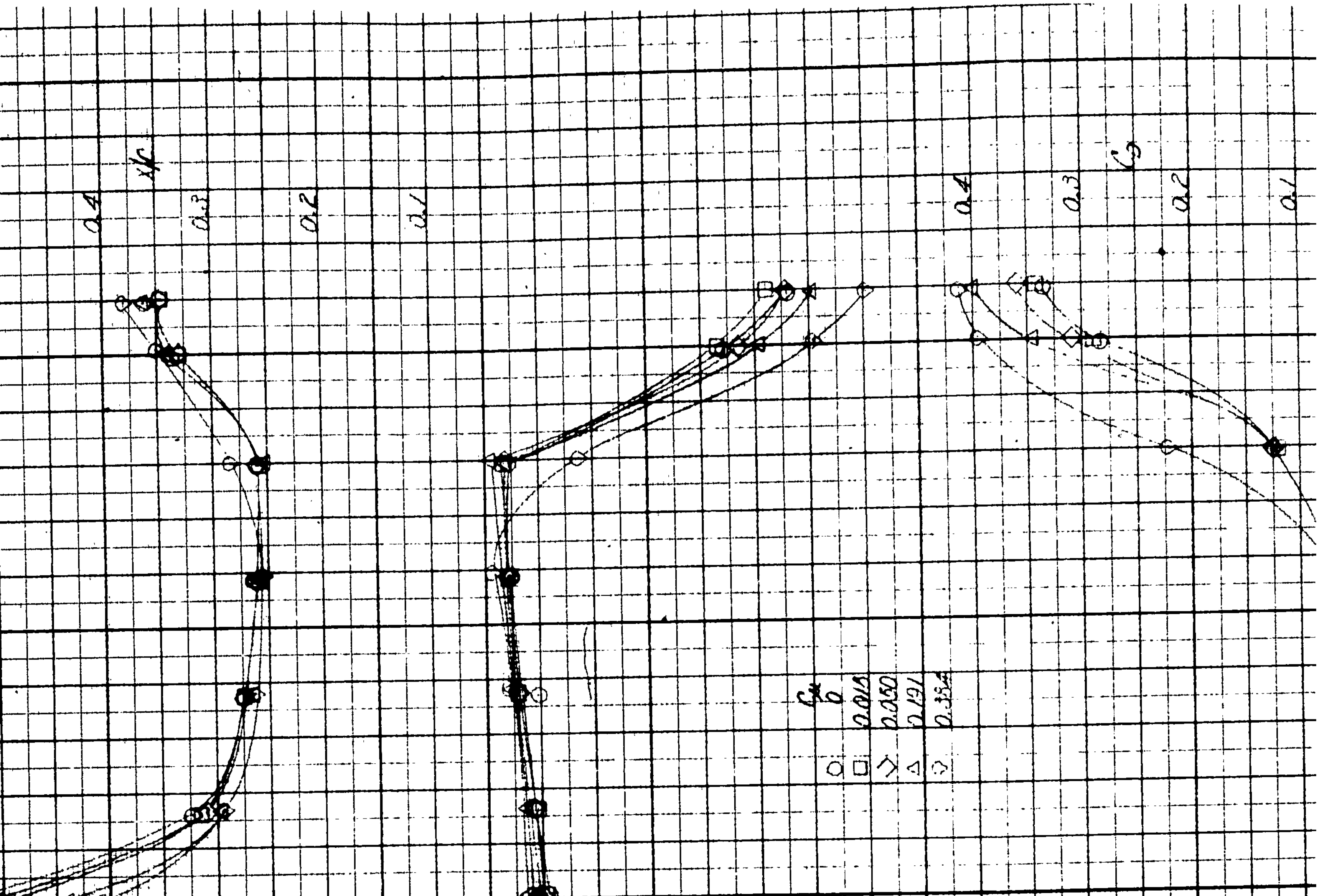
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C_m
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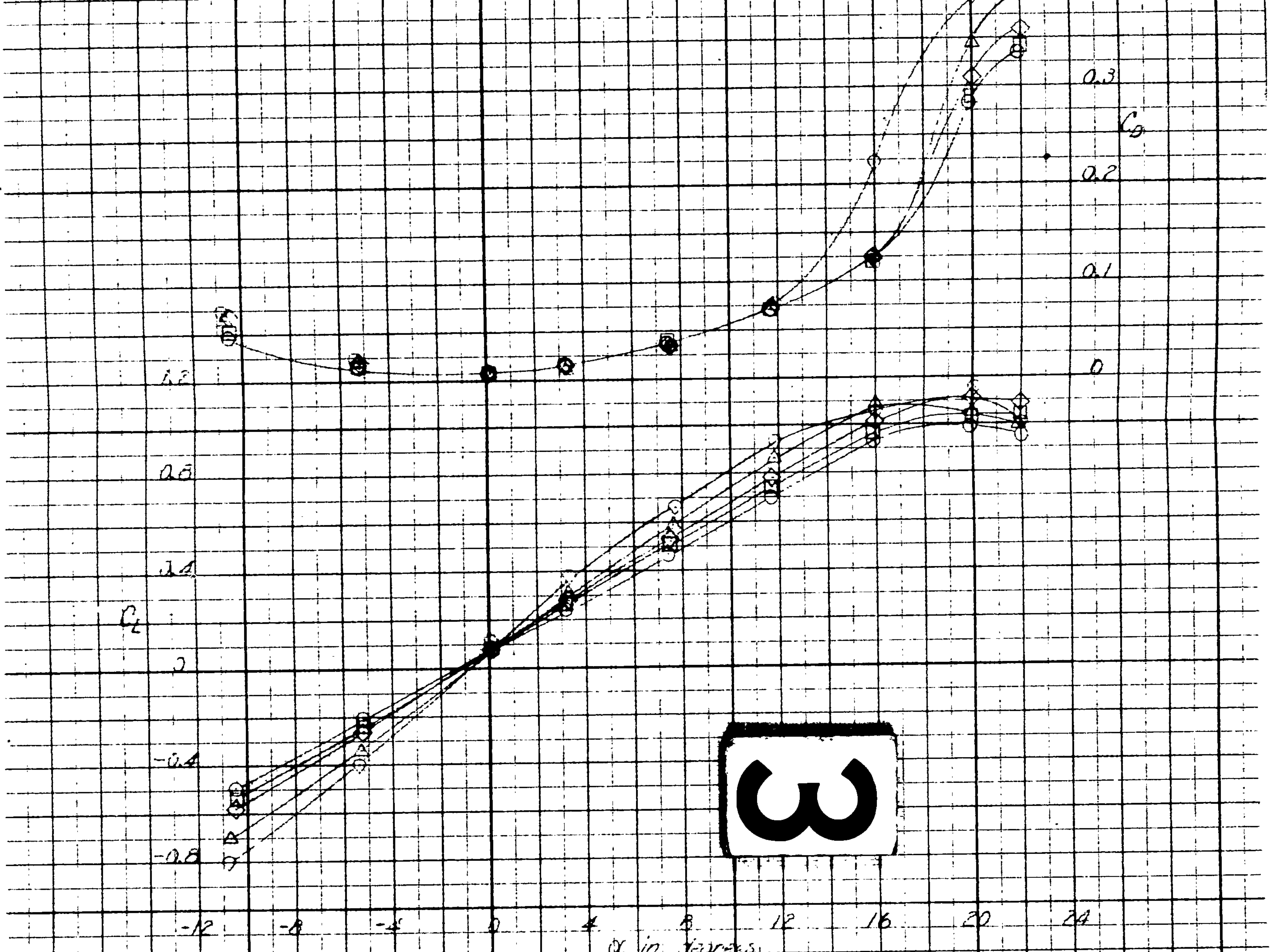
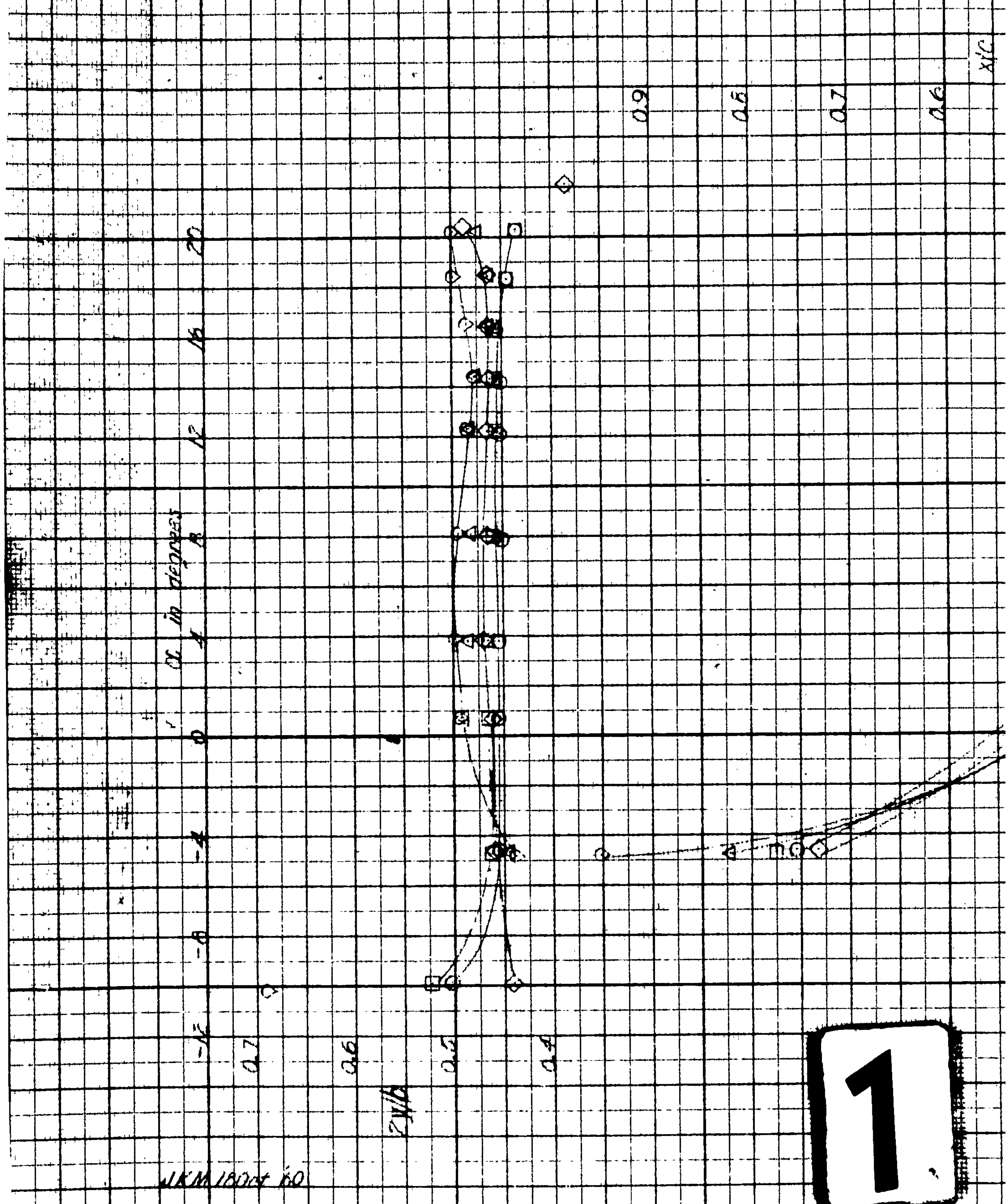


Figure 9 (Continued)

(d) $\theta_j = 38.6^\circ$; $\delta_f = 0^\circ$

AERO 1043



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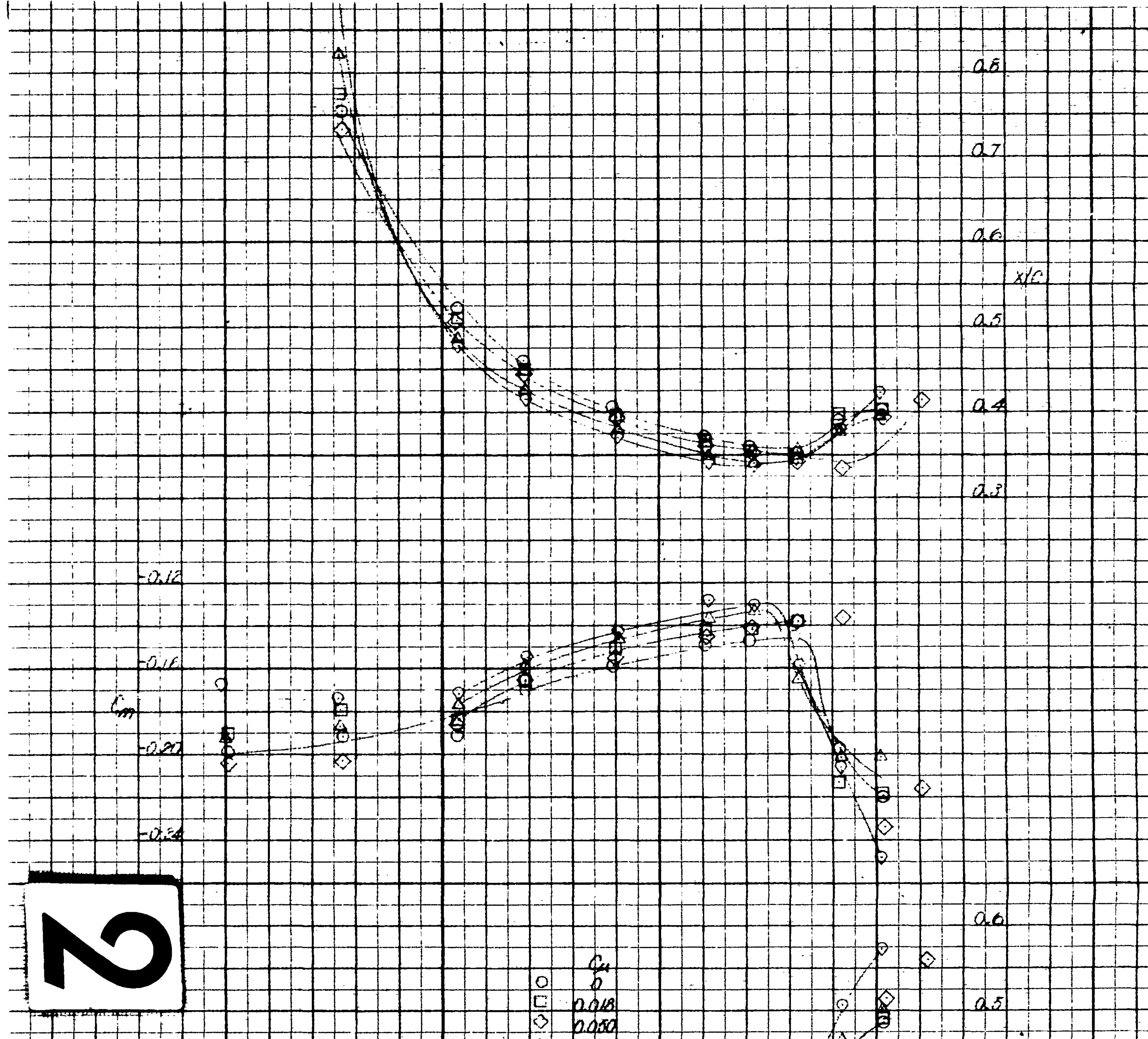

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x/c
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C_m
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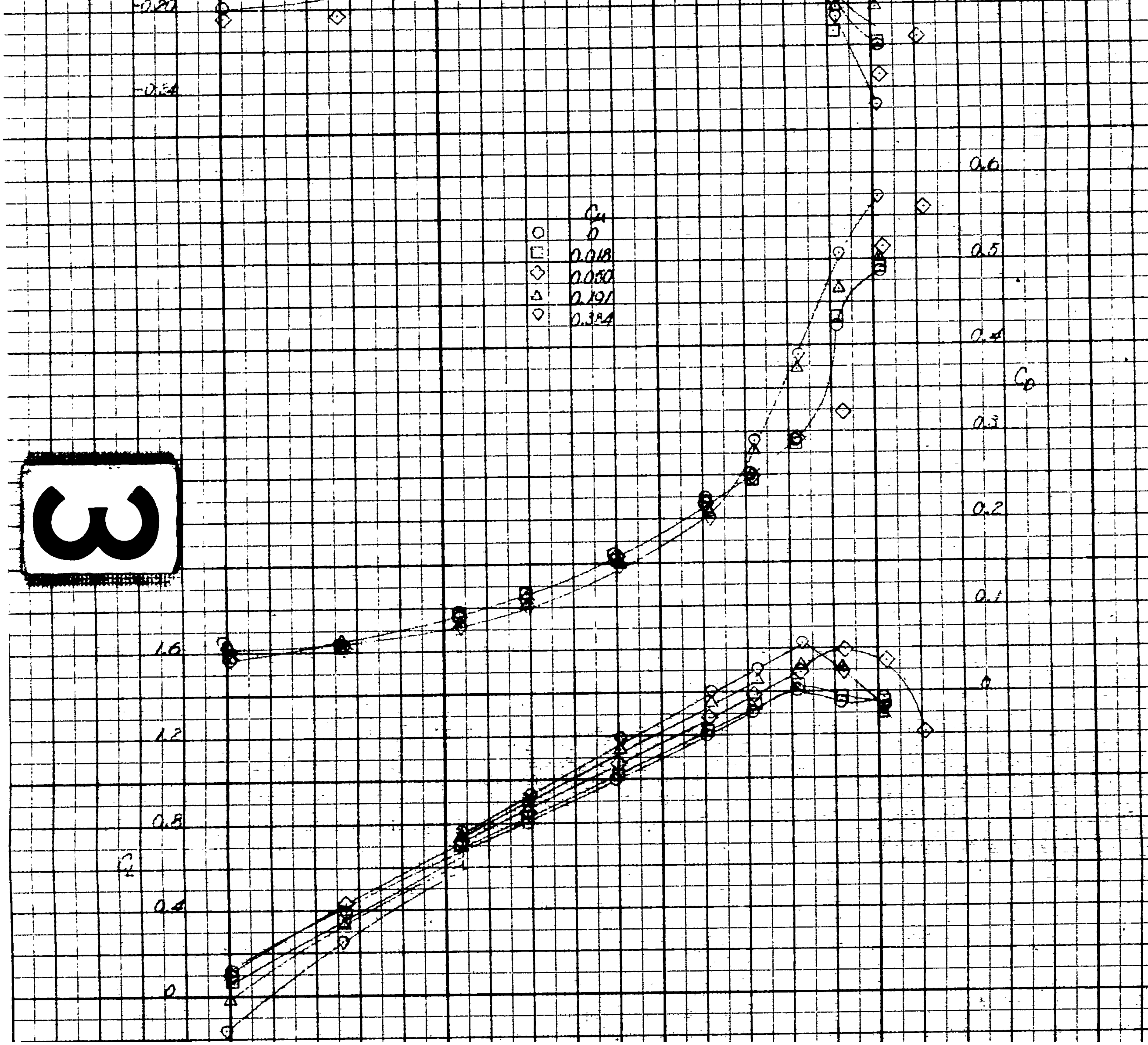

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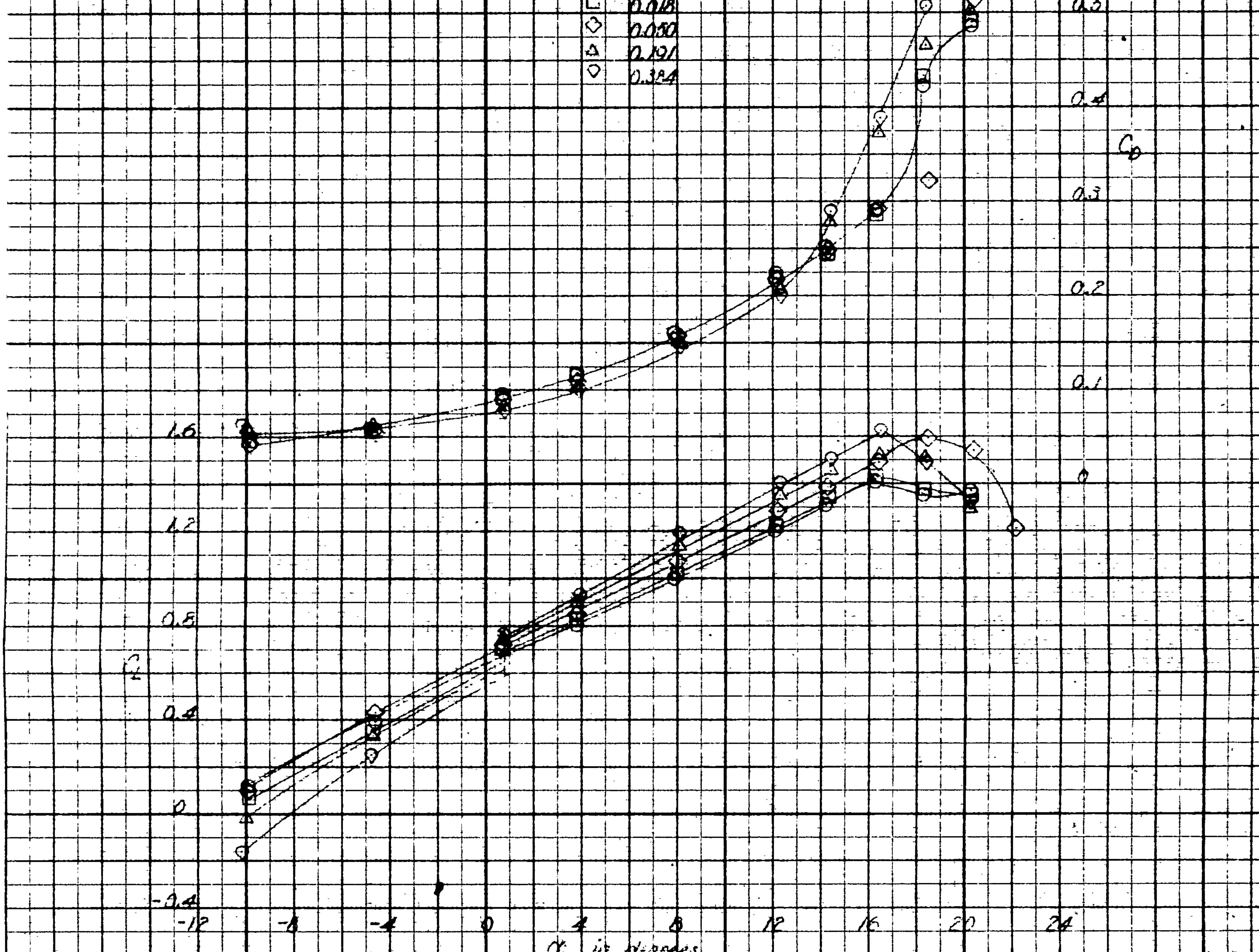
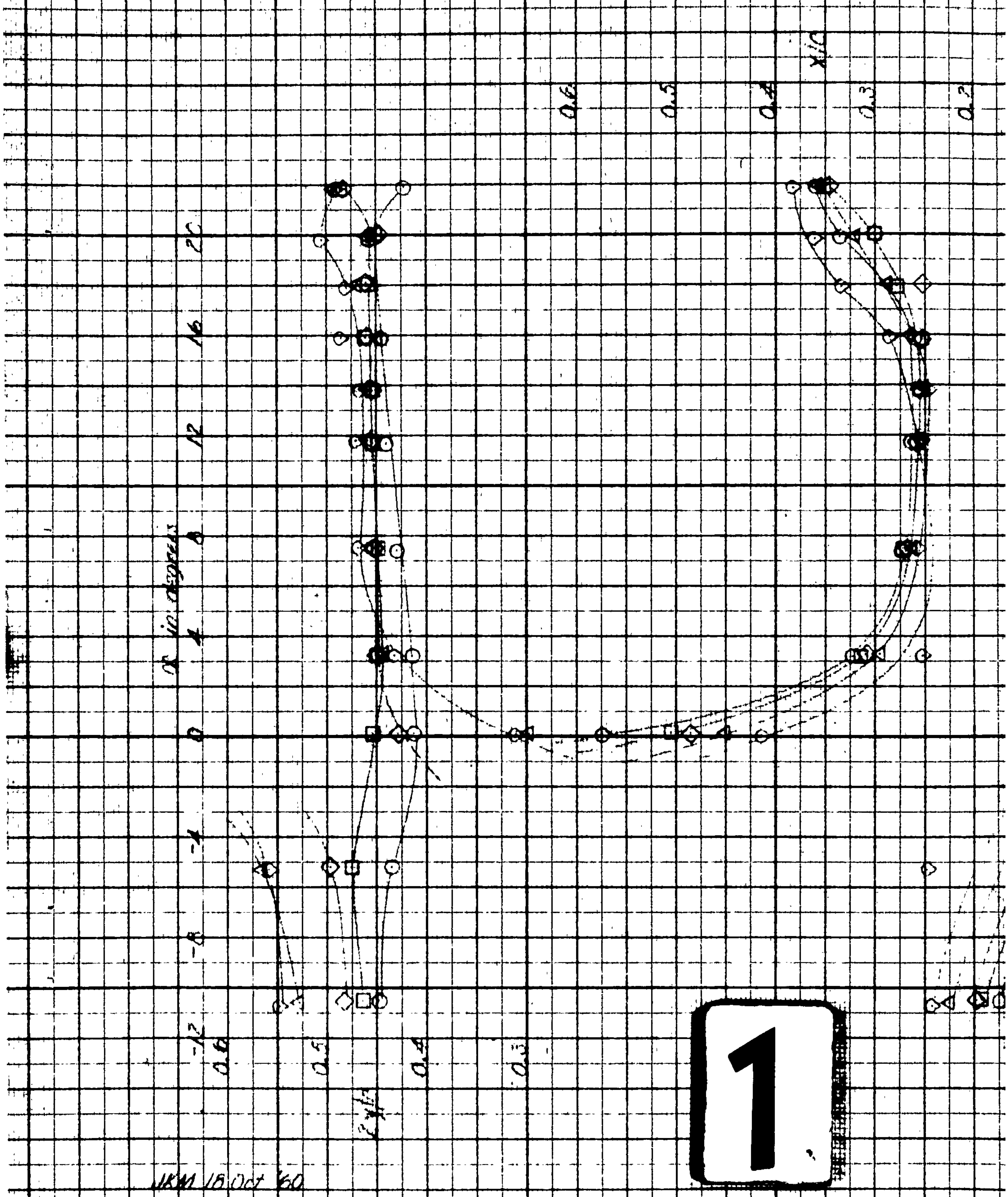


Figure 9 (Continued)

(e) $\theta_y = 38.6^\circ$; $\delta_f = 30^\circ$

FIGURE 9e

AERO 1043



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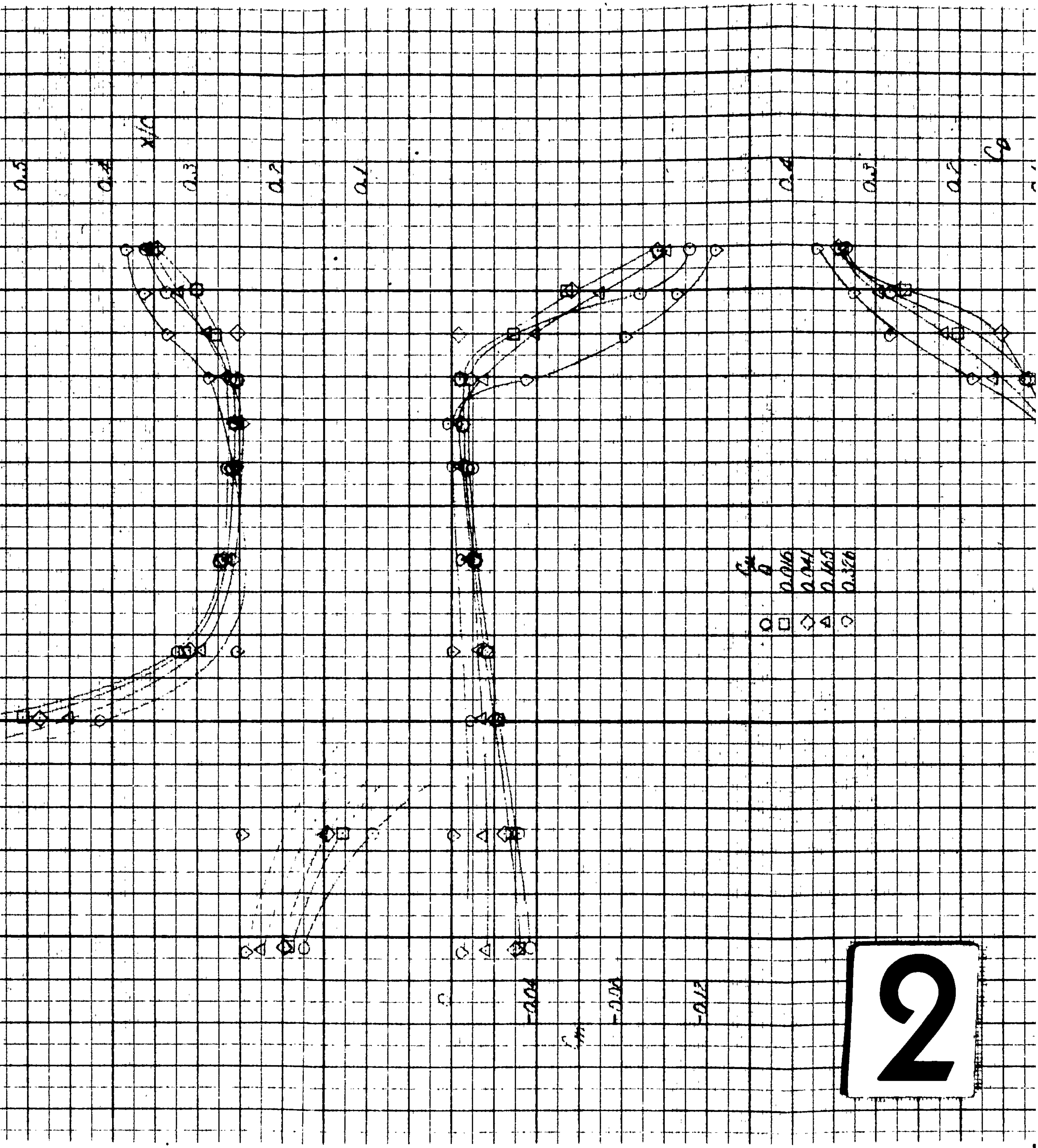
JKM 18 Oct '60



x/c
0.5
0.4
0.3
0.2
0.1
0.4
0.3
0.2
C_D
C_μ
0
0.016
0.041
0.165
0.376
-0.04
-0.08
-0.12
C_m

2

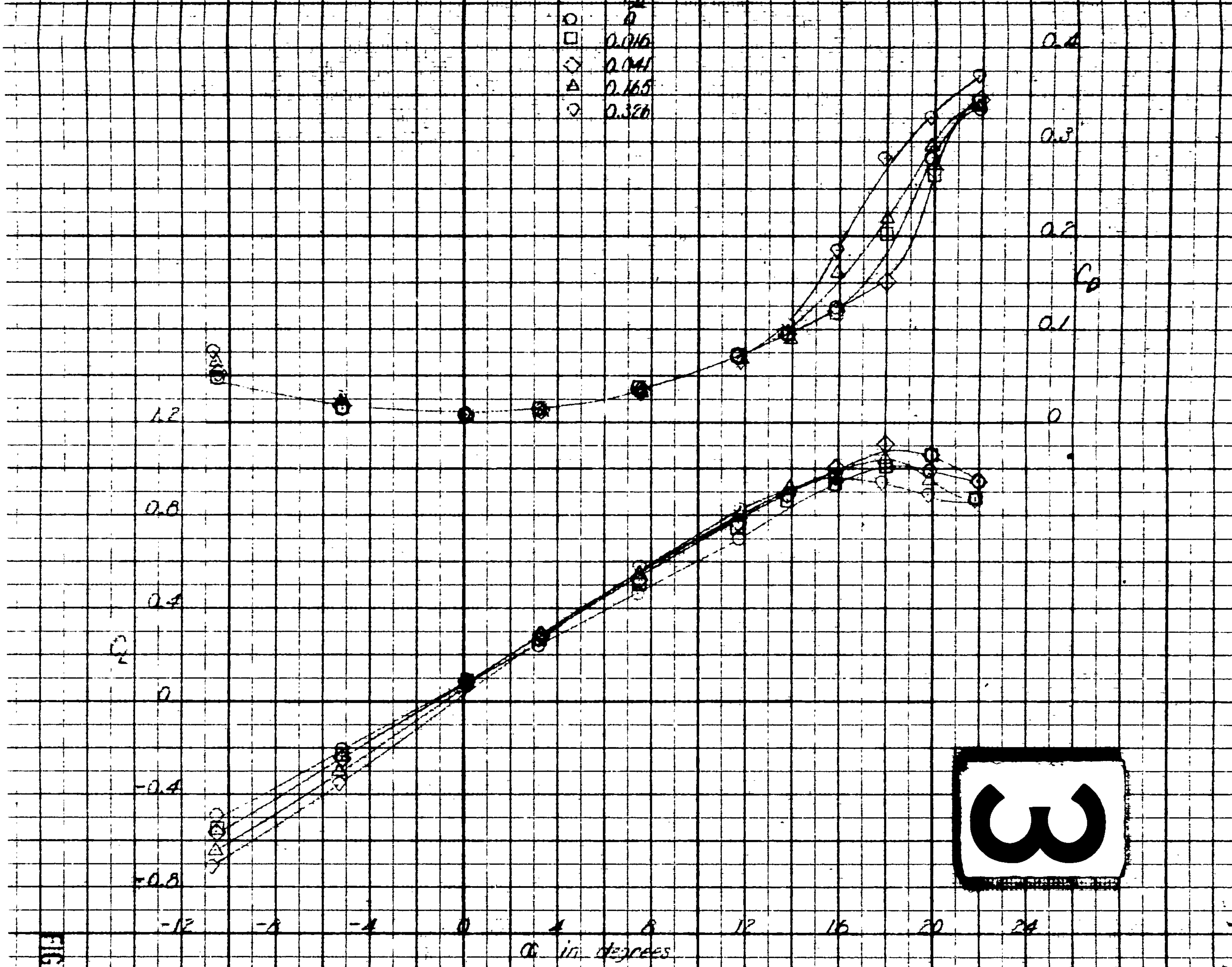
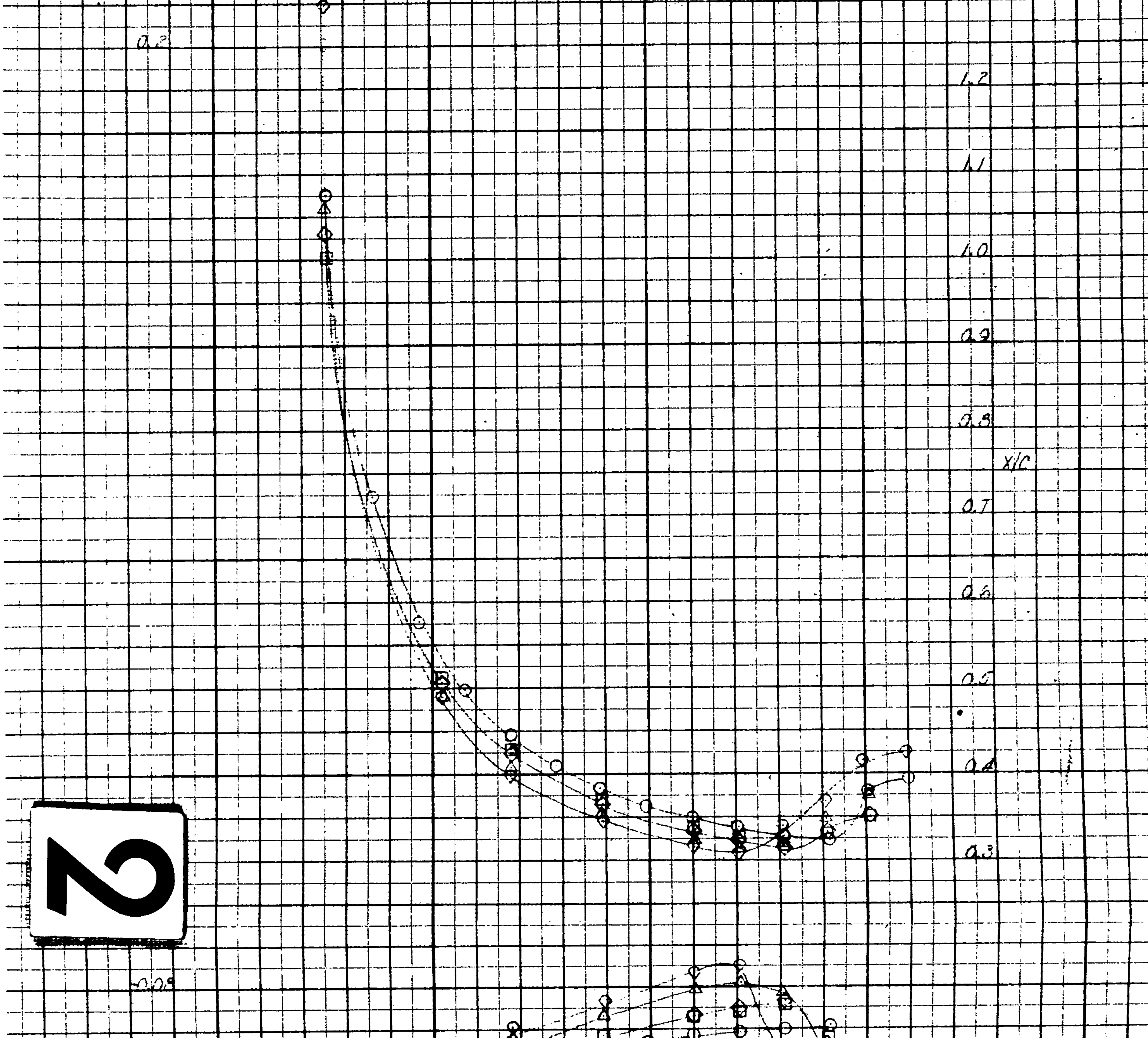


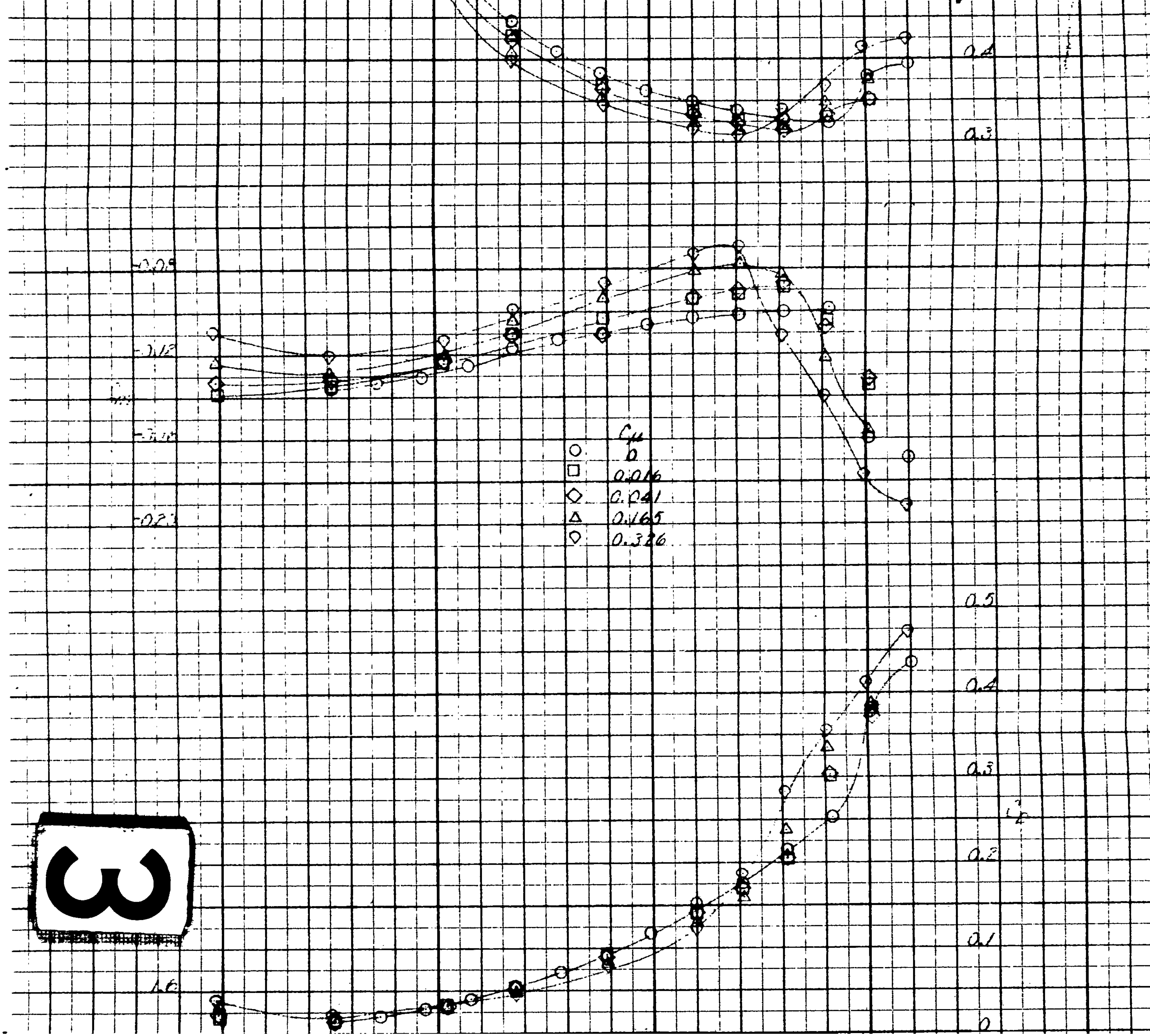
Figure 9 (Continued)

(f) $\theta_j = 72.9°$, $\delta_f = 0°$

FIGURE 9 f

AERO 1043


0.2
1.2
1.1
1.0
0.9
0.8
X/C
0.7
0.6
0.5
0.4
0.3
-0.05
2


Cμ
0
0.016
0.241
0.165
0.326
0.5
0.4
0.3
0.2
0.1
0

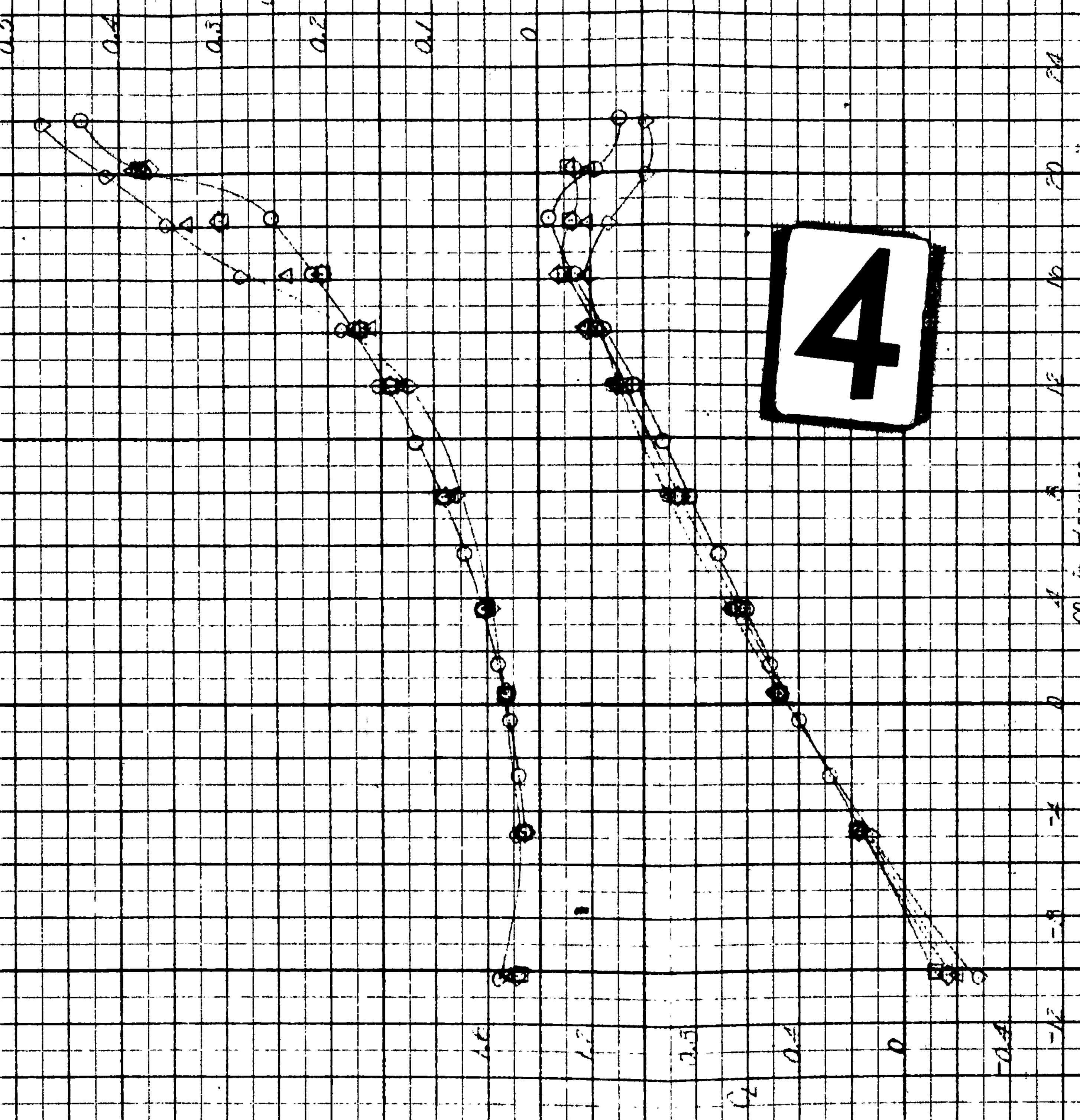
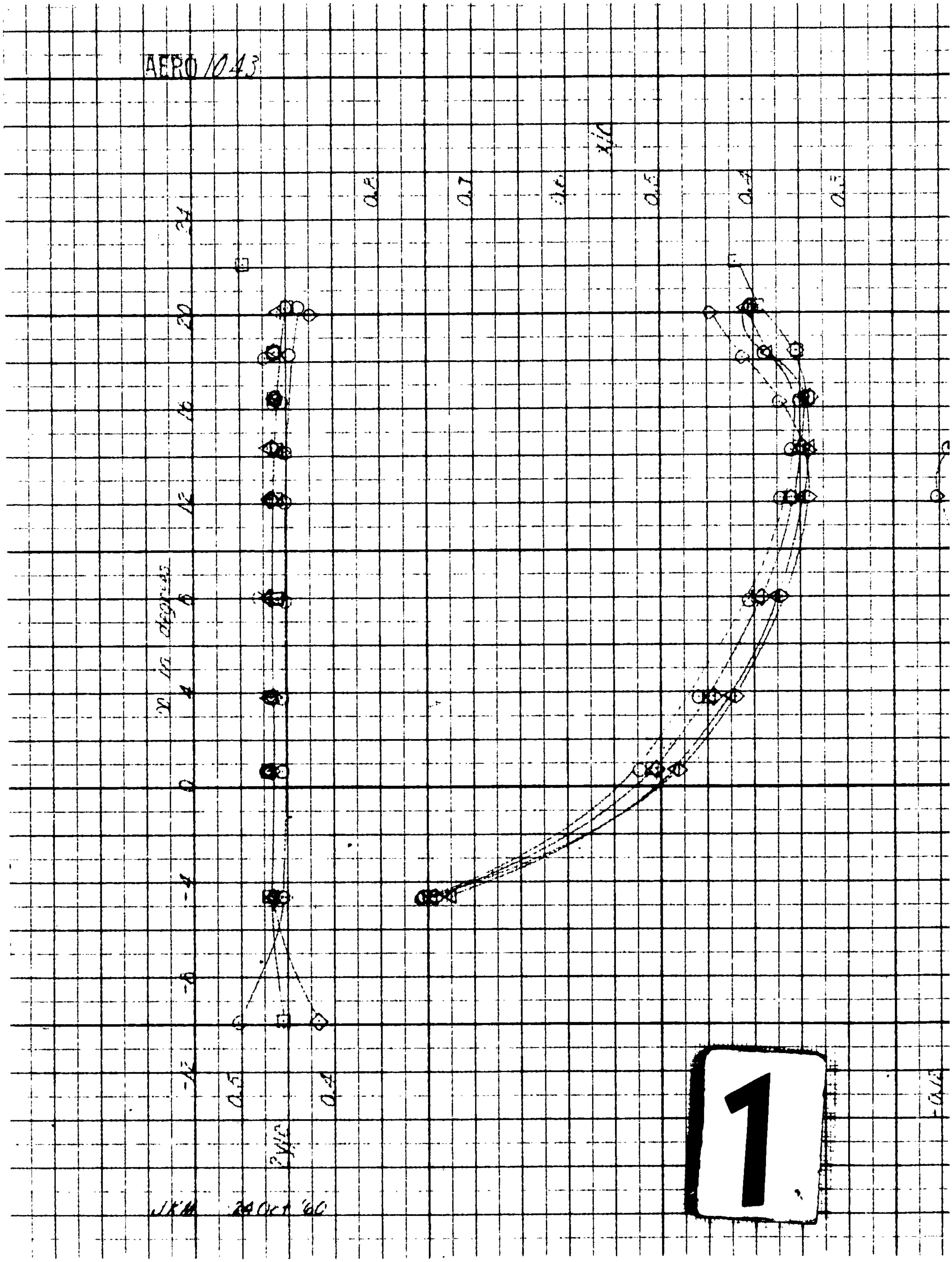
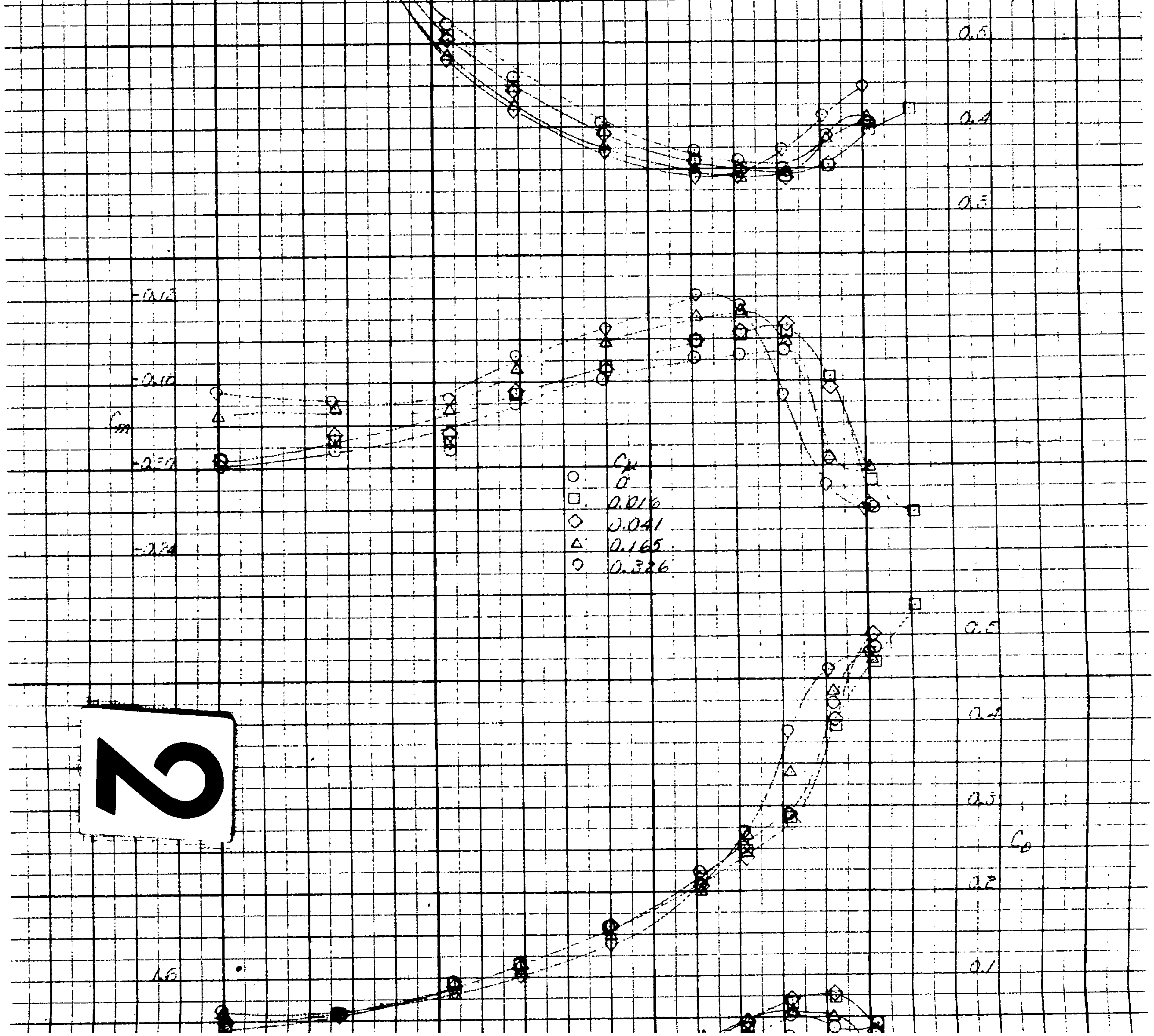


Figure 9 (Continued)

(g) $\theta_J = 72.9°$, $\delta_f = 15°$

FIGURE 9 g


AERO 1043
x/c
0.8
0.7
0.6
0.5
0.4
0.3
24
20
16
12
8
4
0
-4
-8
-12
α in degrees
0.5
0.4
JKM 24 Oct '60
1



0.5
0.4
0.3
-0.12
-0.16
-0.20
-0.24
C_m
C_μ
0
0.016
0.041
0.165
0.326
0.5
0.4
0.3
0.2
0.1
C_D
1.6
2

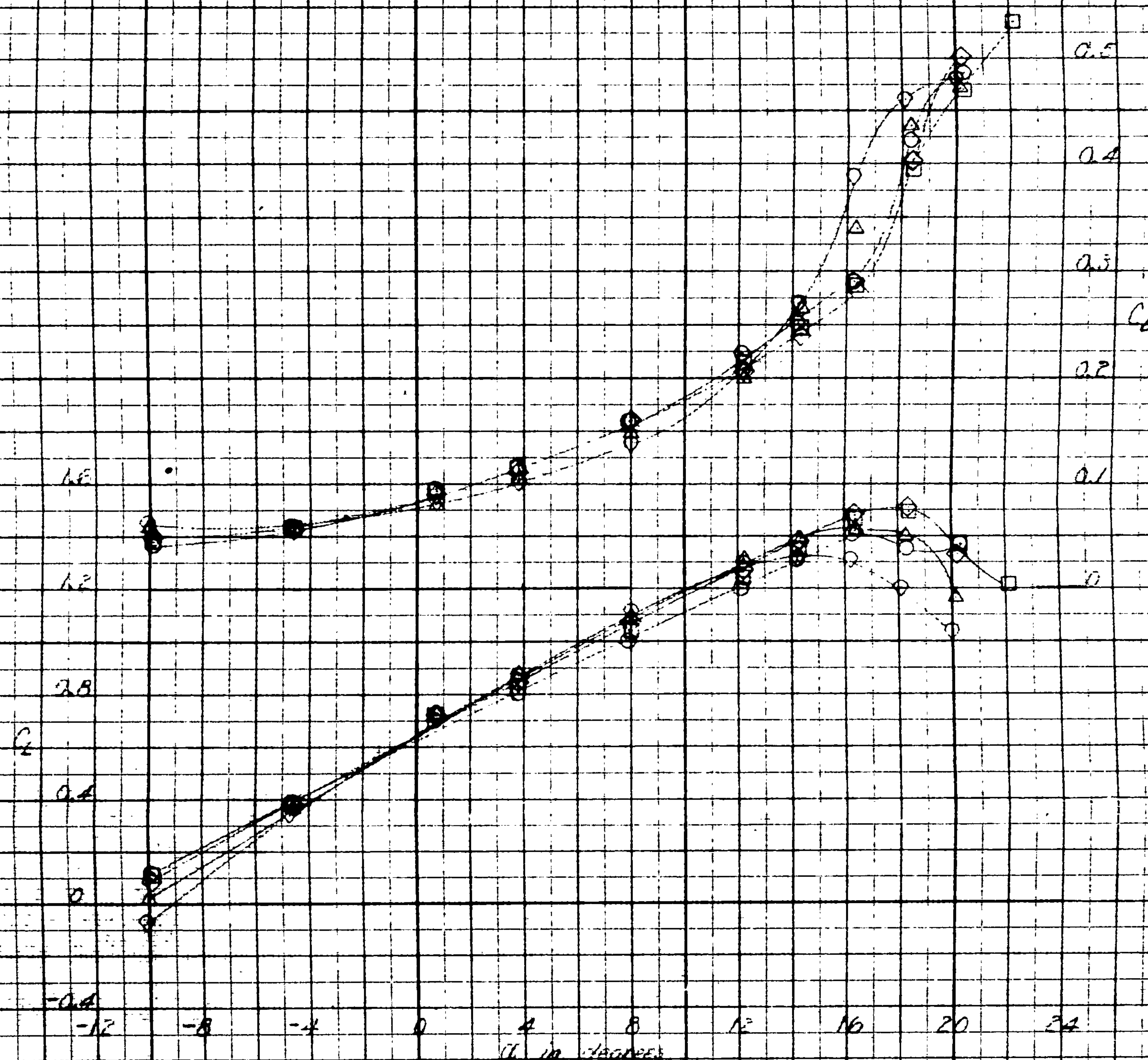


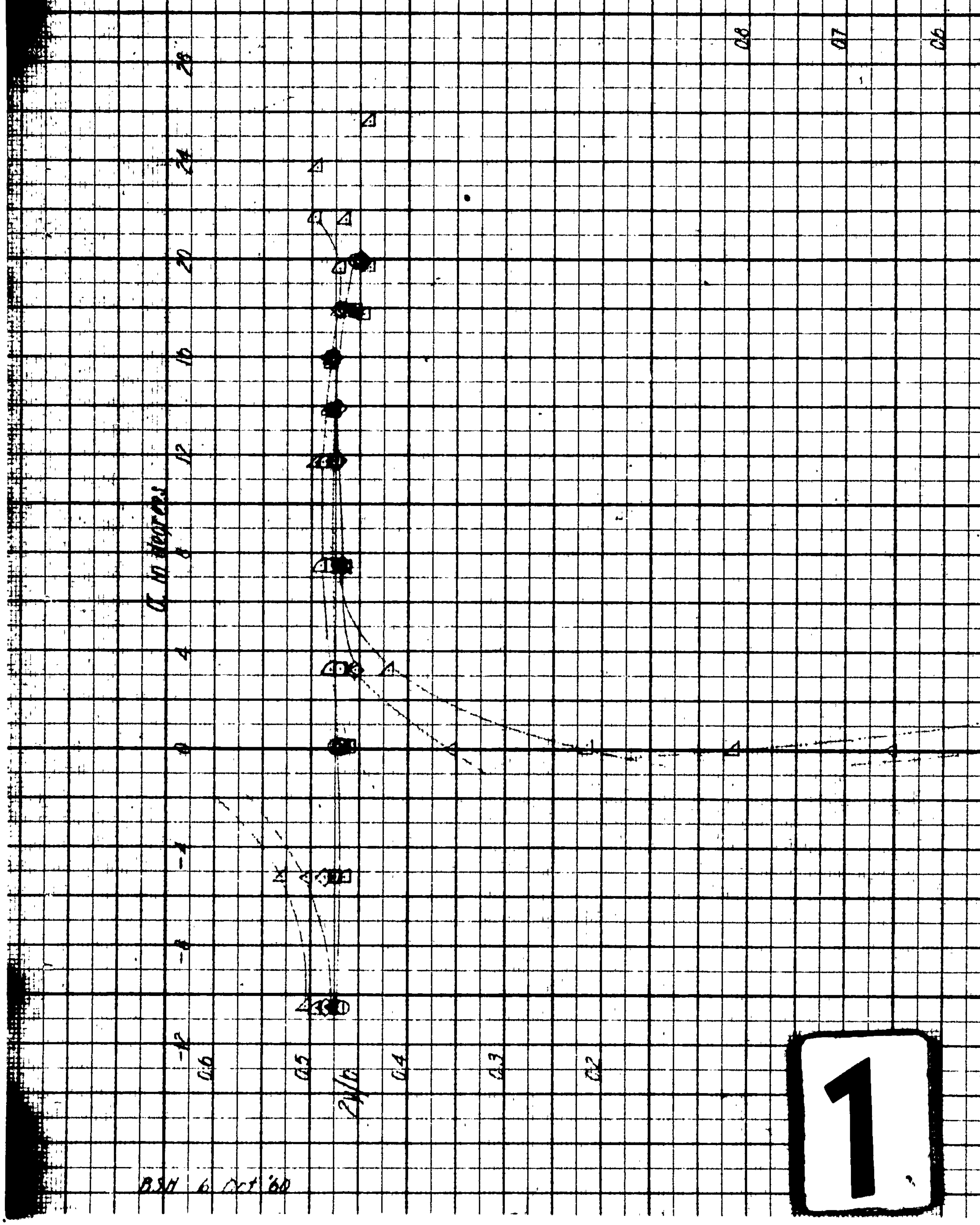
Figure 9 (Concluded)

(h) $\theta_j = 72.9$; $\delta_f = 30°$

3

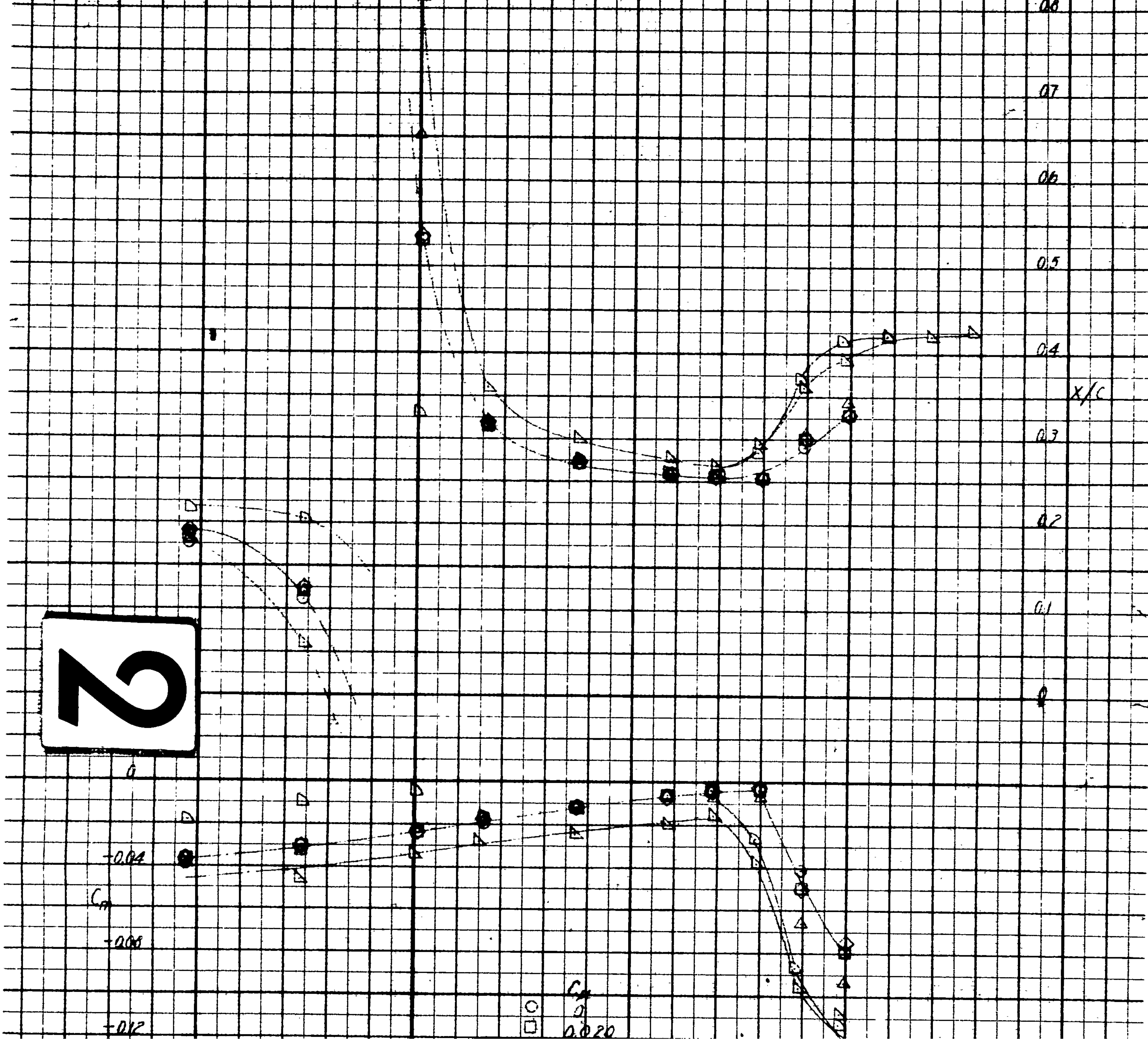
FIGURE 9 h

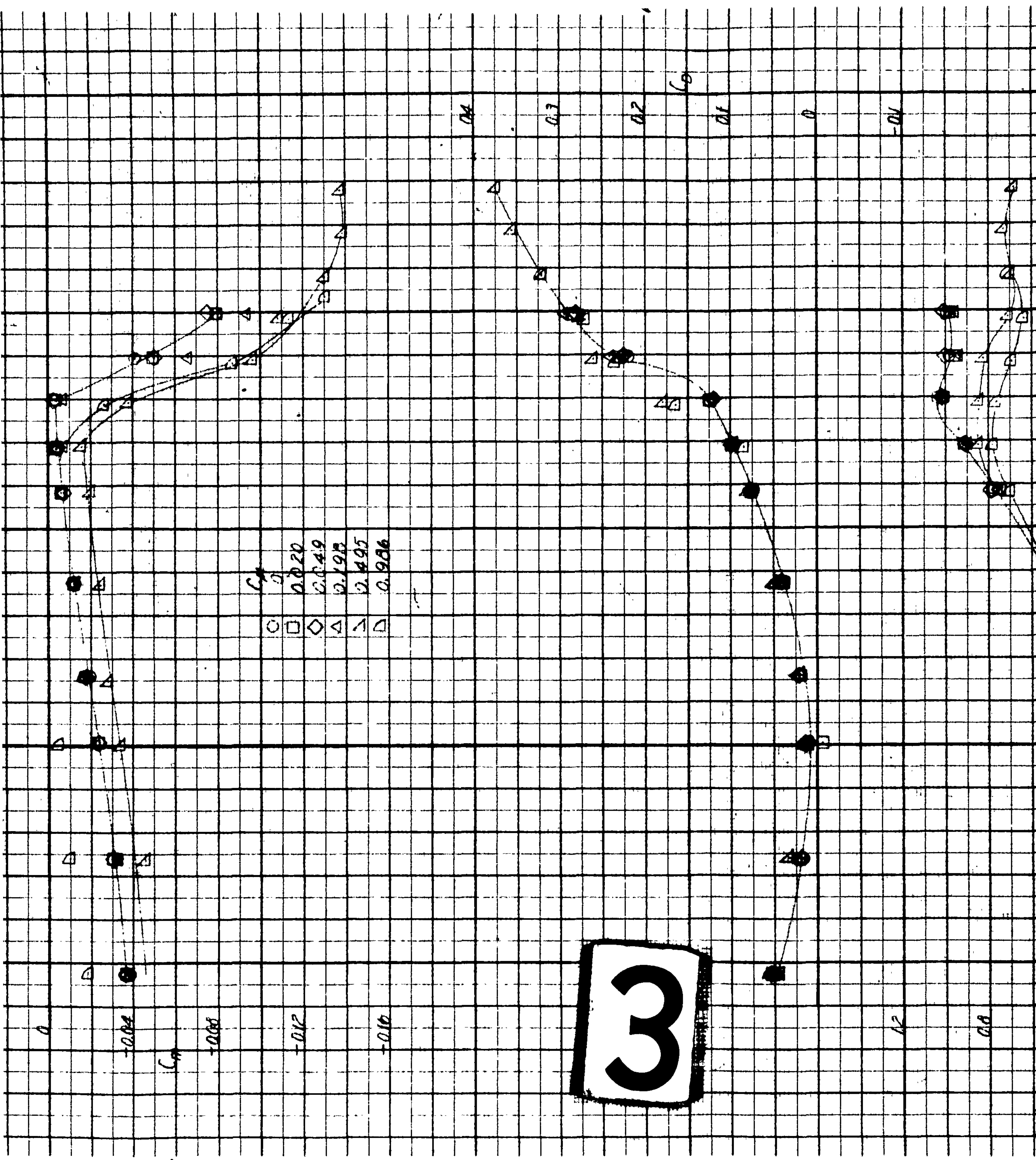
AERO 1043



α in degrees
-12
-8
-4
0
4
8
12
16
20
24
28
2y/b
0.6
0.5
0.4
0.3
0.2
0.8
0.7
0.6
B.S.H. 6 Oct '60

1


x/c
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
C_m
0
-0.04
-0.08
-0.12
C_μ
0
0.020
2



C_D
0.4
0.3
0.2
0.1
0
-0.1
C_L
0
0.020
0.049
0.198
0.495
0.986
0
-0.04
-0.08
-0.12
-0.16
C_m
1.2
0.8
3

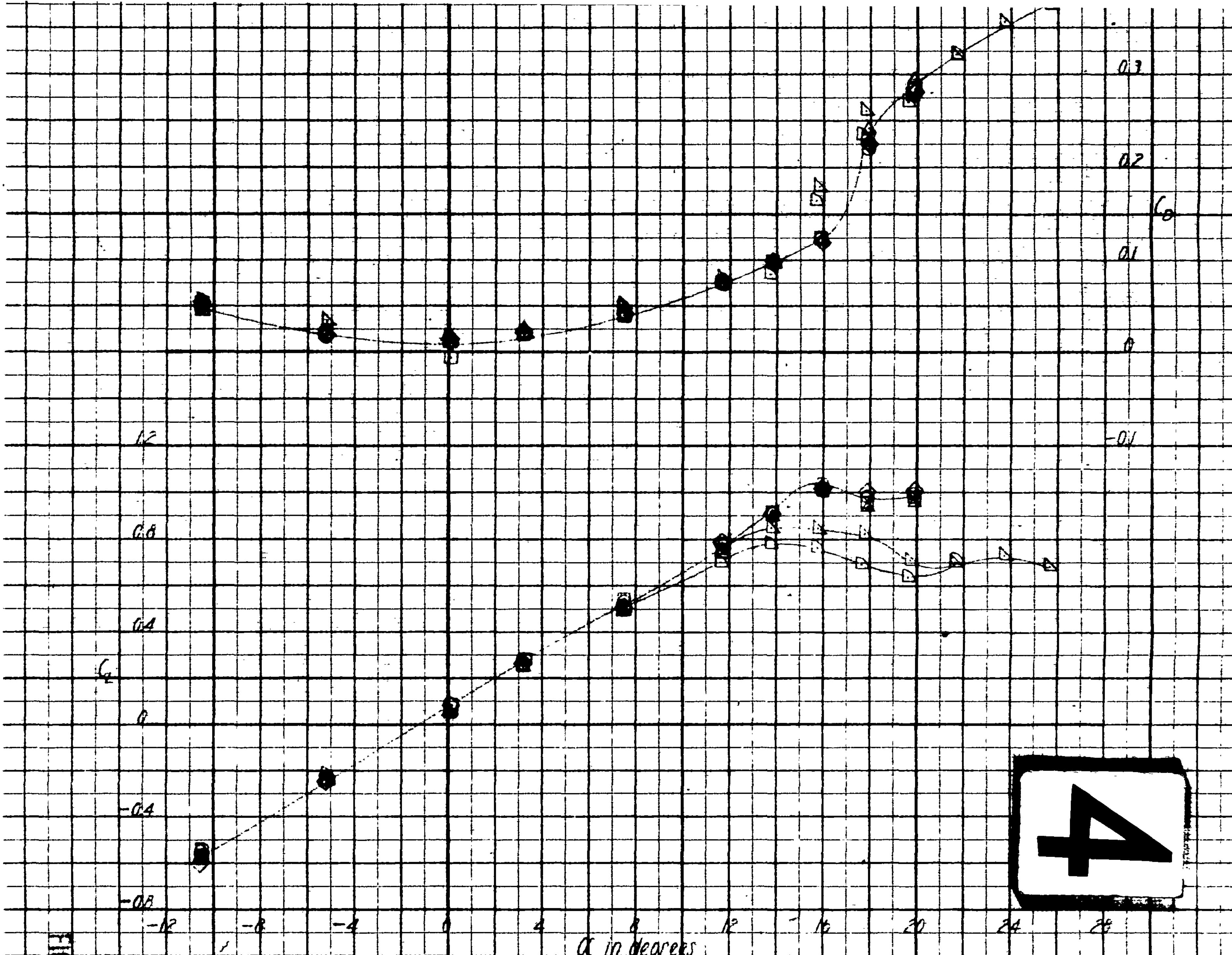
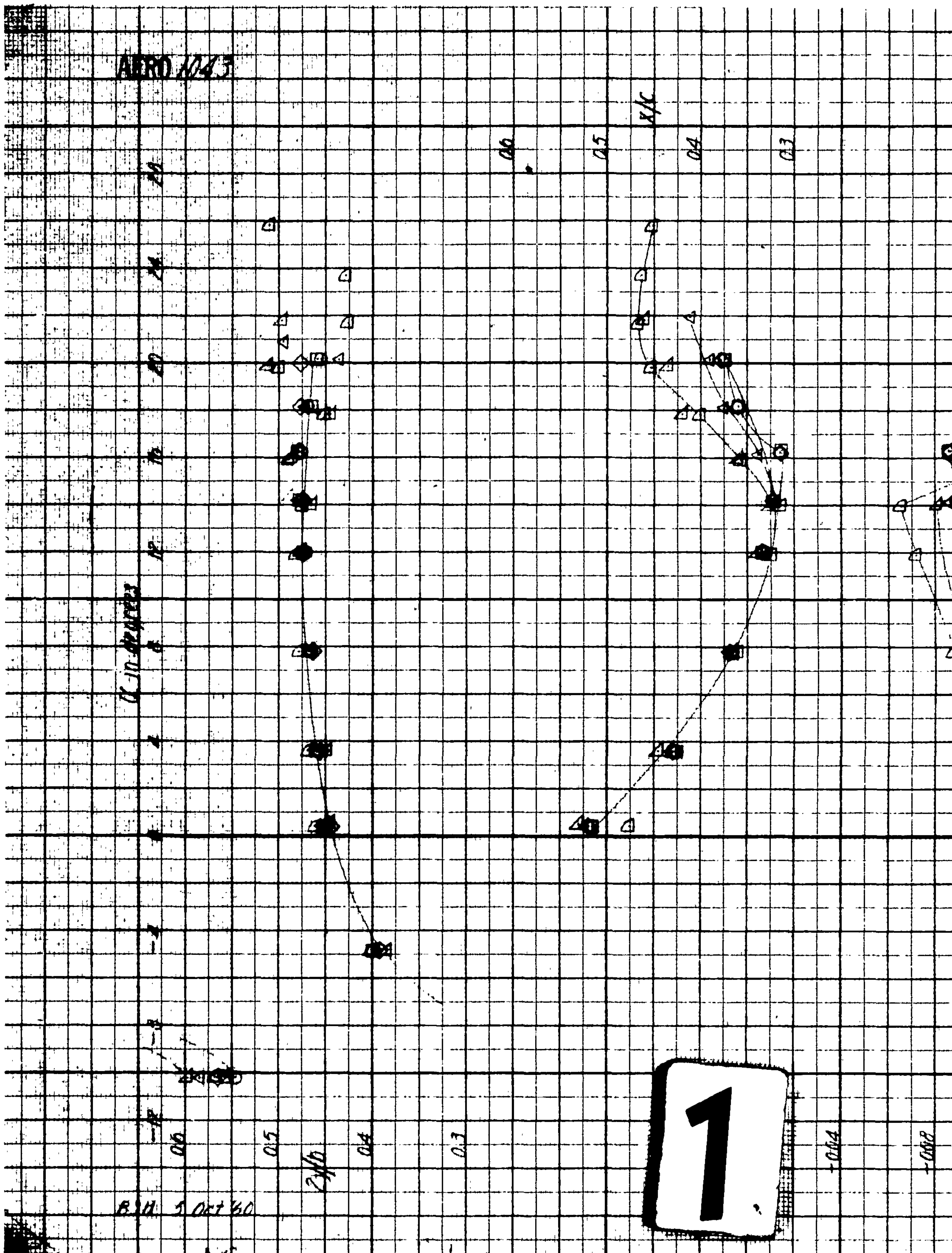
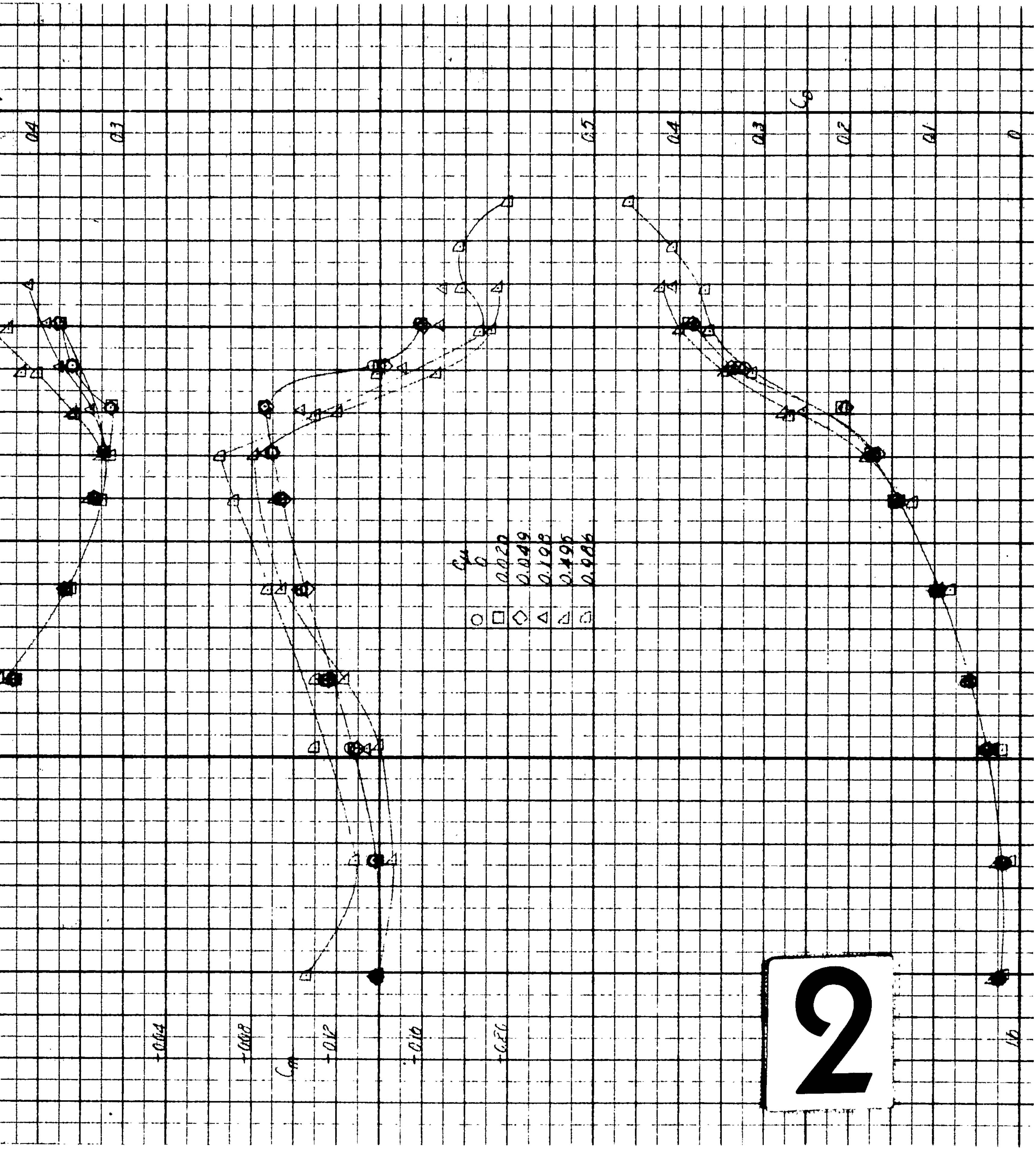


Figure 10 - Effect of Chordwise Blowing on the Aerodynamic Characteristics of the Wing

(a) $\theta_J = 0°$; $\delta_f = 0°$

FIGURE 10 a


AERO 1043
x/c
α in degrees
2y/b
B.J.H. 5 Oct '40
1



C_D
0.5
0.4
0.3
0.2
0.1
0
C_μ
0
0.020
0.049
0.198
0.495
0.986
C_m
+0.04
+0.08
+0.12
+0.16
+0.20
2

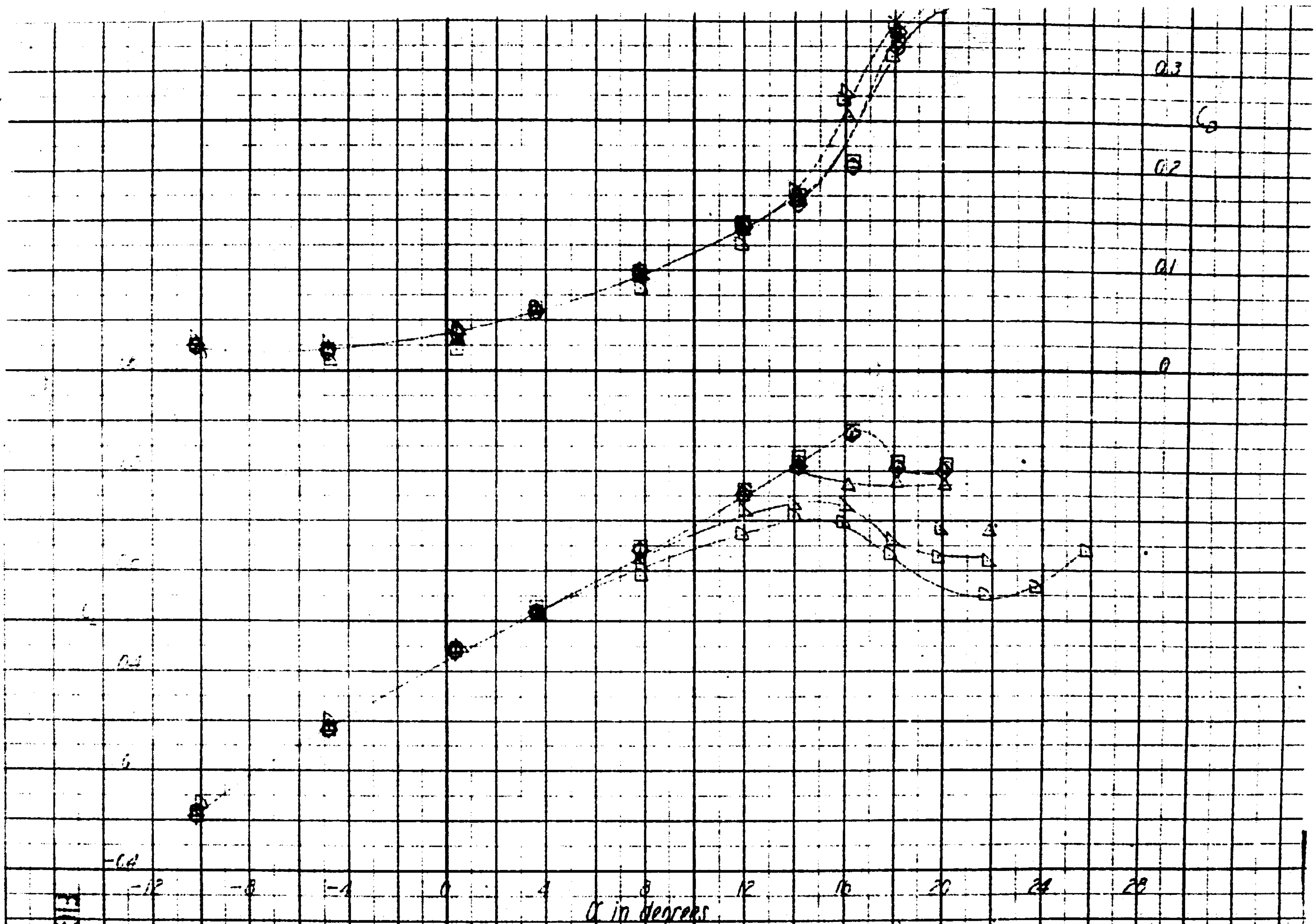
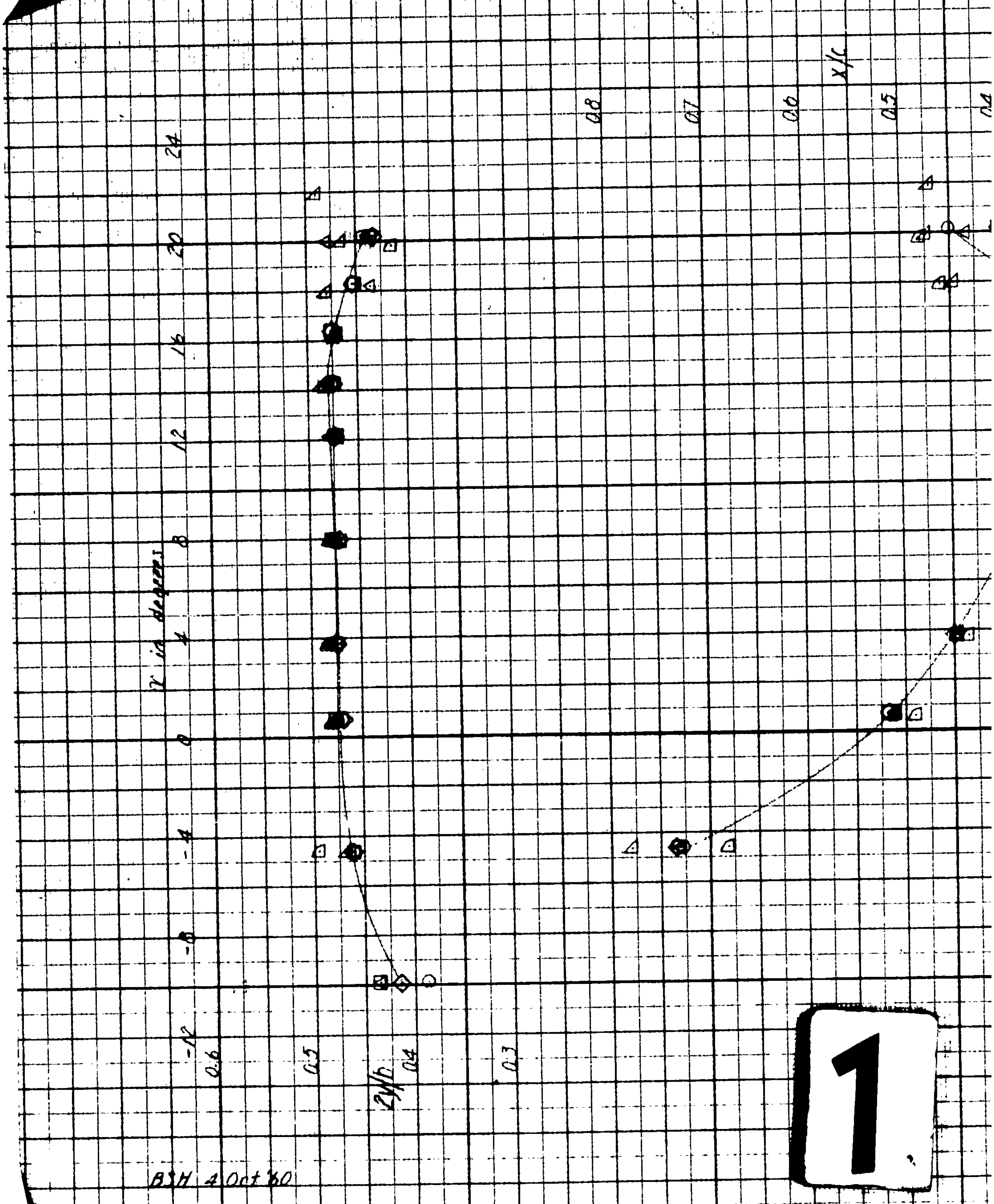


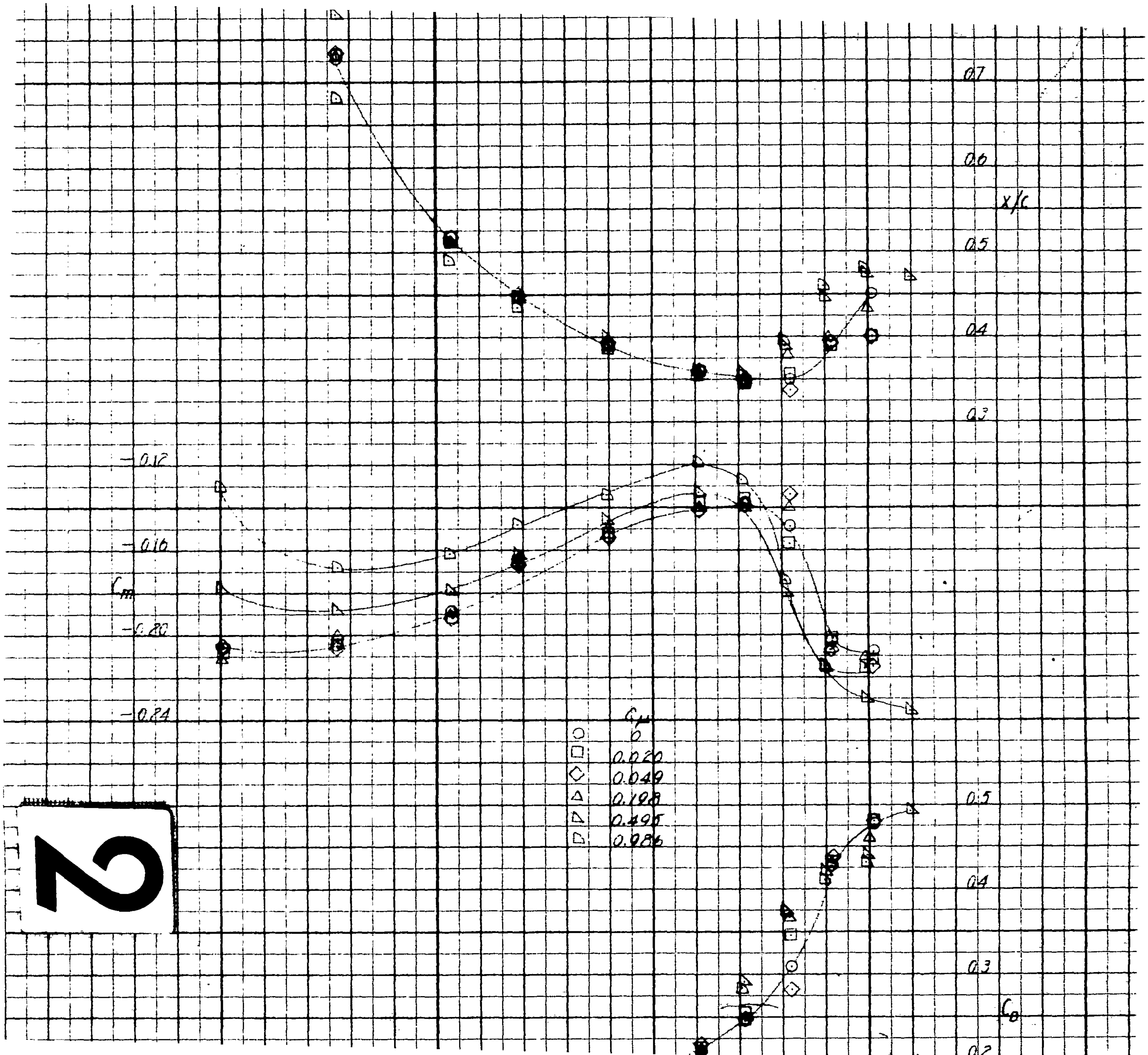
Figure 10 (Continued)

(b) $\theta_j = 0°$; $\delta_f = 15°$

FIGURE 10 b

AERO 1043


x/c
0.8
0.7
0.6
0.5
0.4
γ in degrees
24
20
16
12
8
4
0
-4
-8
-12
2y/b
0.6
0.5
0.4
0.3
BSH 4 Oct '60
1



0.7
0.6
x/c
0.5
0.4
0.3
−0.12
−0.16
C_m
−0.20
−0.24
C_μ
0
0.020
0.049
0.198
0.495
0.986
0.5
0.4
0.3
C_D
0.2
2

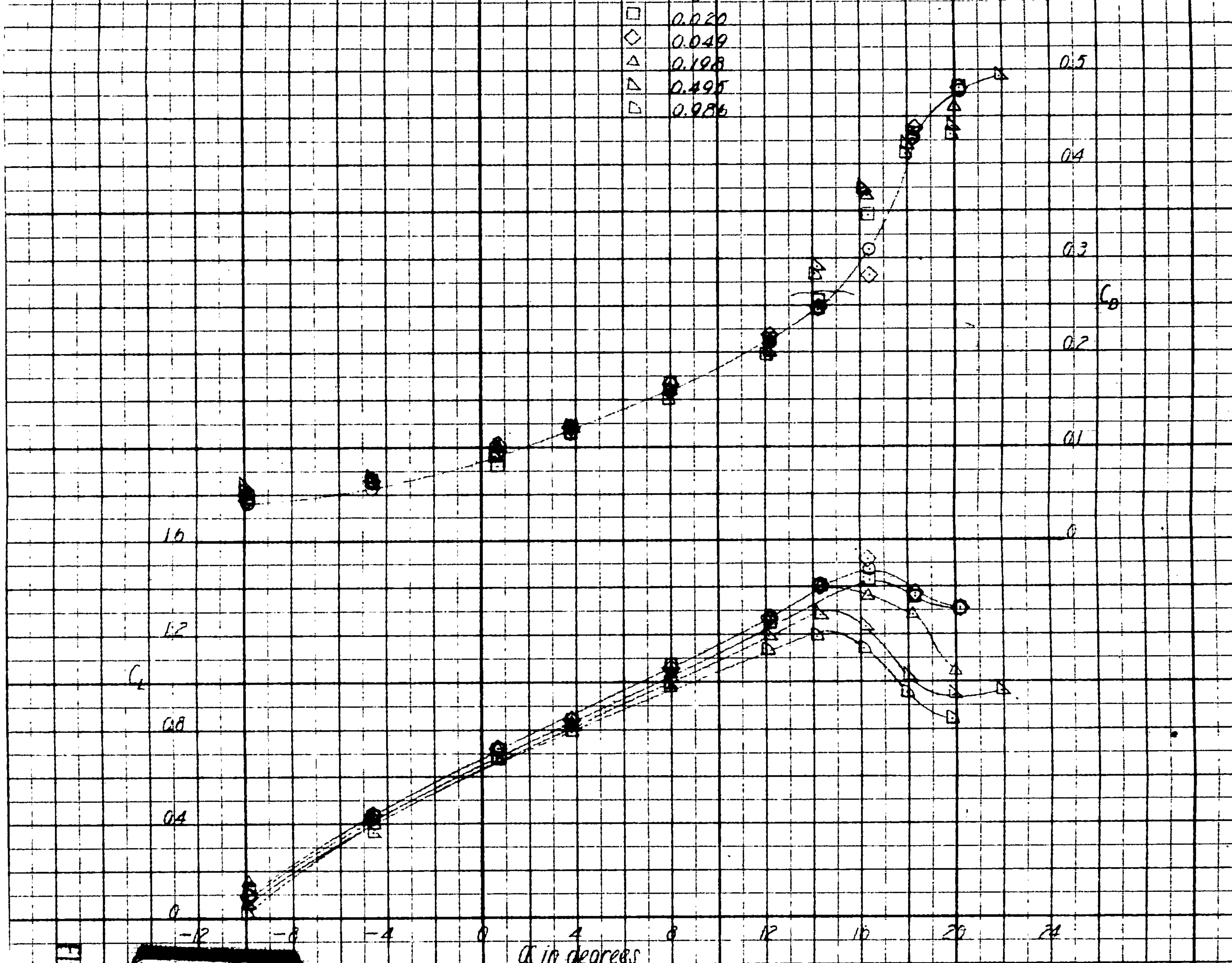


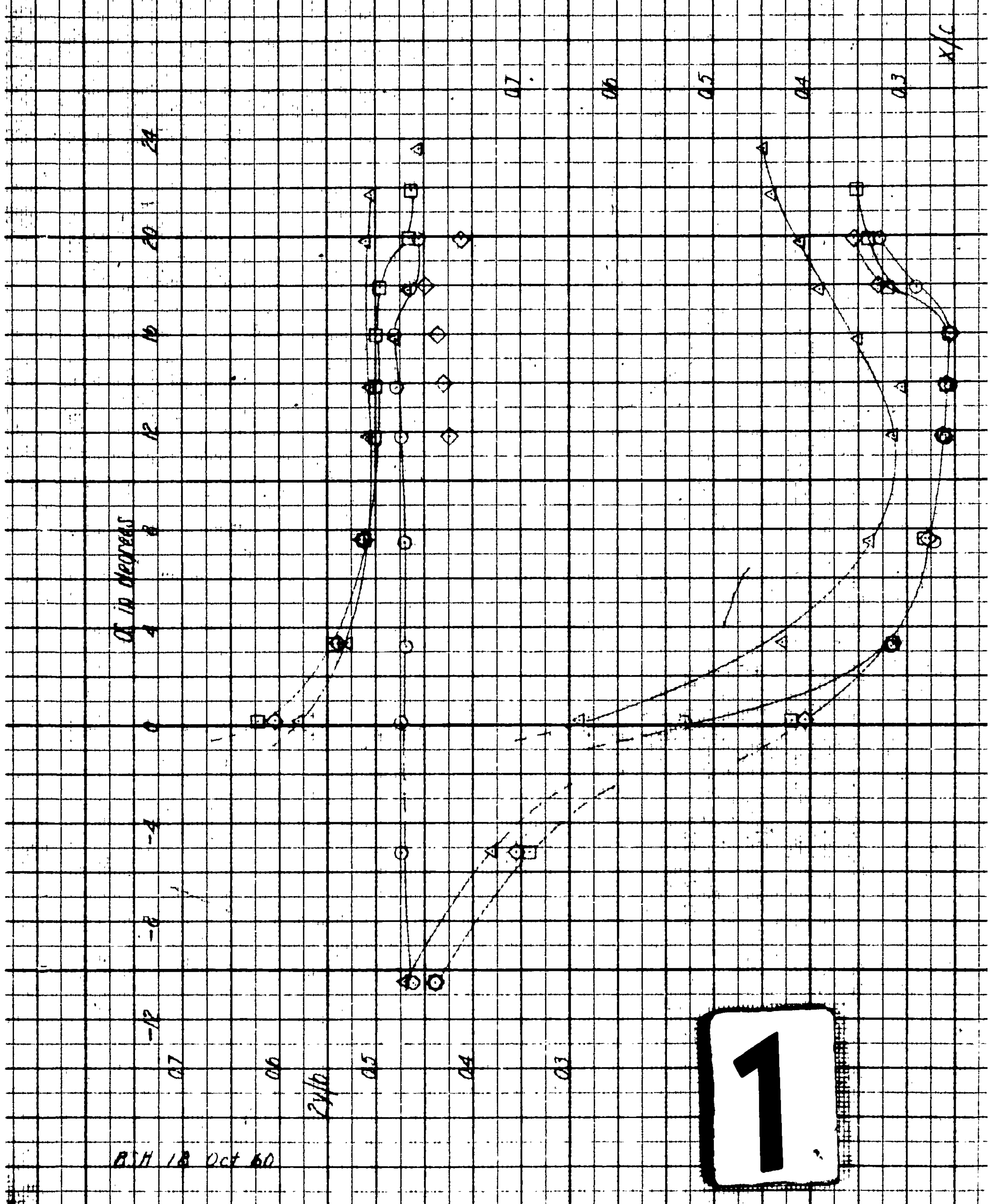
Figure 10 (Continued)

(c) $\theta_J = 0°$; $\delta_f = 30°$

3

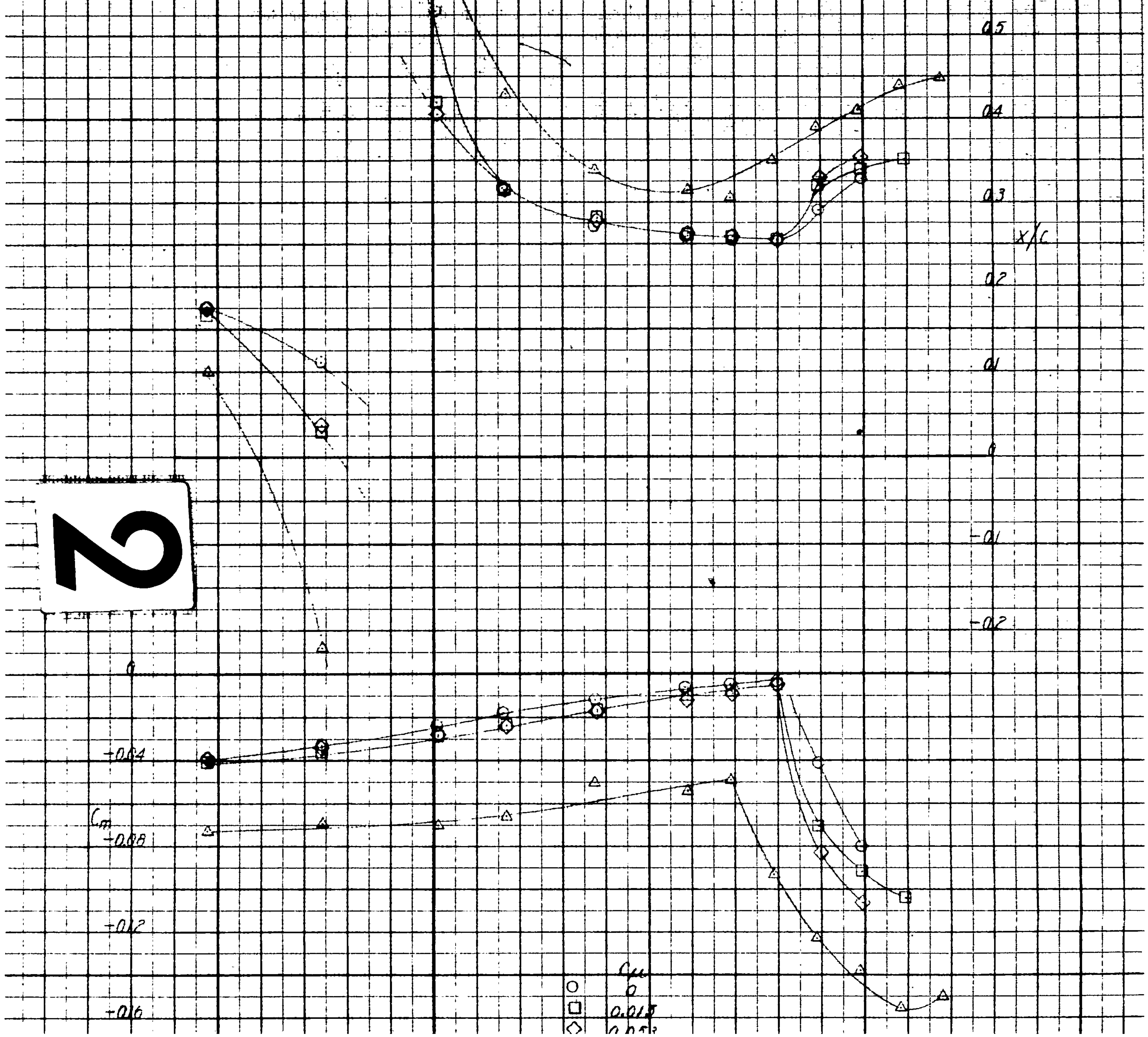
FIGURE 10 c

AERO 1043

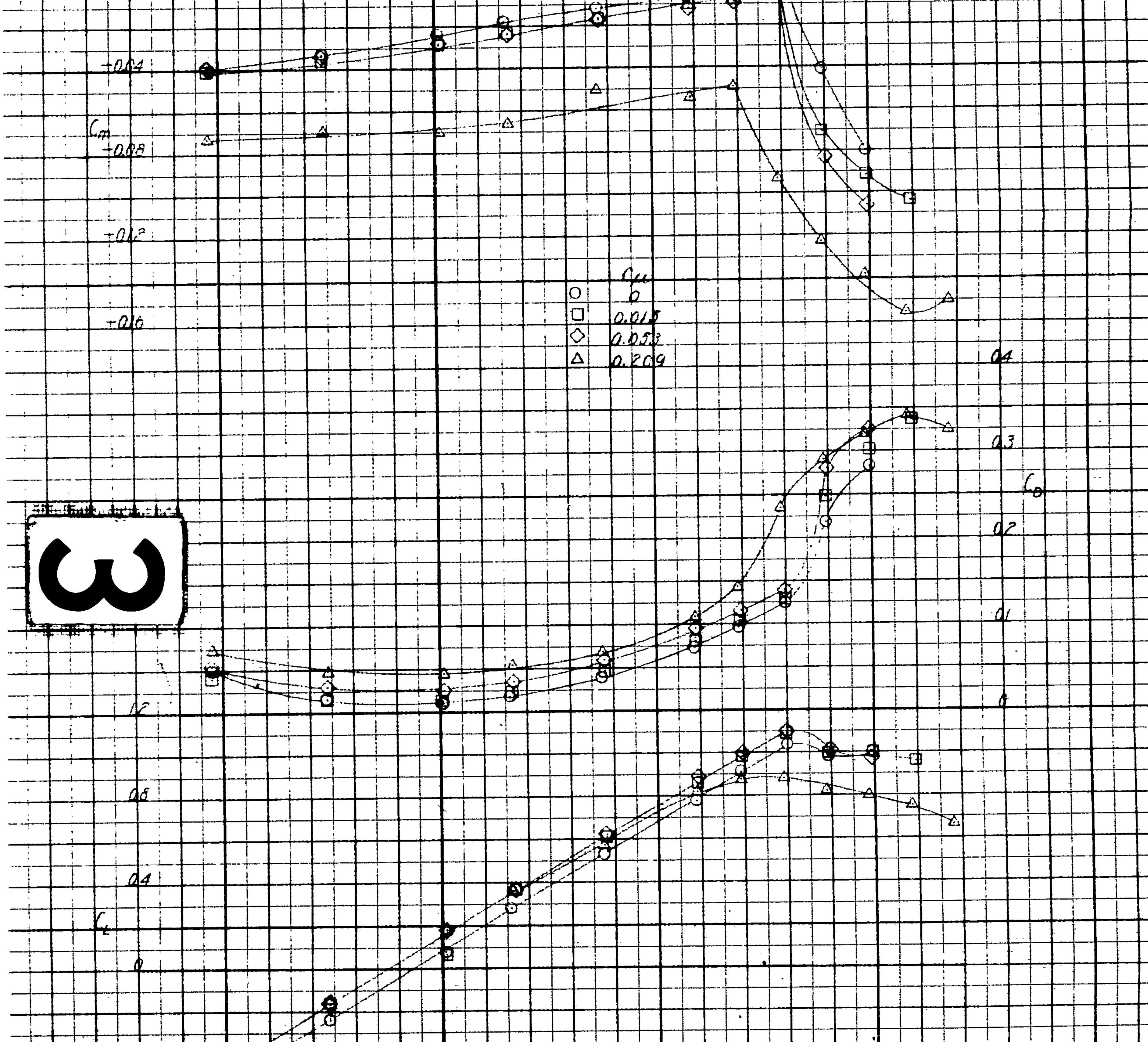


BSH 18 Oct 60

1



x/c
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
Cm
0
+0.04
+0.08
+0.12
+0.16
Cμ
0
0.015
2



C_m
+0.04
+0.08
+0.12
+0.16
C_μ
0
0.015
0.053
0.209
C_D
0.4
0.3
0.2
0.1
0
C_L
1.2
0.8
0.4
0
3

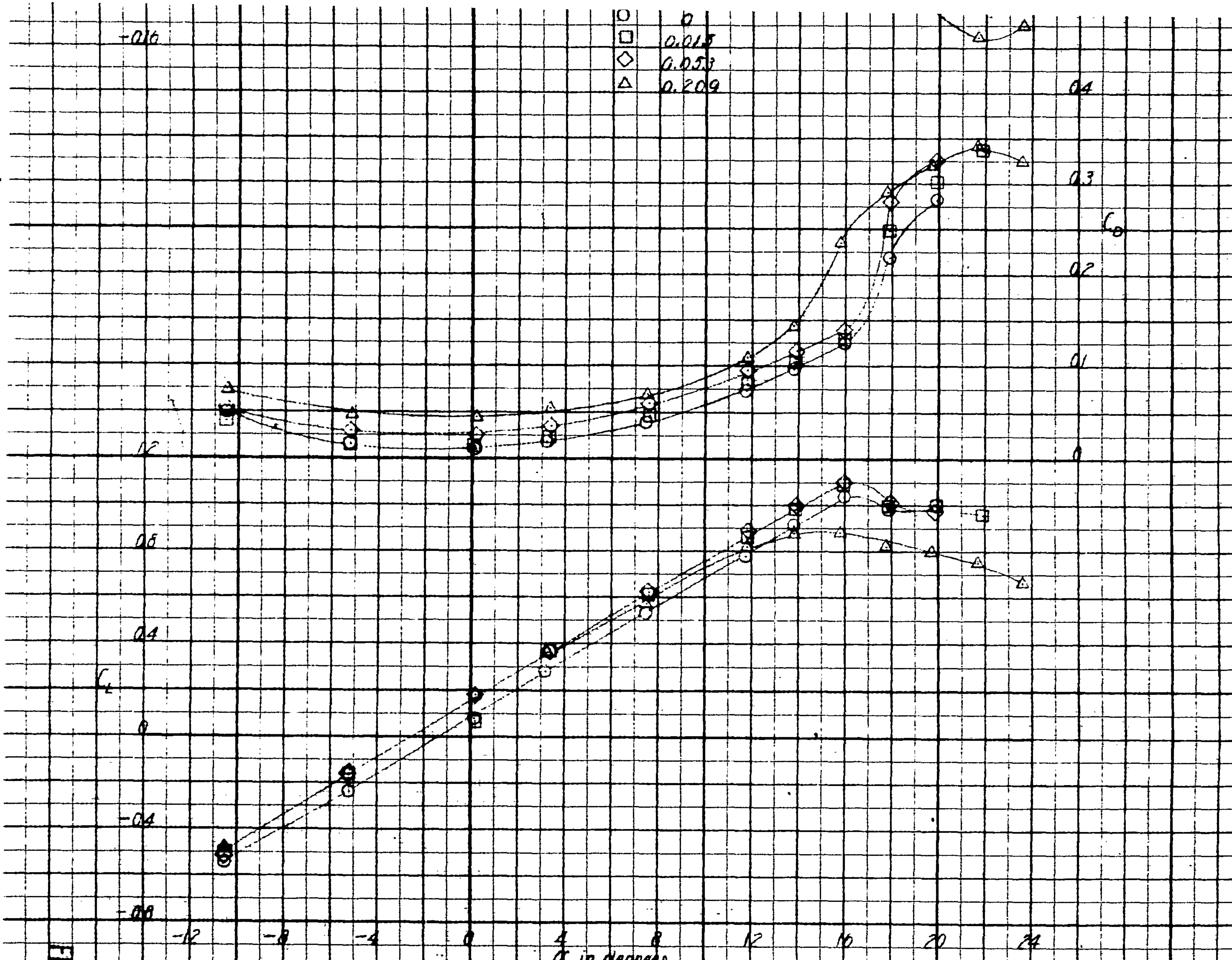
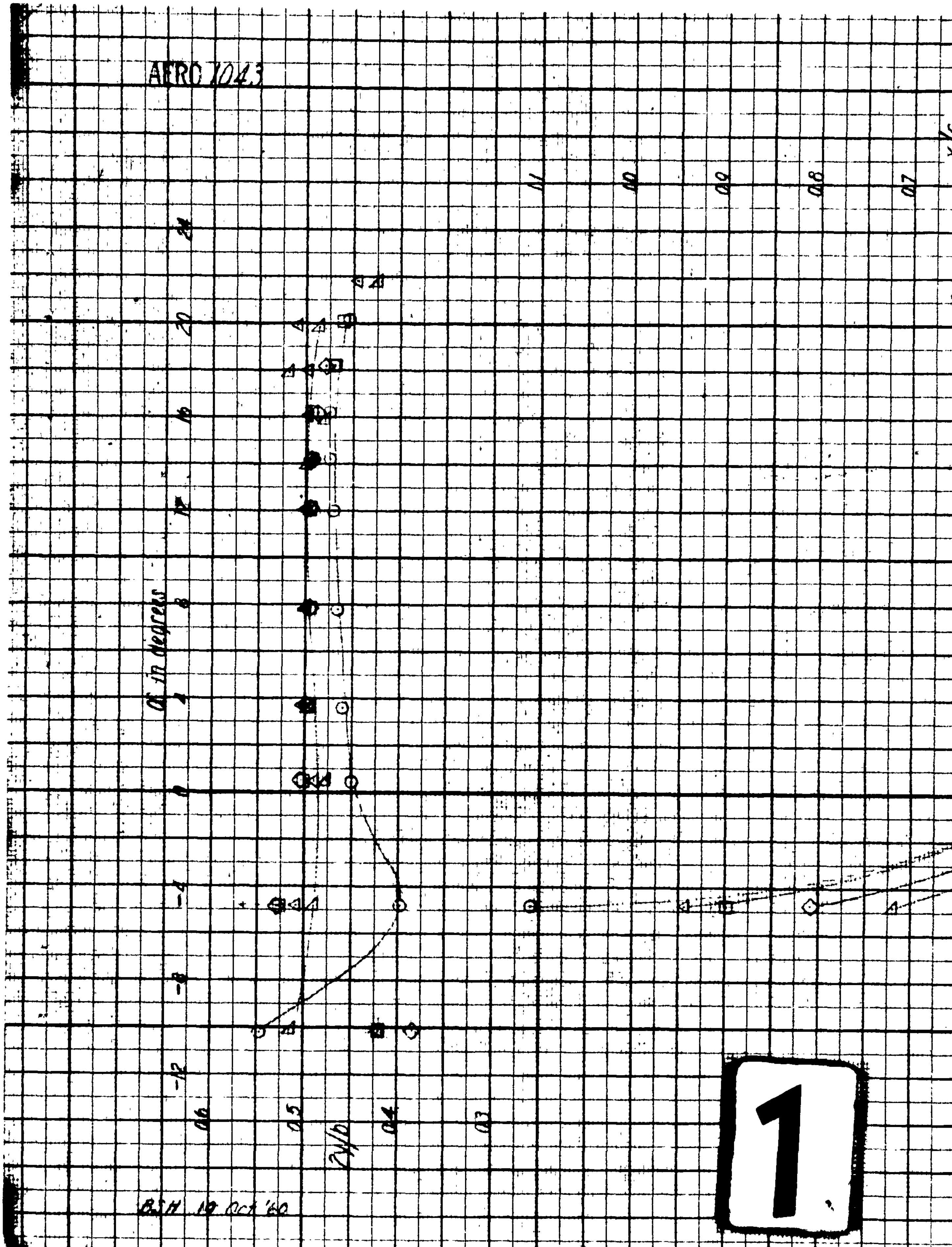
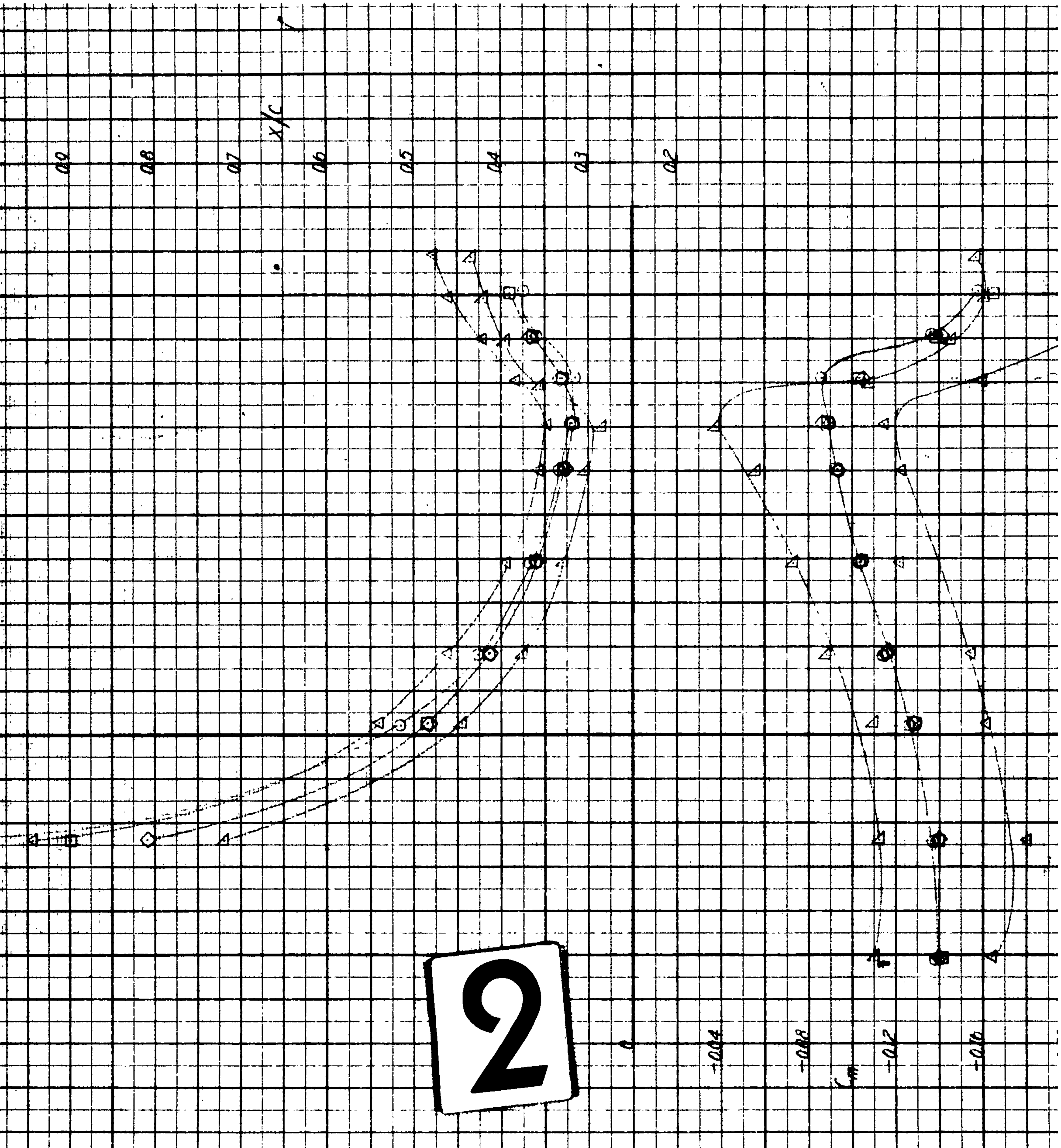


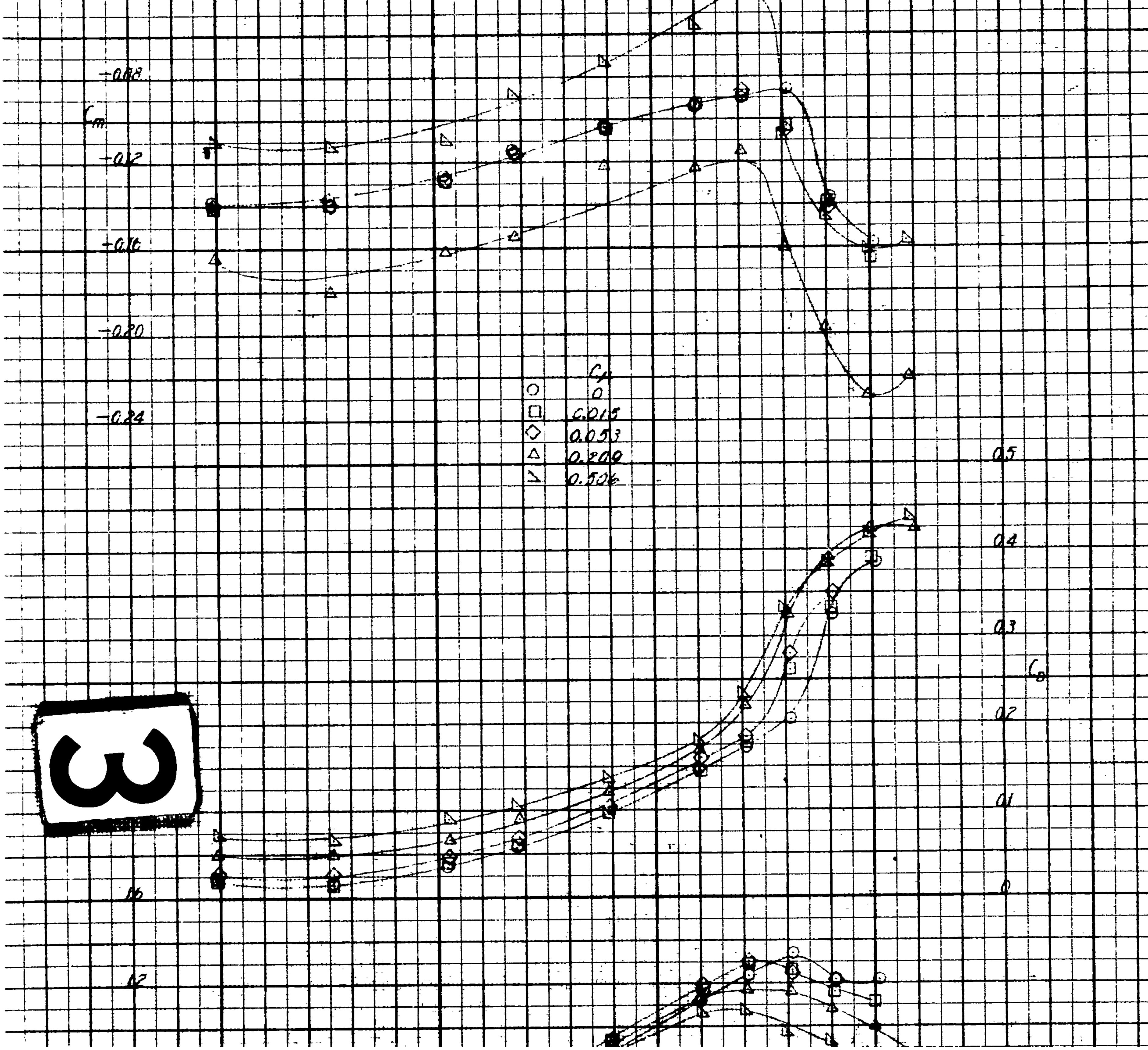
Figure 10 (Continued)

(d) $\theta_J = 37.0°$; $\delta_f = 0°$

FIGURE 10 d


AERO 1043
α in degrees
-12
-8
-4
0
4
8
12
16
20
24
0.6
0.5
ȳ/b
0.4
0.3
1.1
1.0
0.9
0.8
0.7
x/c
B.S.H. 19 Oct '60
1


0.9
0.8
0.7
x/c
0.6
0.5
0.4
0.3
0.2
0
+0.04
+0.08
+0.12
+0.16
Cm
2


C_m
-0.08
-0.12
-0.16
-0.20
-0.24
C_μ
0
0.015
0.053
0.209
0.506
C_D
0.5
0.4
0.3
0.2
0.1
0
16
12
3

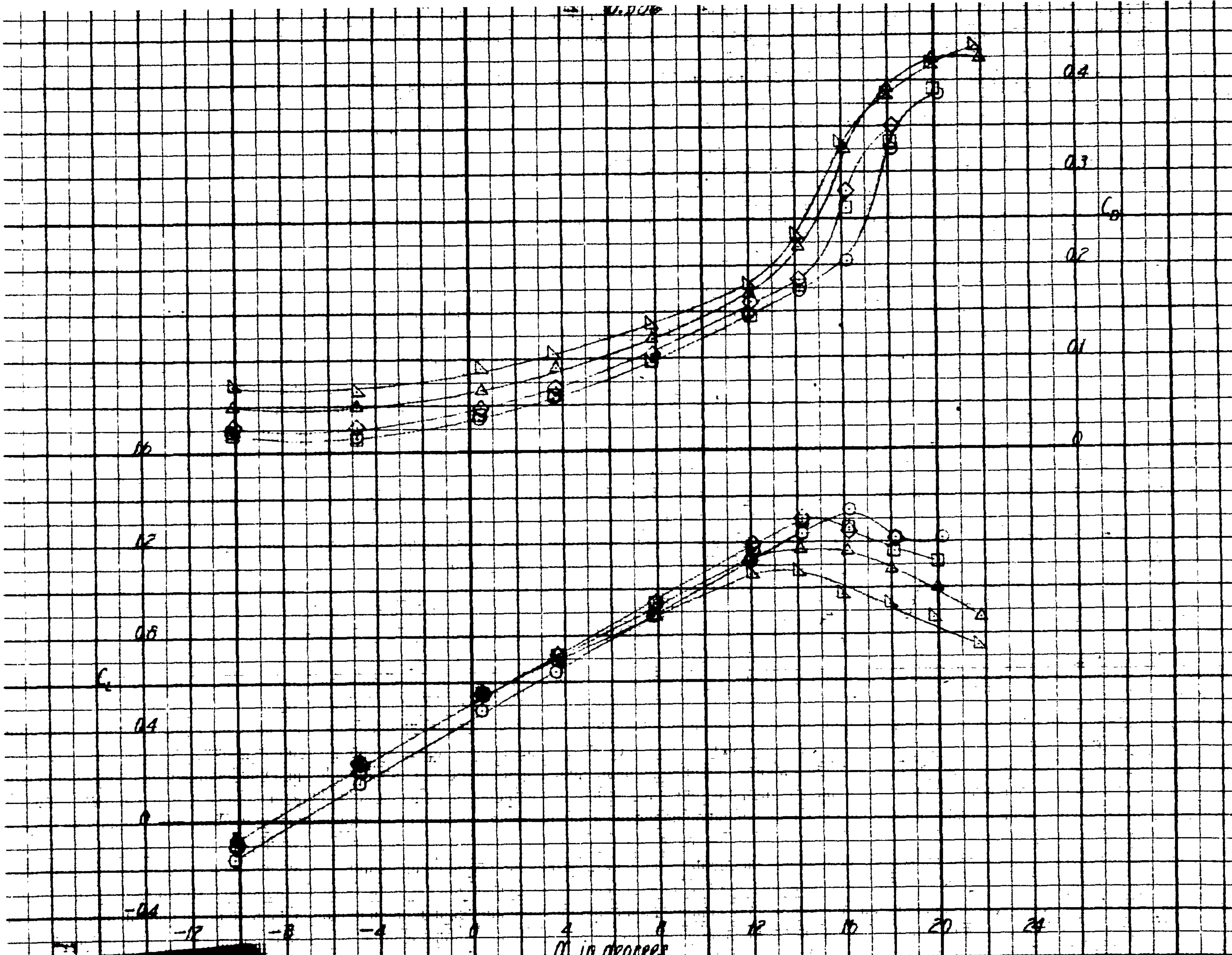
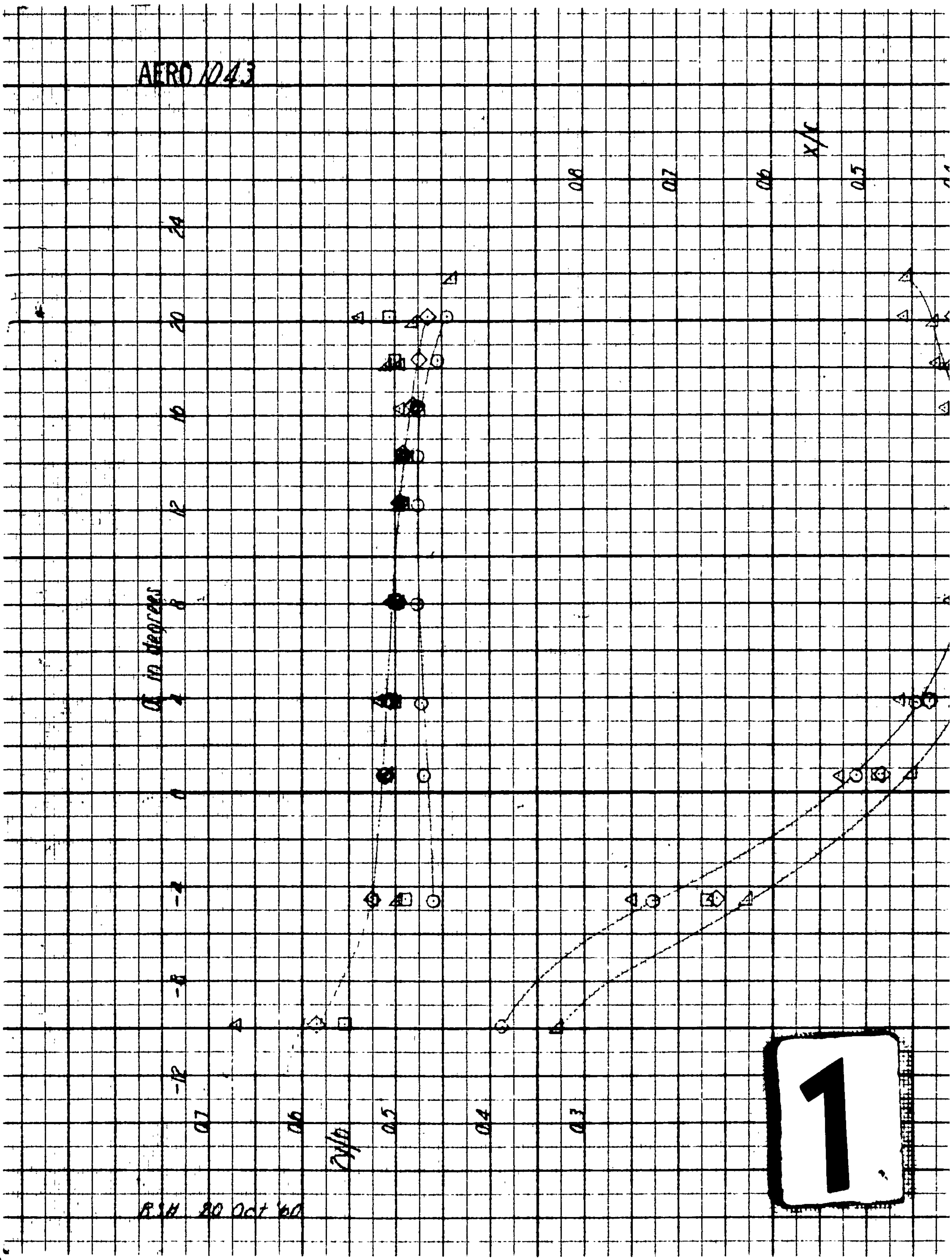
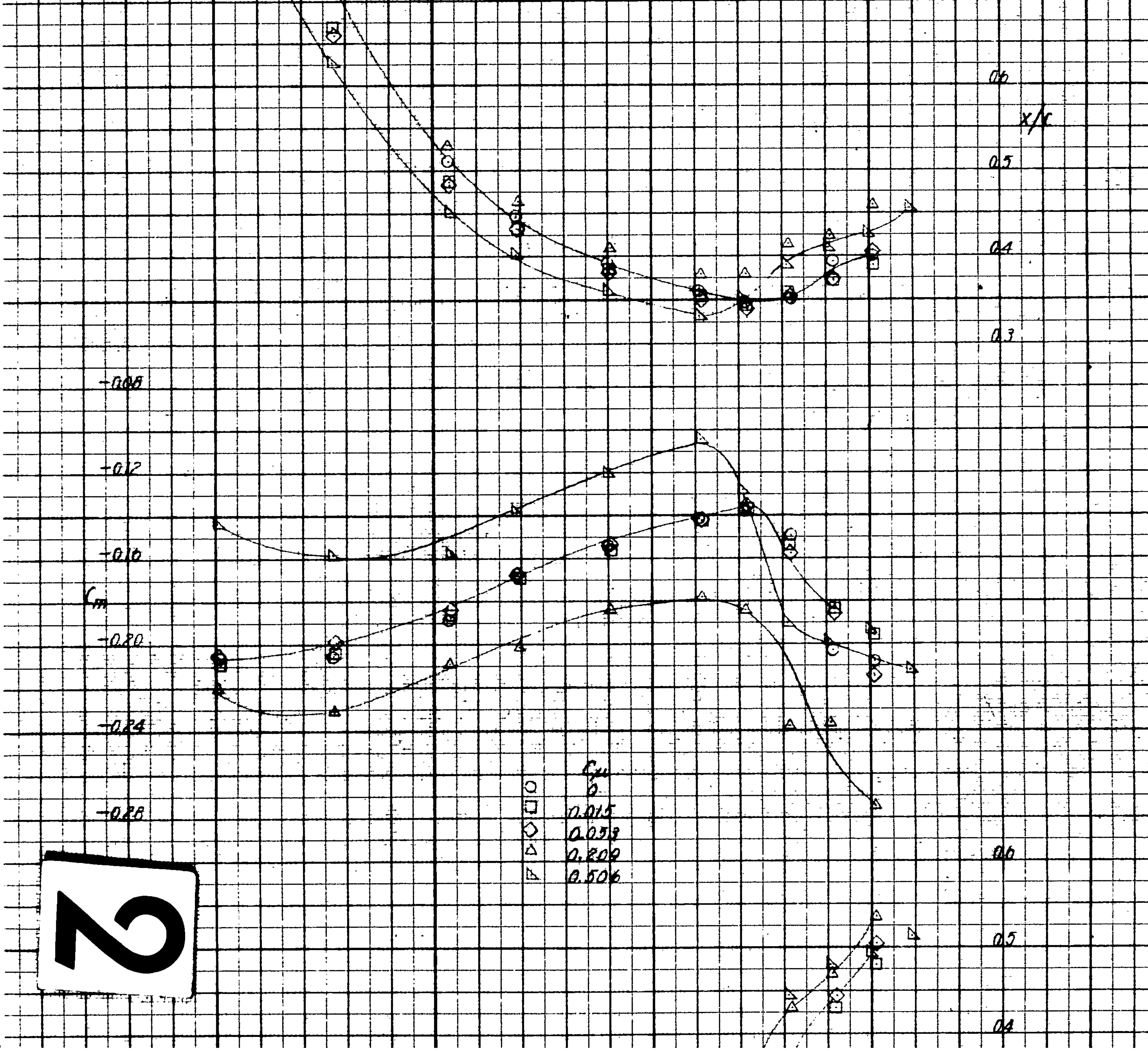


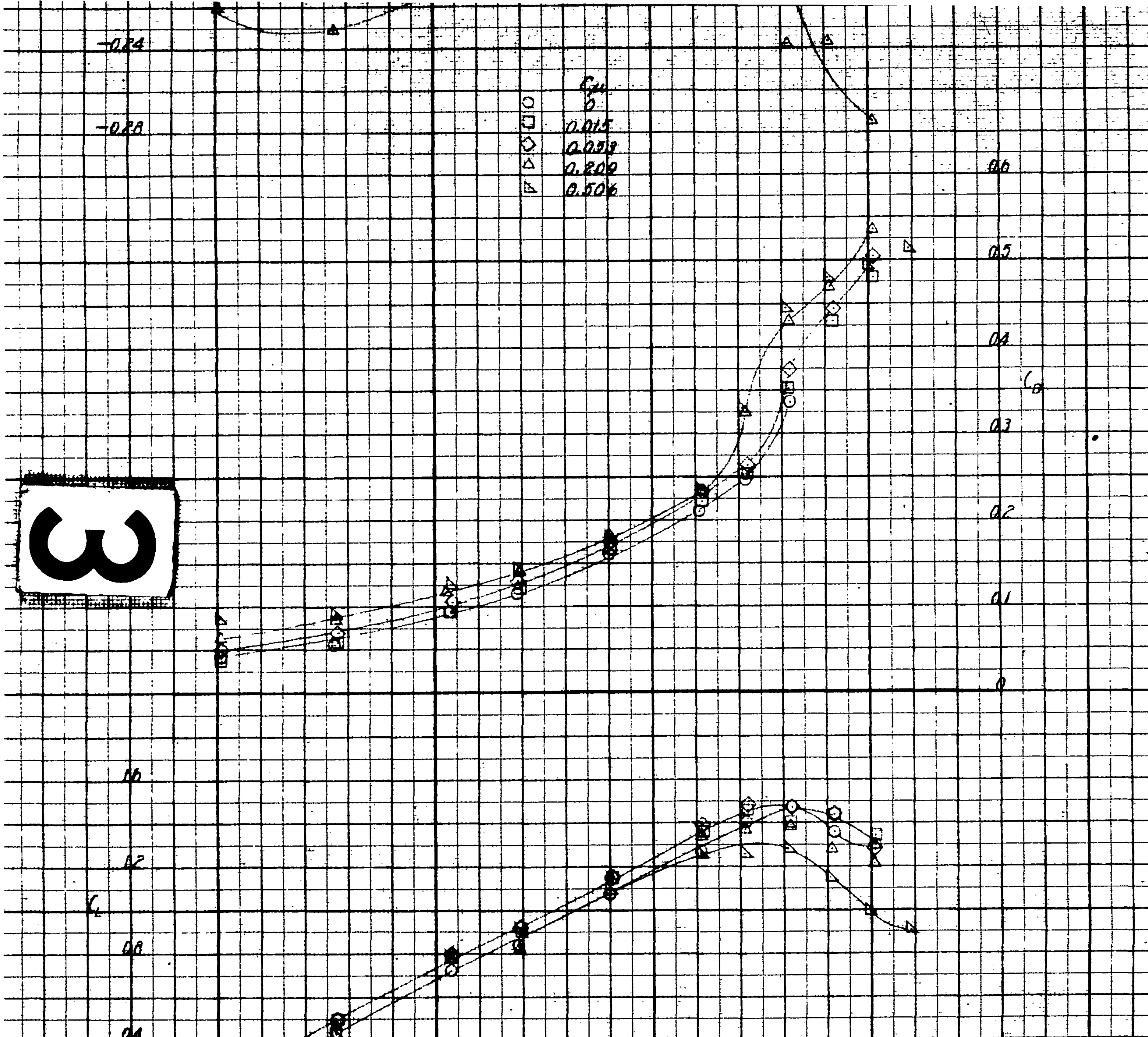
Figure 10 (Continued)

(e) $\theta_{\omega} = 37.0°$; $\delta_f = 15°$

FIGURE 10 e


AERO 1043
α in degrees
x/c
y/b
RSH 20 Oct '60
1


x/c
0.6
0.5
0.4
0.3
-0.08
-0.12
-0.16
C_m
-0.20
-0.24
-0.28
C_μ
0
0.015
0.053
0.209
0.506
0.6
0.5
0.4
2



C_μ
0
0.015
0.053
0.209
0.506
C_D
0.6
0.5
0.4
0.3
0.2
0.1
0
C_L
1.6
1.2
0.8
0.4
−0.24
−0.28
3

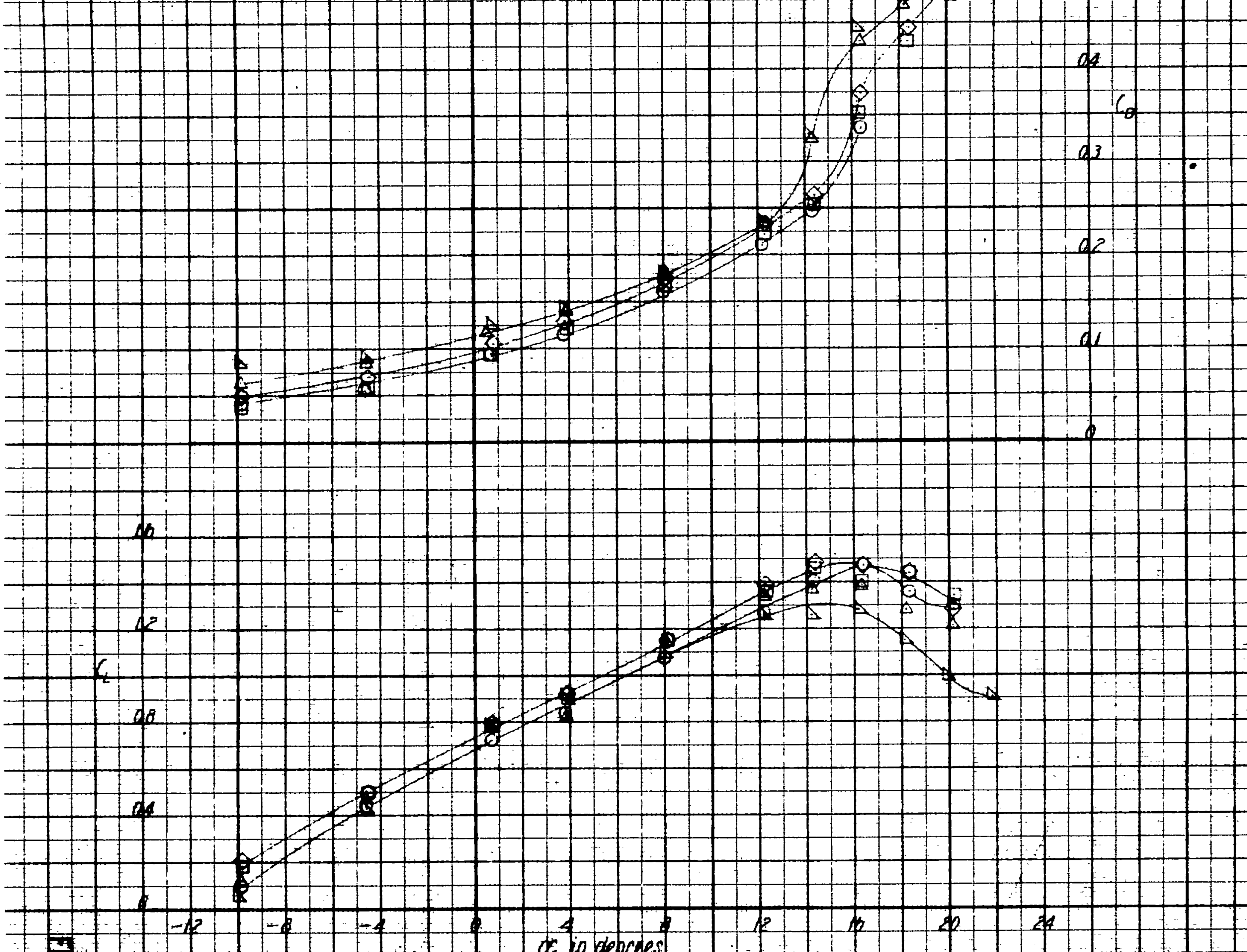
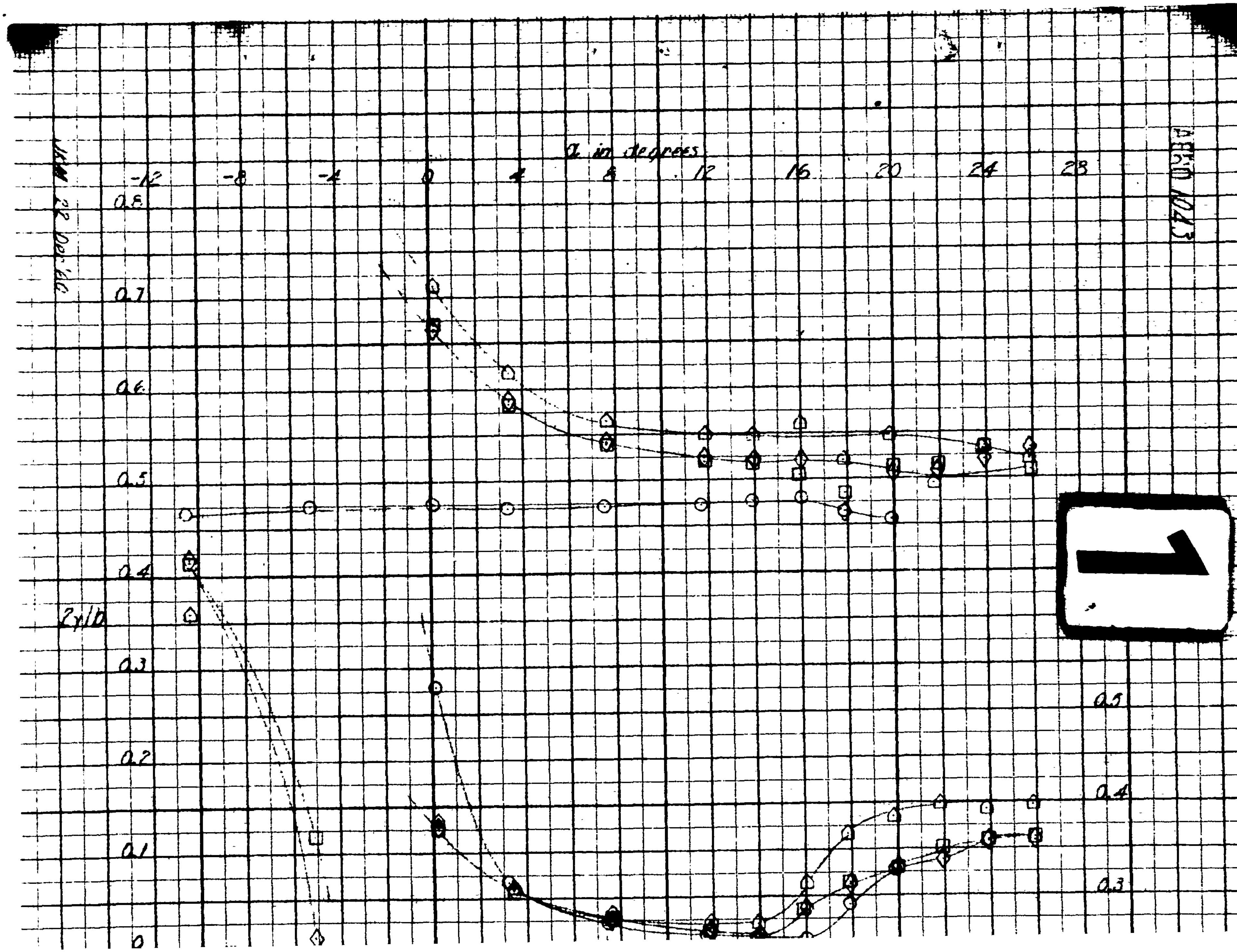
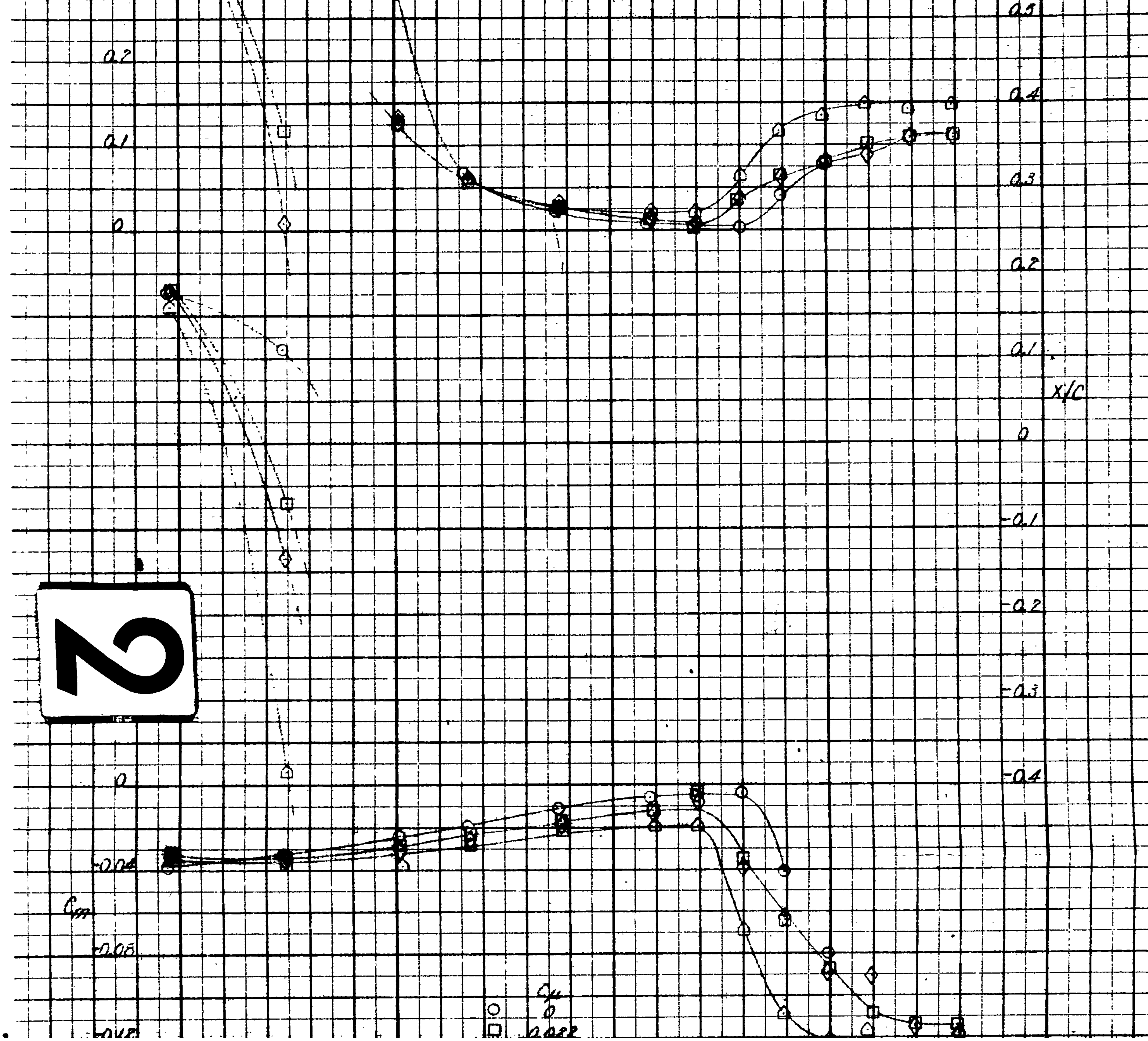


Figure 10 (Continued)

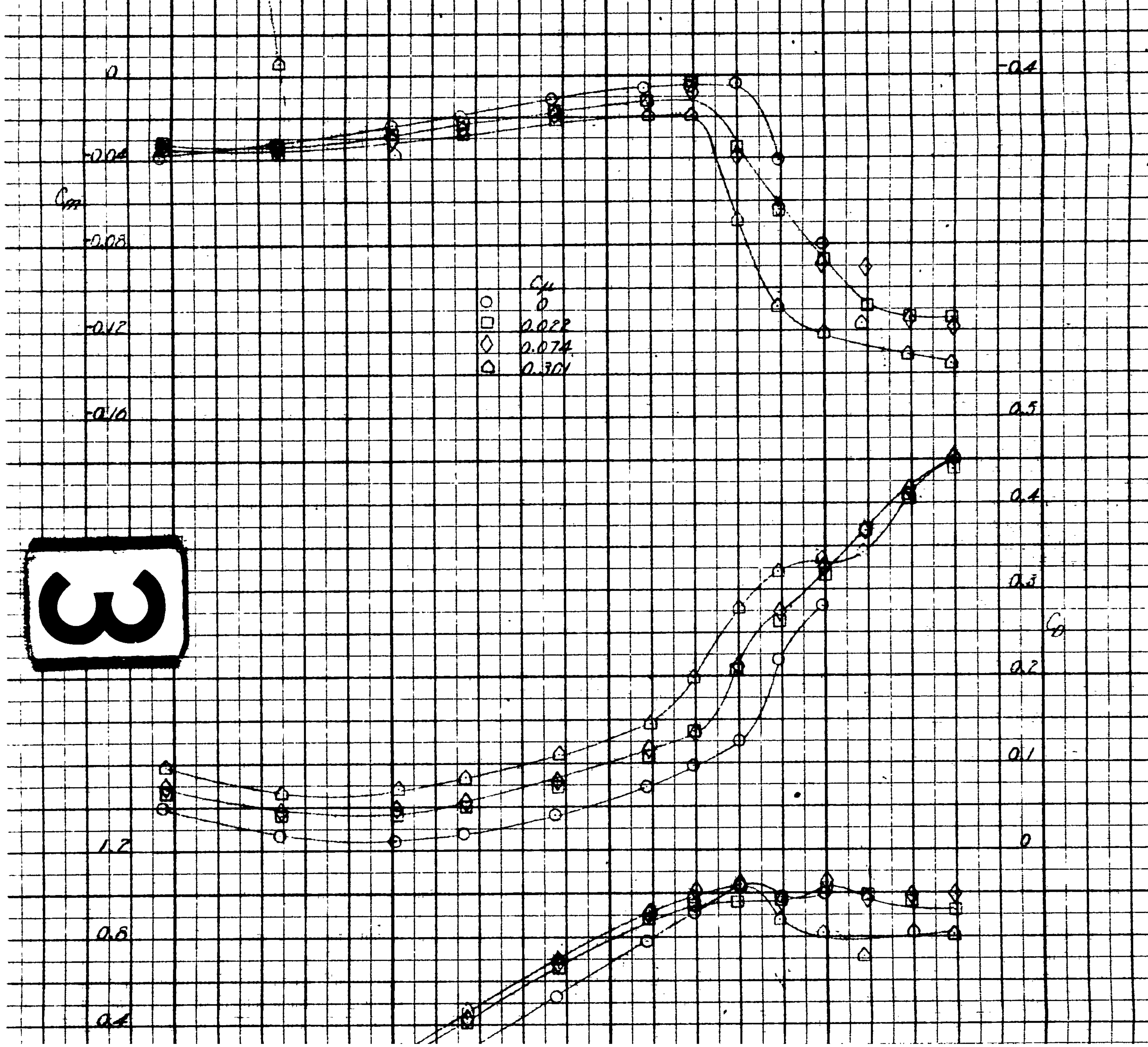
(f) $\theta_j = 37.0°$; $\delta_f = 30°$

FIGURE 10 f


α in degrees
-12
-8
-4
0
4
8
12
16
20
24
28
2y/b
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.5
0.4
0.3
JKM 22 Dec '60



2


C_m
0
-0.04
-0.08
-0.12
-0.16
C_μ
0
0.022
0.074
0.301
-0.4
0.5
0.4
0.3
0.2
0.1
0
C_D
1.2
0.8
0.4
3

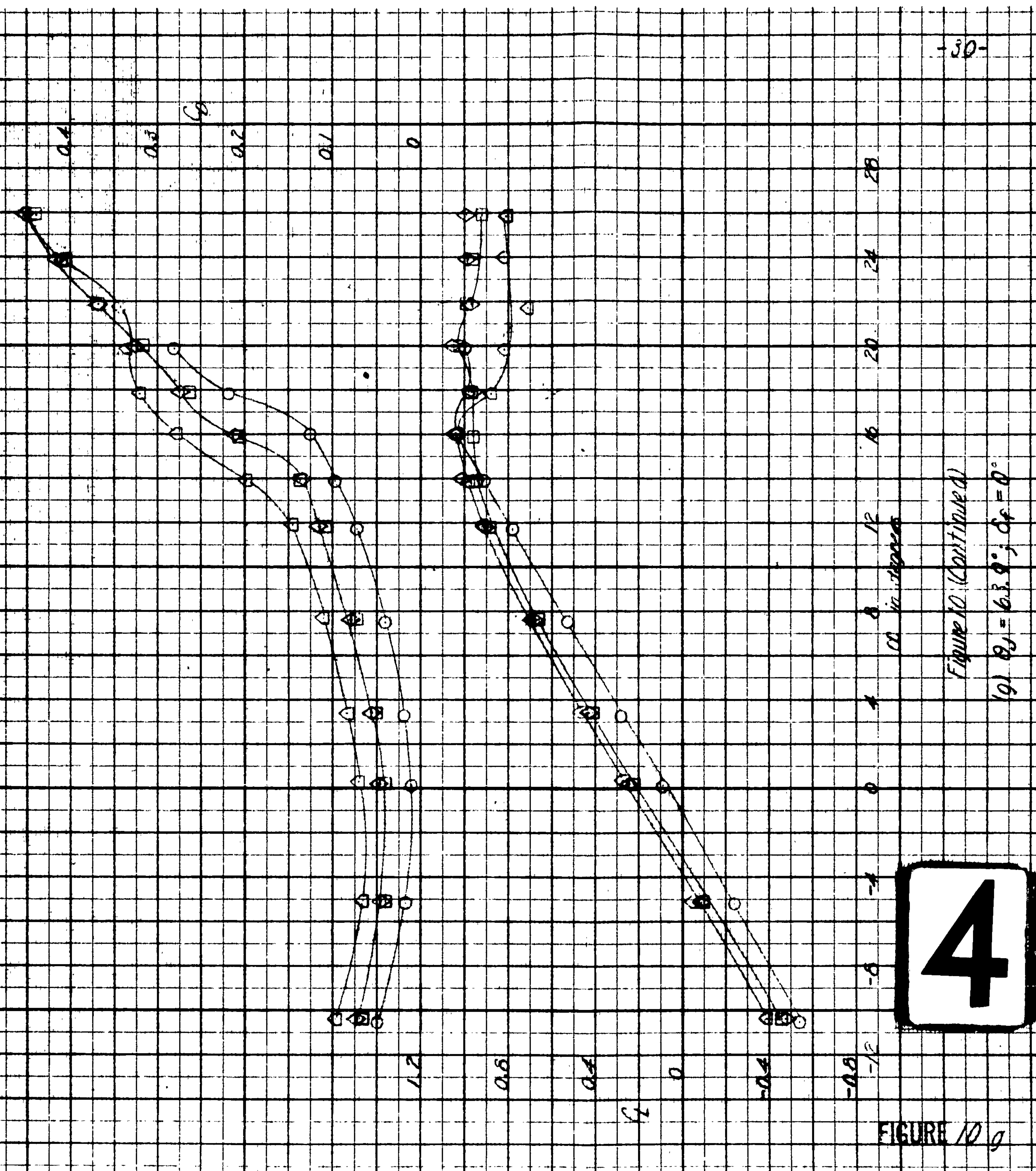
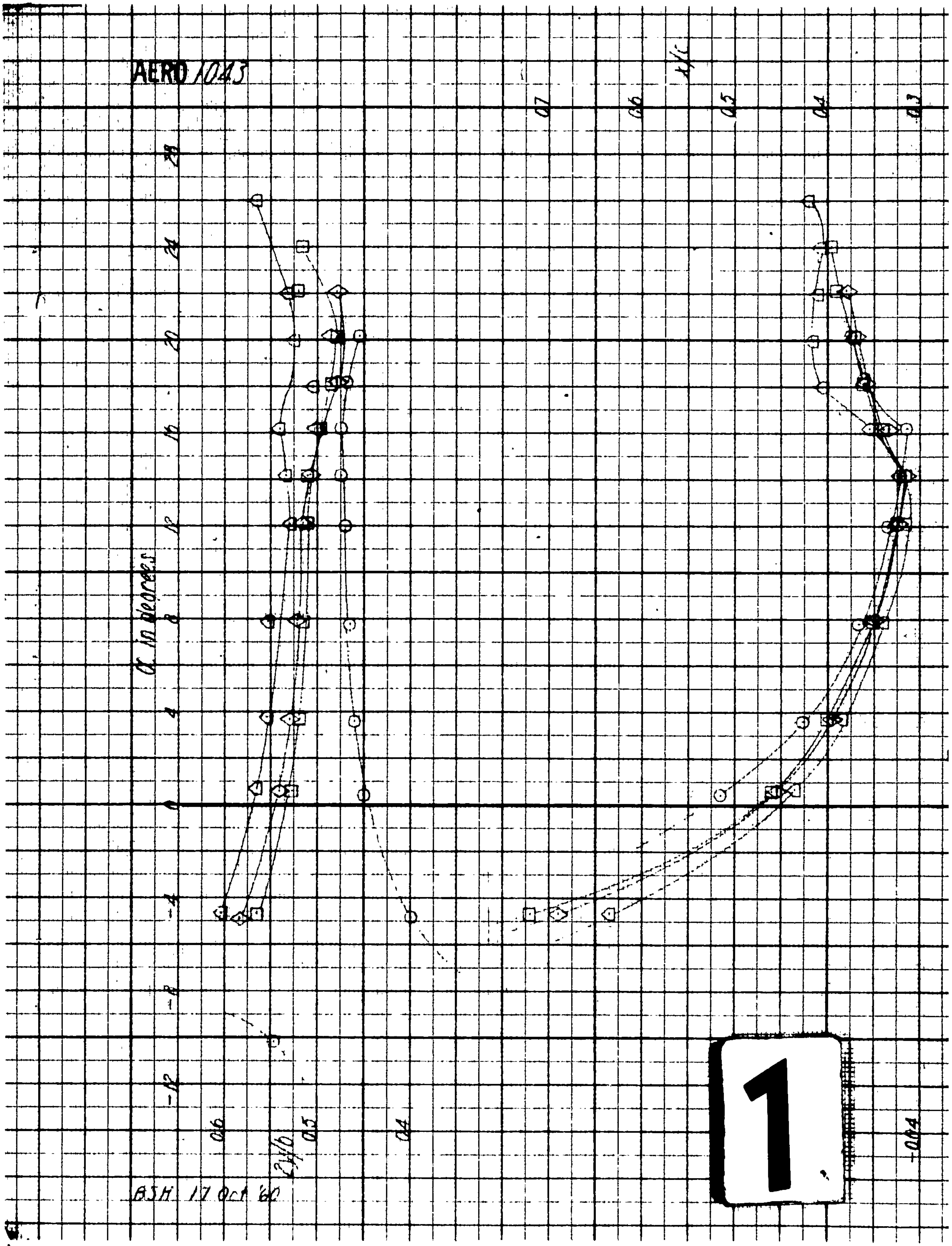
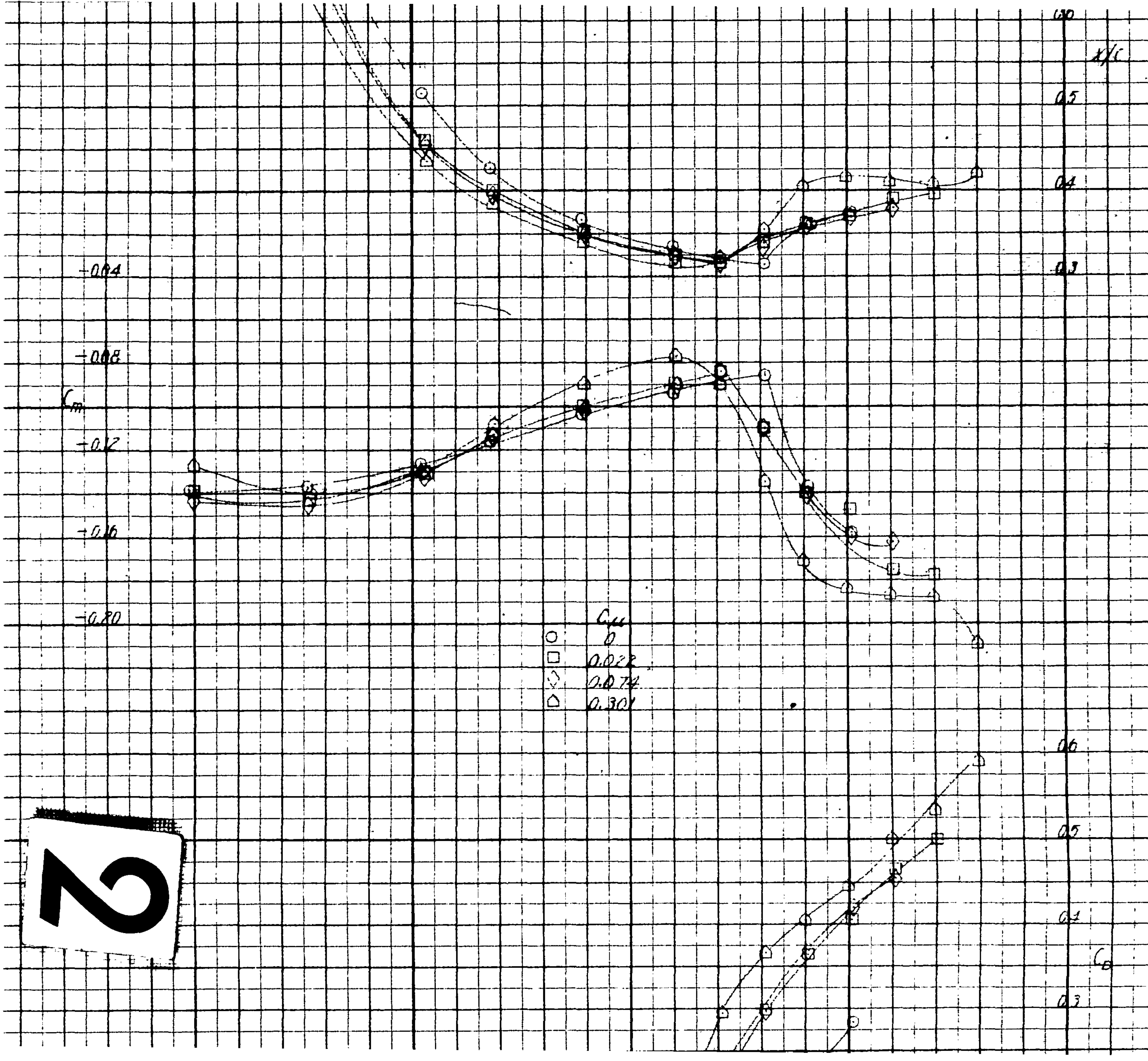


Figure 10 (Continued)

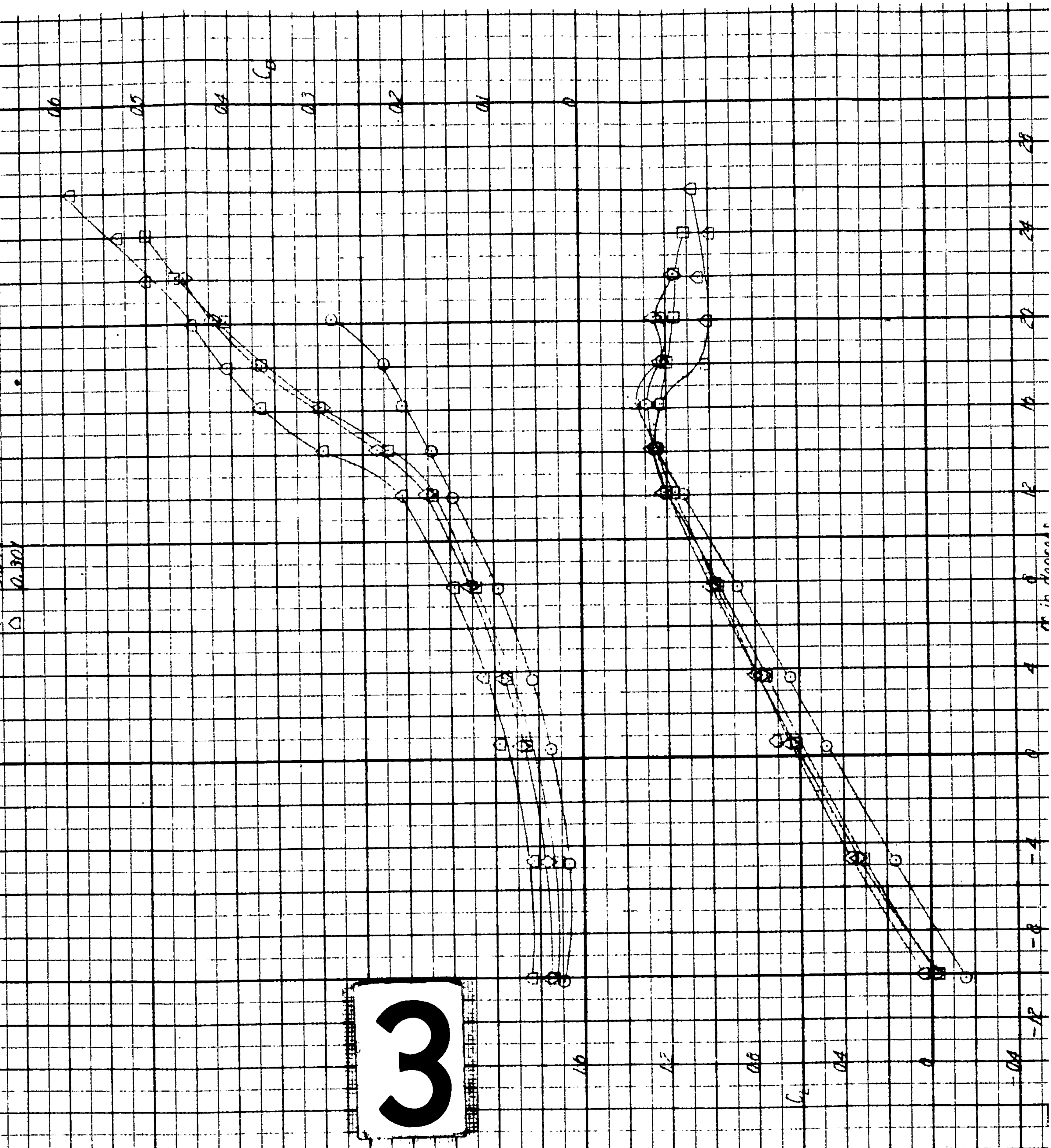
(g) $\theta_J = 63.0°$; $\delta_f = 0°$

FIGURE 10 g


AERO 1043
α in degrees
x/c
$C_{p}/0$
BSH 17 Oct '60
1


x/c
0.6
0.5
0.4
0.3
-0.04
-0.08
C_m
-0.12
-0.16
-0.20
C_μ
0
0.022
0.074
0.301
0.6
0.5
0.4
C_D
0.3

2



3

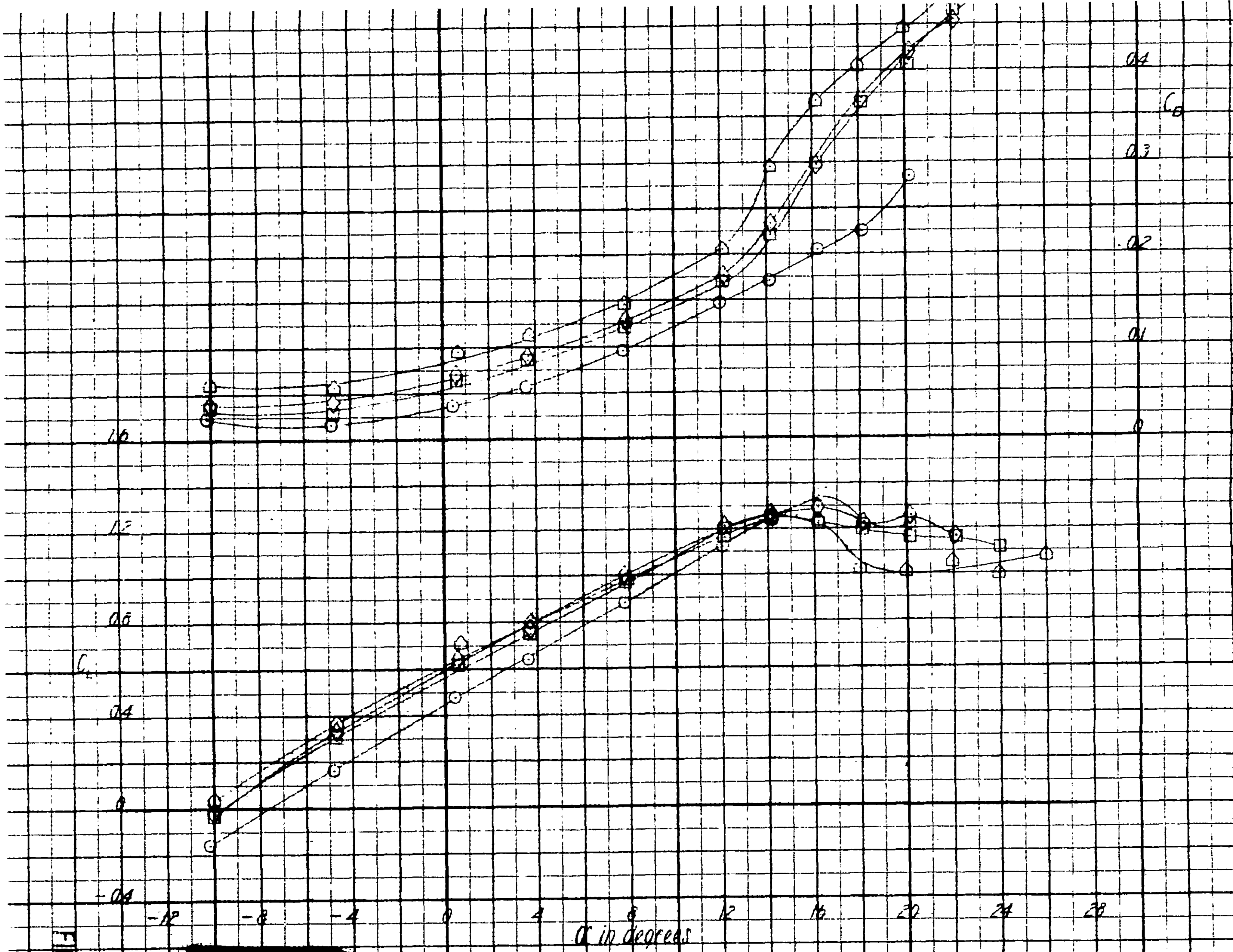
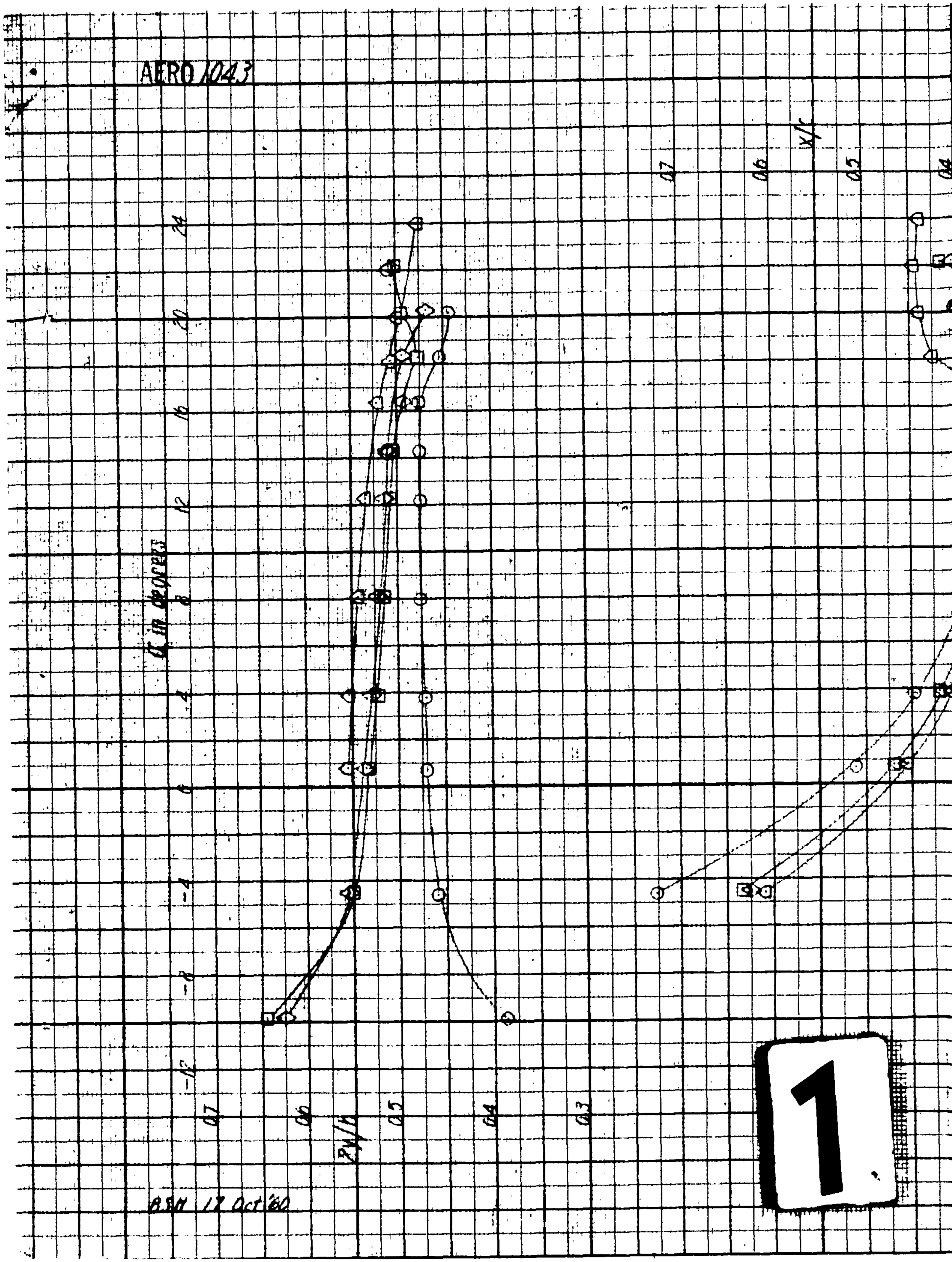
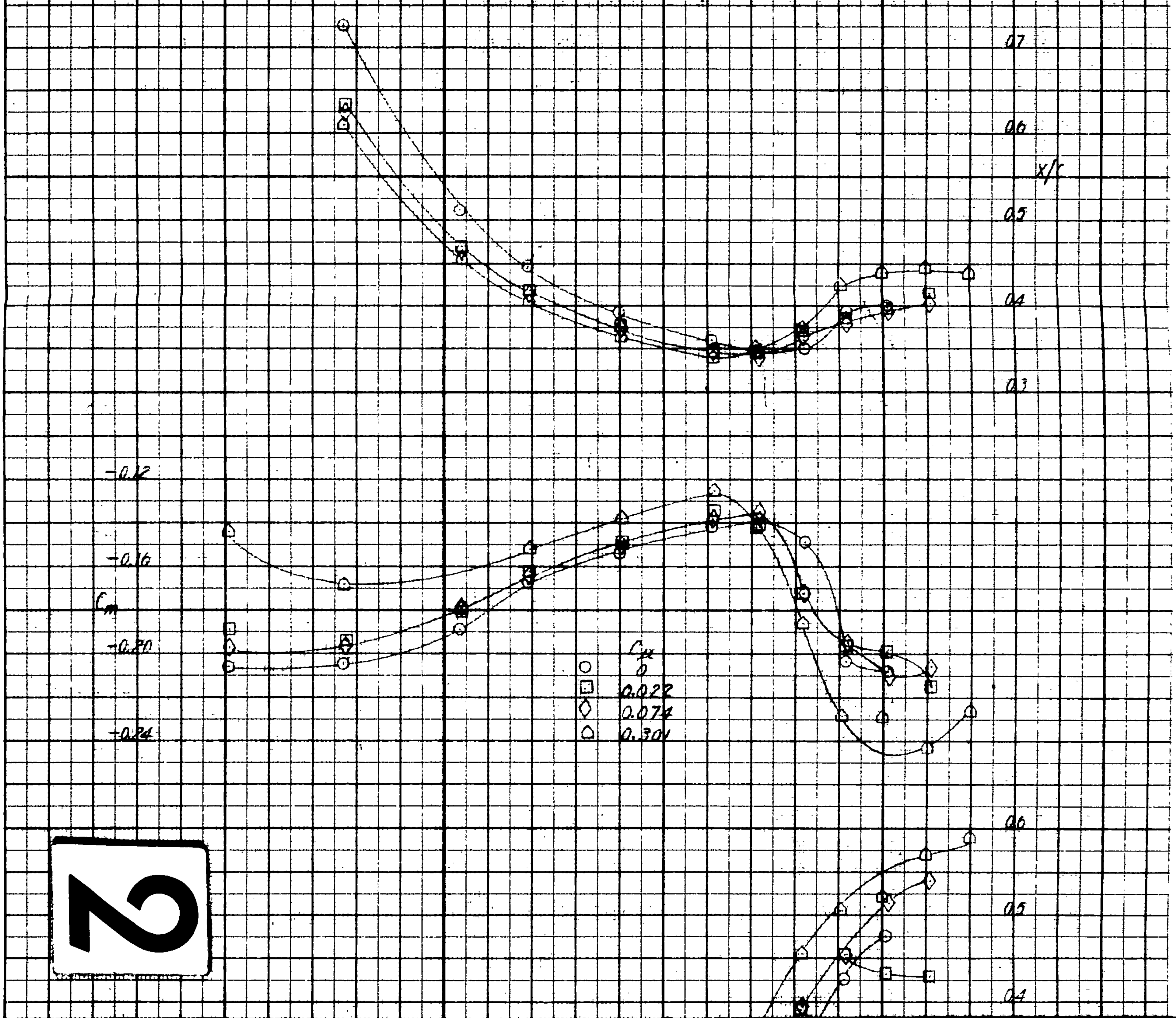


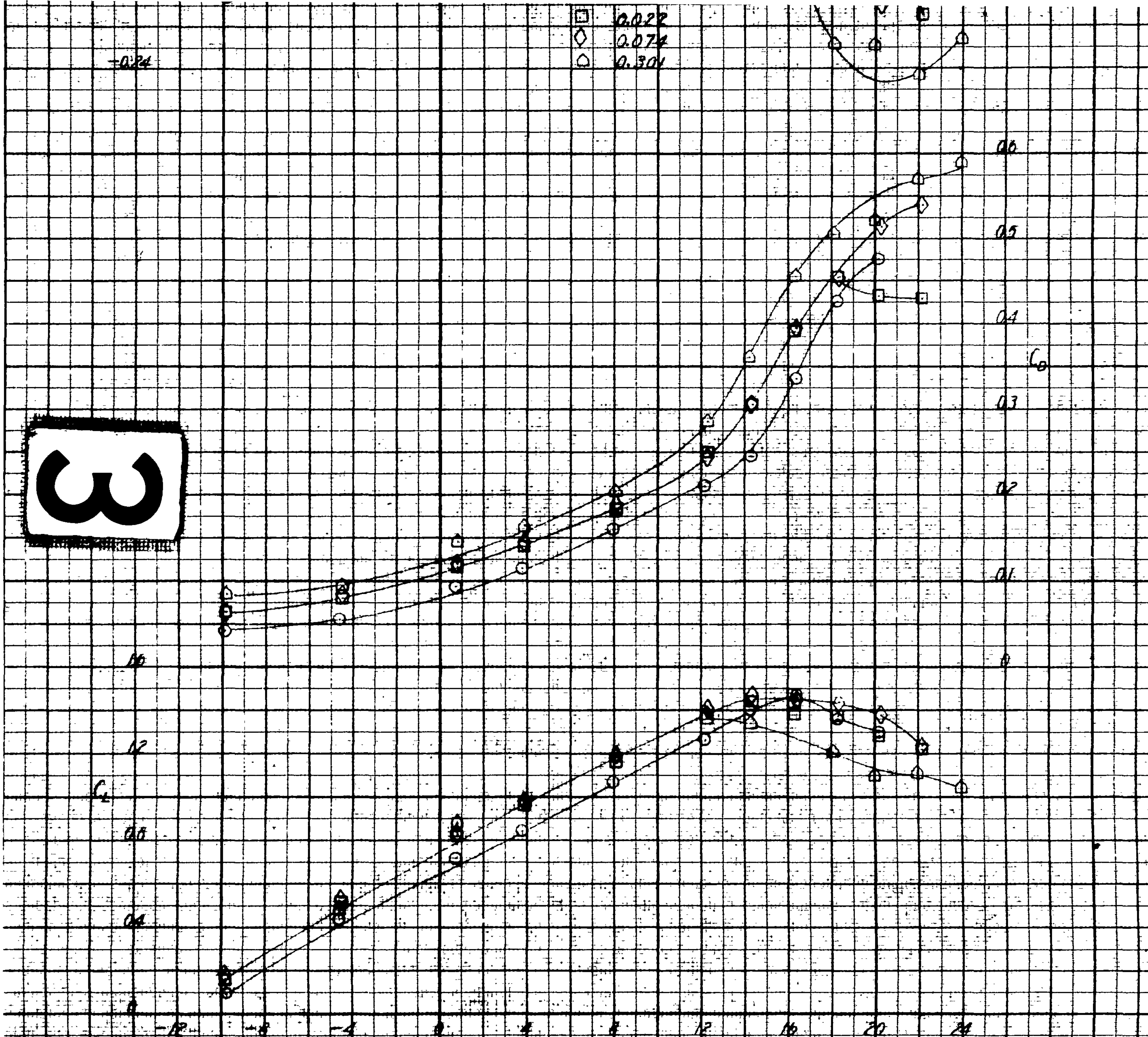
Figure 10 (Continued)

(h) $\theta_J = 63.9°$; $\delta_f = 15°$

FIGURE 10 h


AERO 1043
α in degrees
x/c
B.S.H. 12 Oct '60
1


0.7
0.6
x/c
0.5
0.4
0.3
-0.12
-0.16
C_m
-0.20
-0.24
C_μ
○ 0
□ 0.022
◇ 0.074
⌂ 0.301
0.6
0.5
0.4
2



0.022
0.074
0.301
-0.24
C_D
0.6
0.5
0.4
0.3
0.2
0.1
0
C_L
1.6
1.2
0.8
0.4
0
-12
-8
-4
0
4
8
12
16
20
24
α in degrees

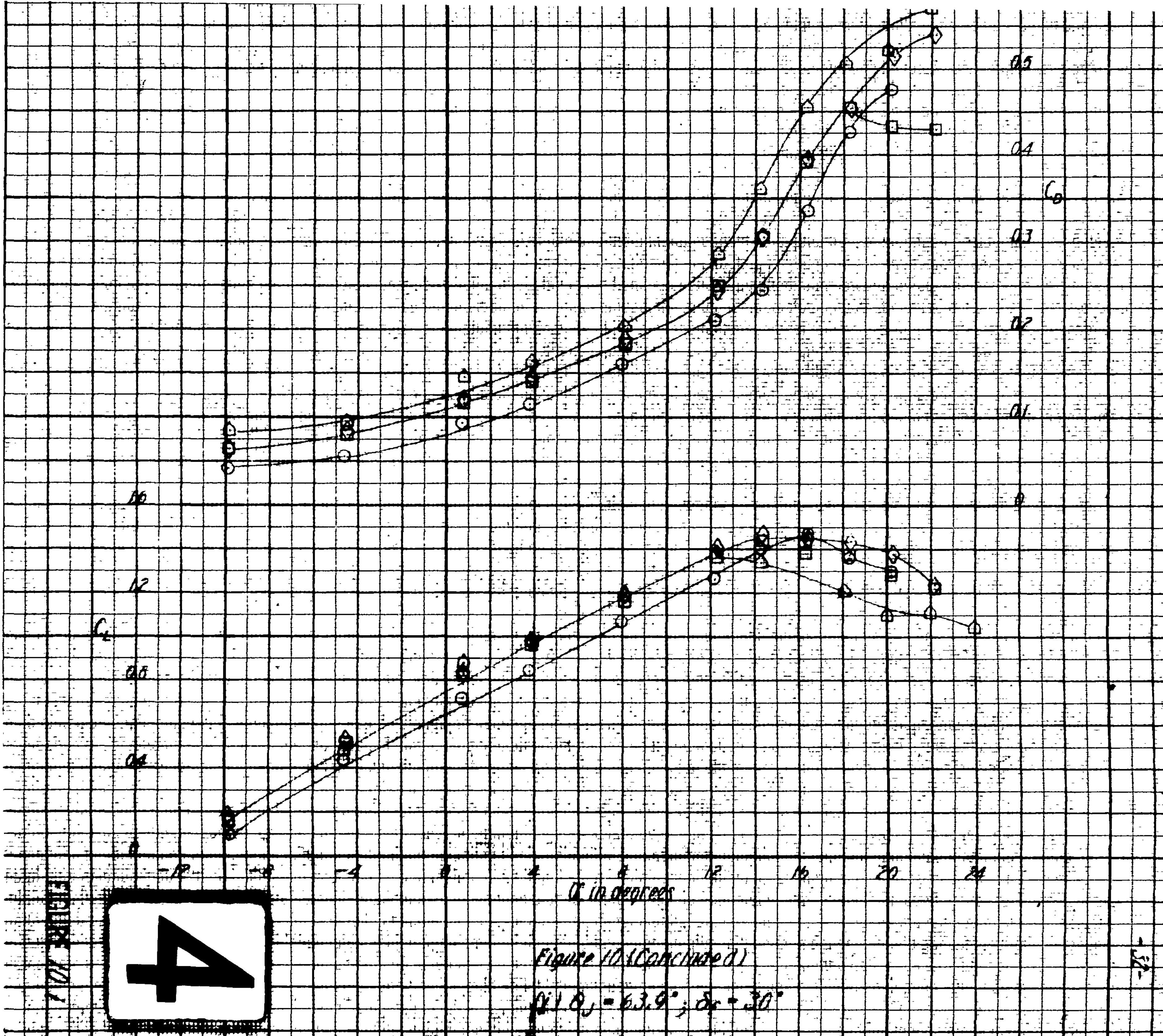


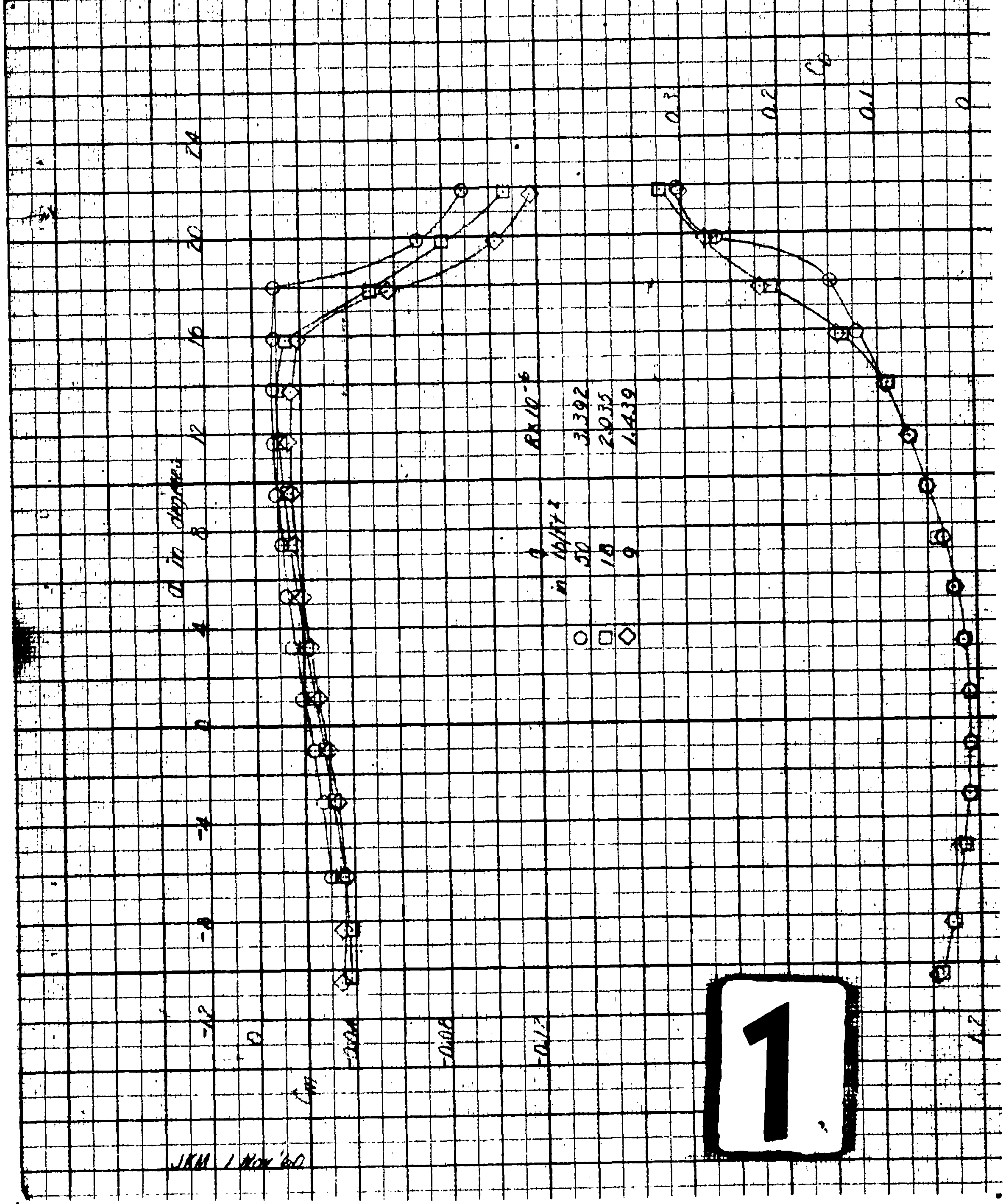
Figure 10.(Concluded)

(j) $\theta_J = 63.9°$; $\delta_F = 30°$

4

FIGURE 10.1

AERO 1043



α in degrees
Cm
CD
R×10⁻⁶
3.392
2.035
1.439
q in lb/ft²
50
18
9
JKM 1 Nov '60
1

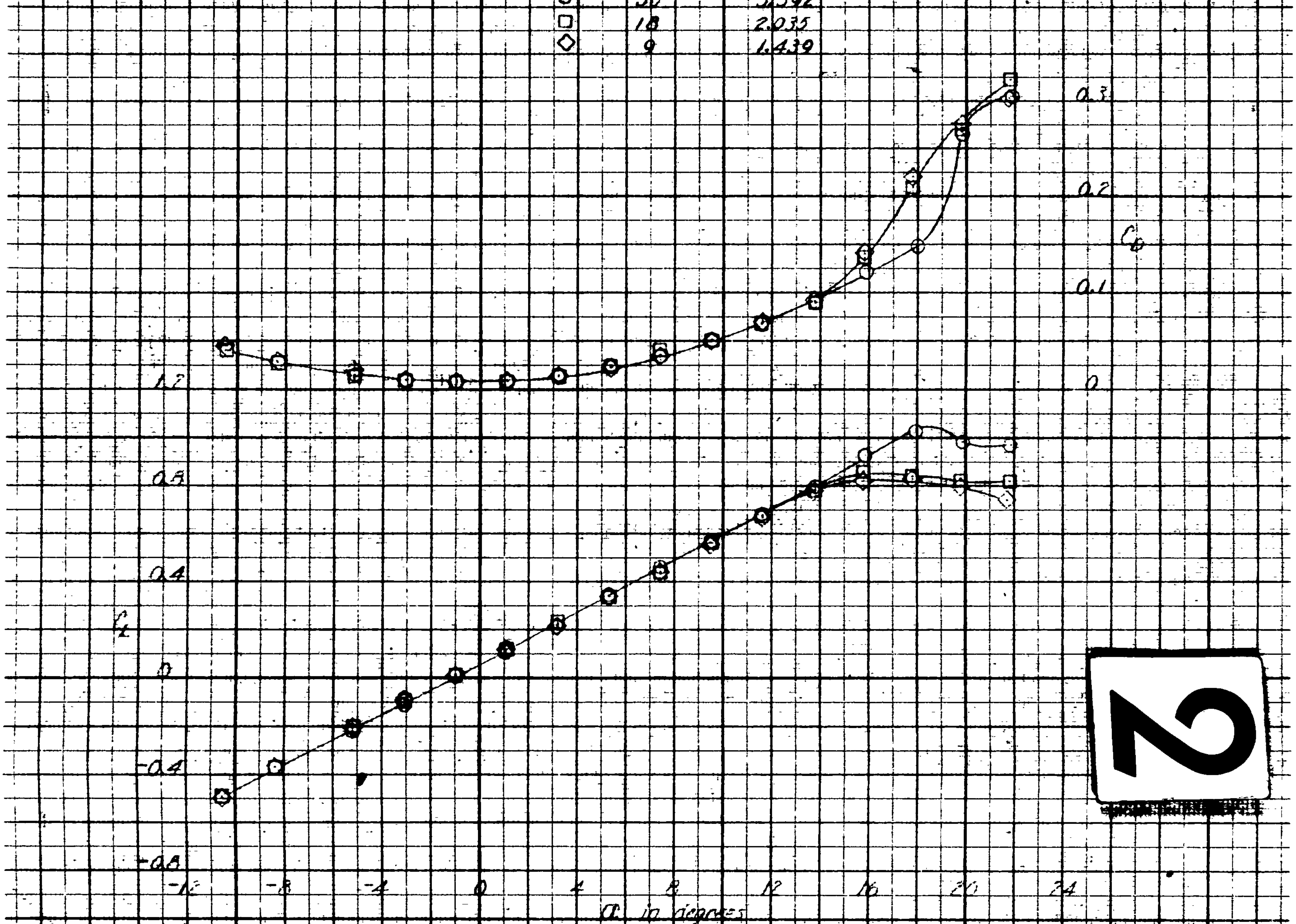


Figure 11 - Effect of Reynolds Number on the Aerodynamic Characteristics of the Wing (Spanwise-Blowing Configuration)

$\delta_f = 0°; C_\mu = 0$

FIGURE 11

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