This contains functional equivalents for plots

THE **BOEING** COMPANY

COMMERCIAL AIRPLANE DIVISION

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TITLE: LOW SPEED AERODYNAMIC PREDICTION METHOD

MODEL

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REVISIONS

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AERODYNAMIC PREDICTION METHOD FOR THE LOW SPEED PERFORMANCE OF THE 767 SERIES OF TRANSPORTS

This note describes the method used by the NAS Aerodynamics Staff to predict the lift, drag and pitching moments for the low speed and high lift configurations of the 767 series of transports.

METHOD BASIS

The procedure given will predict preliminary full scale values of the low speed parameters required to estimate performance of various high lift systems. The method applies to both subsonic and transonic designs and is based on data from the SST Aerodynamics Group and previous work used for NAS performance predictions with modifications and extensions to provide for the higher sweeps and lower aspect ratios typical of the transonic transport configurations.

It should be realized that this document, which relies heavily on measured results, is intended as a working paper to be improved and extended as more pertinent data becomes available.

CONTENTS

DETAILED PROCEDURE

Wing area definitions are given in Figure 1, LE and TE flap geometries together with lift effectiveness equations in Figure 2. For aerodynamic parameters of lift, drag and pitching moment see Figure 3.

1. Lift Curve Build Up

1.1 Linear lift curve slopes

For high and medium aspect ratios, > 5, the basic wing lift curve slope shown in Figure 4 is assumed linear and given by:

$$C_{L_\alpha} = \frac{2\pi\,(1 + t/c)}{\frac{E}{\cos\Lambda_{c/4}} + \frac{2}{AR}} \quad \text{where} \quad E = \sqrt{1 + \left(\frac{2\cos\Lambda_{c/4}}{AR}\right)^2}$$

1.2 Non-linear lift curve slopes

For low aspect ratio wings 5 > AR > 1.0 the total lift is given by:

$$C_L = C_{L_\alpha} \sin\alpha_1 \cos^2\alpha_1 + C_{L_\alpha}\left(1 - \frac{C_{L_\alpha}}{\pi AR}\right)\frac{\cos\alpha_1 \sin^2\alpha_1}{\cos\Lambda c/4}$$

where C_{L_α} = linear lift curve slope, per radian

α_1 = α measured from zero lift α.

This gives higher than linear values?

Note expression reduces to linear lift curve as α tends to zero.

1.3 Effect of fuselage on C_{L_α}

Figure 5 shows effect of body on basic wing C_{L_α}

1.4 Effect of LE and TE device area extensions on C_{L_α}

Increases in lift curve slope (based on S_W) are obtained due to fowler motion of the LE and TE high lift devices. For L E devices full benefit is assumed

$$C_{L_{\alpha_o}} = C_{L_\alpha}\left(1 + \frac{\Delta S_{LE}}{S_W}\right)$$

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For TE flaps full area benefit is realized at low and moderate deflections only, reducing to about 40% at the landing setting. A general variation is suggested in Figure 6.

1.5 Lift decrement due to LE devices

The lift decrement due to the LE device is calculated in a similar way to the following TE flap increment and is added at the basic wing zero lift angle. The equation is

$$\Delta C_{L_{LE}} = C_{L_{\alpha}} \cdot \alpha_{\delta_{LE}} \cdot \delta_{LE} \cdot \frac{C''}{C} \cdot K_b$$

where $C_{L_{\alpha}}$ is basic aircraft lift curve slope. The LE device lift effectiveness, $\alpha_{\delta_{LE}}$, is very close to the potential flow and therefore assumed value in Figure 7. For Kb, part span factor, see Figure 11.

1.6 Lift increment due to TE flaps

The increment in lift due to TE flaps above the LE device down only datum is given by the following expression in the linear region ($\alpha = 8°$)

$$\Delta C_{L_{TE}} = C_{L_{\alpha_o}} \cdot \alpha_{\delta} \cdot \delta_{F_{EFF}} \cdot \frac{C'}{C} \cdot K_{AR} \cdot K_b + C_{L_{o_{\alpha = 8°}}} \cdot \left(\frac{C'}{C} - 1\right) \cdot K_b$$

The geometric and lift terms are defined in Figure 2 with the suffix o pertaining to the TE flaps up, LE device down configuration. The 2-D flap lift effectiveness parameter, α_{δ}, is presented for various types of flaps in Figure 8 for constant flap chord, it is based on 2-D data and 3-D results analyzed by the reverse process. Flap chord factor is given in Figure 9. The conversion of α_{δ} to 3-D requires the factor K_{AR} (to finite Æ) found in Figure 10 which is the correction for lifting-line to lifting surface theory. Flap Fowler motion is accounted for with the extended chord ratio C'/C and part span effects by the factor K_b, Figure 11.

Discontinuous flap systems should be treated separately with the total $\Delta C_{L_{TE}}$ being added to the flaps up, LE down C_L at $\alpha = 8°$.

2. Maximum Lift Prediction

2.1 Basic Wing $C_{L_{MAX}}$

The basic wing $C_{L_{max}}$ including a LE device as required is shown in Figure 12 and is representative of good design practice. Guide lines have been drawn with the aid of simple theoretical considerations anchored to known data points. At high sweeps, say $> 50°$, some account should be taken of LE vortex lift.

Although $C_{L_{max}}$ from Figure 12 does include the effect of a LE device, Figure 13 is provided for separate estimation of $\Delta C_{L_{max_{LE}}}$ if required.

2.2 Maximum lift increment due to TE flaps

$$\Delta C_{L_{max_{TE}}} = C_{L_{max_0}} \cdot \psi \cdot \frac{\Delta S_{TE}}{S_W} + \Delta C_{L_{max_2}} \cdot \frac{S_2}{S_W}$$

where ΔS_{TE} is the area added by the flap fowler motion and S_2 the area of the flapped portion of the wing including flaps. The fowler area efficiency factor ψ is given in Figure 14. The sectional increment in $C_{L_{max}}$ due to flap camber, $\Delta C_{L_{max_2}}$, is found using Figure 15 knowing ΔC_{L_1} which is the zero lift angle part of the previously estimated $\Delta C_{L_{TE}}$.

$$\Delta C_{L_1} = C_{L_{\alpha_0}} \cdot \alpha_\delta \cdot \delta_{F_{EFF}} \cdot \frac{c'}{c} \cdot K_{AR} \cdot K_b$$

to get

$$\Delta C_{L_2} = \Delta C_{L_1} \cdot \theta \cdot \frac{S_W}{S_2}$$

where θ = ratio of lift due to flap on flapped part of wing to total lift due to flap, Figure 16. This is a "carryover" type factor for use in the above sectional lift determination and is a function of net flap span.

2.3 Dynamic Stall Effects

These are added to the total <u>trimmed</u> $C_{L_{max}}$ (1g) to give FAR $C_{L_{STALL}}$. Figure 17 shows flight data for various Boeing aircraft, the mean line giving + 10% for all flap settings. Finally, a check on the estimated approach lift coefficient can be made using Figure 18 where simple theoretical considerations applied to known data points provide guide lines for varying sweep and aspect ratio.

3. Pitching Moment Estimation

3.1 Pitching moment due to flaps

The total $C_{M_{CG}}$, flaps down, is given by the expression:

$$C_{M_{cg}} = C_{M_o} + C_{L_o}\left(\frac{x_{cg}}{\bar{c}} - \frac{x_{ac}}{\bar{c}} - \frac{\Delta x_{ac}}{\bar{c}}\right) + \Delta C_{L_1}\left(\frac{x_{cg}}{\bar{c}} - \frac{x_{cp}}{\bar{c}}_{TE}\right)$$

where ΔC_{L_1} is the TE flap lift at the flaps up zero lift alpha.

The flap pitching moment increment is therefore:

$$\Delta C_{M_{TE}} = C_{L_o}\left(-\frac{\Delta x_{ac}}{\bar{c}}_{TE}\right) + \Delta C_{L_1}\left(\frac{x_{cg}}{\bar{c}} - \frac{x_{cp}}{\bar{c}}_{TE}\right)$$

The rearward shift in aerodynamic center due to Fowler motion of the TE flaps is approximately given by

$$\frac{\Delta x_{ac}}{\bar{c}}_{TE} = \frac{1}{4AR}\left(\frac{\Delta S_{TE}}{S_W} \cdot \frac{S_W}{\bar{c}^2}\right)$$

The spanwise and chordwise position of the flap load center of pressure (CP) can be determined knowing the wing and flap geometries. Firstly, construct lines perpendicular to the C/2 line at the flap

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extremities as described in Figure 19. The CP chordwise position $\frac{x^*_{CPTE}}{c}$ found from Figure 20 can then be marked on these perpendiculars. The flap load CP line is then constructed by joining the two points linearly. The CP spanwise position, η_{CP}, from Figure 21 is located on the flap load CP line. Finally, the distance of the flap CP to the CG can easily be calculated. As before discontinuous flaps are treated separately.

At the stall there is usually some pitching moment relief from the linear variation suggested above due wing tip and flap separations occurring before $C_{L_{max}}$. Results from model tests of various Boeing aircraft suggest at $C_{L_{max}}$ the total pitching moment is approximately 70% of that calculated.

3.2 Trim losses

The down load on the tail required to produce zero overall pitching moment about the c.g.

$$\Delta C_{L_{TO\ TRIM}} = \frac{C_{M_{cg_{TAIL\ OFF}}}}{l_t/\bar{c}}$$

where $l_t/\bar{c}$ is the tail arm usually measured from the wing $\frac{1}{4}$ mac to the tail-plane $\frac{1}{4}$ mac.

4. Drag Polar Build Up

The procedure will assume the following traditional build up of the untrimmed drag polar:

$$C_D = C_{DP_{min\,cruise}} + \frac{C_L^2}{\pi A\!R} + \Delta C_{DP_{min_{LE}}} + \Delta C_{DP_{min_{TE}}} + \Delta C_{Di_{TE}} + \delta C_{DP_{LE}} + \Delta C_{DP}$$

4.1 Basic aircraft (cruise configuration) minimum parasite drag

$C_{D_{P\ mincruise}}$ is calculated at the chosen Reynolds Number by a standard build up procedure described in the Boeing drag document number D6-8195.

4.2 Induced drag of basic wing

This is assumed to be of the form $\frac{C_L^2}{\pi AR}$ with variations from the parabolic shape accounted for in the ΔC_{D_P} term.

4.3 Parasite drag of LE device

$\Delta C_{D_{P\ min\ LE}}$ is found from Figure 22 knowing $\Delta S_{LE}/S_W$. It has been shown that this term decreases in magnitude with increasing flap deflection and hence circulation, although data is scarce a possible variation of $\delta C_{D_{P\ LE}}$ with $\Delta C_{L_{TE}}$ is given in Figure 23.

4.4 Parasite drag of TE flaps

$\Delta C_{D_{P\ minTE}}$ is found from Figure 24 knowing the flap type and geometry.

4.5 Induced drag of TE flaps

ΔC_{D_i} is assumed to be of the form $K^2 \Delta C_{L_{TE}}^2$. The factor K is found from Figures 25a through 25i for various aspect ratios and flap spans. If a high speed aileron cut-out is present, find K by using a reduced flap span assuming the cut-out to be at the inboard end. Unlike the lift and parasite drag calculations the induced drag of discontinuous flaps cannot be found "by parts".

4.6 Variation of polar from parabolic shape

ΔC_{D_P} takes into account the variation of the polar from a parabola and as such includes all unknown lift induced drag. The C_L at which ΔC_{D_P} is zero is termed C_{L_P} and is found, flaps down, by adding to the basic aircraft C_{L_P} increments due to the LE and TE high lift devices, see Figures 26 and 27. The C_{L_P} for the basic aircraft is a function of wing sweep, section camber and thickness (design C_l) and may be calculated using the method in the Boeing Subsonic Drag document or that described in Figures 28 through 30. Various test data for a wide range of wing sweeps and aspect ratios has been analyzed and used to produce the working curves of ΔC_{D_P} , Figures 31 and 32, for high lift configurations. Cruise wing ΔC_{D_P} 's have also been included, Figure 33, for comparison with above methods.

4.7 Final Polar Prediction

A total drag build up format is suggested in Figure 34; the polars then being plotted against lift.

An estimate for the extra trim drag will be required for more forward c.g.'s. In calculating L/D's for takeoff and landing predictions windmill and yaw drag will have to be added for engine out cases. For landing configurations the addition of gear drag is also required.

5. Ground Effect

A further refinement, not dealt with here, would be the effect of ground proximity on lift and drag.

The procedure outlined in this note, though wanting in many respects, should predict estimates of sufficient accuracy for preliminary performance calculations.

6. Appendix

Comparisons of results using the prediction method with those of flight-model testing are shown in appendix Figures 1, 2 and 3 for Boeing transport airplanes.

It should be noted that since these predictions were calculated modifications have been made to the method in an attempt to improve accuracy.

<u>TABLE 1</u>

<u>List of Symbols</u>

AR	= Aspect Ratio
b	= Wing span
bco	= Span of TE flap cut-out due to fuselage
bf	= Span of TE flap
c	= Wing chord
$\bar{c}$	= Mean aerodynamic chord
c'	= Extended wing chord, TE flaps down
c"	= extended wing chord, LE device down
C_{LE}	= LE device chord
C_{MF}	= Main flap chord (including fore-flap if present)
C_{AF}	= Aft flap chord
C_F	= Expanded TE flap chord
C_L	= Lift coefficient
C_D	= Drag coefficient
$C_{M_{cg}}$	= Pitching moment coefficient about c.g.
$\Delta C_{L_{TE}}$	= Lift increment due to TE flaps at constant $\alpha = 8°$
$\Delta C_{L_{LE}}$	= Lift increment due to LE device at cruise zero lift α
$\Delta C_{M_{TE}}$	= Pitching moment increment due to TE flaps at constant $\alpha = 8°$
$C_{L_{max_{1g}}}$	= Maximum trimmed lift coefficient at 1g
FAR $C_{L_{STALL}}$	= Maximum trimmed lift coefficient including dynamic effects
$\Delta C_{L_{max_{TE}}}$	= Increment in maximum lift coefficient due to TE flaps
$\Delta C_{L_{max_{LE}}}$	= Increment in maximum lift coefficient due to LE device
ΔC_{L_2}	= Sectional lift increment due to TE flap camber
$\Delta C_{L_{max2}}$	= Sectional maximum lift increment due to TE flap camber

C_{L_P}	=	Lift for minimum parasite drag in cruise configuration
$\Delta C_{L_{P_{TE}}}$	=	Increment in lift for minimum parasite drag due to TE flaps
$\Delta C_{L_{P_{LE}}}$	=	Increment in lift for minimum parasite drag due to LE device
$C_{DP_{min_{cruise}}}$	=	Minimum parasite drag coefficient in cruise configuration
$\Delta C_{DP_{min}TE}$	=	Increment in minimum parasite drag due to TE flap
$\Delta C_{DP_{min\ LE}}$	=	Increment in minimum parasite drag due to LE device (TE flaps up)
ΔC_{DP_2}	=	Sectional increment in parasite drag due to TE flaps
$\delta C_{DP_{LE}}$	=	Reduction in parasite drag due to LE device with TE flap deflection
$\Delta C_{Di_{TE}}$	=	Induced drag due to TE flaps
ΔC_{DP}	=	Increment in drag due to non-parabolic polar shape
C_{L_α}	=	Lift curve slope
S_{REF}	=	Aerodynamic wing reference
S_W	=	Wing area
S_1	=	Wing area plus area due to extended LE device
S_2	=	Area of flapped part of wing including extended LE & TE devices
ΔS_{LE}	=	Increment in wing area due to extending LE device
ΔS_{TE}	=	Increment in wing area due to extending TE device
(t/c)	=	Section thickness/chord ratio.
K	=	Flap induced drag factor
K_b	=	Flap span factor on lift
K_{AR}	=	Correction factor - lifting line to surface theory
X_{ac}	=	Chordwise position of cruise wing aerodynamic center
X_{cg}	=	Chordwise position of aircraft center of gravity
$X_{CP_{TE}}$	=	Chordwise position of center of pressure of load due to TE flap deflection
$\Delta X_{ac_{TE}}$	=	Shift in aerodynamic center position due to TE flap deflection

α	= Wing angle of attack
α_δ	= Flap effectiveness parameter
β	= Flap pitching moment function
δ_{LE}	= LE device deflection
δ_{MF}	= TE main flap deflection
δ_{AF}	= TE aft flap deflection
$\delta_{F_{EFF}}$	= Effective TE flap deflection
η	= Spanwise station, fraction of semi-span
$f(\eta)$	= Flap spanwise loading function
Θ	= Part span flap lift distribution function
$\Lambda_{c/4}$	= Sweep of wing quarter chord line
ψ	= TE flap fowler area efficiency factor

SUFFICES & ABBREVIATIONS

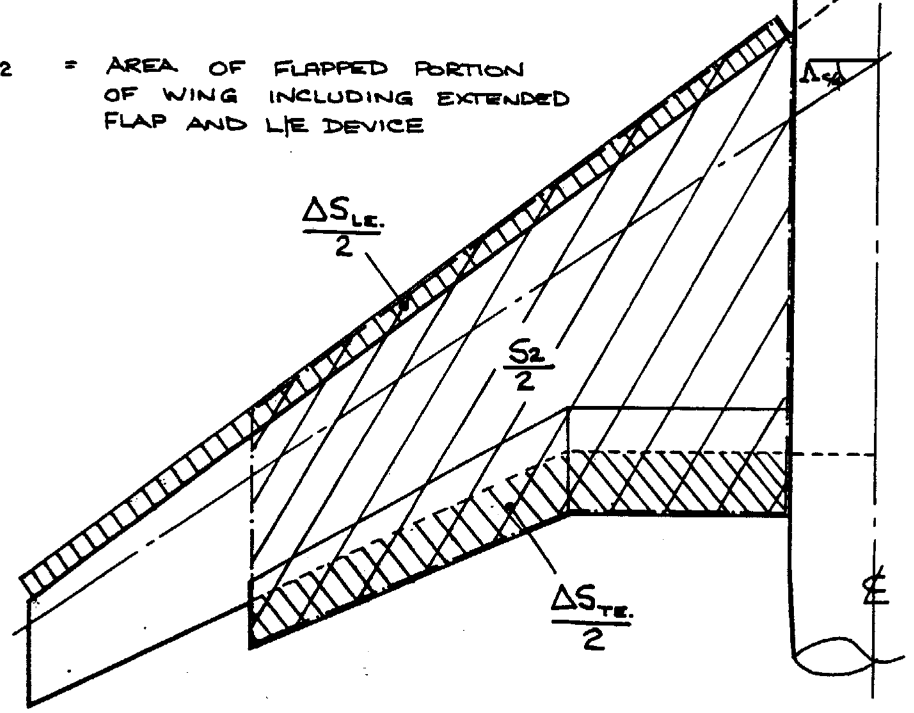
O	= LE device down, TE flaps up configuration
LE	= Leading edge (device)
TE	= Trailing edge (flaps)
I/B	= Inboard
O/B	= Outboard

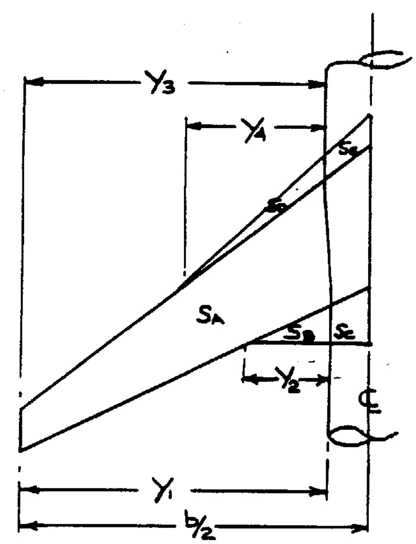
S_{REF} = REFERENCE AREA

S_W = WING PLANFORM AREA

S_1 = $S_W + \Delta S_{LE.}$

S_2 = AREA OF FLAPPED PORTION OF WING INCLUDING EXTENDED FLAP AND L/E DEVICE





S_W = WING PLANFORM AREA

$$= 2\left[S_A + S_B + S_D + S_C\left(\frac{Y_2}{Y_1}\right) + S_E\left(\frac{Y_4}{Y_3}\right)\right]$$

NOTE : $\Delta S_{LE.}$ & $\Delta S_{TE.}$ ARE AREAS FORMED BY FLAP EXTENSIONS MEASURED WITH FLAP CHORD PLANES ROTATED BACK INTO WING CHORD PLANE. SEE FIG. 2.

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AREA DEFINITIONS

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FIG 1

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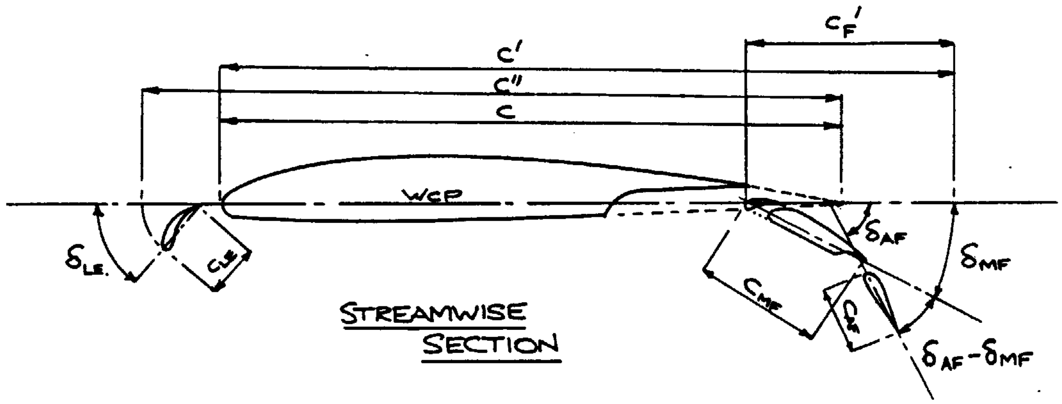
CHORD AND ANGLE DEFINITIONS



ALL CHORDS AND ANGLES MEASURED STREAMWISE

c' = EXTENDED WING CHORD TE. FLAPS DOWN.
c'' = EXTENDED WING CHORD LE. DEVICE DOWN.
c_F' = EXPANDED FLAP CHORD.

L.E. DEVICE LIFT EFFECTIVENESS

$$\alpha_{\delta_{LE}} = \frac{\Delta C_{L_{LE}}}{C_{L\alpha} \cdot \delta_{LE} \cdot \frac{c''}{c} \cdot K_b}$$

WHERE:

$\Delta C_{L_{LE}}$ = LE DEVICE LIFT DECREMENT AT BASIC WING ZERO LIFT ANGLE.

$C_{L\alpha}$ = BASIC WING LIFT CURVE SLOPE

TE. FLAP LIFT EFFECTIVENESS

$$\alpha_{\delta} = \frac{\Delta C_{L_{TE}} - C_{L_{0_{\alpha=8^\circ}}}\left(\frac{c'}{c}-1\right)K_b}{C_{L\alpha_0} \cdot \delta_{F_{EFF}} \cdot \frac{c'}{c} \cdot K_{AR} \cdot K_b}$$

WHERE:

$\Delta C_{L_{TE}}$ = TE FLAP LIFT INCREMENT AT $\alpha = 8^\circ$

K_{AR} = CORRECTION FACTOR ~ LIFTING LINE TO SURFACE THEORY.

K_b = SPAN FACTOR

SUFFIX 0 = TE FLAPS UP, LE DEVICE DOWN CONFIG$^{\underline{N}}$.

$$\delta_{F_{EFF}} = \delta_{MF} + \left(\frac{\alpha_{\delta_{AF}}}{\alpha_{\delta_{MF}}}\right)^{*}(\delta_{AF} - \delta_{MF}) \quad \text{WHERE } \alpha_{\delta_{MF}}^{*} = f\left(\frac{c_F'}{c}\right) \;\&\; \alpha_{\delta_{AF}}^{*} = f\left(\frac{c_{AF}}{c}\right)$$

$\left[\alpha_{\delta_{AF}} / \alpha_{\delta_{MF}} \simeq 0.5\right.$ FOR TYPICAL DOUBLE & TRIPLE SLOTTED FLAP SYSTEMS$\left.\right]$ * FROM FIG. 9.

CALC	M. Grainger	25 MAY 70	REVISED	DATE	LE. AND TE. FLAP GEOMETRY AND LIFT DEFINITIONS	D6-26011 TN FIG. 2
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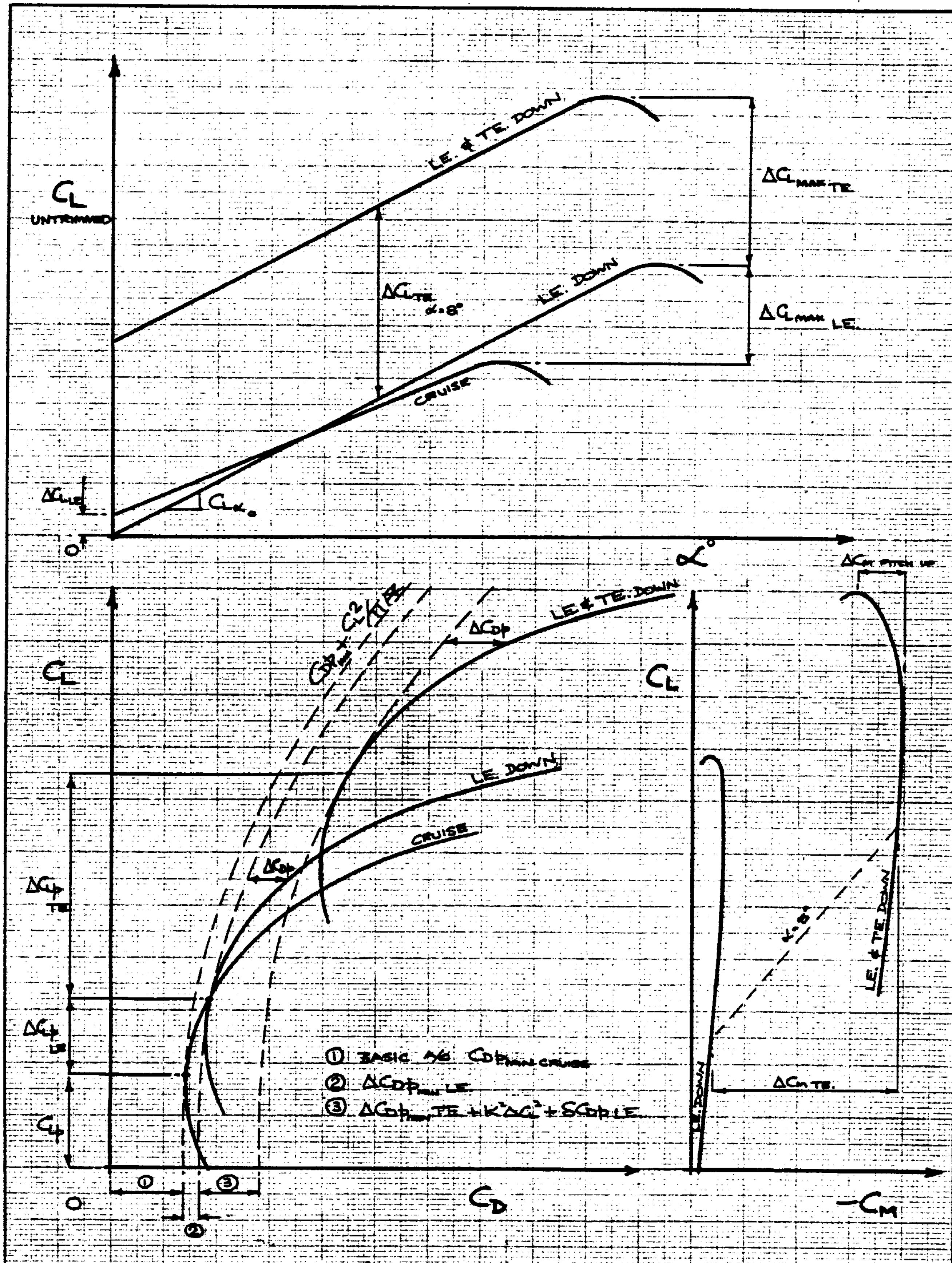

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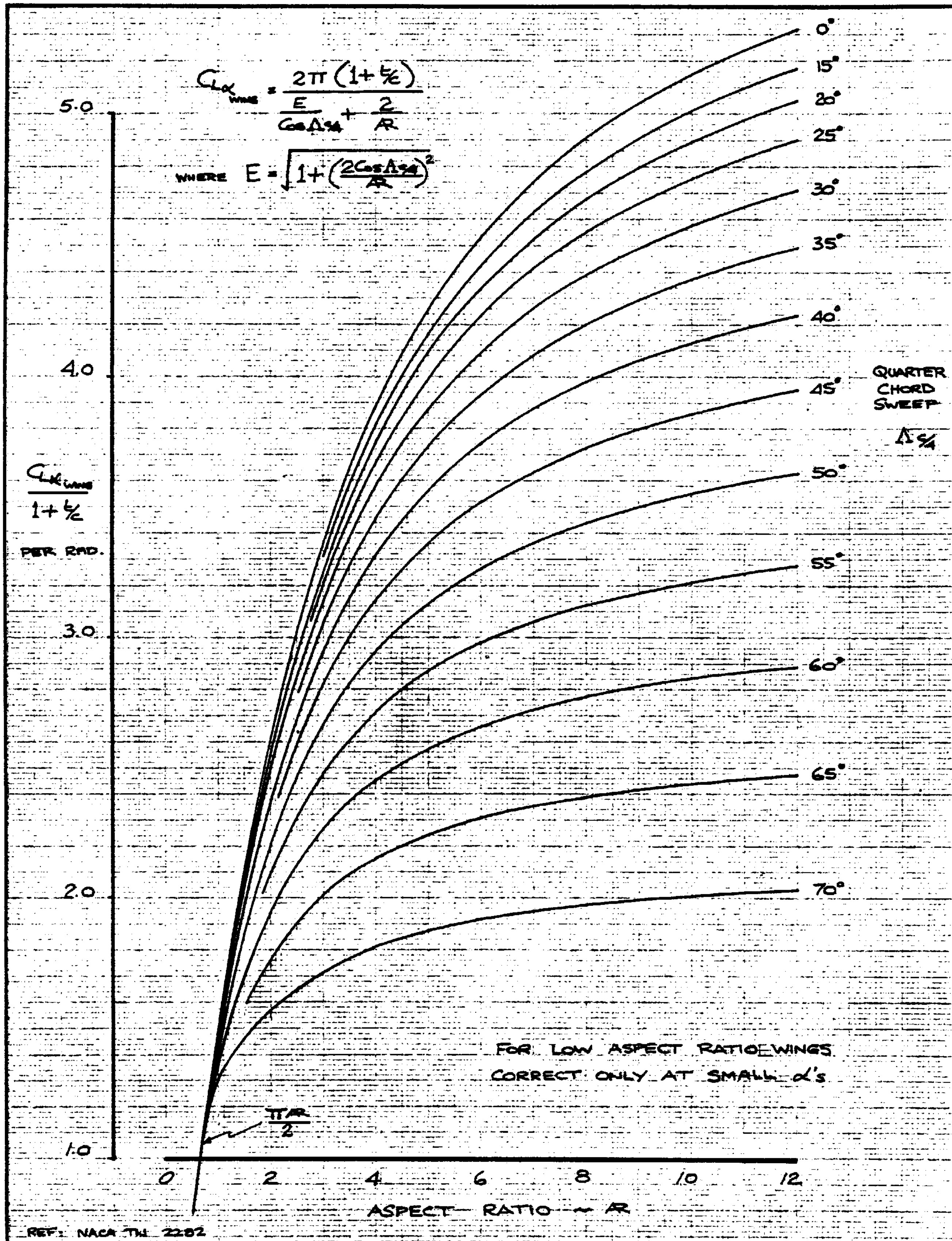

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BASIC WING LINEAR LIFT CURVE SLOPE

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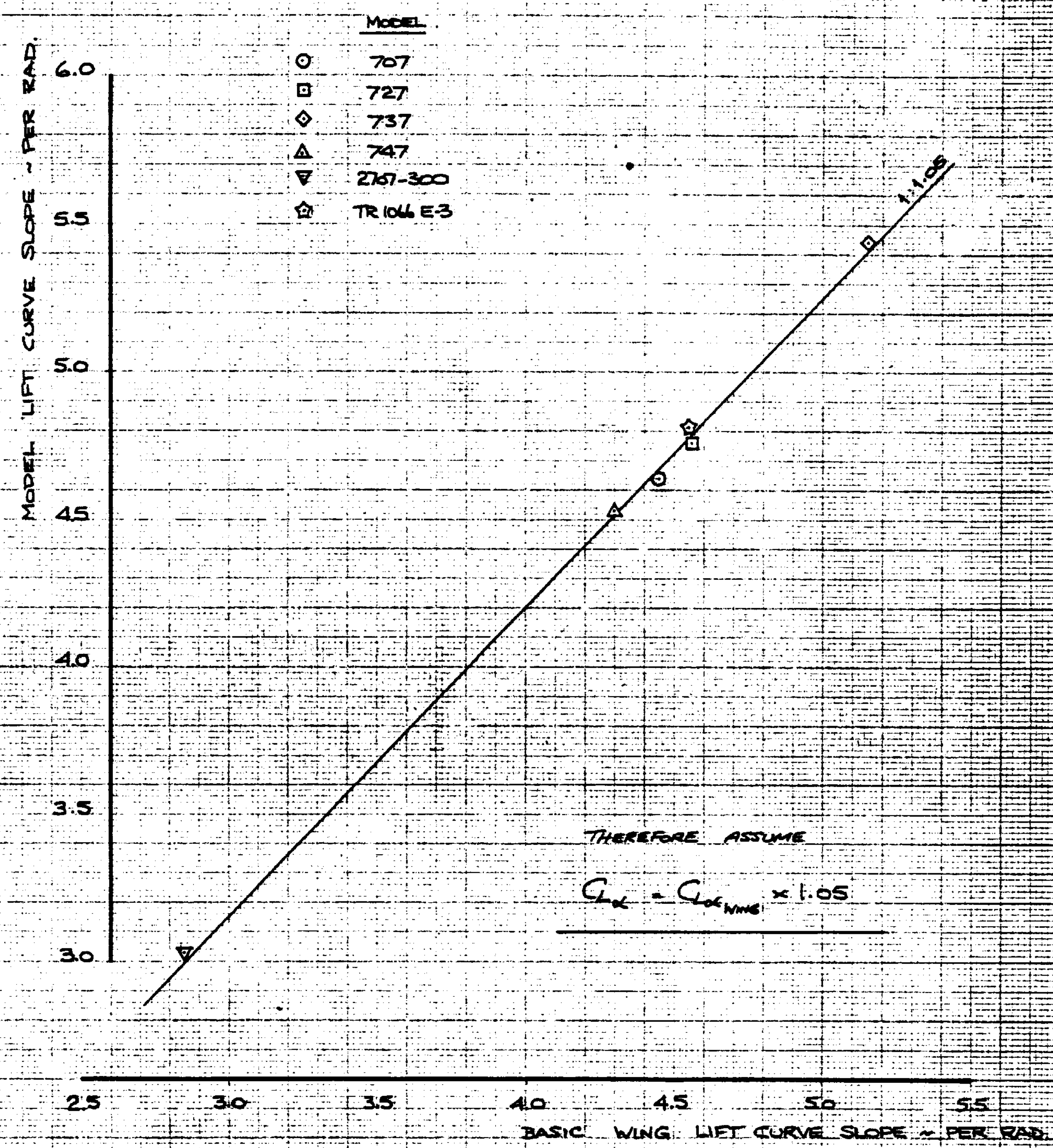
FIG. 4



THEREFORE ASSUME

$$C_{L_\alpha} = C_{L_{\alpha_{WING}}} \times 1.05$$

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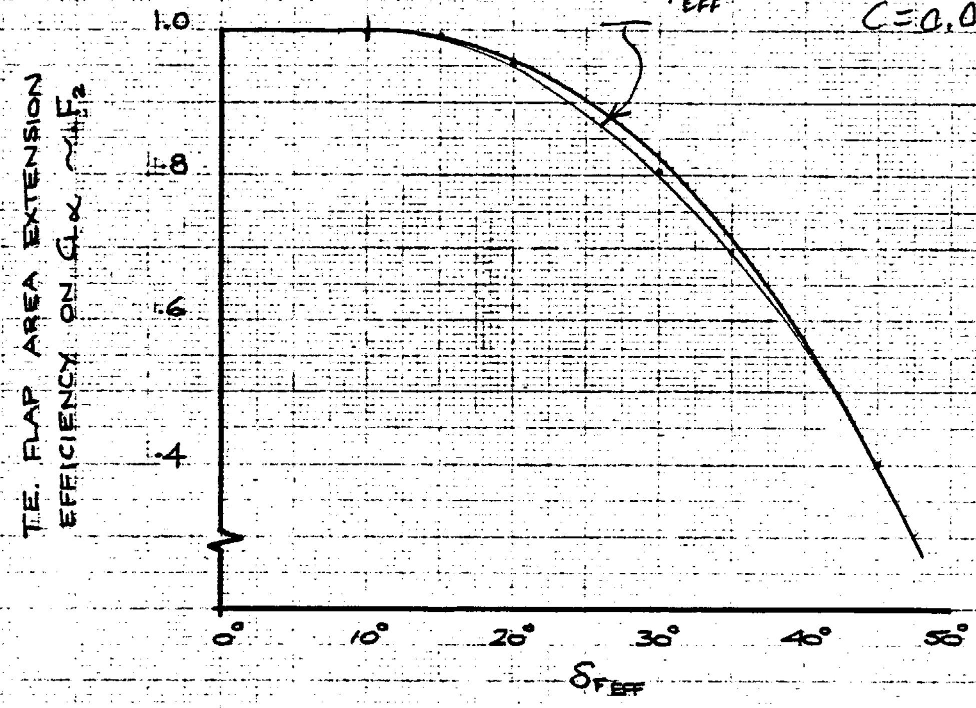
$$C_{L\alpha_{\text{LE DOWN}}} = C_{L\alpha_{\text{CRUISE}}} \times \left(1 + \frac{\Delta S_{LE}}{S_W}\right)$$

$$C_{L\alpha_{\text{LE \& TE DOWN}}} = C_{L\alpha_{\text{LE DOWN}}} \times \left(1 + \frac{\Delta S_{TE}}{S_W} F_2\right)$$

$$F_2 = 1 - C\,(\delta_{F_{EFF}} - 10)^2 \qquad C = 0.0004898$$



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CALC	M. Grainger 6/4/68 %	REVISED	DATE	LEADING AND TRAILING EDGE FLAPS ~ AREA EXTENSION EFFECT ON LIFT CURVE SLOPE.	D6-26011 TN
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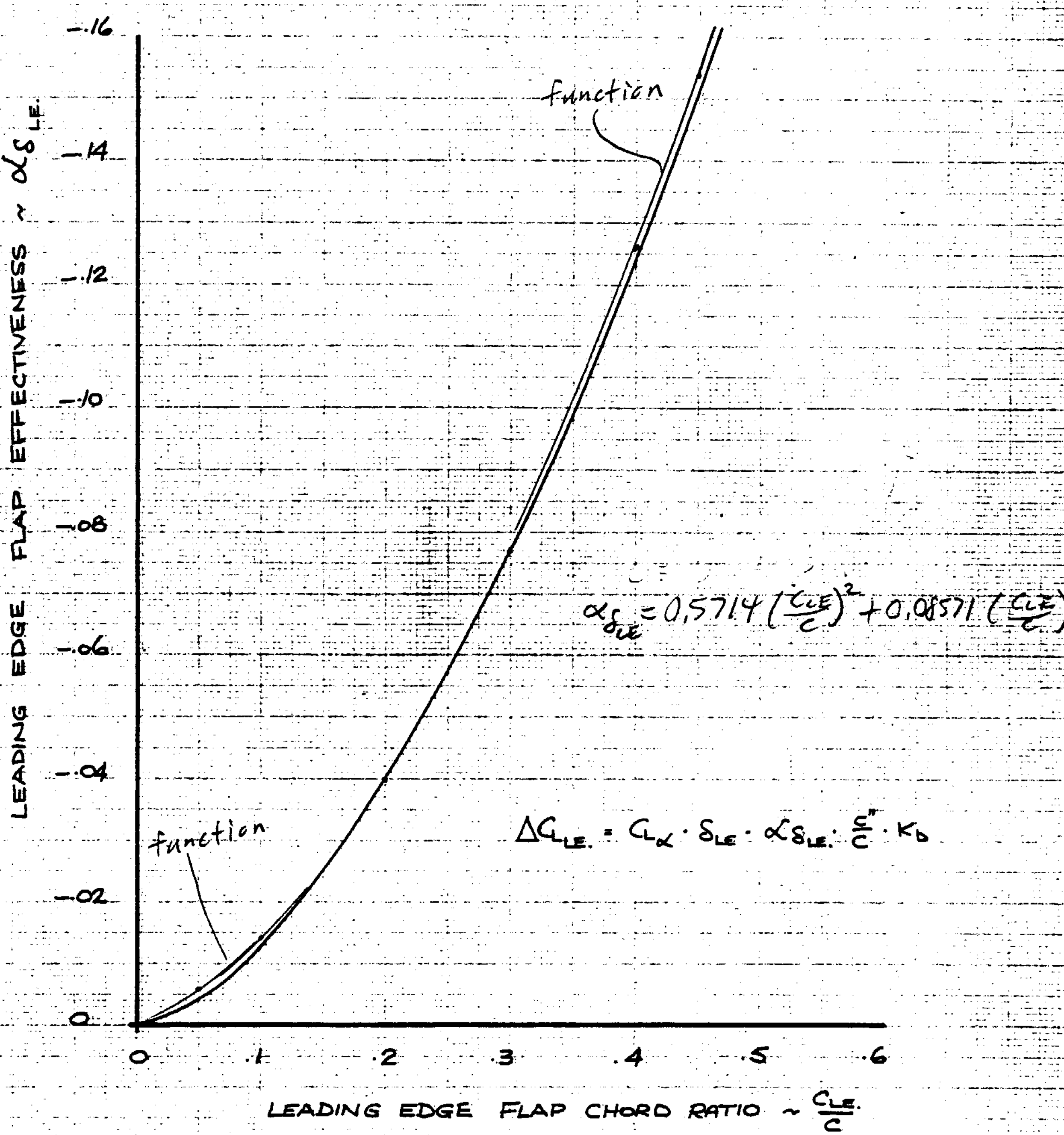

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CALC	From, A.M. Eldridge June '65				LEADING EDGE FLAP EFFECTIVENESS $\alpha_{\delta_{LE}}$	D6-26011 TN
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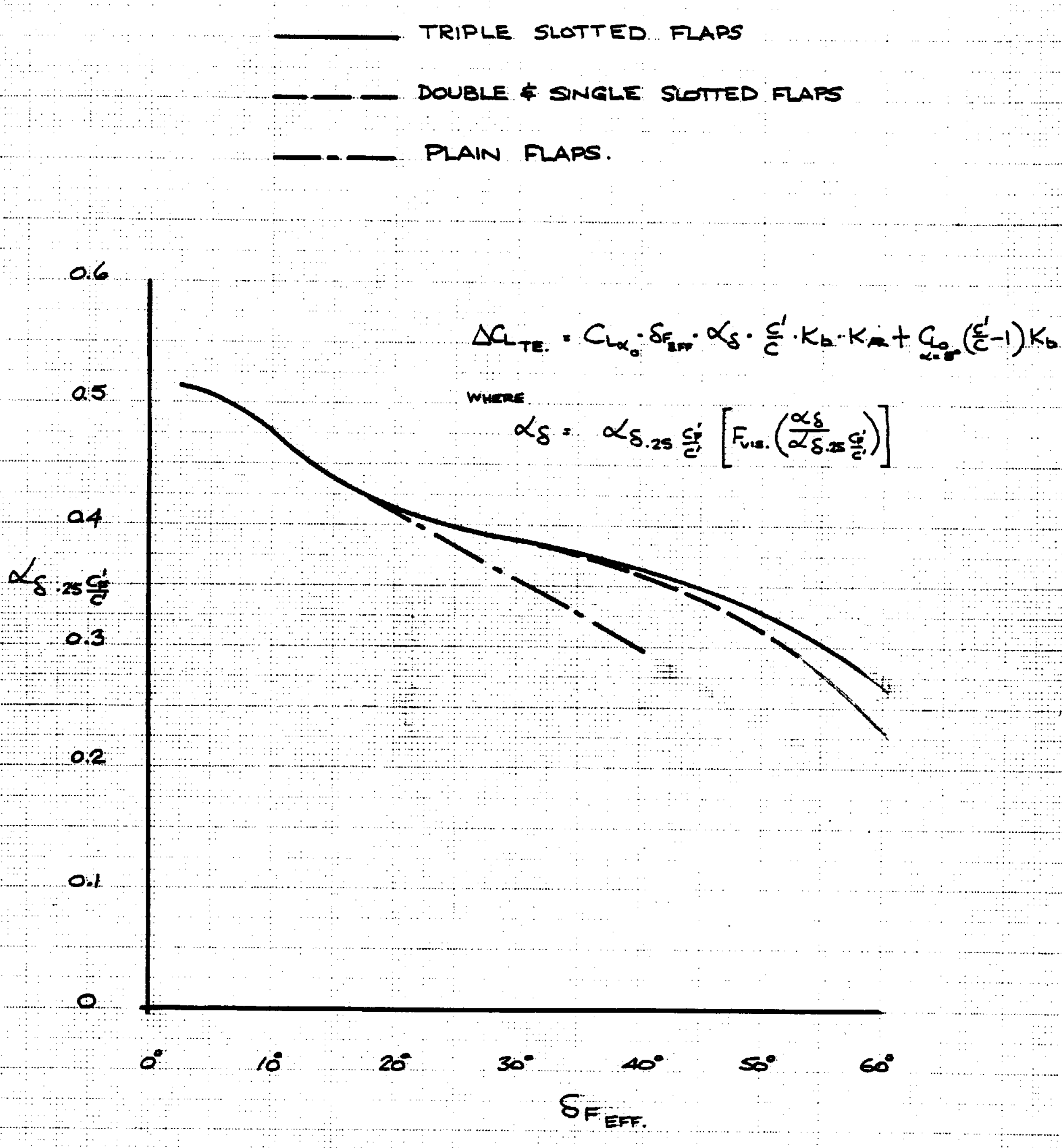
TABLE



$$\Delta C_{L_{TE.}} = C_{L\alpha_0} \cdot \delta_{F_{EFF}} \cdot \alpha_\delta \cdot \frac{c'}{c} \cdot K_b \cdot K_{AR} + C_{L_{0\,\alpha=0°}} \left(\frac{c'}{c} - 1\right) K_b$$

WHERE

$$\alpha_\delta = \alpha_{\delta .25 \frac{c_f'}{c'}} \left[F_{vis.} \left(\frac{\alpha_\delta}{\alpha_{\delta .25 \frac{c_f'}{c'}}} \right) \right]$$

CALC	M. Granger	15 MAY 70	REVISED	DATE	SECTION FLAP EFFECTIVENESS $\alpha_{\delta .25 \frac{c_f'}{c'}} \sim \delta_{F_{EFF.}}$	D6-26011 TN
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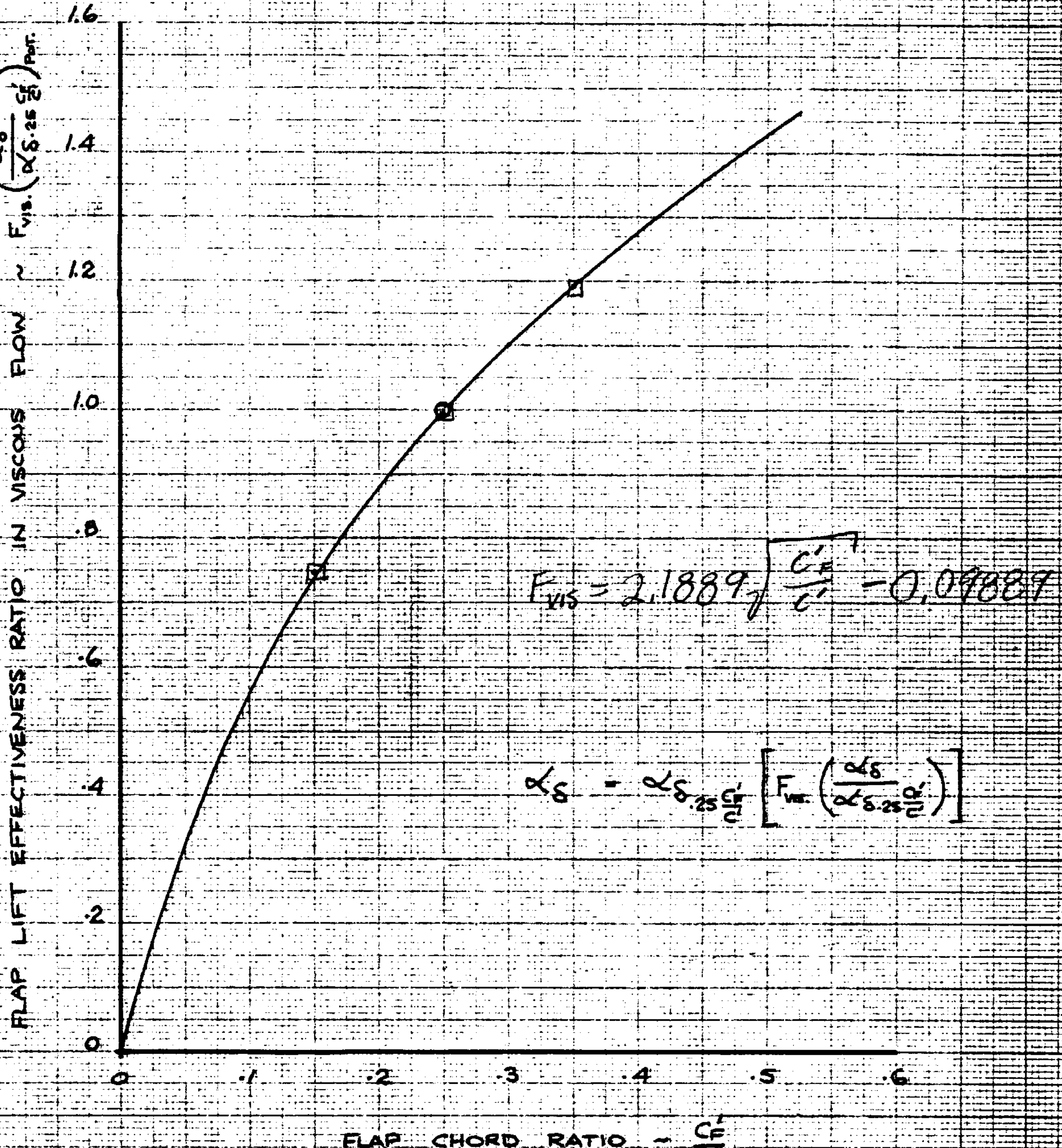

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JUNE 1968

CALC	M. Grainger	FEB '70	REVISED	DATE	FLAP CHORD FACTOR IN VISCOUS FLOW	D6-26011 TN
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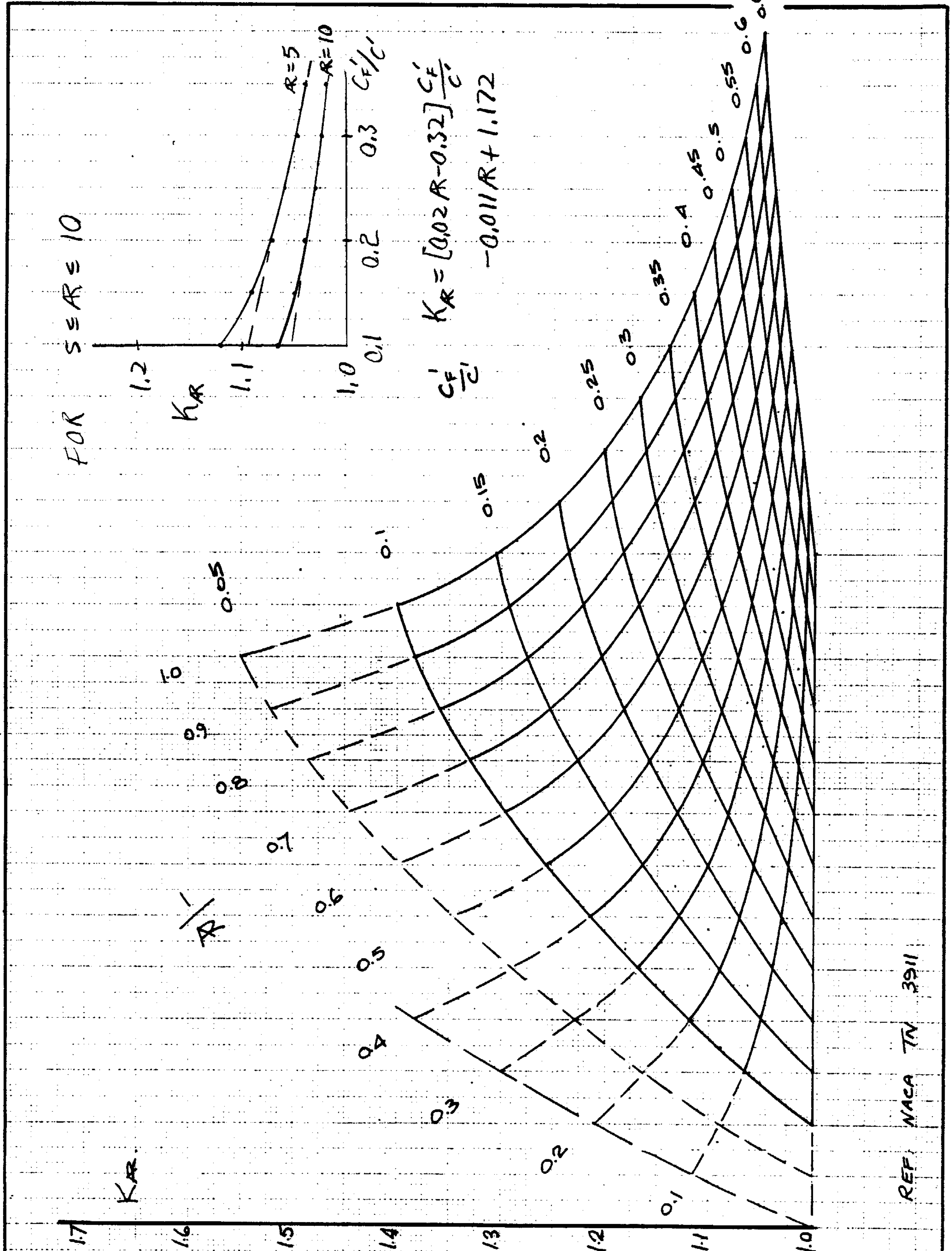

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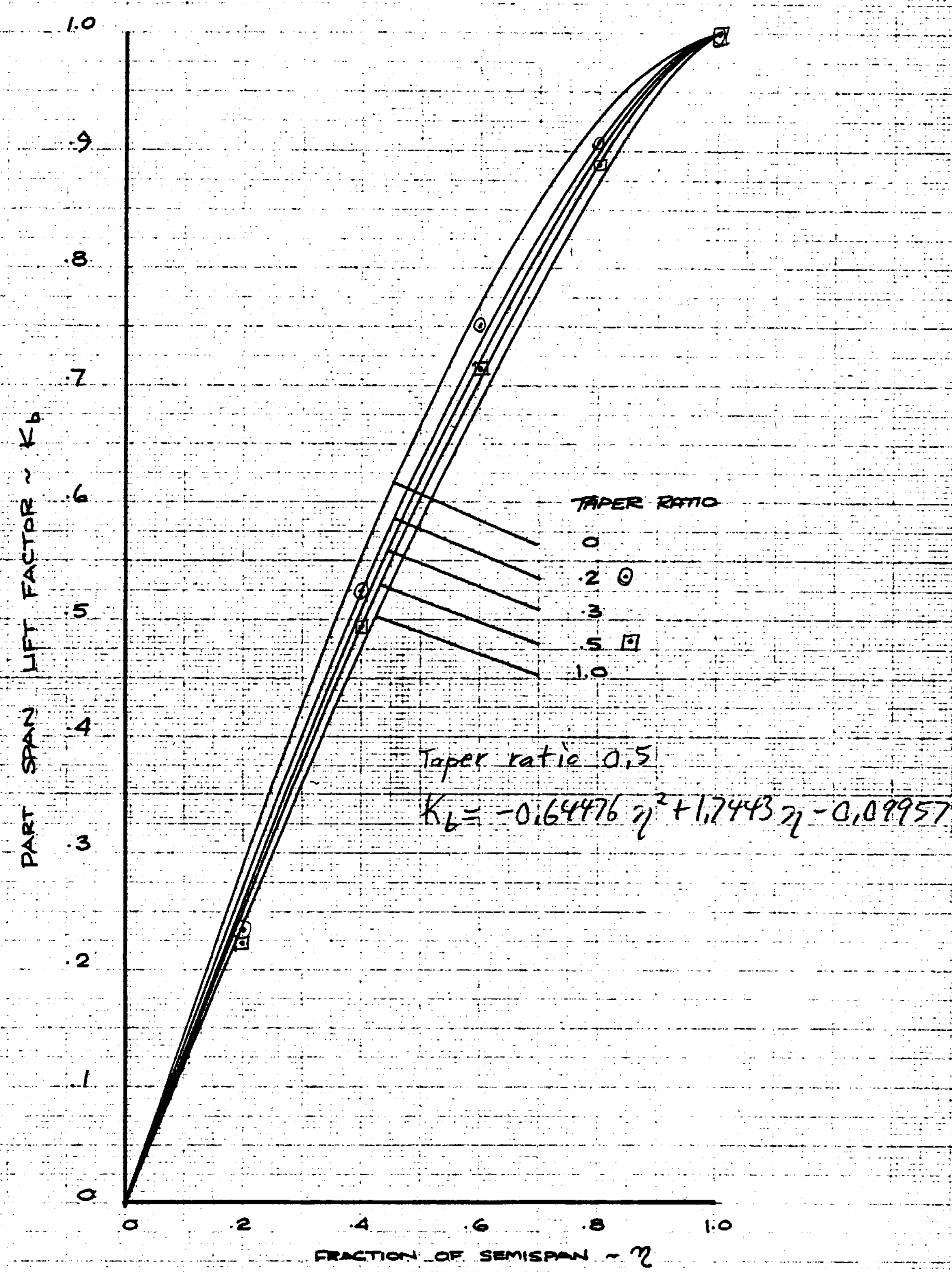
D6-26011 TN

FIG 10

THE BOEING COMPANY

TD 461 D



REF: RAeS DATA SHEETS
FLAPS 01 01 07

CALC	FEB 1970	MY.	REVISED	DATE	PART SPAN FACTOR ON LIFT ~ K_b	D6-26011 TN
CHECK						FIG 11
APR					THE BOEING COMPANY	PAGE 27
APR						

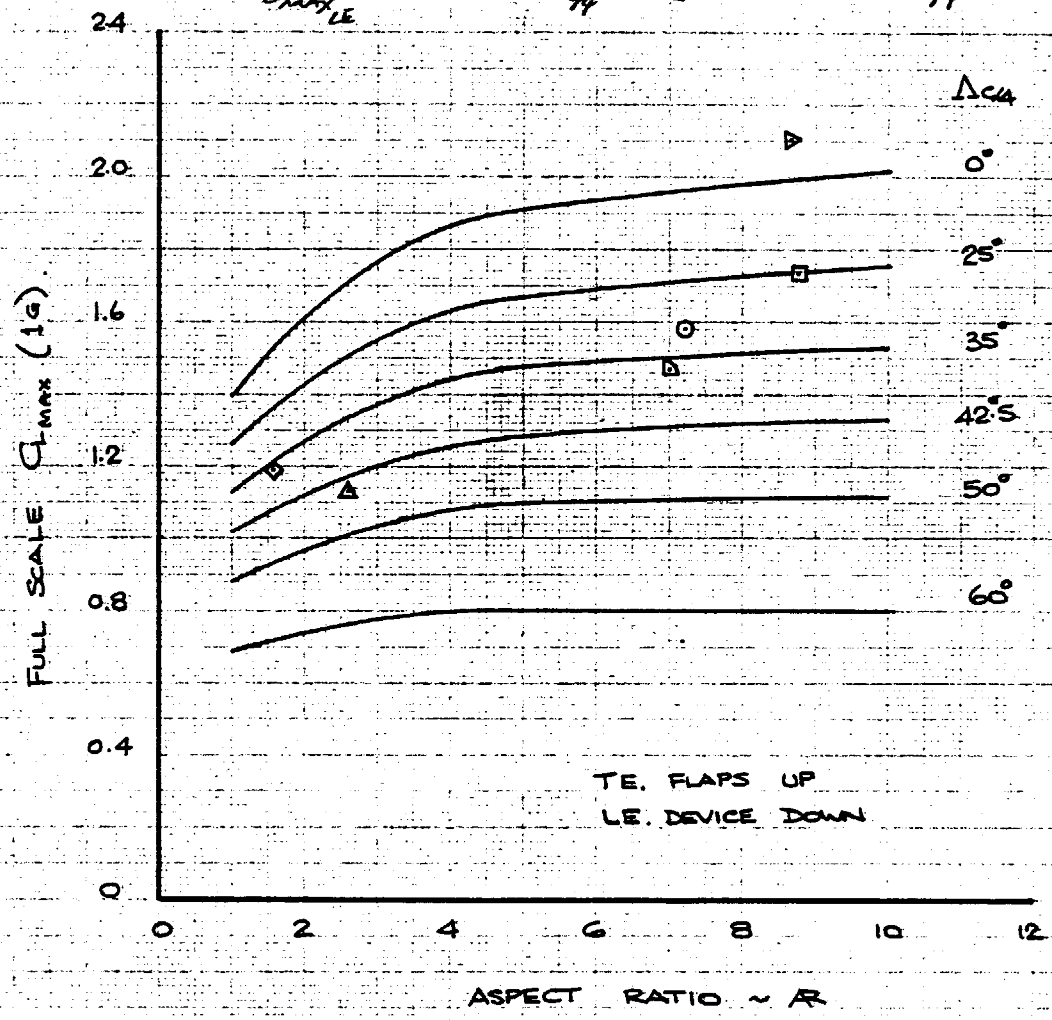
AD 461 C-R4

K+E ALBANENE 196L TRACING PAPER

AIRCRAFT		$\Lambda_{c/4}$
□	737-100	25°
⊙	727	32°
◺	747	37.5°
△	2707-300	42.5°
◇	L-2000	58° (STRONG VORTEX LIFT).
▷	DC-9-30	24°

In the region $5 \leq AR \leq 10$, $0° \leq \Lambda_{c/4} \leq 25°$

$$C_{L_{max_{LE}}} = [-0.00016 \Lambda_{c/4} + 0.02] AR - 0.0092 \Lambda_{c/4} + 1.82$$

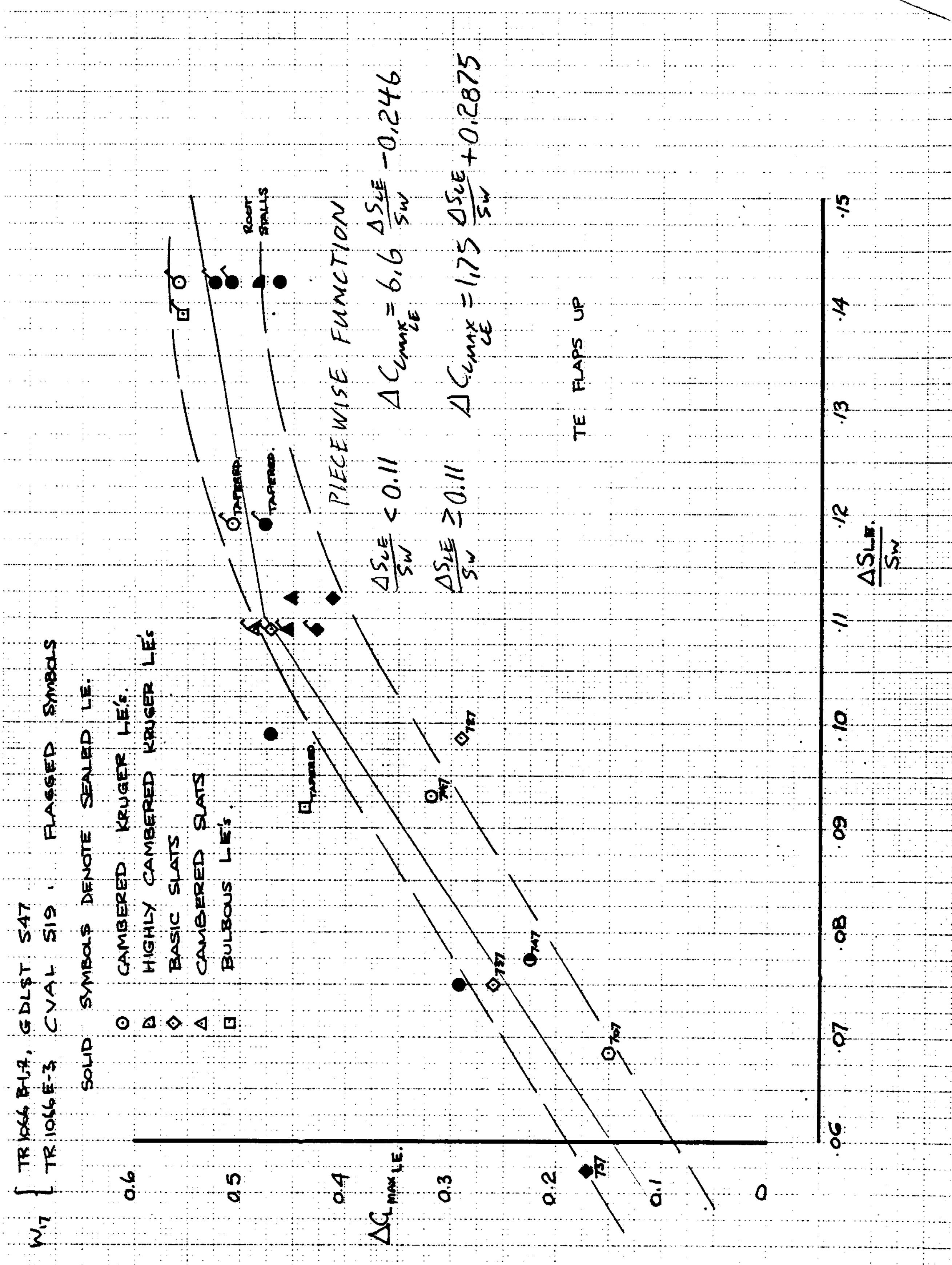


REF: DOC No D6A 11805-1

CALC	From: M.L. JAGER	11.14.69	REVISED	DATE	$C_{L_{MAX}}$ (1G) FOR WINGS WITH TE. FLAPS UP & LE. DEVICES DOWN	D6-26011 TN
CHECK						FIG 12
APR					THE BOEING COMPANY	PAGE 28
APR						

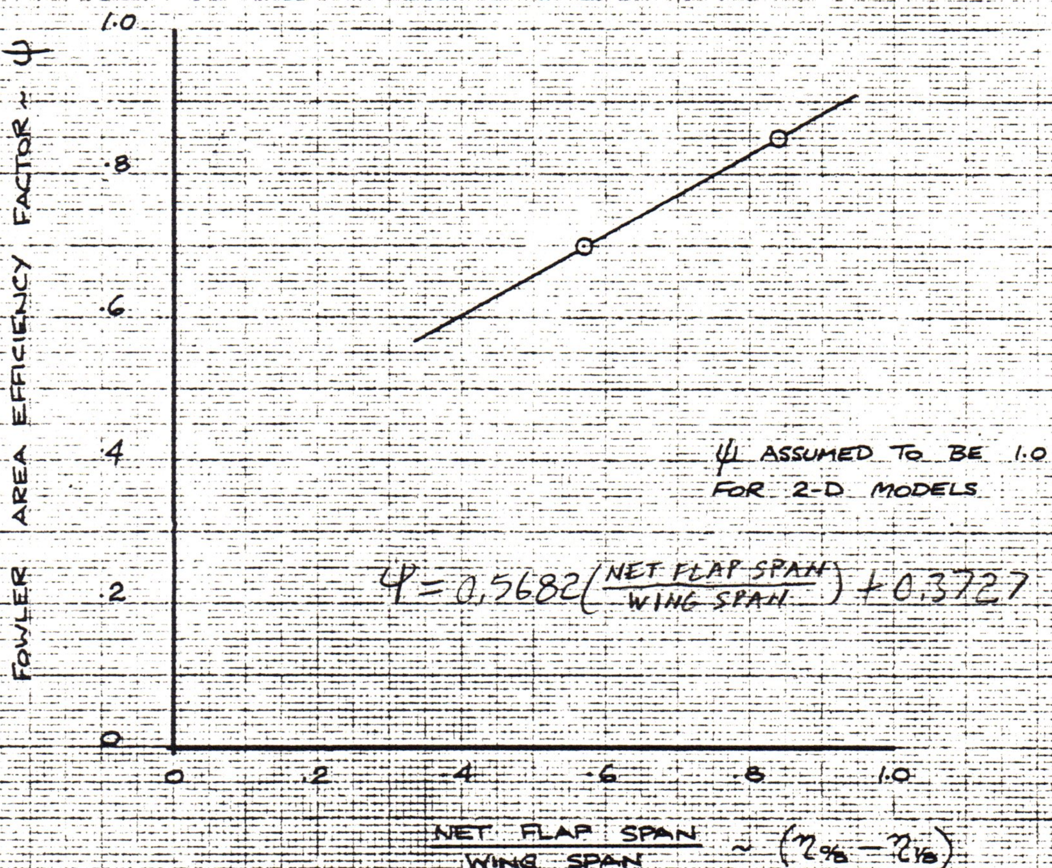
AD 461 C-R4

K+E ALBANENE 196L TRACING PAPER



CALC	19 FEB 70 M. Granger	REVISED	DATE	INCREMENT IN MAX. LIFT DUE TO LE DEVICES ~ $\Delta C_{L_{MAX\,LE}}$	D6-26011 TN
CHECK					FIG 13
APR				THE BOEING COMPANY	PAGE 29
APR					

TD 461 D



$$\psi = 0.5682\left(\frac{\text{NET FLAP SPAN}}{\text{WING SPAN}}\right) + 0.3727$$

$$\Delta C_{L_{MAX\ TE}} = C_{L_{MAX_0}} \cdot \psi \cdot \frac{\Delta S_{TE}}{S_W} + \Delta C_{L_{MAX_2}} \cdot \frac{S_2}{S_W}$$

S_W = WING AREA

ΔS_{TE} = WING AREA ADDED BY FLAP FOWLER MOTION (FLAP EXTENDED & ROTATED INTO WING CHORD PLANE)

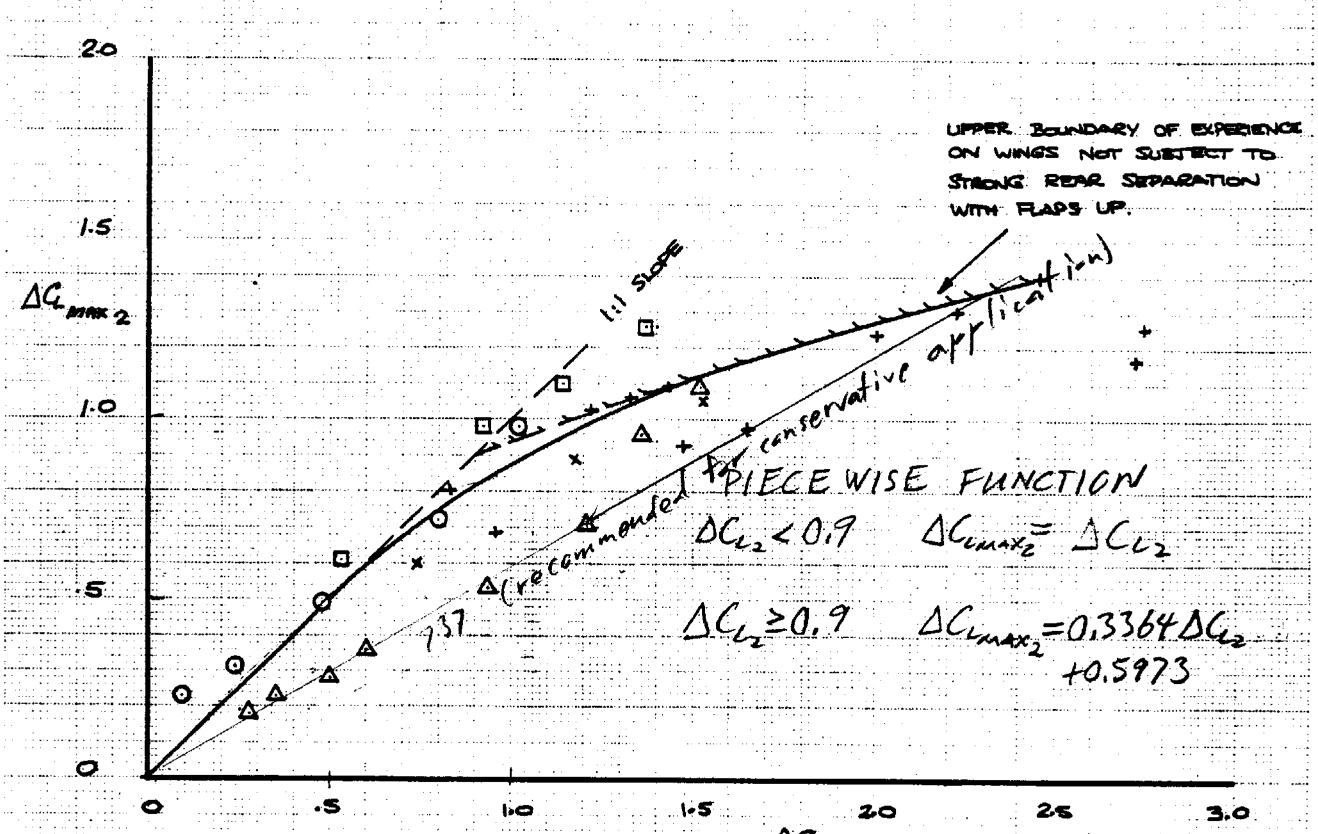
S_2 = AREA OF FLAPPED PORTION OF WING INCLUDING LE. & TE. DEVICES

$\Delta C_{L_{max_2}}$ = SECTIONAL $C_{L_{max}}$ INCREMENT DUE TO FLAP CAMBER

CALC	FROM A.H. ELDRIDGE	JULY '63	REVISED	DATE	FOWLER AREA EFFICIENCY FACTOR TE. FLAP $C_{L_{max}}$ INCREMENT	D6-26011 TN
CHECK		ML.				FIG. 14
APR						
APR					THE BOEING COMPANY	PAGE 30

+ 2-D MODEL DATA: TRIPLE, DOUBLE & SINGLE SLOT FLAPS.
× MODEL DATA: AR = 6, $\Lambda_{c/4}$ = 35°, b_f/b = .566 TRIPLE SLOT FLAP.

⊡ FLIGHT DATA 727
△ ✓ ✓ 737
⊙ ✓ ✓ 747



NOTE: 737 Wing-mounted engines present a "worst case" flap configuration with sizable cutouts.

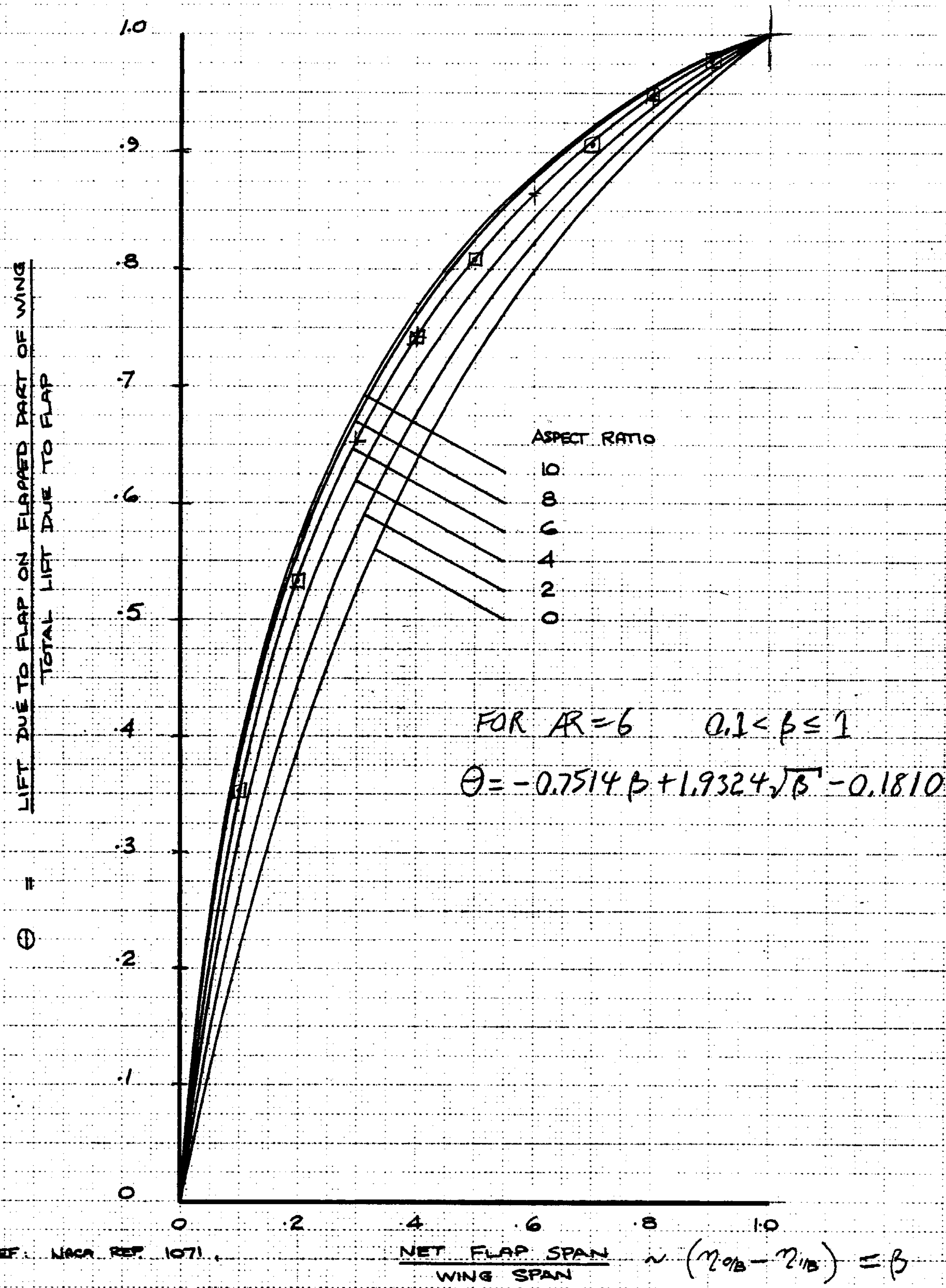
$\Delta C_{L_{MAX\,2}}$ = SECTIONAL MAXIMUM LIFT COEFFICIENT INCREMENT ON FLAPPED PART OF WING.

ΔC_{L_2} = SECTIONAL LIFT INCREMENT ON FLAPPED PART OF WING AT ZERO LIFT ALPHA OF WING + LE DEVICE.

NOTE ! BOTH ABOVE QUANTITIES ARE INCREMENTS DUE TO TE. FLAP CAMBER.

CALC	M Younger	19 MAY 7a	REVISED	DATE	SECTIONAL $\Delta C_{L_{MAX\,TE}}$ CORRELATION	D6-26011 TN
CHECK						FIG. 15
APR						
APR					THE BOEING COMPANY	PAGE 31

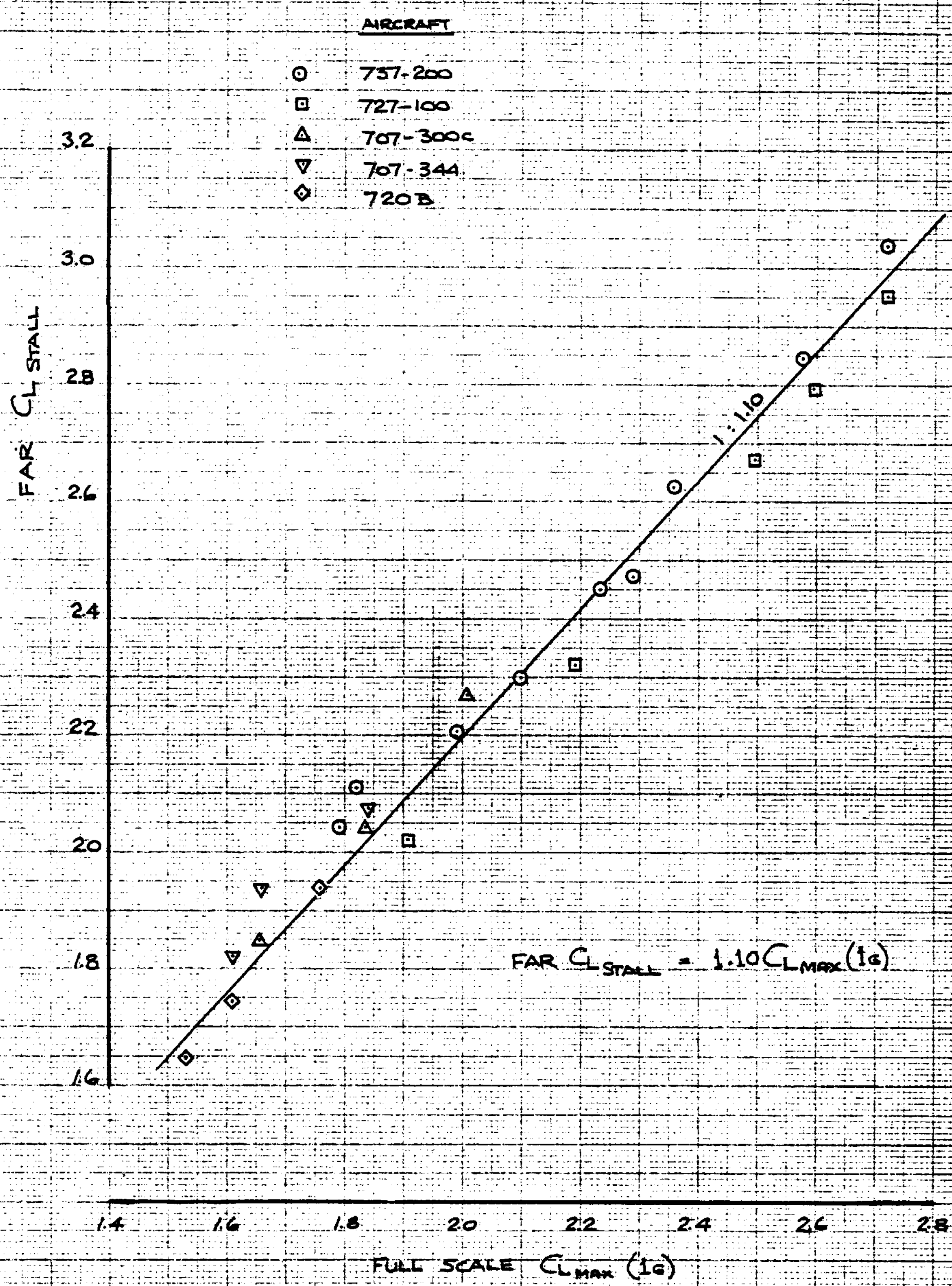
AD 461 D 15.29 6-7000



REF: NACA REP. 1071.

CALC	BASED ON CURVE T.A.P.	6.22.67	REVISED	DATE	DISTRIBUTION OF LIFT DUE PART SPAN [redacted]APS	D6-26011 TN
CHECK	M. Grainger	5 MAR 70				FIG. 16
APR						
APR					THE BOEING COMPANY	PAGE 32

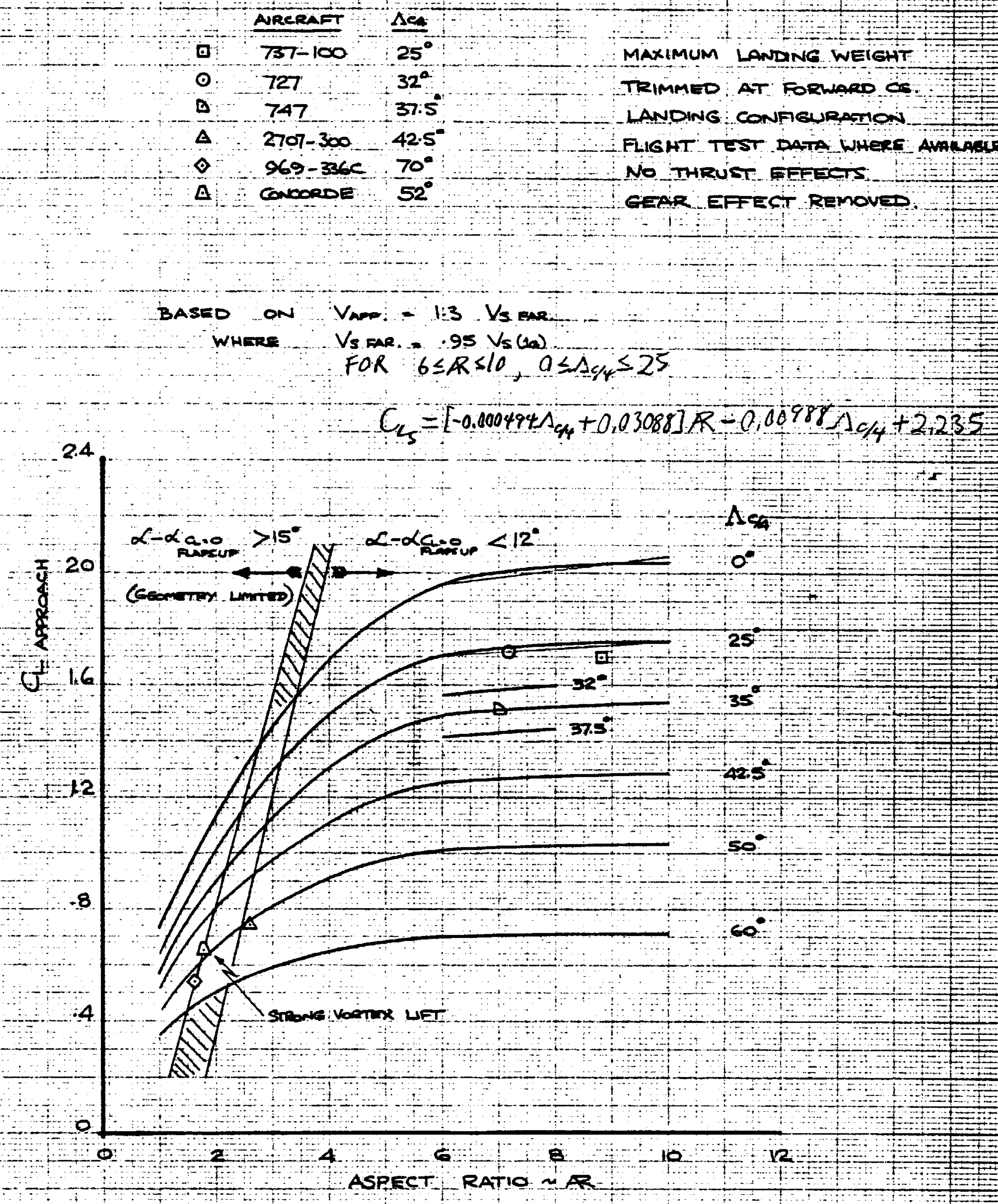
TO 461 D



CALC	E.G. HILL	7/23/68	REVISED	DATE	DYNAMIC STALL EFFECTS ON BOEING AIRCRAFT	D6-26011 TN
CHECK			M. Grainger	MAY 70		FIG. 17
APR					THE BOEING COMPANY	PAGE 33
APR						

AD 461 C-R4

K+E ALBANENE 1961 TRACING PAPER



REF: D6A 11805-1

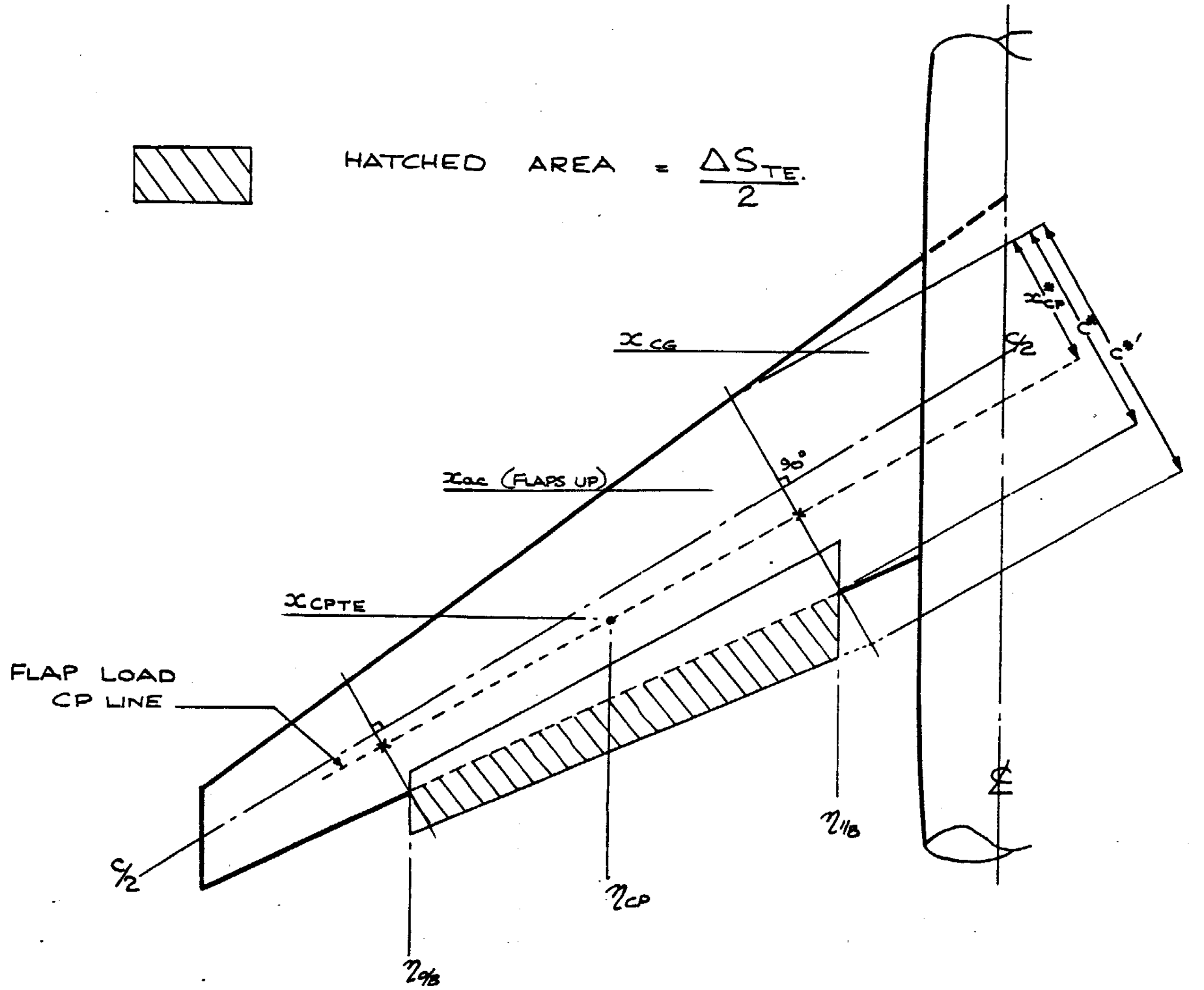
CALC	M.L. JAGER	12.10.69	REVISED	DATE
CHECK				
APR				
APR				

PLANFORM EFFECTS ON APPROACH LIFT COEFFICIENT

THE BOEING COMPANY

D6-26011 TN

FIG. 18



$$C_{M_{CG}} = C_{M_0} + C_{L_0} \cdot \frac{1}{\bar{c}}\left(x_{CG} - x_{ac} - \Delta x_{ac_{TE}}\right) + \Delta C_{L_1} \frac{1}{\bar{c}}\left(x_{ac} - x_{CP_{TE}}\right)$$

WHERE REARWARD SHIFT IN ac DUE TO TE FLAP FOWLER MOTION :

$$\frac{\Delta x_{ac}}{\bar{c}}_{TE} = \frac{1}{4 AR}\left[\frac{\Delta S_{TE}}{S_W} \cdot \frac{S_W}{\bar{c}^2}\right]$$

CALC	M. Granger	18 AUG 70	REVISED	DATE	GEOMETRY FOR FLAP PITCHING MOMENT CALCULATION	D6-26011 TN
CHECK						FIG. 19
APPD						
APPD					THE BOEING COMPANY RENTON, WASHINGTON	PAGE 35

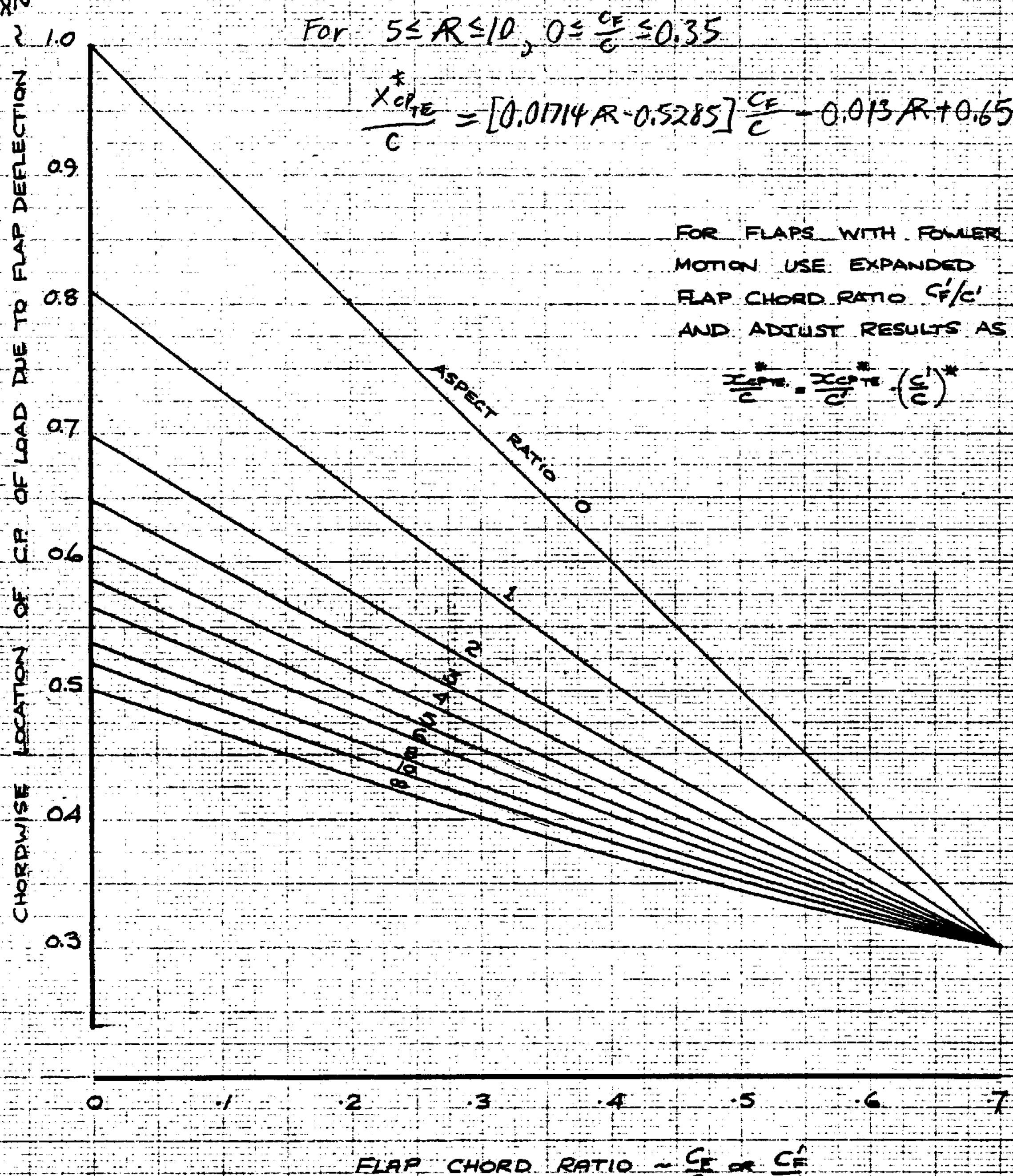
NOTE : THESE VALUES ARE STRICTLY APPLICABLE TO RECTANGULAR WINGS ONLY, LITTLE ERROR WILL BE INCURRED, HOWEVER, IN APPLYING THEM AS LOCAL VALUES ON WINGS OF ARBITRARY PLANFORM.

For $5 \le A\!\!R \le 10$, $0 \le \frac{c_F}{c} \le 0.35$

$$\frac{x^*_{cp_{TE}}}{c} = [0.01714\,A\!\!R - 0.5285]\frac{c_F}{c} - 0.013\,A\!\!R + 0.65$$

FOR FLAPS WITH FOWLER MOTION USE EXPANDED FLAP CHORD RATIO c_f'/c' AND ADJUST RESULTS AS:

$$\frac{x^*_{cp_{TE}}}{c} = \frac{x^*_{cp_{TE}}}{c'} \cdot \left(\frac{c'}{c}\right)^*$$

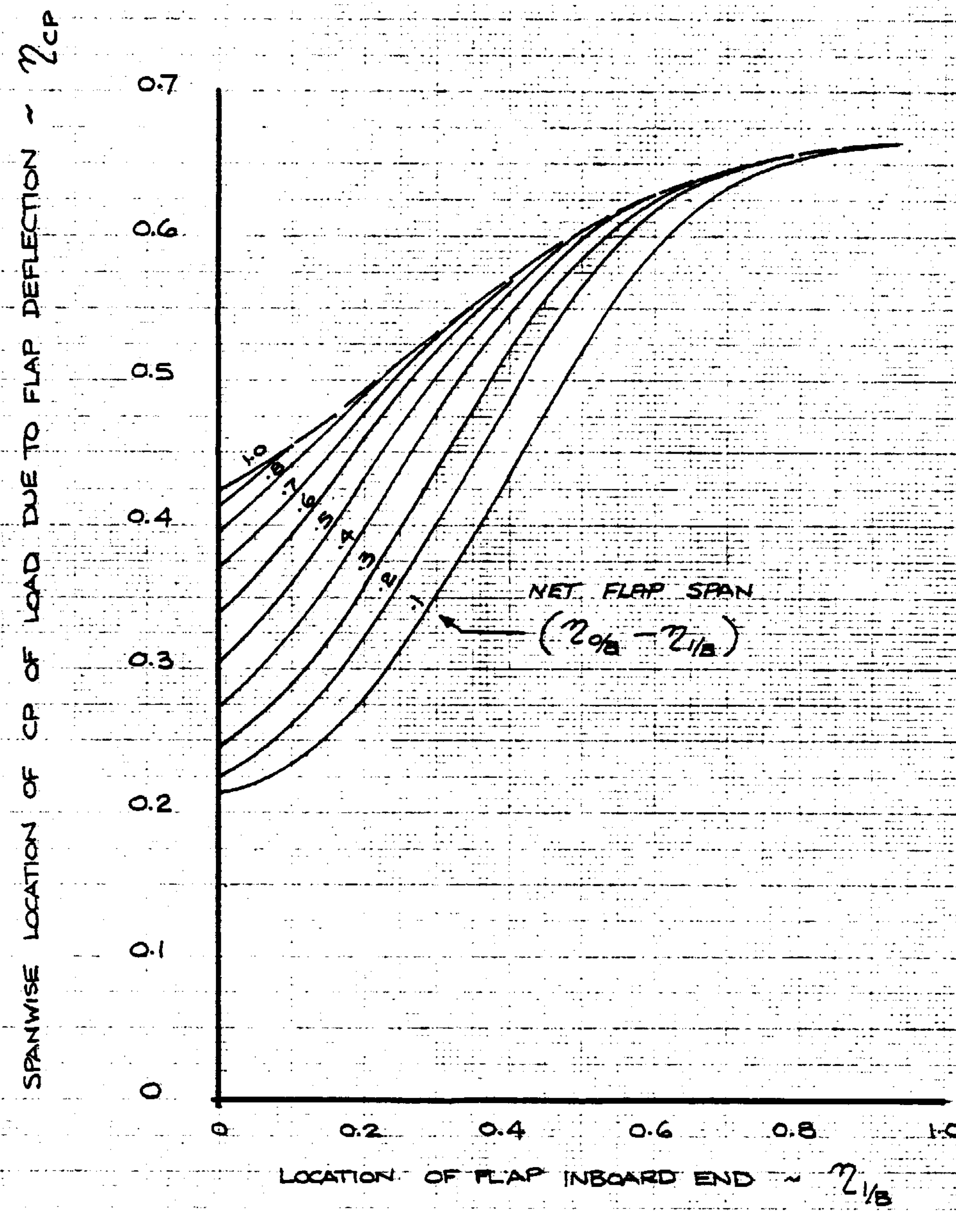


CALC	M. Grainger	12 May 70	REVISED	DATE	CHORDWISE CENTRE OF PRESSURE OF FLAP LIFT	D6-26011 TN
CHECK	FROM A.H. ELDRIDGE					FIG. 20
APR					THE BOEING COMPANY	PAGE 36
APR						

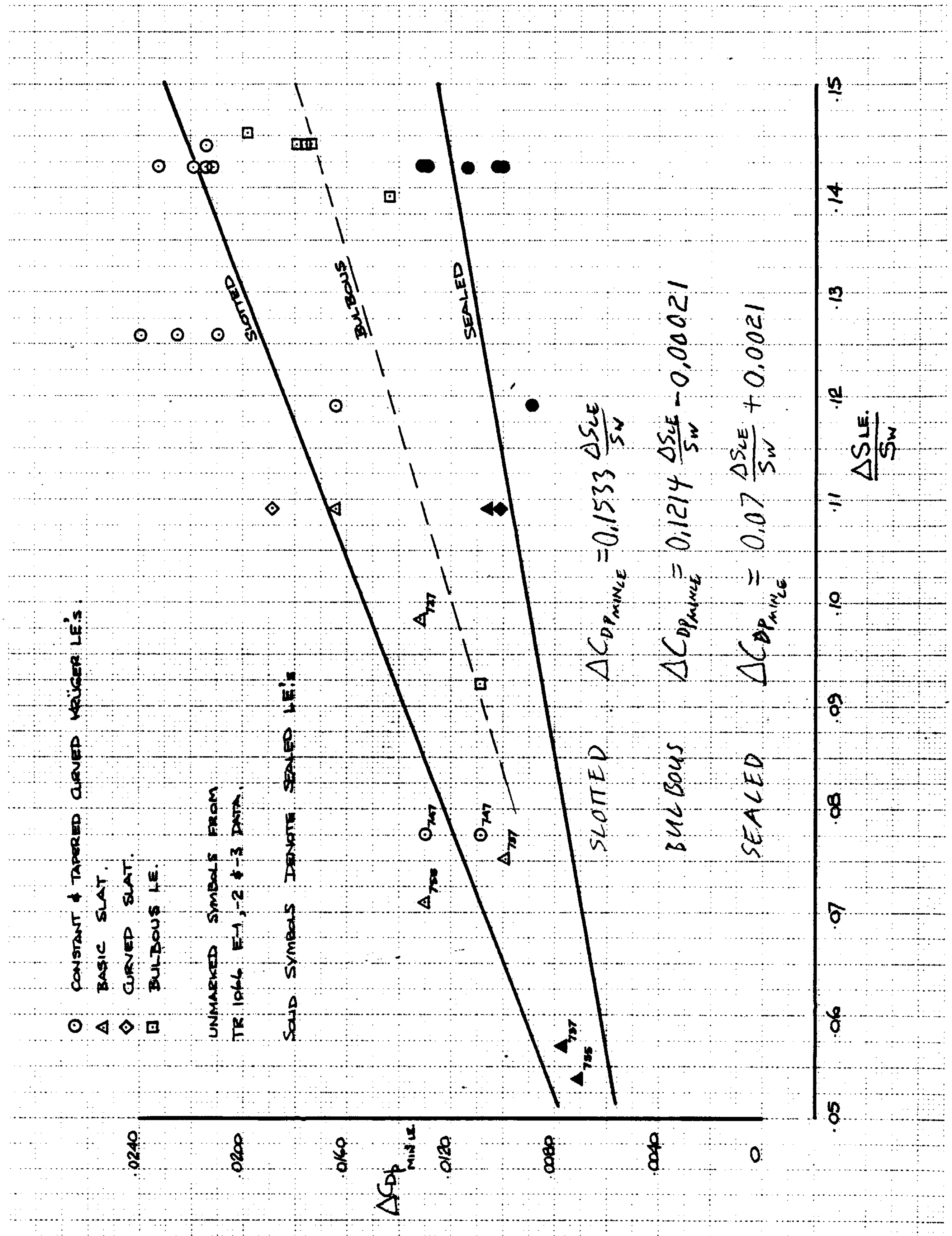
AD 461 C-R4

TABLE

NOTE : ASSUMES ELLIPTIC LOADING FOR FULL SPAN FLAP

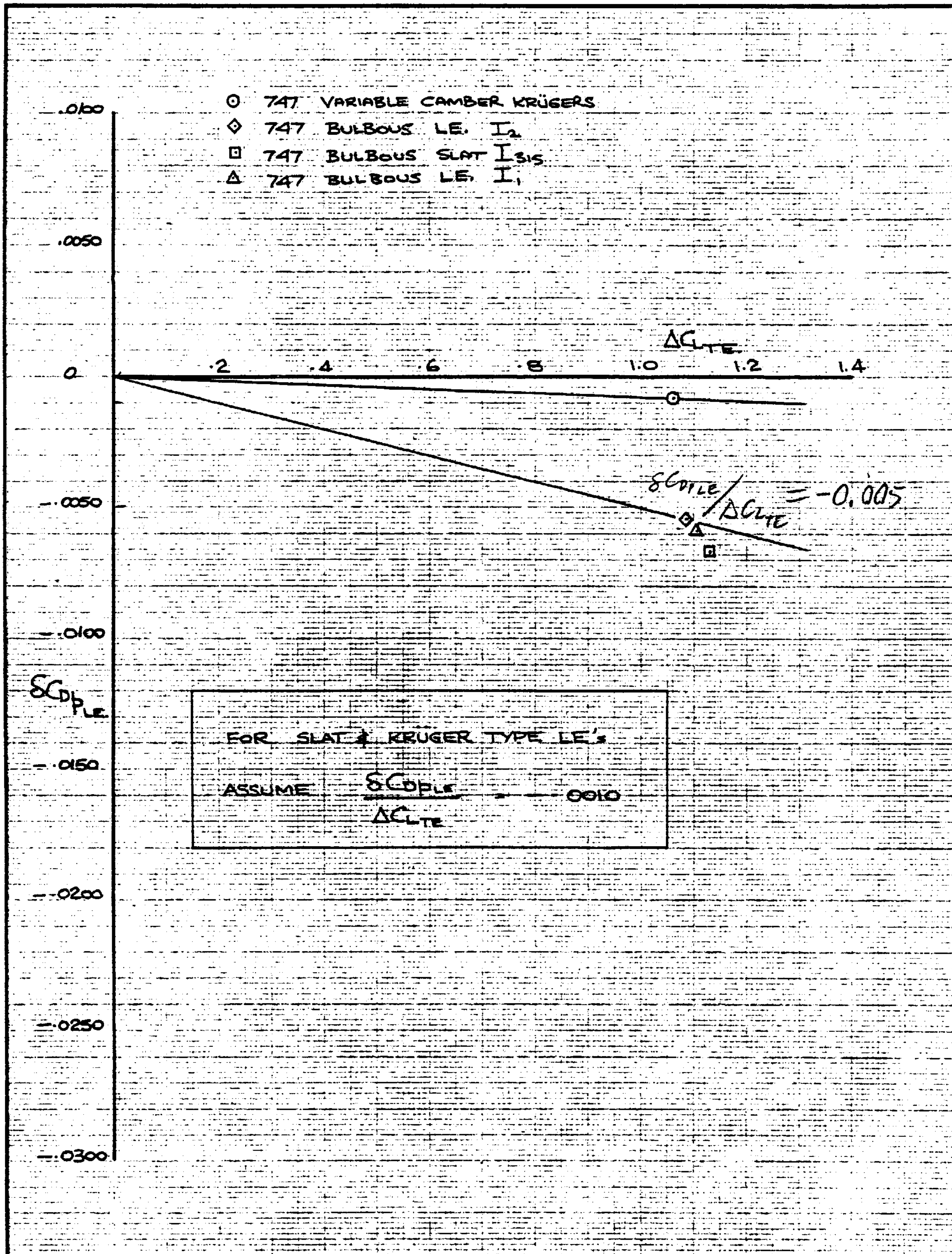


CALC	From A. H. ELDRIDGE	COPY MY 18 AUG 70	REVISED	DATE	SPANWISE CENTRE OF PRESSURE OF FLAP LIFT	D6-26011 TN
CHECK						FIG. 21
APR					THE BOEING COMPANY	PAGE 37
APR						



CALC	M. Grainger	27 FEB 70	REVISED	DATE	PARASITE DRAG DUE TO LE. DEVICE ~ $\Delta C_{DP_{MIN LE.}}$	D6-26011 TN
CHECK						FIG 22
APR					THE BOEING COMPANY	PAGE 38
APR						

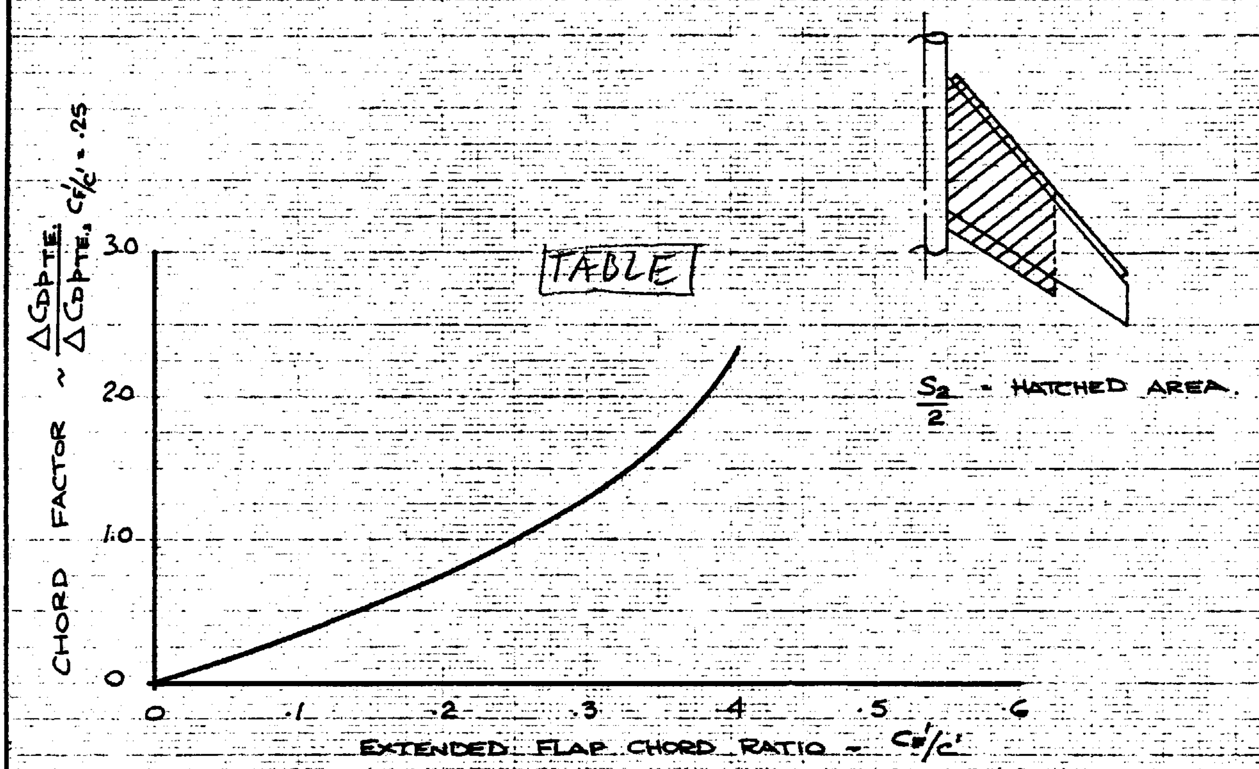
TD 461 D



CALC	R. WICKEMEYER 1.28.69	MK	REVISED	DATE	VARIATION OF $\delta C_{D_{P_{LE}}}$ WITH FLAP LIFT
CHECK					
APR					
APR					THE BOEING COMPANY

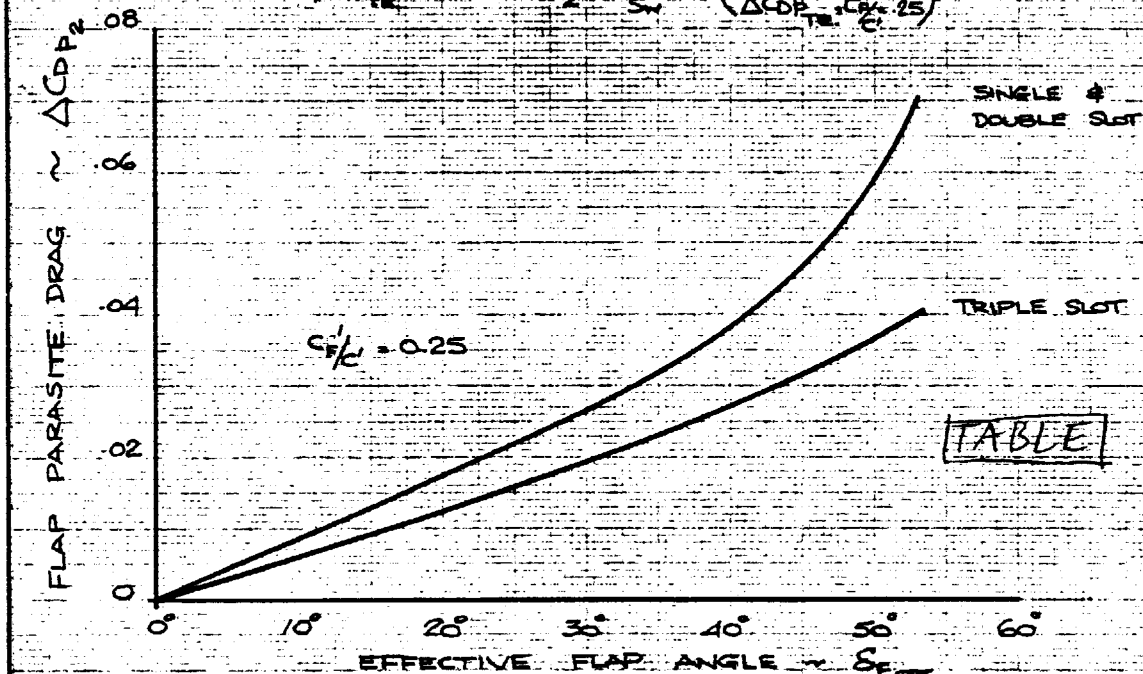
D6-26011 TN

FIG 23



• ΔC_{DP_2} REFERENCED TO FLAPPED AREA S_2 FOR $c_f'/c' = .25$.

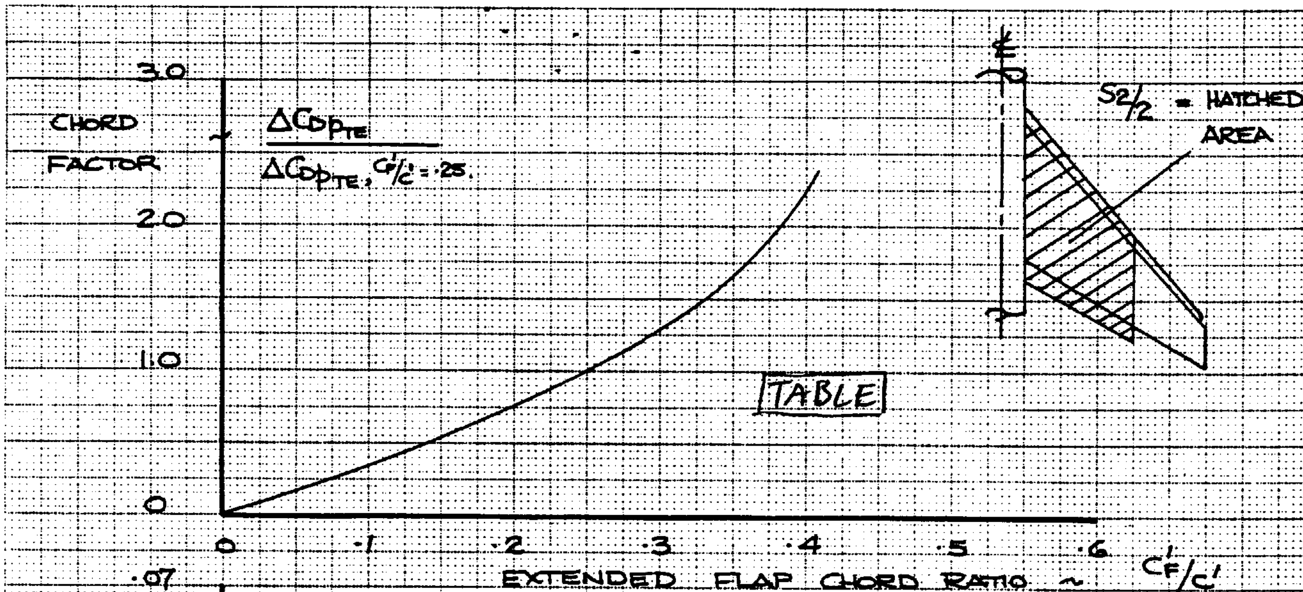
• $\Delta C_{DP_{MIN\,TE}} = \Delta C_{DP_2} \times \frac{S_2}{S_W} \times \left(\frac{\Delta C_{DP\,TE}}{\Delta C_{DP_{TE},\ c_f'/c'=.25}}\right)$

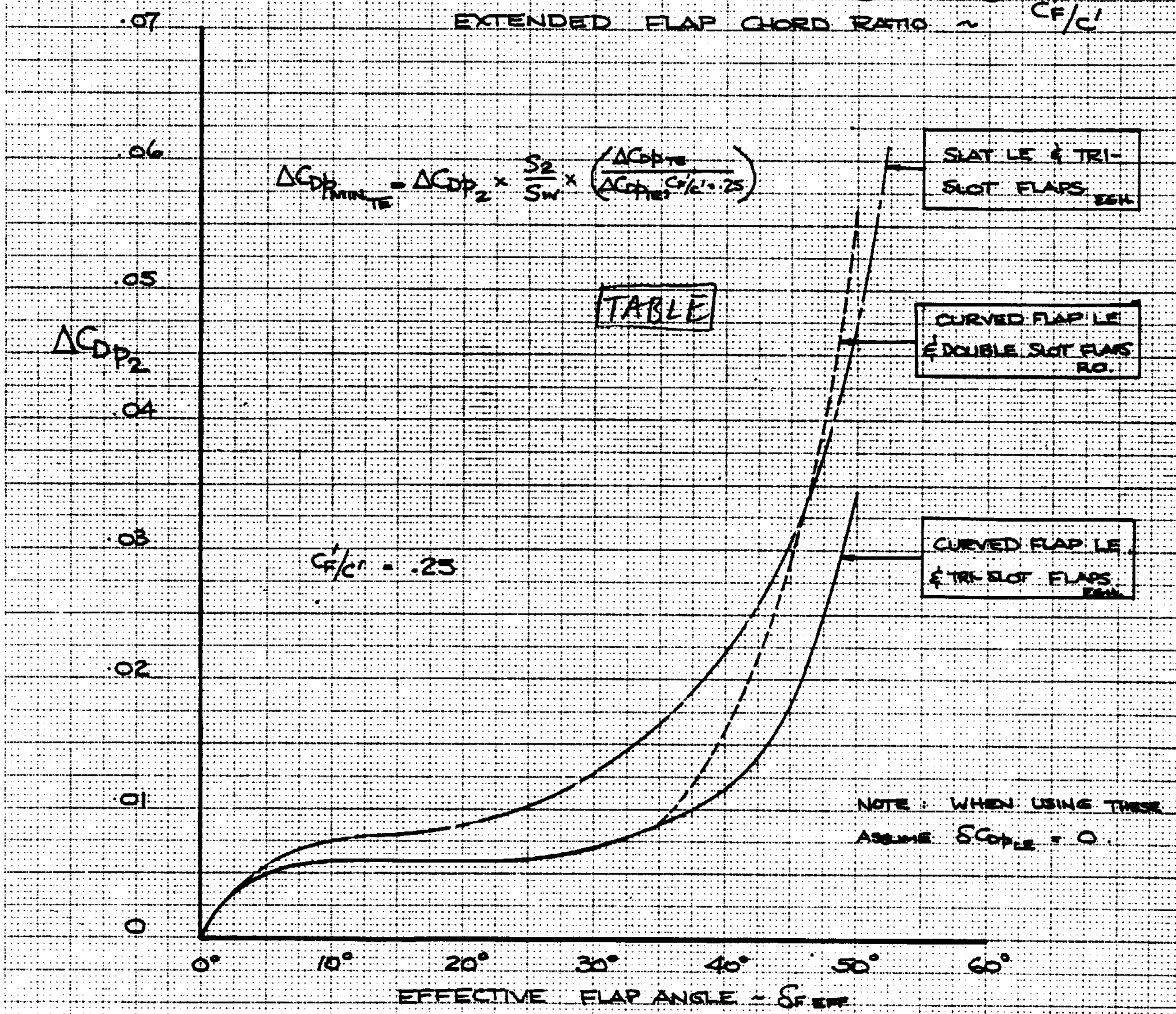


			REVISED	DATE		
CALC	FROM H.L.A.H.				PARASITE DRAG DUE TO T.E. FLAPS ~ $\Delta C_{DP_{MIN\,TE}}$	D6-26011 TN
CHECK	M. Yrungst					FIG 24a
APR						
APR					THE BOEING COMPANY	PAGE 40.1

AD 461 C-R5

6-8000 8.5

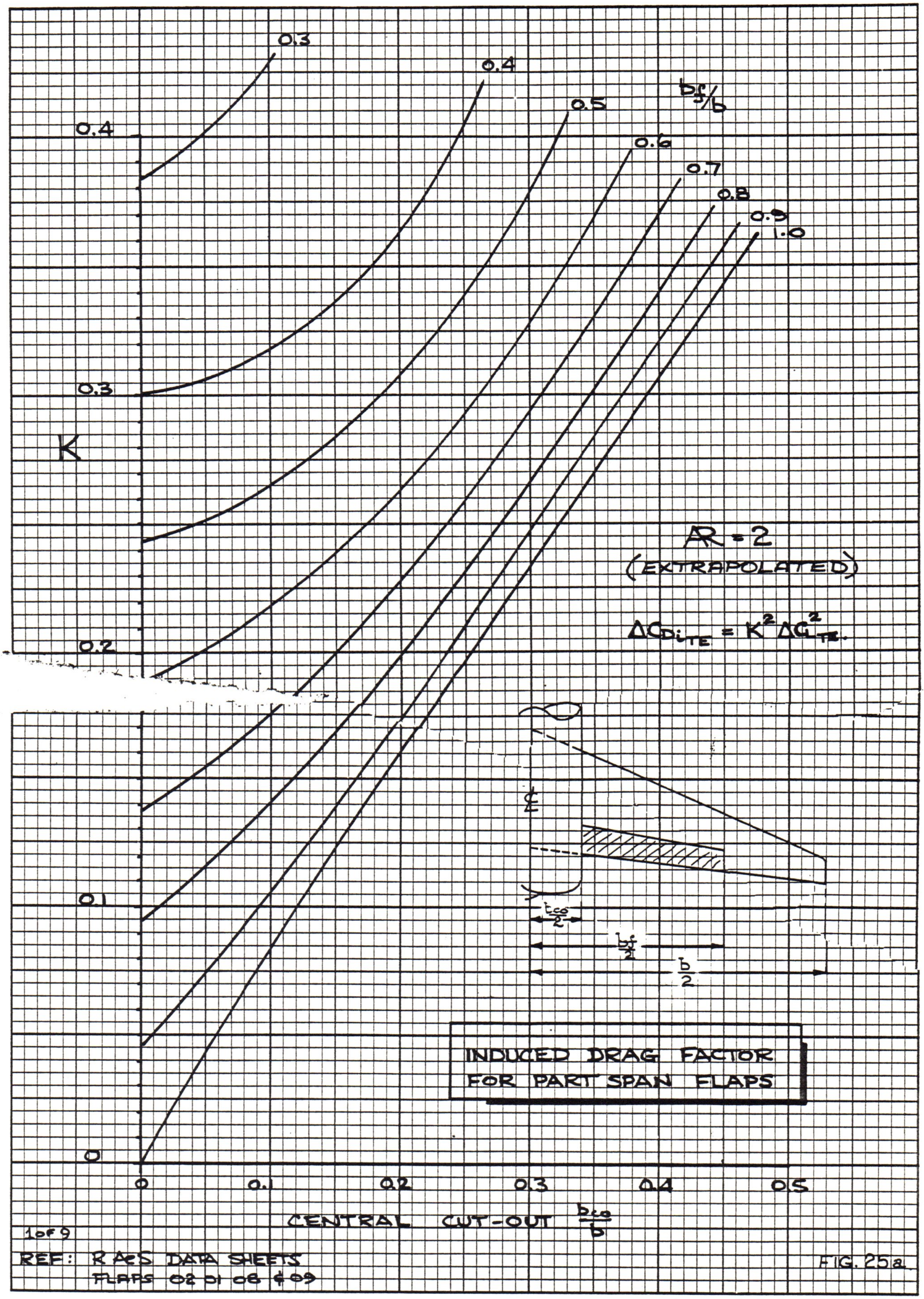




CALC	EGH./RO.	RECEIVED 1/21/72	REVISED	DATE	PARASITE DRAG DUE TO TE FLAPS ~ $\Delta C_{Dp_{MIN\ TE.}}$	D6-26011 TN
CHECK	M. Grainger	4 AUG 72				FIG 24 b
APR					THE BOEING COMPANY	PAGE 40.2
APR						

D1 4100 3260 ORIG 3/71

K+E ALBANENE 196L TRACING PAPER



K
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
CENTRAL CUT-OUT $\frac{b_{co}}{b}$
b_f/b
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
$AR = 2$
(EXTRAPOLATED)
$\Delta C_{Di_{TE}} = K^2 \Delta C_{L_{TE}}^2$
℄
$\frac{b_{co}}{2}$
$\frac{b_f}{2}$
$\frac{b}{2}$
INDUCED DRAG FACTOR
FOR PART SPAN FLAPS
1 of 9
REF: RAeS DATA SHEETS
FLAPS 02 01 08 & 09

FIG. 25a

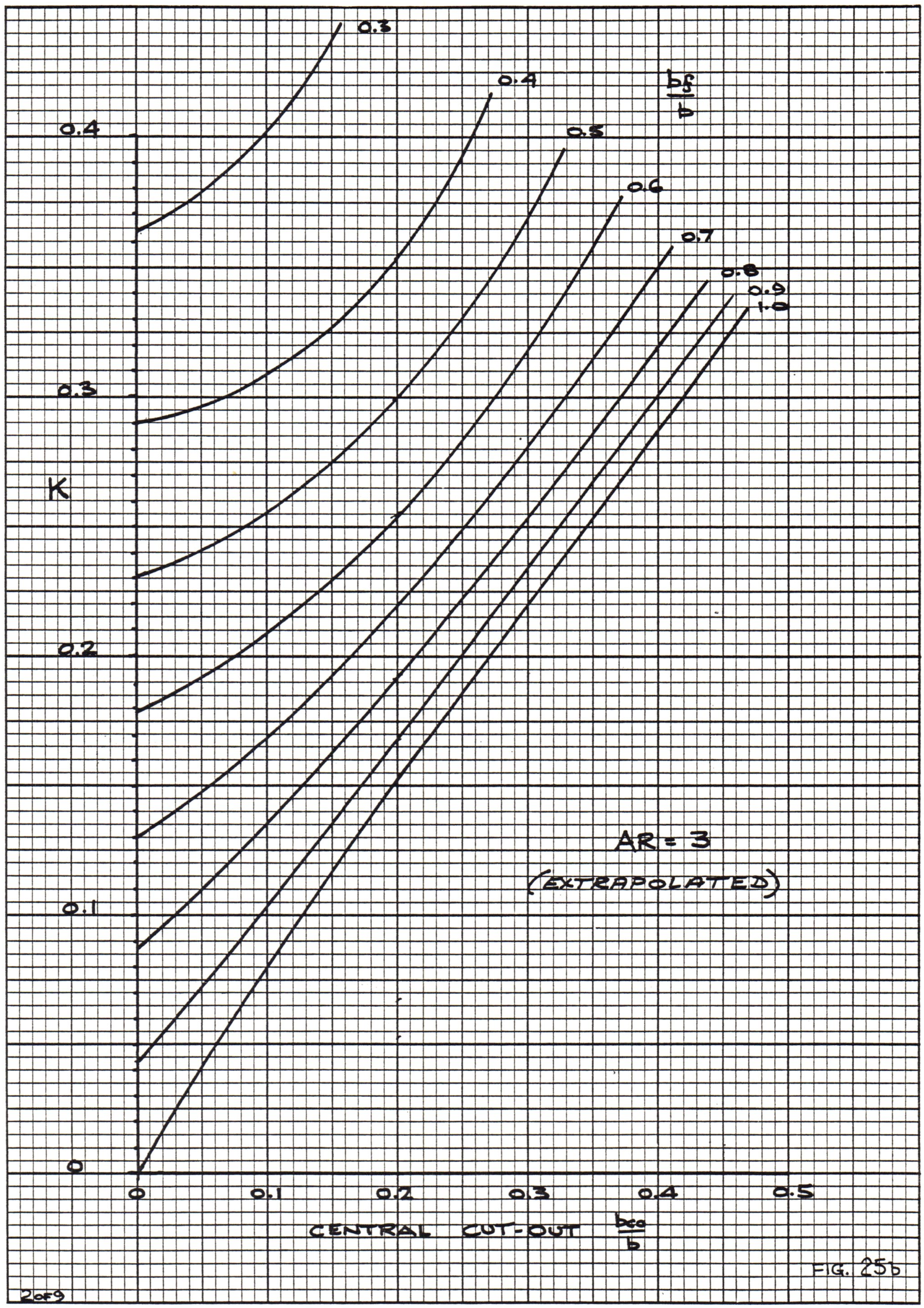

0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
bf/b
K
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
CENTRAL CUT-OUT bco/b
AR = 3
(EXTRAPOLATED)
2 of 9

FIG. 25b

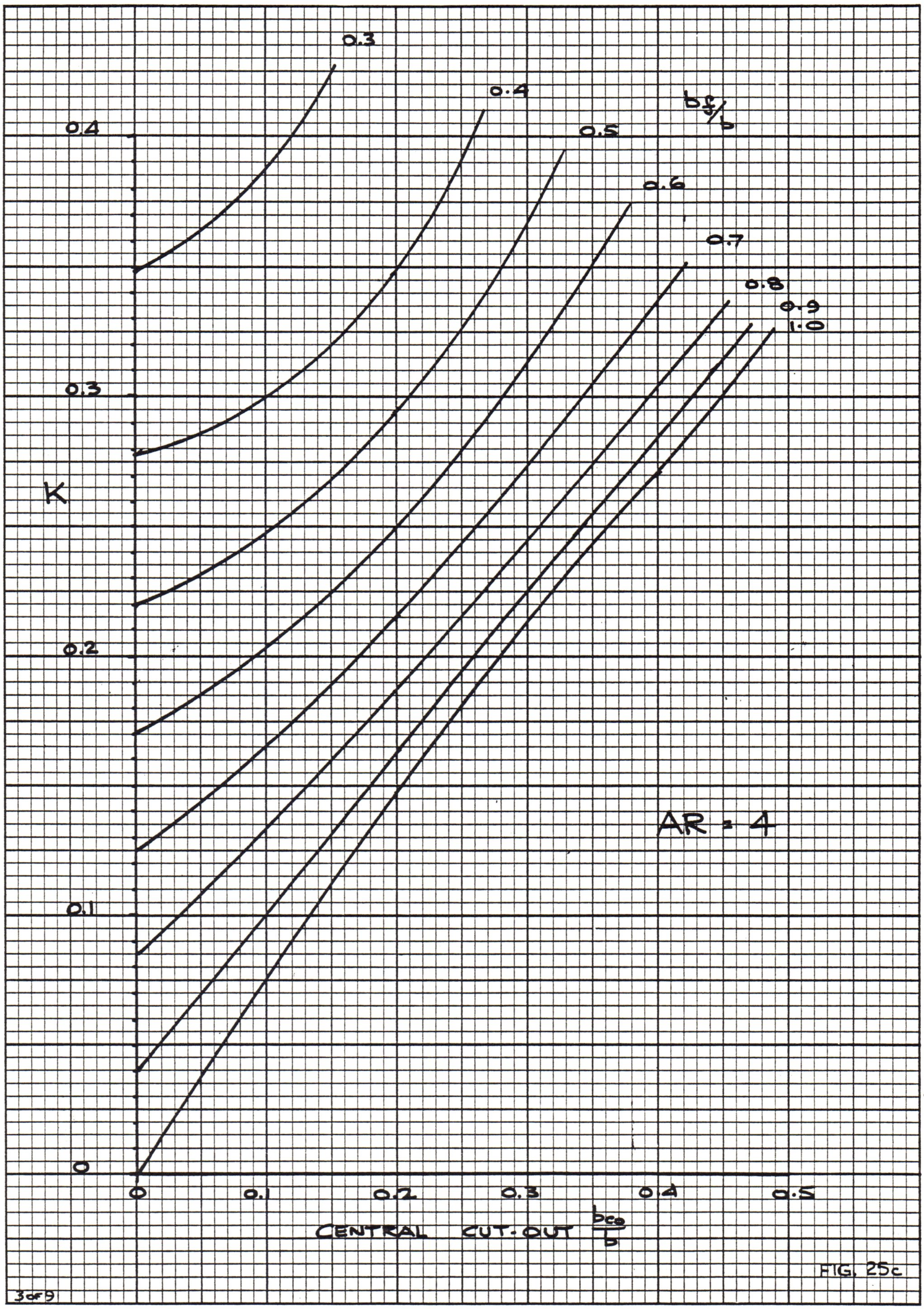

0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
bf/b
K
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
CENTRAL CUT-OUT bco/b
AR = 4
3 of 9

FIG. 25c

TABLE

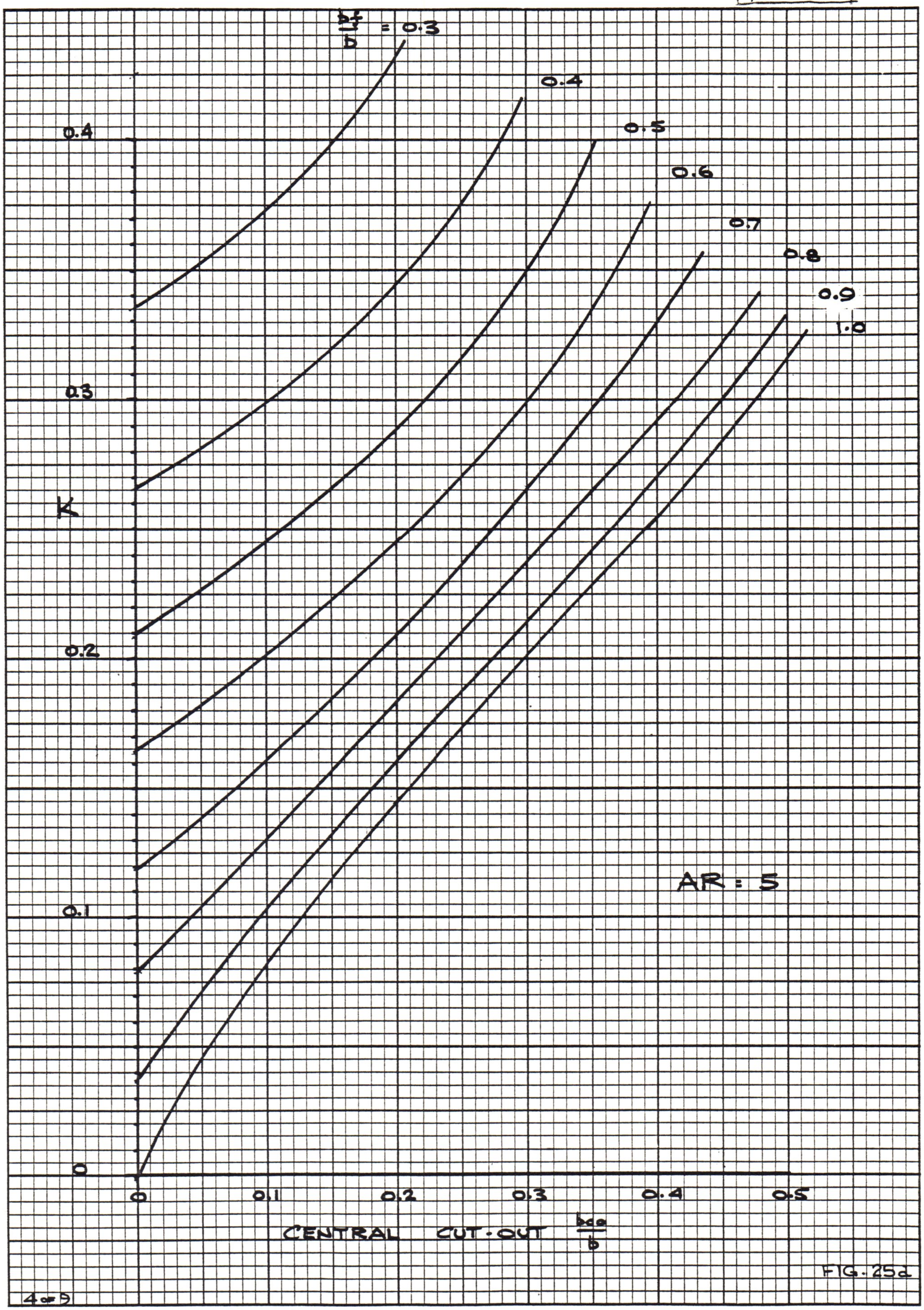


FIG. 25d

NO. 315. 10 DIVISIONS PER INCH BOTH WAYS. 70 BY 100 DIVISIONS.
CODEX BOOK COMPANY, INC. NORWOOD, MASSACHUSETTS. PRINTED IN U.S.A.

D6-26011 TN

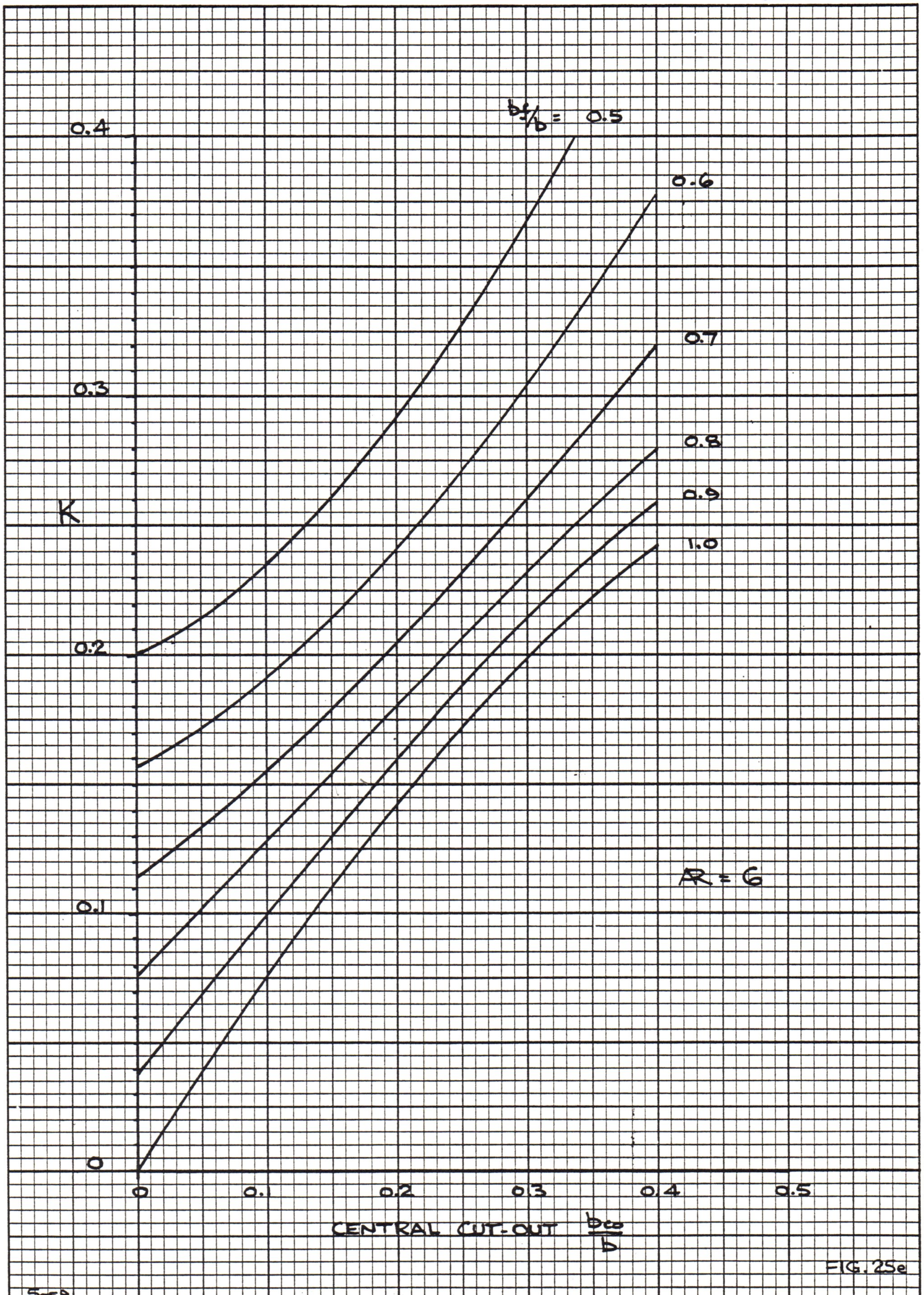

bf/b = 0.5
0.6
0.7
0.8
0.9
1.0
K
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
AR = 6
CENTRAL CUT-OUT bco/b

FIG. 25e

5 of 9

TABLE

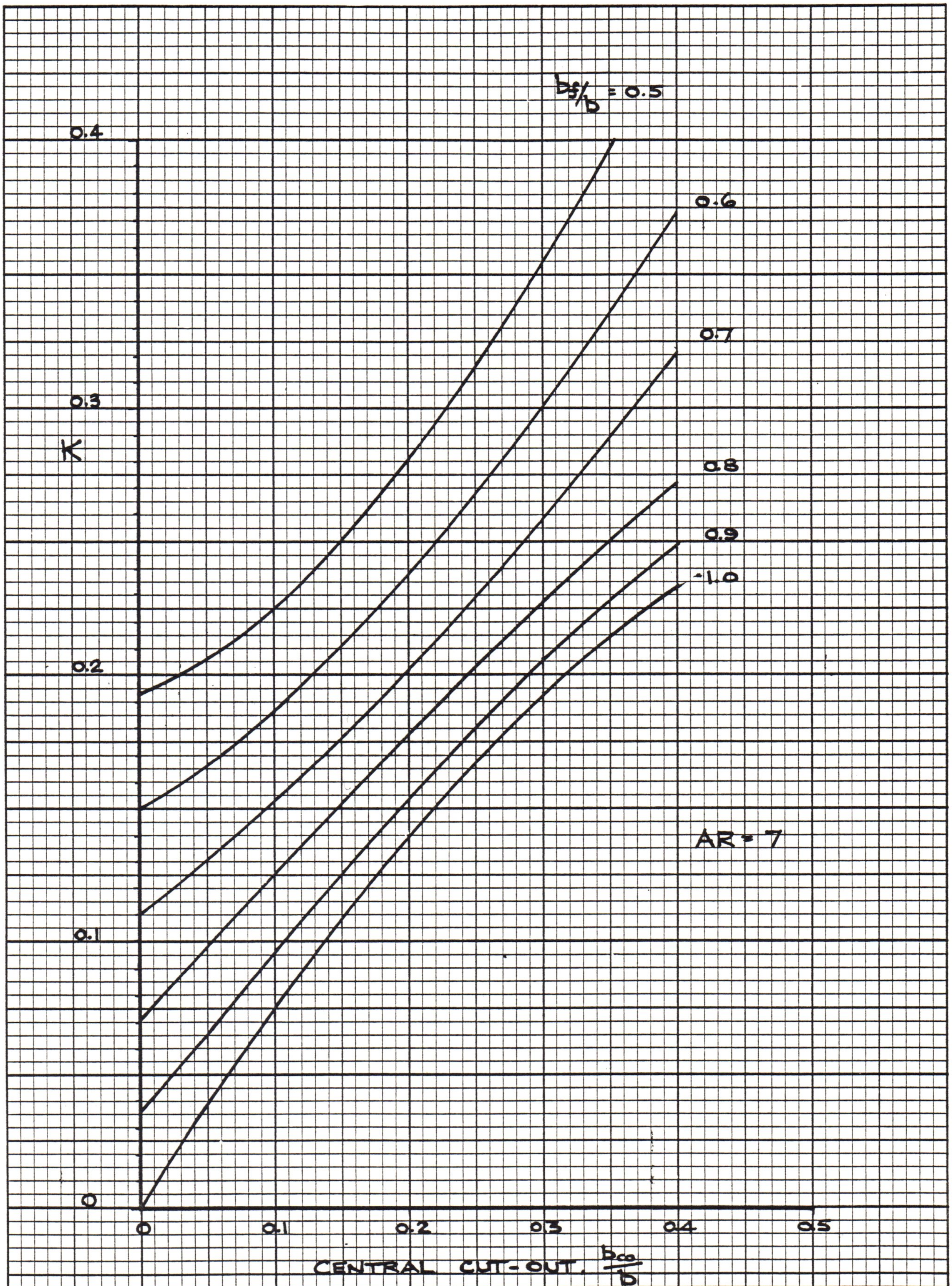
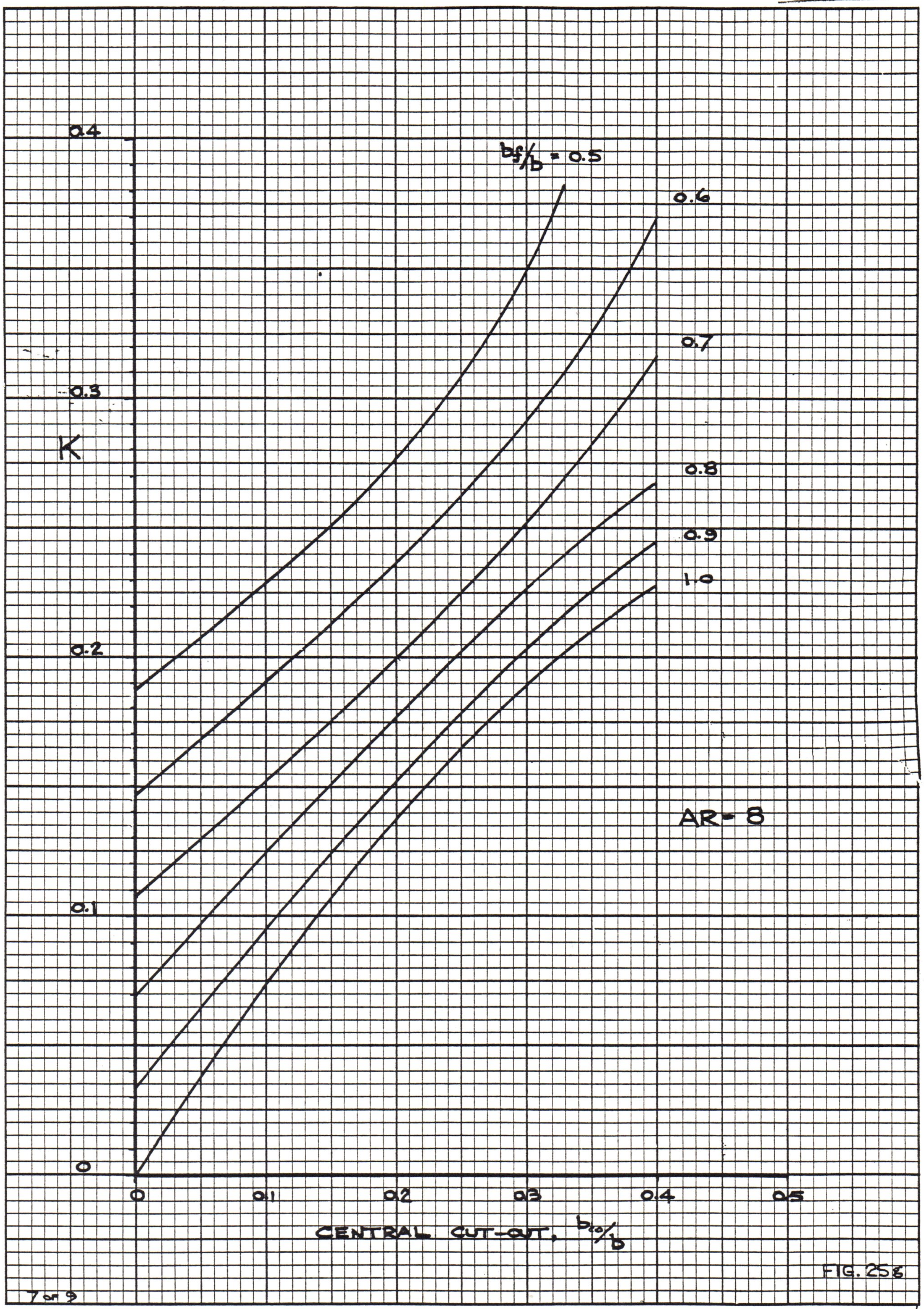


FIG. 25f

6 of 9


0.4
0.3
0.2
0.1
0
K
b_f/b = 0.5
0.6
0.7
0.8
0.9
1.0
AR = 8
0
0.1
0.2
0.3
0.4
0.5
CENTRAL CUT-OUT, b_{co}/b
7 of 9
FIG. 25B

TABLE

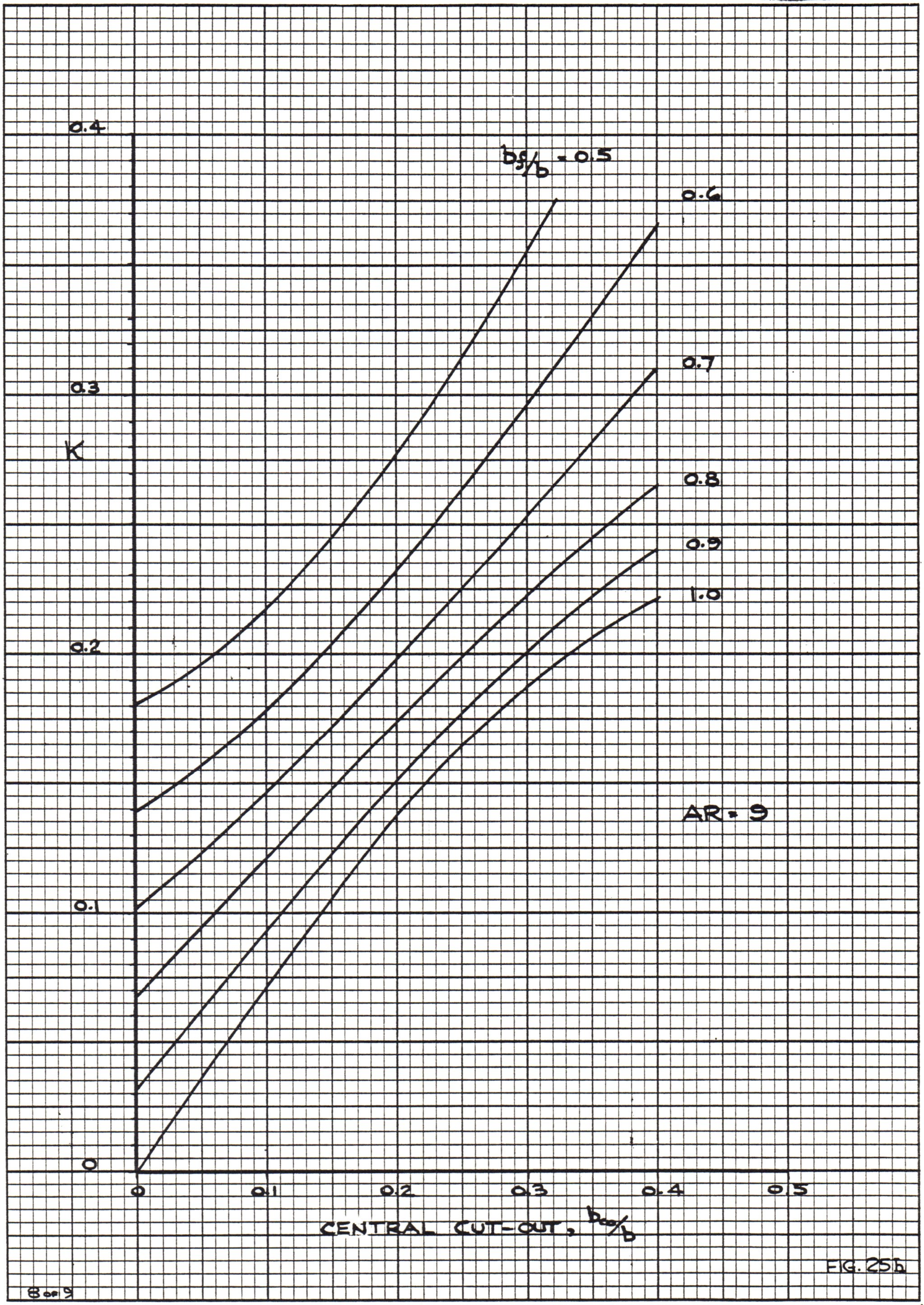


FIG. 25b

8 of 9

TABLE

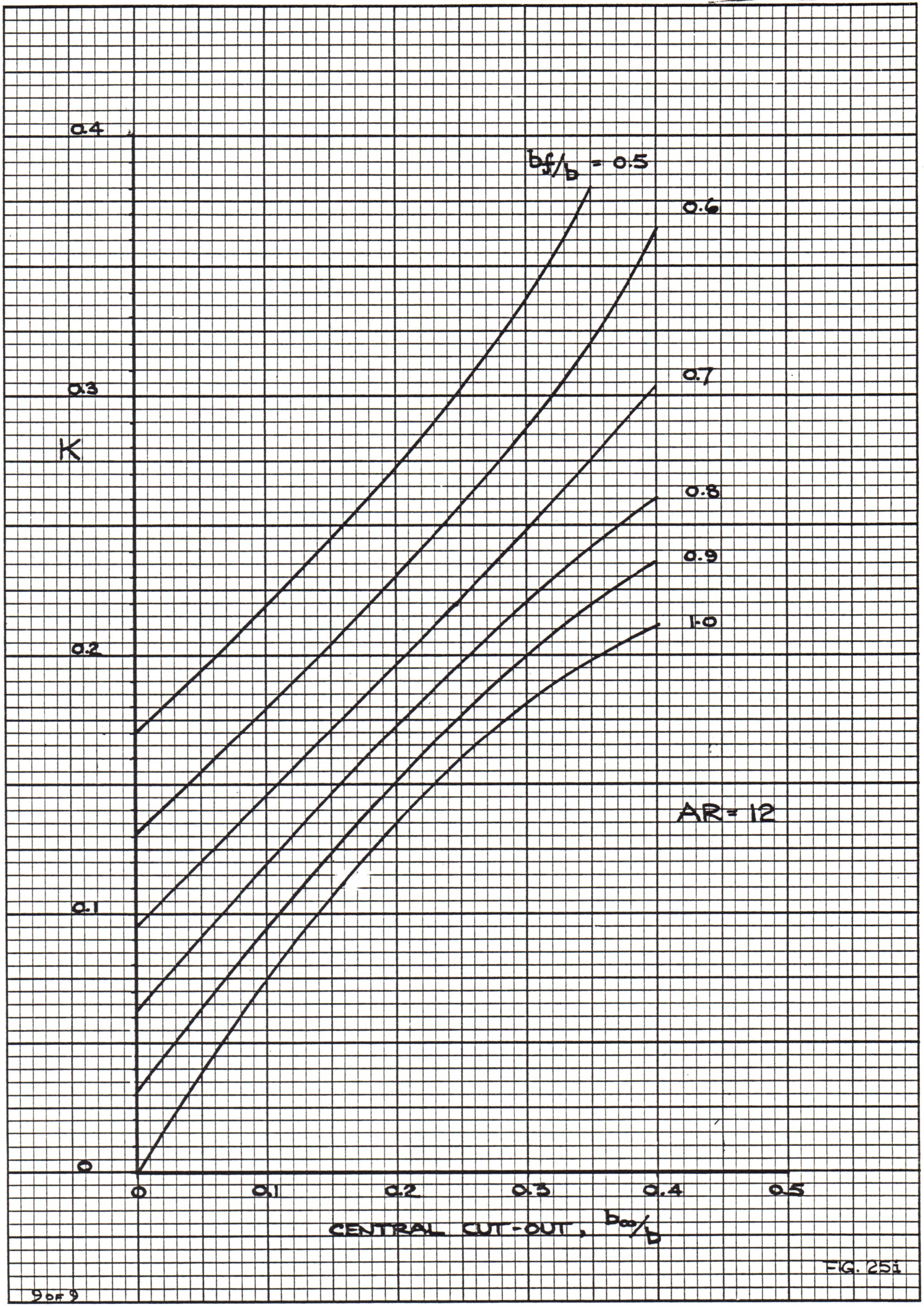
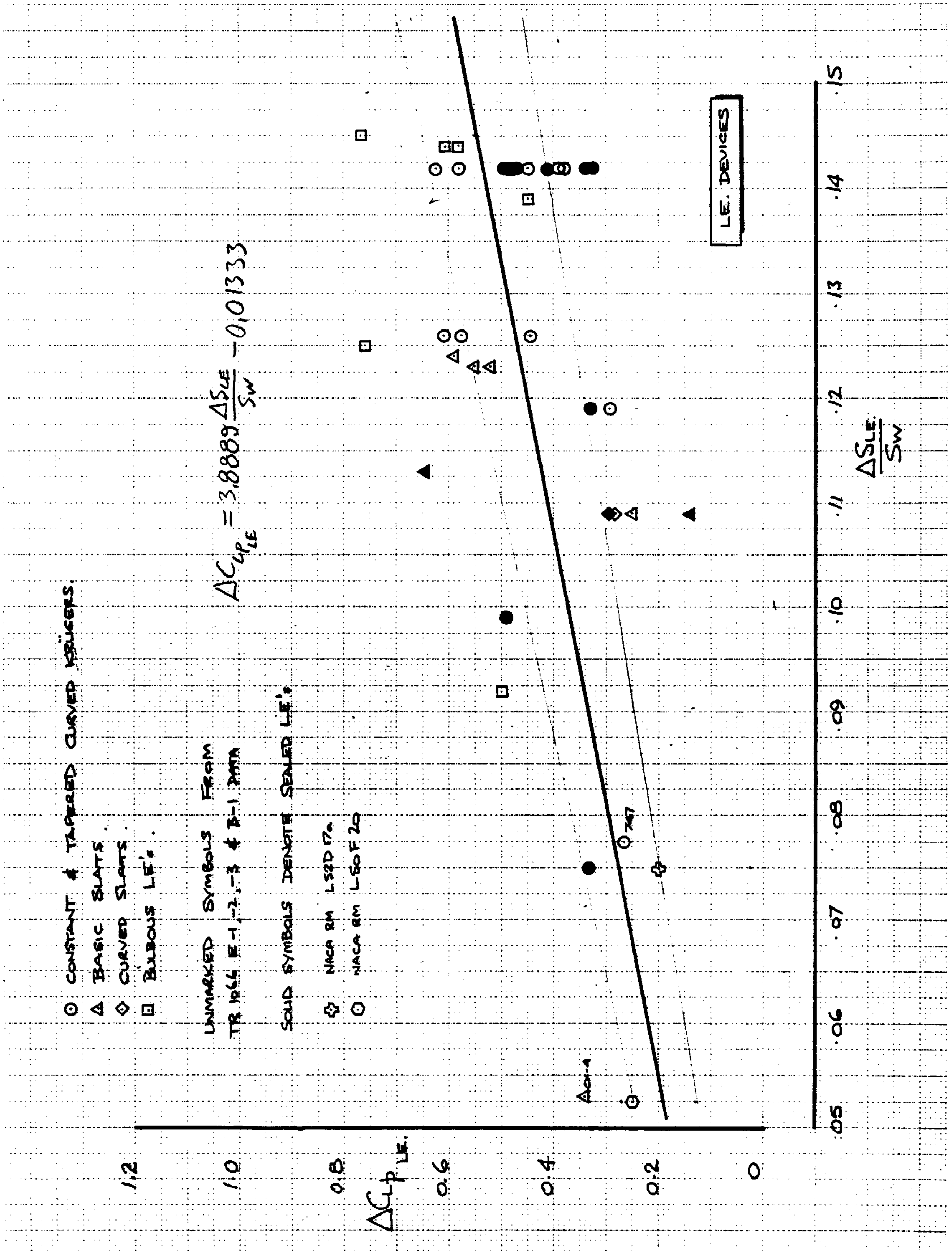


FIG. 25i

9 of 9



CALC	M. Granger	27 FEB 70	REVISED	DATE
CHECK				
APR				
APR				

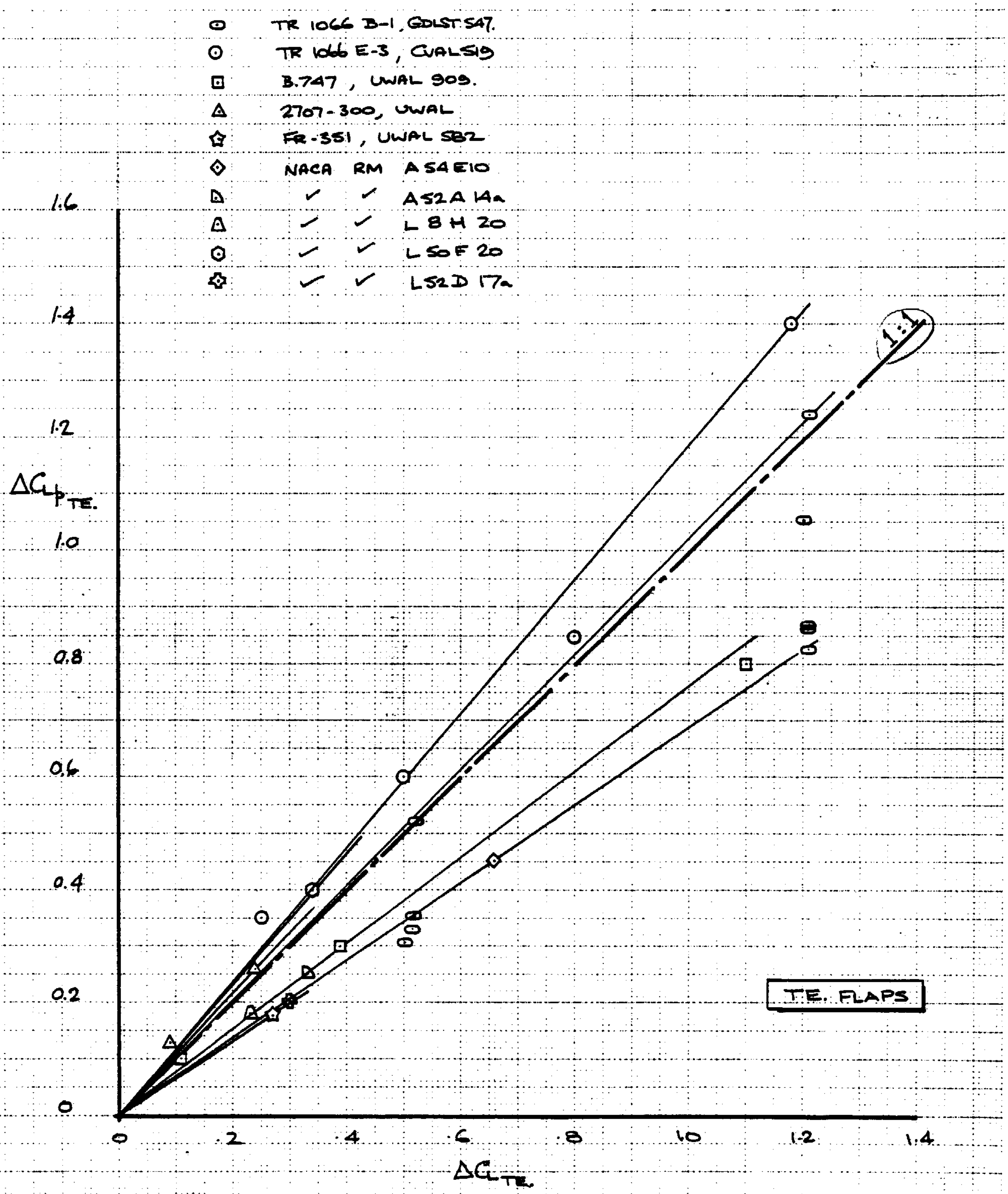
INCREMENT IN C_{Lp} DUE TO L.E. DEVICES ~ $\Delta C_{Lp_{LE}}$

THE BOEING COMPANY

D6-26011 TN

FIG. 26

TD 461 D

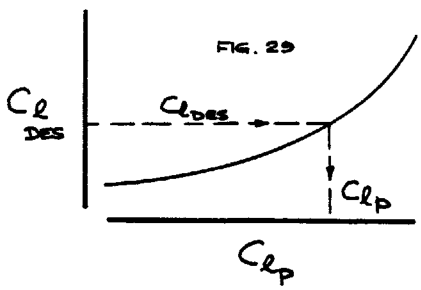


CALC	M Younger	2 FEB 70	REVISED	DATE	INCREMENT IN C_{L_p} DUE TO TE. HIGH LIFT DEVICES	D6-26011 TN
CHECK						FIG 27.
APR					THE BOEING COMPANY	PAGE 51
APR						

CHOOSE: DESIGN LIFT COEFFICIENT ~ $C_{\ell_{DES}}$

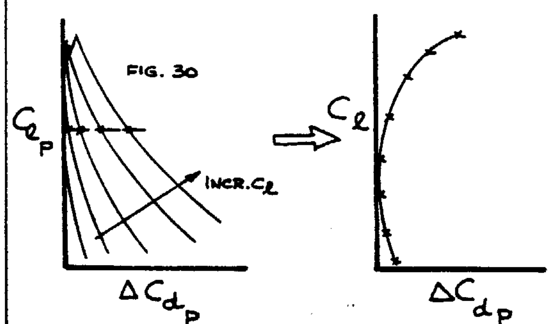
STEP 1

DETERMINE C_{ℓ_p} KNOWING $C_{\ell_{DES}}$



STEP 2

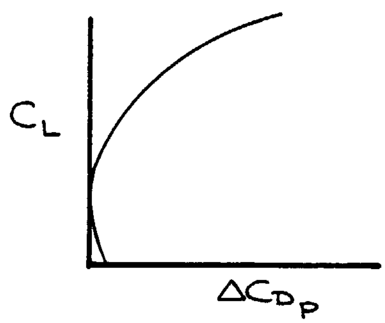
USING C_{ℓ_p} OBTAIN 2D POLAR SHAPE



STEP 3

CONVERT 2D POLAR SHAPE TO 3D USING:

$$C_L = C_\ell \cos^2 \Lambda_{c/4}$$
$$C_D = C_d \cos^2 \Lambda_{c/4}$$

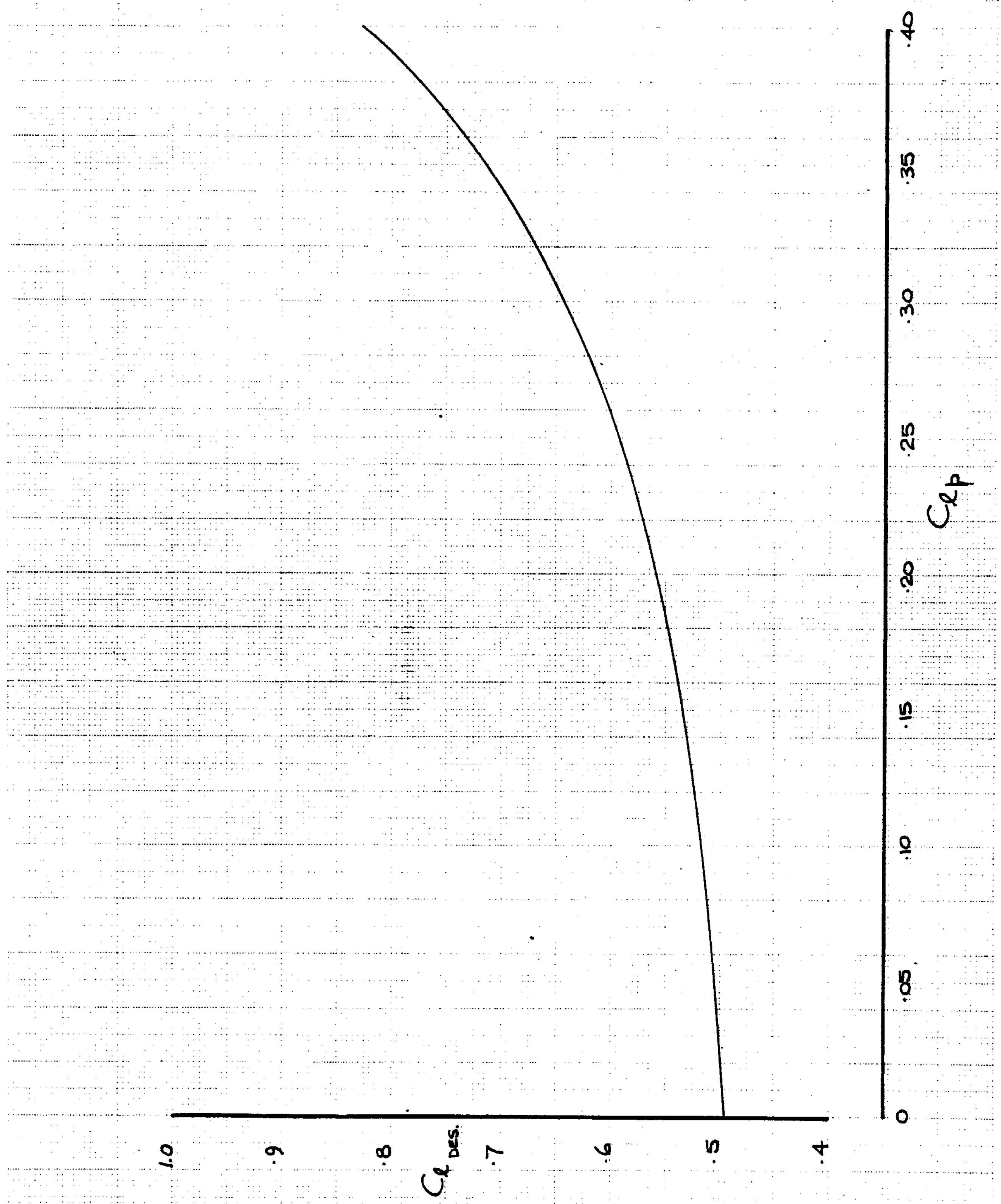


CALC	McINTOSH	4.10.70	REVISED	DATE	METHOD FOR DERIVING POLAR SHAPE
CHECK	M. Grainger	28 MAY 70			
APPD					
APPD					

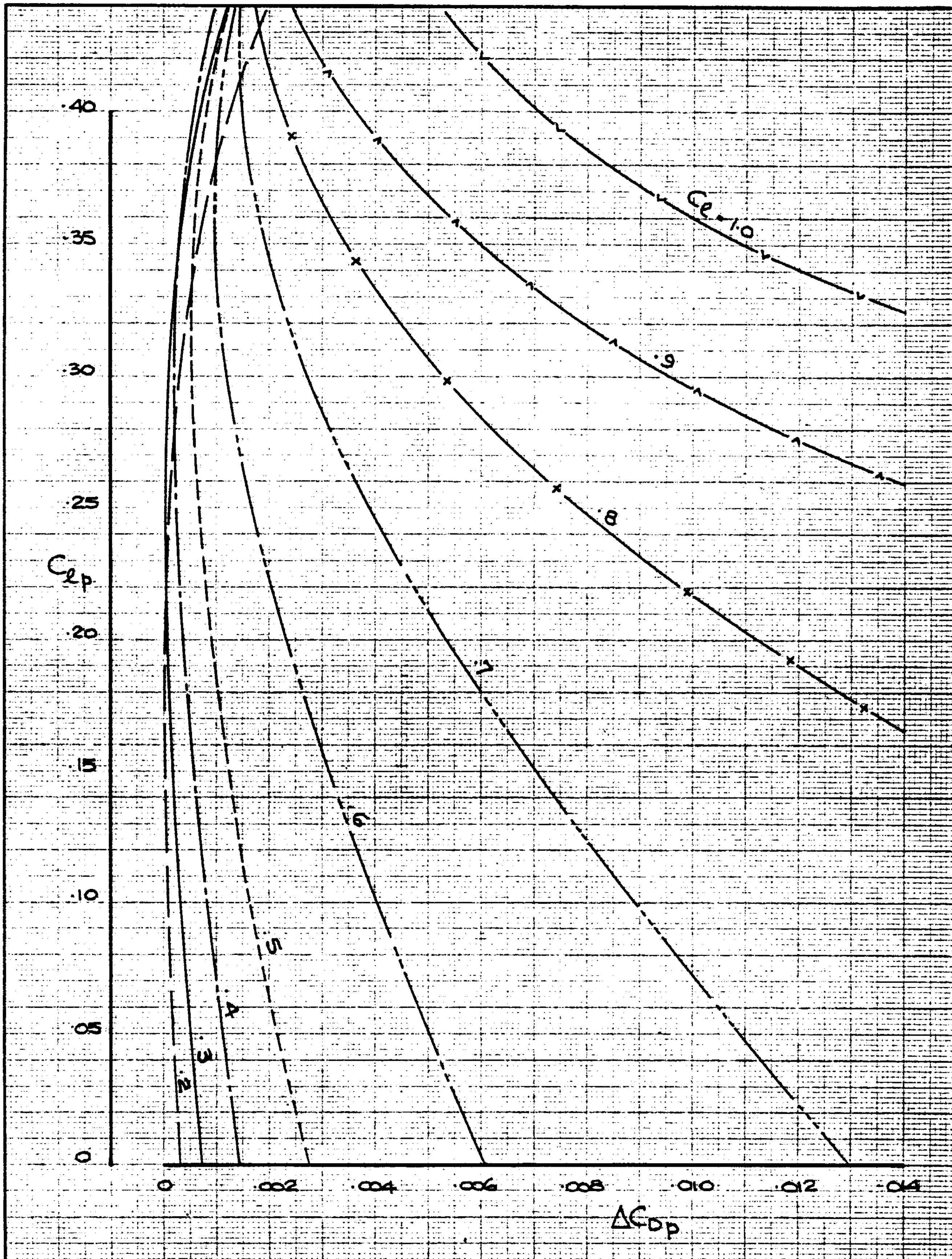
THE BOEING COMPANY
RENTON, WASHINGTON

D6-26011 TN

FIG. 28



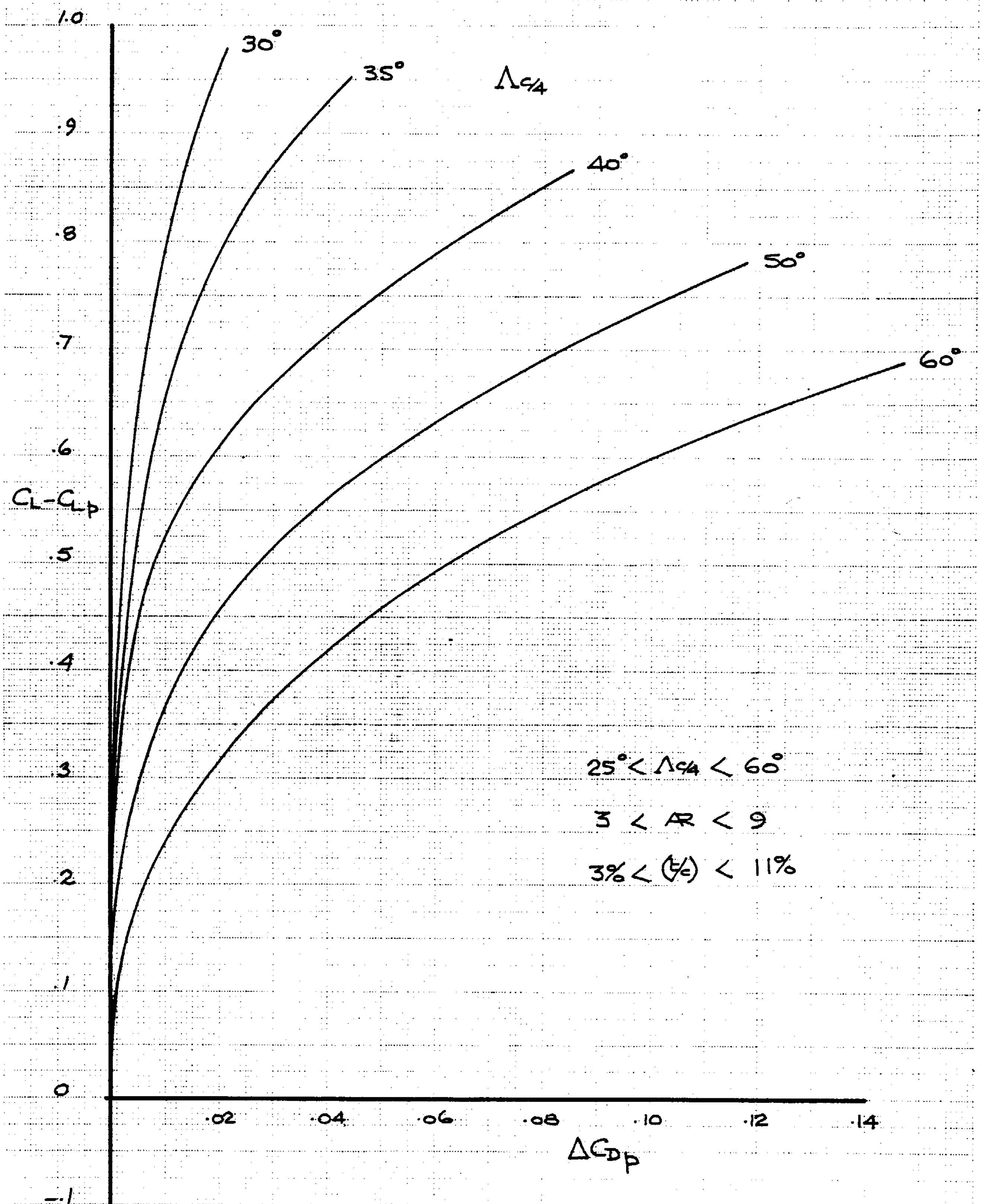
CALC	McINTOSH	3.25.70	REVISED	DATE	EFFECT OF CAMBER ($C_{\ell p}$) ON DESIGN LIFT COEFF. (2 DIMEN.)	D6-26011 TN
CHECK	M Granger	4 JUNE 70				FIG. 29
APR						
APR					THE BOEING COMPANY	PAGE 53



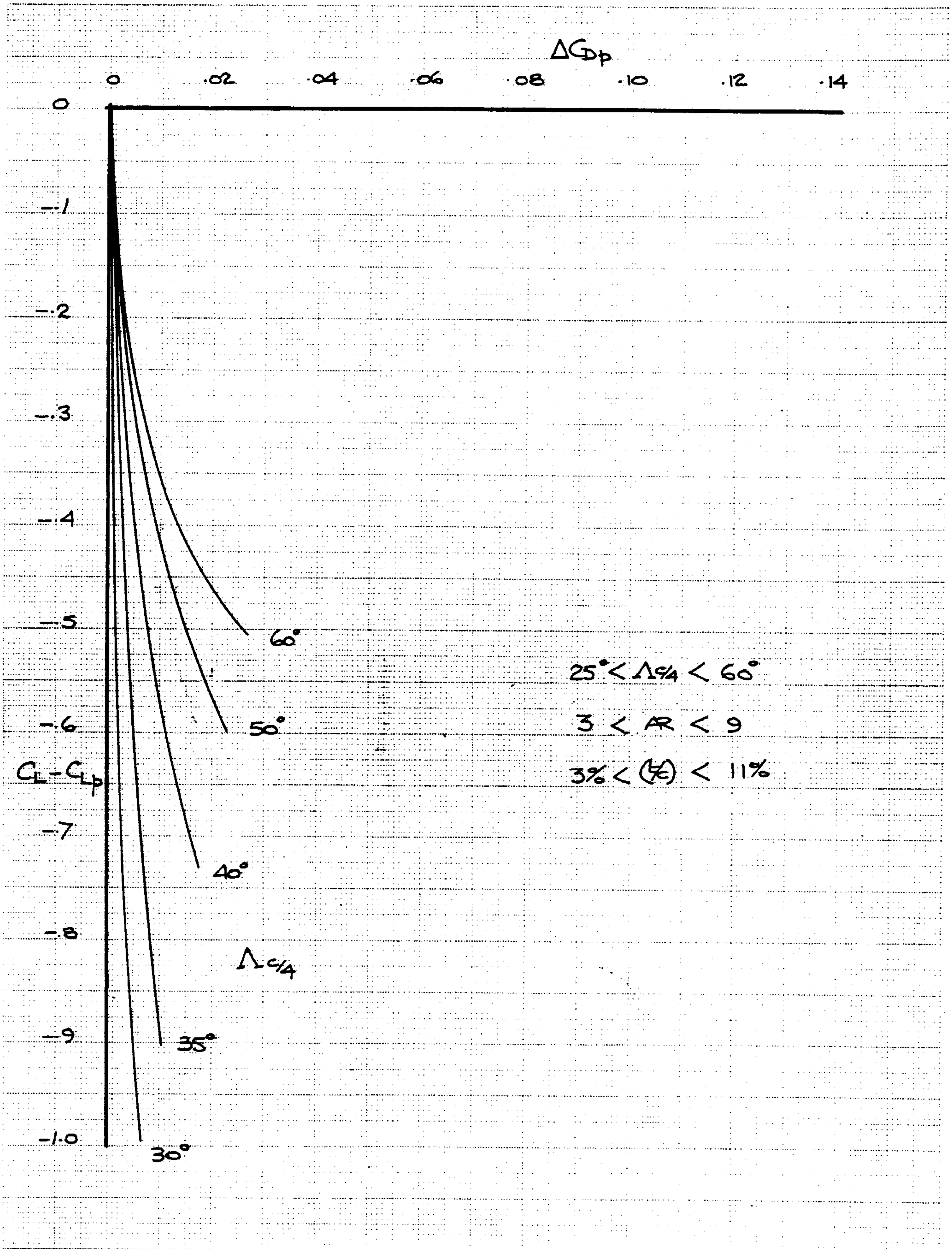
CALC	MC INTOSH	3-24-70	REVISED	DATE	2 DIMENSIONAL POLAR SHAPE GENERATOR	D6-26011 TN
CHECK	M. Yaniger	4 June 70				FIG. 30
APR					THE BOEING COMPANY	PAGE 54
APR						

AD 461 C-R4

K+E ALBANENE 1961 TRACING PAPER

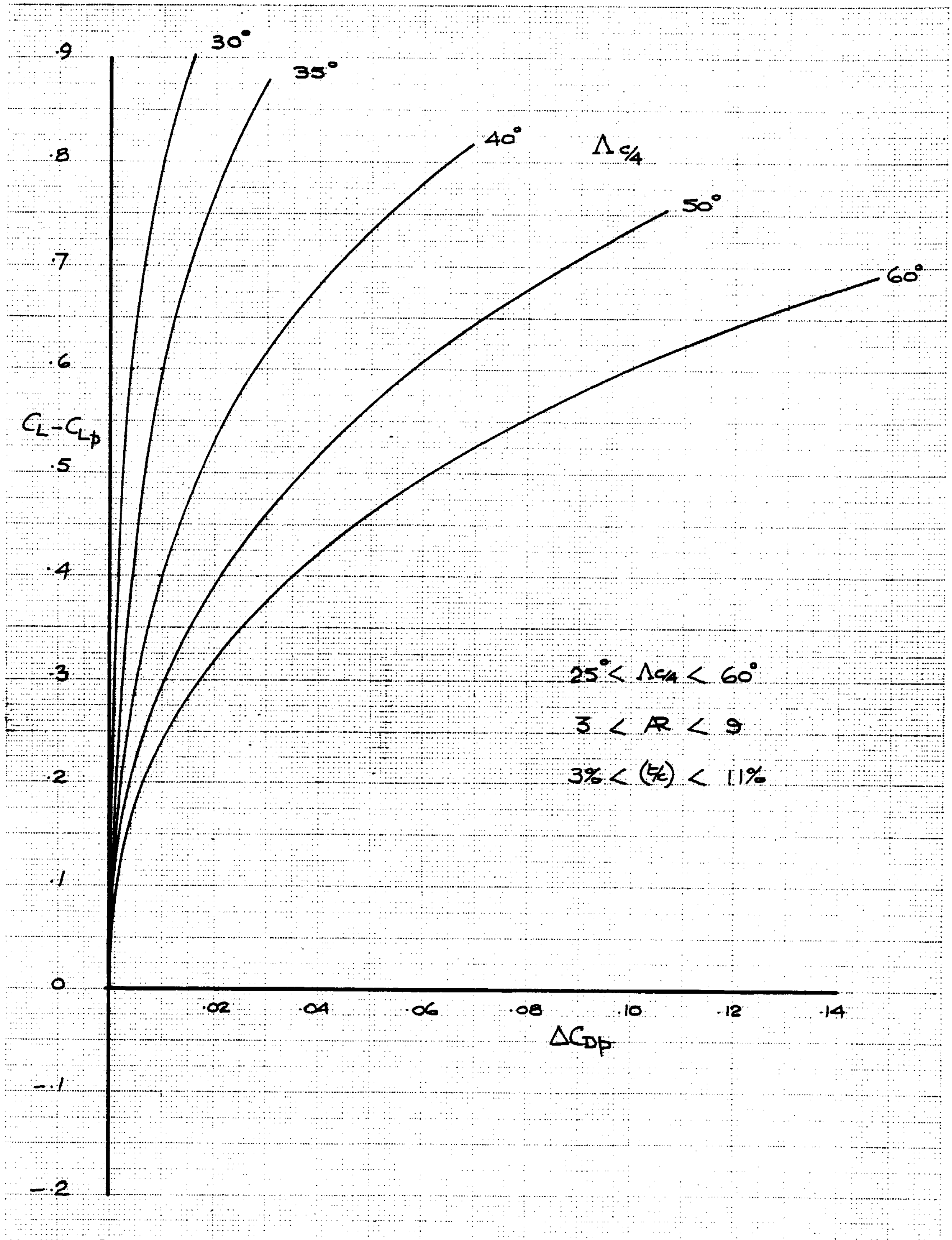


CALC	M. Grainger	30 JAN 70	REVISED	DATE	ΔC_{D_P} WITH LE. AND/OR TE. FLAPS	D6-26011 TN
CHECK			MG	29 MAY 70		FIG. 31
APR					THE BOEING COMPANY	PAGE 55
APR						



CALC	M. Granger	20 MAR 70	REVISED	DATE	ΔC_{Dp}	D6-26011 TN
CHECK			MG	1 June 70		
APR					ALL CONFIGURATIONS	FIG 32
APR						
					THE BOEING COMPANY	PAGE 56

AD 461 D 15.29 6-7000



CALC	M. Granger	30 JAN 70	REVISED	DATE	ΔC_{D_P} CRUISE CONFIGURATION	D6-2604 TN
CHECK			MG.	29 MAY 70		FIG. 33
APR						
APR					THE BOEING COMPANY	PAGE 57

APPENDIX.

TD 1040C-R3 | 6-7000

MODEL :
AR :
$\Lambda_{c/4}$:

$C_{Dp_{MIN\ CRUISE}}$:
πAR :
K^2 :

$\Delta C_{Lp_{LE}}$:

TAIL ARM ℓ_{t}/c :

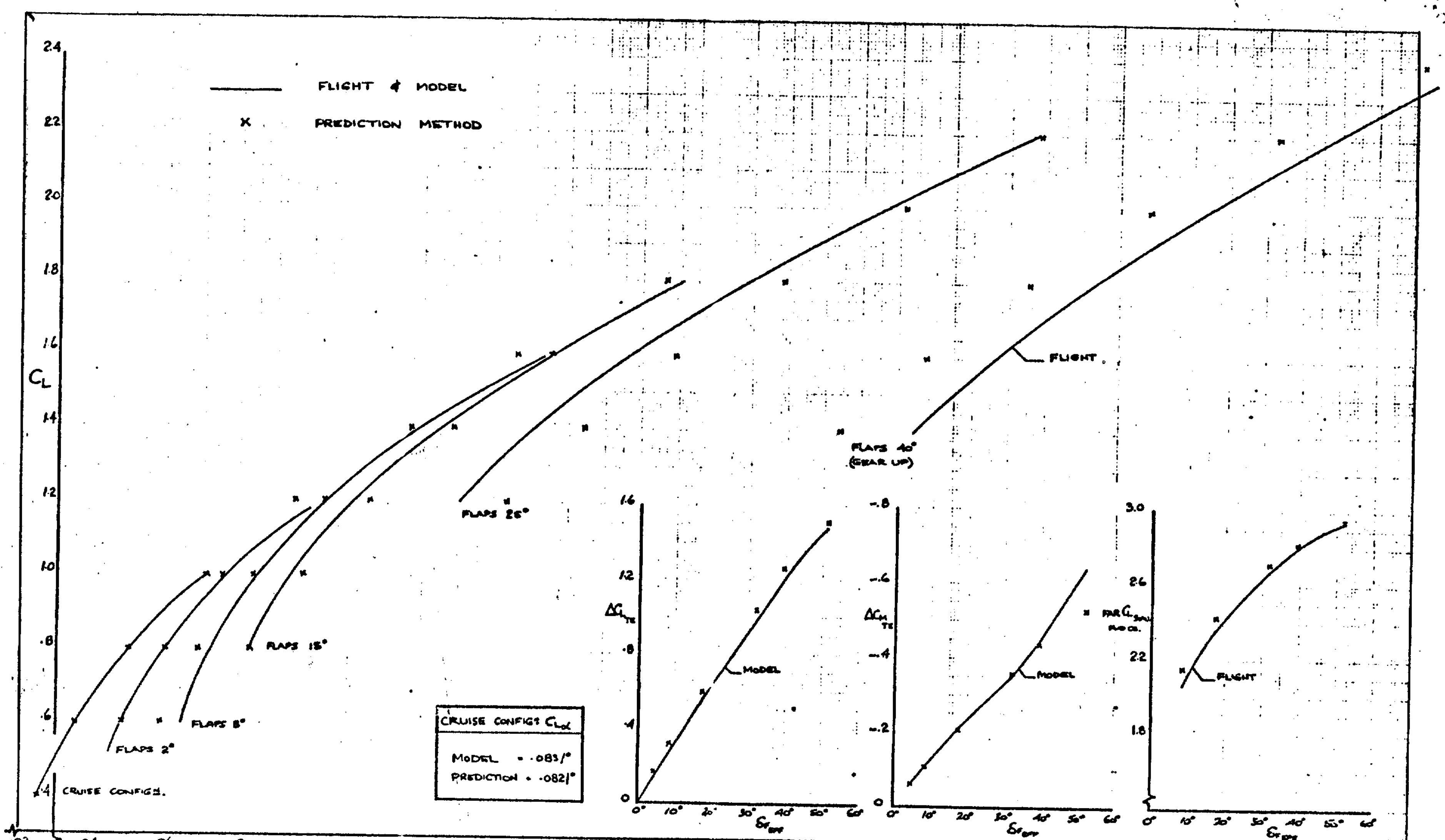
CONFIG.	C_L	$\Delta C_{L_{TE}}$	$\Delta C_{Dp_{MIN\ LE}}$	$\Delta C_{Dp_{MIN\ TE}}$	$K^2 \Delta C_L^2$	$\delta C_{Dp_{LE}}$	$C_L^2/\pi AR$	C_{Lp}	$C_L - C_{Lp}$	ΔC_{Dp}	TOTAL C_D	
CRUISE	↑	—	—	—	—	—						
	SUITABLE RANGE											
	↓											
L ONLY		—		—	—	—						
TAKE-OFF 1.												
TAKE-OFF 2.												
TAKE-OFF ~APPROACH												
LANDING + GEAR.												

CALC	CHECK	APR	APR	REVISED	DATE

DRAG POLAR BUILD UP

THE BOEING COMPANY
RENTON, WASHINGTON

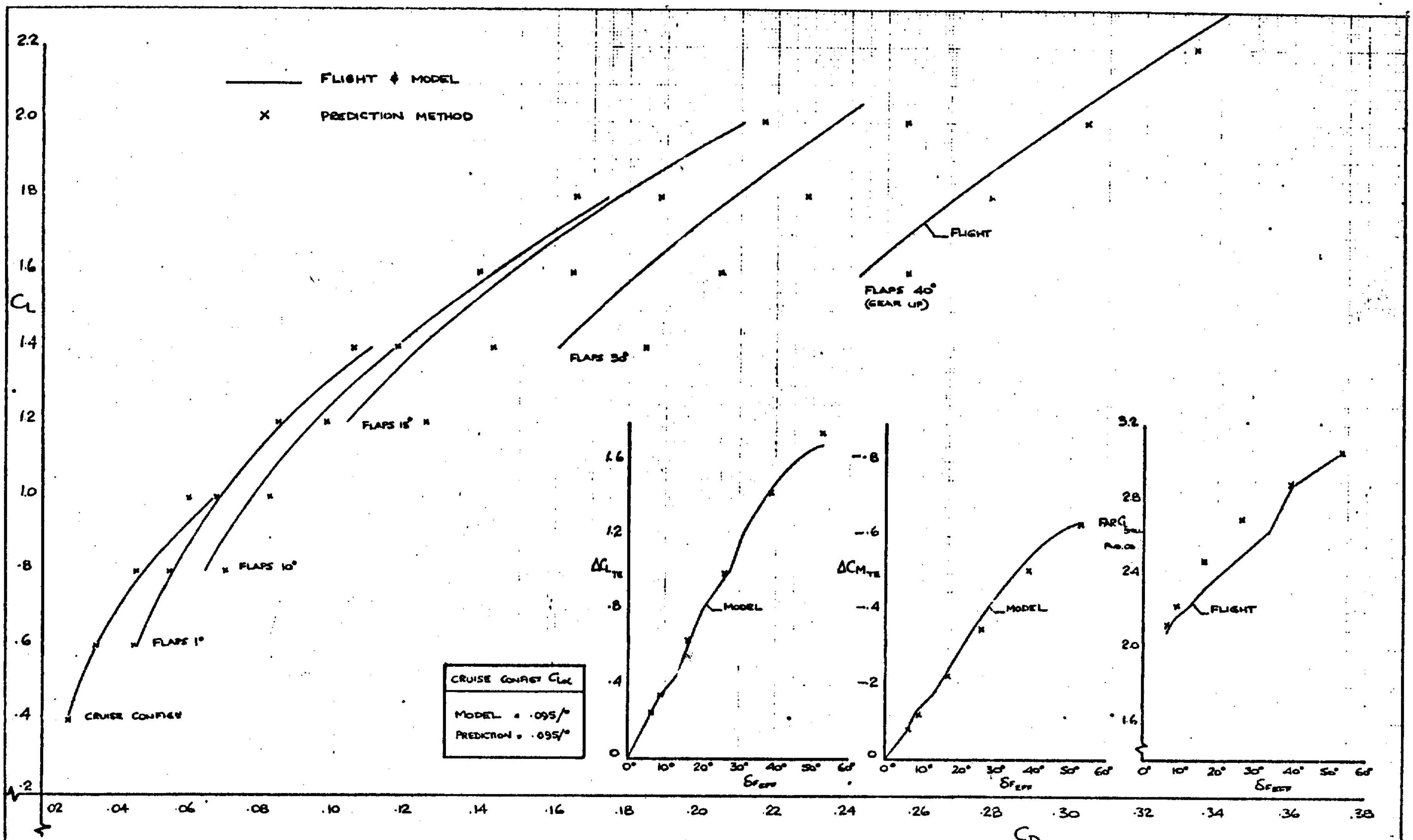
D6-26011 TN
FIG 34



CALC			REVISED	DATE	727 COMPARISON OF FLIGHT & PREDICTION METHOD RESULTS	FIG. A1
CHECK		3 June 70				
APPD					THE BOEING COMPANY	PAGE
APPD						

AD 1083-R6

D6-26011 TN 60



CALC	N. Granger	4 June 70	REVISED	DATE	737 COMPARISON OF FLIGHT & PREDICTION METHOD RESULTS	FIG. A2
CHECK					THE BOEING COMPANY	PAGE
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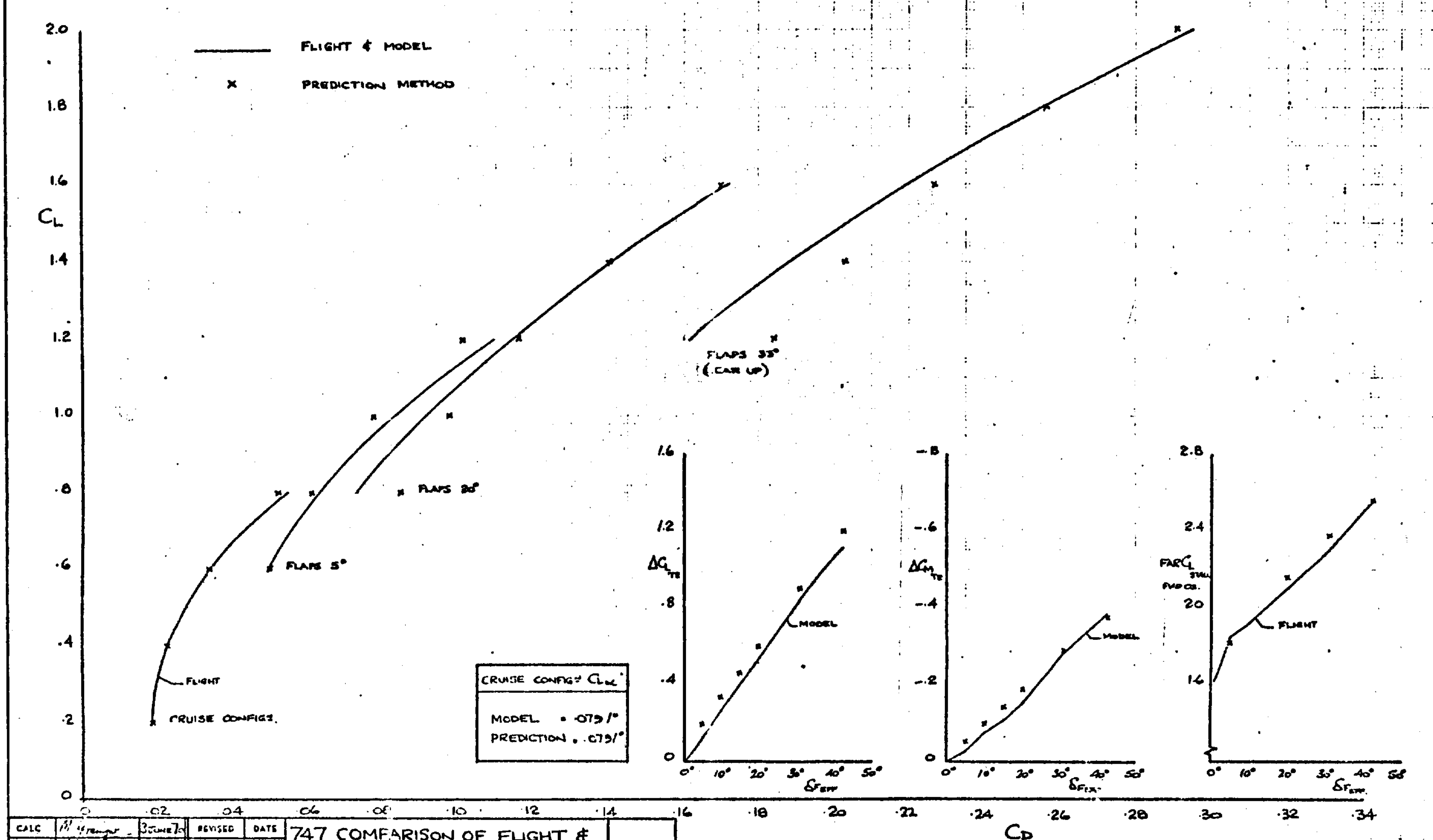
APPD						

AD 1023 R6



747 COMPARISON OF FLIGHT & PREDICTION METHOD RESULTS

FIG. A3

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AD 1053 R6