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COMMERCIAL AIRPLANE DIVISION

RENTON, WASHINGTON

ARED BY M. Grainos 4 JUNE 1970

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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 transenic 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.

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- 1. Lift Curve
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 - 1.2 Non-linear lift curves (Low AR)
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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.

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:

$$C_{L_{\infty}} = \frac{2\pi \left(1 + \frac{C_{\infty}}{2}\right)}{\frac{E}{C_{\infty}\Lambda_{C_{\infty}}} + \frac{2}{AR}}$$
 where $E = \sqrt{1 + \left(\frac{2C_{\infty}\Lambda_{C_{\infty}}}{AR}\right)^2}$

1.2 Non-linear lift curve slopes

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

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

$$C_L = C_{L_{\infty}} \sin \omega_1 \cos^2 \omega_1 + C_{L_{\infty}} \left(1 - \frac{C_{L_{\infty}}}{\pi AR}\right) \frac{\cos \omega_1 \sin^2 \omega_1}{\cos \Lambda c/4}$$

where $C_{L_{\infty}} = \text{linear lift curve slope, per radian}$

$$\omega_1 = \omega \text{ measured from zero lift} \omega.$$

Note expression reduces to linear lift curve as \propto tends to zero.

- 1.3 Effect of fuselage on $C_{L_{\infty}}$ Figure 5 shows effect of body on basic wing ${^{\text{C}}}_{\text{L}}$
- 1.4 Effect of LE and TE device area extensions on $^{\text{C}}_{\text{L}}$ Increases in lift curve slope (based on Sw) are obtained due to fowler motion of the LE and TE high lift devices. For L E devices full benefit is assumed

$$CL_{\infty_{\bullet}} = CL_{\infty} (1 + \frac{\Delta SLE}{SW})$$

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

$$\nabla_{C}\Gamma^{TE} = c\Gamma^{\leftarrow} \cdot \propto \mathcal{E}^{TE} \cdot \mathcal{E}^{TE} \cdot \frac{c}{c_{n}}$$
 . Kp

where $\operatorname{CL}_{\infty}$ is basic aircraft lift curve slope. The LE device lift effectiveness, $\operatorname{Ag}_{\operatorname{LE}}$, 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 ($\propto = 8^{\circ}$) $\Delta^{C}L_{TE} = {}^{C}L \times_{\circ} \cdot \times_{S} \cdot \delta_{F_{EFF}} \cdot \frac{C^{\circ}}{C} \cdot K_{AR} \cdot K_{b} + C_{L_{O}} \cdot \frac{(C^{\circ} - 1) \cdot K_{b}}{C} \cdot \frac{C^{\circ}}{C} - 1$

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, $\ll g$, 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 $\ll g$ to 3-D requires the factor K_{AR} (to finite AR) 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 $K_{\rm b}$, Figure 11.

Discontinuous flap systems should be treated separately with the total ΔCL_{TE} being added to the flaps up, LE down CL at $\alpha = 8^{\circ}$.

2. Maximum Lift Prediction

2.1 Basic Wing CLMAX

The basic wing CL_{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 $>50^{\circ}$, some account should be taken of LE vortex lift.

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

2.2 Maximum lift increment due to TE flaps $\Delta C_{\text{LmaxTE}} = C_{\text{Lmax}_0} \cdot \psi \cdot \frac{\Delta S_{\text{TE}}}{SW} + \Delta C_{\text{Lmax}_2} \cdot \frac{S_2}{SW}$

where \triangle STE is the area added by the flap fowler motion and S2 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 CL_{max} due to flap camber, $\triangle CL_{max2}$, is found using Figure 15 knowing $\triangle CL_1$ which is the zero lift angle part of the previously estimated $\triangle CL_{TE}$.

$$\Delta c_{L_1} = c_{L_{\infty}} \cdot \mathcal{L}_{S_1} \cdot \delta_{F_{EFF}} \cdot \frac{c'}{c} \cdot K_{AR} \cdot K_{b}$$

to get

$$\triangle C_{L_2} = \triangle C_{L_1} \cdot \Theta \cdot \frac{S_W}{S_2}$$

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> CL_{max} (l_g) to give FAR CL_{STALL} . Figure 17 shows flight data for various Boeing aircraft, the mean line giving + lo% 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_{MCG} , flaps down, is given by the expression:

$$C_{\text{Meg}} = C_{\text{M}^{0}} + C_{\text{L}^{0}} \left(\frac{\underline{c}}{x^{\text{cg}}} - \frac{\underline{c}}{x^{\text{ec}}} - \frac{\underline{c}}{\nabla x^{\text{ec}}} \right) + \nabla_{\text{C}} \Gamma^{1} \left(\frac{\underline{c}}{x^{\text{cg}}} - \frac{\underline{x}^{\text{Cb-LE}}}{x^{\text{Cb-LE}}} \right)$$

where ΔC_{L_1} is the TE flap lift at the flaps up zero lift alpha. The flap pitching moment increment is therefore:

$$\Delta C_{MTE} = C_{L_0} \left(-\frac{\Delta X_{ac}}{C} TE \right) + \Delta C_{L_1} \left(\frac{X_{cg}}{C} - \frac{X_{ce}}{C} TE \right)$$

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

$$\frac{\Delta X_{ac}}{\overline{c}} TE = \frac{1}{\mu AR} \left(\frac{\Delta S_{TE}}{SW} \cdot \frac{SW}{\overline{c}^2} \right)$$

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

extremities as described in Figure 19. The CP chordwise position $\frac{\infty_{\text{CPTE}}}{C}$ 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, \mathcal{N}_{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 CL_{max} . Results from model tests of various Boeing aircraft suggest at CL_{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.

$$\Delta C_{L}$$
 TOTRIM = $\frac{C_{MCS}}{It/c}$

where $\frac{1}{\sqrt{C}}$ 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:

$$CD = CDP_{mincruise} + \frac{CL^2}{WAR} + \Delta CDP_{minLE} + \Delta CDP_{minTE} + \Delta CDiTE + \delta CDP_{LE} + \Delta CDP$$

- 4.1 Basic aircraft (cruise configuration) minimum parasite drag

 CDP 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 $\frac{c_L^2}{\pi R} \mbox{ with variations from the} \\ \mbox{parabolic shape accounted for in the $\triangle c_{Dp}$ term.}$
- 4.3 Parasite drag of LE device

 ΔCDP min LE is found from Figure 22 knowing ΔSLE/Sw. 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 δCDP LE with ΔCLTE is given in Figure 23.
- 4.4 Parasite drag of TE flaps $\Delta c_{\rm DP\ minTE} \ \hbox{is found from Figure 24 knowing the flap type and geometry.}$
- 4.5 Induced drag of TE flaps

 ΔCD_i is assumed to be of the form K²ΔC_{LTE}. 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 $\Delta c_{DP} \quad \text{takes into account the variation of the polar from a parabola}$ and as such includes all unknown lift induced drag. The CL at which Δc_{DP} is zero is termed c_{LP} and is found, flaps down, by adding to

the basic aircraft C_{Lp} increments due to

the LE and TE high lift devices, see Figures 26 and 27. The CLp for the basic aircraft is a function of wing sweep, section camber and thickness (design $\operatorname{C_1}$) 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 $\Delta\operatorname{CDp}$, Figures 31 and 32, for high lift configurations. Cruise wing $\Delta\operatorname{CDp}$'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 flightmodel 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.

REV SYM

TABLE 1

List of Symbols	
AR	= Aspect Ratio
Ъ	= Wing span
bco	= Span of TE flap cut-out due to fuselage
bf	= Span of TE flap
c	= Wing chord
- c	= Mean aerodynamic chord
c¹	= Extended wing chord, TE flaps down
c"	= extended wing chord, LE device down
CLE	= LE device chord
СМР	= Main flap chord (including fore-flap if present)
CAF	= Aft flap chord
CF	= Expanded TE flap chord
$c_{\mathbf{L}}$	= Lift coefficient
CD	= Drag coefficient
CM _C g	= Pitching moment coefficient about c.g.
$\Delta c_{ ext{LTE}}$	= Lift increment due to TE flaps at constant & = 8°
$\triangle \mathtt{CL}_{\mathtt{LE}}$	= Lift increment due to LE device at cruise zero lift \propto
$\Delta \mathtt{CM}_{\mathbf{IE}}$	= Pitching moment increment due to TE flaps at constant ≪=8°
CImax1g	= Maximum trimmed lift coefficient at lg
FAR CLSTALL	= Maximum trimmed lift coefficient including dynamic effects
$\Delta_{ ext{CL}_{ ext{max}_{ ext{TE}}}}$	= Increment in maximum lift coefficient due to TE flaps
$\Delta \mathtt{CL}_{ extbf{max}} \mathtt{LE}$	= Increment in maximum lift coefficient due to LE device
Δc_{L_2}	= Sectional lift increment due to TE flap camber
$\Delta c_{ m L_{max2}}$	= Sectional maximum lift increment due to TE flap camber

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CLP	= Lift for minimum parasite drag in cruise configuration
△CL _{PTE}	= Increment in lift for minimum parasite drag due to TE flaps
$\triangle_{\text{C}_{\text{LP}_{\text{LE}}}}$	= Increment in lift for minimum parasite drag due to LE device
CDPmincruise	= Minimum parasite drag coefficient in cruise configuration
$\triangle \mathtt{CDP_{min}}\mathtt{TE}$	= Increment in minimum parasite drag due to TE flap
$\Delta_{ ext{CDP}_{ ext{min LE}}}$	= Increment in minimum parasite drag due to LE device (TE flaps up)
△c _{DP2}	= Sectional increment in parasite drag due to TE flaps
Sc _{DPLE}	= Reduction in parasite drag due to LE device with TE flap deflection
△CD _{iTE}	= Induced drag due to TE flaps
Δc_{DP}	= Increment indrag due to non-parabolic polar shape
CL≪	= Lift curve slope
SREF	= Aerodynamic wing reference
SW	= Wing area
s ₁	= Wing area plus area due to extended LE device
S2	= Area of flapped part of wing including extended LE & TE devices
$\Delta \mathtt{s}_{\mathtt{LE}}$	= Increment in wing area due to extending LE device
$\triangle s_{ ext{TE}}$	= Increment in wing area due to extending TE device
(t/c)	= Section thickness/chord ratio.
K	= Flap induced drag factor
КЪ	= Flap span factor on lift
K _{AR}	= Correction factor - lifting line to surface theory
X ac	= Chordwise position of cruise wing aerodynamic center
Хeg	= Chordwise position of aircraft center of gravity
X CPTE	= Chordwise position of center of pressure of load due to TE flap deflection
ΔX acTE	= Shift in aerodynamic center position due to TE flap deflection

.

≪ = Wing angle of attack = Flap effectiveness parameter = Flap pitching moment function = LE device deflection SME = TE main flap deflection **S**AF = TE aft flap deflection δ_{FEFF} = Effective TE flap deflection = Spanwise station, fraction of semi-span f(7)= Flap spanwise loading function = Part span flap lift distribution function Λ_{4} = Sweep of wing quarter chord line = TE flap fowler area efficiency factor

SUFFICES & ABBREVIATIONS

O = LE device down, TE flaps up configuration

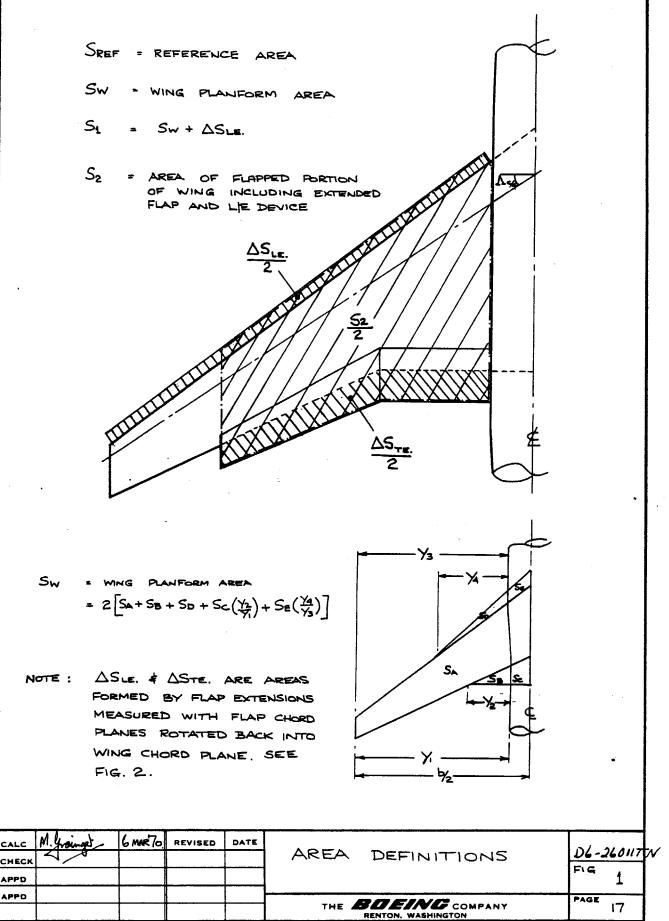
LE = Leading edge (device)

TE = Trailing edge (flaps)

1/B = Inboard

O/B = Outboard

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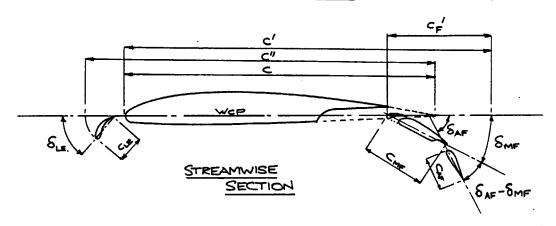


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CHORD AND ANGLE DEFINITIONS



ALL CHORDS AND ANGLES MEASURED STREAMWISE

C' = EXTENDED WING CHORD TE, FLAPS DOWN.

C" = EXTENDED WING CHORD LE. DEVICE DOWN.

CF . EXPANDED FLAP CHORD.

L.E. DEVICE LIFT EFFECTIVENESS

WHERE :

ΔCLLE: LE DEVICE LIFT DECREMENT AT BASIC WING ZERO LIFT ANGLE.

CLX - BASIC WING LIFT CURVE SLOPE

TE. FLAP LIFT EFFECTIVENESS

WHERE :

△CLTE - TE FLAP LIFT INCREMENT AT X=8°

KR : CORRECTION FACTOR " LIFTING LINE TO SURFACE THEORY.

Kb . SPAN FACTOR

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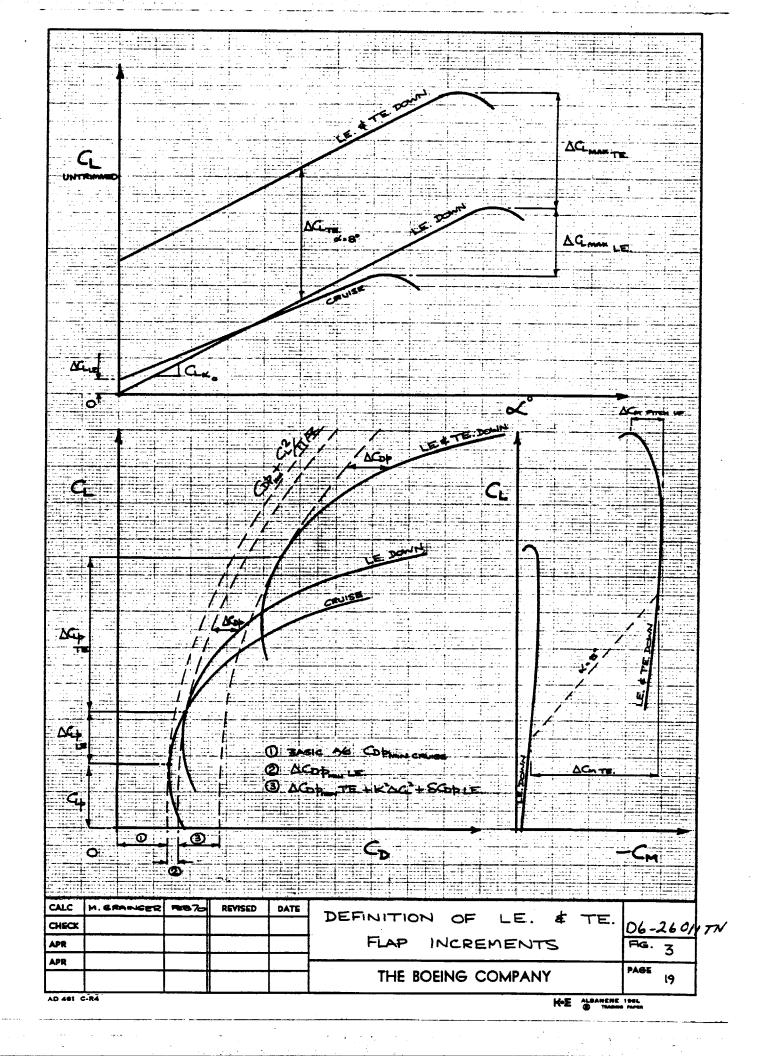
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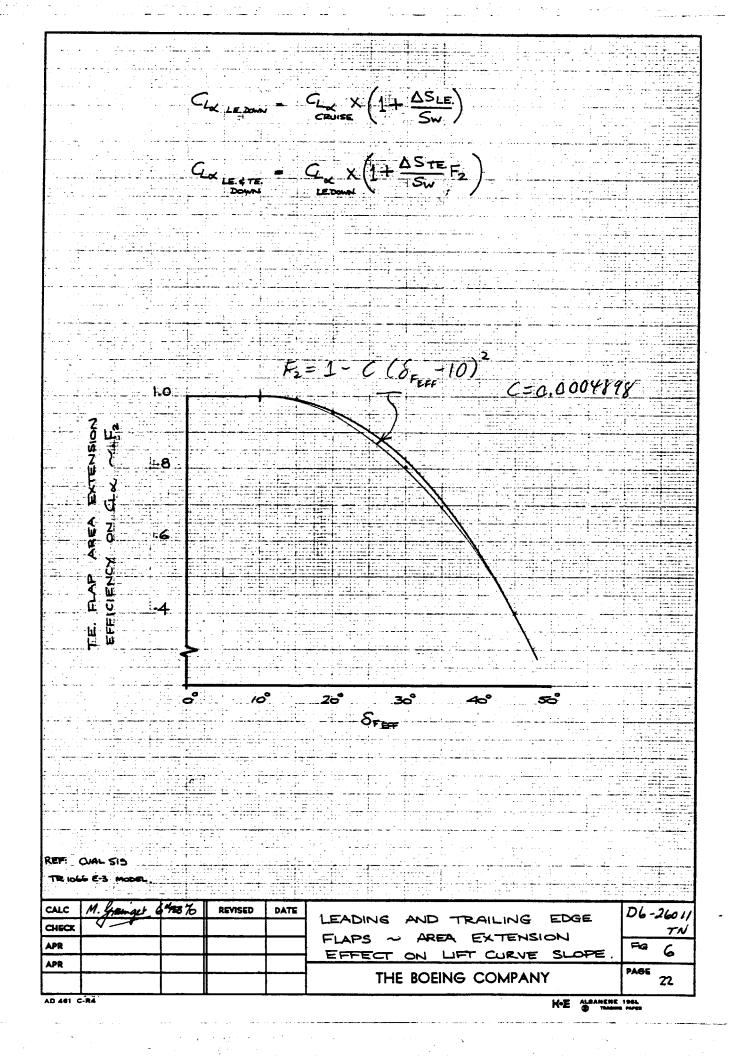
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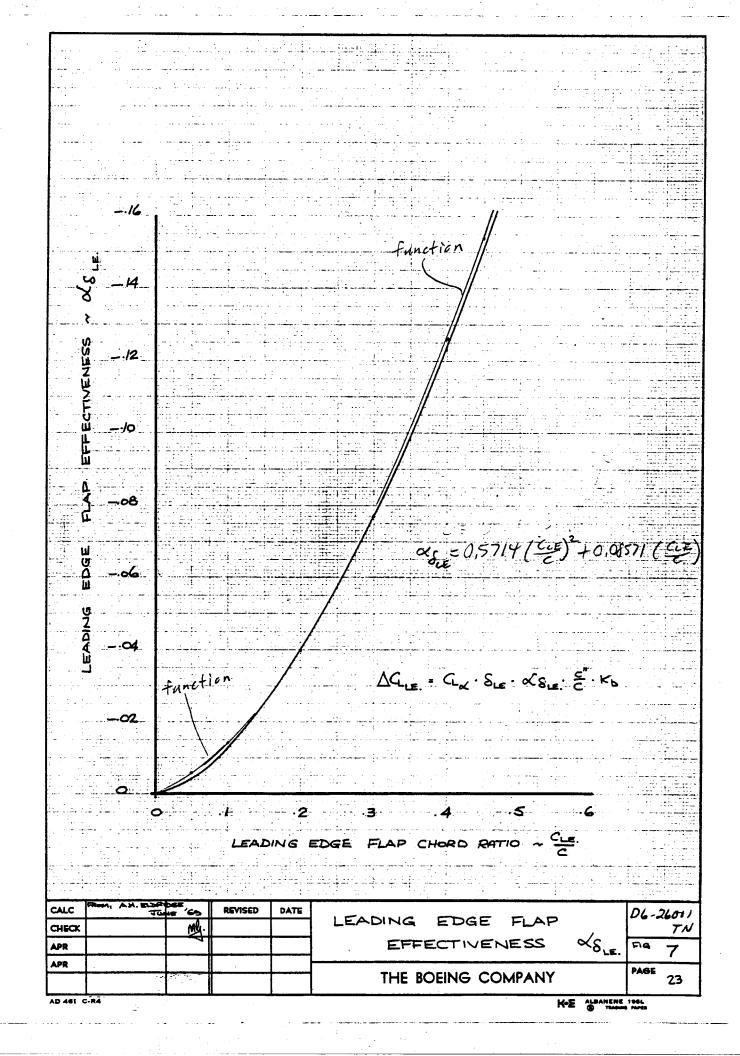


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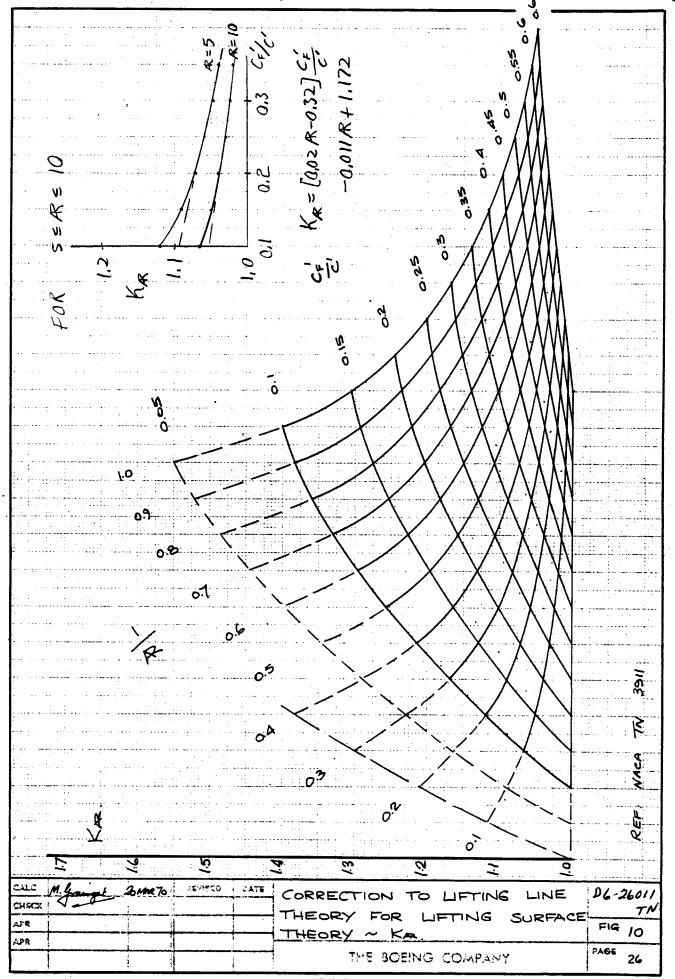
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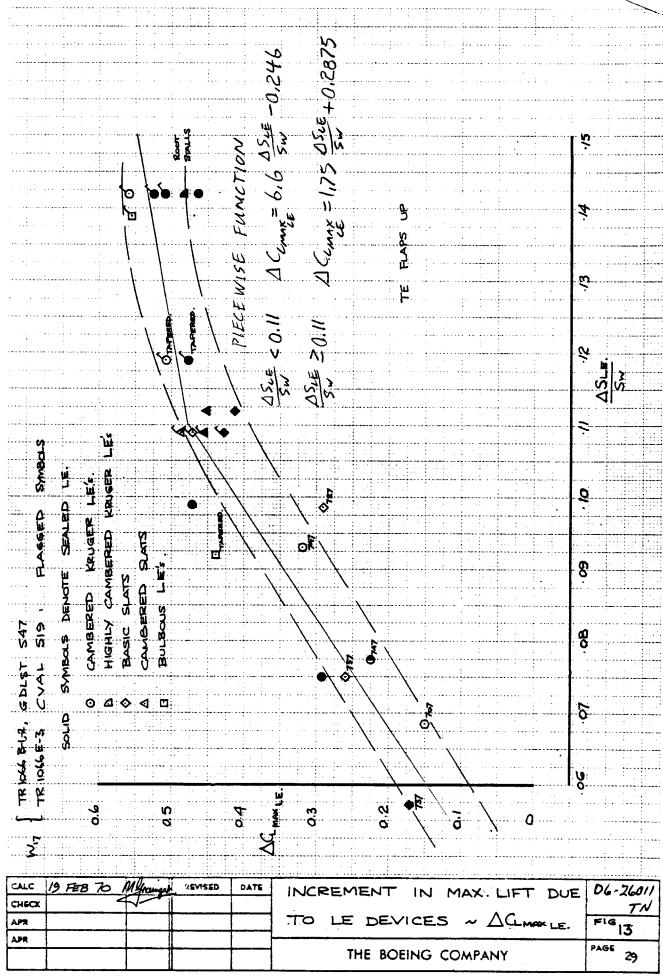
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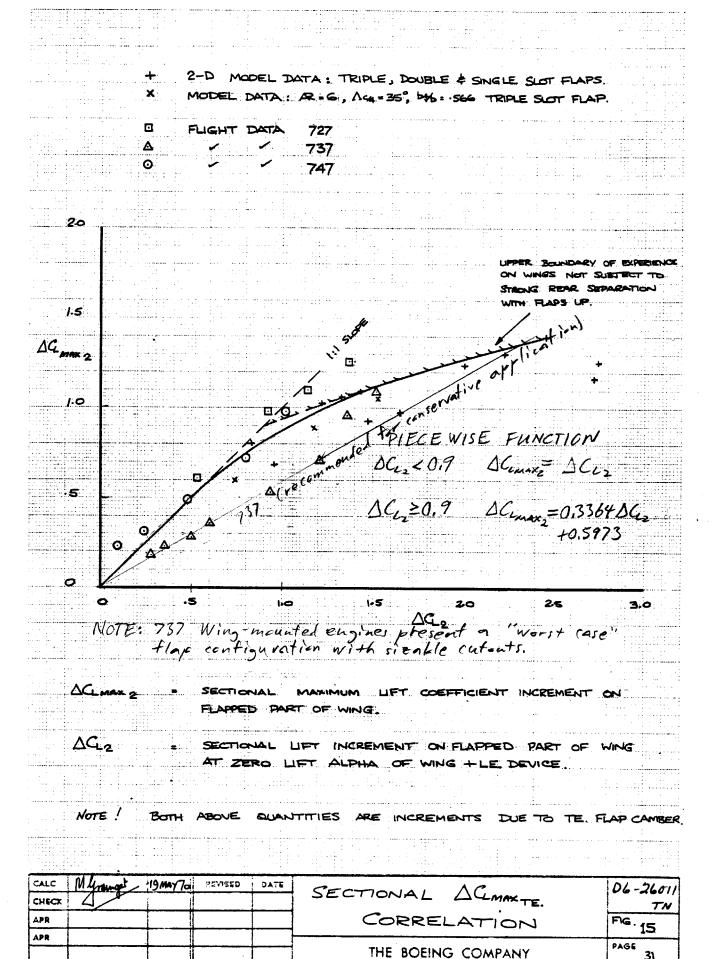
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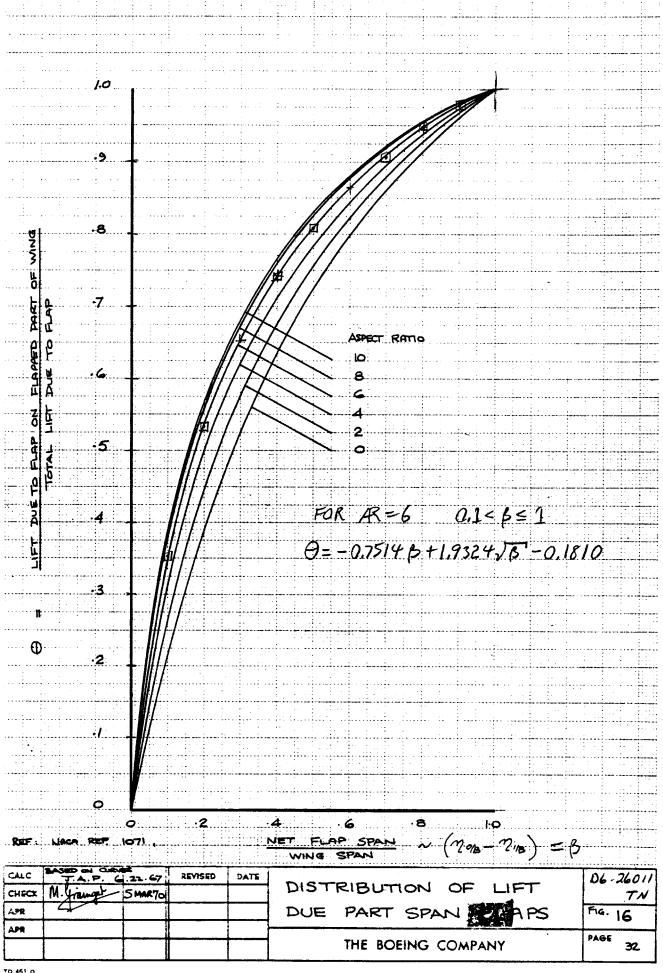


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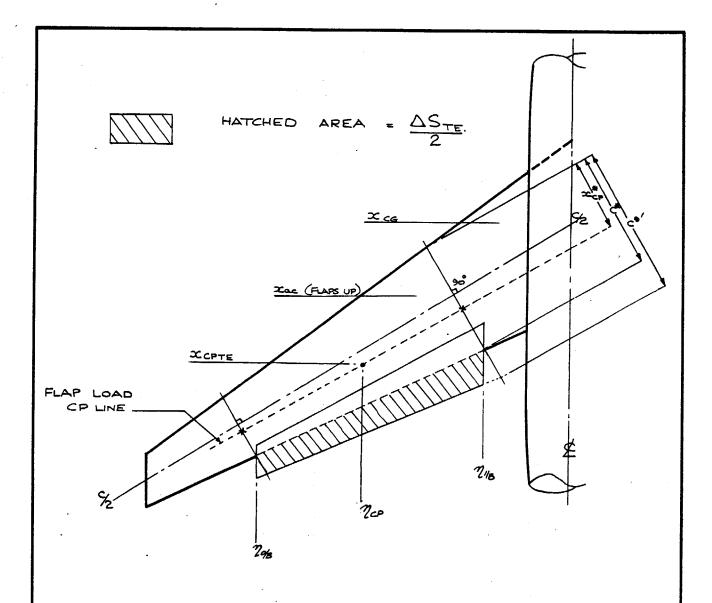


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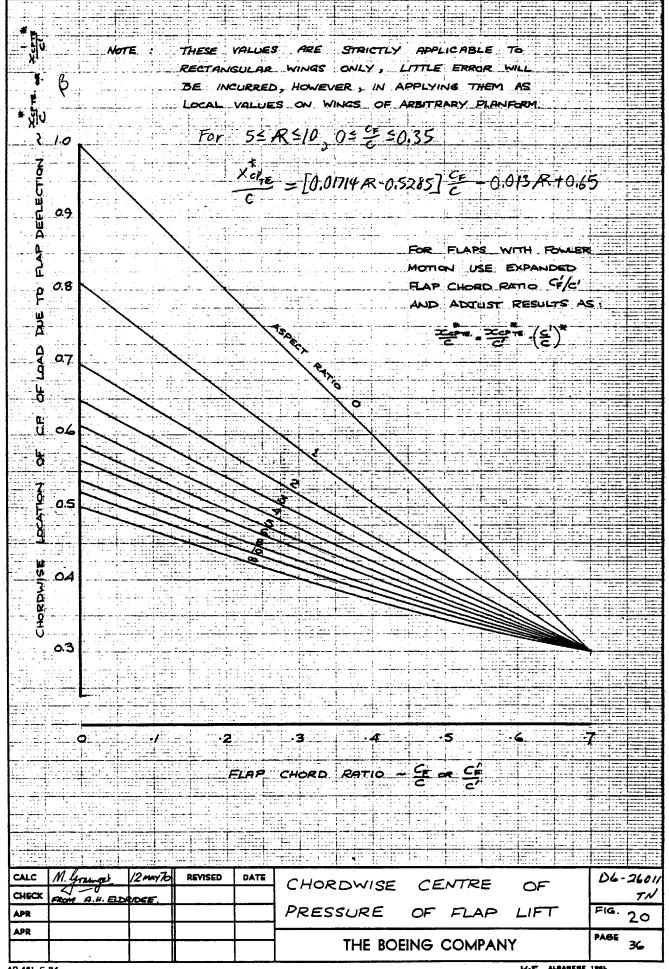
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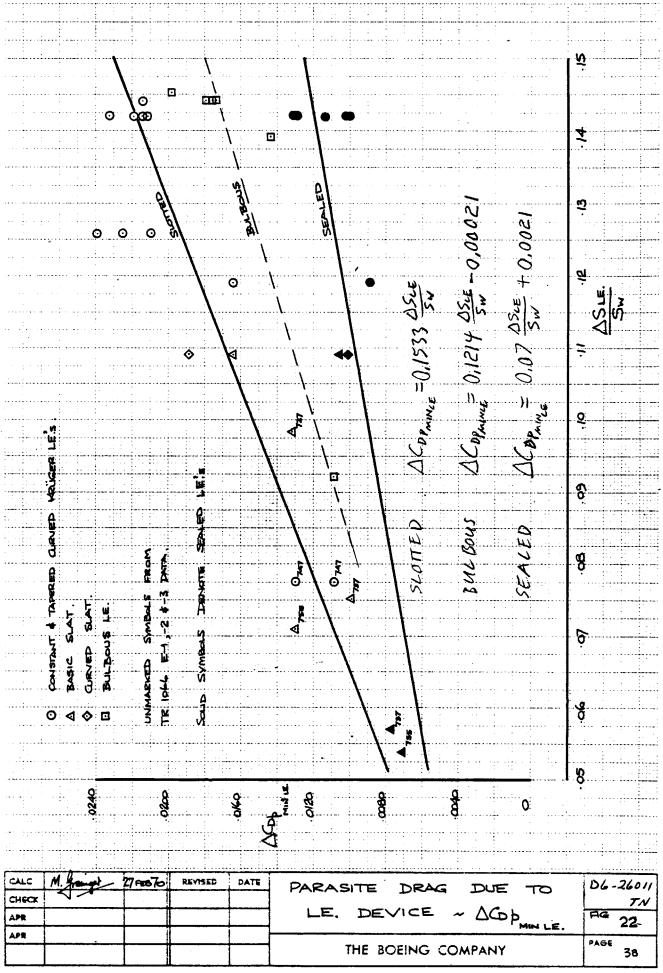
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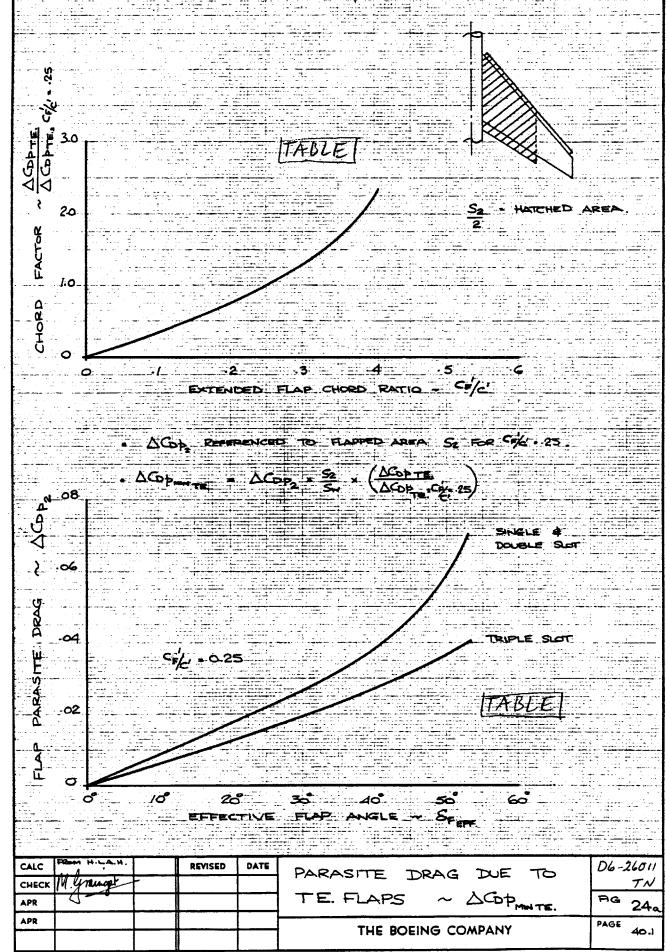
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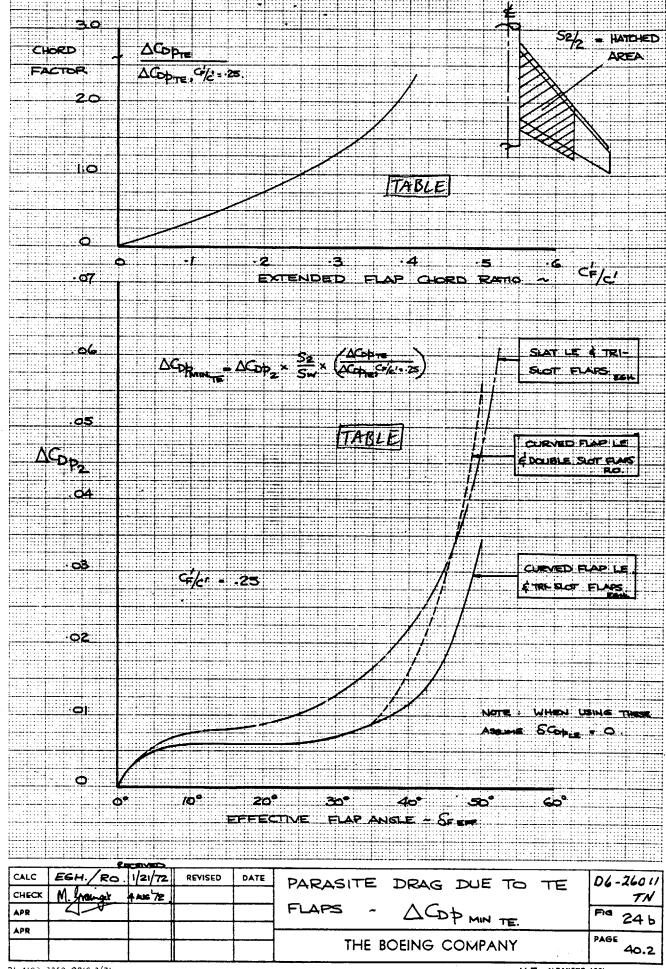
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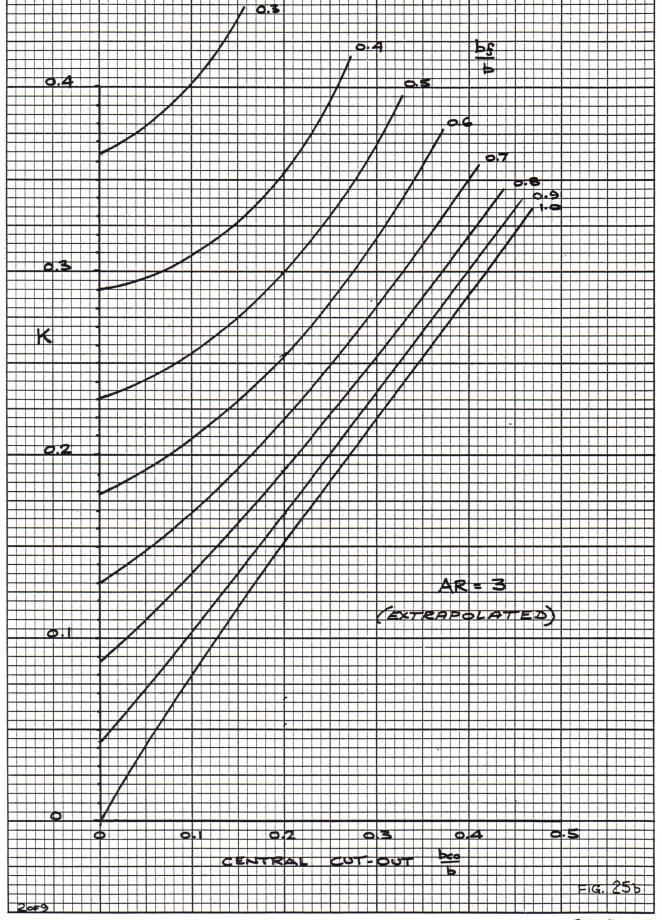
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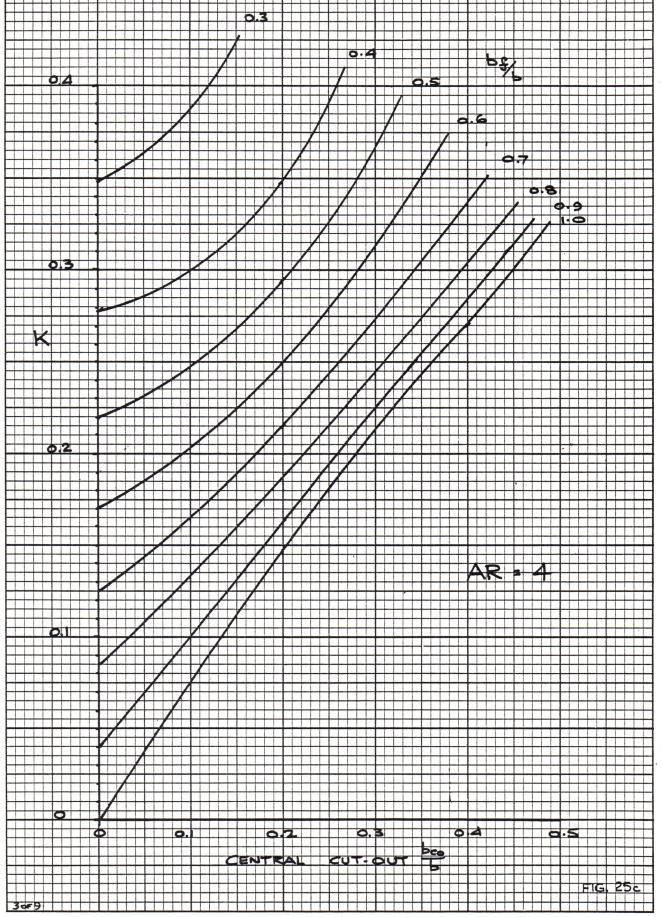


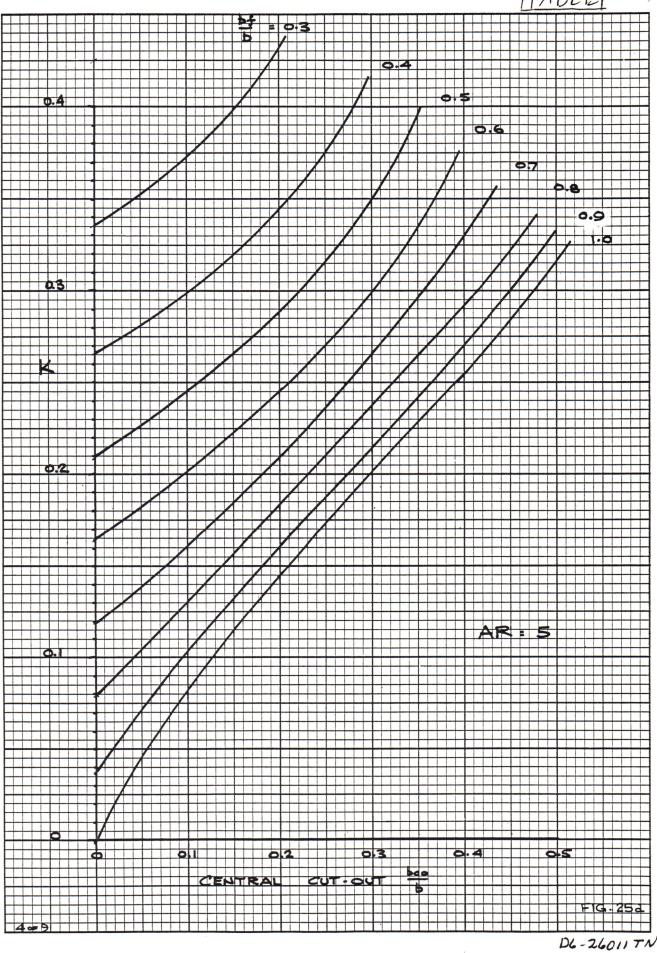
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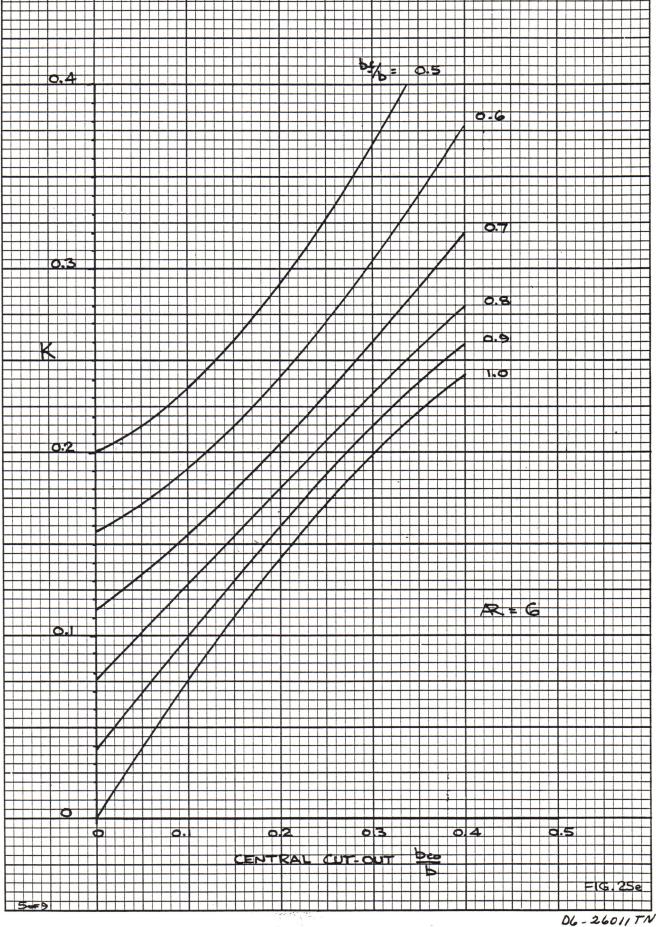


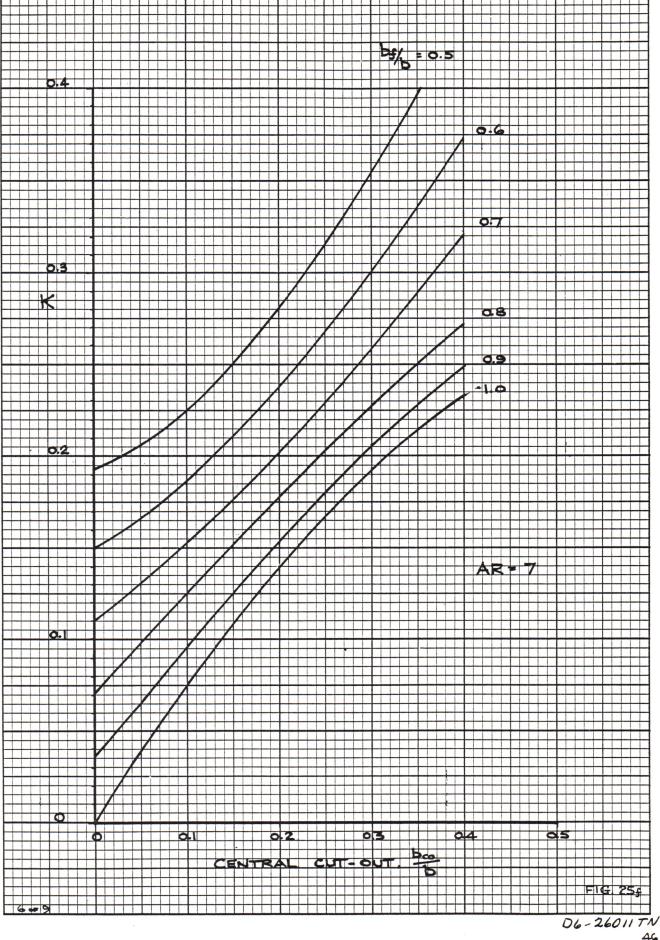


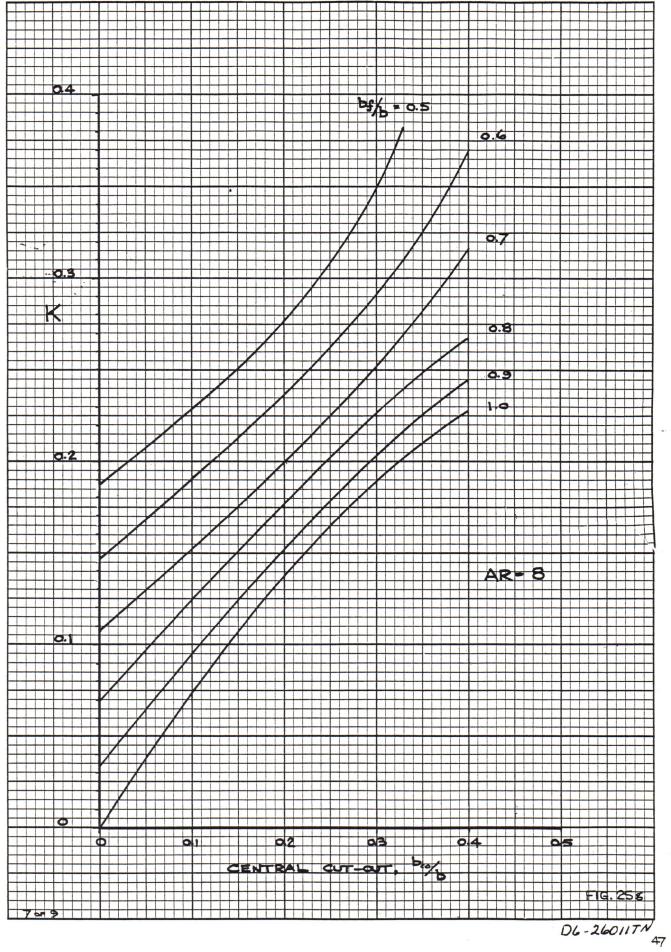


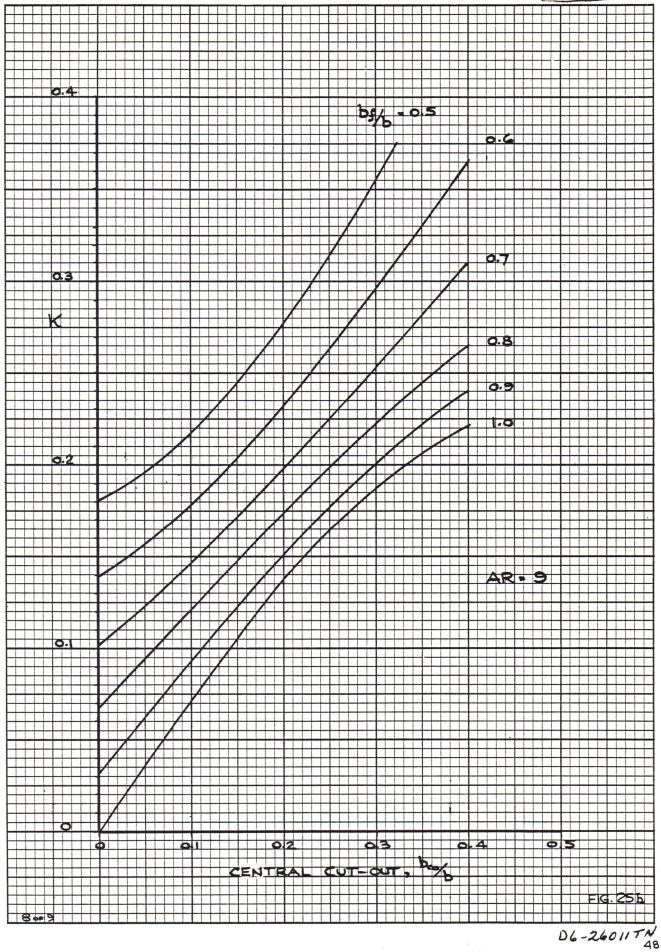




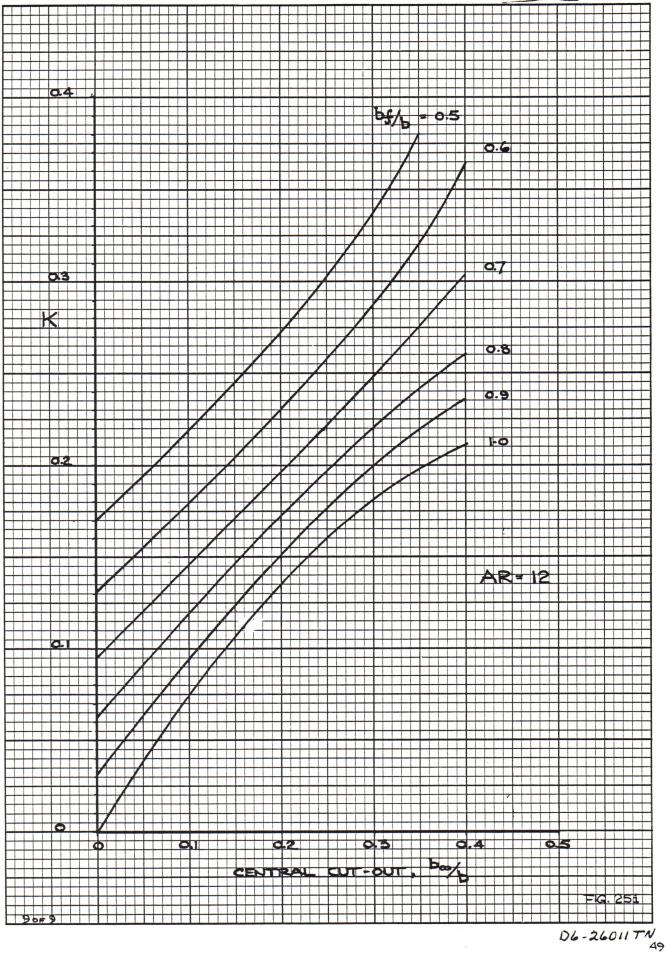


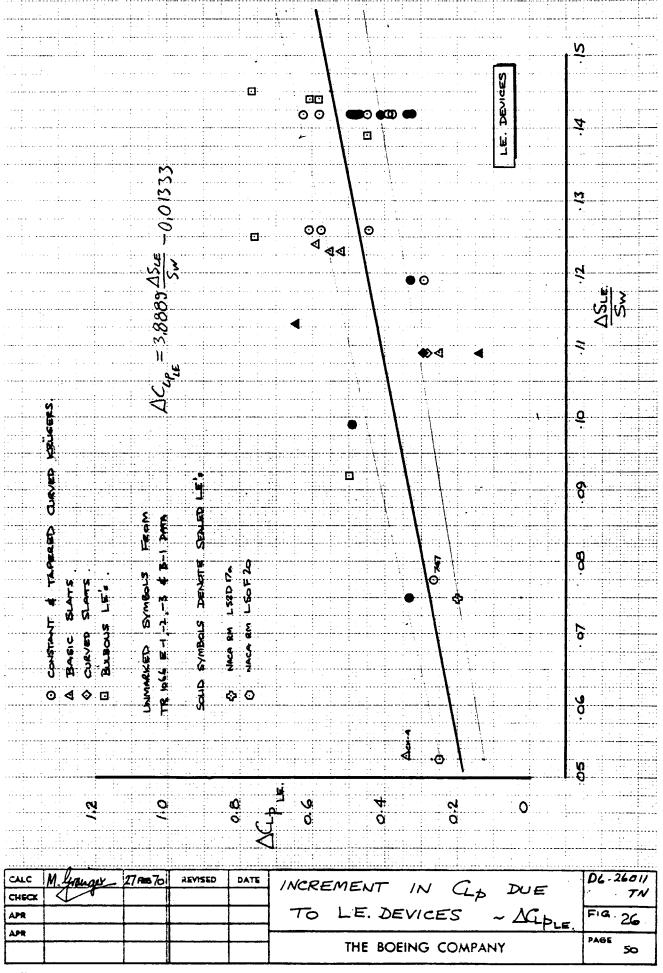






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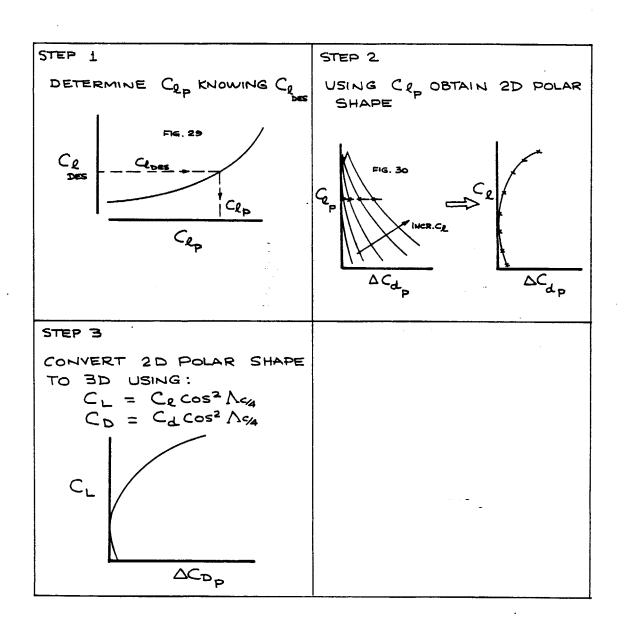


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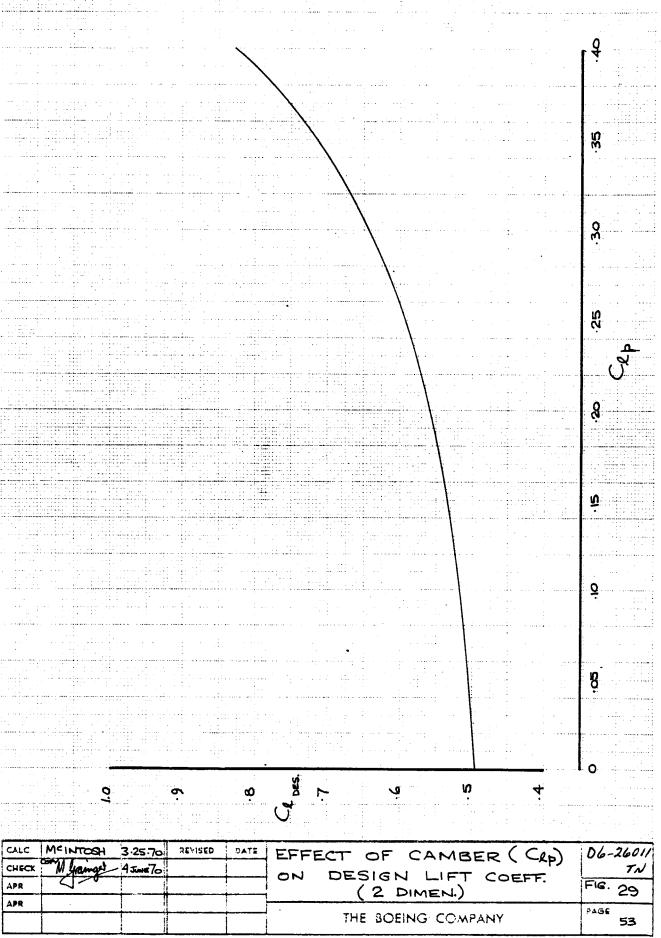
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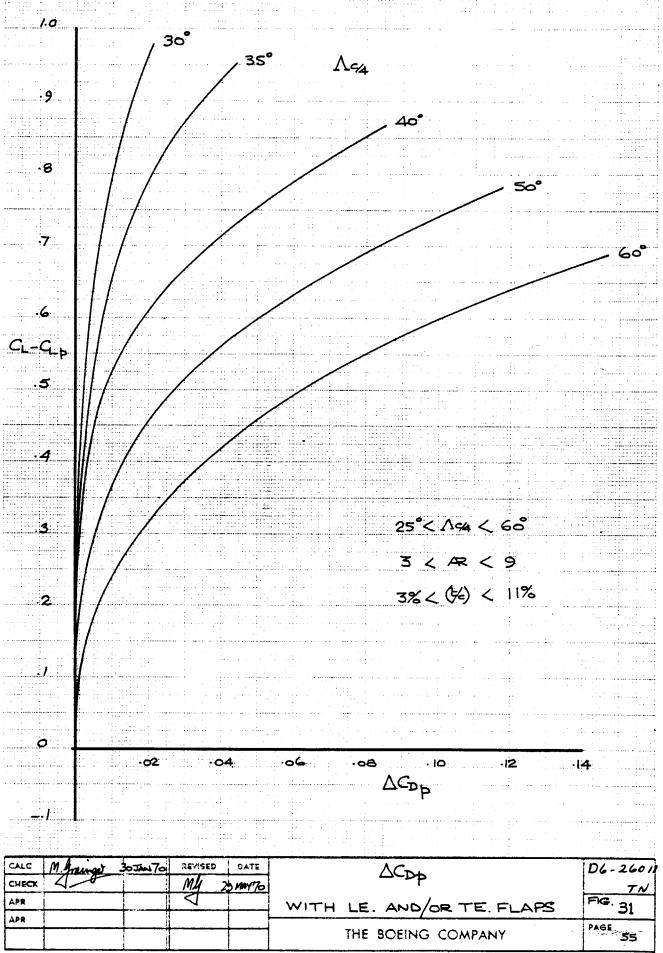
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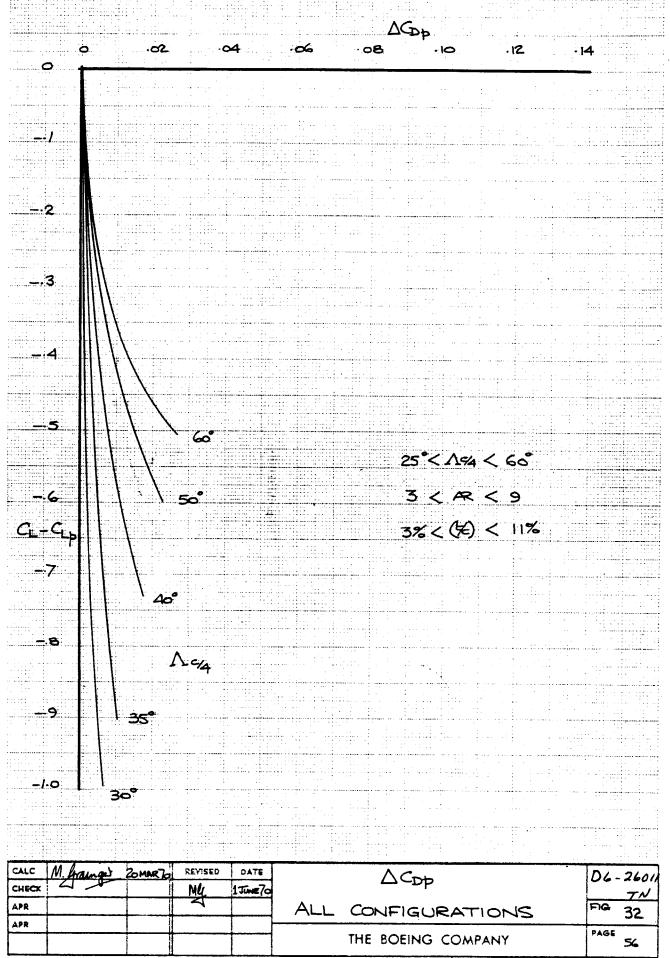
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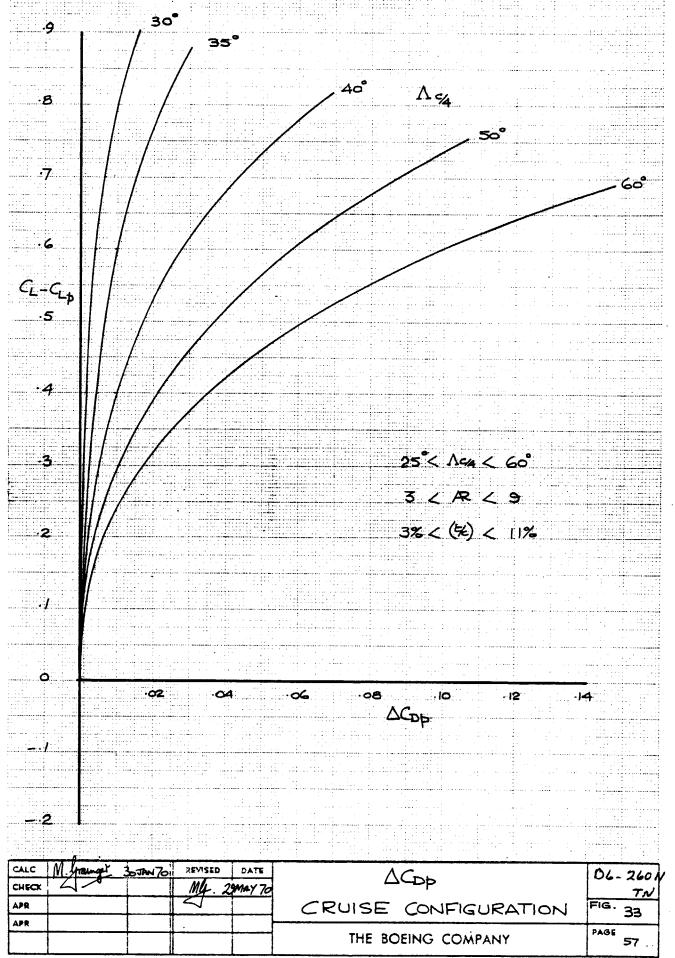
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APPENDIX.

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