HYDRODYNAMIC NOTE AS-25

DERIVATION OF AND INTRODUCTION TO FLAP LIFT CAVITATION EQUATIONS AND CAVITATION BUCKETS

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SUMMARY:

The object of this note is to provide an introduction to a comprehensive and detailed study Of flap lift which is to follow this note.

A very powerful equation for flap lift cavitation has been derived as a result of all previous flap lift investigations. Up until this report flap control of cavitation was not a state of the art concept. Now that an easy to understand, accurate method of determining cavitation characteristics has been derived futher applications and extensive investigations of flap control are possible at a greatly reduced cost since the need for costly computer time and extensive programs is no longer required.

Through tile use of *known* equations *for* incidence lift and Allen's flap velocity distributions the foil cavitation equation was derived. A check was performed on the resulting bucket by assuming a zero pitch angle and trimmed flaps, and comparing it to the curve for zero flap deflection and the curve for incidence lift. Deflection angle equations for the desired lg case have been formulated through the use of "reference terms" which were in themselves derived as a necessity to this note.

INTRODUCTION:

The purpose of this note, first in a series of related notes on flap lift cavitation, is to establish the basis for a detailed and rigorous investigation of the flapped foil for use in hydrofoil designs.

This first note will include the following:

1. A review of previous flap lift cavitation work (Hydrodynamic Note AG-5), and incidence lift cavitation advancements (Hydrodynamic Note AG-18). This will establish the basic equations and concepts involved in the final flap lift cavitation equation.
2. The derivation of the basic section cavitation bucket for the flap lift case and a presentation of the results in graphical form with a practical example.
3. A derivation and illustration of the section cavitation bucket which evolves from the basic foil loading form, w/s. Explanation of all new variables and symbols will be included.
4. A step by step discussion of the unique $W/S)_{ref}$ and $(W/S)'$ terms.
5. Investigation of cavitation flap deflection angles, ($\delta_{cavitation}$).
6. Introduction to future flap lift hydrodynamic notes with a brief consideration of optimizing the characteristics of:

a. Limited Flap Angles

b. Smooth and Rough Water cavitation Characteristics

c. Foil Drag

d. Hinge Moments

Employing the flap lift system to hydrofoil vehicles will expand the realm of hydrofoils in the future. First, larger foils with spans in excess of twenty feet will become possible without the excessively large control system required if only incidence lift control were employed. Second, the problem of cavitation will become slightly reduced by expanding the boundries of the illustrative foil cavitation bucket.

All of the equations have been reduced, and all constants have been selected for application to the AG(EH) forward foil. Application to any other foil may of course be considered.

CONCLUSIONS:

Equations 7 and 14 of this note define the two dimensional section and the three dimensional foil cavitation buckets for the flap lift case. The construction of these buckets allows visualization of how the flaps expand the region of cavitation-free operation, thus allowing performance at reduced speeds and greater foil loadings.

A breakdown of the foil cavitation bucket equation into those terms unique to flaps allows the construction of equations which determine allowable flap deflections for 1g operation, and the first sign of cavitation. With the variation of pitch and incidence angles and the application of the flap deflection equations a complete catalogue of restricting flap angles can be compiled for stability and control purposes. The relationships formulated in this report shall provide a reference and a basis for all flap lift investigations.

DISCUSSION:

PART I: BASIC THEORY AND DERIVATION OF EQUATIONS

In beginning this discussion and evaluation of flap lift and its cavitation characteristics two major assumptions must be made in order to proceed with the derivation of the cavitation bucket.

The first problem considered arises from the fact that the peak values for pitch lift, incidence lift, and flap lift do not occur at the same spanwise locations on the foil. So the first assumption made shall be that the largest $(C_l/C_L)_{max}$ values that occur on each lift coefficient shall be the ones used in the derivation, disregarding their location on the foil. This will assure that the derived cavitation bucket will account for that critical station where the first sign of cavitation begins. Incorporating into the theory the concept of full span flaps the equality $(C_l/C_L)_i = (C_l/C_L)_\delta$ can be made for simplicity. So for a given foil configuration a total C_l can be determined, and since a normal to the quarter chord dynamic pressure is known the total section foil loadings, w/s, at the critical span station can be determined by the relation:

$$C_l q = w/s$$

This directs the theory to a second problem and assumption. If the C_l's vary along the span, what is the average foil loading on the foil? This is necessary to determine because in investigating a single section at an arbituary spanwise location a transformation to a foil cavitation bucket is not possible unless an average section foil loading can be determined. No single C_l/C_L ratio will carry the derivation from the section bucket to the foil bucket because the section loading has, as was stated before, three components associated with C_l/C_L ratios. It is the decomposition of the section loading and the reassembly of the average foil loadings which constitute the bulk of the cavitation bucket. At this point a clarification in foil loading terminology should be made. W/S from this point on will denote the foil loading for the three dimensional foil whereas w/s will be the two dimensional section foil loading. The differing factor being C_L and C_l respectively.

The definition of w/s is:

(1) $$(w/s)_\delta + (w/s)_i + (w/s)_o + (w/s)_\alpha = w/s$$

This relationship can be derived from the terminology just discussed, The only unknown term for flap lift control is $(w/s)_\delta$:

(2) $$(w/s)_\delta = w/s - (w/s)' - (w/s)_\alpha$$

The derivation of the section bucket will proceed from this point starting with Equation 37 of reference 1. The most basic local velocity distribution over the section can be written,

(3) $$\sqrt{S} = v/V \pm \Delta v/V \pm (C_l{}' + C_{laf} - C_{l_{ieff}}) \Delta va/V \pm C_{lb}(\Delta v/V)_f$$

where C_{lb} is basic flap loading and $C_{laf} = C_{lf} - C_{lb}$, and where

$$C_{l_b} = \mathscr{J}(C_l - C_l') \qquad (4)$$
$$C_{l_f} = (1-\mathscr{J})(C_l - C_l')$$

See Ref. 1 for futher explanation

$C_l' = (C_l)_i + C_{l_{ieff}}$. So a general form of Equation 46 of Reference 1 can be written as,

$$\sqrt{S} = V/V \pm \Delta V/V \pm \left[C_l' - (1-\mathscr{J})(C_l - C_l') - C_{l_{ieff}}\right]\frac{\Delta V_s}{V} \pm \mathscr{J}\left(\frac{\Delta V}{V}\right)_F (C_l - C_l')$$
$$= V/V \pm \Delta V/V \pm (\mathscr{J} C_l' - C_{l_{ieff}})\frac{\Delta V_s}{V} \mp (\Delta V/V)_F C_l' \pm \left[(1-\mathscr{J})(\Delta V_s/V) + \mathscr{J}(\Delta V/V)_F\right] C_l \qquad (5)$$
$$= V/V \pm \Delta V/V \pm (\mathscr{J} C_l' - C_{l_{ieff}})\Delta V_s/V \pm \mathscr{J}\left(\frac{\Delta V}{V}\right)_F C_l' \pm \left\{\Delta V_s/V + \mathscr{J}\left[(\Delta V/V)_F - (\Delta V_s/V)\right]\right\} C_l$$

This is now a very basic equation in the linear form of $y = b + mx$. It should be noted that the term C_l' includes both pitch and incidence lift since they are indistinguishable on the section. At this point C_l' will be used for camber and incidence lifts only. Equation 5 becomes,

$$\sqrt{S} = V/V \pm \Delta V/V \pm \left\{\mathscr{J}\left[C_l' + (C_l)_\alpha\right] - C_{l_{ieff}}\right\}\Delta V_s/V \pm \mathscr{J}(\Delta V/V)_F\left[C_l' + (C_l)_\alpha\right] \pm \left\{\Delta V_s/V + \mathscr{J}\left[(\Delta V/V)_F - \Delta V_s/V\right]\right\} C_l \qquad (6)$$
$$= V/V \pm \Delta V/V \pm \Delta V_s/V\, C_{l_{ieff}} \pm \mathscr{J}\left[\Delta V_s/V - \left(\frac{\Delta V}{V}\right)_F\right]\left[C_l' + (C_l)_\alpha\right] \pm \left\{\frac{\Delta V_s}{V} + \mathscr{J}\left[(\Delta V/V)_F - \Delta V_s/V\right]\right\} C_l$$

The equation can be condensed by initiating the parameters [illegible] and [illegible],

$$(7) \qquad \sqrt{S} = \psi \pm w\left[C_l' + (C_l)_\alpha\right] \pm (\Delta va/V - w)C_l$$

Note that this is still in the slope intercept form with $C_l = x$.

Equation 7 is now the equation used to graphically represent the section cavitation bucket. Figure 1 shows a very general section cavitation bucket. It can be seen that the upper area is the allowable and most restricting operating area. A practical application of this representation is seen in the following example.

If a foil <u>section</u> were operating at point A, at a given $\sqrt{S}$, and at a given $C_l = L/\frac{1}{2}\rho V^2 S$, where the S associated with the C_l is area, the section could increase its C_l by decreasing its speed or increasing the lift. This would advance point A towards the right of the graph. Cavitation would not occur anywhere on the section until point A' was reached. At this location cavitation would occur on the upper leading surface. In examining point B as it moves towards the right of the graph it will incur cavitation on a middle chord station before cavitating on the leading stations. What this graph is basically showing is a linear connection of the low pressure regions of the foil section through a range of C_l's or simply a range of speeds.

In order for the derivation to continue an explanation of "cavitation dynamic pressure" must be given.

Since the 16-(.390)08 section for the AG(EH) is defined as a section normal to the quarter chord the velocity component that passes over the

LL Lower Leading Chord Station

UM Upper Middle Chord Station

UL Upper Leading Chord Station

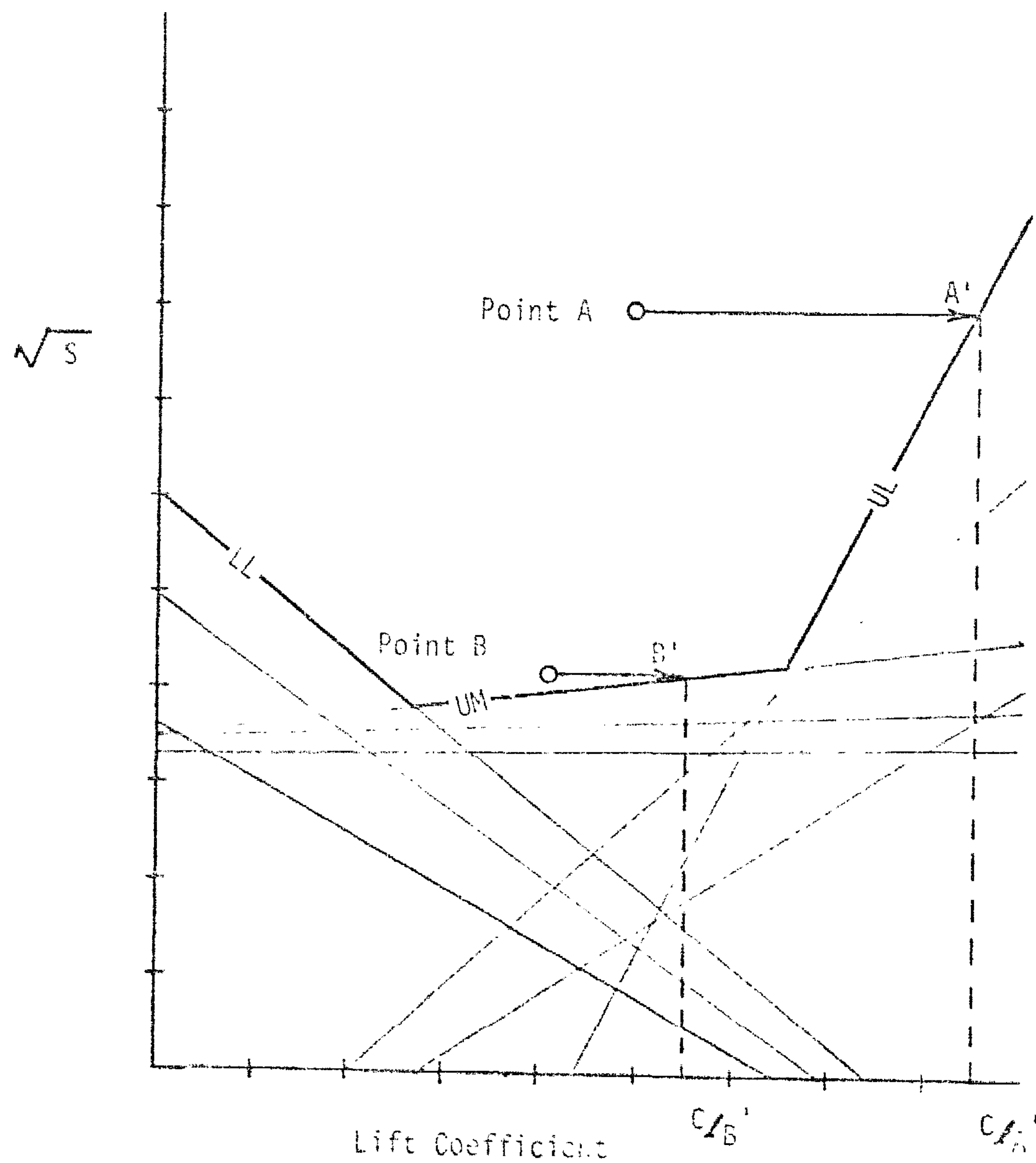


FIGURE 1 Illustrative Example of Section Cavitation Bucket

normal to the quarter chord is the velocity responsible for producing the foil cavitation. See Figure 2. So a new definition of q must be given. Basically, through simple geometry,

$$q' = q \cos^2 \Lambda$$

Now reconsidering the slope intercept form of the cavitation bucket:

$$\sqrt{S} = \psi \pm w \left[C_\ell' + (C_\ell)_\alpha \right] \pm \left(\Delta V_a / V - w \right) C_\ell$$

Rearranging,

$$\pm \left(\Delta V_a / V - w \right) C_\ell = \sqrt{S} - \psi \mp w \left[C_\ell' + (C_\ell)_\alpha \right]$$

(8) $$\left(\Delta V_a / V - w \right) C_\ell = \pm \left(\sqrt{S} - \psi \right) - w \left[C_\ell' + (C_\ell)_\alpha \right]$$

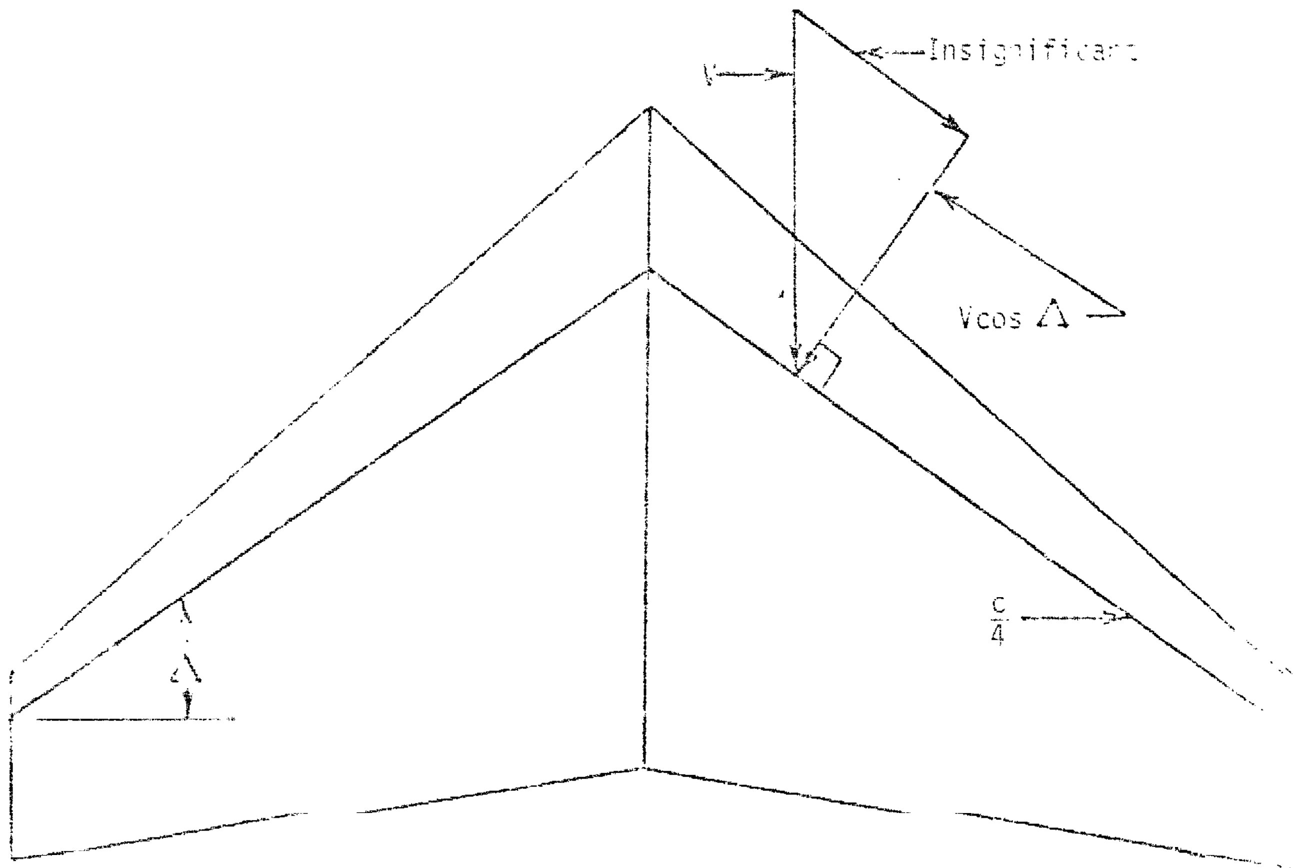
Multiplying through by q', since the interest is in the cavitation of the section and the section foil loading.

(9) $$\left(\Delta V_a / V - w \right) (w/s) = \pm \left(\sqrt{S} - \psi \right) q' - w \left[(w/s)' + (w/s)_\alpha \right]$$

For the flap lift case (w/s)' = $(w/s)_i$ + (w/s),.

$$w/s = (W/S)_\delta (C_\ell/C_L)_\delta + (W/S)' (C_\ell/C_L)_i + (W/S)_\alpha (C_\ell/C_L)_\alpha$$

$$= (W/S)_\delta (C_\ell/C_L)_\delta + (W/S)' (C_\ell/C_L)_\delta + (W/S)_\alpha (C_\ell/C_L)_\delta + (W/S)' (C_\ell/C_L)_i - (W/S)' (C_\ell/C_L)_\delta + (W/S)_\alpha (C_\ell/C_L)_\alpha - (W/S)_\alpha (C_\ell/C_L)_\delta$$



The component of velocity that is responsible for creating the cavitation on the foil is the normal component to the foil. Since there is an infinite amount of normals to a swept-tapered foil, the normal component to the quarter chord is used since the quarter chord marks the location of the aerodynamic center of the foil sections. Thus Vcos Λ is incorporated into the dynamic pressure equation to form q'.

Figure 2 Definition of q'

$$= \left[\left(W/S\right)_\delta - \left(W/S\right)' + \left(W/S\right)_\alpha \right] \left(C_\ell/C_L\right)_\delta$$
$$+ \left(W/S\right)' \left[\left(C_\ell/C_L\right)_i - \left(C_\ell/C_L\right)_\delta \right] + \left(\frac{W}{S}\right)_\alpha \left[\left(C_\ell/C_L\right)_\alpha \right.$$

(10) $$\left. - \left(C_\ell/C_L\right)_\delta \right]$$

$$= W/S \left(C_\ell/C_L\right)_\delta + \left(W/S\right)' \left[\frac{\left(C_\ell/C_L\right)_i}{\left(C_\ell/C_L\right)_\delta} - 1 \right] \left(C_\ell/C_L\right)_\delta$$
$$+ \left(W/S\right)_\alpha \left[\frac{\left(C_\ell/C_L\right)_\alpha}{\left(C_\ell/C_L\right)_\delta} - 1 \right] \left(C_\ell/C_L\right)_\delta$$

Employing the parameter 4 into the equation,

(11) $$\xi_i = \frac{\left(C_\ell/C_L\right)_i}{\left(C_\ell/C_L\right)_\delta} - 1 \qquad \xi_\alpha = \frac{\left(C_\ell/C_L\right)_\alpha}{\left(C_\ell/C_L\right)_\delta} - 1$$

(12) $$\frac{W}{S} = W/S \left(C_\ell/C_L\right)_\delta + \left(W/S\right)' \xi_i \left(C_\ell/C_L\right)_\delta + \left(W/S\right)_\alpha \xi_\alpha \left(C_\ell/C_L\right)_\delta$$

Recalling

$$\left(\frac{\Delta V_a}{V} - w \right) \frac{W}{S} = \pm \left(\sqrt{S} - \psi \right) \rho' - w \left[\left(\frac{W}{S}\right)' + \left(\frac{W}{S}\right)_\alpha \right]$$

and substituting the relations from Equation 9 and expressing the section loadings on the right in terms of foil loadings,

$$\left(\frac{\Delta V_a}{V} - w\right)\left[\frac{W}{S}\left(\frac{C_\ell}{C_L}\right)_\delta + \left(\frac{W}{S}\right)' \mathcal{F}_i \left(\frac{C_\ell}{C_L}\right)_\delta \mathcal{F}_\alpha \left(\frac{C_\ell}{C_L}\right)_\delta \right] =$$

$$\pm\left(\sqrt{S} - \psi\right) q' - w\left(\frac{W}{S}\right)'\left(\frac{C_\ell}{C_L}\right)_i - w\left(\frac{W}{S}\right)_\alpha \left(\frac{C_\ell}{C_L}\right)_\alpha$$

$$\left(\frac{\Delta V_a}{V} - w\right)\left(\frac{C_\ell}{C_L}\right)_\delta = \pm\left(\sqrt{S} - \psi\right) q' - \left(\frac{\Delta V_a}{V} - w\right)\left(\frac{W}{S}\right)' \mathcal{F}_i \left(\frac{C_\ell}{C_L}\right)_\delta - w\left(\frac{W}{S}\right)'\left(\frac{C_\ell}{C_L}\right)_i - \left(\frac{\Delta V_a}{V} - w\right)\left(\frac{W}{S}\right)_\alpha \mathcal{F}_\alpha \left(\frac{C_\ell}{C_L}\right)_\delta - w\left(\frac{W}{S}\right)_\alpha \left(\frac{C_\ell}{C_L}\right)_\alpha \tag{13}$$

$$= \pm\left(\sqrt{S} - \psi\right) q' - \left(\frac{W}{S}\right)'\left\{\frac{\Delta V_a}{V} \mathcal{F}_i \left(\frac{C_\ell}{C_L}\right)_\delta - w\left[\mathcal{F}_i \left(\frac{C_\ell}{C_L}\right)_\delta - \left(\frac{C_\ell}{C_L}\right)_i\right]\right\} - \left(\frac{W}{S}\right)_\alpha \left\{\frac{\Delta V_a}{V} \mathcal{F}_\alpha \left(\frac{C_\ell}{C_L}\right)_\delta - w\left[\mathcal{F}_\alpha \left(\frac{C_\ell}{C_L}\right)_\delta - \left(\frac{C_\ell}{C_L}\right)_\alpha\right]\right\}$$

$$= \pm\left(\sqrt{S} - \psi\right) q' - \left(\frac{W}{S}\right)'\left[\frac{\Delta V_a}{V} \mathcal{F}_i + w\right]\left(\frac{C_\ell}{C_L}\right)_\delta - \left(\frac{W}{S}\right)_\alpha \left[\frac{\Delta V_a}{V} \mathcal{F}_\alpha + w\right]\left(\frac{C_\ell}{C_L}\right)_\alpha$$

$$\left(\frac{\Delta v_c}{V} - w\right)\frac{W}{S} = \pm\frac{(\sqrt{s} - \psi)}{C_l/C_L)_\delta} q' - \left(w + \xi_i \frac{\Delta v_c}{V}\right)\left(\frac{W}{S}\right)' - \left(w + \xi_\alpha \frac{\Delta v_a}{V}\right)\left(\frac{W}{S}\right)_\alpha$$

This is Equation 24 of Reference 2. Reconsidering the fact $(C_l/C_L)_i = (C_l/C_L)_\delta$, the parameter ξ_i reduces to zero.

Thus,

$$(14)\quad \left(\frac{\Delta v_c}{V} - w\right)\left(\frac{W}{S}\right)_H = \pm\frac{(\sqrt{s} - \psi)}{C_l/C_L)_\delta} q' - w\left(\frac{W}{S}\right)' - \left(w - \xi_\alpha \frac{\Delta v_c}{V}\right)\left(\frac{W}{S}\right)_\alpha$$

Where (W/S)' involves all lift coefficients except that coefficient which is associated with the type of lift imposed on the foil in deriving the cavitation bucket. So,

$$(W/S)' = (C_L)_i + (C_L)_\delta + (C_L) + \frac{C_{l_{ieff}}}{C_l/C_L}$$

Ther term for residual lift, $\frac{C_{l_{ieff}}}{C_l/C_L}$, is the lift associated with the sections in the normal plane.

This is now the general equation for the three dimensional foil cavitation bucket. It should be noted that bouyancy is not considered in the derivation, An illustration of this bucket is shown in Figure 3.

Basically the explanation is the same as that regarding Figure 1 but in this case cavitation will appear somewhere on the span as compared to somewhere on the section. In using this foil bucket to determine the non-

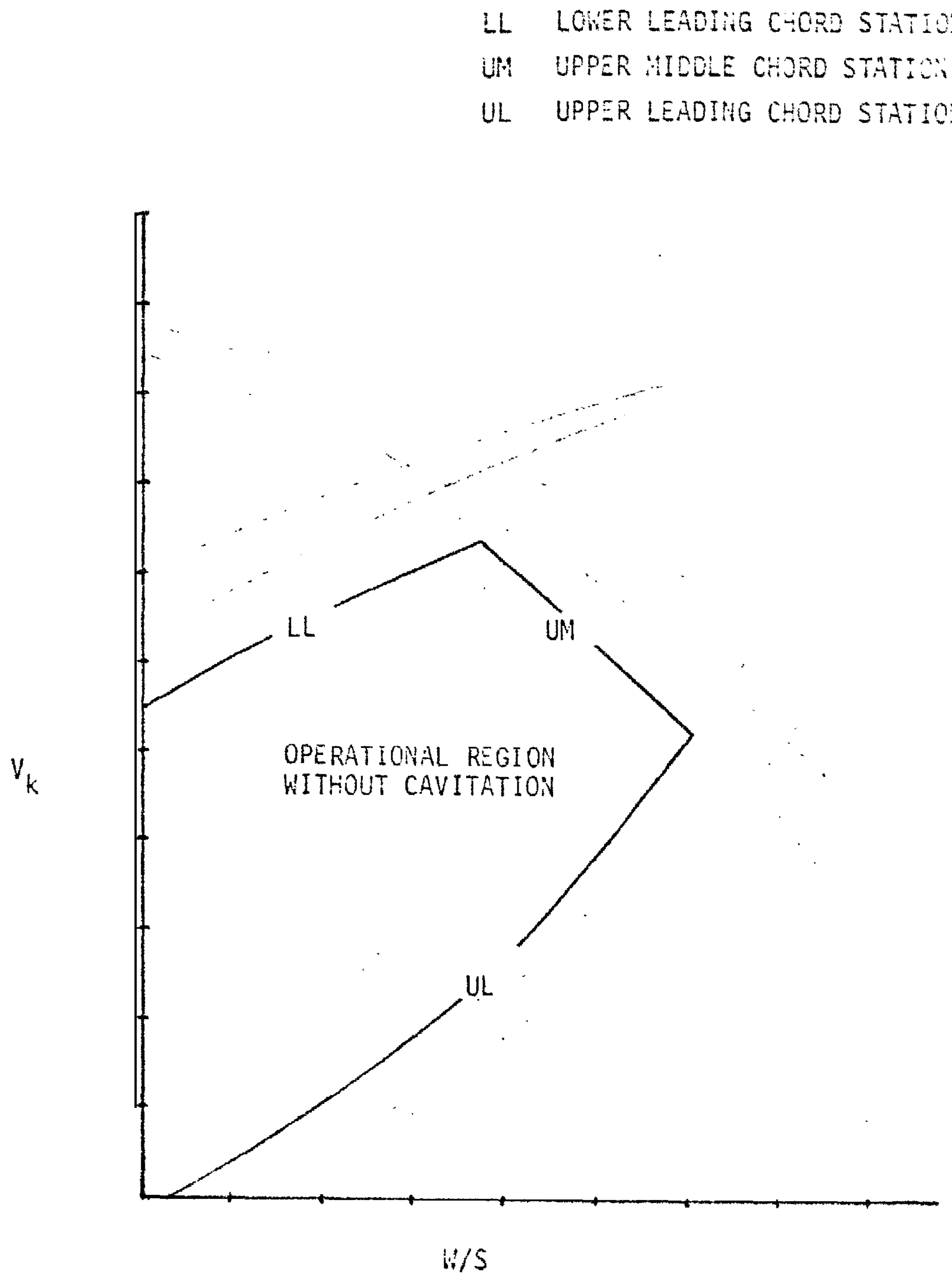


FIGURE 3 ILLUSTRATIVE EXAMPLE OF FOIL CAVITATION BUCKET

cavitating régime of operation it must be noted that the bucket was derived using q' and not q. So in order to determine the correct C_L and thus the correct operating speed, C_L must be multiplied by the factor q/q'.

$$C_L \text{ is not } \frac{W/S}{q}$$

but

$$C_L \text{ is } q/q' \; \frac{W/S}{q}$$

So in summarizing Part I of this discussion it can be seen that the expression for the flap lift foil cavitation bucket is:

$$(15) \quad \left(\frac{\Delta v_o}{V}\cdot w\right)\left(\frac{W}{S}\right)_M = \pm \frac{\left(\sqrt{\sigma}-\psi\right)}{c_f/c_l}\frac{q'}{2} \; w\left(\frac{W}{S}\right)' - \left(w - \frac{[illegible]}{c_\alpha}\frac{\Delta v_o}{V}\right)\left(\frac{W}{S}\right. \ldots$$

which can be derived from the equation for section cavitation bucket,

$$(16) \quad \sqrt{\sigma} = \psi \pm w\left[c_\ell' + (c_\ell)_i\right] \pm \left(\frac{\Delta v_o}{V} - w\right) c_\ell$$

It is to the readers advantage to investigate the derivation of the Incidence Lift Cavitation Bucket discussed in Reference 2. The two equations, incidence lift and flap lift, are derived in quite similar manners. Being exactly the same except for the inclusion of the velocity distribution over the flap, which is in the term, and except for the definition of the $(W/S)'$ term . The incidence lift starts with the basic definition of the cavitation number:

$$\sqrt{S} = \frac{\nu}{V} \pm \frac{\Delta\nu}{V} \pm \frac{\Delta\nu_o}{V}\left[\left(C_{L_H}' - C_{L_t}'\right) - C_{L_{ioff}}\right] \pm$$

(17) $$\left.\frac{\Delta\nu}{V}\right)_F C_{L_t}'$$

and through algebraic manipulation the equation for incidence lift, with zero pitch, reduces to

(18) $$\left(\frac{\Delta\nu_o}{V} - w\right)\left(\frac{w}{S}\right)_H = \pm\left(\frac{\sqrt{S} - \psi}{c_\ell / c_L}\right)_i \phi'$$

It can be seen that the equations for incidence lift and flap lift reduce to the same quanities when the specific case of $\delta = 0$, and $\alpha = 0$ is used.

(Incidence Lift)

$$\frac{\Delta\nu_o}{V}\left(\frac{w}{S}\right)_H = \frac{\sqrt{S} - \psi}{c_\ell / c_L}\phi'$$

$$\frac{\Delta\nu_o}{V}\left(\left(C_L\right)_i + C_{L_\delta}\delta^{0} + C_{L_\alpha}\alpha^{0} + \frac{C_{L_{ioff}}}{c_\ell / c_L}\right)\phi' = \left(\frac{\sqrt{S} - \psi}{c_\ell / c_L}\right)\phi'$$

$$\frac{\Delta\nu_o}{V}\left[\left(C_L\right)_i + \frac{C_{L_{ioff}}}{c_\ell / c_L}\right] = \frac{\sqrt{S} - \psi}{c_\ell / c_L} \checkmark$$

(Flap Li ft)

$$\left(\frac{\Delta\nu_o}{V} - w\right)\left(\frac{w}{S}\right)_H = \frac{\sqrt{S} - \psi}{c_\ell / c_L} - w\left[\left(C_L\right)_i + \left(\frac{C_{L_{ioff}}}{c_\ell / c_L}\right)\right]$$

$$\left(\frac{\Delta\nu_o}{V} - w\right)\left[\left(C_L\right)_i + C_{L_\delta} + C_{L_\alpha} + \frac{C_{L_{ioff}}}{c_\ell / c_L}\right]\phi' = \frac{\sqrt{S} - \psi}{c_\ell / c_L}\phi' - \left[w\left(C_L\right)_i + w\left(\frac{C_{L_{ioff}}}{c_\ell / c_L}\right)\right]\phi'$$

$$\frac{\Delta\nu_o}{V}\left[\left(C_L\right)_i + \frac{C_{L_{ioff}}}{c_\ell / c_L}\right] = \frac{\sqrt{S} - \psi}{c_\ell / c_L} \checkmark$$

At the point on the 1.23 chord station with $\delta = 0$ and $\alpha = 0$, the flapped foil becames an incidence foil. This point can be mathematically computed to be;

$$\frac{\Delta V_0}{V}\left(\frac{W}{S}\right)_H - \left(\frac{\sqrt{S}-\psi}{c\ell/c_L}\right)g' = \left(\frac{\Delta V_0}{V} - w\right)\left(\frac{W}{S}\right)_H - \left(\frac{\sqrt{S}-\psi}{c\ell/c_L}\right)g' - w\left[(C_L)_i + \frac{C_{\ell_{i0ff}}}{c\ell/c_L}\right]$$

$$0 = -\frac{W}{S}\Big)_H + \left[(C_L)_i + \frac{C_{\ell_{i0ff}}}{c\ell/c_L}\right]g'$$

$$\frac{W}{S}\Big)_H = \left[(C_L)_i + \frac{C_{\ell_{i0ff}}}{c\ell/c_L}\right]g'$$

$$= \left[.0869 + \frac{.2990}{1.31}\right]g'$$

$$= .3151\, g'$$

substituting and solving for $\sqrt{S}$ and then V_k,

$$\frac{\Delta V_0}{V}(.3151)g' - \left(\frac{\sqrt{S}-\psi}{c\ell/c_L}\right)g' = 0$$

$$(1.346)(.3151) = \frac{\sqrt{S} - .67}{1.31}$$

$$1.2256 = \sqrt{S}$$

$$= \sqrt{\frac{2641.12}{1.896\, V_k^2} + 1}$$

$$1.5021 = \frac{1392.995}{V_k^2} + 1$$

$$V_k^2 = 2774.339$$

$$= \underline{\underline{52.67 \text{ knots}}}$$

$$\frac{W}{S}\Big)_H = (52.67)^2(1.896)(.3151)$$

$$= 1657.34 \text{ PSF}$$

$$\frac{W}{S} = \underline{\underline{1747.34 \text{ PSF}}}$$

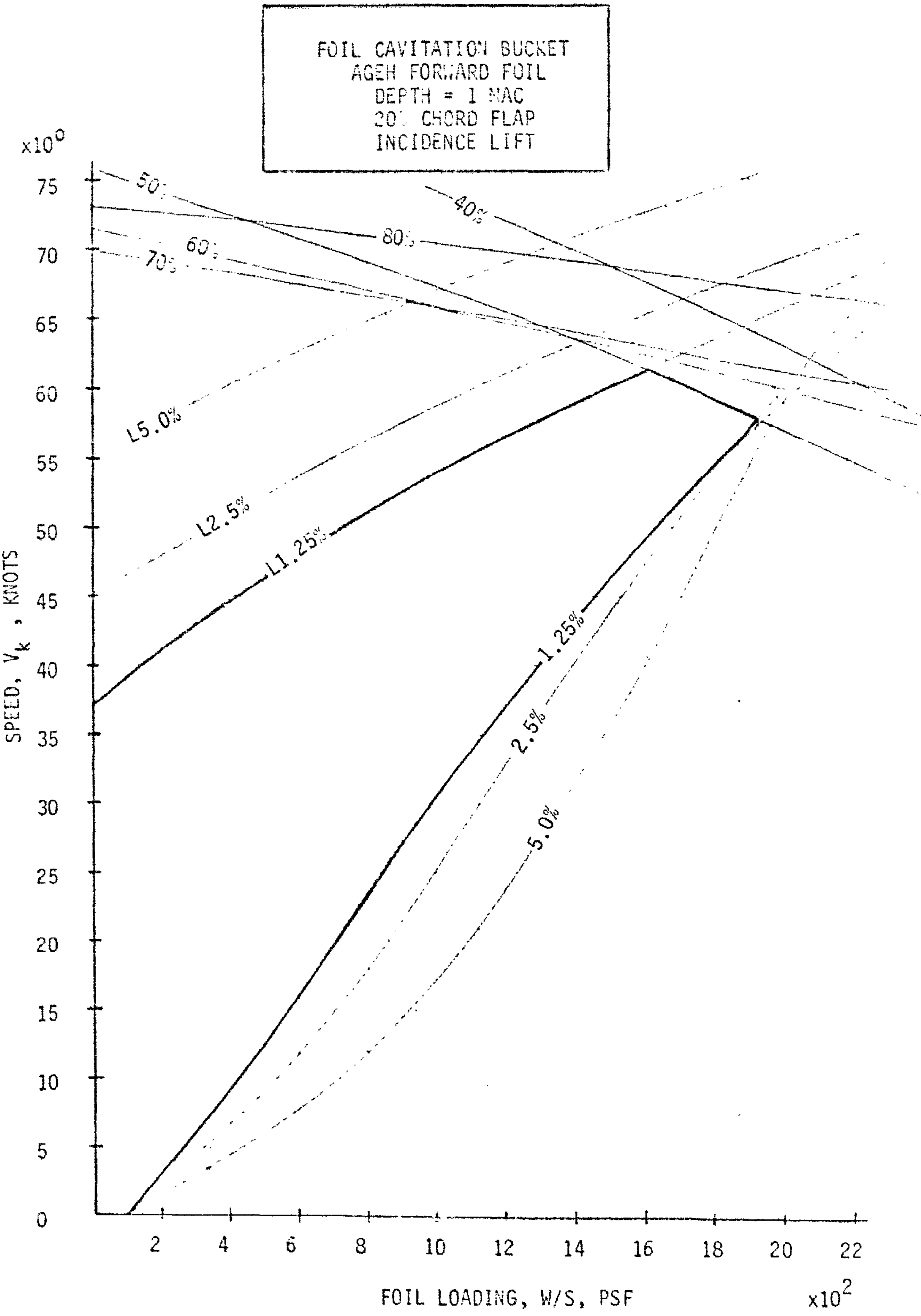

FOIL CAVITATION BUCKET
AGEH FORWARD FOIL
DEPTH = 1 MAC
20% CHORD FLAP
INCIDENCE LIFT
x10^0
SPEED, V_k , KNOTS
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
2
4
6
8
10
12
14
16
18
20
22
FOIL LOADING, W/S, PSF
x10^2
50%
40%
80%
60%
70%
L5.0%
L2.5%
L1.25%
1.25%
2.5%
5.0%

FIGURE 4

The procedure for going from Equation 17 to Equation 18 is the basis for Reference 2 and is too lengthy to be covered in this note. Figure 4 shows the foil incidence bucket using the given section velocity distributions.

PART II: REFERENCE LIFT COEFFICIENTS

It should be noted that the foil lift coefficient, CL does not appear anywhere in the foil cavitation bucket derivation for flap lift. But the foil lift coefficients are found in the terms $W/S)_i$, $W/S)_o$, and $W/S)$, and these foil loadings are related to those loadings of the se section bucket through the terms $(C_l)_i$, $C_{l_{ieff}}$, and $(C_l)_\alpha$. These six above mentioned terms shall be referred to as reference lift coefficients.

The incidence and pitch reference foil loadings are easily defined as:

$$(W/S)_i = (C_L)_i q' \approx C_{L_i} i q'$$

$$(W/S) = (C_L)_\alpha q' \approx C_{L_\alpha} \alpha q'$$

Note that q' is employed and not q. In order to determine a definition far $(W/S)_o$ its definition must be retraced,

The W/S), is loading due to the camber of the foil. $(W/S)_o$ is a component of $(W/S)'$.

$$(W/S)_o = \frac{(W/S)_o}{C_1/C_L)_i} = \frac{C_{1_{ieff}}}{(C_1/C_L)_i} q'$$

The reference section lift coefficients at the critical span stations are:

$$(C_1)_i = (C_L)_i \quad (C_1/C_L)_i$$

$$C_{1_{ieff}} = \frac{C_{1_{ieff}}}{(C_1/C_L)_i} \quad (C_1/C_L)_i$$

In order to interpret the cavitation bucket as it is related to flap deflection another reference foil loading is required. This term shall be denoted $W/S)_{ref}$ which has previously been present in the incidence lift case derivation, (AG-18). The subscript "ref " is reserved for the product of a lift coefficient and the streamwise dynamic pressure,

(19) $$W/S)_{ref} = \left[(C_L)_i + C_{Lo} + (C_L)_\wedge\right] q + \left(\frac{W}{S}\right)_B$$

This term is multipurpose in use in regards to the flap lift case. It takes into consideration all the factors of flap lift, namely the pitch, the incidence, and the flap deflection and determines the operational zero flap deflection range in the bucket. This reference term can also be used to determine the validity of the C_L term used in the previous foil bucket equation derivation.

$$C_L = C_{L\alpha}\alpha + C_{Li}\, i + C_{L\delta}\,\delta + C_{Lo}$$

This term provides a check on the entire theory of deriving the section and foil cavitation buckets. The lift coefficients due to pitch and incidence are obvious in their origin, whereas the residual lift coefficient, or that lift due to camber requires comment at this time,

If the effects of the pod are neglected the zero lift angles for incidence and section zero lift are equal.

$$\alpha_o = \frac{-C_{l_{ieff}}}{C_{L\alpha}}$$

Then C_{Lo} must equal:

(20)

$$C_{Lo} = - C_{Li}\,\alpha_o$$

$$= C_{Li}\ \frac{C_{l_{ieff}}}{C_{l\alpha}}$$

For the best interpretation of the Lindsey, Stevenson, and Daley data available this relation results in

$$C_{Lo} = (2.49)\ (.330/5.72)$$

$$= .144$$

as compared to the value of .111 which was measured on the prototype. An explanation of the results can be seen in Appendix I. For a foil of fixed pitch and incidence the $W/S)_{ref}$ term is a quadratic in V_K extending up to the cavitation bucket boundary, In order to go directly from the given velocity distribution data to a foil cavitation bucket, equation 15 must be used. Recalling equation 15:

$$\left(\frac{\Delta v_a}{V} - w\right)\frac{W}{S} = \pm\frac{(\sqrt{s} - \psi)q'}{C_l/C_L)_\delta} - \left(w - \mathcal{J}_\alpha \frac{\Delta v_a}{V}\right)\left(\frac{W}{S}\right)_\alpha - w\left(\frac{W}{S}\right)'$$

and noting that the W/S present in the equation does not include any buoyancy term,

$$W/S = (W/S)_H + (W/S)_B$$

$(W/S)_B$ = 0 in equation

$(W/S)_H$ = W/S in equation for 3-D flap lift

Equation 15 can be further reduced by remembering the assumption of zero angle of attack. With $\alpha = 0$, $(C_L)_\alpha = 0$, and $(C_l/C_L)_\alpha = 0$ the parameter $\mathcal{J}_\alpha$ reduces to zero. Equation 15 can be simplified to equal:

$$\left(\frac{\Delta v_a}{V} - w\right)\left(\frac{W}{S}\right)_H = \pm\frac{(\sqrt{s} - \psi)q'}{(C_l/C_L)_\delta} - (w)\left(\frac{W}{S}\right)' \tag{22}$$

with

$$\sqrt{S} = \sqrt{1+\sigma}$$

$$\sigma = \frac{2044 + \rho gh}{q'}$$

$$q' = q\cos^2 A$$

$$\left(\frac{W}{S}\right)' = (W/S)_i + (W/S)_o$$

$$(W/S)_i = (C_L)_i q' \approx C_{L_i} q'$$

$$(W/S)_o = C_{l_{ieff}}\, q'/(C_l/C_L)_\delta$$

$$(W/S)_\alpha = (C_L)_\alpha\, q' \approx C_{L\alpha}\, \alpha\, q'$$

to the cavitation bucket boundary,

PART III: CONSTRUCTION OF THE CAVITATION BUCKETS

In order to graphically show the buckets and to in turn check the validity of the theory and graphs (See Part XI) the flap lift case will be compared to the incidence lift case, one assumption will be made. The assumption being that the foil is operating at a zero degree angle of attack.

Equation 7 is the primary equation used in the construction of the section cavitation bucket. An expansion of the term C_l' is necessary in order to see all working terms.

$$(21) \quad \sqrt{S} = \gamma \pm w\left[(C_l)_i + C_{l_{ieff}} + (C_l)_\alpha\right]$$

It is appropriate at this point to introduce the depth effect factor. Because of free surface effects, which have a minor but not negligible effect, Panchenkov's depth effect factor from Figure 13 of Ref. 3 in a value of .923 to be used as an applied factor to all reference loadings. Using the velocity distribution data from Abbot and Von Doenhoff's Theory of Wing Sections, (condensed in Table 1) and Allen's velocity distributions over a flapped section, Figure 5, expressions in the linear form (y=b+mx) can be determined. These specific equations can be seen in Table 2 where Cl has been equated to zero and unity. This then provides the data necessary to construct the section cavitation bucket, Fig. 6, for the AG(EH) forward foil. Access to this graph allows one to follow an alternate method of foil cavitation bucket construction. See Appendix XI for this explanation.

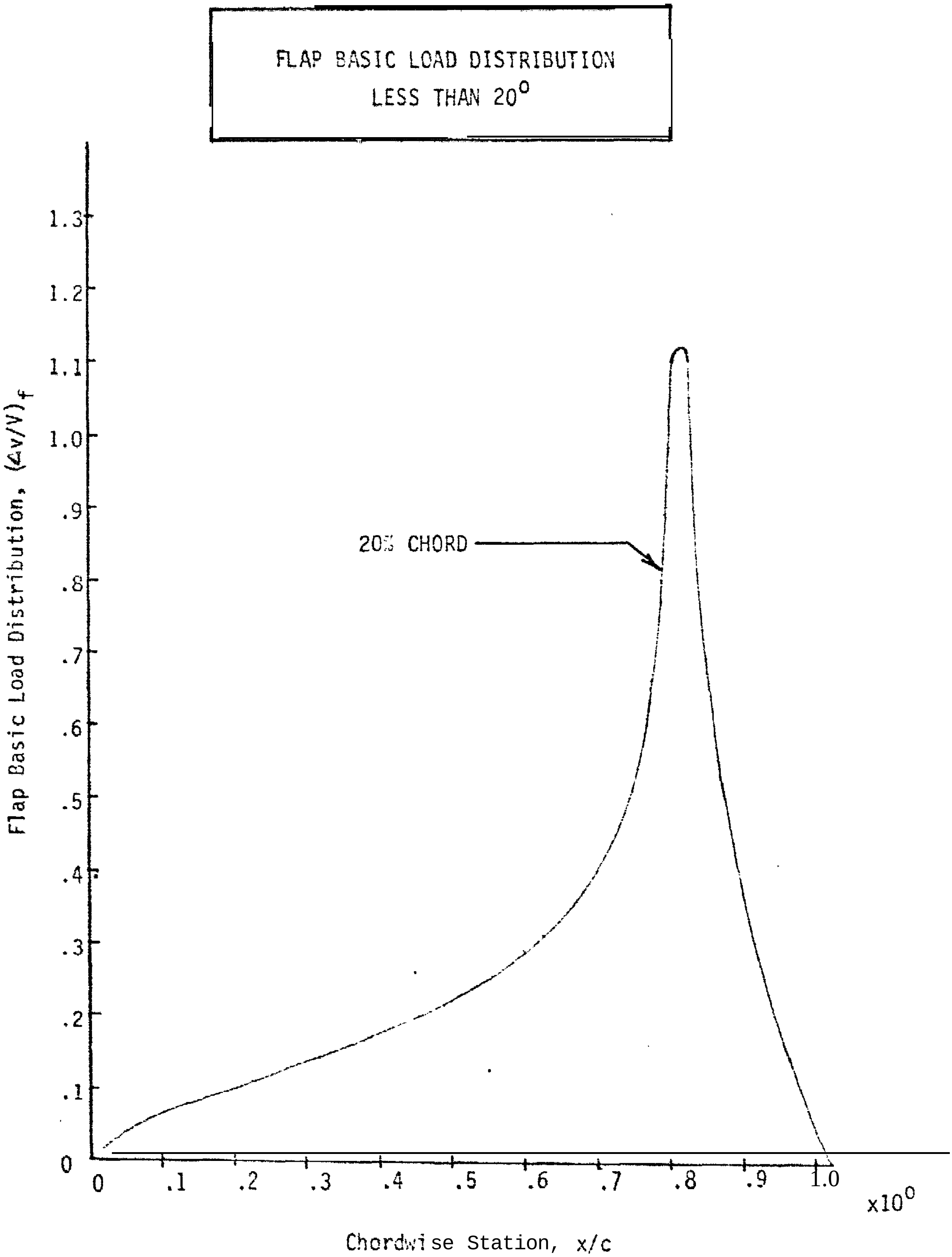

FLAP BASIC LOAD DISTRIBUTION
LESS THAN 20°
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
Flap Basic Load Distribution, (Δv/V)f
20% CHORD
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
x10⁰
Chordwise Station, x/c

FIGURE 5

SECTION CAVITATION BUCKET
AGEH FORWARD FOIL
20% CORD FLAP
FLAP LIFT

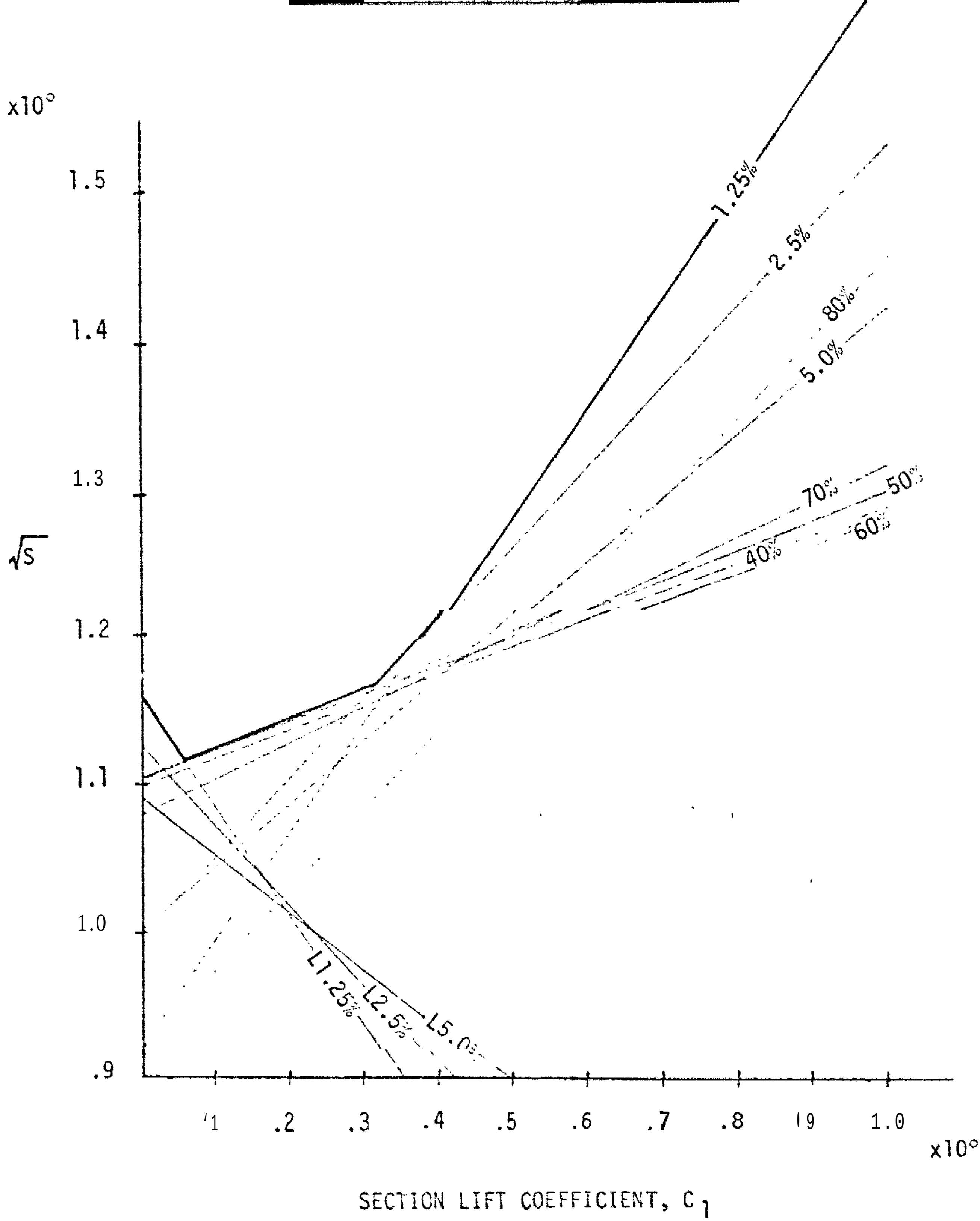


FIGURE 6

where C_{L_i} is derived from

$$(23) \qquad \frac{(W/S)_o - (W/S)_{ref}}{q\, C_{L\delta}} = 0$$

at a design speed of fifty knots, and trimmed flaps

$$(W/S)_{ref} = (W/S)_D = 1435$$

This foil loading, being the design foil loading is then used in determining the value of $(C_L)_i$ for the flap lift case.

$$\left[(C_L)_i + C_{Lo} + (C_L)_{\alpha_I}\right] q_D + \left(\frac{W}{S}\right)_B = 1435$$

$$\left[(C_L)_i + .923\,(.111)\right](7100) = 7435 - 90$$

$$(C_L)_i + .1025 = 1347/7100 = .1894$$

$$(C_L)_i = .0869$$

The corresponding incidence angle is approximately:

$$i = (C_L)_i / C_{L_i} = \frac{.0869}{(.923)\,(.0438)} \doteq 2.16^{\circ}$$

Since all variables and parameters are known for Equation 22 a foil cavitation bucket can be constructed. The equation was programmed and executed on a Hewlett-Packard 9810A calculator and the values are tabulated on Table III. A long hand check can be seen in Appendix III. Figure 7 shows the completed foil cavitation bucket. Also on the graph are the $W/S)_{ref}$ and $W/S)_D$ curves.

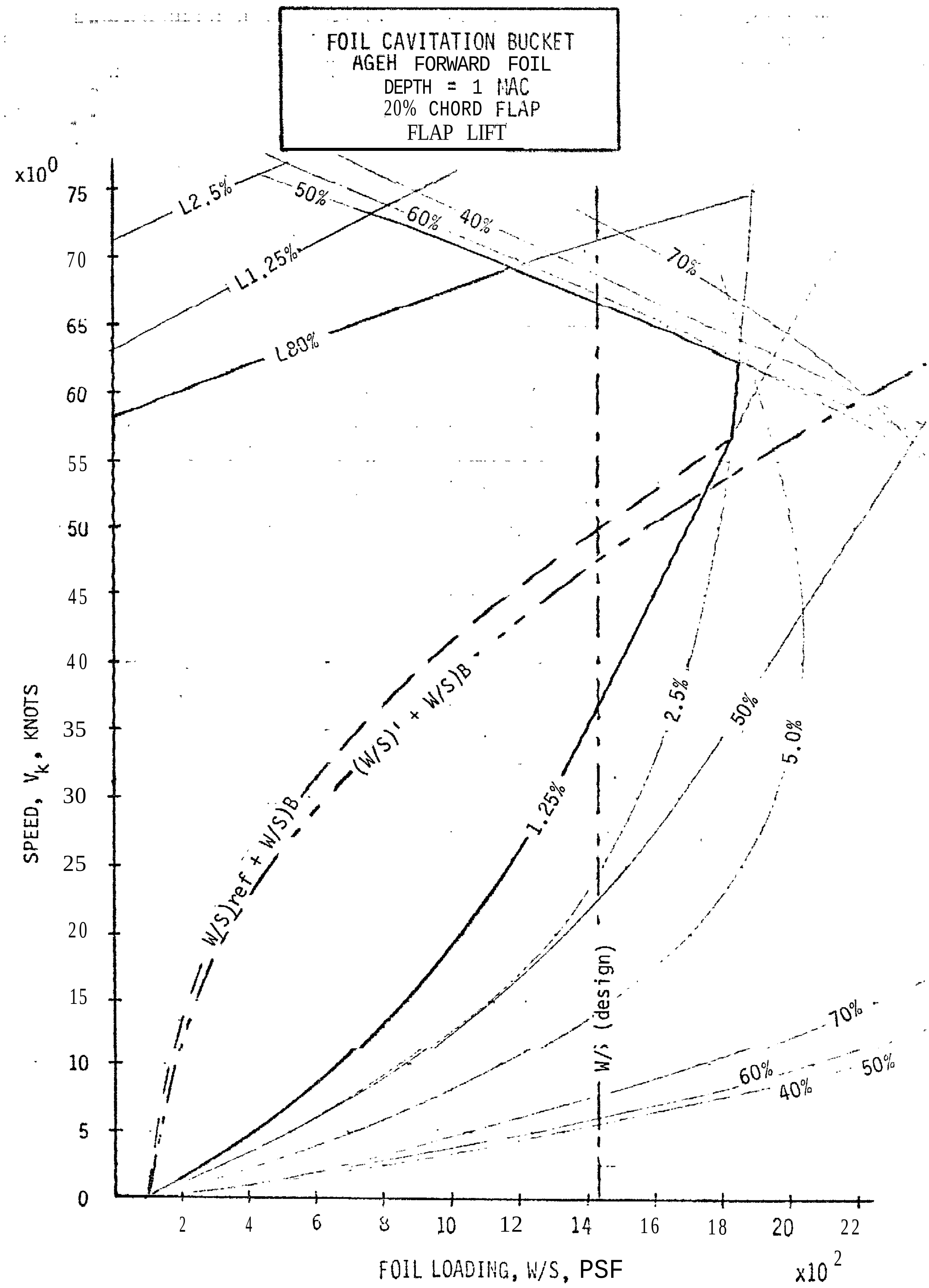

FOIL CAVITATION BUCKET
AGEH FORWARD FOIL
DEPTH = 1 MAC
20% CHORD FLAP
FLAP LIFT
x10^0
SPEED, V_k, KNOTS
FOIL LOADING, W/S, PSF
x10^2
L2.5%
L1.25%
L80%
50%
60%
40%
70%
W/S)ref + W/S)B
(W/S)' + W/S)B
1.25%
2.5%
50%
5.0%
W/S (design)
70%
60%
50%
40%

FIGURE 7

The cavitation bucket equation is a very powerful analytical tool. It allows the term $(C_L)_i$ to be used to compute a $(C_L)_\delta$ independent of the cavitation bucket equation, This then allows the schedule for flap del deflection to be determined. The following equation can be employed when it is desired to compute a $(C_L)_\delta$.

$$\left[(C_L)_i + C_{Lo} + C_{L\alpha} + C_{L\delta}\right] q_D + (W/S)_B = 1435$$

At this point in the discussi.on both the derivation and graphical representation of the foil cavitation bucket have been completed. How do these results compare to the existing incidence lift system? Figure 8 compares the limiting boundries of the two different cavitation buckets. It can be observed that the flap lift case expands the all ready known incidence lift case boundries. In order for the flaps to produce enough lift, g = 1, a flap deflection angle is required. In order to determine this angle Equation 24 is used.

$$(24) \qquad \delta_{1g}^{\circ} = \frac{W/S)_D - W/S)_{ref}}{q\, C_{L\delta}} + W/S)_B$$

This provides a concept that will be investigated in future notes; the idea of combining incidence and pitch angles along with flap deflection to provide the required 1 g lift with a minimum absolute value flap deflection. There also lies in the régime of the cavitation bucket a deflection angle of cavitation:

$$(25) \qquad \delta_{cav}^{\circ} = \frac{(w/s) - (w/s)''}{q' C_{L\delta}}$$

$$= \frac{(W/S)_H + W/S)_B - W/S)' - W/S)_B}{q' C_{L\delta}}$$

Note: Positive deflection is a flap trailing edge downward.

From these last two relations plots can be made, (See Figure 9, and Tables IV, V) and the two deflections can be compared. There are two points on the graph where $\delta_{1g}^{\circ} = \delta_{cav}^{\circ}$. This could pose a grave problem since the deflection angles are within operational range. From Equations 24

RELATIONSHIP BETWEEN FLAP LIFT, INCIDENCE LIFT, AND (W/S)' CURVES

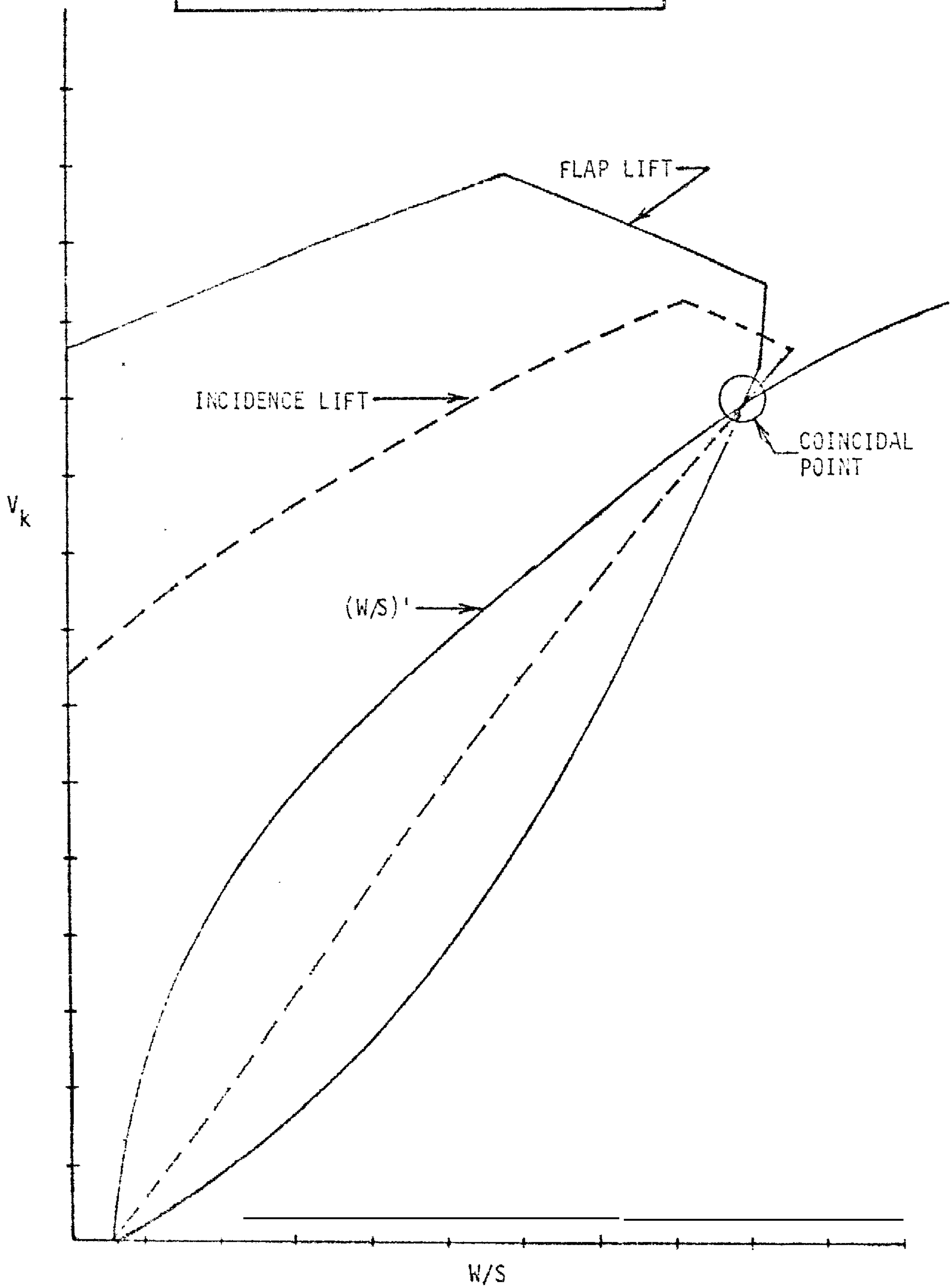


FIGURE 8

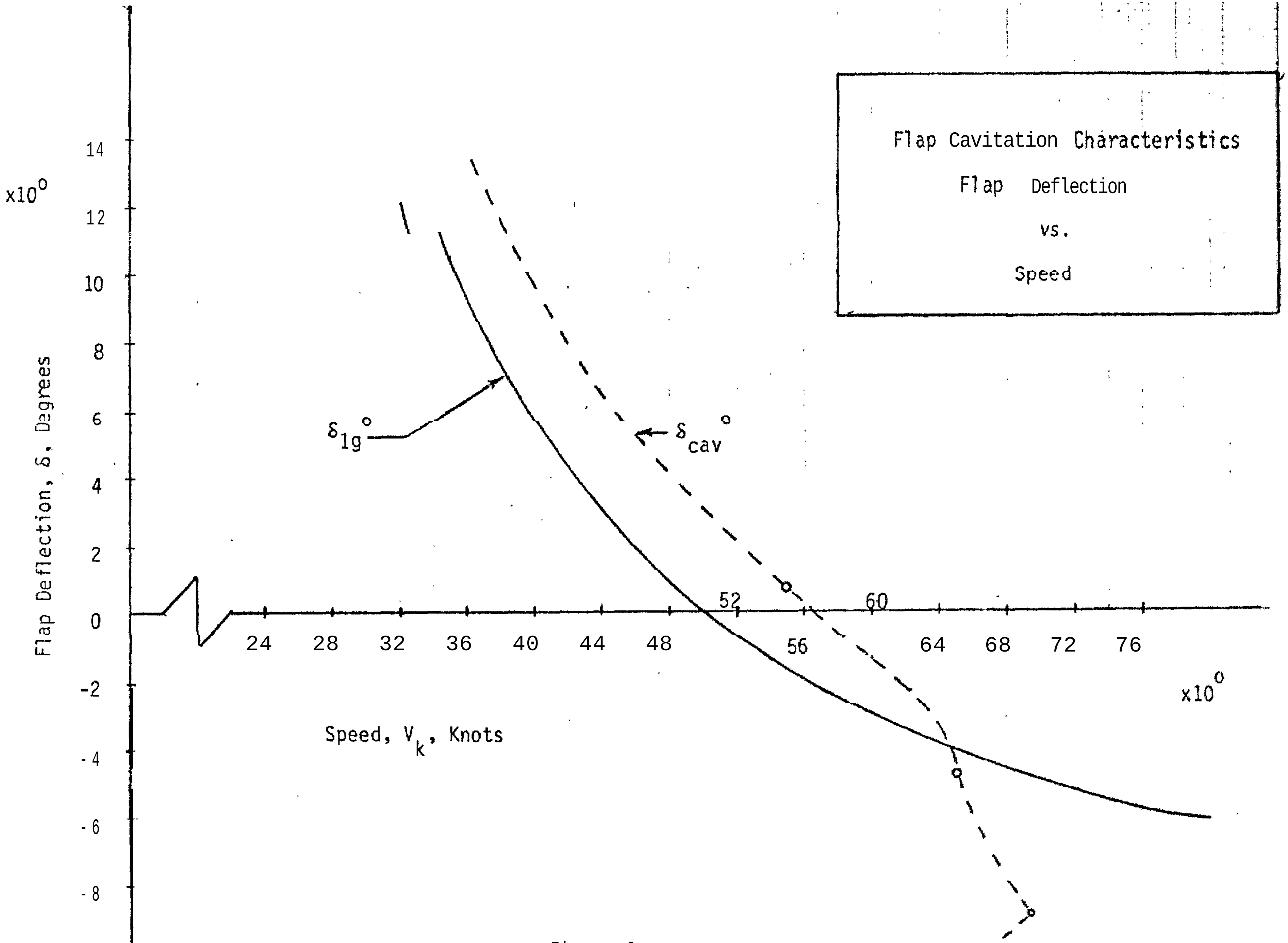

Flap Cavitation Characteristics
Flap Deflection
vs.
Speed
x10°
14
12
10
8
6
4
2
0
-2
-4
-6
-8
Flap Deflection, δ, Degrees
δ1g°
δcav°
24
28
32
36
40
44
48
52
56
60
64
68
72
76
x10°
Speed, Vk, Knots

Figure 9

and 2 5 it can be seen that a positive deflection will move any point on the $W/S)_{ref}$ curve toward the right, and any negative deflection will transfer the point to the left.

In summarizing what has been emphasized in this discussion, it can be seen that a set of very powerful equations have been derived. But the equations are not so complex that a person with minimal knowledge of cavitation cannot comprehend them.

FART IV: OPTIMIZATION CONSIDERATIONS

Configurations which will optimize the flap lift system will be covered in future notes when sufficient data on the system can be gathered.

Major discussions of importance are:

A. Limited Flap Angles:

Determination and evaluation of the optimum flap angles when combined with angles of incidence and pitch, and which combination will result in least drag and incipient cavitation number.

B. Smooth Water Cavitation Bucket:

Investigations in the distortions, expansions, reductions and extentions of the cavitation bucket which is produced in smooth water, with emphasis on various foil loadings, flap, incidence and pitch angles, and speeds.

C. Rough Water Cavitation Bucket:

Investigation in the distortions, expansions, reductions, and extentions of the foil cavitation bucket which is produced in rough water with special emphasis on the effects caused by orbital velocity, and how to compensate for the varying wave heights.

D. Foil Drag

Resistance on the forward foil will be evaluated for the various combinations of flap, incidence, and pitch angles. These values, combined with thedeterminal drag on the pod, will give the total drag on the foil-pod configuration,

E. Hinge Moments

This will not be a consideration for flap lift.

APPENDIX I

SOURCES OF ERROR IN C_{Lo}

If the derivation for C_{Li} is incorporated into Equation 20

Recalling 20:

$$C_{Lo} = - C_{Li} \alpha_o$$

$$= C_{Li} \frac{C_{l_{ieff}}}{C_{l_\alpha}}$$

all of the sources of error can be displayed.

$$C_{Lo} = \frac{C_{Li}}{C_{l_\alpha} \text{ Proto}} \quad C_{l_\alpha} \text{ Proto} \frac{C_{l_{ieff}}}{C_{l_\alpha} \text{ Section}}$$

C_{l_i} / C_{l_α} Proto is the area under the incidence lift circulation distribution on the span. $C_{l_{ieff}}$ and C_1 Section are distinct interpretations of the Lindsey, Stevenson, and Daley data. Thus there are three sources of error.

i) Neither the prototype nor the section experimental data is very reliable.

ii) There is an unestablished precision associated with the circulation distribution, particularly for partial span distributions and most particularly for sections not defined in the streamwise plane. Note that a section defined in a normal plane has its angle of attack reduced by the cosine of the sweep angle. If Equation 20 has this incorporated in it the valve of CL, comes to within 5% of the measured prototype valve.

iii) There is undoubtedly some pod influence, particularly at the foil root, which is not accounted for by treating incidence lift as a full chord, partial span flap case.

SOURCES OF ERROR IN C_{Lo}

The most familiar manifestation of the prototype/theory C_{Lo} discrepancy is the model/theory zero lift angle discrepancy which has been noted for years. Note that for the AGEH:

Prototype	Theory
$\alpha_o = -C_{Lo}/C_{Li}$	$\alpha_o = -C_{l_{ieff}}/C_{l_\alpha}$
$= -.111/2.49$	$= -.324/5.72$
$= -.0496$	$= -.0566$
$= -2.6 \pm 7\%$ extreme	$= -3.24 \pm 13\%\ \sigma$
$= -2.7$ to -2.4	$= -3.66$ to -2.82

It should be noted that α_0 is invariant with depth, and Cl_{ieff} is subject to depth effect.

Applying the $\cos\Delta$ factor to the prototype, where Cl_i is about that much higher than theory, would resolve this discrepancy. A similar discrepancy exists for DOLPHIN and FLAGSTAFF where the section is defined streamwise with a much smaller sweep.

APPENDIX I I

ALTERNATE METHOD OF FOIL CAVITATION BUCKET CONSTRUCTION

A three dimensional foil cavitation bucket can be constructed by the to be mentioned procedure only after the construction of a precise section cavitation bucket has been completed.

The procedure is as follows,

Step 1: Choose a minimum of three valves of $\sqrt{S}$ and its corresponding C_l. Care must be taken when moving from upper to lower surface or vice versa since the ratio $C_l/C_L)_\delta$ changes. Three valves are necessary since the foil bucket is not linear.

Step 2: Calculate corresponding valves of V_K and W/S.

$$S = 1 + \frac{PO - Pv}{q}$$

$$q = \frac{Po - Pv}{q} = \tfrac{1}{2} \rho V$$

$$(.9952)(1.6889)^2 V_K^2 = \frac{Po - Pv}{S-1}$$

$$= \frac{Pa + \rho gh - Pv}{S-1}$$

$$= \frac{2116 + 64(9.33) - 72}{S-1}$$

$$V_k = \sqrt{\frac{2641.12}{2.5387}} \cdot \frac{1}{\sqrt{S-1}}$$

$$= \frac{30.5}{\sqrt{S-1}}$$

and where W/S is simply:

$$W/S = C_l q' / C_l/C_L)_\delta$$

Step 3: Now corresponding values of V_k and W/S can be determined, These can then be plotted with W/S being the dependent variable and V_k being the independent variable.

APPENDIX III

VERIFICATION OF FOIL CAVITATION

BUCKET PROGRAM

$$\left(\frac{\Delta V_a}{V} - w\right)\frac{w}{S}\bigg)_H = \pm \frac{(\sqrt{S} - \gamma')q'_-}{C_i/C_L)_\delta}\left(w + \rho_\alpha \frac{\Delta V_S}{V}\right)\left(\frac{w}{S}\right)'$$

$$\left(\frac{\Delta V_a}{V} - w\right)\left(\frac{w}{S}\right)_H = \frac{(\sqrt{S} - \psi)q'_-}{C_i/C_L)_\delta}(w)\left\{\left(\frac{\cdot}{\cdot L}\right)_i + \frac{C_{l\,i\,eff}}{C_i/C_L)_\delta}\right\}q$$

substituting valves:

$$(.076 + .477)\left(\frac{w}{S}\right)_H = \left(\frac{\sqrt{\frac{2044 + (9.33)(64)}{1.869\,(50)^2} + 1} - 1.123}{1.31}\right) 1.896\,(50^2)$$

$$(-.477)\left[.0869 + \frac{(.923)(.324)}{1.31}\right] 1.896\,(50^2)$$

$$.553\left(\frac{w}{S}\right)_H = \left(\frac{\sqrt{\frac{2641.12}{4740} + 1} - 1.123}{1.31}\right) 4740 + .477(.315)(4740)$$

$$\frac{w}{S}\bigg)_H = \frac{451.84 + 712.62}{.553}$$

= 2105.71 as compared to the HP value of 2105.82

APPENDIX I'.'

DEFINITION OF $C_{l_{ieff}}$:

There is a basic lift curve slope associated with the section camber for every section on the span given any angle of attack. At any angle of attack the camber is producing a lift, which shall be called from this point on in this series of notes, $C_{l_{ieff}}$, at every stat-ion an the span.

$$C_{l_{ieff}} = -C_{l}\,\alpha_{o}$$

The coefficient of C_{l_i} comes from Lindsey, Stevenson, and Daley, Reference 7. This value, multiplied by the section C_{l_i}, results in the value used for $C_{l_{ieff}}$ of ,324.

In comparing the relationship between C_{Lo} and $C_{l_{ieff}}$ it shall be assumed that a zero lift angle is being used so there is no variation in lift and every station on the span will be acting along the zero lift angle.

$$-\alpha_o = \frac{C_{l_{ieff}}}{C_{l_\alpha}} = \frac{C_{Lo}}{C_{L\alpha}}$$

$$C_{Lo} = \frac{C_{l_{ieff}}}{C_{l_\alpha}} (C_l)_i$$

$$= \frac{C_{l_{ieff}}}{C_{l_\alpha}} \cdot \frac{C_{L_i}}{C_{L\alpha}} \cdot \frac{C_{L\alpha}}{C_{l_\alpha}} \quad C_{l_\alpha} \quad \cos\Delta$$

where C_{L_i} / C_L is the ratio of the areas under the lift curve slopes. These curves can be found in Reference 3,

$$C_{L_o} = \frac{(.838)(2.97)(.324)}{(.91)(2\pi)} \cos 35.2^\circ$$

$$= (.141)(.817)$$

$$= .115$$

The number resulting, .141, is larger than the prototype value of .111, which is in itself large since sweep was not taken into consideration, but by applying a factor equal to the cosine of the sweep angle (.817), the value of C_{Lo} can be reduced to near that of the prototype.

REFERENCES

1. Hydrodynamic Note AG-5, "Flap Cavitation Bucket," 8/21/71.

2. Hydrodynamic Note AF-18, "Flap Control of Incidence Hinge Moment and Foil Cavitation," 4/30/73.

3. Hydrodynamic Note AG-21, "Review of Steady State Lift and Moment Characteristics," 5/13/74.

4. "Interim Report on Optimization of Forward Lift Control for AG(EH) Hydrofoil Craft Vol. I: Hydrodynamics," GAC Report No. HCG-72-19(I), 12/72.

5. Abbott and Von Doenhoff, Theory of Wing Sections, 1959.

6. Allen, H. J., "Calculation of the Chordwise Load Distribution Over Airfoil Sections with Plain, Split, on Serially Hinged Trailing-Edge Flaps," NACA Report No. 634, 1938,

7. Lindsey, Stevenson, and Daley, "Aerodynamic Characteristics of 24 Mach Numbers Between .3 and .8," NACATN 1546, 9/48.

SYMBOLS

a. All dimensions in ft./#/sec./rad. unless otherwise noted.

b. Parenthesis read "due to"; e.g. (CL), = CL due to flap deflection, $C_{L\delta}\,\delta$.

c. Primes indicate normal to the quarter chord.

C_L	Foil Lift Coefficient, L/qS
C_{Lo}	Residual Lift Coefficient
C_{Li}	Incidence Lift Curve Slope, dC_i/di
$C_{L\alpha}$	Pitch Lift Curve Slope, $dC_L/d\alpha$
$C_{L\delta}$	Flap Lift Curve Slope, $dC_L/d\delta$
C_l	Section Lift Coefficient
C_l'	C_l at Zero Flap, $(C_l)_i + C_{l_{ieff}}$
C_{l_f}	C_l for flap deflection, $C_{l\alpha}\, d\alpha/d\delta$
C_l/C_L	Measure of Spanwise Lift Distribution
C_{l_i}	Design Lift coefficient
$C_{l_{ieff}}$	See Appendix IV
h	Depth
g	Acceleration of Gravity
i	Incidence Angle
L	Lift
P_A	Atomspheric Pressure (2116 psf)
P_V	Vapor Pressure (72 psf)
q	Dynamic Pressure, $\frac{1}{2}\rho V^2$
$\sqrt{S}$	$1 + \sigma$

V_k	**Speed** in Knots
v/V	Local Velocity Distribution Due to Thickness
$\Delta v/V$	Local Velocity Ratio Increment Due to Camber
$\Delta v/V)_f$	Local Velocity Ratio Increment Due to Flap Basic Load
ova/V	Local Velocity Ratio Increment Due to additional Load, Angle of Attack and/or Flap Deflection
$W/S)_H$	Hydrodynamic Foil Loading
w/s	Section Foil Loading
$W/S)_B$	Buoyant Foil Loading, B/S
$W/S)_D$	Design Foil Loading
$W/S)_\alpha$	Pitch Foil Loading, $C_{L\alpha}\theta q'$
$W/S)_i$	Incidence Foil Loading, $C_{Li}iq'$
$W/S)_\delta$	Flap Foil Loading, $C_{L\delta}Sq'$
$W/S)_{ref}$	Reference Foil Loading
α	Angle of Attack
S	Flap Deflection, Positive Nose Up
ξ_i	Spanwise Load Distribution Parameter, $\frac{C_l/C_L)_i}{C_l/C_L} - 1$
ξ_α	Spanwise Load Distribution Parameter, $\frac{C_l/C_L)_\alpha}{C_l/C_L)} - 1$
ρ	Density, 1.9905 lbf sec^2/ft^4
σ	Cavitation Parameter, $(PA - P_V + \rho gh)/q$
ν	Flap Load Distribution Parameter, $\xi[(\Delta va/V - \Delta v/V)_3$
Λ	Sweep Angle
ψ	Chordwise Velocity Distribution $v/V \pm \Delta v/V \mp va/V \; C_{L_{ieff}}$
ξ	A Flap Chordwise Lift Distribution Parameter

TABLE I

CAVITATION PARAMETERS

AG(EH) FORWARD FOIL PROTOTYPE

Station % chord	1.25	2.5	5.0	40	50	60	70	80
ψ	.670 1,380	.818 1.284	.919 1.201	1.098	1.117	1.131	1.136	1.123
$\Delta va/V$	1.346	.970	.686	.196	.160	.131	.103	.076
w	,620	˄39	.301	.010	-.027	-.071	-.138	-.477

Note: Upper numbers and signs denote upper surface, lowers denote lower surface

16-(.390)08 Section
1 MAC (9.33) Depth
20% Chord Flap

$q = 2.8387\, V_k^2$

$q' = ,668\, V_k^2$

$\psi = v/v \pm \Delta v/V \mp C_{l_{ieff}} \Delta va/V$

$w = f\left[\Delta va/V - (\Delta v/V)_f\right]$

$(C_l/C_L)_\delta = (C_l/C_L)_i = \begin{matrix} 1.31 \\ .71 \end{matrix}$

$f_\alpha = \begin{matrix} -.109 \\ .240 \end{matrix}$

$C_{l_{ieff}} = ,324$

CALCULATION TABLE II

$$\gamma \pm w\left[C_1\right] \pm (\Delta v_a/V - w)C_1 = \sqrt{S}$$

1.25	.670 + (.620)(.4129) + (1.346- .620)C_1 = .925 + .726C_1
2.5	.818 + (.439)(.4129) + (.970 - .439)C_1 = .999 t .531C_1
5.0	.919 t (.301)(.4129) + (.686 - .301)C_1 = 1.04 + .385C_1
40	1.098 + (.010)(.4129) + (.196 t .010)C_1 = 1.102 t .186C_1
50	1.117 + (-.027)(.4129) + (.160 t .027)C_1 = 1.105 t .187C_1
60	1.131 + (-.071)(.4129) + (.131 t .071)C_1 = 1.101 t .202C_1
70	1.136 + (-.138)(.4129) + (.103 + .138)C_1 = 1.079 t .241C_1
80	1.123 + (-.477)(.4129) t (.076 t .477)C_1 = .926 t .553C_1
L1.25	1.380 - (-.620)(.4129) + (-1.346 + .620)C_1 = 1.156 - .726C_1
L2.5	1.284 - (-.439)(.4129) t (-.970 + .439)C_1 = 1.125 - .531C_1
L5.0	1.201 - (-.301)(.4129) + (-.686 + .301)C_1 = 1.092 - .385C_1

RESULTS OF FOIL CAVITATION

BUCKET EQUATION

Station, % Chord

V_K	1.25	2.5	5.0	40	50	60	70	80	LI.25	L2.5	L5.0	L80%
5	329	445	609	1247	1243	1151	968	432	-			
10	585	780	1060	2144	2143	1979	1672	768				
15	787	1031	1385	-			2165	1033				
20	949	1218	1614	-				1247	-	-		
25	7085	1358	1770	-				1424	-	-	-	
30	1202	1464	1870	-				1578	-		-	
35	1308	1544	1927	-				1718			-	
40	1408	1606	1951	-				1849			-	
45	1506	1655	1948	-				1977	-		-	
50	1604	1694	1922	-				2105			-	
55	1703	1725	7878	-	2403	2315	2352	2236		-	-	
60	1806	1750	1818	2138	2001	1960	2132	2371,	-		-	93
65	1913	1771		1704	1545	1556	1880		50.13		-	620
70	2024	1789			1039	1108			416		-	1178
75	2141	1804			483	615			814	243	-	
80										7 1 3	-	
85											13	
90											553	

ADD 90 PSF TO ALL VALUES

CALCULATION TABLE IV

$$\delta_{1g}^{o} = \frac{W/S)_D - W/S)_{ref}}{qC_{L\delta}}$$

V_k	δ_{1g}^{o}	V_k	δ_{1g}^{o}
5	1001.39	45	2.38
10	242.76	50	0.009
15	102.28	55	-1.74
20	53.11	60	-3.08
25	30.35	65	-4.12
30	17.99	70	-4.94
35	10.53	75	-5.61
40	5.69	80	-6.15

CALCULATION TABLE V

$$\delta_{cav}^{o} = \frac{W/S)_H - W/S)'}{q' C_{L\delta}}$$

	V_k	δ_{cav}^{o}
1.25%	5’	355.31
	10	149.54
	15	83.32
	20	51.65
	25	33.73
	30	22.46
	35	14.92
	40	9.64
	45	5.80
	50	2.94
	55	0.71

	V_k	δ_{cav}^{o}
2.5%	60	-1.44
	62.5	-2.33
50%	65	-4.83
	67	-6.91
	69.3	-8.80
L80%	65	-10.99
	61	-13.54
	60	-14.40.

CALCULATION TABLE VI

$$W/S)_{ref} = \left[(C_L)_i + C_{L_o} + C_{L\delta} + C_{L_\alpha}\right]q$$

$$W/S)' = \left[(C_L)_i + C_{L_o} + C_{l_{ieff}}/(C_l/C_L)\right]$$

$W/S)_{ref}$	V_k	$W/S)'$
103,438	5	104.940
143.752	10	149.759
210.941	15	224,457
305.007	20	329.036
425.948	25	463,493
573.765	30	627.830
748,458	35	822.046
950.026	40	1046.142
1178.471	45	1300.117
1433.791	50	1583.972
1715.987	55	1897.706
2025.059	60	2241.320
2361.007	65	2614.813
2723,830	70	3018.185
3113.530	75	3451.437

GRUMMAN AEROSPACE CORPORATION