8. High-Lift Aerodynamics

8.1 Introduction: *Why high lift?*

For transonic transports, the high-lift system design is a critical part of the configuration design. To achieve "reasonable" field performance while also obtaining efficient transonic cruise the design will require a fairly sophisticated high lift system. From a paper by Boeing aerodynamicists[1]: (presumably referring to the B-777)

- "A 0.10 increase in lift coefficient at constant angle of attack is equivalent to reducing the approach attitude by one degree. For a given aft body-to-ground clearance angle, the landing gear may be shortened for a savings of airplane empty weight of 1400 lb.
- "A 1.5% increase in maximum lift coefficient is equivalent to a 6600 lb increase in payload at a fixed approach speed"
- "A 1% increase in take-off *L/D* is equivalent to a 2800 lb increase in payload or a 150 nm increase in range."

For fighters, "devices" are also scheduled allow efficient maneuver.

High-lift systems are also critical for STOVL and V/STOL aircraft. They also use the propulsion system to help generate the lift. It always seemed to me peculiar to design fighter aircraft, or virtually any military aircraft, to operate from traditional runways. The one thing the adversary is going to know is the exact location of your runways. So a STOVL capability seems to be critical in a serious confrontation.

Current status: Typical values of C_{Lmax} are shown in Table 1. They come from papers by Brune and McMasters,[2] Roskam and Lan,[3] and Sanders.[4]

Table 1. Values of C_{Lmax} for some airplanes.*

Model	C_{Lmax}
B-47/B-52	1.8
367-80/KC-135	1.78
707-320/E-3A	2.2
727	2.79
DC-9	3.0
737-200	3.2
747/E-4A	2.45
767	2.45
777	2.5

* Note that there is a significant variation of values from different sources.

Clearly the 727 emphasized short fields, and thus required a higher C_{Lmax} Anyone who ever looked out the window while landing in a 727 noticed the elaborate high lift system employed.

Some Key Aspects:

- Compressibility can be important early.
- Reynolds number scaling from WT to flight may be problematic.
- Today *simple* high lift systems are critical, the high manufacturing cost for high lift systems is important.

Classes of problems

- High lift for a single element airfoil
- Multi-element airfoils
- Use of "blowing" in some form: *Powered Lift*

Computing:

- Requires consideration of viscous immediately. (unlike typical cruise airfoil analysis and design, where some insight can usually be gained ignoring viscous effects).
- Predicting high-lift is done almost entirely with Navier-Stokes (RANS) codes (exception, Prof. Mark Drela's MSES[5] code). A recent summary of the computational capability is by Rumsey and Ying.[6]

Single element airfoils

- The key example of how to obtain high lift on a single element airfoil is the story of Liebeck's high lift airfoil[7] and the Stratford "pressure recovery" shape of the pressure distribution. This introduces the classic paper by A.M.O. Smith.[8] See section 8.5 below.

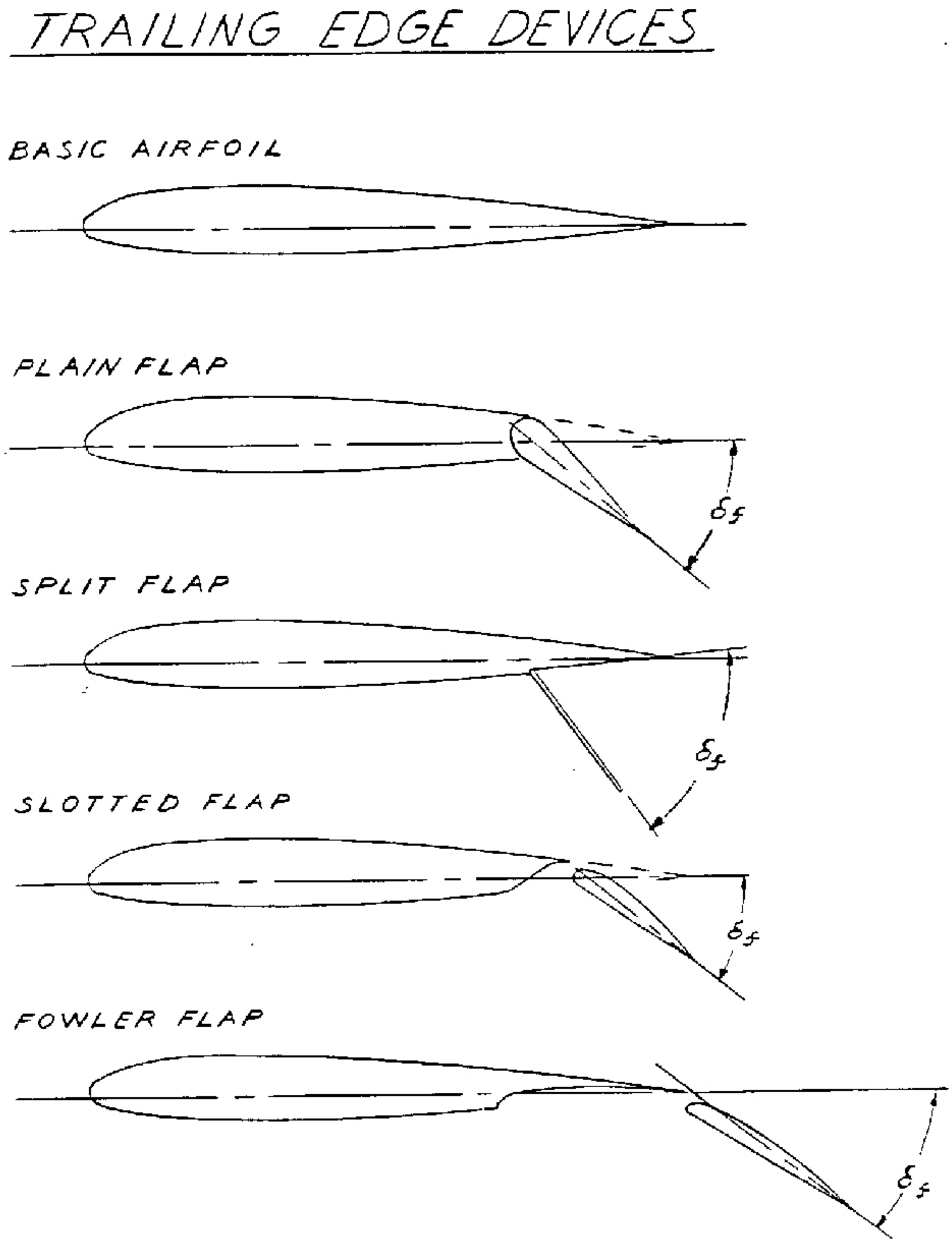
Multi-element airfoils:

- *Understanding the physics*: Section 6.3 of A.M.O. Smith's paper[8] is critical to understanding the physics. Know what is meant by: 1. The slat effect, 2. The circulation effect, 3., The dumping effect, 4. Off-the-surface pressure recovery, and 5. The fresh boundary layer effect. Note: some people combine the circulation and dumping effects and call it the "vane effect". See section 8.5 below for details.
- *Design:* See the recent survey by C.P. van Dam,[9]
- *Existing systems on commercial transports:* Rudolph has surveyed the high-lift systems on current subsonic transport aircraft.[10]

8.2 Types of Trailing Edge Devices

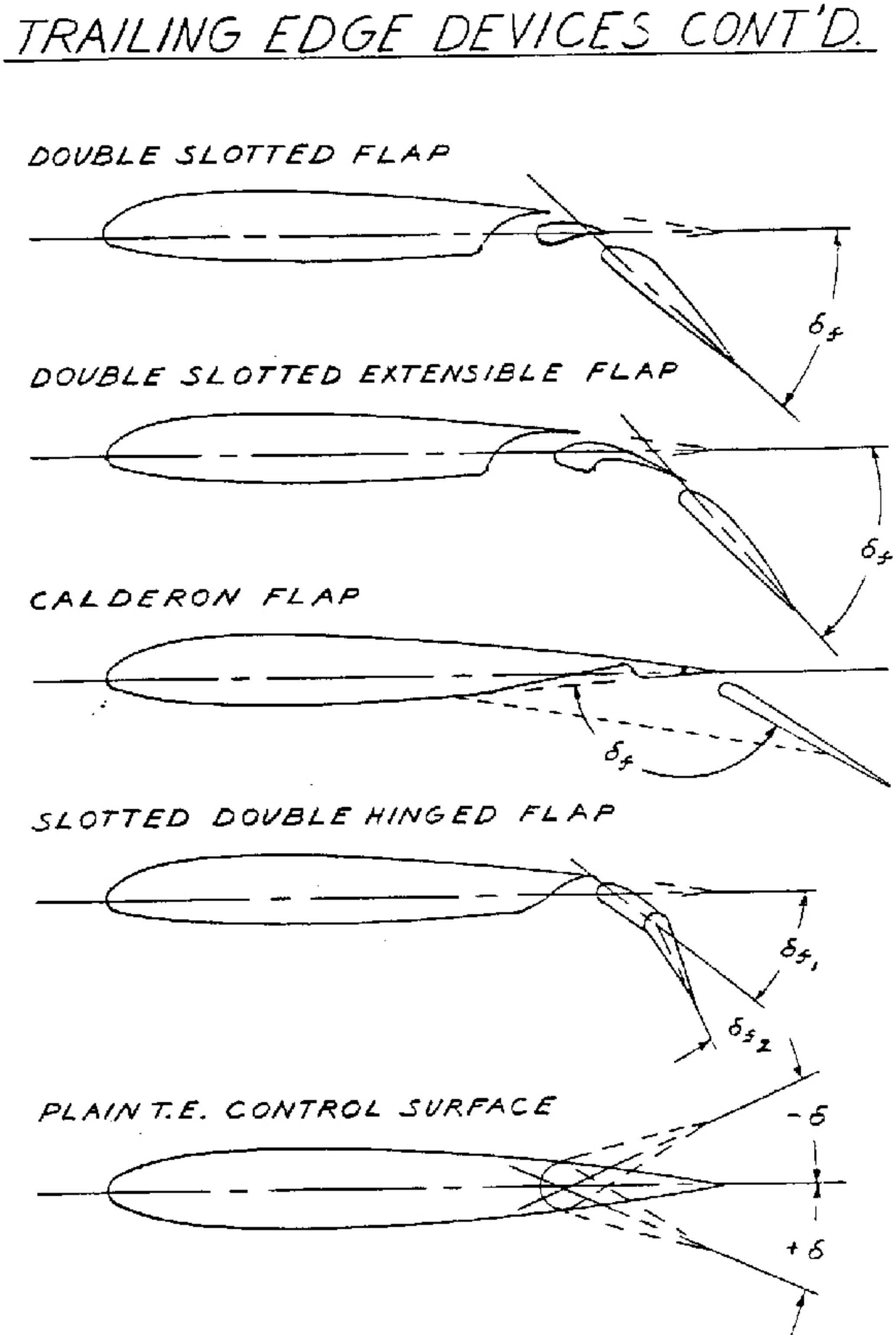
To begin we include a number of examples of high-lift devices as drawn by Dick Kita of Grumman.[11] These are fairly realistic drawings, as opposed to many of the drawings in textbooks, which are cartoonish. Kita worked in high lift for many years. I'm aware of his work on the Gulfstream II and F-14, but he worked on many other Grumman aircraft high-lift systems as well.

Of the large number of papers addressing high lift, several deserve mention. Pepper, et al[12] provides a more current look at high lift, while the Boeing 777 high lift system development, as well as the overall design process, is available in the paper by Nield.[13] A valuable description of high lift on transports in contained in Gratzer.[14] The use of powered lift is covered in the survey by Korbacher.[15] Somewhat dated but valuable resources are the book by Hoerner and Borst,[16] and the book by McCormick[17] (recently reissued unchanged from the 1967 edition as a Dover paperback). Perhaps the best chapter on high lift in a basic text is the chapter in Shevell.[18]



a) basic devices

Figure 8-1. Examples of typical trailing edge devices. Note that the Fowler flap also adds area, so that part of the C_{Lmax} increase is simply due to the use of the original reference area in computing the C_L. (from Dick Kita's Grumman talk, Feb. 1985)



b) other trailing edge devices

Figure 8-1. Examples of typical trailing edge devices.

(from Dick Kita's Grumman talk, Feb. 1985)

8.3 Types of Leading edge devices

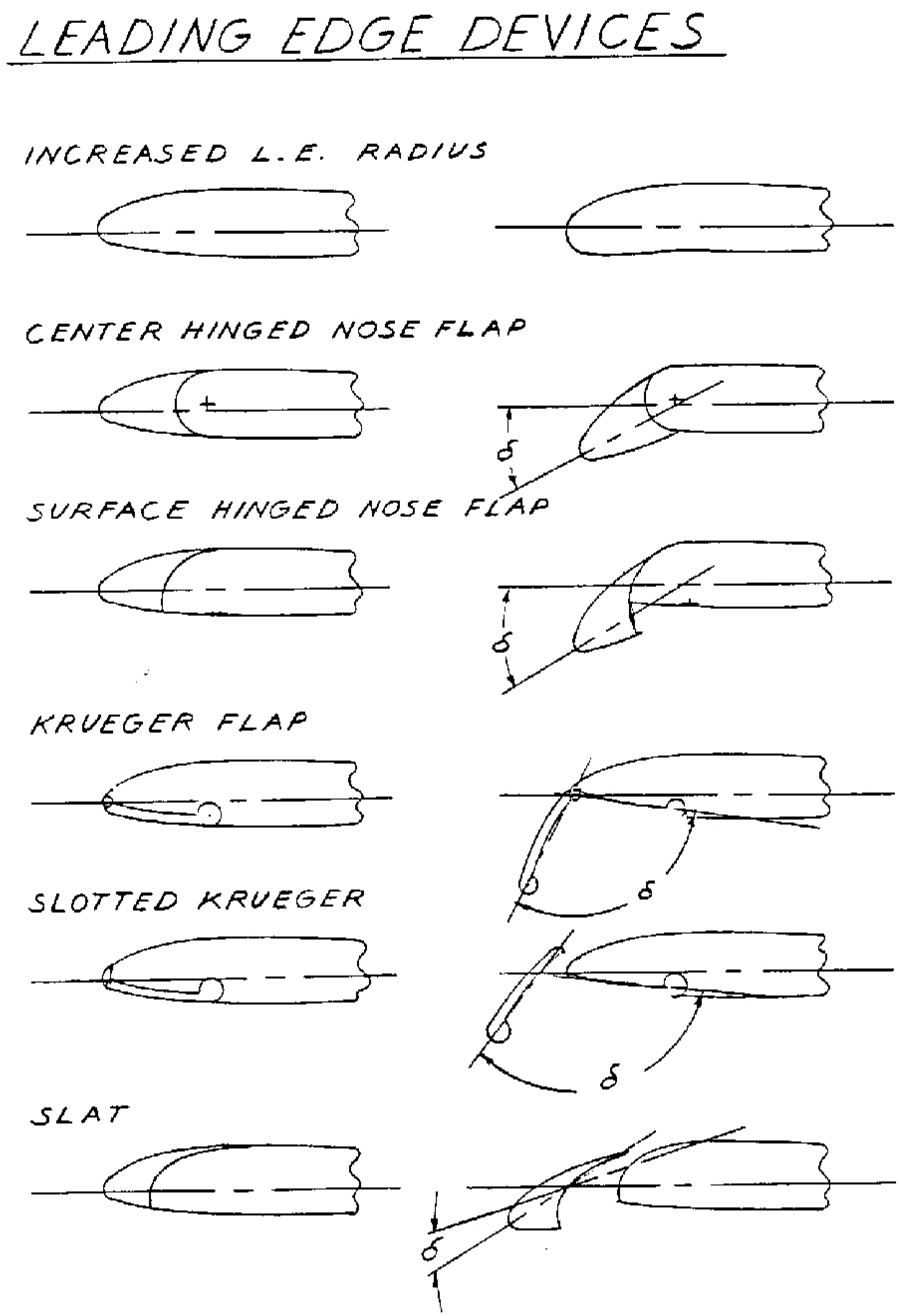


Figure 8-2. Typical leading edge device concepts.
(from Dick Kita's Grumman talk, Feb. 1985)

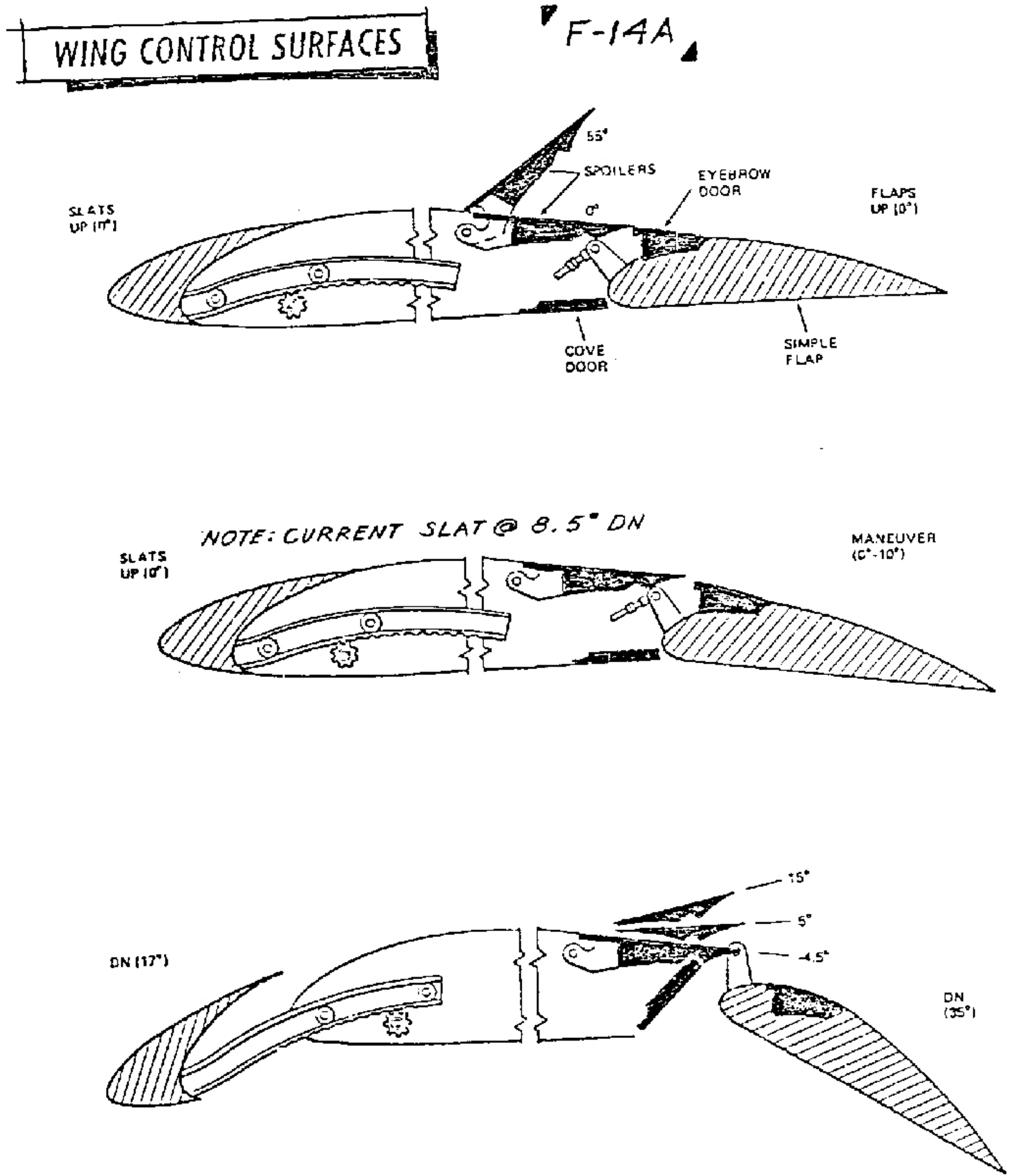


Figure 8-3. The actual high-lift system employed on the F-14.
(from Dick Kita's Grumman talk, Feb. 1985)

Notice that the F-14 has a fairly elaborate scheme, where the cove region is smoothed with a moving flap, and the upper surface of the slat also has a movable piece to fair the flap. Also note the spoilers. Many fighter airplanes use spoilers instead of ailerons for roll control, although their use varies from company to company.

8.4 Aerodynamics of Leading and Trailing Edge Devices

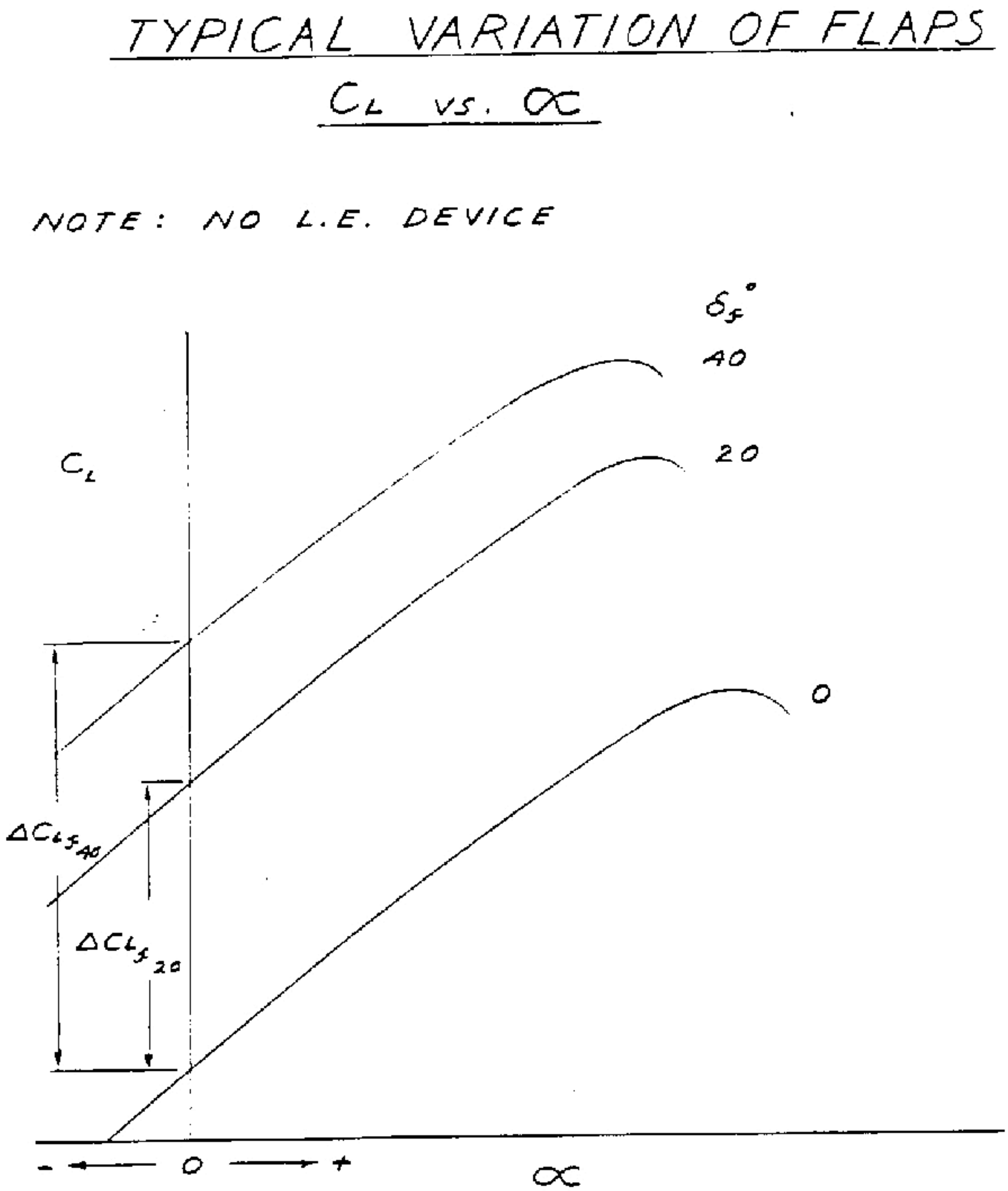


Figure 8-4. Typical effect of flaps on lift (from Dick Kita's Grumman talk, Feb. 1985)

This figure illustrates the effects of flap deflection on lift. Note that the angle of attack for C_{Lmax} actually decreases as the flap is deflected.

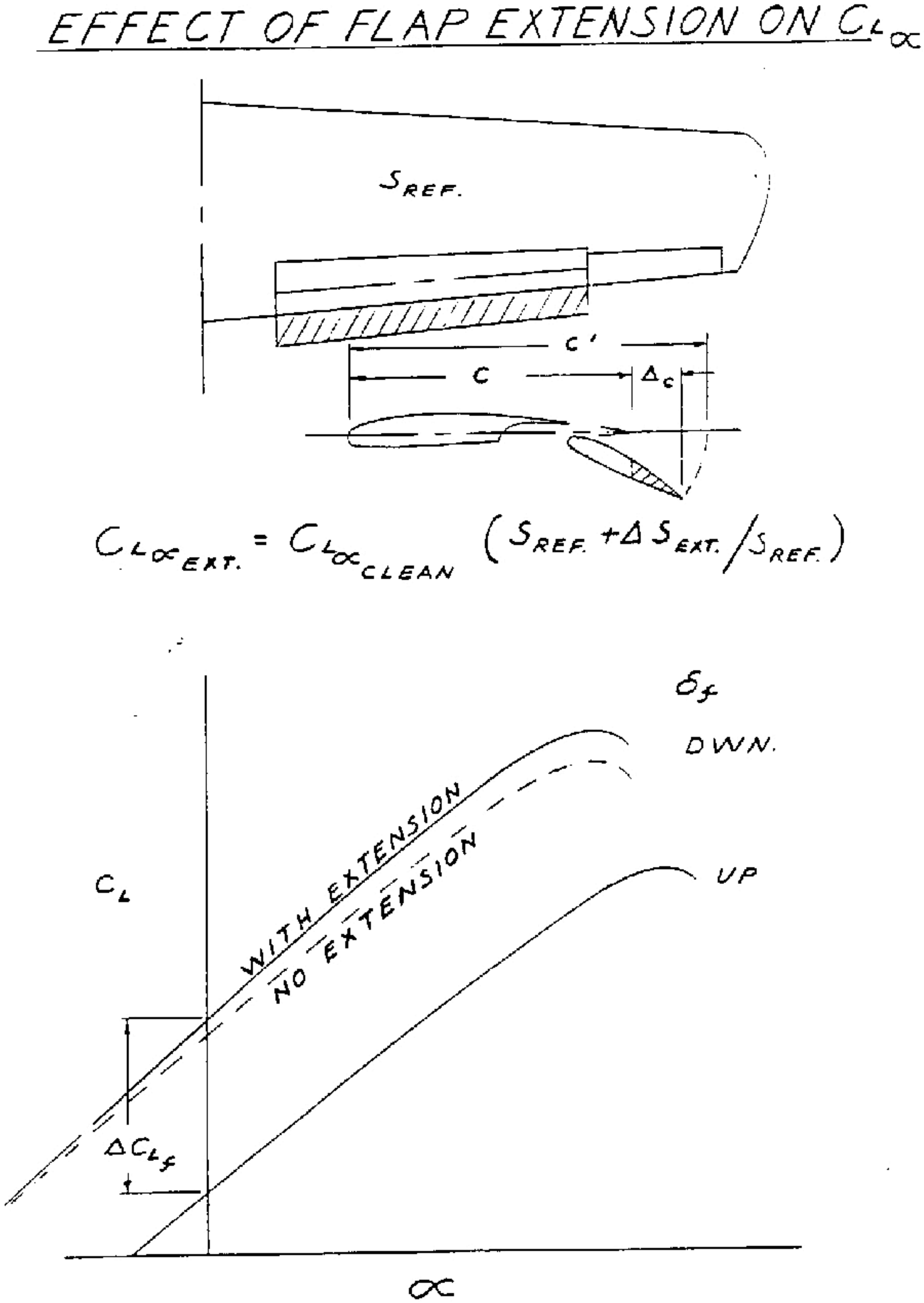


Figure 8-5. Effect of flap extension on lift.
(from Dick Kita's Grumman talk, Feb. 1985)

Flaps that extend in a Fowler motion also benefit from additional wing area. Because we continue to use the same reference area, the C_{Lmax} value increases.

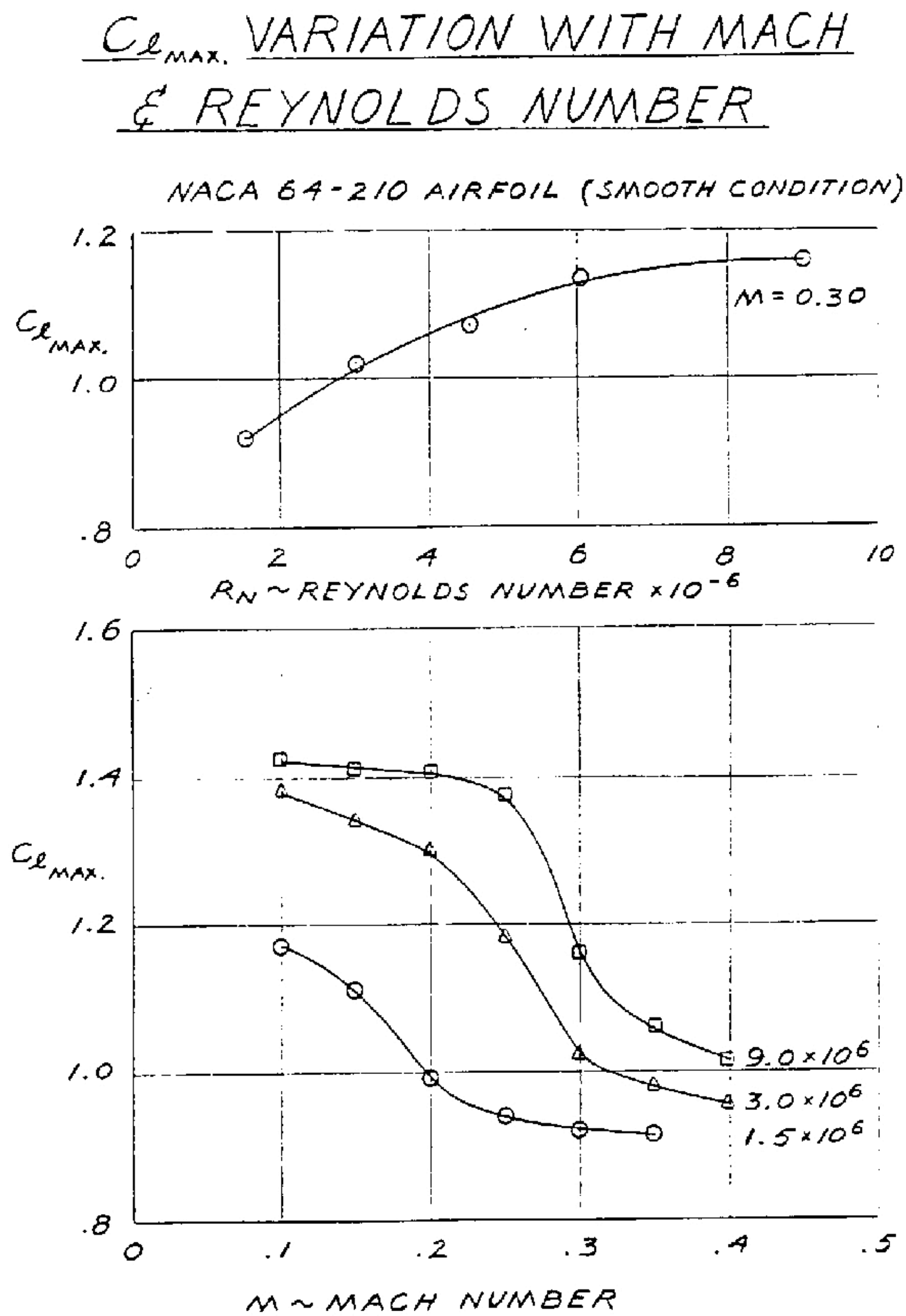


Figure 8-6. Typical variation of C_{Lmax} with Mach and Reynolds Number.
(from Dick Kita's Grumman talk, Feb. 1985)

In general, we expect C_{Lmax} to increase with Reynolds number as shown here for a clean airfoil. However, sometimes the projection is not so straightforward, and C_{Lmax} may even decrease.[19] Considering the adverse effect of Mach number on C_{Lmax}, notice the low Mach numbers at which the effects take place. It's rather surprising to the uninitiated.

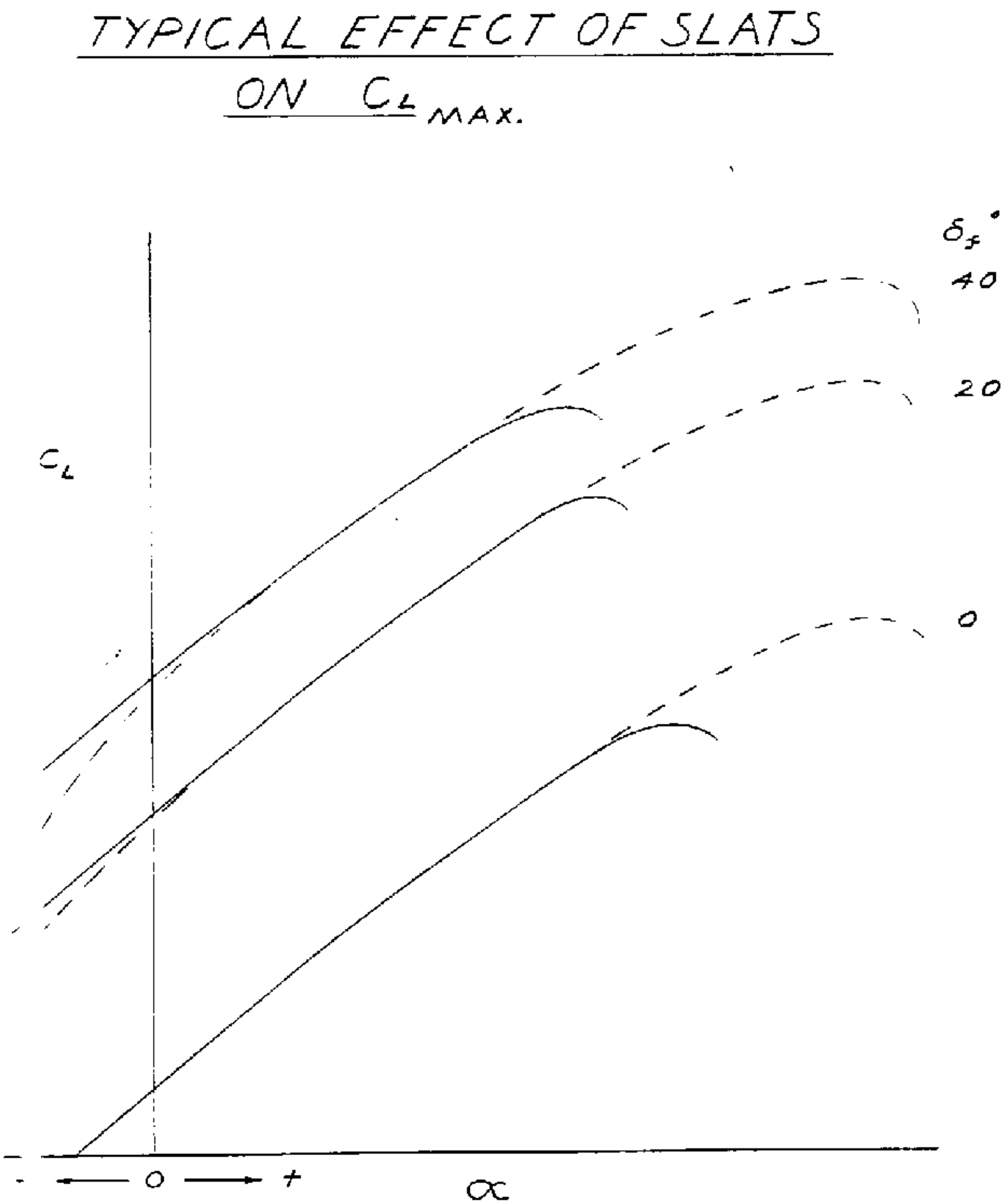


Figure 8-7. Effect of leading edge slats.
(from Dick Kita's Grumman talk, Feb. 1985)

Leading edge slats work to protect the leading edge from separation. Therefore, they don't really "do anything" until you reach the angle of attack where the leading edge flow would "let go" without the slats for protection. Thus the slats allow the lift to continue to rise to higher angles of attack.

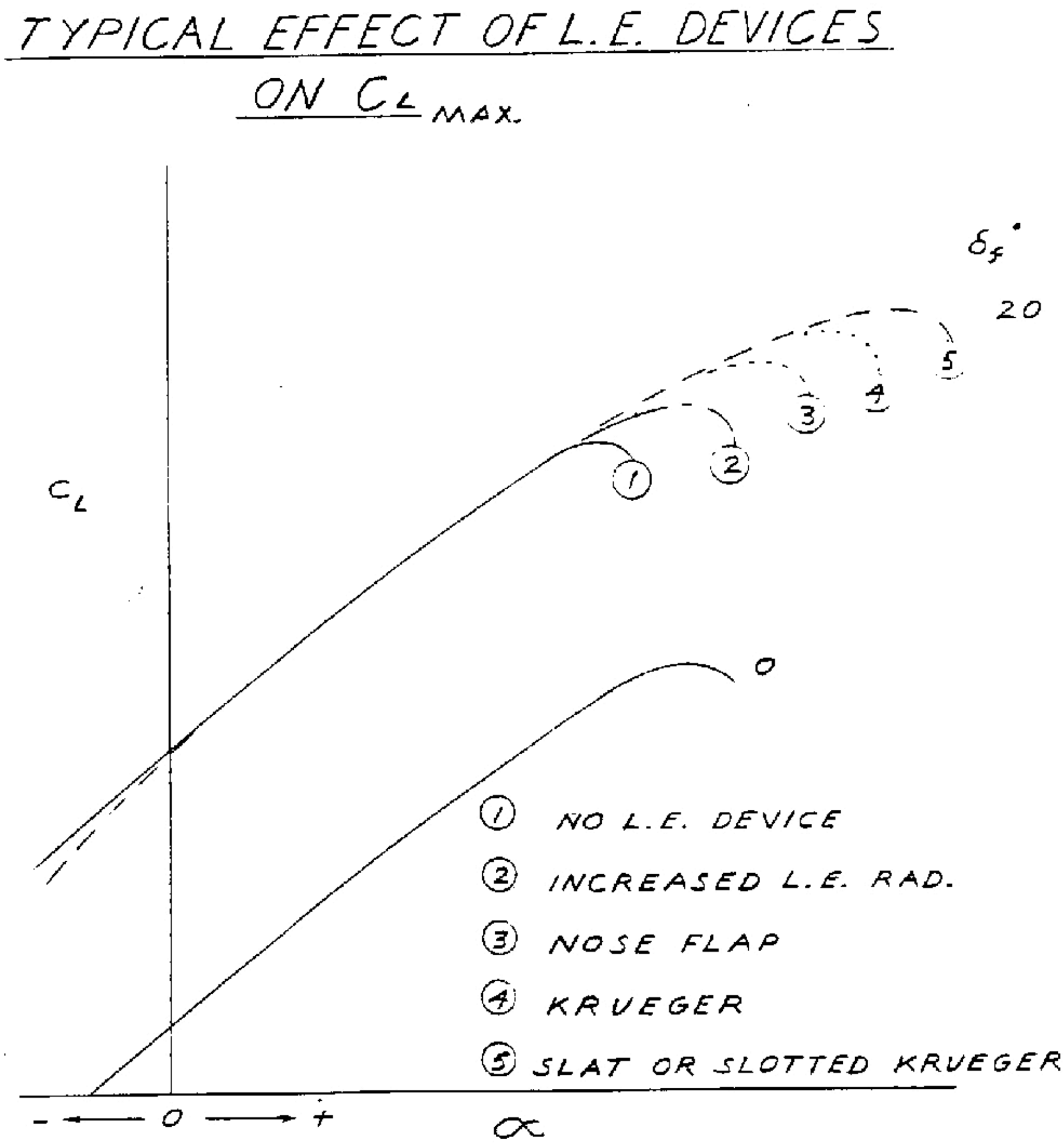


Figure 8-8. Effects of various types of leading edge devices on C_{Lmax}.
(from Dick Kita's Grumman talk, Feb. 1985)

Different leading edge devices differ in their effectiveness. This is Kita's estimate of how each type of device affects the performance of the wing.

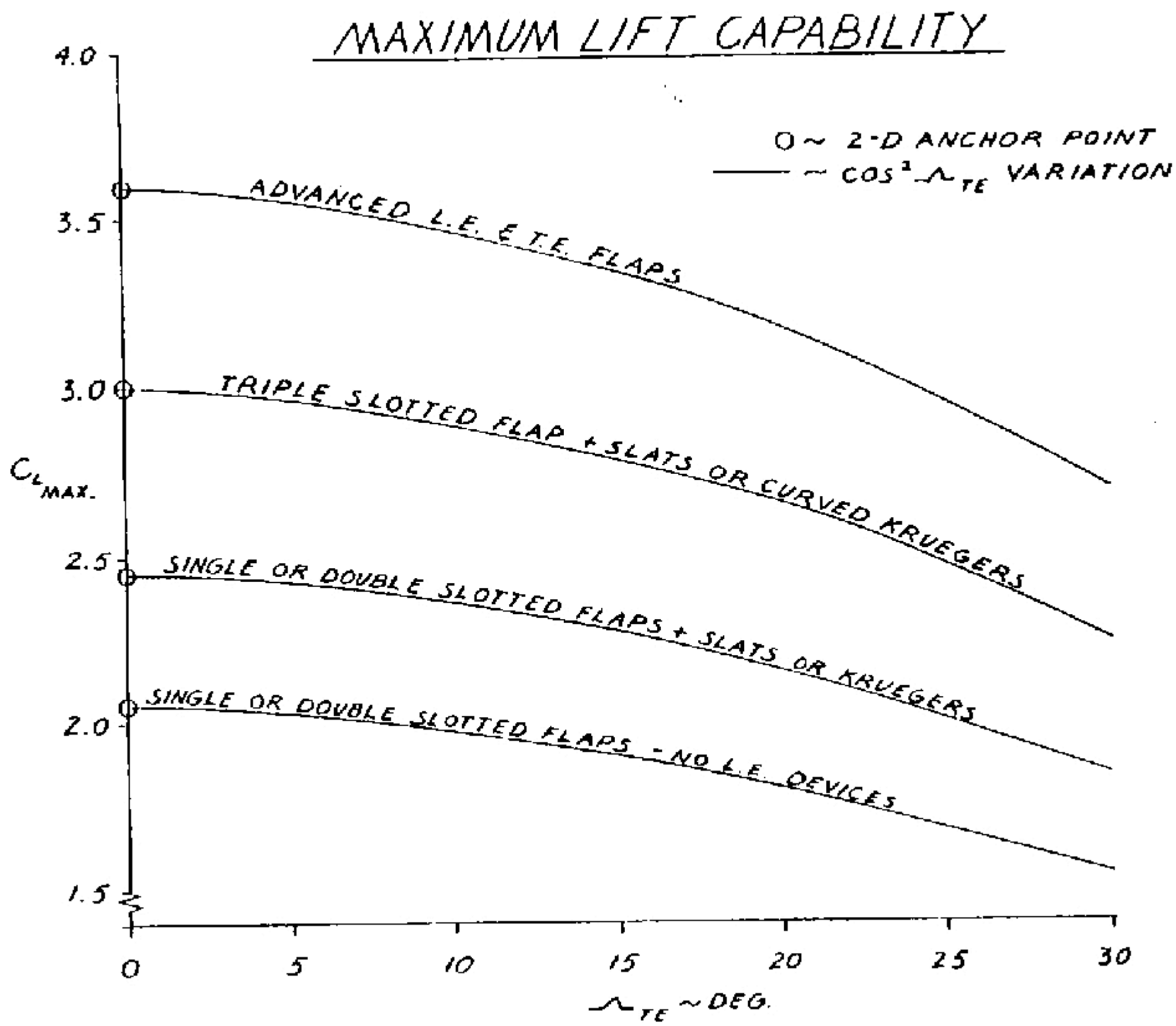


Figure 8-9. Estimated performance of various types of high lift systems.
(from Dick Kita's Grumman talk, Feb. 1985)

This is Kita's estimate of the typical "best" performance you can get from various types of high-lift systems. You can see that sweeping the trailing reduces the effectiveness of all the systems. The curve labeled "advanced" is typical of projections made in advanced departments, where the assumption is that an advanced technology development effort can improve the performance of any system. This may or may not be true.

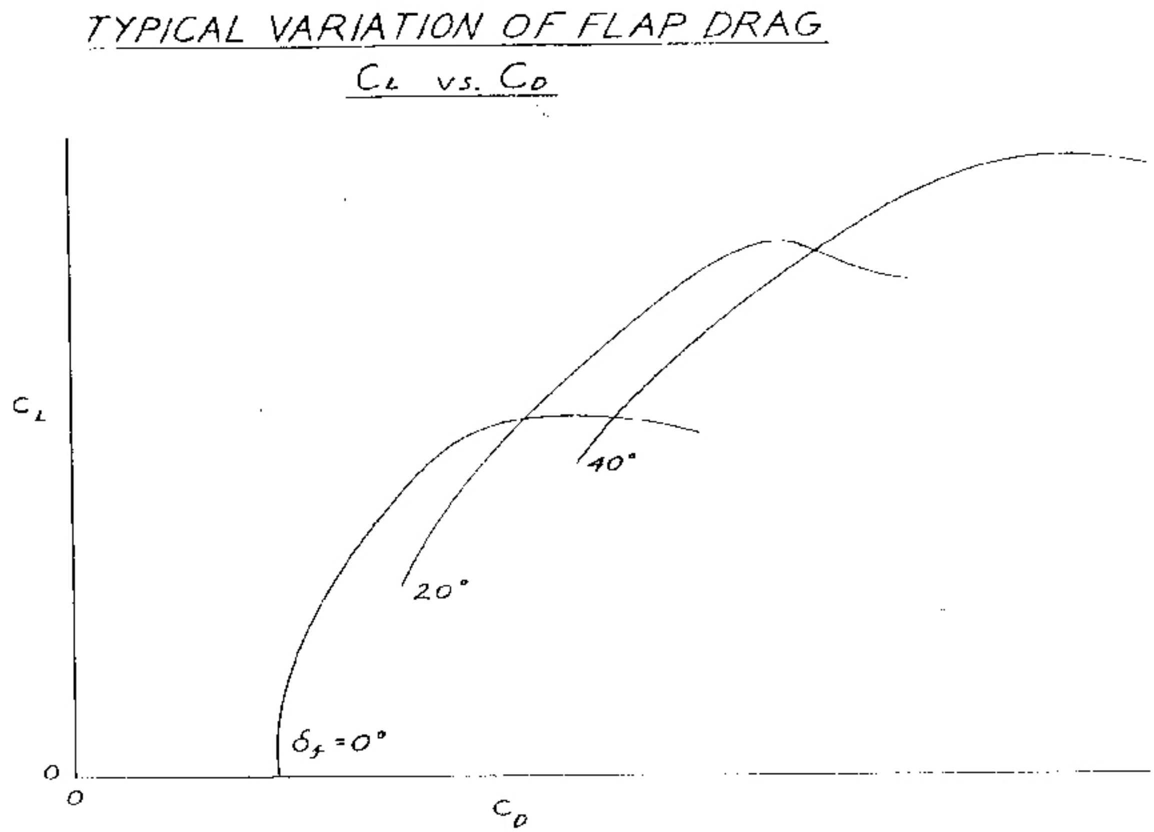


Figure 8-10. Effects of flap deflection on drag.
(from Dick Kita's Grumman talk, Feb. 1985)

In addition to lift, flaps make a large change in drag. Clearly, you don't want the flaps deployed at low lift, and thus flaps aren't deflected in cruise. As lift increases, there may be an optimum flap deflection schedule, and this is done, for example, on the F-18, where the flaps are scheduled with angle of attack and Mach number. This was also done on the Grumman X-29.

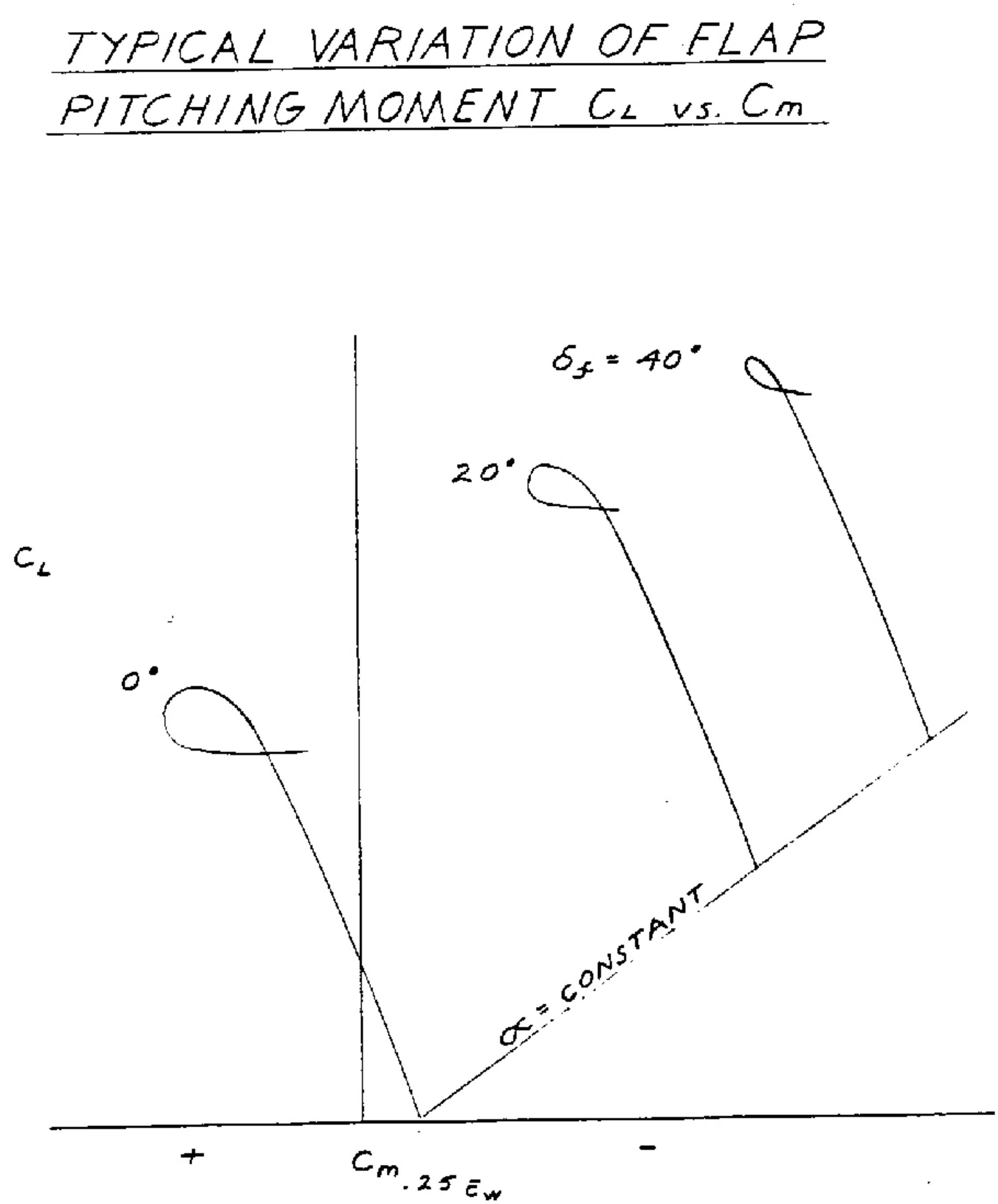


Figure 8-11. Flap effects on pitching moment.
(from Dick Kita's Grumman talk, Feb. 1985)

Flap deflection also produces a large change in pitching moment. This is an important consideration, since you need to be able to trim this pitching moment. In the case of the Beech Starship, the canards actually changed sweep to be able to generate the required force. So this effect cannot be ignored in developing the high lift system.

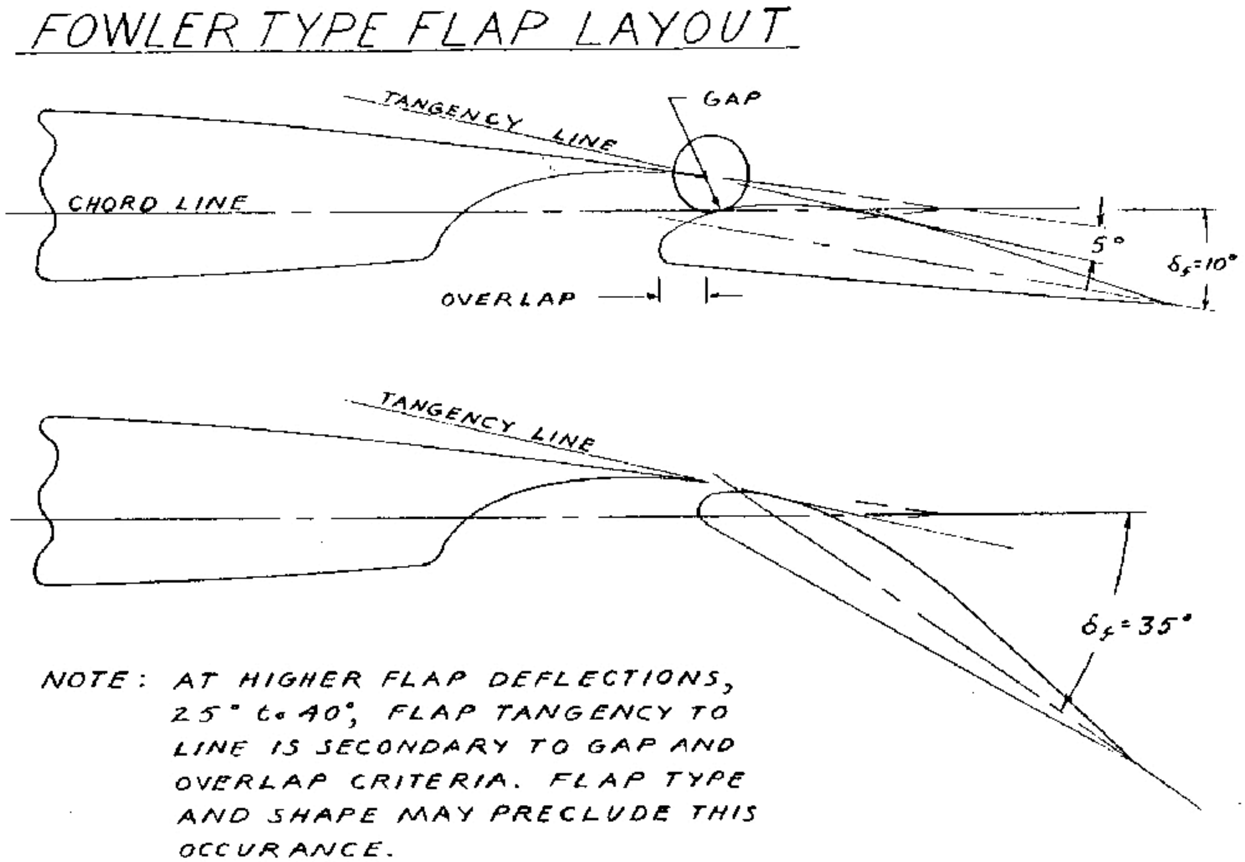


Figure 8-12. Definition of gap and overlap.
(from Dick Kita's Grumman talk, Feb. 1985)

In developing the high lift system, the selection of the "gap" between the slot and main element, and the "overlap" have been found to be two of the key parameters. A lot of wind tunnel time, and more recently computer resources, are spent trying to identify the values of these parameters that produce the highest lift. Figure 8-12 provides Kita's definition of these parameters.

8.5 Physics of high lift: A.M.O. Smith's analysis of the high lift aerodynamics

Now that we've surveyed the characteristics of high lift systems, we need to examine the physical basis for the operation and limits of high lift systems. A.M.O. Smith "wrote the book" on the physics of high-lift systems[8] and is required reading. His message: you need to carry as much lift (load) as you can on the airfoil's upper surface without separating the boundary layer. His classic paper describes the physics associated with the high-lift characteristics we described above, and how to achieve the available high lift performance. We summarize his description here.

To obtain insight into the characteristics of pressure distributions as they affect boundary layer separation, Smith introduced the use of a canonical pressure distribution. He felt strongly that this was necessary to understand and compare possible separation on different airfoils. It is essentially another type of dimensionless or “scaled” pressure distribution. For boundary layer investigations it is found that the best scaling factor is the velocity just before the deceleration begins. In Smith’s canonical system, $\bar{C}_p = 0$ represents the start of the pressure rise and $\bar{C}_p = +1$ the maximum possible value, that is, u_e = 0.The velocity at the start of the pressure rise is u_0. Thus, the canonical pressure distribution is defined as

$$\bar{C}_p = 1 - \left(\frac{u_e}{u_0}\right)^2$$

The next step is to examine the best way to specify the pressure distribution to allow the pressure to recover to as close as possible to $\bar{C}_p = +1$. Smith made a parametric study of various possibilities to gain insight into the “best” way to prescribe a pressure distribution to delay separation. However, here we look at his limiting case. It makes use of an analysis by Stratford that was done to estimate separation before the days when boundary layer computer programs were available and their use routine (1959). Using Stratford’s analysis, it is possible to define a pressure distribution where the boundary layer is everywhere just on the verge of separation. To do this, we manipulate the Stratford criteria:

$$\frac{\bar{C}_p \left[x \left(d\bar{C}_p / dx \right) \right]^{1/2}}{\left(10^{-6} R\right)^{1/10}} = S$$

Note that originally, Stratford used this relation to say that separation occurred when the quantity on the LHS of the equation reached the value of S (typically 0.35). However, we can define a Cp distribution using this relation that is everywhere equal to S, just on the verge of separation, and this pressure distribution is the best way to achieve a very large pressure recovery without separation. Figure 8-13 shows the resulting pressure distribution. Examining this pressure distribution, several key observations can be made. The initial slope is infinite, and then decreases. Thus, when the boundary layer is thin, it can withstand a very large pressure gradient. As the boundary layer thickens (either when it starts to recover, or as it recovers) it cannot sustain the large pressure gradient, and the pressure gradient to maintain attached flow decreases. This illustrates the idea that thick boundary layers are more likely to separate than thin boundary layers. Note also that the Reynolds number effect is relatively weak. Finally, the boundary layer could recover all the way to $\bar{C}_p = +1$, but to attain this, x would need to go to infinity. These shapes are the best possible pressure distributions to use to recover the pressure without separating the boundary layer. as Smith notes, the only way to do better is to use some sort of active boundary layer control (suction or blowing).

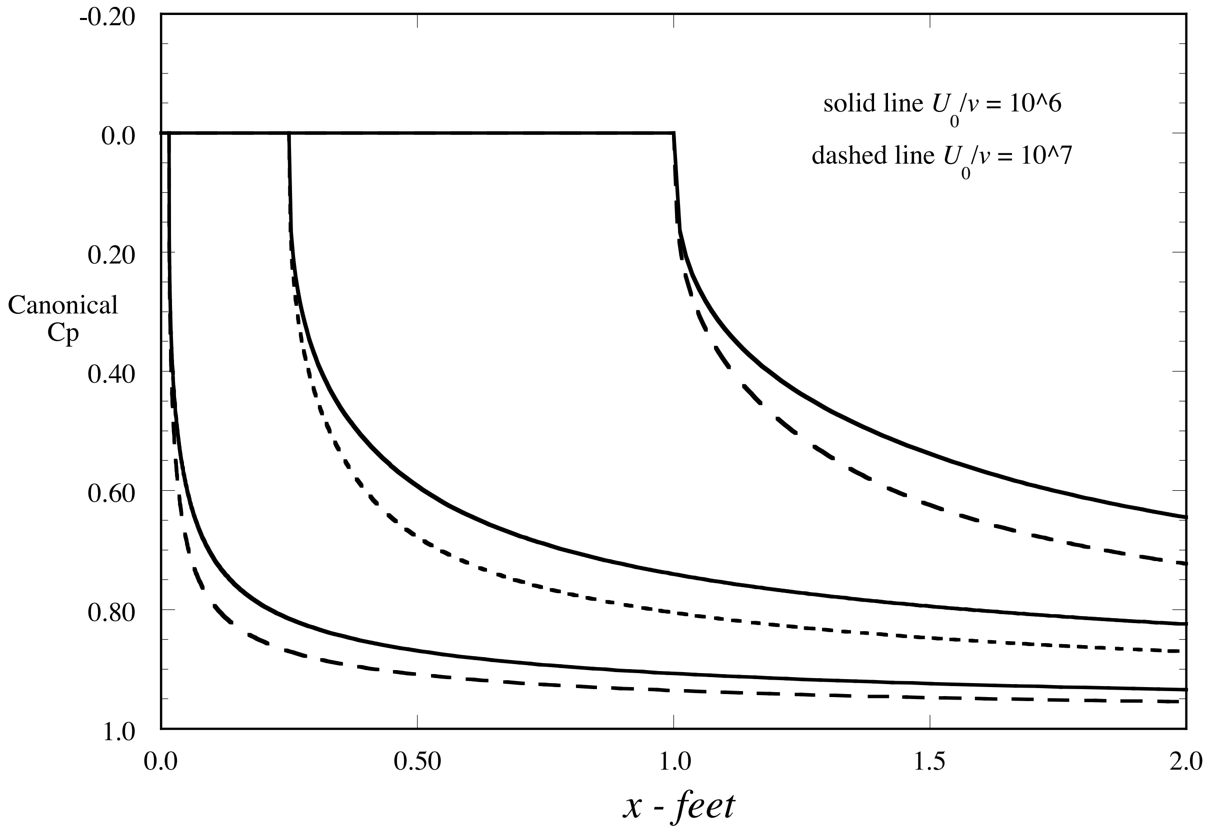


Figure 8-13. Stratford Limiting flows for two different Reynolds numbers.

Single element airfoils: The key is how to obtain high lift on a single element airfoil, and is essentially the story of Liebeck's high lift airfoil[7] and the Stratford "pressure recovery" shape of the pressure distribution described above, as told by Smith.[8] The question of how much lift you can obtain on a single element airfoil involves how low the pressure can be on the upper surface, and how the pressure can recover to a positive pressure coefficient at the trailing edge and keep the boundary layer attached. Smith describes two aspects of the problem. In the first case, he explains the limit of the pressure coefficient in terms of the vacuum C_p when a zero pressure is specified on the airfoil upper surface. Thus, using the definition of C_p,

$$C_p = \frac{p - p_\infty}{\frac{1}{2}\rho_\infty U_\infty^2}$$

we can obtain an alternate form using $q = {}^1\!/_2\, \rho_\infty U_\infty^2 = {}^\gamma\!/_2\, P_\infty M_\infty^2$, that is

$$C_p = \frac{p - p_\infty}{\frac{\gamma}{2} p_\infty M_\infty^2}$$

and vacuum C_p occurs when the pressure is zero:

$$C_{p_{vac}} = \frac{-2}{\gamma M_\infty^2}$$

Then, he points out that only a value of 70% of the vacuum C_p has been achieved in practice. This results in a C_p limit of $M_\infty^2 C_p = -1$ for γ of 1.4.

Next, Liebeck and Smith used the analytical analysis by Stratford illustrated above to specify a pressure distribution that allows the most lift to be obtained. Given this pressure distribution, an inverse method is used to obtain the associated airfoil shape. The result is the Liebeck family of high lift airfoils.

Multi-element airfoils: Understanding the physics: read section 6.3 of A.M.O. Smith's paper. The five ideas are:

1. *The slat effect*. The slat "protect"s the leading edge of the main element. That's why its effect is only observed near C_{Lmax} of the single element. Thought of as a point vortex, the slat velocity acts to reduce the velocity around the leading edge of the main element.

2. *The circulation effect*. The downstream element causes the upstream element to be in a high velocity region, inclined to its mean line. To meet the Kutta condition, the circulation has to be increased. Instead of the airfoil deflecting as a plain flap, the trailing edge is placed in an inclined flow, something else (the downstream element) turns the flow.

3. *The dumping effect*. The trailing edge of the forward element is in a region of velocity appreciably higher than the freestream velocity. Thus, the boundary layer can come off the forward element at a higher velocity. You don't have to recover back to $Cp = +0.2$ for attached flow, relieving the pressure rise on the boundary layer, alleviating separation problems and permitting increased lift. The suction lift can be increased in proportion to U_{TE}^2 for the same margin against separation.

4. *Off-the-surface pressure recovery*. The boundary layer leaves the trailing edge faster than the freestream, and now becomes a wake (a viscous phenomena). The recovery back to freestream velocity can be more efficient way from contact with the wall. Wakes withstand more than boundary layers. Note that the wake can actually "separate" out in the flowfield. Note: for a well designed high lift system the local boundary layers and wakes remain separate. If they merge, everything is more complicated.

5. *The fresh boundary layer effect*. Thin boundary layers can sustain a greater pressure gradient than a thick boundary layer. Thus, three thin boundary layers (on three airfoil elements) are more effective than one thick boundary layer (single element).

Note: some people combine the circulation and dumping effects and call it the "vane effect".

8.6 Computational methods for high lift

Significant effort has been devoted to improving prediction capabilities for high lift systems. As stated in the introduction, the best recent survey is by Runsey and Ying.[6] In the meantime, for low speed predictions of the maximum lift for a single element airfoil, **XFOIL**[20] can be used. experience shows that it's predictions are slightly higher than experimental results. Figure 8-14 shows typical agreement between XFOIL and wind tunnel data for the NACA 0012 and 4412 airfoils. Although the prediction is not perfect at maximum lift, nevertheless, this is a remarkable capability of a code than be run on a laptop PC.

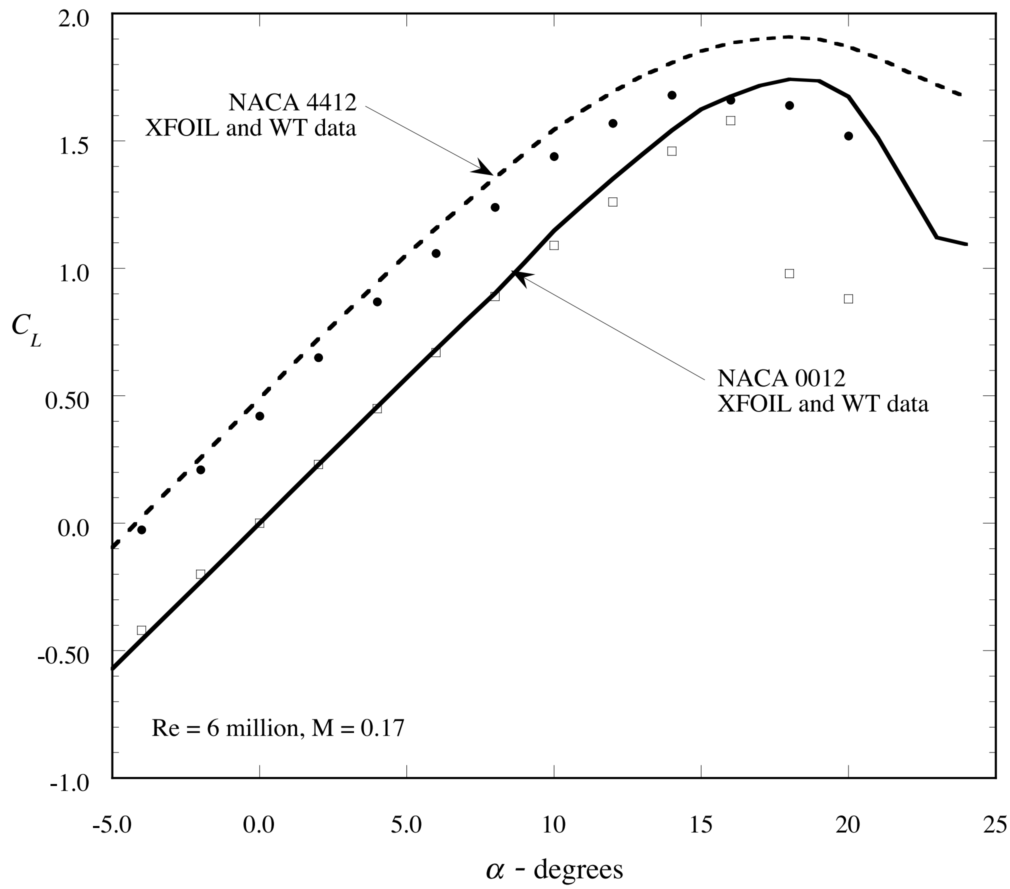


Figure 8-14. Typical agreement between XFOIL and wind tunnel data.
Calculations courtesy of David Lurie.

8.7 Passive and active boundary layer control

Passive Boundary Layer Control: The boundary layer can be prevented from separating by the use of vortex generators, snags and fences.[21]

Active boundary layer control: If suction or blowing is used to suppress boundary layer separation, the blowing (which is generally preferred to suction) is known as boundary layer control (BLC), if the amount of blowing exceeds the value required for BLC, then the blowing is know as "powered lift". The key parameter used to describe the amount of blowing is the blowing coefficient, defined as:

$$C_\mu = \frac{m_j V_j}{qc}$$

where the subscript *j* refers to the jet, and *q* is the dynamic pressure. Blowing for BLC was used often in early fighters, but is not used nearly as much today. The F-4 Phantom originally had blowing on both the leading edges and over the trailing edge flap. However, to improve transonic maneuver characteristics and to improve resistance to departure, the leading edge blowing was replaced by leading edge slats.[22]

8.8 Powered Lift

A huge class of concepts have been tried to increase maximum lift using high pressure air from the engine. Some examples of powered lift concepts are:

- propeller slipstream deflection (Brequet 941/McDonnell Model 188)
- externally blown flaps (McDonnell DouglasYC-15/C-17)
- internally blown flaps
- upper surface blowing (Boeing YC-14, NASA QSRA, Ball-Bartoe JetWing)
- vectored thrust (AV-8 Harrier)
- jet flaps (Hunting H.126)
- jet augmentor wings (NASA-deHavilland Augmentor Wing Aircraft)
- circulation control (advocated by Hokie Bob Englar[23], A-6 CCW)

8-9 Configuration Integration issues

- The best airplane C_{Lmax} you can achieve with a mechanical high lift system is about 3 – 3.5
- The military and civil air regulations require a margin between C_{Lmax} and the operating C_L of the airplane. This must be accounted for during design. For example, the approach speed must be 1.3 times the stall speed. This would suggest that the maximum approach C_L is only 59% of the C_{Lmax}. However, some relief is available because the measured stall speed, V_{smin} is usually about 0.94 times the stall speed in 1*g* steady flight (the wind tunnel case). This means that you can use a C_L of about 67% of the C_{Lmax}.[9,24]
- Increased span can be used to reduce the induced drag, so a bigger flap angle can be used before a climb limit is encountered, but this is a heavy solution.
- Sweep decreases max lift
- *2D to 3D*: lots of losses – don't be mislead by 2D C_{Lmax} values, the real 3D value will be much less.
- The maximum C_L available for takeoff and landing for many swept-wing airplanes is actually the limit on angle of attack to avoid tailscrape.
- Engine out is much more critical with V/STOL airplanes, and typically leads to a complicated engine cross shafting arrangement to ensure uniform thrust on each side of the plane if an engine fails. The ability to do this dictates whether the concept is practical.
- The best high-lift configuration integration description also involves powered lift. The YC-14 AIAA Case Study[25] is highly recommended.

Finally, issues not covered but worth mentioning: the concept of the Gurney flap[7] and the need for accuracy around the leading edge.[*]

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[*] Maintaining an accurate leading edge contour is critical at high lift conditions. Once after a navy depot had repainted an F-14 wing, a small ridge was left on the leading edge where the upper and lower surface paint

8-10 Exercises

1. Examine the predictive capability of **XFOIL** for C_{Lmax}. Use the data from Abbott and von Doenhoff supplied previously for the NACA 0012 and 4412 airfoils at a Reynolds number of 6 million and free transition. Comment on your results.

2. Read the high lift paper by A.M.O. Smith. Summarize what you learned in one page. Pay special attention to the details of single and multielement airfoils described in Sections 3-6.

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overlapped. This was enough to cause early stall. Ed Heinemann reported a similar experience on a Douglas airplane during World War II in his autobiography.

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