Some High Lift Aerodynamics

Part 1
Mechanical High Lift Systems

W.H. Mason

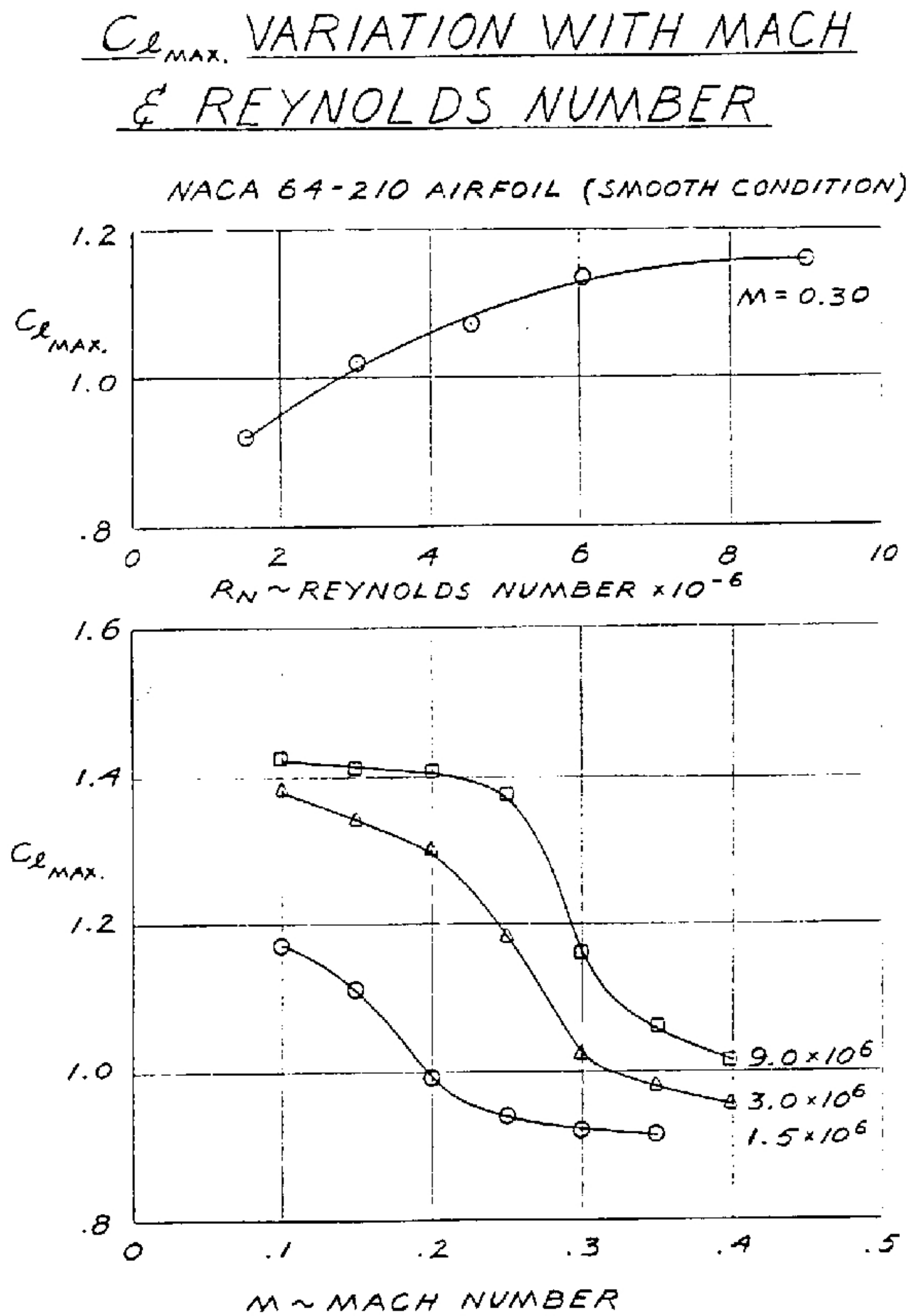
Configuration Aerodynamics Class

Why High Lift is Important

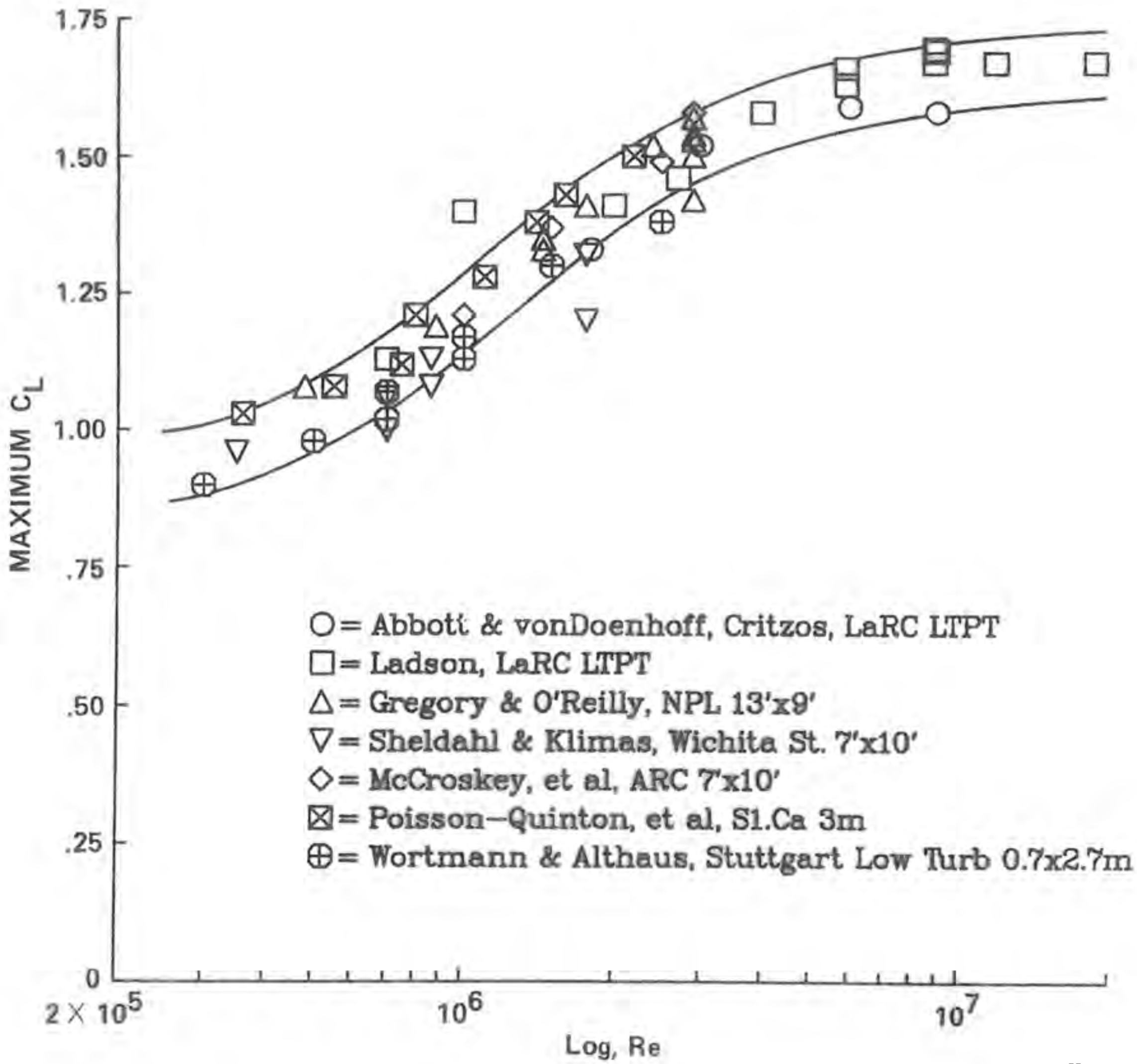
- Wings sized for efficient cruise are too small to takeoff and land in "reasonable" distances.
- From Boeing:
  - "A 0.10 increase in lift coefficient at constant angle of attack is equivalent to reducing the approach attitude by one degree. For a given aft body-to-ground clearance angle, the landing 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 move continuously for minimum drag during maneuvering.
- Powered Lift concepts hold out the hope for STOL operation

CLMAX with Reynolds number and Mach number

From a presentation by Dick Kita
To the new members of the
Grumman aerodynamics section

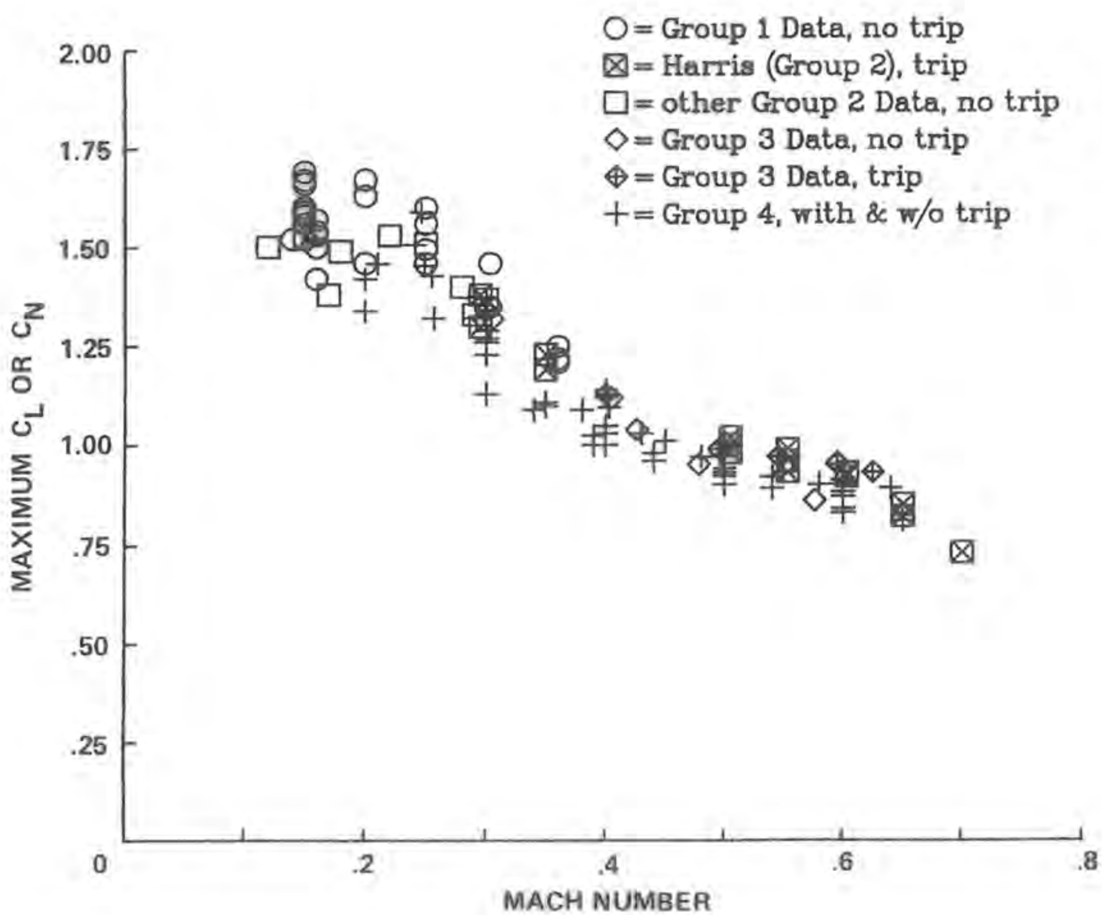


McCroskey's Study of NACA 0012 Data
Reynolds number effects



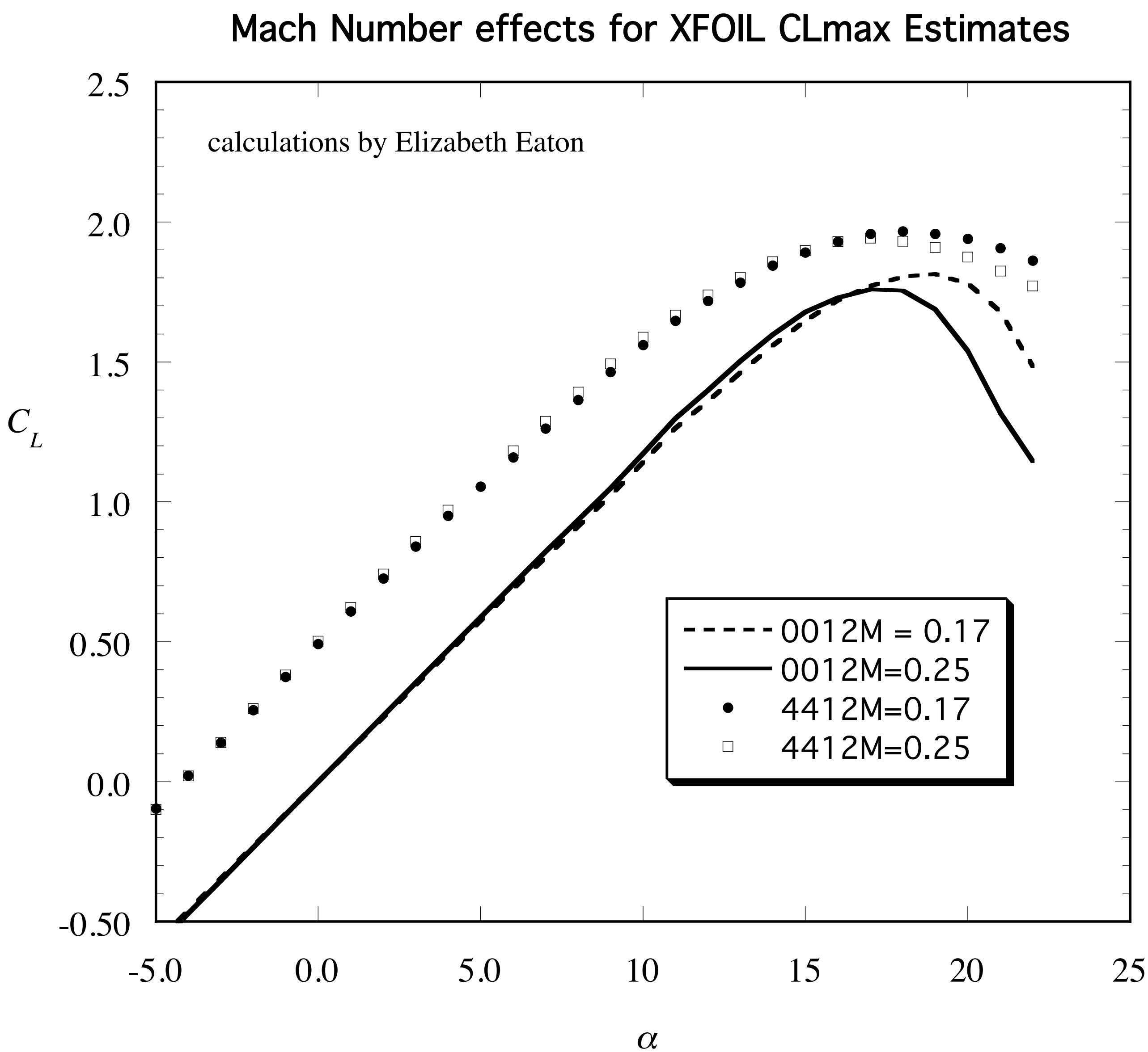
W.J. McCroskey, "A Critical Assessment of Wind Tunnel Results for the NACA 0012 Airfoil" NASA TM-100019, October, 1987

McCroskey's Study of NACA 0012 Data
Mach number effects



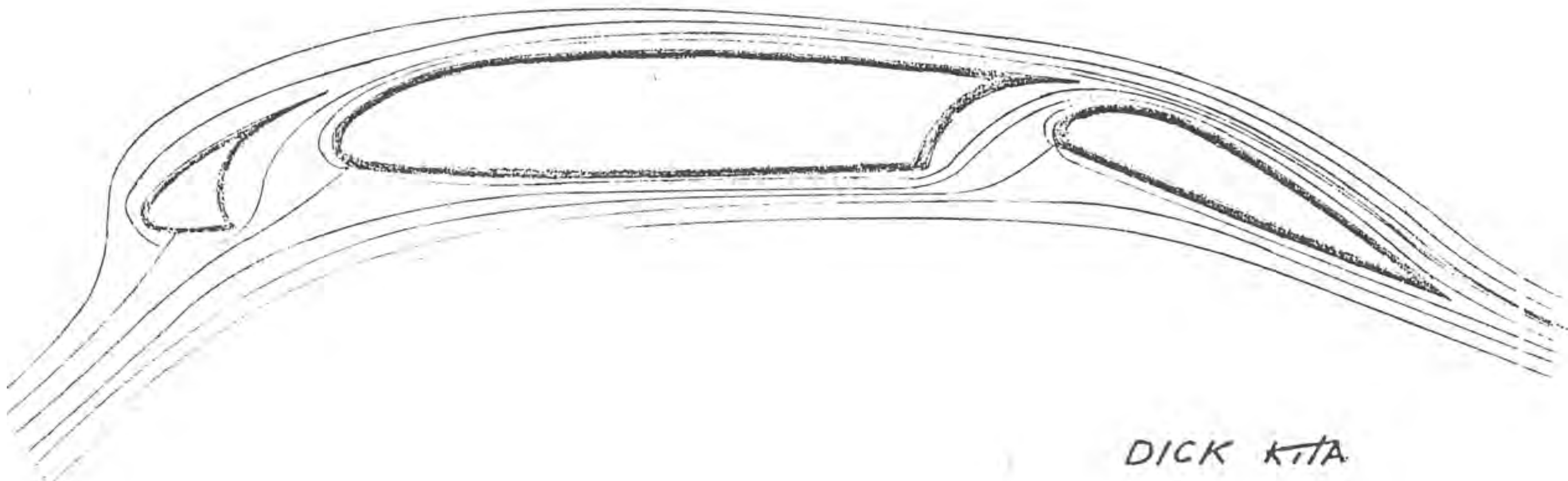
W.J. McCroskey, "A Critical Assessment of Wind Tunnel Results for the NACA 0012 Airfoil"
NASA TM-100019, October, 1987

XFOIL Predictions - Mach Effects



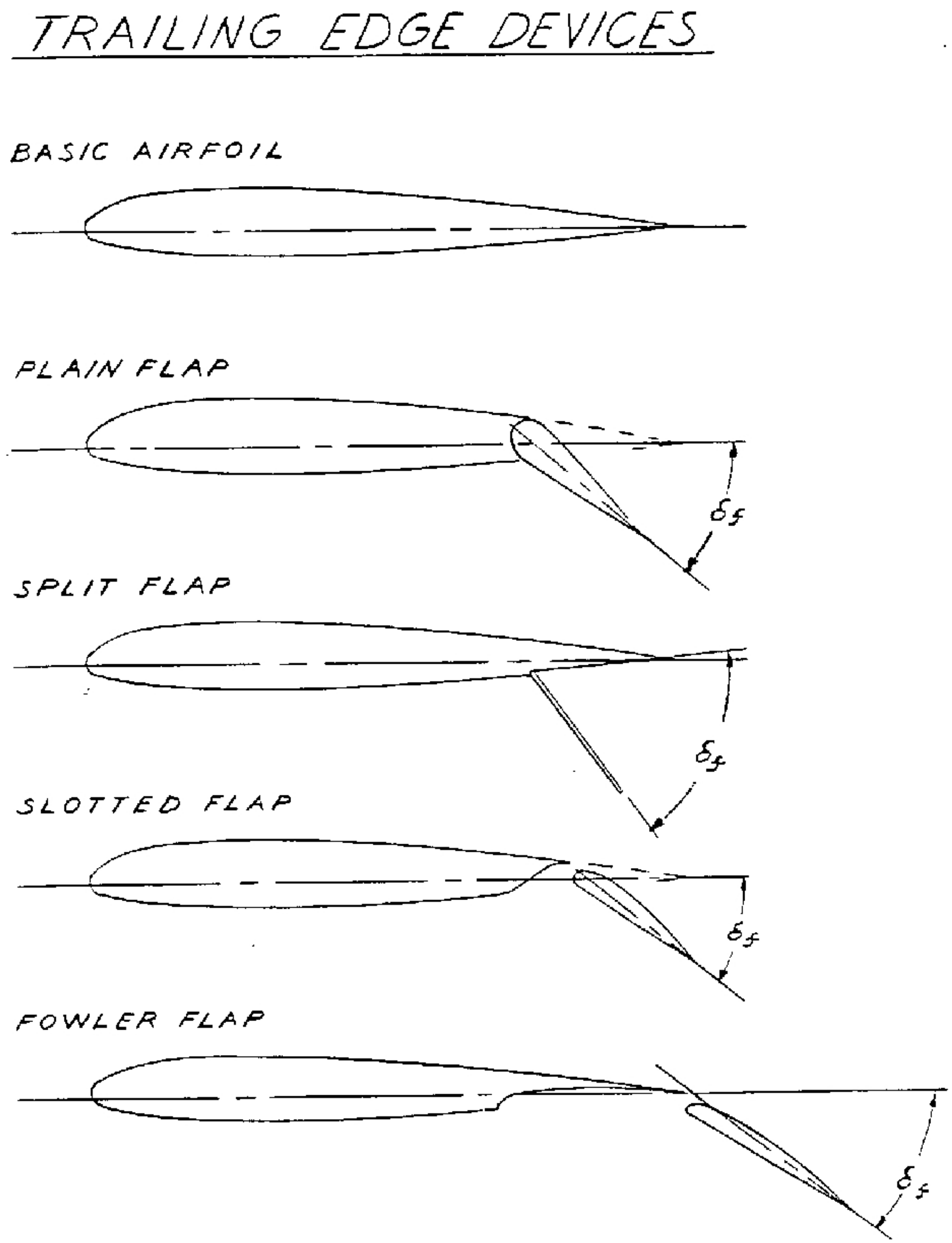
Part 1: Mainly Dick Kita's Charts

MECHANICAL
HIGH LIFT
SYSTEMS



DICK KITA
FEB. 1985

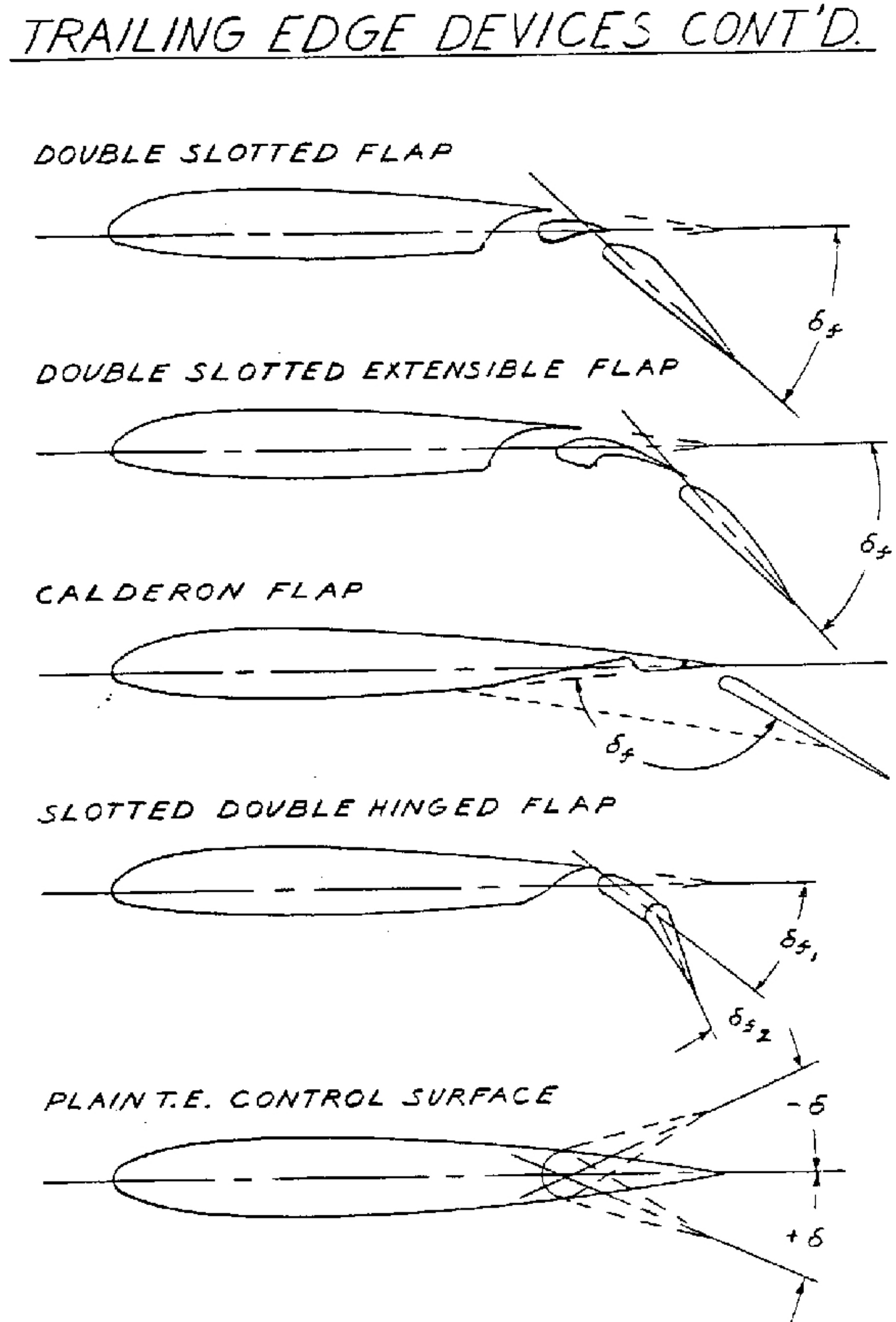
Some Trailing Edge Devices



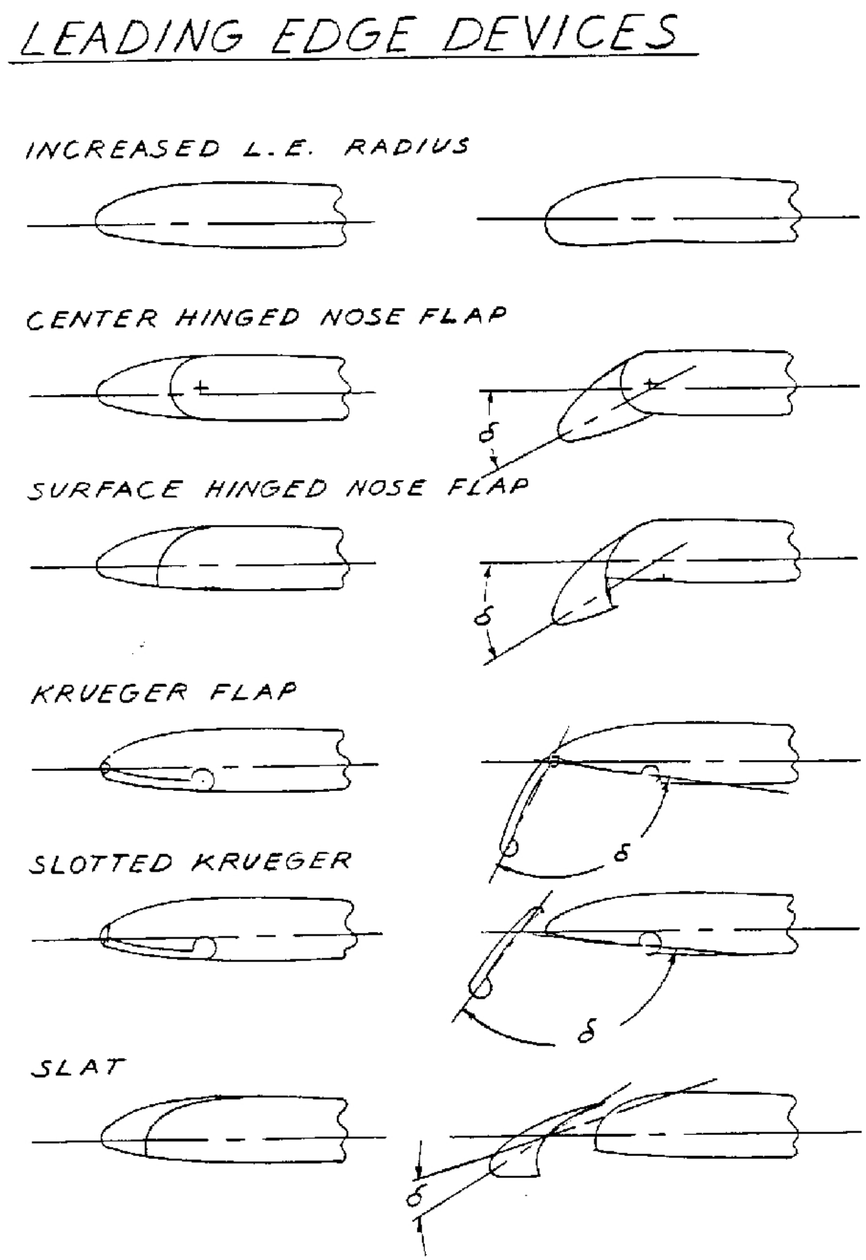
Split Flap

Fleet Aircraft Ltd. Of Canada PT-26 Cornell (Fairchild PT-26) At the Pima Air Museum, out side Tucson, AZ

More Trailing Edge Devices



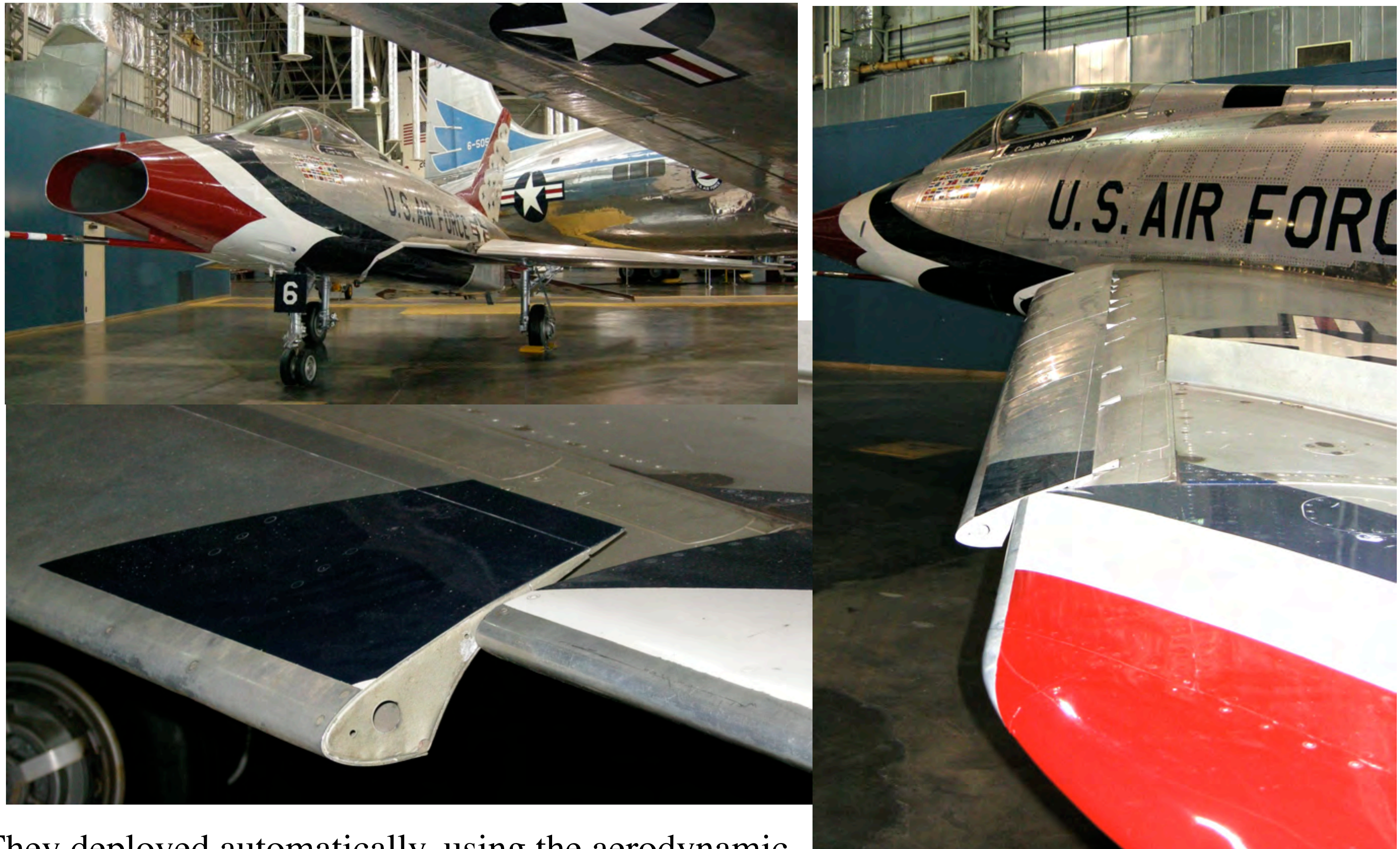
Leading Edge Devices



The Handley Page Fixed Slot

For slow airplanes, a fixed slot is often used. It's always in this position. This is a picture of a Grumman S-2A Tracker at the Pima Air Museum, out side Tucson, AZ

Passive slats” for military fighter/attack aircraft



They deployed automatically, using the aerodynamic suction – eventually abandoned in favor of hydraulics. In use they hung up – one side deploying, one not!

North American Aviation F-100, at the US Air Force Museum, Dayton, OH

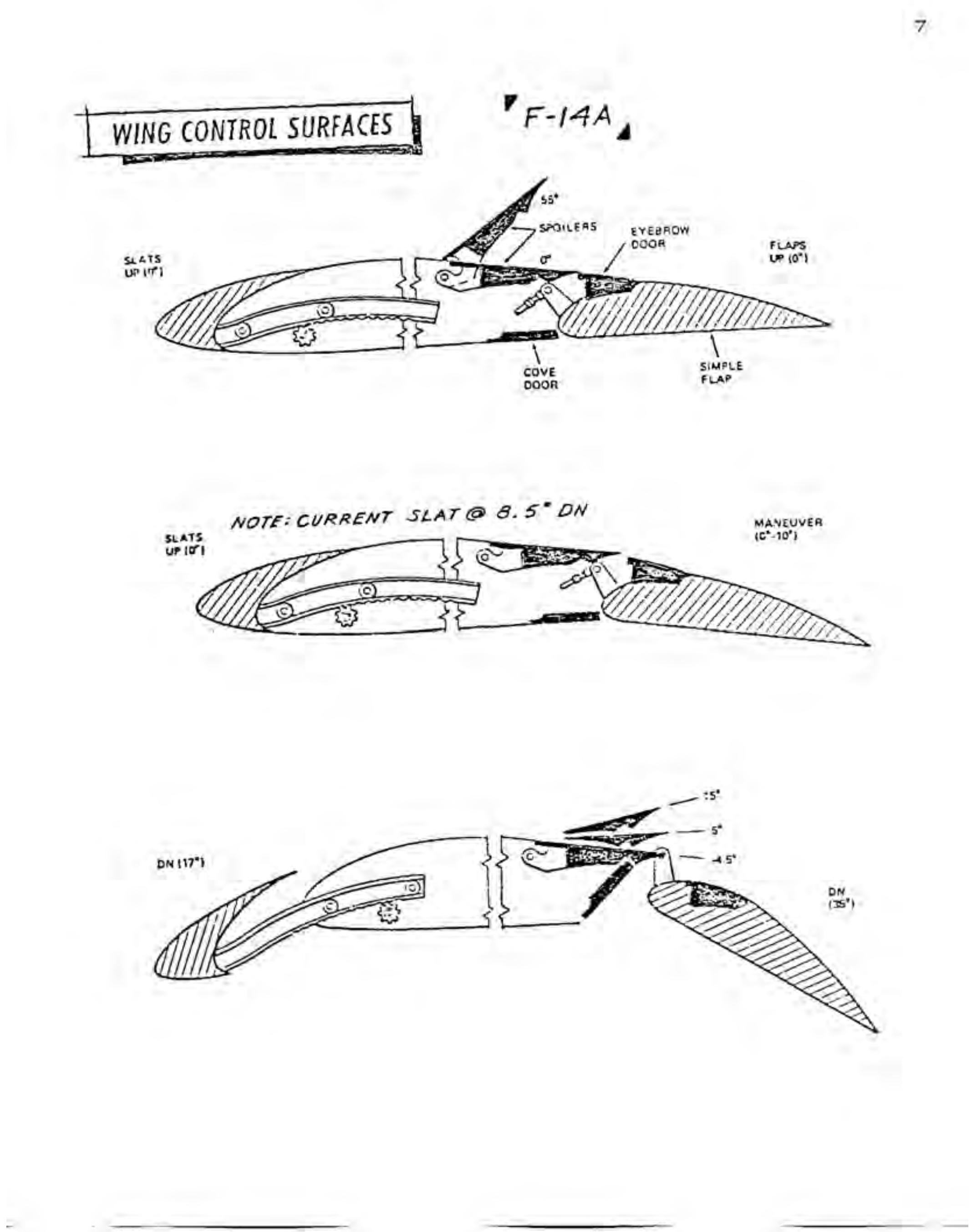
F-4 Maneuver Slat

Fixed position slat seen in the San Diego Aerospace Museum in Balboa Park.

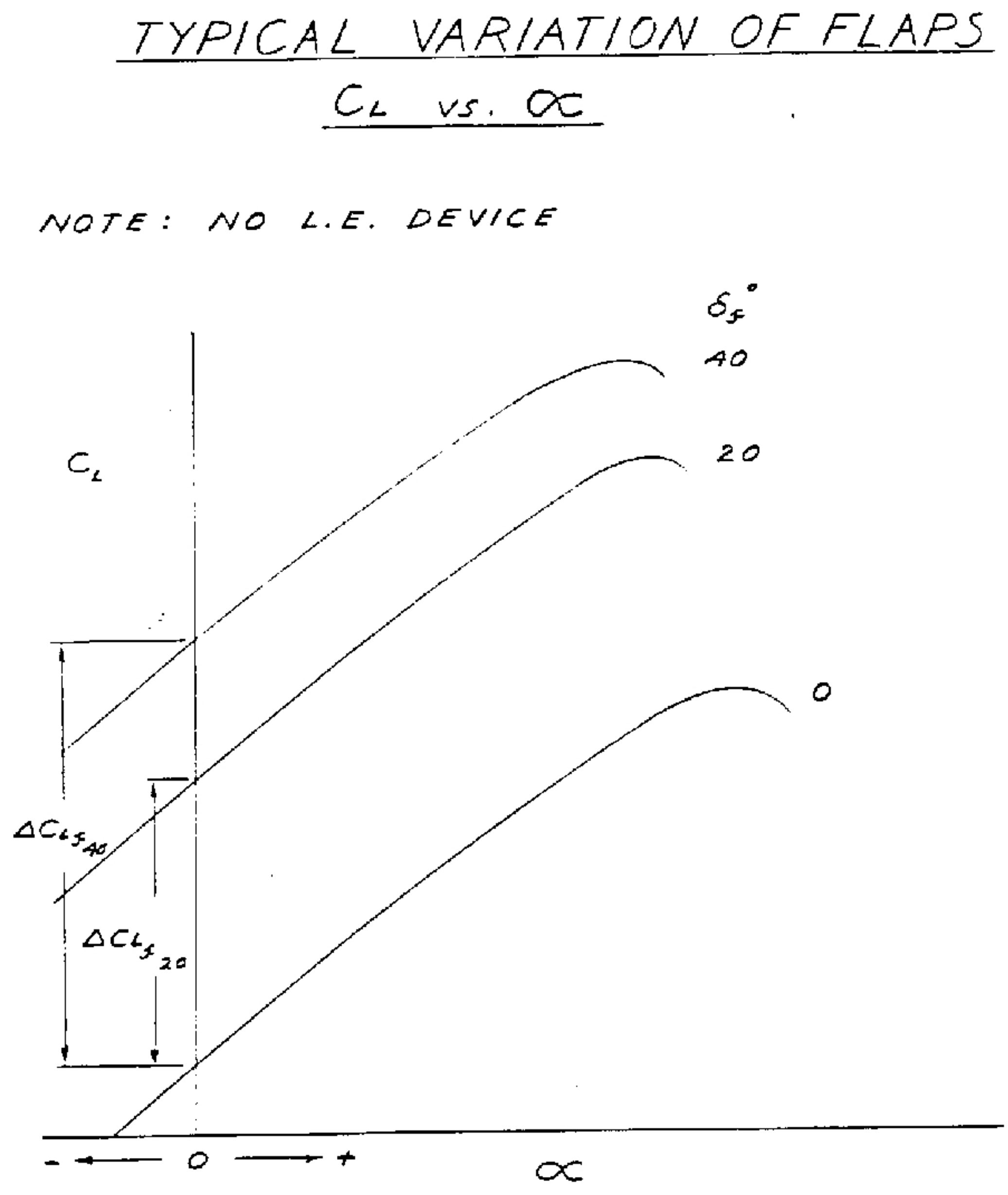
Note fixed slat on horizontal stabilator,
Picture from the Pima Air Museum

F-14 High Lift System

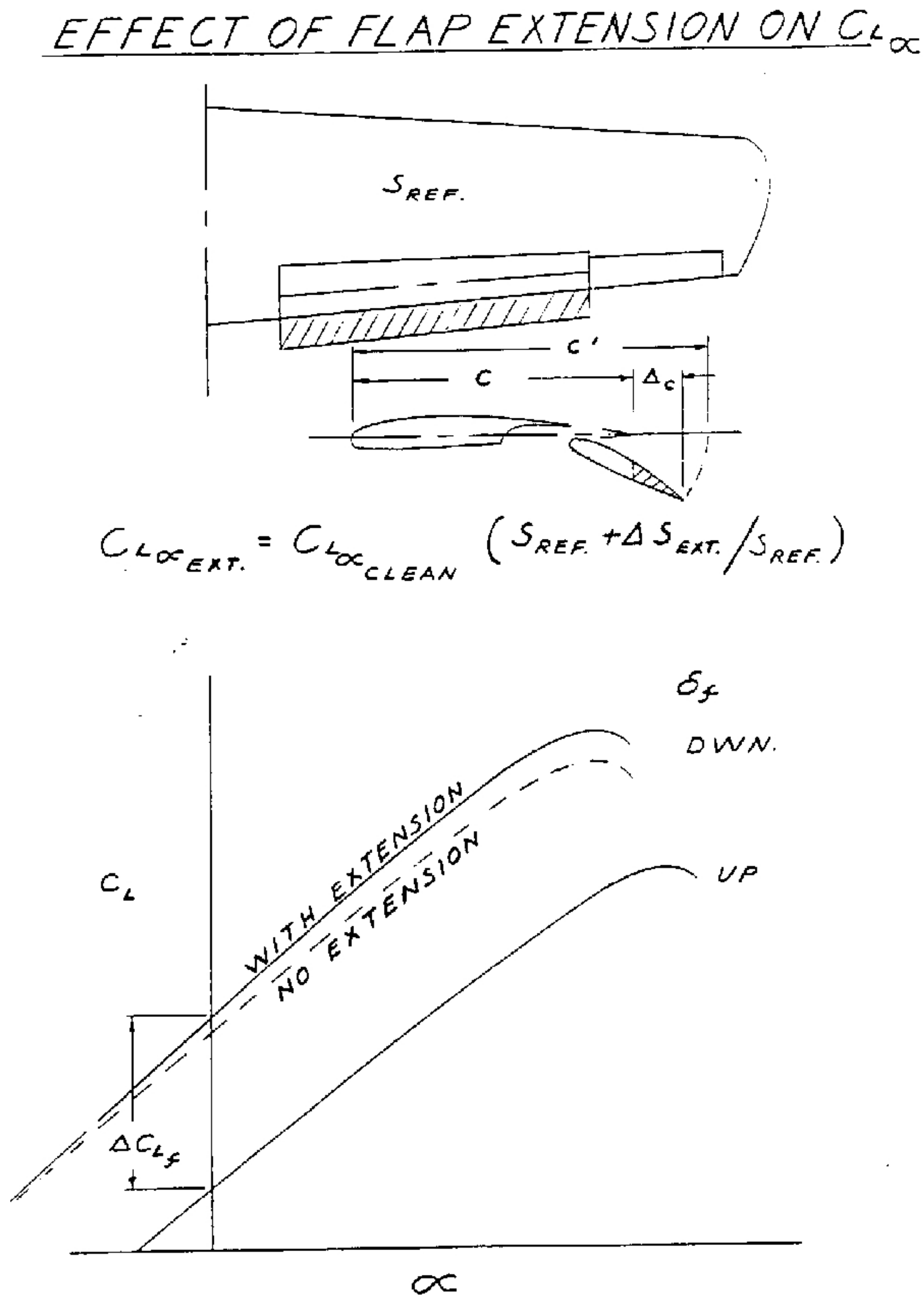
(remember Irv Waaland?)



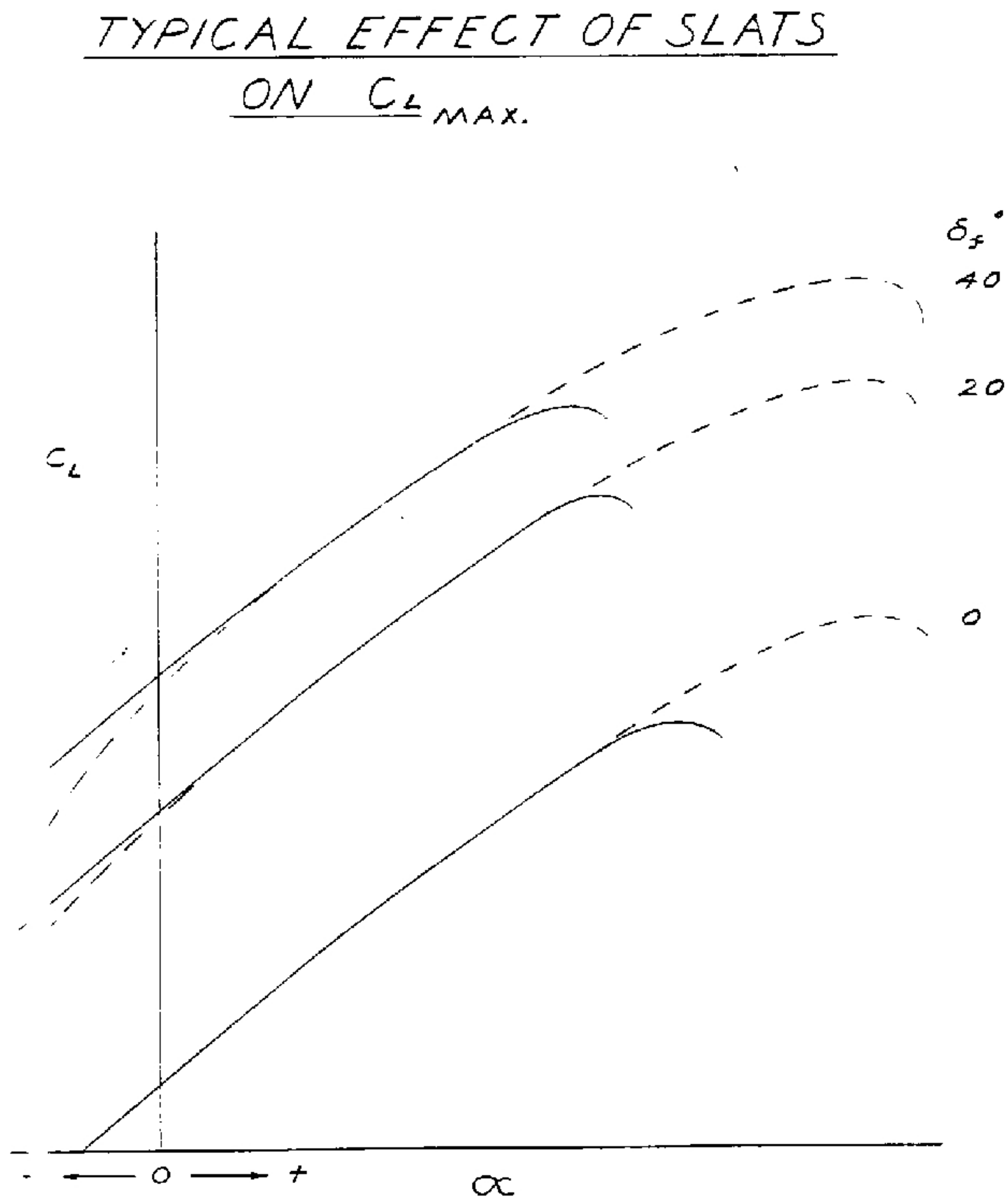
Trailing Edge Flap Effects



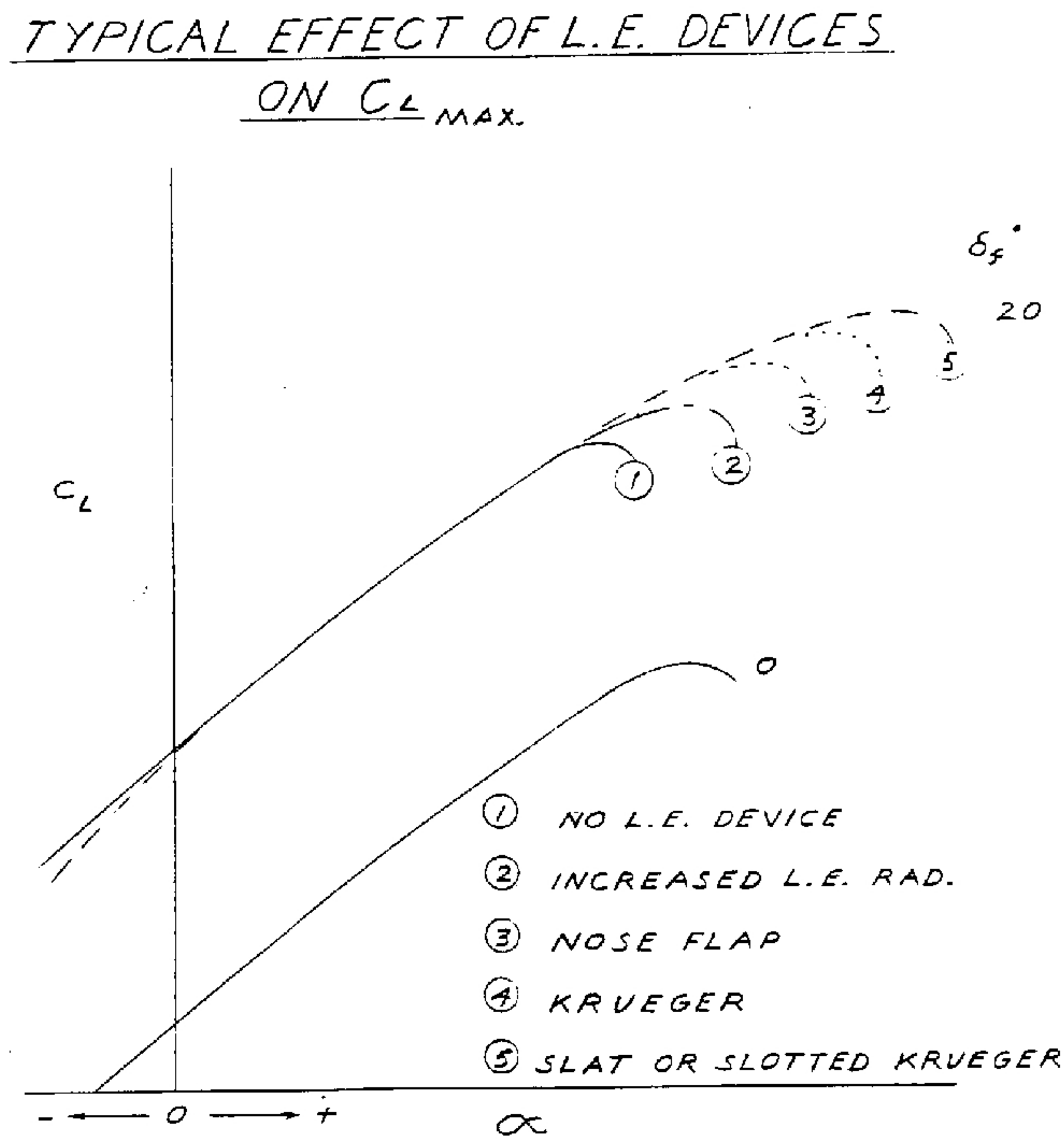
Flap Extension Effect



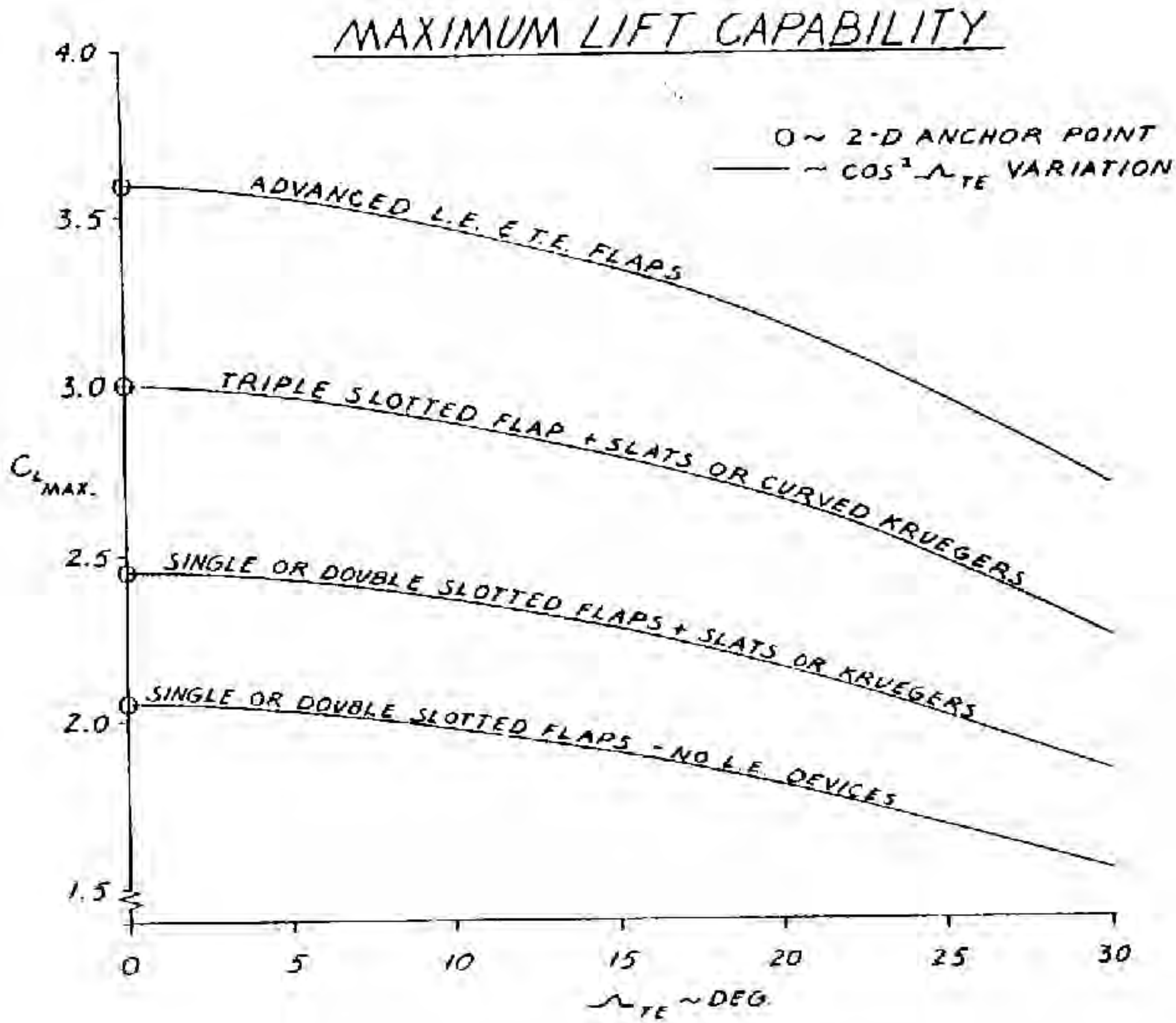
Effect of Slats



Different LE Devices

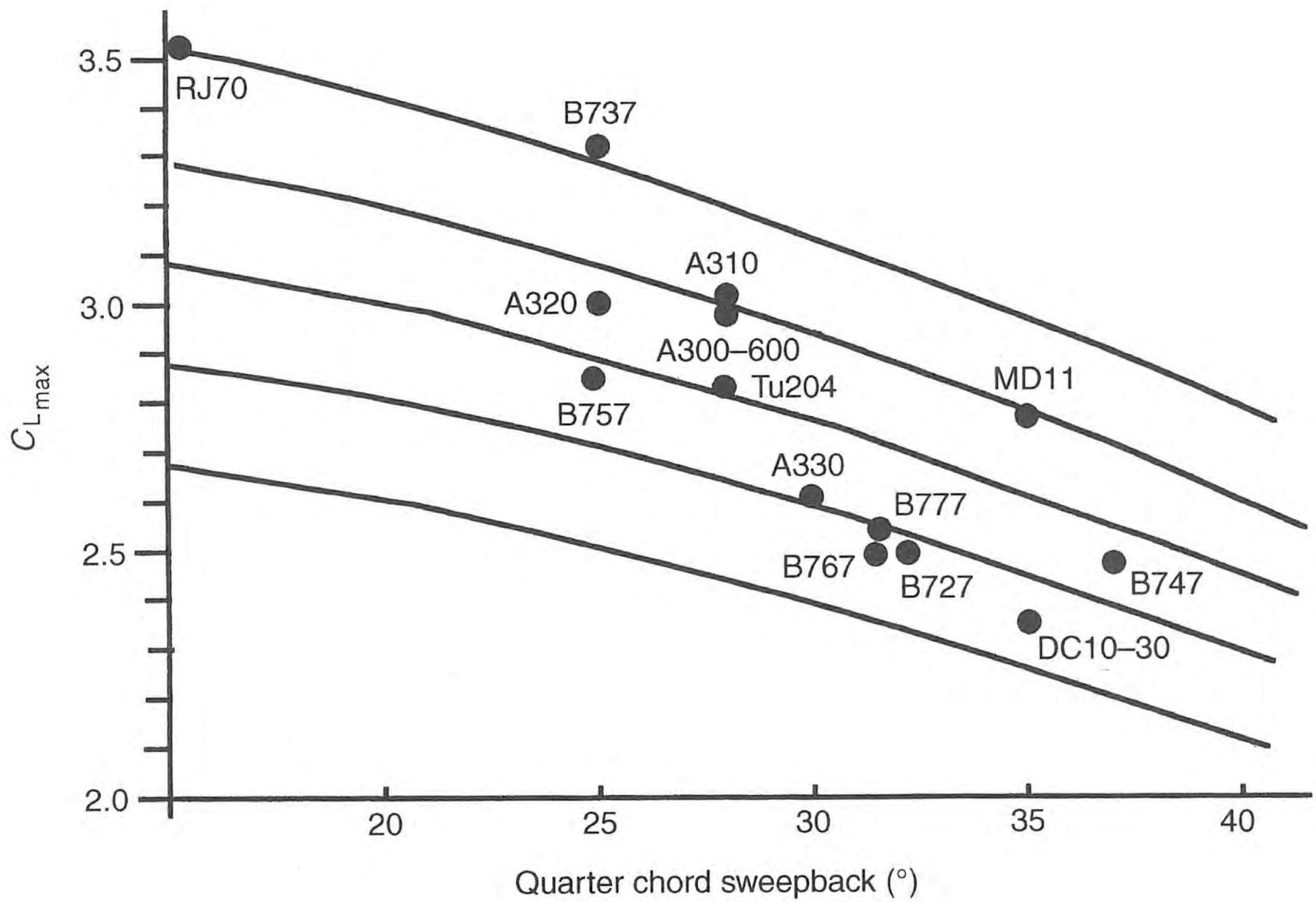


Kita's C_{Lmax} Projections



"Advanced" may be unobtainium

Jenkinson/Simpkins Estimates

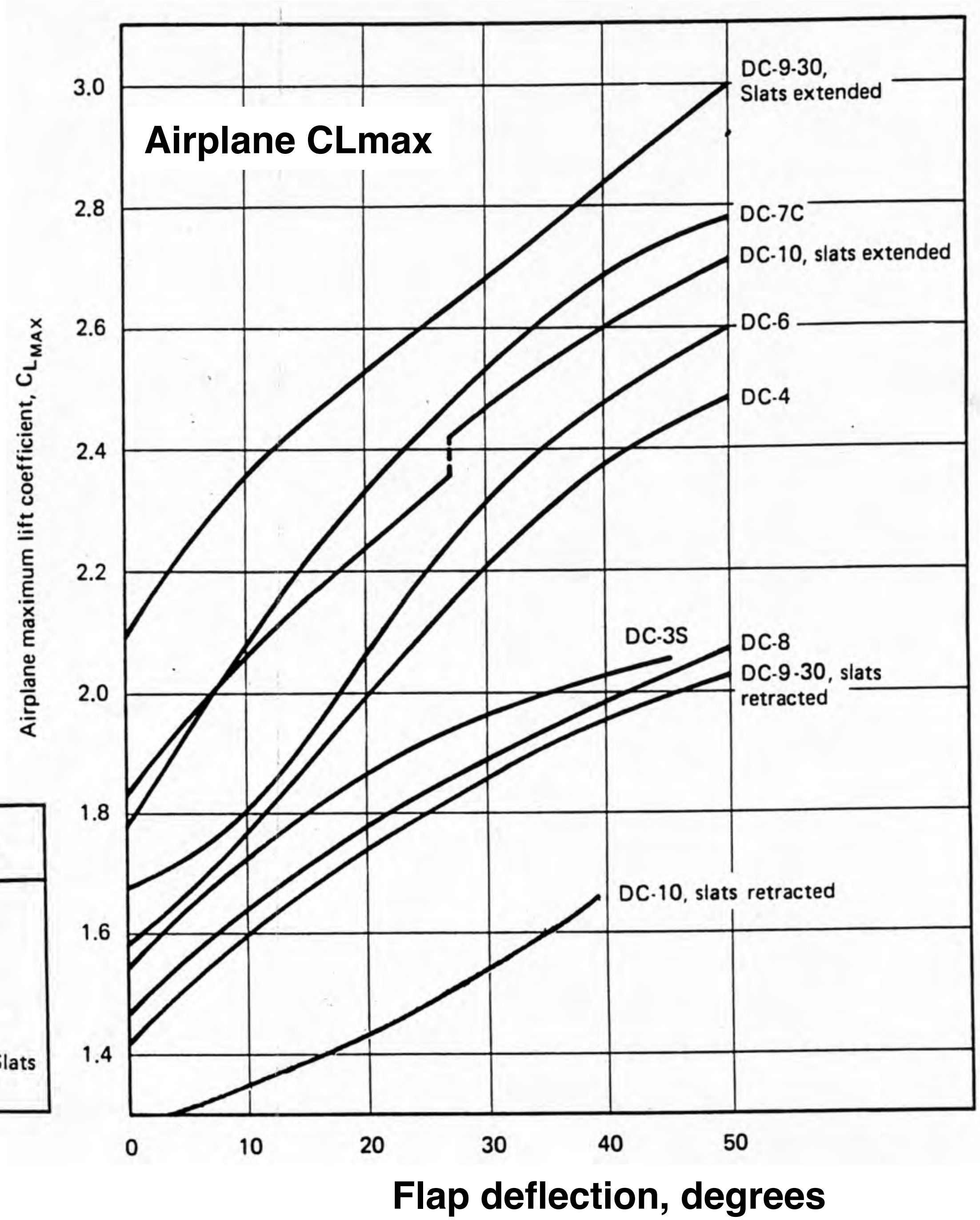


From *Civil Jet Aircraft Design*, by Lloyd Jenkinson, Paul Simpkin and Darren Rhodes

Shevell's C_{Lmax} Chart

Richard S. Shevell,
Fundamentals of Flight,
2nd Ed., Prentice-Hall, 1988

	$\frac{S_{W_F}}{S_W}$	Type of flap	Flap chord (% chord)	$\Lambda_{C/4}$
DC-3S	0.575	Split	0.174	~ 10°
DC-4	0.560	Single slotted	0.257	0°
DC-6	0.589	Double slotted	0.266	0°
DC-7C	0.630	Double slotted	0.266	0°
DC-8	0.587	Double slotted	0.288	30.5°
DC-9-30	0.590	Double slotted	0.360	25° } Slats
DC-10-10	0.542	Double slotted	0.320	35° } Slats



Clark Y High Lift "Build Up"

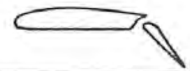
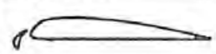
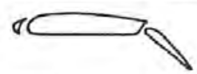
Designation	Diagram	$C_{L_{max}}$	α at $C_{L_{max}}$ (degrees)	L/D at $C_{L_{max}}$	$C_{m_{ac}}$	Reference NACA
Basic airfoil Clark Y		1.29	15	7.5	−.085	TN 459
.30*c* Plain flap deflected 45°		1.95	12	4.0	—	TR 427
.30*c* Slotted flap deflected 45°		1.98	12	4.0	—	TR 427
.30*c* Split flap deflected 45°		2.16	14	4.3	−.250	TN 422
.30*c* hinged at .80*c* Split flap (Zap) deflected 45°		2.26	13	4.43	−.300	TN 422
.30*c* hinged at .90*c* Split flap (Zap) deflected 45°		2.32	12.5	4.45	−.385	TN 422
.30*c* Fowler flap deflected 40°		2.82	13	4.55	−.660	TR 534
.40*c* Fowler flap deflected 40°		3.09	14	4.1	−.860	TR 534
Fixed slot		1.77	24	5.35	—	TR 427
Handley Page automatic slot		1.84	28	4.1	—	TN 459
Fixed slot and .30*c* plain flap deflected 45°		2.18	19	3.7	—	TR 427
Fixed slot and .30*c* slotted flap deflected 45°		2.26	18	3.77	—	TR 427
Handley Page slot and .40*c* Fowler flap deflected 40°		3.36	16	3.7	−.740	TN 459

Chart from Perkins and Hage, page 80.

Boeing Transports

Henne Ed.

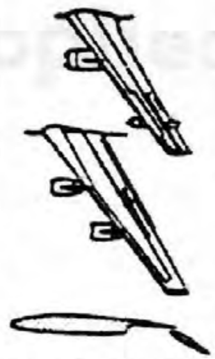
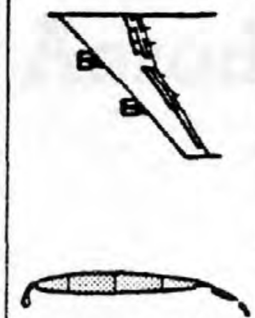
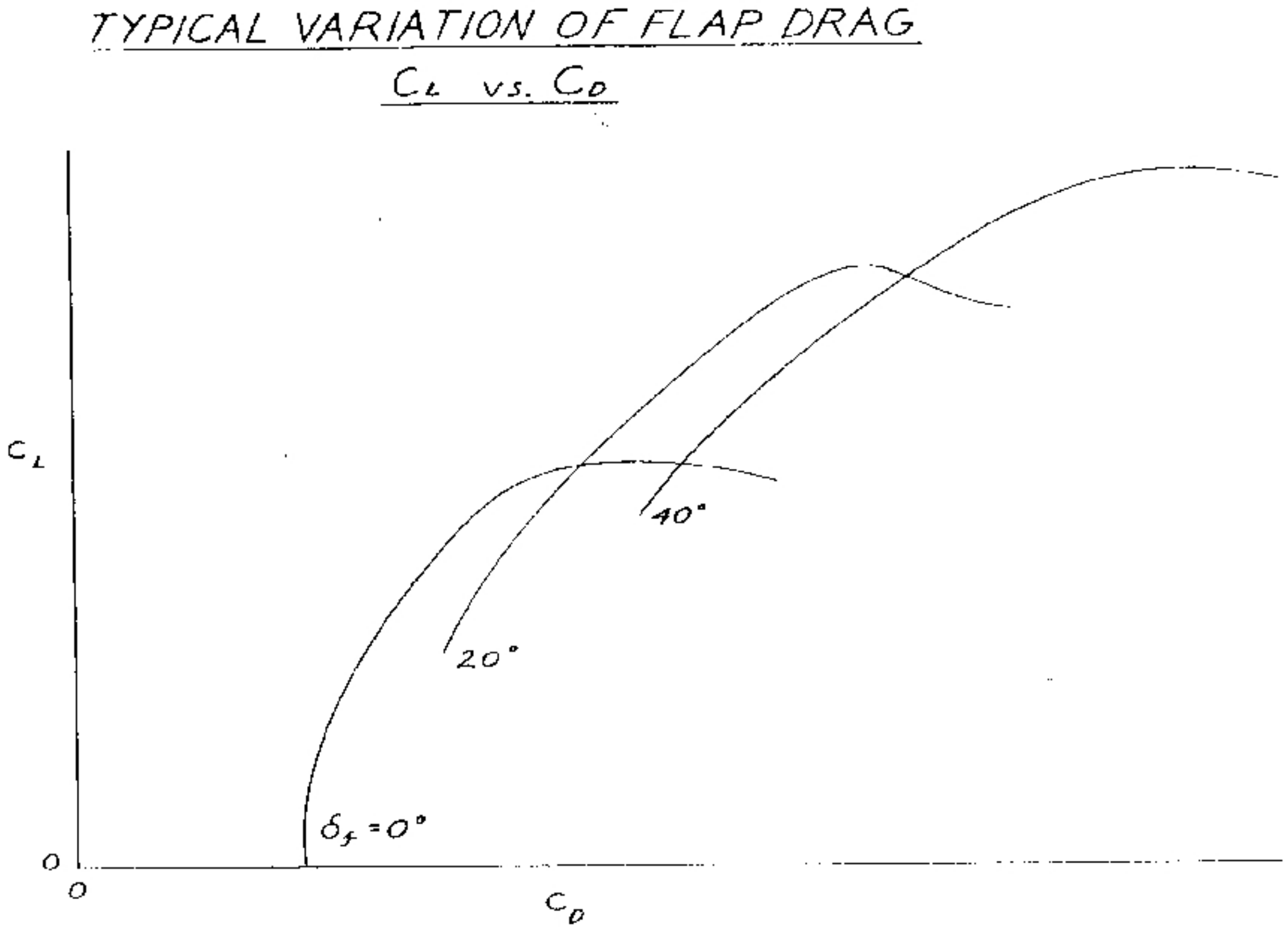
Type	B-47/B-52	367-80/ KC-135	707-320/ E-3A	727	747/E-4A	767
First flight	1947/1952	1954	1962	1963	1969	1981
Planform / Typical airfoil						
	Single-slotted fowler flap	Double-slotted flap	Double slotted flap and Krueger leading edge	Slat and triple-slotted flap	Variable camber Krueger and triple-slotted flap	Slat and single-slotted flap
$C_{L_{max}}$	1.8	1.78	2.2	2.79	2.45	2.45

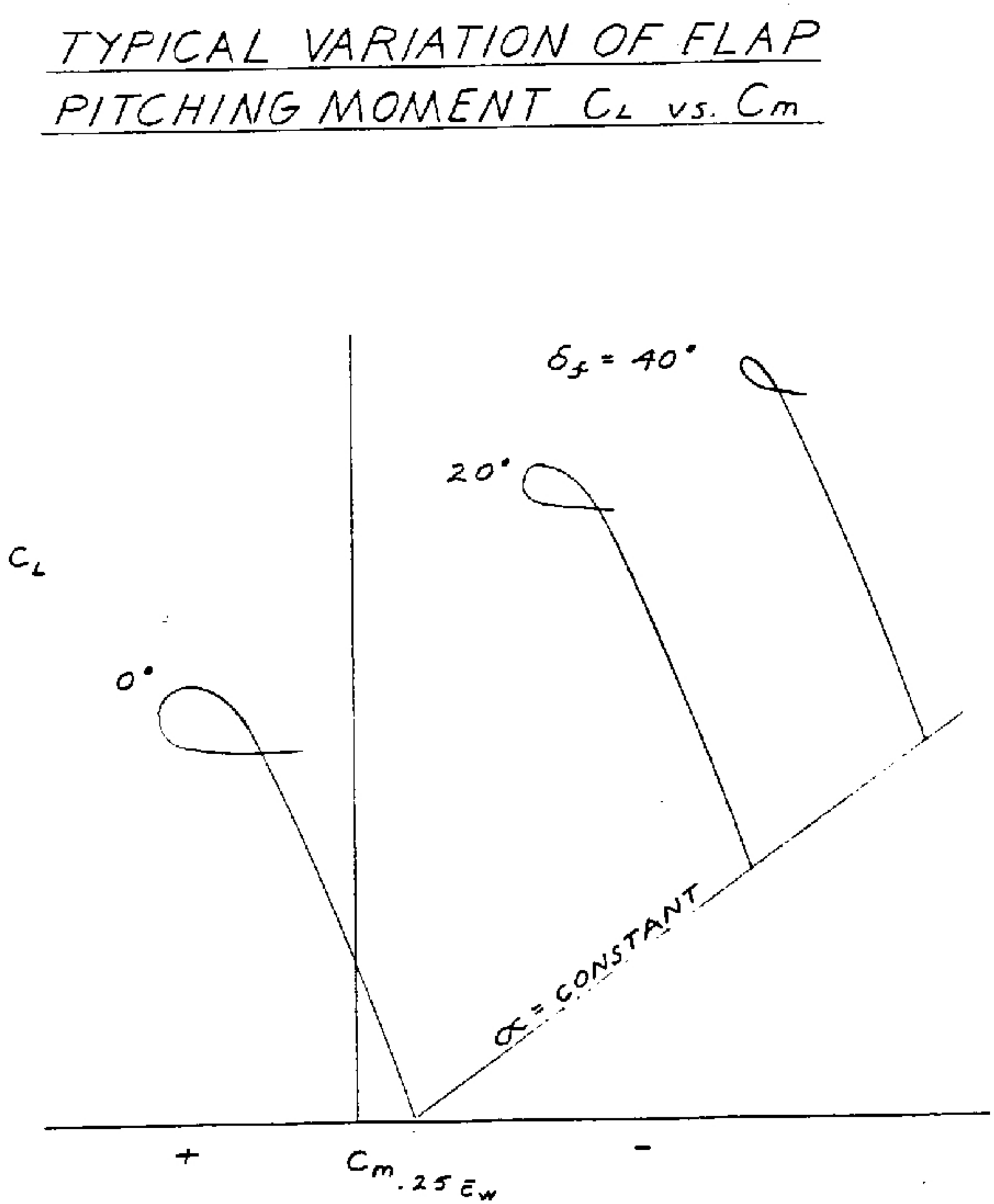
Fig. 1 Trends in Boeing transport high-lift system development.

From *Applied Computational Aerodynamics*, AIAA Progress in Aeronautics Series, edited by Preston Henne

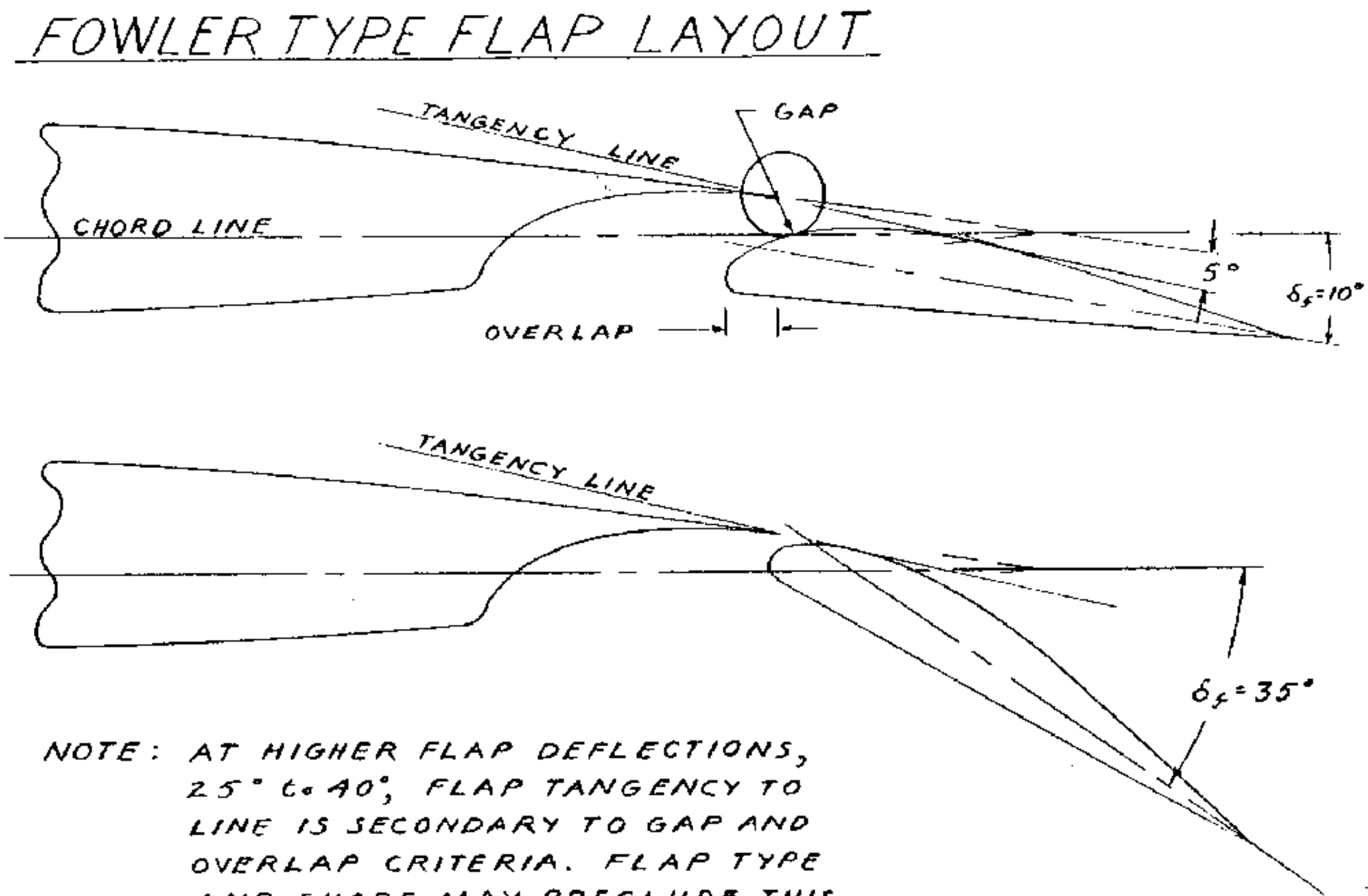
Device Effects on Drag



Device Effect on Pitching Moment



Critical Parameters for High Lift System Development – Gap and Overlap



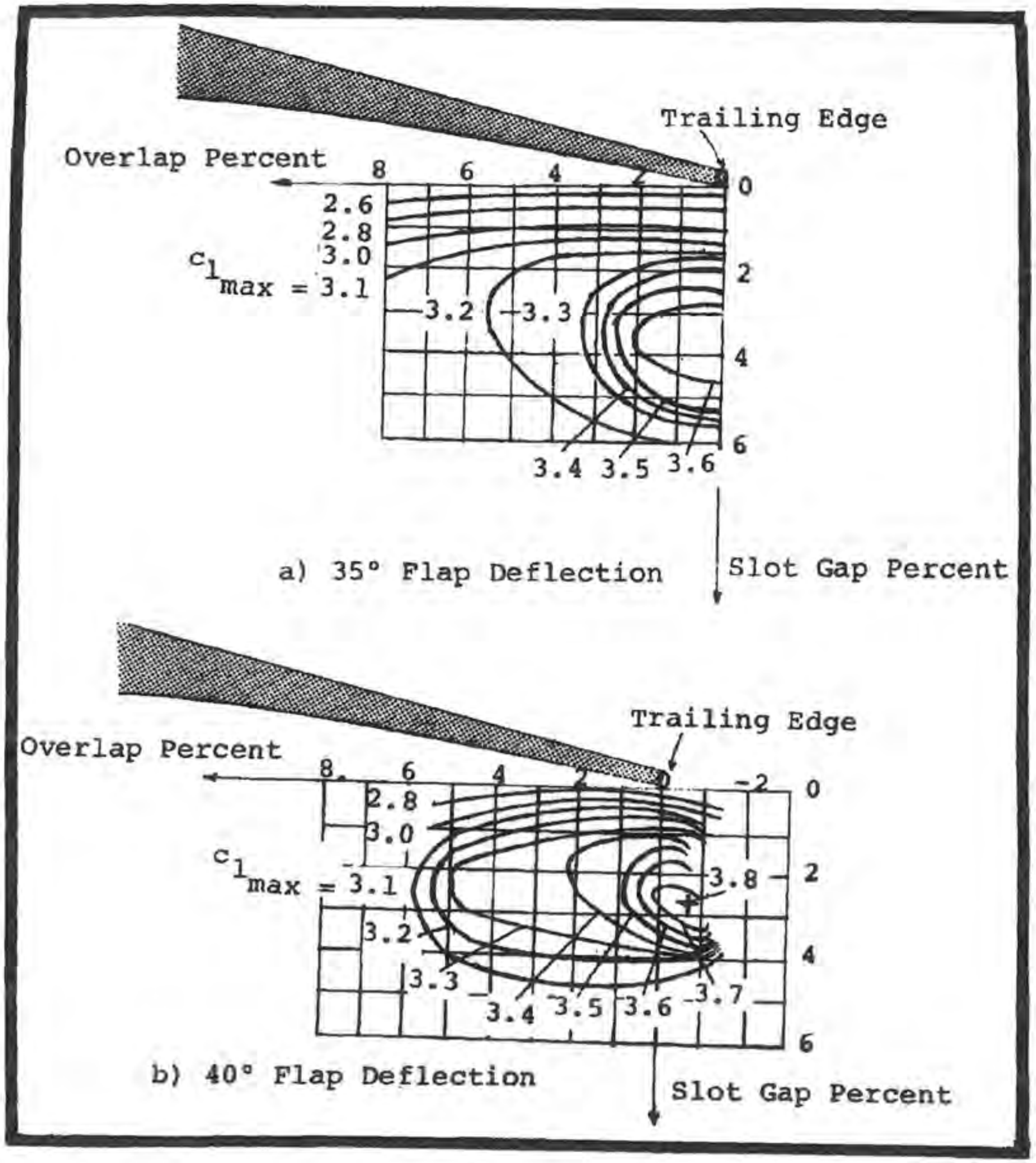
NOTE: AT HIGHER FLAP DEFLECTIONS, 25° to 40°, FLAP TANGENCY TO LINE IS SECONDARY TO GAP AND OVERLAP CRITERIA. FLAP TYPE AND SHAPE MAY PRECLUDE THIS OCCURANCE.

Effect of Gap and Overlap

Bill Wentz, "Development of a Fowler Flap System for a High Performance General Aviation Airfoil," NASA CR-2443, Dec. 1974 (pdf file available)

This is for a GAW(1) airfoil

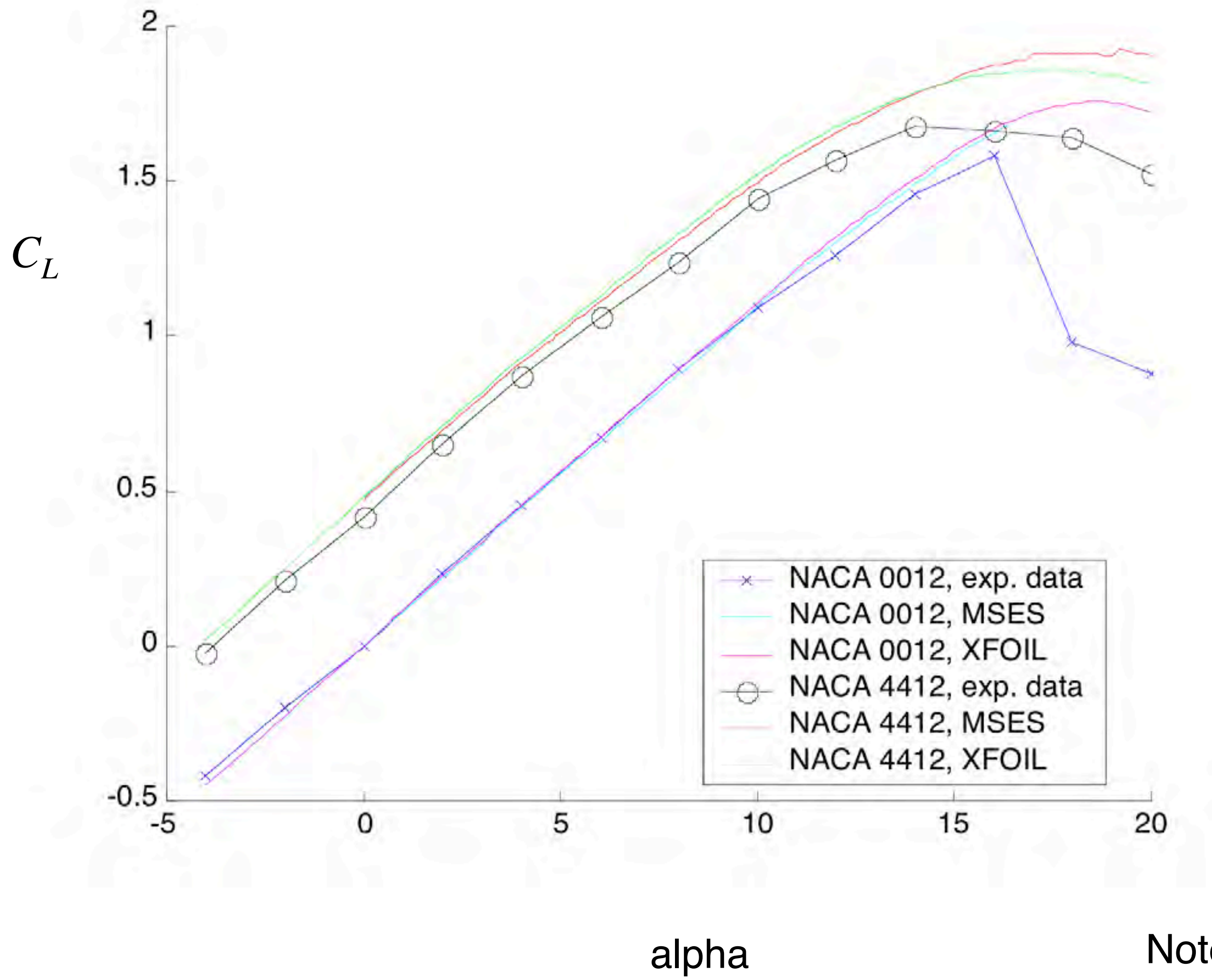
Note that the maximum lift is very sensitive to the high-lift element placement, thus emphasizing the importance of accurately maintaining the correct rigging in operation and maintenance.



A-380 Trailing Edge Flap System

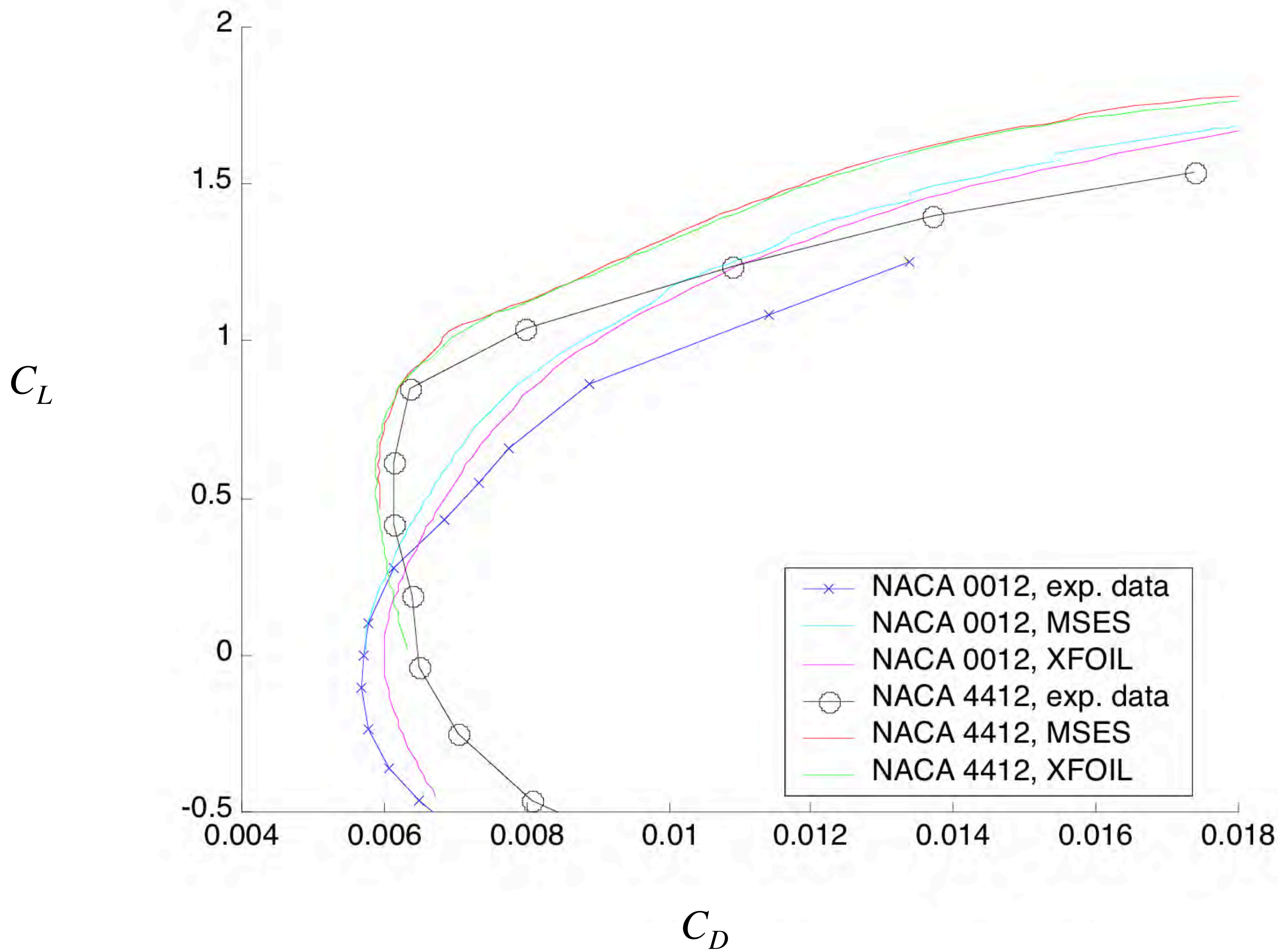
A photo taken during the March 2007 tour of US airports, unknown photographer

Andy Parker's XFOIL results: Lift

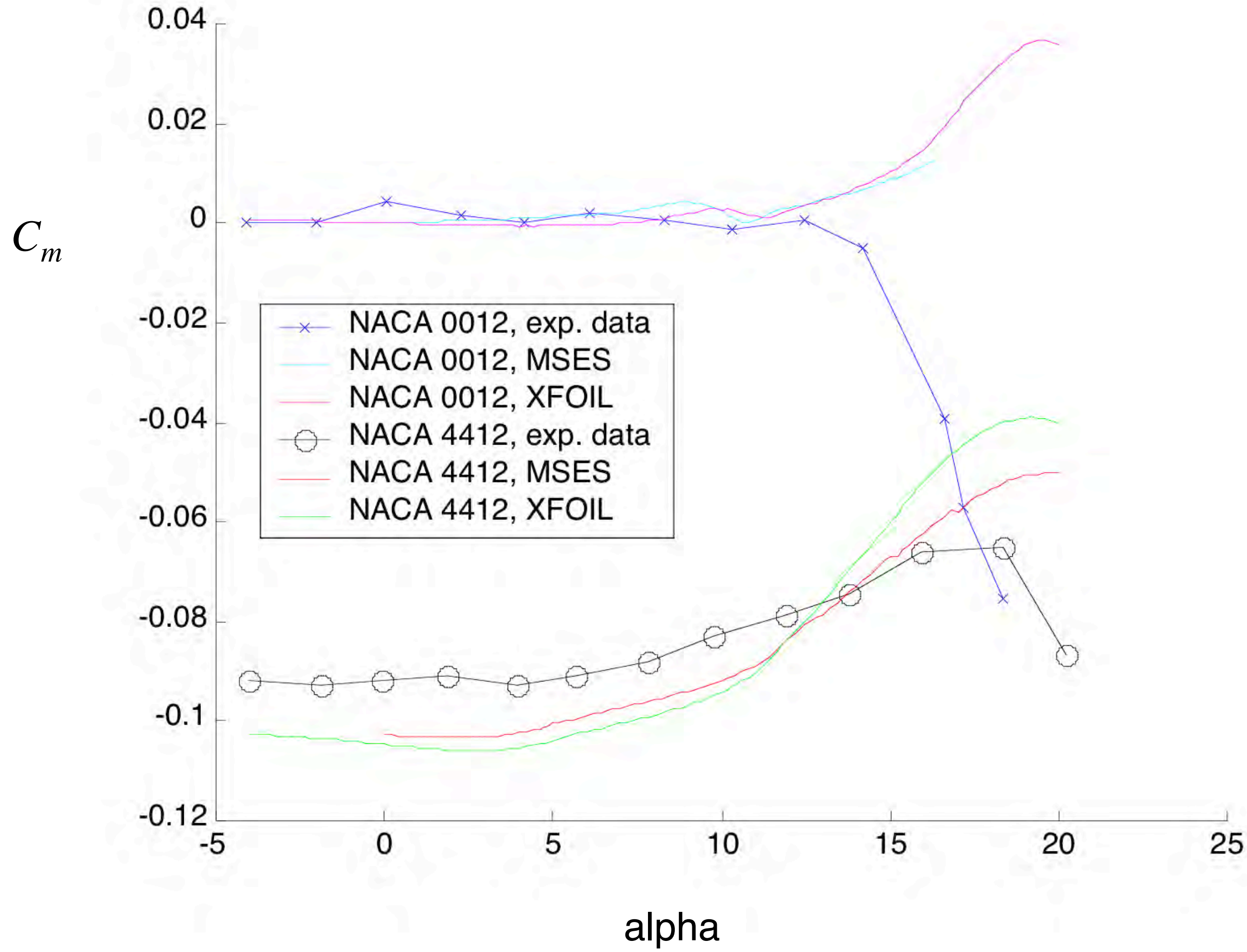


Note: Andy Parker did this as a freshman

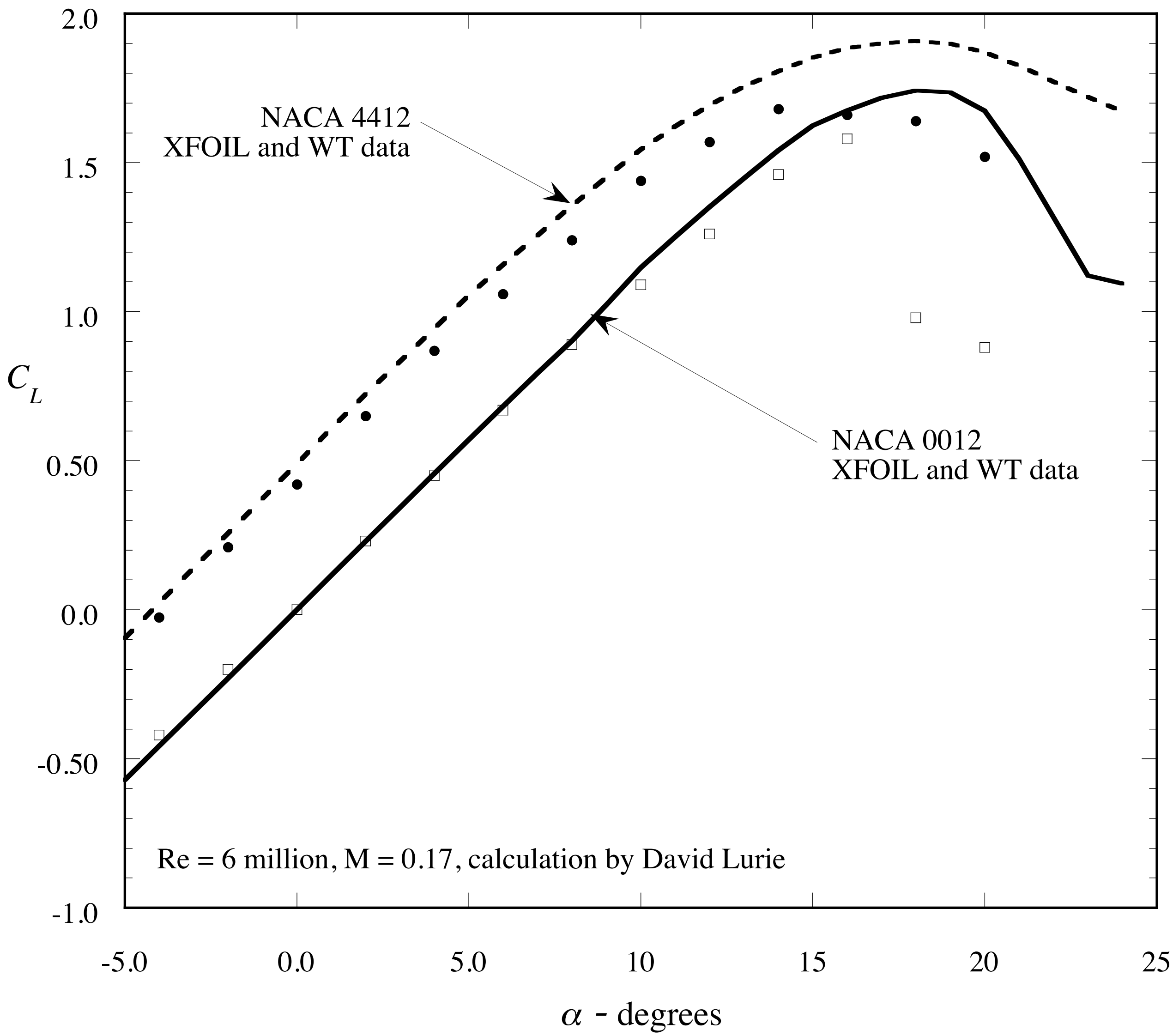
Andy Parker's XFOIL Results: Drag



Andy Parker's XFOIL results: pitching moment



XFOIL - comparison with data: David Lurie



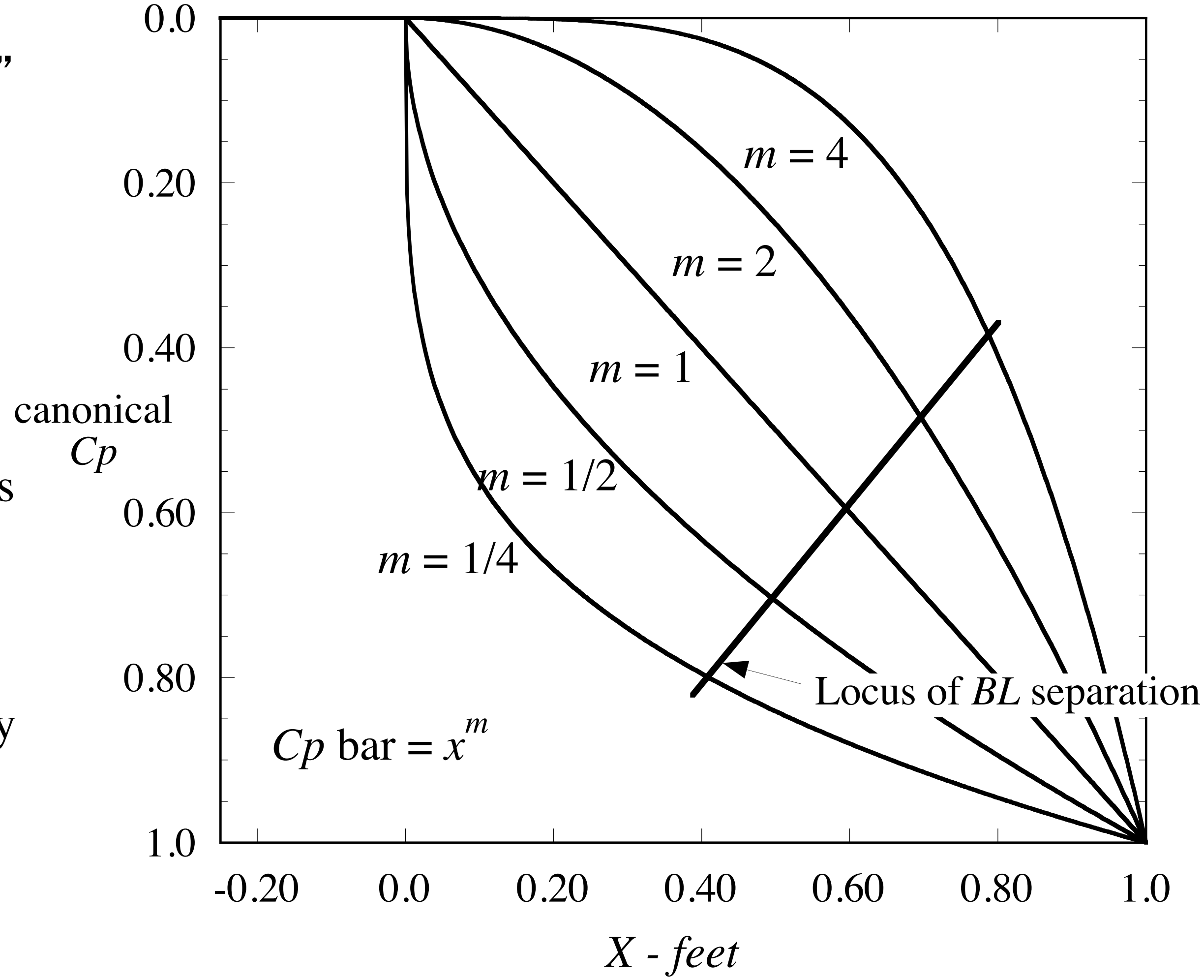
Physics of High Lift: AMO Smith's Classic Paper

- He "wrote the book" with his Wright Brothers Lecture
  - ***It is assumed that every configuration aerodynamicist has read this paper.***
- He showed how to get the boundary layer to carry the maximum "load" (lift)
- Example: Liebeck's Maximum Lift Single Element Airfoil
- The five effects for multielement airfoils
  - The Slat effect
  - The Circulation effect
  - The Dumping effect
  - The Off-the-surface pressure recovery effect
  - The Fresh boundary layer effect
- Etc. (mainly meaning blowing and or sucking)

How to most effectively apply load to the BL

- AMO used a "Canonical" *Cp* to be able to equate different cases, where 0 represents the start of the pressure rise, and 1 means the max possible *Cp*, $u_e = 0$.
- He studied various shapes of pressure recoveries
- Concave pressure distributions allowed the greatest pressure recovery
- Stratford provided the best shape.

Power law pressure distributions studied



The “best” pressure distribution for recovery

Stratford: The pressure distribution that puts the *bl* everywhere on the verge of separation

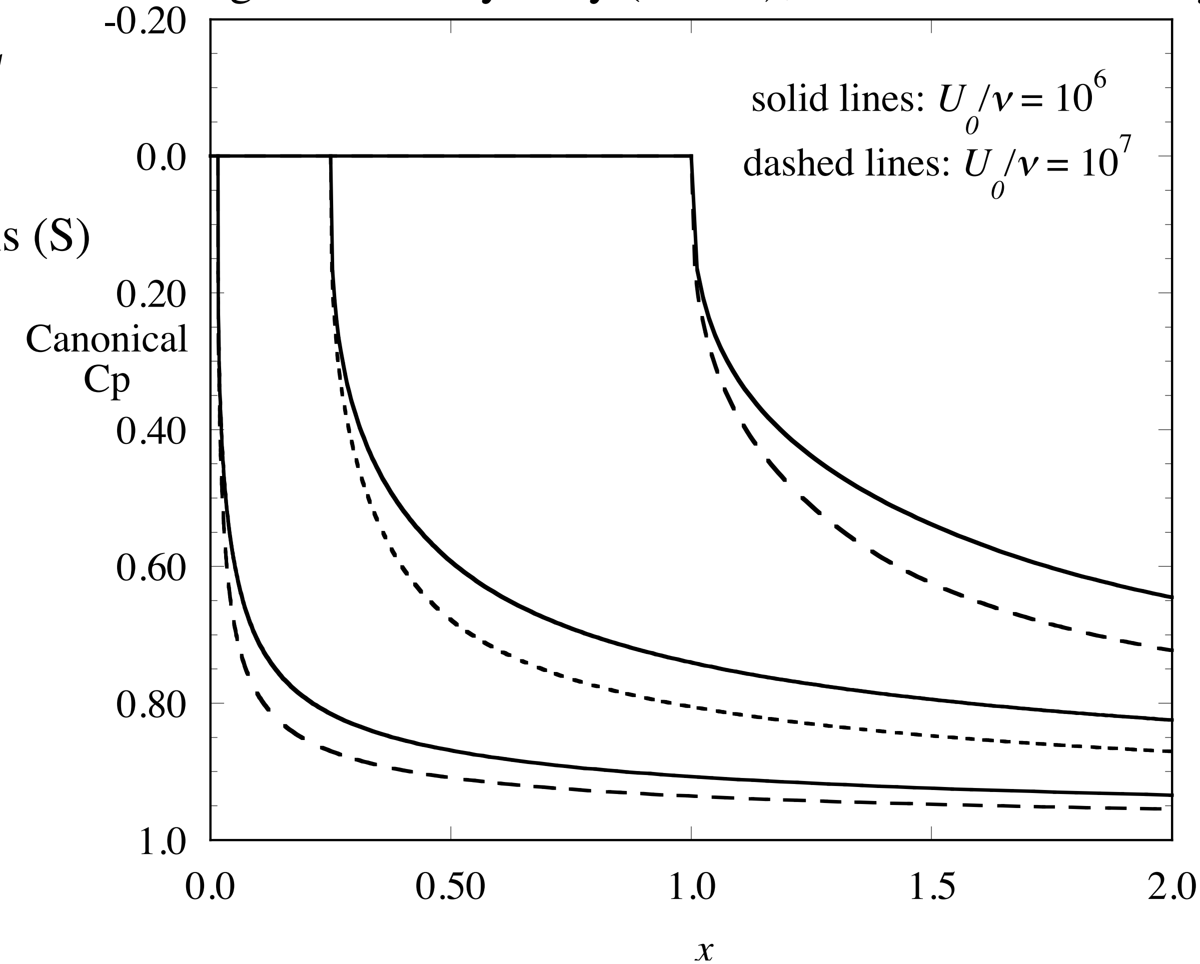
$$\frac{\bar{C}_p \sqrt{x\left(d\bar{C}_p / dx\right)}}{\left(10^{-6} R_e\right)^{1/10}} = S$$

See AMO’s paper for details (S)

Messages

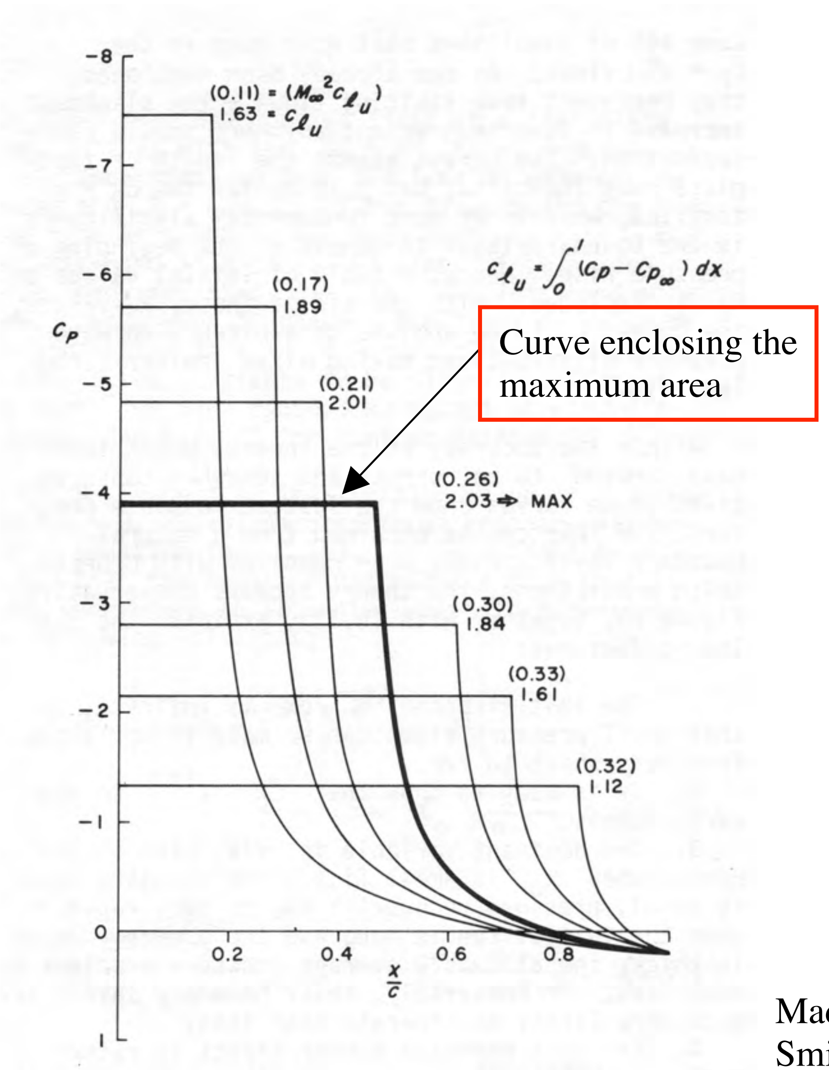
- thin *bl*’s can withstand extreme pressure gradients
- as the *bl* thickens, the gradient must be relaxed
- conversely, thick *bl*’s separate more easily
- you can recover to near zero edge velocity if done right, but it takes a very long distance

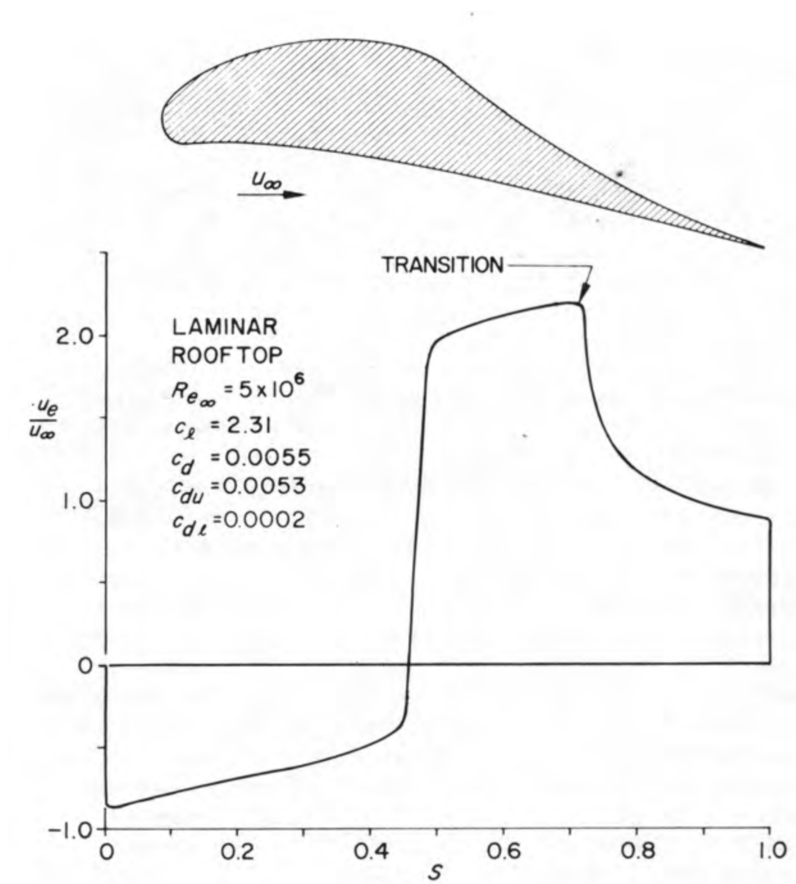
Starting the recovery early (thin *bl*), allows more recovery



Liebeck's High Lift Single Element Airfoil

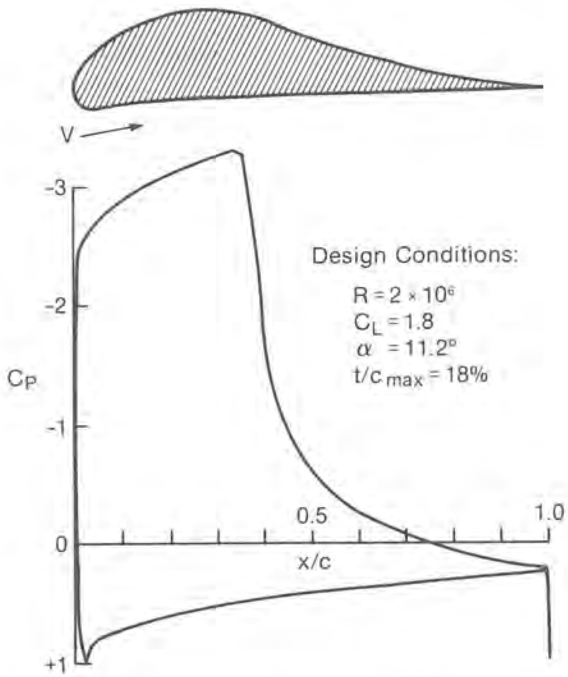
- Knowing the shape of the pressure distribution required:
  - Identify the maximum lift upper surface target distribution pressure distribution
  - Use an inverse method to find the airfoil



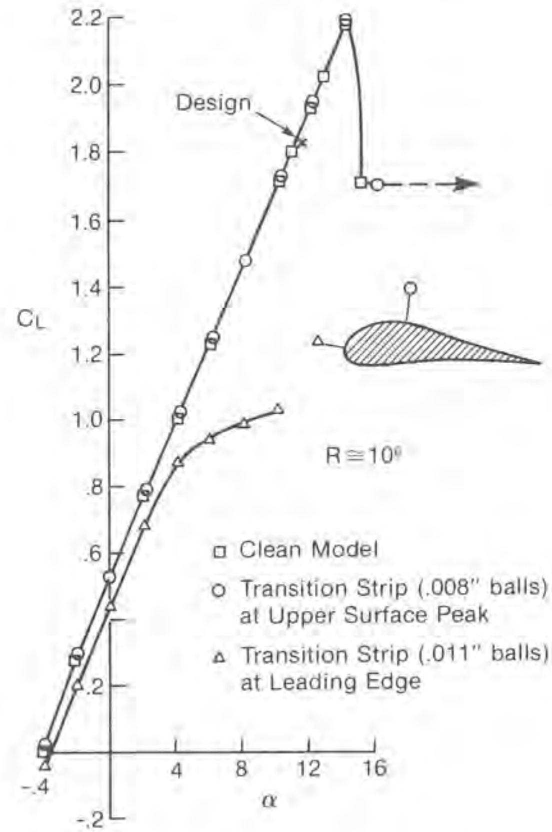


Made to seem way easier than it really was! Scans from A.M.O. Smith's paper. Note the the axis is the airfoil arc length

Liebeck's Hi-Lift Airfoil: it works!



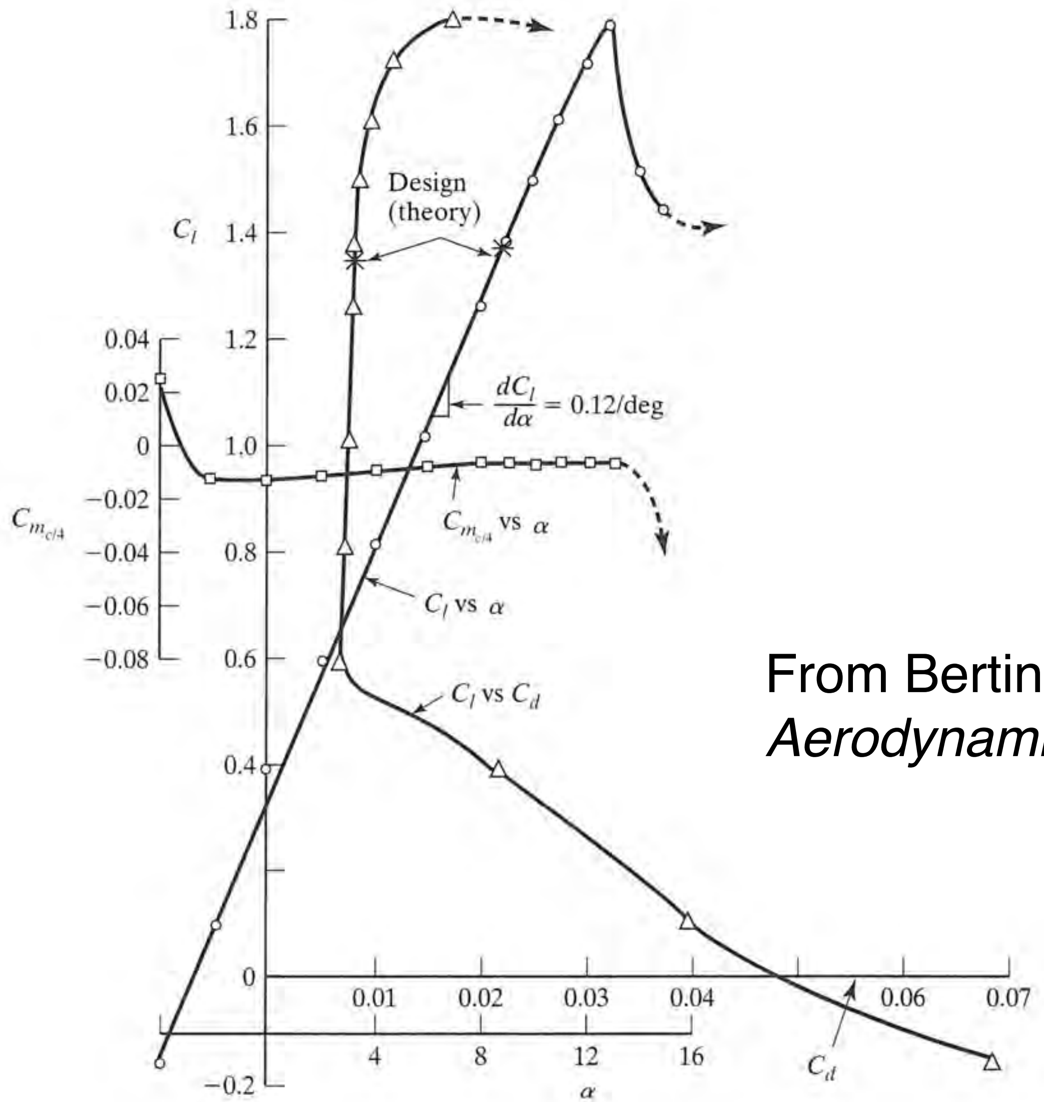
3.19a. Laminar rooftop airfoil, geometry and pressure distributio



3.19b. Laminar rooftop airfoil, lift curves showing the effect of transition strips. (From R. H. Liebeck, "Wind Tunnel Tests of Two Airfoils Designed for High Lift without Separation in Incompressible Flow," Rep. MDC-J5667/01, McDonnell Douglas Aircraft Co., Aug. 1972. With permission of the author.)

From R.T. Jones, *Wing Theory*

Liebeck's Hi-Lift Airfoil: Including Drag



From Bertin,
Aerodynamics for Engineers

Now consider multielement airfoils

- **1. The Slat Effect**

Contrary to old wives tales, the slat is in effect a point vortex that reduces the speed on the main element, thus reducing the chance of separation: the slat "protects" the leading edge.

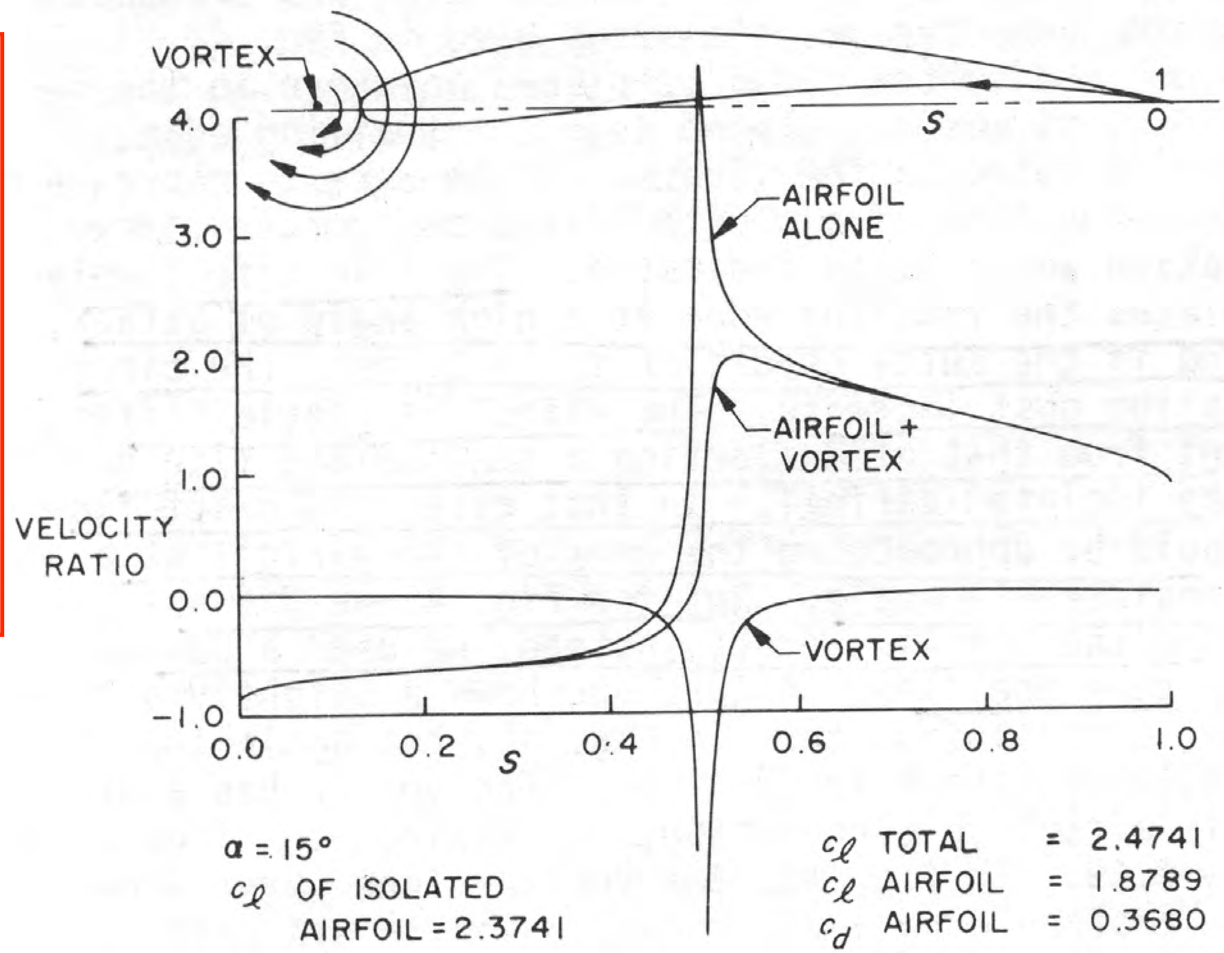


Figure from AMO Smith's paper

Multielement airfoils

2. The Circulation Effect

The downstream element causes the trailing edge of the upstream element to be in a high velocity region inclined to the mean line. To achieve the Kutta condition, the circulation has to be increased

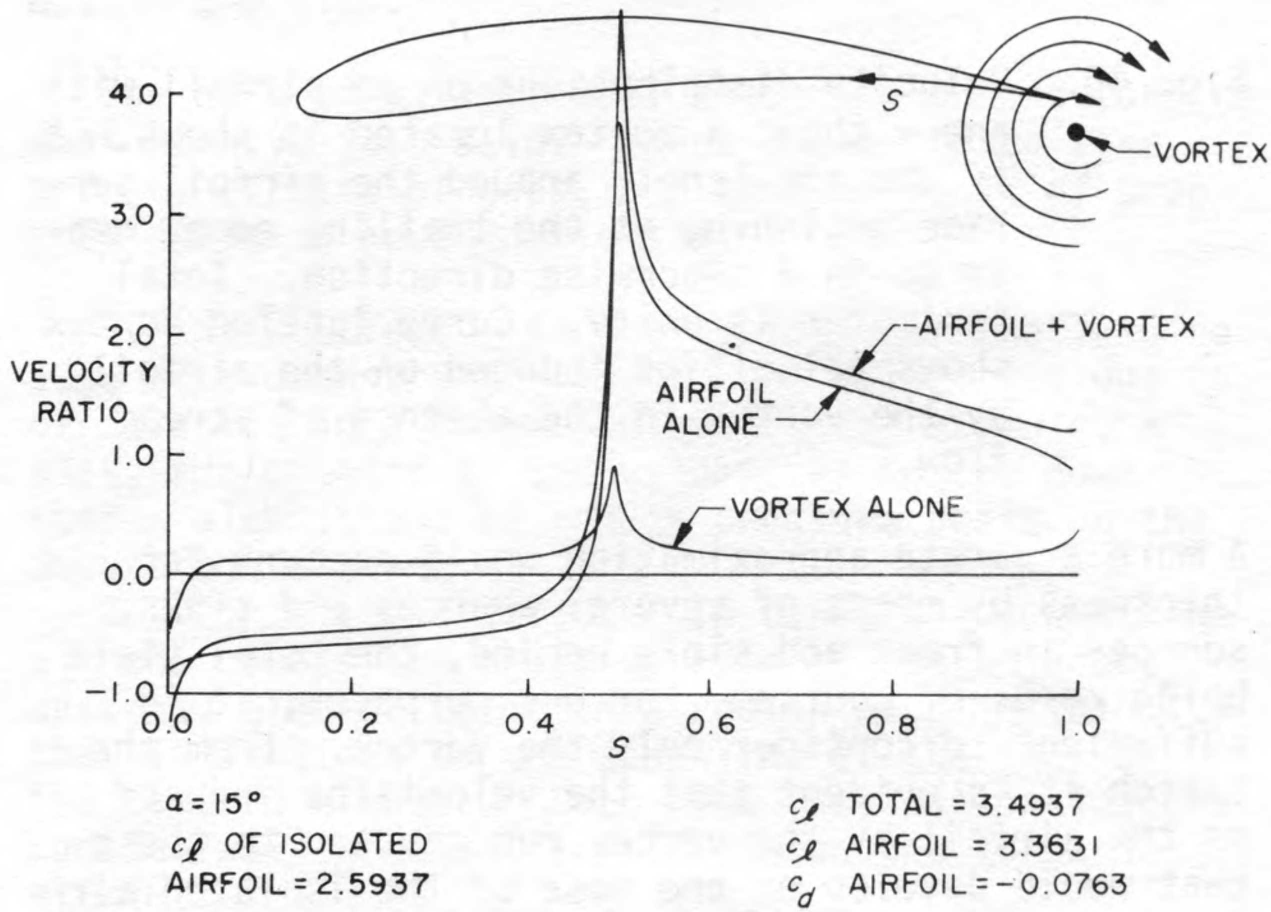
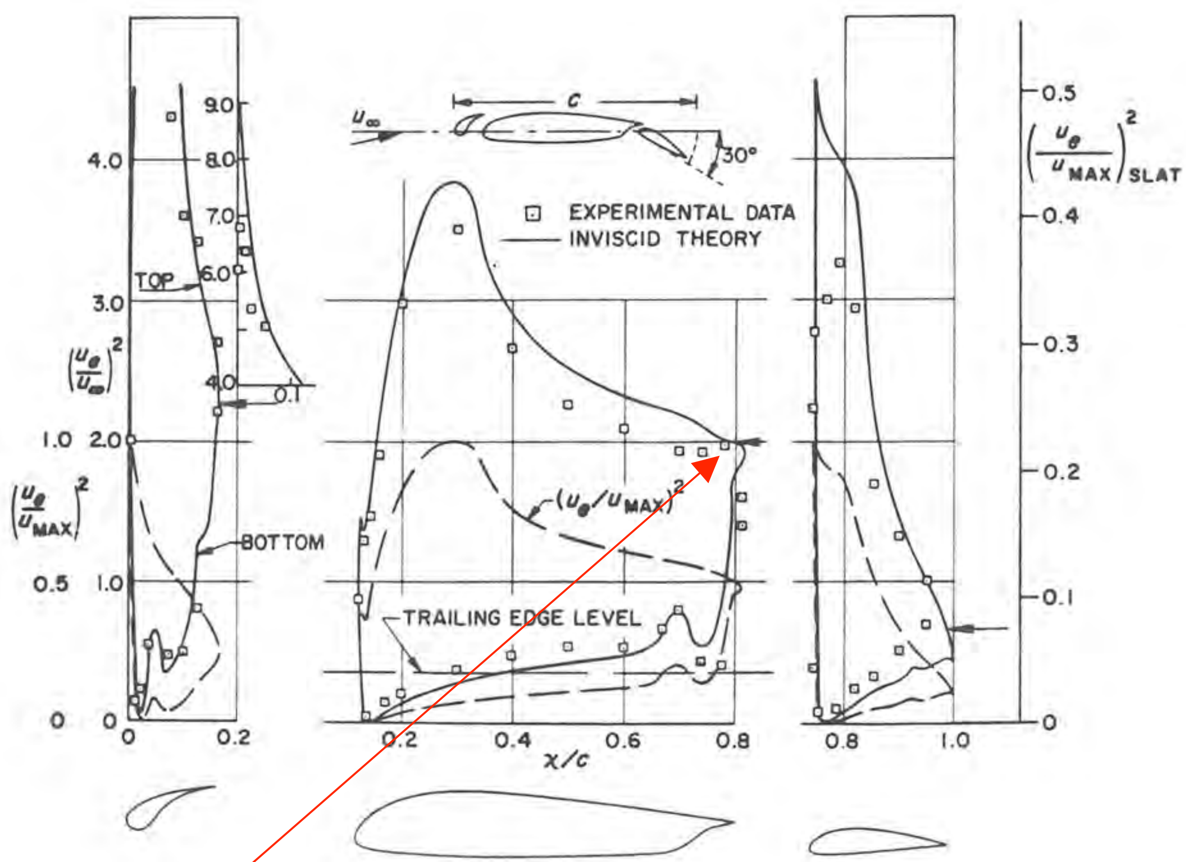


Figure from AMO Smith's paper

Multielement airfoils

3. The Dumping Effect

The TE of the forward element is in a region of velocity appreciably higher than the freestream. Thus, the BL can come off the fwd. element at a higher velocity. You don't have to recover to *Cp* = +0.2 for attached flow, relieving the pressure rise on the BL, and alleviating sep'n problems. The suction lift can be increased in proportion to the TE velocity squared for the same margin against separation.

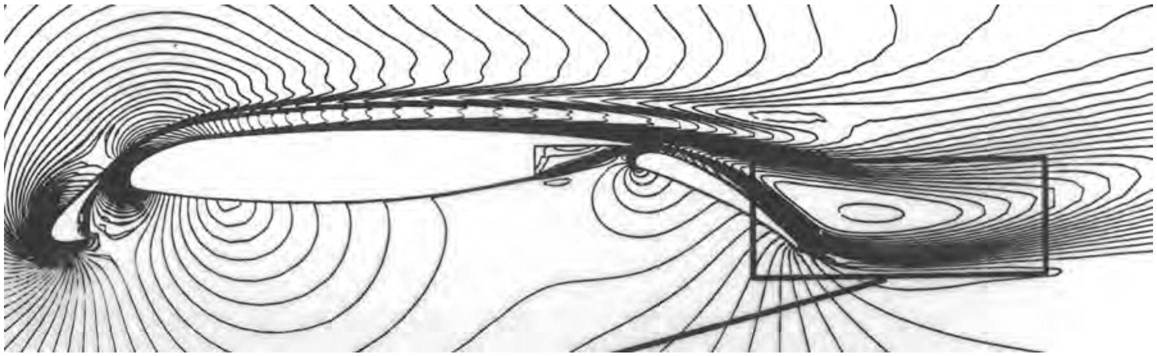


High velocity at the trailing edge, and more lift

Figure from AMO Smith's paper

Multielement airfoils

4. The Off-the-Surface Pressure Recovery Effect



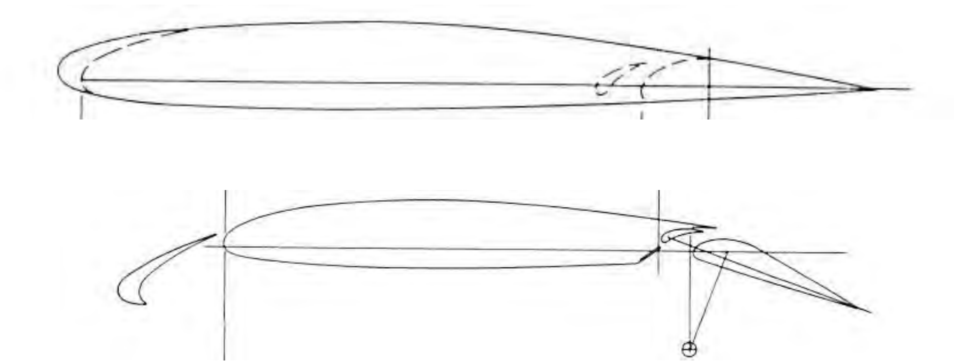
From S.E. Rogers, "Progress in High-Lift Aerodynamic Calculation," AIAA Paper 93-0194, Jan. 1993

The BL leaves the TE faster than the freestream, and becomes a wake. The recovery back to freestream velocity can be more efficient away from contact with the wall. Wakes withstand more adverse pressure gradient than BLs.

Note: for well designed high lift systems the local BLs and wakes remain separate.

Multielement airfoils

5. The Fresh Boundary Layer Effect



Simply put: because thin boundary layers can sustain greater pressure gradients than thick boundary layers, three thin boundary layers are better than one thick boundary layer.

Fixes: Vortex Generators

Photos taken at the Pima Air Museum, out side Tucson, AZ

A-4 Skyhawk

AV-8A Harrier

Lear Jet

Fixes: the F-111 Eyelid Flap

It is very hard to get photos of the eyelid flap deployed. These are scans from a British magazine no longer published, the *World Air Power Journal*

Last, but not least: The Gurney Flap

Invented to add downforce in racing, named after Dan Gurney, but eventually done by Bob Liebeck

Called a Wickerbill in NASCAR

Pictures taken outside Shelor’s QuickLane, Fall 2008

Liebeck's Description of the Gurney Flap

From, Robert H. Liebeck, "Design of Subsonic Airfoils for High Lift," *Journal of Aircraft*, Sept. 1978, pp. 547-561.

Fig. 28 **Indianapolis race car.**

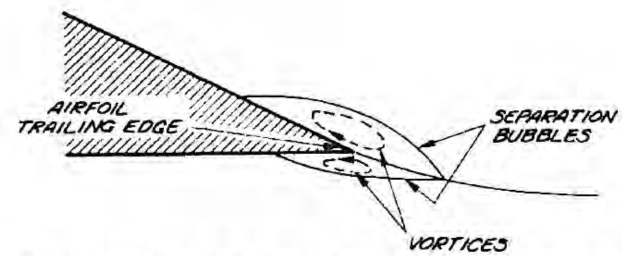
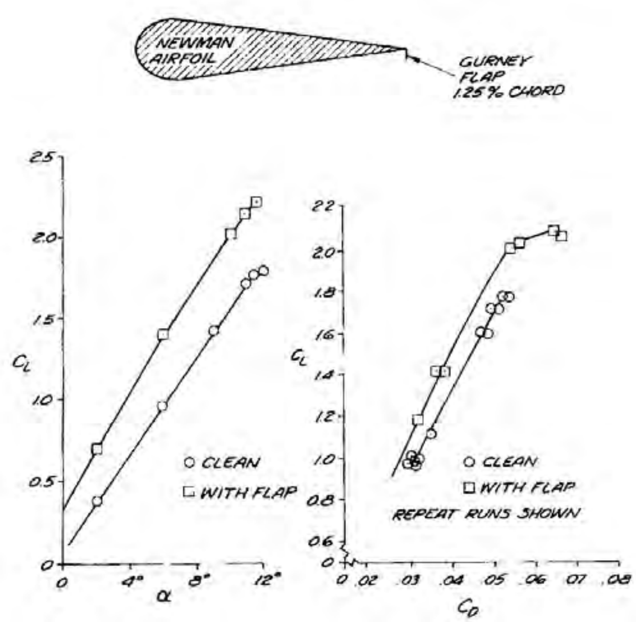


Fig. 30 **Trailing-edge flow conditions of a conventional airfoil at a moderate lift coefficient.**[32]



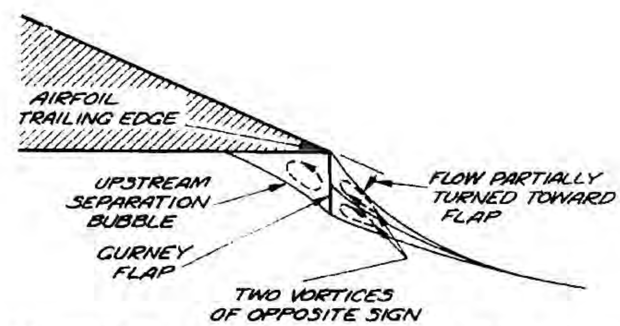


Fig. 31 **Hypothesized trailing-edge flow conditions of the airfoil of Fig. 30 with a Gurney flap.**

See also, Michael Cavanaugh, Paul Robertson and W.H. Mason, "Wind Tunnel Test of Gurney Flaps and T-Strips on an NACA 23012 Wing," AIAA Paper 2007-4175, June 2007.

To Conclude

- These are the high points of mechanical high-lift systems
- It is difficult to get more than a C_{Lmax} of 3 or a little more for practical aircraft
- There are many, many NACA/NASA Reports

Note: the most recent major survey is by C.P. van Dam, "The aerodynamic design of multi-element high-lift systems for transport airplanes," in *Progress in Aerospace Sciences*, Vol. 38, 2002.
-electronic version available through the library

See also: P. K. C. Rudolph, "High-Lift Systems on Commercial Airliners," NASA CR 4746. September 1996.

And the *Journal of Aircraft*, July-August 2015: Special Section: Second High-Lift Predicton Workshop