The Evolution of Airfoil Design

—

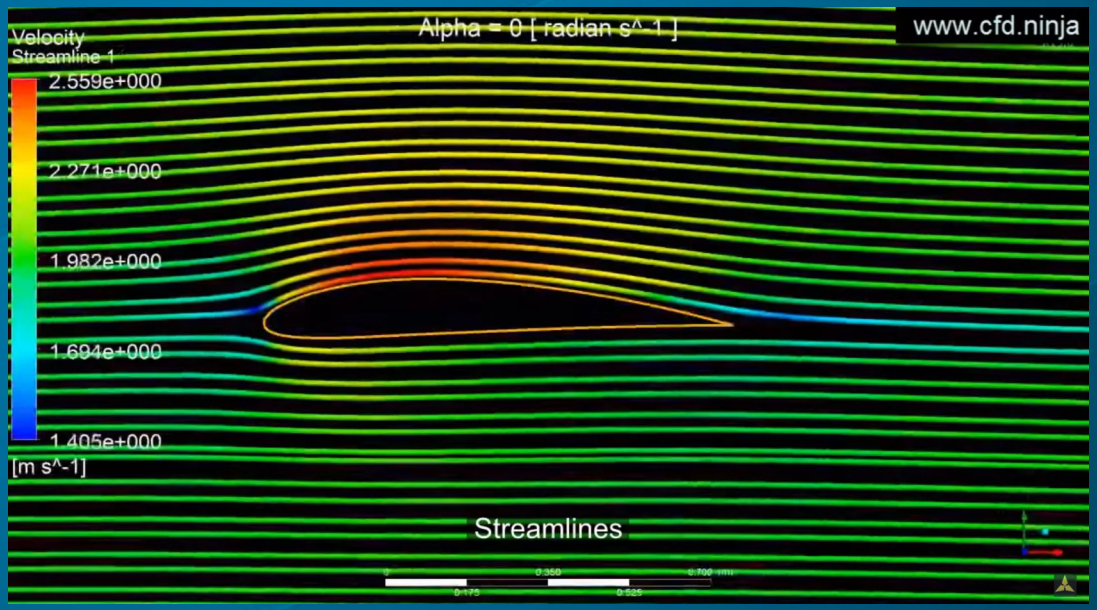
From 1796 to the Present

Bill Kuhlman

Technically, what is an airfoil?

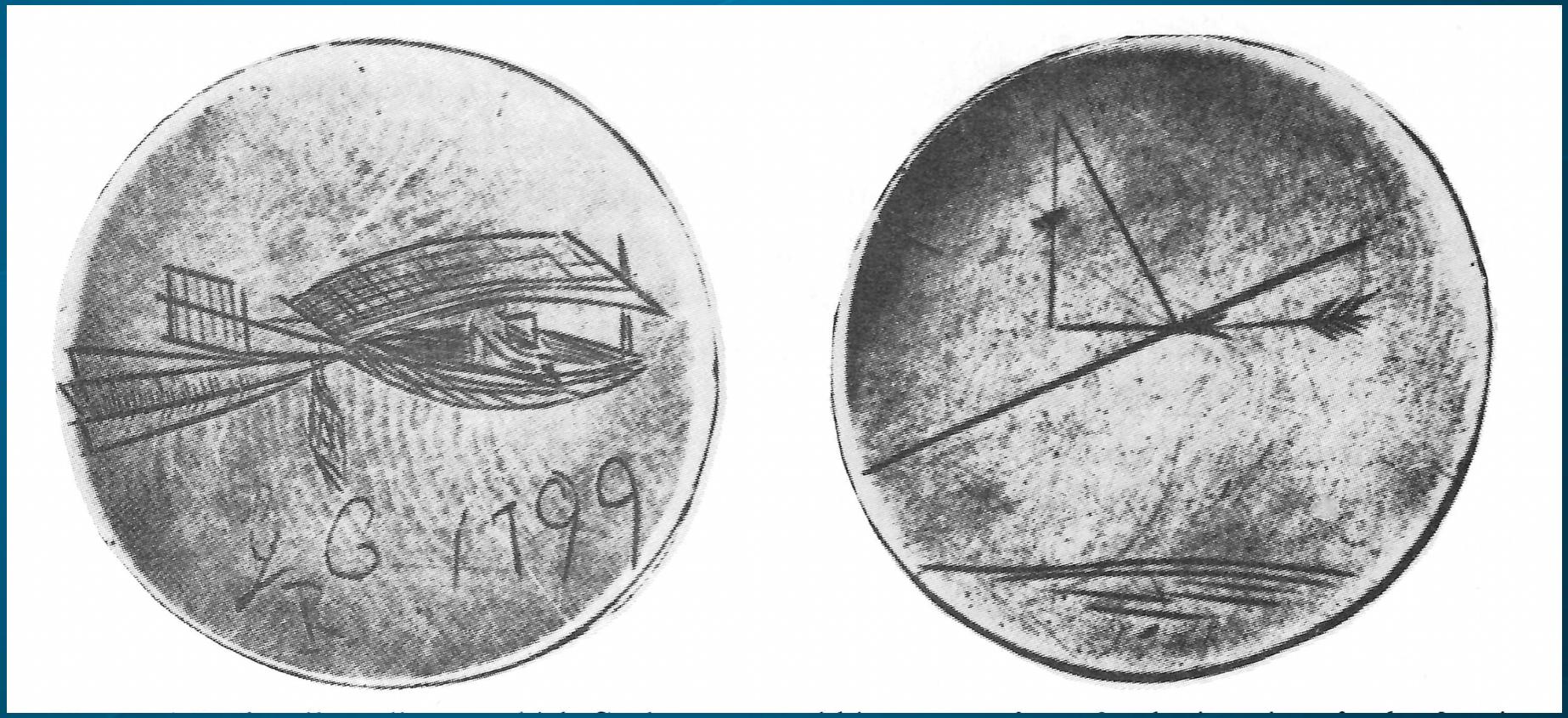
- An airfoil is a streamlined body, a 3-D object, capable of generating significantly more lift than drag. Examples: wing, full-flying stabilizer, hydrofoil
- An airfoil section, or simply section or profile, in contrast, is a 2-D representation of an airfoil at a specific point along the span.
Examples: NACA 6409, Eppler 212
- We commonly use these terms as if they're synonyms, and the term "airfoil" may be used (inappropriately) throughout the presentation.

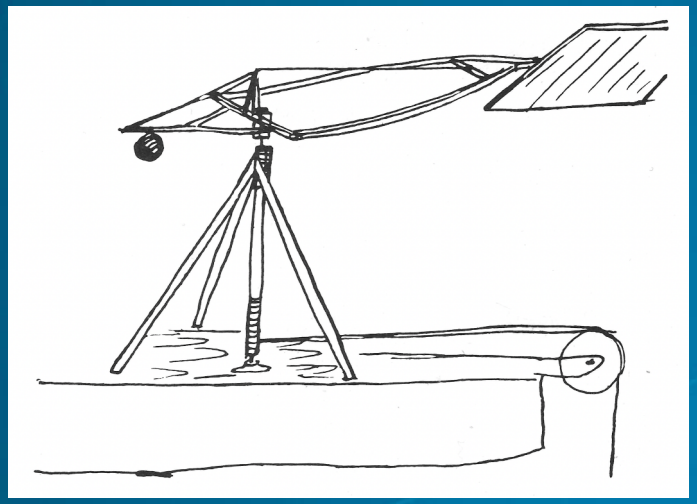
What are the general characteristics of an airfoil section?

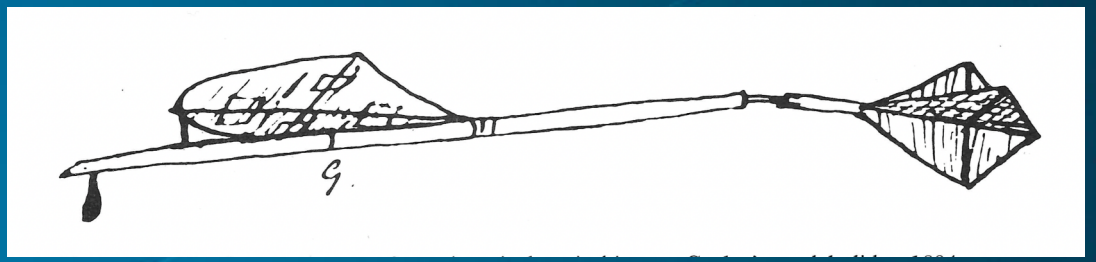


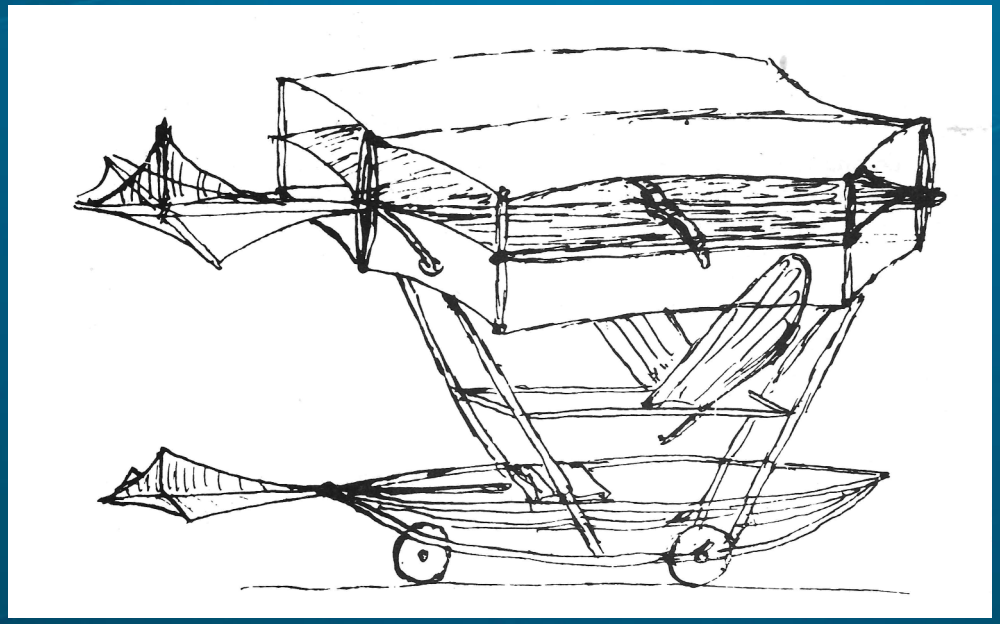
- Rounded leading edge
- Sharp trailing edge
- Recognition of the effects of camber

Sir George Cayley, 1796-1857









Mechanics' Magazine,

MUSEUM, REGISTER, JOURNAL, AND GAZETTE.

No. 1520.] SATURDAY, SEPTEMBER 25, 1852. [Price 3d., Stamped 4d.

Edited by J. C. Robertson, 166, Fleet-street.

SIR GEORGE CAYLEY'S GOVERNABLE PARACHUTES.

Fig. 2.

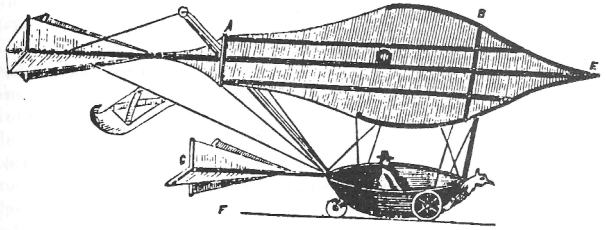
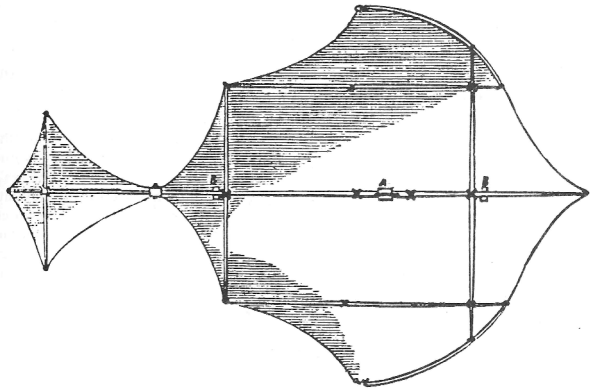
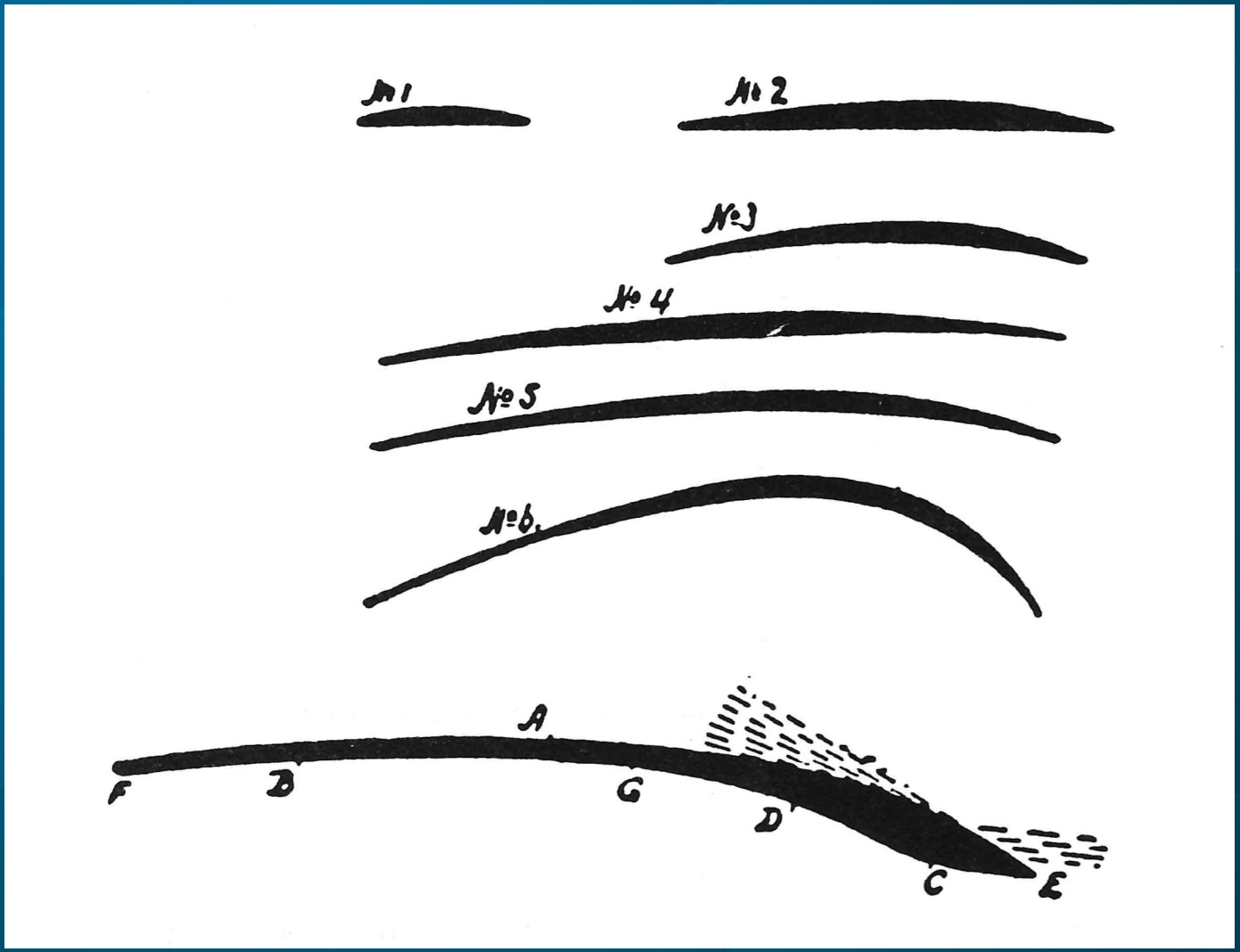


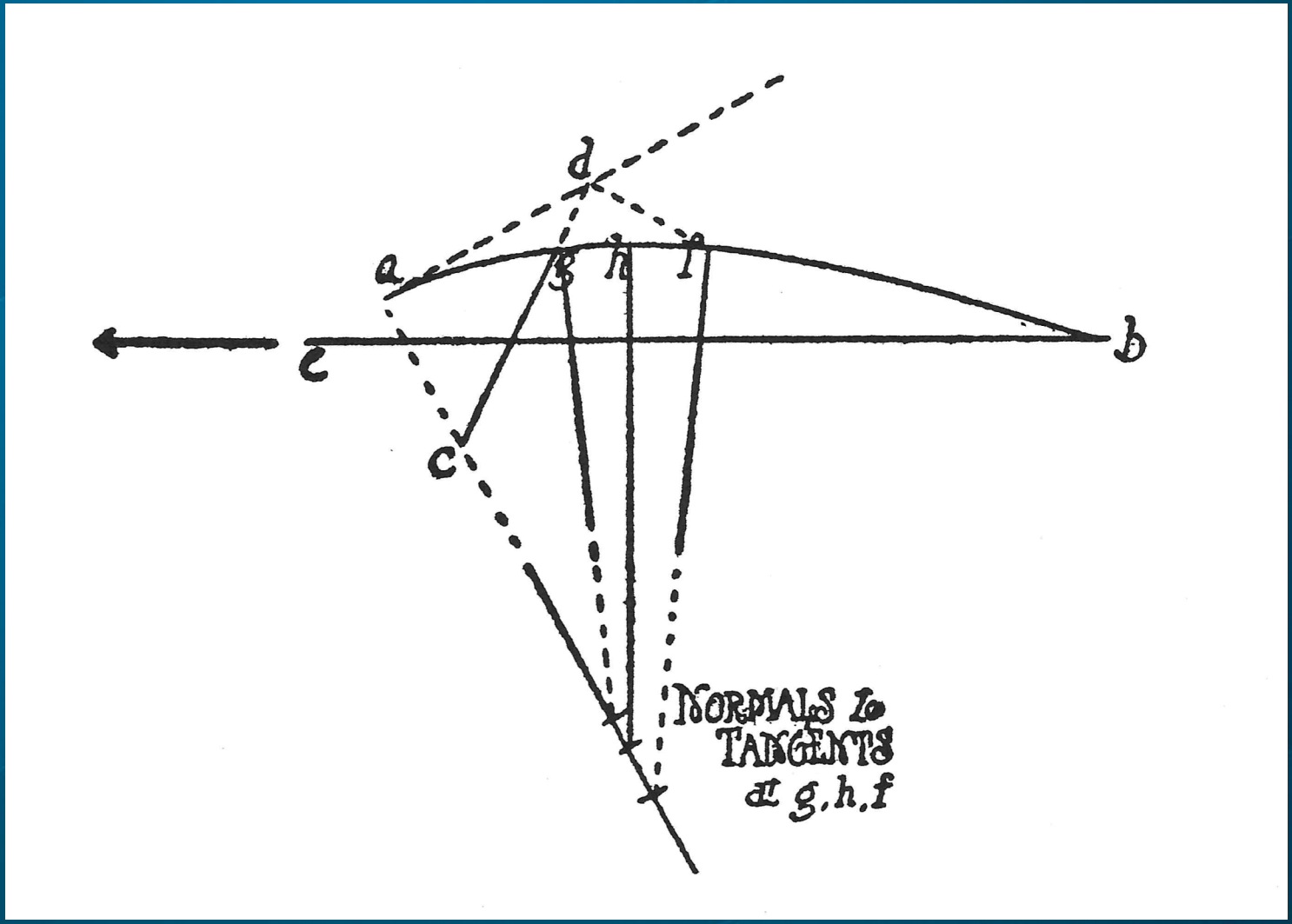
Fig. 1.



Horatio Frederick Philips - 1844



John Joseph Montgomery - 1880-1911



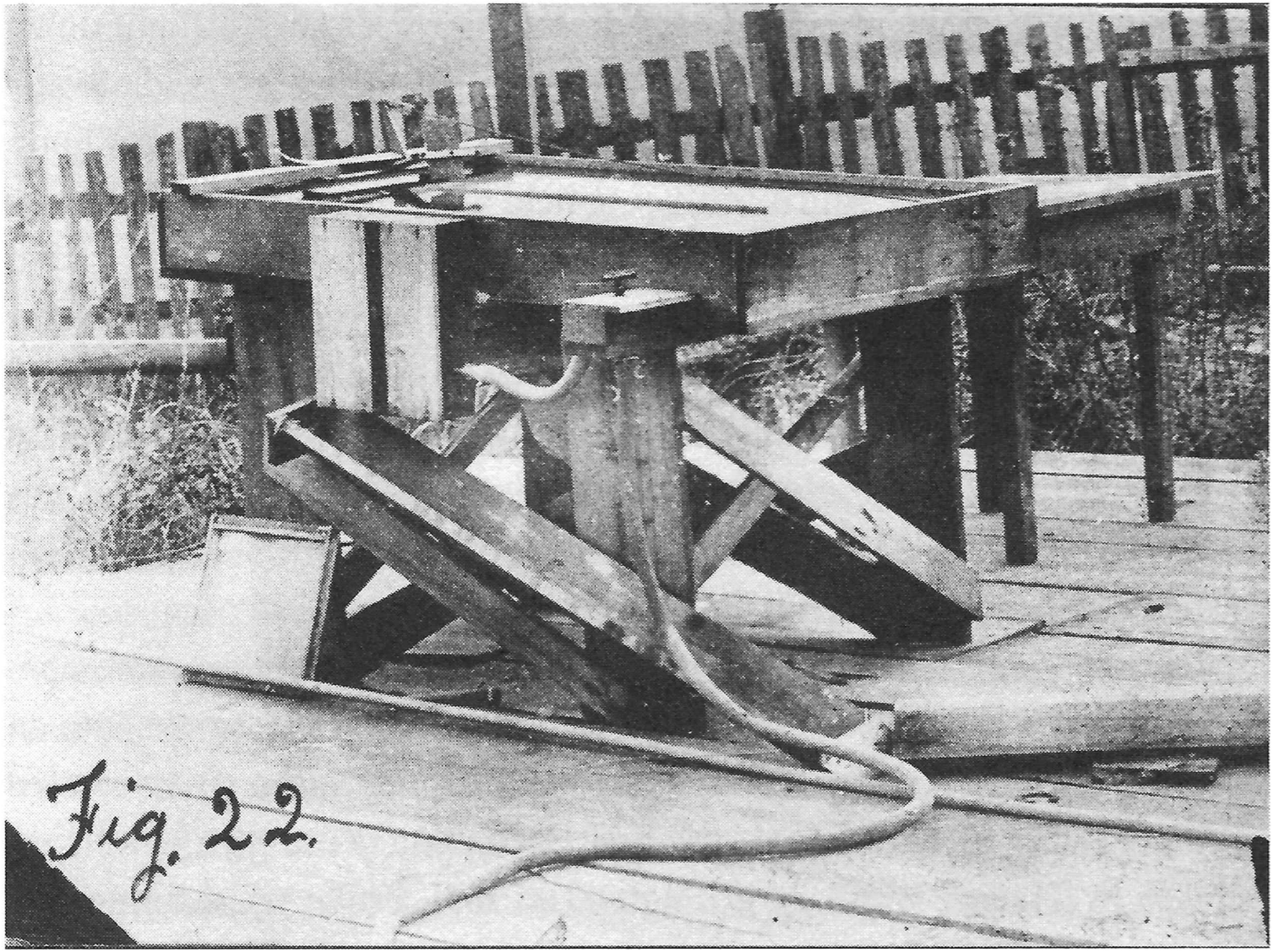
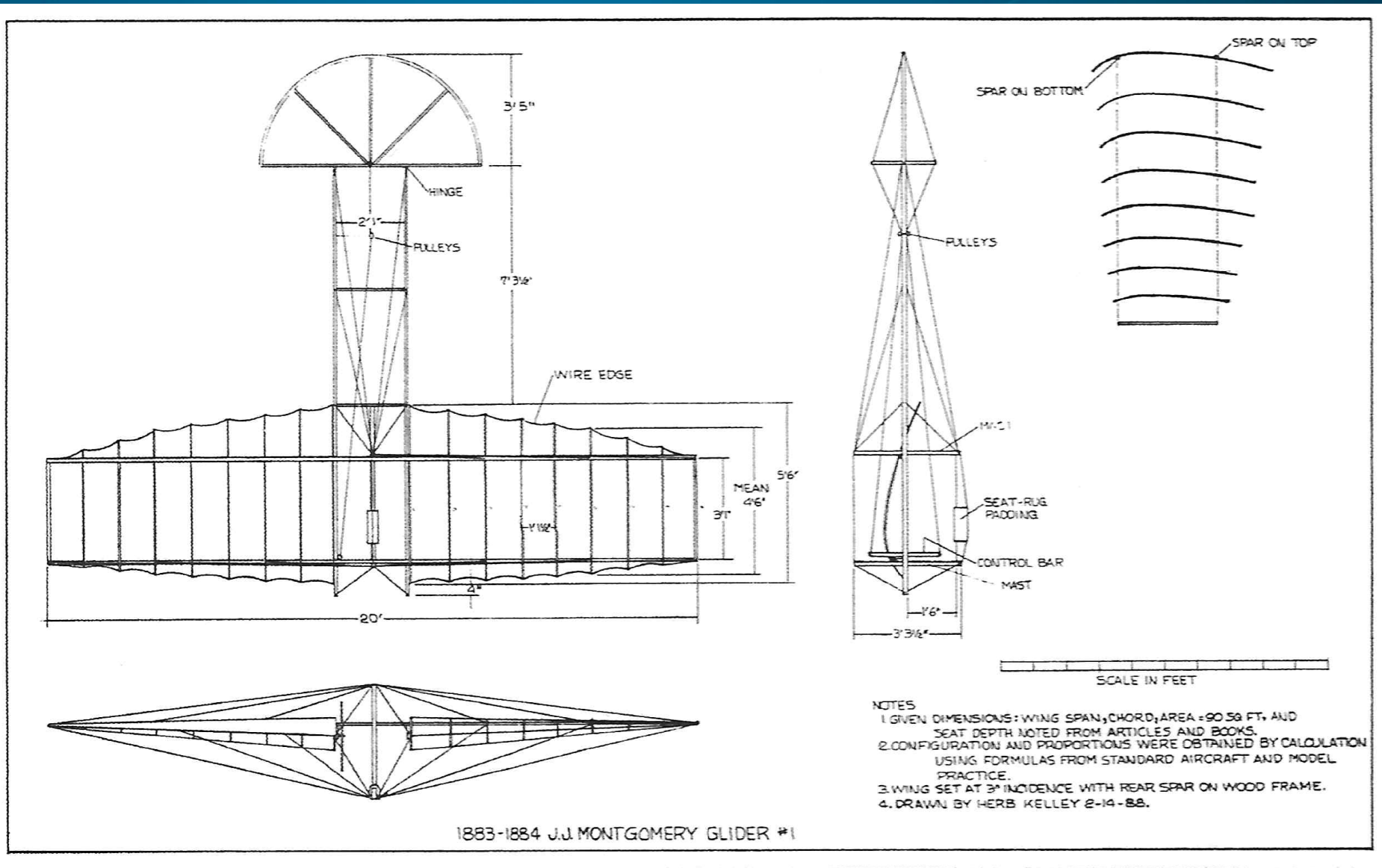
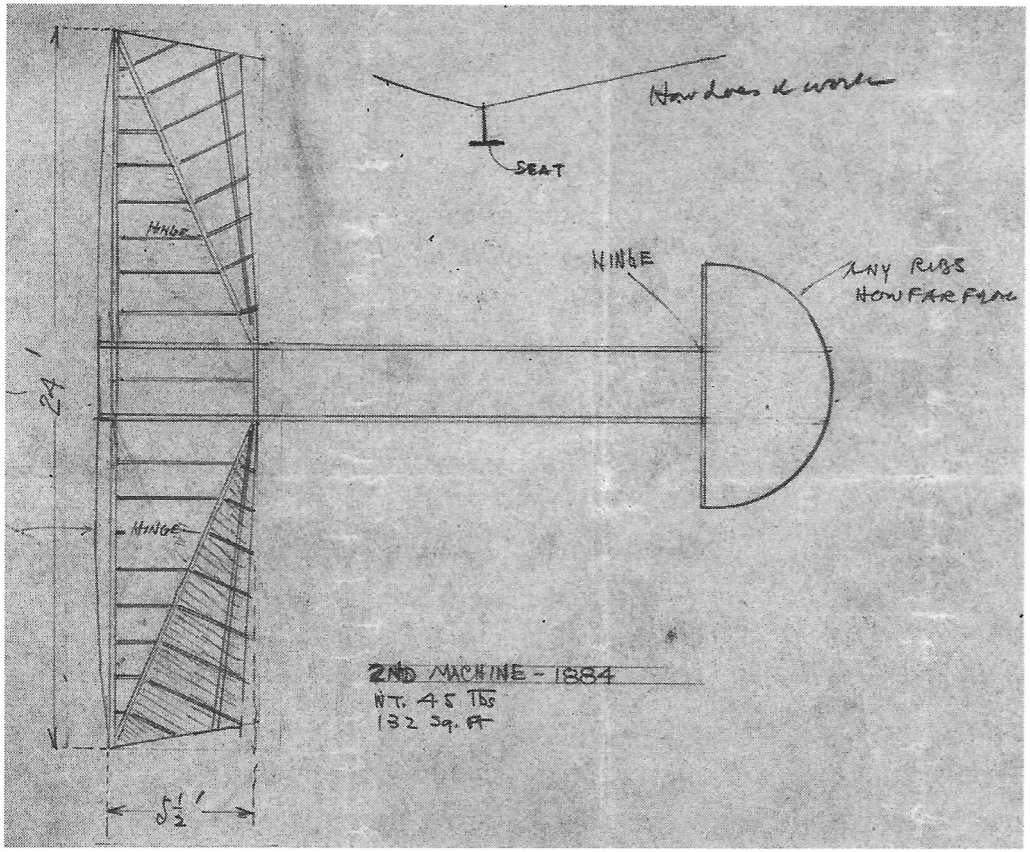


Fig. 22.


3'5"
HINGE
2'1"
PULLEYS
7'3½"
WIRE EDGE
5'6"
MEAN
4'6"
3'1"
1'1½"
4"
20'
SPAR ON TOP
SPAR ON BOTTOM
PULLEYS
SEAT-RUG
PADDING
CONTROL BAR
MAST
1'6"
3'3½"
SCALE IN FEET
NOTES
1. GIVEN DIMENSIONS: WING SPAN, CHORD, AREA = 90.5 SQ FT, AND SEAT DEPTH NOTED FROM ARTICLES AND BOOKS.
2. CONFIGURATION AND PROPORTIONS WERE OBTAINED BY CALCULATION USING FORMULAS FROM STANDARD AIRCRAFT AND MODEL PRACTICE.
3. WING SET AT 3° INCIDENCE WITH REAR SPAR ON WOOD FRAME.
4. DRAWN BY HERB KELLEY 2-14-88.
1883-1884 J.J. MONTGOMERY GLIDER #1



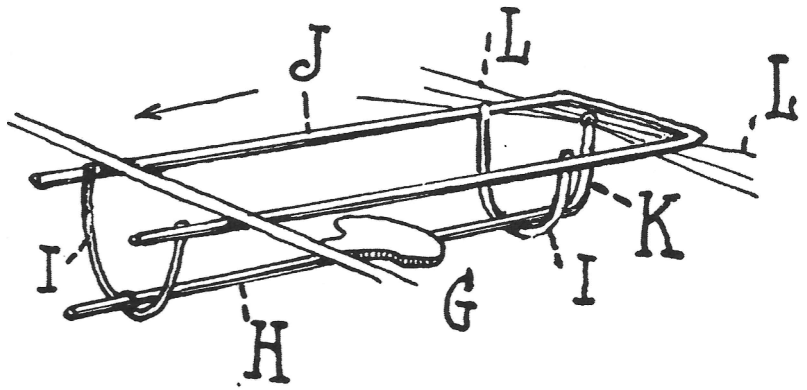
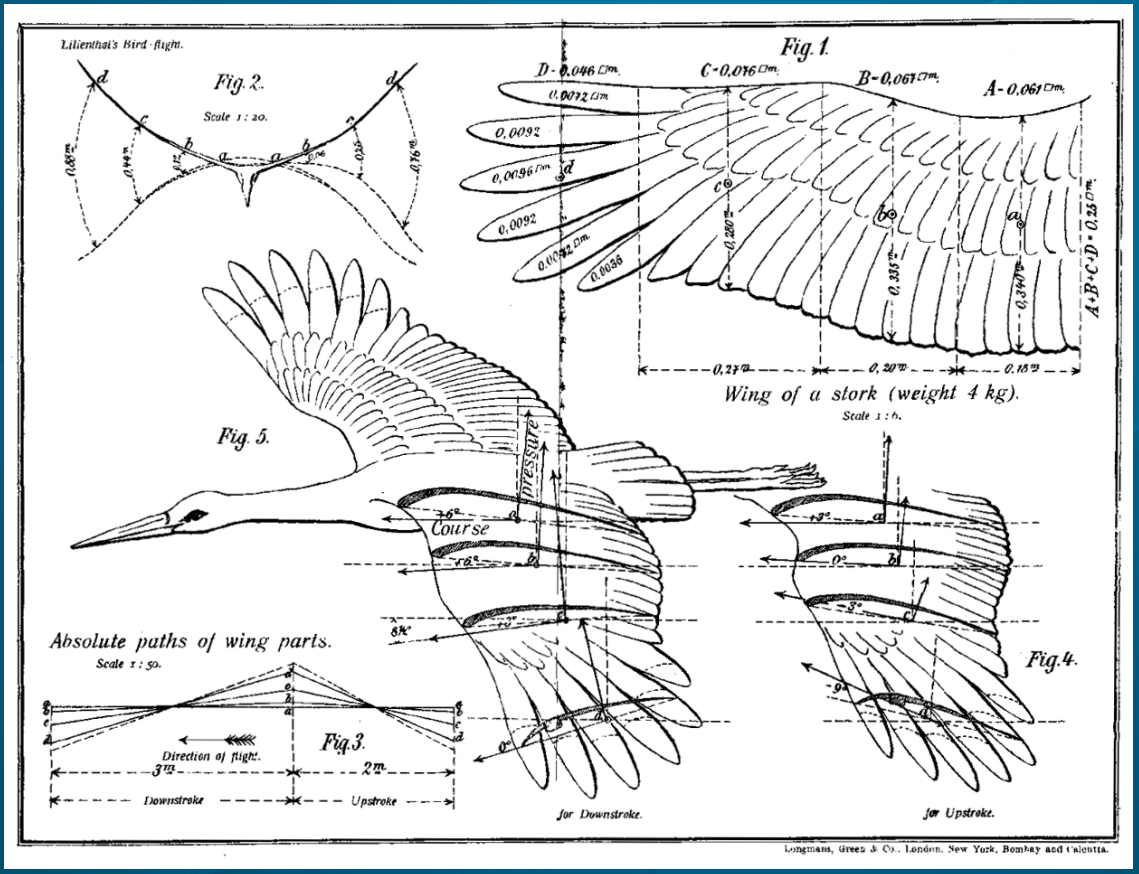
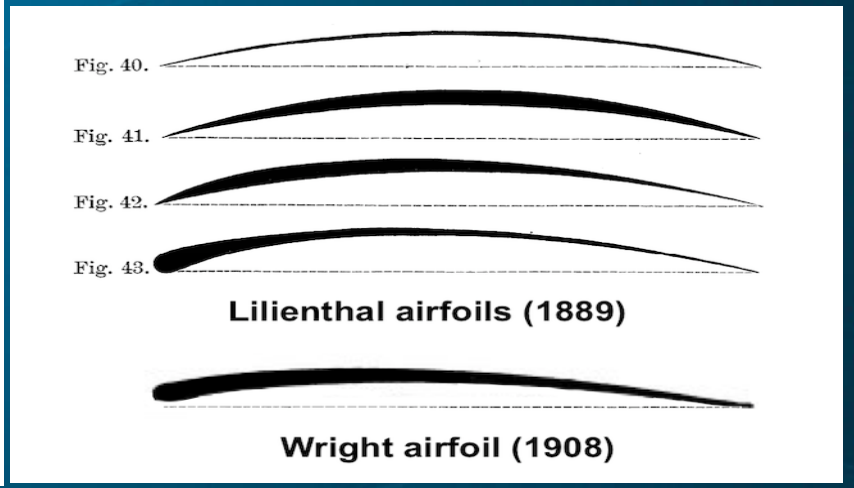


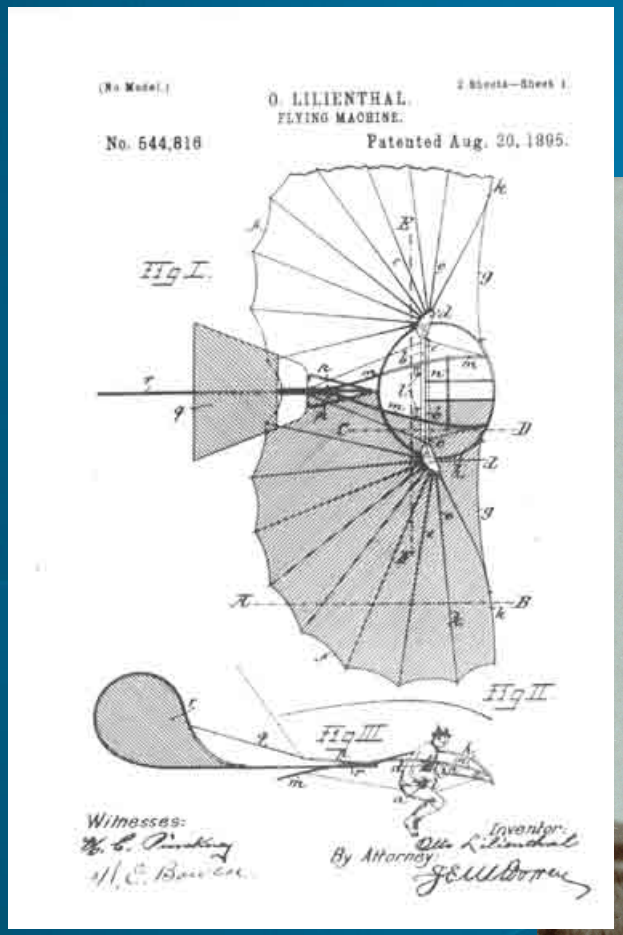
Figure IV.—Second control used on Montgomery ailerons. In this the seat G is fixed rigidly to the bar H, which rocks in the frame ribs II, which are themselves secured to the main frame J. To the upturned rear end of H, at K, are attached the groups of wires LL, one group to each wing, so that as the rider leans to one side or the other the wings are unsymmetrically manipulated.

Otto Lilienthal - 1891-1896



Birdflight as the Basis of Aviation





(No Model.) 2 Sheets—Sheet 1.

O. LILIENTHAL.

FLYING MACHINE.

No. 544,816. Patented Aug. 20, 1895.

Fig I.

Fig II

Fig III

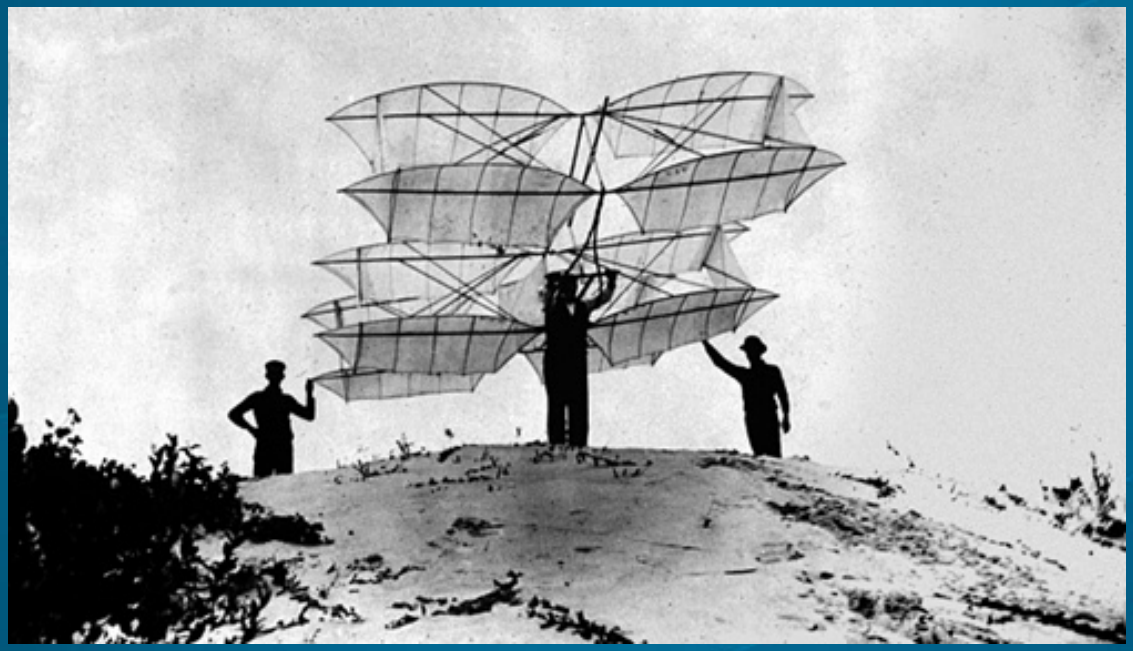
Witnesses:

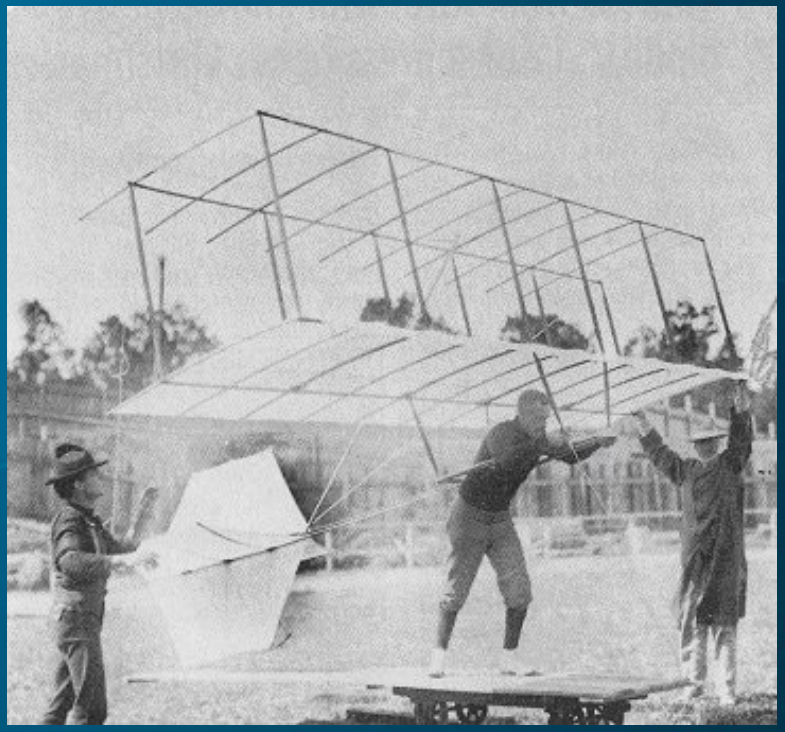
Inventor:

By Attorney:

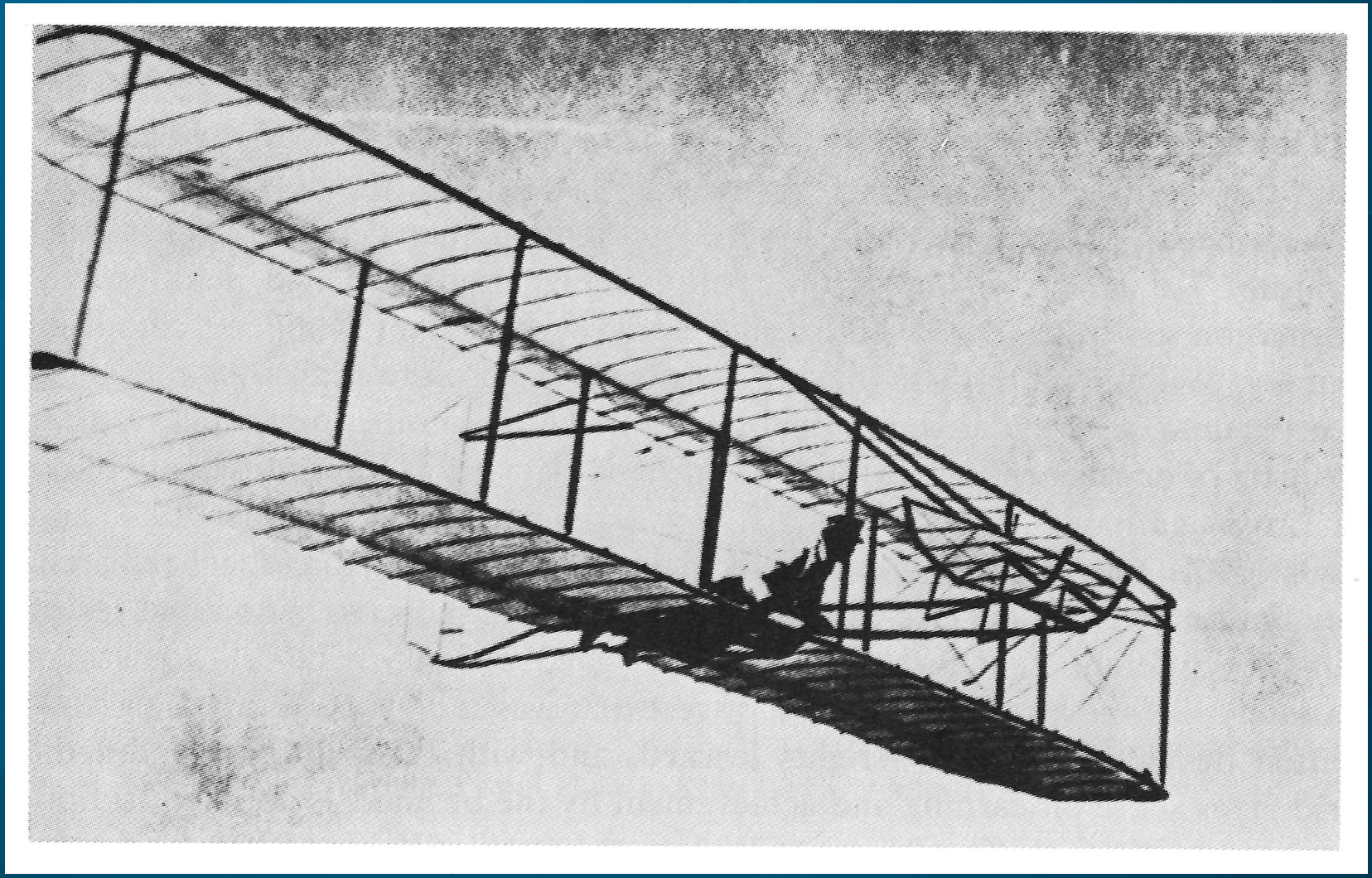


Octave Chanute - 1883-1910

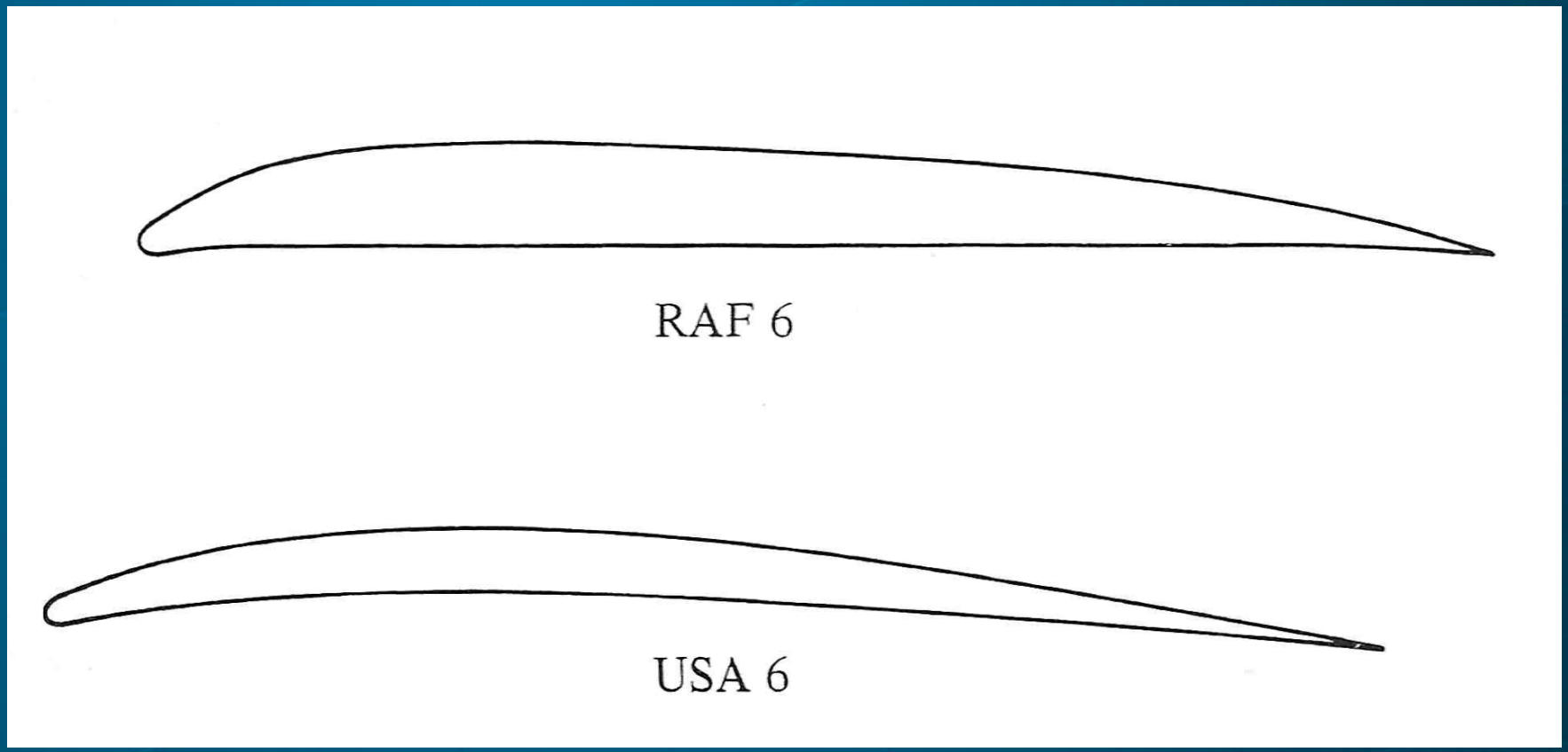




Orville and Wilbur Wright - 1900-1910



World War I - 1914-1918



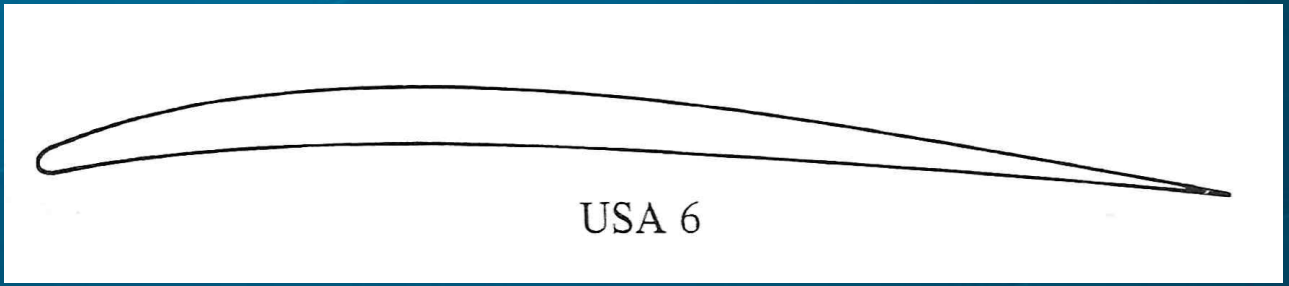
NACA* First Annual Report, 1915

We need more efficient wing sections of practical form and economic structure, and having a large angle of attack range.

* National Advisory Committee for Aeronautics, founded March 3, 1915, dissolved October 1, 1958

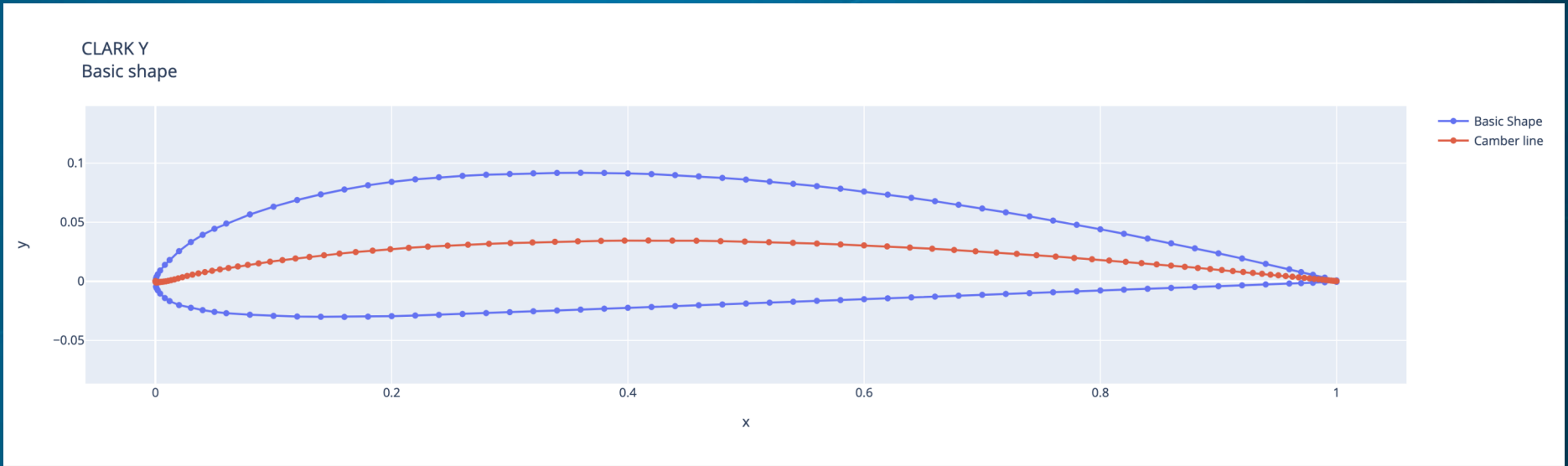
NACA Report No. 18, 1917

- First time using mathematical theories to design airfoils
- Airfoils are based on previously successful designs
- Six new thin airfoils, USA 1 – 6.



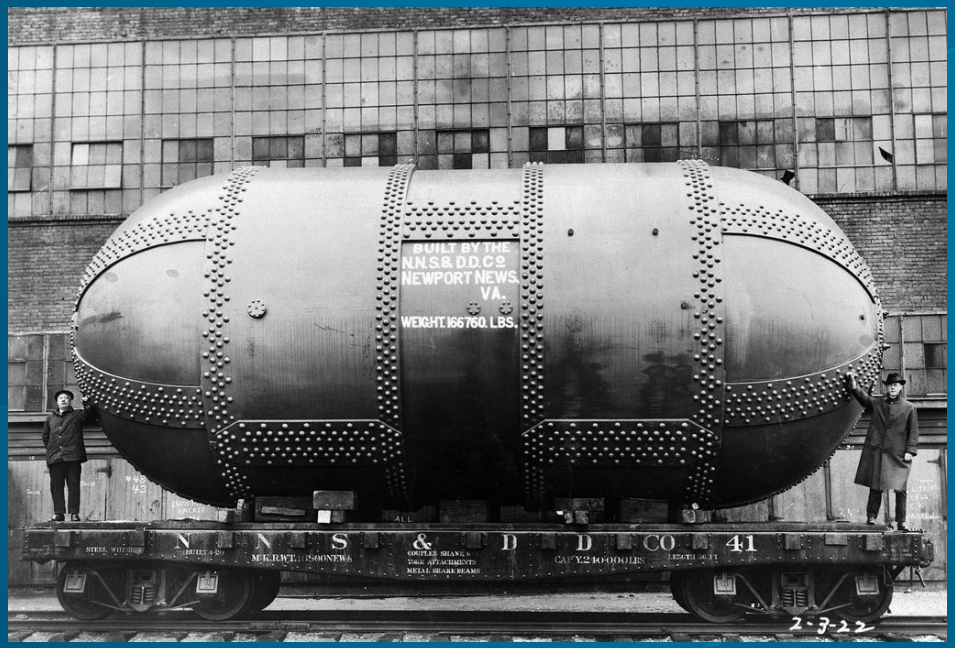
- Produced polar diagrams for those airfoils

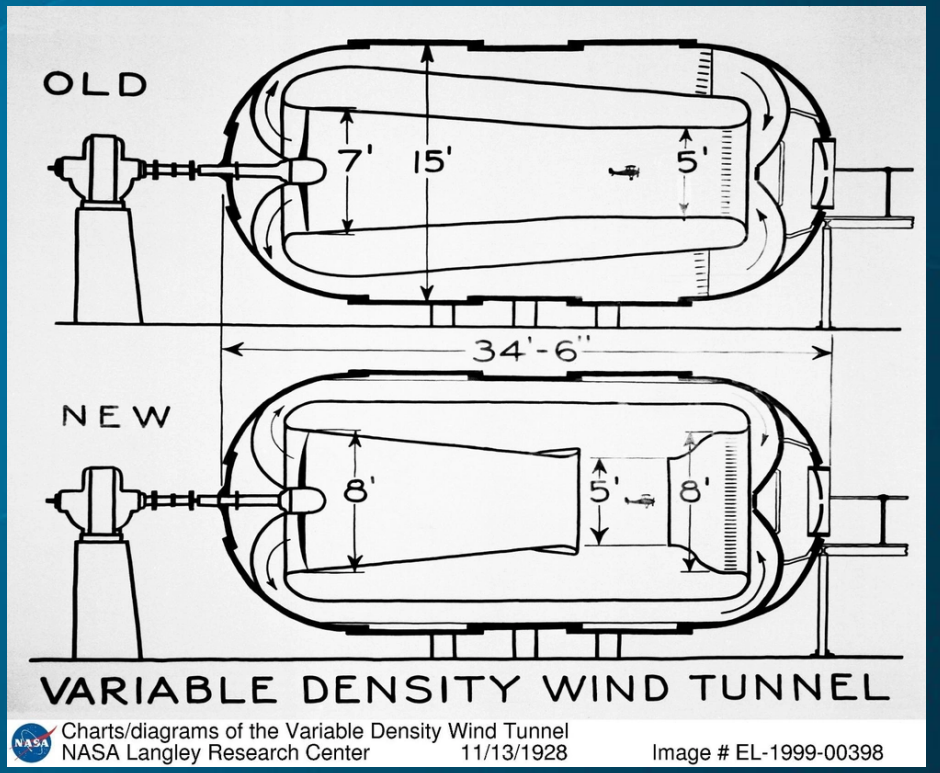
The Clark Y - 1922



- 11.7% thick at 28.24% chord
- 3.4% camber at 41.74% chord
- Flat bottom from 30% chord

1923 - NACA Variable Density Wind Tunnel





1923 and 1927

NACA Report 331, 1929

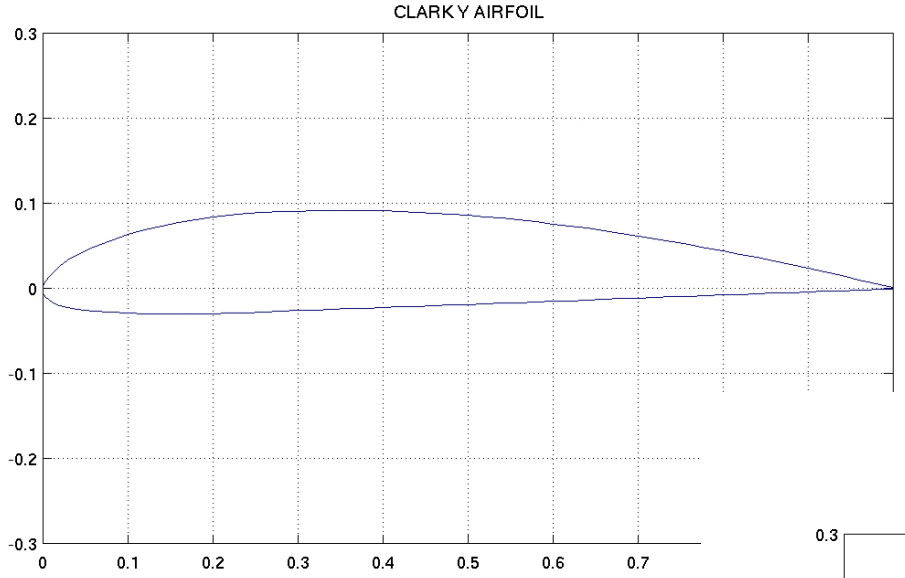
- Collected data for a large number of contemporary airfoils
- Data compiled from several wind tunnels
- Included airfoil coordinates, C_L and C_D
- Included information about spar locations!

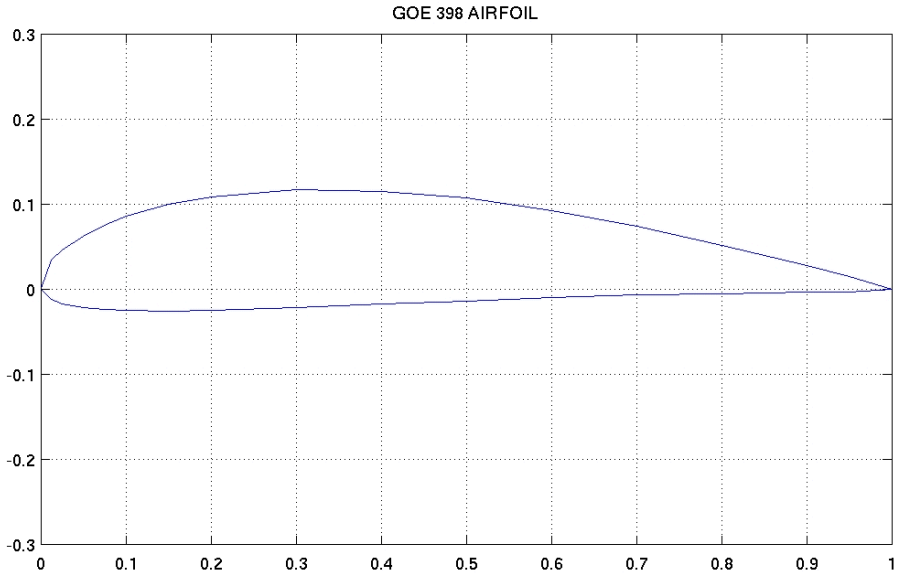
The Golden Age of NACA Airfoil Development

- NACA 4-digit series
- NACA 5-digit series
  - NACA 1-series
  - NACA 6-series
  - NACA 7-series
  - NACA 8-series

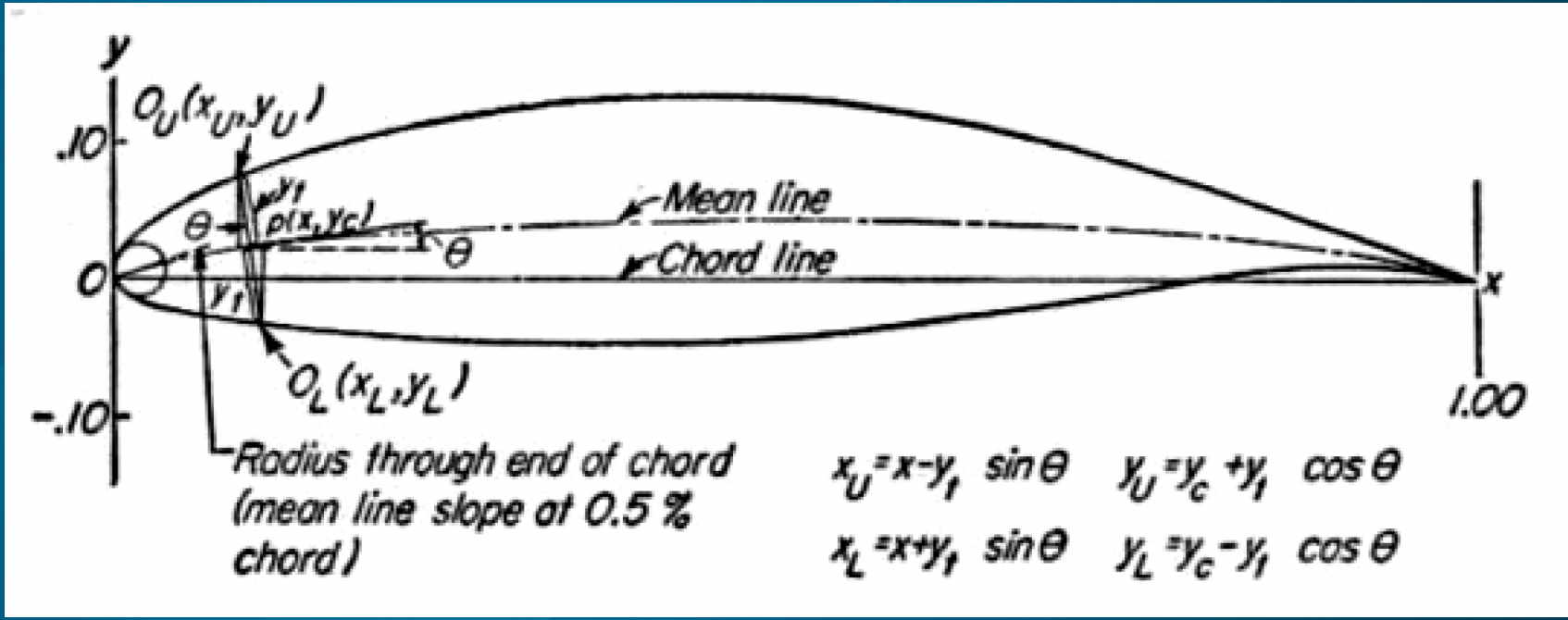
NACA Report 460, 1933

- The landmark publication!
- 78 airfoils tested in NACA Variable Density Wind Tunnel (NACA 4-digit series)
- Defined airfoil sections by camber line (height and position of maximum camber) and thickness
- Data for C_L, C_D, and C_L/C_D

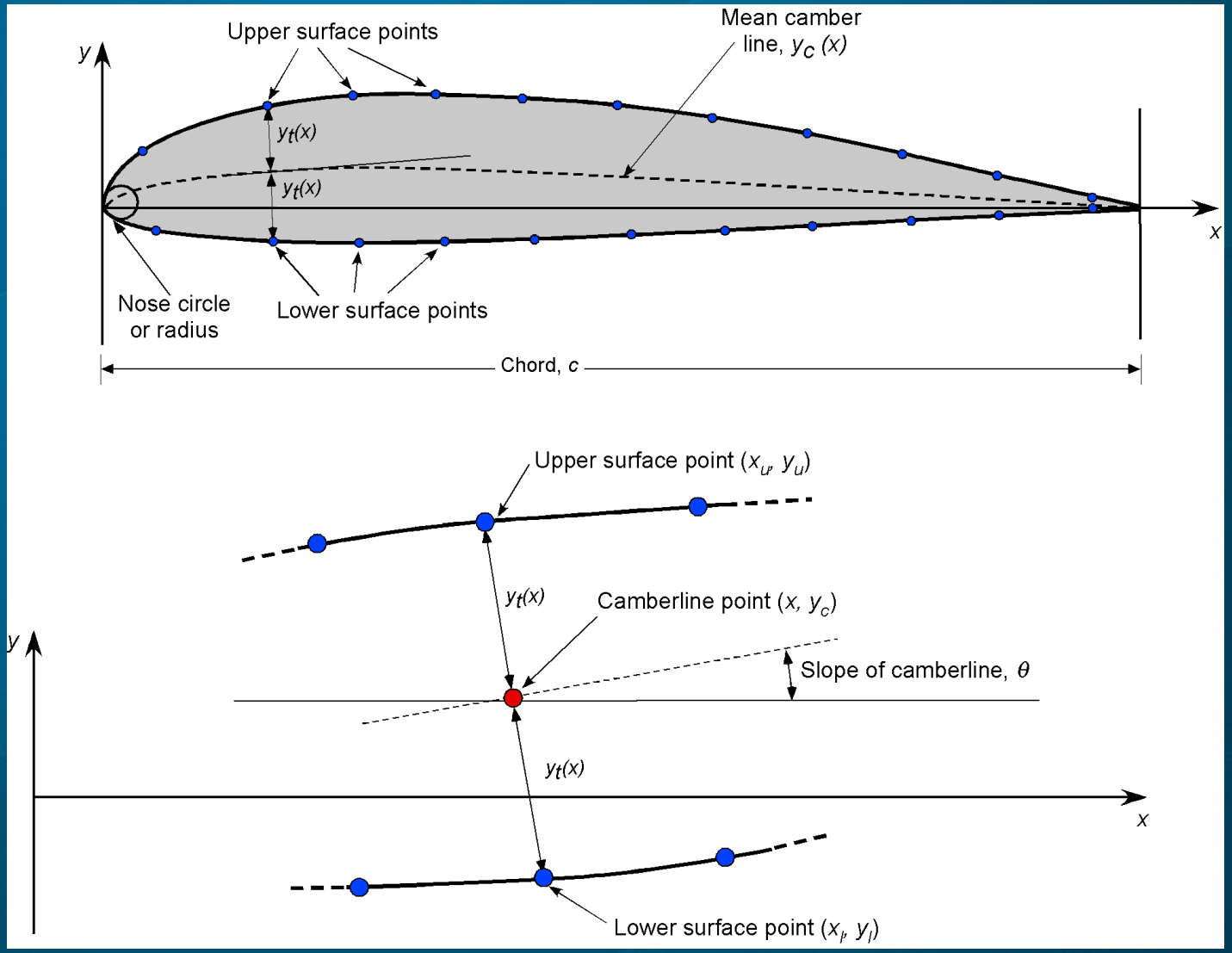

CLARK Y AIRFOIL
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7


GOE 398 AIRFOIL
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Airfoil Nomenclature



Thickness Construction on Camber Line



NACA 4-digit sections

Example: NACA 6409

First digit is % camber

Second digit is position of max camber in 1/10th chord (40% chord in example)

Last two digits are maximum thickness %

The 78 Tested Sections

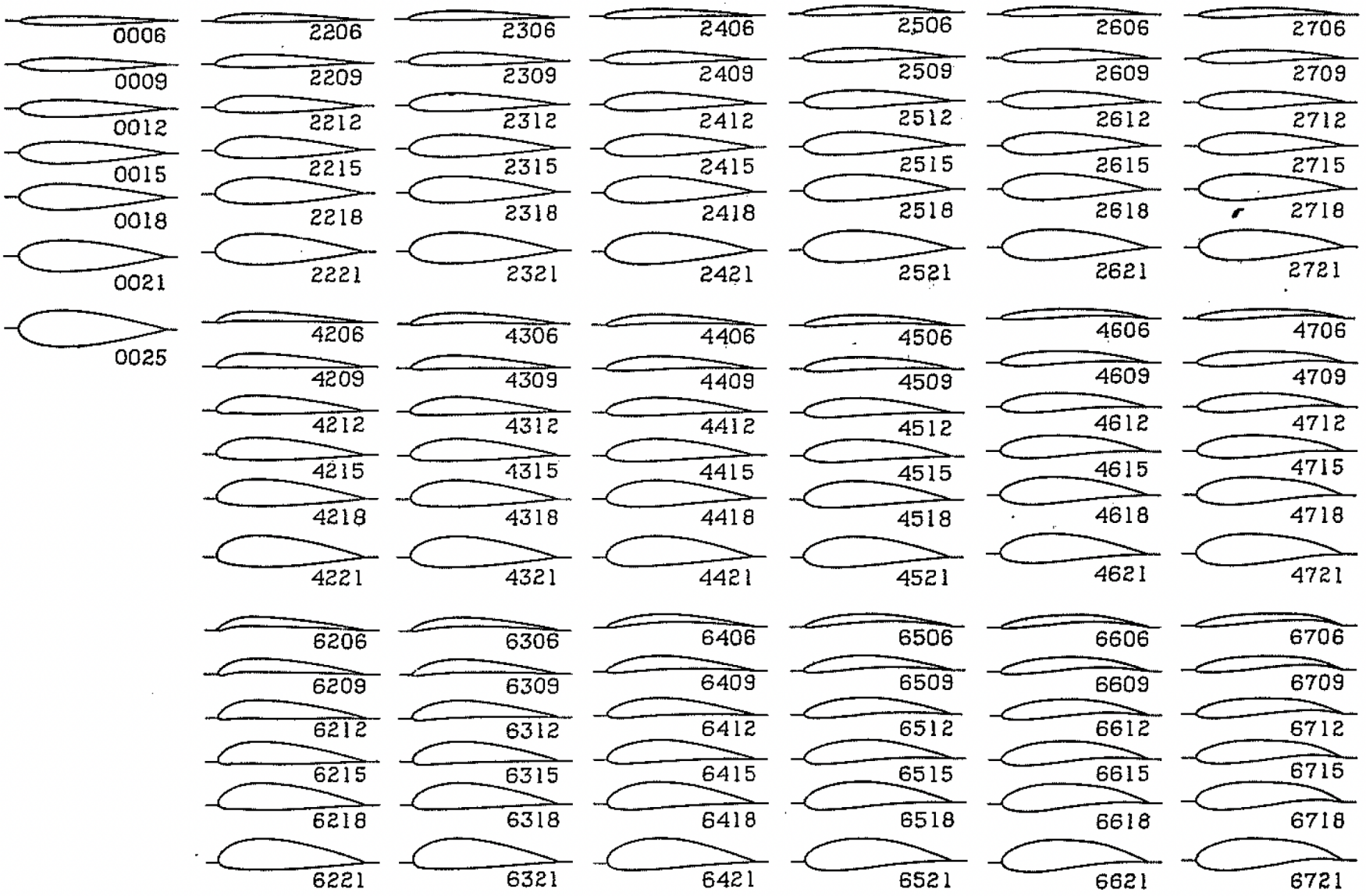
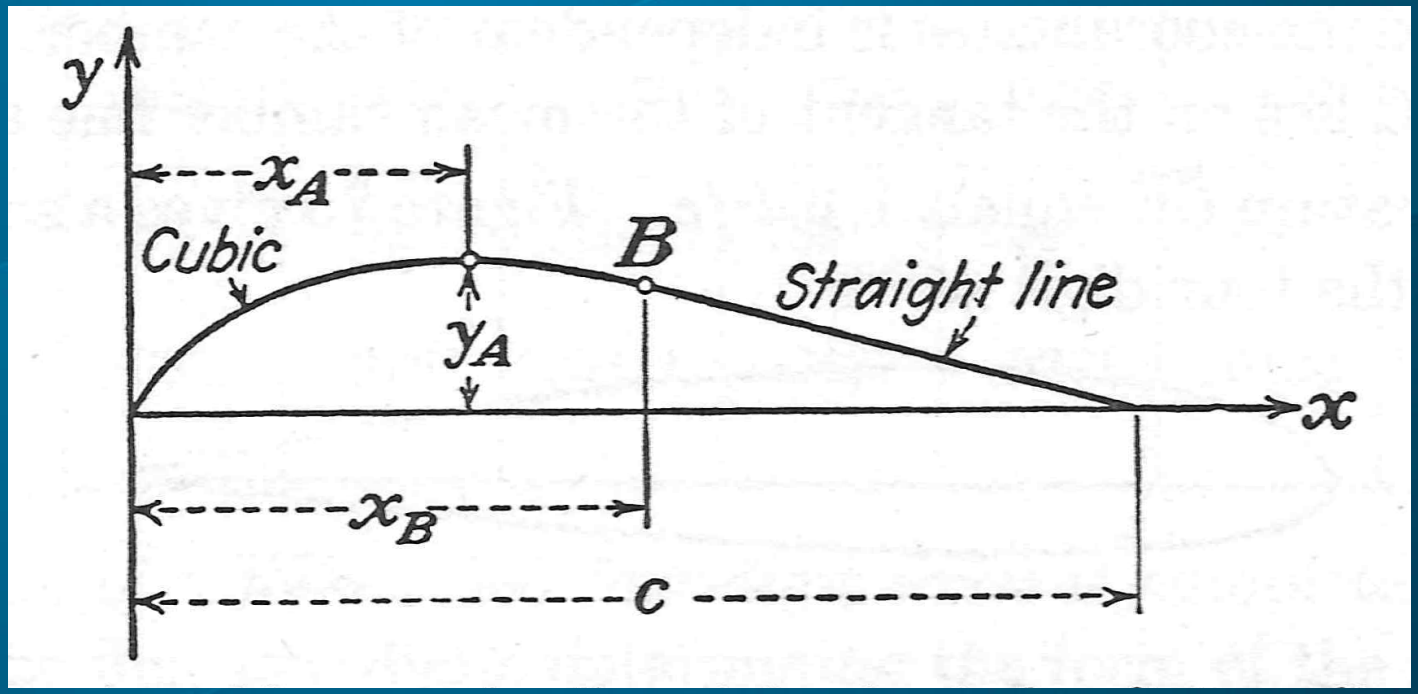


FIGURE 3.—N.A.C.A. airfoil profiles.

1933-1938 NACA 5-digit series



Camber line construction

Example: NACA 23012

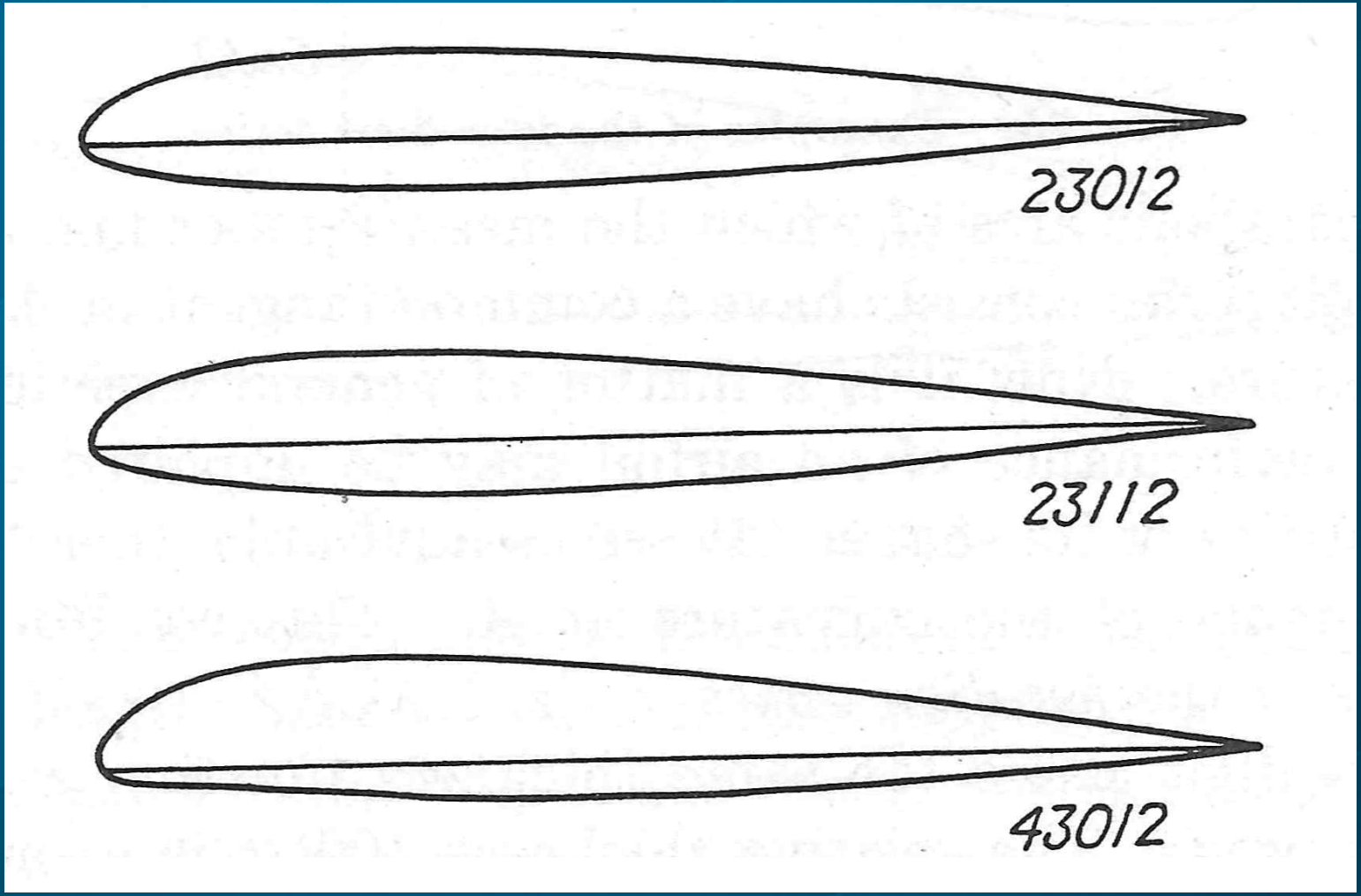
First digit is the maximum camber

Second digit is position of max camber in 1/20th chord (15% in example)

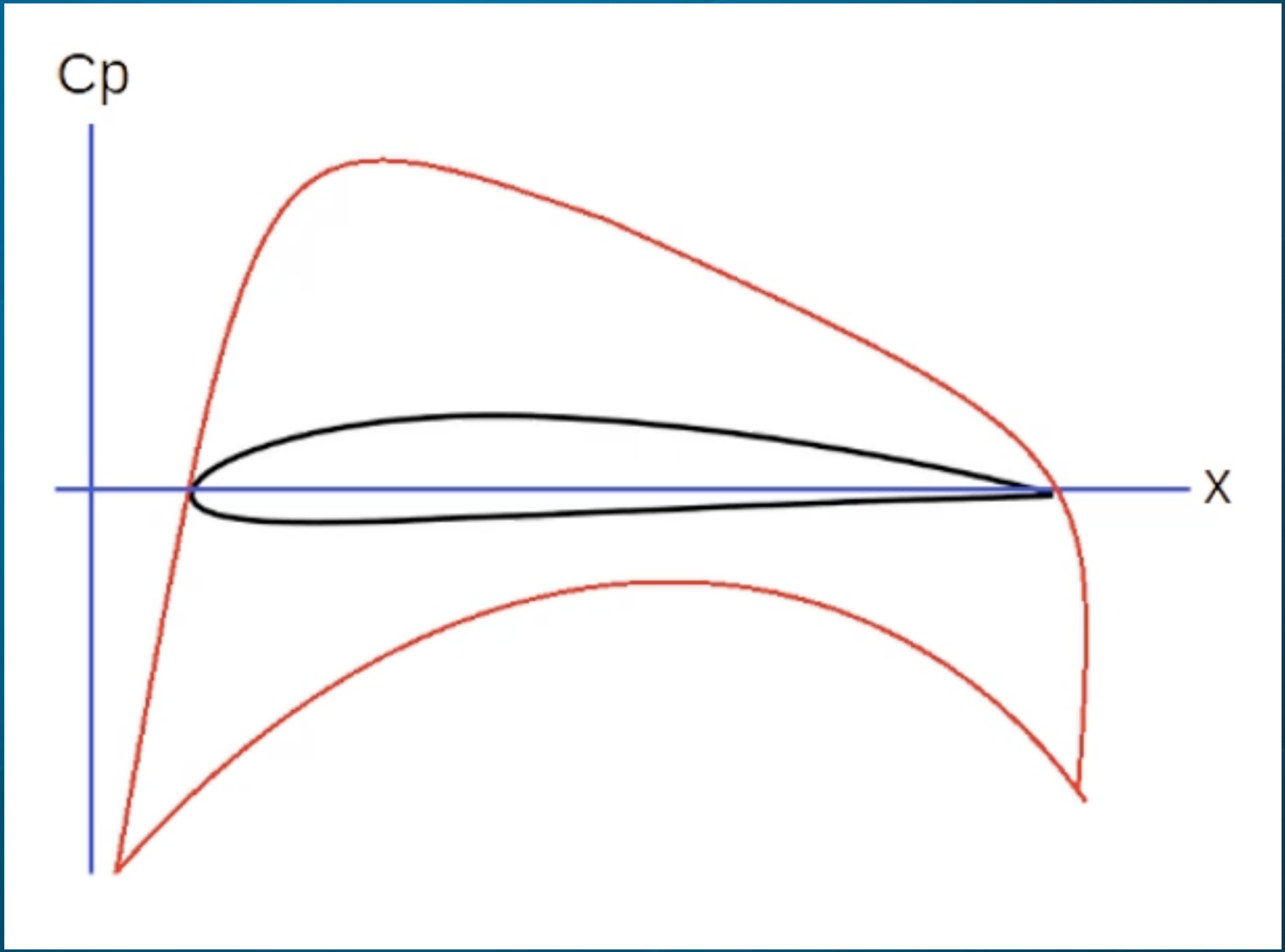
Third digit: 0 = normal camber line,
1 = reflexed camber line (C_M = ~0)

Last two digits denote maximum thickness

NACA 5-digit series examples



Pressure Distribution



About complex numbers

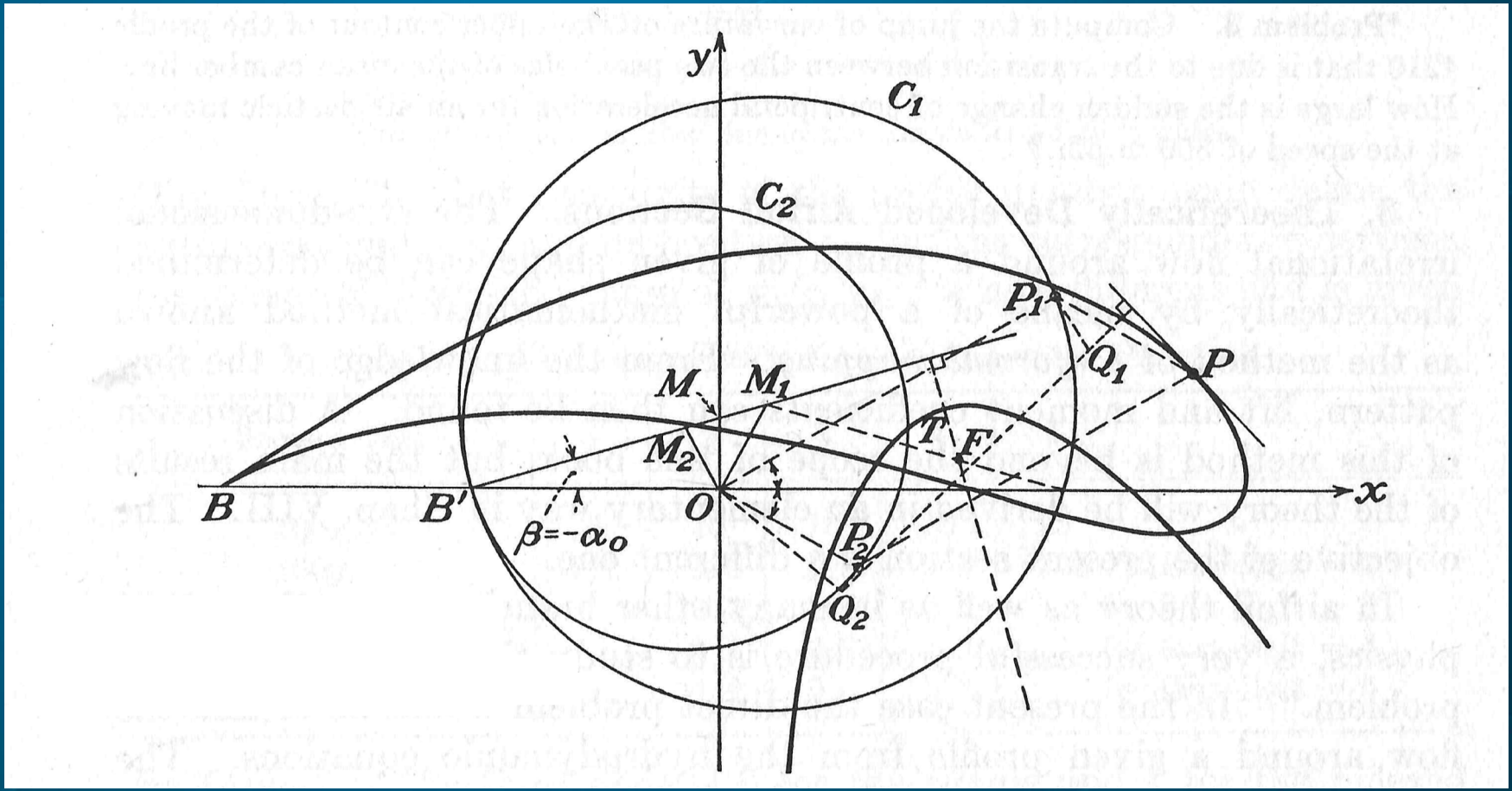
A complex number is a number of form $a + bi$ where a and b are real numbers and i is an imaginary unit ($i^2 = -1$). So there's a real part and an imaginary part.

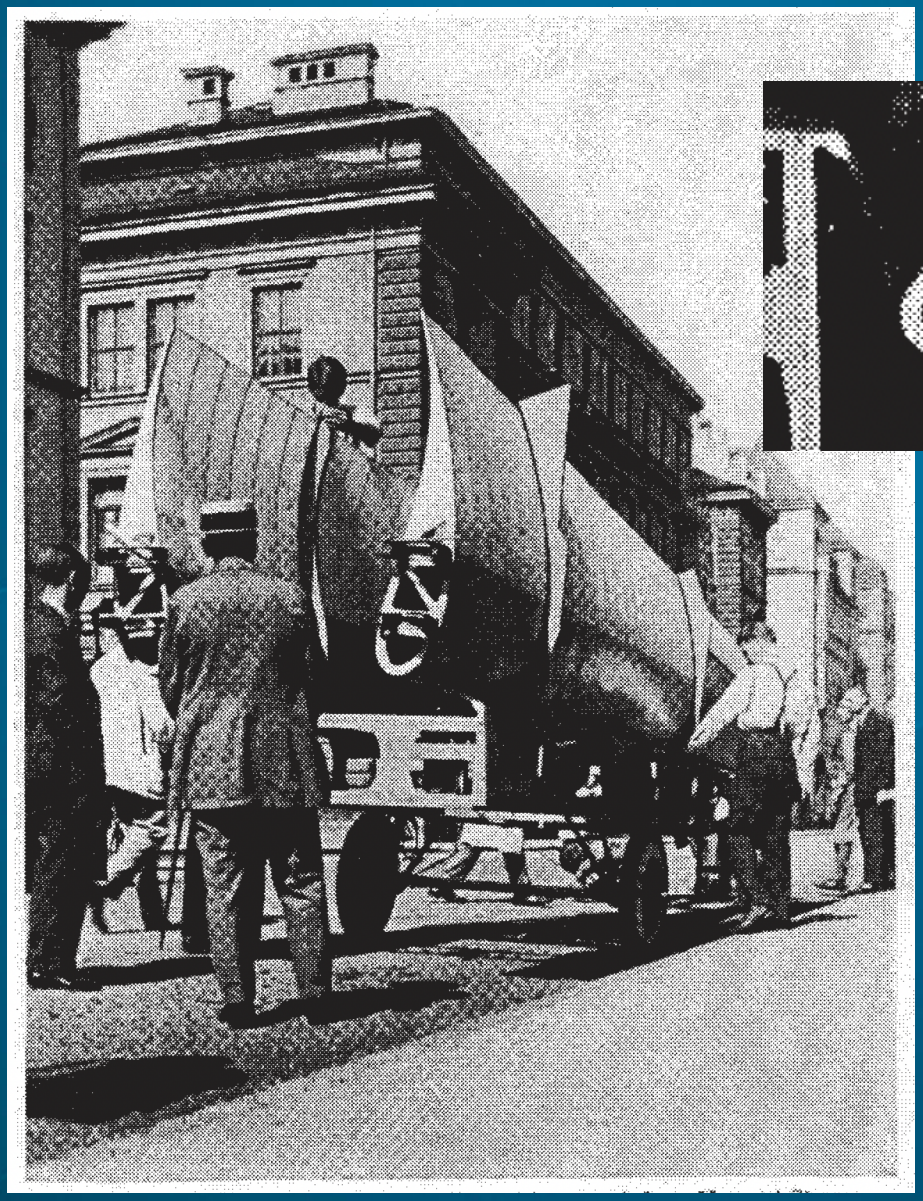
$3 + 4i$ & $-2 - i$ are complex numbers

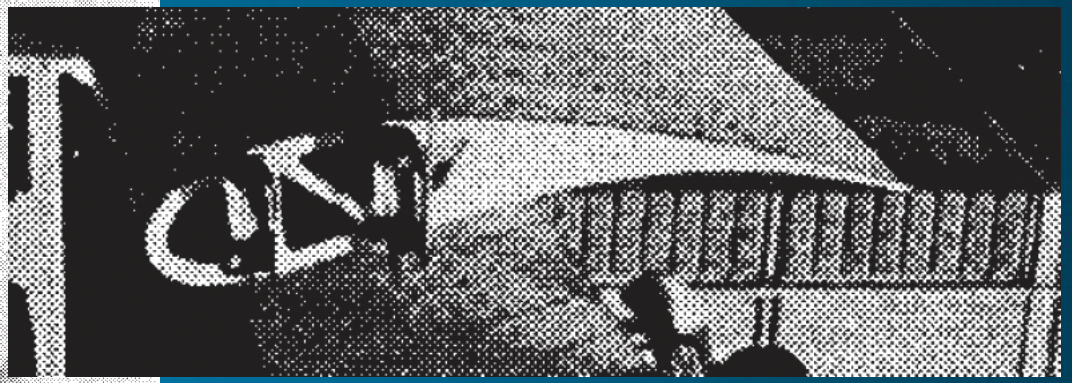
$1 + 0i$ is a real number only

$0 + 5i$ is an imaginary number only

The Joukovsky Transform - 1910



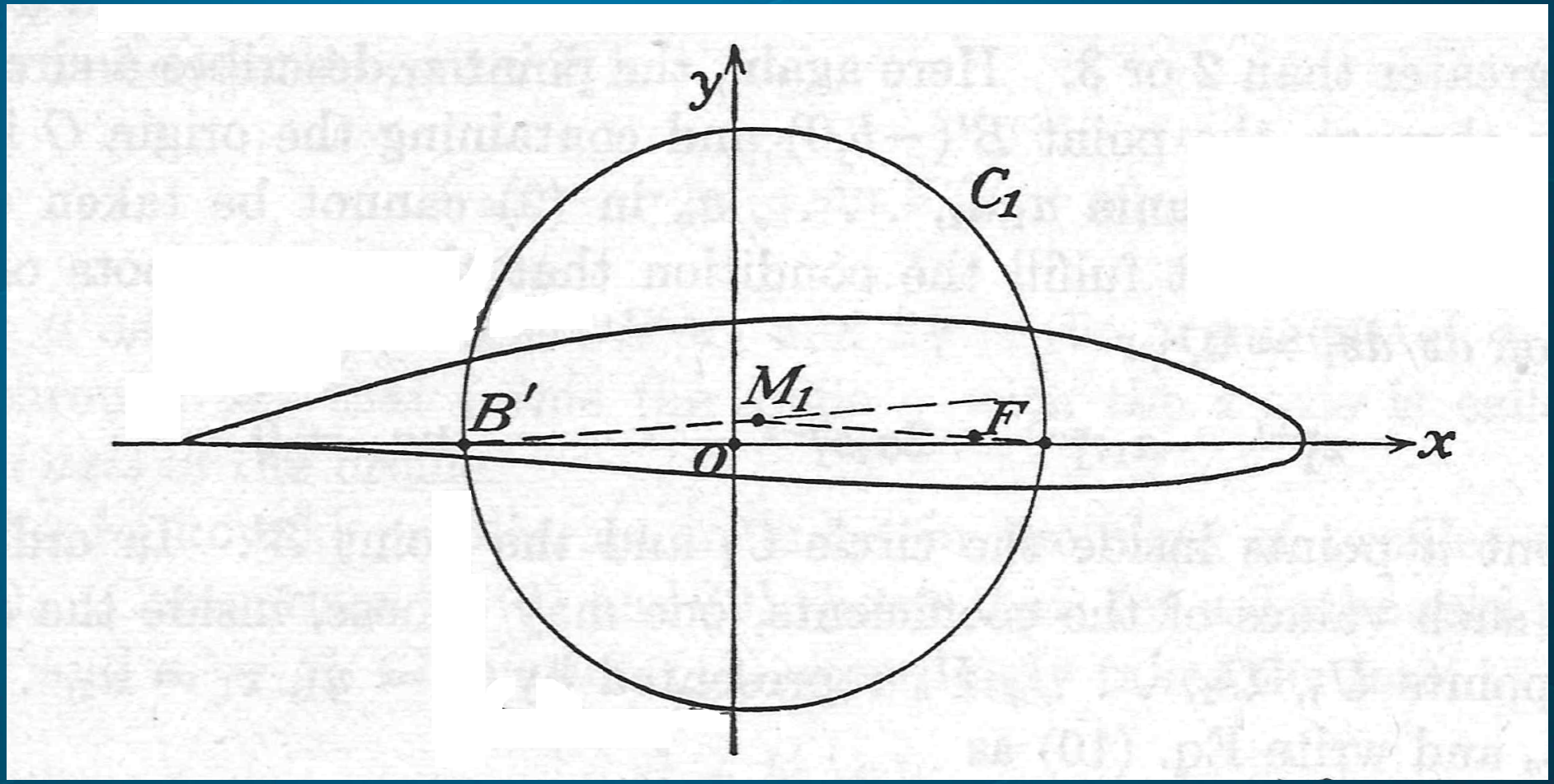




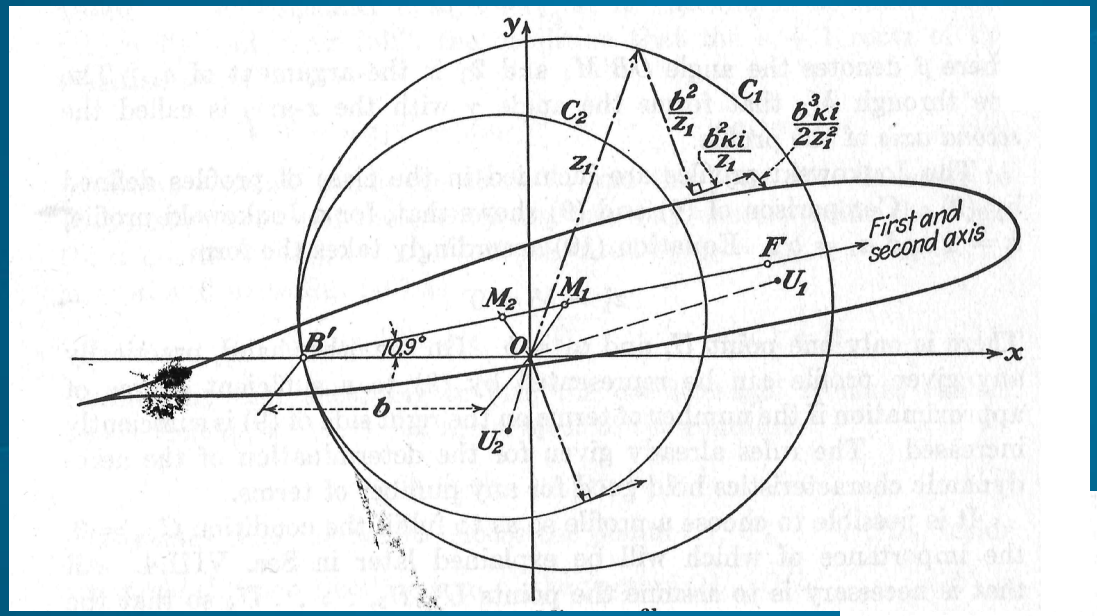
A glider, made by Munich college students, ready for shipment, ready for shipment to the Wasserkuppe flying ground.

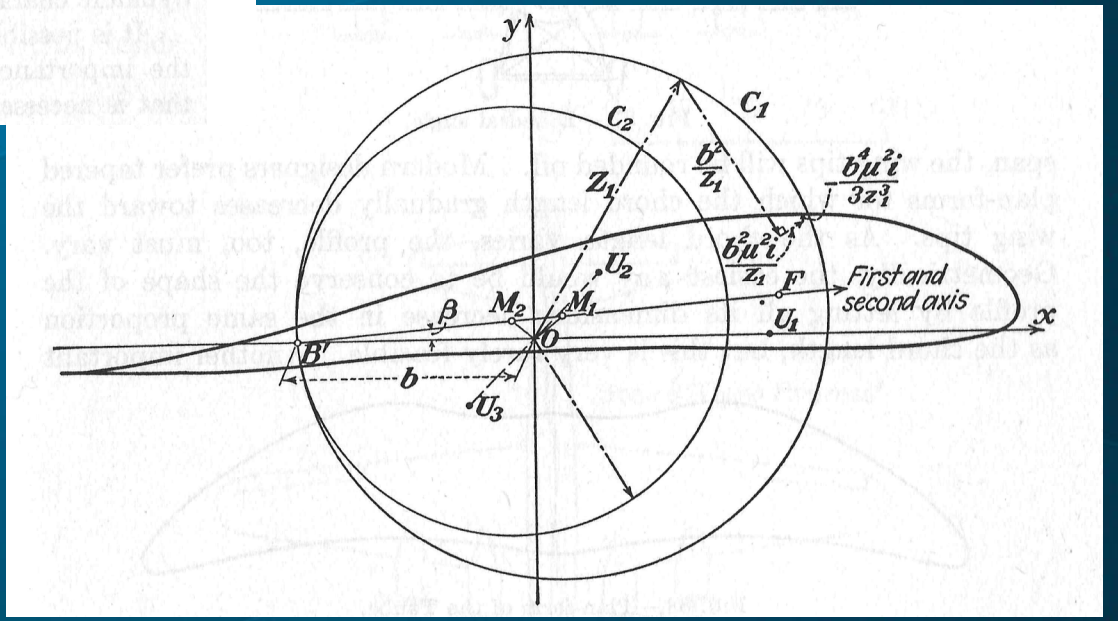
National Geographic, June 1929

Karman-Trefftz Transform - 1911



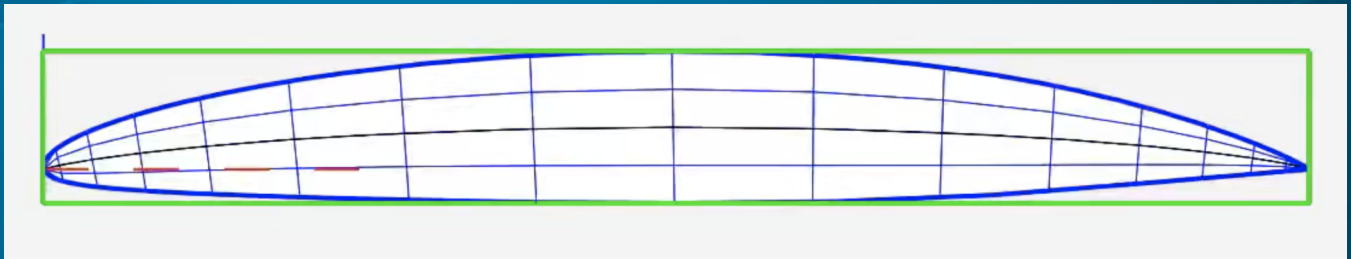
Mises Transform - 1921

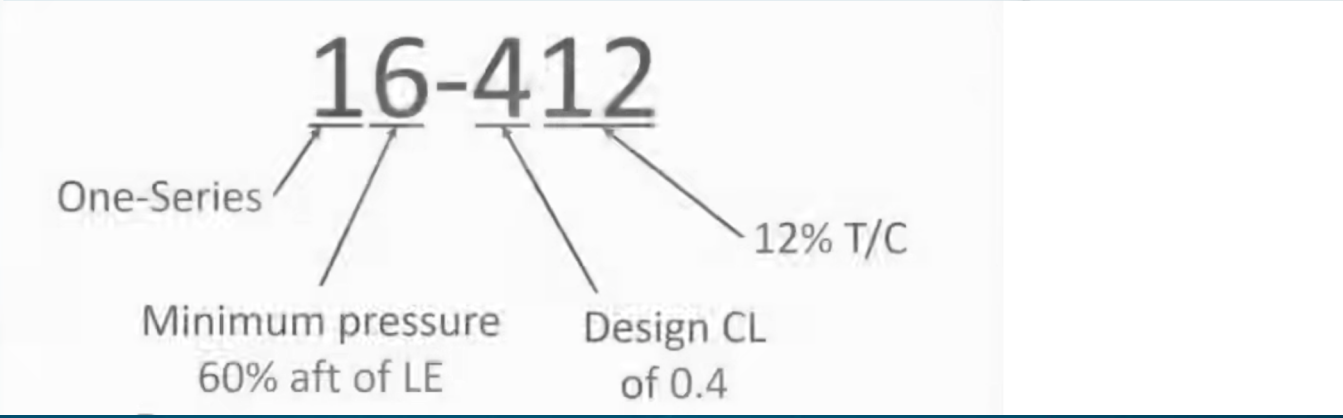




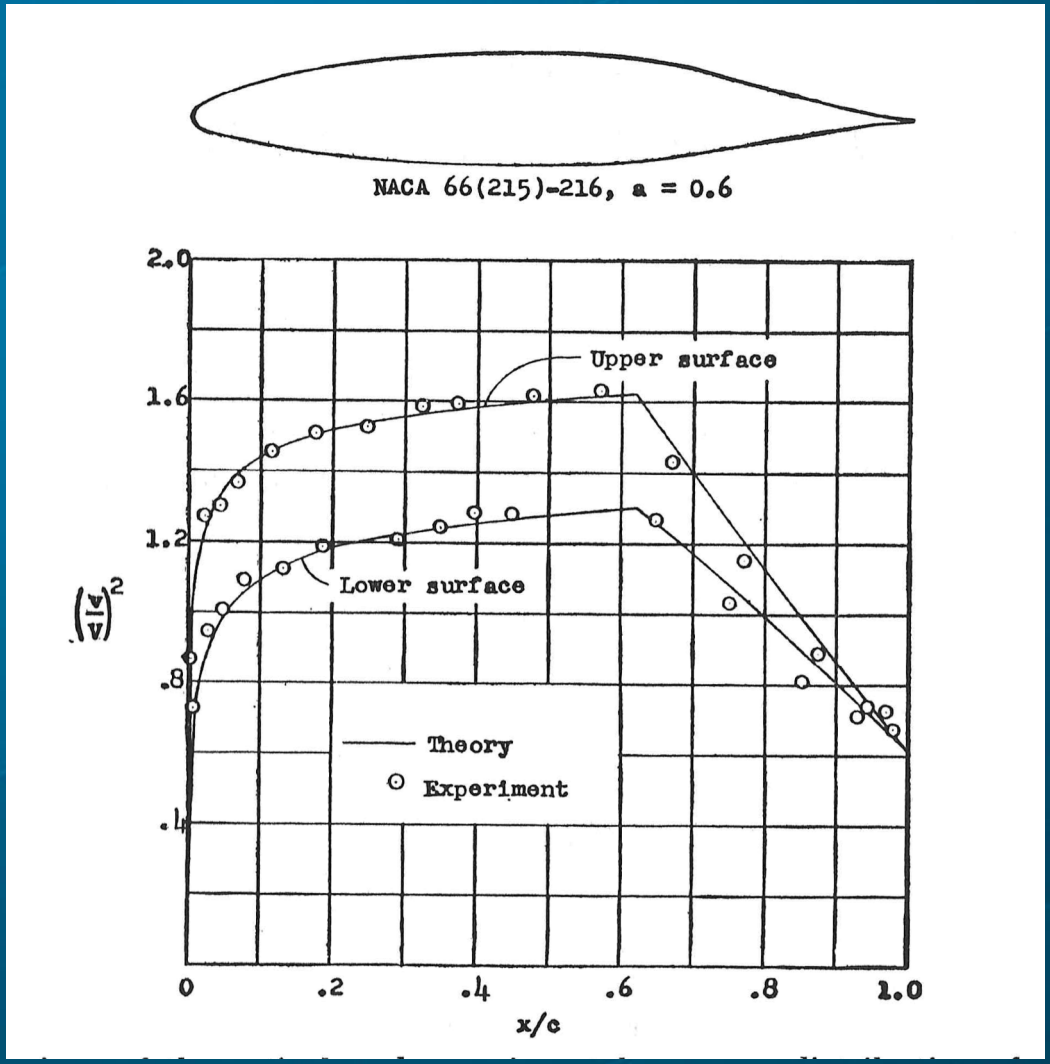
NACA 1-series

First attempt to develop sections with a desired pressure distribution

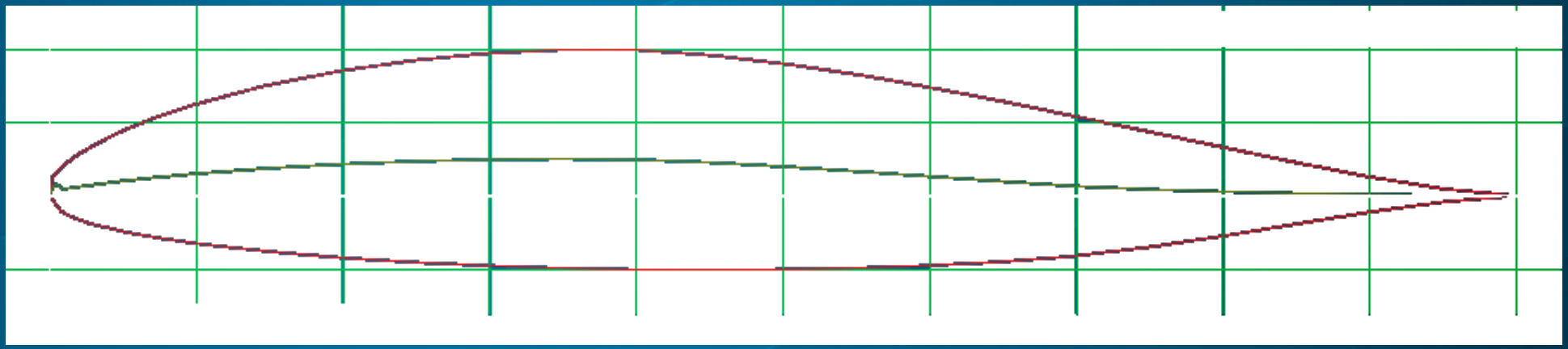




1930s-1940s - NACA 6-series sections



1940s-1950s - NACA 7-series

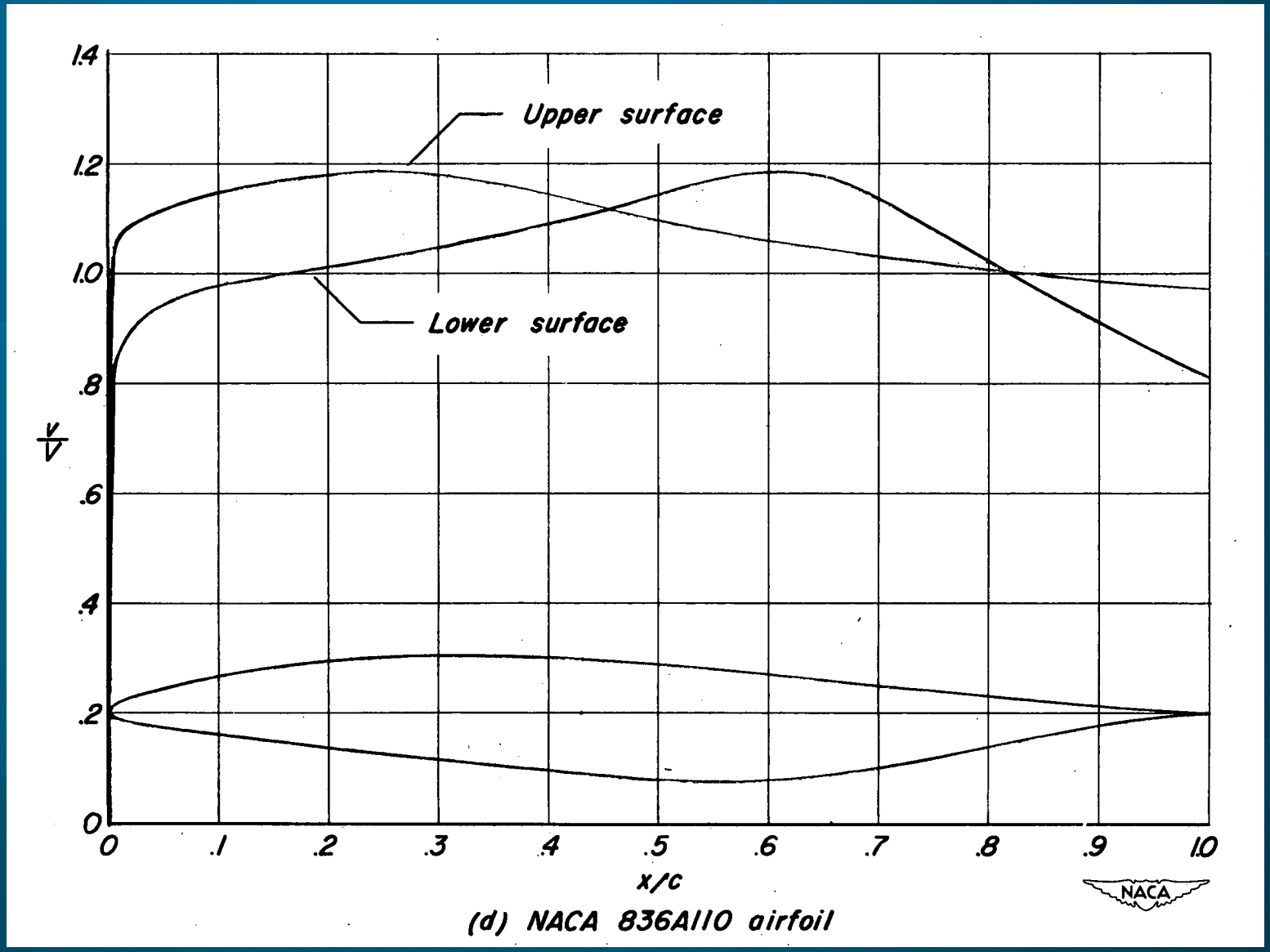


NACA 747A315

1960s – 8-series sections

- Final variation of the 6-series and 7-series
- Greater laminar flow over upper and lower surfaces and controls developing shock wave at transonic speeds
- Low pitching moment, high lift
- First of the ”supercritical” sections
- Evolved further through work of Richard T. Whitcomb

NACA 836A110



Now what?

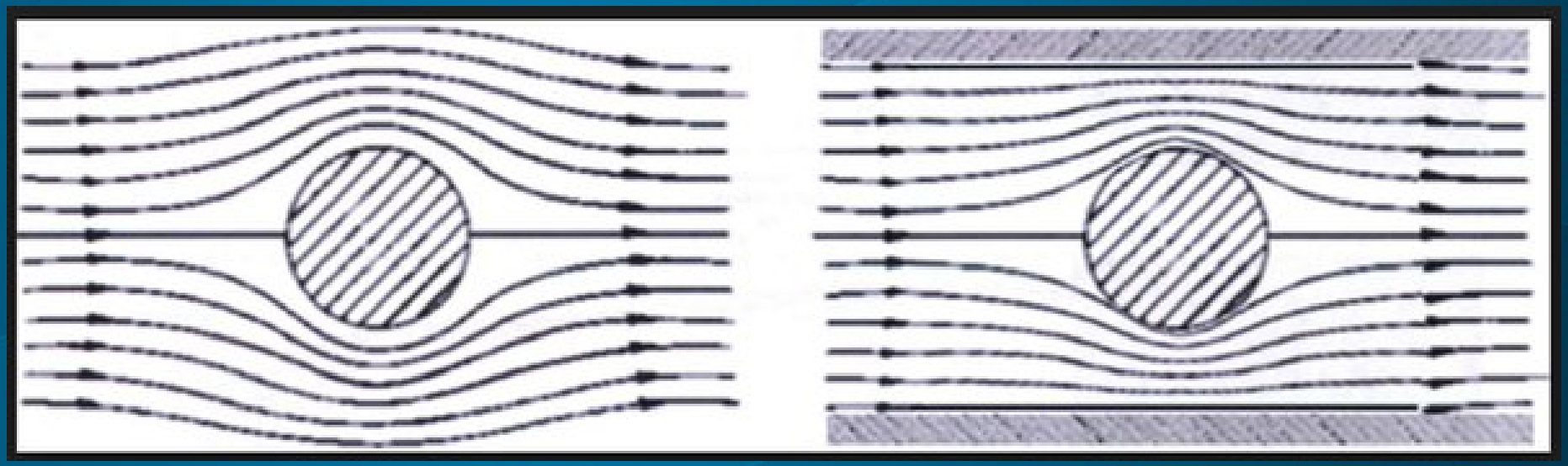
Airfoil Development Changes Course

- Newer transform processes
- Use of Computational Fluid Dynamics (CFD) Panel and Vortex Lattice Method
- Operation in two directions (pressure distribution to coordinates and coordinates to pressure distribution)
- Accounting for the boundary layer (viscid versus inviscid flow)
- **Valid data for Lower Reynolds numbers**

Prof. Dr. Richard Eppler

PROFILE

Dr. Eppler's philosophy



- Wind tunnel results do not necessrily match results from free flight
- More reliable to compare the results of two airfoils via computer programs than two wind tunnels

Dr. Richard Eppler's *PROFILE*

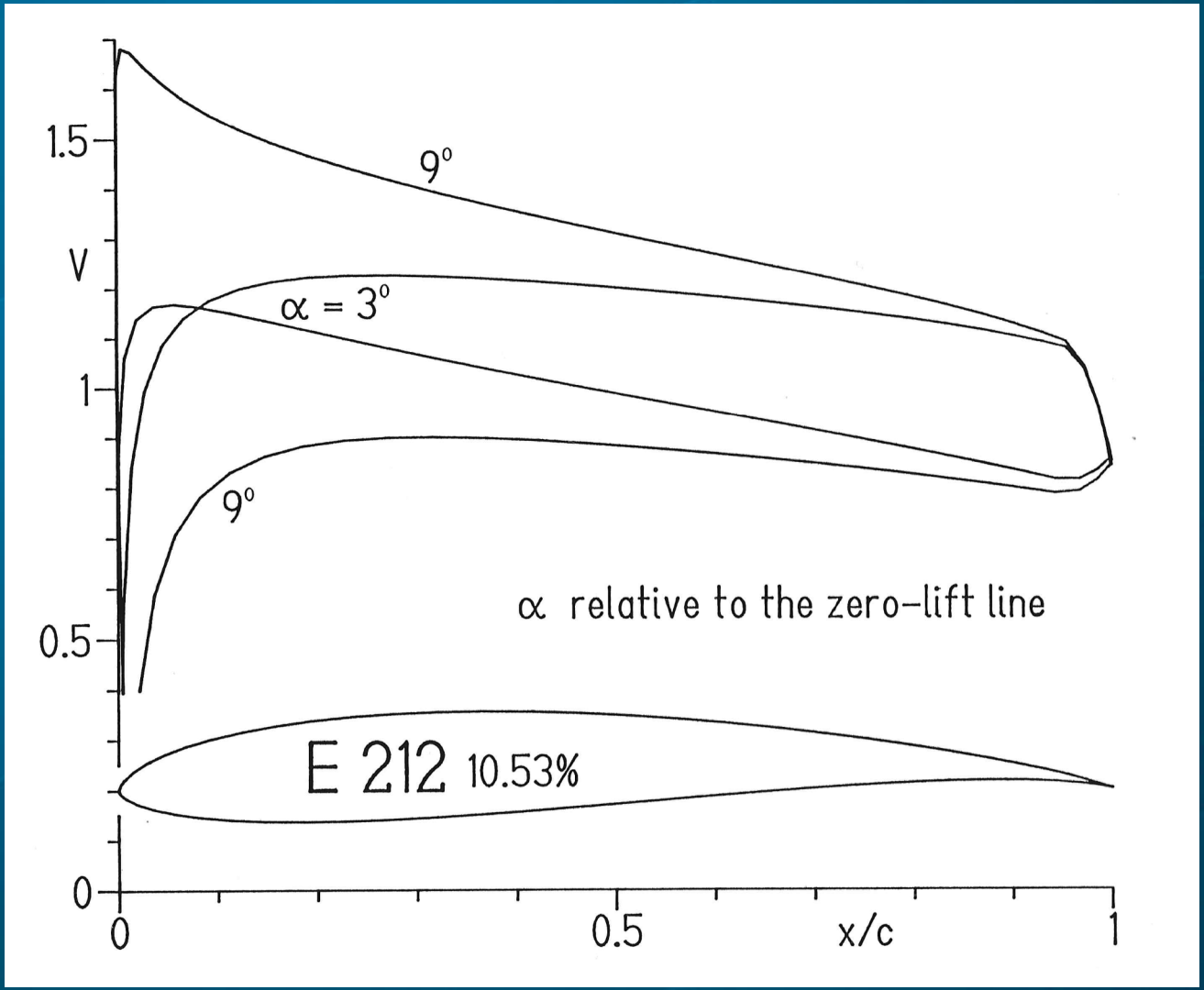
- Starts with a velocity distribution and uses conformal mapping to construct an airfoil

OR

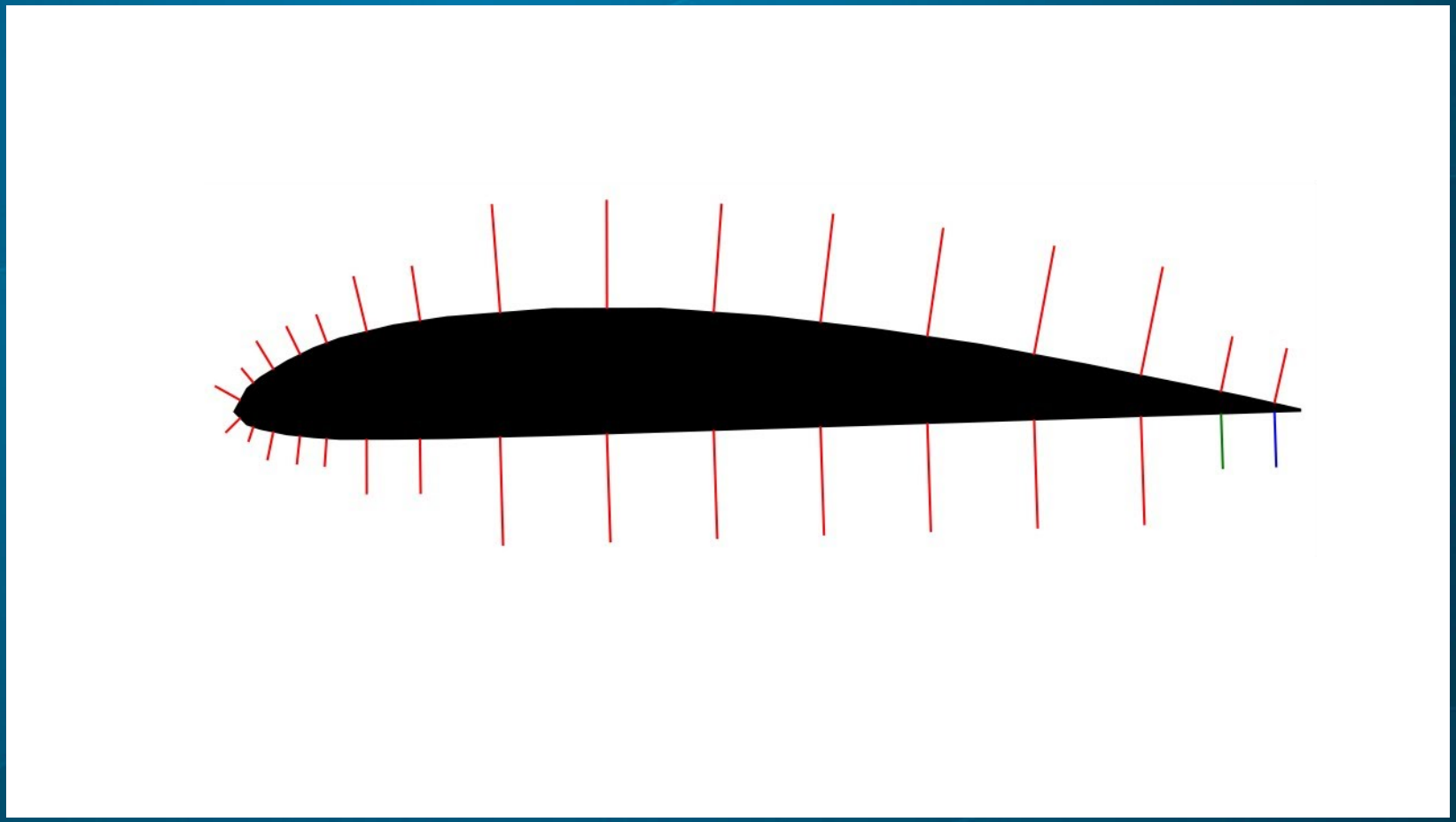
- Starts with airfoil coordinates and uses a panel method to determine the velocity distribution

- Revised version accounts for boundary layer growth and provides bubble warnings

Eppler 212 Velocity Distribution



Panel method

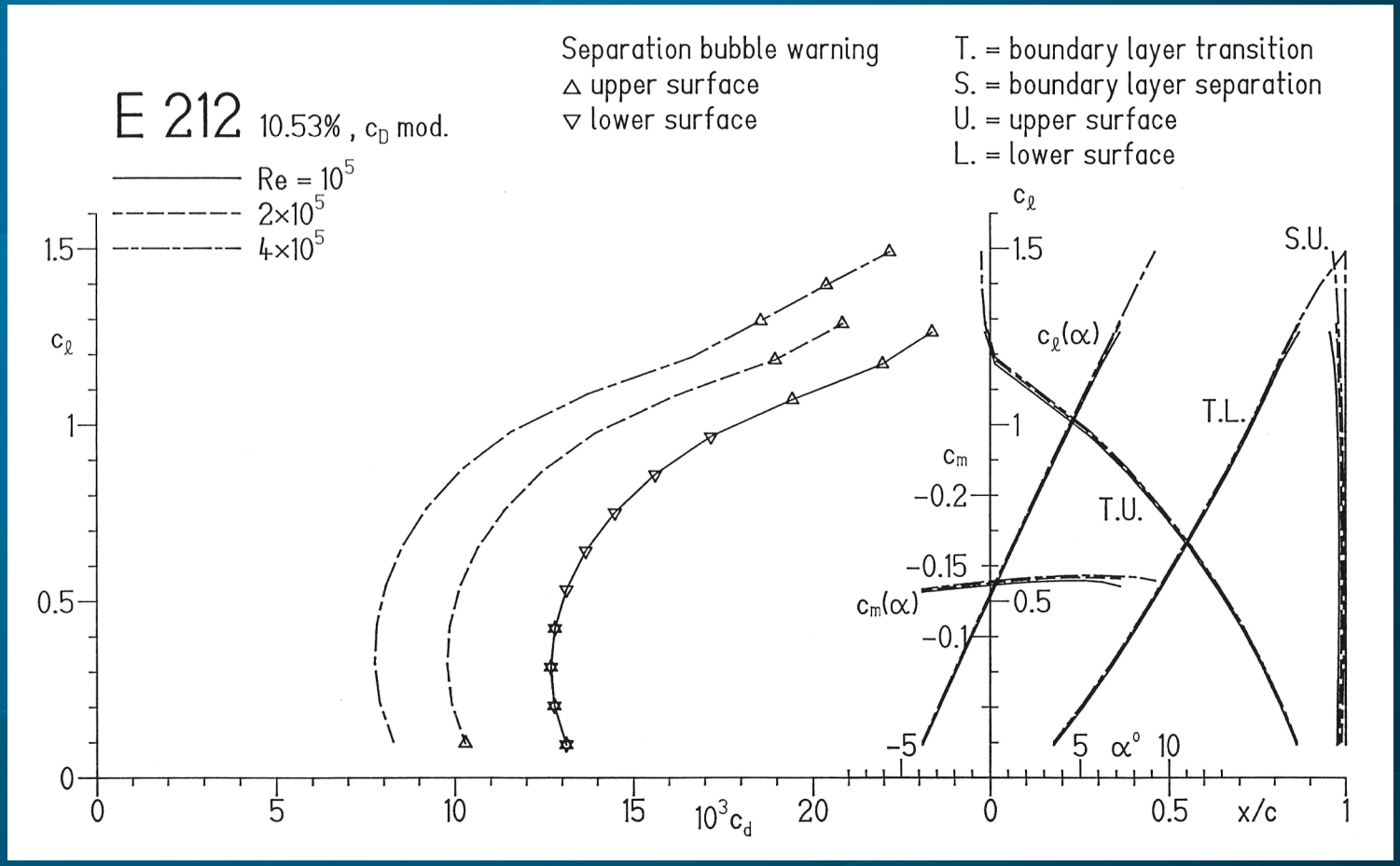


Eppler 212 Polar & Coordinates

E 212 10.54%

X	Y
100.000	0.000
99.676	0.092
98.760	0.372
97.347	0.805
95.475	1.310
93.129	1.848
90.321	2.423
87.092	3.031
83.482	3.655
79.535	4.282
75.295	4.897
70.809	5.484
66.127	6.031
61.298	6.522
56.373	6.945
51.403	7.289
46.437	7.544
41.524	7.701
36.712	7.753
32.048	7.695
27.573	7.525
23.329	7.243
19.353	6.851
15.679	6.356
12.337	5.764
9.356	5.089
6.758	4.342
4.563	3.541
2.787	2.705
1.439	1.860
0.527	1.038
0.196	0.582
0.087	0.364
0.038	0.227
0.008	0.098
0.002	0.037
0.001	-0.021
0.007	-0.075
0.023	-0.127
0.048	-0.181
0.080	-0.236
0.162	-0.347
0.267	-0.461
0.465	-0.635
0.809	-0.875
1.992	-1.439
3.657	-1.954
5.787	-2.397
8.370	-2.753
11.386	-3.013
14.814	-3.171
18.627	-3.224
22.796	-3.175
27.285	-3.030
32.056	-2.796
37.064	-2.488
42.261	-2.120
47.594	-1.709
53.007	-1.275
58.437	-0.838
63.822	-0.417
69.093	-0.033
74.181	0.297
79.017	0.555
83.530	0.730
87.644	0.807
91.285	0.785
94.382	0.665
96.851	0.461
98.615	0.233
99.657	0.061
100.000	-0.000

BETA= 4.81 DEG.
CM0=-0.1343



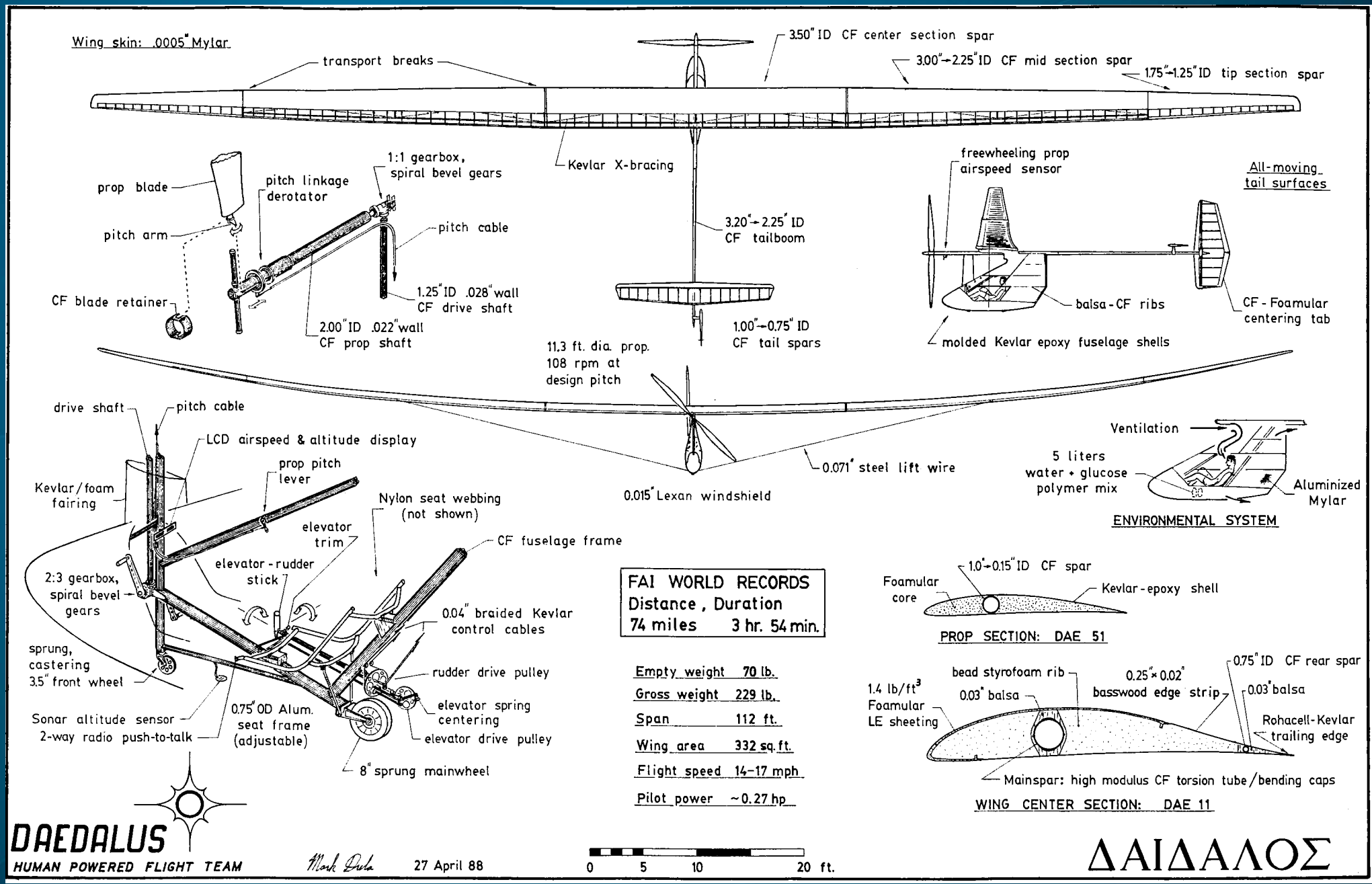
Dr. Mark Drela

XFoil

Daedalus, human-powered aircraft



On April 23, 1988, the Daedalus 88 aircraft, piloted by Greek Olympic cyclist Kanellos Kanellopoulos, flew 115.11 km (71.53 mi) from Heraklion, Crete, to the island of Santorini in 3 hours and 54 minutes. This flight set official FAI world records for total distance, straight-line distance, and duration for human-powered aircraft.


Wing skin: .0005" Mylar
transport breaks
3.50" ID CF center section spar
3.00"→2.25" ID CF mid section spar
1.75"→1.25" ID tip section spar
Kevlar X-bracing
prop blade
pitch arm
pitch linkage derotator
1:1 gearbox, spiral bevel gears
pitch cable
CF blade retainer
1.25" ID .028" wall CF drive shaft
2.00" ID .022" wall CF prop shaft
3.20"→2.25" ID CF tailboom
1.00"→0.75" ID CF tail spars
freewheeling prop airspeed sensor
All-moving tail surfaces
balsa-CF ribs
CF-Foamular centering tab
molded Kevlar epoxy fuselage shells
11.3 ft. dia. prop. 108 rpm at design pitch
0.071" steel lift wire
0.015" Lexan windshield
drive shaft
pitch cable
LCD airspeed & altitude display
prop pitch lever
Kevlar/foam fairing
Nylon seat webbing (not shown)
elevator trim
CF fuselage frame
elevator-rudder stick
2:3 gearbox, spiral bevel gears
0.04" braided Kevlar control cables
sprung, castering 3.5" front wheel
rudder drive pulley
elevator spring centering
elevator drive pulley
Sonar altitude sensor
2-way radio push-to-talk
0.75" OD Alum. seat frame (adjustable)
8" sprung mainwheel
Ventilation
5 liters water + glucose polymer mix
Aluminized Mylar
ENVIRONMENTAL SYSTEM
1.0"→0.15" ID CF spar
Foamular core
Kevlar-epoxy shell
PROP SECTION: DAE 51
bead styrofoam rib
0.25" × 0.02" basswood edge strip
0.75" ID CF rear spar
0.03" balsa
1.4 lb/ft³ Foamular LE sheeting
Rohacell-Kevlar trailing edge
Mainspar: high modulus CF torsion tube/bending caps
WING CENTER SECTION: DAE 11
FAI WORLD RECORDS
Distance, Duration
74 miles 3 hr. 54 min.
Empty weight 70 lb.
Gross weight 229 lb.
Span 112 ft.
Wing area 332 sq. ft.
Flight speed 14-17 mph
Pilot power ~0.27 hp
DAEDALUS
HUMAN POWERED FLIGHT TEAM
Mark Drela
27 April 88
0 5 10 20 ft.
ΔΑΙΔΑΛΟΣ

Dr. Mark Drela's *XFoil*

- Uses either a complex mapping function or geometric parameters/coordinate tables

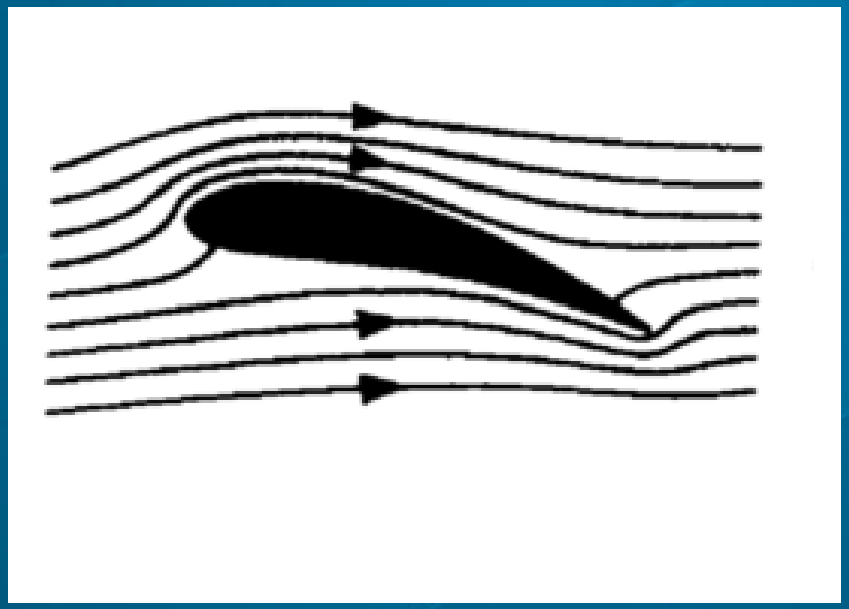
AND

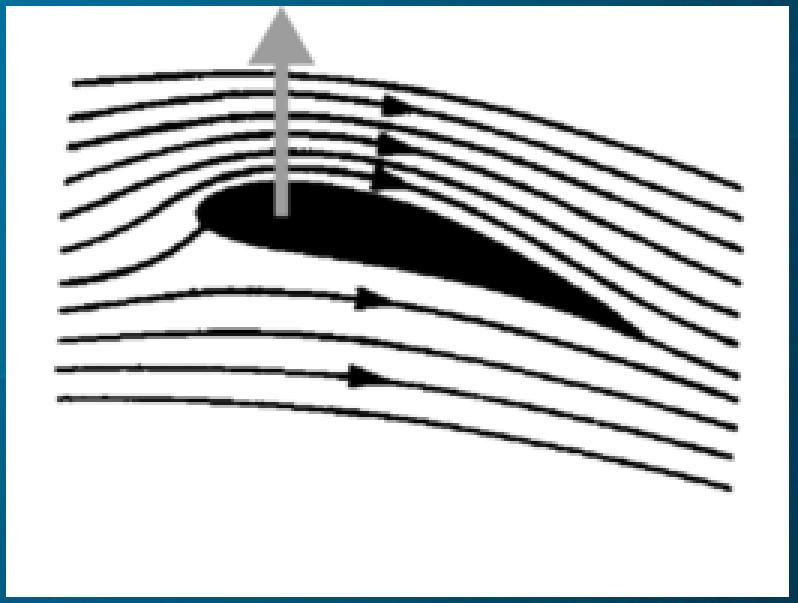
- Breaks the form into discrete segments (panel method)

THEN

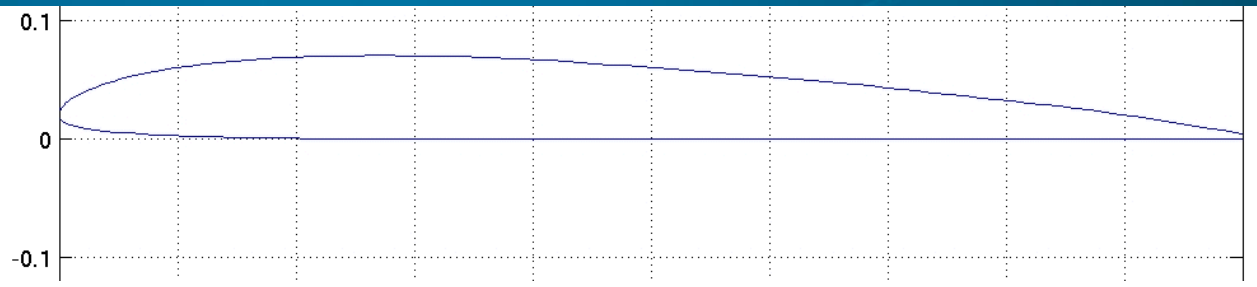
- Solves for flow over each segment/panel, first as inviscid flow, then adds corrections to solve for boundary layer with viscous flow

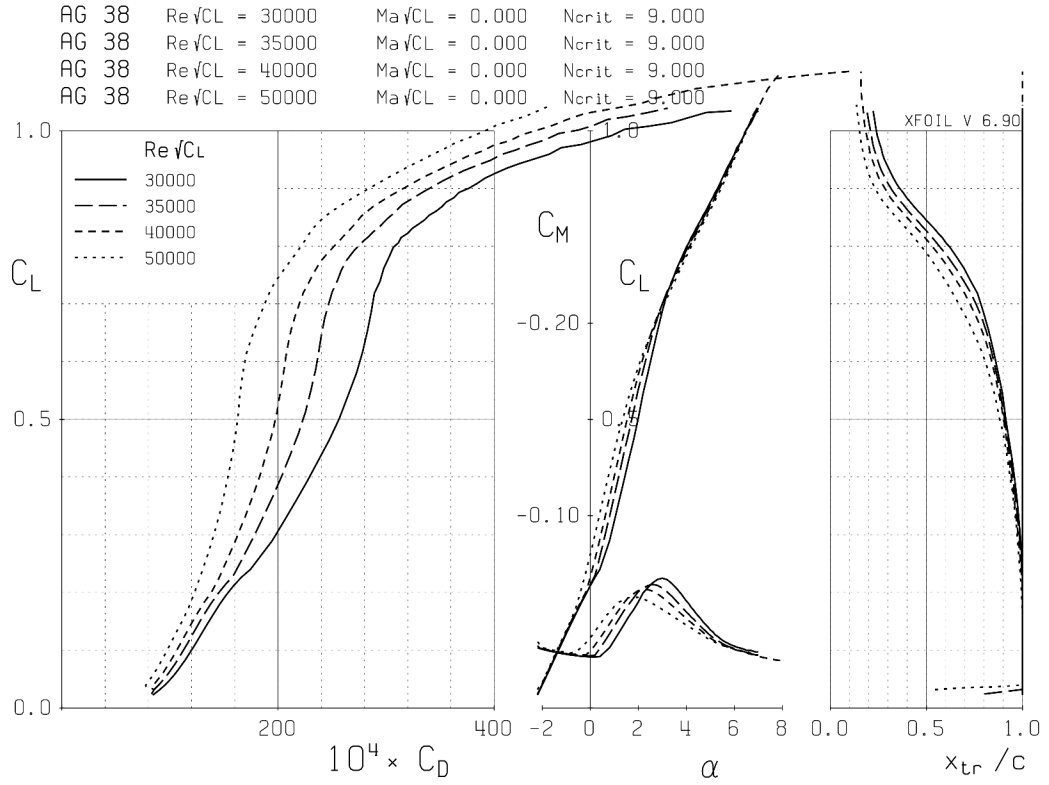
Inviscid flow and viscid flow





Drela AG38 polars





XFLR5

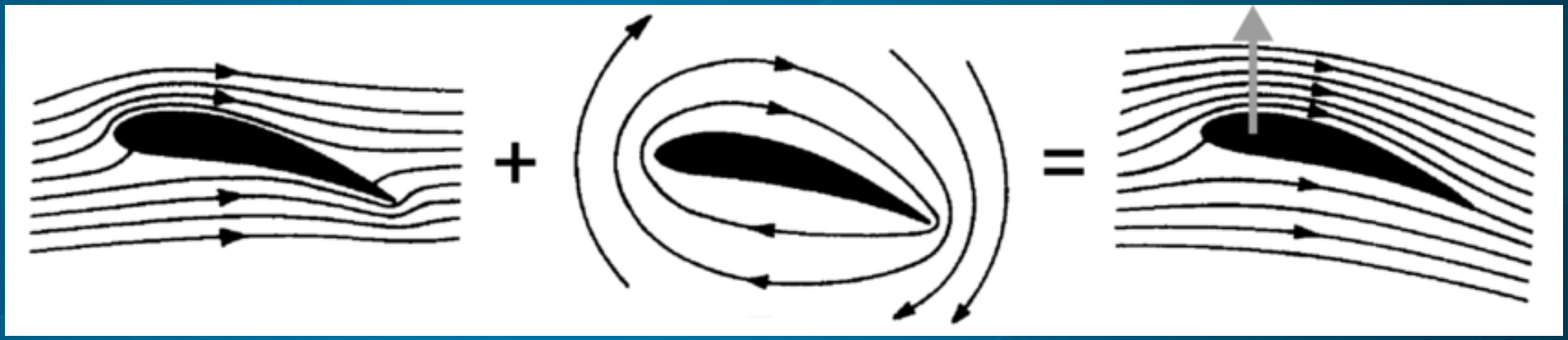
- XFLR5 is built upon XFoil's core 2D airfoil analysis capabilities with focus on low Re
- Imports and creates airfoils
- Performs 2D analysis of airfoil sections
- Uses Lifting Line Theory (LLT), Vortex Lattice Method (VLM), and 3D Panel Methods for wing (3D) analysis
- Can also perform stability analysis

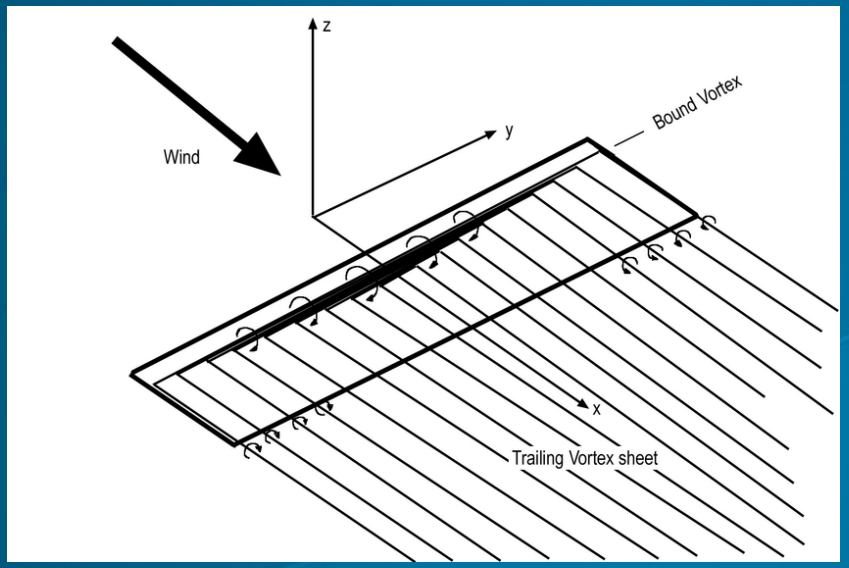
1896 and 1906 - Frederick W. Lanchester

Formulated a circulation theory of flight, now the foundation of airfoil theory, that accounts for downwash. Paper rejected in 1896.

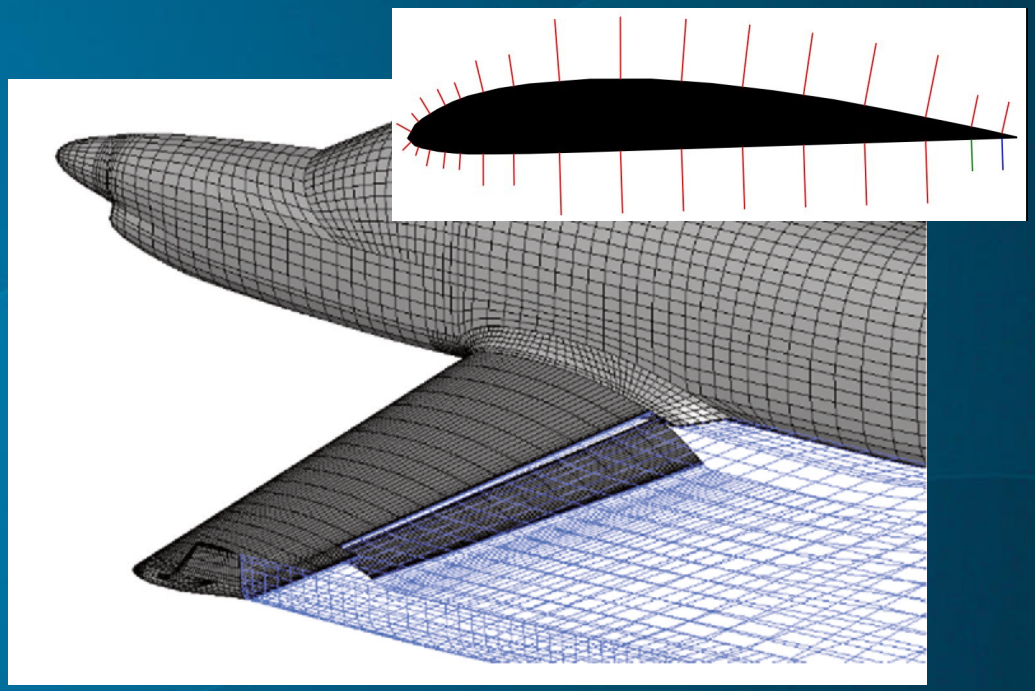
Published the first volume of *Aerial Flight* in 1906 where he presented his bound vortex ”lifting line” theory of lift. Ludwig Prandtl confirmed the theory and expanded it (1918-1919). Lanchester is now pretty much forgotten.

Circulation

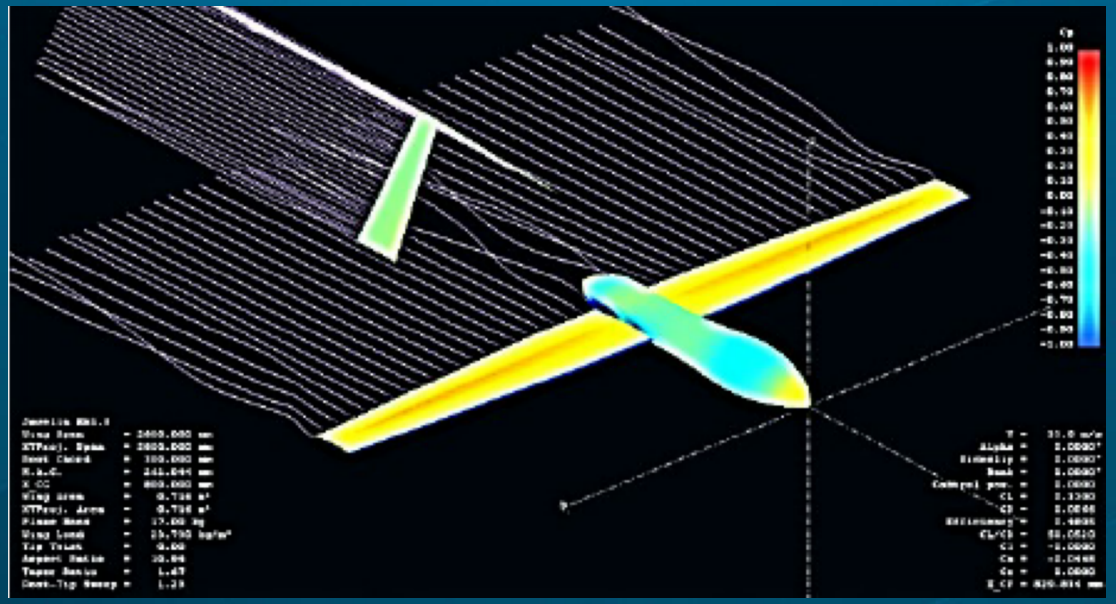




Lifting line theory
(Lanchester and Prandtl)

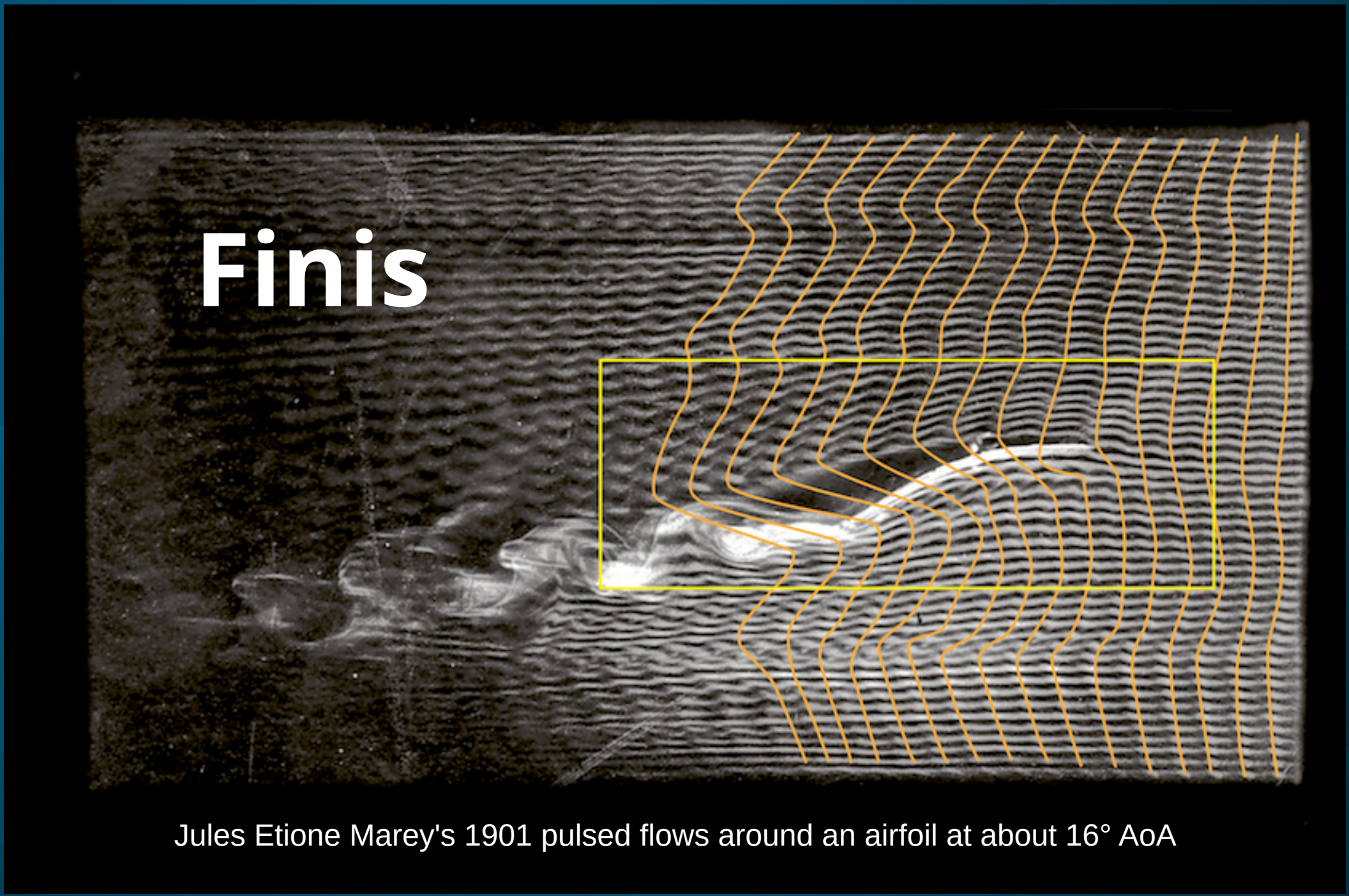


Panel method (2D &
3D)



Vortex lattice method
(2D representation of 3D
lifting surfaces)

http://www.mh-aerotools.de/



Jules Etione Marey's 1901 pulsed flows around an airfoil at about 16° AoA