HALE UAV: AeroVironment Pathfinder

Photo courtesy NASA Dryden Photo Gallery

Aerodynamic and Stability Analysis

Case Study: Planform Optimization

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Pathfinder History

- Designed and fabricated by AeroVironment in 1981
- Determined technology insufficient to support mutli-day duration flights under solar power and Pathfinder was put into storage
- In 1993, brought back to flight by Ballistic Missile Defense Organization
- Transferred to NASA in 1994 to support Environmental Research Aircraft and Sensor Technology (ERAST) program
- ERAST program demonstrated that a high AR, solar-powered lightweight craft could take off and land at an airport and fly at extremely high altitudes (50-80K ft)
- ERAST also determines feasibility of such UAVs for carrying instruments used in scientific studies

Photo courtesy NASA Dryden Photo Gallery

ERAST Milestones

- Sept. 11, 1995: Sets first altitude record for solar-powered aircraft at 50,000 ft during 12-hour flight
- October 21, 1995: Damaged in hangar mishap
- July 7, 1997: Sets new altitude record for solar-powered and propeller-driven aircraft at 71,530 ft
- Modified into the longer-winged Pathfinder Plus, still used for tests at NASA DFRC
- Aug. 6, 1998: Pathfinder Plus breaks old record with flight at altitude of 80,201 ft
- Aug. 13, 2001: Helios sets record at 96,863 ft in near 17-hour flight
- June 26, 2003: Helios lost in flight mishap near Kauai, Hawaii

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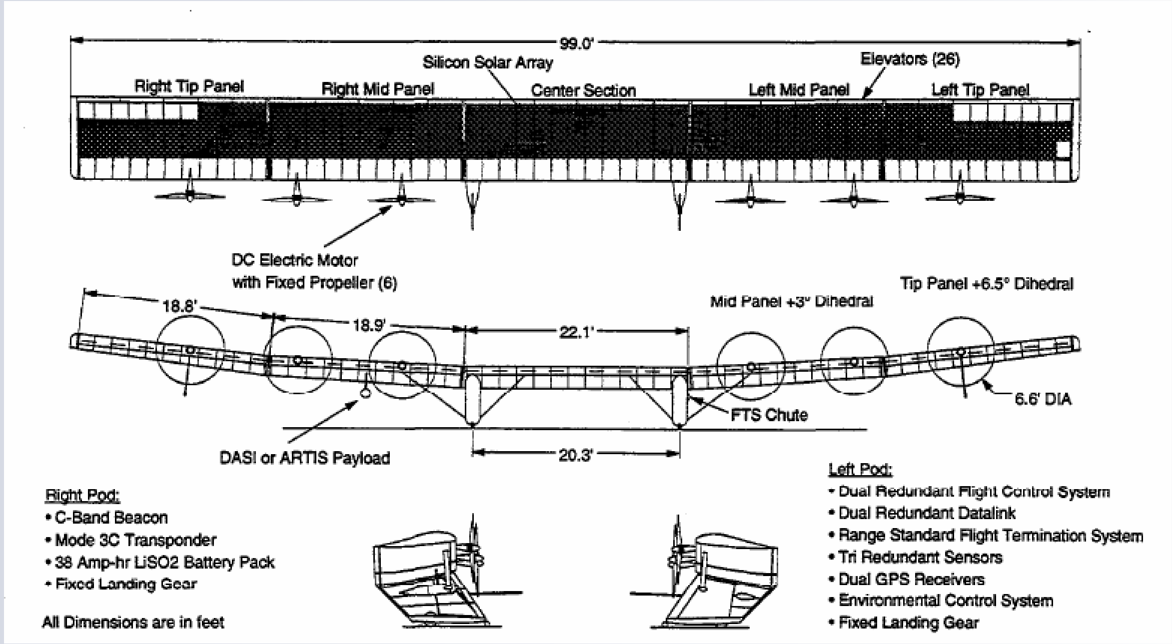
Pathfinder Configuration



Span: 99 ft

Chord: 8 ft

Wing Area: 792 ft^2

AR: 12.375

Elevator Chord: 0.89 ft

Elevators: 26 (full span)

x_{cg} : 0.5 in fwd LE

Center Panel: 22.1 ft span and 0° dihedral

Mid Panel: 18.9 ft span (each) and 3° dihedral

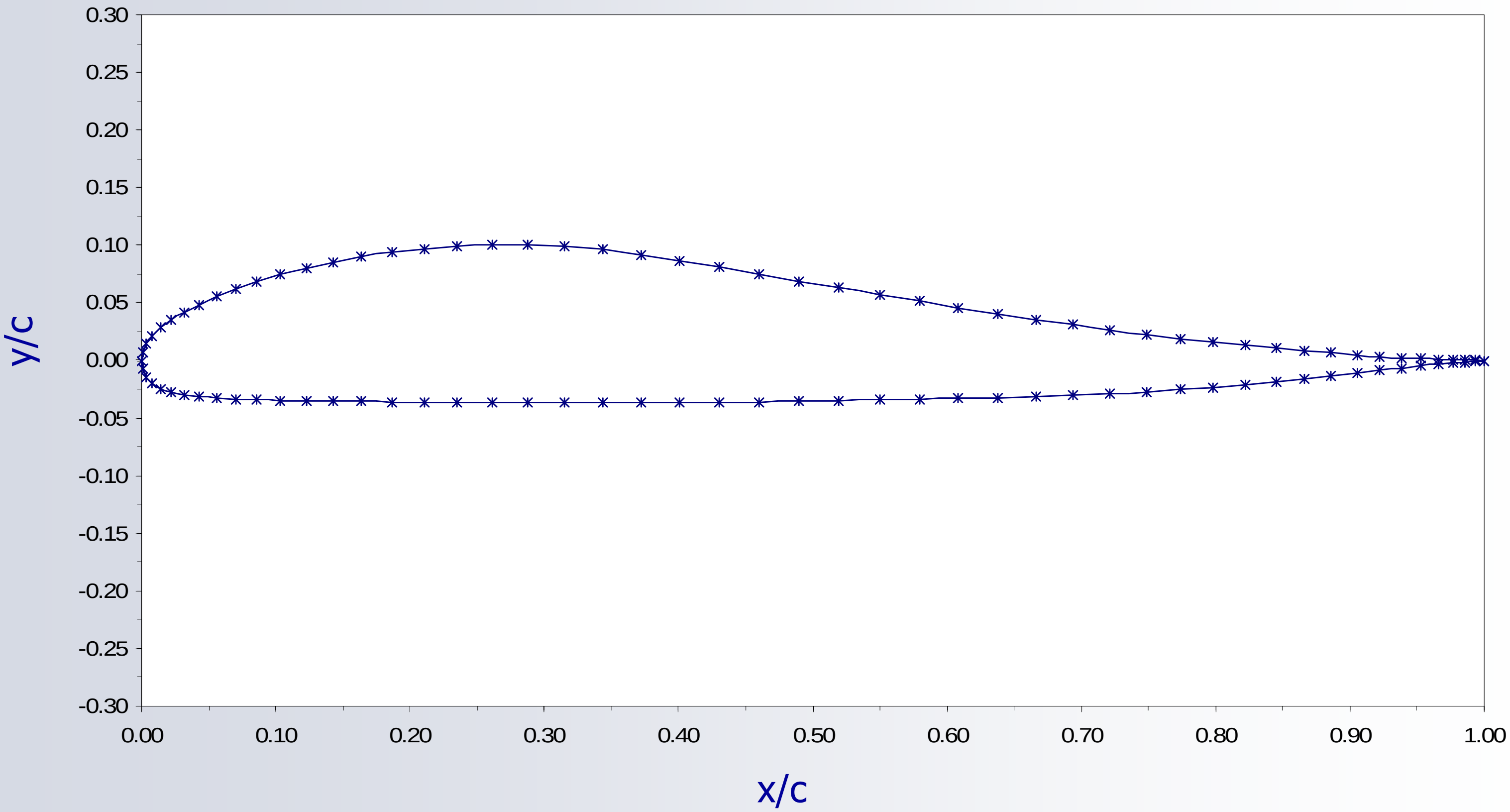
Tip Panel: 18.8 ft span (each) and 6.5° dihedral

Three-View Drawing courtesy AeroVironment, Inc.

Specs and Performance

- W=550 lbs (includes 50 lbs payload)
- - W/S=0.694 psf
- Solar array covers 75% of upper surface and can generate near 8000 W at solar noon
- Six gearless 1.5 hp electric motors consisting of fixed-pitched, 2-bladed 79-inch diameter props, brushless DC motor, nacelle, cooling fins, and composite mounting strut
- - T/W=0.10 at 60,000 ft, P/W = 13.6 W/lb
- Composed of carbon composite spar, lightweight composite ribs and transparent plastic wing skin
- - Can withstand 3.2g
- Flight speed of 94 ft/s at altitude of 60,000 ft

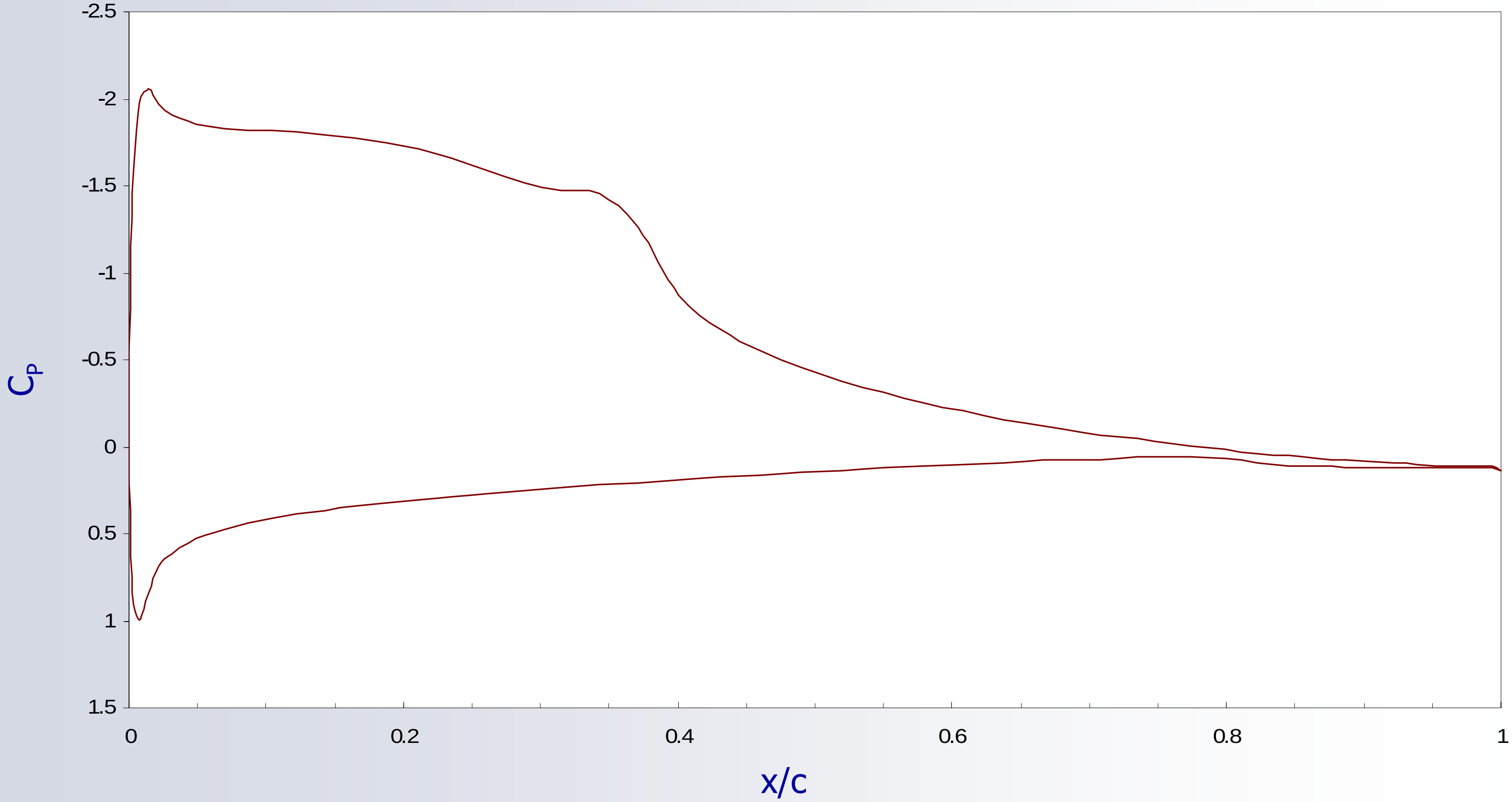
Airfoil: LA2573A



- Modified Liebeck Airfoil
- Max t/c = 0.137
- x/c of max t = 0.288

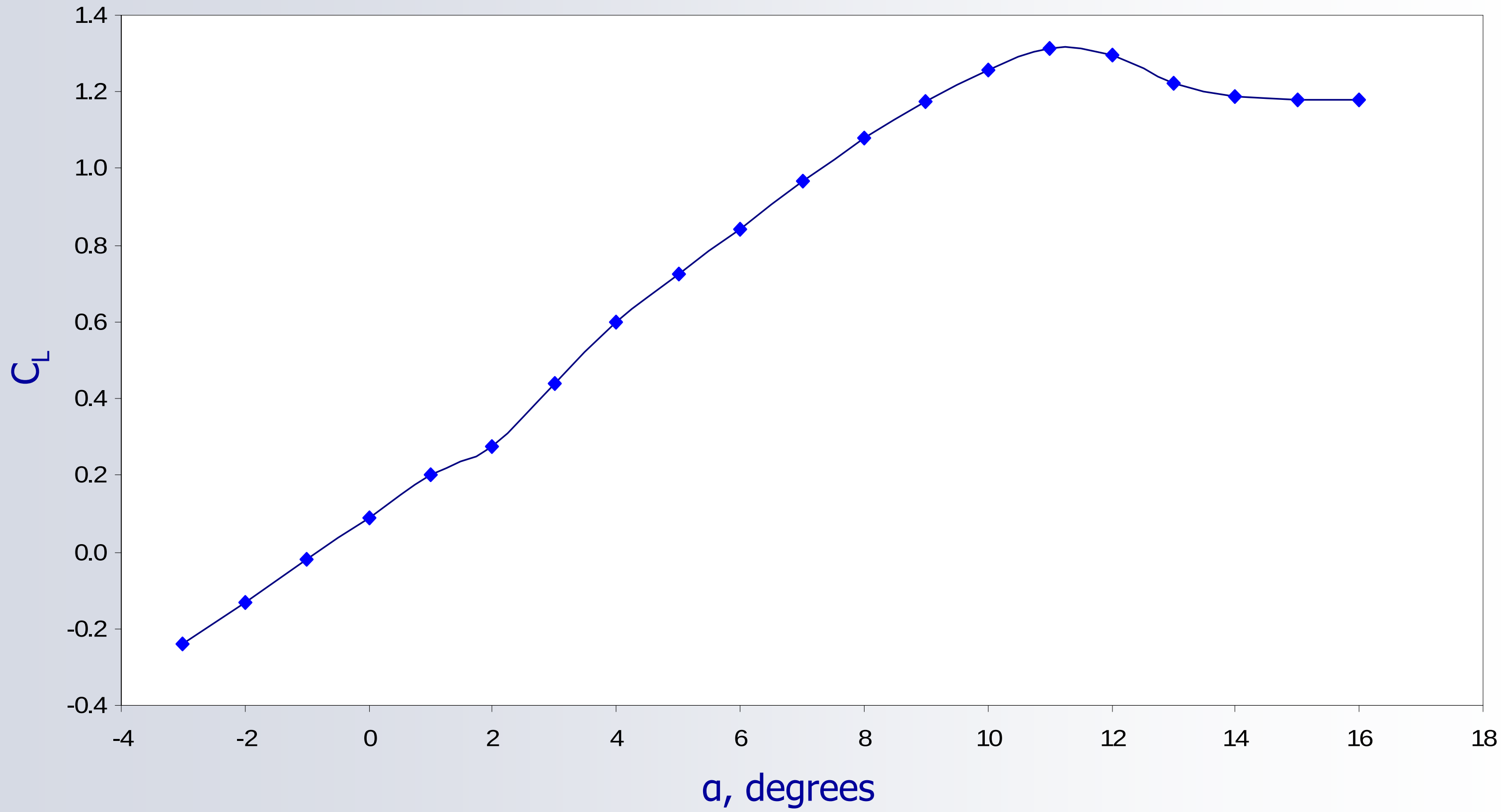
- Max camber/c = 0.032
- x/c of max camber = 0.261

Pressure Distribution



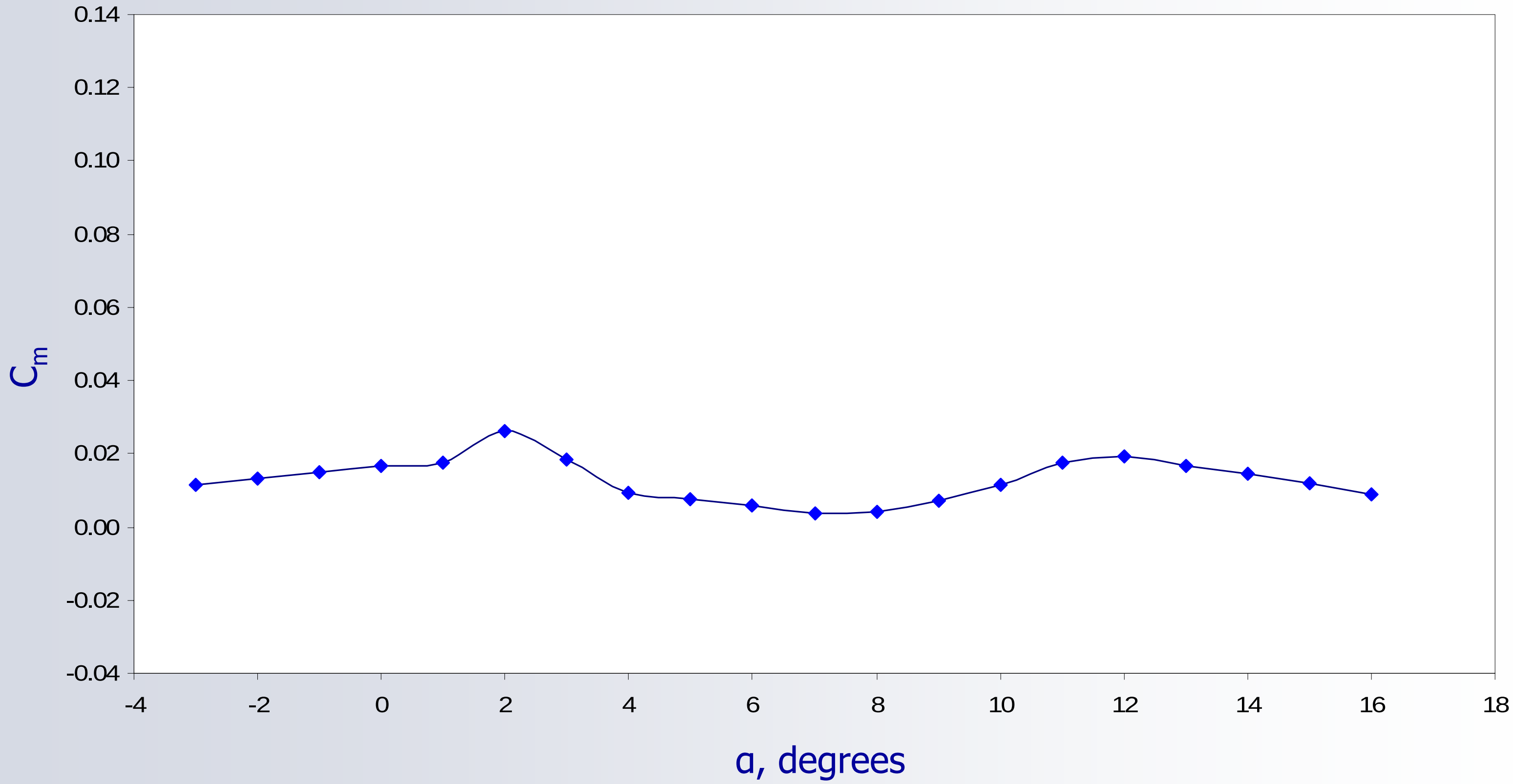
Angle of Attack = 7°

Lift Curve



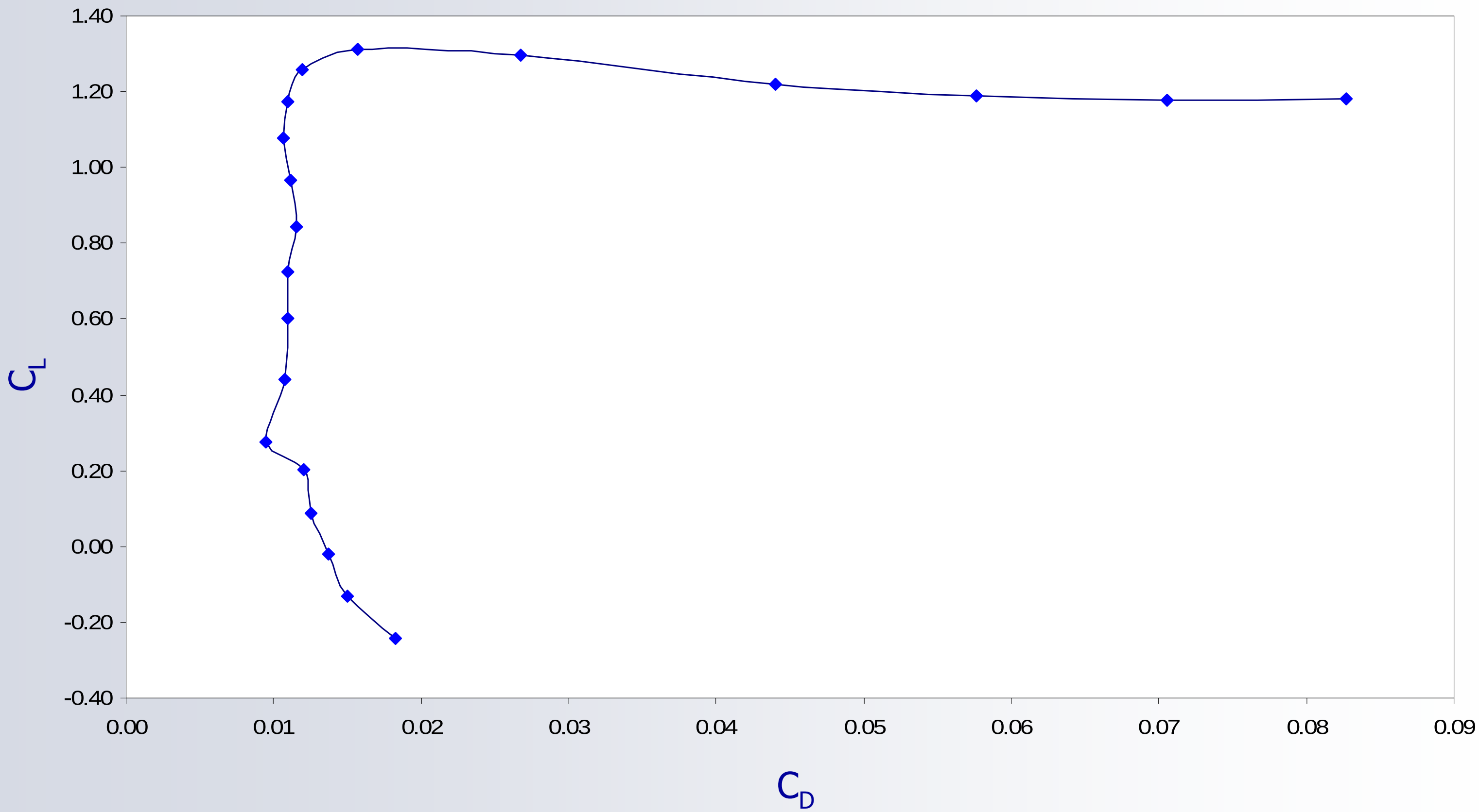
- $C_{L\alpha} = 6.97$
- $C_{Lmax} = 1.3$
- Stall occurs at $\alpha = 11°$
- Zero lift angle $\alpha = -0.82°$

Moment Curve



- $C_{m\alpha} = -0.03$
- Requires positive C_m to trim so must not exceed $\alpha = 18°$

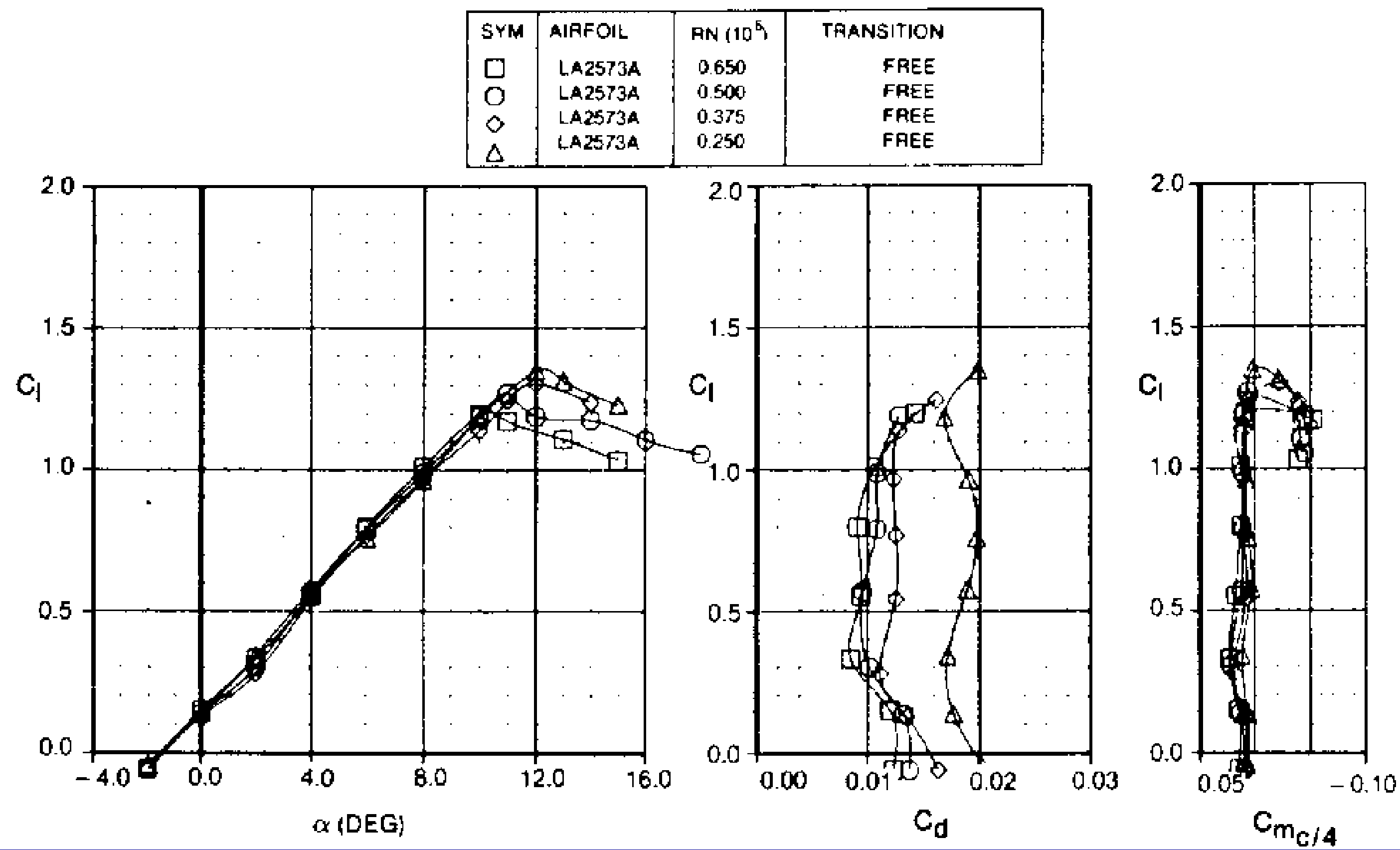
Drag Polar



- $C_{D0} = 0.014$
- $(L/D)_{max} = 25$

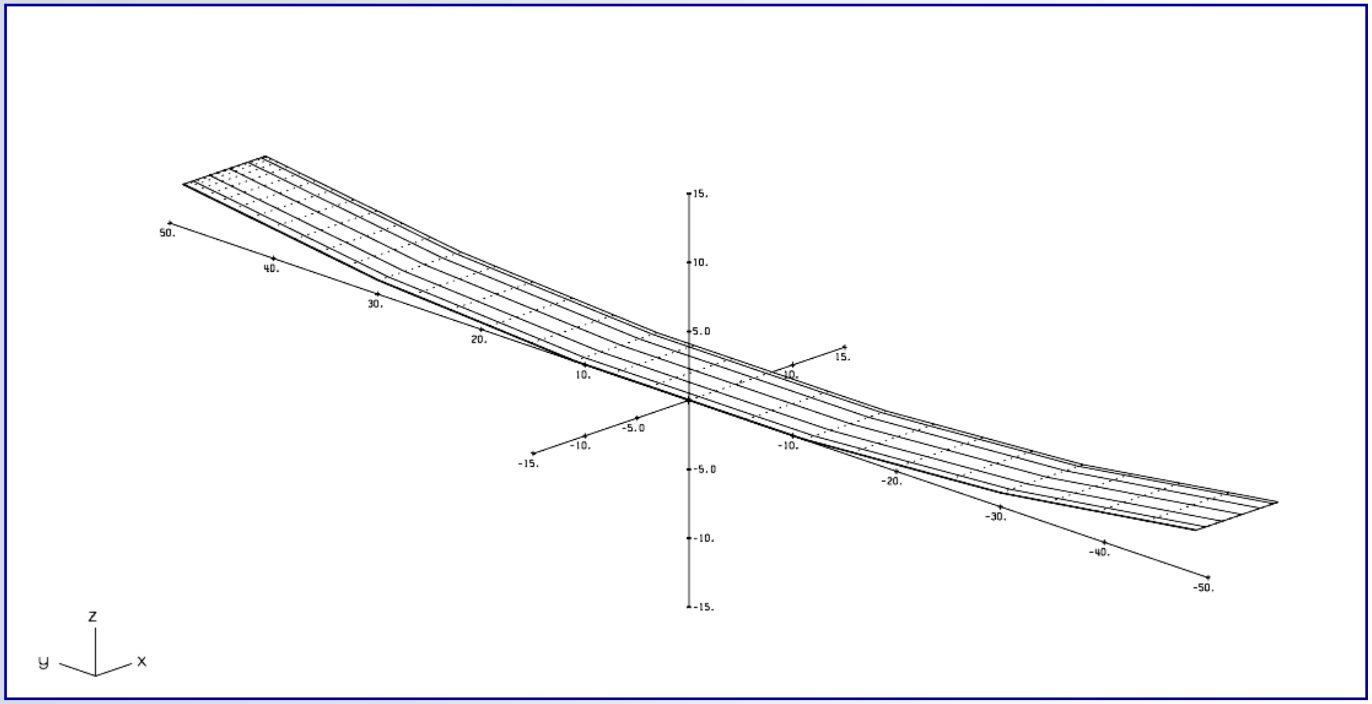
- Best performance of airfoil when CL does not exceed 1.2 ($\alpha = 10°$)

Wind Tunnel Data



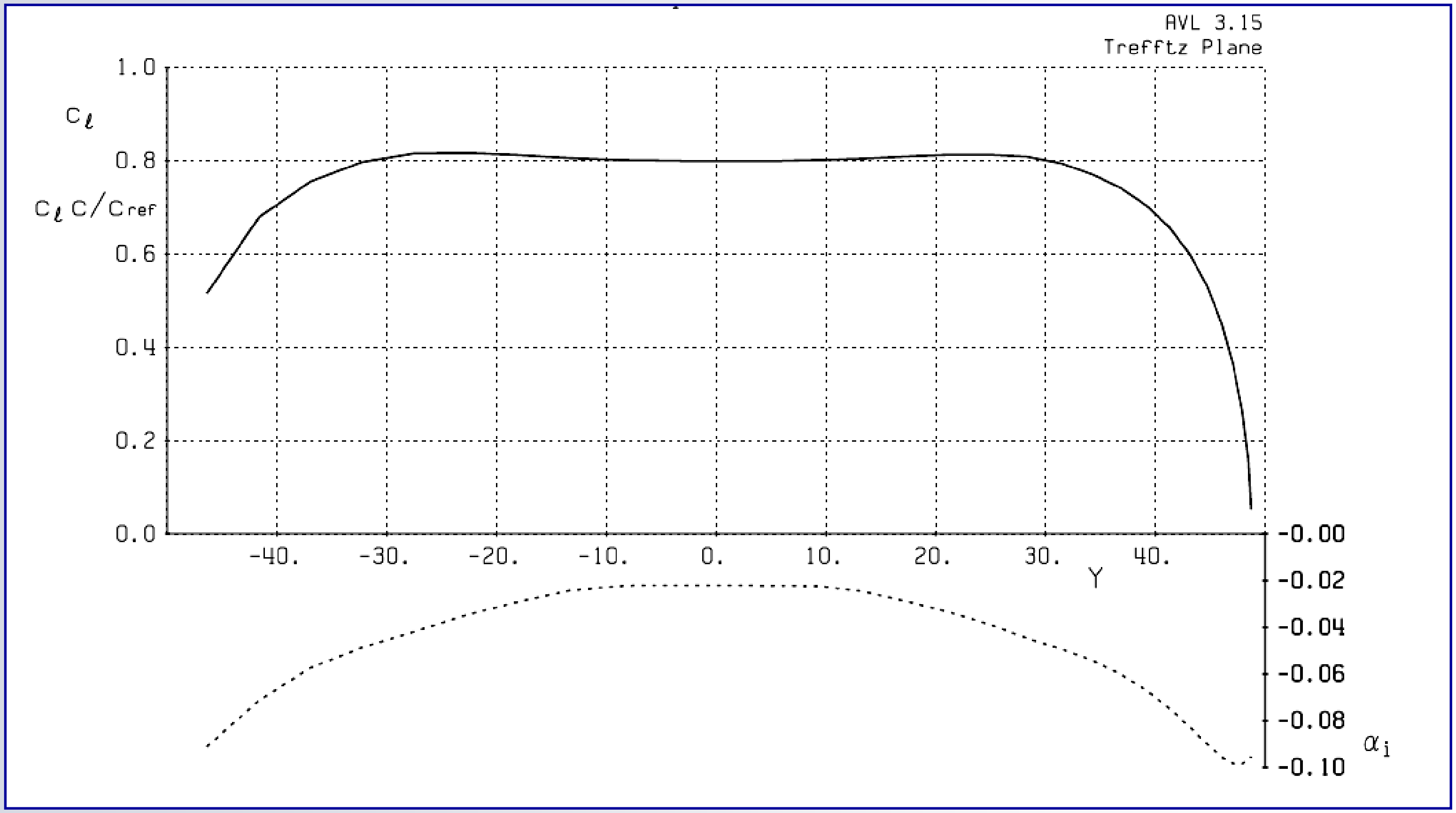
Wind tunnel data courtesy of R.H. Liebeck

Analysis in AVL



- Mach = 0.097
- C_{D0} = 0.017
- CL = 0.745
- # Panels = 20 x 6
- Wing tip panels had 1º twist

Span Loading at α = 7°



Derivatives

	α	β	p	q	r	δ_e
C_L	4.94	-.005	-.050	7.47	.017	.030
C_Y	0.006	-.022	-.066	.009	.044	0
C_l	0.026	-.13	-.61	.036	.22	0
C_m	-1.34	.002	.016	-2.72	-.005	-.015
C_n	0.002	-.001	-.064	-.002	-.008	0

Derivatives, ¾ chord elevator

	α	β	p	q	r	δ_e
C_L	4.94	-.005	-.050	7.47	.017	.048
C_Y	0.006	-.022	-.066	.009	.044	0
C_l	0.026	-.13	-.61	.036	.22	0
C_m	-1.34	.002	.016	-2.72	-.005	-.022
C_n	0.002	-.001	-.064	-.002	-.008	0

Results

- e = 0.92
- Neutral Point = 26% of chord
- $(C_{l\beta}C_{nr})/(C_{lr}C_{n\beta}) = -3.82$

  - This must be greater than 1 to be spirally stable

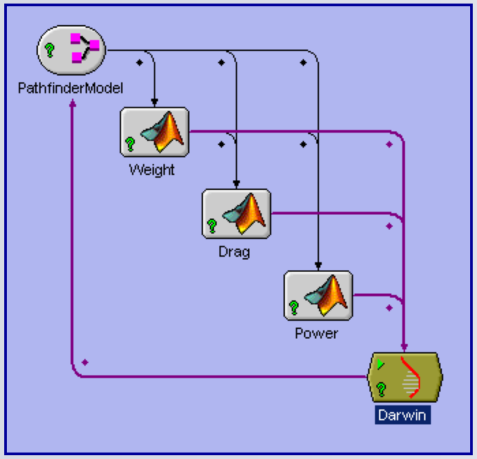
Photo courtesy NASA Dryden Photo Gallery

Optimization of Planform

- Objectives:
  - Maximize Power
  - Minimize Weight
  - Minimize Drag
- Design Variables:
  - Spans of center, mid, and tip panels
  - Chord
- Create model in Model Center using MATLAB modules for weight, drag and power
- Use the Darwin genetic algorithm to perform multi-objective optimization

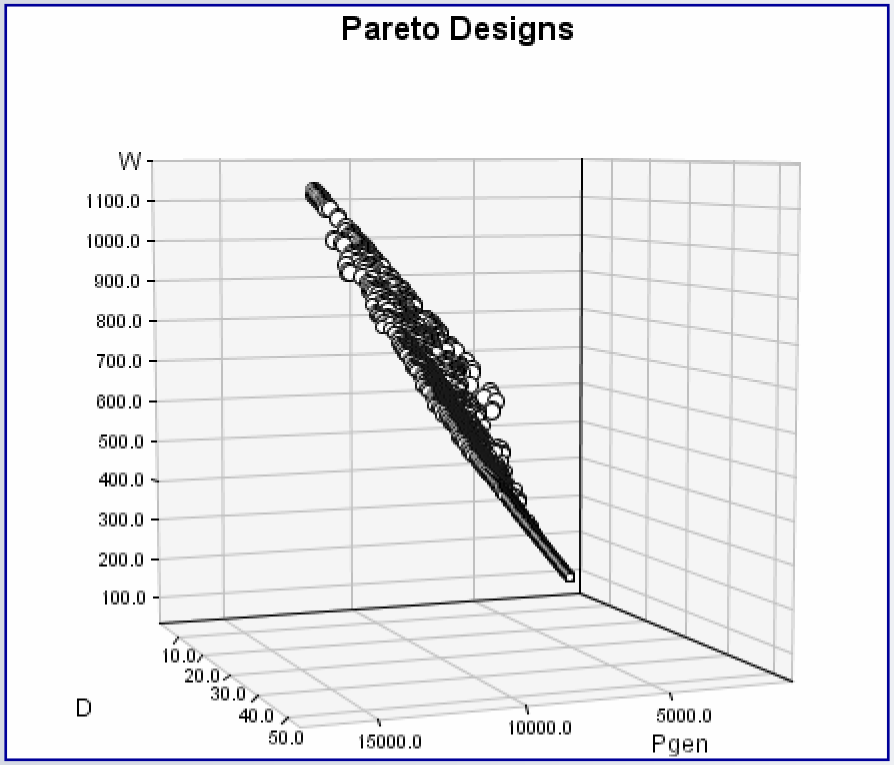
Modules

- Weight: Assumed evenly distributed
- Drag: Assumed a drag polar, $C_D = C_{D0} + C_L^2/(\pi ARe)$
- C_{D0}: Used equations from 'friction' to obtain C_{D0}, assuming a high laminar to turbulent ratio
- Power: Solar panels cover 75% of the upper surface



Constants for Optimization:
- $e = 0.92$ (from AVL)
- $\rho = 0.0002256$ sl/ft^3 (60,000 ft)
- $\mu = 0.297 \cdot 10^{-6}$ sl/ft-s
- $M = 0.097$ (V=94 ft/s at 60K ft)
- $FF = 2.12$
- $Q = 1.0$
- $W/S = 0.694$ psf
- $P/S = 13.5$ W/ft^2

Optimization Results



Pareto designs are those that have a better value for at least one objective function than similar designs.

Nearly linear relationship between objective functions for the non-dominated frontier.

Ideally look for designs with comparatively higher power than those with similar weight and drag. These designs are referred to as "knees in the curve."

Best Design for W=550 Pounds

	Pathfinder	Optimized
Weight	542 lbs	550 lbs
Drag	19.3 lbs	21.8 lbs
Power	7879 W	8002.5 W
Center b	11 ft	13.3 ft
Mid b	18.9 ft	14.9 ft
Tip b	18.8 ft	16 ft
Chord	8 ft	8.96 ft

References

- Curtin, Bob and Kirk Flittie. "Pathfinder Solar-Powered Aircraft Flight Performance." AIAA, 1998.
- Noll, Thomas E, et al. "Investigation of the Helios Prototype Aircraft Mishap." NASA, 2004.
- Liebeck, R. H. "Laminar Separation Bubbles And Airfoil Design at Low Reynolds Numbers." AIAA, 1992.
- Solar-Powered Research and Dryden Fact Sheet, avail. at NASA DFRC website: http://www.nasa.gov/centers/dryden/news/FactSheets/FS-054-DFRC.html
- NASA Dryden Photo Gallery, avail at NASA DFRC website: http://www.dfrc.nasa.gov/gallery/index.html
- UIUC Airfoil Coordinates Database, avail. at UIUC website: http://www.ae.uiuc.edu/m-selig/ads/coord_database.html
- The Incomplete Guide to Airfoil Usage, avail. at UIUC website: http://www.ae.uiuc.edu/m-selig/ads/aircraft.html
- Xfoil Source and Materials: http://raphael.mit.edu/xfoil/
- AVL Source and Materials: http://web.mit.edu/drela/Public/web/avl/
- MATLAB, courtesy MathWorks
- Model Center, courtesy Phoenix Integration

Photo courtesy NASA Dryden Photo Gallery

T/W and P/W supporting calculations

$$P_{total} = (6)(1.5hp) = 9hp * \frac{550ftlb/s}{1hp} = 4950ftlb/s$$

$$T = P/V = \frac{4950ftlb/s}{94ft/s} = 52.66lb$$

$$T/W = \frac{52.66}{550} = 0.096$$

$$P/W = (9hp)(832W/hp)/550lb = 13.6 \text{ Watts/lb}$$