UAV Design Tutorial

Bill Donovan

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NATIONAL SCIENCE FOUNDATION :: KANSAS TECHNOLOGY ENTERPRISE CORPORATION :: NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Overview

- Overview of Design Process
- Requirements Definition
- Takeoff Weight Estimation
- Performance Sizing
- Sensitivity Analysis
- Class I Aerodynamic Analysis

Requirements Definition

- ALL aircraft designs are driven by performance requirements. These can be:
  - Range
  - Endurance
  - Max Payload
  - Operating and manufacturing costs
  - Etc.

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Performance Requirements

Initial science missions developed independently from tiered aircraft definitions, driven by need for "coarse" ice thickness definitions over wide areas and "fine" ice thickness definitions in transition areas or other areas of high interest

- Regional Survey: 500km x 500km x 10-15km
- Local Survey: 100km x 100km x 2.5km
- Fine survey: 20km x 20km x 1km

Missions lend themselves to Tiered aircraft definitions, with Tier A aircraft able to perform fine surveys and local surveys, and Tier B aircraft able to perform local and regional surveys. Time available in a season, number of aircraft, and desired ground infrastructure are variables.

Requirements Definition

Parameter	Value	Importance	Source
Range	950 nm (~1750 km) w/ 1.5 hr Reserve	High	Trade Studies[1]
Endurance	> 9 hrs	Medium	Trade Studies[1]
Cruise Speed	100-120 kts (~180-220 km/hr)	Medium	Technology Requirements[3]
Maximum Ceiling	15,000 ft (4,500 m)	Low	Technology Requirements[3]
Rate of Climb	1,600 ft/min (490 m/min)	Low	Twin Otter Performance[5]
Takeoff Distance	1,500 ft (~450 m)	High	Twin Otter Performance[5]
Landing Distance	1,500 ft (~450 m)	High	Twin Otter Performance[5]
Payload Volume	20" x 20" x 8" (~0.5 x 0.5 x 0.2 m)	High	Technology Requirements[3]
Payload Weight	120 lbs (~55 kg)	High	Technology Requirements[3]
Payload Integration	Wing Mounted Antennas	High	Technology Requirements[3]
Payload Power	300 W	Medium	Technology Requirements[3]
Stall Speed	58 kts (105 km/hr)	Medium	Technology Requirements[3]
Stability and Control	FAR 23, where applicable	Low	www.faa.gov
Maneuvering Requirements	FAR 23, where applicable	Low	www.faa.gov
Aircraft Wingspan	Must fit in 20 ft Container	High	20 ft. Container Dimensions[5]
Aircraft Length	Must fit in 20 ft Container	High	20 ft. Container Dimensions[5]

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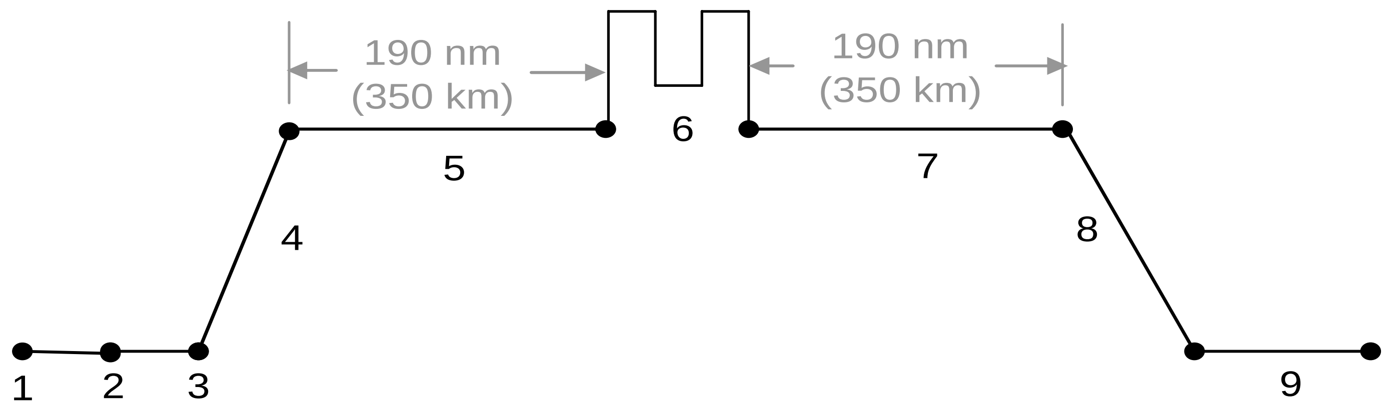
Requirements Definition



1.	Warmup	6.	Data Acquisition (120 kts @ 5,000 ft AGL)
2.	Taxi	7.	Cruise Return (Optimum Alt. and Speed)
3.	Takeoff	8.	Descent (No Range Credit)
4.	Climb (No Range Credit)	9.	Land/Taxi
5.	Cruise Out (Optimum Alt. and Speed)		

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Takeoff Weight Estimation

- W_{TO} – Takeoff Gross Weight
- W_E – Empty Weight
- W_F – Mission Fuel Weight
- W_{OE} – Operating Empty Weight
- W_{PL} – Payload Weight
- W_{tfo} – Trapped Fuel and Oil Weight
- W_{crew} – Crew Weight
  - $W_{TO} = W_{OE} + W_F + W_{PL}$
  - $W_{OE} = W_E + W_{tfo} + W_{crew}$

Takeoff Weight Estimation

- All aircraft designs start with **RESEARCH**

Country	Company	Designation	W_E lb	W_{TO} lb	W_{pay} lb	b_w ft	Length ft	End. hr	Range nm	Ceiling ft	Speed kts
U.S.	General Atomics	Predator B	2,800	6,500	3,800	66.0	36.0	30	OTH*	25,000	220
U.S.	General Atomics	Predator	1,200	2,350	450	48.7	27.0	40	7,400	25,000	220
U.S.	Northrop Grumman	E-Hunter	1,430	2,100	220	54.5	24.5	30	OTH*	25,000	120
U.S.	General Atomics	I-Gnat	850	1,650	650	42.2	20.8	48	1,500	30,000	160
U.S.	AAI	Shadow 600	327	585	85	22.4	15.6	14	-	17,000	108
U.S.	AAI	Shadow 200	200	316	50	12.8	11.2	8	-	15,000	115
U.S.	Geneva Aerospace	Dakota	160	240	80	15.6	9.5	4.5	575	20,000	100

100

Country	Company	Designation	W_E kg	W_{TO} kg	W_{pay} kg	b_w m	Length m	End. hr	Range km	Ceiling m	Speed km/hr
U.S.	General Atomics	Predator B	1,270	2,948	1,723	20.1	11.0	30	OTH*	7622.0	371
U.S.	General Atomics	Predator	544	1,066	204	14.8	8.2	40	13,705	7,622	371
U.S.	Northrop Grumman	E-Hunter	649	952	100	16.6	7.5	30	OTH*	7,622	203
U.S.	General Atomics	I-Gnat	385	748	295	12.9	6.3	48	2,778	9,146	270
U.S.	AAI	Shadow 600	148	265	39	6.8	4.8	14	-	5,183	182
U.S.	AAI	Shadow 200	91	143	23	3.9	3.4	8	-	4,573	194
U.S.	Geneva Aerospace	Dakota	73	109	36	4.8	2.9	4.5	1,065	6,098	169

* OTH - Over The Horizon

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Fuel Fraction Method

- Calculate ratio of aircraft ending weight to starting weight for each mission segment
  - Warmup: 0.980
  - Taxi: 0.9960
  - Takeoff: 0.9960
  - Climb: 0.9988
  - Cruise: 0.9117
  - Descent: 0.9920
  - Land/Taxi 0.9920

$$E = 375\left(\frac{1}{V}\right)\left(\frac{\eta_p}{c_p}\right)\left(\frac{L}{D}\right)\ln\left(\frac{W_{begin}}{W_{end}}\right)$$

$$R_{Cr} = 375\left(\frac{\eta_p}{c_p}\right)_{cr}\left(\frac{L}{D}\right)_{cr}\ln\left(\frac{W_{begin}}{W_{end}}\right)$$

$$W_F = \left(1 - M_{ff}\right)W_{TO} + W_{F_{res}}$$

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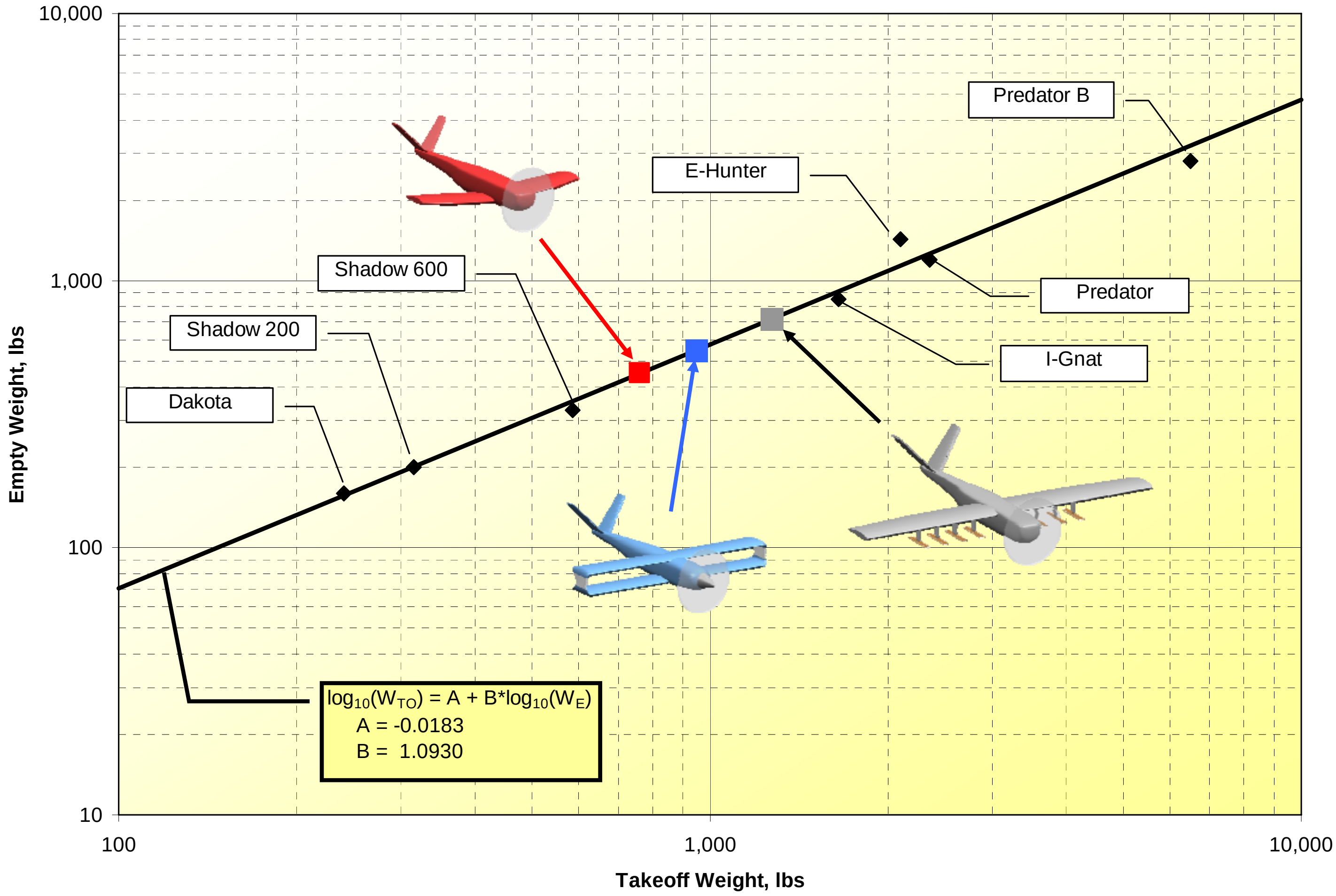
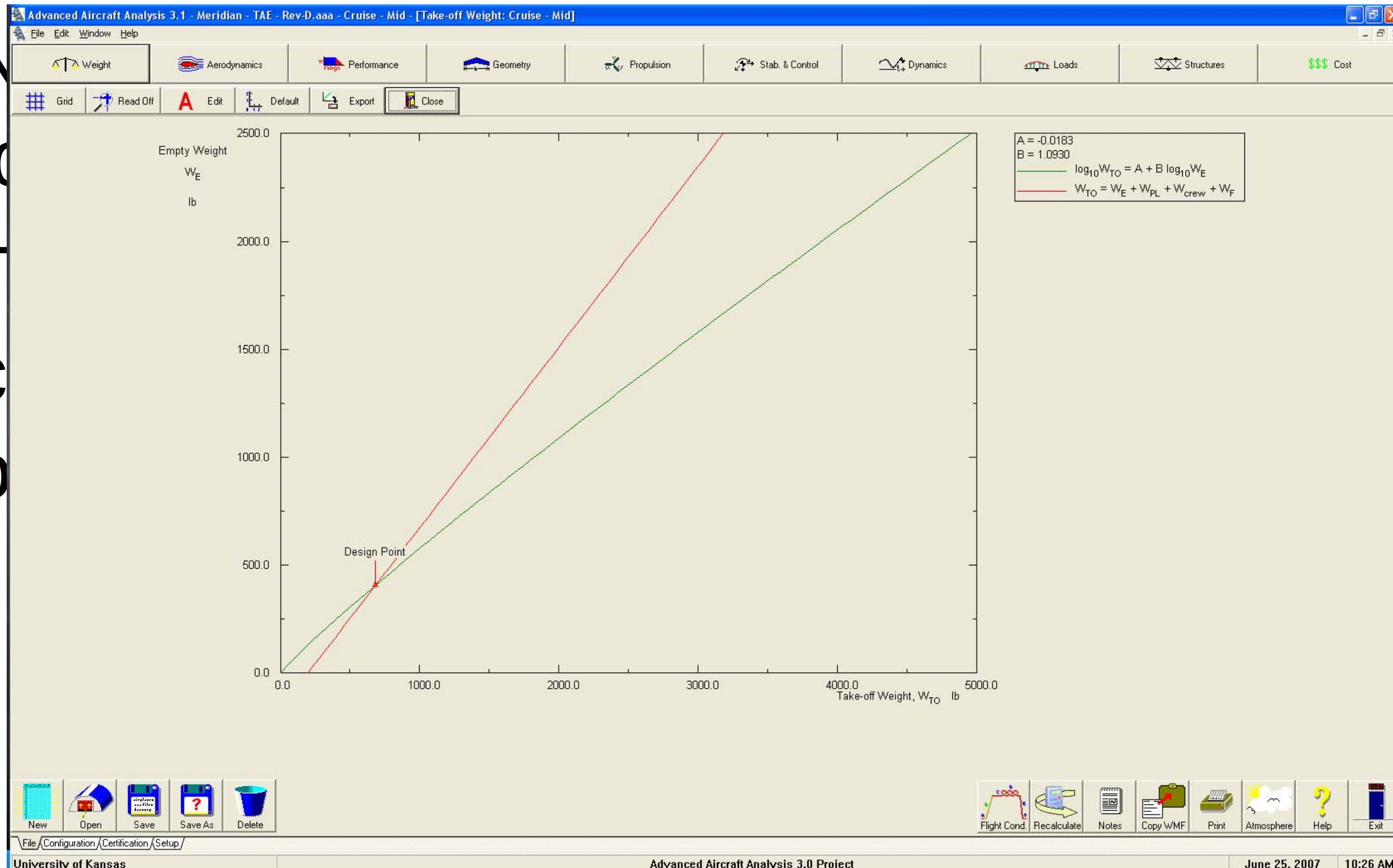
Takeoff Weight Estimation



Takeoff Weight Estimation

- [illegible]
- [illegible]



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Sensitivity Analysis

			Red		White		Blue	
Sensitivity	**-**	**Units**	**Cruise**	**Climb**	**Cruise**	**Climb**	**Cruise**	**Climb**
Payload	$\delta W_{to}/\delta W_{pl}$	~	**4.8**	**4.8**	**6.97**	**6.97**	**5.65**	**5.65**
Empty Weight	$\delta W_{to}/\delta W_{e}$	~	**1.9**	**1.9**	**1.9**	**1.9**	**1.88**	**1.88**
Fuel Consumption	$\delta W_{to}/\delta c_{p}$	hp-hr	**1,100**	**31**	**3,820**	**48**	**1,950**	**29**
Range	$\delta W_{to}/\delta R$	lb/nm	**0.7**	**-**	**2.3**	**-**	**1.2**	**-**
Lift-to-Drag	$\delta W_{to}/\delta(L/D)$	lb	**-50**	**-1.5**	**-267**	**-3**	**-110**	**-1.5**
Propeller Efficiency	$\delta W_{to}/\delta(\eta_{p})$	lb	**-828**	**-19.2**	**-2,850**	**-36**	**-1470**	**-23**

Performance Matching

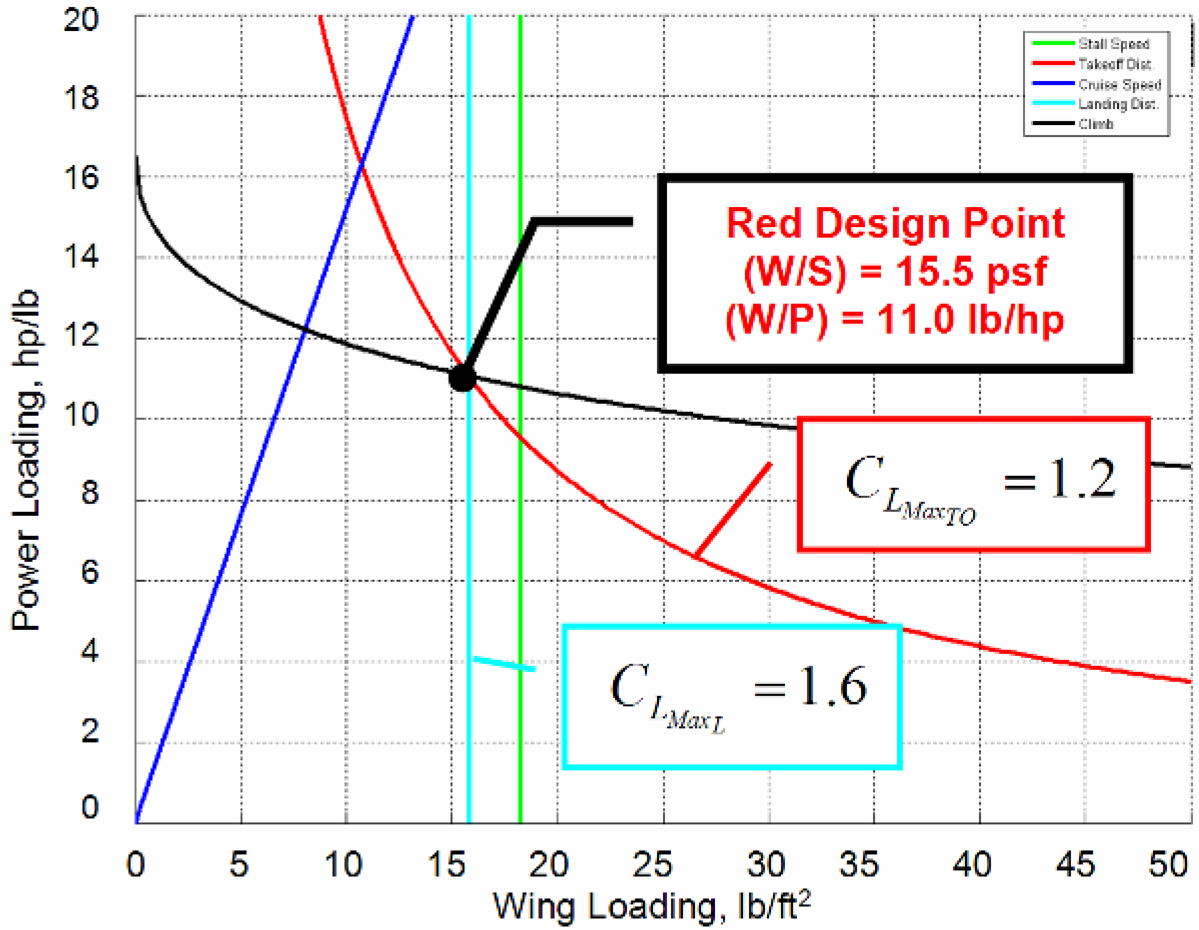
- Often the most important parameters for an aircraft preliminary design are:
  - Wing Loading, W/S (psf)
  - Power Loading, W/P (lbs/hp)
    - Note: T/W (lbs/lbs) for a Jet Aircraft
  - Max Lift Coefficient, $C_{L,max}$

$$C_L = \frac{L}{\overline{q}S}$$

Performance Matching

- Often the most important **requirements** for an aircraft preliminary design are:
  - Stall Speed
  - Takeoff Distance
  - Landing Distance
  - Cruise Speed
  - Climb (Rate of Climb or Climb Gradient)
  - Maneuvering

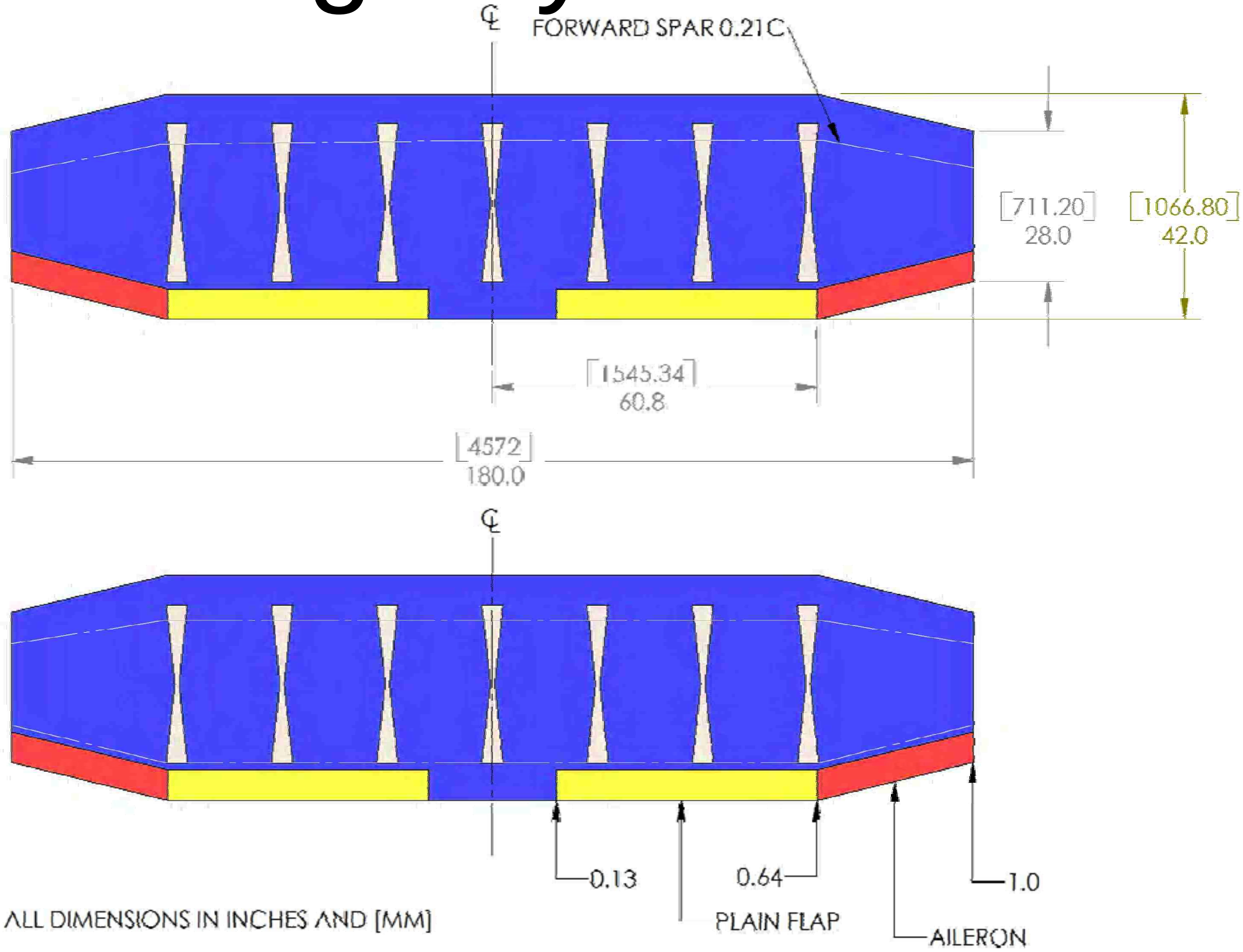
Performance Matching



Wing Layout

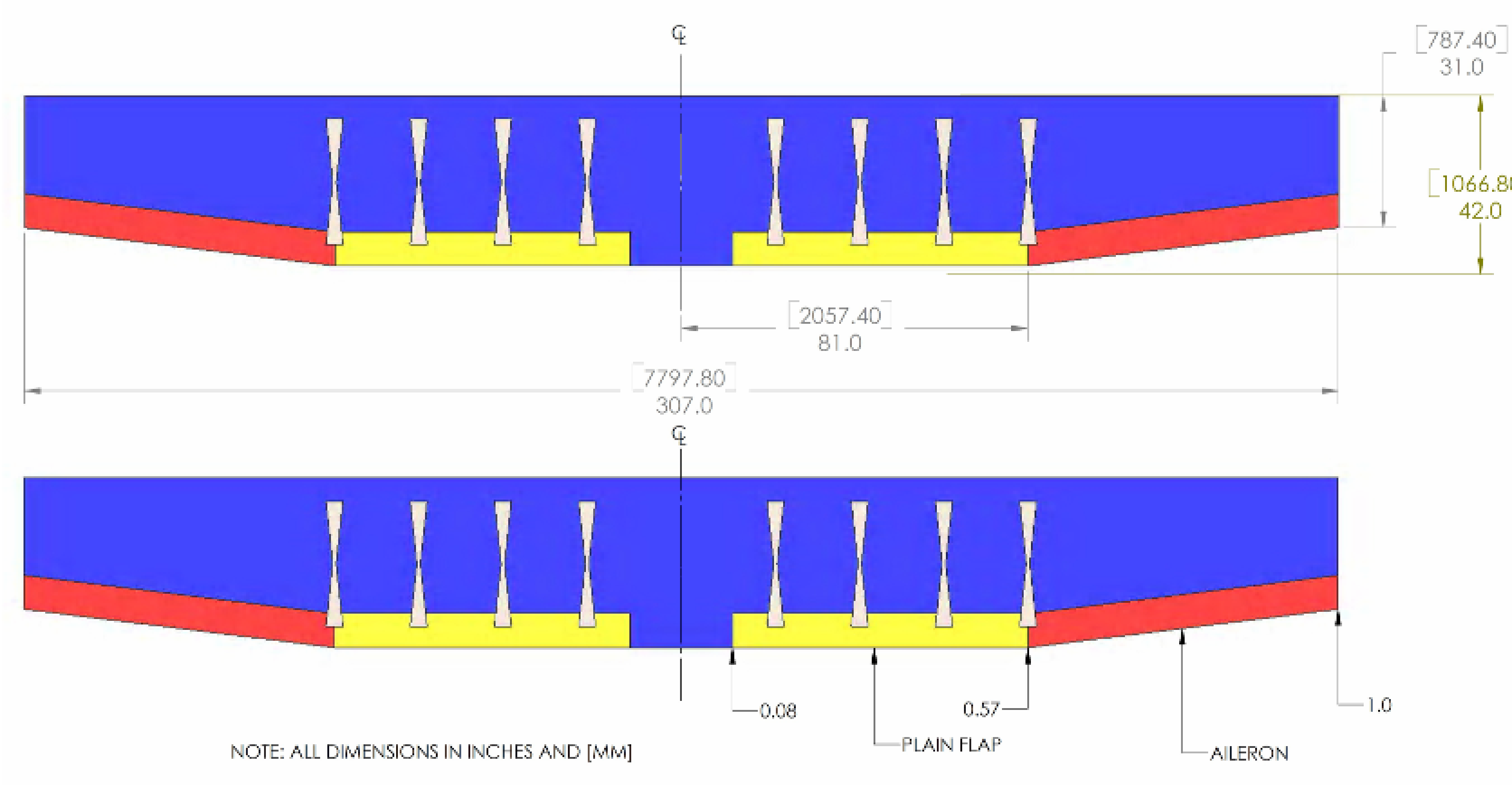
- Upon completion of the Performance Matching you should have selected values for:
  - Wing Area, S
  - Wing Aspect Ratio, AR = b^2/S
    - Where: b – wing span

Wing Layout - Red



NOTE: ALL DIMENSIONS IN INCHES AND [MM]

Wing Layout - White



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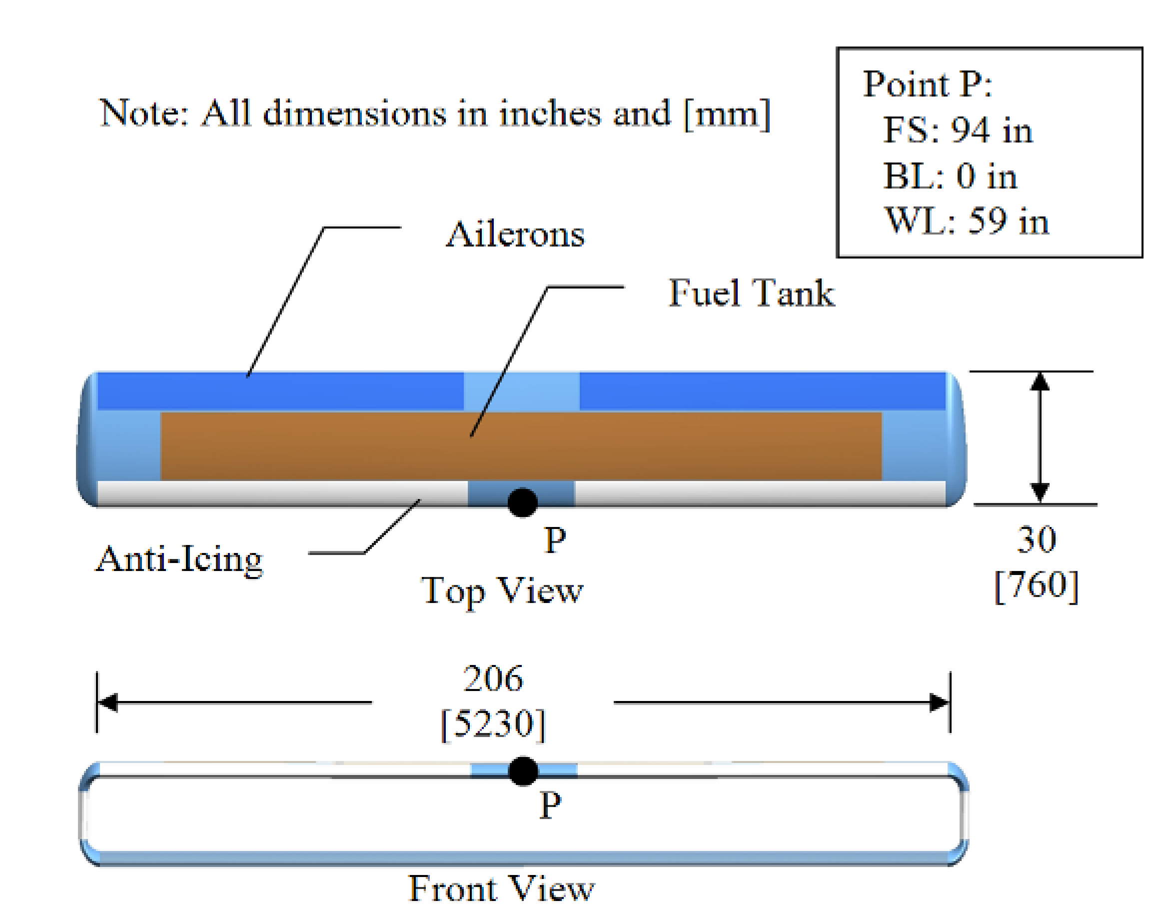
Wing Layout - Blue



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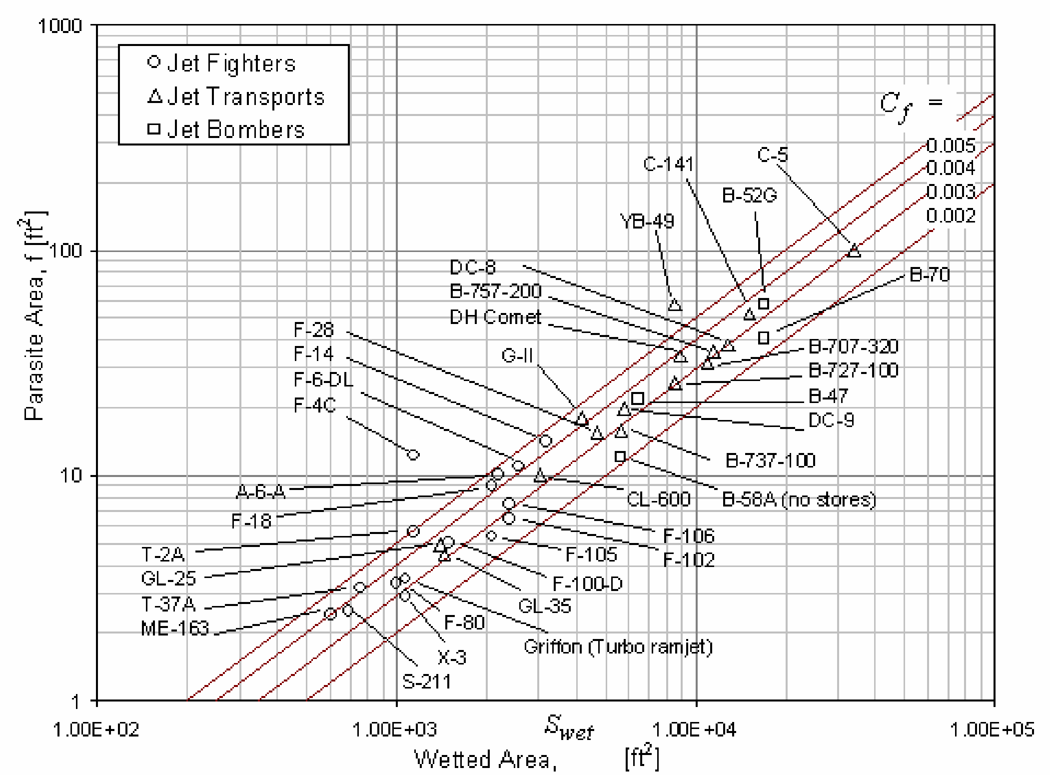
Class I Aerodynamic Analysis

- S_{wet} – Wetted Area – Area exposed to the freestr



Parasite Area vs Wetted Area for Fighters, Bombers, Transport
(Reference: Roskam, J.; *Airplane Design Part VI*, Figure 5.22; 1990.)

$C_L = \frac{(W}{}$

$C_{D_0} =$

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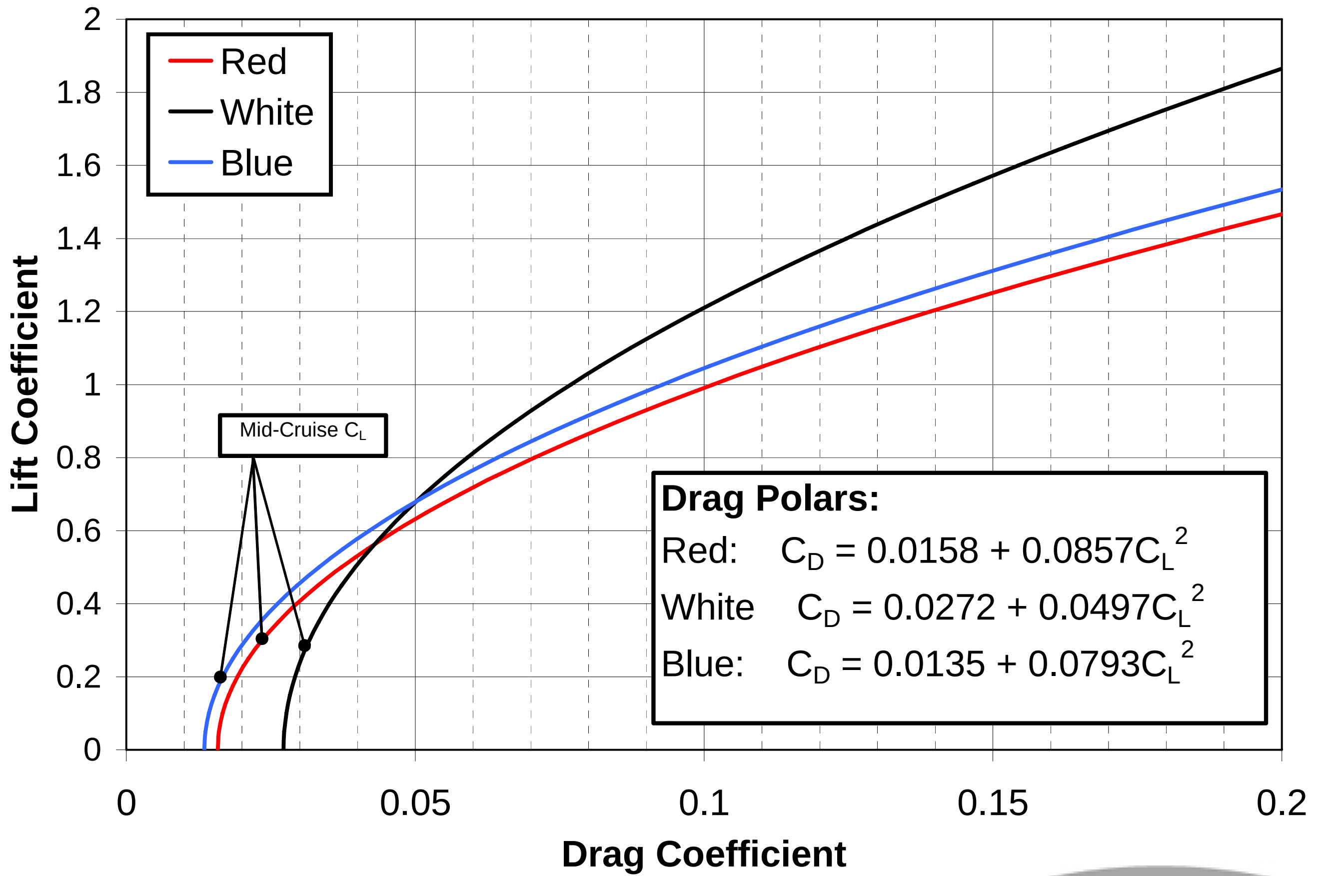
Class I Aerodynamic Analysis



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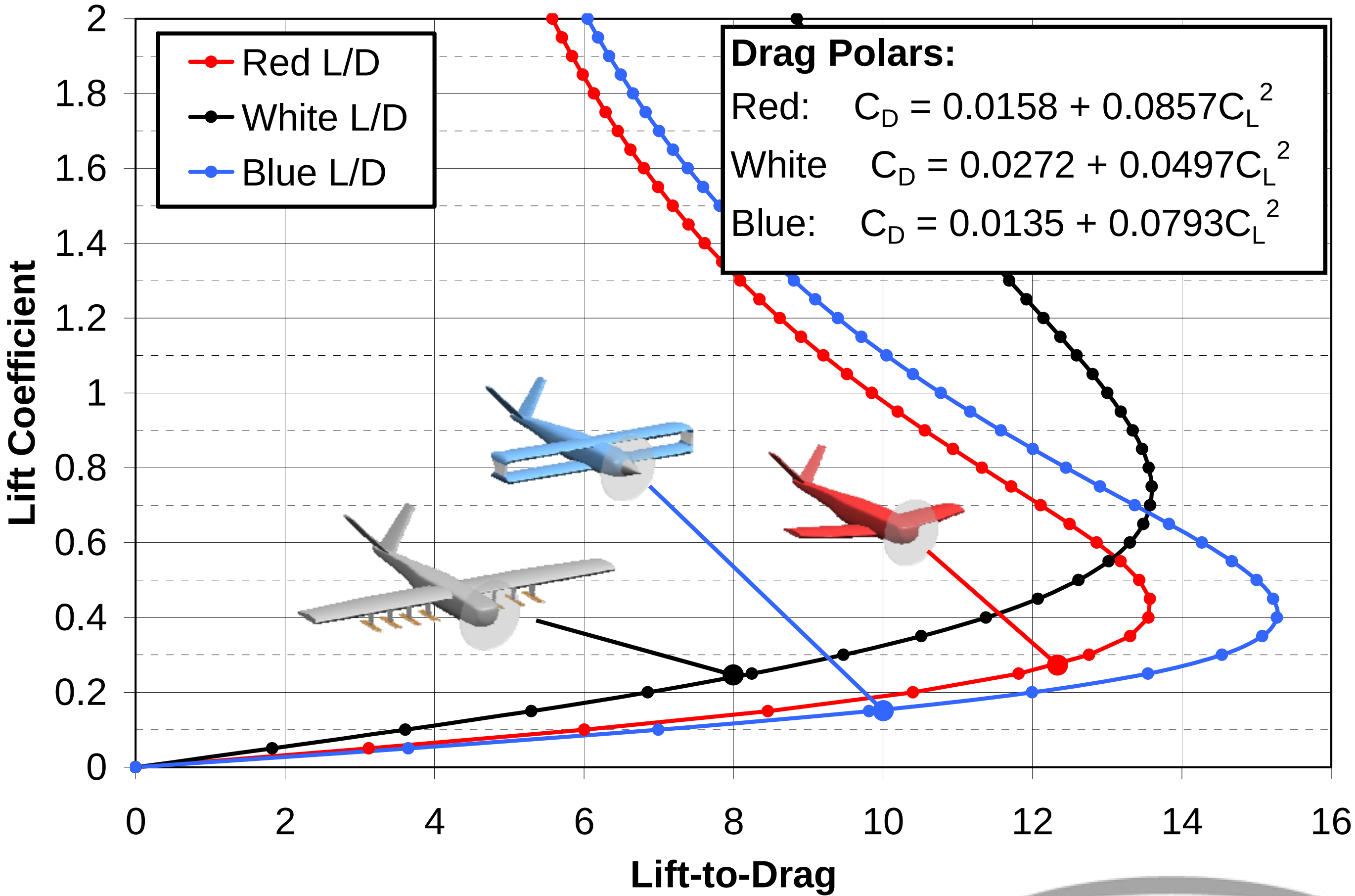

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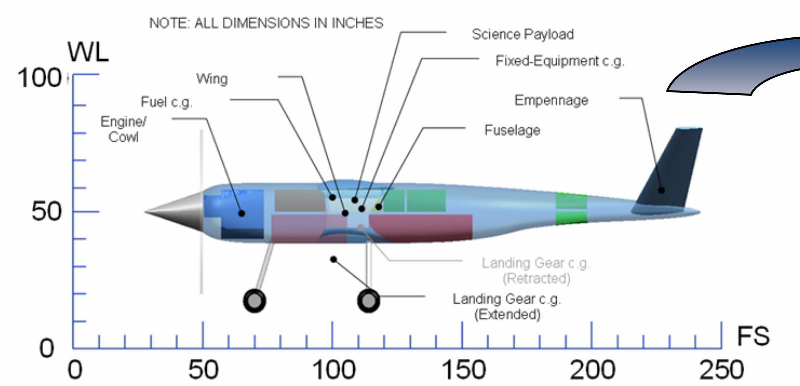
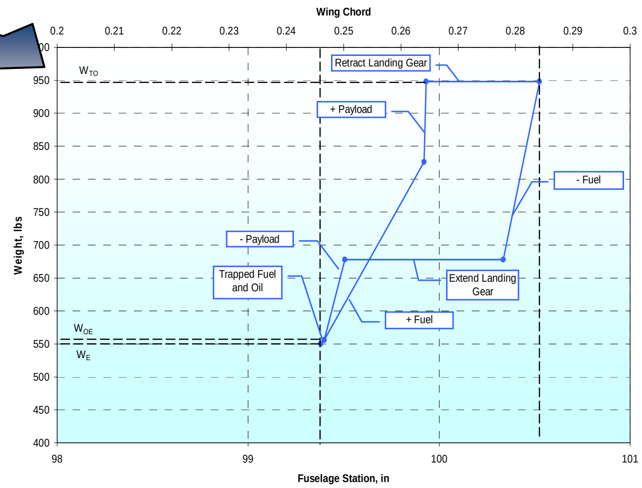
$$W_F = \left(1 - M_{ff}\right)W_{TO} + W_{F_{res}}$$

Weight and Balance

Weight Item, lbs	C-150	C-172	C-175	C-180	C-182	L-19A	Beech J-35
Gross Takeoff Weight, GW	1500	2200	2350	2650	2650	2100	2900
Empty Weight, lbs	946	1243	1319	1526	1545	1527	[illegible]
Structure/GW	0.406	0.352	0.330	0.319	0.326	[illegible]	[illegible]
Powerplant/GW	0.177	0.157	0.177	0.206	0.206	0.262	0.201
Fixed Equipment/GW	0.068	0.072	0.068	0.065	0.065	0.136	0.115
Empty Weight/GW	0.631	0.565	0.561	0.576	0.583	0.727	0.628
Wing Group/GW	0.144	0.103	0.097	0.089	0.089	0.113	0.131
Empennage Group/GW	0.024	0.026	0.024	0.023	0.023	0.030	0.020
Fuselage Group/GW	0.154	0.160	0.149	0.152	0.151	0.103	0.069
Nacelle Group/GW	0.015	0.012	0.013	0.012	0.013	0.016	0.021
Landing Gear Group/GW	0.069	0.050	0.047	0.042	0.050	0.064	0.071
Wing Group/S, psf	1.35	1.29	1.30	1.34	1.34	1.37	2.13
Empennage Group/S_{emp},psf	0.85	1.08	1.08	1.17	1.18	1.19	1.62
Ultimate Load Factor, g's	5.7	5.7	5.7	5.7	5.7	5.7	5.7
Wing Area, ft^2	160	175	175	175	175	174	178
Horizontal Tail Area, ft^2	28.5	34.6	34.6	34.6	34.1	35.2	0
Vertical Tail Area, ft^2	14.1	18.4	18.4	18.4	18.4	18.4	0
Empennage Area, ft^2	42.6	53	53	53	52.5	53.6	35.8

	Initial Estimate lbs	Adjustment lbs	Class I Weight (Alum.) lbs
Wing	104	-7	97
Empennage	23	-2	22
Fuselage	127	-9	119
Nacelles	14	-1	13
Landing Gear	53	-4	50
Power Plant	188	-13	175
Fixed Equipment	80	-5	75
Empty Weight	590	-40	550
Payload			122
Fuel			270
Trapped Fuel and Oil			6.1
Takeoff Gross Weight			**948**





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Nacelle Group/GW	0.015	0.012	0.013	0.012	0.013	0.016	0.021
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Empennage Group/S_{emp},psf	0.85	1.08	1.08	1.17	1.18	1.19	1.62
Ultimate Load Factor, g's	5.7	5.7	5.7	5.7	5.7	5.7	5.7
Wing Area, ft^2	160	175	175	175	175	174	178
Horizontal Tail Area, ft^2	28.5	34.6	34.6	34.6	34.1	35.2	0
Vertical Tail Area, ft^2	14.1	18.4	18.4	18.4	18.4	18.4	0
Empennage Area, ft^2	42.6	53	53	53	52.5	53.6	35.8

Weight and Balance

	Initial Estimate lbs	Adjustment lbs	Class I Weight (Alum.) lbs
Wing	104	-7	97
Empennage	23	-2	22
Fuselage	127	-9	119
Nacelles	14	-1	13
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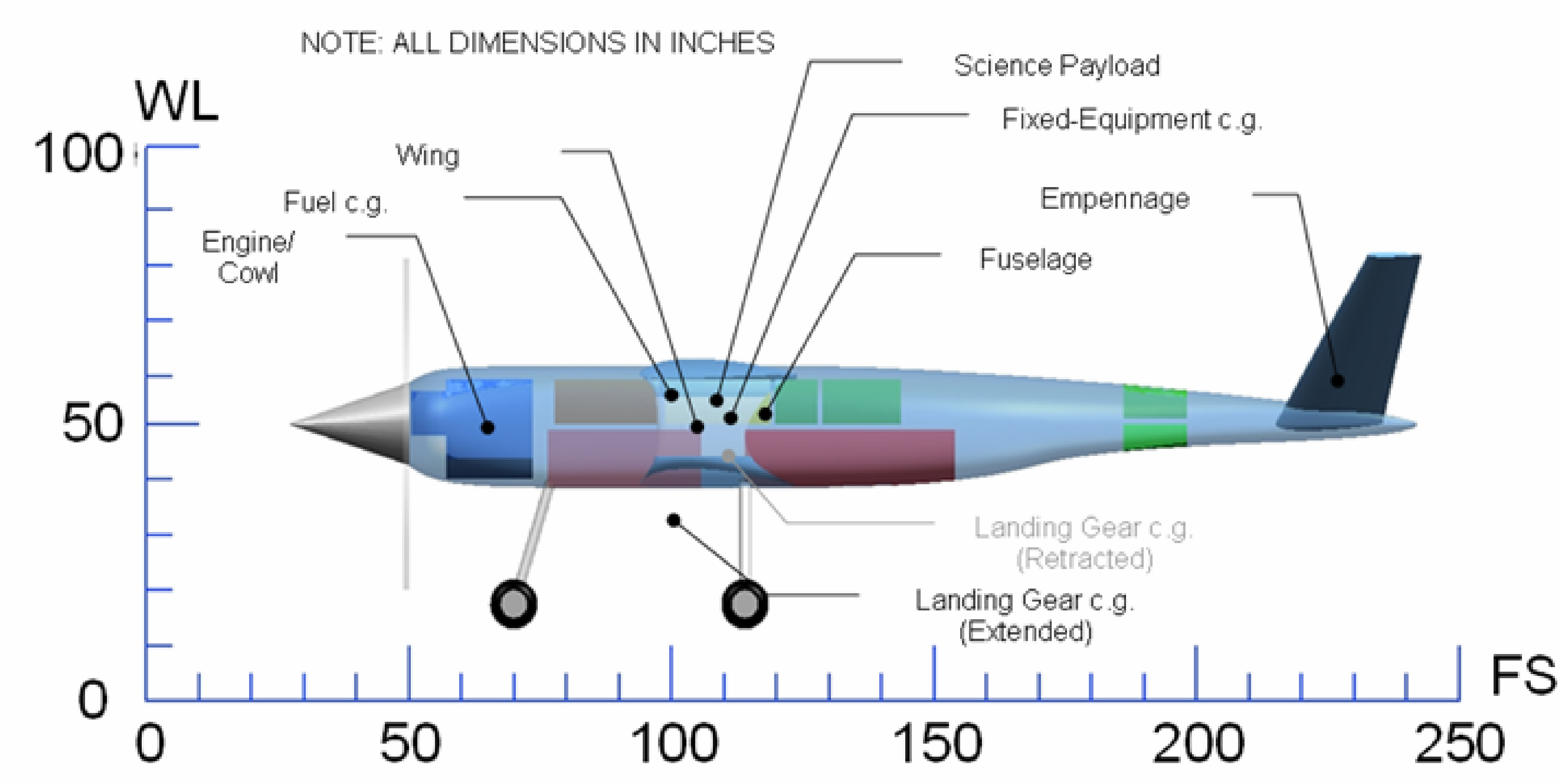
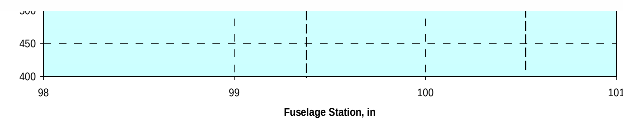
Power Plant	188	-13	175
Fixed Equipment	80	-5	75
Empty Weight	590	-40	550
Payload			122
Fuel			270
Trapped Fuel and Oil			6.1
Takeoff Gross Weight			**948**

Weight and Balance





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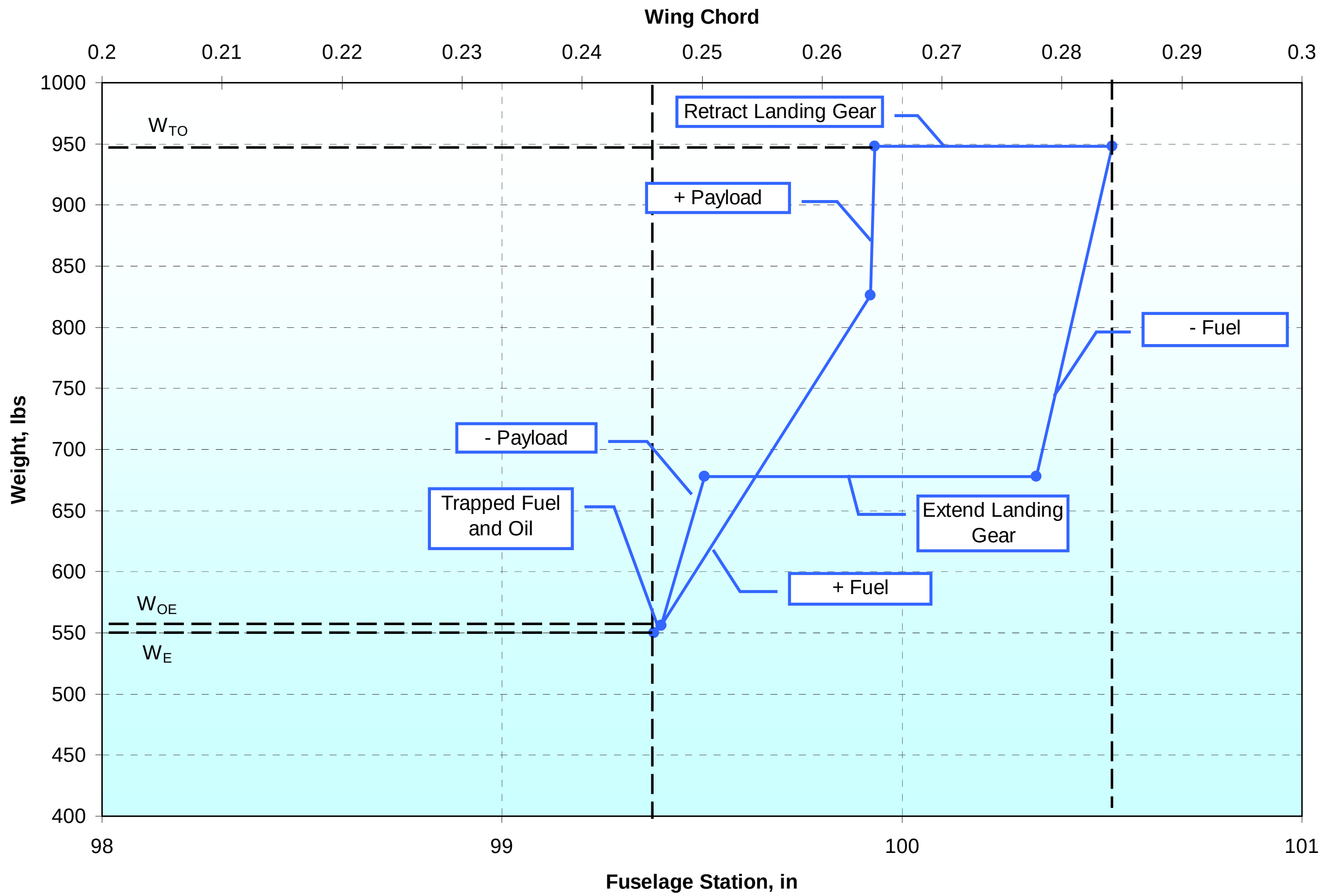
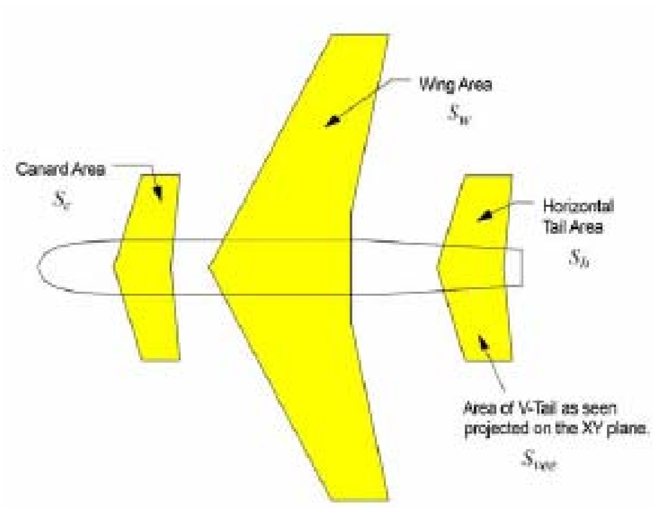
Weight and Balance

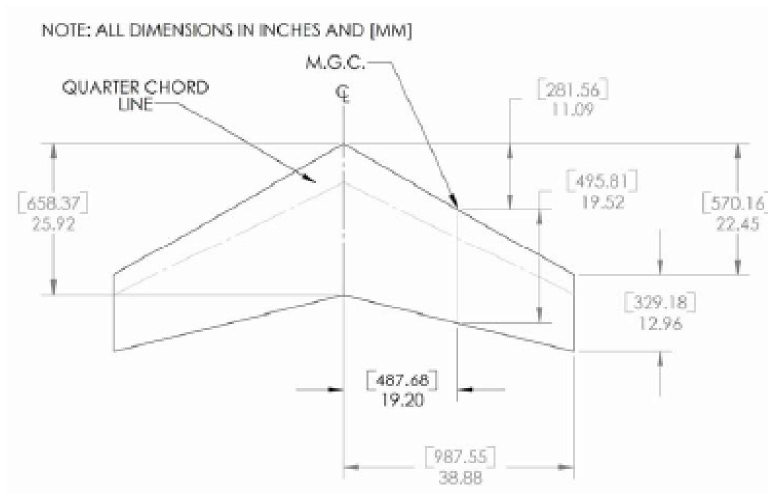


Tail Sizing

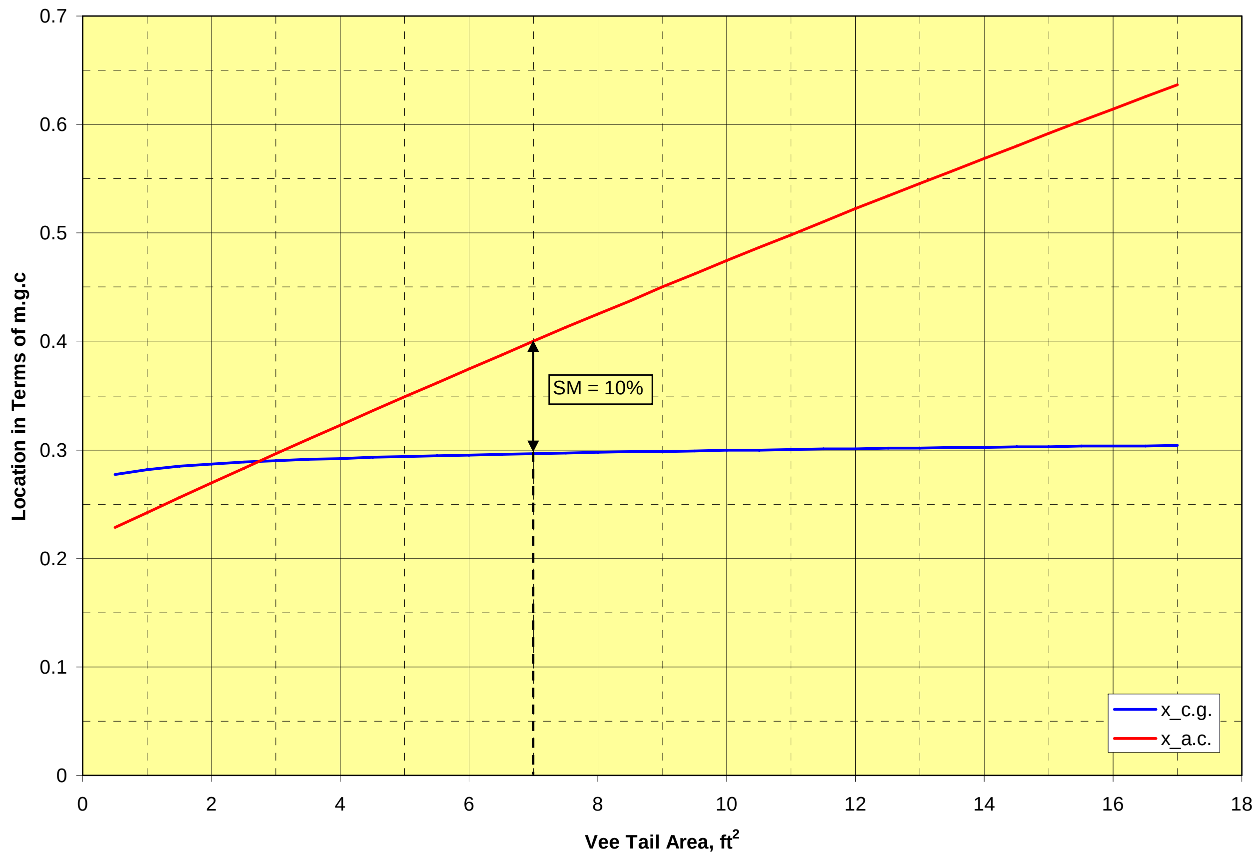
- Volume Coefficients

$$V_{vee} = \frac{S_{vee}\left(W_{ac_{vee}} - X_{c.g.}\right)}{S_w \overline{c}_w}$$





Tail Sizing - Stability



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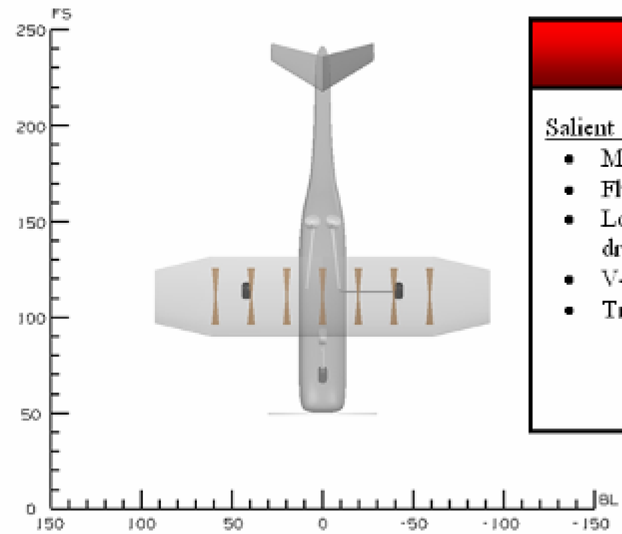
Aerodynamic Three-View

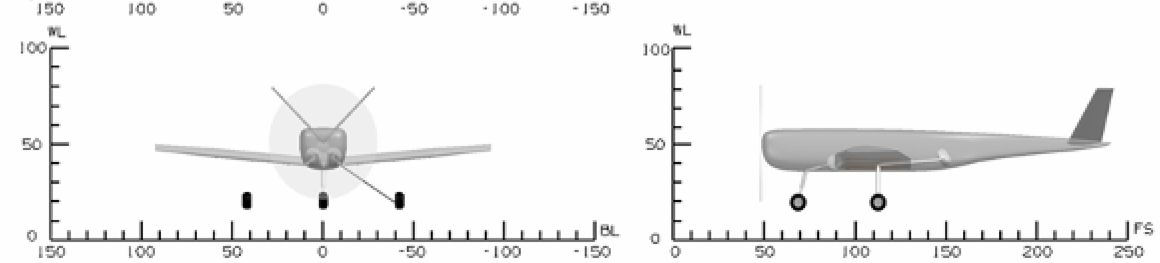


Red Design Summary

Salient Characteristics:

- Monoplane design
- Flush-mounted antennas
- Low wing aspect ratio driven by antennas
- V-Tail
- Tricycle Landing Gear

Parameter	Value	Units
$(W/S)_{TO}$	15.5	lb/ft^2
$(W/P)_{TO}$	11.6	lb/hp
W_{TO}	760	lbs
W_E	450	lbs
W_{Fuel}	185	lbs
W_{Fuel_Res}	34	lbs
Wing AR	4.6	–
Wing Area	49	ft^2
P_{req}	66	hp

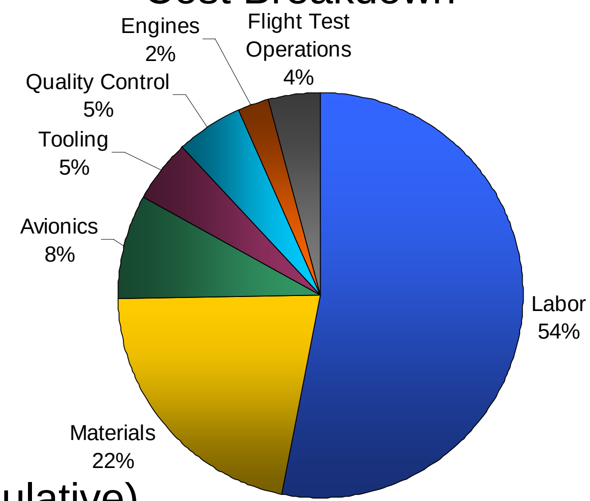


Cost Estimation

Labor Rates

	Engineering Labor		Manufacturing Labor	
	% of Total Time	Rate	% of Total Time	Rate
	%	$/hr (2006)	%	$/hr (2006)
Undergraduate	15	$16.00	30	$16.00
Graduate	60	$24.00	60	$24.00
Professor	15	$96.00	0	$96.00
Industry	10	$60.00	10	$60.00
Total (Averaged)		**$37.20**		**$25.20**

Cost Breakdown



Acquisition Cost Estimates (Cumulative)

Item	Cost (10^6\$ 2006)									
	Number of Aircraft Produced									
	1	2	3	4	5	6	7	8	9	10
Engineering and Design	0.169	0.192	0.207	0.218	0.228	0.235	0.242	0.248	0.253	0.258
Development, Support, and Testing	0.064	0.081	0.094	0.103	0.112	0.119	0.125	0.131	0.137	0.142
Manufacturing Labor	0.651	0.936	1.158	1.346	1.513	1.665	1.805	1.936	2.059	2.176
Material/Equipment	0.210	0.364	0.501	0.630	0.751	0.868	0.981	1.090	1.197	1.301
Tooling	0.120	0.120	0.120	0.120	0.120	0.120	0.120	0.120	0.120	0.120
Quality Control	0.085	0.122	0.151	0.175	0.197	0.216	0.235	0.252	0.268	0.283
Engine	0.035	0.070	0.105	0.140	0.175	0.210	0.245	0.280	0.315	0.350
Flight Test Operations	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100
Acquisition Cost	**1.434**	**1.985**	**2.436**	**2.833**	**3.195**	**3.534**	**3.853**	**4.157**	**4.449**	**4.730**

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Summary

- "Aircraft Design is a highly iterative, non-unique process."
  - Dr. Jan Roskam
- "In aircraft design, everything depends on everything else."
  - Dr. Jan Roskam

Questions?

National Science Foundation
WHERE DISCOVERIES BEGIN

KTEC
KANSAS
TECHNOLOGY
ENTERPRISE
CORPORATION

KU THE UNIVERSITY OF KANSAS