Air Vehicle Design

AOE 4065 – 4066

III. Air Vehicle Design Fundamentals

Course Module A10

Preliminary Design: *Refine & Validate Baseline Design*

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AOE 4065-4066:
Capstone Air Vehicle Design (AVD) Course Modules (CMs)

Overview of AVD Courses

I. Foundational Elements

F1. Design: ***An Engineering Discipline***

F2. Systems and Systems Thinking

F3. Basics of Systems Engineering

F4. Decision Making with Ethics and Integrity

II. Air Vehicle Design Fundamentals

A1. Purpose & Process

Conceptual Design

A2. Understand the Problem

A3. Solve the Problem

A4. Initial Sizing: ***Takeoff Weight Estimation***

A5. Initial Sizing: ***Wing Loading and Thrust Loading Estimation***

A6. Cost Considerations

A7. Concept to Configuration: ***Key Considerations***

A7A. Configuration Layout: ***Drawings & Loft***

Conceptual & Preliminary Design

A8. Trade Studies

A9. Use of Software Tools

A10. Preliminary Design: ***Baseline Design Refinement & Validation***

III. Project Management Topics

P1. Basics of Project Management and Project Planning

P2. Project Organization

P3. Roles & Responsibilities of Team Members

P4. Project Execution: ***Teamwork for Success***

P5. Project Risk Management

P6. Delivering Effective Oral Presentations

P7. Writing Effective Design Reports

Disclaimer

Prof. Pradeep Raj, Aerospace and Ocean Engineering, Virginia Tech, collected and compiled the material contained herein from publicly available sources solely for educational purposes.

Although a good-faith attempt is made to cite all sources of material, we regret any inadvertent omissions.

CRUCIALLY IMPORTANT

CMs only introduce key topics and highlight some important concepts and ideas…but without sufficient detail.

We must use lots of Reference Material* to add the necessary details!

(*see Appendix in the Overview CM)

Outline

A10. Preliminary Design: Refine & Validate Baseline Design

A10.1 General Remarks

A10.2 Integrated System

A10.3 Aerodynamics

A10.4 Aeropropulsion Integration

A10.5 Vehicle Performance

A10.6 Structures & Materials

A10.7 Subsystems

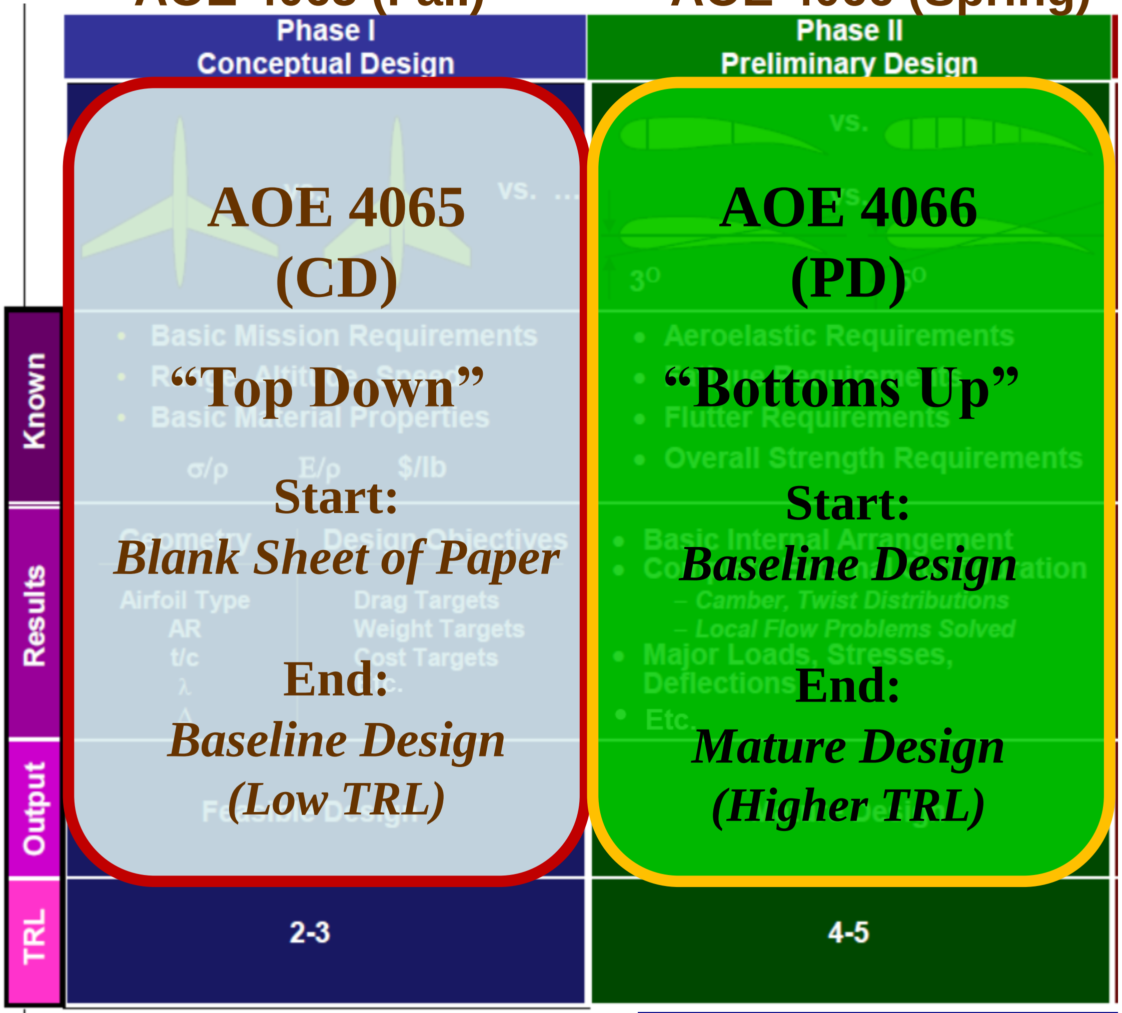
A10.8 Stability & Control

A10.9 Weights (Mass Properties) & Balance

A10.10 Cost & Manufacturing

Preliminary Design (PD) Builds Upon the Outcome of Conceptual Design (CD)

AOE 4065 (Fall) **AOE 4066 (Spring)**



AOE 4065
(CD)

“Top Down”

Start:
Blank Sheet of Paper

End:
Baseline Design
(Low TRL)

AOE 4066
(PD)

“Bottoms Up”

Start:
Baseline Design

End:
Mature Design
(Higher TRL)

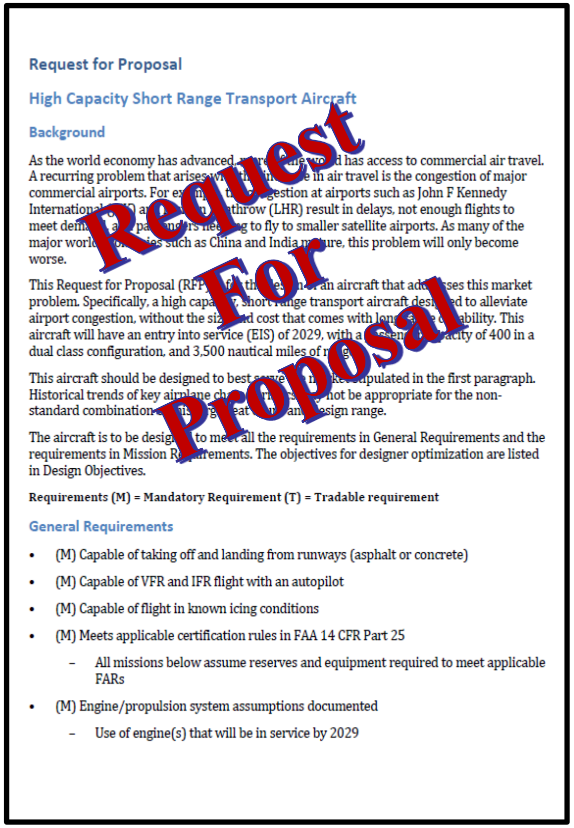
You Create a Feasible Baseline Design in AOE 4065

You Generate a More Mature Design in AOE 4066

TRL: *Technology Readiness Level*

Capstone Air Vehicle Design Project

The First Day!



Request For Proposal

Request for Proposal

High Capacity Short Range Transport Aircraft

Background

As the world economy has advanced, more of the world has access to commercial air travel. A recurring problem that arises with the increase in air travel is the congestion of major commercial airports. For example, the congestion at airports such as John F Kennedy International (JFK) and London Heathrow (LHR) result in delays, not enough flights to meet demand, and passengers needing to fly to smaller satellite airports. As many of the major world economies such as China and India mature, this problem will only become worse.

This Request for Proposal (RFP) is for the design of an aircraft that addresses this market problem. Specifically, a high capacity, short range transport aircraft designed to alleviate airport congestion, without the size and cost that comes with long range capability. This aircraft will have an entry into service (EIS) of 2029, with a passenger capacity of 400 in a dual class configuration, and 3,500 nautical miles of range.

This aircraft should be designed to best serve the market stipulated in the first paragraph. Historical trends of key airplane characteristics may not be appropriate for the non-standard combination of this large seat count and design range.

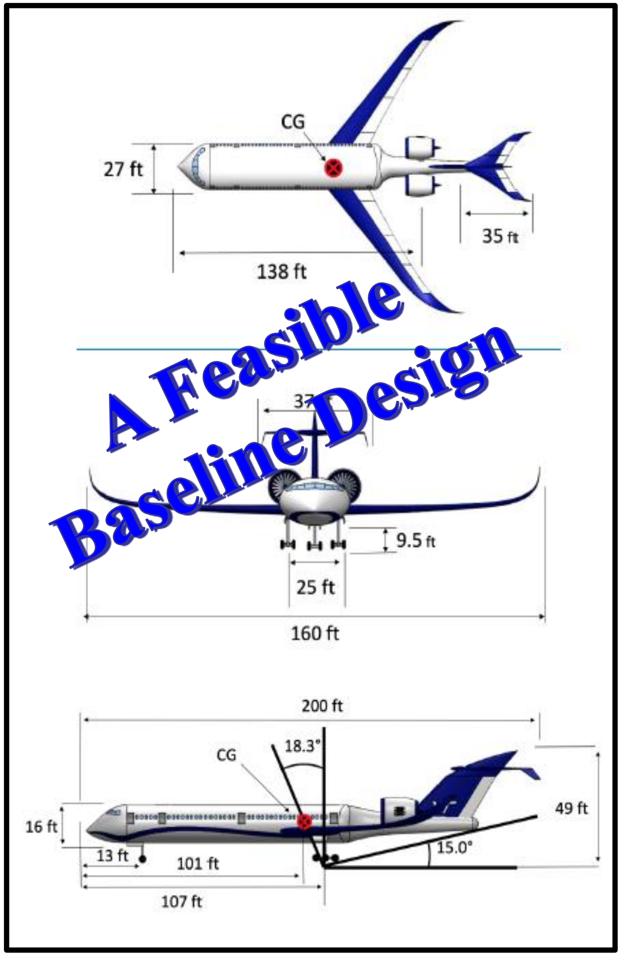
The aircraft is to be designed to meet all the requirements in General Requirements and the requirements in Mission Requirements. The objectives for designer optimization are listed in Design Objectives.

Requirements (M) = Mandatory Requirement (T) = Tradable requirement

General Requirements

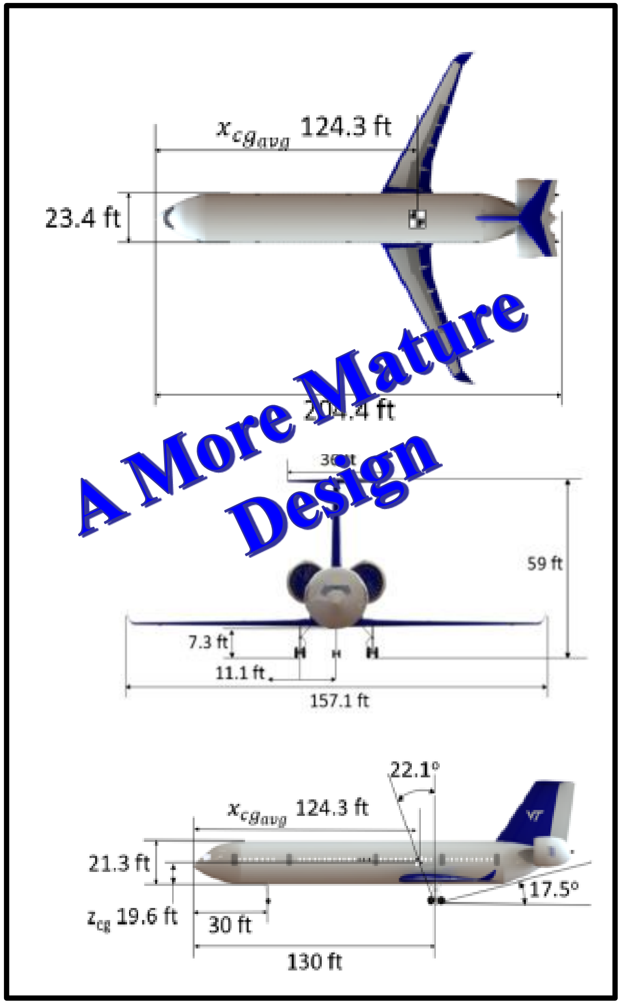
- (M) Capable of taking off and landing from runways (asphalt or concrete)
- (M) Capable of VFR and IFR flight with an autopilot
- (M) Capable of flight in known icing conditions
- (M) Meets applicable certification rules in FAA 14 CFR Part 25
    - All missions below assume reserves and equipment required to meet applicable FARs
- (M) Engine/propulsion system assumptions documented
    - Use of engine(s) that will be in service by 2029

The Last Day of AOE-4065



A Feasible Baseline Design

The Last Day of AOE-4066



A More Mature Design

Baseline Design: *Recap*

We *estimated* values of parameters for the Baseline Design or the Preferred System Concept based on many *simplifying assumptions*

- **Initial W_{TO} Sizing**
  - ***Empty Weight***: *Historical trends for our class of aircraft*
  - **Fuel Weight**: *Assumed/estimated values of several parameters*
    - AR, $(L/D)_{max}$ or C_{D0}
    - Cruise and/or loiter *speed*, V_{cr} or V_{lo}; altitude, h_{cr} or h_{lo}; and $tsfc$ or $bsfc$ for the cruise or loiter mission phases
- **Initial $(W/S)_{TO}$ and $(T/W)_{TO}$ Estimation**
  - ***Feasible Design Space (or Domain):*** *Used approximate form of vehicle performance equations* to define a *Design Space*
  - Selected more parameters, such as, C_{Lmax} , V_{TO} , ROC, etc.
- **Empennage Sizing**
  - *Used empirical values of Tail Volume Coefficients*
- **Component Weights & System Cost**
  - *Used parametric and empirical relationships*
- **Etc., Etc.**

Baseline Design Has Low Level of Maturity (TRL ~ 2-3)

Baseline Design Needs
Refinement & Validation

- **Validate <u>all</u> assumptions and parameter values used to create your feasible Baseline Design**
  - *If the assumptions turn out to be flawed or the parameter values wrong, you may not necessarily have a feasible design, do you?*
- **Tweak the design to conform to the *validated* parameters while constantly making sure that the design is feasible**
- **Develop a project plan that integrates inputs from all sub-teams and disciplines**
  - Each sub-team should prepare a list questions that need to be answered. For example,
    - <u>What</u> assumptions/ parameters need to be validated? *These lead to tasks*
    - <u>How</u> do we validate? *Defines scope of a task based on desired output*
    - <u>When</u> do we need to complete each task? *Defines schedule and milestones*
    - <u>Who</u> else needs the results? *Defines dependencies for scheduling tasks*
  - Each sub-team should prepare a Gantt chart for their own tasks; all sub-team charts then roll up into full project level Gantt chart

Refined Design Has Higher Level of Maturity (TRL ~ 4-5)

Validation Example 1
Empty Weight

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Initial Sizing

TOGW = Empty Weight
+ Fuel Weight
+ Fixed (Payload) Weight

"Top down"

Estimation of TOGW and its constituents including empty weight

AOE 4066

Empty Weight = ∑ Component Weights

- ✓ Airframe Structure: *wing, fuselage, tail, landing gear,...*
- ✓ Propulsion: *engine, inlet, fuel system, engine controls, and thrust reversers*
- ✓ Control system: *hydraulic, pneumatic, actuators, …*
- ✓ Instruments
- ✓ Electrical system
- ✓ Furnishings
- ✓ Avionics
- ✓ Air-conditioning and anti-icing
- ✓ Other: *drag chutes, etc.*

"Bottoms up"

Analysis of the baseline design to validate estimated empty weight

- Known weights
- Direct weight estimates
- Statistical weight estimates

Get precise estimates of CG and Moments of Inertia based on component locations

Change in CG affects all subteams!!

In case you missed it…

> ***"…estimation of the aircraft empty weight is the weakest part of the conceptual design process and it has tremendous leverage on the aircraft takeoff weight. It is almost impossible to estimate the empty weight of something that has not been built…However, it is important to press on or aircraft will never be designed."***
>
> ***-- Lee Nicolai***

That is why we start with a "Top Down" approach and end with "Bottoms up".

Source: Chapter 5, Ref. 1, (Nicolai & Carichner);

Validation Example 2

Aerodynamics

Aerodynamics subteam should review their R&Rs, and any project data deliverables in the RFP

- ○ Identify all parameters that need to be validated and approaches
- ○ Let us consider one of the parameters, C_{D0}
  - ▪ Do we need to validate the assumed value of C_{D0}?
    - ✓ Yes!
  - ▪ How will we validate C_{D0}?
    - ✓ Use analysis and testing methods
    - ✓ Research relevant reference material for applicable methods
      - Options include (a) Drag Build-up method which sums up individual component parasitic drag values to estimate aircraft zero-lift drag; or (b) computational methods, such as, FRICTION or VSPAero or some other code to analyze the baseline design; or…
    - ✓ Select some or all methods based on available resources and constraints!
- ○ Investigate other parameters, such as, AR, S_{ref}, $(L/D)_{max}$, C_{Lmax} , etc.

Engineers Should Use/Choose Validation Approach Wisely

"Just because you can doesn't mean you should."

1. Understand Customer's Problem

- Develop a *comprehensive* understanding of the scope of customer needs (potential impact of solution, desired level of accuracy, type and amount of data, etc.) and constraints (cost and schedule)

2. Devise a Practical Approach to Solving the Problem

- Examine available computational simulation codes for solving your problem with *effectiveness* as the key measure of merit
- Choose a code based on your understanding of the problem [the type, amount and quality of aerodynamic data required to meet customer needs subject to the specified constraints]

3. Deliver a *Best Solution* that Adds Value

- Provide a solution that *best* meets customer needs while satisfying all constraints

Don't Use a Hammer When You Need a Screwdriver!

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A10.5 Vehicle Performance
A10.6 Structures & Materials
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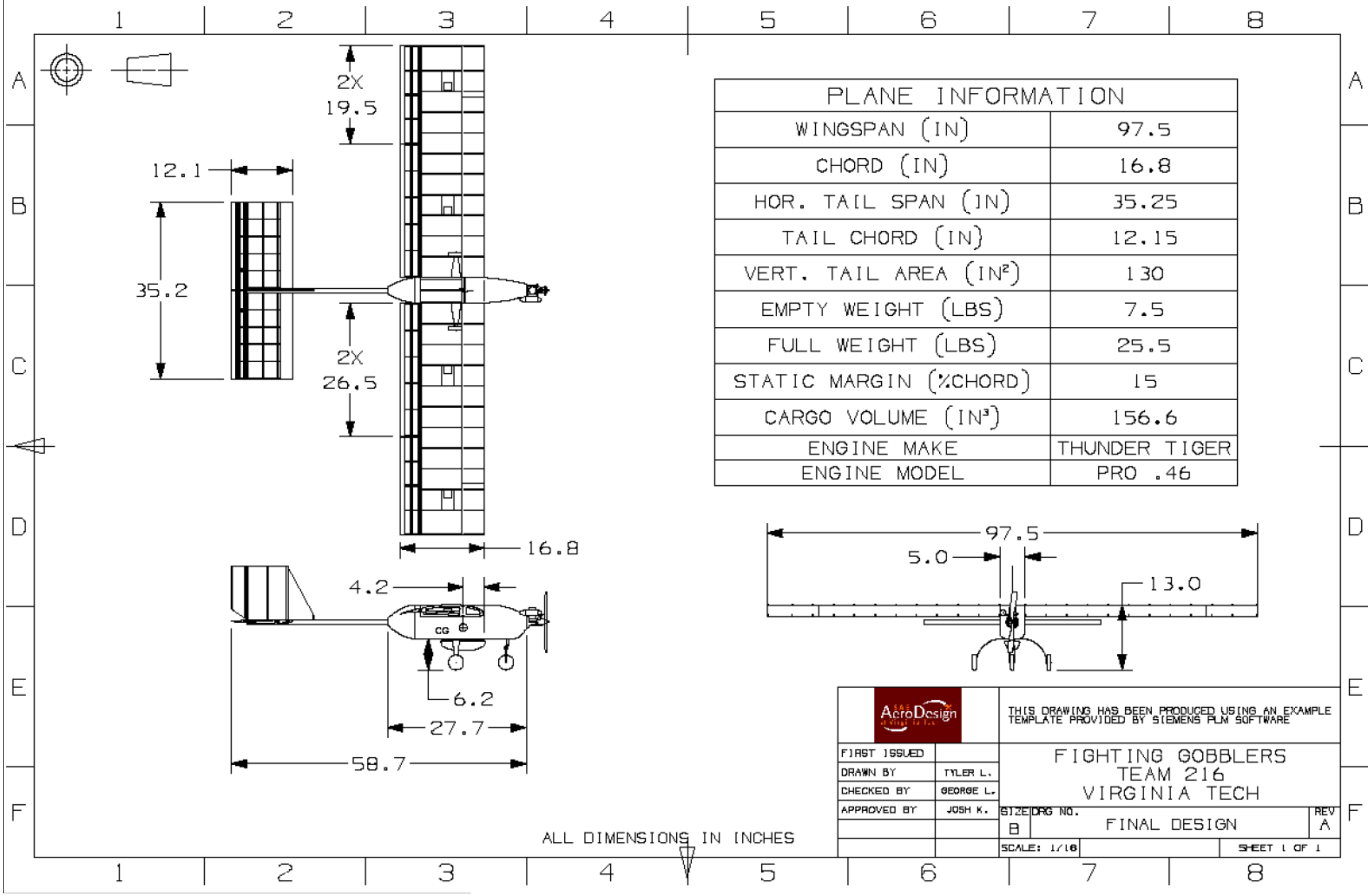
A10.8 Stability & Control
A10.9 Weights (Mass Properties) & Balance
A10.10 Cost & Manufacturing

A10.2   Configuration Layout and Loft

Configuration Layout and Loft subteam members should review their R&Rs, and any project data deliverables in the RFP

Three-view Drawing of RC Airplane:
A Good Example Using SAE Specs



PLANE INFORMATION	
WINGSPAN (IN)	97.5
CHORD (IN)	16.8
HOR. TAIL SPAN (IN)	35.25
TAIL CHORD (IN)	12.15
VERT. TAIL AREA (IN^2)	130
EMPTY WEIGHT (LBS)	7.5
FULL WEIGHT (LBS)	25.5
STATIC MARGIN (%CHORD)	15
CARGO VOLUME (IN^3)	156.6
ENGINE MAKE	THUNDER TIGER
ENGINE MODEL	PRO .46

ALL DIMENSIONS IN INCHES

THIS DRAWING HAS BEEN PRODUCED USING AN EXAMPLE TEMPLATE PROVIDED BY SIEMENS PLM SOFTWARE

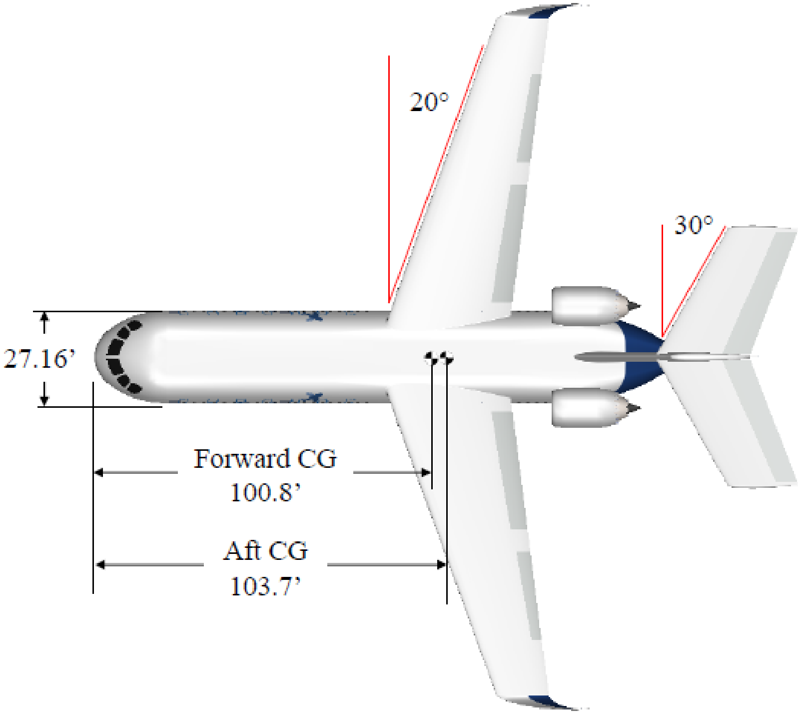
FIRST ISSUED	
DRAWN BY	TYLER L.
CHECKED BY	GEORGE L.
APPROVED BY	JOSH K.

FIGHTING GOBBLERS
TEAM 216
VIRGINIA TECH

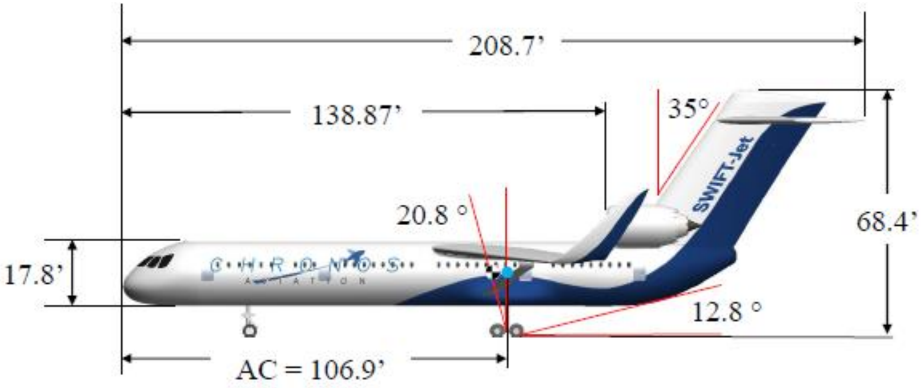
SIZE B
DRG NO. FINAL DESIGN
REV A
SCALE: 1/16
SHEET 1 OF 1

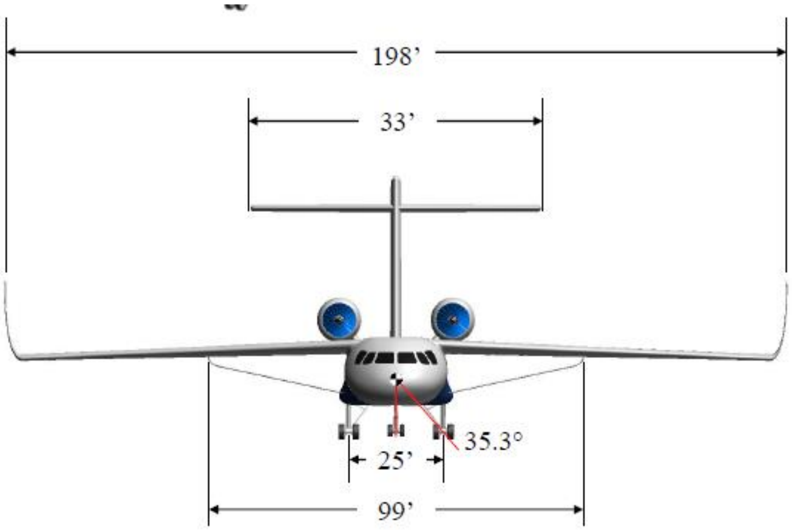
Final Configuration Layout:

A Transport Aircraft Example



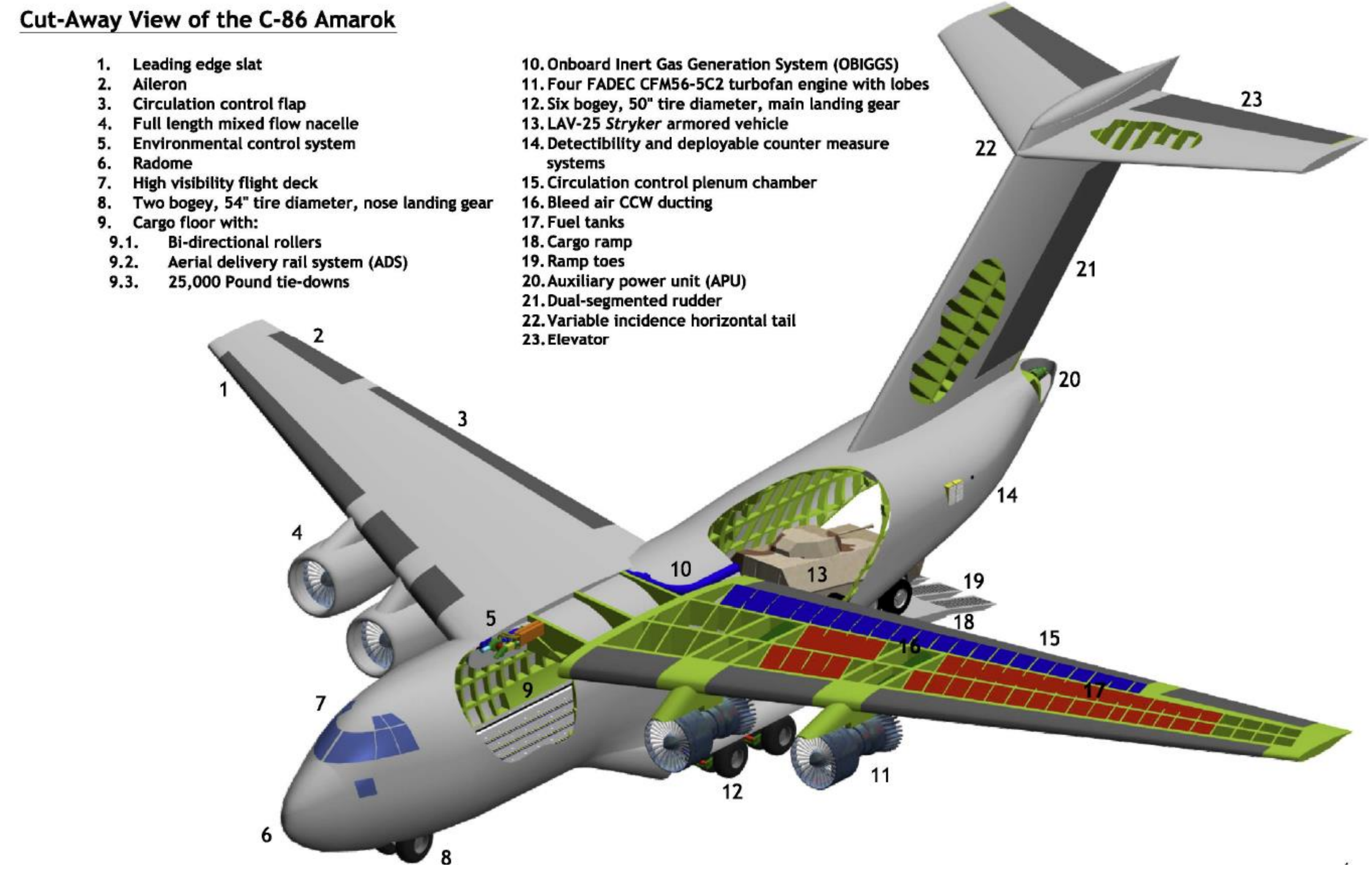
Aircraft Specifications	
Max. TOGW (lbs)	453,156
Seat Capacity	400
Design Range (nm)	3,500
Max. Climb Rate (fpm)	5,500
Cruise Mach No.	0.78
Cruise Altitude (ft)	40,000
Service Ceiling (ft)	43,500





Source: 2020 VT Swift-Jet (AIAA Undergrad Team Aircraft Design)

An Example to Emulate:
Cal Poly SLO Student Team Project

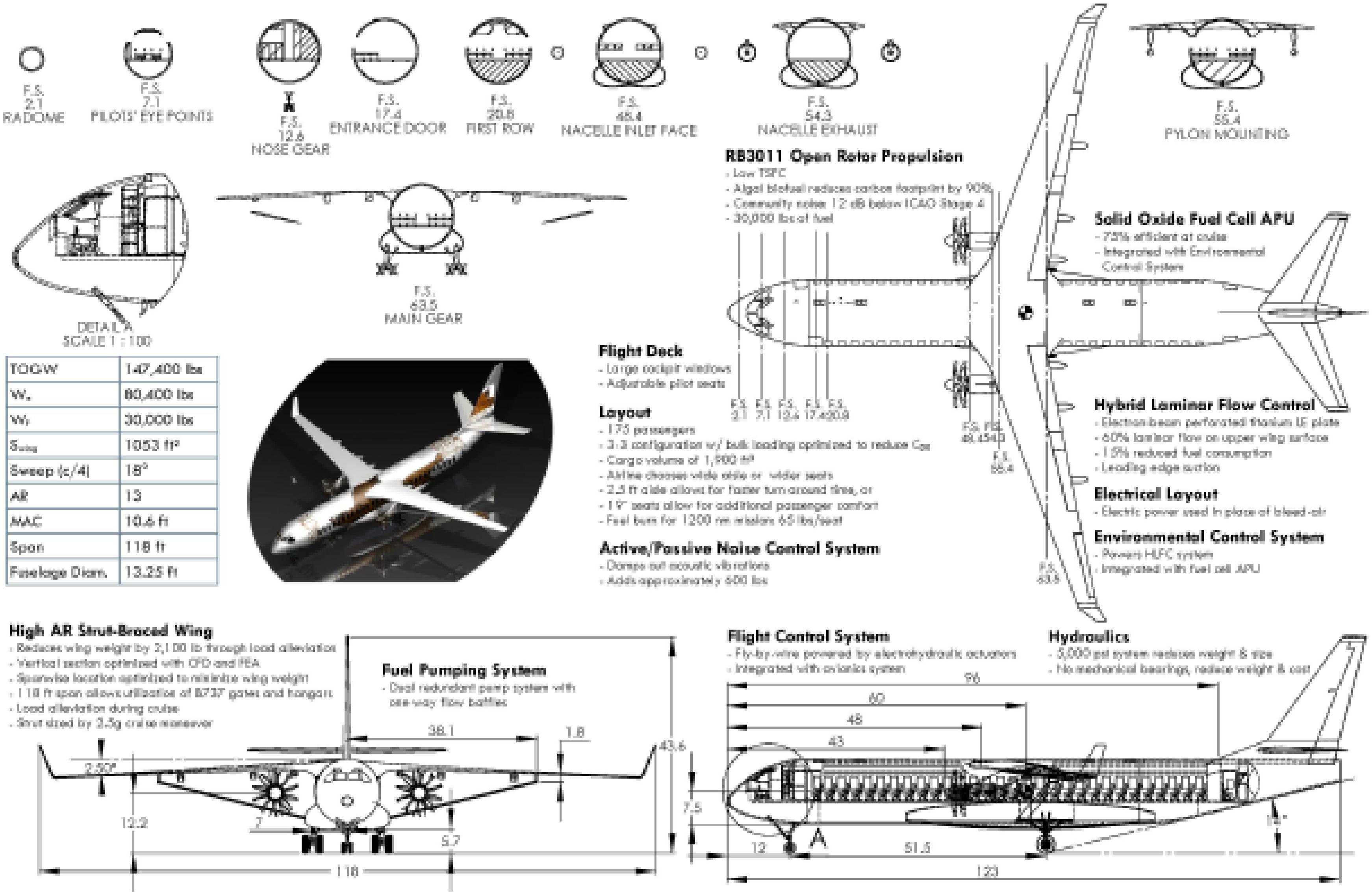


Cut-Away View of the C-86 Amarok

1. Leading edge slat
2. Aileron
3. Circulation control flap
4. Full length mixed flow nacelle
5. Environmental control system
6. Radome
7. High visibility flight deck
8. Two bogey, 54" tire diameter, nose landing gear
9. Cargo floor with:
   - 9.1. Bi-directional rollers
   - 9.2. Aerial delivery rail system (ADS)
   - 9.3. 25,000 Pound tie-downs
10. Onboard Inert Gas Generation System (OBIGGS)
11. Four FADEC CFM56-5C2 turbofan engine with lobes
12. Six bogey, 50" tire diameter, main landing gear
13. LAV-25 *Stryker* armored vehicle
14. Detectibility and deployable counter measure systems
15. Circulation control plenum chamber
16. Bleed air CCW ducting
17. Fuel tanks
18. Cargo ramp
19. Ramp toes
20. Auxiliary power unit (APU)
21. Dual-segmented rudder
22. Variable incidence horizontal tail
23. Elevator

Source: 2007 AIAA Undergrad Team Competition Winner, Cal Poly, SLO

An Example to Emulate:
Cal Poly SLO Student Team Project



TOGW	147,400 lbs
W_e	80,400 lbs
W_f	30,000 lbs
S_{wing}	1053 ft²
Sweep (c/4)	18°
AR	13
MAC	10.6 ft
Span	118 ft
Fuselage Diam.	13.25 ft

RB3011 Open Rotor Propulsion
- Low TSFC
- Algal biofuel reduces carbon footprint by 90%
- Community noise 12 dB below ICAO Stage 4
- 30,000 lbs of fuel

Flight Deck
- Large cockpit windows
- Adjustable pilot seats

Layout
- 175 passengers
- 3-3 configuration w/ bulk loading optimized to reduce C_{D0}
- Cargo volume of 1,900 ft³
- Airline chooses wide aisle or wider seats
- 2.5 ft aisle allows for faster turn around time, or
- 19" seats allow for additional passenger comfort
- Fuel burn for 1200 nm mission 65 lbs/seat

Active/Passive Noise Control System
- Damps out acoustic vibrations
- Adds approximately 600 lbs

Solid Oxide Fuel Cell APU
- 75% efficient at cruise
- Integrated with Environmental Control System

Hybrid Laminar Flow Control
- Electron-beam perforated titanium LE plate
- 60% laminar flow on upper wing surface
- 13% reduced fuel consumption
- Leading edge suction

Electrical Layout
- Electric power used in place of bleed-air

Environmental Control System
- Powers HLFC system
- Integrated with fuel cell APU

High AR Strut-Braced Wing
- Reduces wing weight by 2,100 lb through load alleviation
- Vertical section optimized with CFD and FEA
- Spanwise location optimized to minimize wing weight
- 118 ft span allows utilization of B737 gates and hangars
- Load alleviation during cruise
- Strut sized by 2.5g cruise maneuver

Fuel Pumping System
- Dual redundant pump system with one-way flow baffles

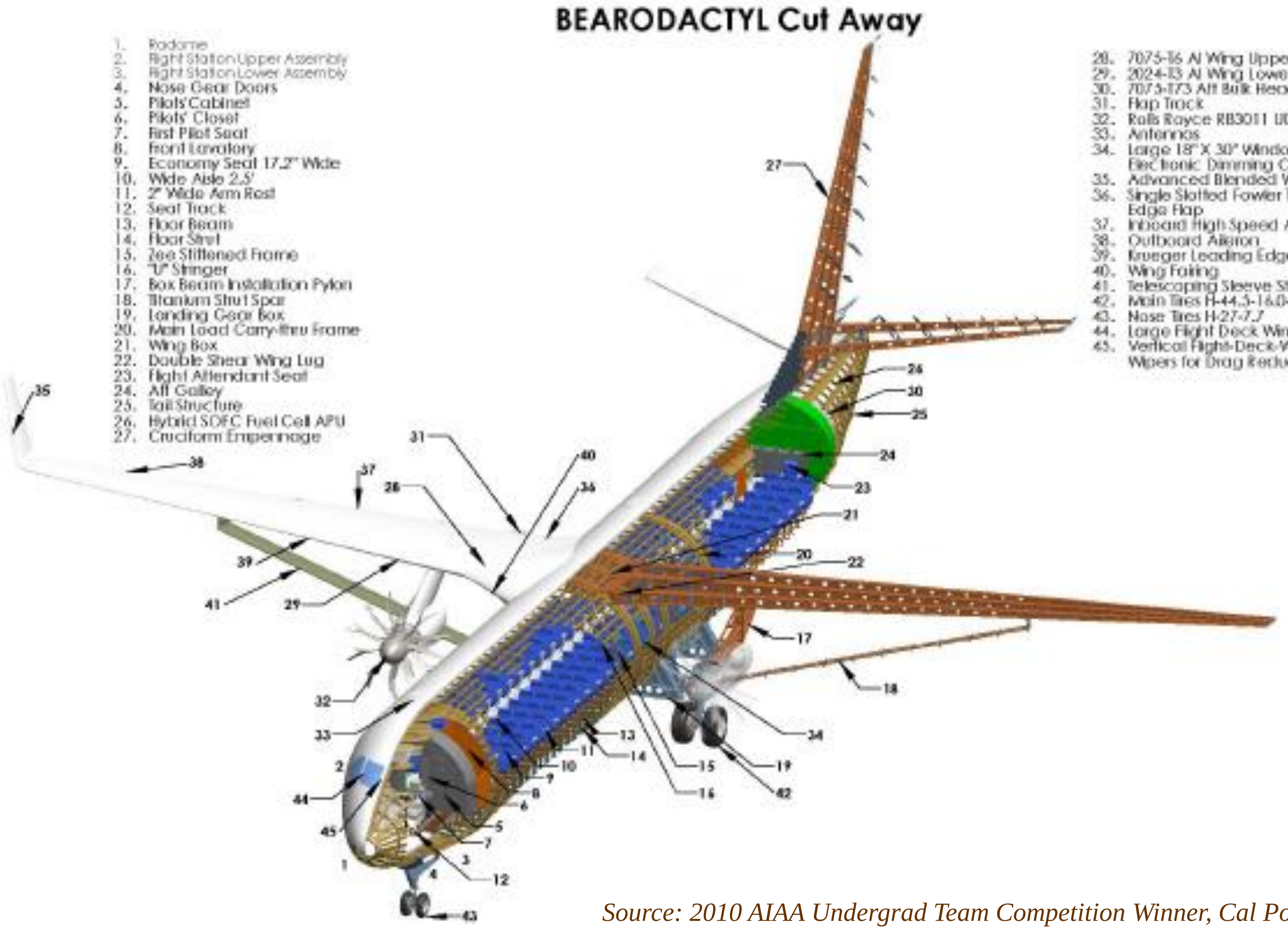
Flight Control System
- Fly-by-wire powered by electrohydraulic actuators
- Integrated with avionics system

Hydraulics
- 5,000 psi system reduces weight & size
- No mechanical bearings, reduce weight & cost

Source: 2010 AIAA Undergrad Team Competition Winner, Cal Poly, SLO

Aircraft Structure & Systems Layout

Student Design Project Example to Emulate



BEARODACTYL Cut Away

1. Radome
2. Right Station Upper Assembly
3. Right Station Lower Assembly
4. Nose Gear Doors
5. Pilots' Cabinet
6. Pilots' Closet
7. First Pilot Seat
8. Front Lavatory
9. Economy Seat 17.2" Wide
10. Wide Aisle 2.5'
11. 2" Wide Arm Rest
12. Seat Track
13. Floor Beam
14. Floor Strut
15. Zee Stiffened Frame
16. "U" Stringer
17. Box Beam Installation Pylon
18. Titanium Strut Spar
19. Landing Gear Box
20. Main Load Carry-thru Frame
21. Wing Box
22. Double Shear Wing Lug
23. Flight Attendant Seat
24. Aft Galley
25. Tail Structure
26. Hybrid SOFC Fuel Cell APU
27. Cruciform Empennage
28. 7075-T6 Al Wing Upper Skin
29. 2024-T3 Al Wing Lower Skin
30. 7075-T73 Aft Bulk Head
31. Flap Track
32. Rolls Royce RB3011 UDF Engine
33. Antennas
34. Large 18" X 30" Window w/ Electronic Dimming Capability
35. Advanced Blended Winglet
36. Single Slotted Fowler Trailing Edge Flap
37. Inboard High Speed Aileron
38. Outboard Aileron
39. Krueger Leading Edge Flap
40. Wing Fairing
41. Telescoping Sleeve Strut
42. Main Tires H-44.5-16.0-21
43. Nose Tires H-27-7.7
44. Large Flight Deck Windows
45. Vertical Flight-Deck-Window Wipers for Drag Reduction

Source: 2010 AIAA Undergrad Team Competition Winner, Cal Poly, SLO

Configuration Layout and Loft

Recommended Reading for Topics in Configuration Layout and Loft

Topic	Recommended References
Configuration Layout and Loft	
Configuration Layout and Loft	Chapter 7, Raymer, Ref. AVD 2
Aircraft Design Aid and Layout Guide	All chapters, Kirschbaum with Mason, Ref. AVD 6

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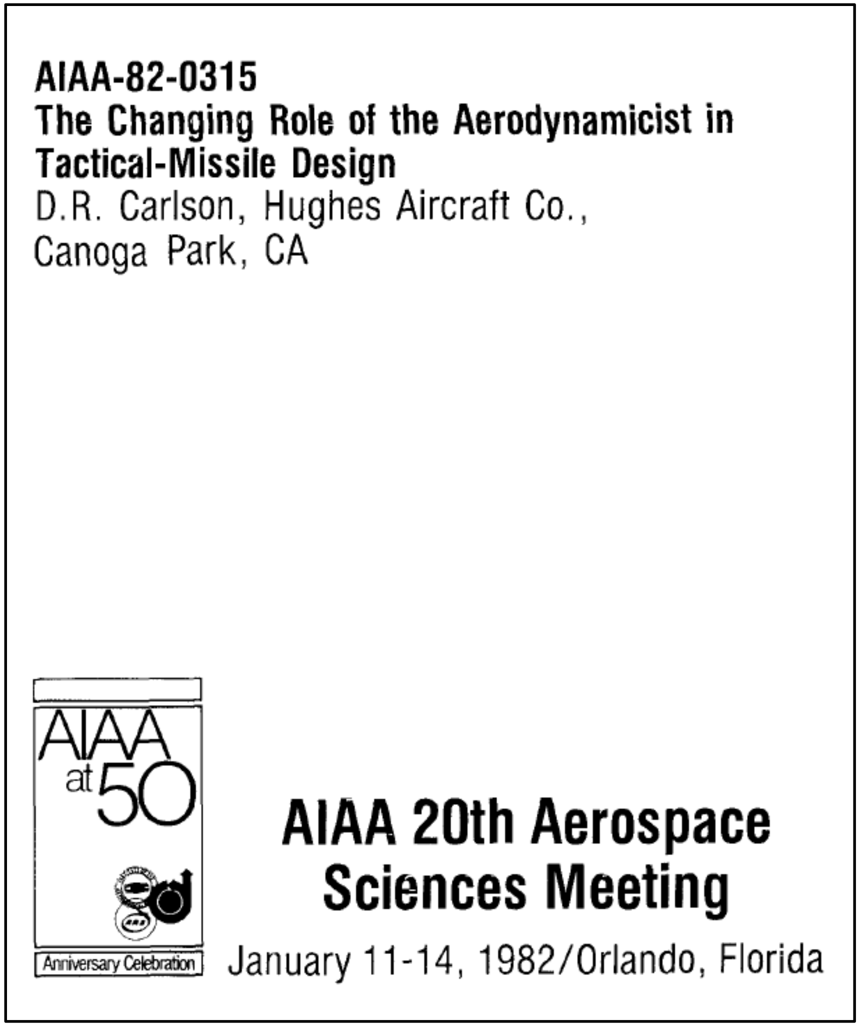
A10.3 Aerodynamics

Aerodynamics subteam members should review their R&Rs, and any project data deliverables in the RFP

Role of Aerodynamicist

- **AIAA-82-0315: An Excellent Reference**
  - 40 years “new”
  - Highly relevant—just replace “Tactical-Missile” with Aircraft!
  - A copy is in the *Aerodynamics* subfolder on Canvas
  - *Aerodynamicists help ensure that aircraft delivers targeted flight performance. Period.*



AIAA-82-0315
The Changing Role of the Aerodynamicist in Tactical-Missile Design
D.R. Carlson, Hughes Aircraft Co.,
Canoga Park, CA

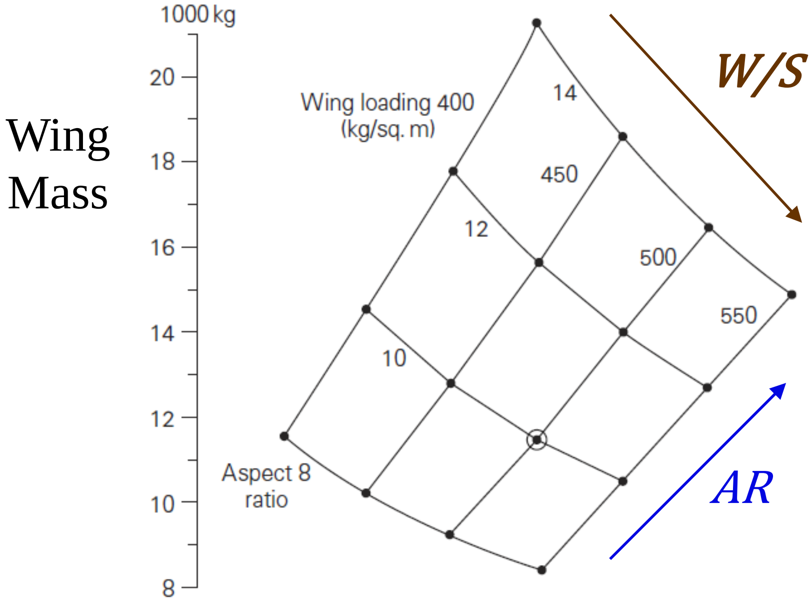
AIAA at 50
Anniversary Celebration

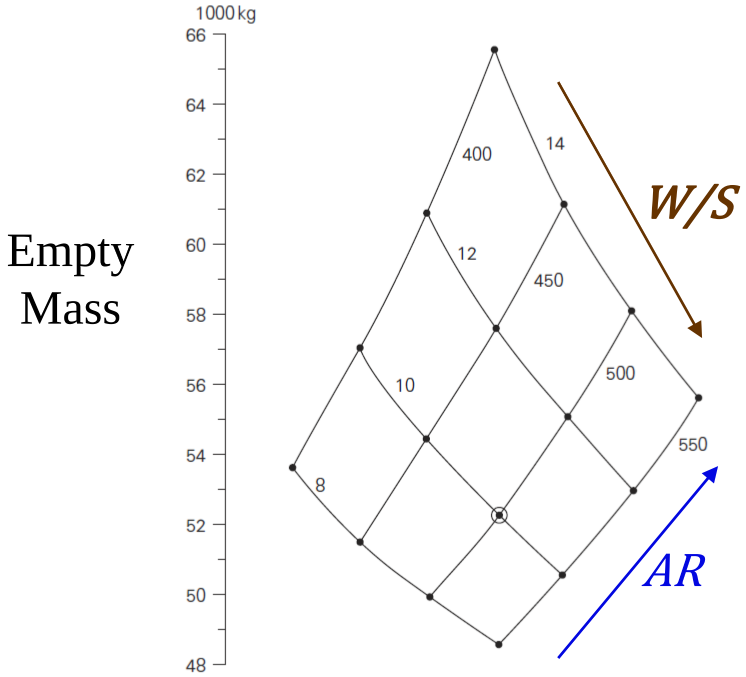
AIAA 20th Aerospace Sciences Meeting
January 11-14, 1982/Orlando, Florida

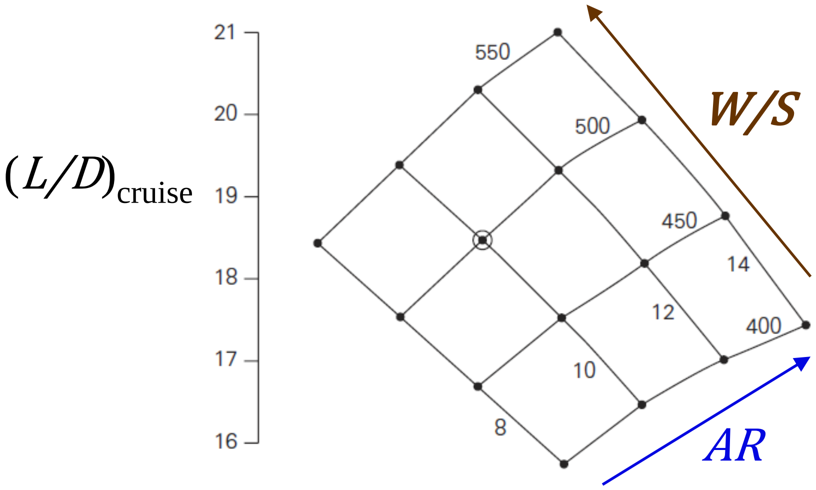
“*They own OML (Outer Mold Line)*” – Lee Nicolai

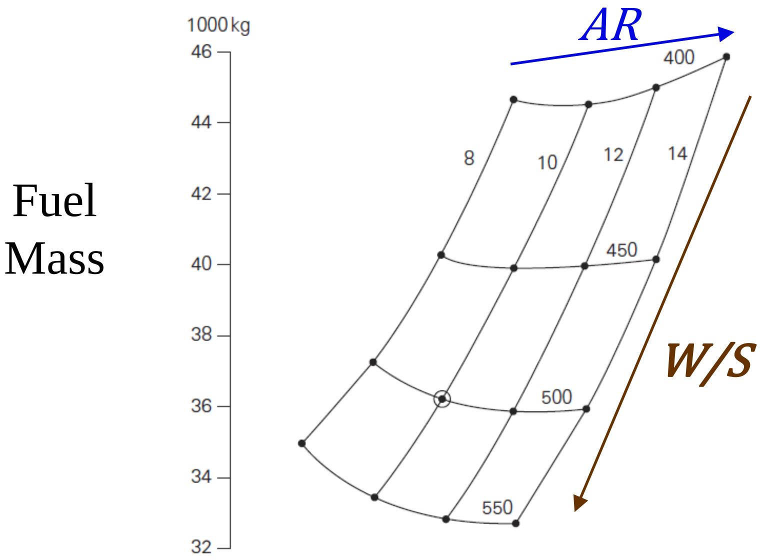
Trade Studies

- **Wing Geometry (AR and S or W/S)**





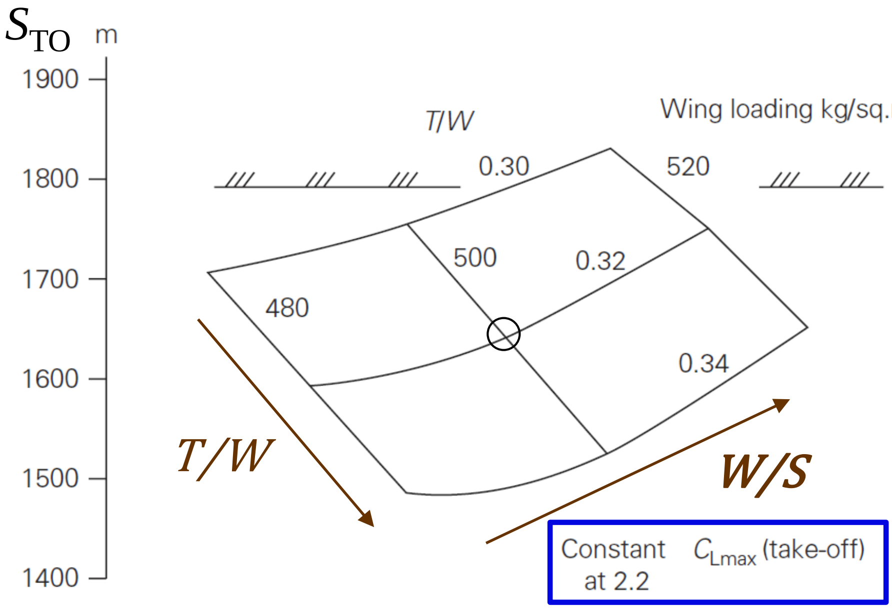




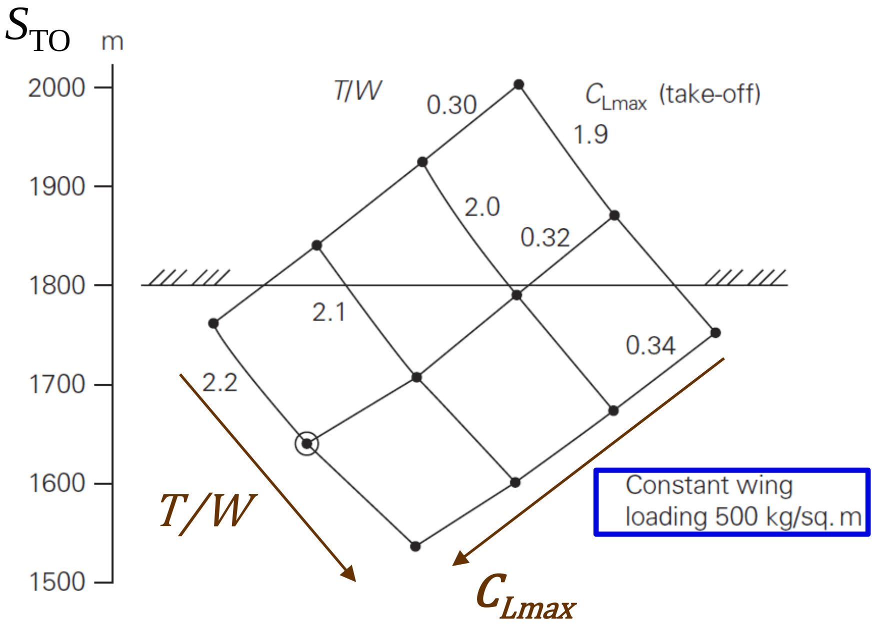
Source: Chapter 4, Ref. AVD 21 (Jenkinson)

Trade Studies

- **Take-off Parameters**

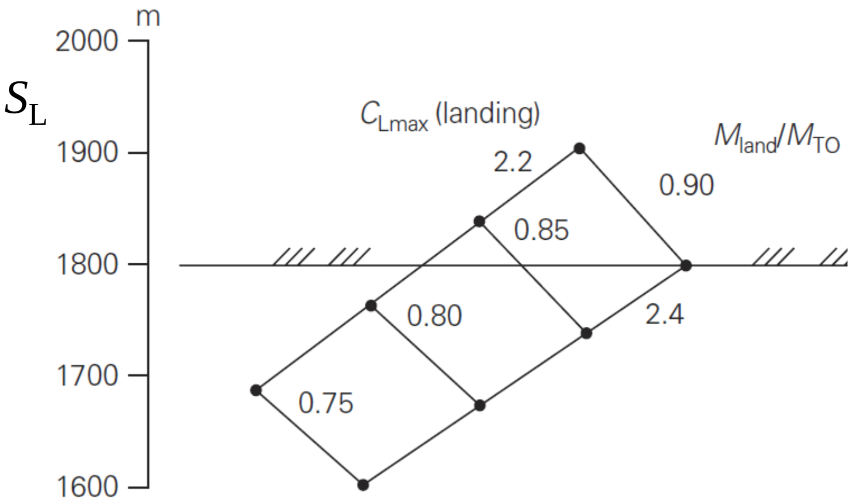


Constant C_{Lmax} (take-off) at 2.2



Constant wing loading 500 kg/sq. m

- **Landing Parameters**



Source: Chapter 4, Ref. AVD 21 (Jenkinson)

Aerodynamic Coefficients

- **Estimate Key Non-dimensional Parameters**

Forces

$C_L = L/qS_{ref}$

$C_D = D/qS_{ref}$

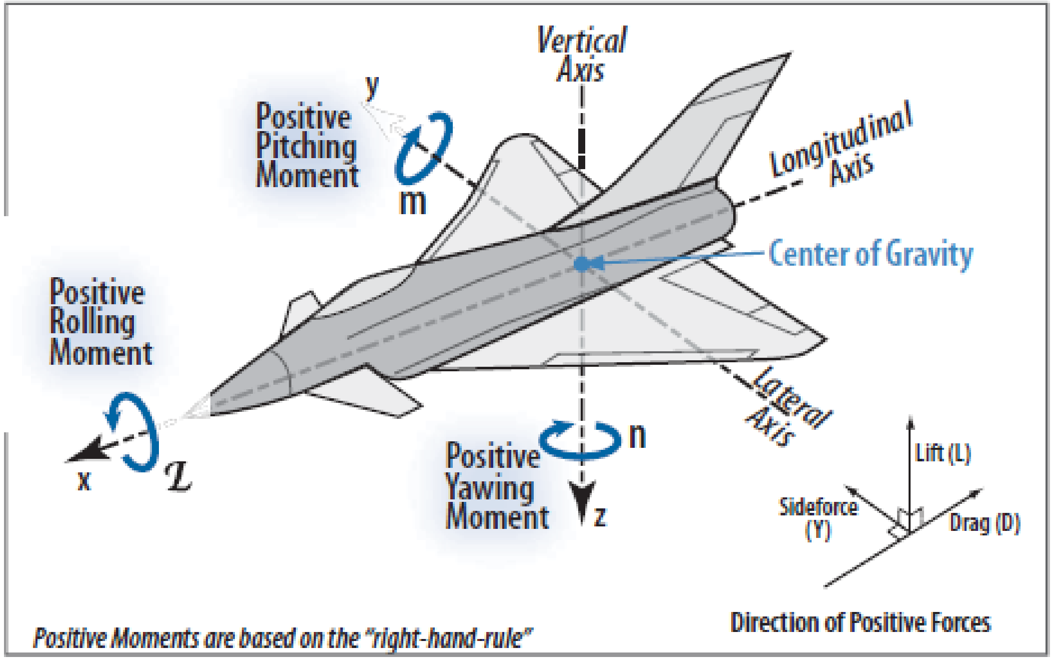
$C_Y = Y/qS_{ref}$

Moments

$C_m = m/qS_{ref}\bar{c}$

$C_l = \mathcal{L}/qS_{ref}b$

$C_n = n/qS_{ref}b$



Derivatives

$C_{L_\alpha} = \Delta C_L/\Delta\alpha$

$C_{m_\alpha} = \Delta C_m/\Delta\alpha$

$C_{n_\beta} = \Delta C_n/\Delta\beta$

$C_{\ell_\beta} = \Delta C_\ell/\Delta\beta$

$C_{y_\beta} = \Delta C_y/\Delta\beta$

Effectiveness

$C_{m_{\delta e}} = \Delta C_m/\Delta \mathrm{elev}$

$C_{\ell_{\delta a}} = \Delta C_\ell/\Delta \mathrm{aileron}$

$C_{n_{\delta r}} = \Delta C_n/\Delta \mathrm{rudder}$

q = Dynamic Pressure = ½ρV^2

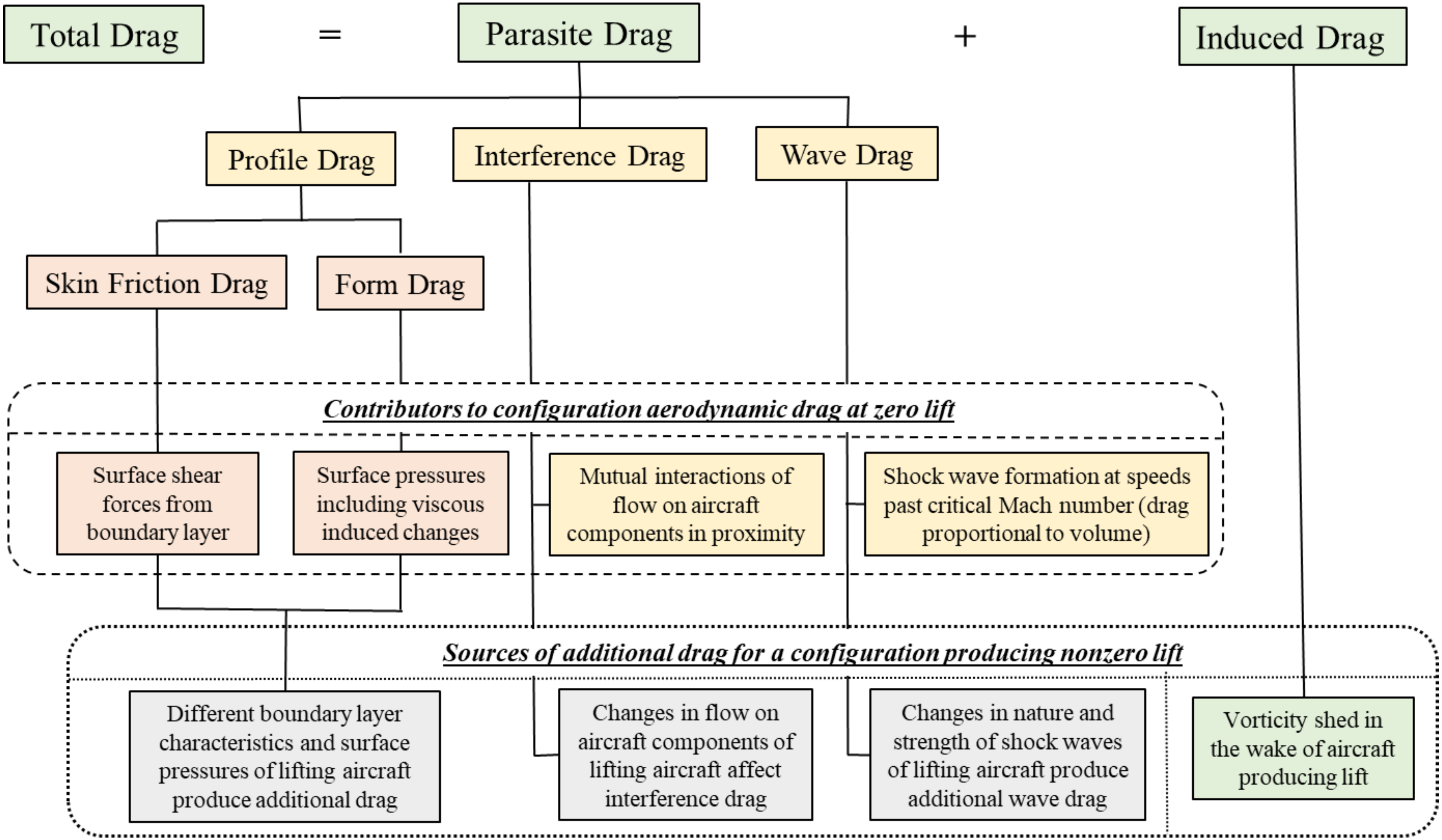
Reference Areas and Lengths Are Just That — *References*

- **Accurate C_L estimation is relatively easy; C_D and C_m not so!**

Source: Chapter 2, Ref. AVD 1 (Nicolai)

COLLEGE OF ENGINEERING
KEVIN T. CROFTON DEPARTMENT OF AEROSPACE AND OCEAN ENGINEERING
VIRGINIA TECH.

Broad Categorization of Configuration Aerodynamic Drag



Total Drag = Parasite Drag + Induced Drag

Profile Drag

Interference Drag

Wave Drag

Skin Friction Drag

Form Drag

Contributors to configuration aerodynamic drag at zero lift

Surface shear forces from boundary layer

Surface pressures including viscous induced changes

Mutual interactions of flow on aircraft components in proximity

Shock wave formation at speeds past critical Mach number (drag proportional to volume)

Sources of additional drag for a configuration producing nonzero lift

Different boundary layer characteristics and surface pressures of lifting aircraft produce additional drag

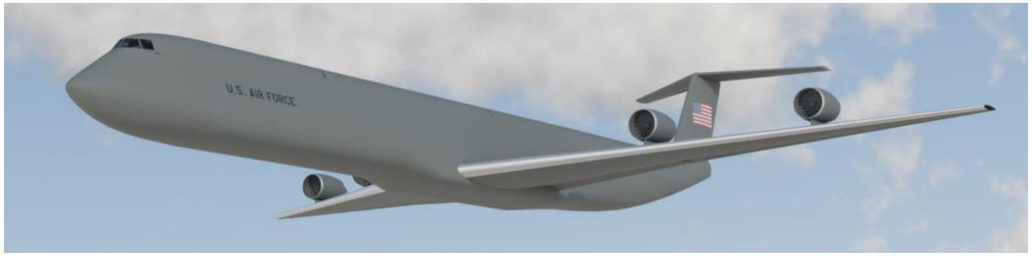
Changes in flow on aircraft components of lifting aircraft affect interference drag

Changes in nature and strength of shock waves of lifting aircraft produce additional wave drag

Vorticity shed in the wake of aircraft producing lift

Zero-lift Drag Build-up

Example: Atlas



Zero Lift Drag Build-up On Aircraft	
Component	**CD0**
Main Wing	0.00507
Body	0.00855
Vertical Tail	0.00065
Horizontal Tail	0.00095
All Engines	0.00164
Total:	0.01686
Initial Sizing:	0.017

Source: 2023-24 AIAA Heavy Lift Mobility Platform: VT Aero Sub-team Lead: Durgin)

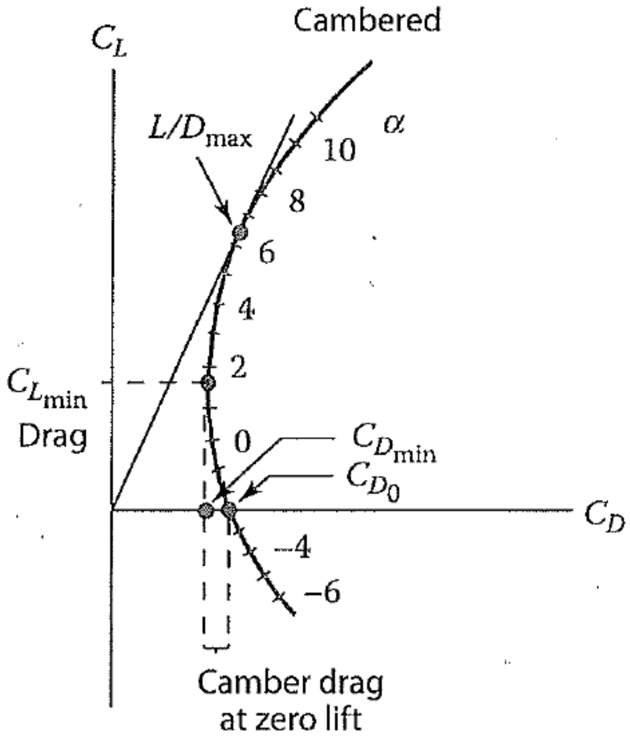
Drag Polars

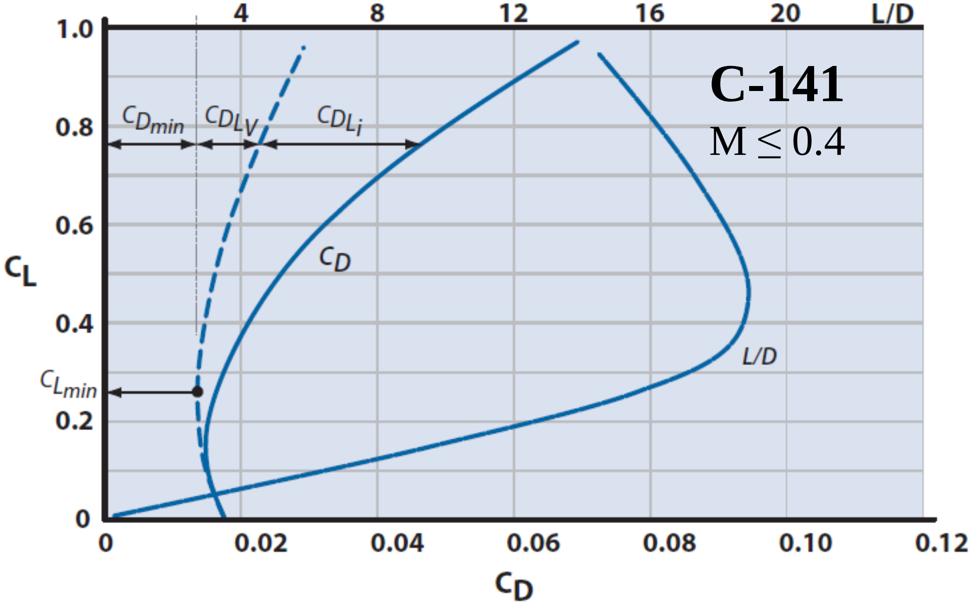
Cambered Wings

$$C_D = C_{D\min} + K''\left(C_L - C_{\ell\min}\right)^2 + K'C_L^2$$

$$K'' = \Delta\left(C_d - C_{d\min}\right)/\Delta\left(C_l - C_{l\min}\right)^2$$

$$K' = 1/\pi \text{ AR } e$$

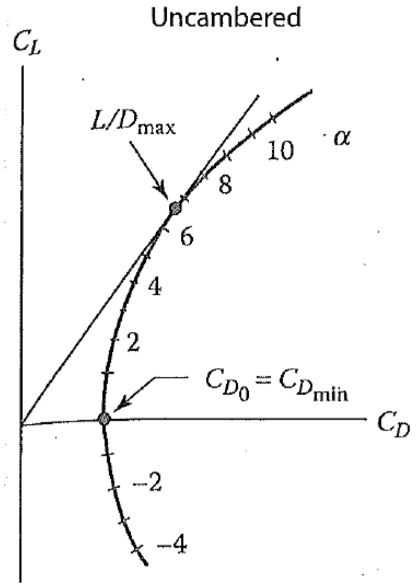




Uncambered Wings

$$C_D = C_{D0} + KC_L^2$$

$$C_{D0} = C_{D\min}$$



Source: Chapter 2, Ref. AVD 1 (Nicolai)

Aerodynamics

Recommended Reading for Topics in Aerodynamics

Topic	Recommended References
Aerodynamics	
Review of Practical Aerodynamics	Chapter 2, Nicolai & Carichner, Ref. AVD 1
Selecting the Planform and Airfoil Selection	Chapter 7, Nicolai & Carichner, Ref. AVD 1
High-Lift Devices	Chapter 9, Nicolai & Carichner, Ref. AVD1
Estimating Wing-Body Aerodynamics	Chapter 13, Nicolai & Carichner, Ref. AVD 1
Aerodynamics	Chapter 12, Raymer, Ref. AVD 2 in PR
Wing Design	Chapter 5, Sadraey, Ref. AVD 5
The Anatomy of the Wing	Chapter 9, Gudmundsson, AVD 4
Aircraft Drag Analysis	Chapter 15, Gudmundsson, Ref. AVD 4
Aircraft Drag	Chapter 9, Kundu, Ref. AVD 8
Aircraft Drag and Wing Design	*See Aerodynamics folder in Supplemental Reference Material folder on course site*

Outline

A10. Preliminary Design: Refine & Validate Baseline Design

A10.1 General Remarks
A10.2 Configuration Layout and Loft
A10.3 Aerodynamics
A10.4 Aeropropulsion Integration
A10.5 Vehicle Performance
A10.6 Structures & Materials
A10.7 Subsystems
A10.8 Stability & Control
A10.9 Weights (Mass Properties) & Balance
A10.10 Cost & Manufacturing

A10.4 AeroPropulsion Integration

Aeropropulsion Integration subteam members should review their R&Rs, and any project data deliverables in the RFP

Propulsion System Types

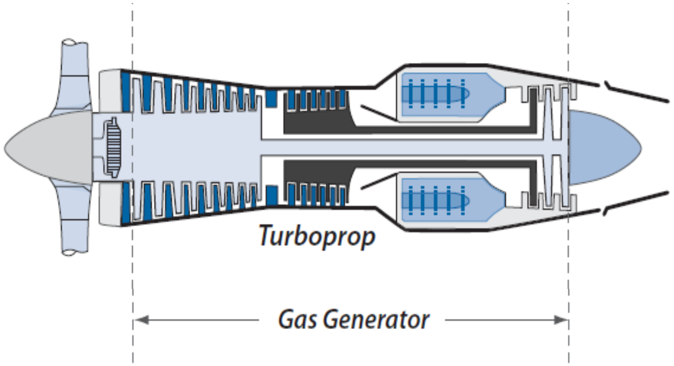
- **Two main options to produce forward thrust**

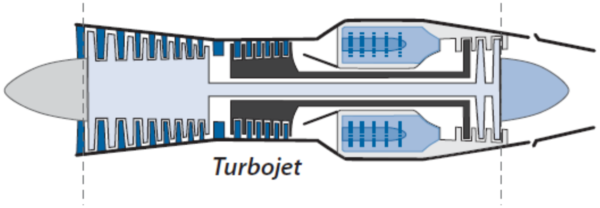
1. Propellers

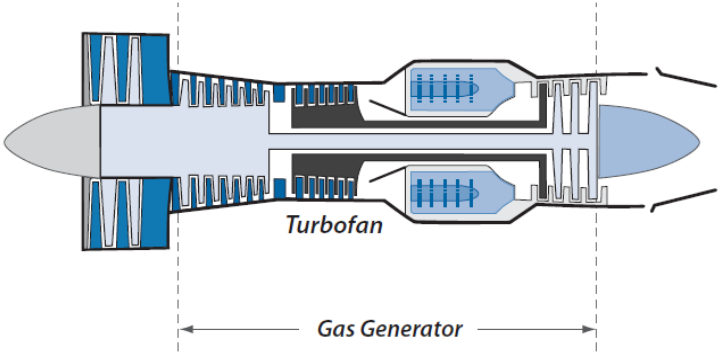
- Powered by reciprocating piston engines, gas turbines (turboprops), or electric motors
- Keeping tip speed less than sonic restricts practical use to flight speeds < 500 kt

2. Jet Engines

- Variants include turbojets; afterburning turbojets; and turbofans
- Can operate supersonically to Mach 3.5

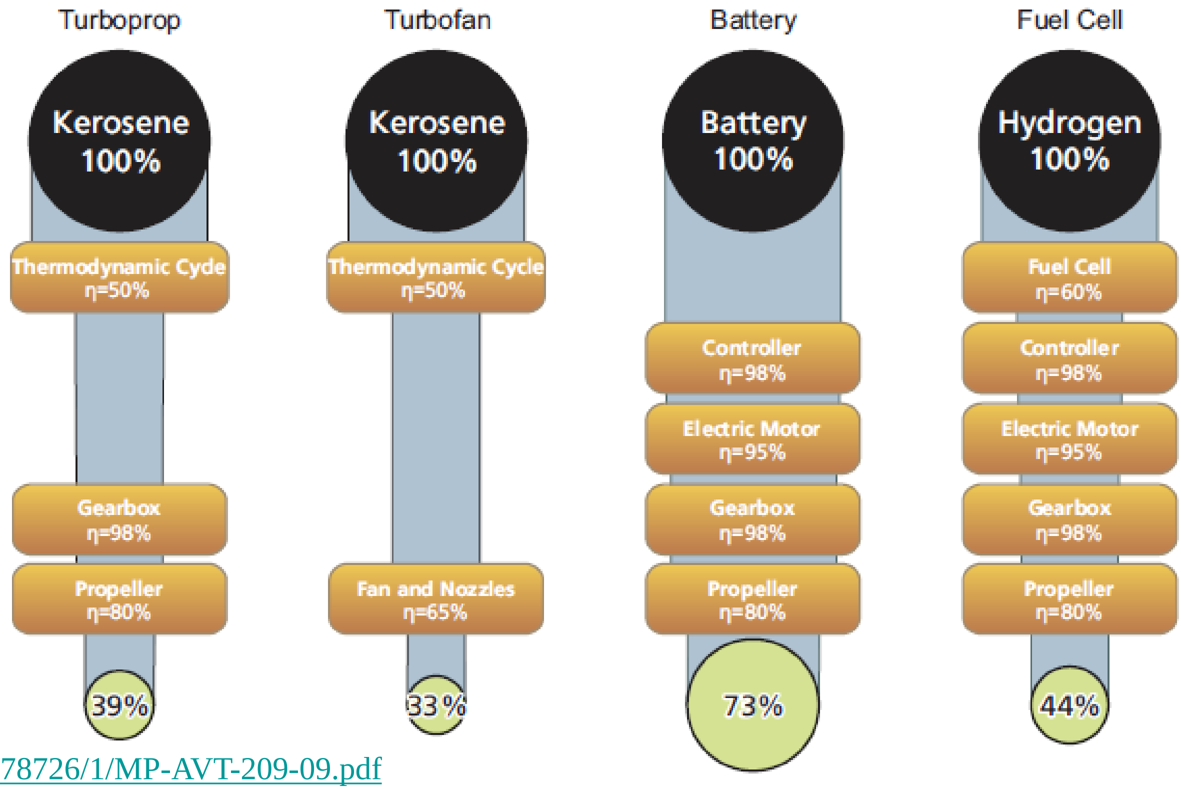






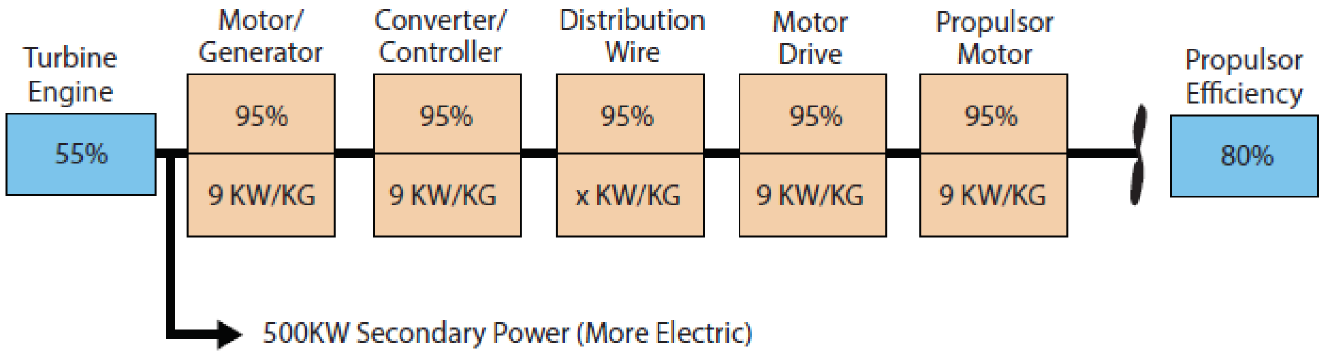
Source: Ch. 14, Ref. AVD 1 (Nicolai & Carichner)

Onboard Propulsive Efficiency Chains



Source: https://elib.dlr.de/78726/1/MP-AVT-209-09.pdf

Turboelectric
(component efficiency and specific power)



Source: https://www.nap.edu/download/23490

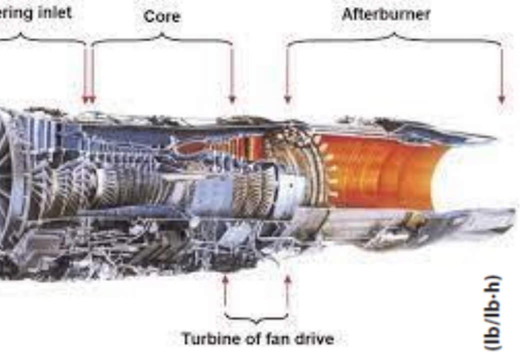
Turbine Engine Selection Considerations

- **Choose a suitable engine that can supply the required thrust**
- **Realistic propulsion expectations are essential**
  - New engines built from scratch are VERY (VERY, VERY, VERY) expensive
    - Deciding to use a 'rubber' engine should take this real cost into account
  - Much of your load is fuel, so you better know how your engine will perform to justify fuel load
  - Real engines have real dimensions, (dry) weights, mass flow rates, inlet and exhaust flow effects, and noise
  - **Use extensive engine databases** for availability, performance, cost, etc.
- **Sometimes new airframes do require new engines to meet stringent efficiency and emissions requirements**
  - New technologies enable engines with (i) lean combustion for low Nox; (ii) high-temperature turbine materials for efficiency; (iii) transonic compressor/turbine designs; (iv) noise reducing inlets and exhausts

Courtesy of Profs. Mason and Lowe

Turbine Engine Performance Modeling

Aircraft designers in industry obtain “Engine Decks” built by engine manufacturers that provide engine performance data (thrust, fuel flow, mass flow, pressures and temperatures at specified stations) for a wide range of Mach numbers and altitudes in the flight envelope, sorted by throttle setting



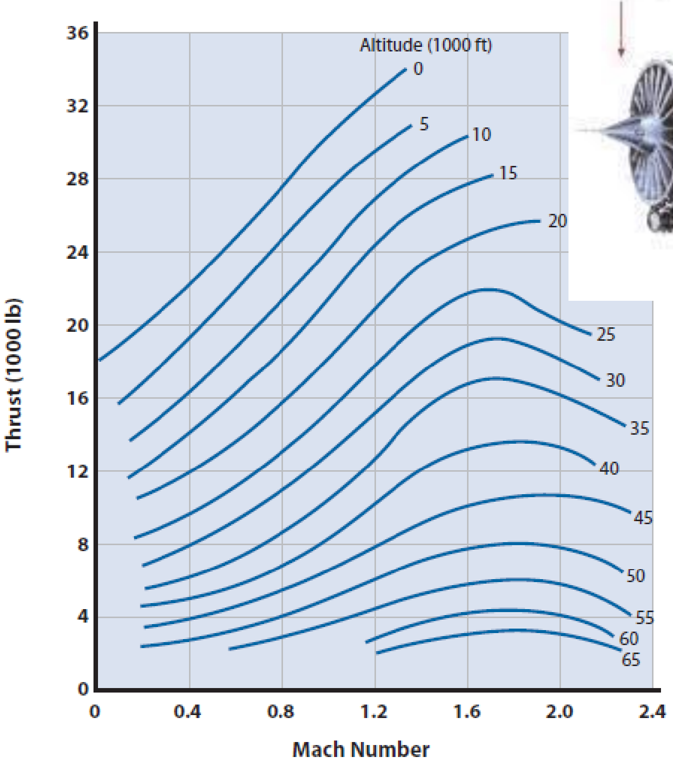


Figure 14.8a F-100 installed thrust, maximum afterburning.

Pratt &Whitney
F100-PW229

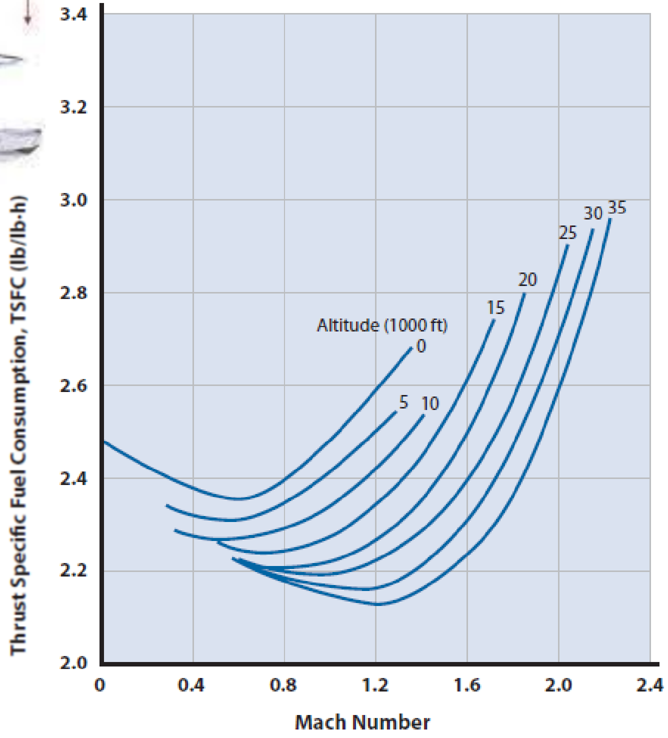


Figure 14.8b F-100 TSFC for maximum afterburning (low altitudes).

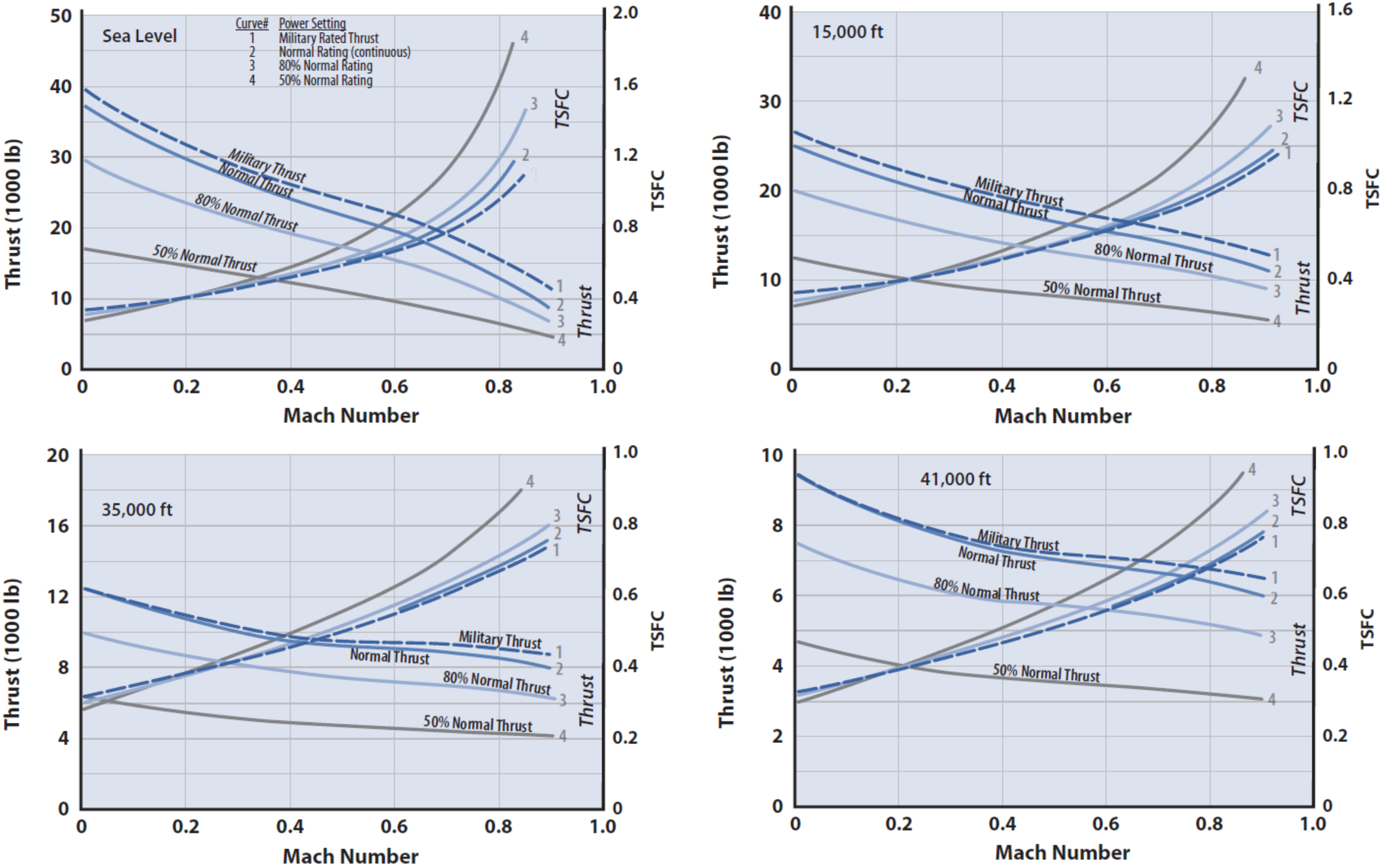
“Engine Decks”--the best performance model!

Source: Ref. AVD 1 (Nicolai & Carichner)

Turbine Engine Performance Modeling

Partial-power Performance Model

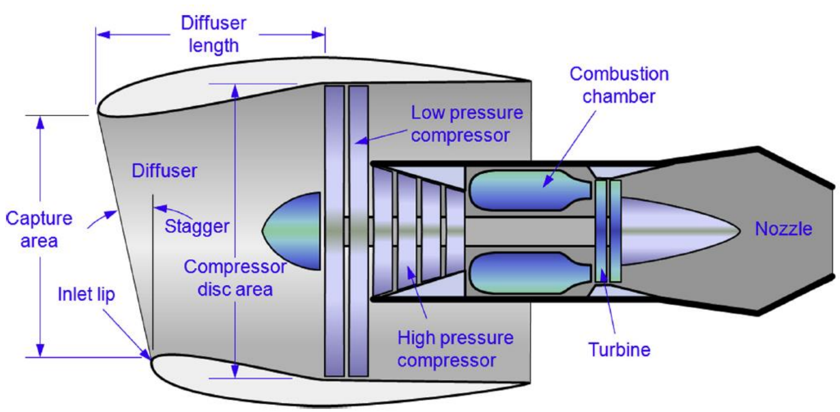
General Electric TF-39-GE-1

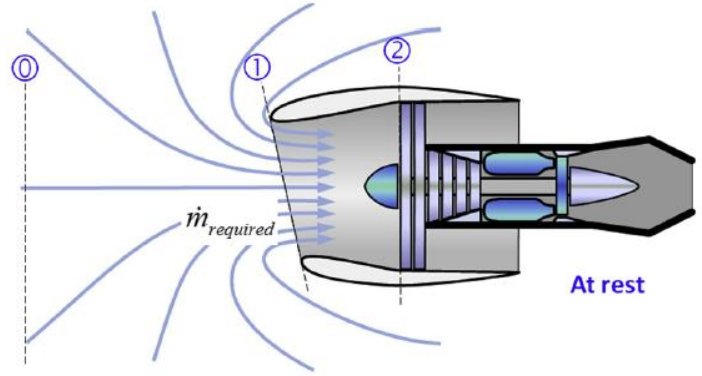


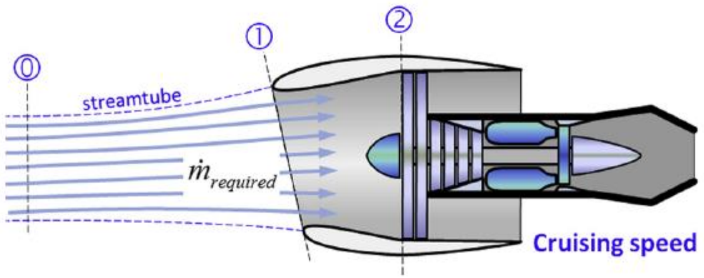
Source: Ref. AVD 1 (Nicolai & Carichner)

Turbine Engine Inlets

- **Purpose: To slow down oncoming air to speeds suitable for combustion**
  - Typical target Mach number is 0.4 to 0.6 at the compressor face







- **Design Criteria**
  - Deliver engine air with minimum distortion
  - Maximize pressure recovery
  - Minimize spillage drag throughout the flight regime
  - Minimize losses due to flow separation

Installed Performance Greatly Depends Upon Inlet Design

- **Strongly recommend looking at Sect. 10.3, Ch. 10, PS 1 (Mattingly) and Sect. 7.3.4, Ch. 7, AVD 4 (Gudmundsson)**

Turbine Engine Nozzles

- **Typical Nozzle Types**

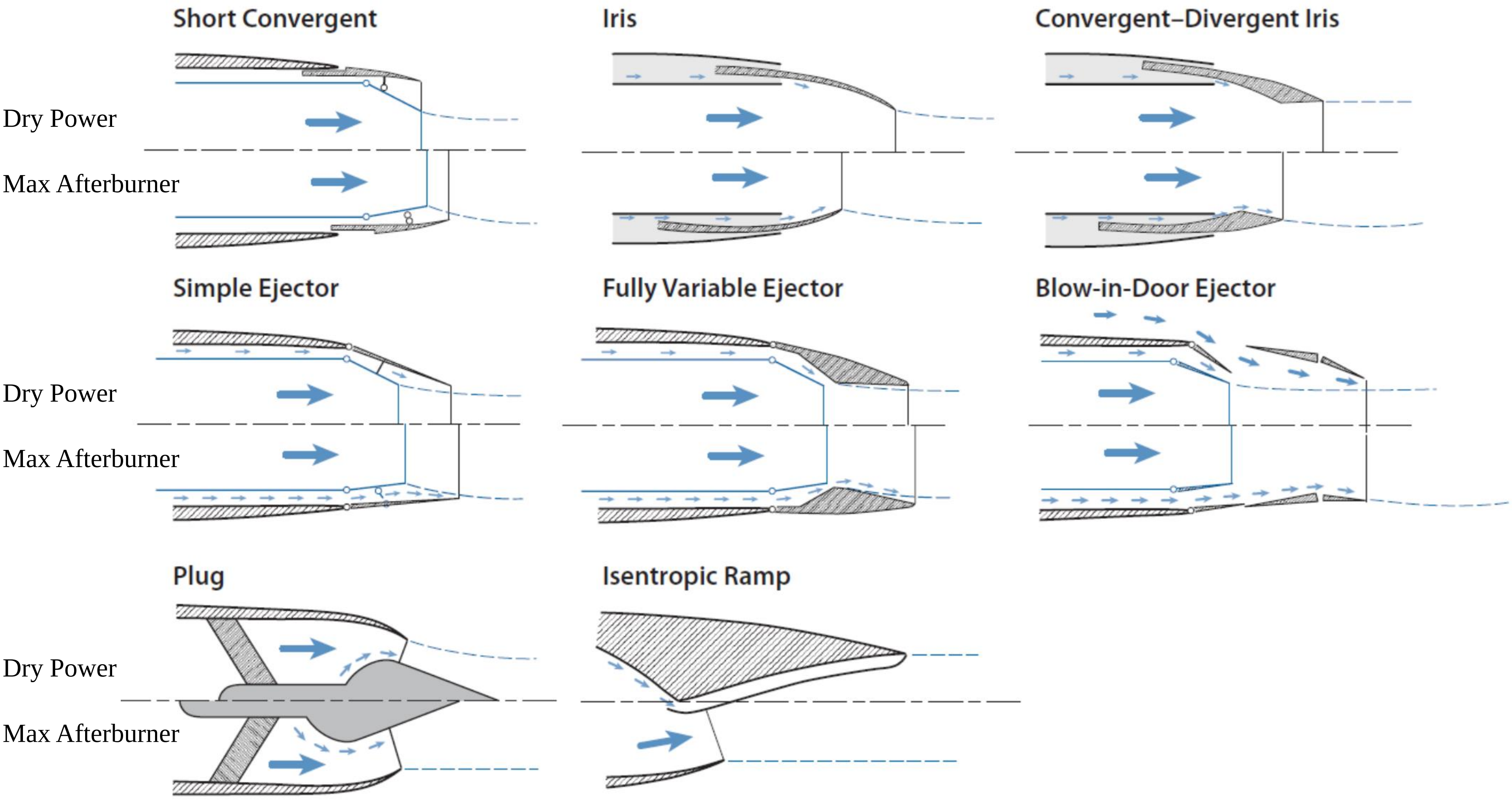
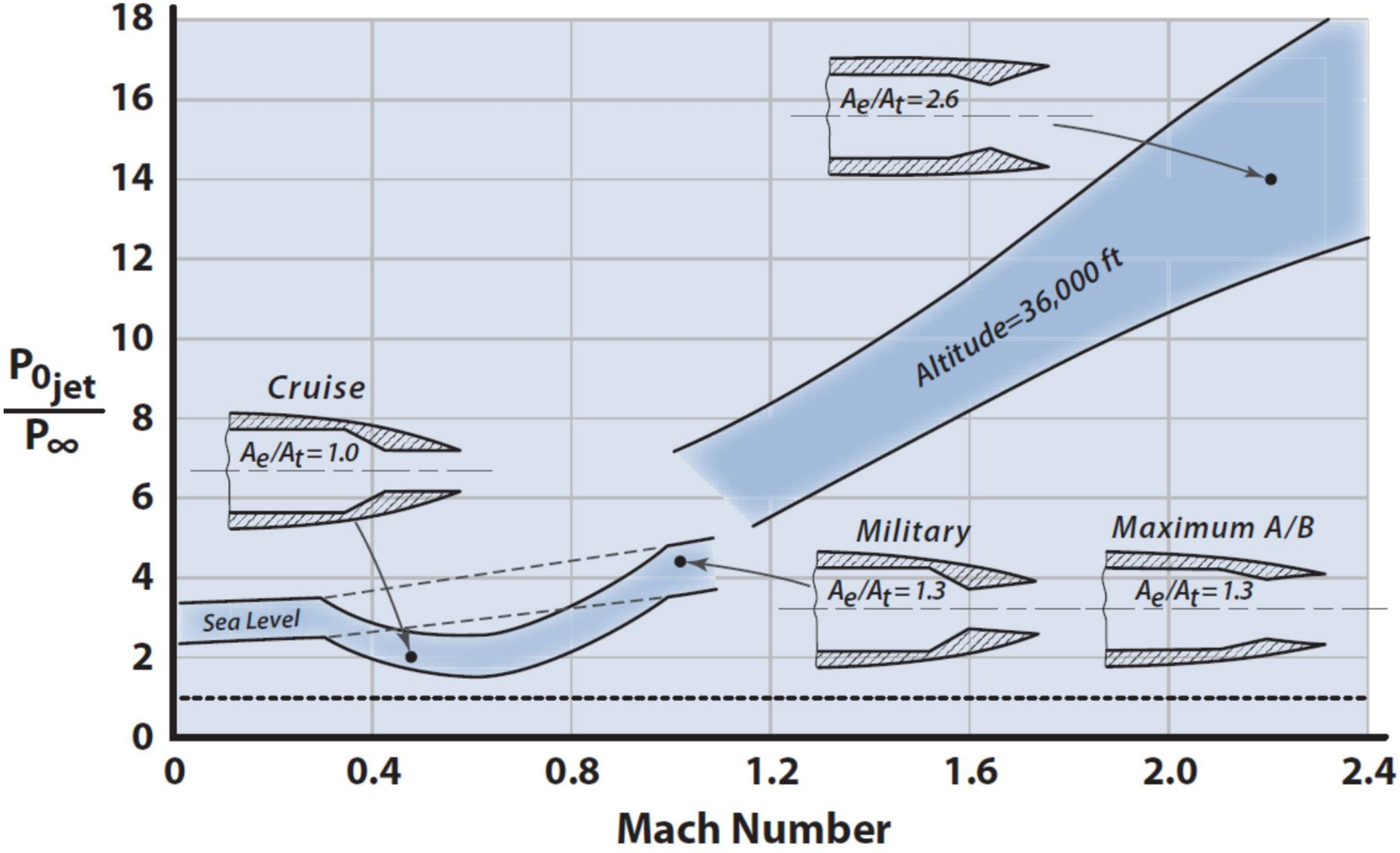


Figure 16.10 Typical nozzle concepts for afterburning engines (upper half of each sketch denotes dry power; lower half is maximum afterburning) [5].

Source: Ref. AVD 1 (Nicolai & Carichner)

Turbine Engine Nozzles

- **Required Nozzle Geometry Variation During Flight**

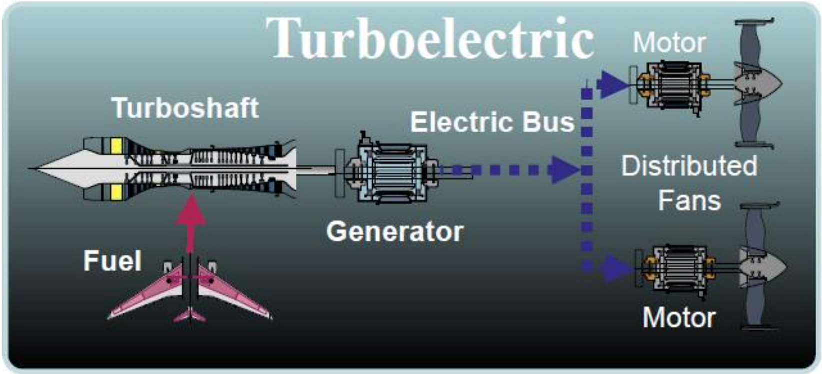


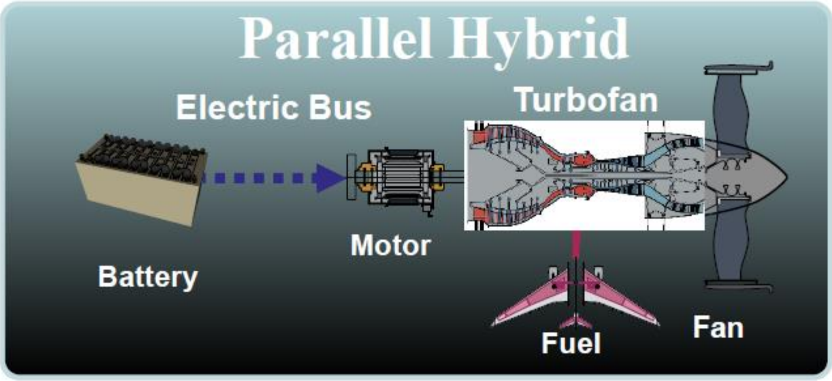
- **Make sure to account for engine installation losses (See Ch. 16 in AVD 1, and also look at AVD 2)**

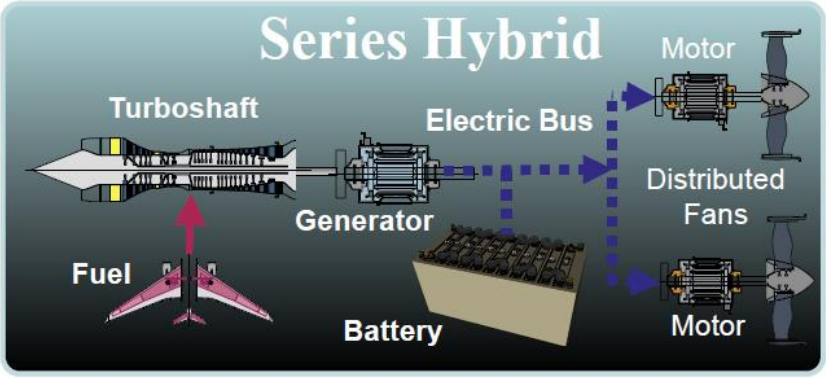
Source: Ref. AVD 1 (Nicolai & Carichner)

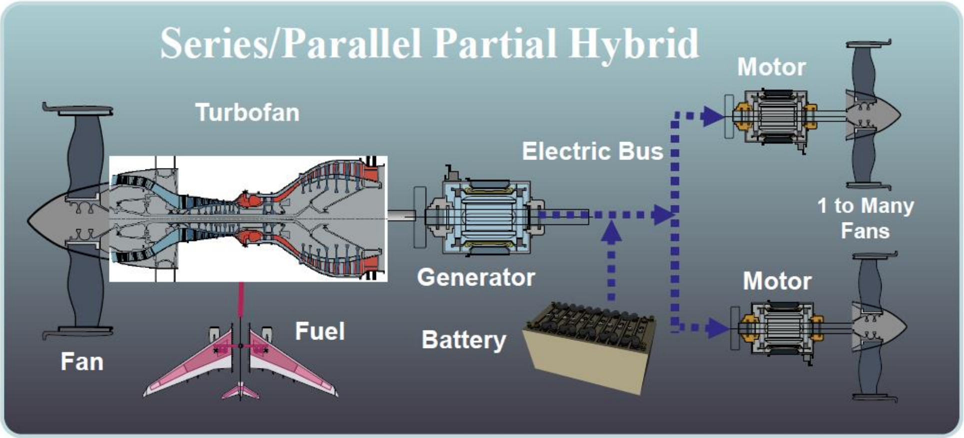
Hybrid-Electric Power Train Options

- **Powered by both Batteries (Electrical Energy) and Fossil Fuel**
  - Several options for integrating fossil-fuel engines with electric motors
  - All reduce emissions and fuel burn
  - Potential reduction in total energy consumption and total energy cost:
    - ✓ Jet-A: ~$5 per gallon
    - ✓ Electricity: ~$1.2 per equivalent gallon

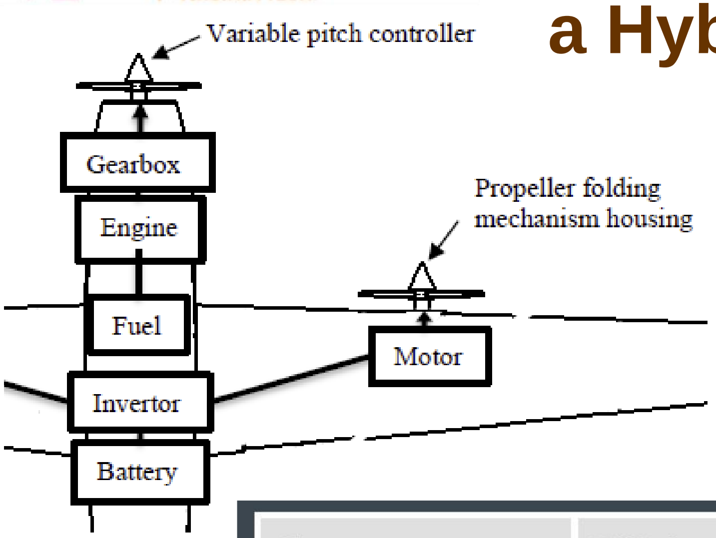


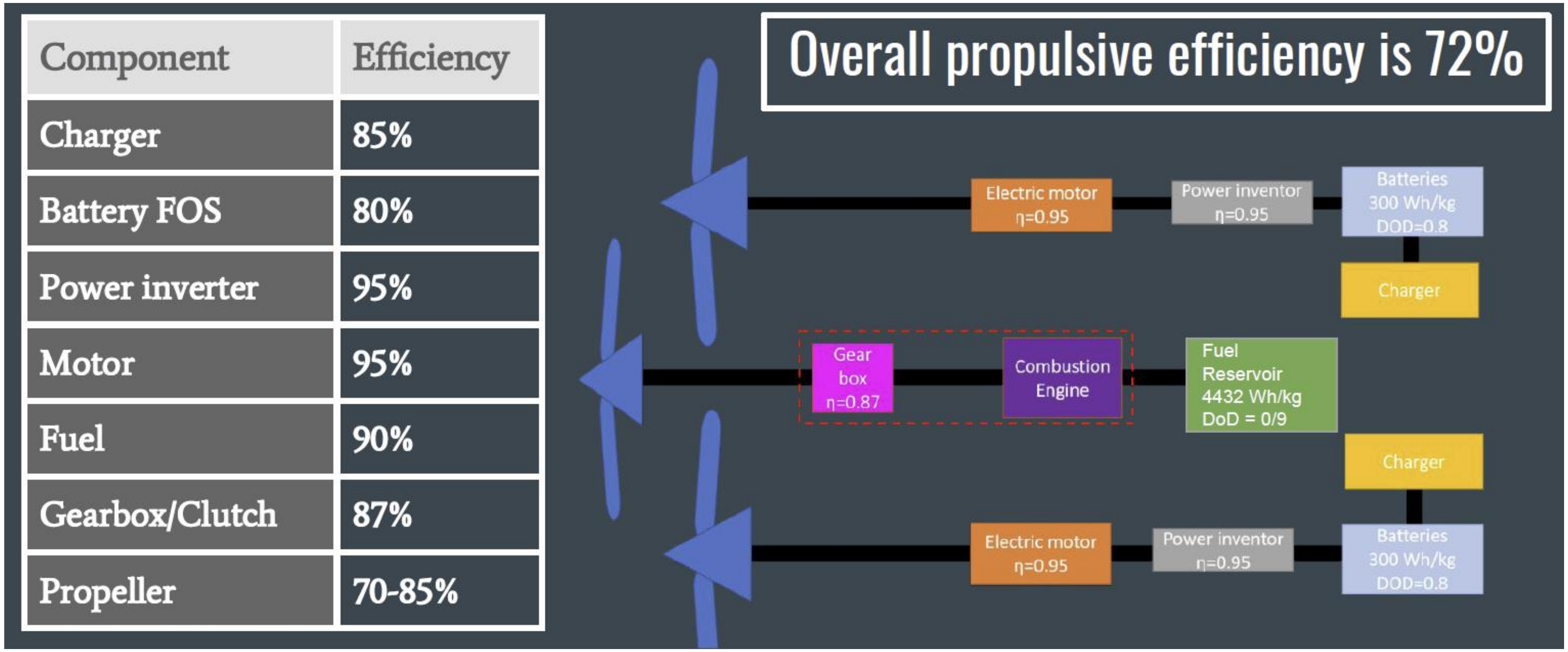






Propulsive Efficiency of a Hybrid Electric (HE) System





Component	Efficiency
Charger	85%
Battery FOS	80%
Power inverter	95%
Motor	95%
Fuel	90%
Gearbox/Clutch	87%
Propeller	70-85%

Overall propulsive efficiency is 72%

https://canvas.vt.edu/courses/143566/files/folder/Project%20Report%20(Spring)/Winning%20Reports%20-%20Past%20Years/VT%20AOE%20Prize%20for%20Excellence?preview=21392423

Electric Motors

- **Simple and Reliable (design life of 30,000 hrs. when operated at ~60% rated power)**
- **Typical specific power: 3 to 5 hp/lb**

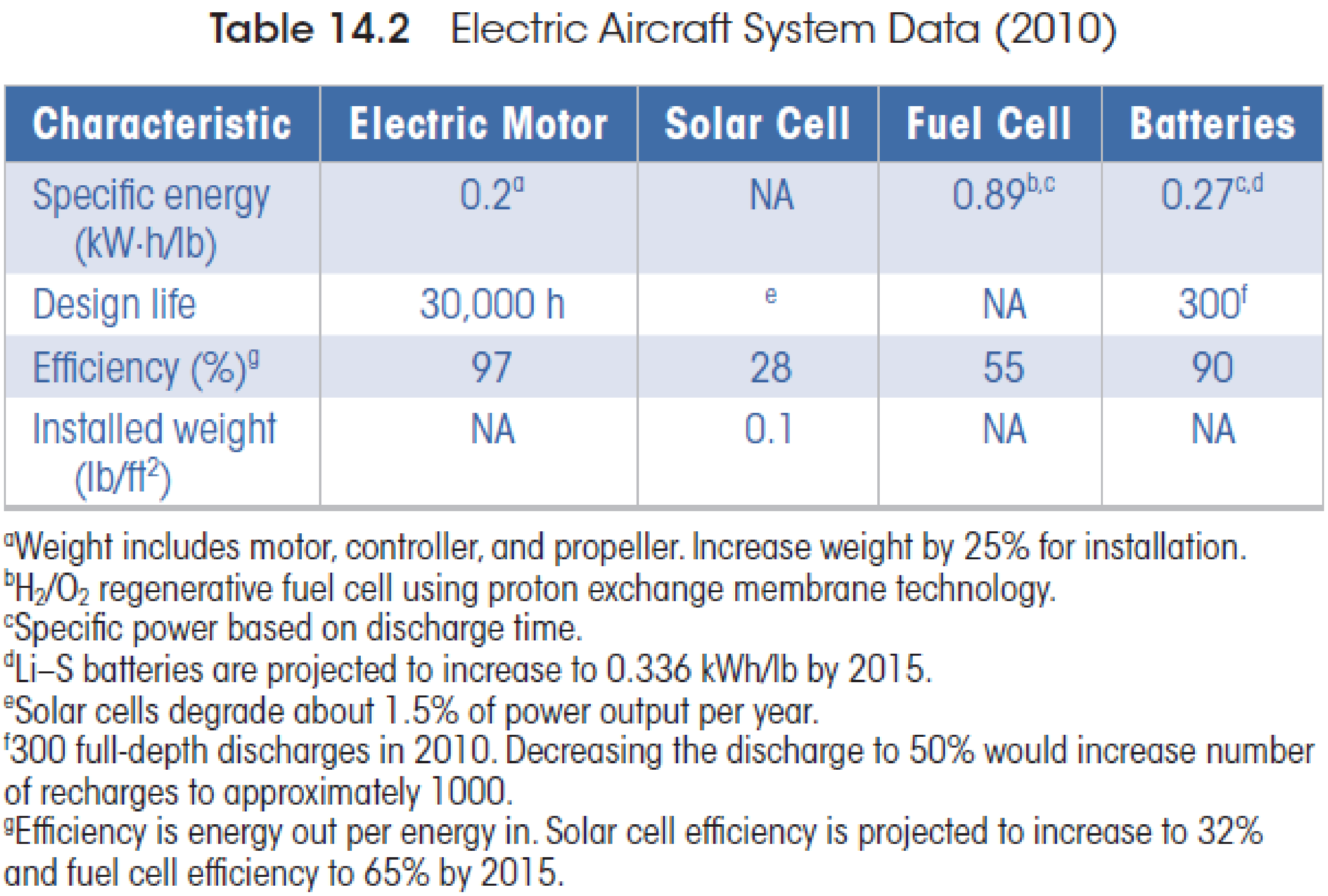


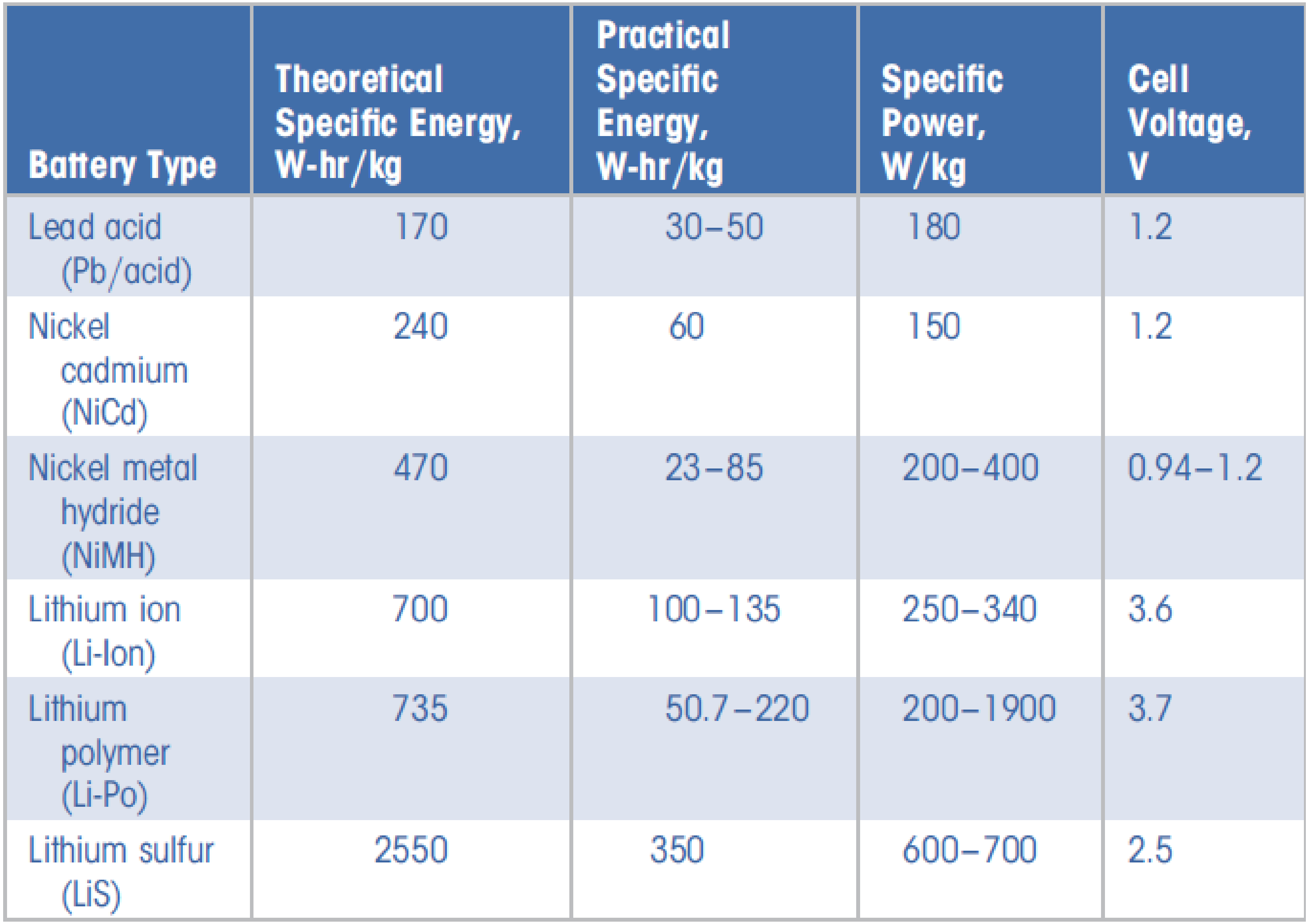
Table 14.2 Electric Aircraft System Data (2010)

Characteristic	Electric Motor	Solar Cell	Fuel Cell	Batteries
Specific energy (kW·h/lb)	0.2[a]	NA	0.89[b,c]	0.27[c,d]
Design life	30,000 h	[e]	NA	300[f]
Efficiency (%)[g]	97	28	55	90
Installed weight (lb/ft^2)	NA	0.1	NA	NA

[a] Weight includes motor, controller, and propeller. Increase weight by 25% for installation.
[b] H_2/O_2 regenerative fuel cell using proton exchange membrane technology.
[c] Specific power based on discharge time.
[d] Li–S batteries are projected to increase to 0.336 kWh/lb by 2015.
[e] Solar cells degrade about 1.5% of power output per year.
[f] 300 full-depth discharges in 2010. Decreasing the discharge to 50% would increase number of recharges to approximately 1000.
[g] Efficiency is energy out per energy in. Solar cell efficiency is projected to increase to 32% and fuel cell efficiency to 65% by 2015.

Source: Ref. AVD 1 (Nicolai & Carichner)

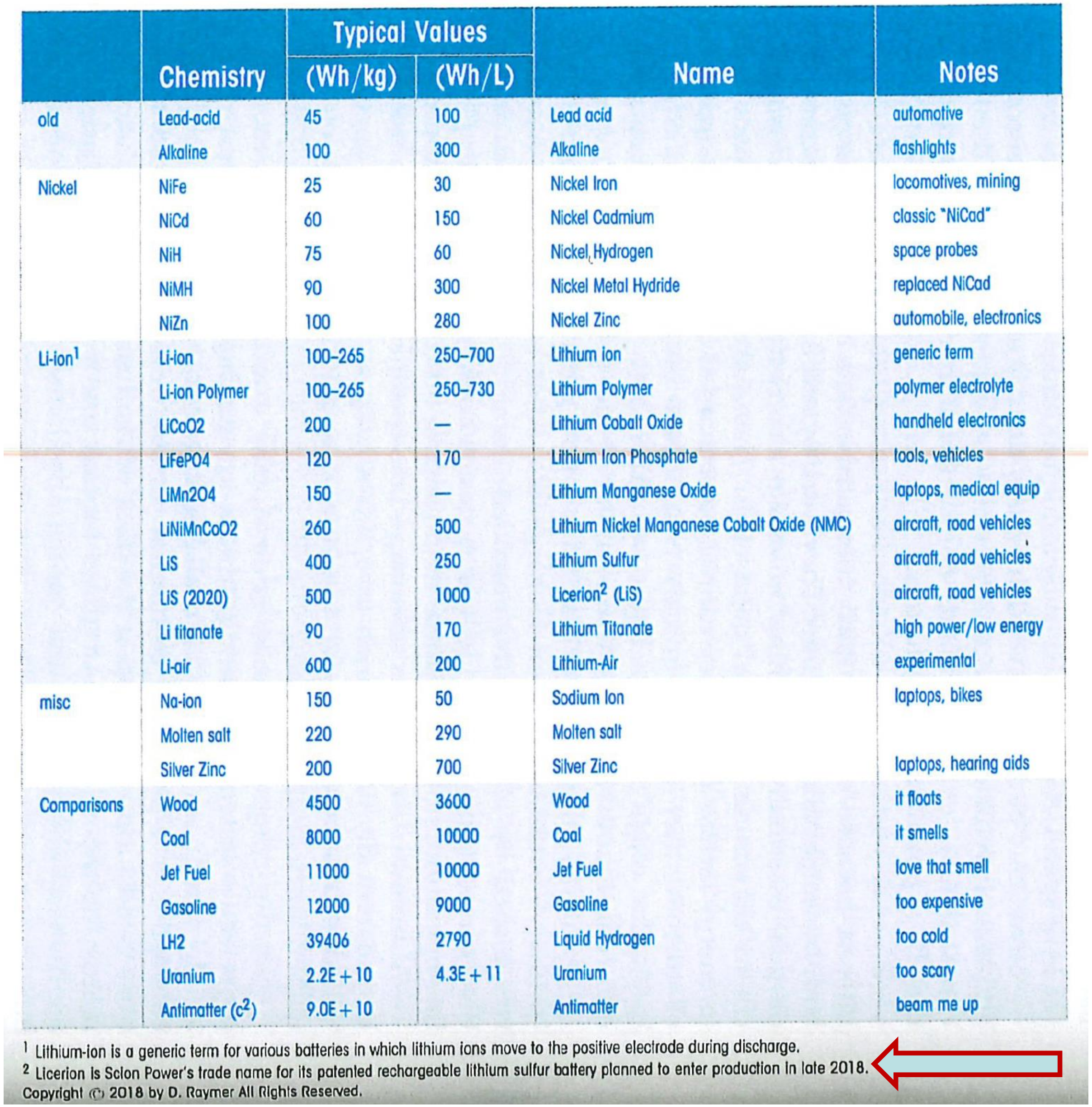
Battery Characteristics



Battery Type	Theoretical Specific Energy, W-hr/kg	Practical Specific Energy, W-hr/kg	Specific Power, W/kg	Cell Voltage, V
Lead acid (Pb/acid)	170	30–50	180	1.2
Nickel cadmium (NiCd)	240	60	150	1.2
Nickel metal hydride (NiMH)	470	23–85	200–400	0.94–1.2
Lithium ion (Li-Ion)	700	100–135	250–340	3.6
Lithium polymer (Li-Po)	735	50.7–220	200–1900	3.7
Lithium sulfur (LiS)	2550	350	600–700	2.5

Source: Ref. AVD 3 (Gundlach)

Battery Specific Energy & Density



	Chemistry	Typical Values		Name	Notes
		(Wh/kg)	(Wh/L)		
old	Lead-acid	45	100	Lead acid	automotive
	Alkaline	100	300	Alkaline	flashlights
Nickel	NiFe	25	30	Nickel Iron	locomotives, mining
	NiCd	60	150	Nickel Cadmium	classic "NiCad"
	NiH	75	60	Nickel Hydrogen	space probes
	NiMH	90	300	Nickel Metal Hydride	replaced NiCad
	NiZn	100	280	Nickel Zinc	automobile, electronics
Li-ion[1]	Li-ion	100–265	250–700	Lithium Ion	generic term
	Li-ion Polymer	100–265	250–730	Lithium Polymer	polymer electrolyte
	LiCoO2	200	—	Lithium Cobalt Oxide	handheld electronics
	LiFePO4	120	170	Lithium Iron Phosphate	tools, vehicles
	LiMn2O4	150	—	Lithium Manganese Oxide	laptops, medical equip
	LiNiMnCoO2	260	500	Lithium Nickel Manganese Cobalt Oxide (NMC)	aircraft, road vehicles
	LiS	400	250	Lithium Sulfur	aircraft, road vehicles
	LiS (2020)	500	1000	Licerion[2] (LiS)	aircraft, road vehicles
	Li titanate	90	170	Lithium Titanate	high power/low energy
	Li-air	600	200	Lithium-Air	experimental
misc	Na-ion	150	50	Sodium Ion	laptops, bikes
	Molten salt	220	290	Molten salt	
	Silver Zinc	200	700	Silver Zinc	laptops, hearing aids
Comparisons	Wood	4500	3600	Wood	it floats
	Coal	8000	10000	Coal	it smells
	Jet Fuel	11000	10000	Jet Fuel	love that smell
	Gasoline	12000	9000	Gasoline	too expensive
	LH2	39406	2790	Liquid Hydrogen	too cold
	Uranium	2.2E+10	4.3E+11	Uranium	too scary
	Antimatter (c^2)	9.0E+10		Antimatter	beam me up

[1] Lithium-ion is a generic term for various batteries in which lithium ions move to the positive electrode during discharge.

[2] Licerion is Sclon Power's trade name for its patented rechargeable lithium sulfur battery planned to enter production in late 2018.

Source: *Ref. AVD 2 (Raymer)*

Propeller Performance

(Sect. 14.3 and 14.4, Ch. 14, AVD 4 Gudmundsson)

Propeller performance characterized by propeller efficiency and several coefficients:

Power coefficient:

$$C_P = \frac{P}{\rho n^3 D^5} = \frac{550 \times P_{BHP}}{\rho \left(\frac{RPM}{60}\right)^3 D^5}$$

Thrust coefficient:

$$C_T = \frac{T}{\rho n^2 D^4} = \frac{3600 \cdot T}{\rho \cdot RPM^2 D^4}$$

Torque coefficient:

$$C_Q = \frac{Q}{\rho n^2 D^5} = \frac{3600 \cdot Q}{\rho \cdot RPM^2 \cdot D^5} = \frac{C_P}{2\pi}$$

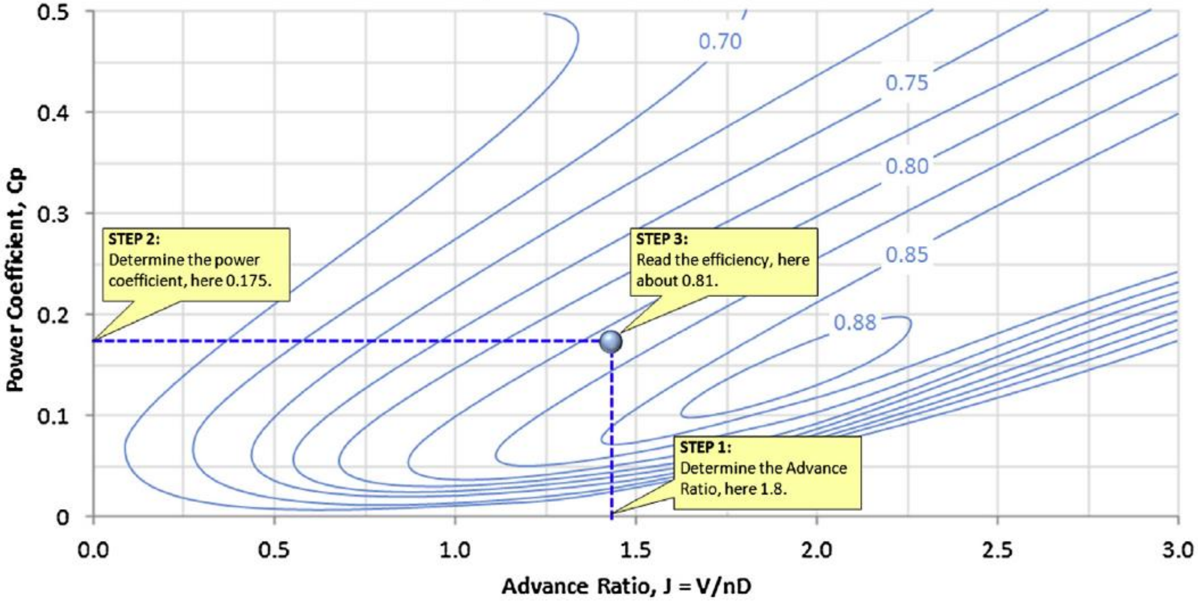
Power-Torque relation:

$$C_Q = \frac{Q}{\rho n^2 D^5} = \frac{C_P}{2\pi} = \frac{P/\rho n^3 D^5}{2\pi} \quad \Rightarrow \quad P = 2\pi n Q$$

Sample Propeller Efficiency Map

Propeller efficiency:

$$\eta_p = \frac{\mathrm{TV}}{\mathrm{P}} = \frac{TV}{550BHP} = J\frac{C_T}{C_P}$$



STEP 2: Determine the power coefficient, here 0.175.

STEP 3: Read the efficiency, here about 0.81.

STEP 1: Determine the Advance Ratio, here 1.8.

Advance ratio:

$$J = \frac{V_0}{nD} = \frac{60 \cdot V_0}{RPM \cdot D}$$

Note: See CM A7 for Generic Propeller Maps

AeroPropulsion Integration

Recommended Reading for Topics in Aeropropulsion Integration

Topic	**Recommended References**
AeroPropulsion Integration	
Propulsion System Fundamentals	Chapter 14, Nicolai & Carichner, Ref. AVD 1
Turbine Engine Inlet Design	Chapter 15, Nicolai & Carichner, Ref. AVD 1
Corrections for Turbine Engine Installation	Chapter 16, Nicolai & Carichner, Ref. AVD 1
Propeller Propulsion Systems	Chapter 17, Nicolai & Carichner, Ref. AVD 1
Propulsion System Thrust Sizing	Chapter 18, Nicolai & Carichner, Ref. AVD 1
Propulsion	Chapter 13, Raymer, Ref. AVD 2
Propulsion and Fuel System Integration	Chapter 10, Raymer, Ref. AVD 2
Propulsion System Design	Chapter 8, Sadraey, Ref. AVD 5
Selecting the Power Plant	Chapter 7, Gudmundsson, Ref. AVD 4
The Anatomy of the Propeller	Chapter 14, Gudmundsson, Ref. AVD 4
Aircraft Power Plant and Integration	Chapter 10, Kundu, Ref. AVD 8
DEP, Hybrid Electric, Propellers and Open Rotors	*See API folder in Supplemental Reference Material folder on course site*

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A10.10 Cost & Manufacturing

A10.5 Vehicle Performance

Vehicle Performance subteam members should review their R&Rs, and any project data deliverables in the RFP

Importance of the Role of Vehicle Performance Team

- **Predict flight performance for all segments of the mission using appropriate analyses and simulations**
- **If actual flight performance differs from predictions, adverse project risks include:**
  - **Loss of Credibility**
    - “Cannot Deliver What Was Promised”
  - **Potential for Schedule Slip and Additional Cost**
    - Flight Test “Surprises” →Schedule Slips and Additional Costs due to Design Modifications
  - **Dissatisfied Customer**
    - Do Not Like Out-of-Spec Product or Late Delivery or Increased Cost

Mitigate Risk Through Design, Analysis, and Test

Flight Performance: *Take-off*

$$V_{\mathrm{TO}} = 1.2\,V_{\mathrm{stall}} = 1.2\sqrt{\frac{W_{\mathrm{TO}}}{S_{\mathrm{ref}}}\frac{2}{\rho C_{L\max}}}$$

$$\boxed{S_G = \frac{1.44\left(W/S_{\mathrm{ref}}\right)_{\mathrm{TO}}}{g\rho C_{L\max}\left[\left(T/W\right)-\left(D/W\right)-\mu\left(1-L/W\right)\right]}}$$

$$D = (0.5)\rho V^2 S_{\mathrm{ref}}\left[C_{D0} + \Delta C_{D\mathrm{flap}} + \Delta C_{D\mathrm{gear}} + K C_{LG}^2\right]$$

$$L = (0.5)\rho V^2 S_{\mathrm{ref}} C_{LG}$$

$$V = 0.707\,V_{\mathrm{TO}}$$

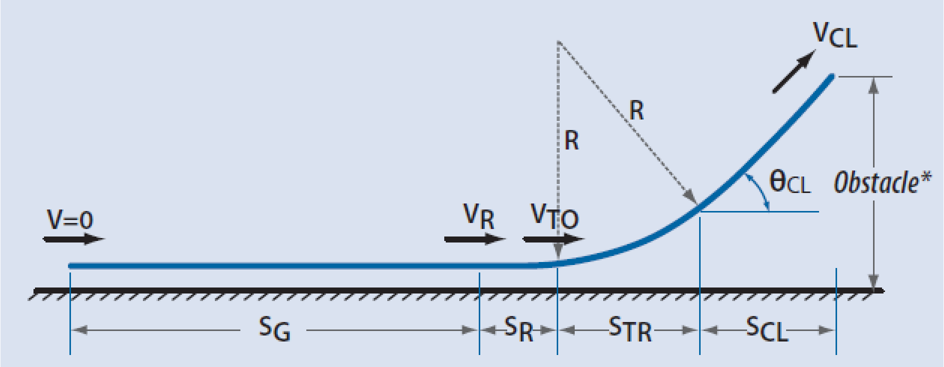
$$\boxed{S_R = 2V_{\mathrm{TO}}}$$

$$\boxed{S_{\mathrm{TR}} = R\sin\theta_{\mathrm{CL}}} \qquad R = \frac{V_{\mathrm{TO}}^2}{0.15\,g}$$

$$\text{Rate of climb} = V_{\mathrm{TO}}\,\sin\theta_{\mathrm{CL}}$$

$$\boxed{S_{\mathrm{CL}} = \frac{50 - h_{\mathrm{TR}}}{\tan\theta_{\mathrm{CL}}}}$$

Assumption: *unaccelerated climb*



*Obstacle height=35ft for commercial and 50ft for the military.

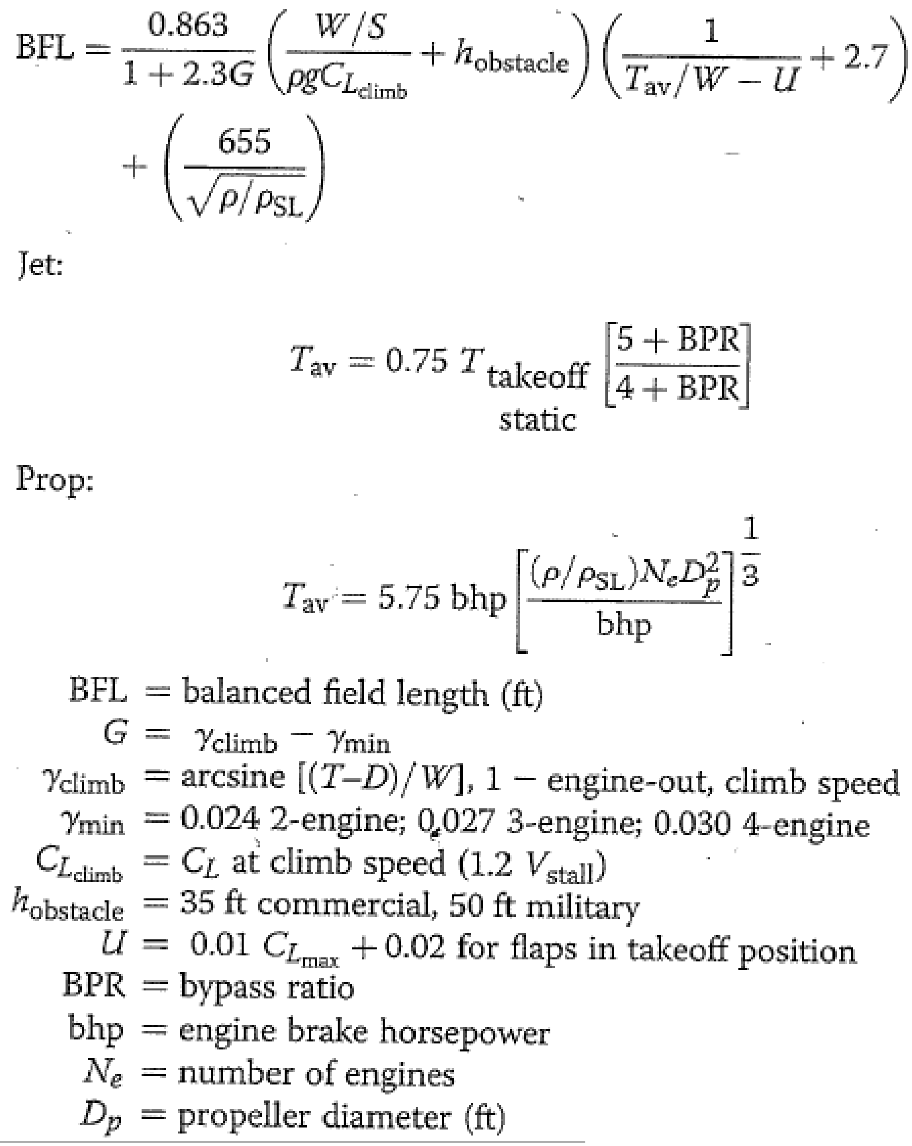
Type of Surface	Brakes Off, Average Ground Resistance Coefficient	Brakes Fully Applied, Average Wheel-Braking Coefficient
Concrete or macadam	0.015–0.04	0.3–0.6
Hard turf	0.05	0.4
Firm and dry dirt	0.04	0.30
Soft turf	0.07	0.5
Wet concrete	0.05	0.2
Wet grass	0.10	0.2
Snow- or ice-covered field	0.01	0.07–0.10

See Sect. 10.3, Ch. 10, AVD 1, for more details and recommended values of parameters

Source: Chapter 10, Ref. AVD 1 (Nicolai)

Flight Performance: *BFL*

1. BFL Estimation*



$$\text{BFL} = \frac{0.863}{1+2.3G}\left(\frac{W/S}{\rho g C_{L_{\text{climb}}}} + h_{\text{obstacle}}\right)\left(\frac{1}{T_{\text{av}}/W - U} + 2.7\right) + \left(\frac{655}{\sqrt{\rho/\rho_{\text{SL}}}}\right)$$

Jet:

$$T_{\text{av}} = 0.75\, T_{\substack{\text{takeoff}\\ \text{static}}} \left[\frac{5+\text{BPR}}{4+\text{BPR}}\right]$$

Prop:

$$T_{\text{av}} = 5.75\ \text{bhp}\left[\frac{(\rho/\rho_{\text{SL}})N_e D_p^2}{\text{bhp}}\right]^{\frac{1}{3}}$$

BFL = balanced field length (ft)

G = $\gamma_{\text{climb}} - \gamma_{\text{min}}$

γ_{climb} = arcsine $[(T–D)/W]$, 1 – engine-out, climb speed

γ_{min} = 0.024 2-engine; 0.027 3-engine; 0.030 4-engine

$C_{L_{\text{climb}}}$ = C_L at climb speed (1.2 V_{stall})

h_{obstacle} = 35 ft commercial, 50 ft military

U = $0.01\ C_{L_{\max}} + 0.02$ for flaps in takeoff position

BPR = bypass ratio

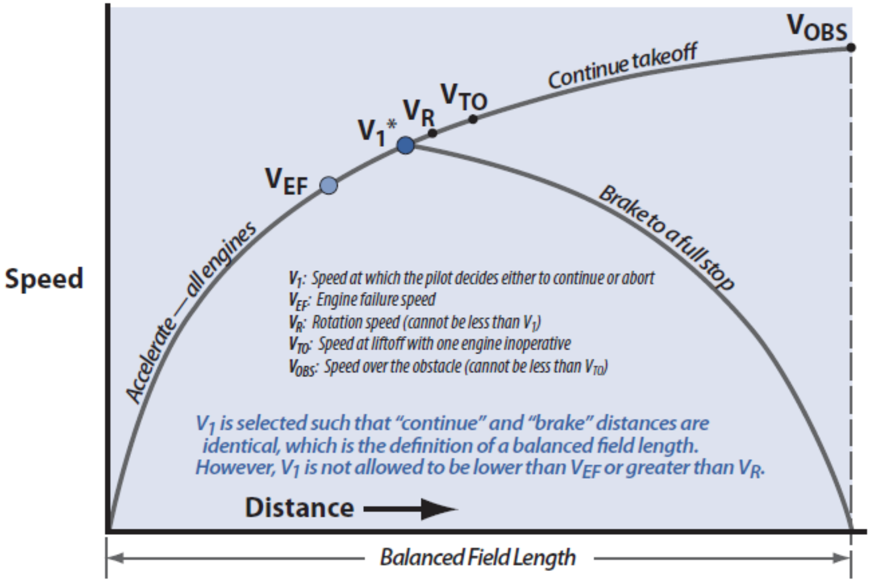
bhp = engine brake horsepower

N_e = number of engines

D_p = propeller diameter (ft)

2. More Accurate BFL Estimation**

- *Assume failure recognition speed V_{EF}*
- *Calculate LAB: accelerate to V_{EF} ,free roll for 3 sec., brake to full stop*
- *Calculate LAC: accelerate to V_{EF} , continue OEI takeoff over 35 ft. obstacle*
- *Estimate refusal speed, V_{EF} , when LAB = LAC*



V_1: Speed at which the pilot decides either to continue or abort
V_{EF}: Engine failure speed
V_R: Rotation speed (cannot be less than V_1)
V_{TO}: Speed at liftoff with one engine inoperative
V_{OBS}: Speed over the obstacle (cannot be less than V_{TO})

V_1 is selected such that "continue" and "brake" distances are identical, which is the definition of a balanced field length. However, V_1 is not allowed to be lower than V_{EF} or greater than V_R.

***See Sect. 17.8, Ch. 17, AVD 2**

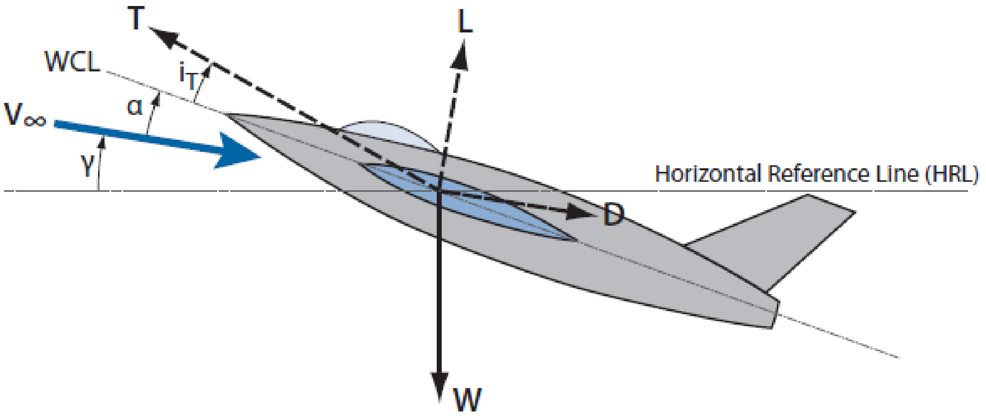
****See Sect. 10.6, Ch. 10, AVD 1**

Flight Performance: *Climb*

- **Rate of Climb (ROC)**

$$V\sin\gamma = \frac{P_S}{1+(V/g)(\mathrm{d}V/\mathrm{d}h)}$$

$$P_S = \frac{\mathrm{d}h_e}{\mathrm{d}t} = \frac{V\left[T\cos\left(\alpha+i_T\right)-D\right]}{W}$$



- **Constant Speed Climb**

$$V\sin\gamma = \frac{V\left[T\cos\left(\alpha+i_T\right)-D\right]}{W}$$

- **Best ROC (maximum vertical velocity)**

<u>Assumption:</u> all angles are small

  - ***Jet aircraft***

$$V = \sqrt{\frac{W/S}{3\rho C_{D_0}}\left[T/W+\sqrt{(T/W)^2+12C_{D_0}K}\right]}$$

  - ***Propeller aircraft***

$$V = V_{\min PR} = \sqrt{\frac{2W}{\rho S}\sqrt{\frac{K}{3C_{D_0}}}}$$

- **Best Angle of Climb (maximum γ)**
  - ***Jet aircraft***

$$V = \sqrt{\frac{2W}{\rho S}\sqrt{\frac{K}{C_{D_0}}}}$$

  - ***Propeller aircraft***
    - *85-90% of best ROC speed is a good estimate*

See Ch. 3, AVD 1, and Ch. 17, AVD 2 for more details

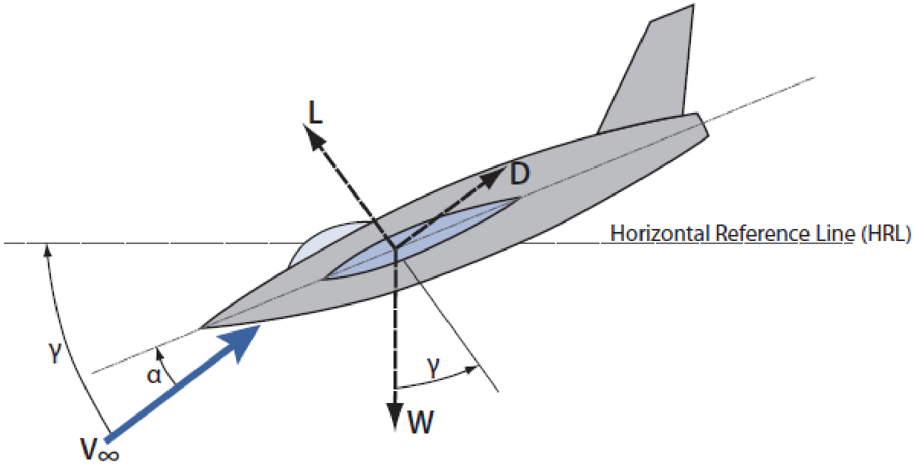
Source: Ch. 3, Ref. AVD 1 (Nicolai) & Ch. 17 AVD 2 (Raymer)

Flight Performance: *Descent*

- **Gliding Flight *(T = 0)***

$$\gamma = \operatorname{arc\,sin}\left(-D/W\right)$$

$$\gamma = \operatorname{arc\,tan}\left(-D/L\right)$$



- **Maximum Range *(minimum γ)***

$$V = \sqrt{\frac{2W}{\rho S}\sqrt{\frac{K}{C_{D0}}}}$$

- **Maximum Endurance (minimum rate of descent, ROD)**

$$V_{\mathrm{RODmin}} = \sqrt{\frac{2W}{\rho S}\sqrt{\frac{K}{3C_{D0}}}}$$

See Ch.3, AVD 1 (Nicolai & Carichner), for more details

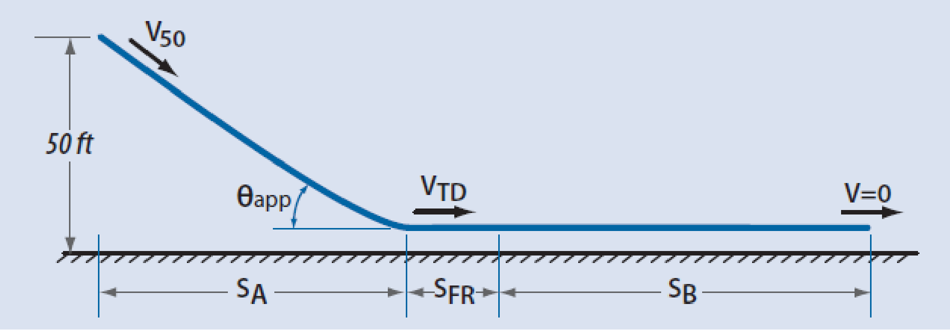
Source: Ch. 3, Ref. AVD 1 (Nicolai) & Ch. 17 AVD 2 (Raymer)

Flight Performance: *Landing*

$$\boxed{S_A = \frac{L}{D}\left[\frac{V_{50}^2 - V_{TD}^2}{2g} + 50\right]}$$

$V_{50} = 1.3 V_S$ $\quad V_{TD} = 1.15 V_S$

$L = W_L =$ aircraft weight with 1/2 fuel remaining



$C_{L_{land}} = C_{L_{max}}$ for flaps in landing configuration $\quad C_D = C_{D_0} + K C_{L_{max}}^2 + \Delta C_{D_{flaps}} + \Delta C_{D_{gear}}$

$S_A = 50/\tan\theta_{app}$, θ_{app} = approach glide slope (3 deg for typical CTOL, 7 deg for STOL)

$$\boxed{S_{FR} = 3 V_{TD}}$$

$$\boxed{S_B = \frac{W_L}{g\mu\rho S_{ref}\left[(C_D/\mu) - C_{LG}\right]} \ln\left[1 + \frac{\rho}{2}\frac{S_{ref}}{W_L}\left(\frac{C_D}{\mu} - C_{LG}\right)V_{TD}^2\right]}$$

$$C_D = C_{D_0} + K C_{LG}^2 + \Delta C_{D_{flaps}} + \Delta C_{D_{gear}} + \Delta C_{D_{misc}} + \Delta C_{D_{spoilers}}$$

Type of Surface	Brakes Off, Average Ground Resistance Coefficient	Brakes Fully Applied, Average Wheel-Braking Coefficient
Concrete or macadam	0.015–0.04	0.3–0.6
Hard turf	0.05	0.4
Firm and dry dirt	0.04	0.30
Soft turf	0.07	0.5
Wet concrete	0.05	0.2
Wet grass	0.10	0.2
Snow- or ice-covered field	0.01	0.07–0.10

Assumptions:

Neglect reverse thrust

Zero forward thrust

See Section 10.4, AVD 1, for more details and recommended values of parameters

Source: Chapter 10, Ref. AVD 1 (Nicolai)

Flight Performance: *Cruise & Loiter*

- **Level unaccelerated flight of symmetric aircraft with uncambered wing**

$$W \approx L = C_L q S \qquad T \approx D = \left(C_{D0} + K C_L^2\right) q S$$

$$\frac{T}{W} = \frac{1}{L/D} = \frac{q C_{D_0}}{(W/S)} + \left(\frac{W}{S}\right)\frac{K}{q}$$

- **Required Thrust and Power**

$$T_R = D = C_{D0} q S + K W^2 / q S \qquad P_R = DV = T_R V = \left(C_{D0} + K C_L^2\right)\frac{W}{C_L}\sqrt{\frac{2W}{\rho C_L S}}$$

- **Range**

$$R = \frac{V}{C}\frac{L}{D}\ln\left[\frac{W_i}{W_f}\right]$$

- **Endurance**

$$E = \frac{L}{D}\frac{1}{C}\ln\left[\frac{W_i}{W_f}\right]$$

- **<u>Jet</u> aircraft**
  - **Most Efficient cruise** occurs near
    $L/D = 0.943\,(L/D)_{max}$ *(constant throttle)*
    $L/D = 0.866\,(L/D)_{max}$ *(constant altitude)*
  - **Most Efficient loiter** occurs near
    $L/D \sim (L/D)_{max}$ *(minimum thrust)*

- **<u>Propeller</u> aircraft**
  - **Most Efficient cruise** occurs near
    $L/D = (L/D)_{max}$ *(minimum thrust)*
  - **Most Efficient loiter** occurs near
    $L/D = 0.866\,(L/D)_{max}$ *(minimum power)*

Flight Performance: *Cruise & Loiter*

- **Max Loiter (Jets) and Max Range (Propellers)**

$$V_{(L/D)_{\max}} = \sqrt{\frac{2W}{\rho C_{L_{\text{opt}}} S}} = \sqrt{\frac{2W}{\rho S}\boxed{\sqrt{\frac{K}{C_{D_0}}}}}$$

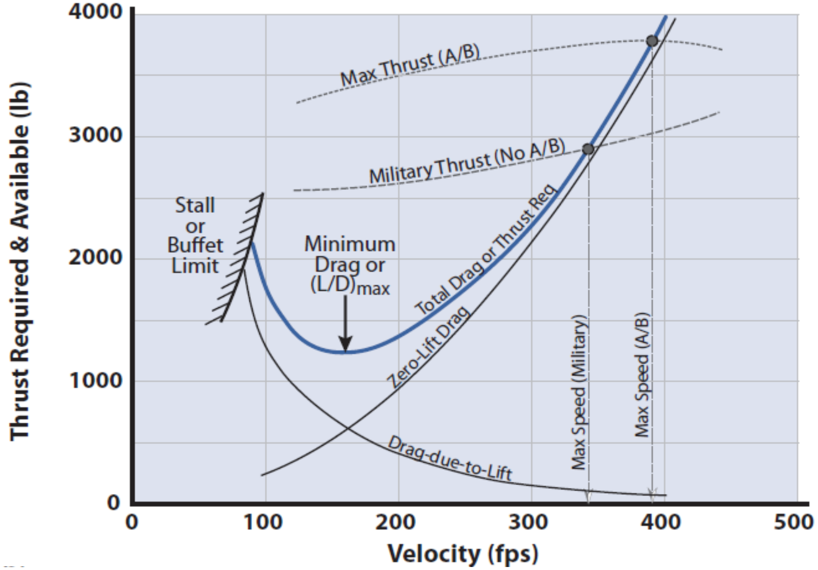
- **Max Range Speed (Jets)**

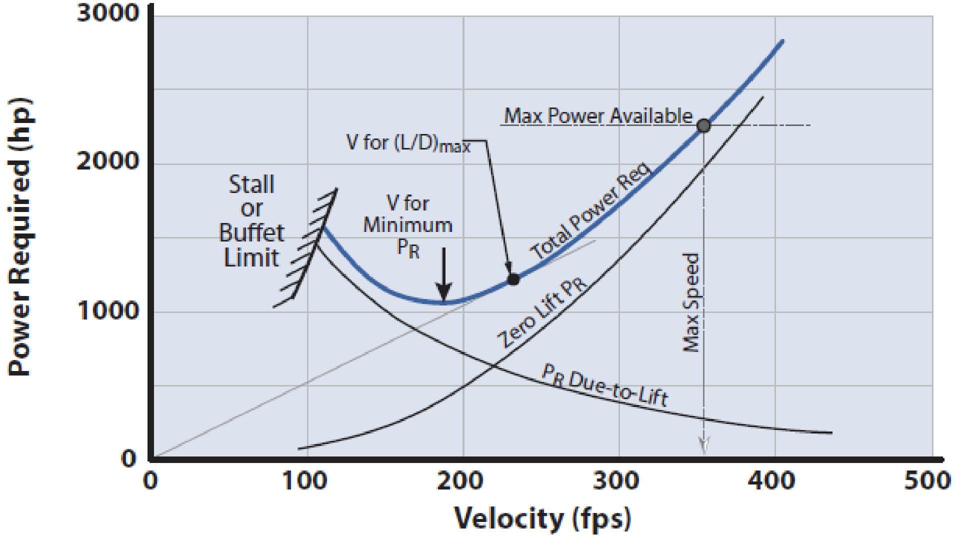
$$V_{\text{best range}} = \sqrt{\frac{2W}{\rho S}\boxed{\sqrt{\frac{3K}{C_{D_0}}}}}$$

C_L

- **Max Loiter (Propellers)**

$$V_{\min P_R} = \sqrt{\frac{2W}{\rho S}\boxed{\sqrt{\frac{K}{3C_{D_0}}}}}$$





Vehicle Performance

Recommended Reading for Topics in Vehicle Performance

Topic	Recommended References
Vehicle Performance	
Aircraft Performance Methods	Chapter 3, Nicolai & Carichner, Ref. AVD 1
Takeoff and Landing Analysis	Chapter 10, Nicolai & Carichner, Ref. AVD 1
Performance and Flight Mechanics	Chapter 17, Raymer, Ref. AVD 2
Performance (GA Aircraft)	Chapters 16 thru 22, Gudmundsson, Ref. AVD 4
Aircraft Performance	Chapter 13, Kundu, Ref. AVD 8
Aircraft Flight Performance	Chapters 1 thru 16, Filippone, Ref. FM 4
Aircraft Noise and Emissions	Chapters 17 thu 23, Filippone, Ref. FM 4
Performance	*See Performance folder for misc documents in Supplemental Reference Material on course site*

Outline

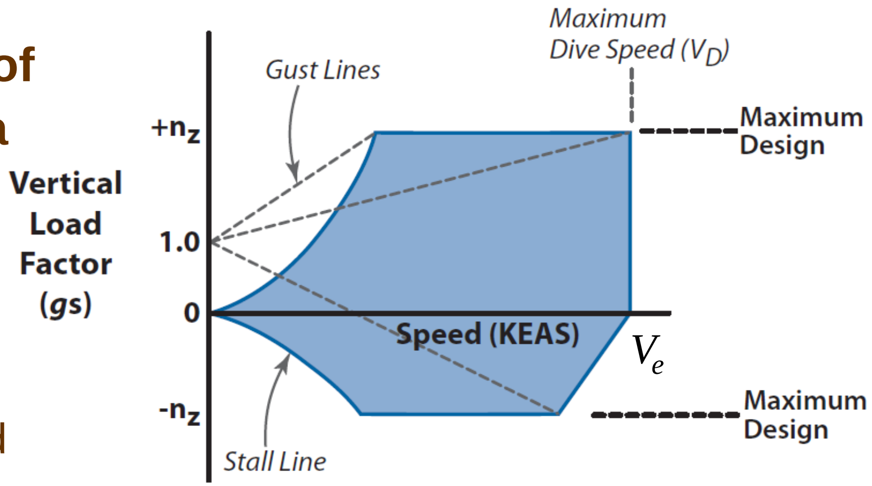
A10. Preliminary Design: Refine & Validate Baseline Design

A10.1 General Remarks
A10.2 Configuration Layout and Loft
A10.3 Aerodynamics
A10.4 Aeropropulsion Integration
A10.5 Vehicle Performance
A10.6 Structures & Materials
A10.7 Subsystems
A10.8 Stability & Control
A10.9 Weights (Mass Properties) & Balance
A10.10 Cost & Manufacturing

10.6 Structures & Materials

Structures & Materials subteam members should review their R&Rs, and any project data deliverables in the RFP

Structural Design Criteria



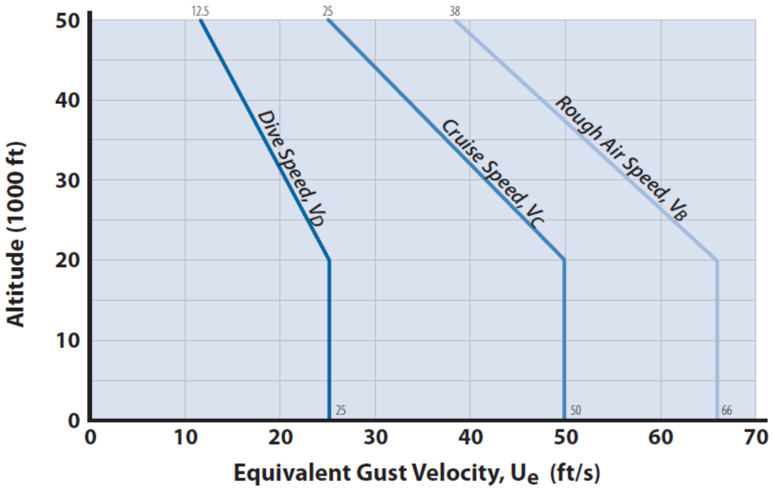
- **Use relevant FAR or MIL-A-8860 series of documents for structural design criteria**
- ***V-n* diagram is the starting point!**
  - ○ Speed V_e is always written in knots as KEAS given by $V_e = \sqrt{\sigma}\, V_t$

    $\sigma = \rho_{\text{alt}}/\rho_{\text{SL}}$ (air density ratio) $V_t =$ true airspeed
  - ○ n_z ranges from +3 to -1 for transport-type and +7.5 to -3 for fighter-type aircraft
  - ○ Gust load factors estimated using $n = 1 \pm \dfrac{K_g C_{L_\alpha} U_e V_e}{498\, W/S}$

    where

    C_{L_α} = lift curve slope (per radian) for the complete airplane
    U_e = equivalent gust velocity (ft/s)
    V_e = equivalent airspeed (KEAS)
    W/S = wing loading (lb/ft^2)
    K_g = gust alleviation factor $= 0.88\mu/(5.3 + \mu)$ (subsonic aircraft)

    $\mu = (2\, W/S)/(\rho\, \bar{c}\, C_{L_\alpha} g)$
    ρ = air density (slug/ft^3)
    $\bar{c}$ = mean aerodynamic chord (ft)
    C_{L_α} = lift curve slope (per radian)
    g = acceleration due to gravity (ft/s^2)

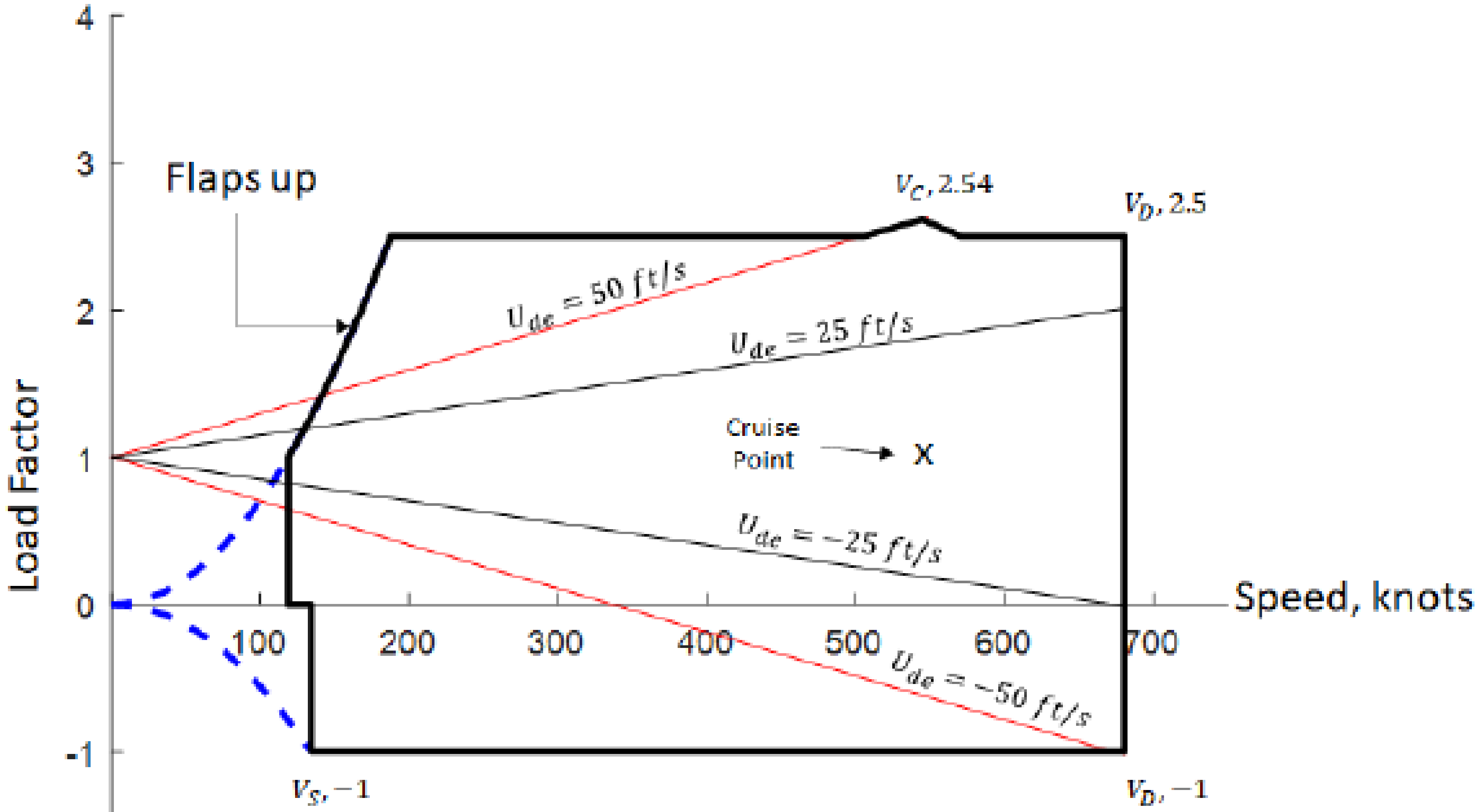


- ***Loads Engineers* develop a set of external loads (aerodynamic and inertia loads) that a 'lightest weight' structure must withstand without failing**

Source: Ch 19, Ref. AVD 1 (Nicolai & Carichner)

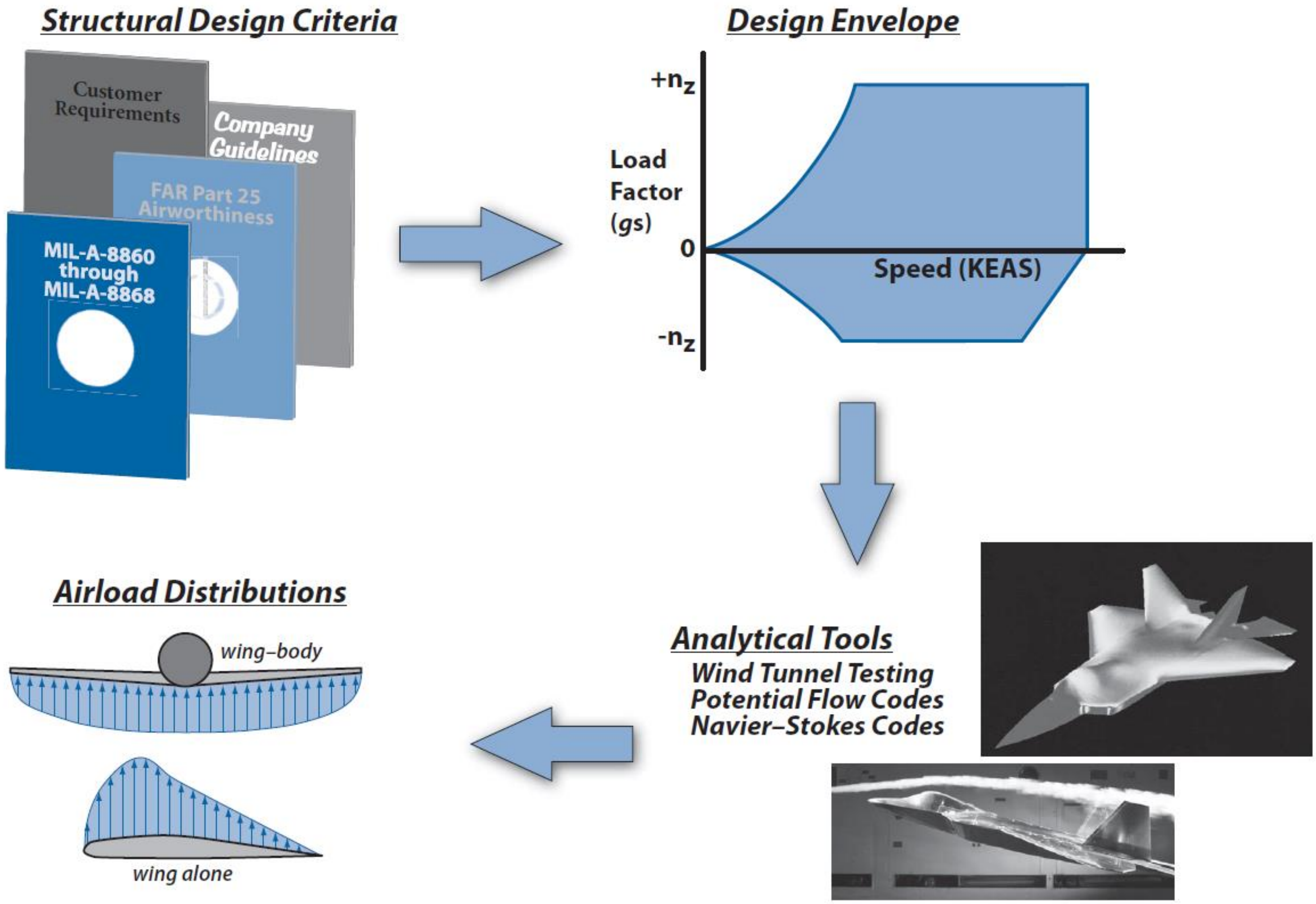
Typical V-n Diagram

Student Design Team Example



Source: 2020 AIAA Undergrad Team Aircraft Design, Virginia Tech

External Loads Development Process



Source: Ch 19, Ref. AVD 1 (Nicolai & Carichner)

Aircraft Structure & Systems Layout

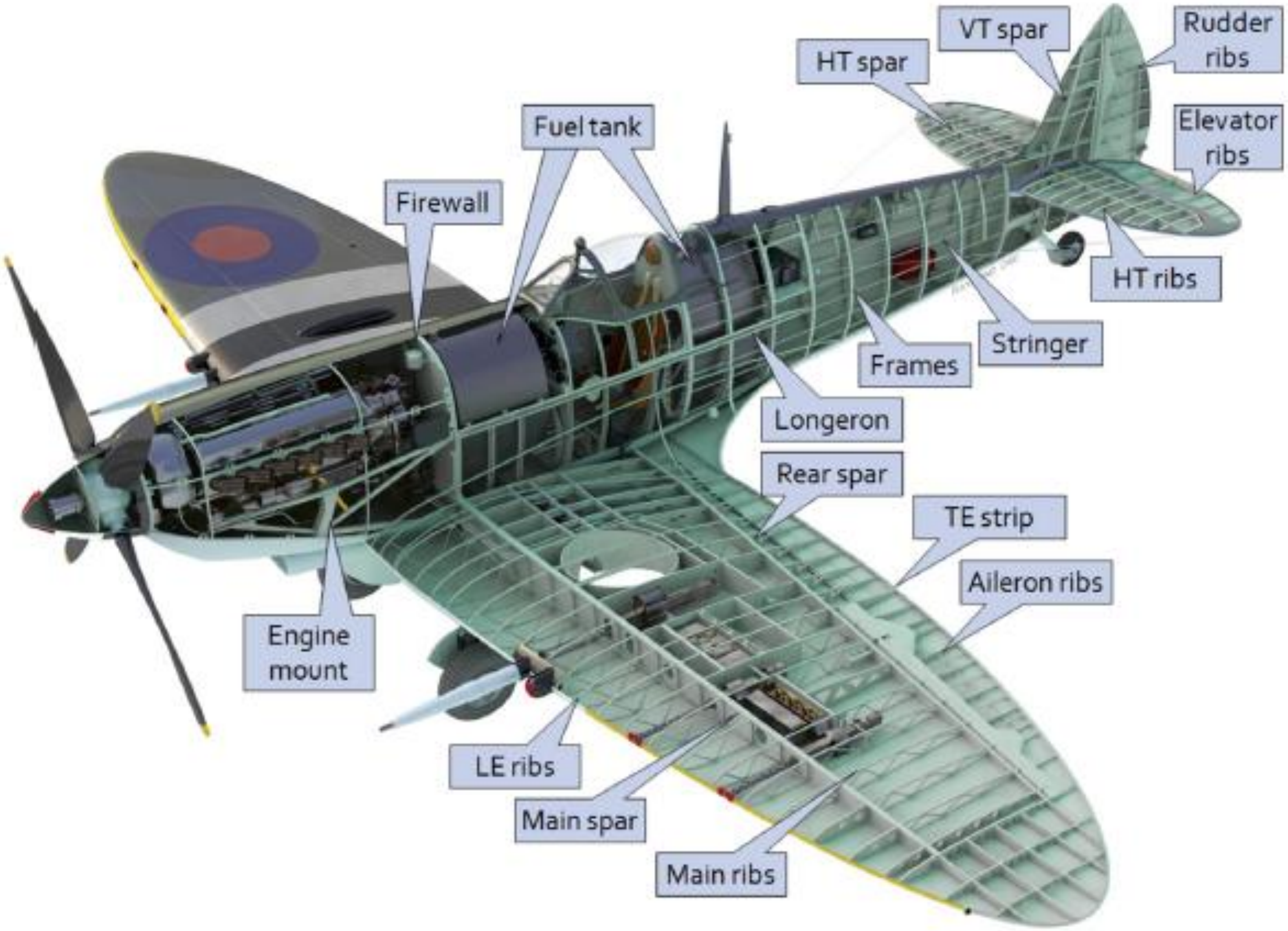
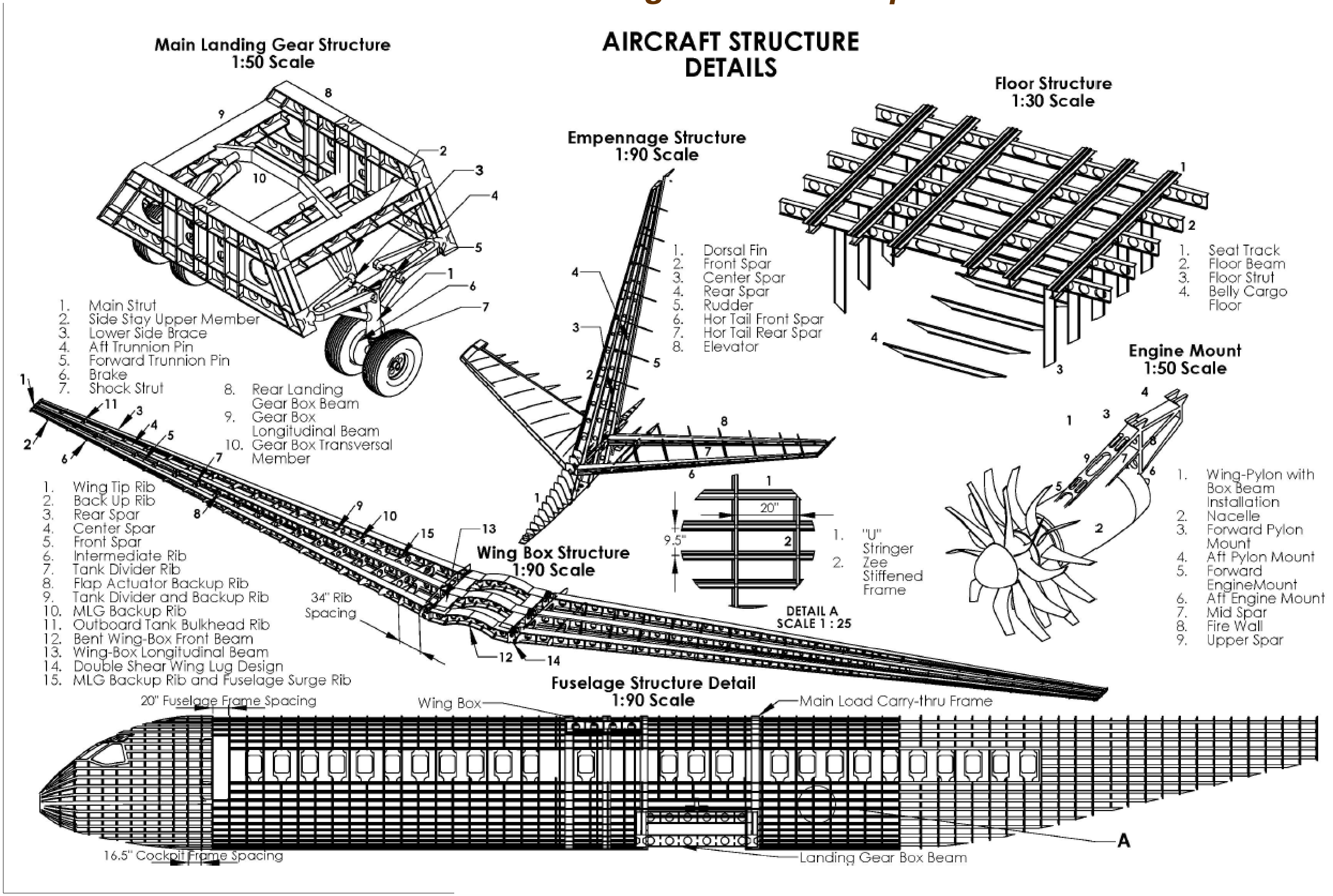


FIGURE 5-15 A cutaway of the Supermarine Spitfire, showing important elements of its aluminum construction. *(Courtesy of Raymond Ore, www.raymondore.co.uk)*

Source: Ch. 5, Ref. AVD 4 (Gudmundsson)

Aircraft Structural Layout Example

Student Design Team Example to Emulate



Source: 2010 AIAA Undergrad Team Competition Winner, Cal Poly, SLO

Typical Wing Box:

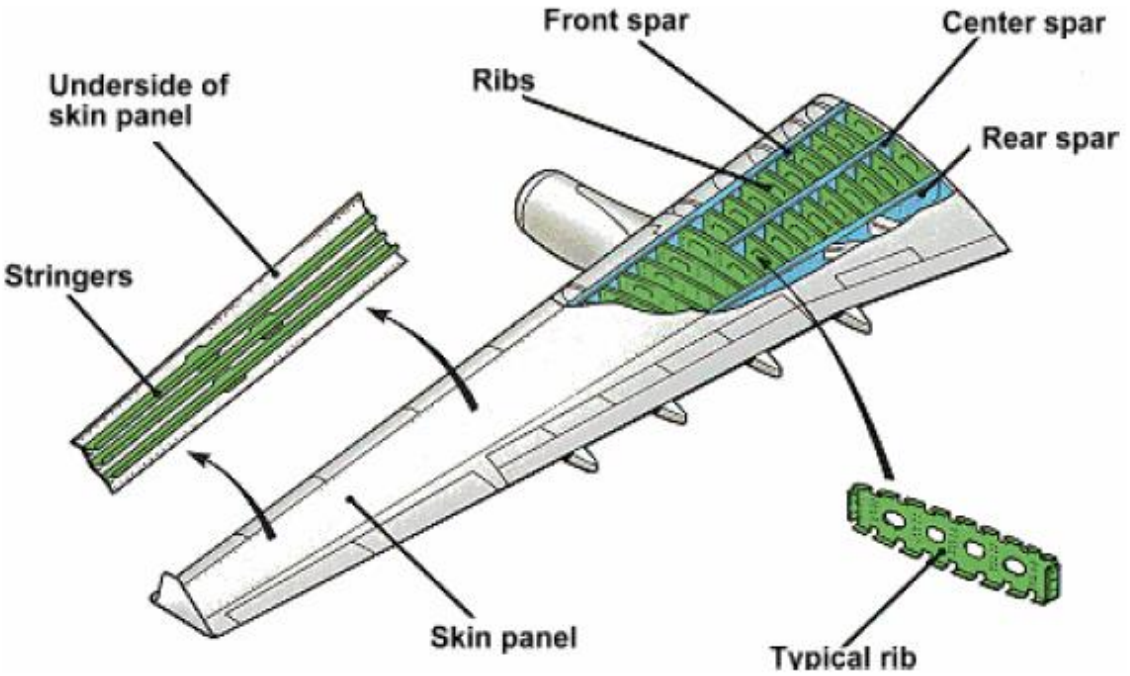
Structural Components

A wing box is made of three structural members: wing skin, spars, and ribs.

Wing skin panels are located on the top and bottom of the wings. Skin can aid in the reaction of bending moments, but it primarily carries shear loading.

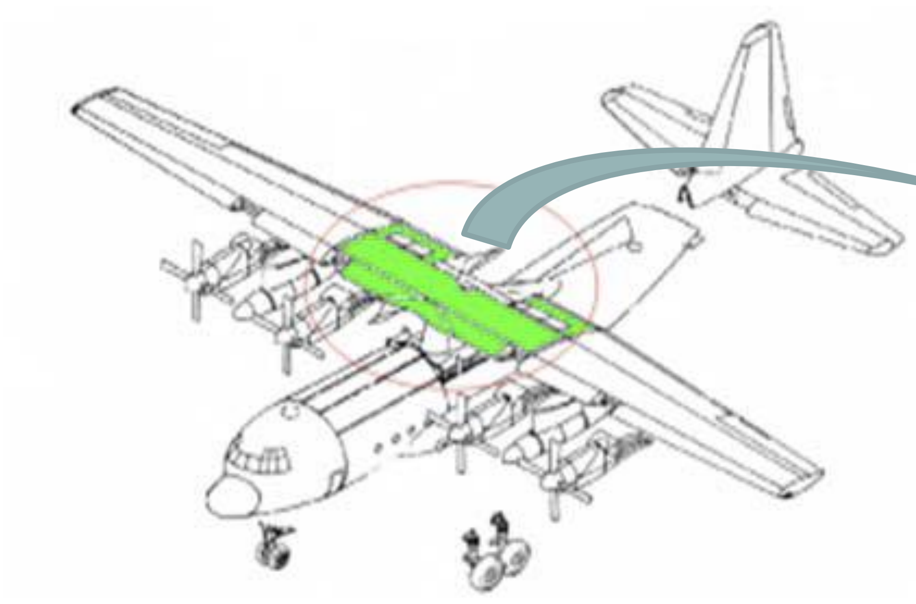
Spars are members that run along the span of the wing and react carry bending and shear loads from lift.

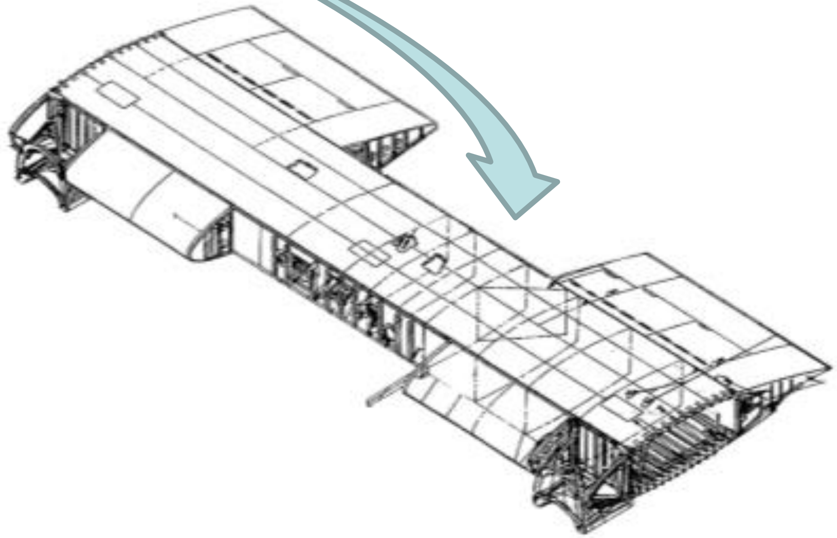
Ribs run across the spars and they give form to the wing covers as well as prevent buckling of the wing covers.



Source:
Arevalo, PT, "Design Optimization of a Composite Wing Box for a High-Altitude Long-Endurance Aircraft," Ph.D. Thesis, Embry-Riddle Aeronautical University, Florida, May 2014

C-130 Center Wing Box

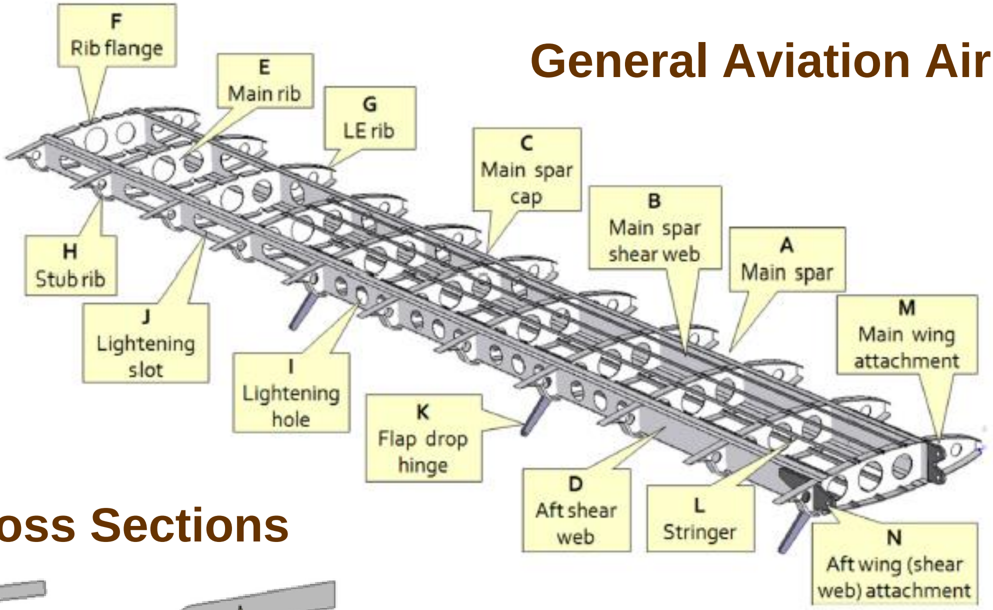




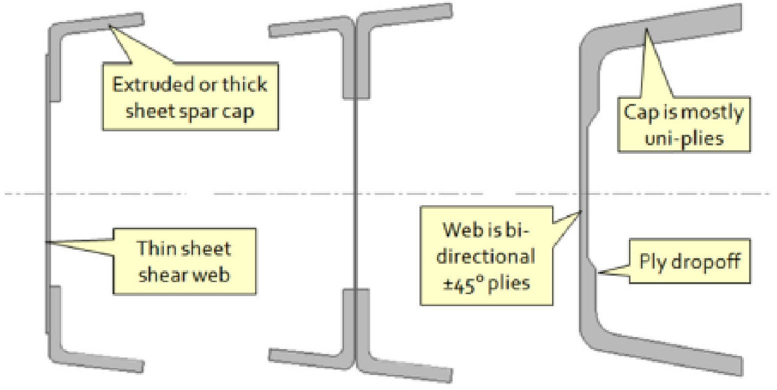
Source: Strul, E., "IAI C-130 Life Extension Program CWB Replacement," C-130 Hercules Operators Council, 2013

Typical Wing Structural Layout

General Aviation Aircraft Example



Main Spar Cross Sections



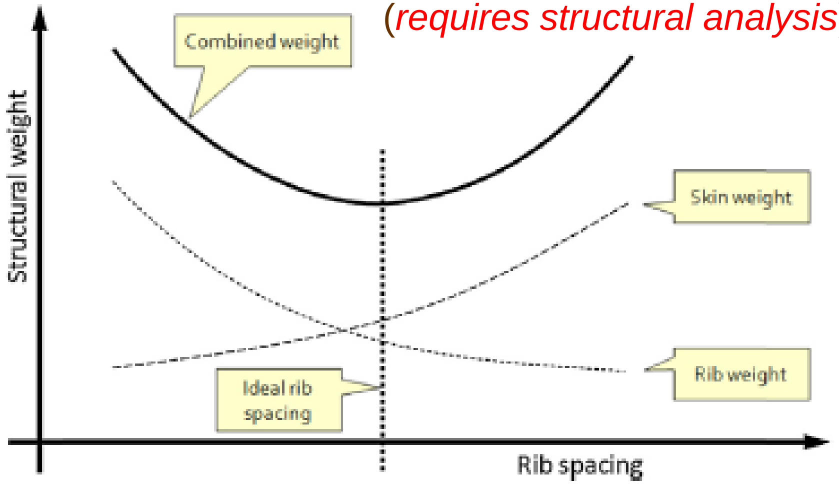
C
Aluminum C-channel spar for a light aircraft

D
Aluminum I-beam spar for a small twin engine aircraft

E
Composite C-channel spar for a high performance composite aircraft

Rib Spacing Criterion

(*requires structural analysis*)



Refine/validate Structural Layout Through Analyses

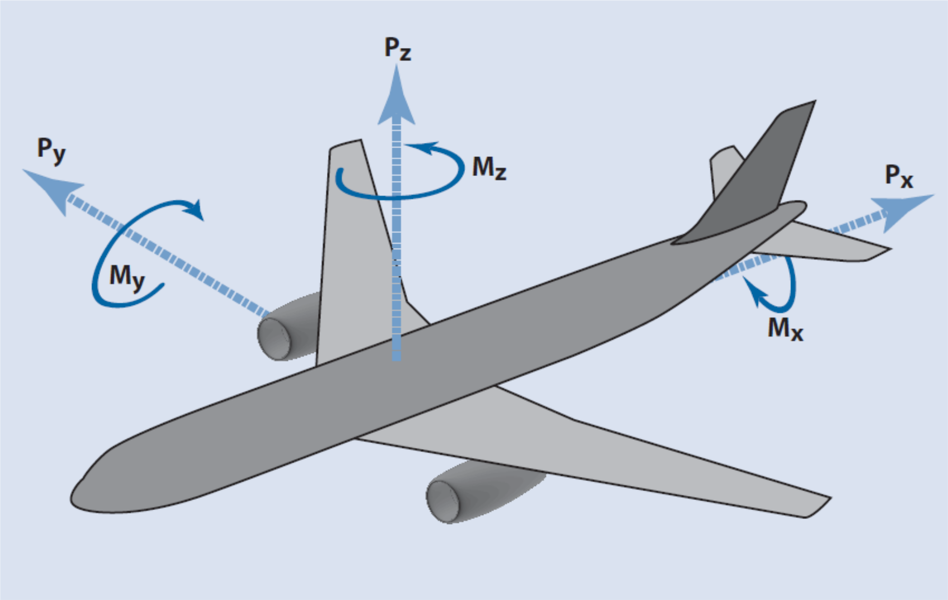
Source: Ch. 5, Ref. AVD 4 (Gudmundsson)

Structural Design Rules of Thumb

1. Keep load paths simple and direct

2. All six components of structural loading must be considered

3. A statically determinate structure is usually preferred for minimum weight (Fail safe requirements might dictate a statically indeterminate design)



4. Each structural component should serve multiple functions

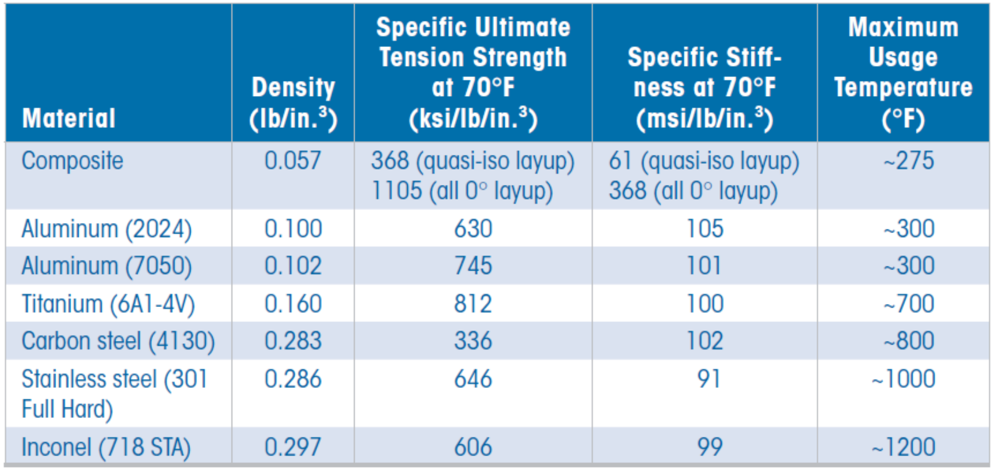
5. Subsystems integration requirements must be considered early

Source: Ch 19, Ref. AVD 1 (Nicolai & Carichner)

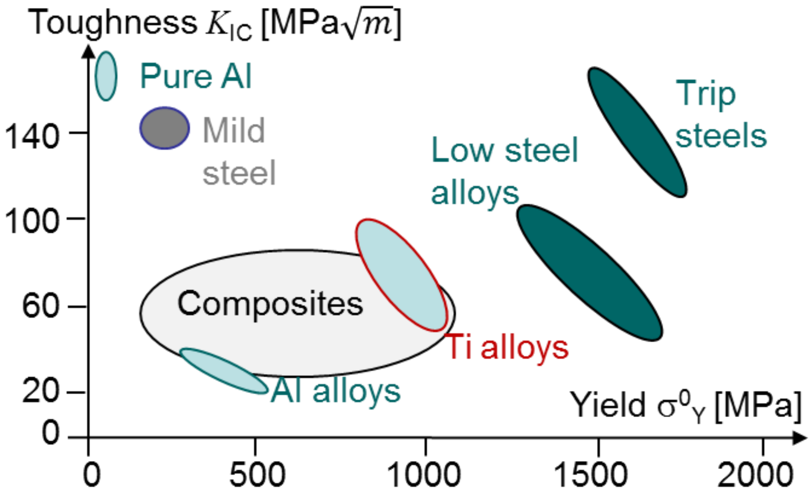
Materials Selection

- **One of the most important decisions with far-reaching implications for vehicle weight, performance, manufacturing schedule, reliability, maintainability, and cost**
- **Key parameters to consider in selecting airframe materials include:**
  - ○ specific strength—*ultimate tension strength (F_{tu}) divided by material density*
  - ○ specific stiffness—*Young's modulus (E) divided by density*
  - ○ operational environment—*for example temperature range, humidity, etc.*
  - ○ fracture toughness (K_{IC})—*inherent capability to resist crack growth*
  - ○ manufacturability—*ability to fabricate an end product using standard tools and methods*
  - ○ minimum gage limitations—*minimum thickness to which material can be produced*
  - ○ availability—*long lead times from several months to well over a year*

Table 19.2 Comparison of Material Specific Properties and Maximum Use Temperatures



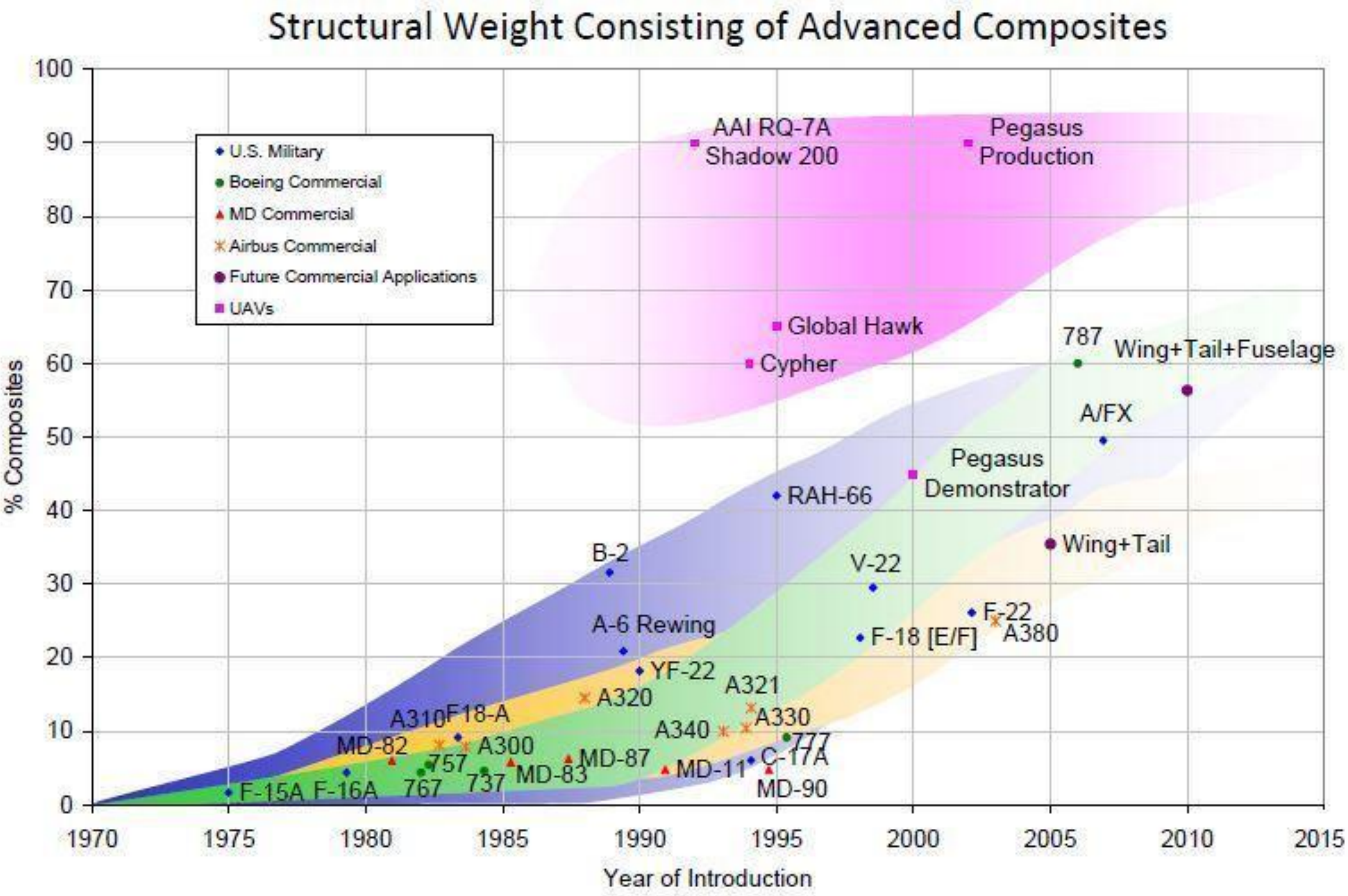
Material	Density (lb/in.^{3})	Specific Ultimate Tension Strength at 70°F (ksi/lb/in.^{3})	Specific Stiffness at 70°F (msi/lb/in.^{3})	Maximum Usage Temperature (°F)
Composite	0.057	368 (quasi-iso layup) 1105 (all 0° layup)	61 (quasi-iso layup) 368 (all 0° layup)	~275
Aluminum (2024)	0.100	630	105	~300
Aluminum (7050)	0.102	745	101	~300
Titanium (6A1-4V)	0.160	812	100	~700
Carbon steel (4130)	0.283	336	102	~800
Stainless steel (301 Full Hard)	0.286	646	91	~1000
Inconel (718 STA)	0.297	606	99	~1200



http://www.ltas-cm3.ulg.ac.be/FractureMechanics/index.php?p=overview_P4

Source: Ch. 19, Ref. AVD 1 (Nicolai & Carichner)

Aerospace Advanced Composite Usage



Source: Arris Composites, Inc.
(Alex Huckstepp, LinkedIn post, July 2020)

Structures & Materials

Recommended Reading for Topics in Structures & Materials

Topic	Recommended References
Structures & Materials	
Structures and Materials	Chapter 19, Nicolai & Carichner, Ref. AVD 1
Structures and Loads	Chapter 15, Raymer, Ref. AVD 2
Aircraft Structural Layout	Chapter 5, Gudmundsson, Ref. AVD 4
Aircraft Loads	Chapter 5, Kundu, Ref. AVD 8
Airframe Structural Design	Book by Michael C.Y. Niu, Ref. STR 1
Composite Airframe	Book by Michael C.Y. Niu, Ref. STR 2
Structural Sizing	*See Structures folder in Supplemental Reference Material on course site*

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10.7 Subsystems

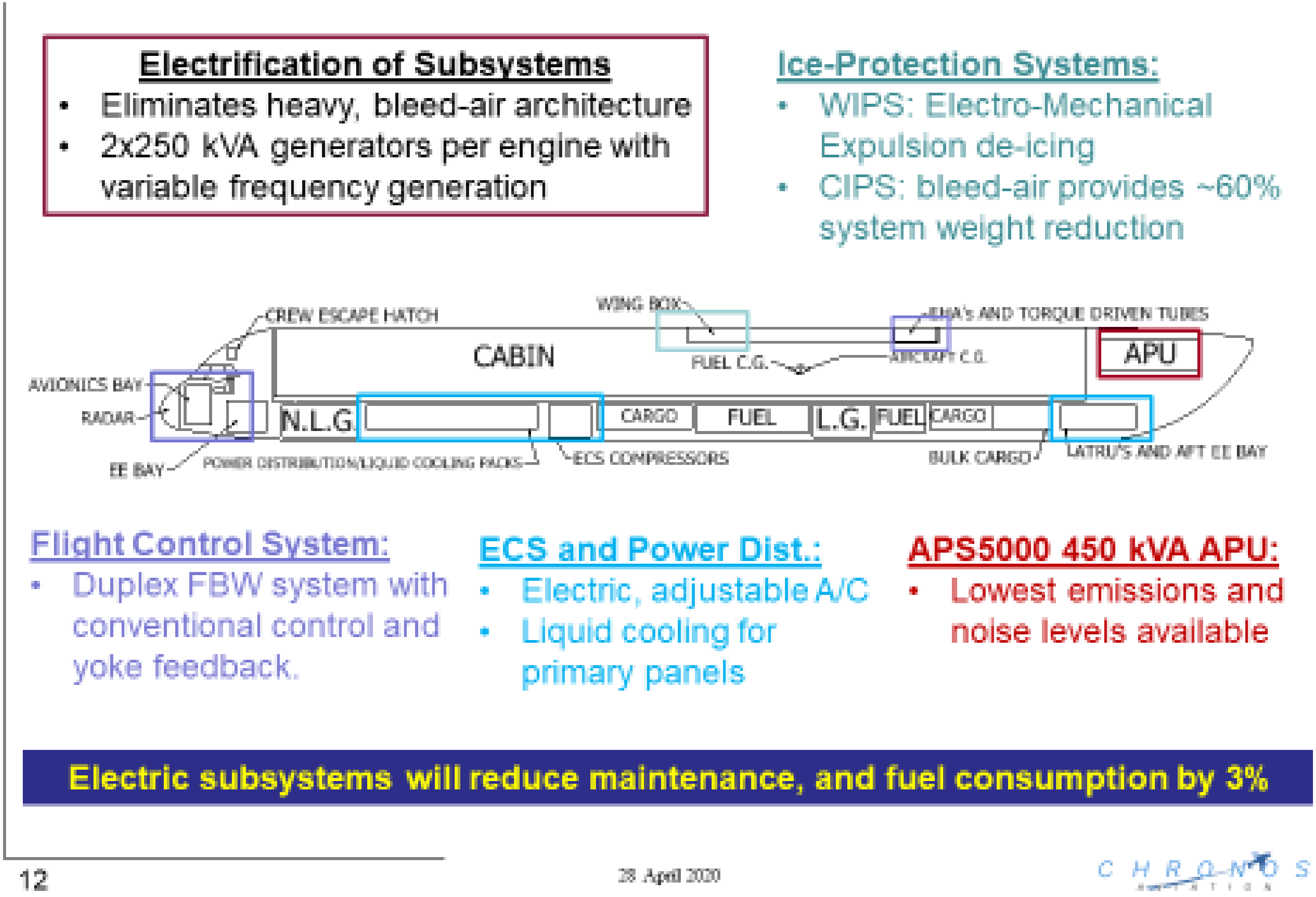
Subsystems subteam members should review their R&Rs, and any project data deliverables in the RFP

Subsystems

- **Typical Air Vehicles Subsystems**
  - Landing Gear
  - Crew station requirements and cockpit layout
  - Avionics system
  - Flight control system and actuators
  - Passenger and cargo arrangement (volume and weight)
  - Weapons system if appropriate
  - Environmental Control System (ECS)
  - Thermal Management System
  - Fuel system
  - De-icing system
  - …
- **In Conceptual Design phase:**
  - Focus on relevant technology developments and current systems used
  - Concentrate on **SWaP**, i.e., size (volume), weight, and power requirements
- **In Preliminary Design phase:**
  - **Select specific systems with *actual* SWaP values**

The following slides show examples of subsystems integration—many from previous years' student design reports—to illustrate the nature of deliverables expected of the Air Vehicle Subsystems team at the end of the project.

More Electric Aircraft Subsystems



Electrification of Subsystems
- Eliminates heavy, bleed-air architecture
- 2x250 kVA generators per engine with variable frequency generation

Ice-Protection Systems:
- WIPS: Electro-Mechanical Expulsion de-icing
- CIPS: bleed-air provides ~60% system weight reduction

Flight Control System:
- Duplex FBW system with conventional control and yoke feedback.

ECS and Power Dist.:
- Electric, adjustable A/C
- Liquid cooling for primary panels

APS5000 450 kVA APU:
- Lowest emissions and noise levels available

Electric subsystems will reduce maintenance, and fuel consumption by 3%

12

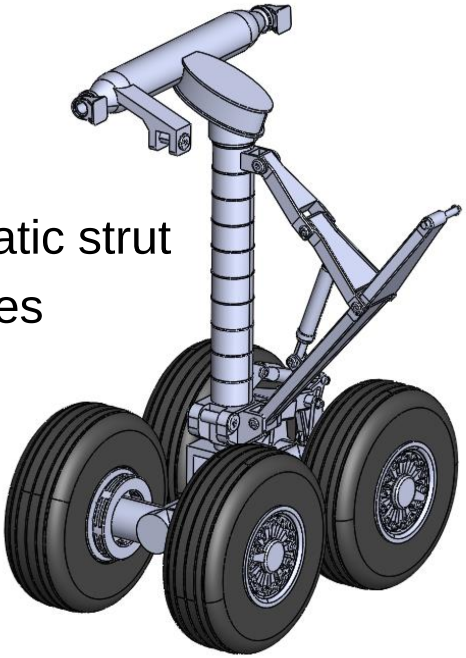
28 April 2020

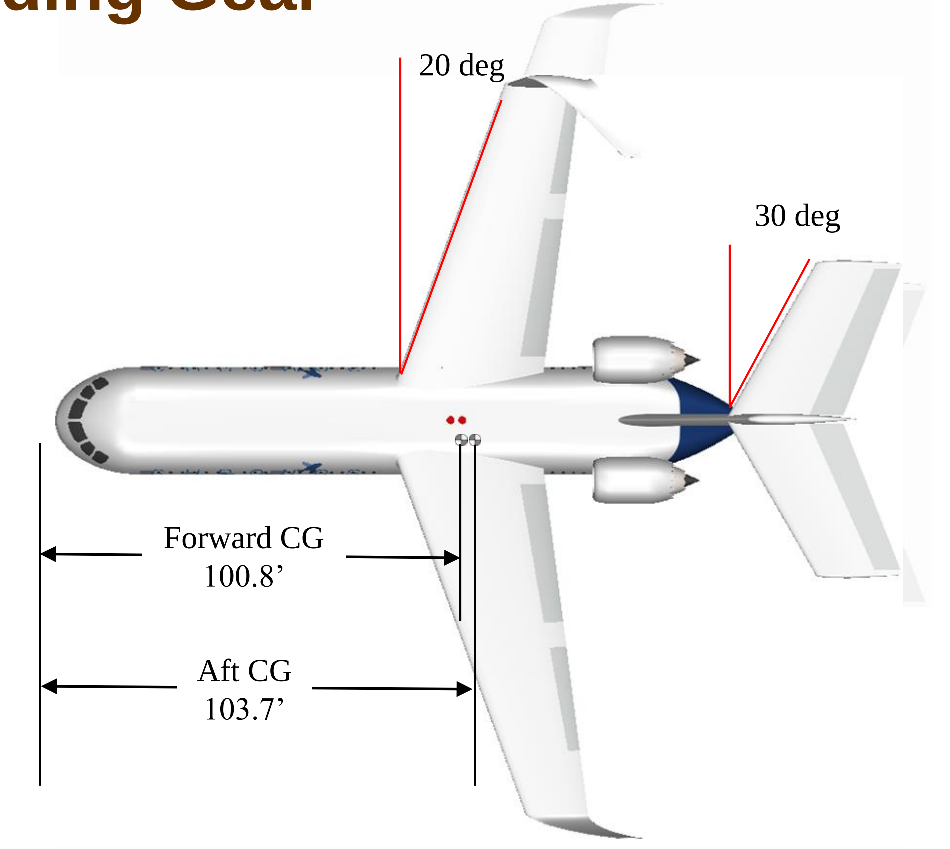
CHRONOS AVIATION

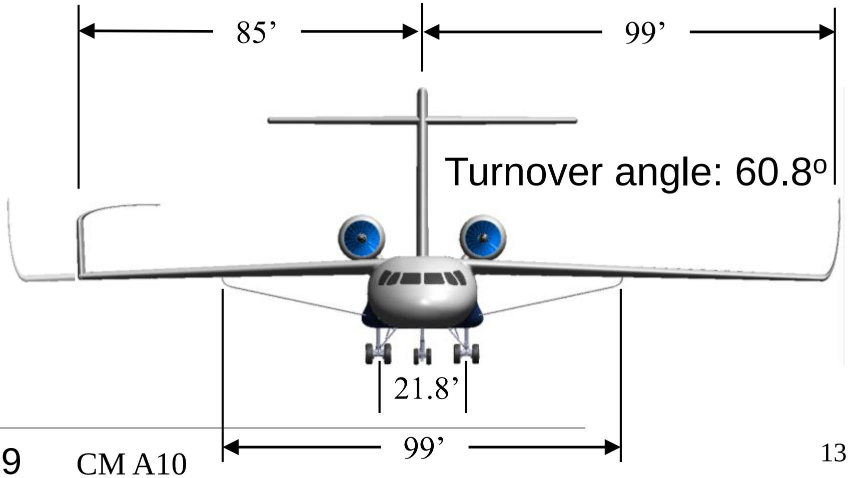
Landing Gear

Landing Gear

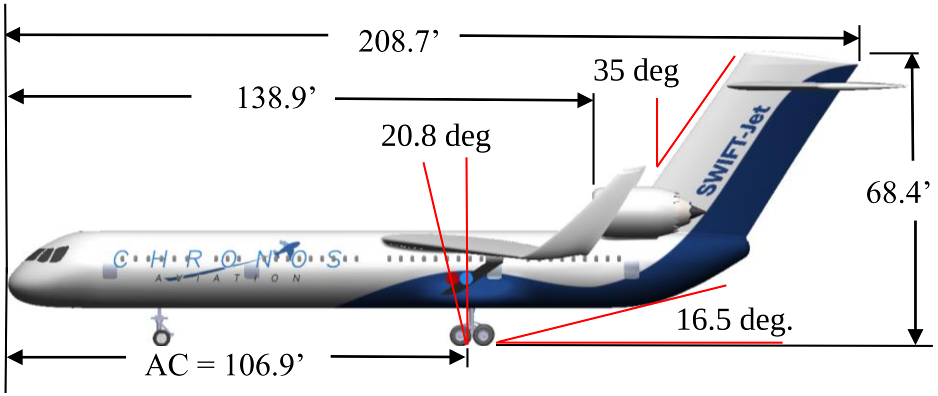
- Oleo pneumatic strut
- Carbon brakes
- Radial tires



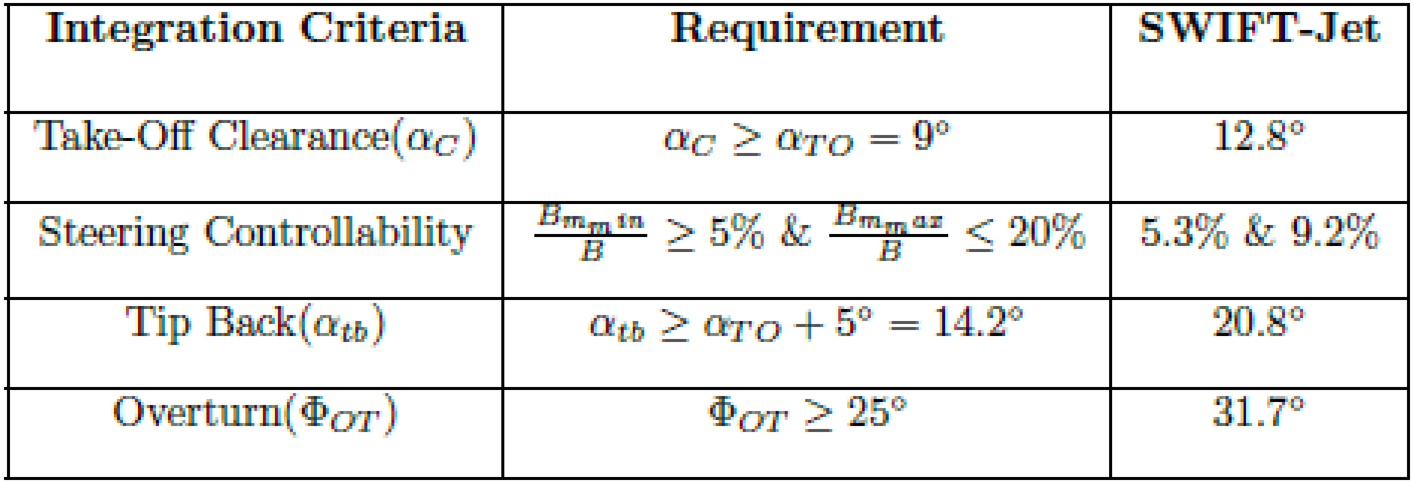




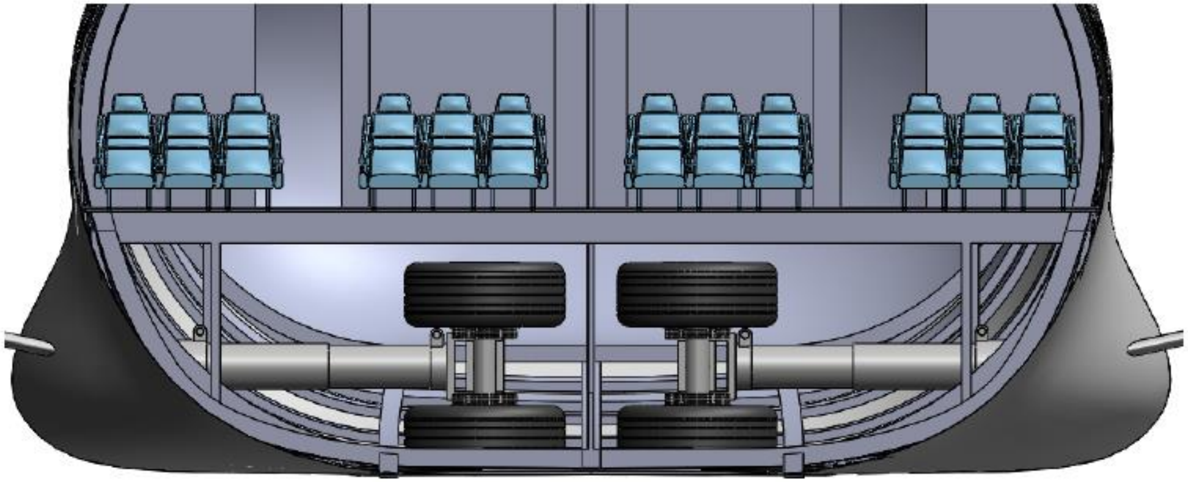
Turnover angle: 60.8°



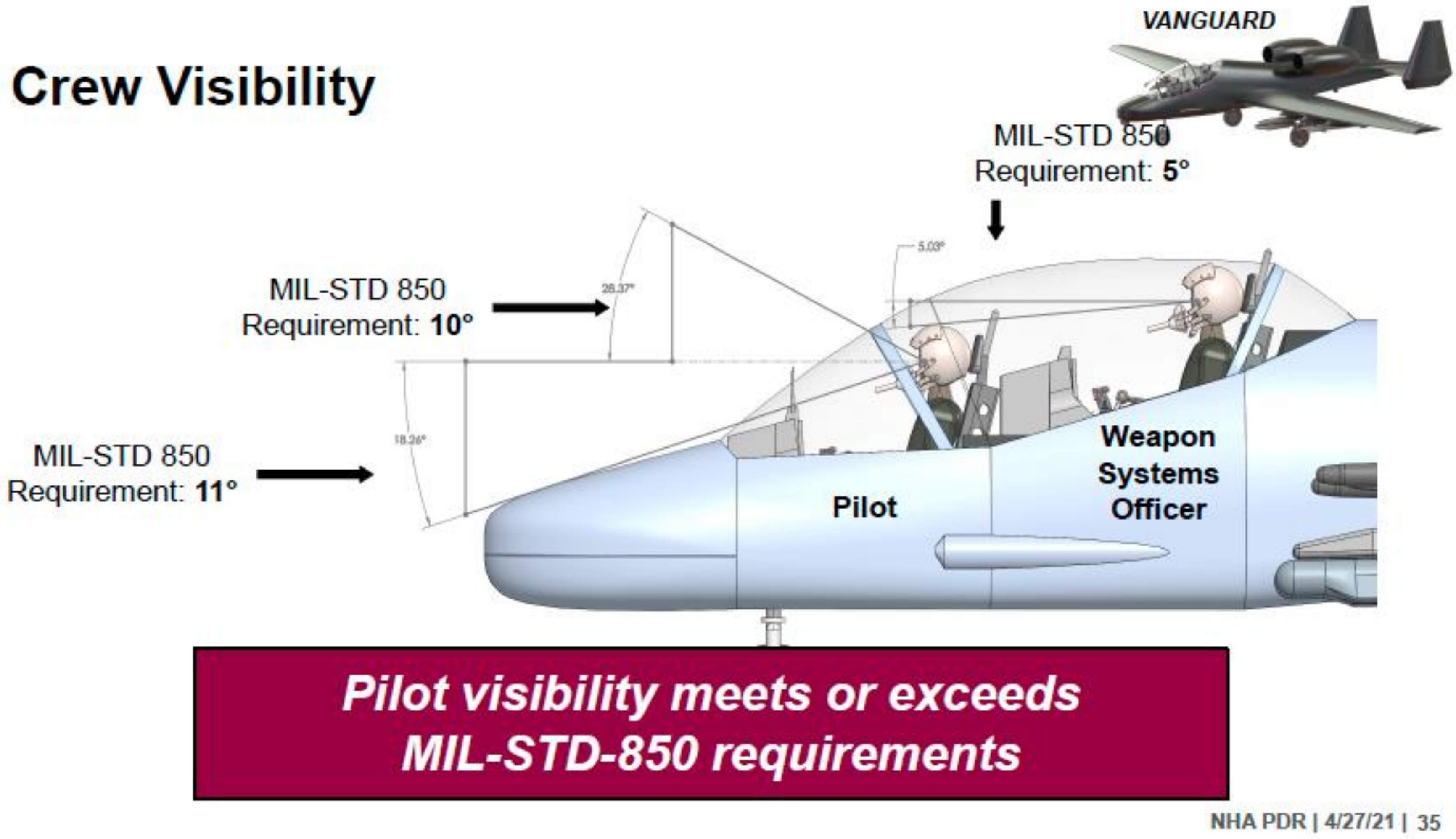
Landing Gear



Integration Criteria	Requirement	SWIFT-Jet
Take-Off Clearance(α_C)	$\alpha_C \geq \alpha_{TO} = 9^\circ$	12.8°
Steering Controllability	$\frac{B_{m_{min}}}{B} \geq 5\%$ & $\frac{B_{m_{max}}}{B} \leq 20\%$	5.3% & 9.2%
Tip Back(α_{tb})	$\alpha_{tb} \geq \alpha_{TO} + 5^\circ = 14.2^\circ$	20.8°
Overturn(Φ_{OT})	$\Phi_{OT} \geq 25^\circ$	31.7°



Crew Station



Crew Visibility

MIL-STD 850
Requirement: **5°**

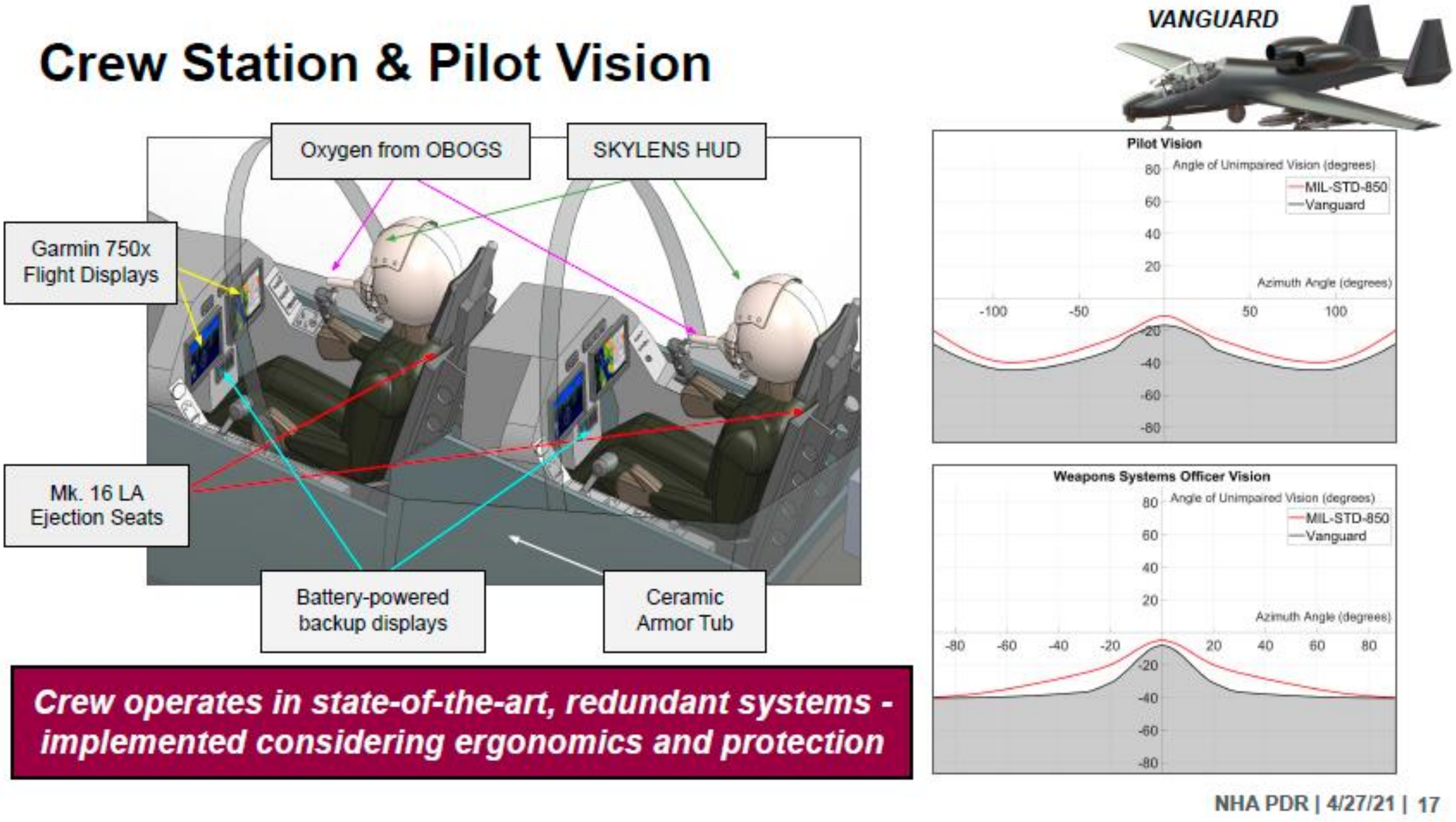
MIL-STD 850
Requirement: **10°**

MIL-STD 850
Requirement: **11°**

Pilot visibility meets or exceeds MIL-STD-850 requirements

NHA PDR | 4/27/21 | 35

Crew Station



Crew Station & Pilot Vision

Oxygen from OBOGS

SKYLENS HUD

Garmin 750x Flight Displays

Mk. 16 LA Ejection Seats

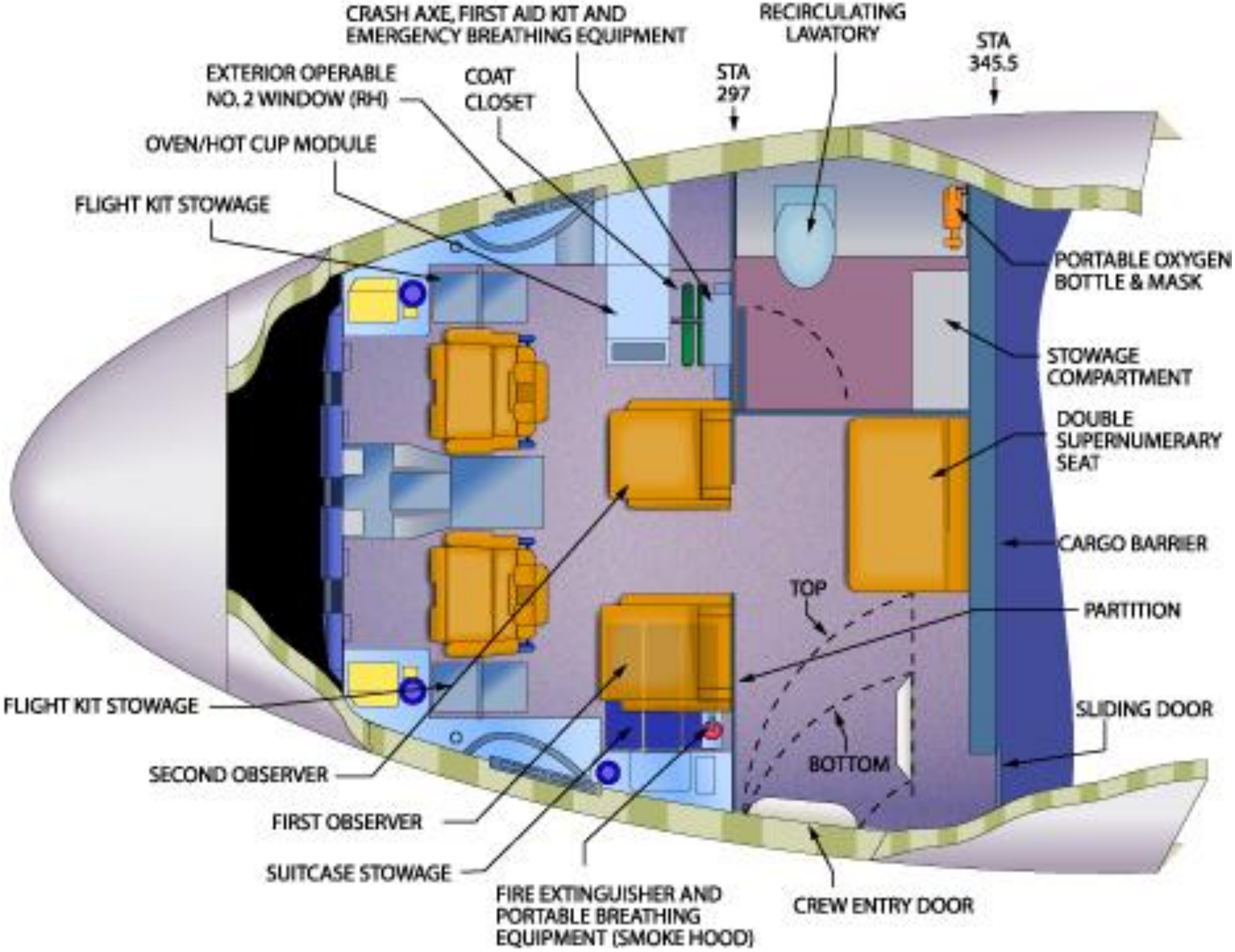
Battery-powered backup displays

Ceramic Armor Tub

Crew operates in state-of-the-art, redundant systems - implemented considering ergonomics and protection

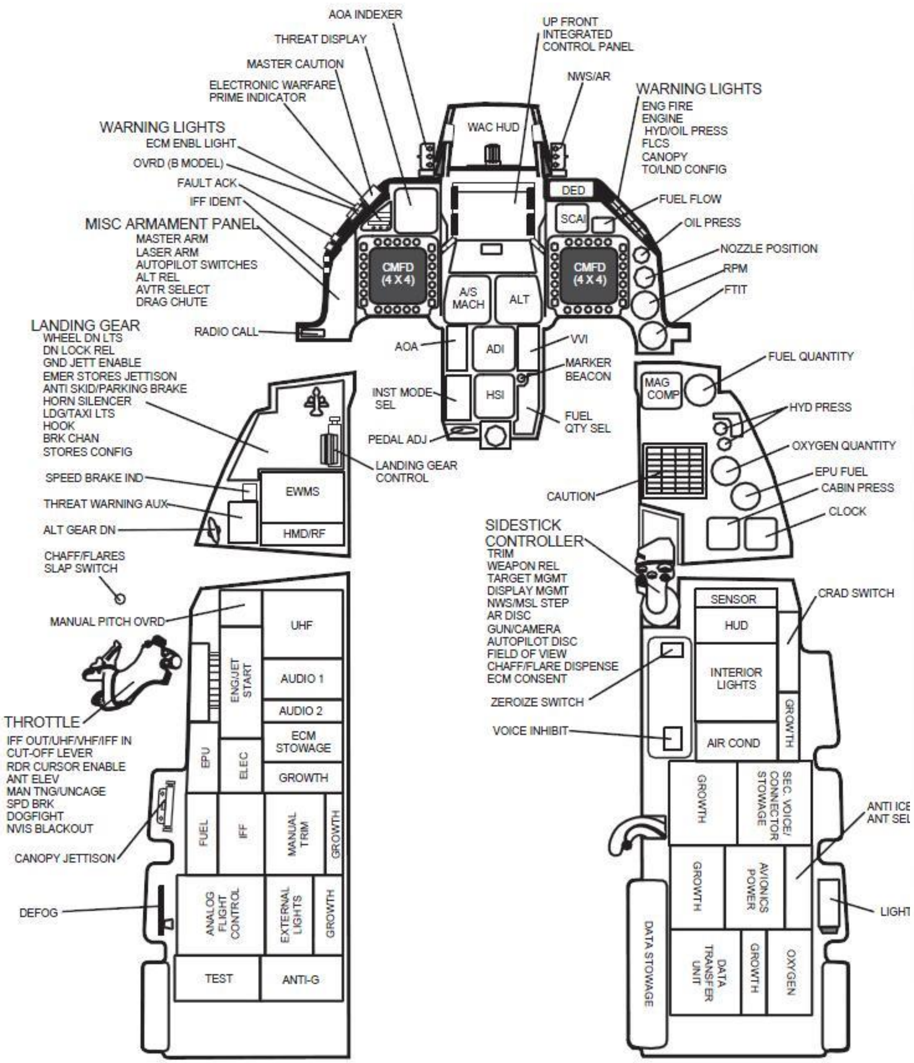
NHA PDR | 4/27/21 | 17

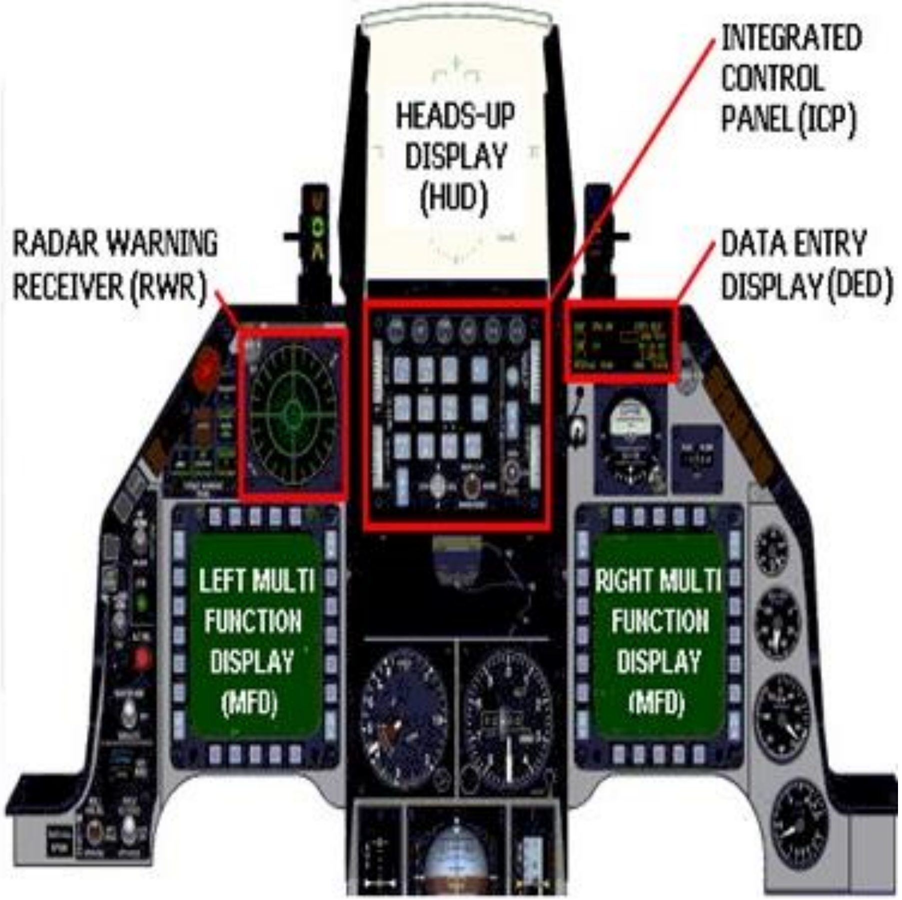
B757-300 Cockpit Plan



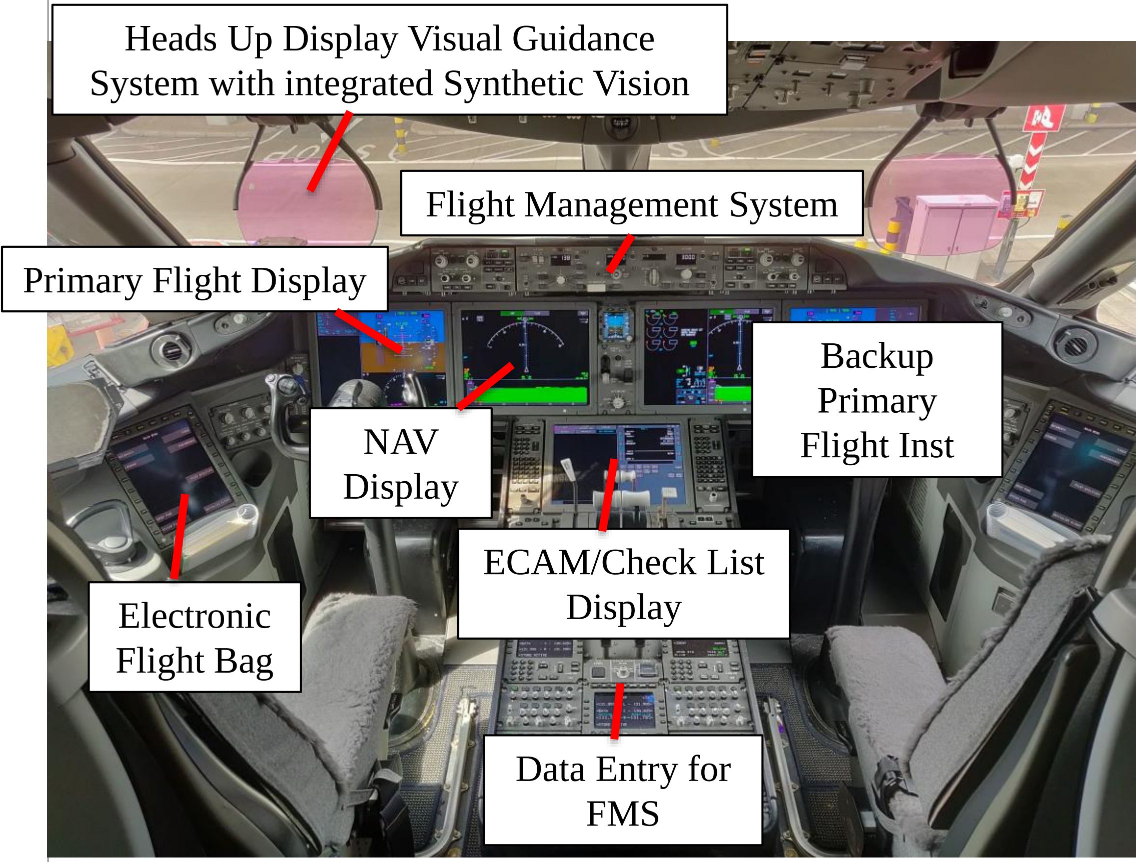
Source: https://forum.flightgear.org/

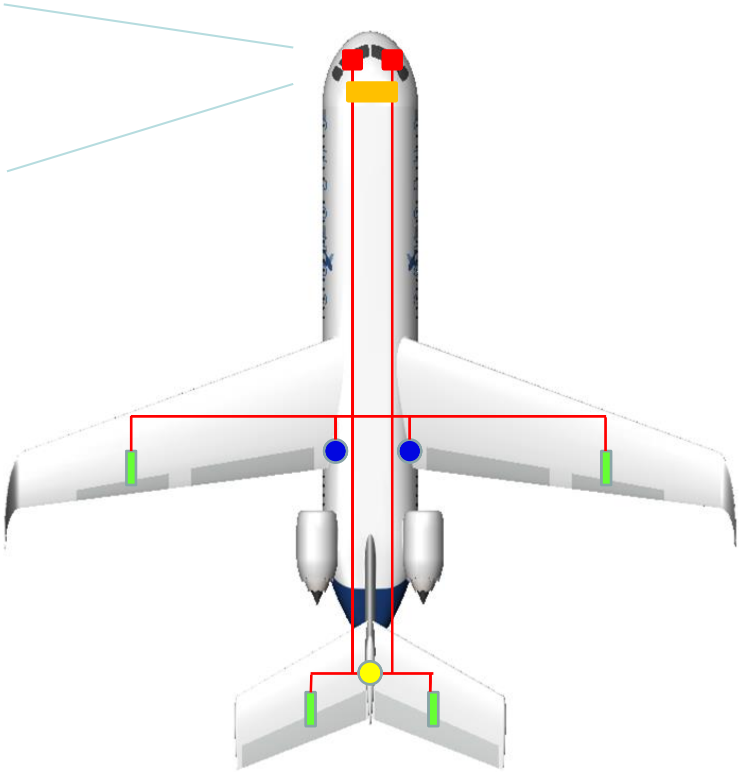
F-16 Cockpit: Avionics Layout





Flight Crew Interface/Control

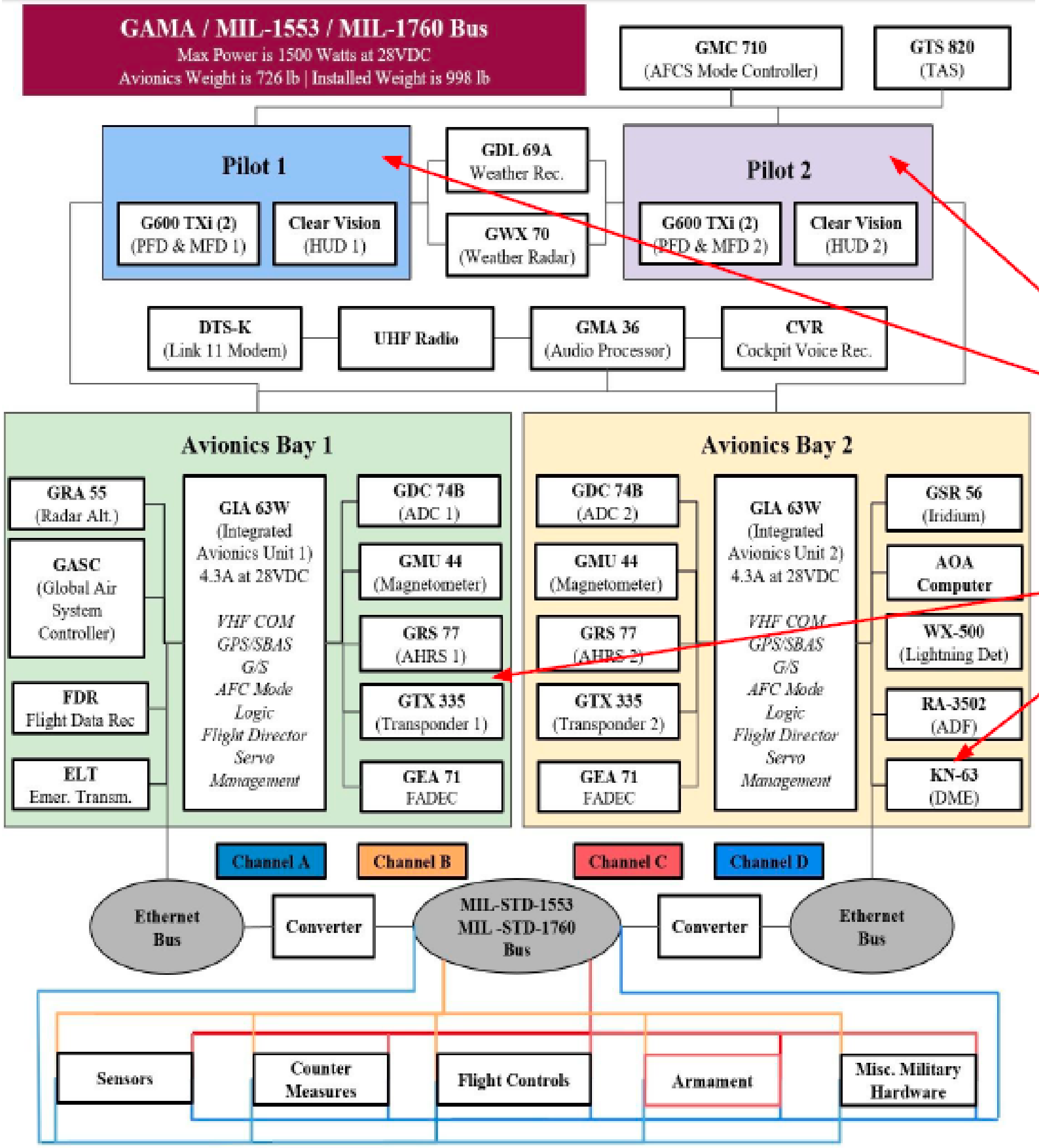




🟥 Controls
🟧 Flight Control Computer
🟩 Electro-Hydrostatic Actuators
🔵 Electric Torque Driven Tubes
🟡 Electric Screw Jack

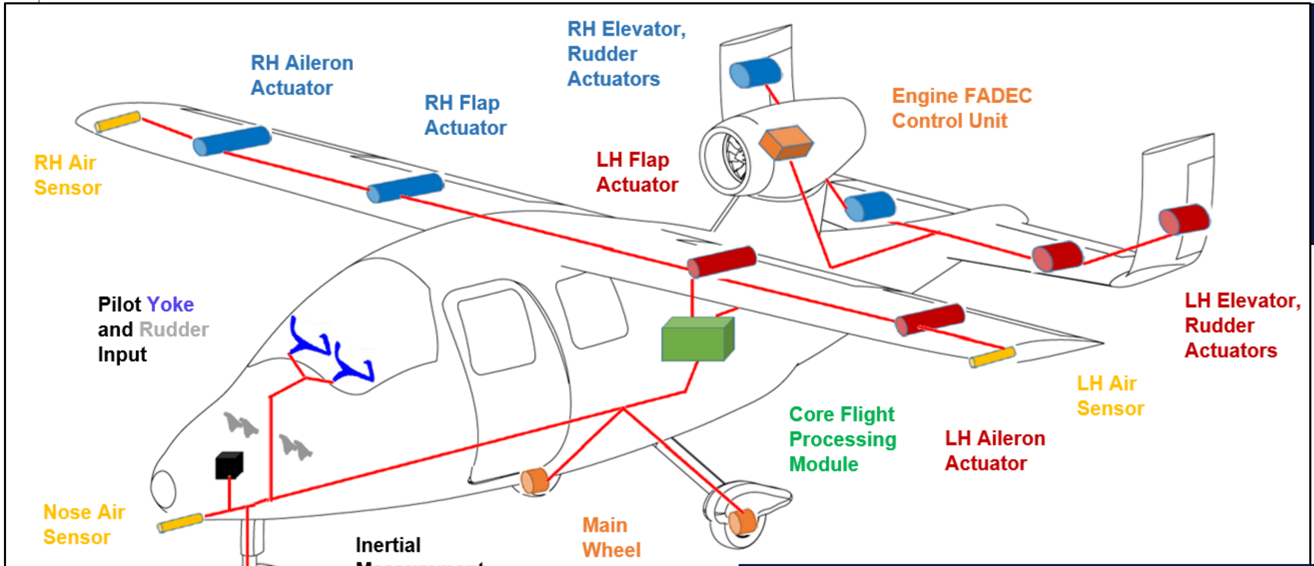
FBW and control systems reduce workload and increase efficiency

Garmin G-3000 Avionics Architecture



Redundant Architecture

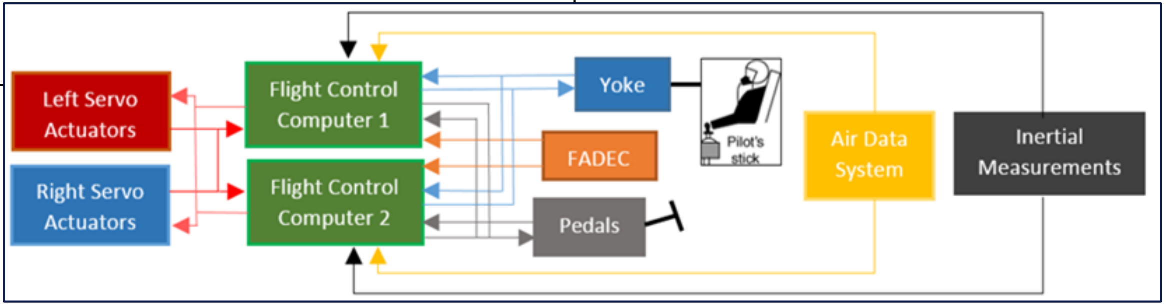
Flight Control System: Fly-By-Wire



*From 2012: "Diamond plans to bring FBW in as an option under $100,000, but it might **<u>cost as much as $150,000.</u>** If it's accepted by the market in volume, the price would come down." - AVWeb*

<u>Computers Have Multiple Control Law Choices:</u>

1. Novice
2. Standard
3. Advanced

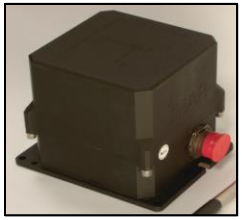


[20] Design Based on SAFAR

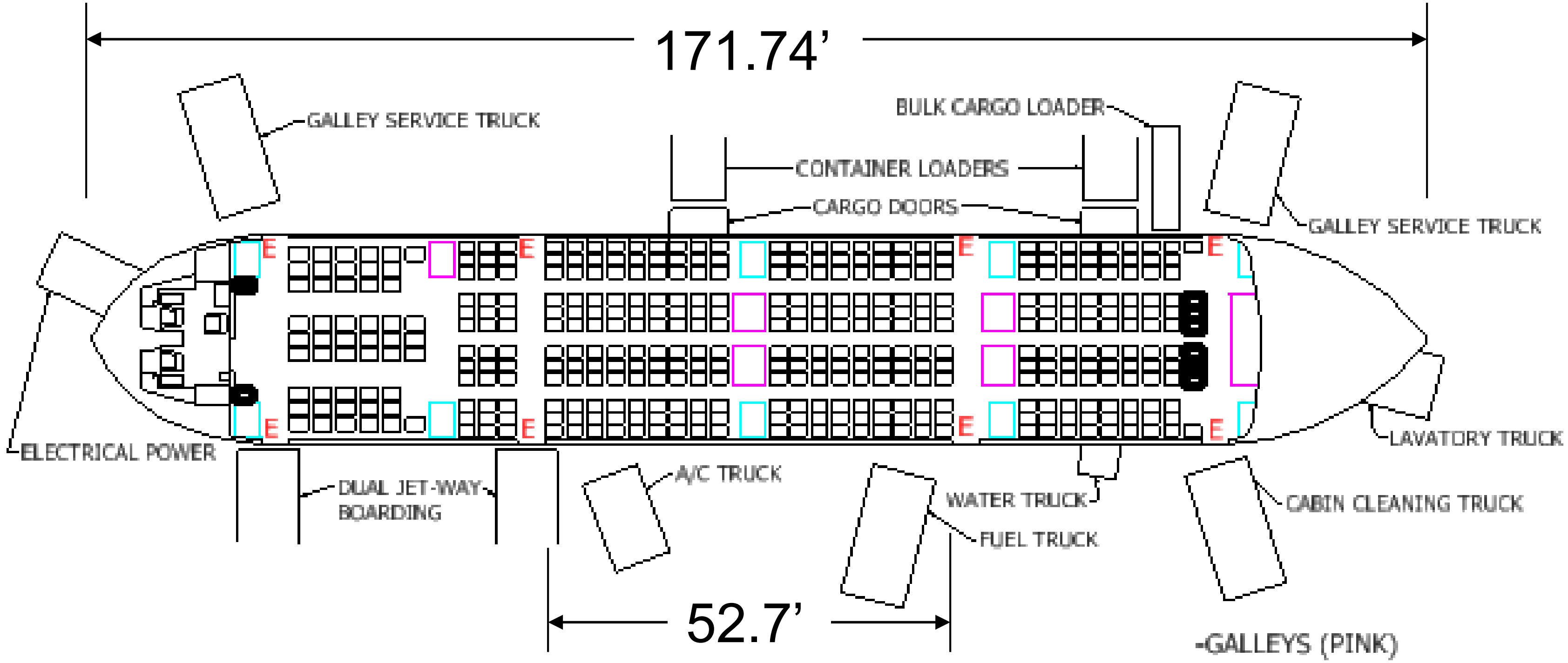
SAFAR
Small Aircraft Future Avionics Architecture

Key Components of Fly-By-Wire System

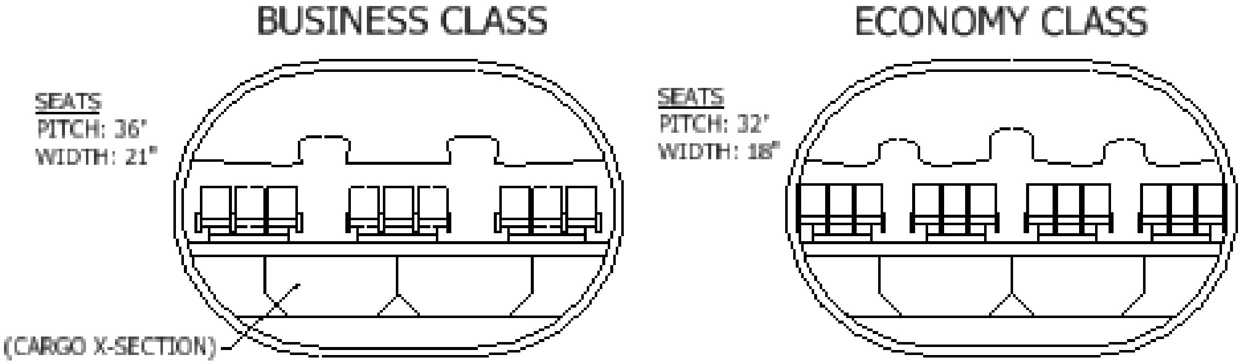
Fly By Wire System	Power Demand (Watts)	Weight (lbs)
Rockwell-Collins Flight Computer	175	14
(8x) Moog 863 Rotary Servo Actuators (+/- 45 deg @ 150 in-lb torque)	16	14.4
iMAR Inertial Measurement Sensor	35	18.7
Septino GNSS (Global Navigation Satellite System)	6	2.2
(3x) Simtec ADS-7 Heated Air Pitots	120	13.2
FJ33 Engine FADEC	200	11
Totals	**552**	**73.5**

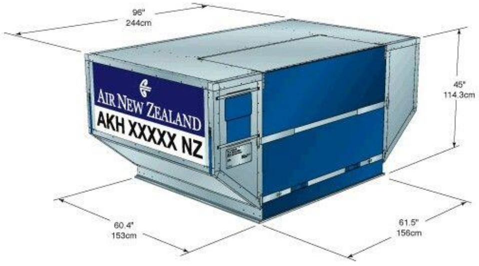


Gate Integration & Cabin Layout



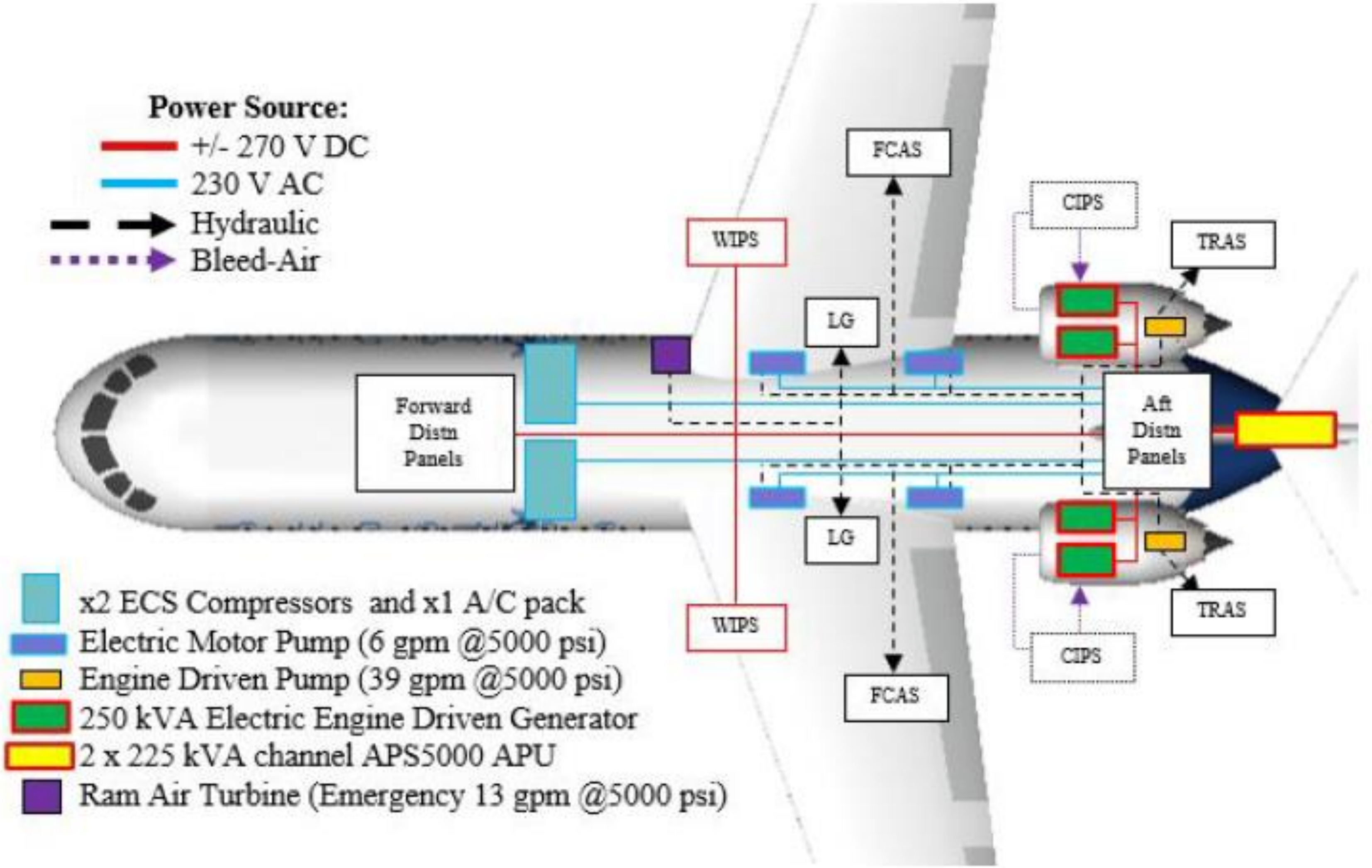
-GALLEYS (PINK)
-LAVATORIES (BLUE)
-FLGHT ATT. SEATS (BLACK)





SWIFT-Jet seamlessly integrates within existing infrastructure to solve worldwide airport congestion

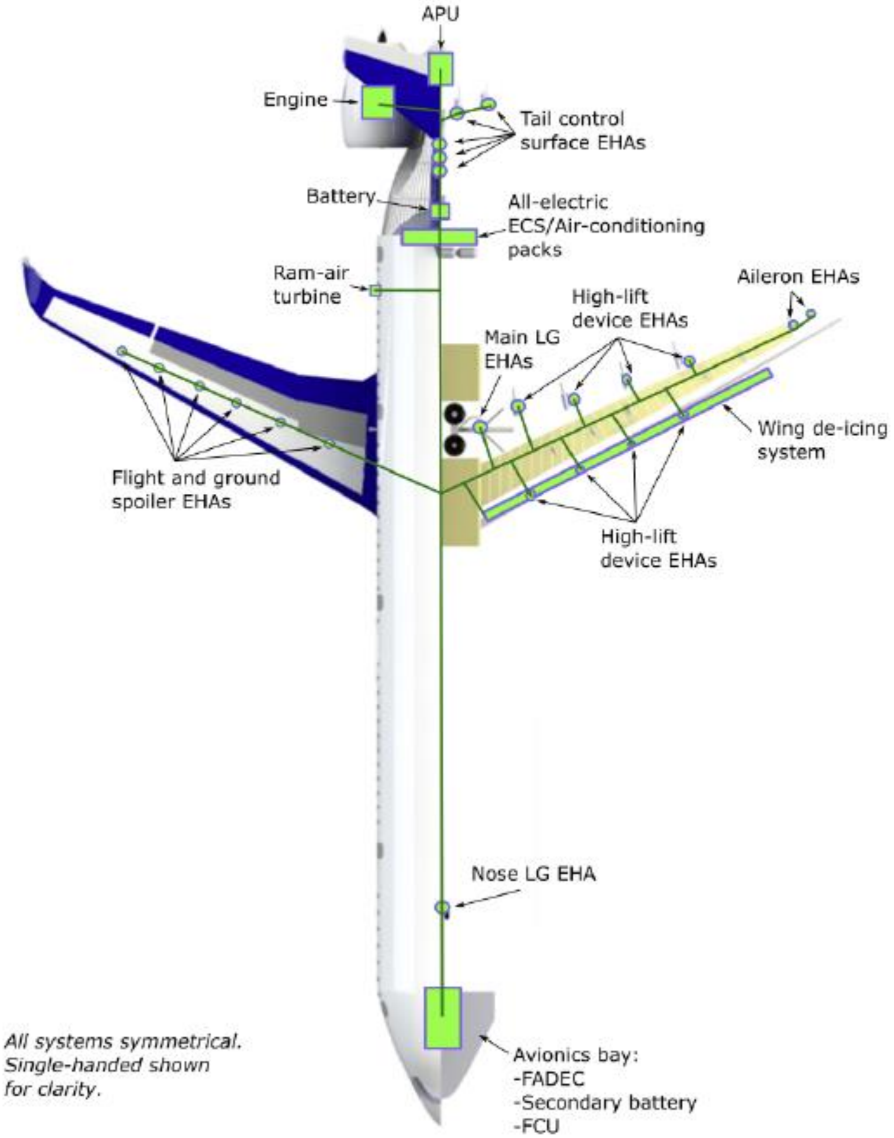
Electric Power Generation & Distribution to Major Subsystems



CIPS – Cowl Ice Protection System
TRAS – Thrust Reverser Actuation System

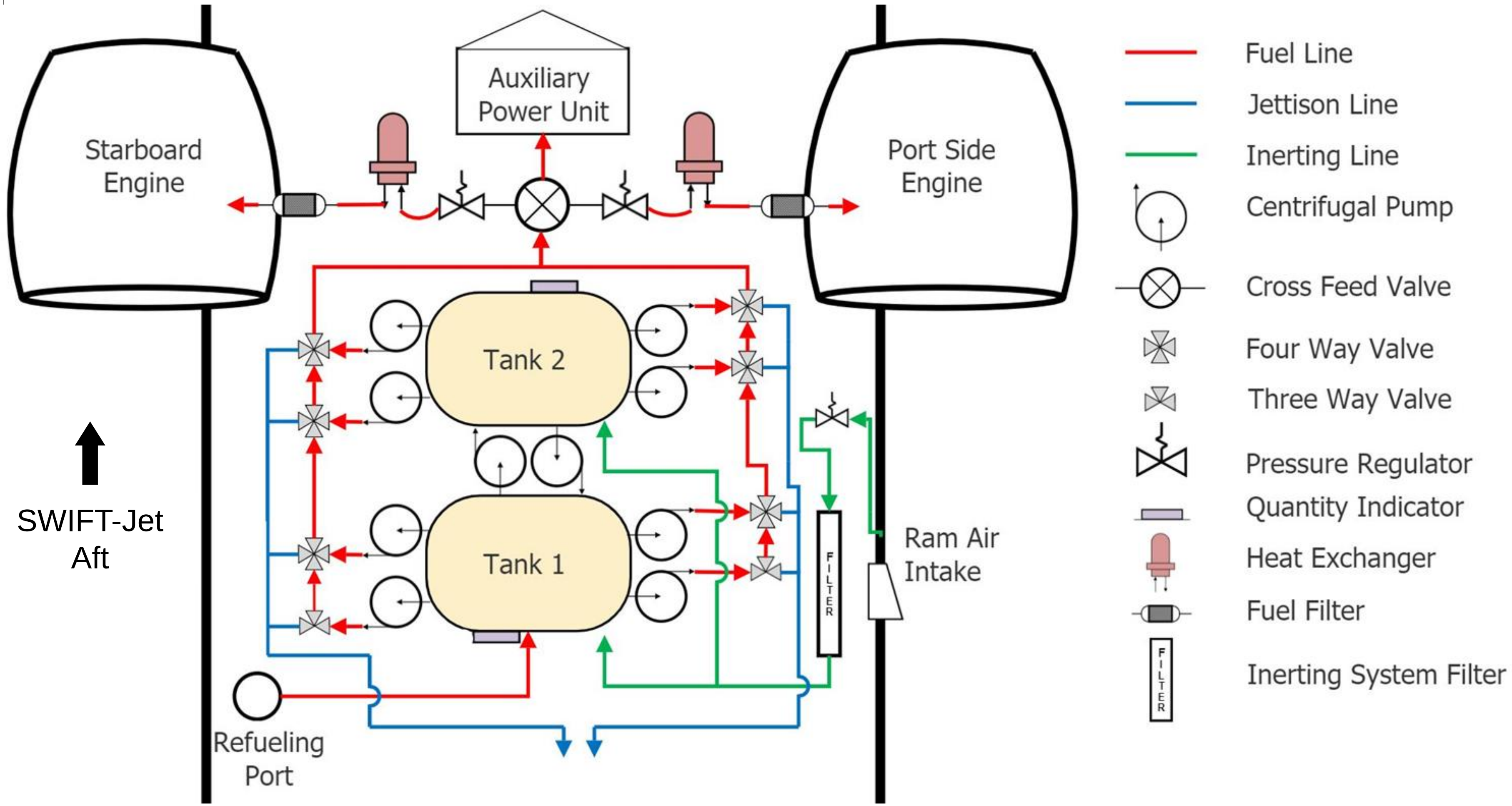
FCAS – Flight Control Actuation System
WIPS – Wing Ice Protection System

Electric & Hydraulic Systems Integration



All systems symmetrical. Single-handed shown for clarity.

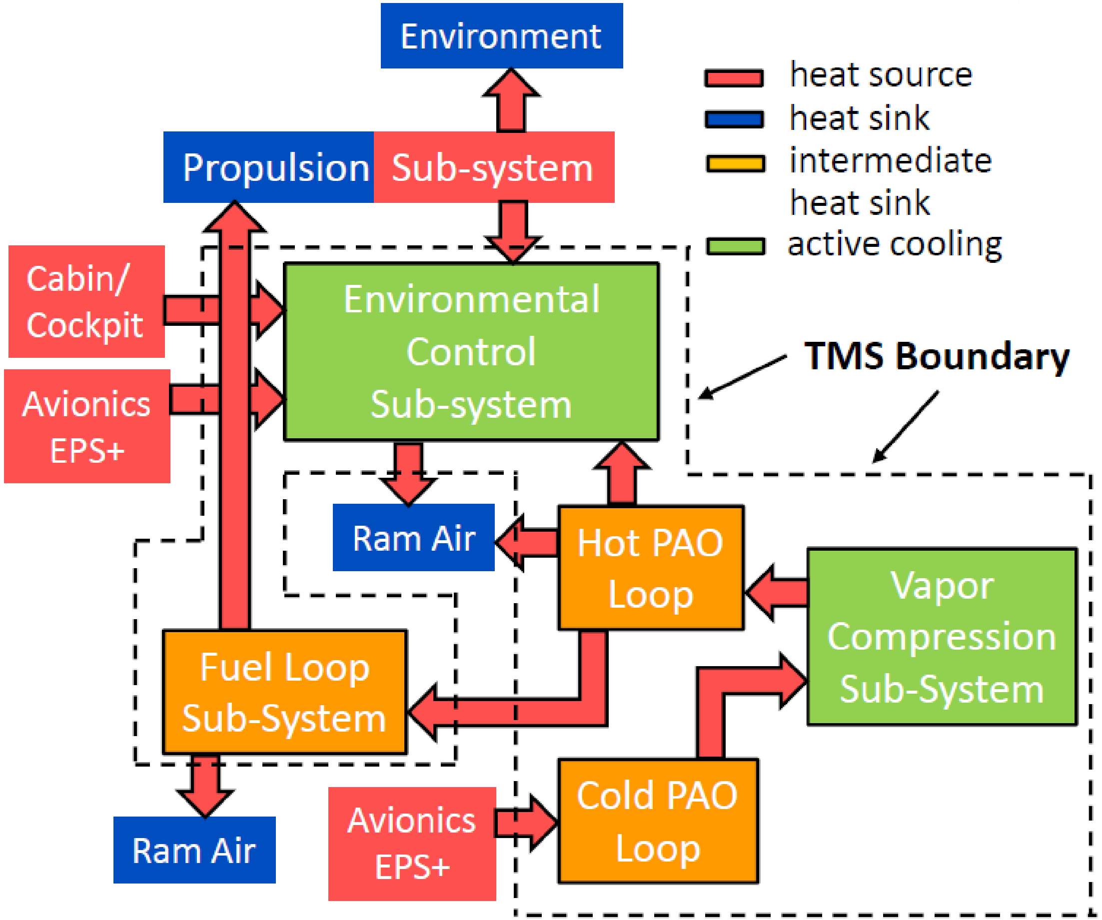
Fuel System Architecture



The fuel system will ensure both engines receive the necessary amount of fuel to produce the required thrust throughout the flight envelope

A Typical Aircraft Thermal Management System (TMS)

- **Numerous heat sources**
  - Cabin/cockpit
  - Air-cooled avionics
  - Liquid-cooled avionics
  - Engine
  - EPS+ (generators, motors, pumps, compressors, e-actuators, power network, controllers, etc.)
- **Few heat sinks**
  - Ram air
  - Engine
  - Environment



PAO: polyalphaolefin

TMS detailed design usually deferred to later stages of the Design Cycle

Source: Reed, W.C., et al, AIAA 2016-1023, Jan 2016

Air Vehicle Subsystems

Recommended Reading for Topics in Air Vehicle Subsystems

Topic	Recommended References
Air Vehicle Subsystems	
Crew Station, Passengers, and Payload	Chapters 9 & 11, Raymer, Ref. AVD 1
Fuselage Design	Chapter 7, Sadraey, Ref. AVD 5
Systems Architecures	Chapter 5, Moir & Seabridge, Ref. AS 1
Aircraft Systems Examples	Chapter 10, Moir & Seabridge, Ref. AS 1
Power Systems Issues	Chapter 11, Moir & Seabridge, Ref. AS 1
Key Characteristics of Aircraft Systems	Chapter 12, Moir & Seabridge, Ref. AS 1
Aircraft Subsystems Integration	Book by Moir and Seabridge, Ref. AS 2
Civil Avionics Systems	Book by Moir and Seabridge, Ref. AS 3
Military Avionics Systems	Book by Moir and Seabridge, Ref. AS 4
Undercarriage	Chapter 7, Kundu, Ref. AVD 8
Landing Gear and Subsystems	Chapter 11, Raymer, Ref. AVD 2
Landing Gear Design	Chapter 9, Sadraey, Ref. AVD 5
The Anatomy of the Landing Gear	Chapter 13, Gudmundsson, Ref. AVD 4
Aircraft Landing Gear Design	Book by Currey, Ref. AS 5
Fuselage, Fuel Systems and Landing Gear	*See Subsystems folder in Supplemental Reference Material folder on course site*

Outline

A10. Preliminary Design: Refine & Validate Baseline Design

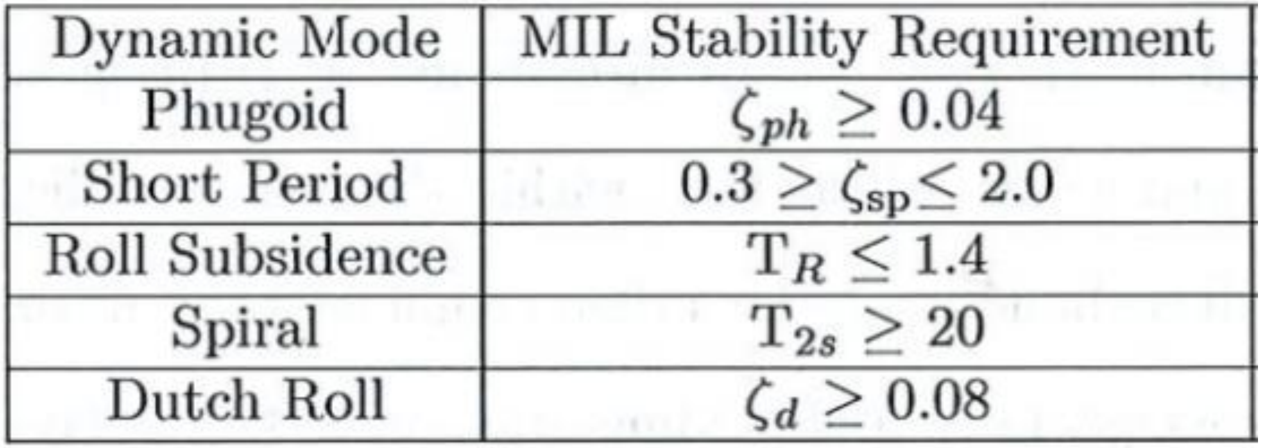
A10.1 General Remarks
A10.2 Configuration Layout and Loft
A10.3 Aerodynamics
A10.4 Aeropropulsion Integration
A10.5 Vehicle Performance
A10.6 Structures & Materials
A10.7 Subsystems
A10.8 Stability & Control
A10.9 Weights (Mass Properties) & Balance
A10.10 Cost & Manufacturing

A10.8 Stability & Control

Stability & Control (S&C) subteam members should review their R&Rs, and any project data deliverables in the RFP

Provide Evidence that the Design Meets S&C Requirements

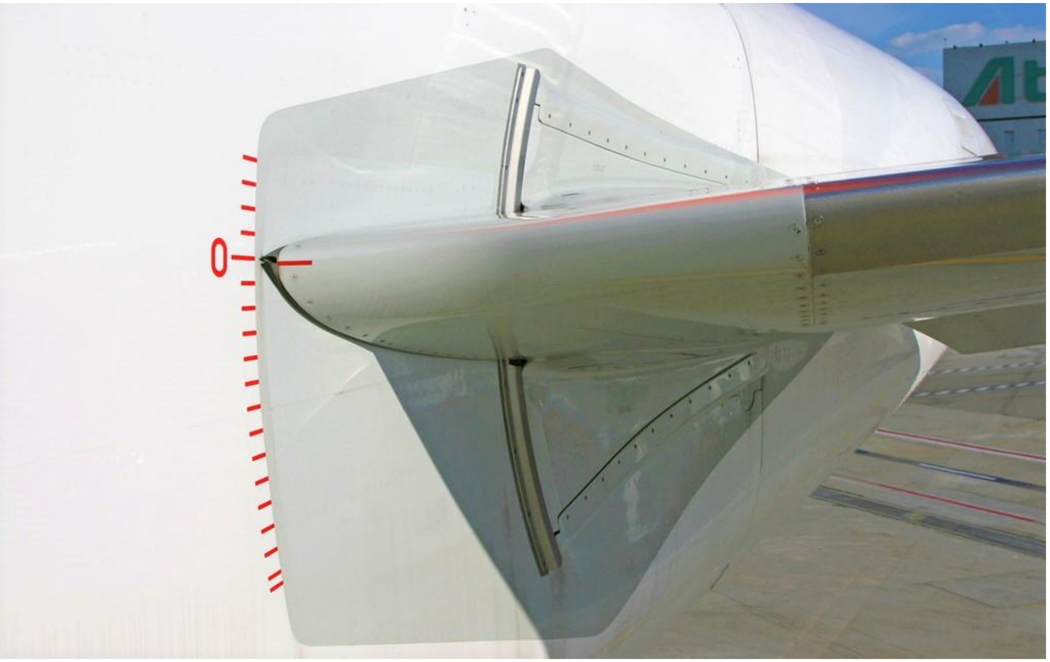
- FAR Requirements on Stability are comparatively vague by design
- MIL-F-8785C provides more useful numbers for requirements
  - Based on aircraft class (Transport, Fighter) and Flight Phase
- Roll Control in time to certain bank angle (Dependent on class)
- Pitch Control in takeoff rotation at Stall Speed in 3-5s at specified angular rate



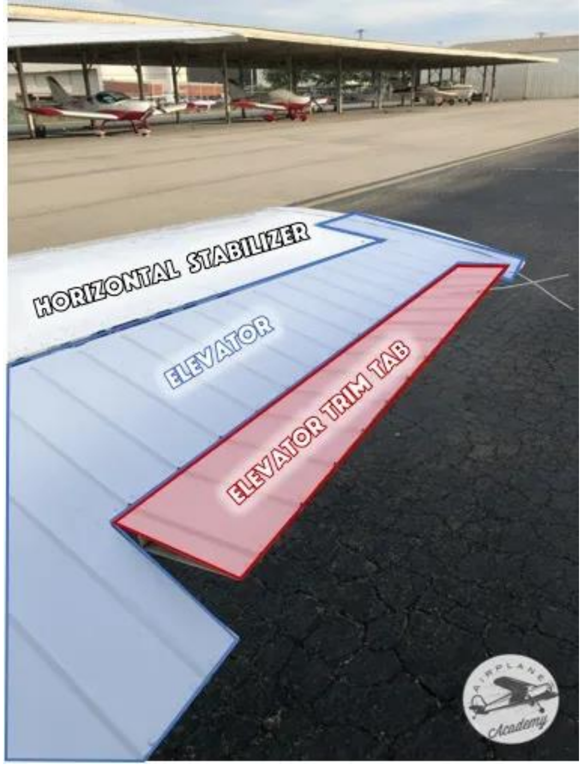
Dynamic Mode	MIL Stability Requirement
Phugoid	$\zeta_{ph} \geq 0.04$
Short Period	$0.3 \geq \zeta_{\mathrm{sp}} \leq 2.0$
Roll Subsidence	$\mathrm{T}_R \leq 1.4$
Spiral	$\mathrm{T}_{2s} \geq 20$
Dutch Roll	$\zeta_d \geq 0.08$

Aircraft Trim vs Control

- Separate systems for each or a single system that provides both?
  - Adjustable elevators, flaps, trim tabs
  - Define their respective regimes and ensure compatibility

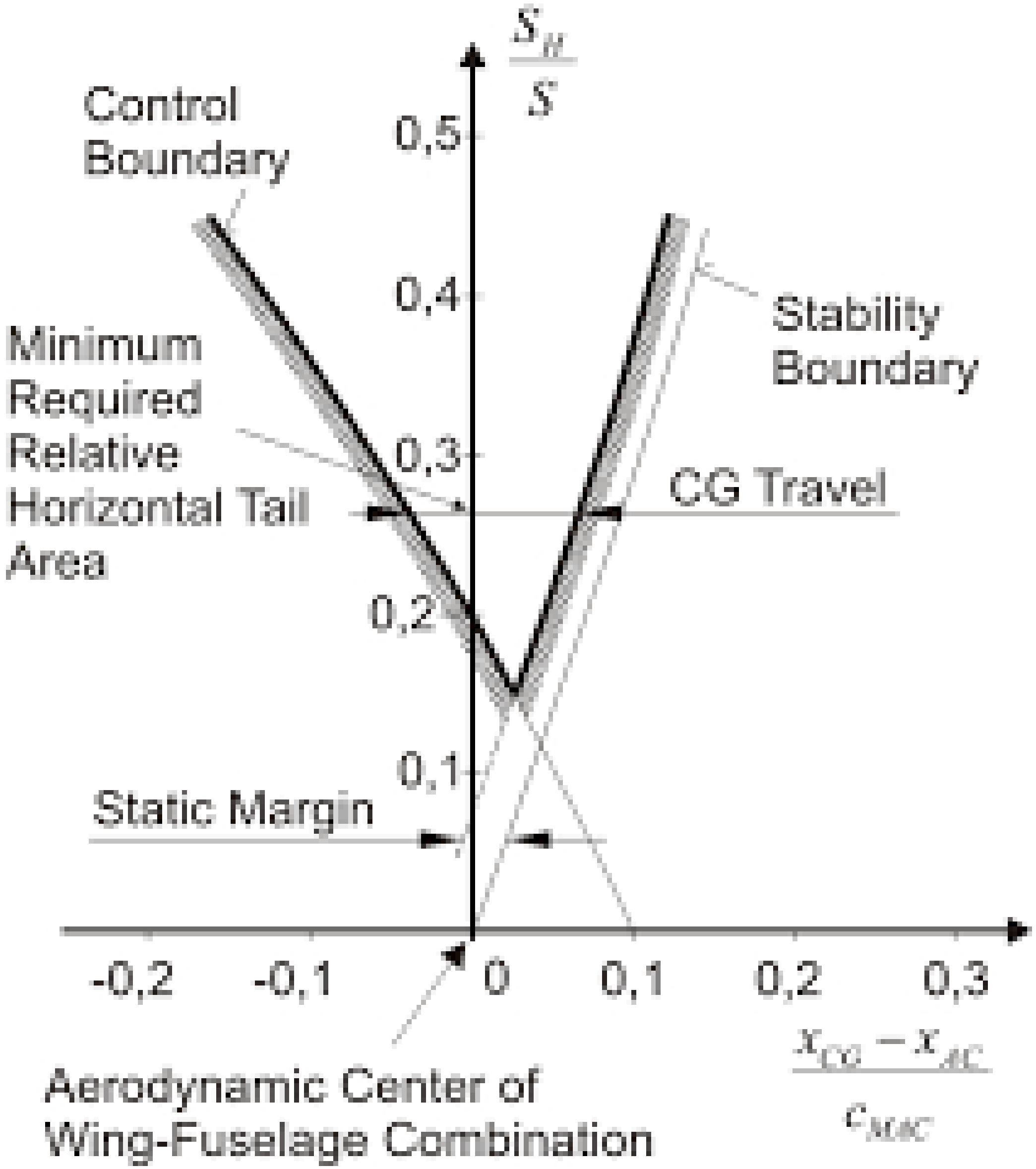


https://fl360aero.com/detail/aircraft-pitch-trim-system-how-does-a-stab-trim-or-trimmable-horizontal-stabilizer-work/276



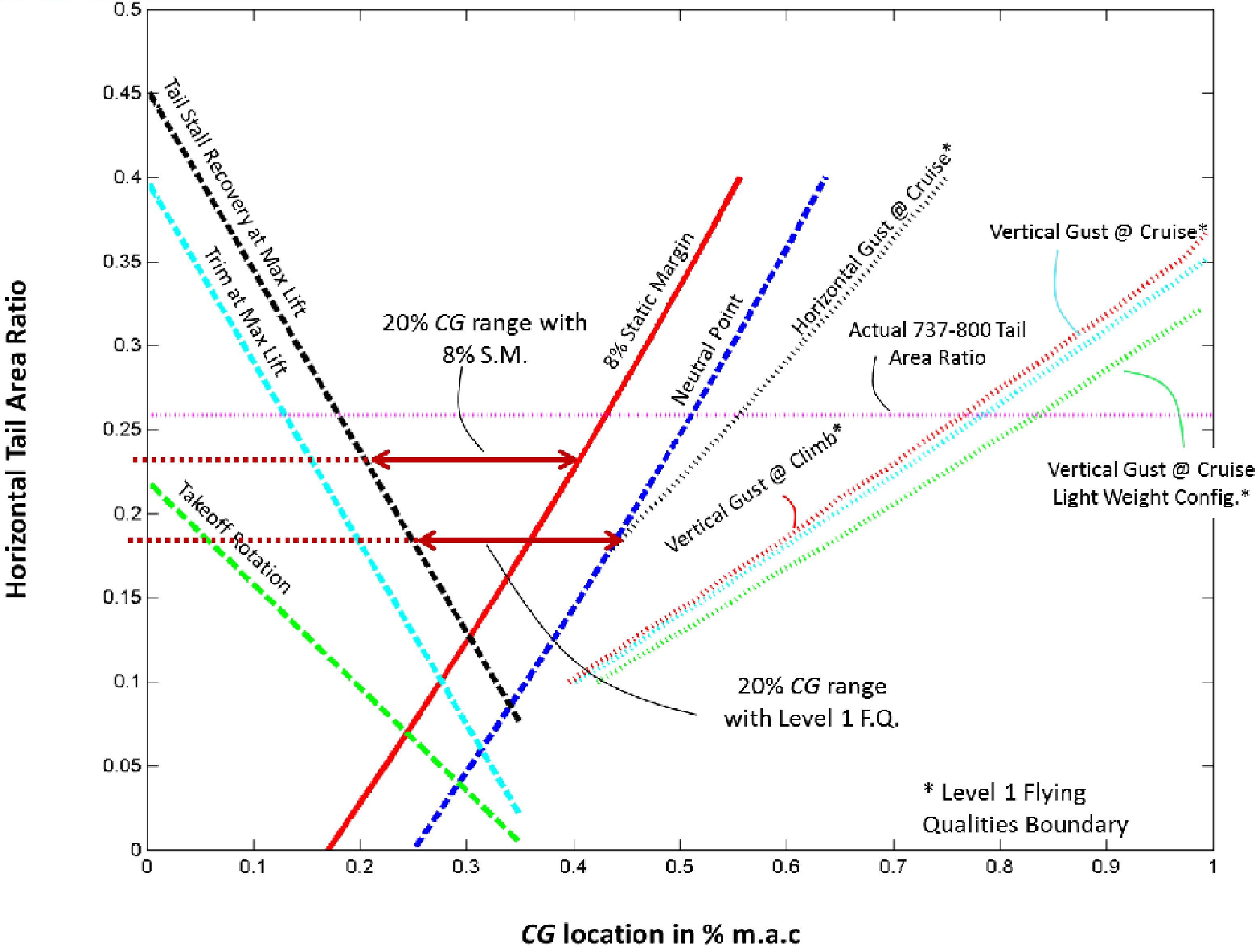
https://airplaneacademy.com/aircraft-trim-explained-with-pictures/

Scissor Plot (X-plot) Example



Source: https://www.fzt.haw-hamburg.de/pers/Scholz/HOOU/AircraftDesign_11_EmpennageSizing.pdf

Scissor Plot (X-plot) Example



Source: https://www.semanticscholar.org/paper/FLYING-QUALITIES-CONSTRAINTS-IN-THE-DESIGN-OF-A-Morris-Schetz/6eee07c8221cccdd2f3060f044c5b33a086e4e40/figure/6

Stability & Control

Recommended Reading for Topics in S&C

Topic	Recommended References
Stability & Control	
Static Stability and Control	Chapter 21, Nicolai & Carichner, Ref. AVD 1
Trim Drag and Maneuvering Flight	Chapter 22, Nicolai & Carichner, Ref. AVD 1
Control Surface Sizing Criteria	Chapter 23, Nicolai & Carichner, Ref. AVD 1
Stability, Control, and Handling Qualities	Chapter 16, Raymer, Ref. AVD 2
The Anatomy of the Tail	Chapter 11, Gudmundsson, Ref. AVD 4
Tail Design	Chapter 6, Sadraey, Ref. AVD 5
Design of Control Surfaces	Chapter 12, Sadraey, Ref. AVD 5
Stability Considerations Affecting Aircraft Configuration	Chapter 12, Kundu, Ref. AVD 8
Boeing S&C Course Notes and Empennage Design	*See Stabilty & Control folder in Supplemental Reference Material on course site*

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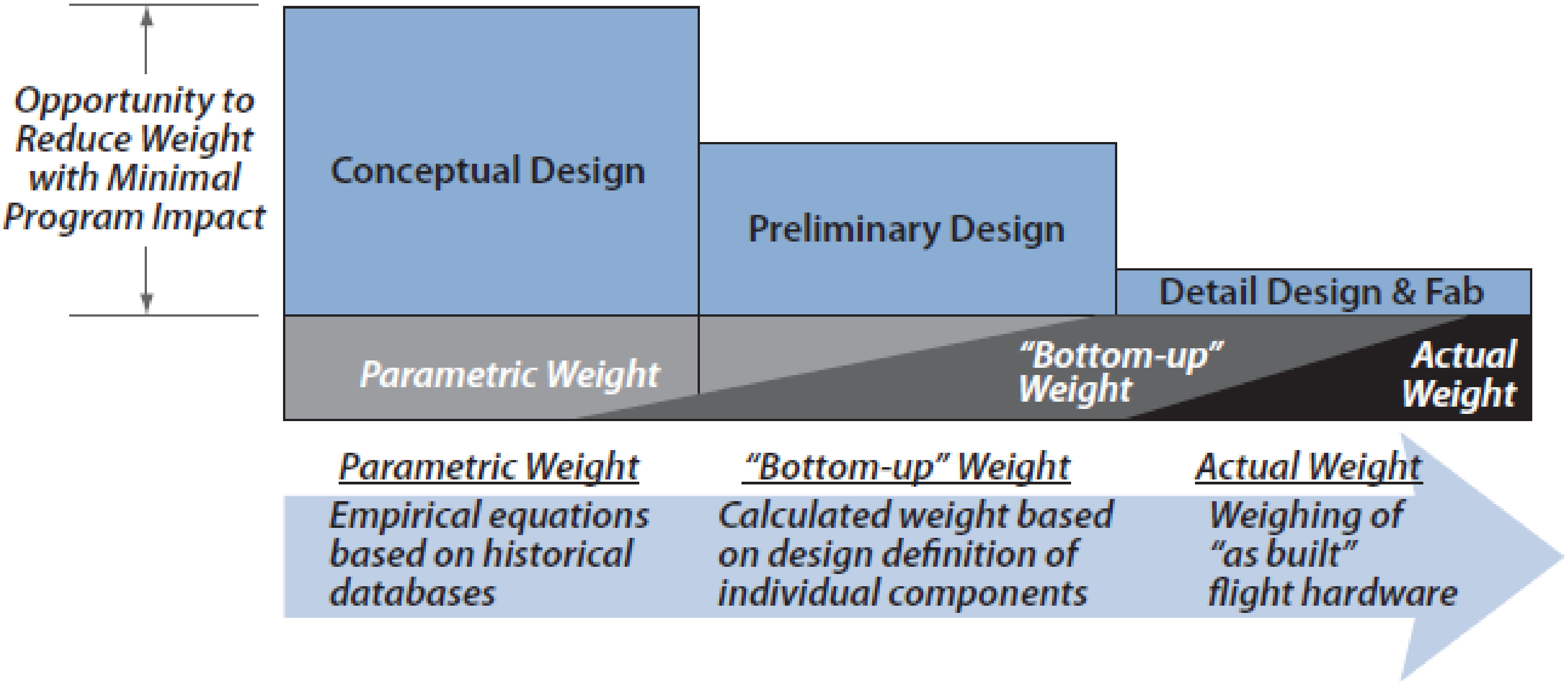
- **A10.9 Weights (Mass Properties) & Balance**
- A10.10 Cost & Manufacturing

A10.8 Weights (Mass Properties) & Balance

Weights & Balance subteam members should review their R&Rs, and any project data deliverables in the RFP

Weight Estimation Methods



Parametric Weight
Empirical equations based on historical databases

"Bottom-up" Weight
Calculated weight based on design definition of individual components

Actual Weight
Weighing of "as built" flight hardware

Source: Ch 19, Ref. AVD 1 (Nicolai & Carichner)

Final “Weight Statement”

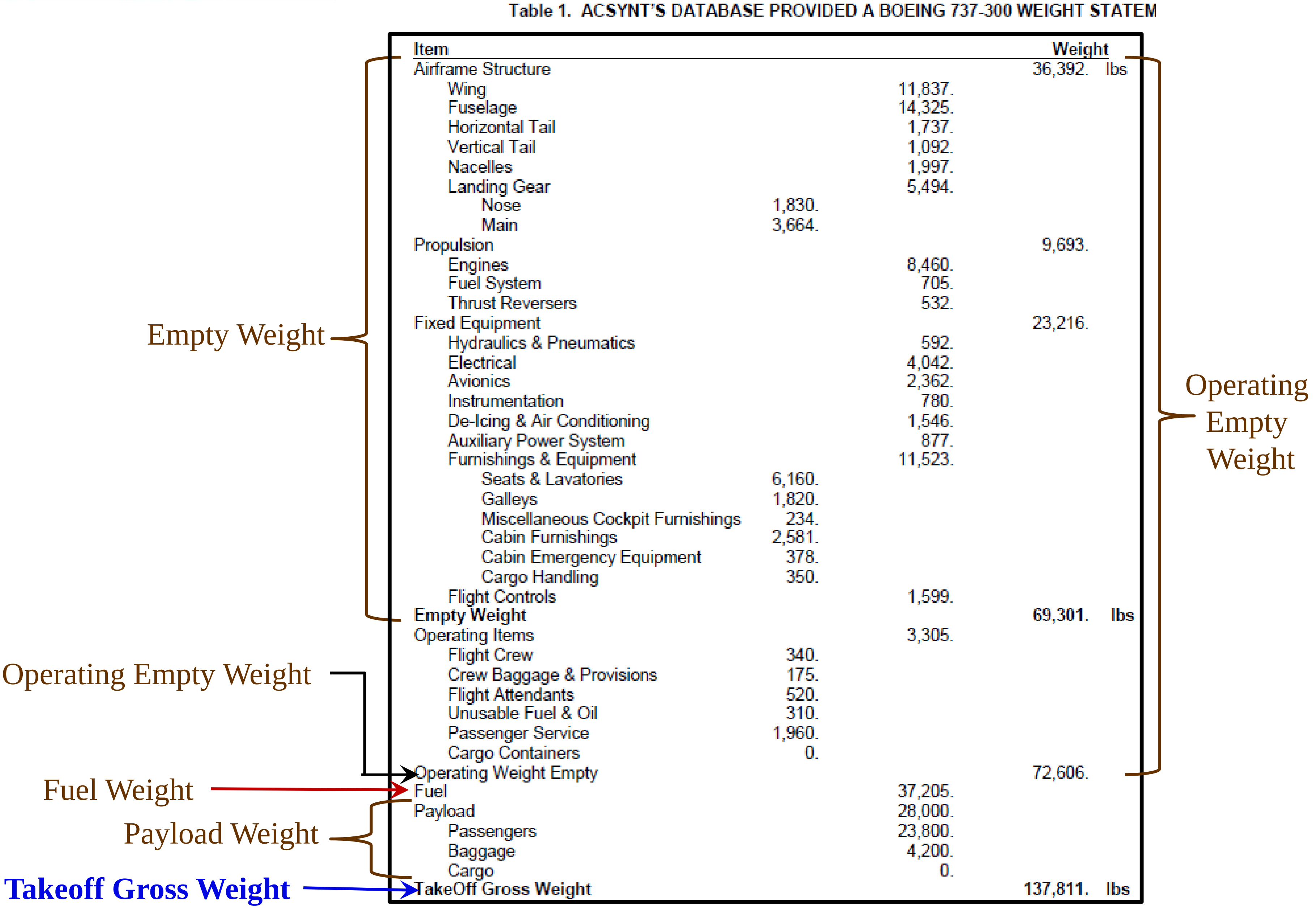
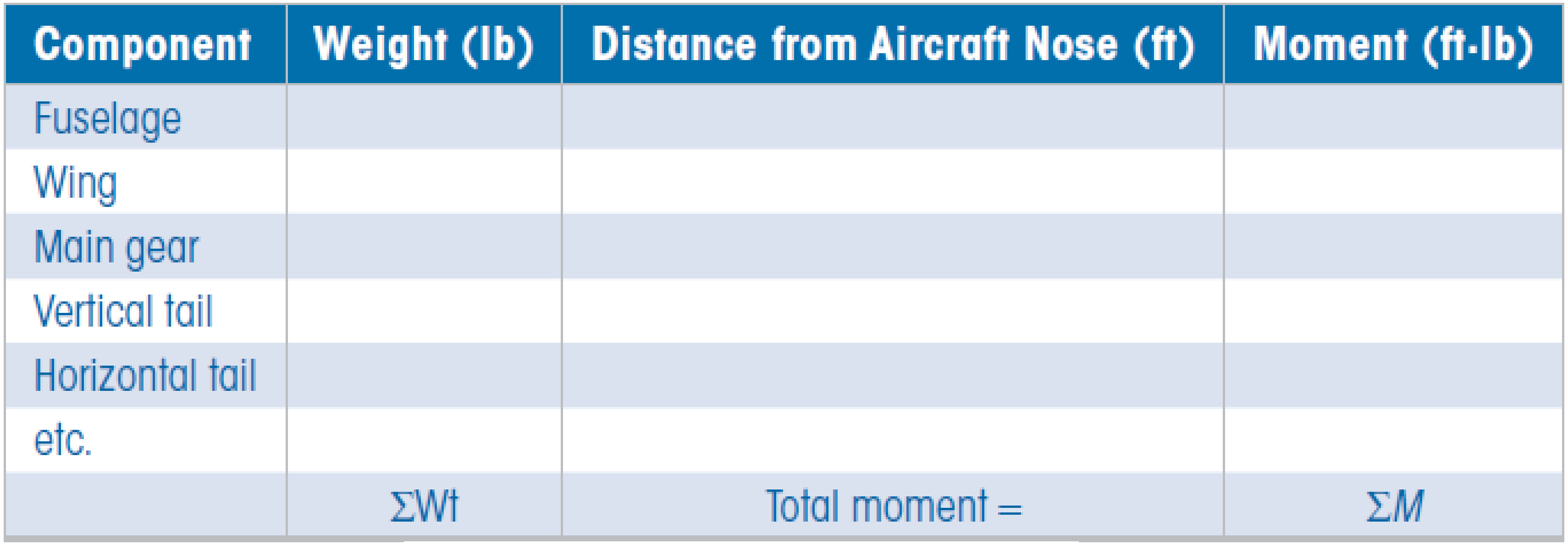


Table 1. ACSYNT'S DATABASE PROVIDED A BOEING 737-300 WEIGHT STATEM

Item			Weight	
Airframe Structure			36,392.	lbs
Wing		11,837.		
Fuselage		14,325.		
Horizontal Tail		1,737.		
Vertical Tail		1,092.		
Nacelles		1,997.		
Landing Gear		5,494.		
Nose	1,830.			
Main	3,664.			
Propulsion			9,693.	
Engines		8,460.		
Fuel System		705.		
Thrust Reversers		532.		
Fixed Equipment			23,216.	
Hydraulics & Pneumatics		592.		
Electrical		4,042.		
Avionics		2,362.		
Instrumentation		780.		
De-Icing & Air Conditioning		1,546.		
Auxiliary Power System		877.		
Furnishings & Equipment		11,523.		
Seats & Lavatories	6,160.			
Galleys	1,820.			
Miscellaneous Cockpit Furnishings	234.			
Cabin Furnishings	2,581.			
Cabin Emergency Equipment	378.			
Cargo Handling	350.			
Flight Controls		1,599.		
Empty Weight			**69,301.**	**lbs**
Operating Items		3,305.		
Flight Crew	340.			
Crew Baggage & Provisions	175.			
Flight Attendants	520.			
Unusable Fuel & Oil	310.			
Passenger Service	1,960.			
Cargo Containers	0.			
Operating Weight Empty			72,606.	
Fuel		37,205.		
Payload		28,000.		
Passengers		23,800.		
Baggage		4,200.		
Cargo		0.		
TakeOff Gross Weight			**137,811.**	**lbs**

Weight & Moment Summary

Table 20.1 Weight and Moment Summary



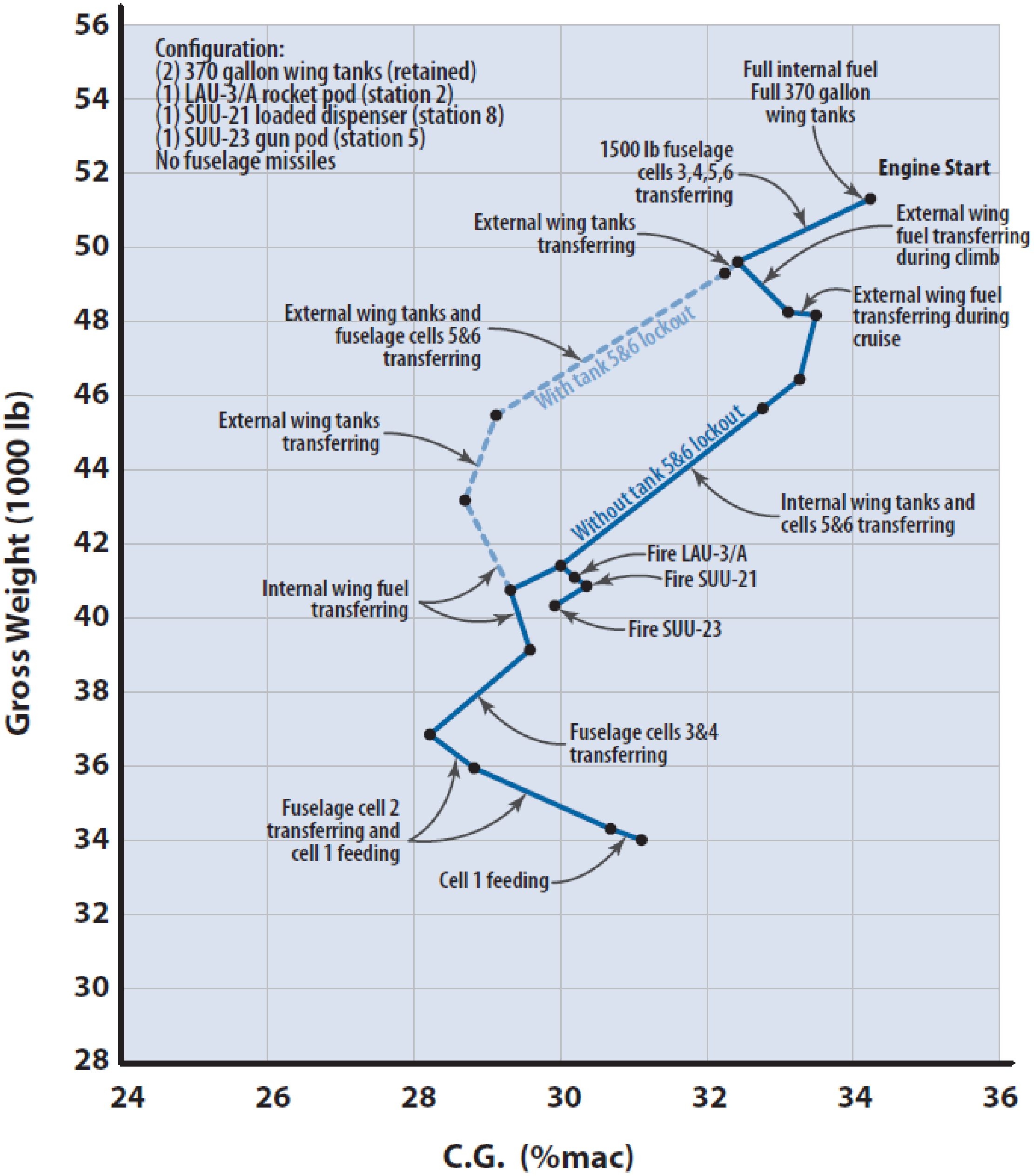
Component	Weight (lb)	Distance from Aircraft Nose (ft)	Moment (ft-lb)
Fuselage			
Wing			
Main gear			
Vertical tail			
Horizontal tail			
etc.			
	ΣWt	Total moment =	Σ*M*

$$X_{c.g.} = \text{Total Moment}/\Sigma\text{Wt}$$

- **C.G. location reported as distance from the nose and % MAC**
- **Determine C.G. location for full and empty aircraft and report as most forward and most aft locations**

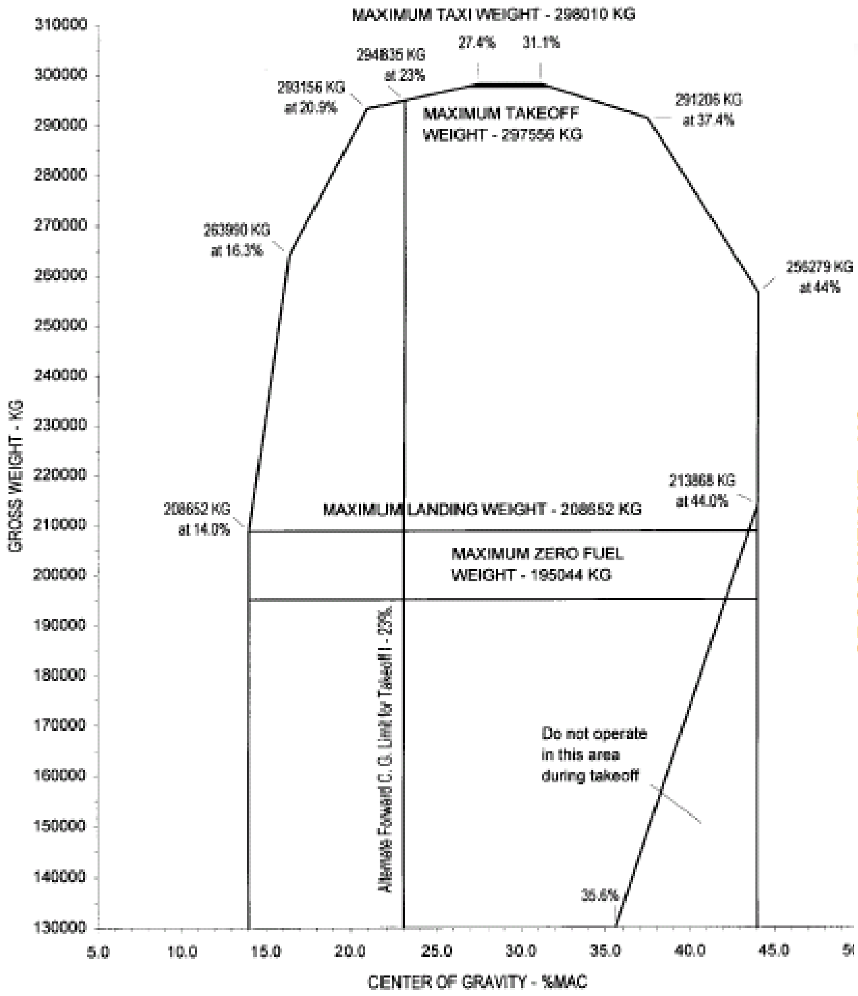
Source: Chapter 20, AVD 1 (Nicolai & Carichner)

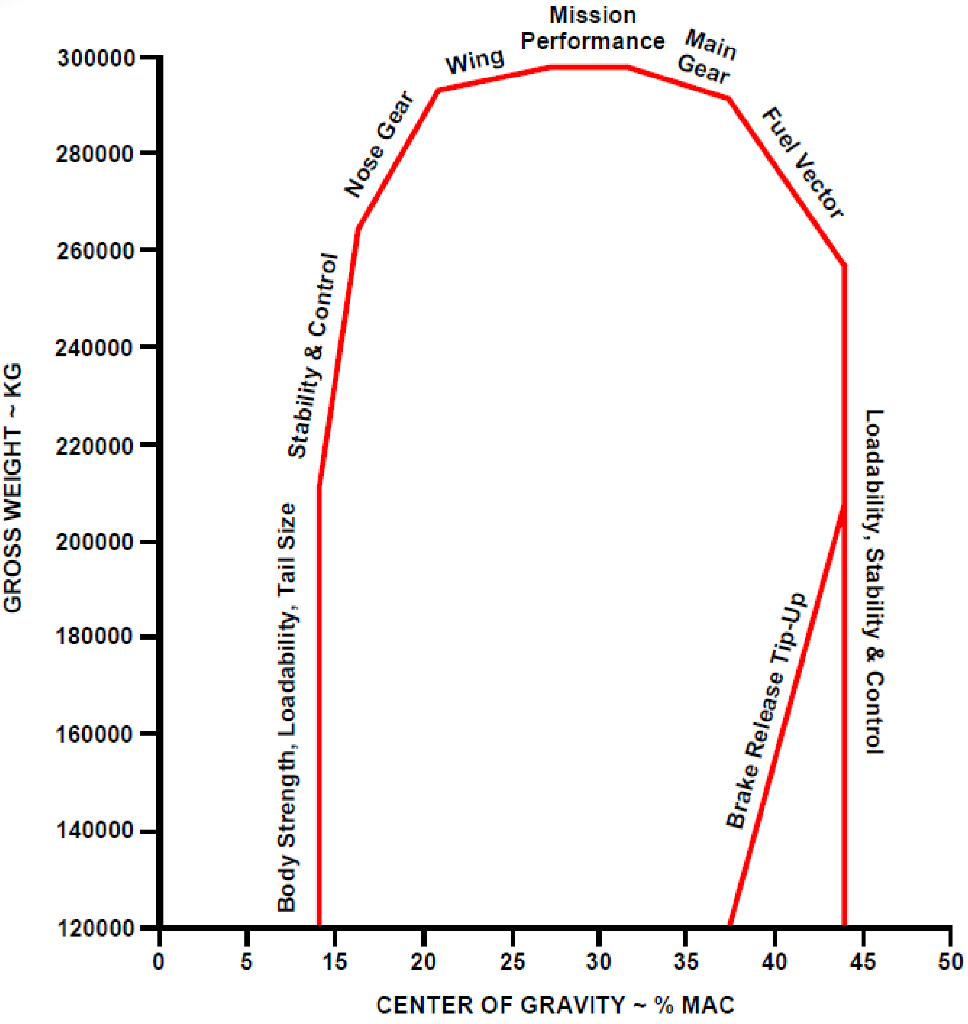
C.G. Travel Example (F-4D)



Source: Fig. 23.2, Chapter 23, AVD 1 (Nicolai & Carichner)

Boeing 777 C.G. Limits





Weights & Balance

Recommended Reading for Topics in Weights & Balance

Topic	Recommended References
Weights & Balance	
Refined Weight Estimate	Chapter 20, Nicolai & Carichner, Ref. AVD 1
Weights	Chapter 15, Raymer, Ref. AVD 2
Weight Control and Balance	Chapter 16, Niu, Ref. AS 1
Aircraft Weight and Center of Gravity Estimation	Chapter 8, Kundu, Ref. AVD 8
Aircraft Weight Analysis	Chapter 6, Gudmundsson, Ref. AVD 4
Weight of Components	Chapter 10, Sadraey, Ref. AVD 5
Aircraft Weight Distribution	Chapter 11, Sadraey, Ref. 9 in PR
CG Limits and Weights & Balance	*See Weights & Balance folder in Supplemental Reference Material on course site*

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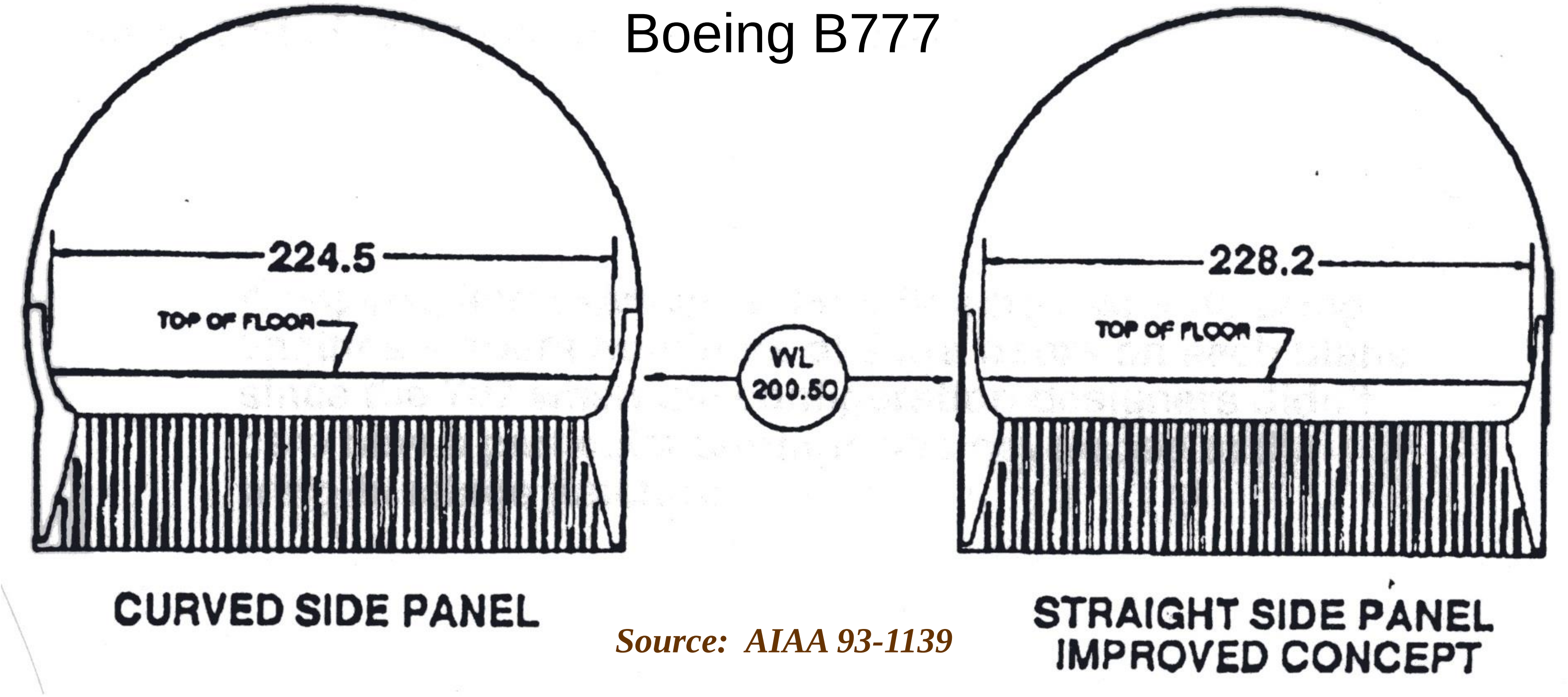
A10.10 Cost & Manufacturing

Cost & Manufacturing subteam members should review their R&Rs, and any project data deliverables in the RFP

Cost & Manufacturing

- **Cost estimation: The Critical Area—Start Early!**
  - *All Team members should factor in cost considerations of their assigned area into every decision*
  - *See CM A6*
- **Manufacturing planning**



Boeing B777

Source: AIAA 93-1139

Cost & Manufacturing

Recommended Reading for Topics in Cost & Manufacturing

Topic	Recommended References
Cost & Manufacturing	
Life Cycle Cost	Chapter 24, Nicolai & Carichner, Ref. 1 in PR
Cost Analysis	Chapter 18, Raymer, Ref. 2 in PR
Aircraft Cost Analysis	Chapter 2, Gudmundsson, Ref. 10 in PR
Aircraft Cost Considerations	Chapter 16, Kundu, Ref. 8 in PR
Design for Manufacturing	Chapter 2, Niu, Ref. 24 in PR
Composite Manufacturing	Chapters 3 & 4, Niu, Ref. 25 in PR
Aircraft Manufacturing Considerations	Chapter 17, Kundu, Ref. 8 in PR
Cost Estimation & Manufacturing Consideerations	*See Cost and Manufacturing folders in Supplemental Reference Material on course site*