Air Vehicle Design

AOE 4065 – 4066

II. Air Vehicle Design Fundamentals

Course Module A7

Concept to Configuration: *Key Considerations*

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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.

<u>CRUCIALLY IMPORTANT</u>

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 <u>Appendix</u> in the Overview CM)

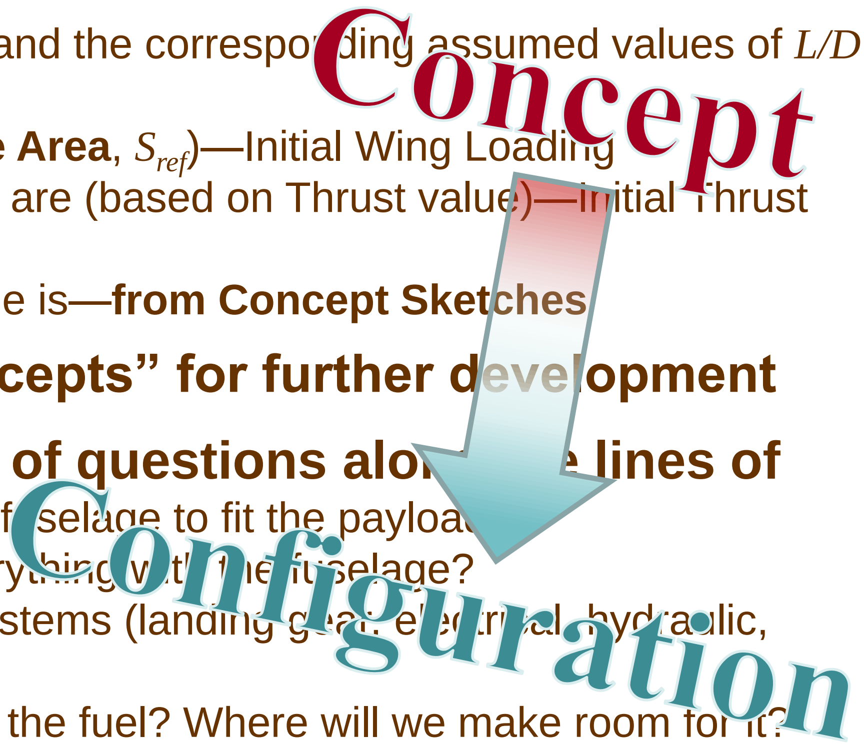
Outline

A7.0 Key Considerations for Configuration Layout

- A7.1 “Concept to Configuration”
- A7.2 Fuselage
- A7.3 Wing
- A7.4 Empennage
- A7.5 Propulsion
- A7.6 Landing Gear
- A7.7 Materials & Structures

“Concept to Configuration”

- **Having completed Initial Sizing of a concept, we know**
  - What the **payload** is (from customer requirements)
  - How heavy the airplane is - Initial **TOGW** along with **empty weight**, **fuel weight**, and **fixed weight**
  - How many phases the **mission** has, and the corresponding assumed values of L/D, speeds, sfc, etc.
  - How big the wing is (**Wing Reference Area**, S_{ref})—Initial Wing Loading
  - How many, and how big, the **engines** are (based on Thrust value)—Initial Thrust Loading
  - What the general shape of the airplane is—**from Concept Sketches**
- **We then select a few “good concepts” for further development**
- **The next step is to answer a set of questions along the lines of**
  - What shape and size are best for the fuselage to fit the payload?
  - What is the best way to integrate everything with the fuselage?
    - ○ Where should the needed subsystems (landing gear, electrical, hydraulic, avionics, etc.) be located?
    - ○ How much volume will it take for the fuel? Where will we make room for it?
    - ○ Where on the fuselage will we locate the wing, engines, empennage (if any)?
  - What is the wing shape (planform, sweep, aspect ratio, thickness, camber, etc.)?
    - ○ What type of high-lift systems we need to generate required L/D for takeoff?

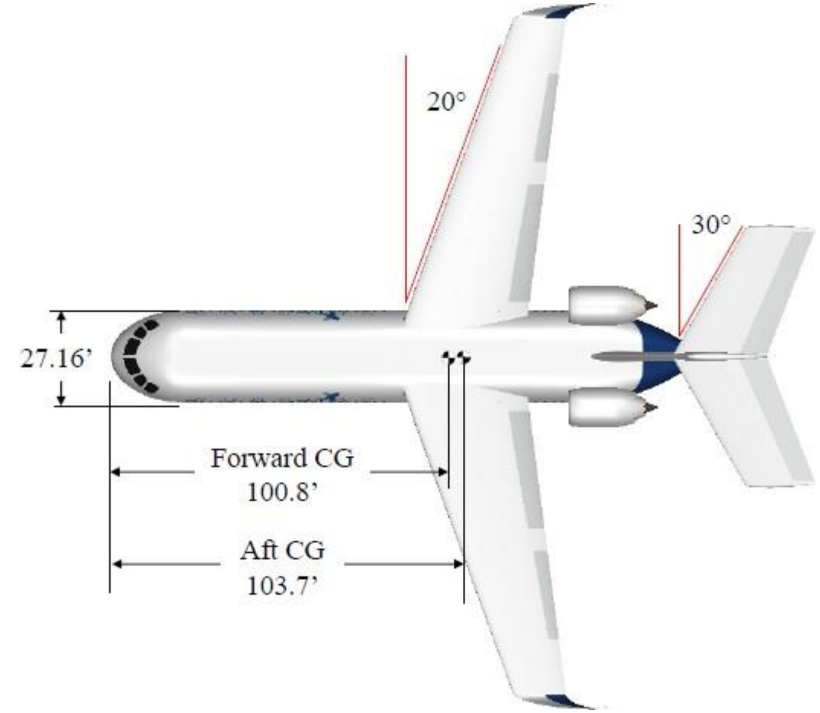


Now, The “Real Work” Begins to Finalize the OML!

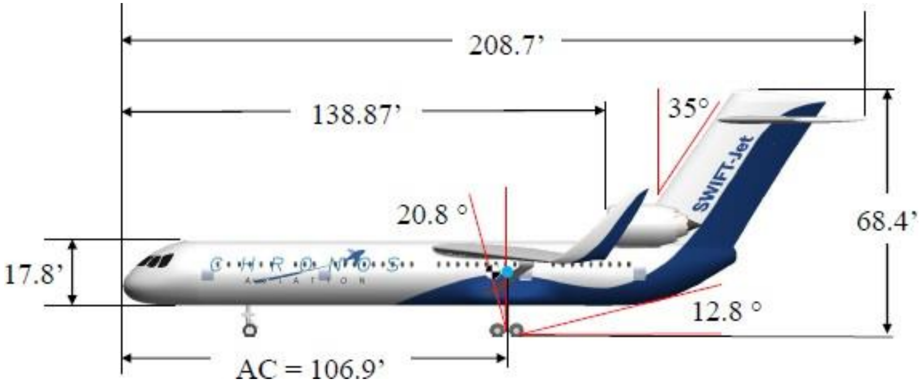
Configuration Layout Team Uses CAD to Integrate Inputs from Various Sub-teams to Generate Dimensioned Drawings of Configuration OML and Inboard Profile!

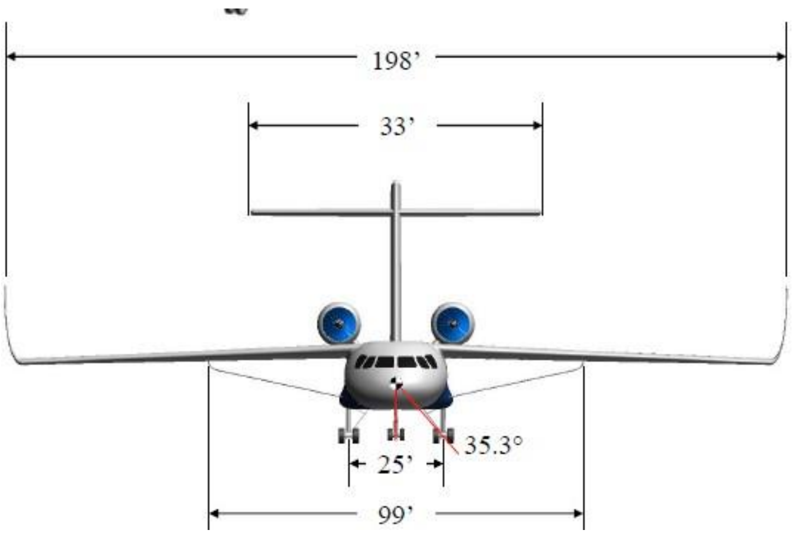
Final Configuration Layout:

A Student Team Design 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



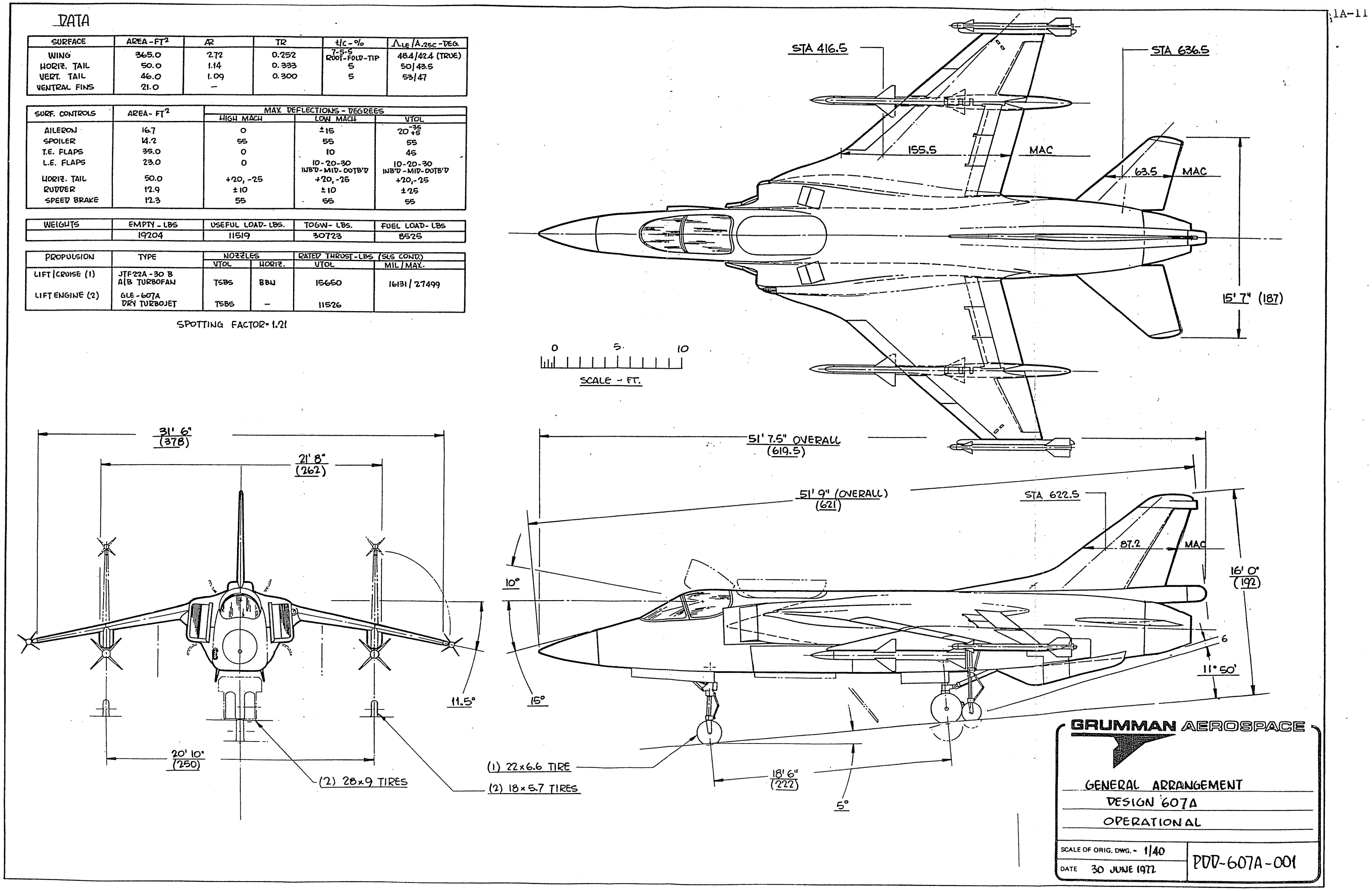


Source: 2020 VT Swift-Jet (AIAA Undergrad Team Aircraft Design)

Three-view (or 3-vu) Drawings:

Standard for Depicting Configuration Layout

Common Standard Language of Designers for Communication with everyone



DATA

SURFACE	AREA - FT²	AR	TR	t/c - %	$\Lambda_{LE}/\Lambda_{.25c}$ - DEG
WING	365.0	2.72	0.252	7-5-5 ROOT-FOLD-TIP	48.4/42.4 (TRUE)
HORIZ. TAIL	50.0	1.14	0.333	5	50/43.5
VERT. TAIL	46.0	1.09	0.300	5	53/47
VENTRAL FINS	21.0	—			

SURF. CONTROLS	AREA - FT²	MAX. DEFLECTIONS - DEGREES		
		HIGH MACH	LOW MACH	VTOL
AILERON	16.7	0	±15	20^{-35}_{+5}
SPOILER	14.2	55	55	55
T.E. FLAPS	35.0	0	10	45
L.E. FLAPS	23.0	0	10-20-30 INB'D-MID-OUTB'D	10-20-30 INB'D-MID-OUTB'D
HORIZ. TAIL	50.0	+20, -25	+20, -25	+20, -25
RUDDER	12.9	±10	±10	±25
SPEED BRAKE	12.3	55	55	55

WEIGHTS	EMPTY - LBS	USEFUL LOAD - LBS.	TOGW - LBS.	FUEL LOAD - LBS
	19204	11519	30723	8525

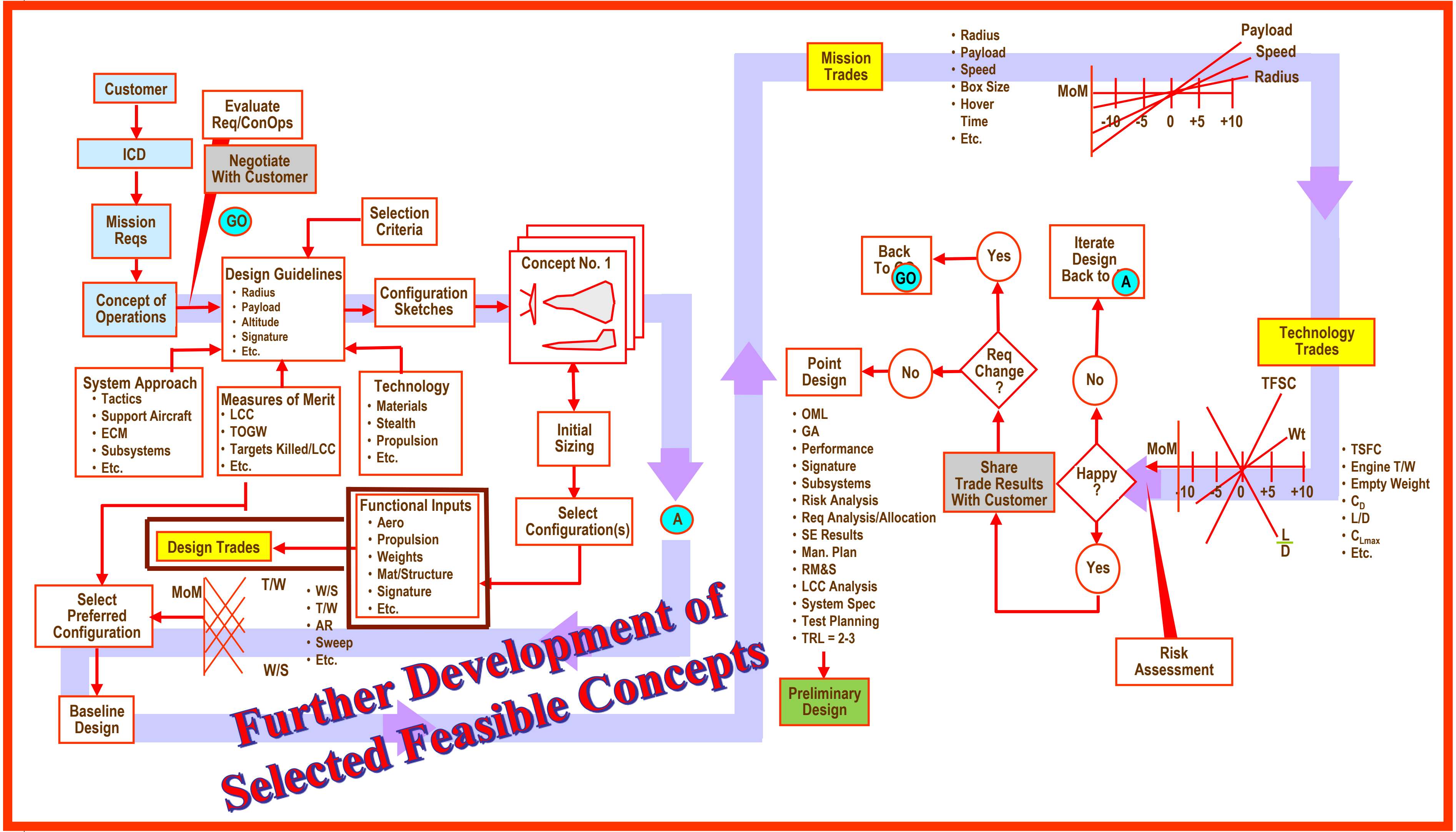
PROPULSION	TYPE	NOZZLES		RATED THRUST - LBS (SLS COND.)	
		VTOL	HORIZ.	VTOL	MIL/MAX.
LIFT/CRUISE (1)	JTF22A-30 B A/B TURBOFAN	TSBS	BBN	15650	16131/27499
LIFT ENGINE (2)	GLE-607A DRY TURBOJET	TSBS	—	11526	

SPOTTING FACTOR = 1.21

Figure 1A-1. Three View - Grumman Design 607A, Lift+Lift/Cruise VSTOL Navy Fighter

Source: Figure 1A-1, Ref. AVD 6 (Kirschbaum and Mason)

Aircraft Conceptual Design (CD) Process



Customer

ICD

Mission Reqs

Concept of Operations

Evaluate Req/ConOps

Negotiate With Customer

GO

Selection Criteria

Design Guidelines
- Radius
- Payload
- Altitude
- Signature
- Etc.

Configuration Sketches

Concept No. 1

System Approach
- Tactics
- Support Aircraft
- ECM
- Subsystems
- Etc.

Measures of Merit
- LCC
- TOGW
- Targets Killed/LCC
- Etc.

Technology
- Materials
- Stealth
- Propulsion
- Etc.

Initial Sizing

Select Configuration(s)

A

Functional Inputs
- Aero
- Propulsion
- Weights
- Mat/Structure
- Signature
- Etc.

Design Trades

MoM

T/W

W/S

- W/S
- T/W
- AR
- Sweep
- Etc.

Select Preferred Configuration

Baseline Design

Further Development of Selected Feasible Concepts

Mission Trades

- Radius
- Payload
- Speed
- Box Size
- Hover Time
- Etc.

MoM

-10 -5 0 +5 +10

Payload

Speed

Radius

Back To GO

Yes

Iterate Design Back to A

Point Design

No

Req Change ?

No

- OML
- GA
- Performance
- Signature
- Subsystems
- Risk Analysis
- Req Analysis/Allocation
- SE Results
- Man. Plan
- RM&S
- LCC Analysis
- System Spec
- Test Planning
- TRL = 2-3

Preliminary Design

Share Trade Results With Customer

Happy ?

Yes

Risk Assessment

Technology Trades

TFSC

Wt

MoM

-10 -5 0 +5 +10

$\frac{L}{D}$

- TSFC
- Engine T/W
- Empty Weight
- C_D
- L/D
- C_{Lmax}
- Etc.

Courtesy of Lee Nicolai

Configuration Features to Consider

- **Fuselage size and shape** (fineness ratio, cross-sectional area distribution, basic structural layout, etc.)
- **Wing size, shape and location** (span, sweep, AR, taper ratio, basic structural layout, etc.)
- **High-lift devices** (mechanical vs. powered)
- **Empennage type and size** (aft tail, canard, tailless, etc.)
- **Static stability level** (static margin in %MAC for degree of stability)
- **Propulsion system** (turboprop, turbofan, turbojet, all-electric, or hybrid electric; number of engines; podded or buried, etc.)
- **Inlet and nozzle** (location and type)
- **Landing gear type & location** (tricycle, bicycle, tail dragger, etc.)
- **Subsystems** (avionics, environmental control system, flight control system, thermal management system, fuel system, etc.)
- **Materials** (metals or composites or both)
- **Etc.**

Each subteam needs to make many decisions!

Design Trades
(aka Configuration Trades)

What would be the impact on MoMs if configuration features were changed?

For Example:

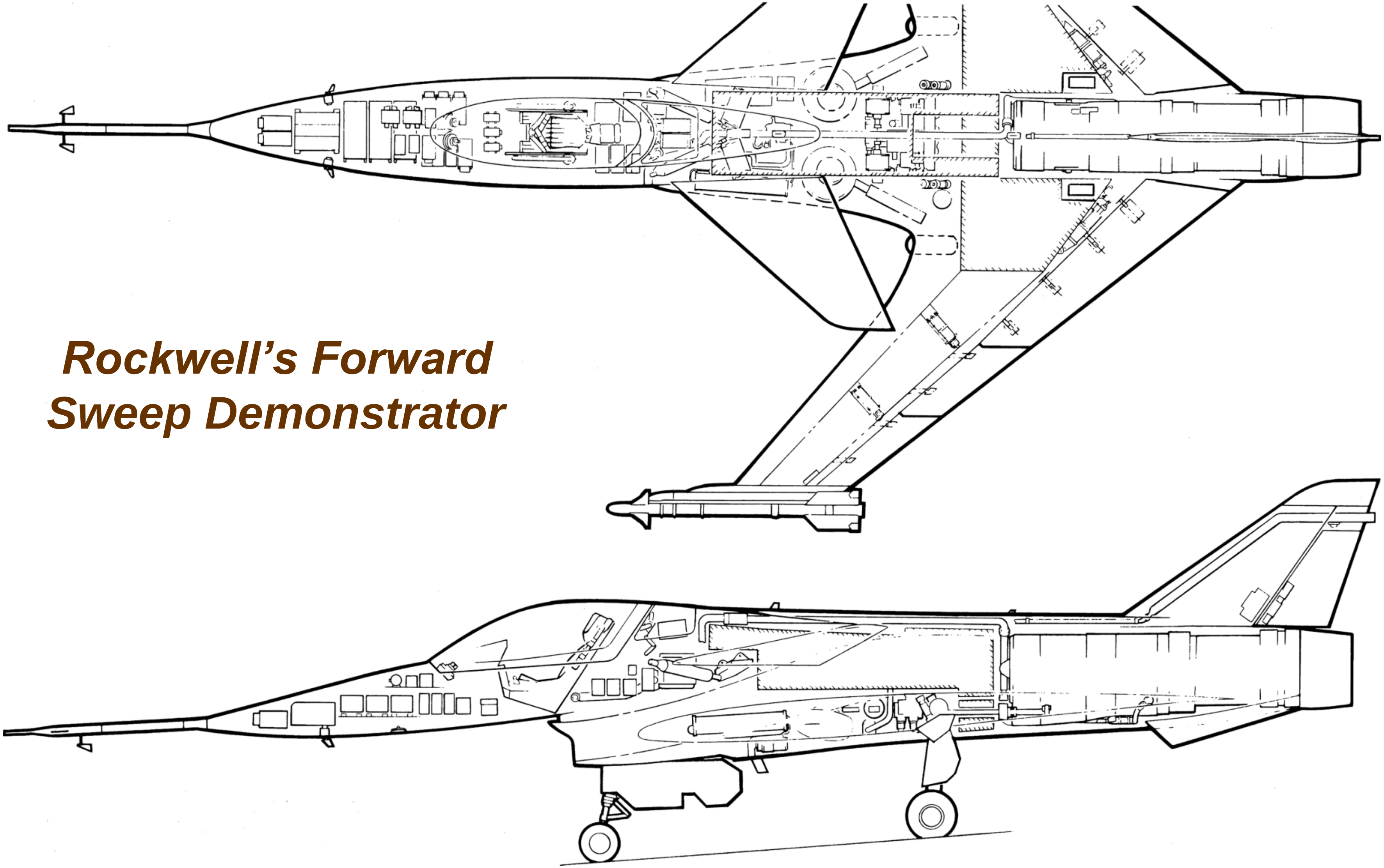
- Wing size (W/S) and shape (AR, Λ, λ, etc.): *effect on lift, drag, and wing weight*
- High-lift devices (mech. vs. powered): *effect on takeoff & landing performance*
- Fuselage size and shape (fineness ratio, cross-sectional area distribution, etc.): *effect on payload capacity, fuselage weight, and drag*
- Tail configuration (aft tail vs. canard vs. tailless): *effect on S&C characteristics and trim drag*
- Control Surfaces (elevators, flaps, ailerons): *effect on maneuvering performance*
- Engine (turboprop, turbofan, turbojet, all-electric, hybrid electric; number of engines; podded or buried, etc.) *effect on fuel/energy consumption, emissions, noise, maintenance, etc.*
- Inlet and nozzle integration (location, type): *effect on propulsive efficiency*
- Materials (metals or composites): *effect on weight, fatigue life, etc.*
- …

Design Trades facilitate selection of the right design features for the most efficient vehicle configuration to meet MoMs

Interior Arrangement (*aka Inboard Profile*)

- **Used to locate internal equipment to satisfy equipment fit, accessibility, and volumetric requirement (fuel, passengers, cargo, avionics, weapons systems, etc.)**
- **Essentially employs two of three views: side & top view and includes cross sectional cuts**
  - See Figs. 1A-4 and 1A-5 in Ref. AVD 6 (Kirschbaum and Mason) in the list of Primary References
- ***Cross sections* taken at critical areas of layout; for example**
  - Radar dish envelope (for clearance requirements)
  - Pilot's eye (for vision requirements)
  - Jet engine inlet (establish inlet capture area, boundary layer bypass shape)

Typical Inboard Profile Drawing to Show Interior Arrangement

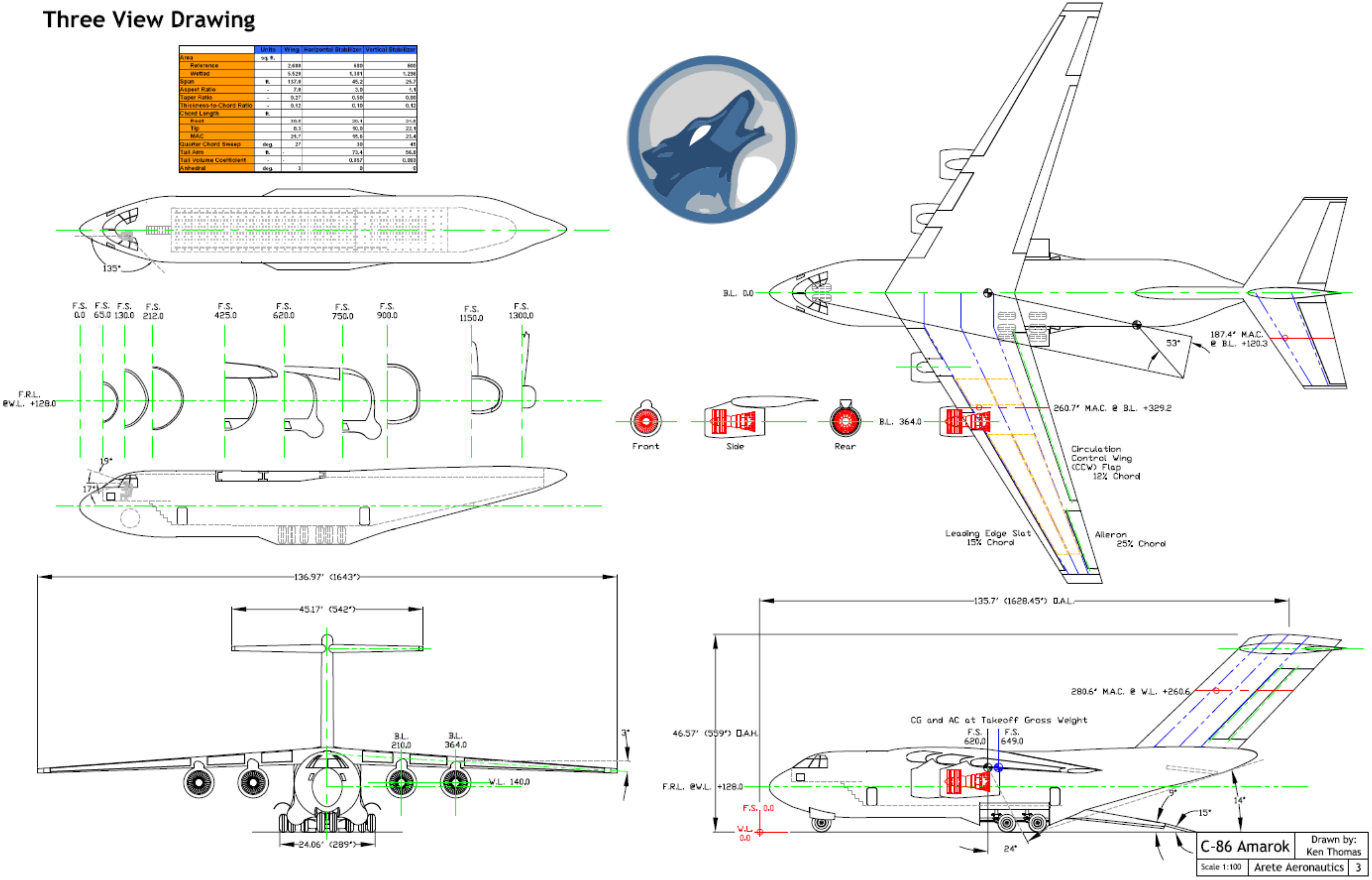


Rockwell's Forward Sweep Demonstrator

Source: Figure 7.6, Ref. AVD 2 (Raymer)

Final Configuration Example to Emulate

2007 Cal Poly SLO Student Team Project



Three View Drawing

	Units	Wing	Horizontal Stabilizer	Vertical Stabilizer
Area	sq. ft.			
Reference		2,680	680	600
Wetted		5,529	1,381	1,238
Span	ft.	137.0	45.2	25.7
Aspect Ratio	-	7.0	3.0	1.1
Taper Ratio	-	0.27	0.50	0.80
Thickness-to-Chord Ratio	-	0.12	0.10	0.12
Chord Length	ft.			
Root		30.8	[illegible]	[illegible]
Tip		8.3	10.0	22.1
MAC		21.7	15.6	23.4
Quarter Chord Sweep	deg.	27	30	45
Tail Arm	ft.	-	73.4	56.8
Tail Volume Coefficient	-	-	0.857	0.083
Anhedral	deg.	3	0	0

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

Outline

A7.0 Key Considerations for Configuration Layout

A7.1 “Concept to Configuration”

A7.2 Fuselage

A7.3 Wing

A7.4 Empennage

A7.5 Propulsion

A7.6 Landing Gear

A7.7 Materials & Structures

Fuselage

Shape and size dictated by the "Stuff" that needs to be "Packaged"

- ***Payload***
  - *Passengers*
  - *Cargo*
    - *Luggage + Revenue Cargo*
    - *Flat pellets*
  - *Crew Compartment*
- ***Subsystems***
  - *Fuel*
  - *Landing Gear*
  - *Avionics System*
  - *Power System*
  - *Hydraulic or Pneumatic or Electrical Actuation Systems*
  - *Environmental Control Systems*
- ***Other***
  - *Wing Carry Through*
  - *Armament*

How do we get an initial estimate of size (volume) and shape (length and cross section) of the fuselage?

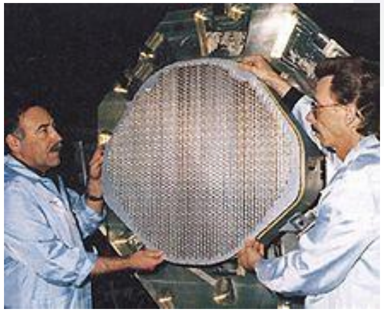


Image Source: Internet

Fuselage Sizing

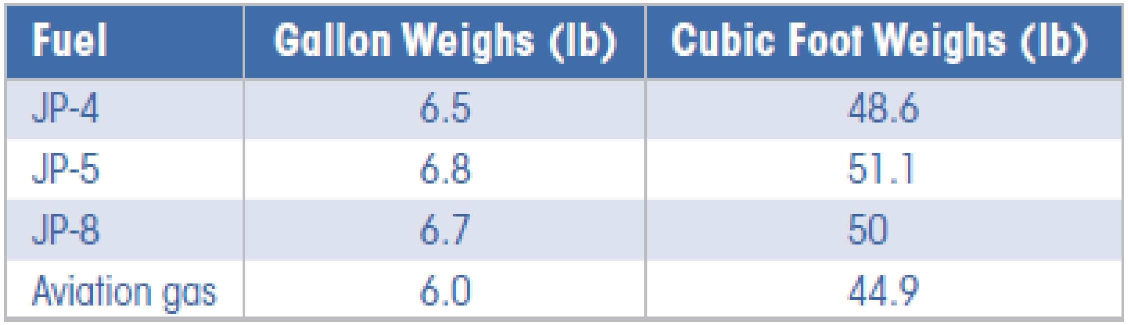
Let’s start with estimating volumes and weights of the “stuff” to be packaged into the fuselage

- **We typically know, or can relatively easily estimate, payload related weights and volumes**
- **We also know fuel weight (from initial sizing) and we should be able to estimate fuel volume**
- ***But we haven’t chosen most of the subsystems “stuff” yet, have we?***
- **Examples of subsystems include**
  - **Fuel system; landing gear; electrical system; air conditioning and anti-icing or deicing systems; avionics; to name a few**
- **We can’t get started without SWaP (size, weight and power) estimates of various subsystems!**
- **What should we do?**

We Resort to Parametric Relationships!

Fuel Tank Volume Estimation

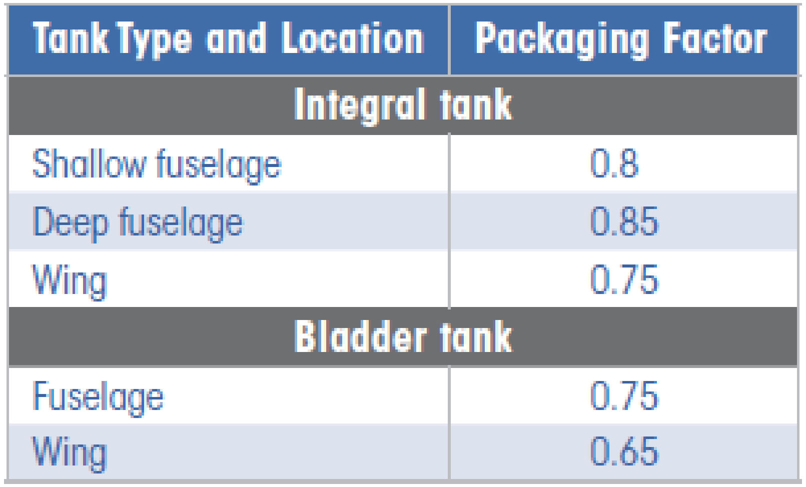
1. **Estimate <u>fuel volume</u> using fuel densities based on estimated fuel weight from Initial Weight Sizing**



Fuel	Gallon Weighs (lb)	Cubic Foot Weighs (lb)
JP-4	6.5	48.6
JP-5	6.8	51.1
JP-8	6.7	50
Aviation gas	6.0	44.9

2. **Estimate <u>fuel tank volume</u> using 'packaging factor' to account for structure, pumps, baffles, fuel lines, etc.**

Tank Volume = (Fuel Volume)/(Packaging Factor)



Tank Type and Location	Packaging Factor
Integral tank	
Shallow fuselage	0.8
Deep fuselage	0.85
Wing	0.75
Bladder tank	
Fuselage	0.75
Wing	0.65

Source: Section 8.1.10, Ref. AVD 1 (Nicolai & Carichner)

Subsystems Weight Estimation

Let’s illustrate for a Conventional Metal Aircraft—Moderate Subsonic to Supersonic Performance (*See reference books for other types of aircraft*)

- **Fuel System (weight in pounds)**

Self-Sealing Bladder Cells:

$$\mathrm{Wt} = 41.6\left[\left(F_{\mathrm{GW}} + F_{\mathrm{GF}}\right)\times 10^{-2}\right]^{0.818} \qquad (20.16)$$

where F_{GW} = total wing fuel in gallons and F_{GF} = total fuselage fuel in gallons.

- **Landing Gear (weight in pounds)**

USAF and Commercial:

$$\mathrm{Wt} = 62.21\left(W_{\mathrm{TO}}\times 10^{-3}\right)^{0.84} \qquad (20.6)$$

USN:

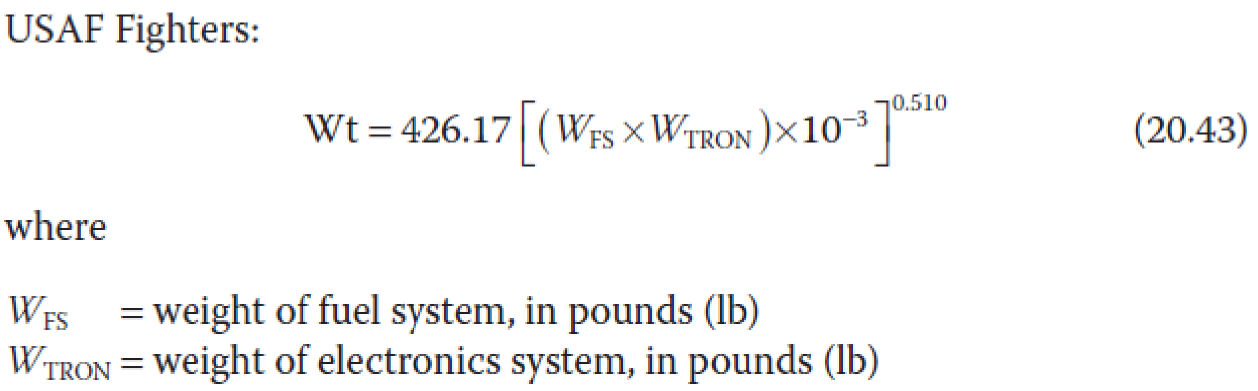
$$\mathrm{Wt} = 129.1\left(W_{\mathrm{TO}}\times 10^{-3}\right)^{0.66} \qquad (20.7)$$

Source: Section 8.1.10, Ref. AVD 1 (Nicolai & Carichner)

Subsystems Weight Estimation (contd.)

Let’s illustrate for a Conventional Metal Aircraft—Moderate Subsonic to Supersonic Performance (*See reference books for other types of aircraft*)

- **Electrical System (weight in pounds)**



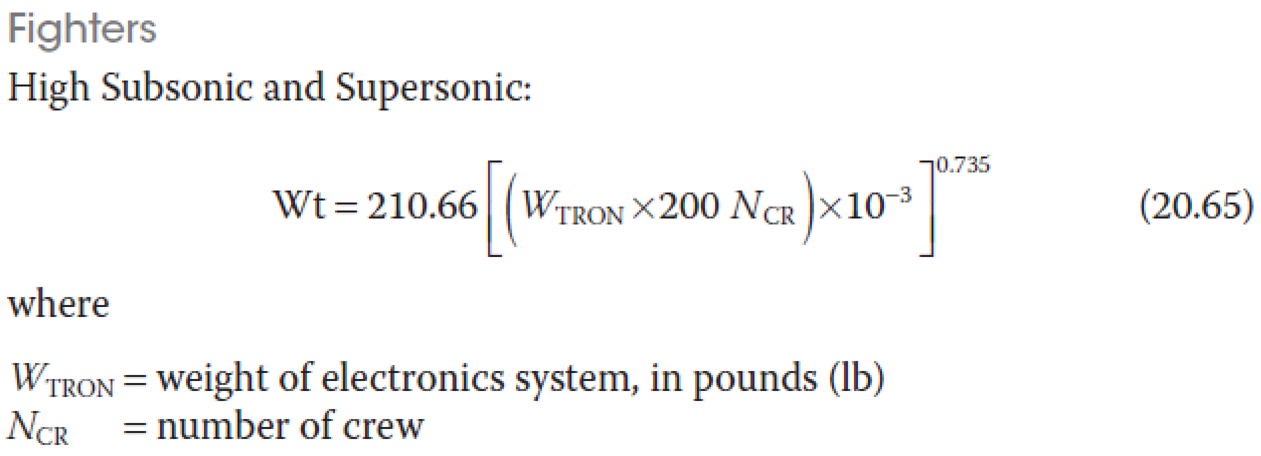
USAF Fighters:

$$\mathrm{Wt} = 426.17\left[\left(W_{\mathrm{FS}} \times W_{\mathrm{TRON}}\right)\times 10^{-3}\right]^{0.510} \qquad (20.43)$$

where

W_{FS} = weight of fuel system, in pounds (lb)
W_{TRON} = weight of electronics system, in pounds (lb)

- **Air Conditioning and Anti-icing System (weight in pounds)**



Fighters

High Subsonic and Supersonic:

$$\mathrm{Wt} = 210.66\left[\left(W_{\mathrm{TRON}} \times 200\, N_{\mathrm{CR}}\right)\times 10^{-3}\right]^{0.735} \qquad (20.65)$$

where

W_{TRON} = weight of electronics system, in pounds (lb)
N_{CR} = number of crew

Note: Interpret electronics system as avionics system

Source: Section 8.1.10, Ref. AVD 1 (Nicolai & Carichner)

Avionics System Weight Estimation

- **Avionics includes communication systems (radios, radars, etc.), flight instruments, navigational aids, flight control computers, infrared detectors, and other equipment**
- **Approach 1: Use** $W_{avionics} = f \cdot W_{TO}$ **with** $0.06 \le f \le 0.16$**, and** 0.1 **as the recommended nominal value**
- **Approach 2: Use** $W_{avionics} = C \cdot W_{empty}$

where the value of C is shown in the table for various types of aircraft

Aircraft Type	C
General Aviation-single engine	0.01-0.03
Light twin	0.02-0.04
Turboprop transport	0.02-0.04
Business jet	0.04-0.05
Jet transport	0.01-0.02
Fighters	0.03-0.08
Bombers	0.06-0.08
Jet trainers	0.03-0.04

Source: Table 11.6, Ref. AVD 2 (Raymer)

- **Note that most aircraft have avionics bay located just in front of, or below, the cockpit**
- **Make sure to allow for radar installation which is usually in the nose region**
- **Estimate avionics volume assuming average density of 30 – 45 lb/ft^3**

Avionics Equipment Weights & Volumes

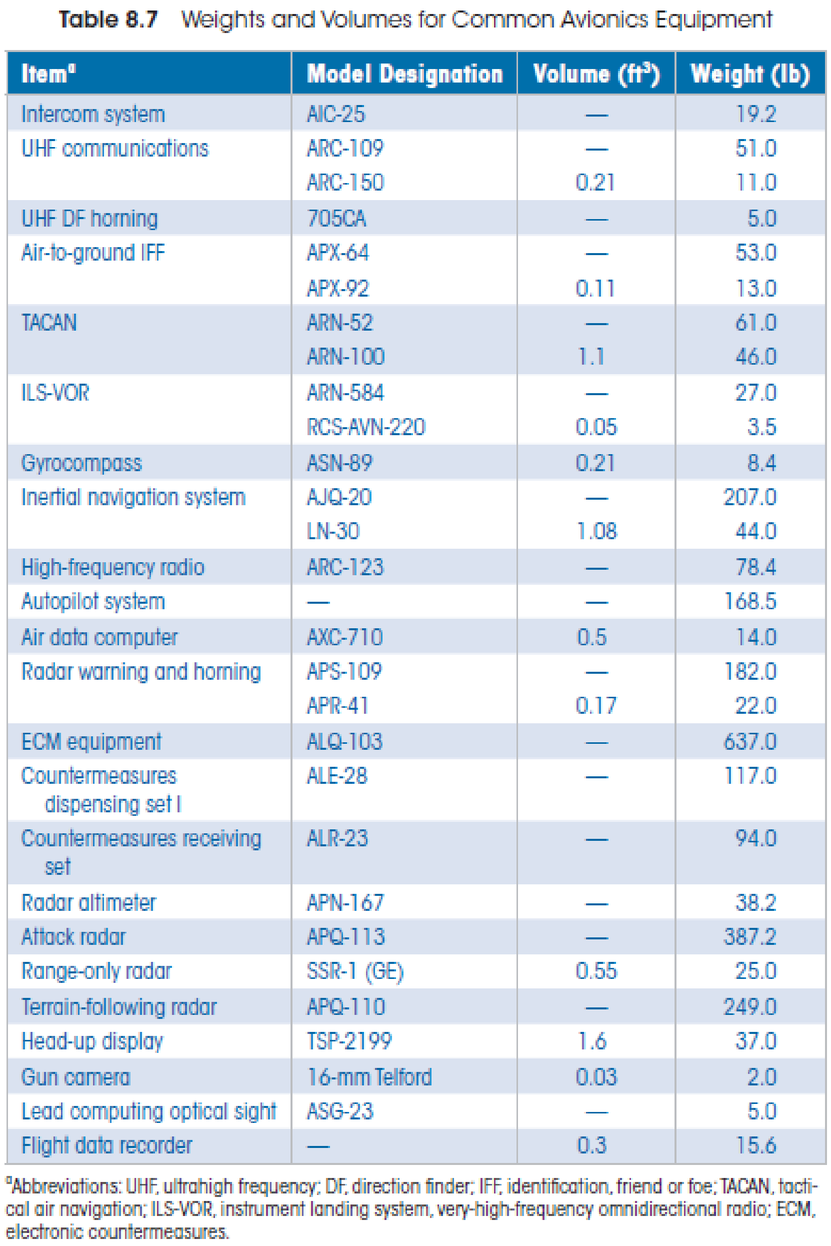


Table 8.7 Weights and Volumes for Common Avionics Equipment

Item[a]	Model Designation	Volume (ft^3)	Weight (lb)
Intercom system	AIC-25	—	19.2
UHF communications	ARC-109	—	51.0
	ARC-150	0.21	11.0
UHF DF homing	705CA	—	5.0
Air-to-ground IFF	APX-64	—	53.0
	APX-92	0.11	13.0
TACAN	ARN-52	—	61.0
	ARN-100	1.1	46.0
ILS-VOR	ARN-584	—	27.0
	RCS-AVN-220	0.05	3.5
Gyrocompass	ASN-89	0.21	8.4
Inertial navigation system	AJQ-20	—	207.0
	LN-30	1.08	44.0
High-frequency radio	ARC-123	—	78.4
Autopilot system	—	—	168.5
Air data computer	AXC-710	0.5	14.0
Radar warning and homing	APS-109	—	182.0
	APR-41	0.17	22.0
ECM equipment	ALQ-103	—	637.0
Countermeasures dispensing set I	ALE-28	—	117.0
Countermeasures receiving set	ALR-23	—	94.0
Radar altimeter	APN-167	—	38.2
Attack radar	APQ-113	—	387.2
Range-only radar	SSR-1 (GE)	0.55	25.0
Terrain-following radar	APQ-110	—	249.0
Head-up display	TSP-2199	1.6	37.0
Gun camera	16-mm Telford	0.03	2.0
Lead computing optical sight	ASG-23	—	5.0
Flight data recorder	—	0.3	15.6

[a] Abbreviations: UHF, ultrahigh frequency; DF, direction finder; IFF, identification, friend or foe; TACAN, tactical air navigation; ILS-VOR, instrument landing system, very-high-frequency omnidirectional radio; ECM, electronic countermeasures.

Source: Table 8.7, Ref. AVD 1 (Nicolai & Carichner)

Avionics Weight Estimation

Table 8.8 Statistical Methods for Estimating Avionics Weight Given Volume or Power

Radar Systems:

$\mathrm{Wt} = 0.431(\mathrm{Power})^{0.777}$ $\mathrm{Wt} = 38.21(\mathrm{Volume})^{0.873}$

for radar weight (less antenna) in pounds, power in watts, and volume (less antenna) in cubic feet

Doppler Navigation Systems:

$\mathrm{Wt} = 0.408(\mathrm{Power})^{0.868}$ $\mathrm{Wt} = 29.67(\mathrm{Volume})^{0.662}$

for weight in pounds, power in watts, and volume in cubic feet

Inertial Navigation Systems:

$\mathrm{Wt} = 0.465(\mathrm{Power})^{0.848}$ $\mathrm{Wt} = 51.85(\mathrm{Volume})^{0.738}$

for weight in pounds, power in watts, and volume in cubic feet

TACAN Systems:

$\mathrm{Wt} = 13.61 + 0.104(\mathrm{Power})$ $\mathrm{Wt} = 0.311(\mathrm{Volume})^{0.704}$

for weight in pounds, power in watts, and volume in cubic inches

Receiver Systems:

$\mathrm{Wt} = 6.3 + 0.17(\mathrm{Power})$ $\mathrm{Wt} = 44.5(\mathrm{Volume})^{0.737}$

for weight in pounds, power in watts, and volume in cubic feet

Transmitter Systems:

$\mathrm{Wt} = 0.73(\mathrm{Power})^{0.610}$ $\mathrm{Wt} = 6.4 + 40.2(\mathrm{Volume})$

for weight in pounds, power in watts, and volume in cubic feet

Identification Systems:

$\mathrm{Wt} = 0.607(\mathrm{Power})^{0.724}$ $\mathrm{Wt} = 0.069(\mathrm{Volume})^{0.868}$

for weight in pounds, power in watts, and volume in cubic inches

Computers:

$\mathrm{Wt} = 2.246(\mathrm{Power})^{0.630}$ $\mathrm{Wt} = 0.123(\mathrm{Volume})^{0.817}$

for weight in pounds, power in watts, and volume in cubic inches

Electronic Countermeasures (ECM):

$\mathrm{Wt} = 0.429(\mathrm{Power})^{0.771}$ $\mathrm{Wt} = 0.055(\mathrm{Volume})^{0.912}$

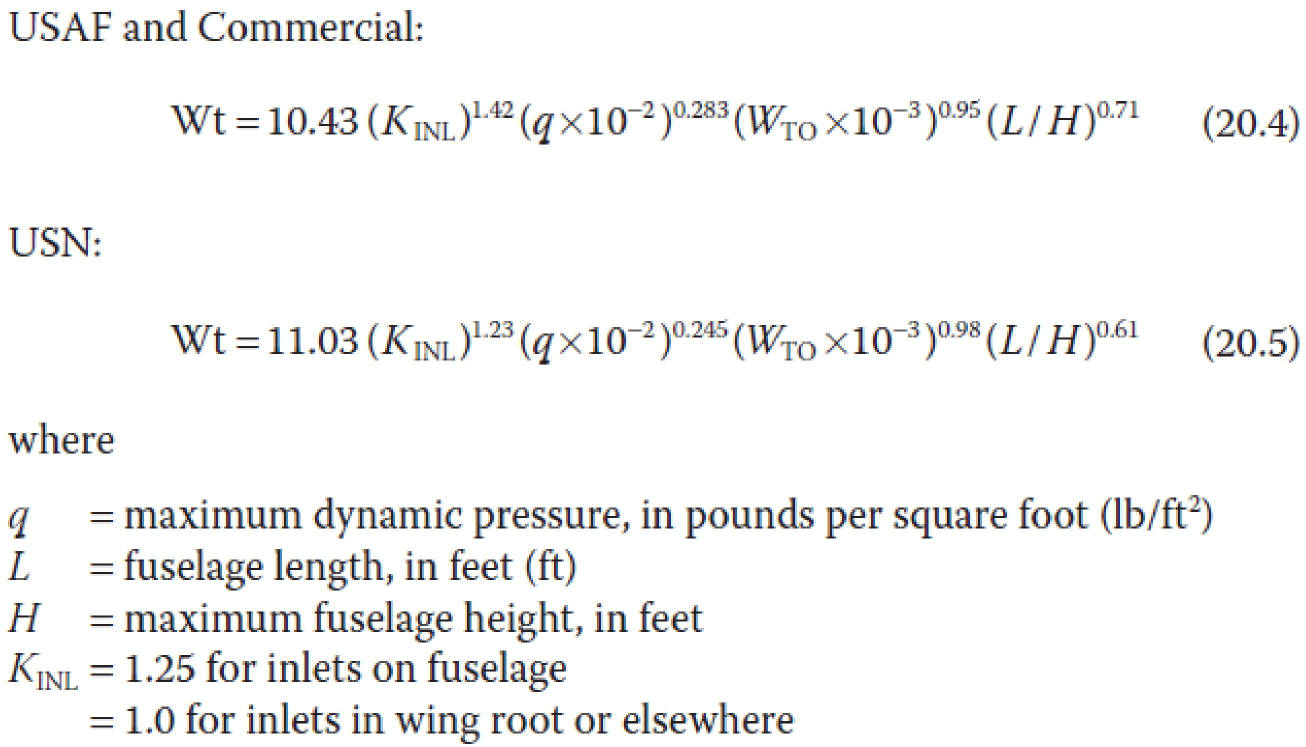
for weight in pounds, power in watts, and volume in cubic inches

Source: Table 8.8, Ref. AVD 1 (Nicolai & Carichner)

Fuselage Structural Weight Consideration

Let’s illustrate for a Conventional Metal Aircraft—Moderate Subsonic to Supersonic Performance (*See reference books for other types of aircraft*)

- **Fuselage structural weight**



USAF and Commercial:

$$\mathrm{Wt} = 10.43\,(K_{\mathrm{INL}})^{1.42}(q \times 10^{-2})^{0.283}(W_{\mathrm{TO}} \times 10^{-3})^{0.95}(L/H)^{0.71} \qquad (20.4)$$

USN:

$$\mathrm{Wt} = 11.03\,(K_{\mathrm{INL}})^{1.23}(q \times 10^{-2})^{0.245}(W_{\mathrm{TO}} \times 10^{-3})^{0.98}(L/H)^{0.61} \qquad (20.5)$$

where

q = maximum dynamic pressure, in pounds per square foot (lb/ft^2)
L = fuselage length, in feet (ft)
H = maximum fuselage height, in feet
K_{INL} = 1.25 for inlets on fuselage
= 1.0 for inlets in wing root or elsewhere

- **The weight equation tells us: For low fuselage weight**
  - Reduce length to maximum height ratio
- ***But…***
  - *Beware of any detrimental effect on aerodynamic performance!*

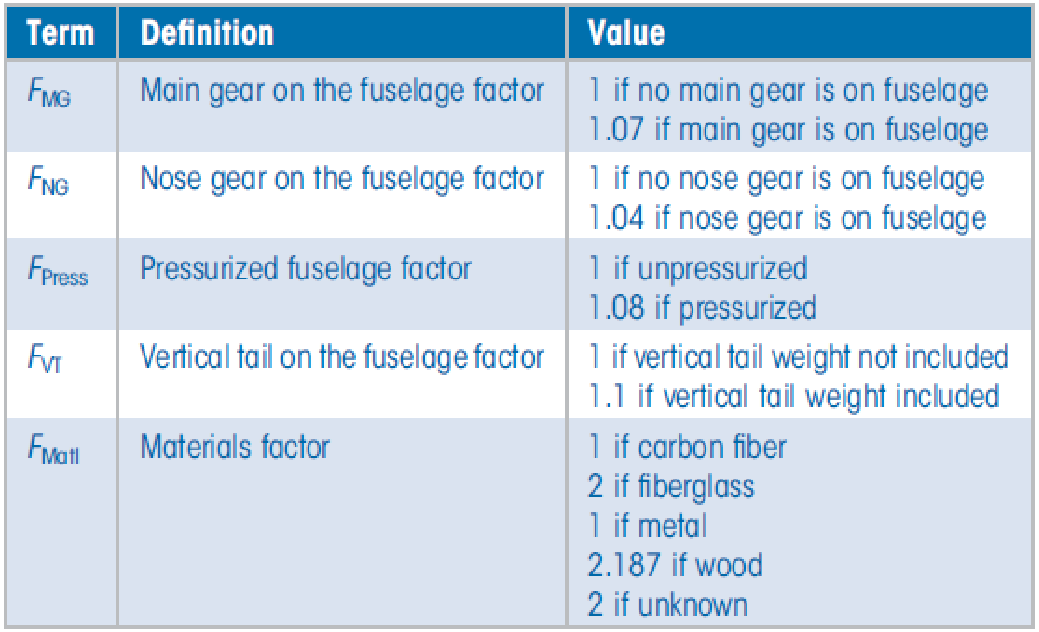
Source: Ch. 20, Ref. AVD 1 (Nicolai and Carichner)

UAS Fuselage Structural Weight Estimation

Example of a Semimonocoque or composite shell fuselage for subsonic or transonic UAS weighing between 1 and 800,000 pounds

$$W_{\text{Fuse}} = 0.5257 \times F_{\text{MG}} \times F_{\text{NG}} \times F_{\text{Press}} \times F_{\text{VT}} \times F_{\text{Matl}} \times L_{\text{Struct}}^{0.3796} \times \left(W_{\text{Carried}} \times N_Z\right)^{0.4863} \times V_{\text{EqMax}}^2 \text{ lb} \qquad (6.40)$$

- F parameter values based on data for 197 fuselages with a fineness ratio at least 0.25
- L_{Struct} is the structural length of the fuselage in feet
- W_{Carried} is the weight of the components carried within the structure in pounds
- N_Z is load factor
- V_{EqMax} is max equivalent speed in knots



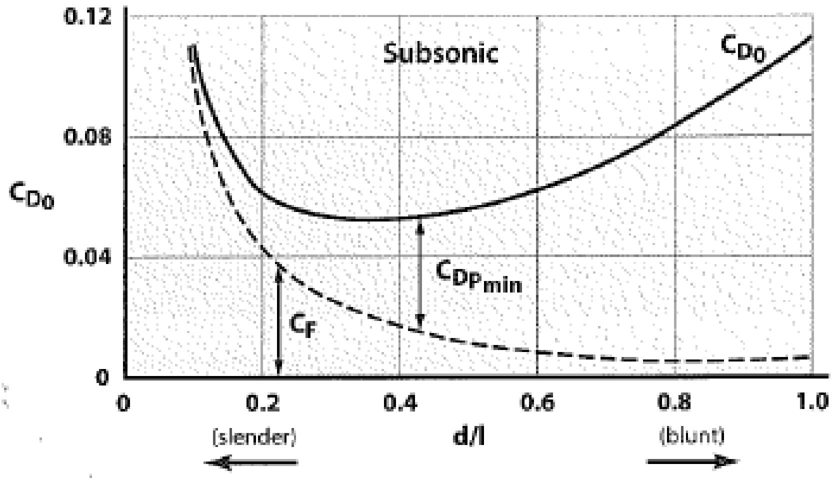
Term	Definition	Value
F_{MG}	Main gear on the fuselage factor	1 if no main gear is on fuselage 1.07 if main gear is on fuselage
F_{NG}	Nose gear on the fuselage factor	1 if no nose gear is on fuselage 1.04 if nose gear is on fuselage
F_{Press}	Pressurized fuselage factor	1 if unpressurized 1.08 if pressurized
F_{VT}	Vertical tail on the fuselage factor	1 if vertical tail weight not included 1.1 if vertical tail weight included
F_{Matl}	Materials factor	1 if carbon fiber 2 if fiberglass 1 if metal 2.187 if wood 2 if unknown

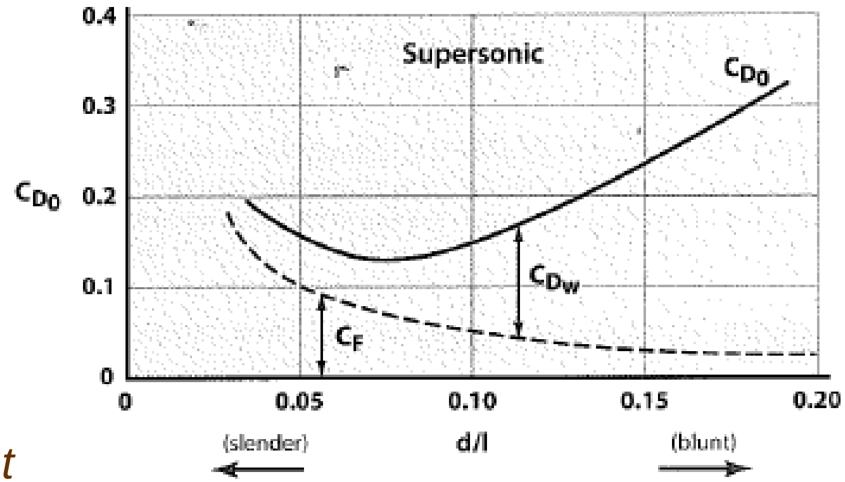
- ***Use this method when better alternatives are not available***

Source: Ch. 6, Ref. AVD 3 (Gundlach)

Fuselage Shape Considerations: d/l

- **Assume cone-cylinder shape; then assume diameter to determine length**
  - *Iterate for desired fineness ratio, d/l*
  - *Convert the assumed cone-cylinder shape to a streamlined shape!*
- **Center Fuselage**
  - *Integration nightmare: crammed with wing carry-thru structure, propulsion ducts, landing gear mountings, fuel tanks, etc., etc., etc.*
  - *“Area Ruling” may further compound the challenge*
- **Pay Attention to “Design for Maintainability” Rules**
  - *Place equipment one deep*
  - *Place equipment chest high*
  - *Make all replaceable equipment (except engines) less than 40 lbs.*
  - …





Source: Figure 8.11, Ref. AVD 1 (Nicolai and Carichner)

Fuselage Length Estimation

Fuselage Length, $L = aW_{TO}^{C}$ (ft.)

Aircraft Type	a	C
Sailplane-unpowered	0.86	0.48
Sailplane-powered	0.71	0.48
Homebuilt-metal/wood	3.68	0.23
General Aviation-single engine	4.37	0.23
General Aviation-twin engine	0.86	0.42
Agricultural	4.04	0.23
Twin turboprop	0.37	0.51
Flying boat	1.05	0.4
Jet trainer	0.79	0.41
Jet fighter	0.93	0.39
Military cargo/bomber	0.23	0.5
Jet transport	0.67	0.43

- **Table may be used for initial estimation or sanity check**

Source: Table 6.3, Ref. AVD 2 (Raymer)

Fuselage Wrap-up: *Initial C.G. Location*

- **Locate the Empennage (horizontal + vertical tail) at the aft end of the fuselage**
- **Estimate initial empennage weight using *historical data***

Aircraft Type	Empennage Area/ Wing Area	Empennage Weight per Area
Jet transports	0.44	5
Business jets	0.43	4.3
General aviation		
Single engine	0.3	1.1
Twin engine	0.45	1.44
ISR	0.2	3.0
Supersonic fighters		
Land based	0.39	7
Carrier based	0.48	6

***Estimate Initial C.G. Location* for ALL Items of the Aircraft**

***EXCEPT* weight of fuselage, wing, and any items on the wing**

Source: Table 8.9, Ref. AVD 1 (Nicolai & Carichner)

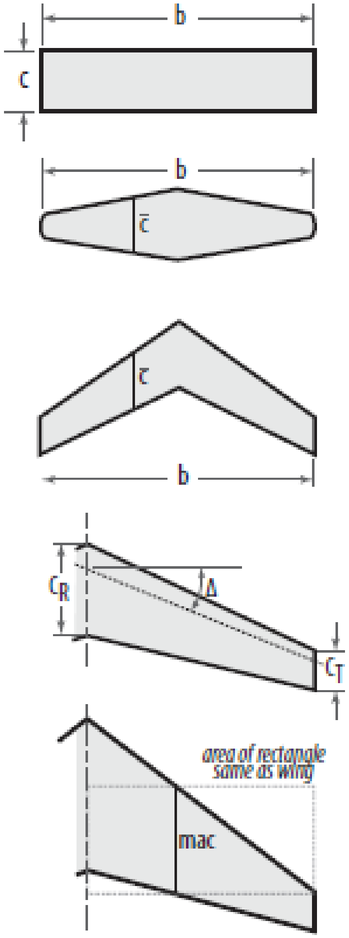
Outline

A7.0 Key Considerations for Configuration Layout

- A7.1 “Concept to Configuration”
- A7.2 Fuselage
- **A7.3 Wing**
- A7.4 Empennage
- A7.5 Propulsion
- A7.6 Landing Gear
- A7.7 Materials & Structures

Wing Geometry

- **Estimate Wing Area (S_{ref}) using W/S from Initial Wing Sizing**
- **Need to Select Planform Parameters:** Aspect Ratio, Span, Sweep, Taper Ratio
- **Need to Select Shape Parameters:** Select airfoil(s) with desired maximum thickness and add along the span



S_{ref} = Wing Area (ft^2)
b = Span (ft)
c = Average Chord (ft)

AR = Aspect Ratio
AR = b/c
AR = b^2/S_{ref}

C_R = Root Chord (ft)
C_T = Tip Chord (ft)
λ = Taper Ratio
λ = C_T/C_R

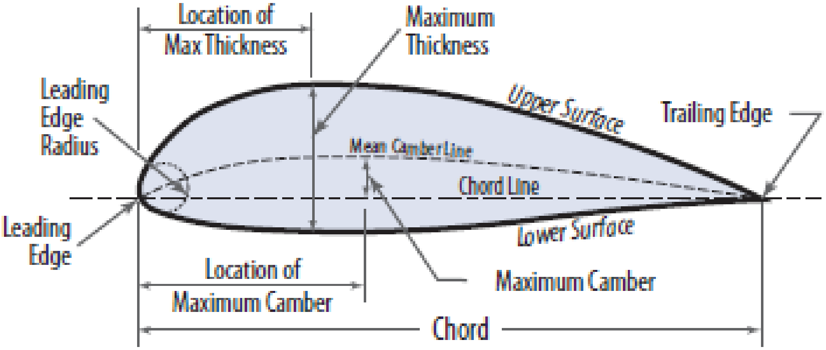
Λ = Sweep Angle (deg)

mac = Mean Aerodynamic Chord (ft)

mac = $\bar{c}$

$$mac = \frac{2}{3} C_R \frac{1+\lambda+\lambda^2}{1+\lambda}$$

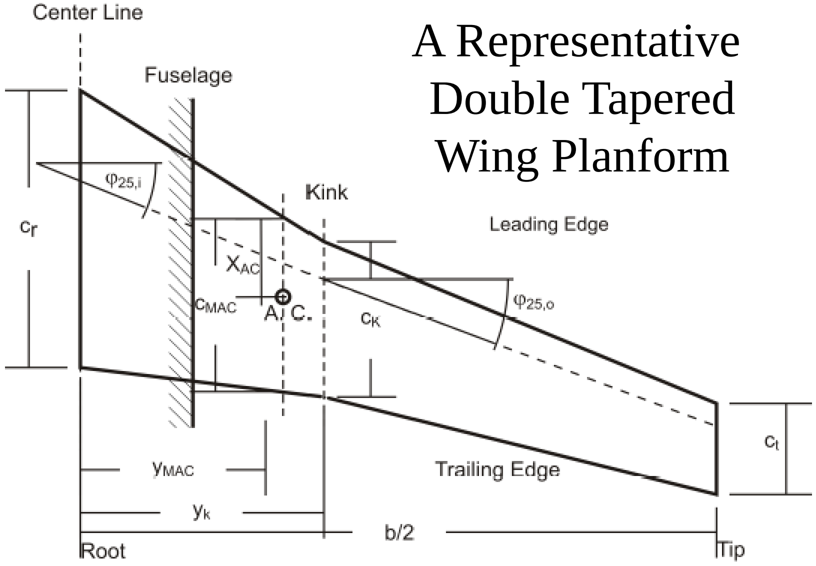
Airfoil Nomenclature



Source: Figure 2.1, Ref. AVD 1 (Nicolai & Carichner)

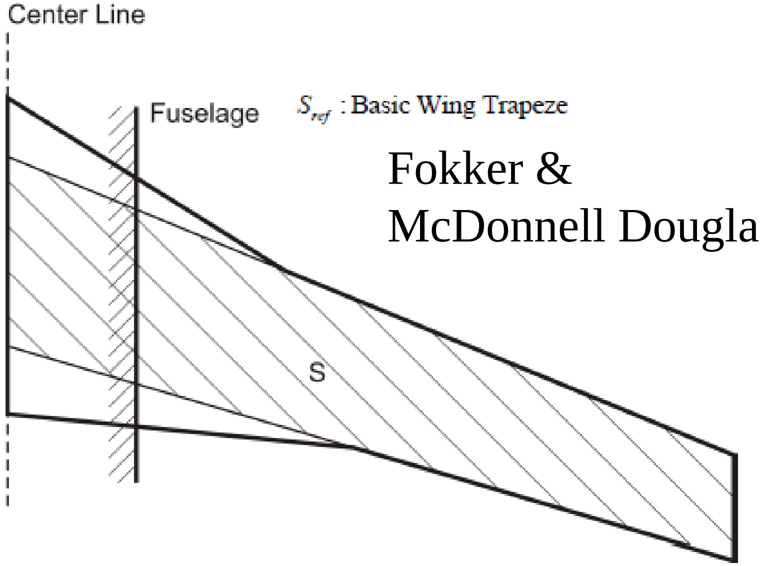
Wing S_{ref} Definition

A Representative Double Tapered Wing Planform



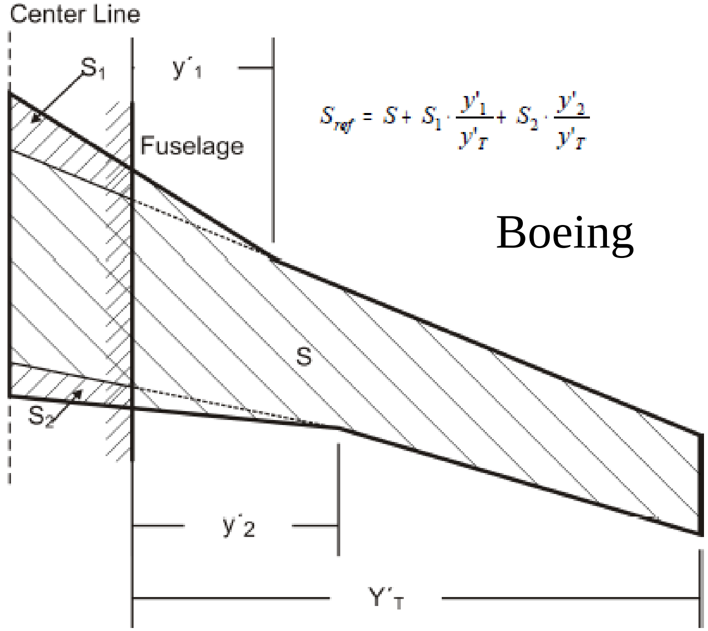
Fokker & McDonnell Douglas

S_{ref} : Basic Wing Trapeze

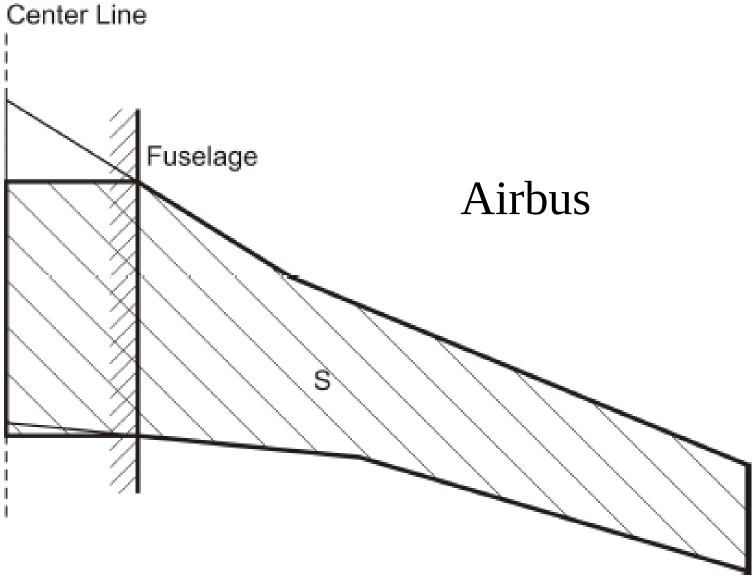


Boeing

$$S_{ref} = S + S_1 \cdot \frac{y'_1}{y'_T} + S_2 \cdot \frac{y'_2}{y'_T}$$



Airbus

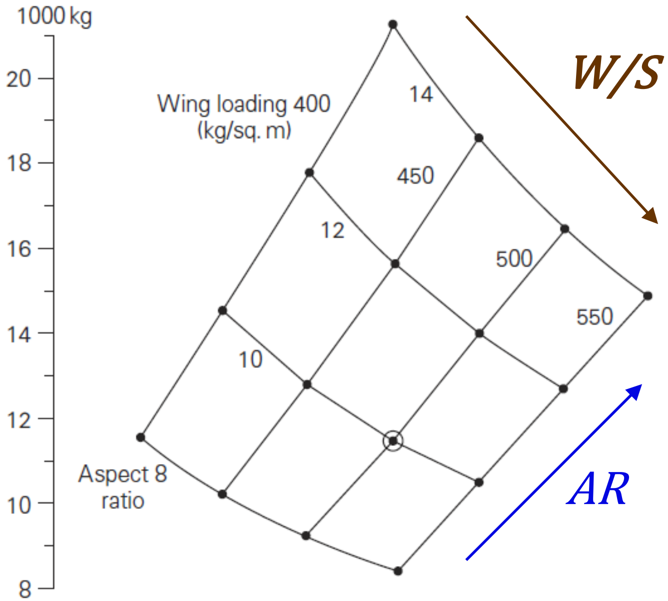


Source: Aircraft Design Short Course (Scholz, HAW)

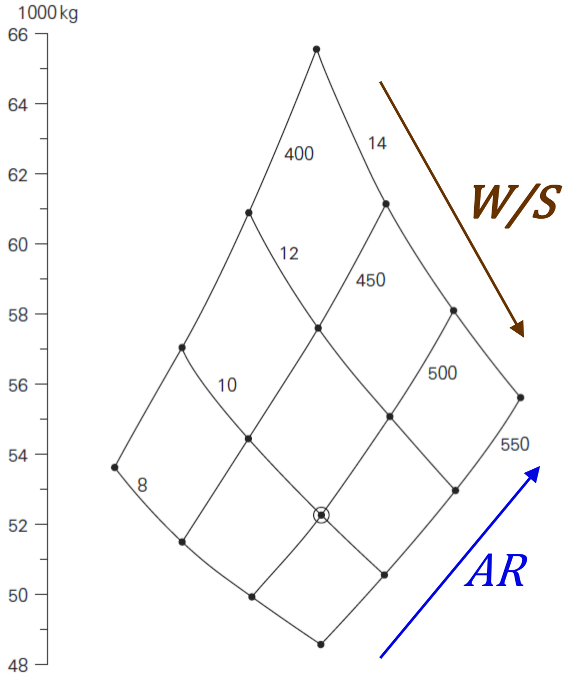
Wing Geometry Trade Studies

Sensitivity to Variations in AR and W/S

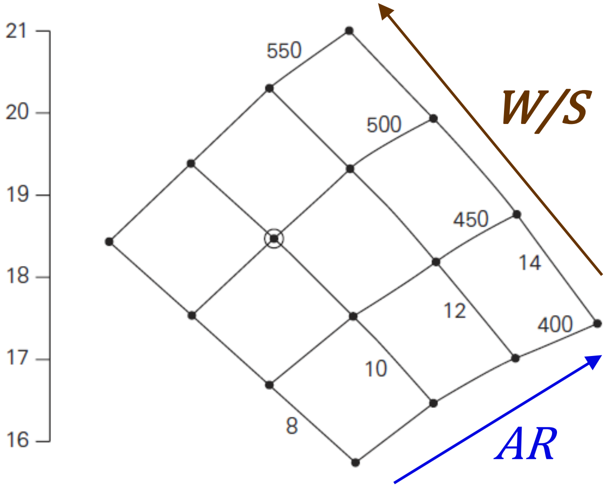
Wing Mass



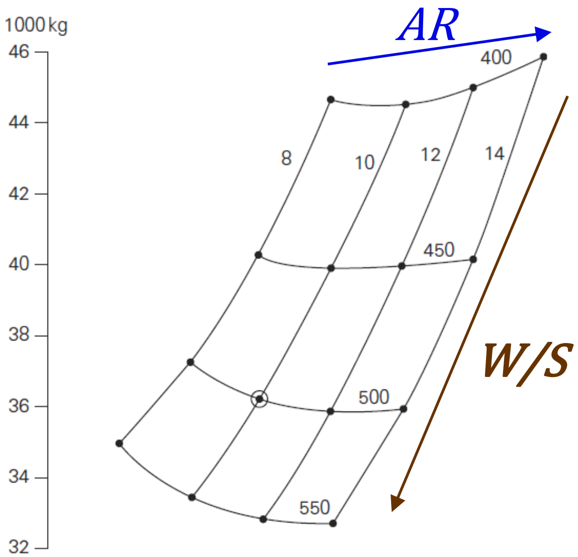
Empty Mass



$(L/D)_{\text{cruise}}$



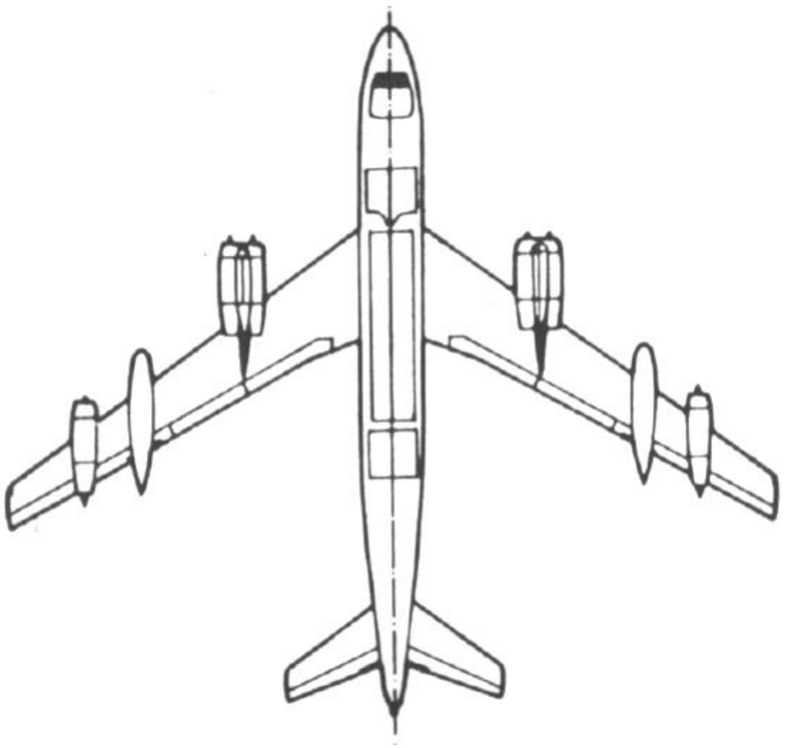
Fuel Mass



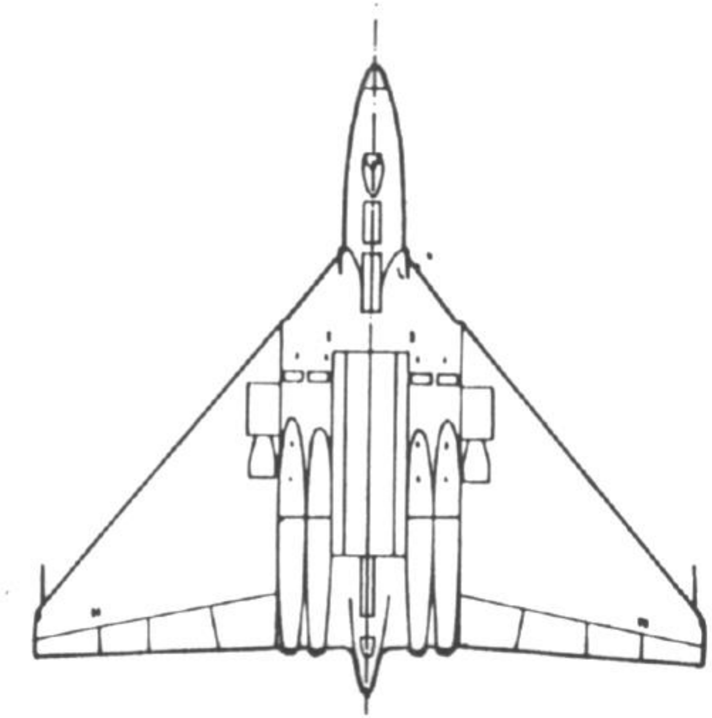
Source: Chapter 4, Ref. AVD 21 (Jenkinson)

AR - Span Tradeoff

B-47 vs. Avro Vulcan B-1
A Classic Example of Innovation



$AR = 9.43$ $b = 116$ ft.



$AR = 2.84$ $b = 99$ ft.

Conventional Wisdom: “Higher AR, Lower Drag”

B-47 and Vulcan Have Comparable $(L/D)_{max}$

	Boeing B-47	**Avro Vulcan**
Aspect Ratio	**9.43**	**2.84**
Span (ft)	**116**	**99**
Wing area, S (sq ft)	1430	3446
Airplane wetted area, S_w (sq ft)	7070	9500
Wing Loading (W/S)	140	43
Span Loading (W/b)	1750	1520
C_{Dmin} (est.)	**0.0198**	**0.0069**
L/D_{max}	**17.25**	**17.0**
C_{Lopt}	0.682	0.235
$C_{Dmin}\ S$	28.3	23.8
C_L (max cruise)	0.48	0.167
S_w/S	4.9	2.8

Vulcan Used Blended Wing-Fuselage Configuration to Reduce Wetted Area for Low C_{Dmin}

Wing Planform: *Sweep* (Λ)

Aft-Swept Wings

Pros

- *Delays <u>drag-divergence Mach number</u> for higher cruise speeds*
- *More freedom to adjust wing aerodynamic center relative to c.g.*
- *Longer moment arm for control on flying wing aircraft*

Cons

- *Increasing sweep increases wing weight for fixed span*
- *Highly swept planforms have poor low-speed performance*

Forward-swept Wings

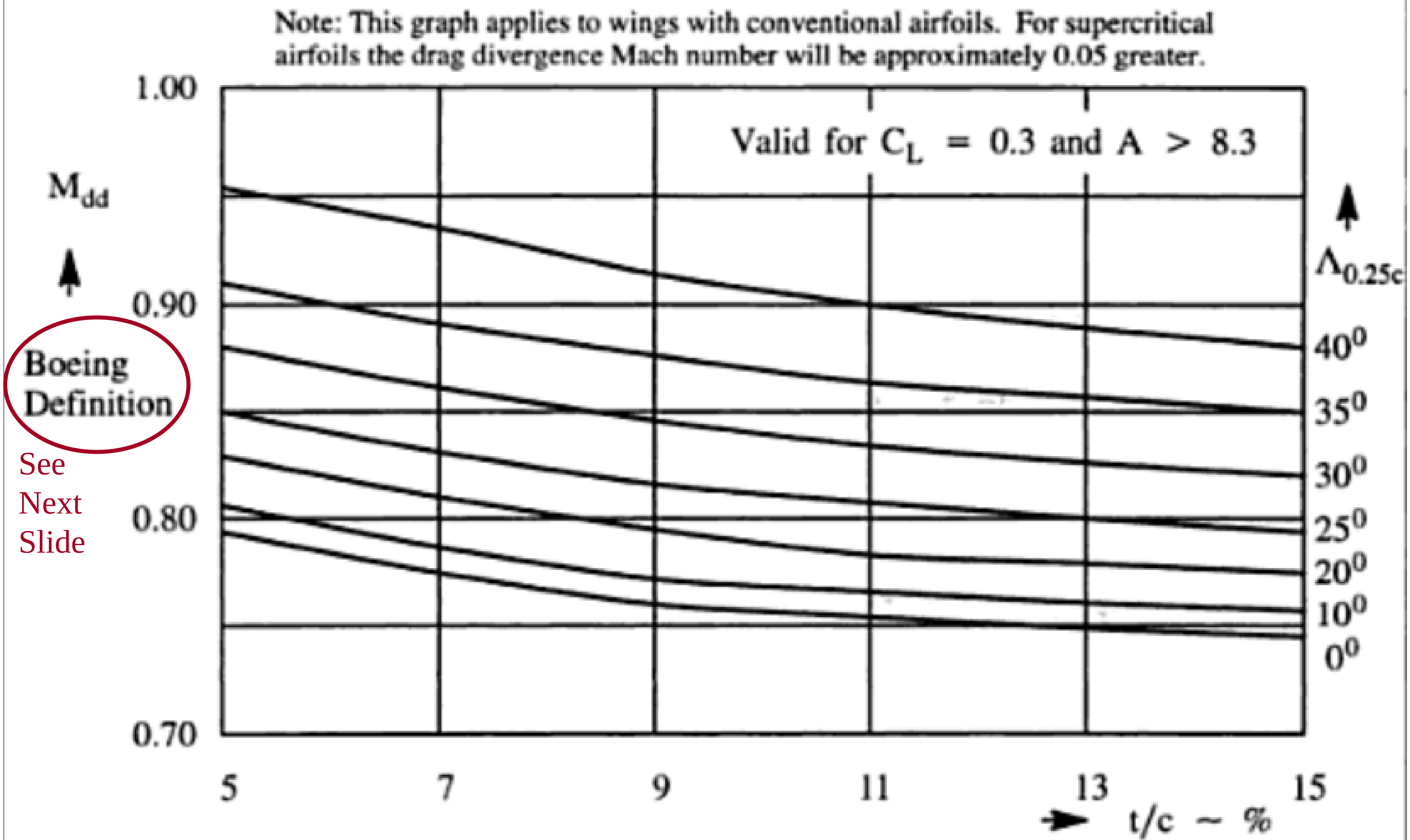
Pros

- *Good transonic maneuverability*
- *Longer lever arm between the wing and tail mac's*
- *Reduced tip stall and lower landing speeds*

Cons

- *Introduces the need to manage aeroelastic divergence*
- *Potentially added weight penalty to arrest aeroelastic divergence*

Effect of Sweep and Thickness on Drag Divergence Mach Number



Note: This graph applies to wings with conventional airfoils. For supercritical airfoils the drag divergence Mach number will be approximately 0.05 greater.

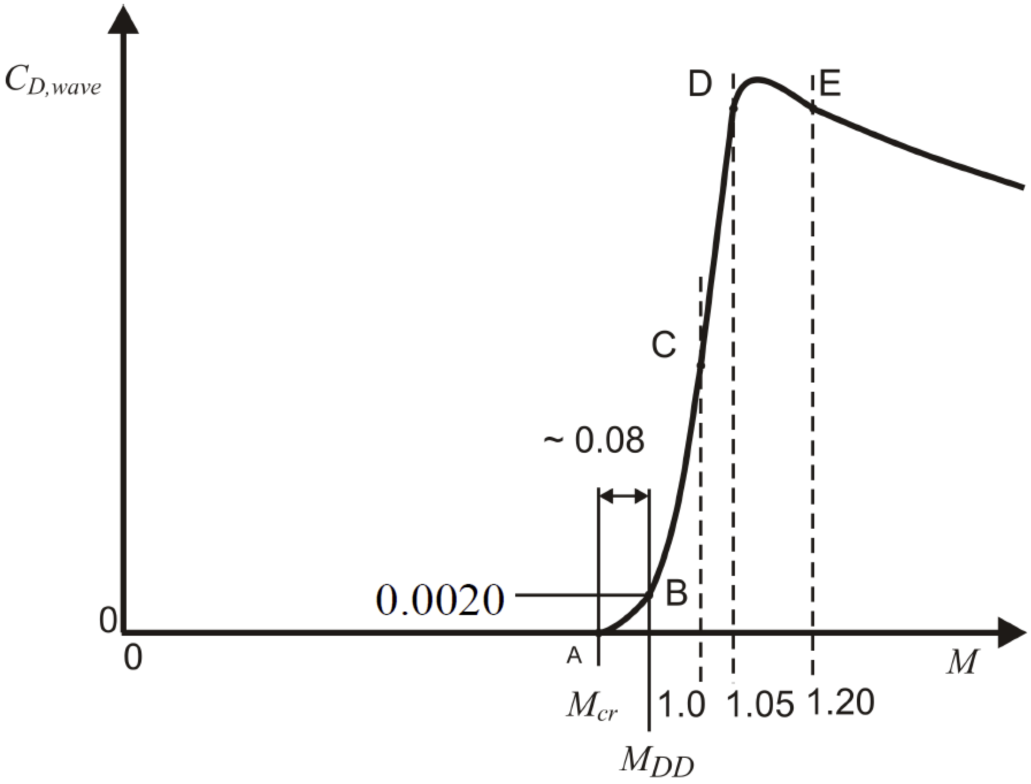
See Next Slide

Source: Trivedi, Akash. Aerospace Vehicle Design: Regional Jet Transport - An Aerodynamics Perspective. (2013).

Drag Divergence Mach Number, M_{DD}

- ***Boeing Definition of*** M_{DD} **: the flight Mach number where wave drag due to compressibility,** $C_{D_{wave}} = 0.0020$
- **Flight Mach number should be at or below** M_{DD} **in order to keep** $C_{D_{wave}}$ **from exceeding 20 counts**
- M_{DD} **corresponds to a flight Mach number where**

$$\partial C_D / \partial M = 0.1$$



- M_{DD} **is related to** M_{crit} **as follows:**

$$M_{DD} = M_{crit} + (0.1/80)^{1/3}$$

This is based on the empirical expression for C_D **and** M_{crit}

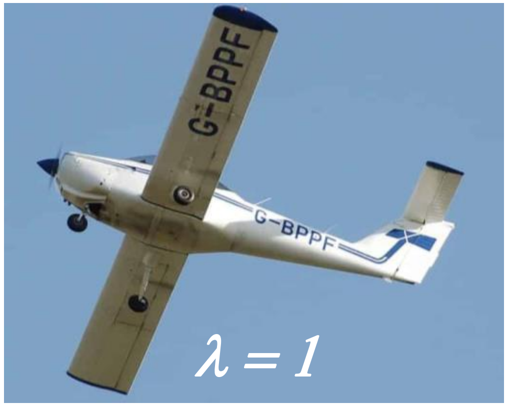
- **Another approximate expression relating** M_{crit} **and** M_{DD} **is:**

$$M_{DD} = M_{crit}\,[1.02 + 0.08(1 - \cos \Lambda_{c/4})]$$

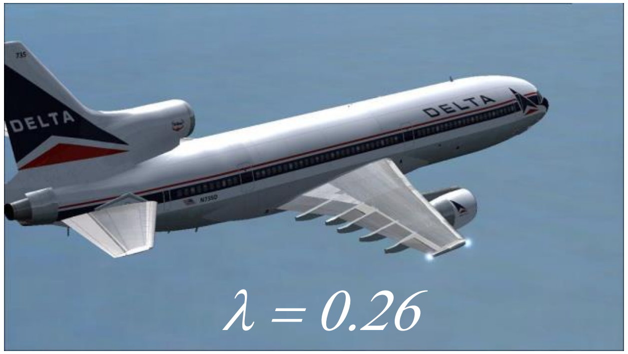
Source: Chapter 7, https://www.fzt.haw-hamburg.de/pers/Scholz/HOOU/AircraftDesign_Contents.pdf

Wing Planform: *Taper Ratio* (λ)

- **Taper ratio ($\lambda = C_{tip}/C_{root}$) offers an option to fine tune wing performance**
- **Wing spanload distribution is almost elliptic for $\lambda \cong 0.35$ which corresponds to**
  - *Minimum finite-span downwash effects*
  - *Minimum induced drag*
- **Wing weight decreases with taper ratio decreasing from 1 to 0 due to increased root depth and low tip loading**
- **For a given wing area and thickness ratio, a delta wing planform will have a larger root chord than a rectangular planform, resulting in approximately 40% more volume available for fuel**



$\lambda = 1$



$\lambda = 0.26$

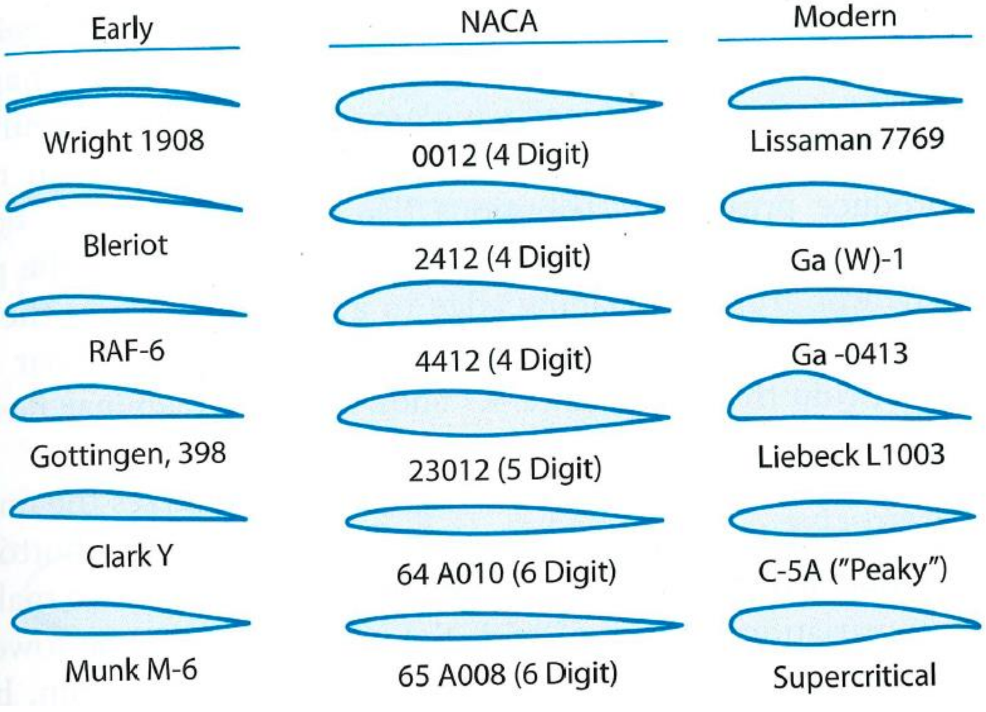
$\lambda \cong 0$

Source: Ch. 7, Ref. AVD 1 (Nicolai and Carichner)

Wing Planform: *Twist*

- **Twist offers an option to fine tune the wing performance**
- **Designers consider varying local geometric angle of wing sections along the span to**
  - *Reduce wingtip stall tendencies*
  - *Tailor spanwise load distribution to reduce induced drag*
  - *Tune pitching moment coefficient*
- ***But…***
  - *Complex variations in twist (combined with variations in camber and thickness) may cause undesirable structural effects*
    - *Curved spar running from root to tip – undesirable*
    - *Curved hinge lines for ailerons and flaps resulting in multi-segment control surfaces – undesirable*

Airfoil Selection Considerations

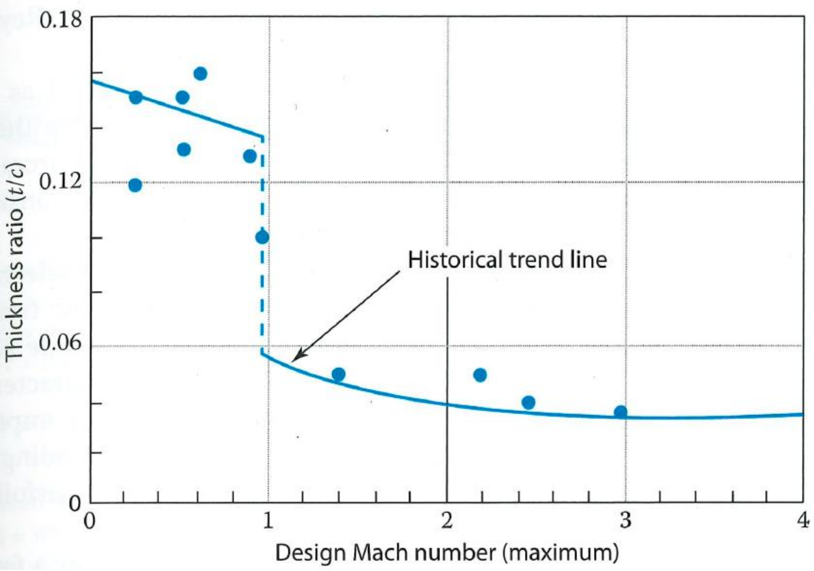


- ***In the CD phase, select one of the existing airfoils that meets the requirements***
- ***"Design Lift Coefficient"*** C_L
  - For best aerodynamic efficiency, aircraft should fly the dominant part of its mission at a C_L where the airfoil has its maximum (l/d)
  - As a crude first approximation, assume *airfoil design* C_l = *wing design* C_L which can be estimated using parameters from initial sizing
  - Range-dominated aircraft typically require [airfoil] design C_l between 0.3 and 0.5
- **Camber**
  - Select camber based on the required design C_l; greater camber gives more lift at given α
  - Aft camber has powerful effect on C_l at specific α; leading-edge camber not much but it delays flow separation on the forward portion
  - Positive camber will shift $C_{l\alpha}$ curve to the left; gives negative $C_{m_{ac}}$; and higher $C_{l\max}$
  - Range-dominated aircraft use airfoils with high camber, fighters with low camber
  - Supersonic aircraft prefer no camber which reduces wave drag penalty

Source: Ref. AVD 1 (Nicolai & Carichner) & Ref. AVD 2 (Raymer)

Airfoil Selection Considerations

- **Maximum thickness ratio (t/c)**
  - Higher t/c reduces wing weight and increases available wing volume for fuel, landing gear, actuators, etc.
    - Halving the thickness ratio will increase wing weight by 41% (and empty weight by about 6%)!
  - Higher t/c increases drag and decreases M_{crit} and M_{DD}
  - Higher t/c gives larger nose radius resulting in higher stall angle and greater C_{lmax}
  - In supersonic flight, wave drag increases almost as the square of t/c
  - "Fat" airfoils (round leading edge and t/c > 14%) exhibit gradual stall which is preferable over abrupt change in lift and pitching moment exhibited by thin airfoils (t/c ~ 6-14%)
  - Front-loaded airfoils with maximum thickness location forward of the a.c. typically produce nose-up pitching moment (positive C_{mac}); and aft-loaded ones produce nose-down moment (negative C_{mac})
    - *Pitching moment directly affects horizontal tail or canard size*
  - Historical trend data can be used for initial selection of t/c; increase by 10% if using supercritical airfoils



"Don't waste a lot of time picking a perfect airfoil—it will change soon!" - Raymer

Source: Ref. AVD 1 (Nicolai & Carichner) & Ref. AVD 2 (Raymer)

Airfoil Technology Affects M_{DD}

- **Efficient transonic cruise depends critically on airfoil parameters.**
- **For 2D airfoils, drag divergence Mach number is given by the Korn equation:**

$$M_{DD_{2D}} = \kappa_A - 0.1C_{L_{2D}} - (\mathrm{t/c})_{2D}$$

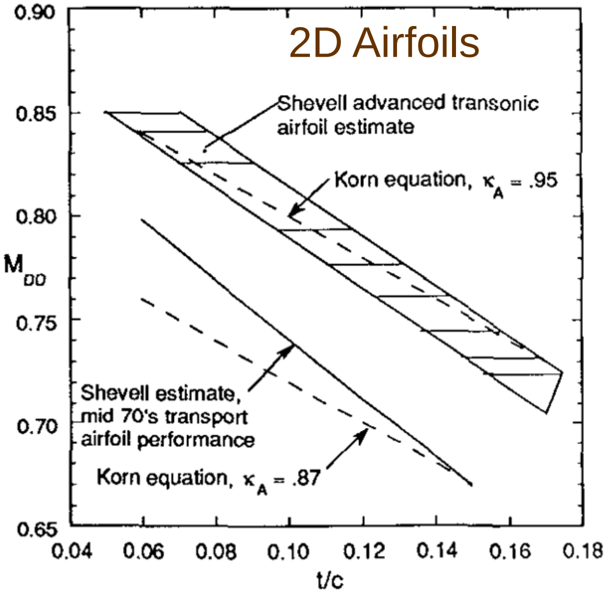
κ_A = 0.95 for NASA supercritical airfoils

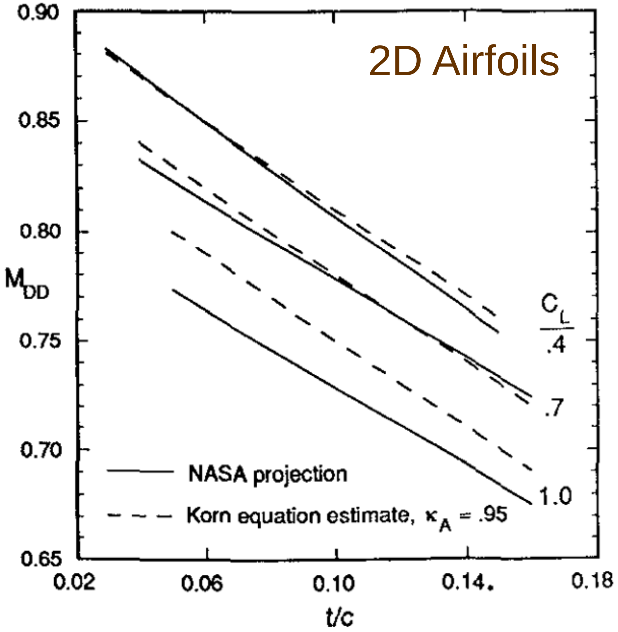
κ_A = 0.87 for conventional 6-series airfoils

- **Using simple sweep theory, the following relation for drag divergence Mach number has been obtained for a 3D wing**

$$M_{DD} = \frac{\kappa_A}{\cos\Lambda} - \frac{t/c}{\cos^2\Lambda} - \frac{C_L}{10\cos^3\Lambda}$$

This relation permits investigation of the relative importance of wing sweep and thickness ratio for a chosen airfoil technology and desired flight Mach number and lift coefficient



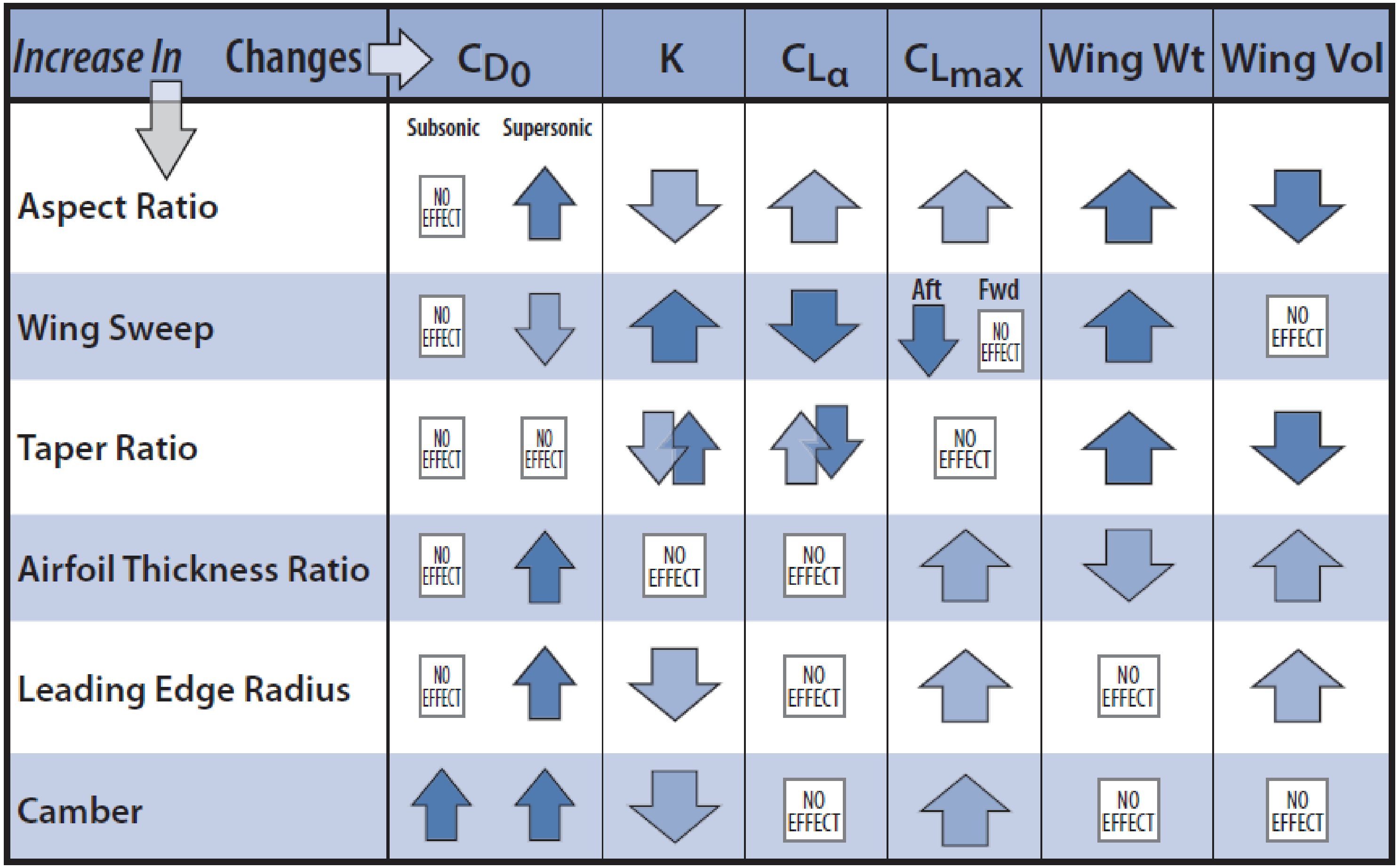


Wing Planform and Airfoil Shape Selection

Challenge: **Must strike the right balance between two sets of figures of merit**

i. maximizing C_{L_α}, $C_{l_{max}}$, and wing volume (for fuel)

ii. minimizing C_{D0}, K, and wing weight



Increase In ↓ Changes →	C_{D0} Subsonic	C_{D0} Supersonic	K	$C_{L\alpha}$	C_{Lmax}	Wing Wt	Wing Vol
Aspect Ratio	NO EFFECT	↑	↓	↑	↑	↑	↓
Wing Sweep	NO EFFECT	↓	↑	↓	Aft ↓ Fwd NO EFFECT	↑	NO EFFECT
Taper Ratio	NO EFFECT	NO EFFECT	↓↑	↑↓	NO EFFECT	↑	↓
Airfoil Thickness Ratio	NO EFFECT	↑	NO EFFECT	NO EFFECT	↑	↓	↑
Leading Edge Radius	NO EFFECT	↑	↓	NO EFFECT	↑	NO EFFECT	↑
Camber	↑	↑	↓	NO EFFECT	↑	NO EFFECT	NO EFFECT

Tradeoff is the name of the game!

Source: Table 7.1, Ref. AVD 1 (Nicolai & Carichner)

Wing Structural Weight Consideration

Let’s illustrate for a <u>Conventional Metal Aircraft</u>—Moderate Subsonic to Supersonic Performance (*See reference books for other types of aircraft*)

- **Wing weight estimation**

$$\mathrm{Wt} = 96.948\left[\left(\frac{W_{\mathrm{TO}}N}{10^5}\right)^{0.65}\left(\frac{\mathrm{AR}}{\cos\Lambda_{1/4}}\right)^{0.57}\left(\frac{S_w}{100}\right)^{0.61}\left(\frac{1+\lambda}{2t/c}\right)^{0.36}\left(1+\frac{V_e}{500}\right)^{0.5}\right]^{0.993} \tag{20.69}$$

where

W_{TO} = takeoff weight, in pounds (lb)
N = ultimate load factor ($1.5 \times$ limit load factor)
AR = wing aspect ratio
$\Lambda_{1/4}$ = wing quarter-chord sweep
S_w = wing area in square feet (ft^2)
λ = wing taper ratio
t/c = maximum wing thickness ratio
V_e = equivalent maximum airspeed at sea level, in knots

- **The weight equation tells us: For low wing weight**
  - Use ***thick wings***, ***low sweep***, ***low AR***, ***low wing area***, etc.
- ***But…***
  - *Beware of any detrimental effect on aerodynamic performance!*

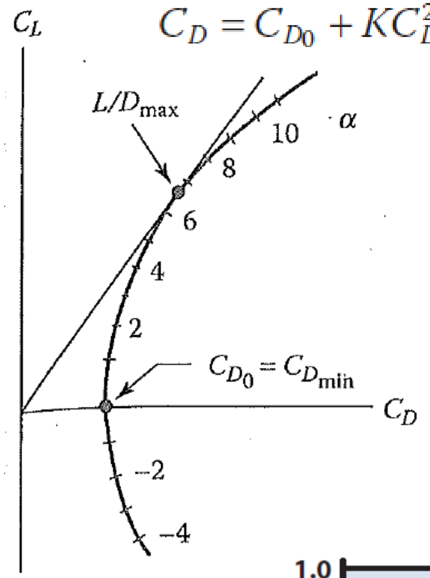
Source: Ch. 20, Ref. AVD 1 (Nicolai and Carichner)

Drag Polars

Needed for Vehicle Performance Estimation

Uncambered Wings

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

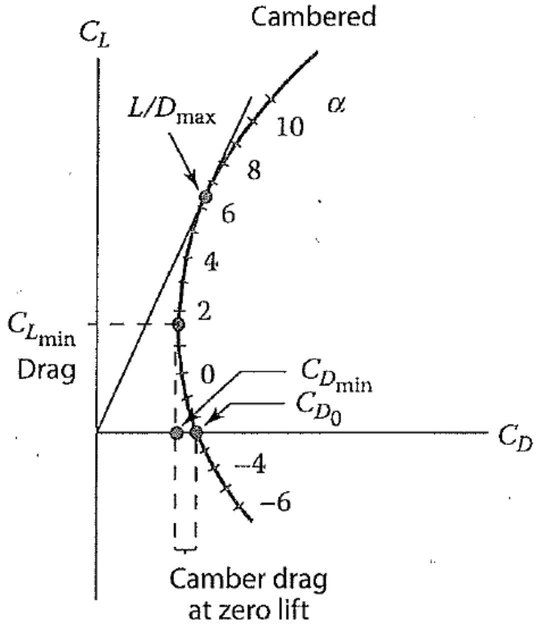


Cambered Wings

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

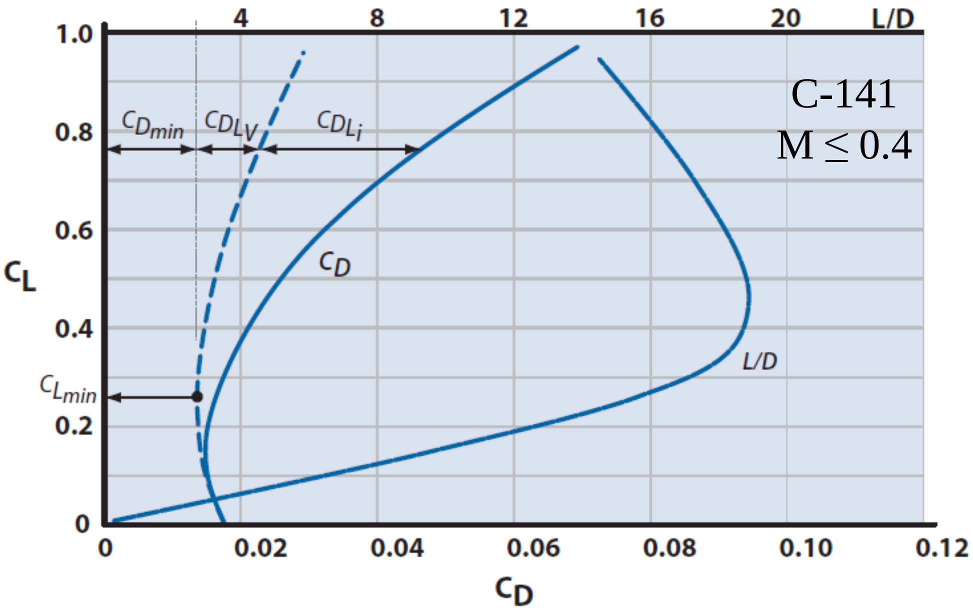
$$K'' = \Delta\left(C_d - C_{d\min}\right) / \Delta\left(C_l - C_{l\min}\right)^2$$

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



Aircraft Drag Polar Example

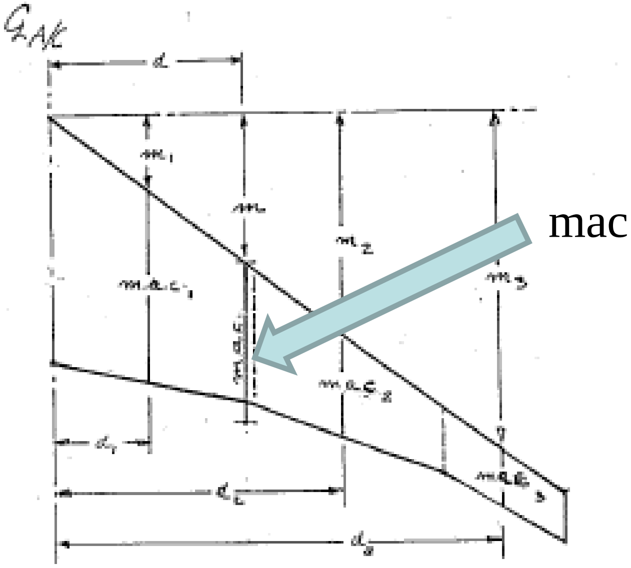
To be built for full configuration



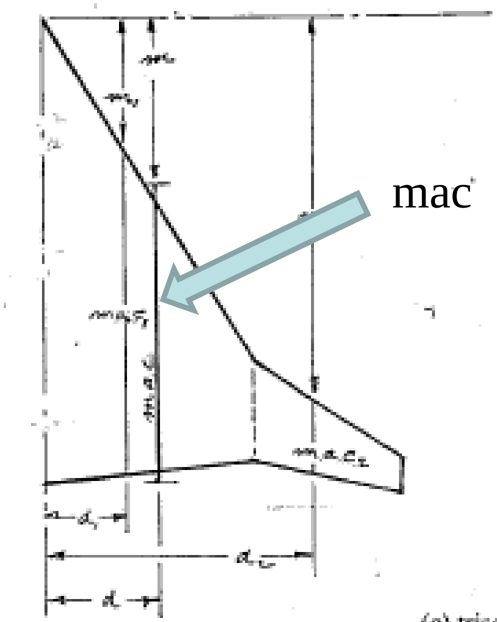
Source: Chapter 2, Ref. AVD 1 (Nicolai)

Wing Location on the Fuselage

- **Determine the wing Mean Aerodynamic Chord (**mac **or** MAC**)**
- **Select the quarter-chord point of the *Equivalent* Wing** mac



(b) subsonic B767 type wing



(c) trisonic high speed aircraft type wing

Source: Figure 1-3, Ref. 4 (Kirschbaum and Mason)

- **Draw the wing in planview; <u>align c.g. with select %mac</u>**
  - ***Pure Flying Wing:*** align c.g. with 25% mac point for neutral stability
  - ***Aft-tail stable aircraft:*** align c.g. with 30% mac point
  - ***Aft-tail unstable aircraft:*** align c.g. with 40% mac point
  - ***Canard unstable aircraft:*** c.g. should fall between 15 to 20% mac

Source: Ref. AVD 2 (Raymer) & AVD 6 (Kirschbaum and Mason)

Outline

A7.0 Key Considerations for Configuration Layout

Empennage Layout

Empennage Provides Longitudinal and Lateral Stability, Control Power, and Spin Recovery

Many Options!


Horizontal (aft) and Vertical


No tails


Canard and vertical


Vertical only


"Vee"


"Vee"

Image Source: Internet

Applicable Federal Regulations

Civilian Aircraft

- **FAR 23 (normal, utility, acrobatic category small aircraft,**
- **9 or less passengers), Paragraph 23.171**
- **FAR 25 (transport category aircraft), Paragraph 25.171**

Same Wording for both

"The airplane must be longitudinally, directionally, and laterally stable. In addition, the airplane must show suitable stability and control "feel" (static stability) in any condition normally encountered in service."

Military Aircraft

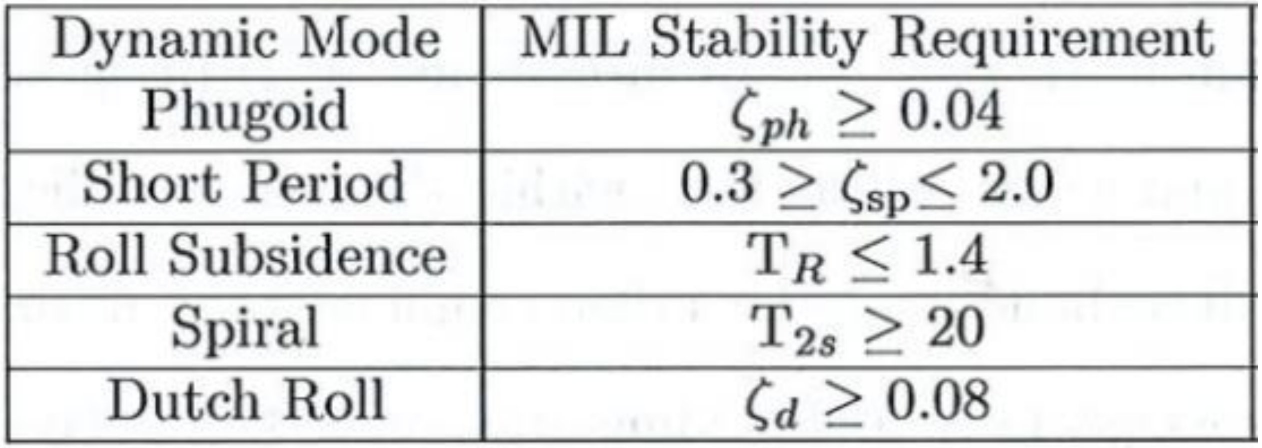
- **MIL-HDBK-1797 (1997)** Flying Qualities of Piloted Aircraft
  - Contains requirements for qualitative and quantitative flying qualities for all military aircraft, latest theories, and information relating to pilot opinion.
- **MIL-F-9490** Flight Control Systems—Design, Installation and Test for Piloted Aircraft
- **MIL-F-1873** Flight Control Systems—Design, Installation and Test for Aircraft
- **MIL-C-18244** Control and Stabilization Systems, Automatic for Piloted Aircraft

All Require Dynamically Stable Aircraft—either inherently stable or with Stability Augmentation System

Source: Ch. 21, Ref. AVD 1 (Nicolai & Carichner)

Stability and Control 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	$0.3 \geq \zeta_{sp} \leq 2.0$
Roll Subsidence	$T_R \leq 1.4$
Spiral	$T_{2s} \geq 20$
Dutch Roll	$\zeta_d \geq 0.08$

Accepted Guidelines for S&C

- **Static Longitudinal (Pitch) Stability Derivative** (FAR Part 23 & 25; MIL-HDBK-1797)
  - Elevator fixed neutral point should be aft of the c.g. for all loading conditions to insure

$$C_{m_\alpha} < 0$$

- **Static Lateral (Roll) Stability Derivative** (MIL-HDBK-1797)

$$C_{l_\beta} < 0$$

- **Static Directional (Yaw) Stability Derivative** (FAR Part 23 & 25, MIL-HDBK-1797)

$$C_{n_\beta} > 0$$

- **Roll Damping Derivative** (important for roll-handling qualities)

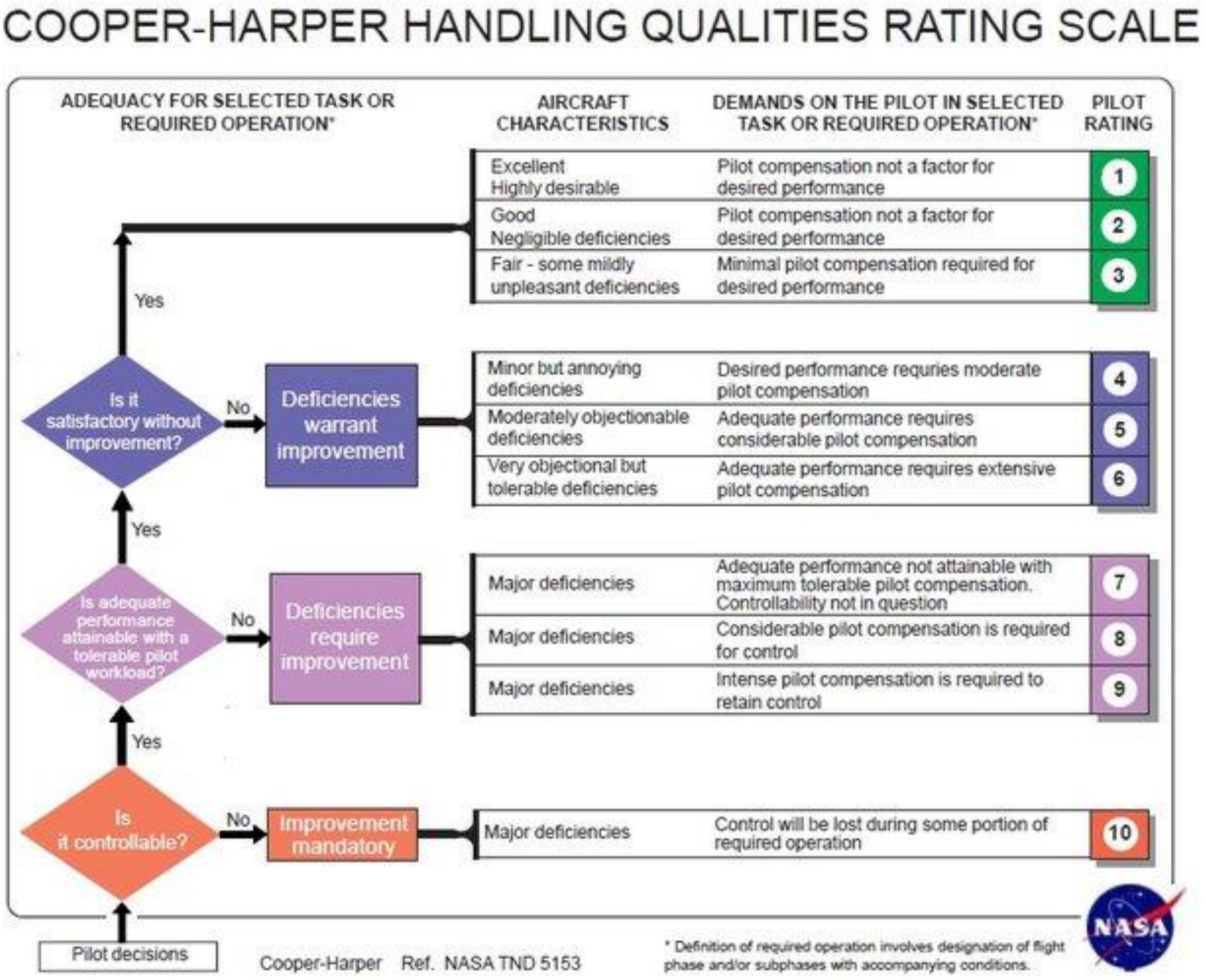
$$C_{l_p} < 0$$

- **Pitch Damping Derivative** (important for short period damping requirements)

$$C_{m_q} < 0$$

Source: Ch. 23, Ref. AVD 1 (Nicolai & Carichner)

Aircraft Handling Qualities Requirements



COOPER-HARPER HANDLING QUALITIES RATING SCALE

ADEQUACY FOR SELECTED TASK OR REQUIRED OPERATION*

Pilot decisions

Is it controllable? No → Improvement mandatory; Yes

Is adequate performance attainable with a tolerable pilot workload? No → Deficiencies require improvement; Yes

Is it satisfactory without improvement? No → Deficiencies warrant improvement; Yes

AIRCRAFT CHARACTERISTICS	DEMANDS ON THE PILOT IN SELECTED TASK OR REQUIRED OPERATION*	PILOT RATING
Excellent Highly desirable	Pilot compensation not a factor for desired performance	1
Good Negligible deficiencies	Pilot compensation not a factor for desired performance	2
Fair - some mildly unpleasant deficiencies	Minimal pilot compensation required for desired performance	3
Minor but annoying deficiencies	Desired performance requries moderate pilot compensation	4
Moderately objectionable deficiencies	Adequate performance requires considerable pilot compensation	5
Very objectional but tolerable deficiencies	Adequate performance requires extensive pilot compensation	6
Major deficiencies	Adequate performance not attainable with maximum tolerable pilot compensation. Controllability not in question	7
Major deficiencies	Considerable pilot compensation is required for control	8
Major deficiencies	Intense pilot compensation is required to retain control	9
Major deficiencies	Control will be lost during some portion of required operation	10

Cooper-Harper Ref. NASA TND 5153

* Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.

Empennage Sizing Considerations

Vertical Tail

- **Sized by one or more of the following criteria**
  - **Landing and Takeoff—**one-engine-out or severe crosswind conditions
  - **Maneuverability—**required maneuverability for a fighter aircraft
  - **Subsonic Cruise Directional Stability—**directional stability derivative $C_{n\beta} > 0$; typical values are 0.08 to 0.17 per radian at 0.8 Mach number
  - **High-speed Directional Stability—**For M > 2, tail might be sized to have a minimum value of 0.08 for $C_{n\beta}$

Horizontal (Aft) Tail

- **Sized by one or more of the following criteria**
  - **Landing and Takeoff—**large enough to rotate the aircraft at takeoff speed, and trim it at low speeds for landing approach
  - **Maneuverability—**for fighter aircraft, $C_{m\alpha}$ should be near zero even positive (with SAS)
  - **Static Longitudinal Stability—**static longitudinal stability derivative $C_{m\alpha} < 0$ at all flight speeds; should not be too negative to ensure reasonable trim drag; typical values are between -0.7 and -1.4 per radian
  - **Low Trim Drag—**trim drag should be < 10% of total aircraft drag

In early stages of design, we do NOT have sufficient information to size the tail using these criteria—so we use historical trends!

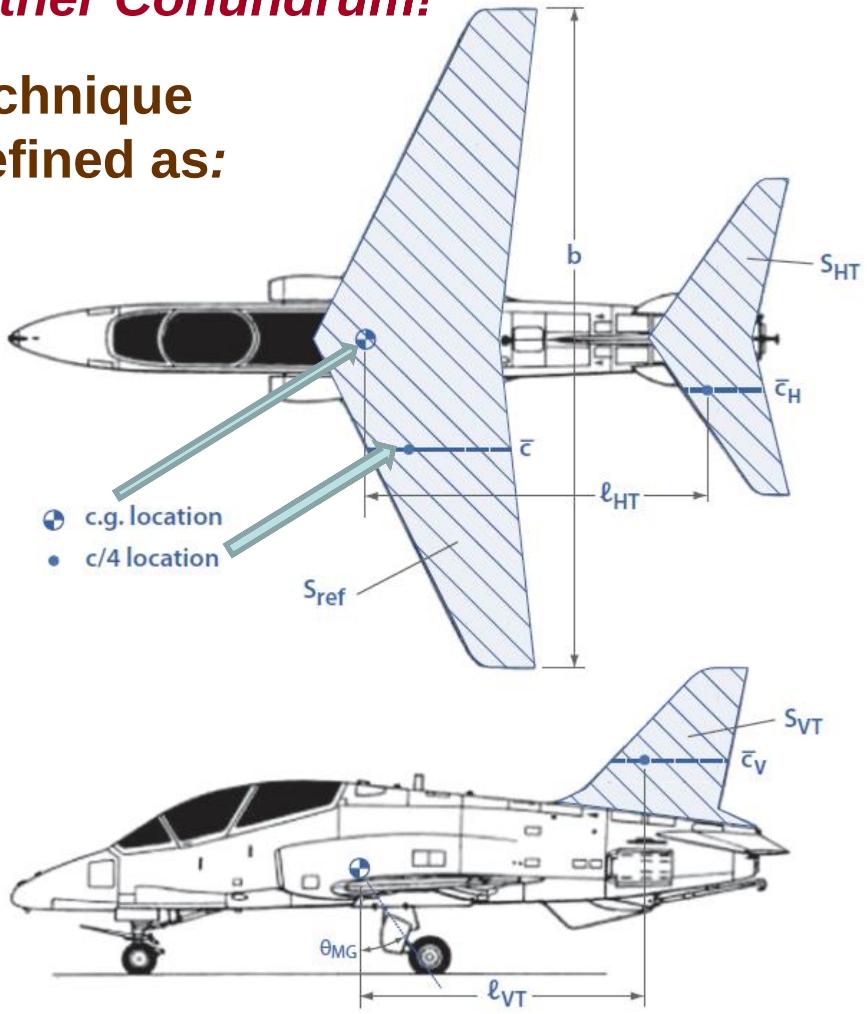
Source: Ch 11, Ref. AVD 1 (Nicolai & Carichner)

Empennage Layout

- **Sizing of tail surfaces requires *precise location of c.g.***
- **Precise location of c.g. depends on the weight and location of tails that we don't have—*Yet Another Conundrum!***
- **At this stage, adopt a shortcut technique using *Tail Volume Coefficients* defined as:**
  - ***Horizontal Tail Volume Coefficient***

    $C_{HT} = l_{HT} S_{HT} / \bar{c}\, S_{ref}$
  - ***Vertical Tail Volume Coefficient***

    $C_{VT} = l_{VT} S_{VT} / b\, S_{ref}$
- **Use wing geometry guidelines to define horizontal and vertical tail parameters**
- **Choose a target static margin**



Source: Figure 11.1, Ref. AVD 1 (Nicolai & Carichner)

Typical Tail Volume Coefficients

Aircraft	C_{HT}	C_{VT}
Sailplane	0.53	0.022
ISR	0.34	0.014
General aviation (one-engine propeller)	0.7	0.032
General aviation (two-engine propeller)	0.76	0.06
Business aircraft (two engine)	0.91	0.09
Commercial jet transports	1.0	0.083
Military jet trainer	0.6	0.06
Jet fighter (all speeds)	0.5	0.076

Source: Table 11.8, Ref. AVD 1 (Nicolai & Carichner)

Static Margin (SM)

$$\mathrm{SM} = \frac{X_{\mathrm{n.p.}} - X_{\mathrm{c.g.}}}{\bar{c}}$$

SM should be expressed as % of MAC

- **Design team must choose a target value for Static Margin for their aircraft**
- **If aircraft neutral point (where $C_{m\alpha}$ is zero) is ahead of C.G., SM < 0, and aircraft is UNSTABLE; typical values of SM range from 5% to 40% for STABLE aircraft**
- **Rule of thumb: +4% to +7% for transport aircraft; neutral (0%) to +3% for fighters**
- **Static Margin and longitudinal stability derivative are related as**

$$SM = -\frac{C_{m_\alpha}}{C_{L_\alpha}}$$

- **To resolve S&C issues, payload, subsystems, and fuel should be shifted around to locate c.g. at a desired position; *shifting the wing should be the last resort***

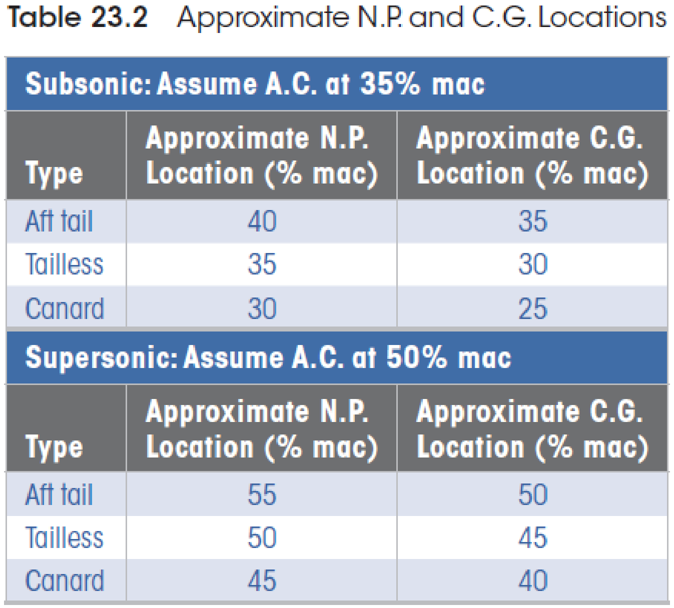
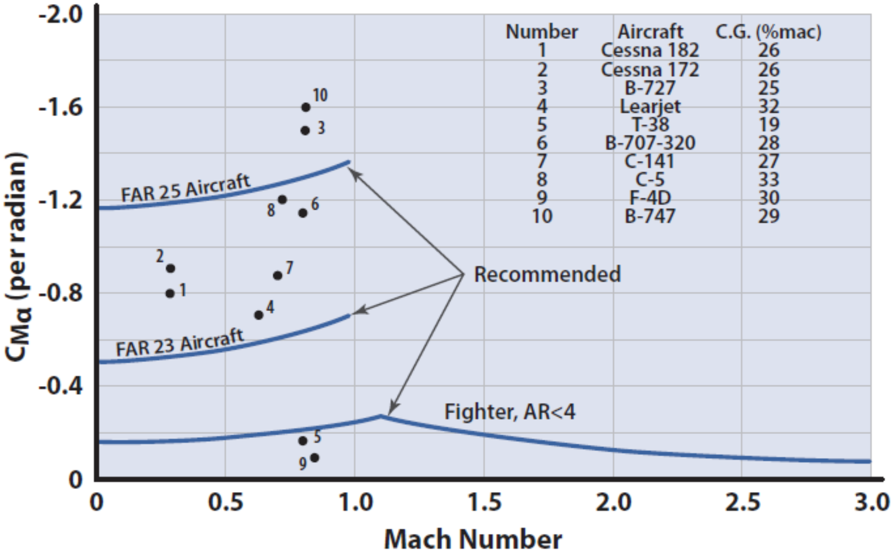


Table 23.2 Approximate N.P. and C.G. Locations

Type	Approximate N.P. Location (% mac)	Approximate C.G. Location (% mac)
Subsonic: Assume A.C. at 35% mac		
Aft tail	40	35
Tailless	35	30
Canard	30	25
Supersonic: Assume A.C. at 50% mac		
Aft tail	55	50
Tailless	50	45
Canard	45	40



Number	Aircraft	C.G. (%mac)
1	Cessna 182	26
2	Cessna 172	26
3	B-727	25
4	Learjet	32
5	T-38	19
6	B-707-320	28
7	C-141	27
8	C-5	33
9	F-4D	30
10	B-747	29

Source: Ch. 23, Ref. AVD 1 (Nicolai & Carichner)

Remember

We are at the starting point—not the end point—of sizing the empennage!

> ***"After the initial layout is completed and analyzed using modern methods for aerodynamic simulation, the wing will probably need to be moved and the tails resized to meet all required stability and control characteristics." -- Raymer***

Source: Ref. AVD 2 (Raymer)

Outline

A7.0 Key Considerations for Configuration Layout

A7.1 “Concept to Configuration”

A7.2 Fuselage

A7.3 Wing

A7.4 Empennage

A7.5 Propulsion

A7.6 Landing Gear

A7.7 Materials & Structures

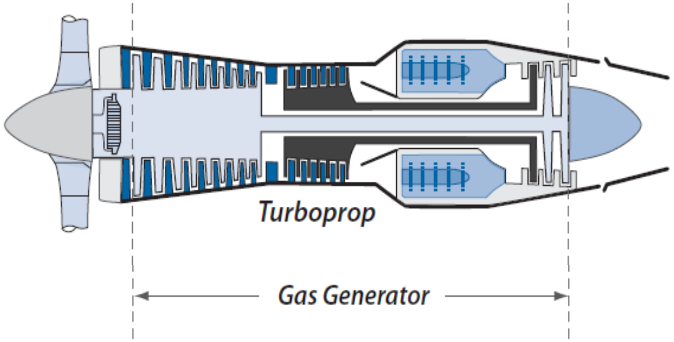
Propulsion System Selection

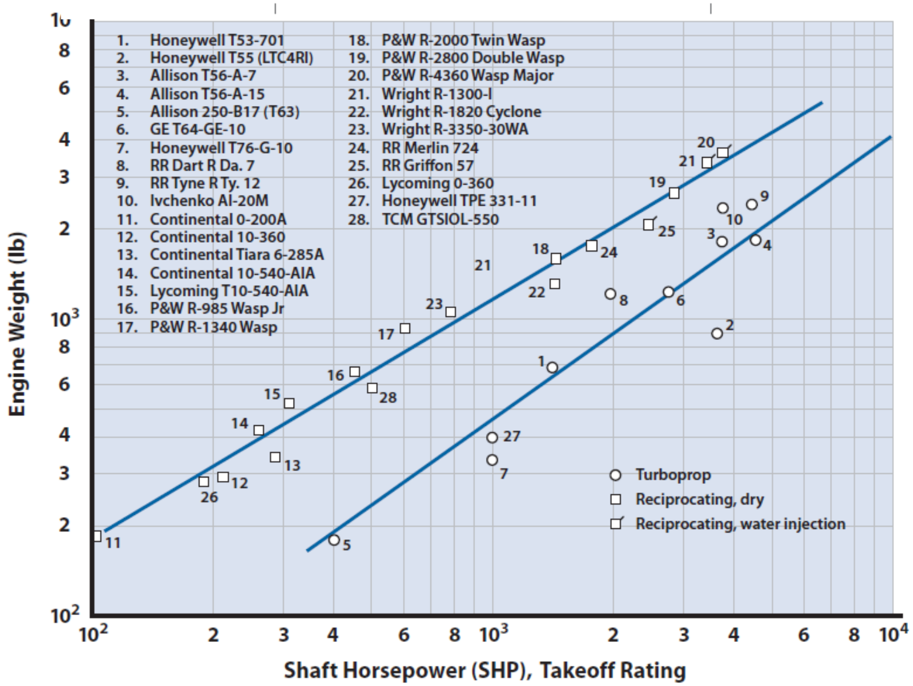
- **Using the required thrust, T, value, and specified design requirements, choose *a suitable propulsion system***
- **Two Main Options for producing thrust: (1) Propellers and (2) Jet engines**
- **Propellers**
  - Powered by reciprocating piston engines, gas turbines (turboprops), or electric motors
  - Keeping tip speed less than sonic restricts practical use to flight speeds < 500 kt
  - Required power:

$$\text{hp}_{\text{Req}} = DV/550\eta_p$$

$$\eta_p = \frac{(\text{propeller thrust power})}{(\text{engine shaft brake horsepower})}$$

  - Select appropriate propeller with target efficiency of around 85% to 90%





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

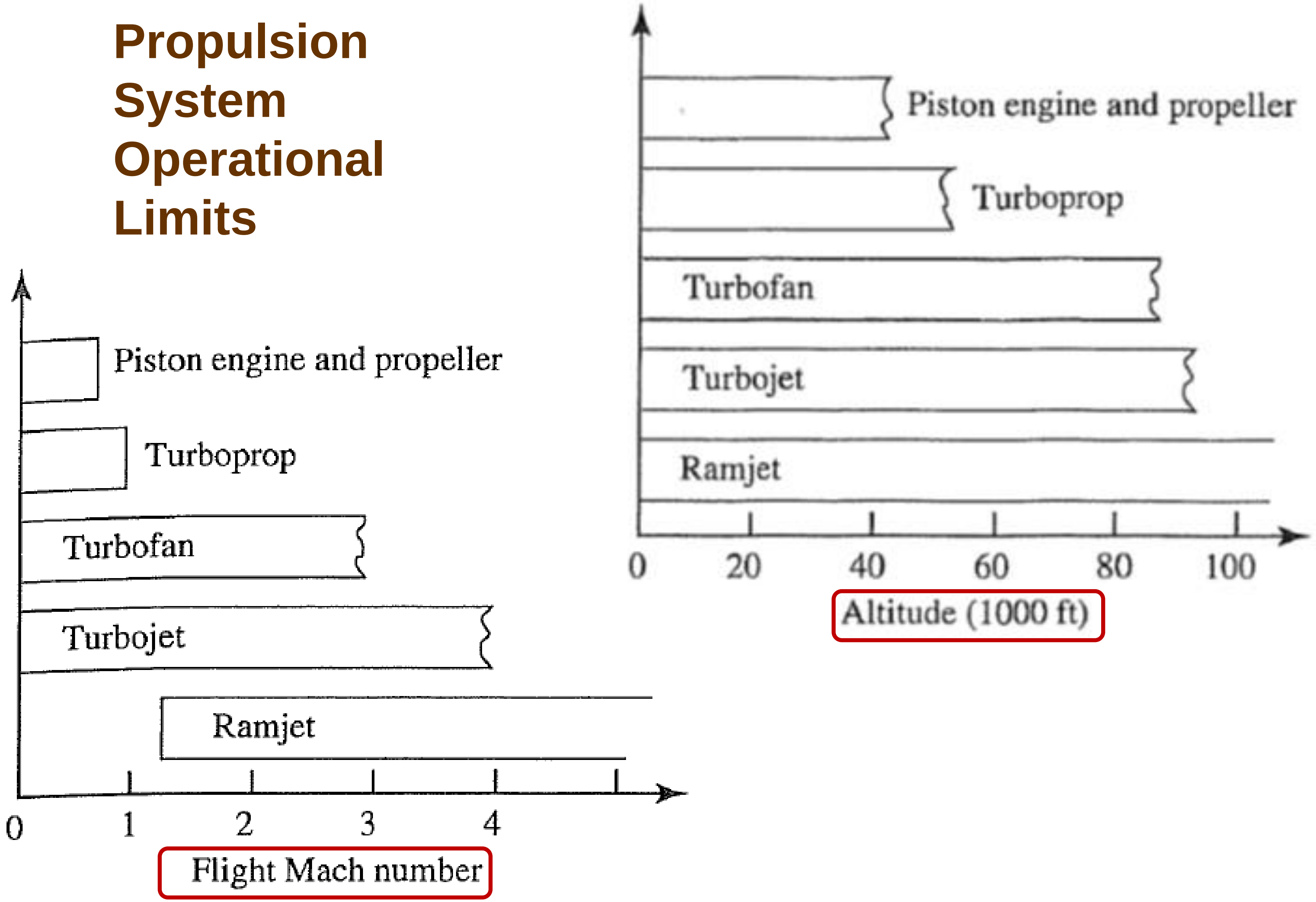
7.5.1 Turbine Engine (TE) Selection

Propulsion System Selection Key Considerations

- **Once we know the required thrust, T, the next challenge is to choose an engine—or more appropriately: *a suitable propulsion system***
- **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

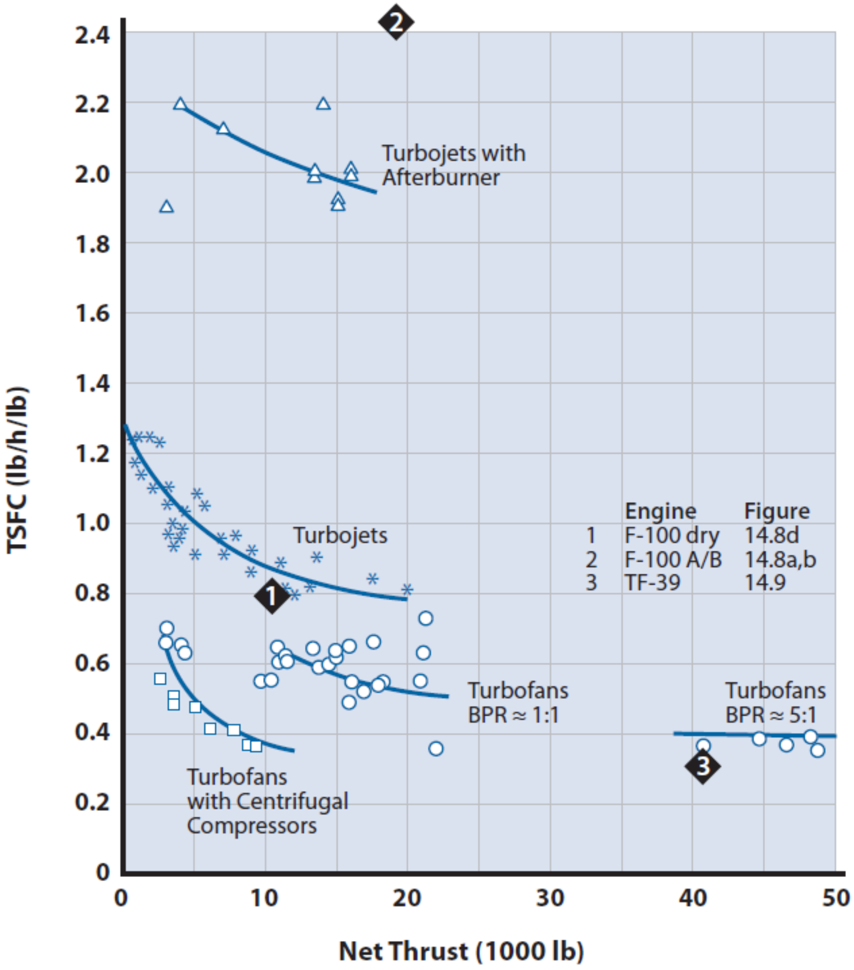
Propulsion System Operational Limits

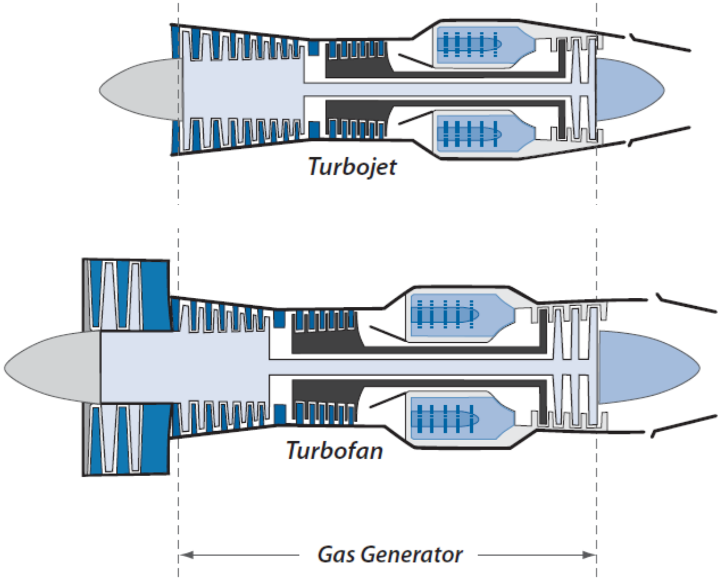


Source: Figs. 1.2 & 1.17b, Ref. PS 1 (Mattingly)

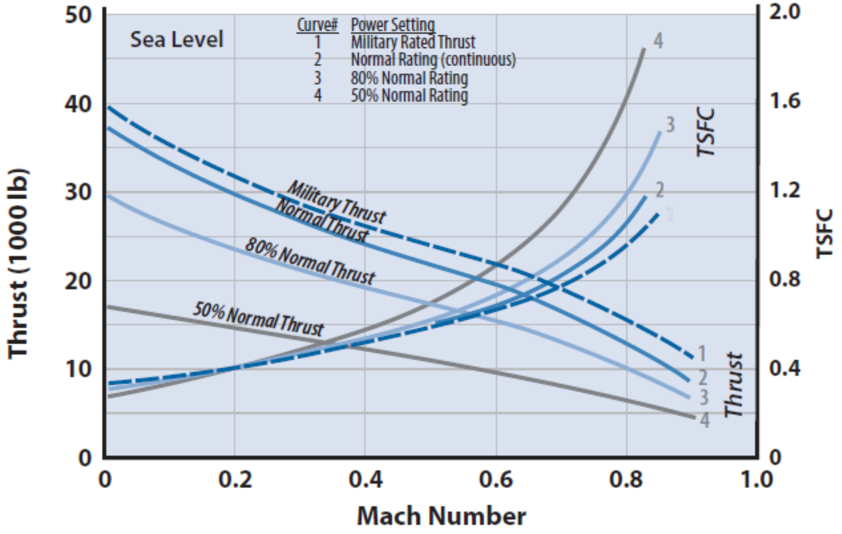
TE Propulsion System Selection

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





GE TF-39 Turbofan: Installed Thrust



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

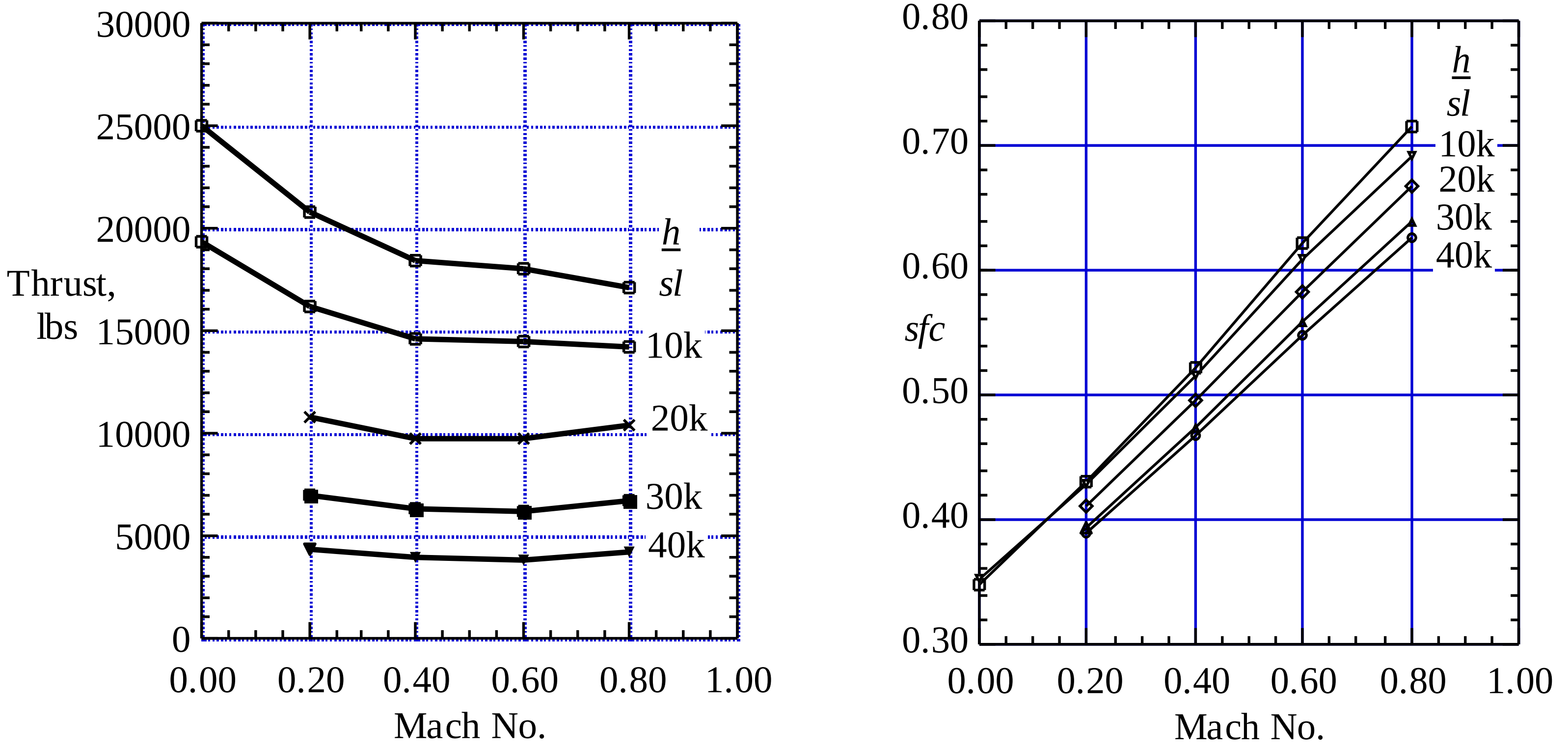
Propulsion Airframe Integration

- If at all possible, select an **available engine** that can meet the requirements
  - ***New engines built from scratch are VERY (VERY, VERY, VERY) expensive!***
- **Define the thrust and fuel flow** for the selected engine **throughout the flight envelope (various speeds and altitudes).** As a table, this is known as the *"Engine Deck"* from the days when the data was contained in a box of computer cards.
- Supply "engine deck" along with scaling and weight data to the performance team.
- Define the ***appropriate engine inlet and nozzle***, or propeller system, for each aircraft concept the team is investigating.
- Size the inlet capture area or the propeller diameter.
- **Estimate the installation losses.**
- With the aero and controls team– **define the thrust-drag bookkeeping system.**

Engine Airframe Integration

Obtain Thrust and *sfc* characteristics for your selected engine for various flight speeds and altitudes over the entire flight envelope for use in mission analysis

Examples from an AIAA Supplied Data Package



Note: Info from engine manufacturers is often nondimensionalized, the so-called “corrected” values. Make sure you know what you have!

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

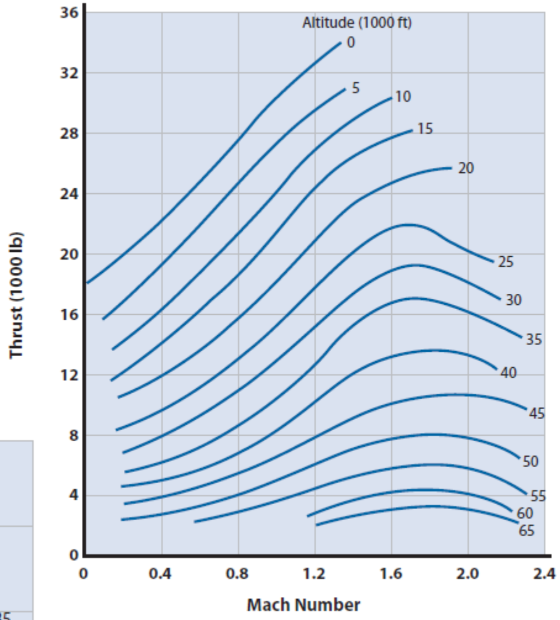
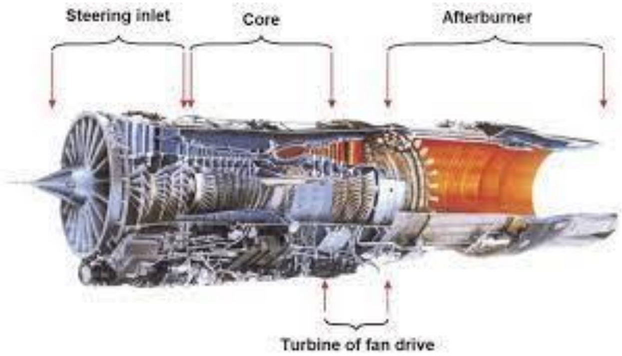


Figure 14.8a F-100 installed thrust, maximum afterburning.



Pratt & Whitney F100-PW229

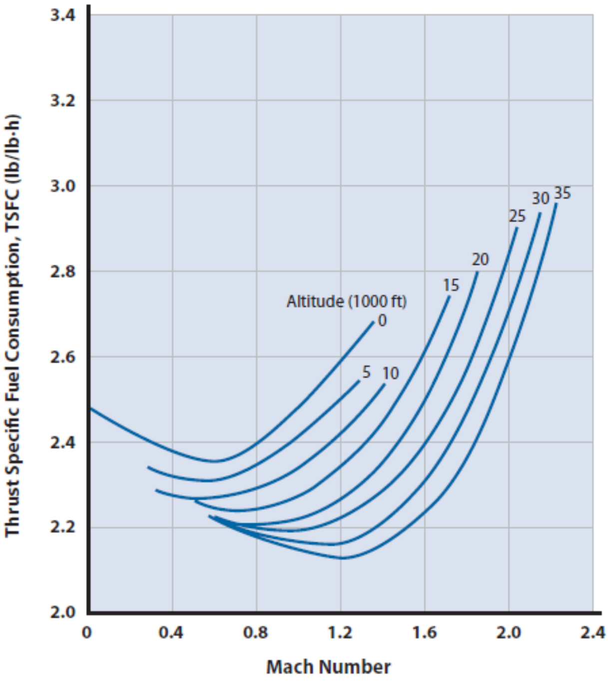


Figure 14.8b F-100 TSFC for maximum afterburning (low altitudes).

"Engine Decks" are the best performance model!

Source: Ref. AVD 1 (Nicolai & Carichner)

Thrust and TSFC Modeling

- **<u>If "Engine Deck" isn't available</u>, useful data might be available in *Flight Manuals* of aircraft equipped with the engine of interest**
- **More common problem: designers can obtain only *sketchy* information abut an engine, such as sea-level static thrust and associated TSFC, dry weight, and BPR from sources like *Jane's All the World's Aircraft Engines***
- **Designers then have no choice but to develop performance models from the available sketchy data**
- **Examples of simple Thrust Models (GED 2, Brandt *et al*) are shown in the table**
- **For TSFC and BSFC, Brandt *et al.* suggest ignoring small variations with Mach number and air temperature, and use the following expression *(for TSFC)***

$$c_t = c_{t_{\mathrm{SL}}}\sqrt{\frac{T}{T_{\mathrm{SL}}}}$$

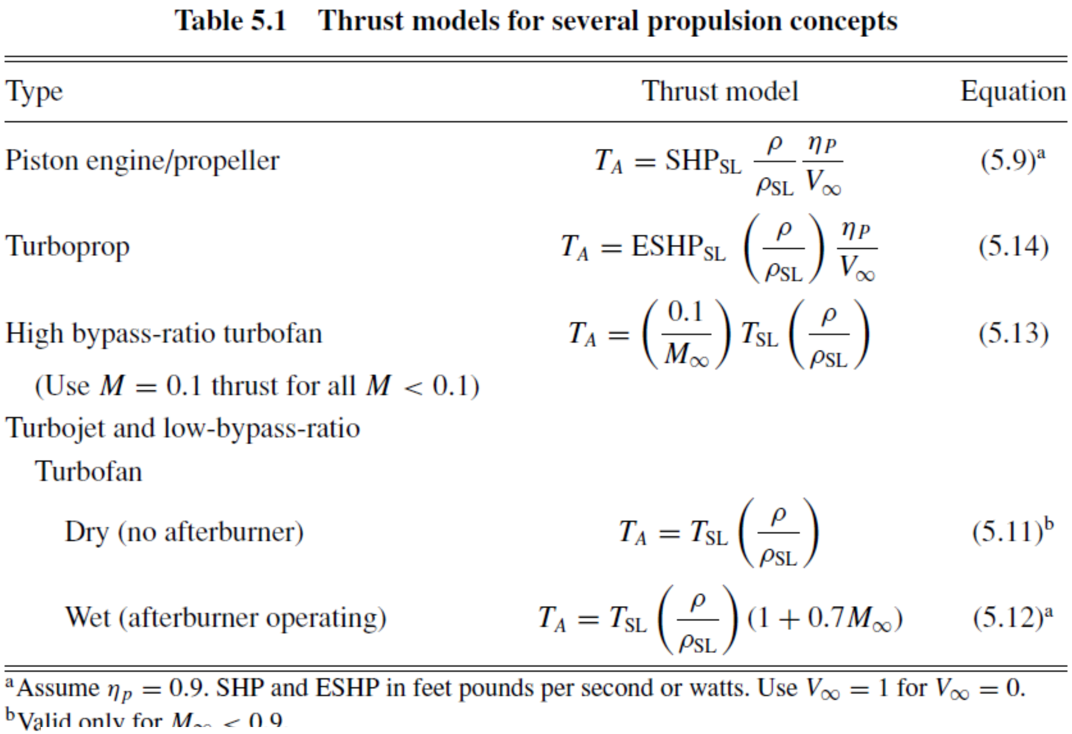


Table 5.1 Thrust models for several propulsion concepts

Type	Thrust model	Equation
Piston engine/propeller	$T_A = \mathrm{SHP}_{\mathrm{SL}}\,\frac{\rho}{\rho_{\mathrm{SL}}}\,\frac{\eta_P}{V_\infty}$	(5.9)[a]
Turboprop	$T_A = \mathrm{ESHP}_{\mathrm{SL}}\left(\frac{\rho}{\rho_{\mathrm{SL}}}\right)\frac{\eta_P}{V_\infty}$	(5.14)
High bypass-ratio turbofan	$T_A = \left(\frac{0.1}{M_\infty}\right)T_{\mathrm{SL}}\left(\frac{\rho}{\rho_{\mathrm{SL}}}\right)$	(5.13)
(Use $M = 0.1$ thrust for all $M < 0.1$)		
Turbojet and low-bypass-ratio Turbofan		
Dry (no afterburner)	$T_A = T_{\mathrm{SL}}\left(\frac{\rho}{\rho_{\mathrm{SL}}}\right)$	(5.11)[b]
Wet (afterburner operating)	$T_A = T_{\mathrm{SL}}\left(\frac{\rho}{\rho_{\mathrm{SL}}}\right)(1 + 0.7M_\infty)$	(5.12)[a]

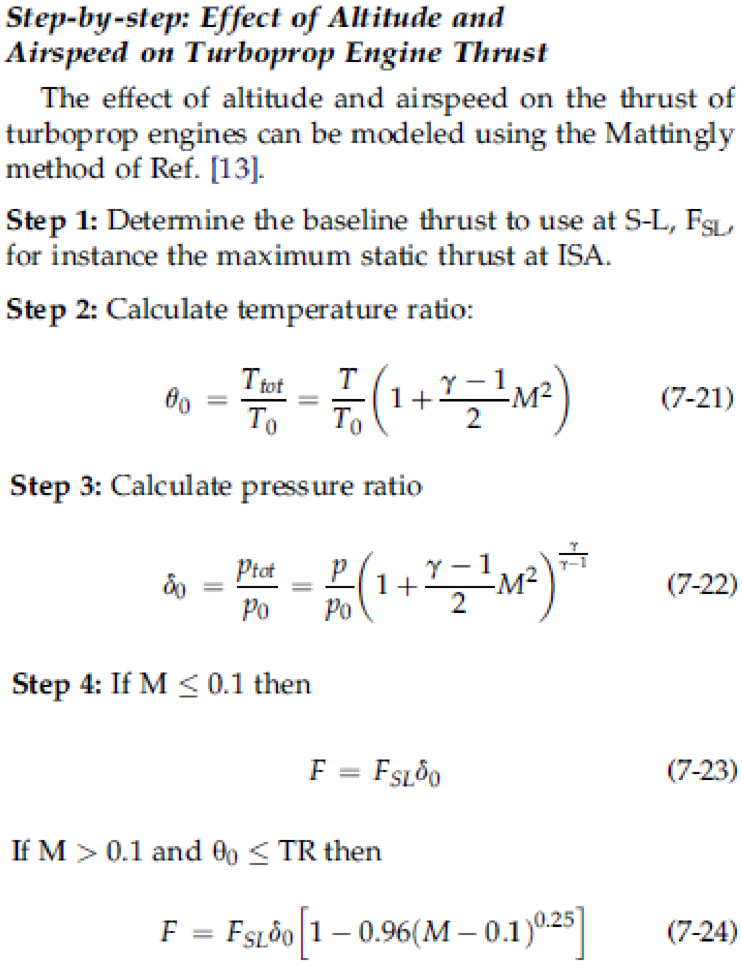
[a] Assume $\eta_p = 0.9$. SHP and ESHP in feet pounds per second or watts. Use $V_\infty = 1$ for $V_\infty = 0$.

[b] Valid only for $M_\infty < 0.9$

$$\mathrm{ESHP} = \mathrm{SHP} + T_j V / (0.8)(550)$$

Turbine Engine Thrust Modeling

- **AVD 4 (Gudmundsson) has more sophisticated performance models based on the Mattingly method (see PS 2):**
- **Turboprops Example**



Step-by-step: Effect of Altitude and Airspeed on Turboprop Engine Thrust

The effect of altitude and airspeed on the thrust of turboprop engines can be modeled using the Mattingly method of Ref. [13].

Step 1: Determine the baseline thrust to use at S-L, F_{SL}, for instance the maximum static thrust at ISA.

Step 2: Calculate temperature ratio:

$$\theta_0 = \frac{T_{tot}}{T_0} = \frac{T}{T_0}\left(1 + \frac{\gamma - 1}{2}M^2\right) \tag{7-21}$$

Step 3: Calculate pressure ratio

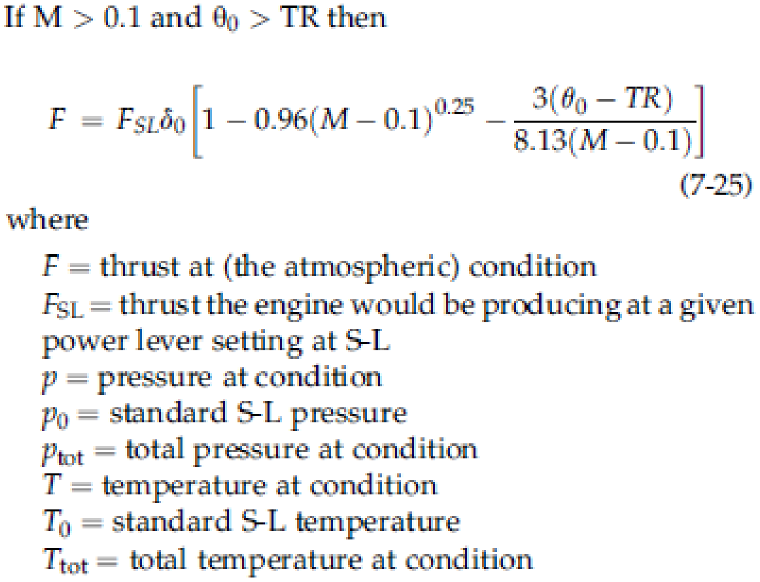
$$\delta_0 = \frac{p_{tot}}{p_0} = \frac{p}{p_0}\left(1 + \frac{\gamma - 1}{2}M^2\right)^{\frac{\gamma}{\gamma-1}} \tag{7-22}$$

Step 4: If $M \le 0.1$ then

$$F = F_{SL}\delta_0 \tag{7-23}$$

If $M > 0.1$ and $\theta_0 \le TR$ then

$$F = F_{SL}\delta_0\left[1 - 0.96(M - 0.1)^{0.25}\right] \tag{7-24}$$



If $M > 0.1$ and $\theta_0 > TR$ then

$$F = F_{SL}\delta_0\left[1 - 0.96(M - 0.1)^{0.25} - \frac{3(\theta_0 - TR)}{8.13(M - 0.1)}\right] \tag{7-25}$$

where

F = thrust at (the atmospheric) condition
F_{SL} = thrust the engine would be producing at a given power lever setting at S-L
p = pressure at condition
p_0 = standard S-L pressure
p_{tot} = total pressure at condition
T = temperature at condition
T_0 = standard S-L temperature
T_{tot} = total temperature at condition

TR = throttle ratio (see Sec. 7.2.2, AVD 4)

- **See Sec. 7.2.3 in AVD 4 (Gudmundsson) for Turbojets model, and Sec. 7.2.4 for Turbofans**

Turbine Engine TSFC Modeling

- **In the absence of "Engine Decks," installed sfc (or $TSFC$) may be estimated for various altitudes and Mach numbers using these expressions:**
    - **High-bypass-ratio turbofan** $sfc = (0.4 + 0.45M)\sqrt{\theta}$
    - **Low-bypass-ratio, mixed-flow turbofan**
        - Military and lower power settings $sfc = (1.0 + 0.35M)\sqrt{\theta}$
        - Maximum power setting $sfc = (1.8 + 0.30M)\sqrt{\theta}$
    - **Turbojet**
        - Military and lower power settings $sfc = (1.0 + 0.35M)\sqrt{\theta}$
        - Maximum power setting $sfc = (1.7 + 0.26M)\sqrt{\theta}$
    - **Turboprop** $sfc = (0.2 + 0.9M)\sqrt{\theta}$

where M is Mach number, and θ is static absolute temperature ratio at a given altitude from U.S. Standard Atmosphere table

- **For off-design conditions, increased sfc may be estimated using***

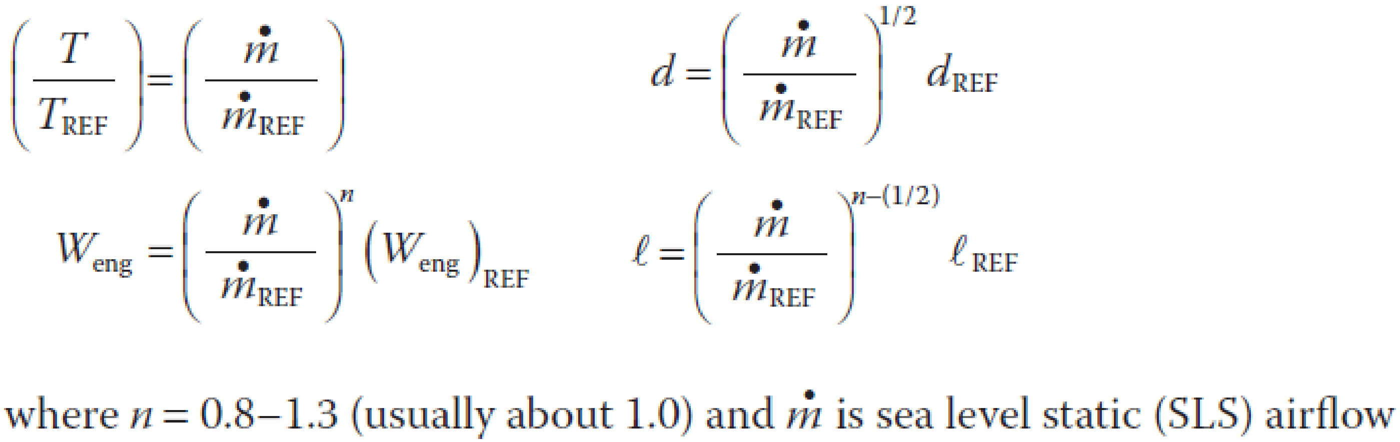
$$sfc_{off\text{-}des} = sfc\left[1 + 0.01\left\{(T/T_{offdes}) - 1\right\}\right]$$

**Dr. Bray, Cranfield University*

Source: Ref. PS 1 (Mattingly), pp 39-40

Turbine Engine Scaling for Performance Modeling

- **Turbine Engine Scaling is another approach to model the performance of the engine of interest for which we have estimated a sea-level static thrust**
- **We can use a <u>Reference Engine</u> for which the manufacturer has established the scaling laws**
- **Starting point for turbine engine scaling (AVD 1, Nicolai & Carichner)**



$$\left(\frac{T}{T_{\mathrm{REF}}}\right)=\left(\frac{\dot{m}}{\dot{m}_{\mathrm{REF}}}\right) \qquad d=\left(\frac{\dot{m}}{\dot{m}_{\mathrm{REF}}}\right)^{1/2} d_{\mathrm{REF}}$$

$$W_{\mathrm{eng}}=\left(\frac{\dot{m}}{\dot{m}_{\mathrm{REF}}}\right)^{n}\left(W_{\mathrm{eng}}\right)_{\mathrm{REF}} \qquad \ell=\left(\frac{\dot{m}}{\dot{m}_{\mathrm{REF}}}\right)^{n-(1/2)} \ell_{\mathrm{REF}}$$

where $n = 0.8$–1.3 (usually about 1.0) and $\dot{m}$ is sea level static (SLS) airflow

- **<u>Be careful of scaling engines more than 20%</u>**

7.5.2 Turbine Engine Integration

- **Strongly recommend looking at Sect. 10.3, Ch. 10, PS 1 (Mattingly) and Sect. 7.3.4, Ch. 7, AVD 4 (Gudmundsson)**
- **Make sure to account for engine installation losses (See Ch. 16 in AVD 1, and also look at AVD 2)**

7.5.3 Propeller Selection

Propeller Selection

(Sect. 14.3 & 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:

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

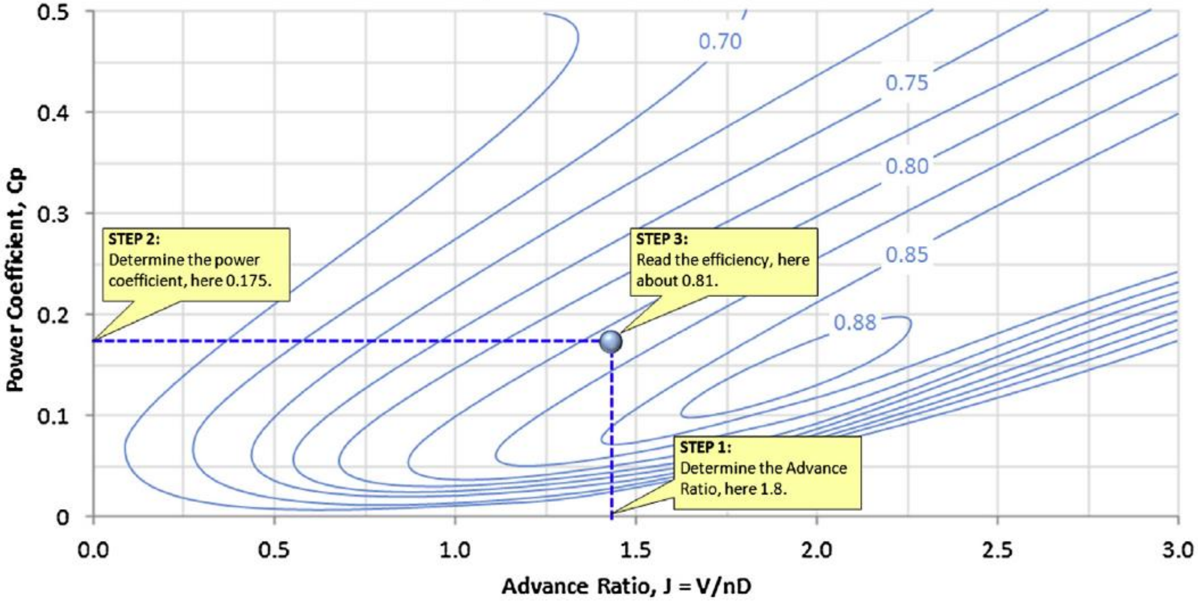
Power-Torque relation:

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

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: Sec. 14.4 discusses converting BHP into thrust

Required Propeller Size and Efficiency

- **Engine Power Supplied to the Propeller**

Estimate Power (P_{BHP}) using W/P or P/W vs. W/S from Initial Sizing data or Constraint Plot

- **Required Diameter**

Two-bladed metal propellers:

$$D = 22\sqrt[4]{P_{BHP}}\ (\text{in inches})$$

Three-bladed metal propellers:

$$D = 18\sqrt[4]{P_{BHP}}\ (\text{in inches})$$

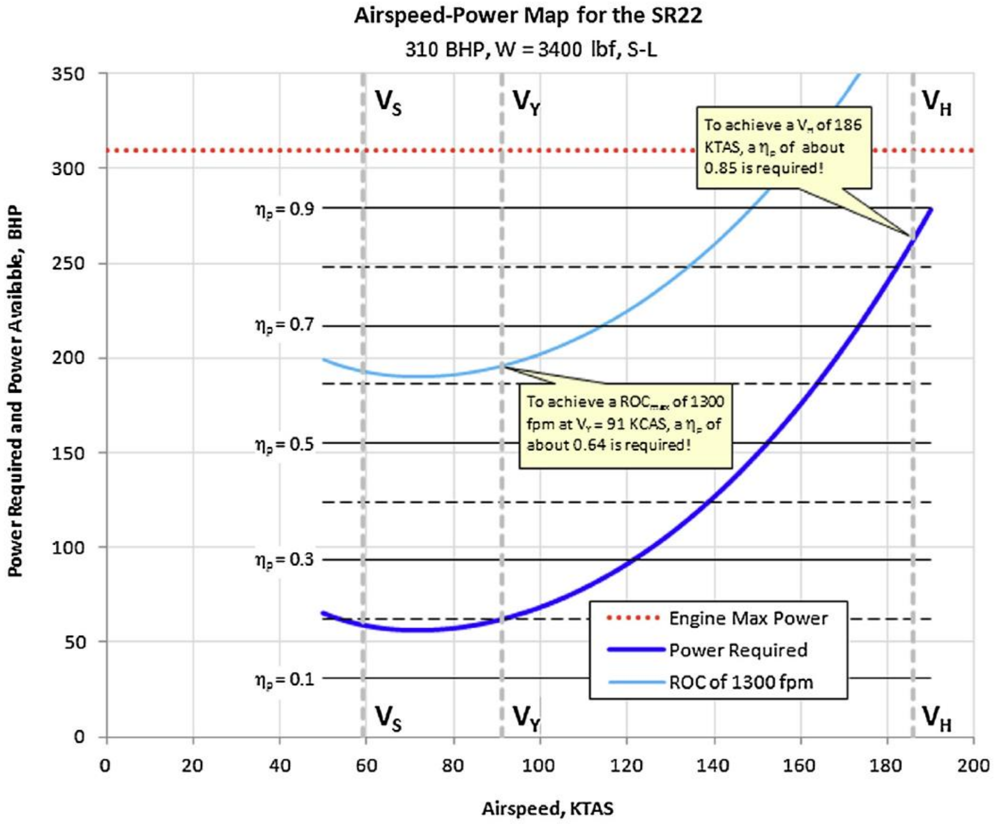
Propeller diameter:

$$D = K_p\sqrt[4]{P_{BHP}}$$

TABLE 14-2 Factor K_p for Typical Propeller Types

Type of Propeller	K_p for P in BHP and D in Inches	K_p for P in kW and D in m
Two-bladed	20.4	0.56
Three-bladed	19.2	0.52
Four or more blades	18.0	0.49

- **Required Efficiency (for ROC)**



Airspeed-Power Map for the SR22

310 BHP, W = 3400 lbf, S-L

To achieve a V_H of 186 KTAS, a η_p of about 0.85 is required!

To achieve a ROC_{max} of 1300 fpm at V_Y = 91 KCAS, a η_p of about 0.64 is required!

Source: Sect. 14.3, Ch. 14, AVD 4 Gudmundsson)

Generic Propeller Information

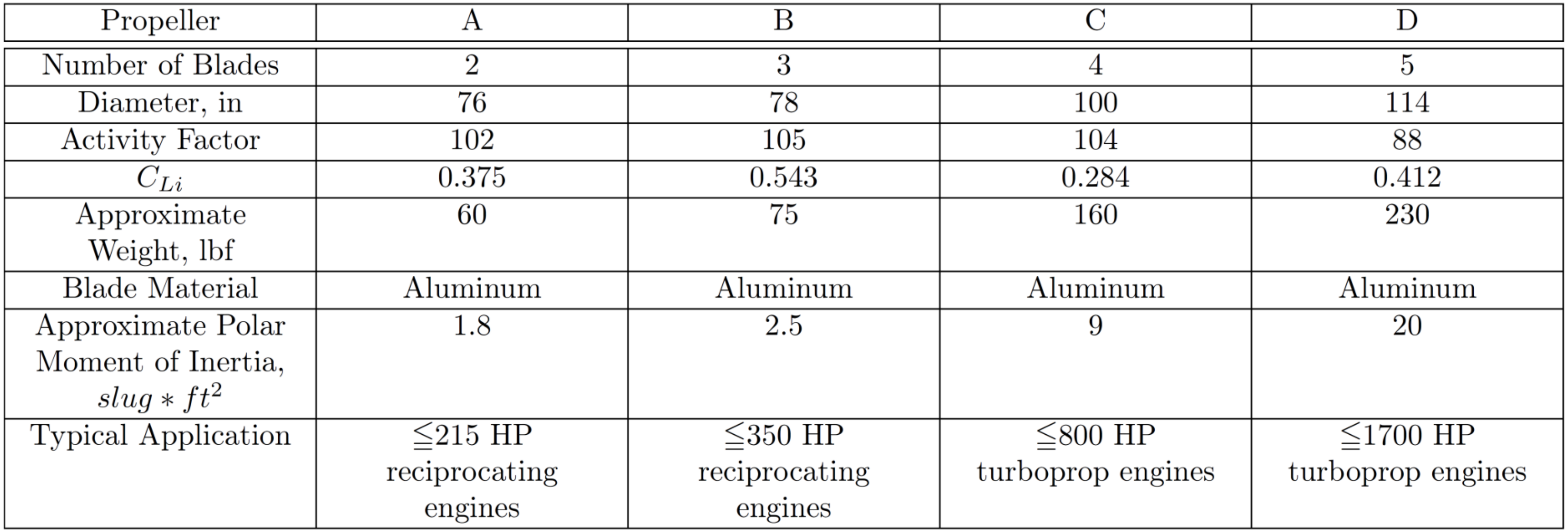
Provided by Hartzell Propeller, Inc. (April 12, 2022)

- **Motivation**

  Hartzell is unable to field the number and variety of requests for information from individuals for their own specific project of interest. Sometimes the requested information is proprietary and/or confidential and cannot be shared. However, we still wish to help, so we have assembled the following document and attachments to provide some technical information to assist you in your efforts.

- **Basic Data**

  The table below shows some basic geometric data for four general propellers. These propellers do not correspond to any real, particular propeller configuration, but are representative.



Propeller	A	B	C	D
Number of Blades	2	3	4	5
Diameter, in	76	78	100	114
Activity Factor	102	105	104	88
C_{Li}	0.375	0.543	0.284	0.412
Approximate Weight, lbf	60	75	160	230
Blade Material	Aluminum	Aluminum	Aluminum	Aluminum
Approximate Polar Moment of Inertia, $slug * ft^2$	1.8	2.5	9	20
Typical Application	≦215 HP reciprocating engines	≦350 HP reciprocating engines	≦800 HP turboprop engines	≦1700 HP turboprop engines

Generic Propeller Information

Provided by Hartzell Propeller, Inc. (April 12, 2022)

- **Performance Data**

Hartzell provided tabular data for Thrust Coefficient (C_T), Blade Angle (β), and Efficiency (η) as a function of Power Coefficient (C_P) and Advance Ratio (J) that can be calculated using the following expressions

(a) Power Coefficient

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

P = shaft horse power (HP) delivered to propeller
ρ = air density at flight conditions in slugs/ft^3
n = propeller speed in RPM
D = propeller diameter in ft.

(b) Advance Ratio

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

V_0 = true airspeed in ft/s (=1.688V_K)
V_K = true airspeed in knots

(c) Helical Tip Mach Number

$$M_{HT} = \frac{\sqrt{(V_K \times 1.688)^2 + (\pi \times n \times D)^2}}{a}$$

a = speed of sound for the flight condition

(d) Use C_P, J, and M_{HT} to look up or interpolate C_T, β, and η from the maps

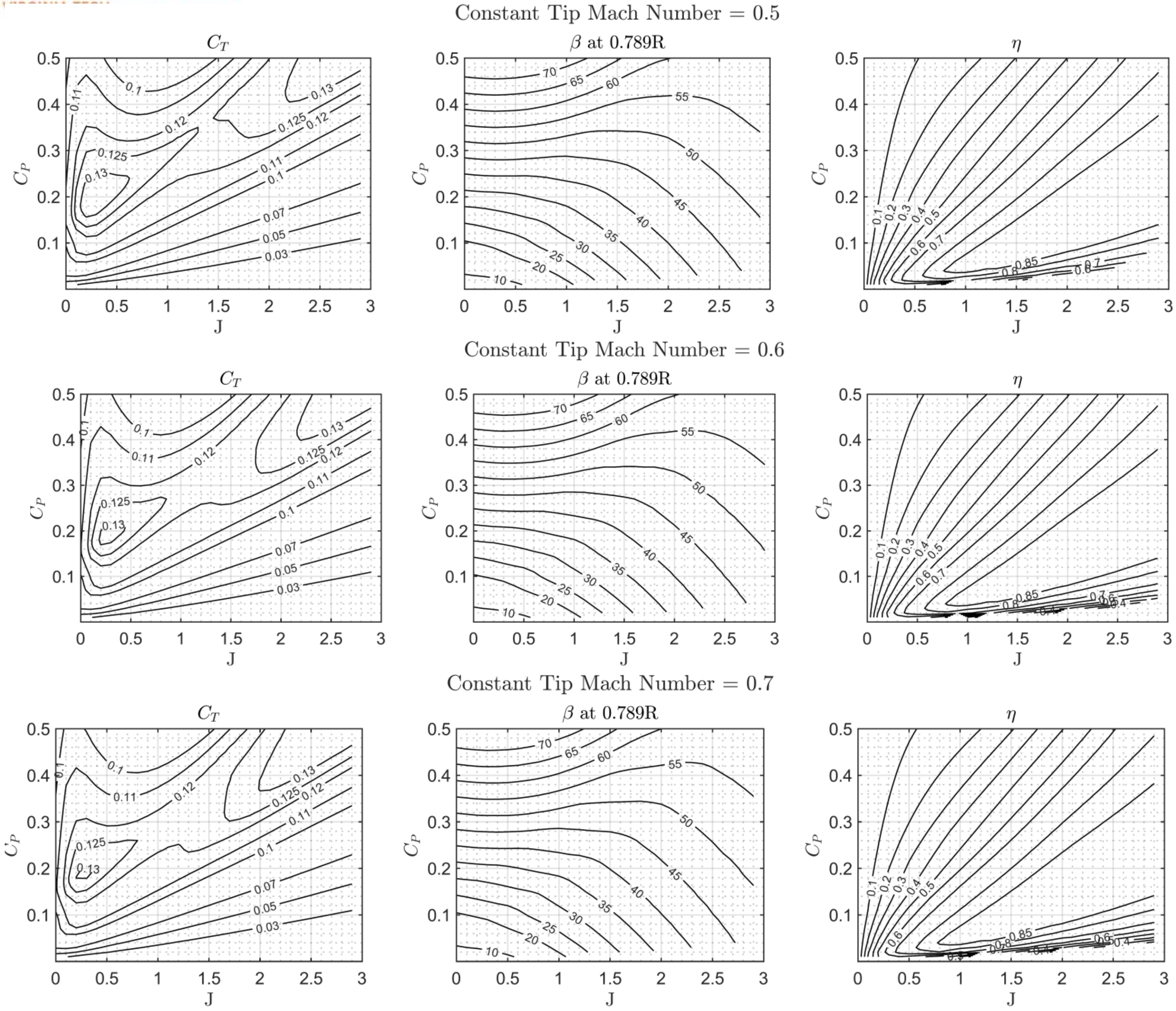
(e) Calculate pounds of thrust: $Thrust = C_T \times \rho \times n^2 \times D^4$

- **Requirements for Using Data:** Must credit the source of data as **Hartzell Propeller, Inc.**

You must agree and acknowledge:

(1) Hartzell Propeller, Inc., assumes no obligation or liabilities associated with this distribution of data
(2) Hartzell Propeller, Inc., provides no warranties or guarantees associated with this distribution of data

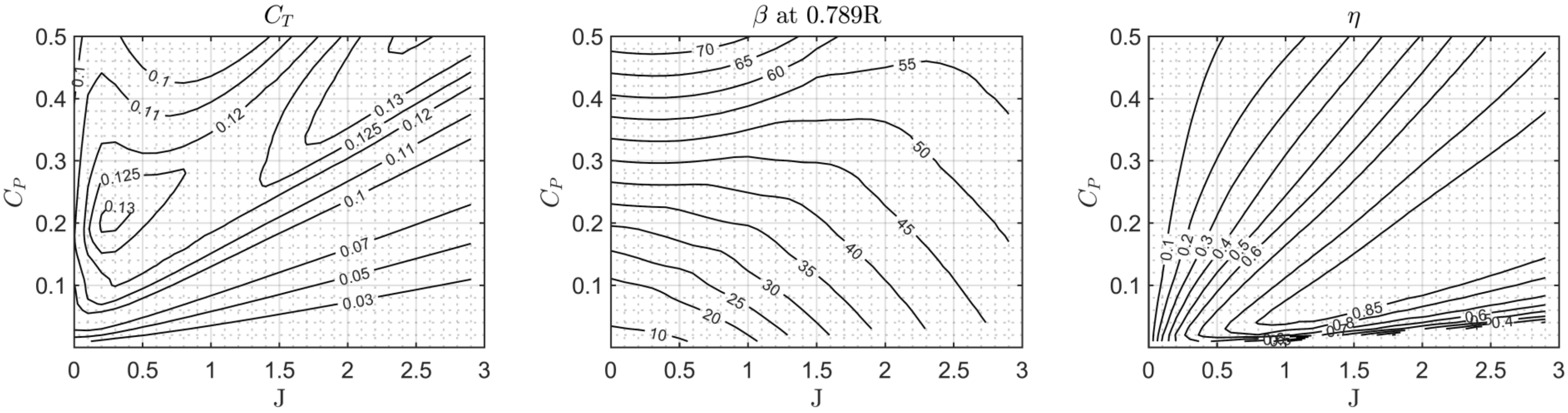
Propeller A Data (1 of 2)



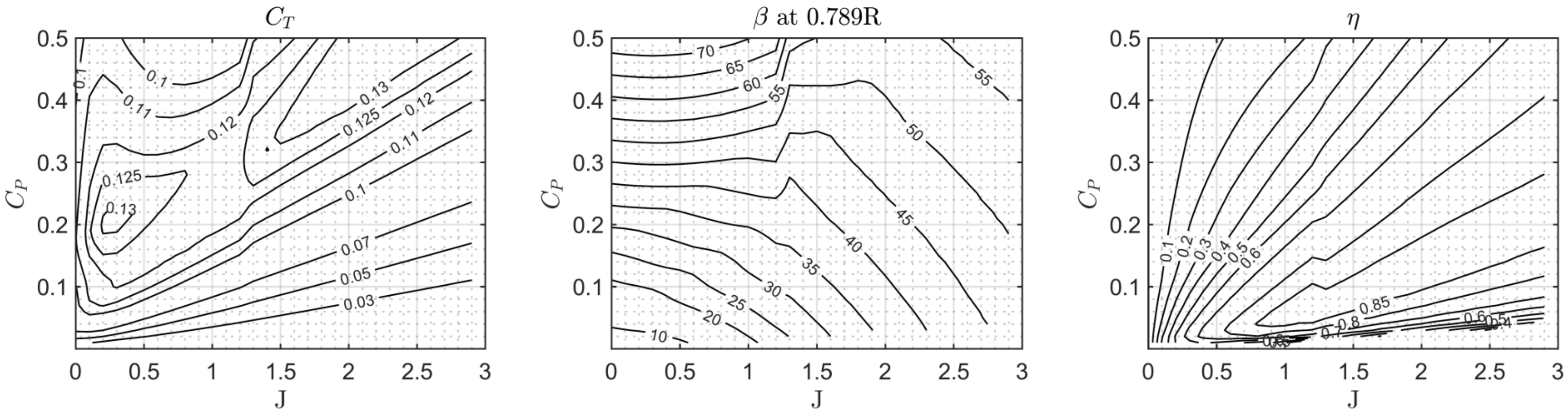
Source: Provided by Hartzell Propeller, Inc. (April 12, 2022)

Propeller A Data (2 of 2)

Constant Tip Mach Number = 0.8



Constant Tip Mach Number = 0.9

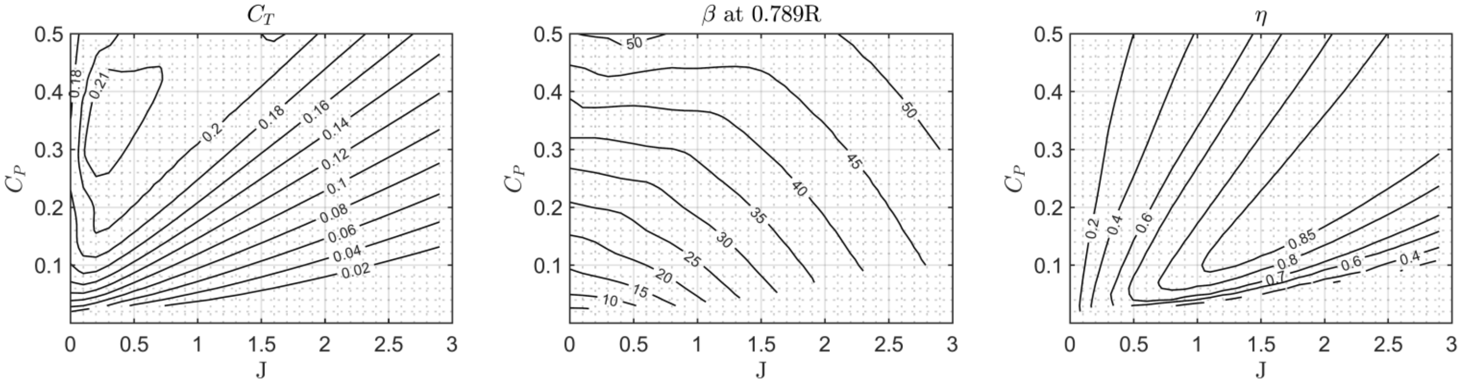


Note: Please see the instructor for tabular data

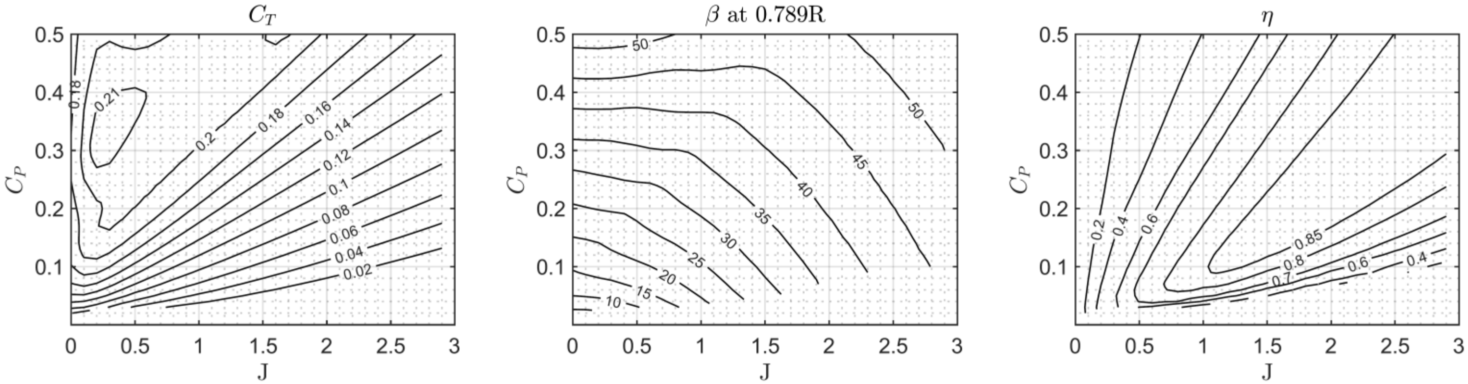
Source: Provided by Hartzell Propeller, Inc. (April 12, 2022)

Propeller B Data (1 of 2)

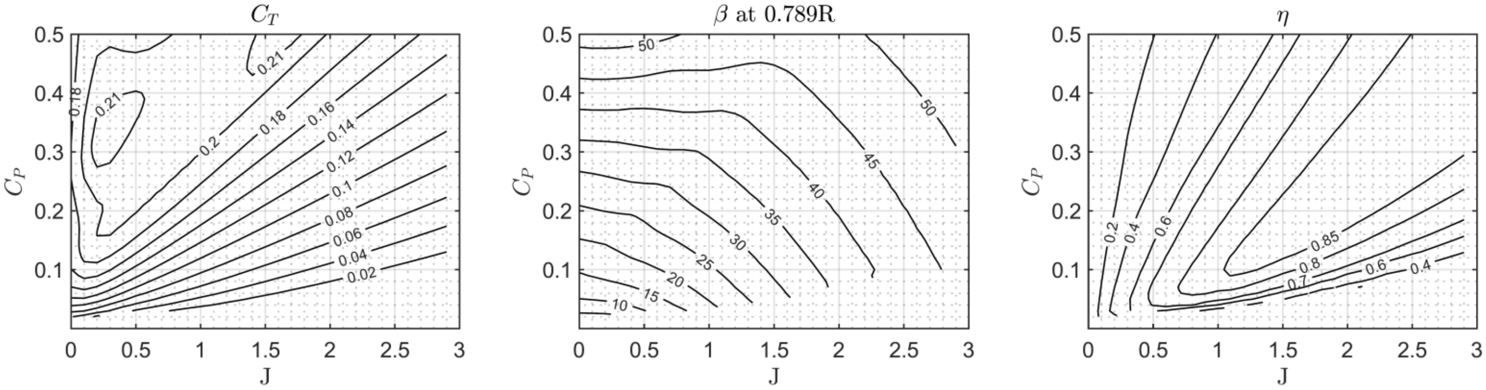
Constant Tip Mach Number = 0.5



Constant Tip Mach Number = 0.6

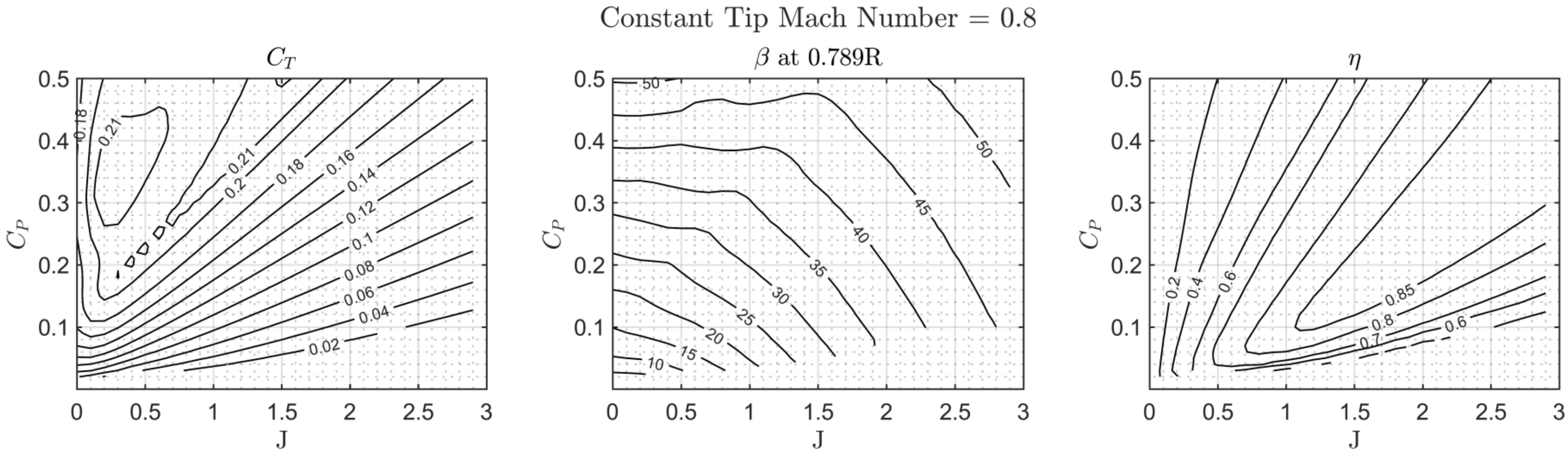


Constant Tip Mach Number = 0.7



Source: Provided by Hartzell Propeller, Inc. (April 12, 2022)

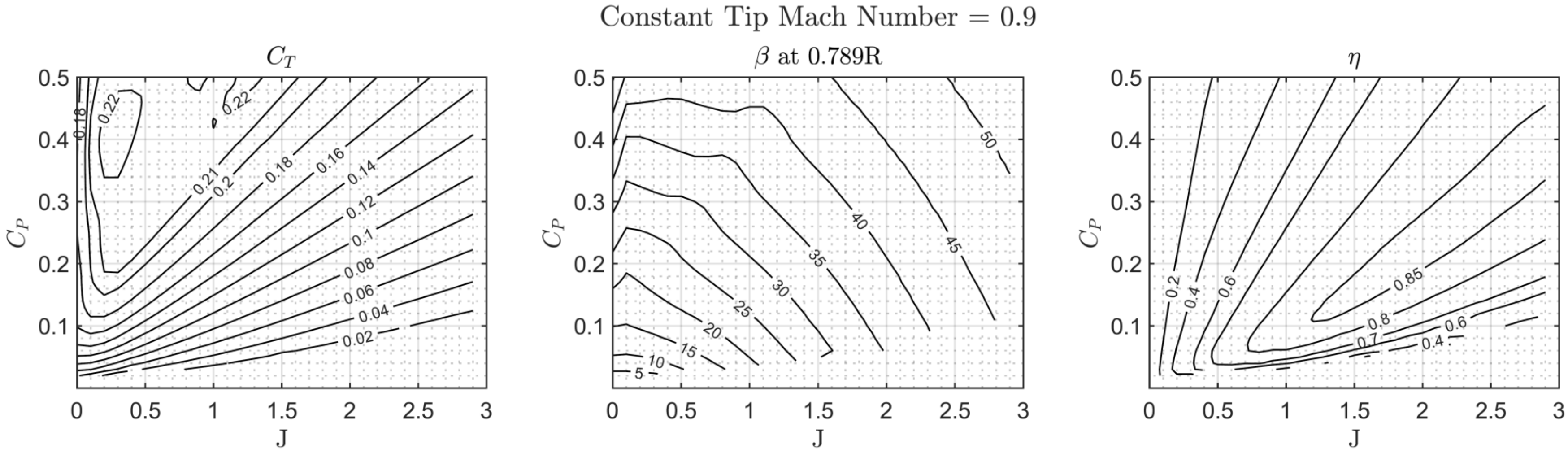
Propeller B Data (2 of 2)


Constant Tip Mach Number = 0.8

C_T

β at 0.789R

η


Constant Tip Mach Number = 0.9

C_T

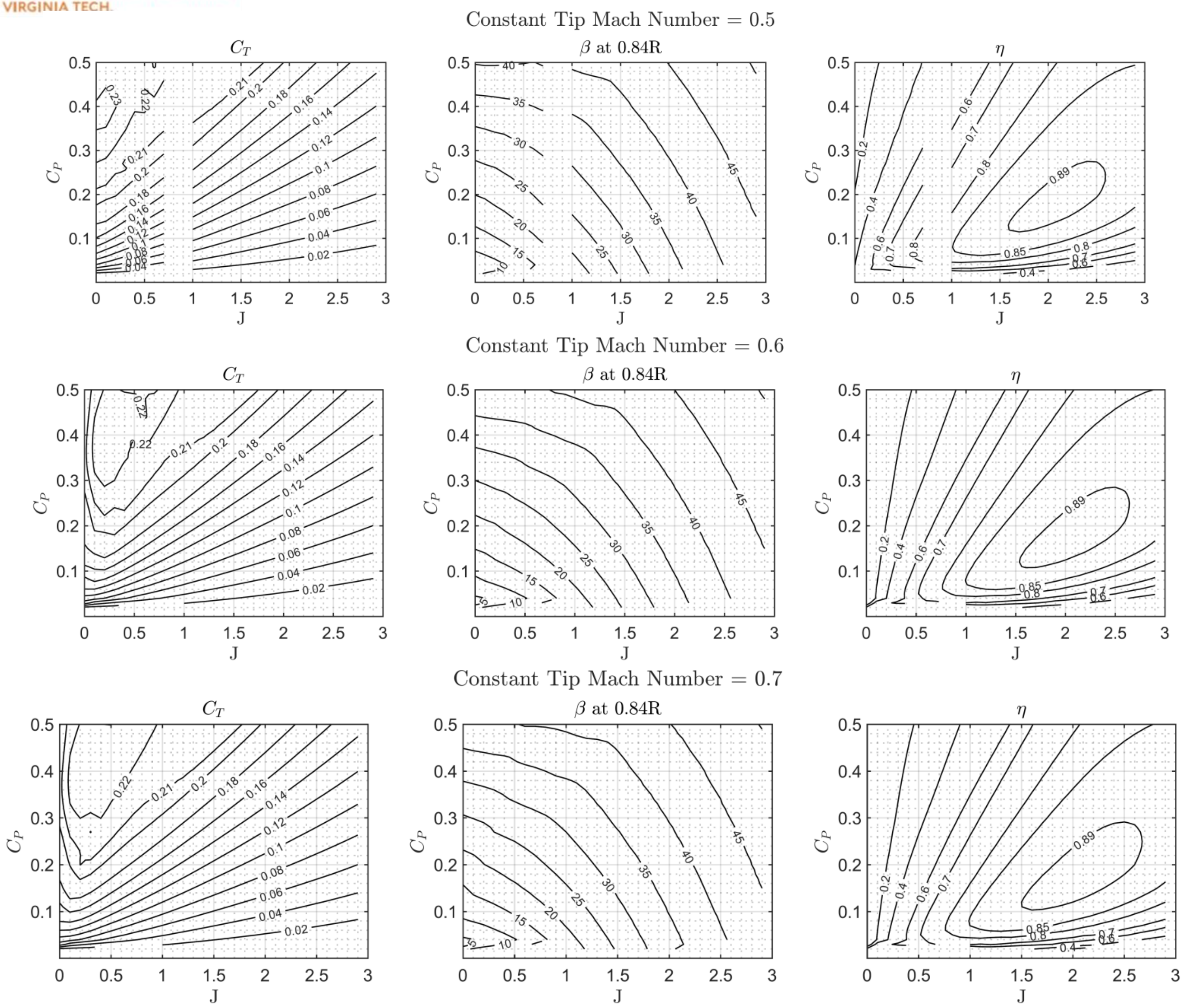
β at 0.789R

η

Note: Please see the instructor for tabular data

Source: Provided by Hartzell Propeller, Inc. (April 12, 2022)

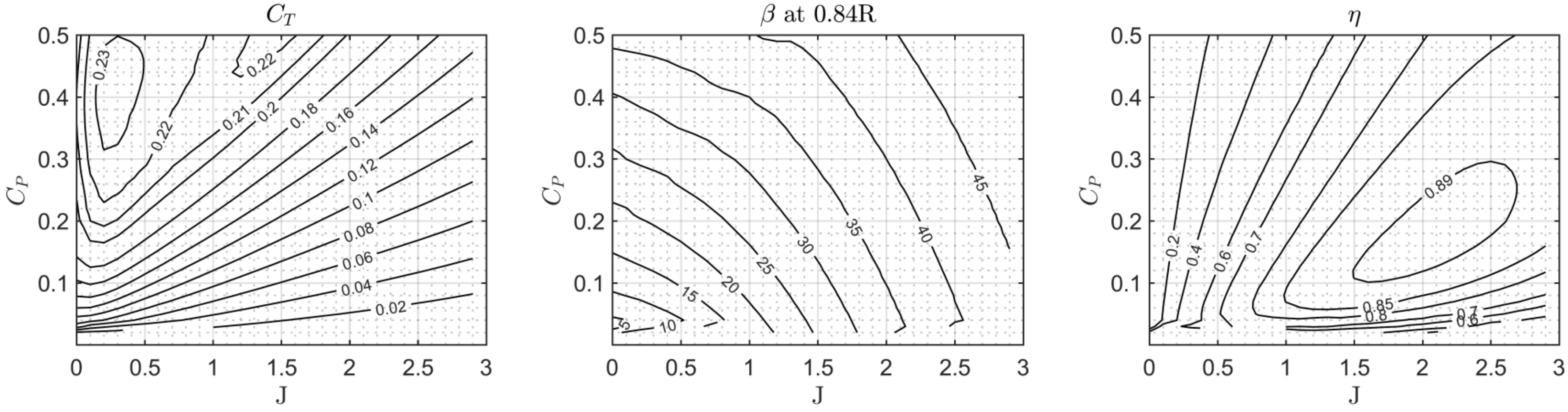
Propeller C Data (1 of 2)



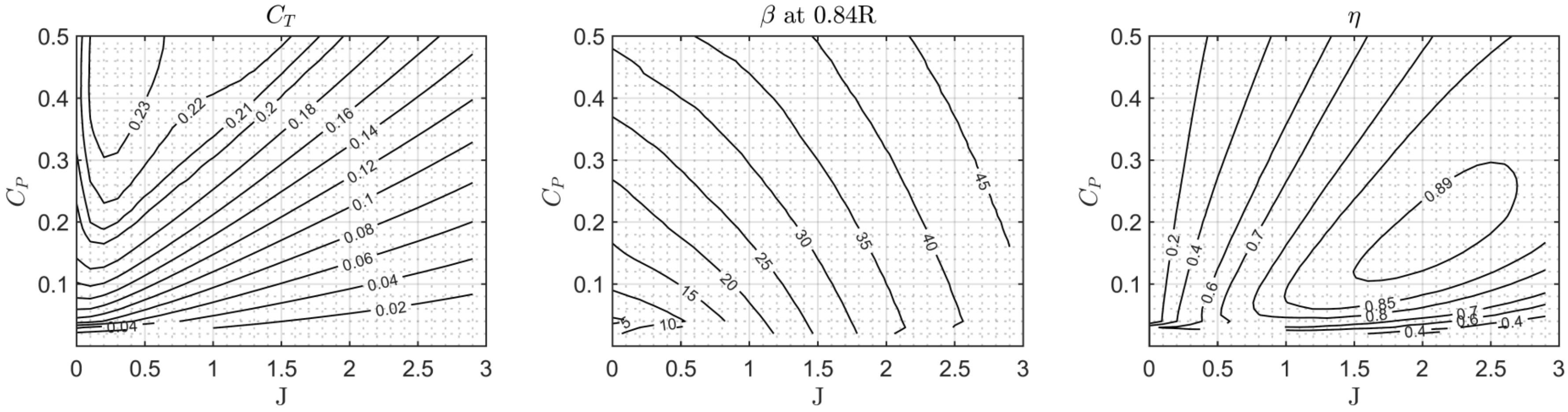
Source: Provided by Hartzell Propeller, Inc. (April 12, 2022)

Propeller C Data (2 of 2)

Constant Tip Mach Number = 0.8



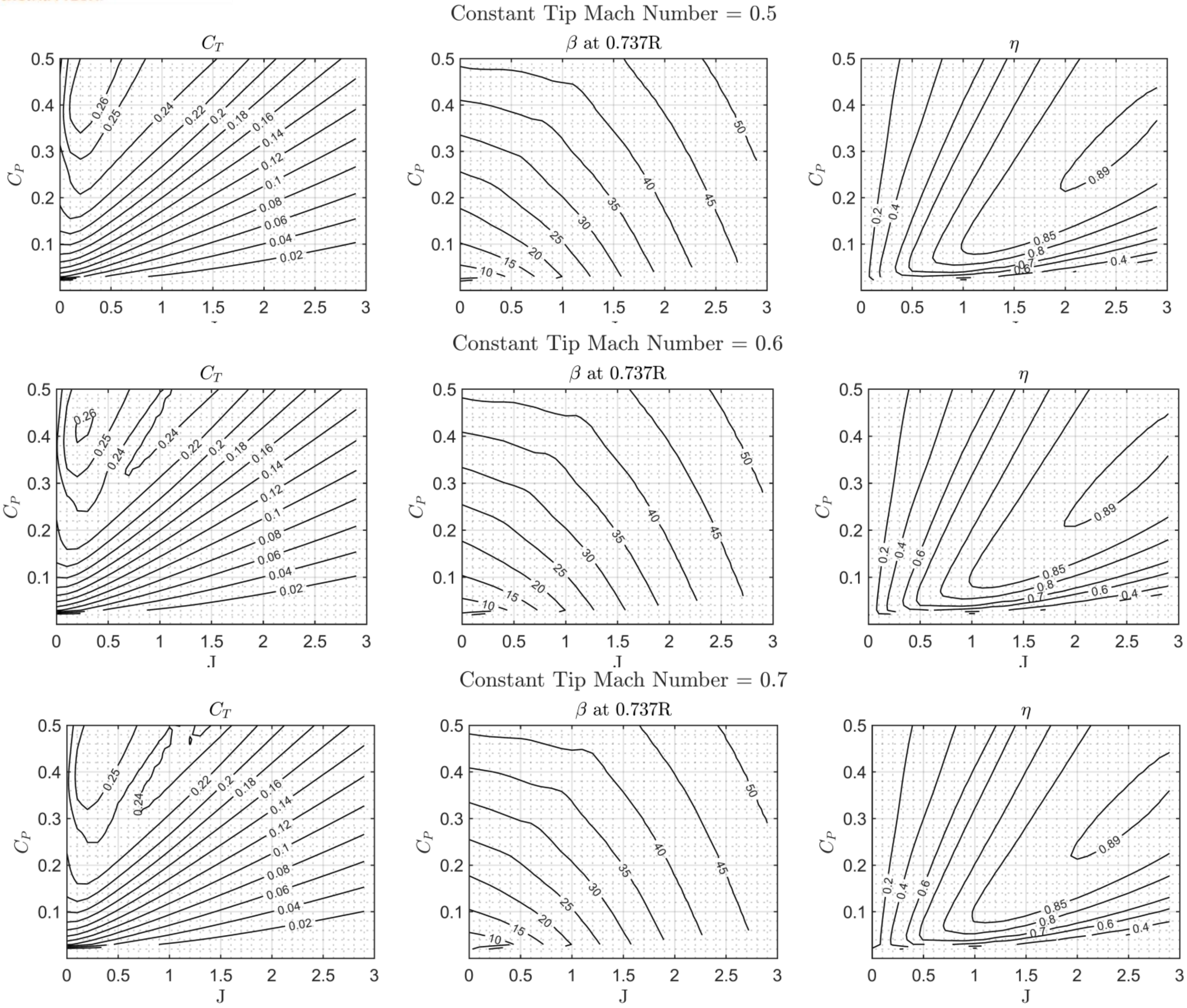
Constant Tip Mach Number = 0.9



Note: Please see the instructor for tabular data

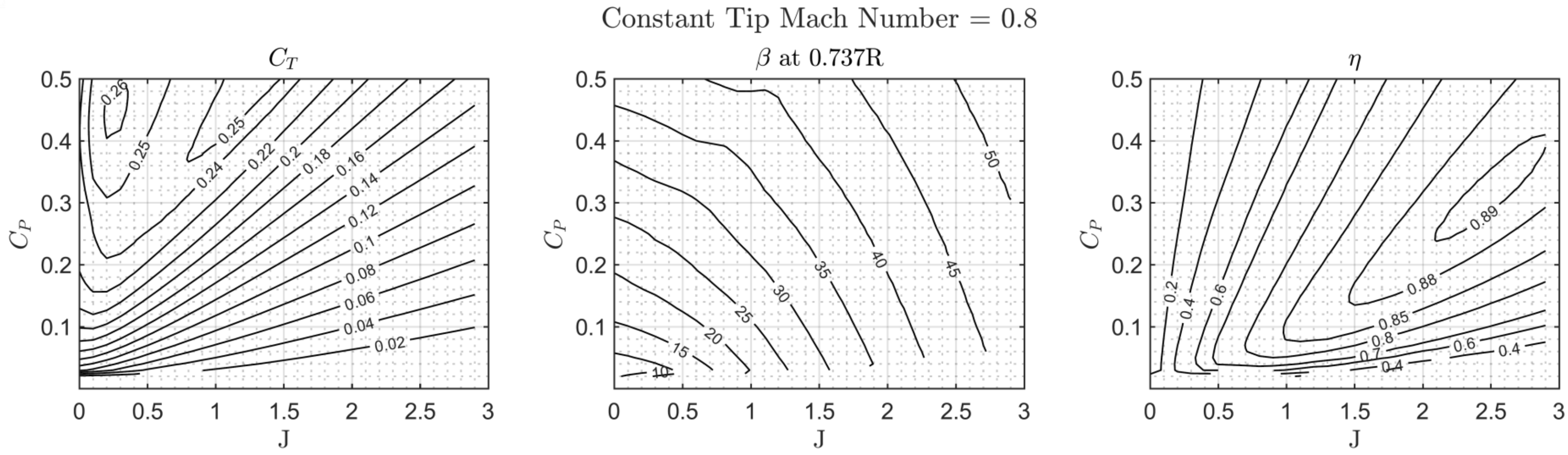
Source: Provided by Hartzell Propeller, Inc. (April 12, 2022)

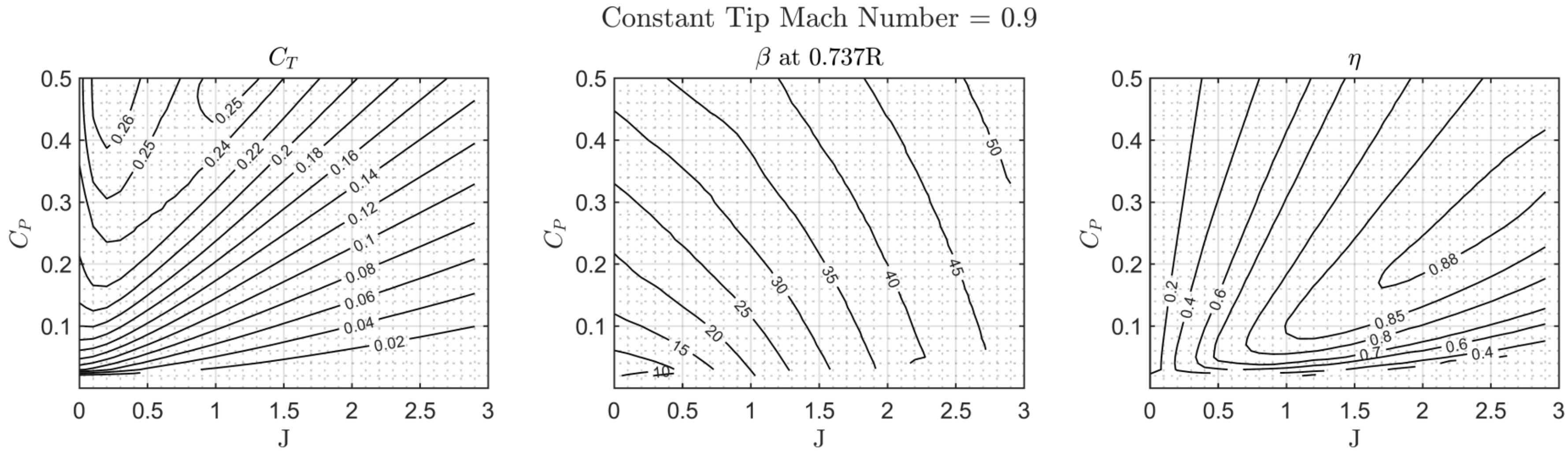
Propeller D Data (1 of 2)



Source: Provided by Hartzell Propeller, Inc. (April 12, 2022)

Propeller D Data (2 of 2)





Note: Please see the instructor for tabular data

Source: Provided by Hartzell Propeller, Inc. (April 12, 2022)

Outline

A7.0 Key Considerations for Configuration Layout

Many Choices for Landing Gear: *Highly Aircraft Dependent*

Things to Consider

- *Tipback and turnover*
- *Number and size of tires and wheels, brakes and shock absorbers--comply with industry best practices and federal standards*
- *Floatation*
- *Light weight*
- *Static and dynamic loads*
- *Runway surfaces*
- *Stability during taxi and takeoff*
- *Stability during touchdown and braking*
- *Ground maneuvers*
- *Steering qualities*
- *…*
- *…*


Tricycle

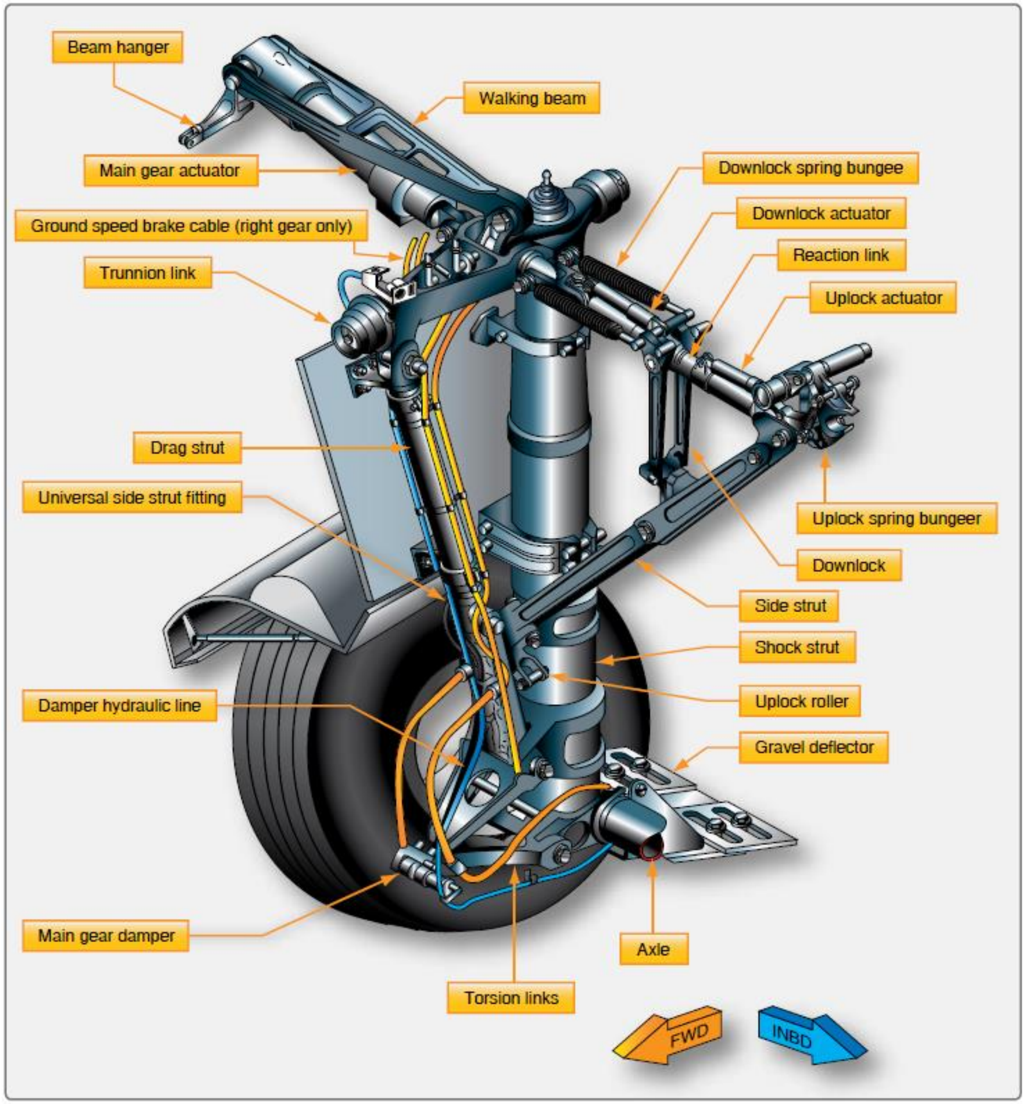

Tricycle


Quadricycle


Bicycle

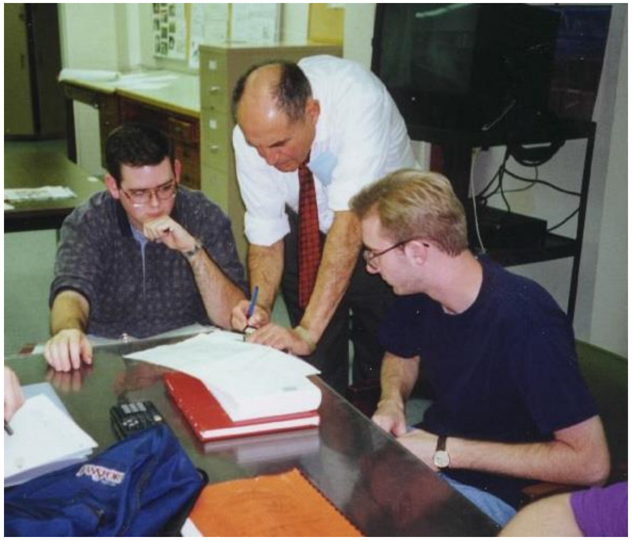

Taildragger

Landing Gear—*A Marvelous Piece of Machinery*!



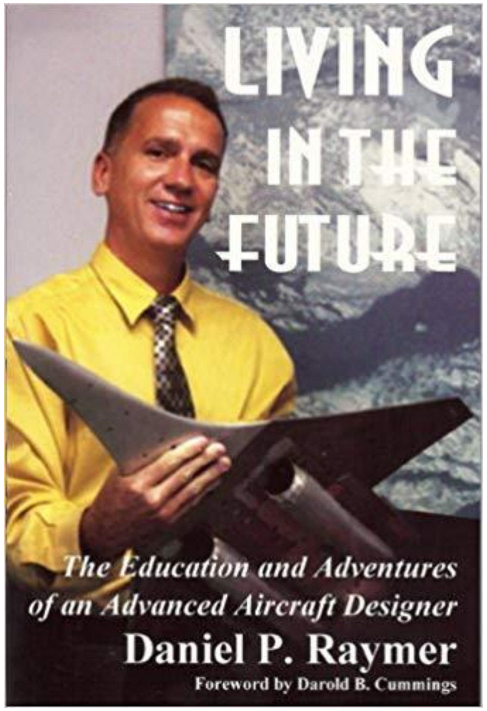
Source:https://www.faa.gov/regulations_policies/handbooks_manuals/aircraft/amt_airframe_handbook/media/ama_Ch13.pdf

> ***"…you do not have an airplane if you cannot attach the landing gear and stow it away upon retraction."***
> ***-- Kirschbaum***



Nathan Kirschbaum

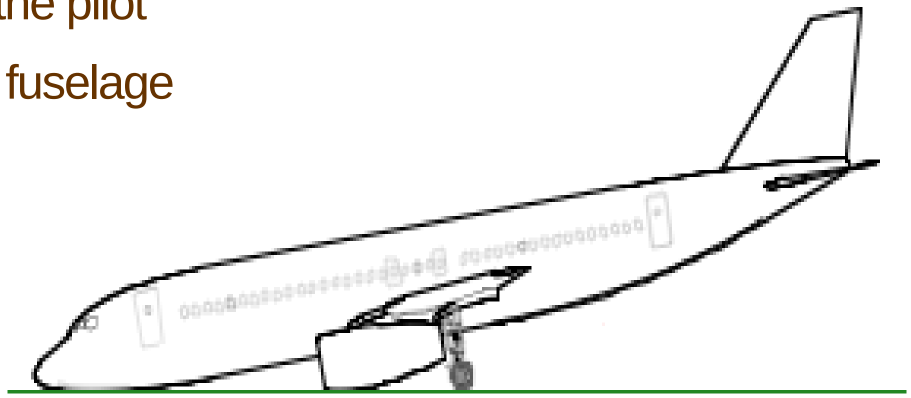
Helping students, mid 1990s

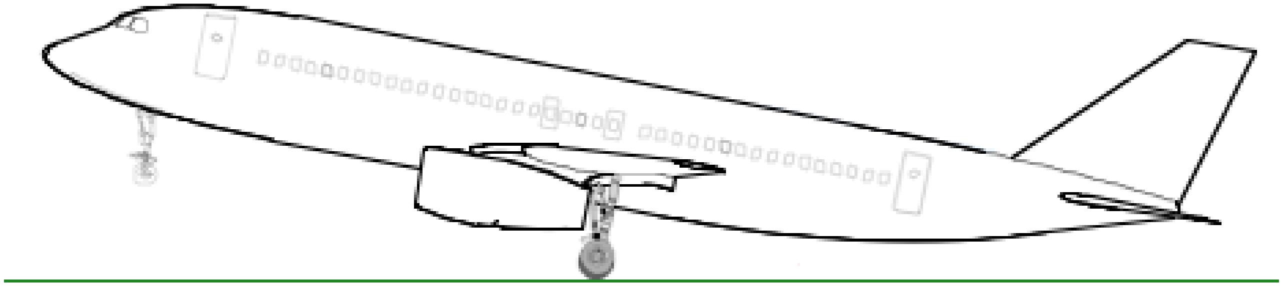


> ***"Landing gear will ruin your layout more than anything else, so plan ahead."***
> ***-- Raymer***

Landing Gear:
Sizing Considerations (Civil Aircraft)

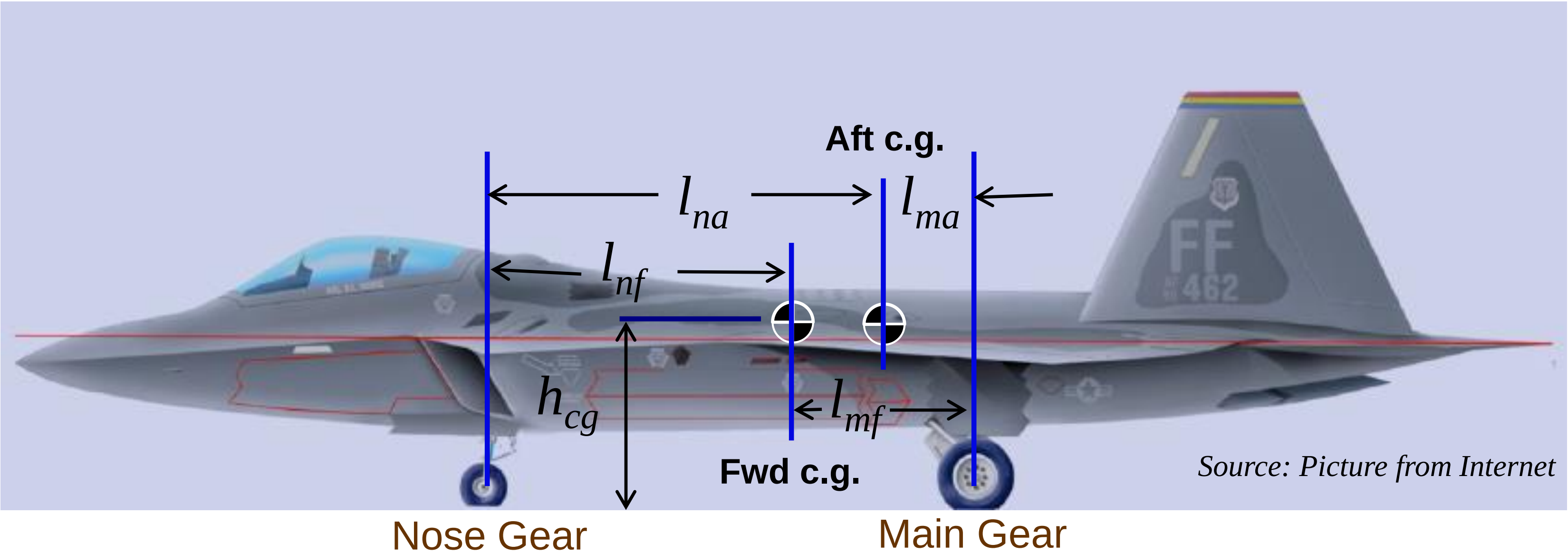
- Nose gear should be located beneath the pilot
- Wing should be located as high on the fuselage as possible but beneath the cabin floor
- Design options are:
  - Lengthen the landing gear
  - Increase inboard section dihedral
  - Flatten nacelle lower mold line





- Designer should define the tail cone upsweep angle and required clearance
- Wing location and dihedral are fixed, so landing gear length becomes the design parameter
- Either tail cone clearance or nacelle clearance may determine main gear length

[Tricycle] Landing Gear Sizing and Arrangement for Load Sharing and Steering



Source: Picture from Internet

Nose Gear

Max Static Load = $W*l_{mf}/(l_{na} + l_{ma})$

Min Static Load = $W*l_{ma}/(l_{na} + l_{ma})$

Dynamic Braking Load = $10W*h_{cg}/g(l_{na} + l_{ma})$
corresponds to 10 ft/sec sink rate

Main Gear

Max Static Load = $W*l_{na}/(l_{na} + l_{ma})$

Correctly locating Landing Gears requires c.g. location

For good steering, nose gear must not carry too much or too little load:

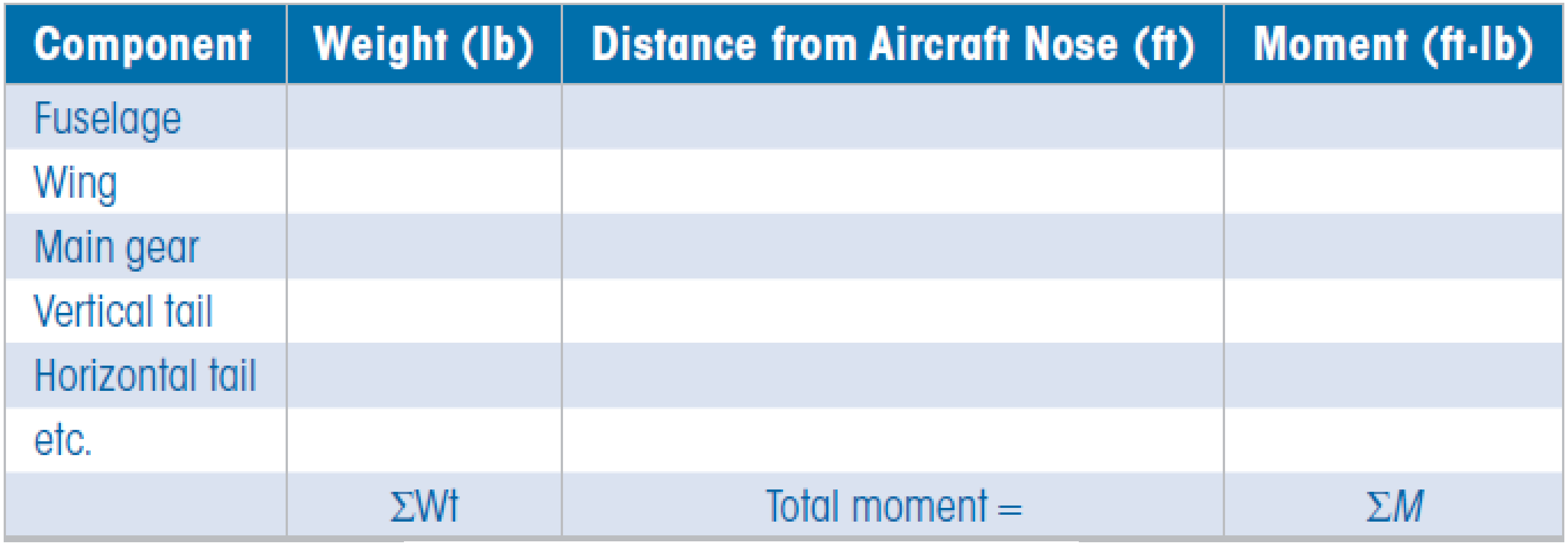
$l_{ma}/(l_{na} + l_{ma}) > 0.05$ **and** $l_{mf}/(l_{na} + l_{ma}) < 0.2$ ***(preferably 0.08 and 0.15)***

Source: Ch. 11, Ref. AVD 2 (Raymer)

Determining C.G. Locations

Use 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 =	ΣM

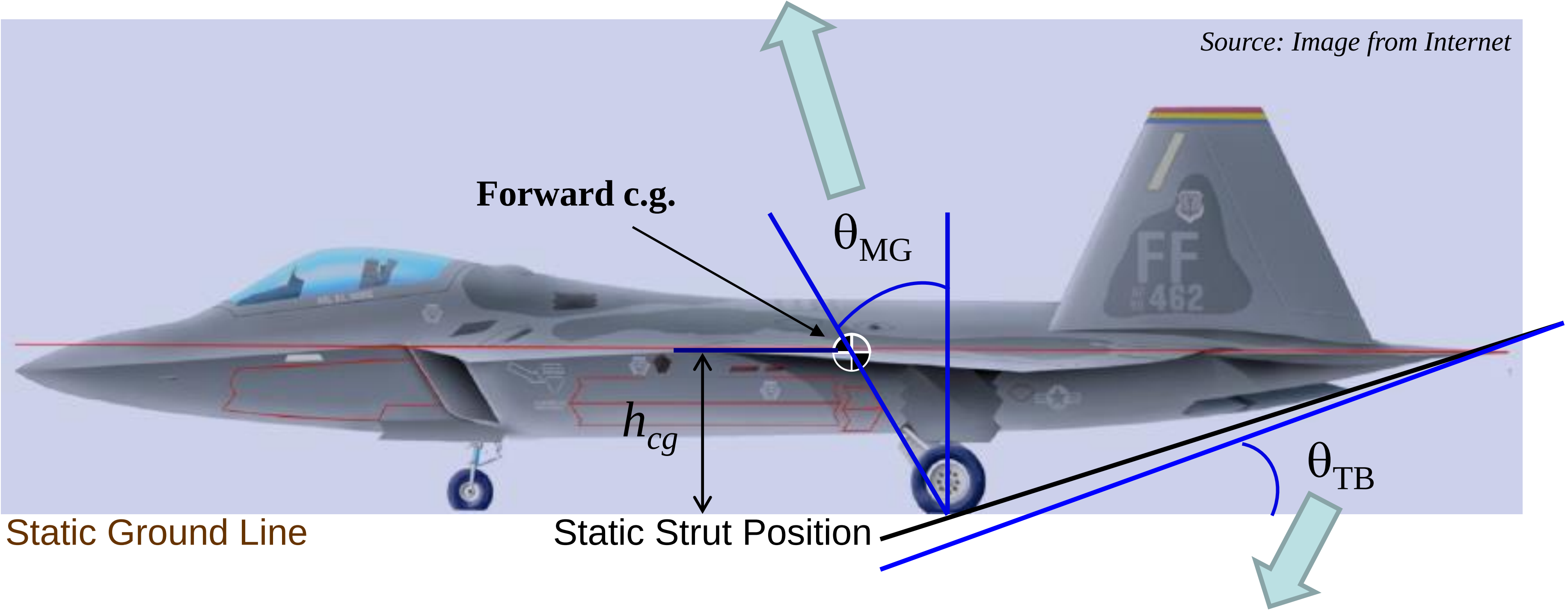
$$X_{\text{c.g.}} = \text{Total Moment}/\Sigma\text{Wt}$$

- 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 (Fwd) and most aft (Aft) locations

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

Landing Gear Arrangement to Prevent Tip Back

Design gross weight c.g. must fall within 10 to 15 degrees (USAF Requirement: 16 to 25 degrees)



Source: Image from Internet

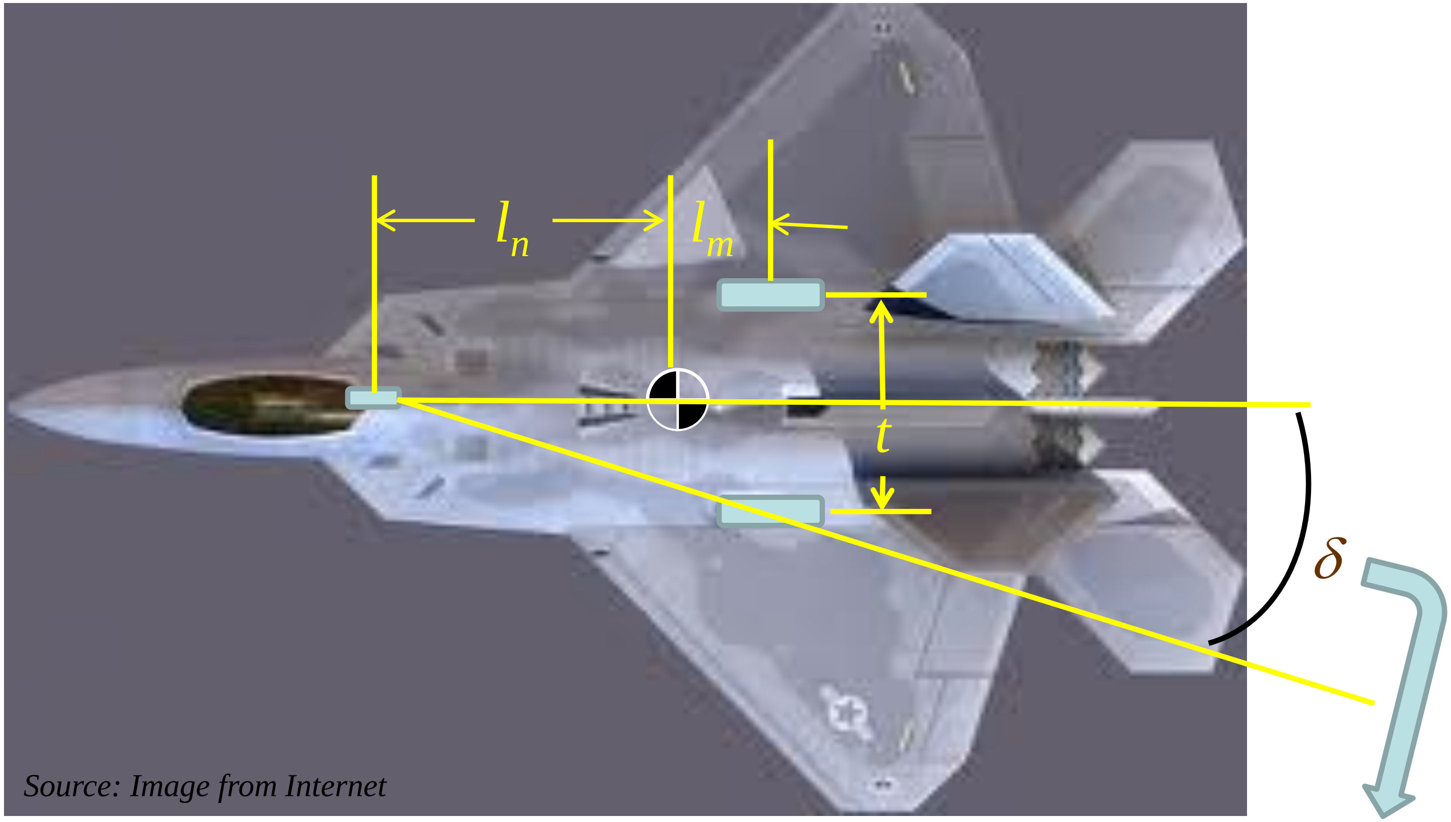
Aft-most structure (fuselage, control surfaces, etc.) must not contact ground when rotated to α for 0.9 C_{Lmax}

Protect airplane from damage during takeoff and prevent Tipping Back on its tail (or nose) at *any possible loading condition*

Source: Ch. 11, Ref. AVD 2 (Raymer)

Landing Gear Arrangement to Prevent Turnover

The turnover (aka overturn) angle, ψ (not shown), should not exceed 63° (USAF spec) or 54° (USN spec) to ensure that the airplane does not turnover on its side during cross-wind landing or high-speed taxiing

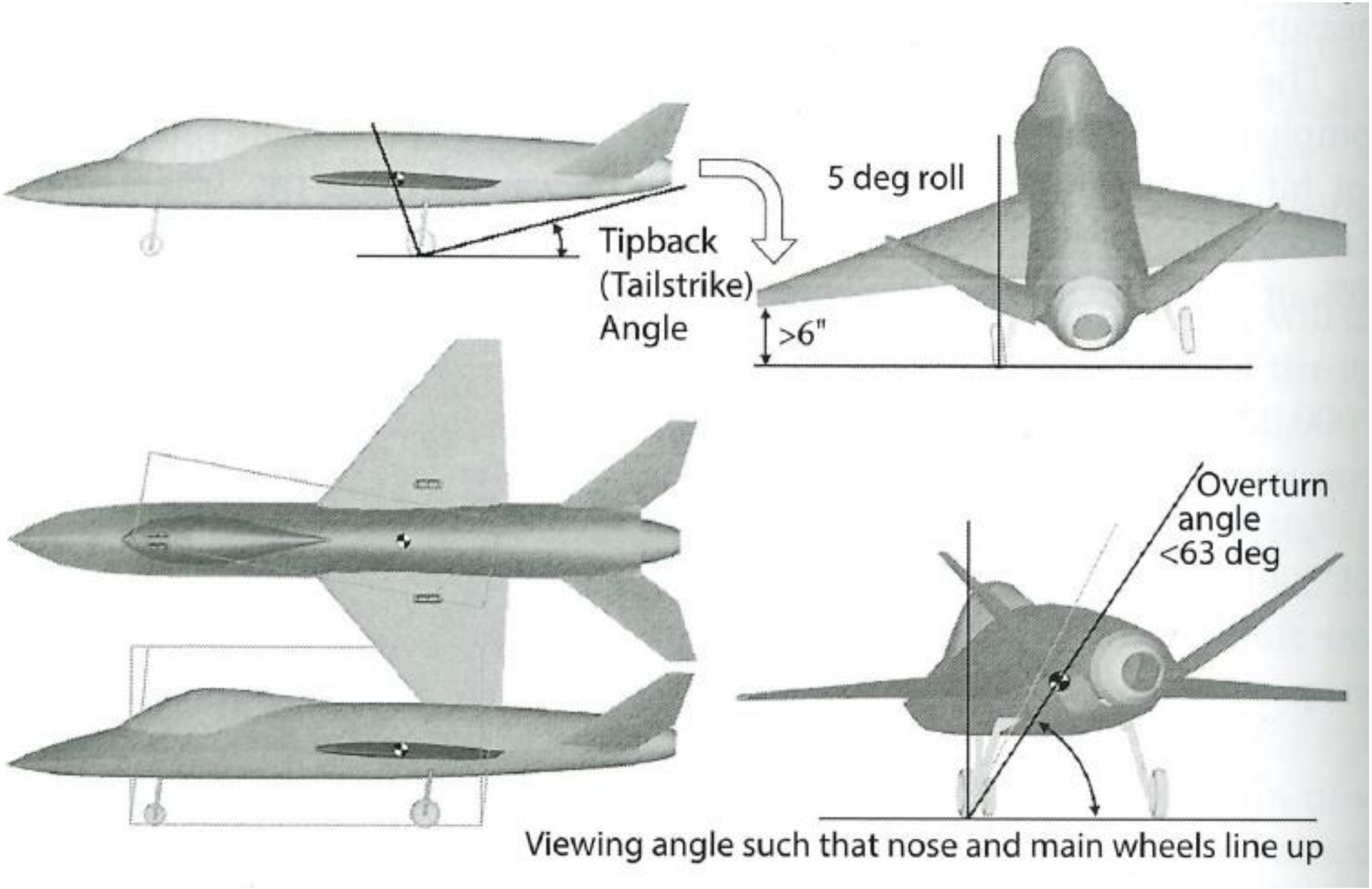


Source: Image from Internet

$$\tan \delta = 0.5 * t / (l_m + l_n)$$

$$\tan \psi = h_{cg} / (l_n \sin \delta)$$

Landing Gear Arrangement Summary



Viewing angle such that nose and main wheels line up

Source: Fig. 11.5, Ref. AVD 2 (Raymer)

Landing Gear

Wheel & Tire Sizing Considerations

- **Heavier aircraft typically use multiple wheels to share the load and keep the tire size reasonable; multiple wheels are also desirable for safety (for both main and nose gears)**
  - < 50K lbs, one wheel is adequate, but two might be preferred for safety
  - > 50,000 but < 150,000 lbs, typically two wheels per strut
  - For aircraft weighing 200K to 400K lbs, four-wheel bogey is more common
  - > 400K lbs, four bogeys, each with four or six wheels, are typically employed
- **Tires are sized to carry the aircraft weight—main gear carries about 90%**
  - **Use statistical data to rapidly size the main wheel tires:**

    Diameter or Width = $AW_w^{\,B}$
  - W_w **is load <u>per wheel</u>**
  - **Increase estimates by about 30% for rough unpaved runways**
  - **Assume nose tires to be about 60-100% size of the main tire**
  - **Select tire from manufacturer's catalog**

	Diameter (in)		**Width (in)**	
	A	B	A	B
General Aviation	1.51	0.349	0.715	0.312
Business twin	2.69	0.251	1.170	0.216
Transport/bomber	1.63	0.315	0.1043	0.480
Jet fighter/trainer	1.59	0.302	0.0980	0.467

Source: Table 11.1, Ref. AVD 2 (Raymer)

Landing Gear

Tire Pressure Considerations

- **A tire supports a load almost entirely by its internal pressure, P**

$W_w = P\,A_p$ **where is the tire contact area (aka footprint area)**

- **See the table for the recommended tire pressures for various pavement surfaces**
- **Leave sufficient clearance around tires while designing wheel wells**
  - Provide allowance for slight relative motion between wheel assembly and aircraft structure
  - Swelling of tires with age
  - Don’t locate the tire such that it’s tangent to the OML
- **As a rule of thumb, allow about 3-5% of tire width as clearance all around it**

> ***“A home for the gear: find it early, or pay the price!   -- Raymer***

Surface	**Max. Pressure (psi)**
Aircraft carrier	200+
Major military airfields	200
Major civil airfields	120
Tarmac runway, good condition	70-90
Tarmac runway, poor condition	50-70
Temporary metal runway	50-70
Dry grass on hard soil	45-60
Wet grass on soft soil	30-45
Hard packed sand	40-60
Soft sand	25-35

Source: Table 11.3, Ref. AVD 2 (Raymer)

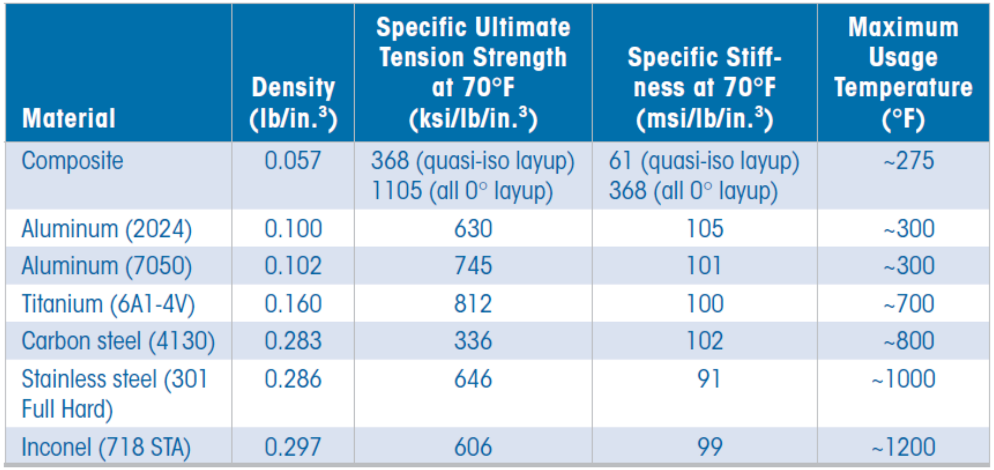
Outline

A7.0 Key Considerations for Configuration Layout

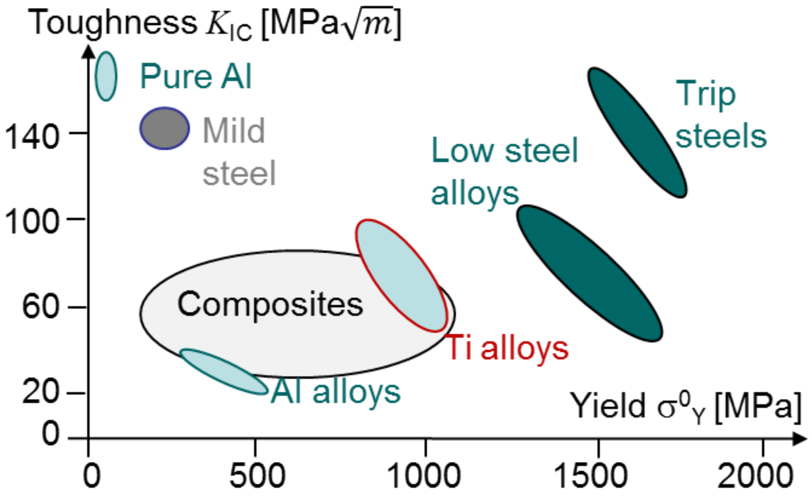
Material Selection

- **Material selection is 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



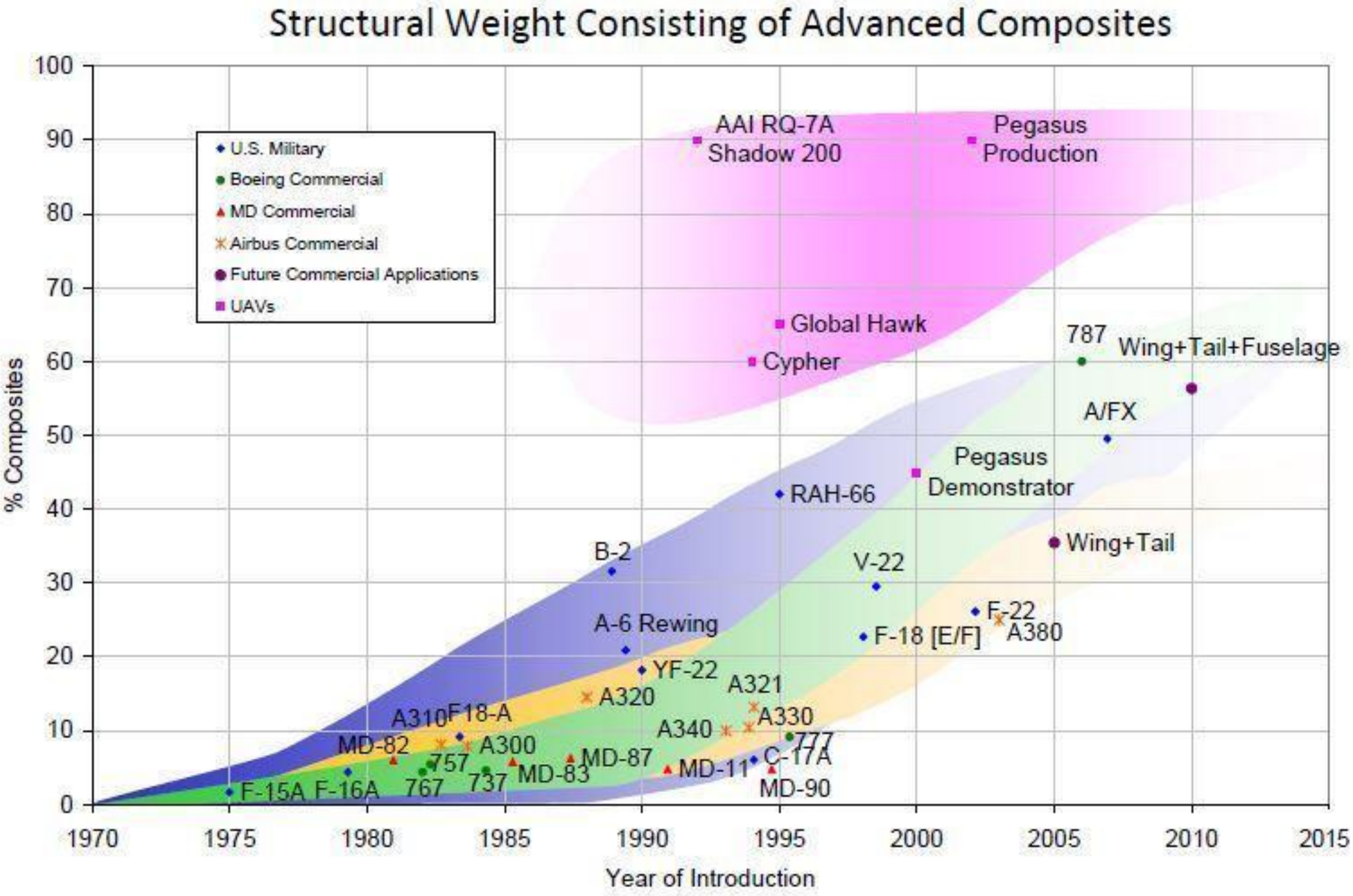
Material	Density (lb/in.^{3})	Specific Ultimate Tension Strength at 70°F (ksi/lb/in.^{3})	Specific Stiffness at 70°F (msi/lb/in.^{3})	Maximum Usage Temperature (°F)
Composite	0.057	368 (quasi-iso layup) 1105 (all 0° layup)	61 (quasi-iso layup) 368 (all 0° layup)	~275
Aluminum (2024)	0.100	630	105	~300
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)

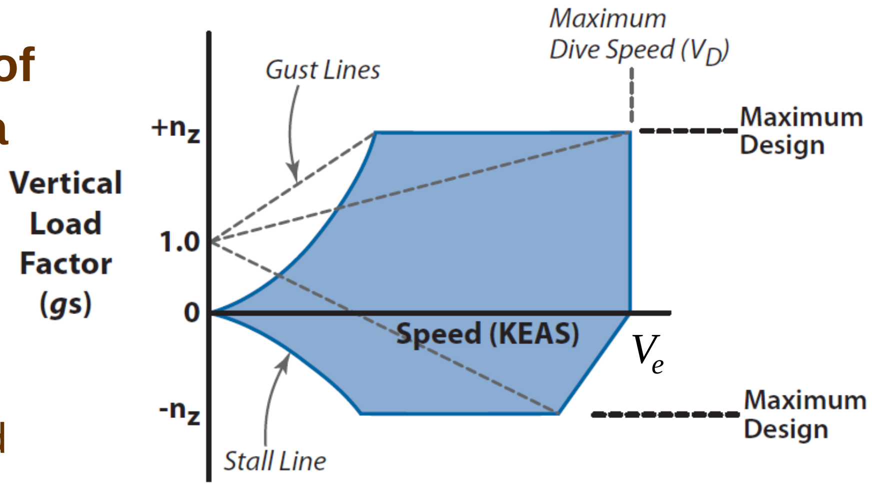
Structural Design Criteria

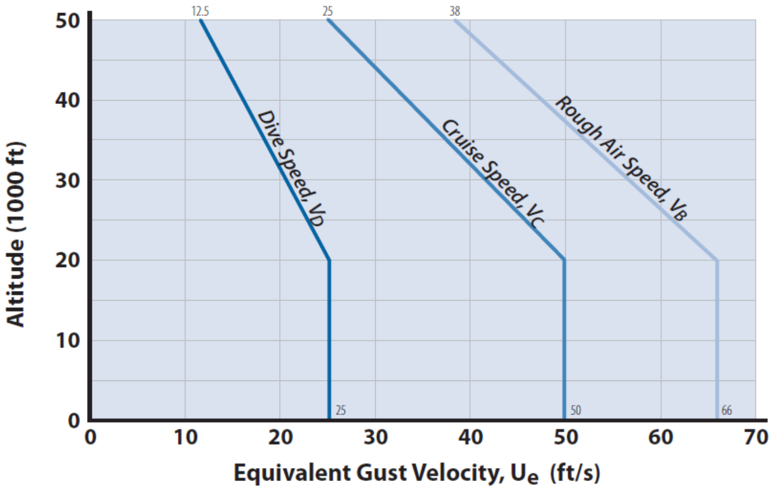
- **Use relevant FAR or MIL-A-8860 series of documents for structural design criteria**
- ***V-n* diagram is the starting point!**
  - Speed V_e is always written in knots as KEAS given by $V_e = \sqrt{\sigma}\, V_t$
    $\sigma = \rho_{alt}/\rho_{SL}$ (air density ratio) V_t = true airspeed
  - n_z 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)

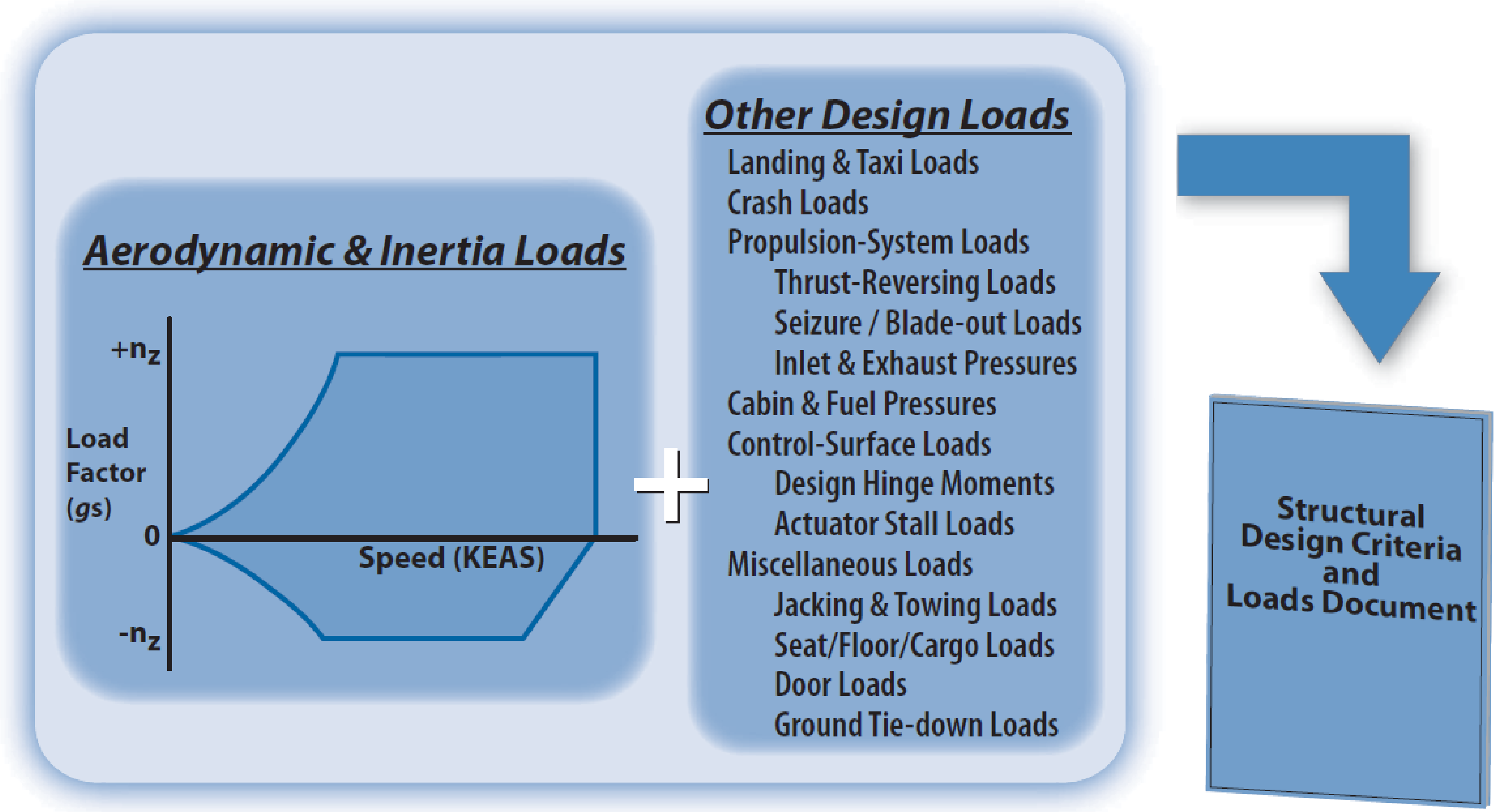




- ***Loads Engineers* develop a set of external loads (aerodynamic and inertia loads) that a ‘lightest weight’ structure must withstand without failing**

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

Design Loads



Aerodynamic & Inertia Loads

Other Design Loads

- Landing & Taxi Loads
- Crash Loads
- Propulsion-System Loads
  - Thrust-Reversing Loads
  - Seizure / Blade-out Loads
  - Inlet & Exhaust Pressures
- Cabin & Fuel Pressures
- Control-Surface Loads
  - Design Hinge Moments
  - Actuator Stall Loads
- Miscellaneous Loads
  - Jacking & Towing Loads
  - Seat/Floor/Cargo Loads
  - Door Loads
  - Ground Tie-down Loads

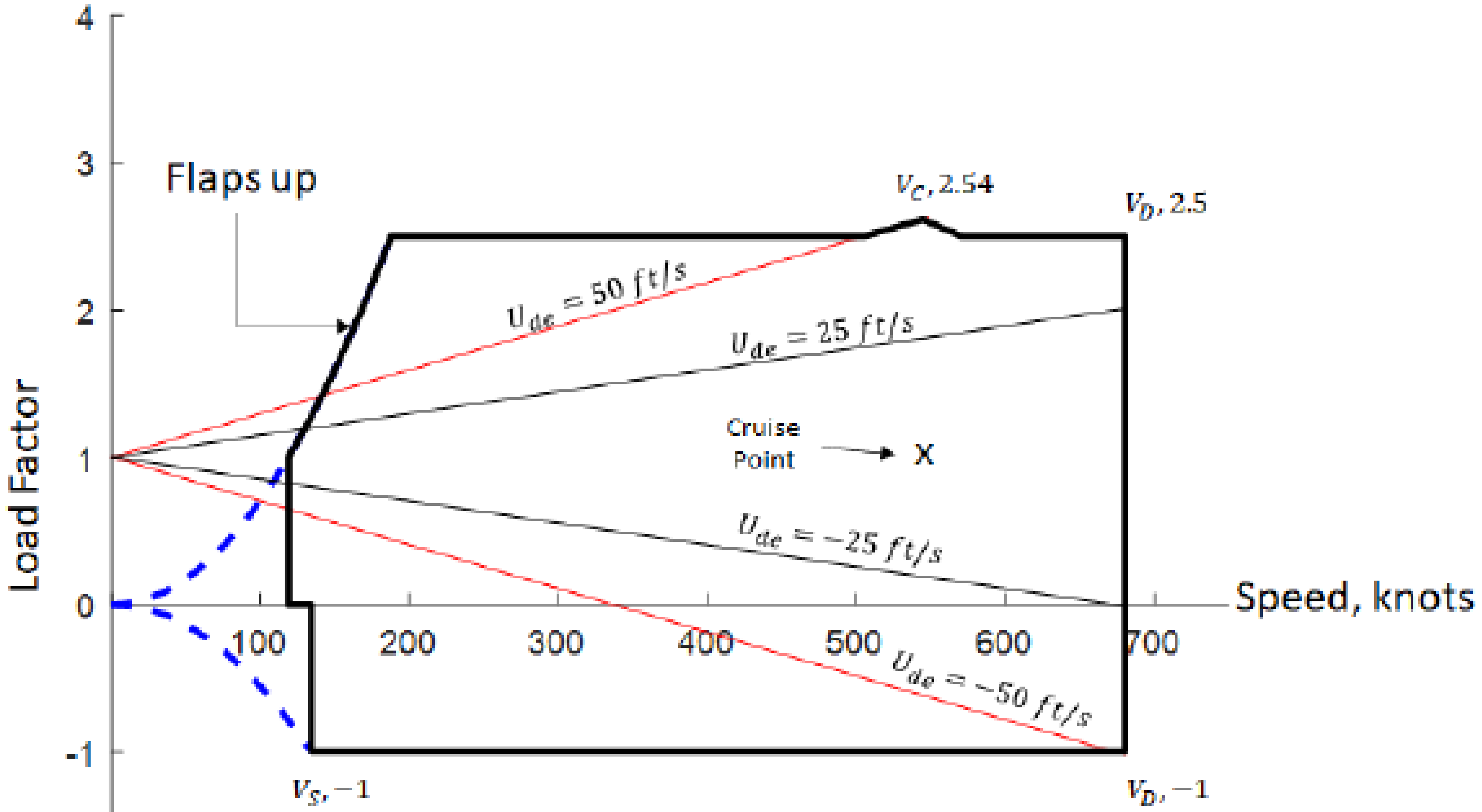
Structural Design Criteria and Loads Document

“Although there are many powerful analytical tools and wind tunnel testing methods available to the Loads Engineer, a key ingredient that should always be used in generating design load conditions is sound reasoning and good judgment based on a thorough understanding of how the aircraft will be flown and operated. Ensuring safety-of-flight must always be of paramount importance.”

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

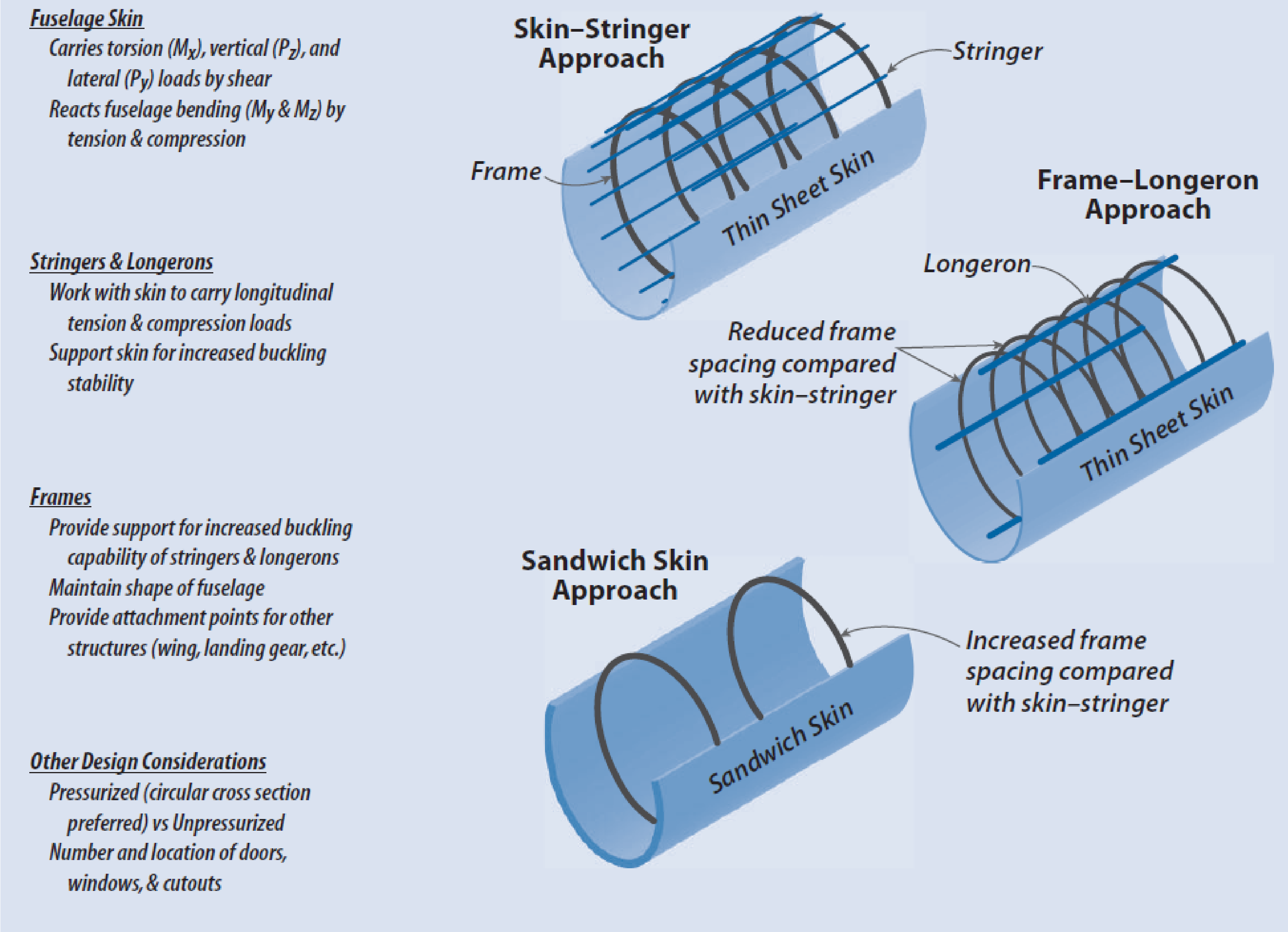
Typical V-n Diagram

Student Design Team Example



Source: 2020 AIAA Undergrad Team Aircraft Design, Virginia Tech

Typical Fuselage Structural Layout Approaches



Fuselage Skin

- *Carries torsion (M_x), vertical (P_z), and lateral (P_y) loads by shear*
- *Reacts fuselage bending (M_y & M_z) by tension & compression*

Stringers & Longerons

- *Work with skin to carry longitudinal tension & compression loads*
- *Support skin for increased buckling stability*

Frames

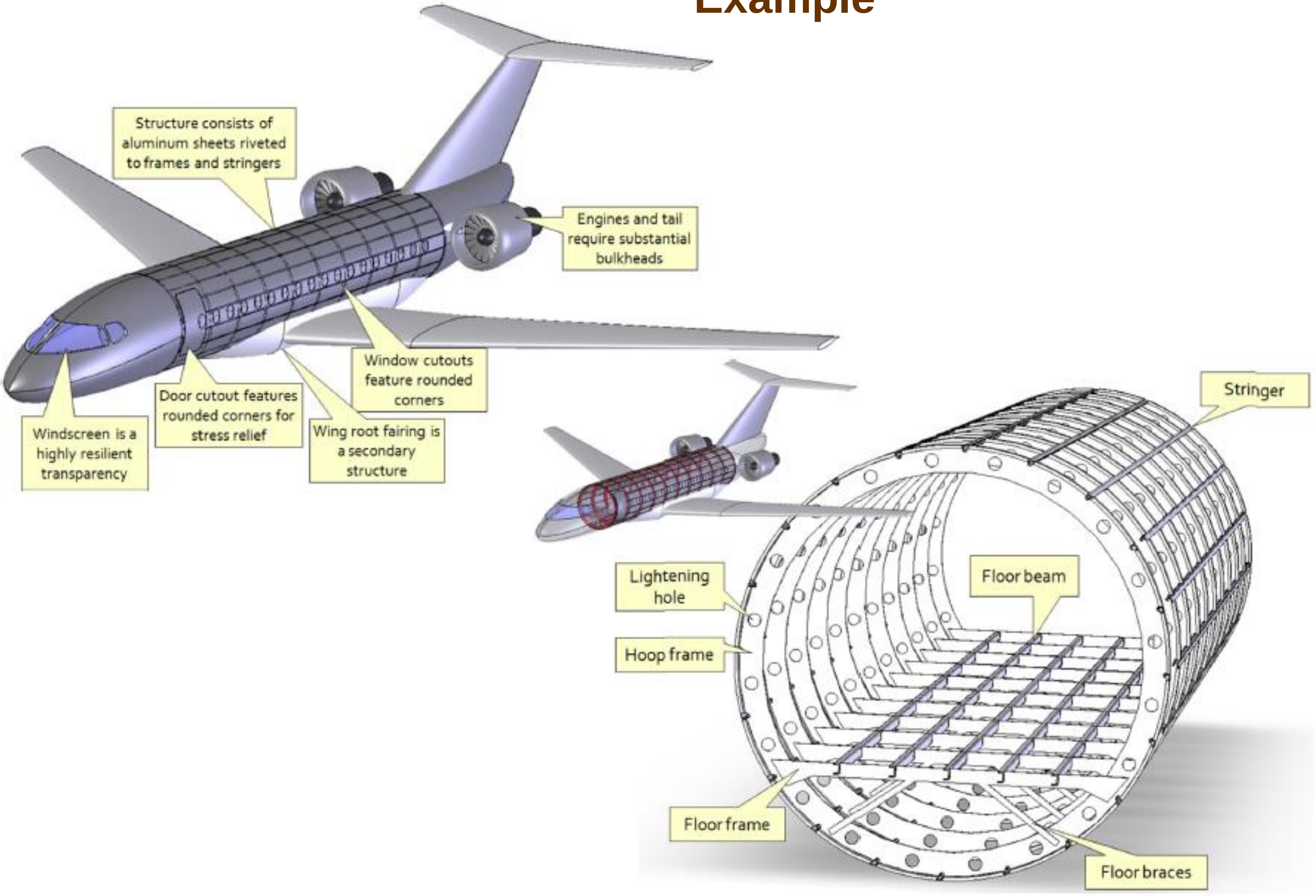
- *Provide support for increased buckling capability of stringers & longerons*
- *Maintain shape of fuselage*
- *Provide attachment points for other structures (wing, landing gear, etc.)*

Other Design Considerations

- *Pressurized (circular cross section preferred) vs Unpressurized*
- *Number and location of doors, windows, & cutouts*

Source: Figure 19.18, Ref. AVD 1 (Nicolai & Carichner)

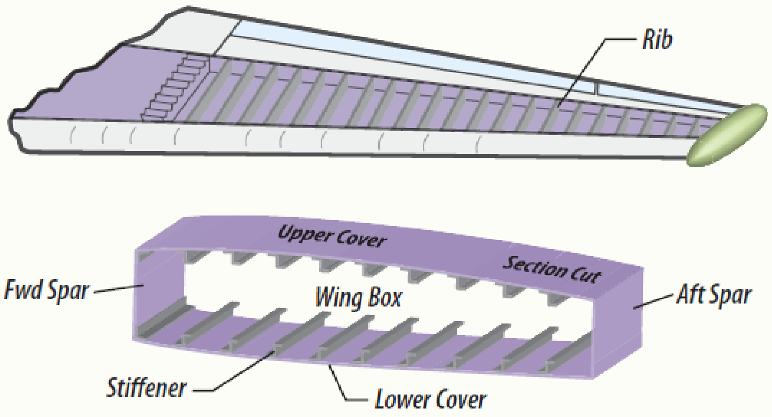
Typical Fuselage Structural Layout Example



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

Typical Wing Structural Layout Approaches

Multi-Rib-Wing



Upper & Lower Covers

Carry spanwise bending (Mx) loads (reacted as tension and compression)

Carry wing torsional (My) loads (reacted as shear around wing box periphery)

Ribs

Support upper and lower covers for increased buckling stability

Maintain airfoil shape

Multi-Spar-Wing

Spars

Spar webs carry vertical (Pz) loads from lift

Spar caps work with wing covers to carry spanwise bending (Mx)

Other Design Considerations

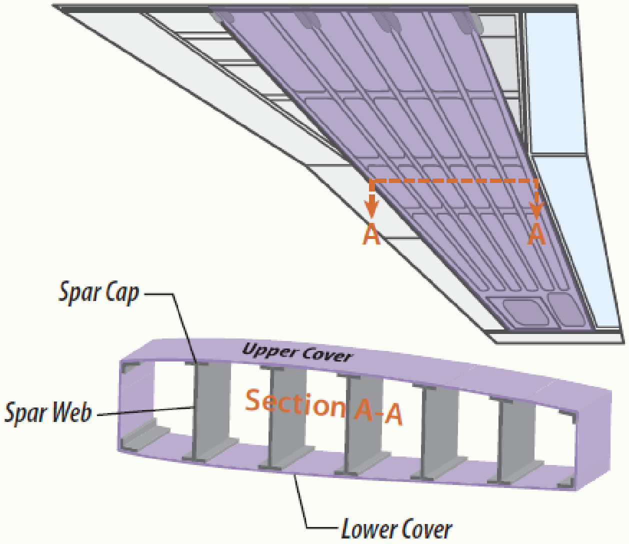
Win attachment concept (tension joint vs shear joint)

Fuel pressures

Landing gear installation

Leading & Trailing edge surfaces & actuation

Access panels



Source: Figure 19.16, Ref. AVD 1 (Nicolai & Carichner)

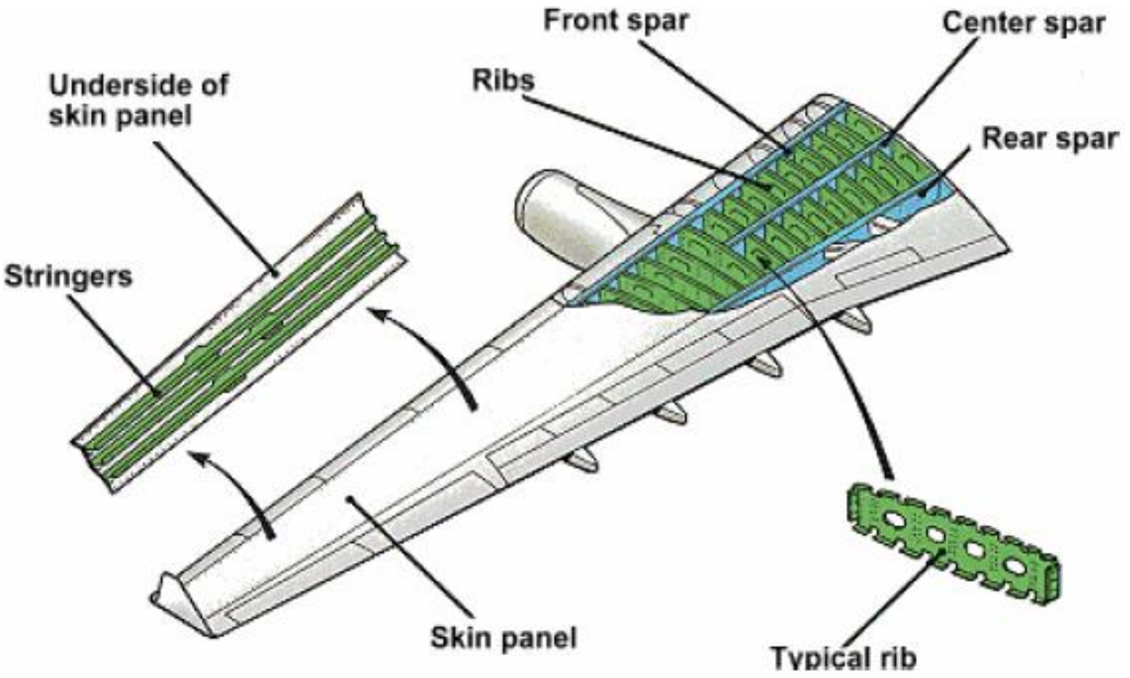
Typical Wing Box:
Structural Components

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.

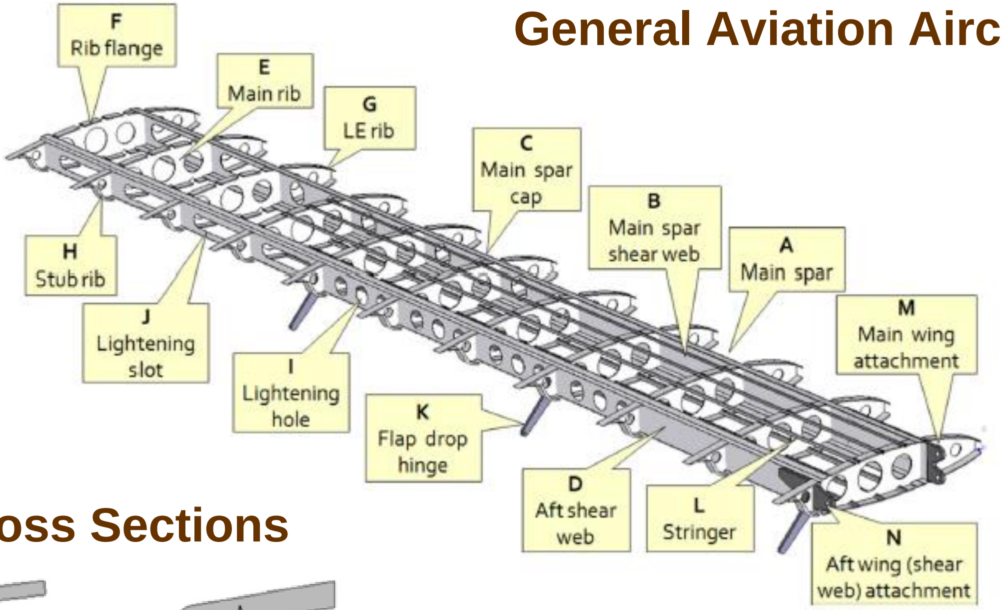
Ribs run across the spars and they give form to the wing covers as well as prevent buckling of the wing covers.



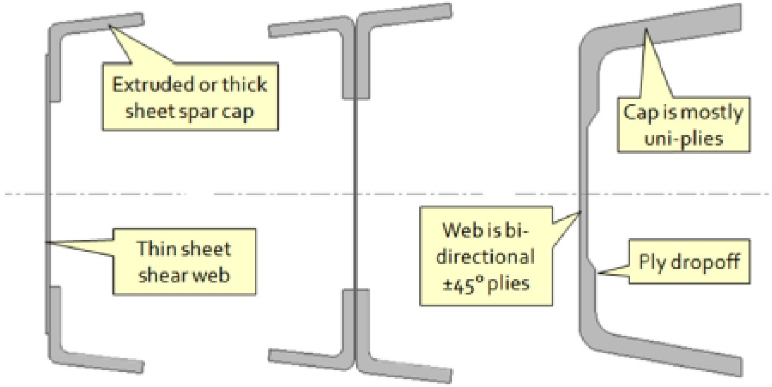
Source:
Arevalo, PT, "Design Optimization of a Composite Wing Box for a High-Altitude Long-Endurance Aircraft," Ph.D. Thesis, Embry-Riddle Aeronautical University, Florida, May 2014

Typical Wing Structural Layout

General Aviation Aircraft Example



Main Spar Cross Sections



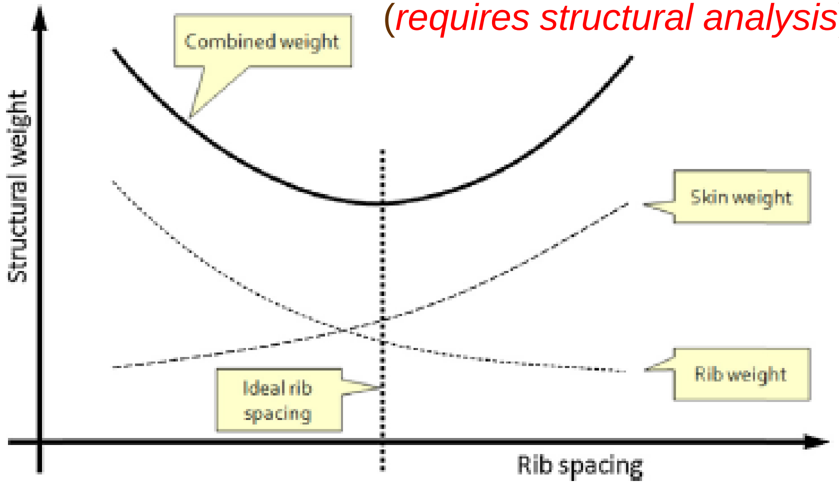
C
Aluminum C-channel spar for a light aircraft

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*)



To get started, use spacing for an aircraft similar to yours

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

Epilogue

Now you’re ready for a first cut at drawing the full airplane OML and Inboard Profile!

Recommended Readings

Ref. No.	Chapter	Author(s)	Title
AVD 1	**Chapters 7, 8, 11, and 23**	Nicolai, L.M. and Carichner, G.E.	***Fundamentals of Aircraft and Airship Design*** **,** ***Volume I—Aircraft Design*** **,** AIAA Education Series, AIAA, Reston, VA, 2010.
AVD 2	**Chapters 4, 7, 8, 9, 10, and 11**	Raymer, D.P.	***Aircraft Design*** **:** ***A Conceptual Approach*** **,** AIAA Education Series, AIAA, Reston, VA, 2012.
AVD 4	**Chapters 4, 7**	Gudmundsson, S.	***General Aviation Aircraft Design: Applied Methods and Procedures*** **,** 1st Ed., Butterworth-Heinemann, September 2013.

NOTE: See Appendix in Overview CM