Air Vehicle Design

AOE 4065 – 4066

II. Air Vehicle Design Fundamentals

Course Module A3

Solve the Problem

Kevin T. Crofton Department of Aerospace and Ocean Engineering
Blacksburg, VA

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

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

Profs. Pradeep Raj and Wm. Michael Butler, 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 the material, we regret any inadvertent omissions.

CRUCIALLY IMPORTANT

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

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

(*see Appendix in the Overview CM)

Aircraft CD Process: *The HOWs!*

"Top Down" – 3 Steps

1. Comprehensive Understanding of the Problem (Initial Step)

1.1 Analyze RFP to understand genesis and nature of customer's problem

1.2 Collect Design Requirements

(a) RFP—mission (speed, range, payload, etc), cost (acquisition, production, LCC, etc.), RM&S, and scheduling (EIS, tech freeze) requirements

(b) FAR (or CFR) and/or DoD documents—regulatory requirements & constraints

(c) ConOps—any additional requirements based on end-user perspective

1.3 Select Comparator Aircraft, Measures of Merit (MoMs), and Key Design Drivers

1.4 Identify Promising Technologies to tackle most difficult challenges

1.5 Investigate Proposal Selection Criteria

1.6 Develop Design Objectives & Strategy, and Prepare *Design Guidelines* document

First, Fully Understand the Problem

2. Generation of Feasible Concepts (Intermediate Step)

2.1 Sketch multiple viable concepts—the ones you *think* could meet the need

2.2 Size all viable concepts; estimate TOGW, Wing Loading, Thrust or Power Loading

2.3 Down-select the most promising ones as a set of preferred system concepts (PSCs) using decision-making tools

Then and Only Then Begin to Solve it

3. Selection of Best PSC as Baseline Design (Final Step)

3.1 Create outer mold line (OML) and interior profile of PSCs by choosing and integrating fuselage; wing; high-lift system; empennage; subsystems; C.G.; etc.

3.2 Conduct Design Trade Studies—Mission and Technology, if possible

3.3 Compare *feasible* configurations using MoMs and select "best" design!

Aircraft CD Process: *The HOWs!*
"Top Down" – 2nd Step

1. Comprehensive Understanding of the Problem (Initial Step)

- 1.1 Analyze RFP to understand genesis and nature of customer's problem
- 1.2 Collect Design Requirements
  - (a) RFP—mission (speed, range, payload, etc), cost (acquisition, production, LCC, etc.), RM&S, and scheduling (EIS, tech freeze) requirements
  - (b) FAR (or CFR) and/or DoD documents—regulatory requirements & constraints
  - (c) ConOps—any additional requirements based on end-user perspective
- 1.3 Select Comparator Aircraft, Measures of Merit (MoMs), and Key Design Drivers
- 1.4 Identify Promising Technologies to tackle most difficult challenges
- 1.5 Investigate Proposal Selection Criteria
- 1.6 Develop Design Objectives & Strategy, and Prepare *Design Guidelines* document

2. Generation of Feasible Concepts (Intermediate Step)

- 2.1 Sketch multiple viable concepts—the ones *you think* could meet the need
- 2.2 Size all viable concepts; estimate TOGW, Wing Loading, Thrust or Power Loading
- 2.3 Down-select the most promising ones as a set of preferred system concepts (PSCs) using decision-making tools

3. Selection of Best PSC as Baseline Design (Final Step)

- 3.1 Create outer mold line (OML) and interior profile of PSCs by choosing and integrating fuselage; wing; high-lift system; empennage; subsystems; C.G.; etc.
- 3.2 Conduct Design Trade Studies—Mission and Technology, if possible
- 3.3 Compare *feasible* configurations using MoMs and select "best" design!

Aircraft CD Process—Intermediate Step

2. Generation of Feasible Concepts (3 elements)

Questions to ask for each element

2.1 Create Multiple Viable Concepts ⟸ CM A3

- What should the air vehicle look like to best perform the mission?
- Should it have a wing? Or two? Or more? Should it have a fuselage? Should it be tailless or have an empennage? What type of landing gear should it have? What kind of engines? Turbojets, turbofans, turboprops, piston-props? Etc.
- *How do you choose?*
  - *Use your understanding and knowledge of the pros & cons of available options*

2.2 Perform Initial Sizing ⟸ CM A4 & A5

- How big should be the air vehicle?
- What is its TOGW? Wing Loading? Thrust or Power Loading?
  - Size all viable concepts or choose a few to size; use qualitative decision-making tools to choose a few

2.3 Select Promising Feasible Concepts ⟸ CM A3

- Are all airplane concepts you sized feasible?

Outline

A3. Solve the Problem

A3.1 Prerequisites for *Solving the Problem*

A3.1.1 Design Objectives and Design Strategy

A3.1.2 Three-view CAD Drawings

A3.2 Create Multiple Viable Concepts

A3.2.1 Initial Concept Sketches

A3.2.2 Initial Concept Models

A3.3 Choose a Few “Good” Feasible Concepts

A3.4 Select Best PSC as Baseline Design

Two Must-Do's Before You Begin to *Solve the Problem*

1. **Define "Design Objectives"**
   - ***What*** **important expectations of the customer does the team need to meet?**
2. **Develop "Design Strategy"**
   - ***How*** **will the design team go about achieving the objectives?**

Image Source: Internet

1. Define "Design Objectives"

- ***What*** **primary expectations of the customer need to be met?**
- **Sometimes spelled out in the RFP. If not, Design Team should define them.**

Goal?

2016-17 AIAA RFP

The design objective is to minimize the acquisition and operating cost. Advanced technologies should be used only where justified based on performance and cost (note entry into service date) and within acceptable cost and schedule risk.

Design Objectives

- The re-use of at least 70% of the airframe structure and systems by weight for both the 6 and 8 seat variants is a design objective. This includes everything in the empty weight of the airplane with the exception of the engine.
- Minimize production cost by choosing materials and manufacturing methods appropriate for the production rate that is supported.
- Make the aircraft visually appealing so it will be marketable and identify what features are important to the pilot, passengers, and owners.
- Make the aircraft maintainable and reliability at least as good as comparable aircraft.

- **Many times, you see 'goals' and 'objectives' used interchangeably—even in RFPs. However, it's very helpful to think about the two as separate but tightly linked entities.**

Distinction Between Goals and Objectives

- **Goal is a *statement of aim***
  - **What do you want to achieve?** *The answer is your "Goal"*
- **Objectives *are steps required to achieve the goal***
  - **What specifically needs to done by whom, when and where to realize your goal?** *The answer is your "Objectives"*
- **Examples**
  - *Goal: I want to get a better grade in chemistry.*
  - *Objective: I need to memorize the periodic table before my next quiz.*
  - *Goal: I want to lose weight.*
  - *Objective: I need to reduce 20 pounds by the end of the year.*
- **Goals and objectives are both <u>tools</u> for achieving what you want**
- **Goals without objectives can never be accomplished while objectives without goals will never get you what you want**
- **Objectives are very concrete, goals are less structured**
- **Goals may be nebulous, objectives must be S.M.A.R.T.**

Teams Must Understand Project Goals and Objectives

Source: Miscellaneous

Objectives Must Be S.M.A.R.T.

- **S**pecific
  - Consider five "W" questions:
    - ***Who*** are the stakeholders?
    - ***What*** specifically does the team need to, and want to, achieve?
    - ***Where*** will the team demonstrate its achievements?
    - ***Which*** requirements and constraints [technical and non-technical] must be met to achieve the objective?
    - ***Why*** *does* the team need to accomplish the objective *(reason, relevance, benefit).*
- **M**easurable
  - ***How*** will we know we got there, i.e., we have achieved the objective?
- **A**ttainable
  - Are we *willing* and *able* to develop the attitudes, abilities, skills, and financial capacity to achieve the objectives?
- **R**ealistic
  - Are we *willing* and *able* to work hard to achieve the objectives?
- **T**ime-bound
  - When does the team need to fully achieve the objectives? What is the time frame? Deadlines? *Creates a sense of urgency!*

2. Develop "Design Strategy"

- **Design Strategy outlines *how you are going to achieve the design objectives***
  - **It is less specific than a project plan** (à la Gantt chart) which details tasks, milestones, schedules, and resources (personnel, level of effort, etc.)
  - It tries to broadly answer the question, ***"How do we get there from here?"*** (Should we take a train or airplane or automobile for getting to the destination on time and within budget?)
- **Strategy gives *overall direction***
  - A strategy should point out the **overall path without dictating a particular narrow approach**
  - **Each design team needs to create an effective design strategy**
- **Examples**
  - If a design objective is emissions reduction, a strategy might be to explore *alternative fuels* to minimize fossil fuel consumption; another might be *alternative propulsion* systems but *without dictating specific fuels or engines*
  - If design objective is cost reduction, a strategy might be using commercial off the shelf (COTS) components *without dictating specific components*

Outline

A3. Solve the Problem

Three-view (or 3-vu) CAD Drawings

Design teams use three-view CAD drawings* as the common standard language for communicating about the aircraft system with customers, production teams, etc.

***See CM A7a for more details**

WS: Wing Station

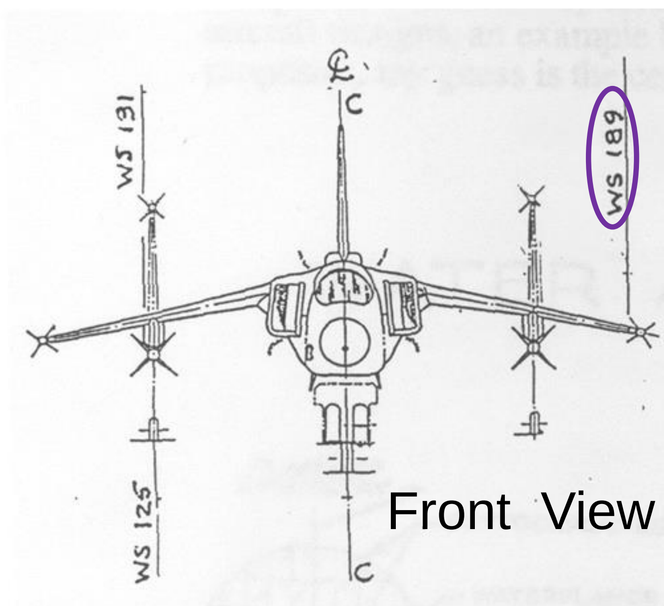
FS: Fuselage Station

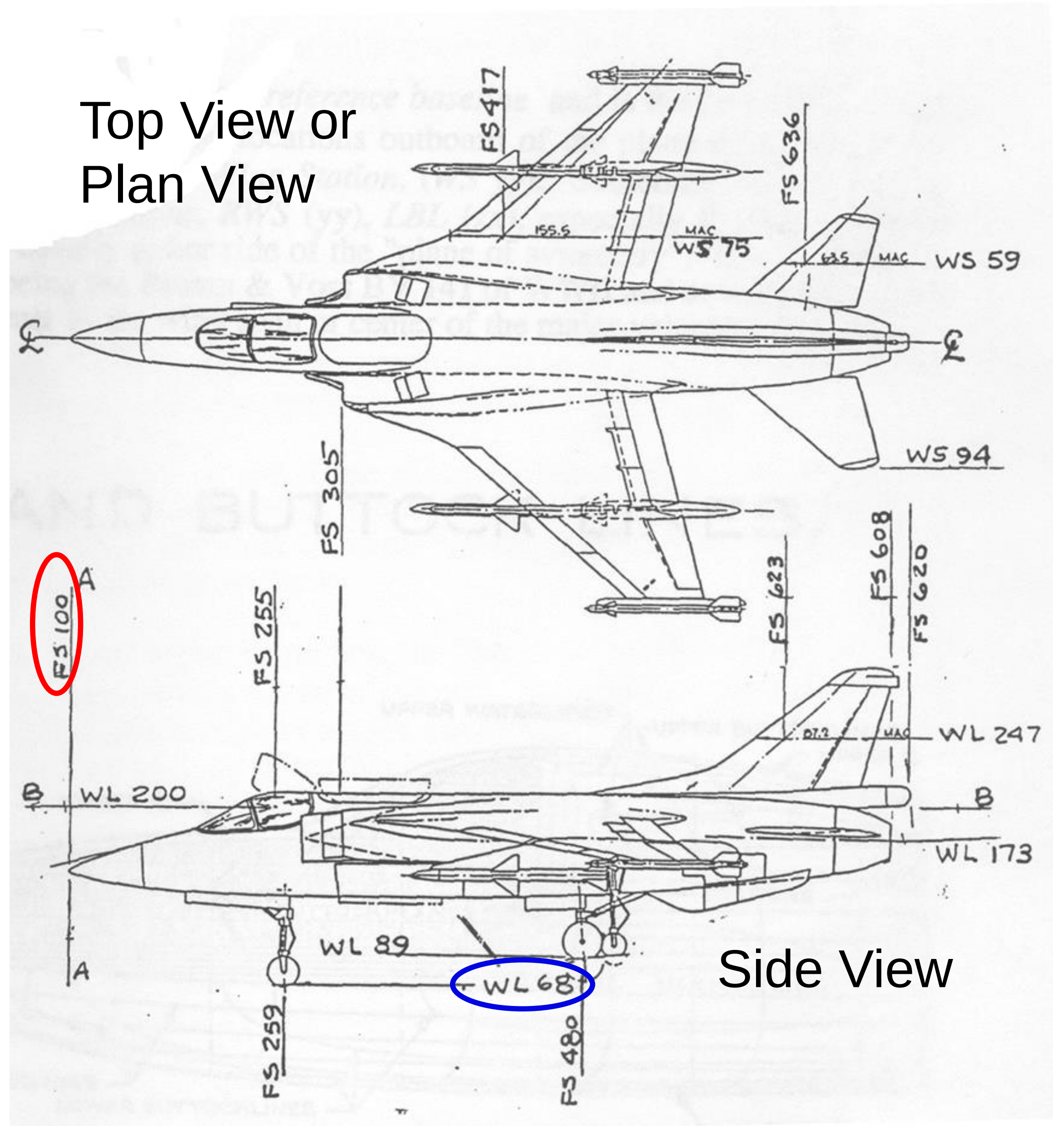
WL: Water Line

A-A: Vertical Reference Plane

B-B: Fuselage Reference Plane

C-C: Centerline Plane of Symmetry

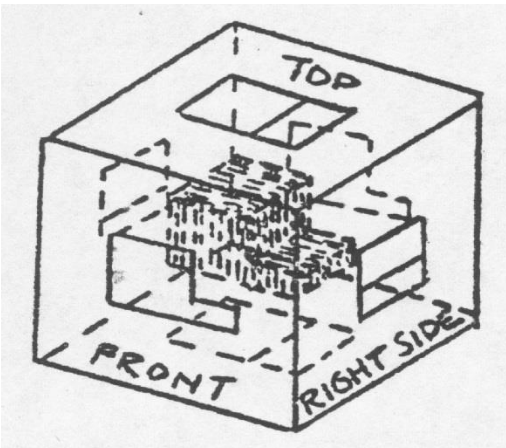


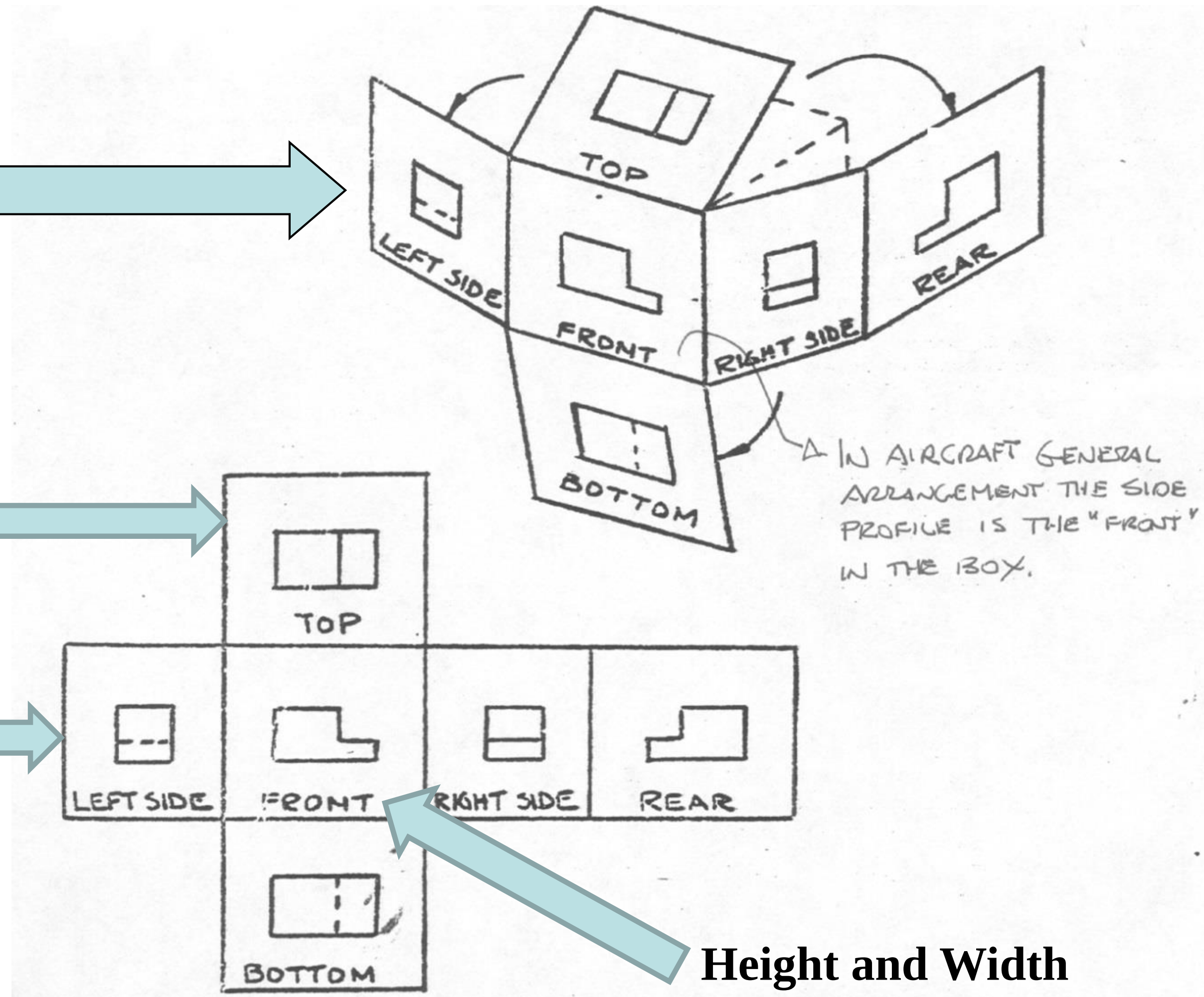


Source: Figure 1-1, Ref. AVD 4 (Kirschbaum and Mason)

Underlying Principle of 3-vu Drawing: *Orthographic Projection*

Consider an object inside a box; project image; open the box





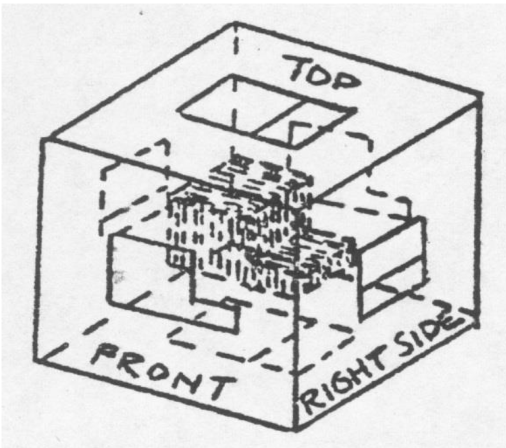
Width and Depth

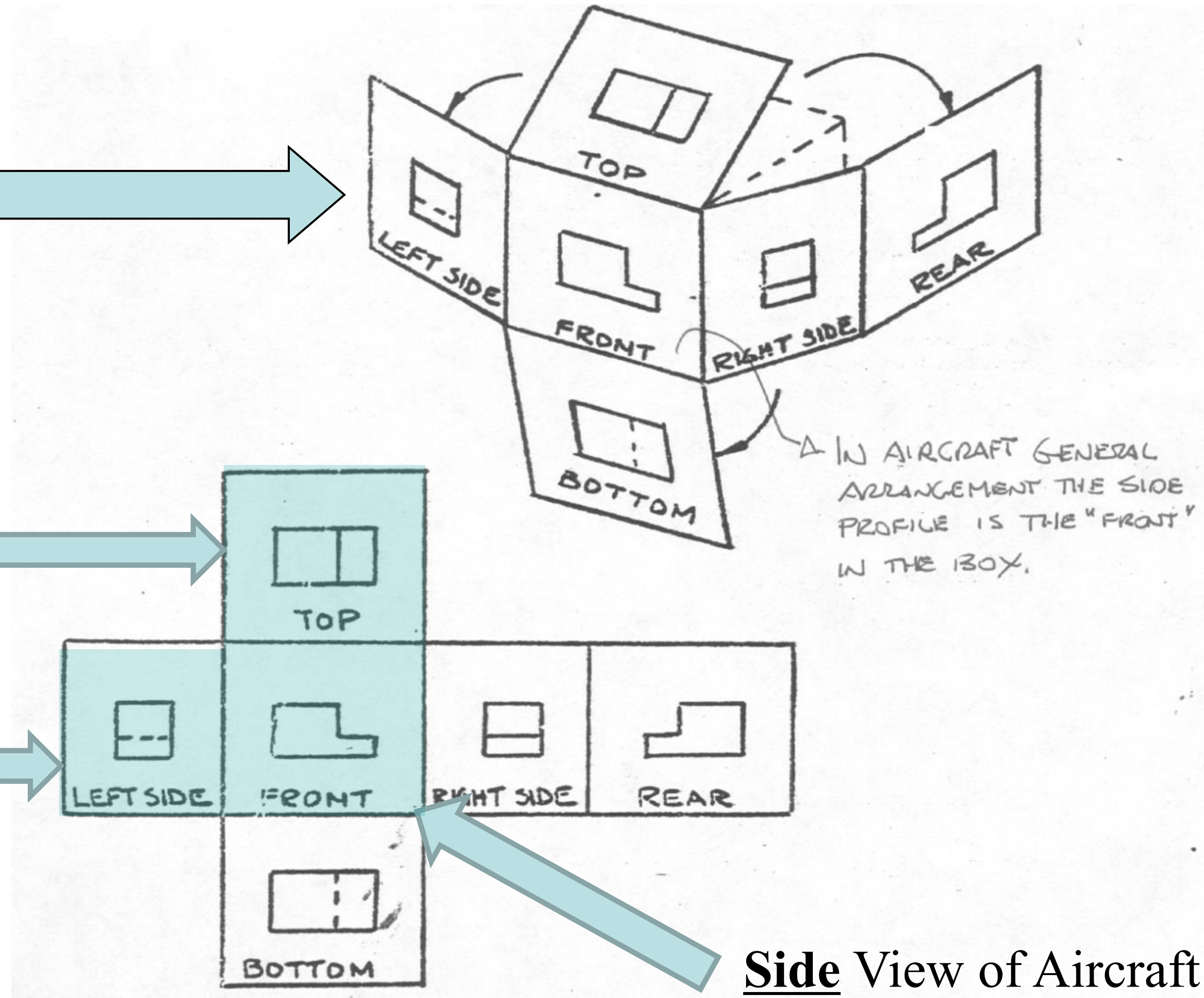
Depth and Height

Height and Width

Courtesy of W.H. Mason

Orthographic Projection for Aircraft Three-View Drawing





Top View
Length and Span

Front View
Height and Span

Side View of Aircraft
Height and Length

Shaded sections are standard for Aircraft drawing

Length is Width
Span is Depth

Courtesy of W.H. Mason

SAE Specs for Aircraft Three-view

- **Required Views**

  The plans shall consist of a standard aeronautical three-view, using a US-standard third-order projection:

  1. Show Side view (right) in the lower left with the nose pointing right
  2. Show Top view above the right side view also with the nose pointing right
  3. Show Front view in the lower right.

- **Dimensions**

  At a minimum, all aircraft must have the length, width, height, and CG location clearly marked and dimensioned on the submitted engineering drawings.

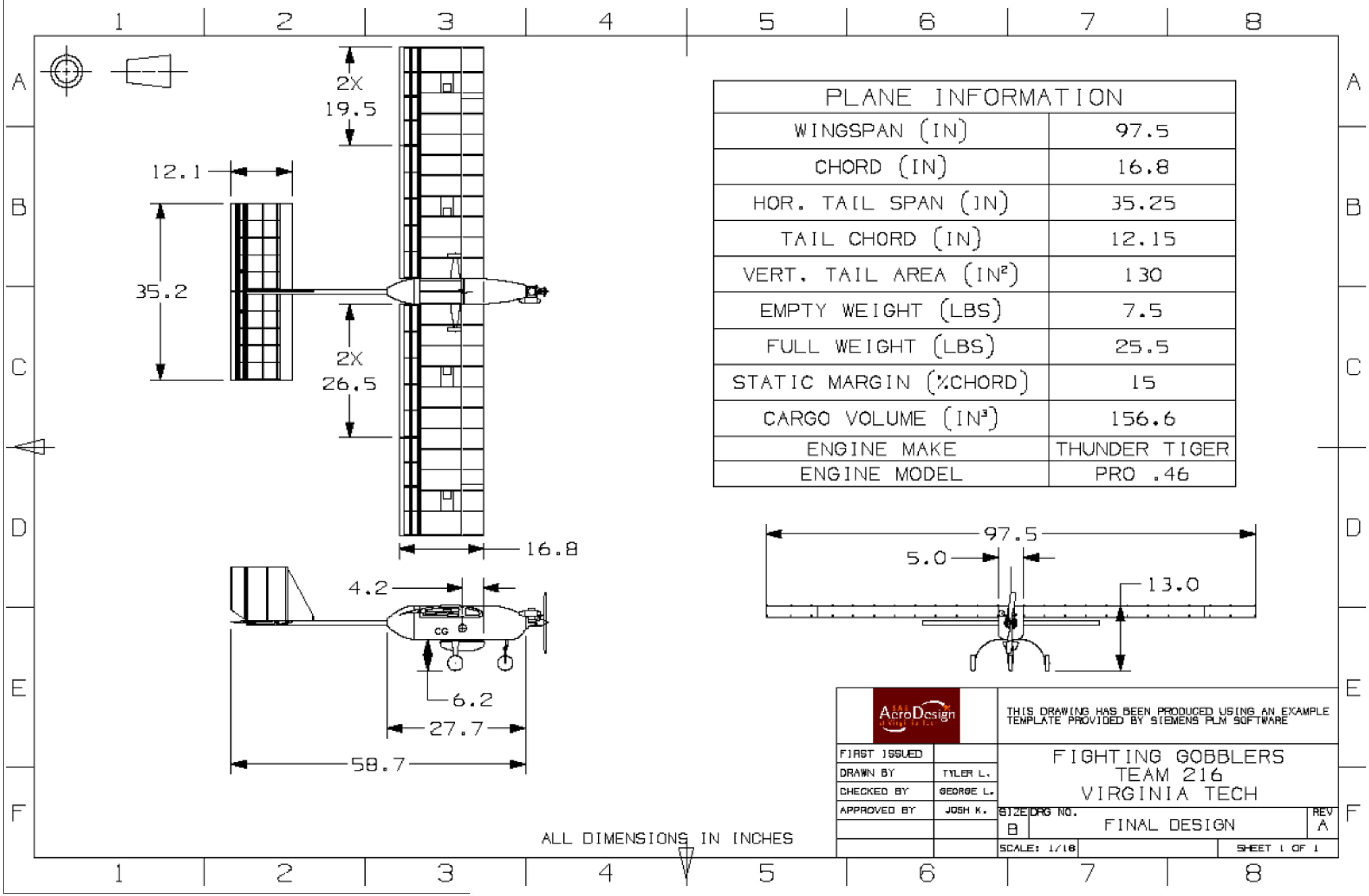
  All dimensions must be in set of units (e.g., inches and decimal inches) to an appropriate level of precision. **(*Hint: four decimal places are too many*!)**

- **Summary Data**

  Include a table with a summary of pertinent aircraft data such as wingspan, empty weight, engine make and model, etc.

Use SAE Specs

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

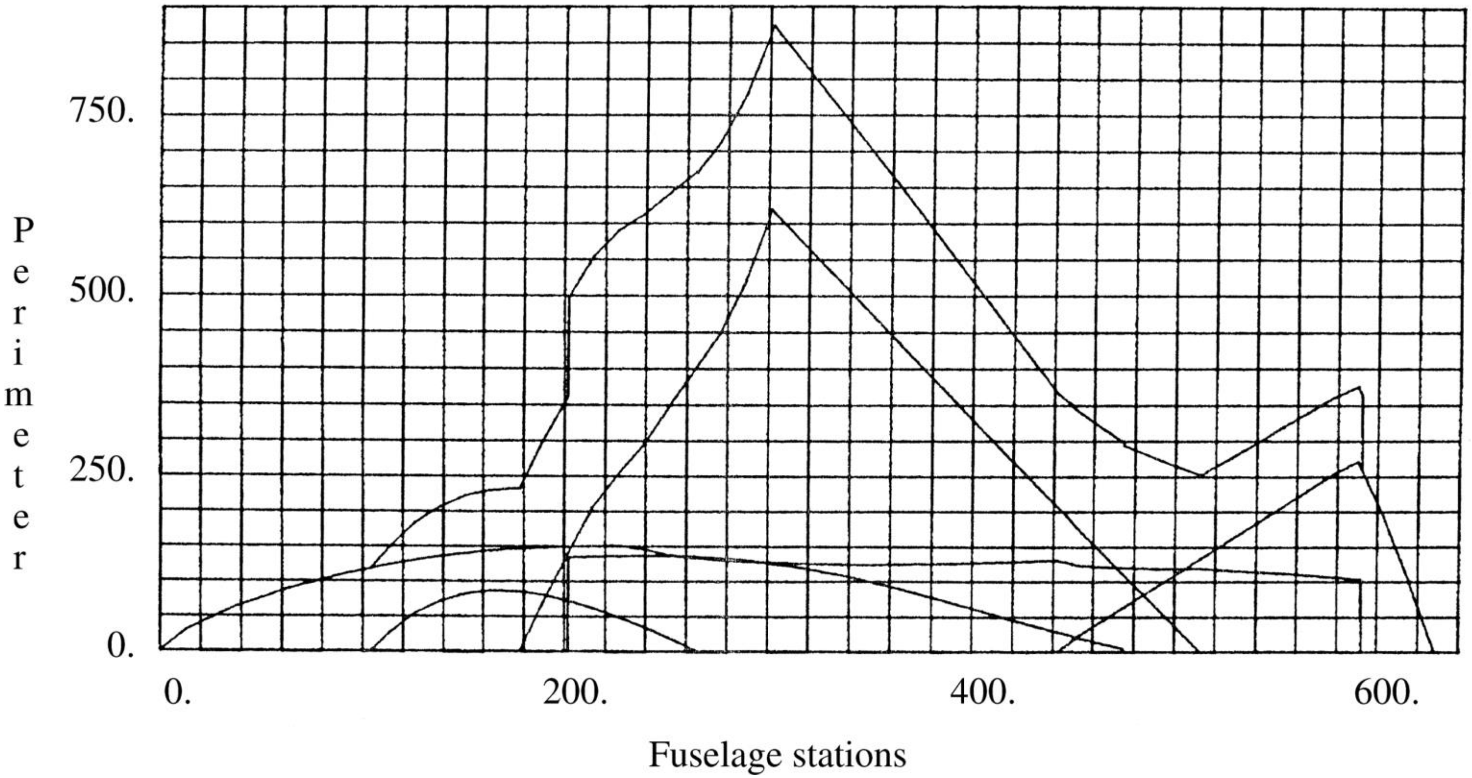


PLANE INFORMATION	
WINGSPAN (IN)	97.5
CHORD (IN)	16.8
HOR. TAIL SPAN (IN)	35.25
TAIL CHORD (IN)	12.15
VERT. TAIL AREA (IN^2)	130
EMPTY WEIGHT (LBS)	7.5
FULL WEIGHT (LBS)	25.5
STATIC MARGIN (%CHORD)	15
CARGO VOLUME (IN^3)	156.6
ENGINE MAKE	THUNDER TIGER
ENGINE MODEL	PRO .46

3-view Drawings Provide Key Inputs for Analysis

Example 1. Wetted Areas for Performance and Weight Estimation

Component	Surface
Fuselage	70344.8
Vert tail	26165.3
Wing	102636.7
Circular arc canopy	9071.4
Nacelle	25462.9
Total	233681.0

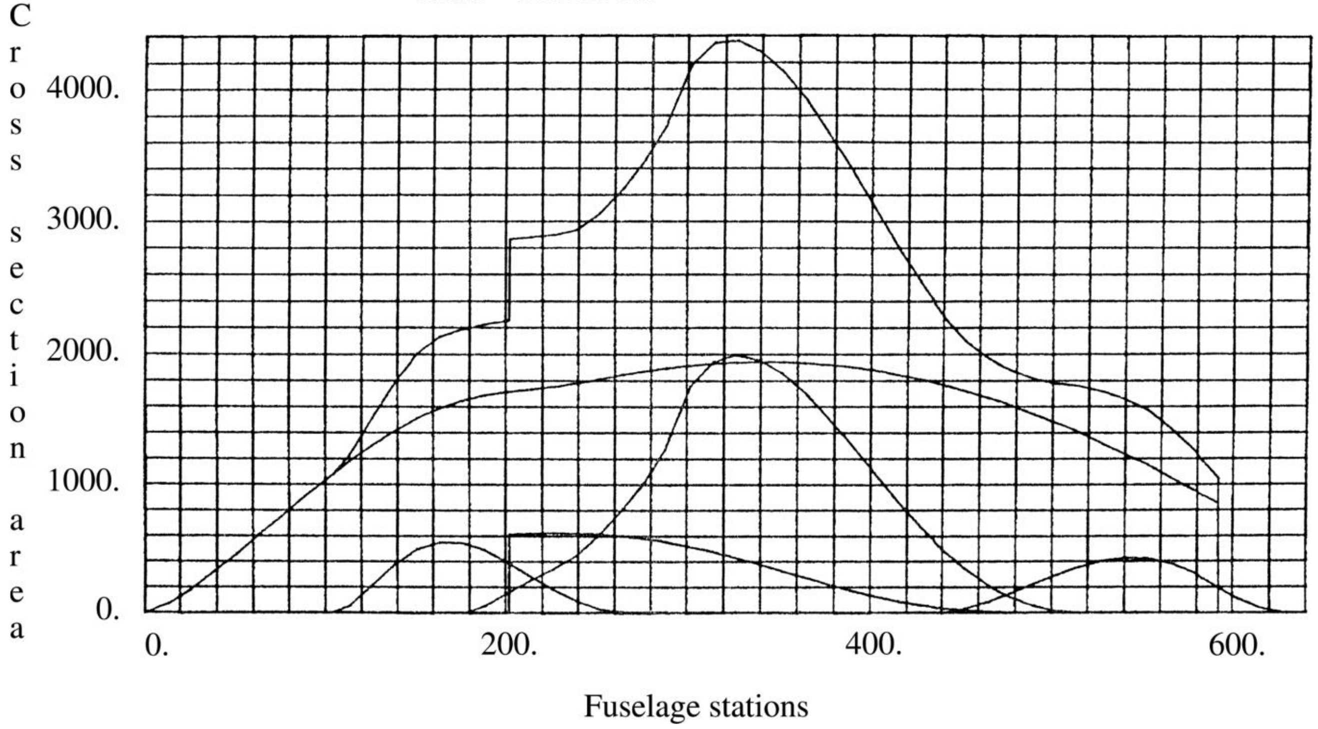


Source: Figure 7.4, Ref. AVD 2 (Raymer)

3-view Drawings Provide Key Inputs for Analysis

Example 2. Cross-sectional Area Distribution for Transonic and Supersonic Wave Drag Estimation

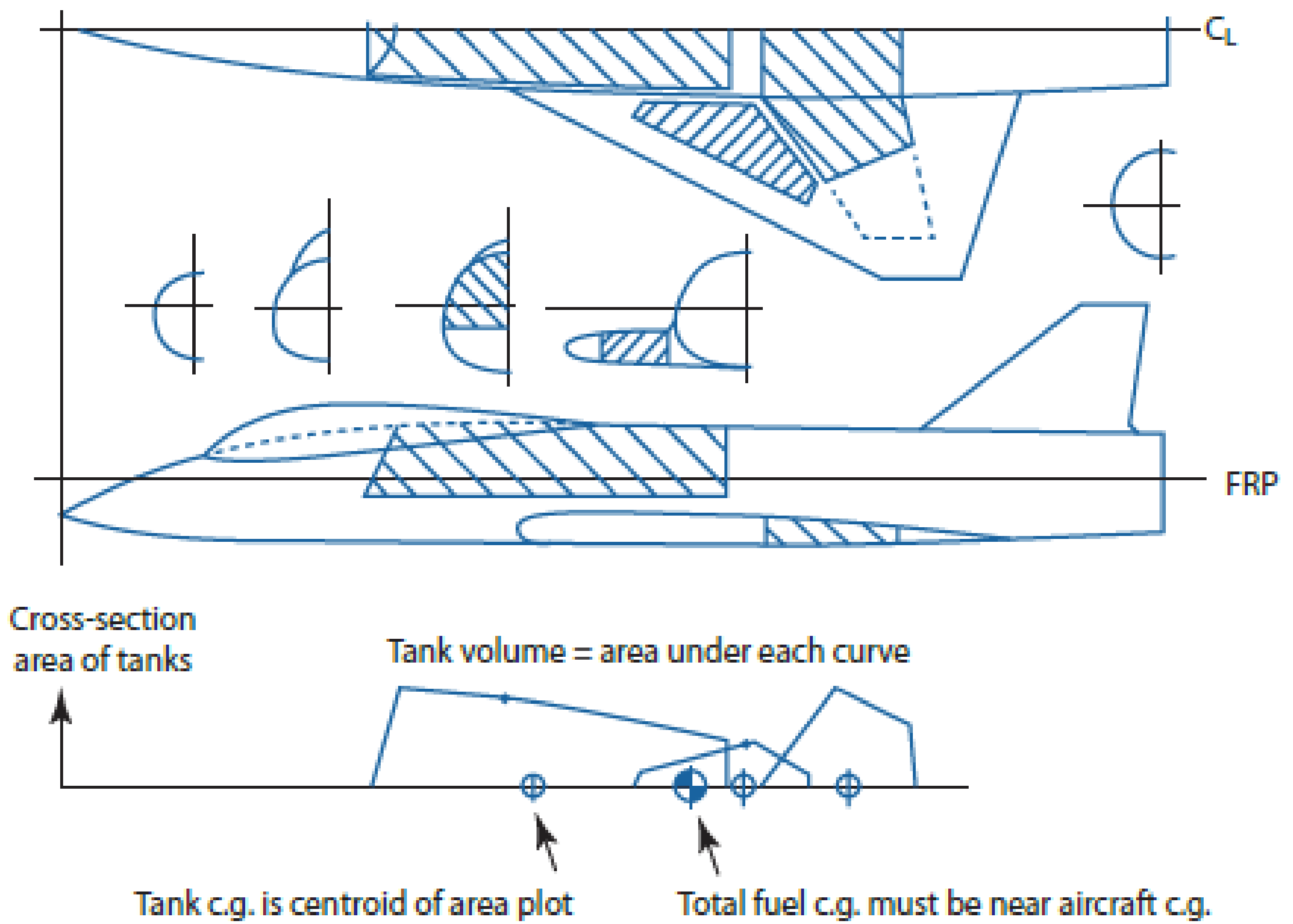
Component	Volume
Fuselage	847124.4
Vert tail	42903.5
Wing	287005.5
Circular arc canopy	46014.0
Nacelle	95149.8
Total	1318196.8



Source: Figure 7.5, Ref. AVD 2 (Raymer)

3-view Drawings Provide Key Inputs for Analysis

Example 3. Fuel volume and weight for c.g. estimation



Source: Figure 10.29, Ref. AVD 2 (Raymer)

Outline

A3. Solve the Problem

A3.1 Prerequisites for *Solving the Problem*

A3.1.1 Design Objectives and Design Strategy

A3.1.2 Three-view CAD Drawings

A3.2 Create Multiple Viable Concepts

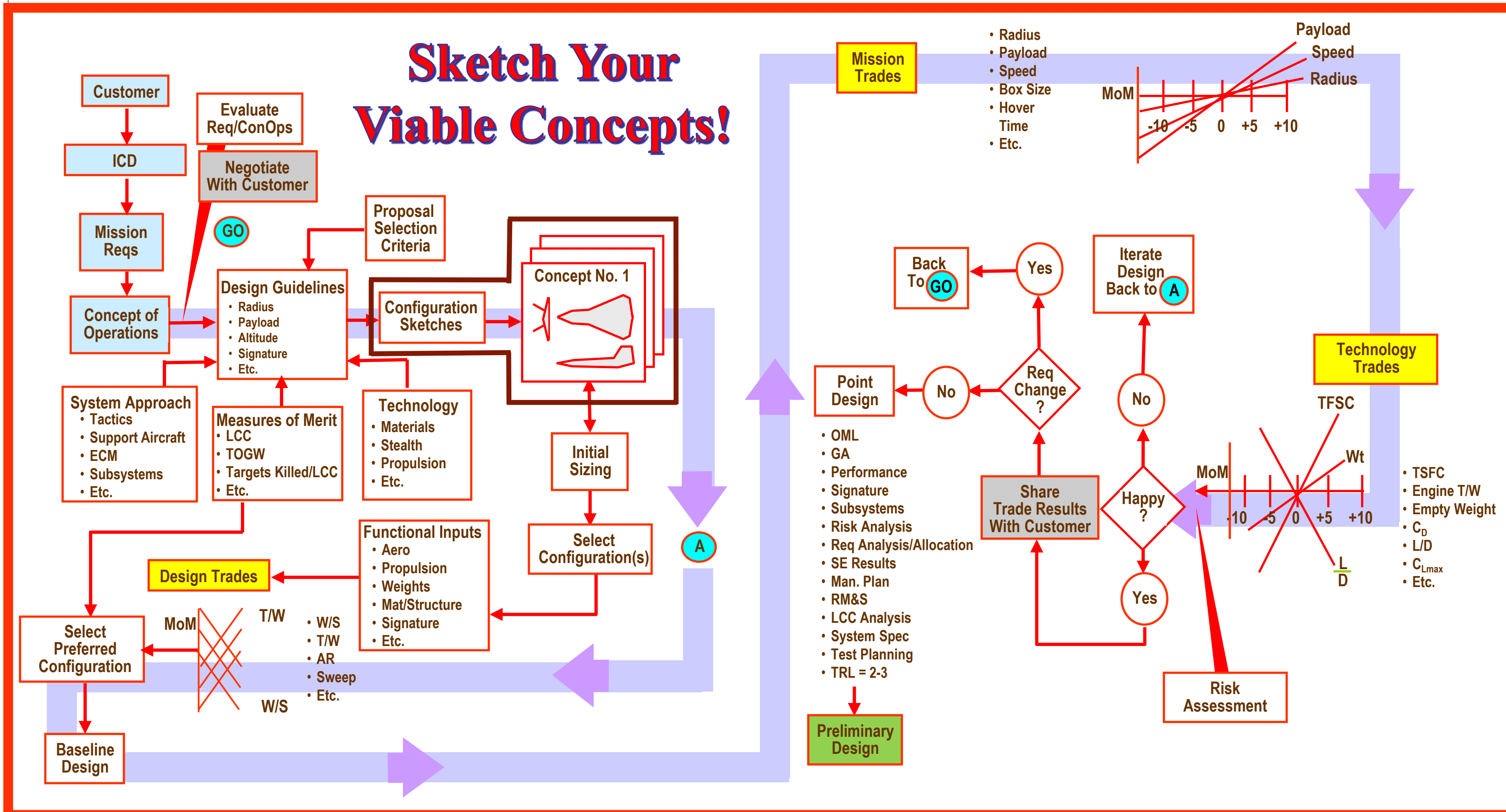
A3.2.1 Initial Concept Sketches

A3.2.2 Initial Concept Models

A3.3 Choose a Few "Good" Feasible Concepts

A3.4 Select Best PSC as Baseline Design

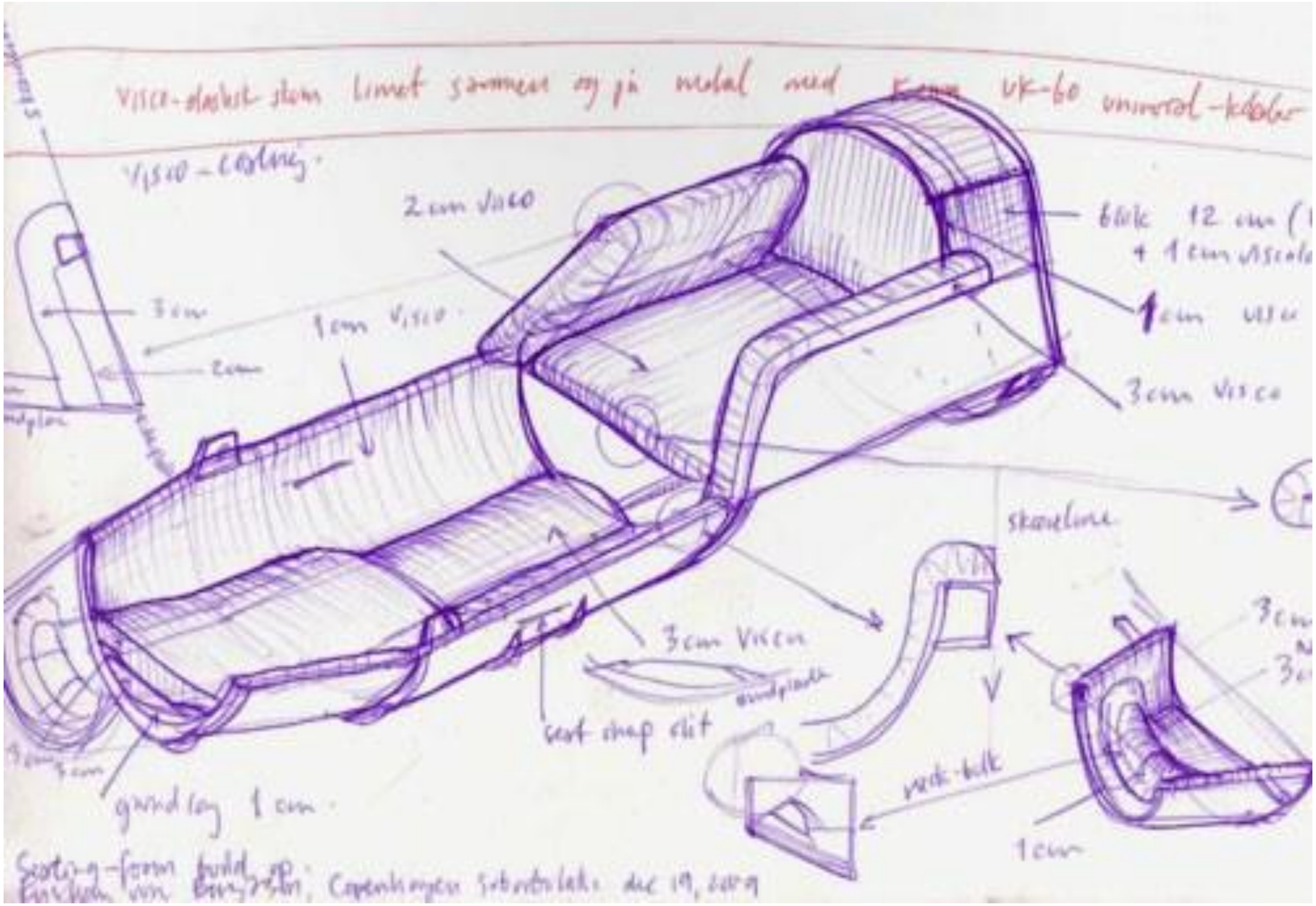
Aircraft Conceptual Design (CD) Process



Time for Creative Synthesis!

Adapted from Dr. Lee Nicolai's lecture slides

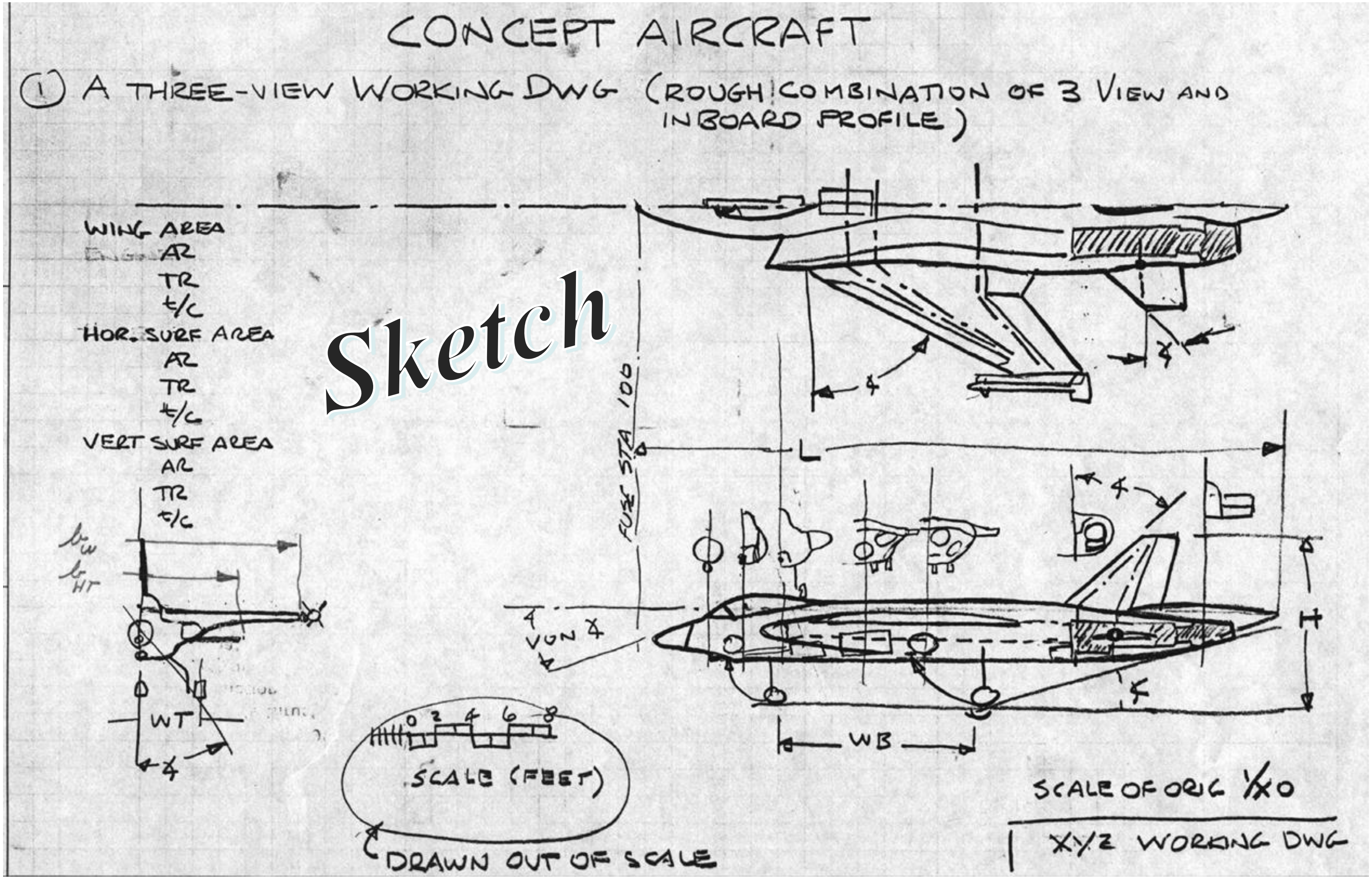
Initial Concept Sketching



A way to quickly capture and convey ideas to others!

http://engineeringisawesome.com/post/13113817812/engineering-sketches

Example of Concept Aircraft Sketch



Sketching a Concept: 1st Step

Ask Relevant Questions

- **What should the air vehicle look like to best perform the mission?**
- **Should it have a wing? Or two? Or more?**
- **Should it have a fuselage?**
- **Should it be tailless or have an empennage?**
- **What type of landing gear should it have?**

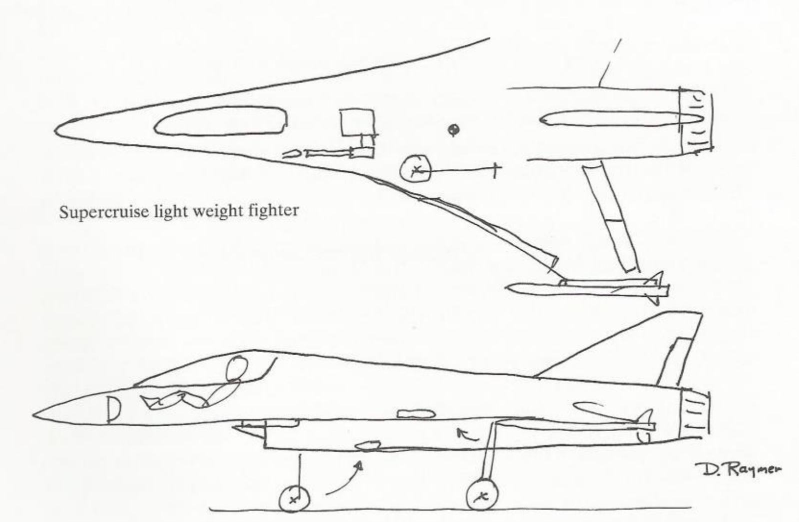


Fig. 2.5 Initial sketch.

- **What kind of engines? Turbojets, turbofans, turboprops, piston-props? Etc.**
- ***How do you decide?***
  - *Use your understanding and knowledge of the pros & cons of available options*
- **At this stage it is just initial impressions and getting ideas on paper.**
- **This can serve as a starting point for initial CAD work or work using tools like NASA OpenVSP.**

Use Your "Design Smarts" (see CM A1)

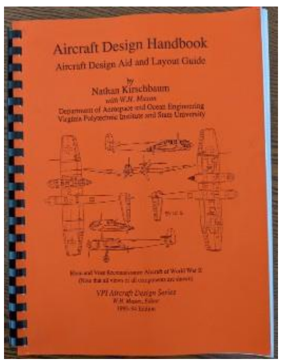
Source: Figure 10.29, Ref. AVD 2 (Raymer)

Plan of Action for Sketches

- **Requirements Review** – What are the key configuration drivers? What need are we trying to fulfill with the new design?

- **Research –** What has been done in the past and currently to address the design need? You need to know the competition?
  - Jane's All the World's Aircraft
  - Aviation Week
  - Flight International

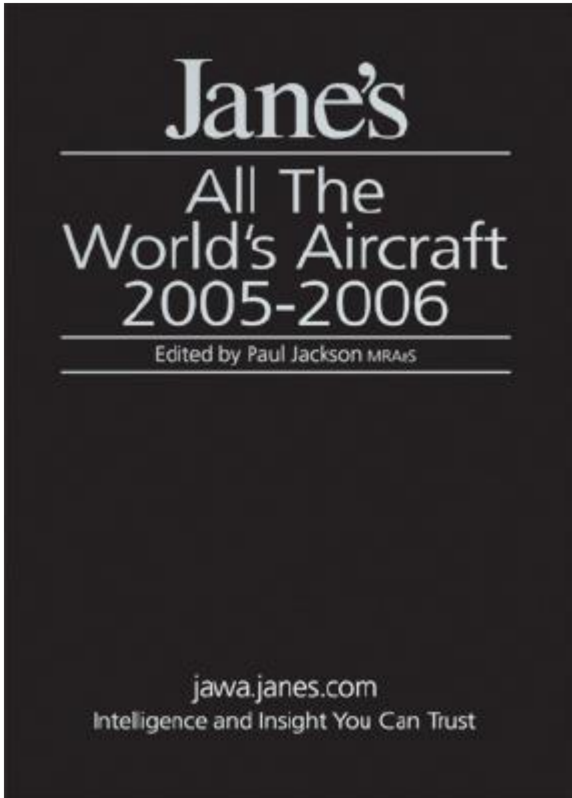
    and others

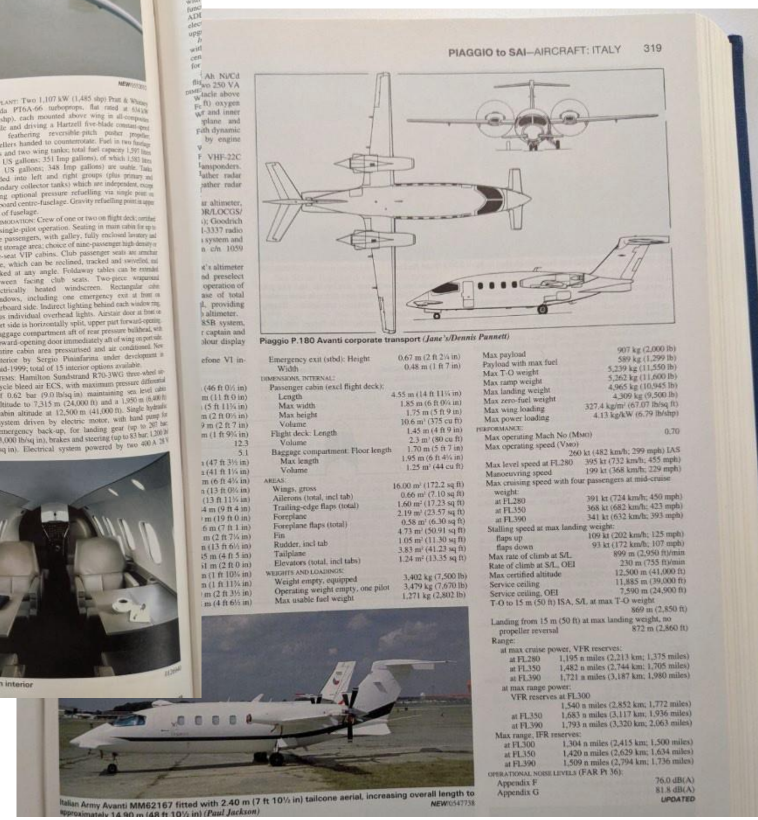


- **Initial Brainstorming** – If some ideas come to mind, make initial sketches, capture the ideas and record them
  - What kind of configuration comes to mind?
  - These are ideas that can be explored later (don't get too invested into these)

Adapted from Dr. Wm. Butler's lecture slides

A Quick Word about Jane's





Lots of good information in these books

Source: Jane's All the World's Aircraft 2005

A Quick Word about Jane's

Example of information for Piaggio P.180

...with two EFD-85 dual colour CRT MFDs for captain and central MFD-85B radar display; EHSI-74 colour display for co-pilot.

Mission: Optional Global/Wulfsberg Flitefone VI in-flight telephone.

DIMENSIONS, EXTERNAL:	
Wing span	14.035 m (46 ft 0½ in)
Foreplane span	3.355 m (11 ft 0 in)
Wing chord: at root	1.82 m (5 ft 11¾ in)
at tip	0.62 m (2 ft 0½ in)
Foreplane chord: at root	0.79 m (2 ft 7 in)
at tip	0.55 m (1 ft 9¾ in)
Wing aspect ratio	12.3
Foreplane aspect ratio	5.1
Length overall	14.41 m (47 ft 3½ in)
Fuselage: Length	12.53 m (41 ft 1¼ in)
Max width	1.95 m (6 ft 4¾ in)
Height overall	3.98 m (13 ft 0¾ in)
Tailplane span	4.26 m (13 ft 11¾ in)
Wheel track	2.84 m (9 ft 4 in)
Wheelbase	5.79 m (19 ft 0 in)
Propeller diameter	2.16 m (7 ft 1 in)
Propeller ground clearance	0.795 m (2 ft 7¼ in)
Distance between propeller centres	4.125 m (13 ft 6½ in)
Passenger door (fwd, port): Height	1.345 m (4 ft 5 in)
Width	0.61 m (2 ft 0 in)
Height to sill	0.58 m (1 ft 10¾ in)
Baggage door (rear, port): Height	0.60 m (1 ft 11¾ in)
Width	0.70 m (2 ft 3½ in)
Height to sill	1.38 m (4 ft 6½ in)

Piaggio P.180 Avanti corporate transport *(Jane's/Dennis Punnett)*

Emergency exit (stbd): Height	0.67 m (2 ft 2¼ in)
Width	0.48 m (1 ft 7 in)
DIMENSIONS, INTERNAL:	
Passenger cabin (excl flight deck):	
Length	4.55 m (14 ft 11¼ in)
Max width	1.85 m (6 ft 0¾ in)
Max height	1.75 m (5 ft 9 in)
Volume	10.6 m³ (375 cu ft)
Flight deck: Length	1.45 m (4 ft 9 in)
Volume	2.3 m³ (80 cu ft)
Baggage compartment: Floor length	1.70 m (5 ft 7 in)
Max length	1.95 m (6 ft 4¾ in)
Volume	1.25 m³ (44 cu ft)
AREAS:	
Wings, gross	16.00 m² (172.2 sq ft)
Ailerons (total, incl tab)	0.66 m² (7.10 sq ft)
Trailing-edge flaps (total)	1.60 m² (17.23 sq ft)
Foreplane	2.19 m² (23.57 sq ft)
Foreplane flaps (total)	0.58 m² (6.30 sq ft)
Fin	4.73 m² (50.91 sq ft)
Rudder, incl tab	1.05 m² (11.30 sq ft)
Tailplane	3.83 m² (41.23 sq ft)
Elevators (total, incl tabs)	1.24 m² (13.35 sq ft)
WEIGHTS AND LOADINGS:	
Weight empty, equipped	3,402 kg (7,500 lb)
Operating weight empty, one pilot	3,479 kg (7,670 lb)
Max usable fuel weight	1,271 kg (2,802 lb)
Max payload	907 kg (2,000 lb)
Payload with max fuel	589 kg (1,299 lb)
Max T-O weight	5,239 kg (11,550 lb)
Max ramp weight	5,262 kg (11,600 lb)
Max landing weight	4,965 kg (10,945 lb)
Max zero-fuel weight	4,309 kg (9,500 lb)
Max wing loading	327.4 kg/m² (67.07 lb/sq ft)
Max power loading	4.13 kg/kW (6.79 lb/shp)
PERFORMANCE:	
Max operating Mach No (MMO)	0.70
Max operating speed (VMO)	260 kt (482 km/h; 299 mph) IAS
Max level speed at FL280	395 kt (732 km/h; 455 mph)
Manoeuvring speed	199 kt (368 km/h; 229 mph)
Max cruising speed with four passengers at mid-cruise weight:	
at FL280	391 kt (724 km/h; 450 mph)
at FL350	368 kt (682 km/h; 423 mph)
at FL390	341 kt (632 km/h; 393 mph)
Stalling speed at max landing weight:	
flaps up	109 kt (202 km/h; 125 mph)
flaps down	93 kt (172 km/h; 107 mph)
Max rate of climb at S/L	899 m (2,950 ft)/min
Rate of climb at S/L, OEI	230 m (755 ft)/min
Max certified altitude	12,500 m (41,000 ft)
Service ceiling	11,885 m (39,000 ft)
Service ceiling, OEI	7,590 m (24,900 ft)
T-O to 15 m (50 ft) ISA, S/L at max T-O weight	869 m (2,850 ft)

Dimensional, Mass Properties & Performance Data

Source: Jane's All the World's Aircraft 2005

A Quick Word about Jane's

plus one option.
COSTS: US$4.995 million (2002).
DESIGN FEATURES: Intended to provide jet-type speeds with turboprop economy. Three-surface control with foreplane and T tail to allow unobstructed cabin with maximum headroom to be placed forward of mid-mounted wing carry-through structure; pusher turboprops aft of cabin and wing reduce cabin noise and propeller vortices on wing, assisting in achievement of 50 per cent laminar flow; mid-wing avoids root bulges of low-set wings and spar does not pass through cabin; lift from foreplane allows horizontal tail to act as lifting surface and thereby reduce required wing area by 34 per cent.

Laminar flow wing section Piaggio PE 1491 G (mod) at root, PE 1332 G at tip; thickness/chord ratio 13 per cent at tip, 14.5 per cent at root; dihedral 2°; sweepback 1° 11′ 24″; taper ratio 0.34; foreplane aerofoil Piaggio PE 1300 GN4 unswept; 5° anhedral on foreplane and tailplane; latter sweptback 29° 48′ at 25 per cent chord. Tailplane swept 40° at 25 per cent chord.
FLYING CONTROLS: Manual. Aerodynamically and mass-

Example of information for Piaggio P.180

Source: Jane's All the World's Aircraft 2005

An Example of Creating an Initial Sketch Based on a Good Understanding of Customer Requirements

The Scenario

Billionaire couple Mr. & Mrs. Olson have always had an interest in aviation and aviation history. They donate to the Smithsonian Air & Space Museum and are regular attendees of Oshkosh. Both of them have a pilot's license and have been flying for years.

Mr. Olson is a warbird enthusiast and has great recollections of stories told by his father of flying the Lockheed Ventura in the 1940s. Some of his favorite aircraft of all-time include the Ventura and the B-25.

The Olsons want to make an impact on current aviation while still paying homage to what many consider as the *Golden Age of Aviation* (1920s-1940s).

In particular they are interested in a new aircraft design that has the following characteristics:

- Range of at least 1,500 miles
- Service ceiling of 30,000 feet
- Top speed in the subsonic range *(interested in getting to a destination faster than in the 1930s and 1940s but flying from point A to B in as short a time as possible is not a goal)*
- Able to carry up 9 people which includes 3 crew with luggage in a reconfigurable cabin
- Should be able to operate from small regional airports
- At least two engines in case of an engine out. No jet engines
- "*Elegance of the Golden Age of Aviation with a modern treatment*"
- There is an interest in alternative uses for this recreational transport vehicle

Requirements and Desires

Billionaire couple Mr. & Mrs. Olson have always had an interest in aviation and aviation history. They donate to the Smithsonian Air & Space Museum and are regular attendees of Oshkosh. Both of them have a pilot's license and have been flying for years.

Mr. Olson is a warbird enthusiast and has great recollections of stories told by his father of flying the Lockheed Ventura in the 1940s. Some of his favorite aircraft of all-time include the Ventura and the B-25.

The Olsons want to make an impact on current aviation while still paying homage to what many consider as the *Golden Age of Aviation* (1920s-1940s).

In particular they are interested in a new aircraft design that has the following characteristics:

- Range of at least 1,500 miles
- Service ceiling of 30,000 feet
- Top speed in the subsonic range *(interested in getting to a destination faster than in the 1930s and 1940s but flying from point A to B in as short a time as possible is not a goal)*
- Able to carry up 9 people which includes 3 crew with luggage in a reconfigurable cabin
- Should be able to operate from small regional airports
- At least two engines in case of an engine out. No jet engines
- "*Elegance of the Golden Age of Aviation with a modern treatment*"
- There is an interest in alternative uses for this recreational transport vehicle

Adapted from Dr. Wm. Butler's lecture slides

Requirements and Desires

Billionaire couple Mr. & Mrs. Olson have always had an interest in aviation and aviation history. They donate to the Smithsonian Air & Space Museum and are regular attendees of Oshkosh. Both of them have a pilot's license and have been flying for years.

Mr. Olson is a warbird enthusiast and has great recollections … his father of flying the Lockheed Ventura in the 1940s. Some of his favorite … the Ventura and the B-25.

The Olsons want to make an impa… what many consider as the *Golden Age*…

In particular they a… …ollowing characteristics:

- Range of a…
- Service ceili…
- Top speed in th… *…ted in getting to a destination faster than in the 1930s and 194… …point A to B in as short a time as possible is not a goal)*
- Able to carry up 9… which includes 3 crew with luggage in a reconfigurable cabin
- Should be able to operate from small regional airports
- At least two engines in case of an engine out. No jet engines
- "*Elegance of the Golden Age of Aviation with a modern treatment*"
- There is an interest in alternative uses for this recreational transport vehicle

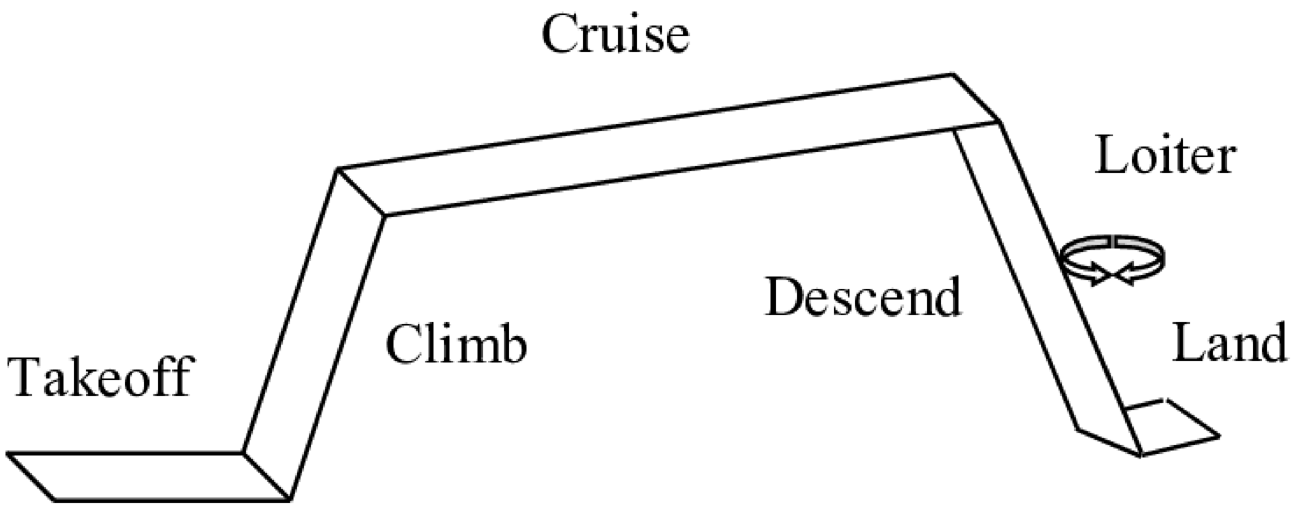
These statements give us some initial guidance on bounding the design problem (KPP, SPP, DPP)

Adapted from Dr. Wm. Butler's lecture slides

The Mission

- 30,000 foot service ceiling
- 1,500 mile range
- Subsonic cruise

Mission similar to a regional airliner



- 5,000 to 7,000 ft runway possible

Source: ResearchGate

Research

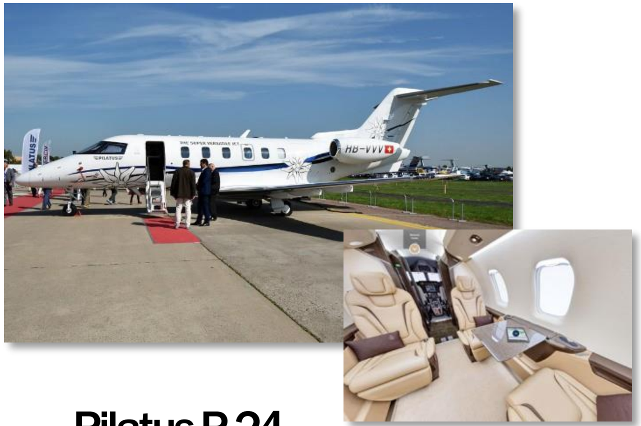
Lockheed Ventura & B-25

De Havilland Canada Dash 8

Piaggio P.180 Avanti

King Air 360

Cessna CJ4



Pilatus P-24

Some initial thoughts: W_{empty} ~10,000 lbs, W/S ~ 50-60 lb/ft^2

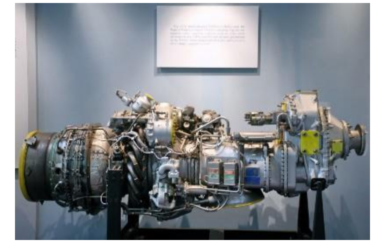
Some Initial Decisions to be Made for a Sketch

Engine possibilities: PT6A, PW123

Electric?

Hybrid?

PT6A



PW123

Space Allocation for a cabin:

Business jet?

Passenger Amenities of the 1930s?

Attempt to integrate some new technologies?

Increased aerodynamic efficiency?

Otto Aviation Celera 500L

Airbus A220

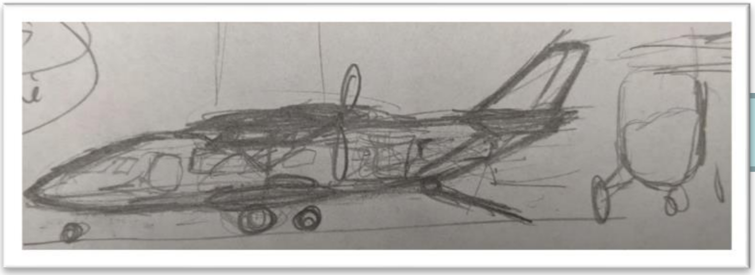
Alternative uses? Small cargo transport?

Bush plane alternative?

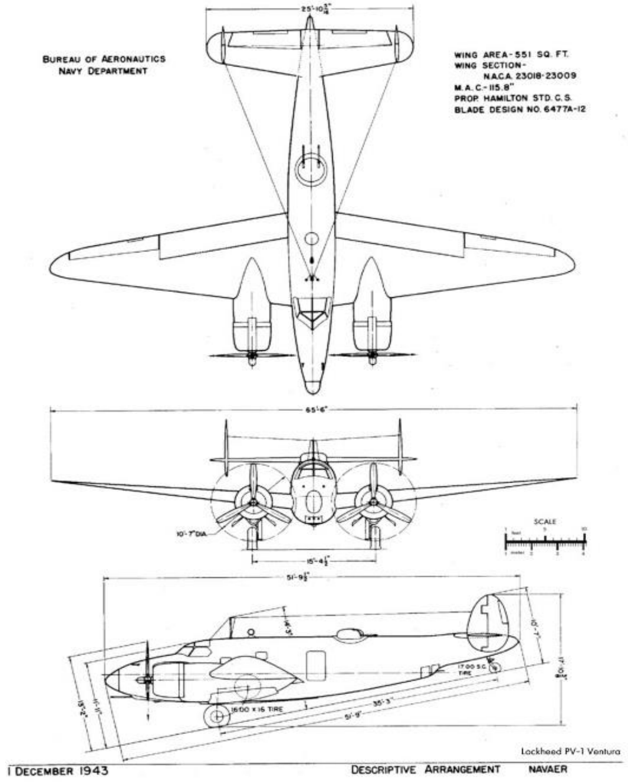
Cabin reconfiguration?

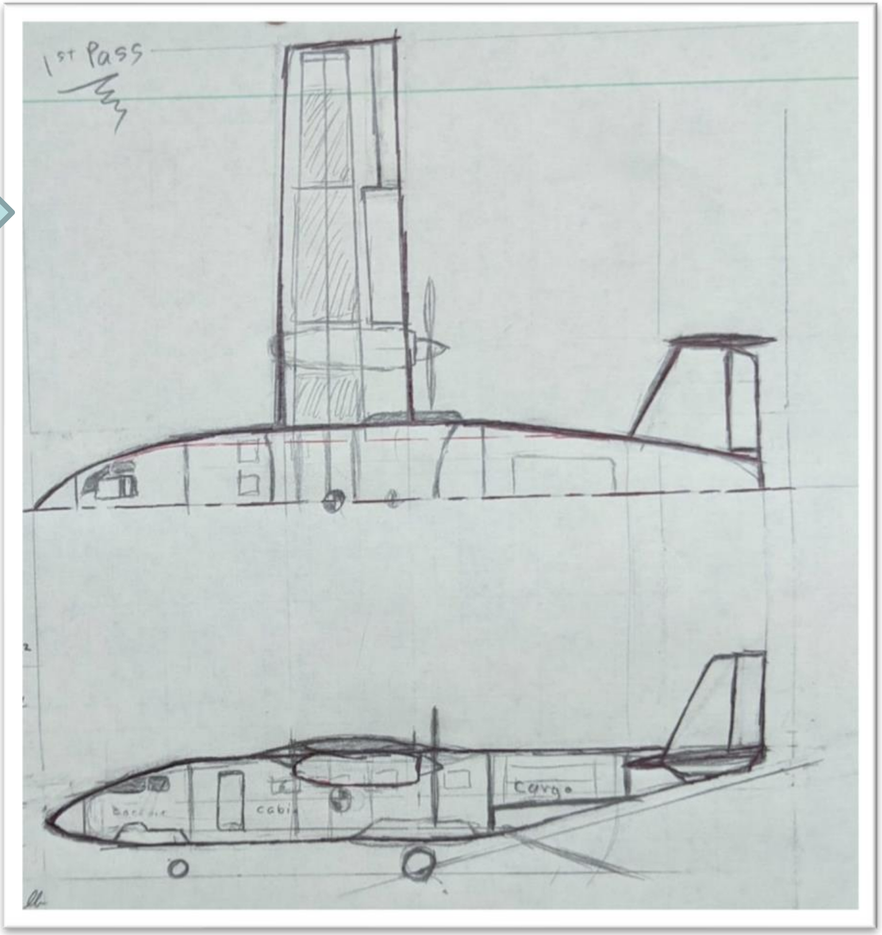
Doodles to More Formal Sketches

Very first ideas



Ventura



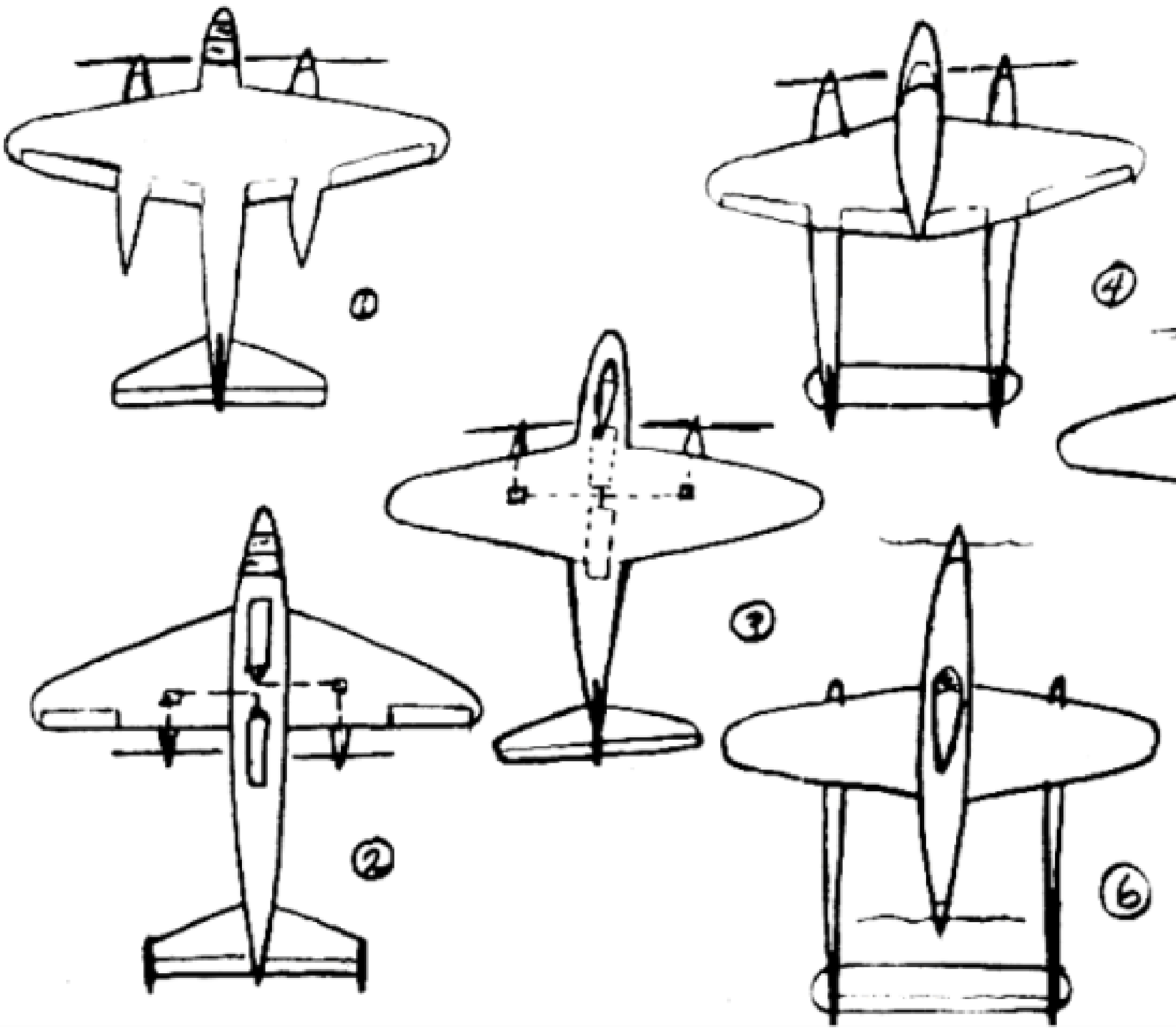


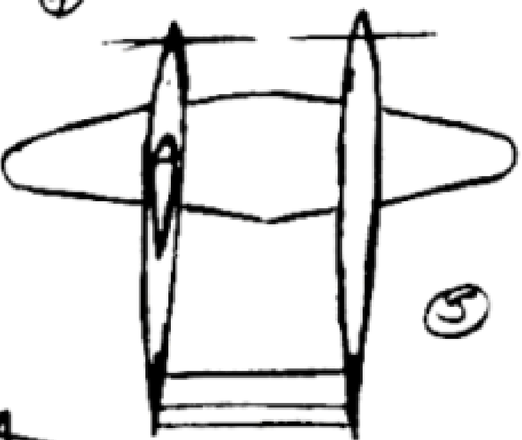
More Examples of Initial Sketches

Example of Hand-drawn Sketches

(P-38: ca late 1930s)

The Good Old Days!

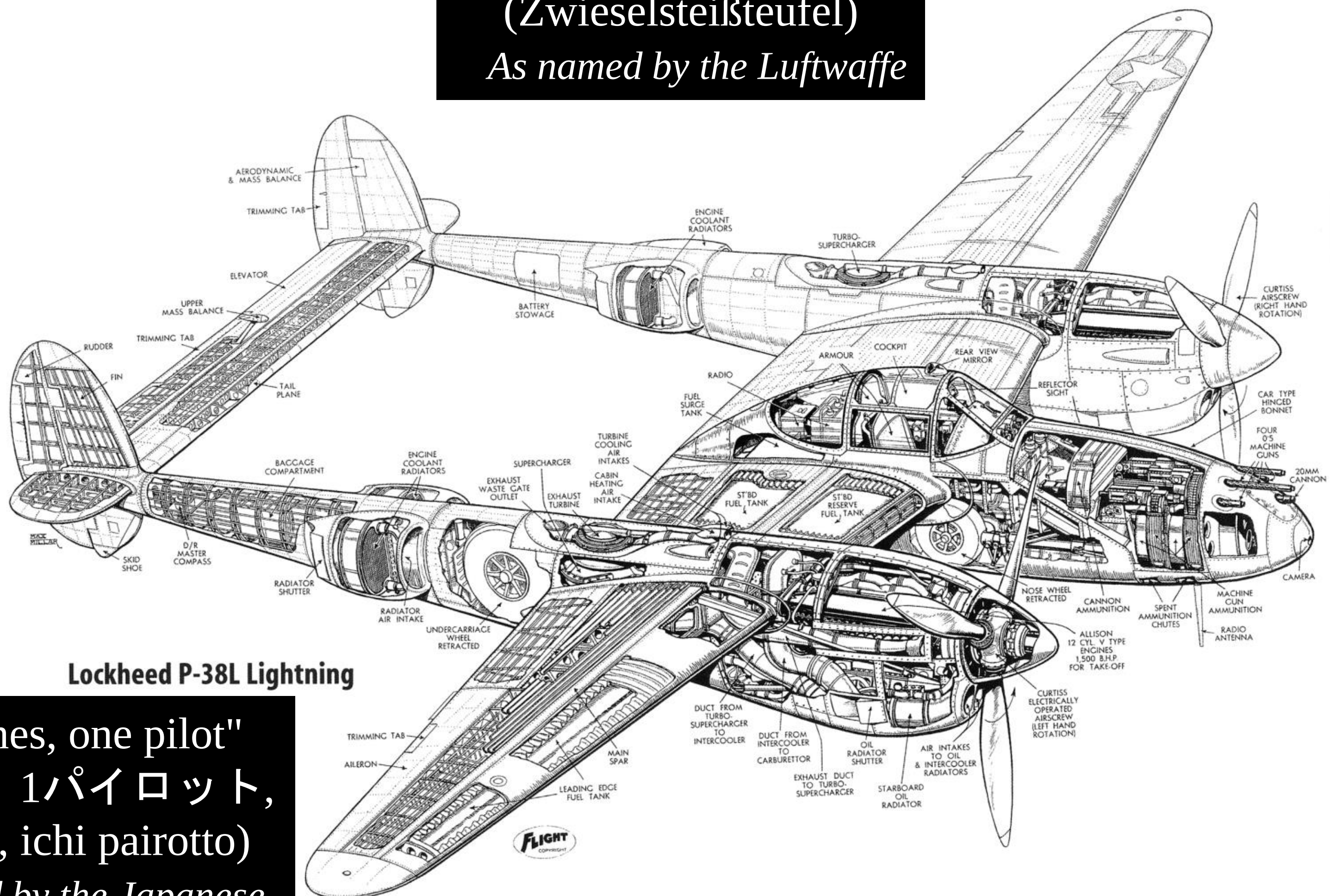




Courtesy of Lee Nicolai

The P-38 Lightning

"fork-tailed devil"
(Zwieselsteißteufel)
As named by the Luftwaffe



"two planes, one pilot"
(2飛行機、1パイロット,
Ni hikoki, ichi pairotto)
As named by the Japanese

https://www.youtube.com/watch?v=p26NYiRXm2s

Source: Internet

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

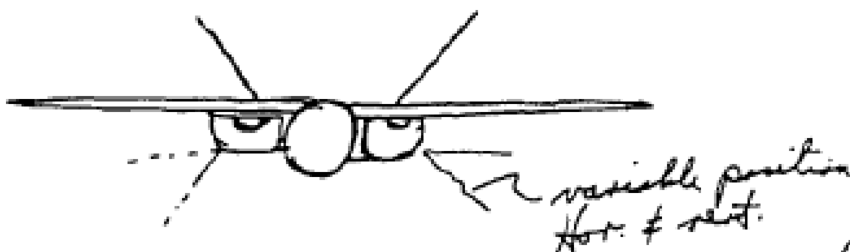
Example of Hand-drawn Sketches

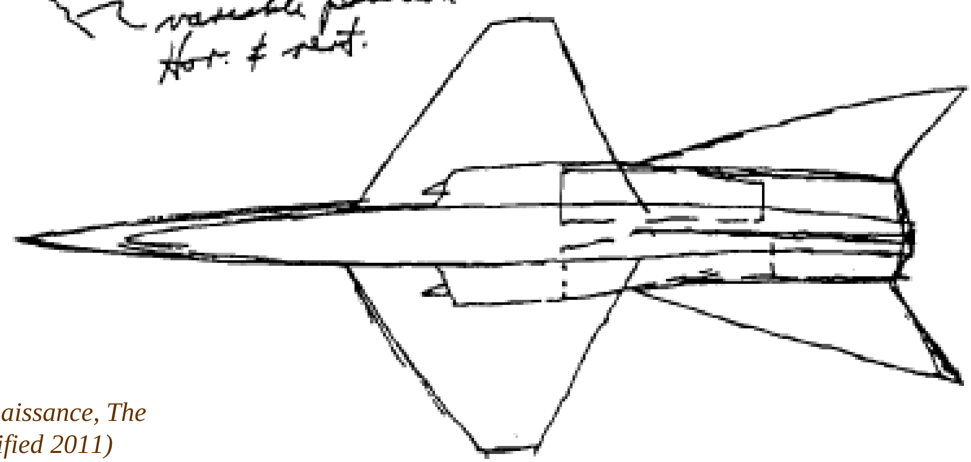
Archangel (eventual SR-71)

Concept Formulation Phase: 1958-1959

Cruise Mach Number:	3.0
Altitude At Maximum Radius:	100,000 ft.
Radar Detectability:	Minimal
Recon. Camera Payload:	500 lbs.
Unrefueled Mission Radius:	2,000 nm
Go-ahead to First Flight:	18 - 24 months

A-1, 23 April 1958





Kelly Johnson's hand-drawn sketch of the first concept, A-1

Source: Pedlow & Welzenbach, The CIA and Overhead Reconnaissance, The Story of U-2 and OXCART Programs, HR70-14, 1992 (Declassified 2011)

Outline

A3. Solve the Problem

A3.1 Prerequisites for *Solving the Problem*

A3.1.1 Design Objectives and Design Strategy

A3.1.2 Three-view CAD Drawings

A3.2 Create Multiple Viable Concepts

A3.2.1 Initial Concept Sketches

A3.2.2 Initial Concept Models

A3.3 Choose a Few "Good" Feasible Concepts

A3.4 Select Best PSC as Baseline Design

Initial Concept Models

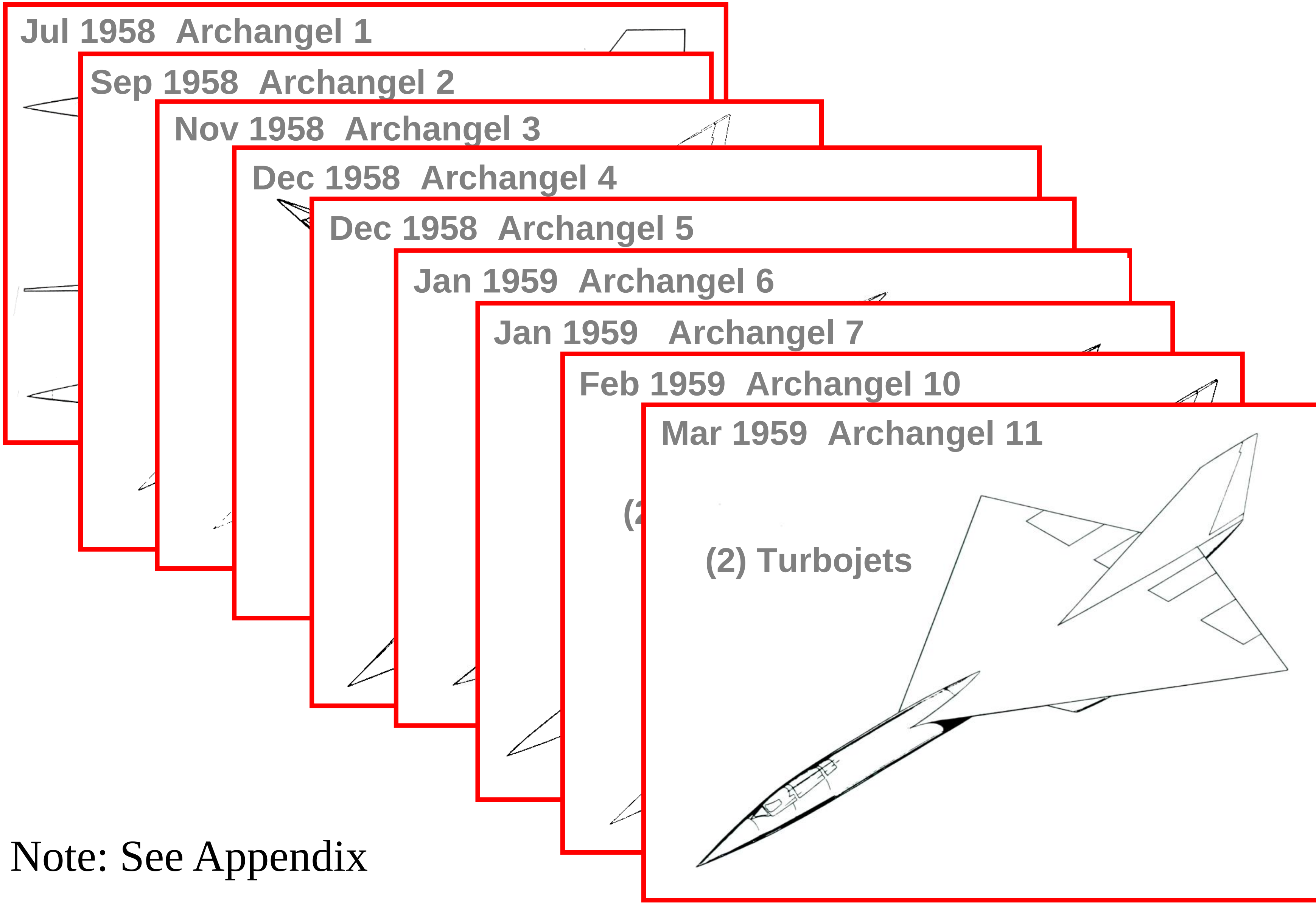
Hand-drawn sketches are often a basis for *Initial Concept Models.*

In the past, draftsmen generated Initial Concept Models.

Today, Concept Models are generated using CAD.

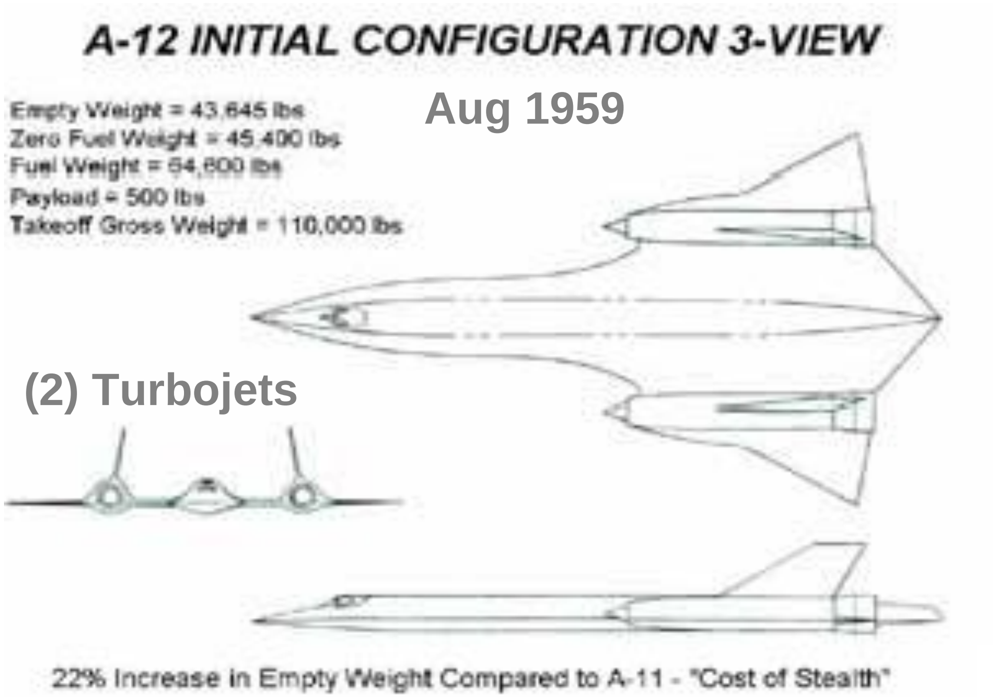
Lest You Forget: Who uses CAD? Human Configurators!

Example of Initial Concept Models
Archangel (eventual SR-71)



Note: See Appendix

Lockheed's Archangel-12



Source: Robarge, ARCHANGEL: CIA's Supersonic A-12 Reconnaissance Aircraft, Jan 2012

Example of Initial Concept Models
C-X (eventual C-5) ca early 1960s

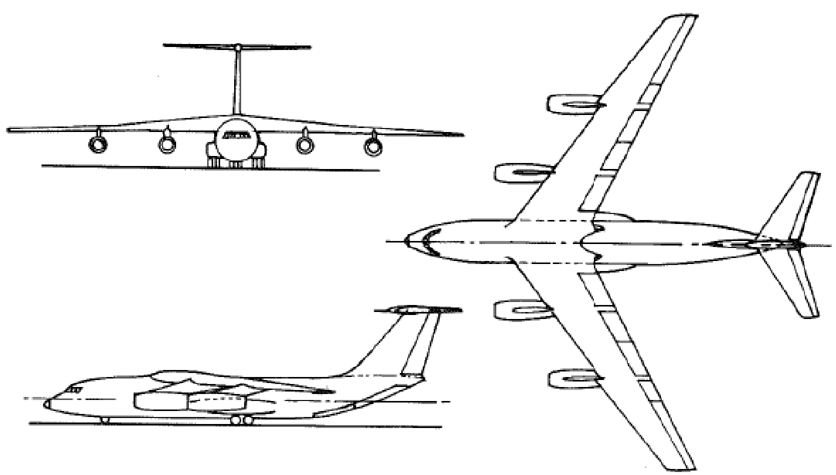
Specific Operational Requirement
DRAFT JUNE 1963 (1)

BASIC DESIGN MISSION (LF 2.5)	100,000 - 130,000 LB FOR 4,000 NM	
ALTERNATE MISSION	50,000 LB FOR 5,500 NM	
MAX. DESIGN PAYLOAD	130,000 - 150,000 LB	
CRUISE SPEED	≮ 440 KTAS	
CRUISE CEILING	≮ 30,000 FT	
TAKEOFF OVER 50 FT. AT MAX. G.W.	≯ 8,000 FT	89.5°F S.L.
TAKEOFF OVER 50 FT AT G.W. FOR 4,000 NM	≯ 4,000 FT	S.D. S.L.
LANDING OVER 50 FT WITH 100,000 LB AND FUEL RESERVES FOR 4,000 NM	≯ 4,000 FT	S.D. S.L.
AIRFIELD FLOTATION	REAR OR SUPPORT AREA FIELDS	
CARGO COMPARTMENT	LENGTH	100 - 110 FT
	WIDTH	16 - 17.5 FT
	HEIGHT	13.5 FT

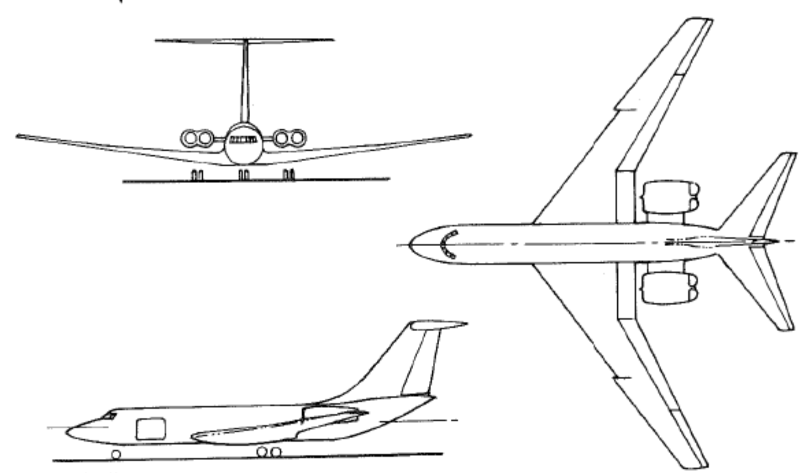
Specific Operational Requirement
DRAFT JUNE 1963 (2)

CARGO LOADING	STRAIGHT-THROUGH ONE FULL CROSS SECTION OPENING ONE 9 X 10 FT OPENING TRUCK-BED HEIGHT FLOOR DESIRABLE
POWER PLANT	SIX TURBOFAN ENGINES MIL QUAL. OR FAA CERT. BY JUNE 1967
RELIABILITY	95% PROBABILITY OF COMPLETING 10 HR MISSION
MAINTAINABILITY	MIL-M-26512 QUANTITATIVE TREATMENT
AVAILABILITY	JUNE 1970

Conventional Configuration



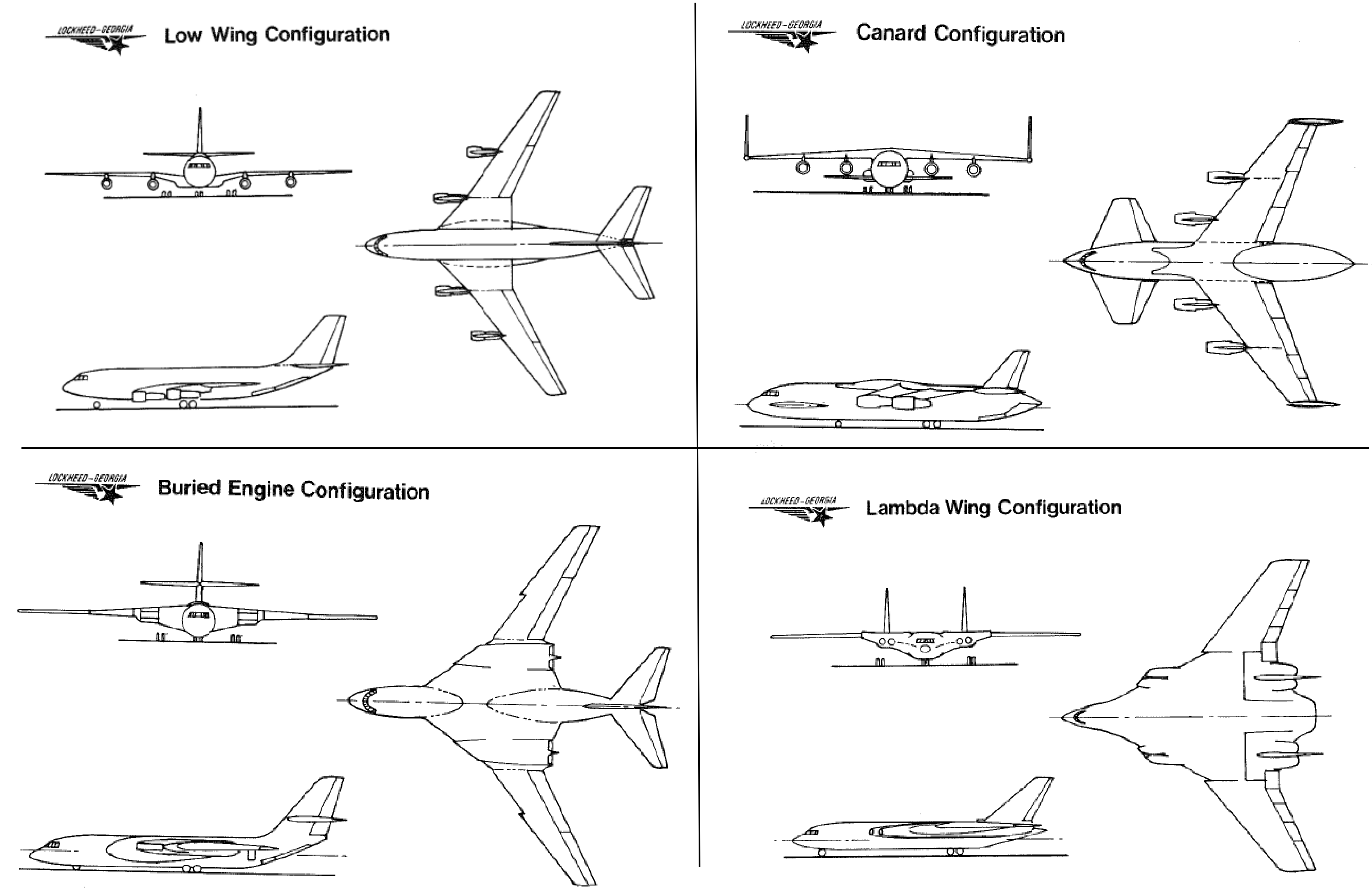
Low Wing Fuselage Mounted Engine Configuration



Source: Garrard, The Lockheed C-5 Case Study in Aircraft Design

Example of Initial Concept Models

C-X (eventual C-5) ca early 1960s

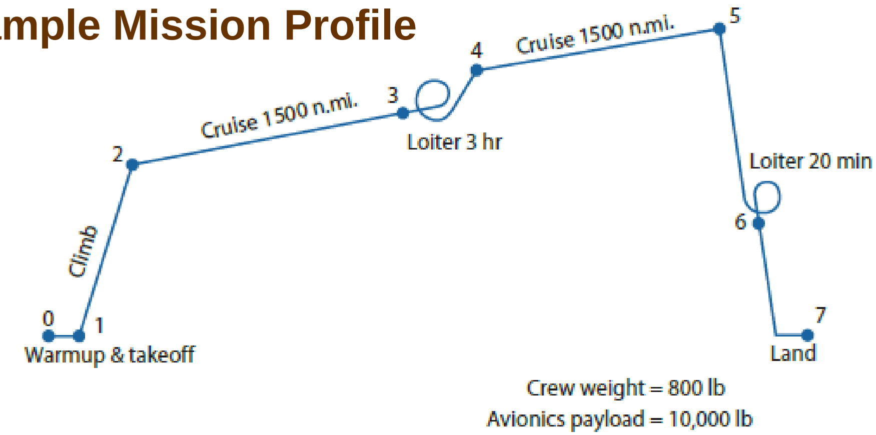


Source: Garrard, The Lockheed C-5 Case Study in Aircraft Design

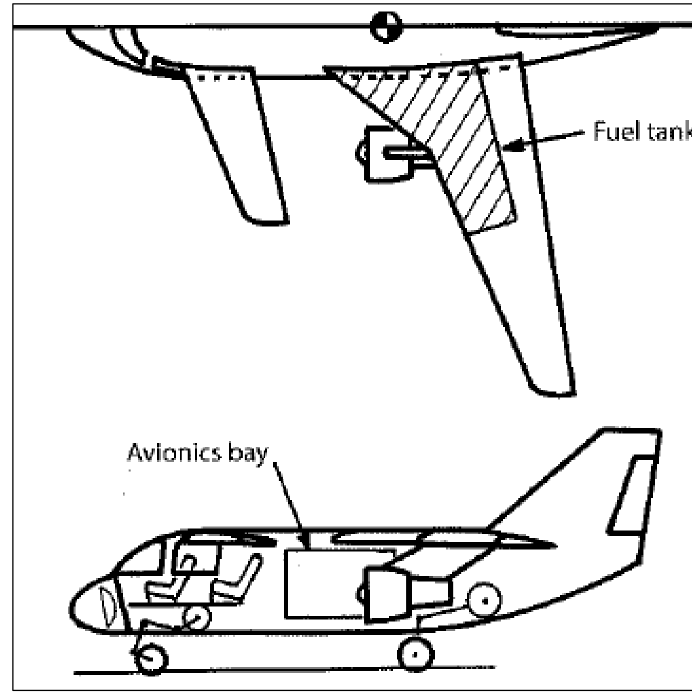
Example of Initial Concept Models

Hypothetical ASW Aircraft*

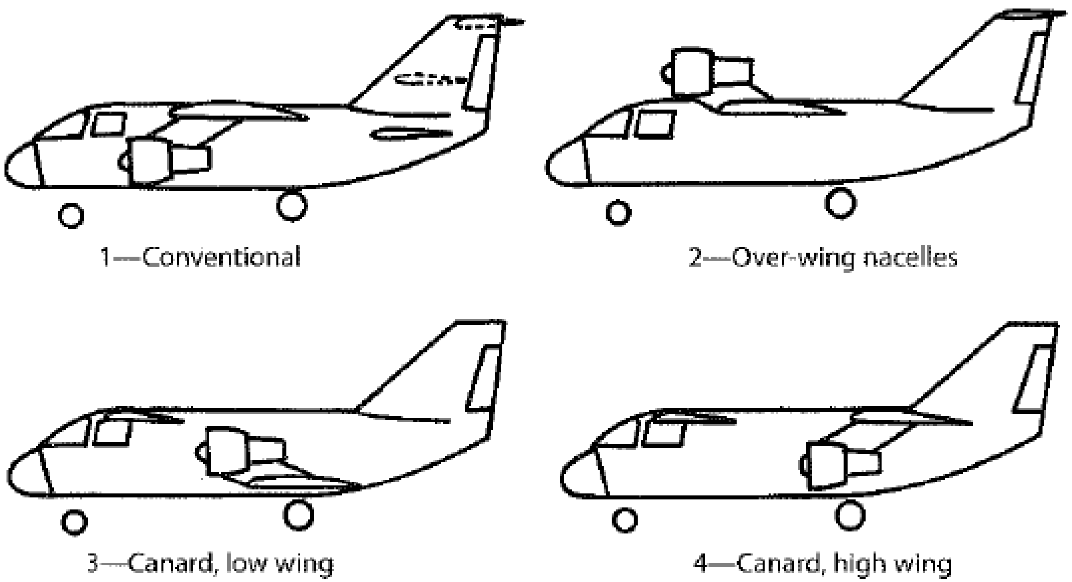
Sample Mission Profile



Completed Configuration Sketch



Initial Configuration Sketches (OML)



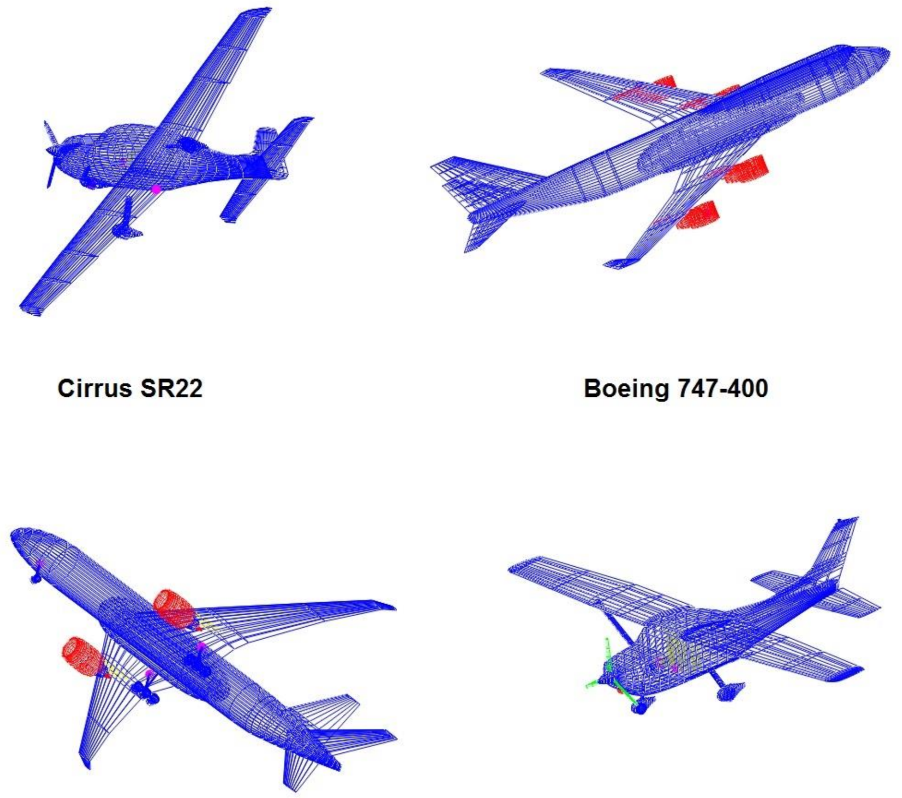
***ASW: Anti-Submarine Warfare**

Source: Fig. 3.8, 3.9 & 3.10, Ref. AVD 2 (Raymer)

Recommended Tool for Initial Concept Models

NASA Vehicle Sketch Pad (VSP) – Open Source

http://www.openvsp.org/



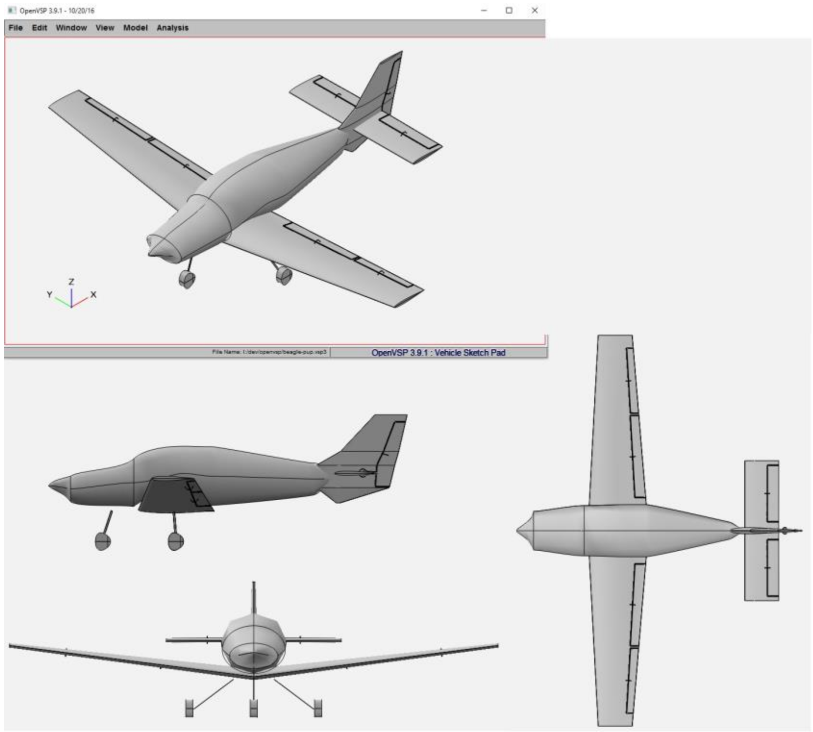
Cirrus SR22

Boeing 747-400

Boeing 777-200

Cessna 182

Perspectives for Laymen



3-vus for Engineers!

AIAA Paper 2010-0658

AIAA Paper 2013-0331

AIAA Paper 2022-0004

Outline

A3. Solve the Problem

A3.1 Prerequisites for *Solving the Problem*

A3.1.1 Design Objectives and Design Strategy

A3.1.2 Three-view CAD Drawings

A3.2 Create Multiple Viable Concepts

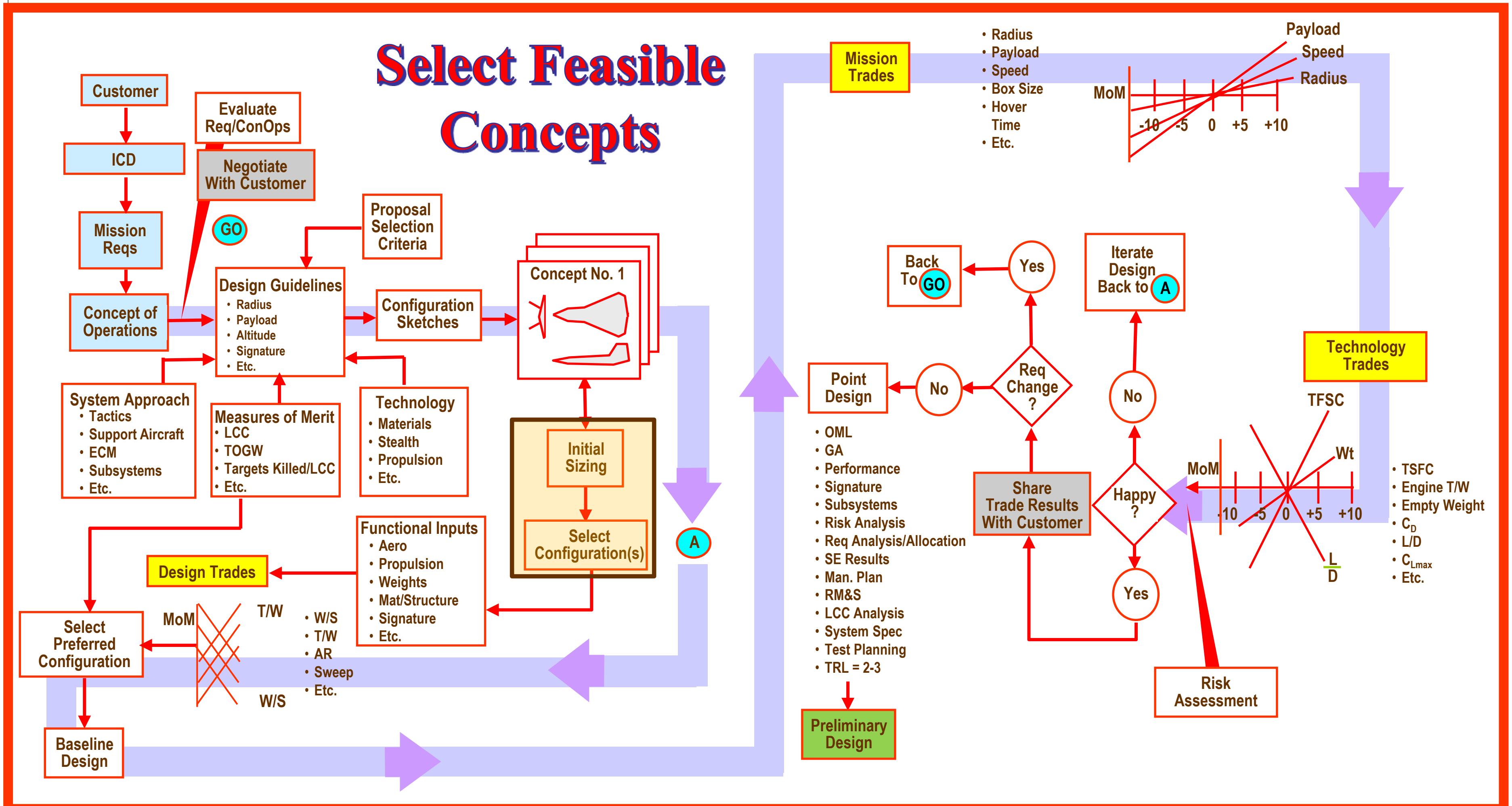
A3.2.1 Initial Concept Sketches

A3.2.2 Initial Concept Models

A3.3 Choose a Few "Good" Feasible Concepts

A3.4 Select Best PSC as Baseline Design

Aircraft Conceptual Design (CD) Process



Adapted from Dr. Lee Nicolai's lecture slides

Initial Sizing is the 1st Step in Assessing Feasibility

Initial Sizing is the starting point for defining the basic characteristics of the aircraft to be designed to perform a *prescribed mission.*

In aircraft conceptual design, we initially do three types of sizing:

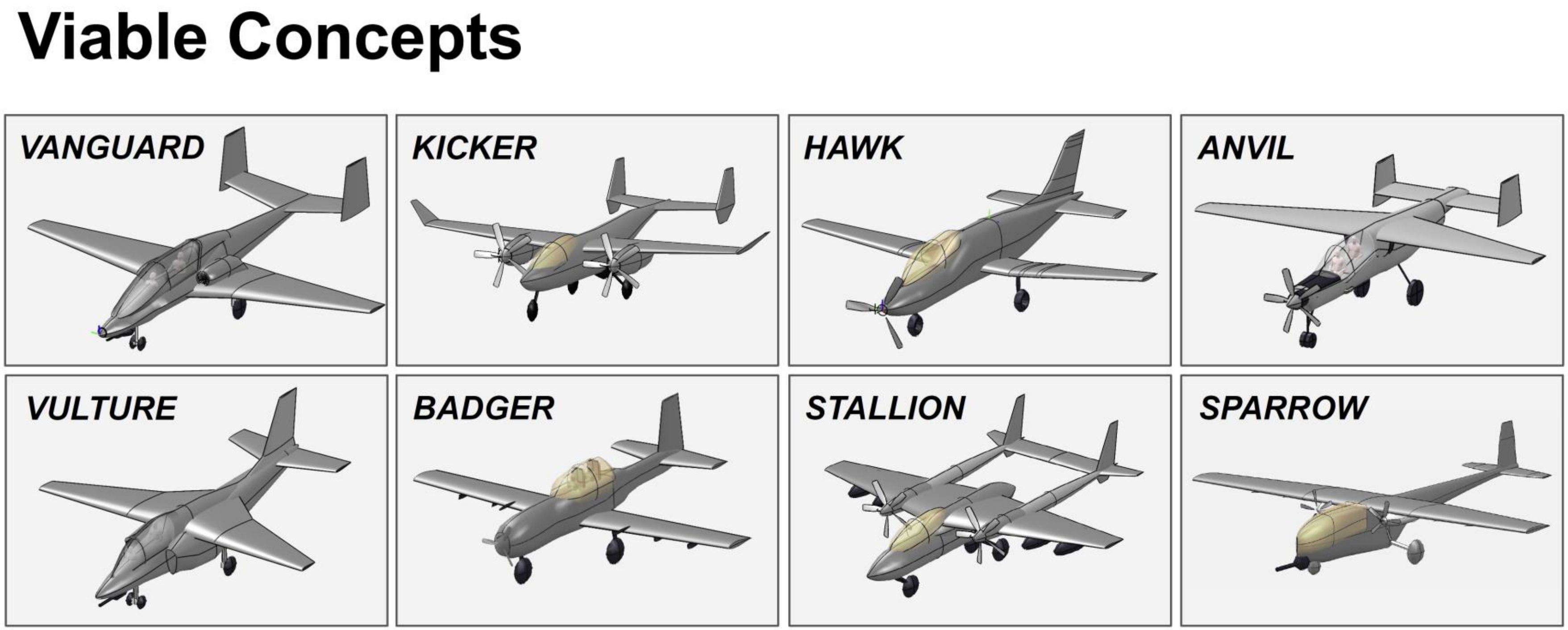
- **Initial Weight Sizing**
- **Initial Wing Sizing**
- **Initial Engine Sizing**

See Initial Sizing Modules for TOGW, Wing, and Engine Sizing

Most design efforts conduct initial sizing (and more!) of *<u>many</u>* viable concepts to assess their feasibility. An *expedient alternative* is to use qualitative decision-making tools to reduce the number of viable concepts down to a handful which are then sized to assess their feasibility. *We recommend this alternative option to student teams to accommodate schedule and resource constraints. Examples from student design project presented next.*

VT Student Design Project Example

Eight Viable Concepts



Source: 2020-2021 AIAA Vanguard Team (Lead: Snellings)

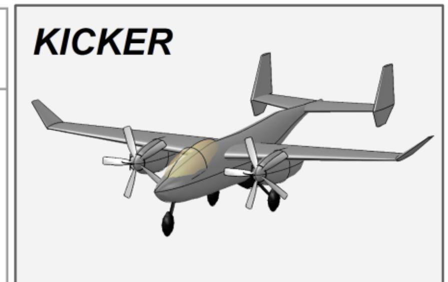
VT Student Design Project Example

Pros/Cons of Each Viable Concept

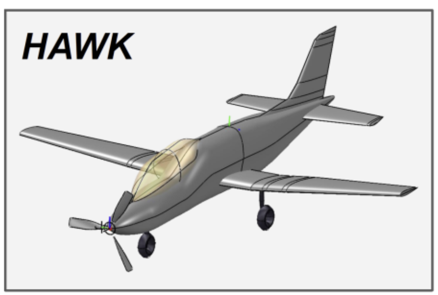
NHA

Viable Concepts

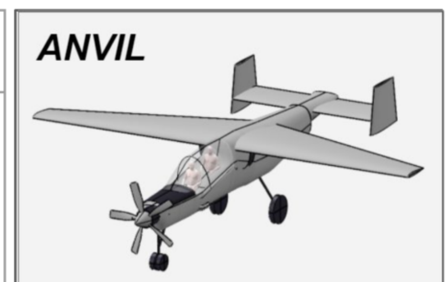
Pros	Cons
• Simple configuration • High wing for loading stores • Turbofan for speed and service ceiling	• Conventional tail lacks redundancy • Engines not protected



Pros	Cons
• 2-engine redundancy • Turret for ToT • H-tail redundancy	• 2-engine cost, fuel burn, maintenance • H-tail is more complex than a conventional tail



Pros	Cons
• Simple to manufacture • Pilot visibility • Landing gear can easily be placed in low wing	• Low wing may be hard to load payload • 1-engine lacks redundancy



Pros	Cons
• H-tail redundancy • High wing for loading stores • Turbofan for speed, turboprop for endurance	• Prop adds drag during sprint • Complex ducting with engine arrangement

NHA SCR Presentation | 10/28/20 | Slide 89

Source: 2020-2021 AIAA Vanguard Team (Lead: Snellings)

VT Student Design Project Example

Pros/Cons of Each Viable Concept

NHA

Viable Concepts

VANGUARD

Pros	Cons
• H-tail redundancy • Engines are protected, IR signature hidden • Low wing has large in ground effect	• Low wing harder to load

STALLION

Pros	Cons
• 2-engine redundancy • Turret for ToT • Reduce FOD risk	• Twin boom complexity • Dive capability • Takeoff tilt

BADGER

Pros	Cons
• Conventional design • Two integrated guns • Low initial cost	• Lacks originality • Lacks mission flexibility

SPARROW

Pros	Cons
• High wing, low FOD • Engine Redundancy • Turret	• Two engines may increase cost • Risk of tail strike

NHA SCR Presentation | 10/28/20 | Slide 90

Source: 2020-2021 AIAA Vanguard Team (Lead: Snellings)

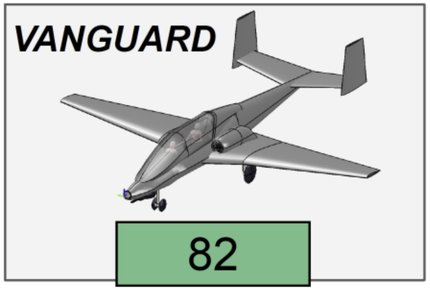
VT Student Design Project Example

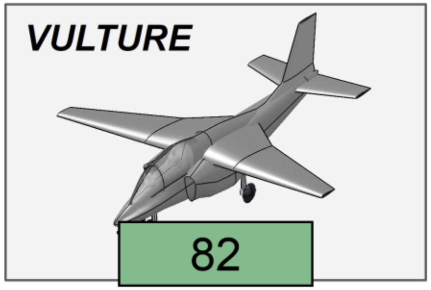
Down-selection of 3 Most Promising Concepts!

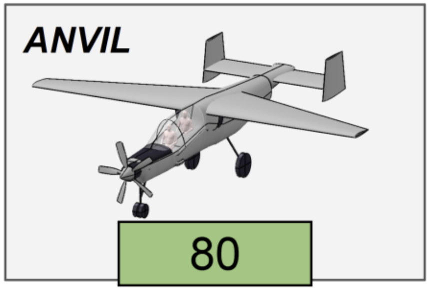
NHA

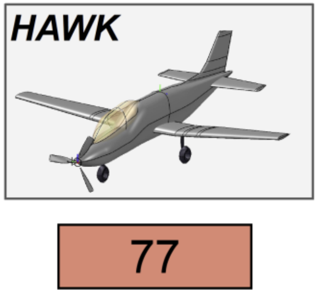
Viable Concepts

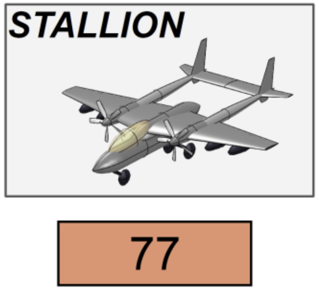
Decision Matrix Criteria and Weights			
Criteria	**Weight**	**Criteria**	**Weight**
Survivability	25	Mission Flexibility	5
Cost	15	Manufacturability	5
CAS Capability	12	Originality	5
Austere Operability	12	Pilot Visibility	5
Growth	7	Appearance	3
Serviceability	6	Total	100

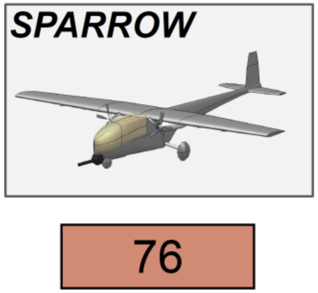


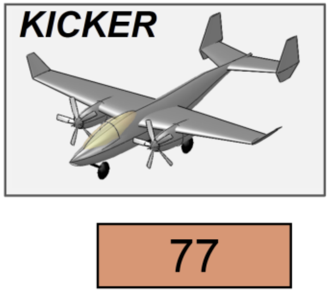












NHA SCR Presentation | 10/28/20 | Slide 20

Source: 2020-2021 AIAA Vanguard Team (Lead: Snellings)

VT Student Design Project Example

Qualitative Decision-Making Matrix

Scores based on qualitative inputs of team members

Decision Matrix for Identifying Promising Designs

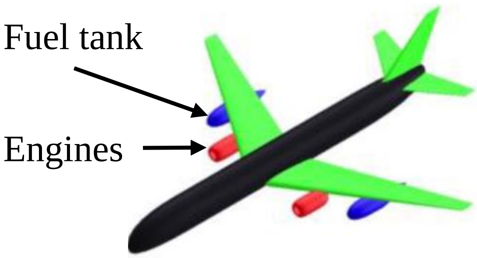
Criteria	Weighting	Kicker	Sparrow	Hawk	Stallion	Badger	Anvil	Vanguard	Vulture
Survivability	25	7	5	7	7	10	8	9	9
Cost	15	8	8	5	9	5	9	9	8
Combat	12	7	7	7	6	6	6	9	9
Austere Operability	12	9	10	9	8	9	10	6	6
Growth	7	7	10	9	9	7	8	8	9
Serviceability	6	8	8	10	8	10	9	8	8
Mission Flexibility	5	8	10	10	8	8	8	9	10
Visibility	5	8	8	10	9	5	9	8	9
Originality	5	9	7	5	8	5	8	8	10
Manufactura bility	5	7	8	10	9	10	7	7	5
Appearance	3	10	8	9	9	3	6	10	10
Weighted Sum	100	77	76	77	77	76	80	82	82
Rank		5	8	6	4	7	3	2	1

NHA SCR Presentation | 10/28/20 | Slide 94

Source: 2020-2021 AIAA Vanguard Team (Lead: Snellings)

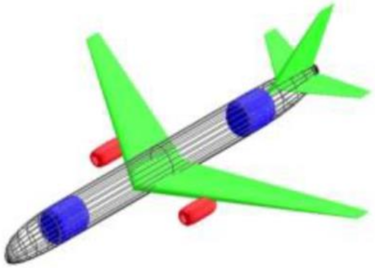
RMIT Univ. Student Design Project Example

Pros/cons of Bio-LNG viable aircraft concepts



Pros
- Reduces bending moment on wing
- Ease of maintenance
- Short fuel piping

Cons
- Wing flow interference
- Reduced cruise lift-to-drag ratio



Pros
- Large volume-to-area ratio
- Reduced boil-off
- No possibility of bird strike damage

Cons
- Tank mounting must meet higher FAA g-load limits
- Possibility of vapor leakage into fuselage
- Lost cargo volume

Pros
- Reduced ground noise
- Improved cruise lift-to-drag ratio
- Reduced bending moment on wing

Cons
- Long fuel pipes through fuselage
- Shorter tail moment
- Must increase wing box volume

Pros
- Improved cruise lift-to-drag ratio
- Reduced bending moment on wing
- No cryogenic fuel lines in fuselage

Cons
- Long fuel pipes through fuselage
- Shorter tail moment
- Must increase wing box volume

Source: Burston et al," Conceptual Design of Sustainable Liquid Methane Fueled Passenger Aircraft,' 20th ISPE, 2013, pp 391-400

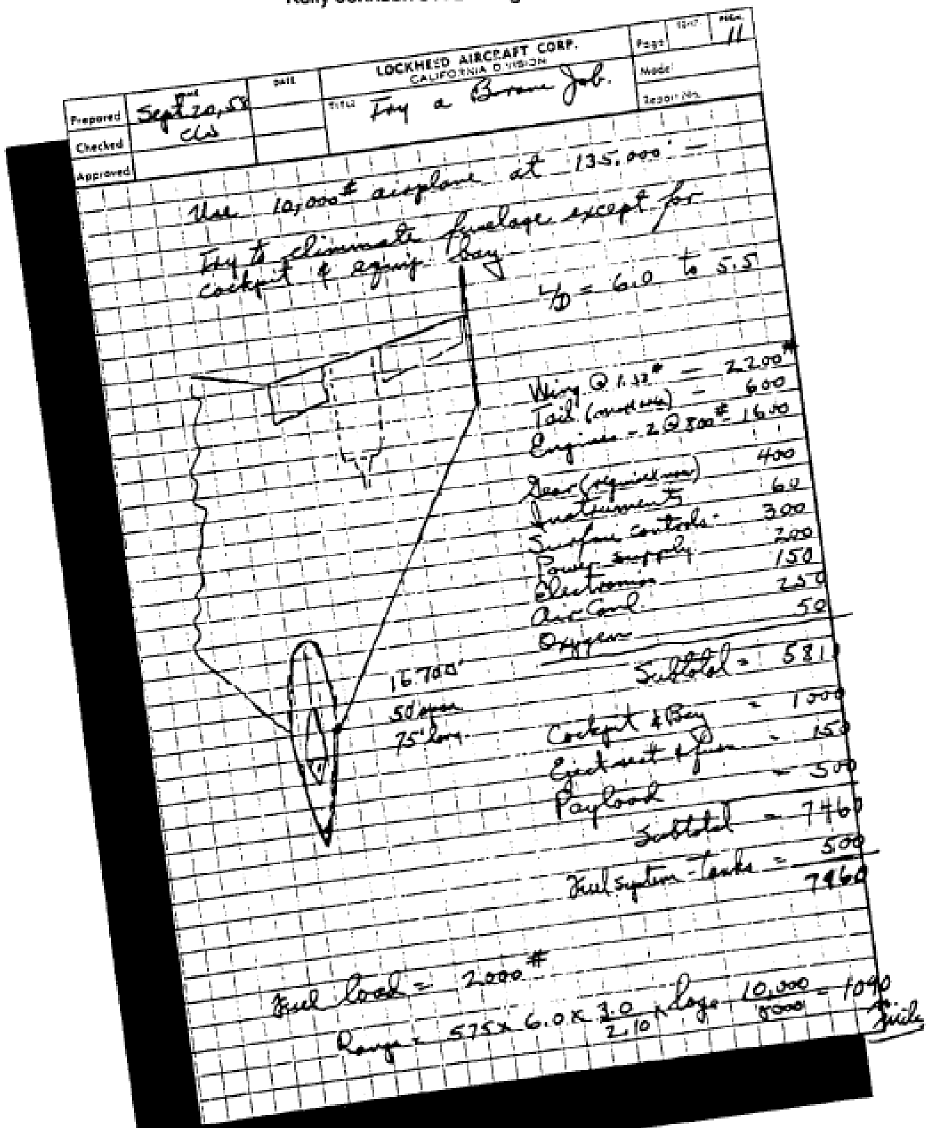
We defer discussion of Initial Sizing procedures to CM A4 and A5.

Instead, we look at examples of *how Initial Sizing results are used in making decisions*.

Archangel (eventual SR-71)

Initial Sizing of A-2 and A-3

Kelly Johnson's A-2 Design



LOCKHEED AIRCRAFT CORP.
CALIFORNIA DIVISION

Prepared	Sept 20, 58 CLJ	Title: Try a Brown Job.	Page 11
Checked			Model
Approved			Report No.

Use 10,000# airplane at 135,000' —
Try to eliminate fuselage except for cockpit & equip. bay
L/D = 6.0 to 5.5

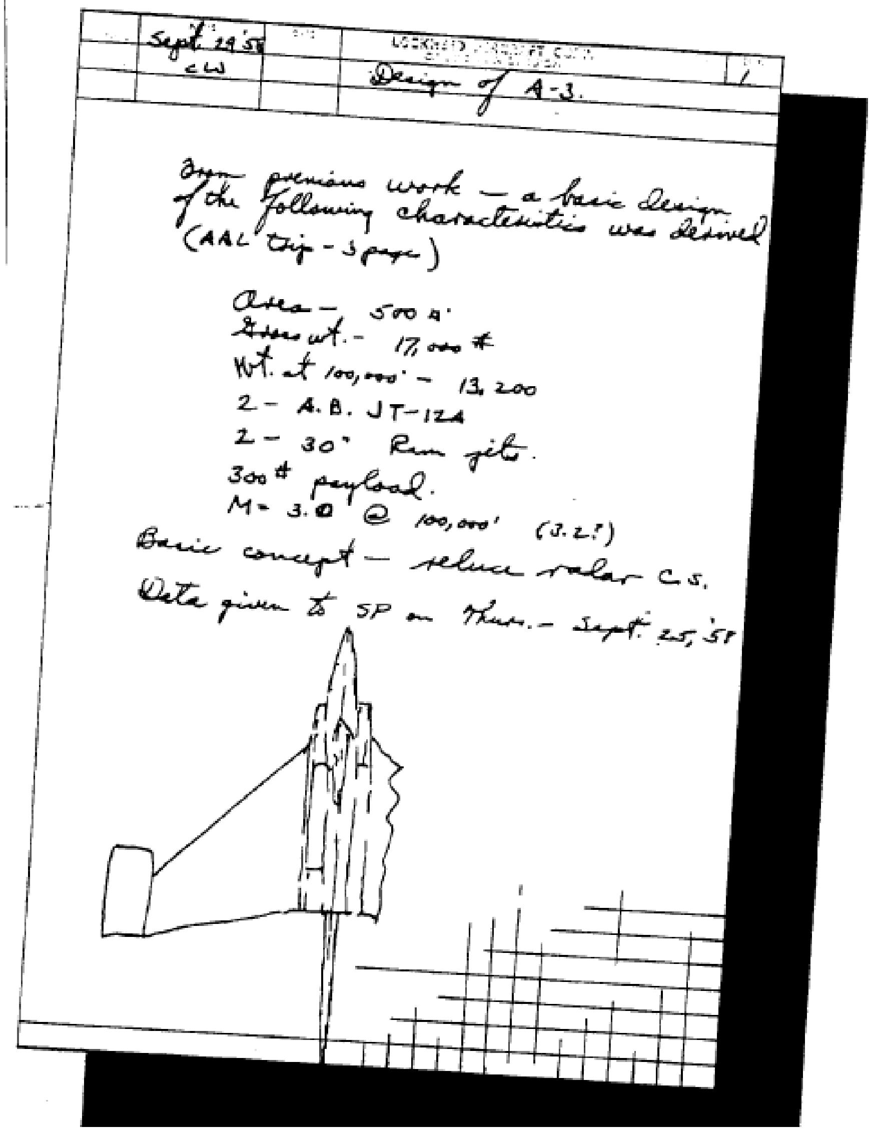
Wing @ 1.33# — 2200#
Tail (modded) — 600
Engines — 2 @ 800# = 1600
400
Gear (?) 60
Instruments 300
Surface controls 200
Power supply 150
Electronics 250
Air Cond 50
Oxygen
Subtotal = 5810

16,700'
50' span
75' long

Cockpit & Bay = 1000
Eject seat & pers. = 150
Payload = 500
Subtotal = 7460
Fuel system - tanks = 500
7960

Fuel load = 2000#
Range = 575 x 6.0 x 3.0/2.10 x log 10,000/8000 = 1090 miles

Kelly Johnson's A-3 Design



LOCKHEED AIRCRAFT CORP.

Sept 29 '58 CLJ — Design of A-3. Page 1

From previous work — a basic design of the following characteristics was derived (AAL trip - 3 pages)

Area — 500 ft²
Gross wt. — 17,000 #
Wt. at 100,000' — 13,200
2 — A.B. JT-12A
2 — 30" Ram jets.
300 # payload.
M = 3.0 @ 100,000' (3.2?)

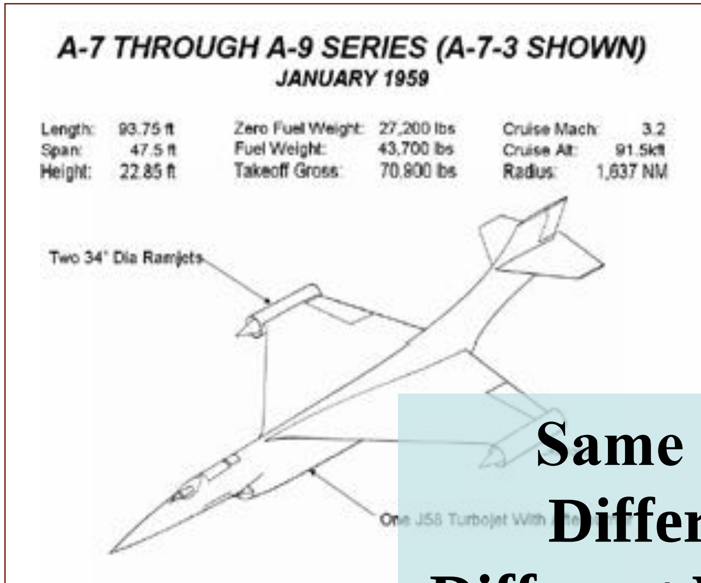
Basic concept — reduce radar C.S.
Data given to SP on Thurs. — Sept. 25, '58

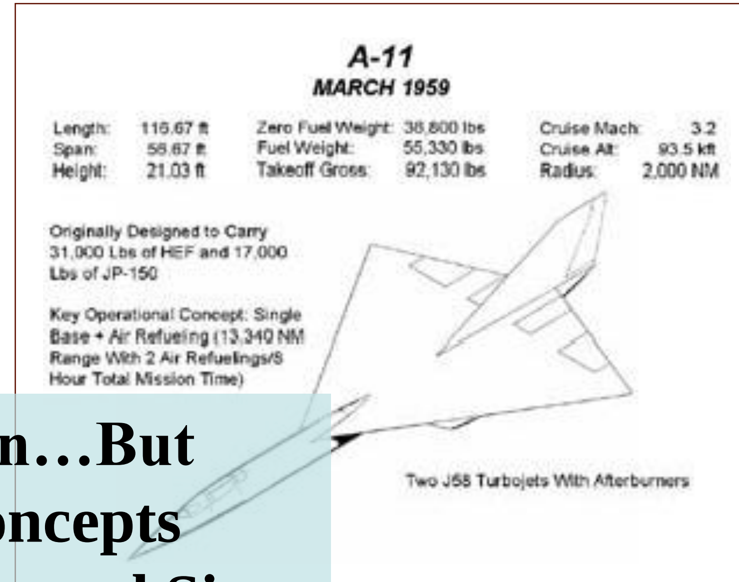
Source: Pedlow & Welzenbach, The CIA and Overhead Reconnaissance, The Story of U-2 and OXCART Programs, HR70-14, 1992 (Declassified 2011)

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

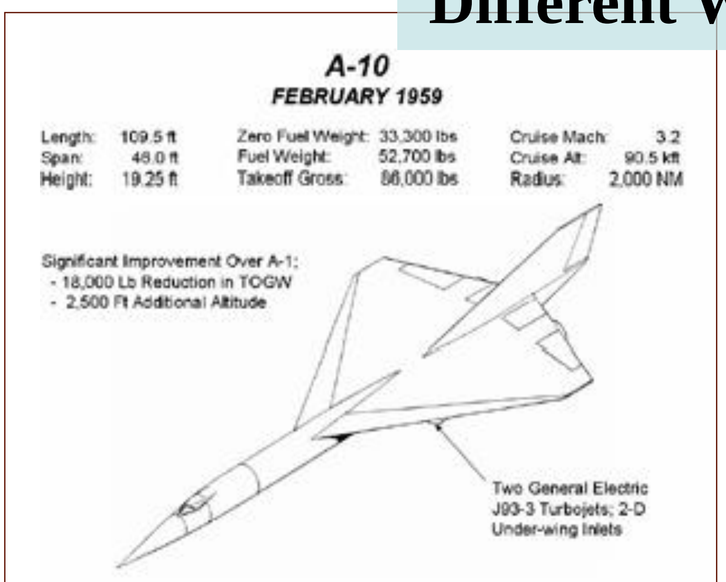
Archangel (eventual SR-71)

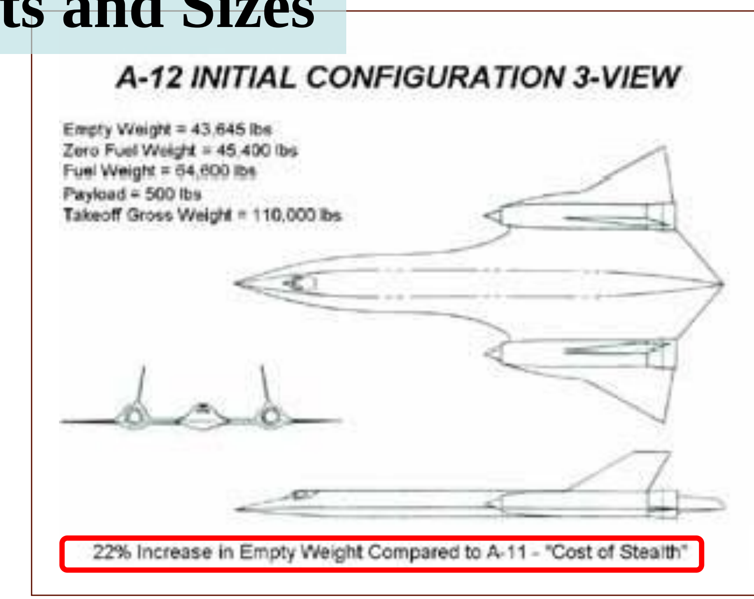
Concept Feasibility: 1958-1959





Same Mission…But Different Concepts Different Weights and Sizes





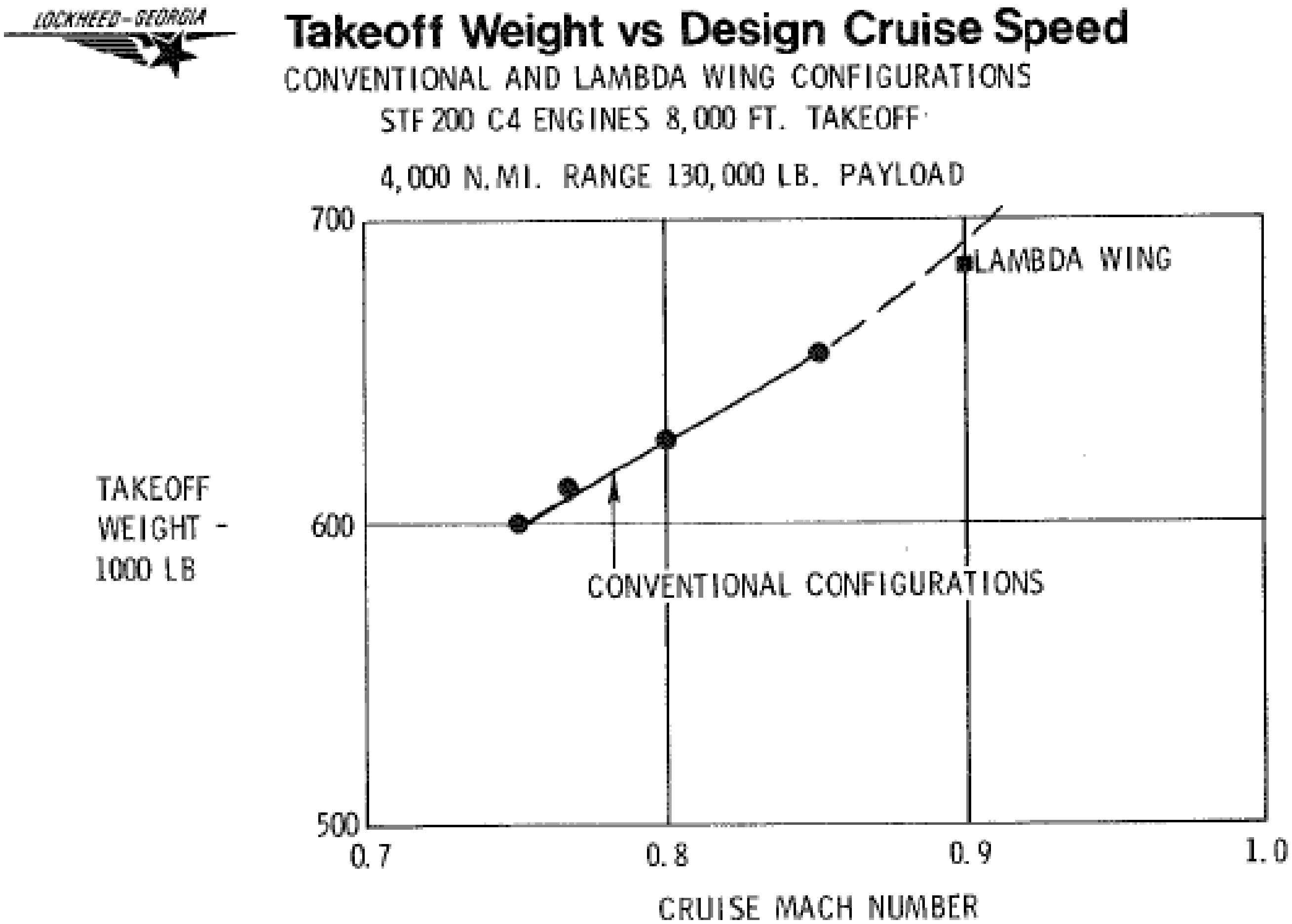
 13 August 2024

Source: Pedlow & Welzenbach, The CIA and Overhead Reconnaissance, The Story of U-2 and OXCART Programs, HR70-14, 1992 (Declassified 2011)

C-X (eventual C-5) Example

Concept Formulation Phase: ca early 1960s

Initial Weight Sizing Helped Identify Promising Concepts



Conventional concepts preferable over unconventional ones!

Source: Garrard, The Lockheed C-5 Case Study in Aircraft Design

Outline

A3. Solve the Problem

A3.1 Prerequisites for *Solving the Problem*

A3.1.1 Design Objectives and Design Strategy

A3.1.2 Three-view CAD Drawings

A3.2 Create Multiple Viable Concepts

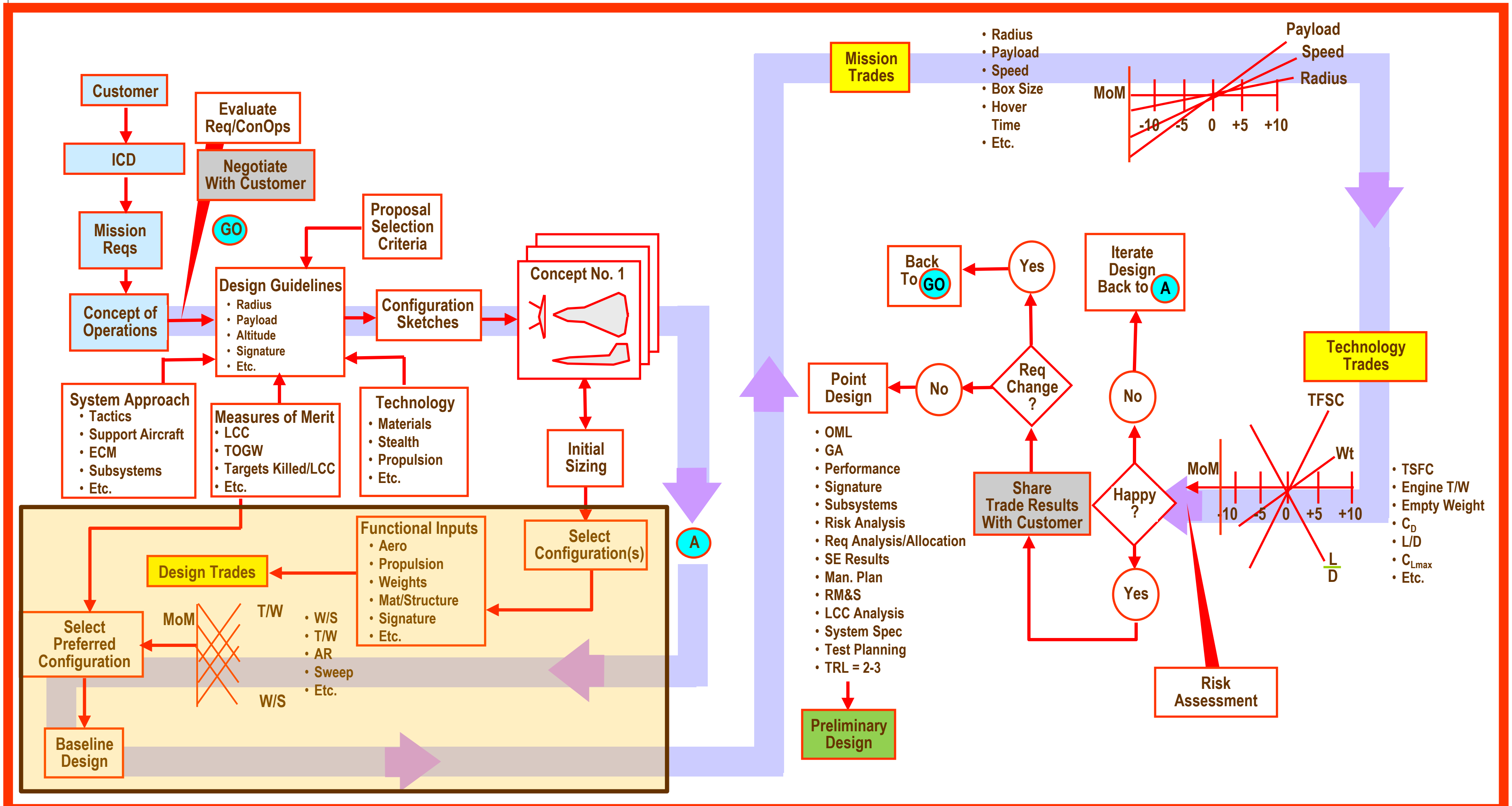
A3.2.1 Initial Concept Sketches

A3.2.2 Initial Concept Models

A3.3 Choose a Few "Good" Feasible Concepts

A3.4 Select Best PSC as Baseline Design

Aircraft Conceptual Design (CD) Process



Select "Best" Baseline Design

Adapted from Dr. Lee Nicolai's lecture slides

Aircraft CD Process: *The HOWs!*
"Top Down" – 3rd and Final Step

1. *Comprehensive Understanding of the Problem* (Initial Step)

1.1 Analyze RFP to understand genesis and nature of customer's problem

1.2 Collect Design Requirements

- (a) RFP—mission (speed, range, payload, etc), cost (acquisition, production, LCC, etc.), RM&S, and scheduling (EIS, tech freeze) requirements
- (b) FAR (or CFR) and/or DoD documents—regulatory requirements & constraints
- (c) ConOps—any additional requirements based on end-user perspective

1.3 Select Comparator Aircraft, Measures of Merit (MoMs), and Key Design Drivers

1.4 Identify Promising Technologies to tackle most difficult challenges

1.5 Investigate Proposal Selection Criteria

1.6 Develop Design Objectives & Strategy, and Prepare *Design Guidelines* document

2. *Generation of Feasible Concepts* (Intermediate Step)

2.1 Sketch multiple viable concepts—the ones you *think* could meet the need

2.2 Size all viable concepts; estimate TOGW, Wing Loading, Thrust or Power Loading

2.3 Down-select the most promising ones as a set of preferred system concepts (PSCs) using decision-making tools

3. *Selection of Best PSC as Baseline Design* (Final Step)

3.1 Create outer mold line (OML) and interior profile of PSCs by choosing and integrating fuselage; wing; high-lift system; empennage; subsystems; C.G.; etc.

3.2 Conduct Design Trade Studies—Mission and Technology Trades, if possible

3.3 Compare *feasible* configurations using MoMs and select "best" design!

Aircraft CD Process—3rd & Final Step

3. Selection of Best PSC as Baseline Design (3 Elements)

Questions to ask for each element

3.1 Concept to Configuration: Generate Integrated System OML

(see CM A6, A7, A7a & A9)

- Is the fuselage sized and shaped right?
- Is there enough room to pack payload, subsystems, fuel, etc.?
- Where is the C.G. location?
- What should be the initial values of wing span, MAC, sweep, taper, etc.?
- Is the tail sized right? Is the static margin adequate?
- Are the wing and landing gear correctly located relative to C.G.?
- Is the number of engines right? Are they sized and placed correctly?
- Are the inlet and nozzle properly sized for each engine?
- Etc., Etc.

3.2 Conduct Trade Studies (see *Trade Studies* module) ⟸ **CM A8**

- What is the effect of varying geometric or flight parameters on the MoMs?

3.3 Select "BEST" PSC as Baseline Design

- How to use MoMs to select a Preferred System Concept (PSC)?
  see the following slides

VT Student Design Project Example

Selection of Preferred System Concept as Baseline Design

PSC Selection Process and Criteria

ITEM	VANGUARD	VULTURE	ANVIL
VULNERABILITY*, vulnerable area FT^2	17	34	17
MISSION FLEXIBILITY, hardpoints	8	8	8
FLYAWAY COST, $M	13.4	14.0	15.0
OPERATIONAL COST, $/FH	3,360	3,400	3,660
LIFE CYCLE COST, $M	64	65	70
SPRINT SPEED, KNOTS	330	334	323
PROJECTED RELIABILITY, MMH/FH	8	8	10
GROSS TAKEOFF WEIGHT, LB	11800	12000	12200**

Source: 2020-2021 AIAA Vanguard Team (Lead: Snellings)

VT Student Design Project Example

VANGUARD: Preferred System Concept as Baseline Design

PSC Selection

Measure of Merit	Weight	VANGUARD		VULTURE		ANVIL	
		Value	Normalized Value	Value	Normalized Value	Value	Normalized Value
Survivability	25	17	0.500	34	0.000	17	0.500
Flyaway Cost	15	13.4	0.107	14	0.067	15	0.000
Mission Flexibility	13	8	1.000	8	1.000	8	1.000
Reliability	12	8	0.200	8	0.200	10	0.000
Sprint Speed	10	330	0.988	334	1.000	323	0.967
Operational Cost	10	3360	0.082	3400	0.071	3660	0.000
Life Cycle Cost	10	65.4	0.070	66.5	0.054	70.3	0.000
Gross Takeoff Weight	5	11800	0.033	12000	0.016	12200	0.000
Weighted Sum	100	41.06		27.73		35.17	

NHA SDR Presentation | 12/02/20 | Slide 59

Source: 2020-2021 AIAA Vanguard Team (Lead: Snellings)

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

C-X Identified Parameters for Optimized Design for Different MoMs

RFP Objective: Design an aircraft to meet the following requirements

Range = 3,600 nm; Payload = 200,000 lbs; Propulsion = 4 Turbofans at 30,000 lbs SLST (Nominal)

But designs differ when optimized for different MoMs (Measures of Merit)

Measures of Merit (MoMs)

ITEM	MINIMUM GROSS WEIGHT	MINIMUM LIFE CYCLE COST	MINIMUM ACQUISITION COST	MINIMUM FLYAWAY COST	MINIMUM LCC/ PRODUCTIVITY	MINIMUM DOC	MINIMUM FUEL
GROSS WEIGHT, LB	504,000	524,000	530,000	525,000	519,000	508,000	547,000
WING LOADING, LB/FT²	135	128	131	133	141	142	115
THRUST/WEIGHT	0.239	0.202	0.207	0.029	0.270*	0.238	0.191
WING ASPECT RATIO							
STRUCTURAL	15*	10.2	11.0	9.8	8.5	13.2	15*
AERODYNAMIC	8.5	9.9	10.1	9.5	5.6	8.6	14.2
WING LEADING EDGE SWEEP, DEG	41	10*	17	10	36	36	13
WING MEAN THICKNESS RATIO	0.122	0.128	0.150*	0.137	0.090*	0.090*	0.090
LIFE CYCLE COST, $B	17.7	16.6	16.8	16.7	18.0	17.7	18.0
ACQUISITION COST, $B	11.4	10.7	10.7	10.7	11.4	11.4	12.1
FLYAWAY COST, $M	43.5	40.9	40.9	40.9	43.6	43.6	46.1
LCC/PRODUCTIVITY, $/TON-MI-DAY	165	185	180	192	153	162	200
DIRECT OPERATING COST, $/TON-MI	0.0516	0.0587	0.0557	0.0563	0.0511	0.0497	0.0567
FUEL, LB	115,000	127,000	133,000	123,000	138,000	119,000	111,080
TAKEOFF DISTANCE, FT	8,000*	8,000*	8,000*	8,000*	7,380	8,000*	7,080
SECOND SEGMENT OEI CLIMB GRADIENT	0.0597	0.0454	0.0509	0.0444	0.0300*	0.0579	0.0643
FAR FIELD LENGTH, FT	8,230	8,150	8,030	8,360	8,770	8,120	6,480
INITIAL CRUISE ALTITUDE, FT	32,600	28,000*	28,000*	28,000*	29,800	32,500	31,200
INITIAL CRUISE MACH NUMBER	0.782	0.645	0.642	0.655	0.8902	0.700	0.550
WING AREA, FT²	3,706	4,094	4,046	3,055	3,631	3,577	4,757
WING SPAN, FT	177.5	201.3	202.1	103.8	143.6	175.4	259.9
SLS THRUST PER ENGINE, LB	30,110	36,460	27,430	27,480	35,040	30,230	26,120

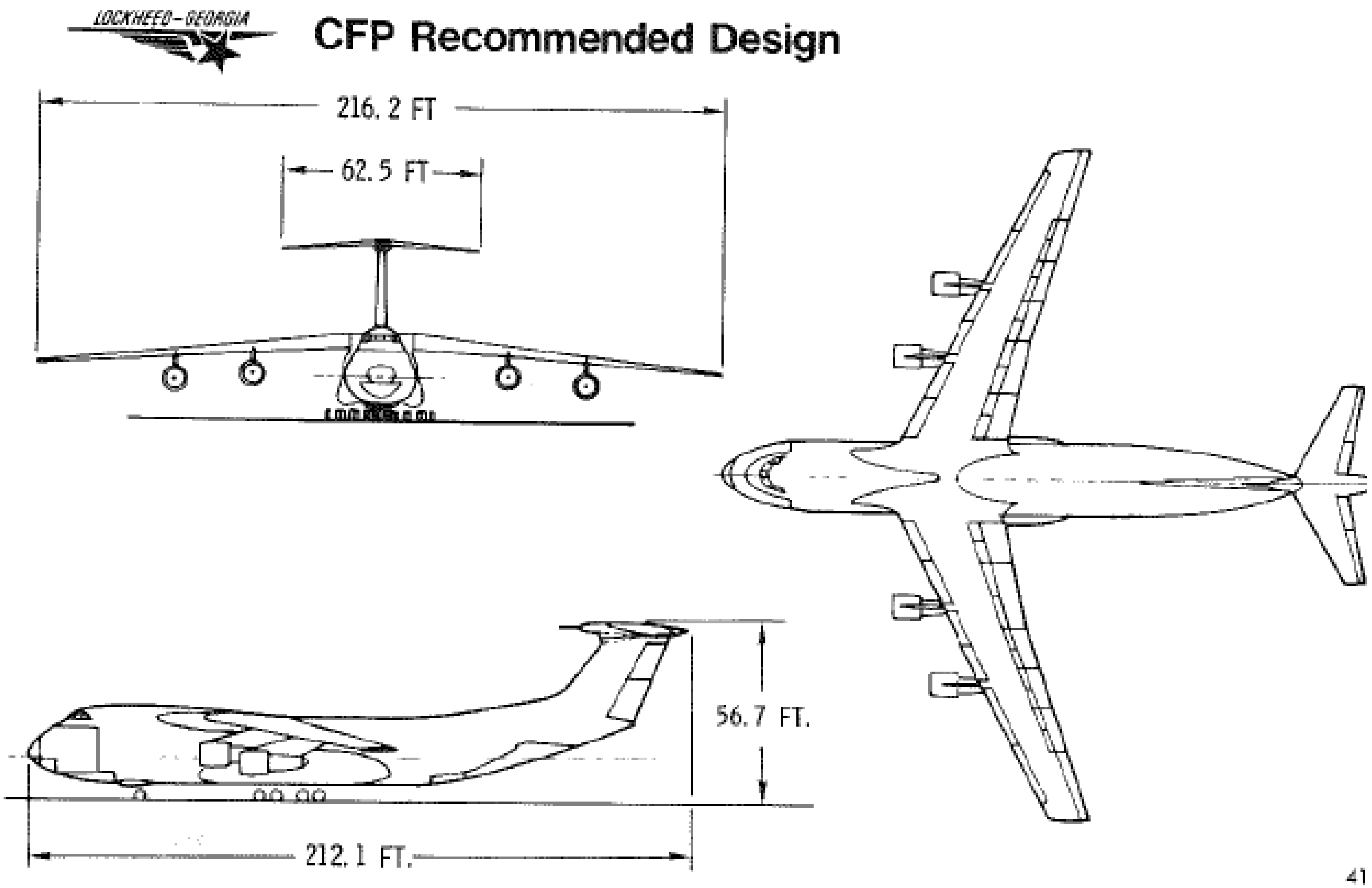
*BOUNDARY VALUE

Courtesy of Lee Nicolai

C-X Recommended Design

Concept Formulation Phase: ca early 1960s

C-X Preferred System Concept (PSC) as Baseline Design!



Source: Garrard, The Lockheed C-5 Case Study in Aircraft Design

Epilogue

Three Essential Ingredients of Air Vehicle Design

1. The Science

The physics and mechanics … $F = ma$, $C_D = C_{D0} + KC_L^2$

The tools … CATIA, CFD, FEM, NASTRAN, M&S, MATLAB, Simulink

Left Brain

2. The Art

The beauty … the creative genius… the timeless elegance

"If it looks good … it flies good" CLJ (Kelly Johnson)

Right Brain

3. The Process and State-of-Mind

Be passionate … think out of the box … horizons unlimited

Question, then meet the requirements … work the MoMs

Be willing to compromise

Yearn for the unachievable

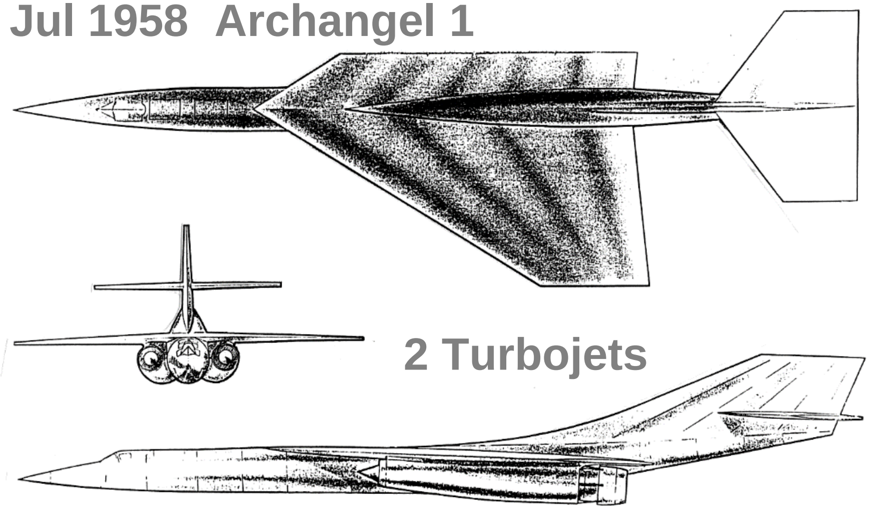
Courtesy of Lee Nicolai

Appendix

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

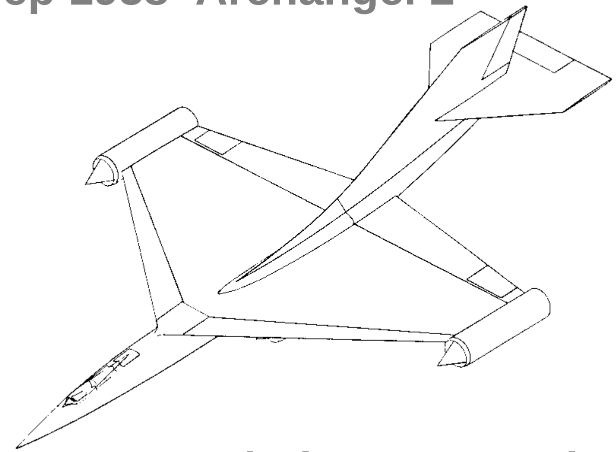
Archangel (eventual SR-71)
Initial Concept Models

Jul 1958 Archangel 1



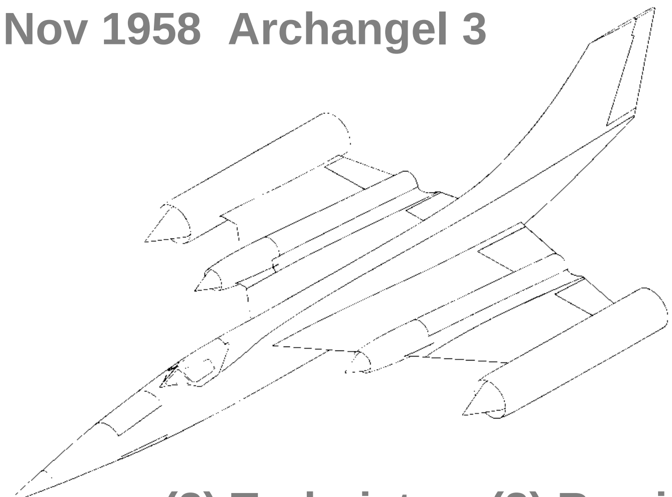
2 Turbojets

Sep 1958 Archangel 2



2 Turbojets + 2 Ramjets

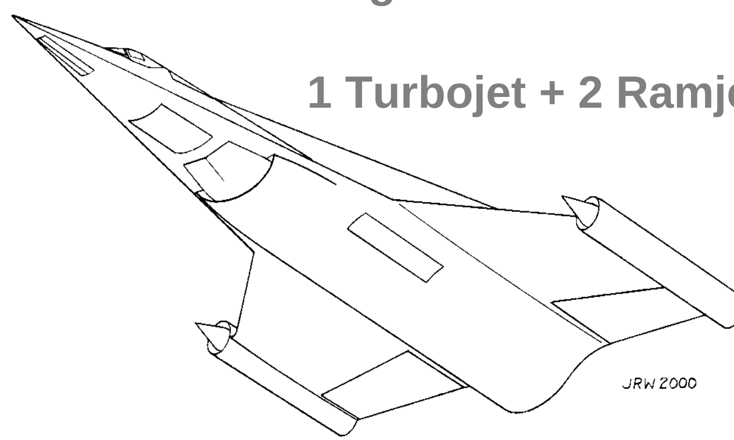
Nov 1958 Archangel 3



(2) Turbojets + (2) Ramjets

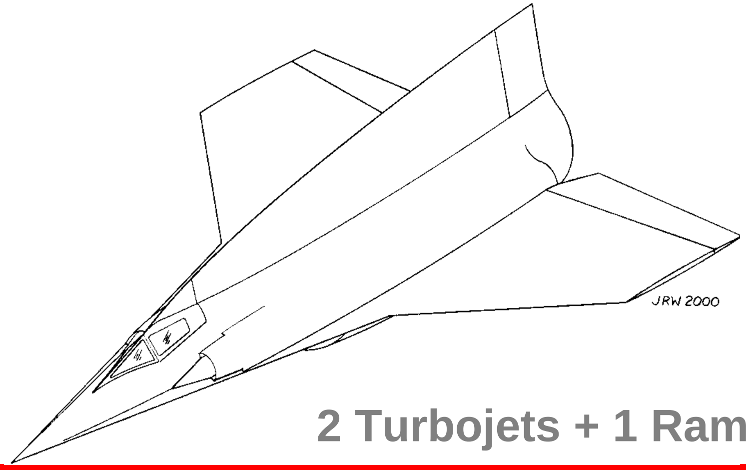
Dec 1958 Archangel 4

1 Turbojet + 2 Ramjets



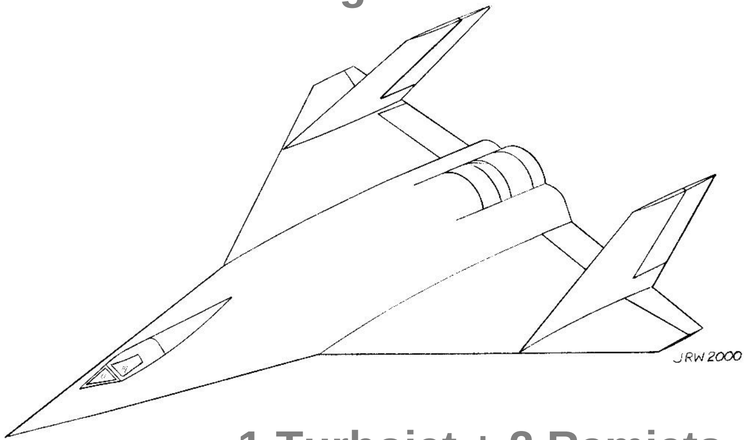
Archangel (eventual SR-71)
Initial Concept Models

Dec 1958 Archangel 5



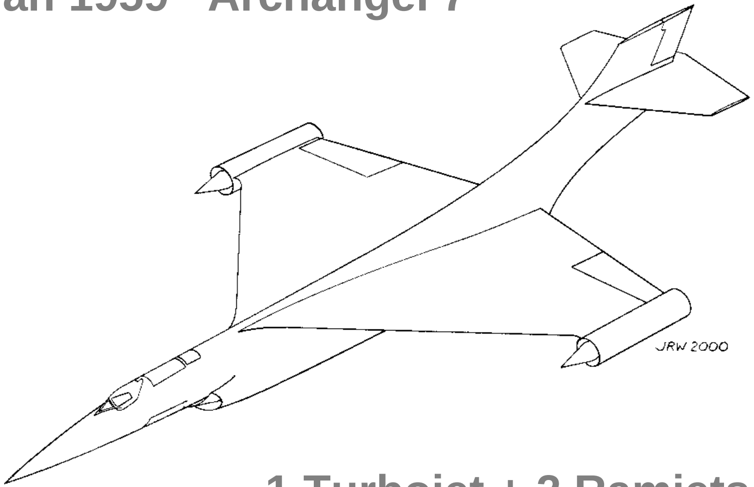
2 Turbojets + 1 Ramjet

Jan 1959 Archangel 6



1 Turbojet + 2 Ramjets

Jan 1959 Archangel 7



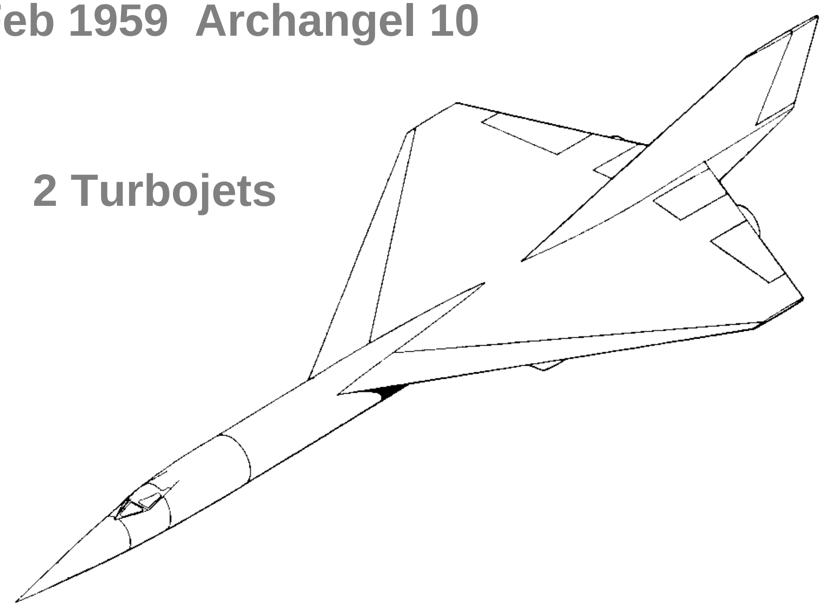
1 Turbojet + 2 Ramjets

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

Archangel (eventual SR-71)
Initial Concept Models

Feb 1959 Archangel 10

2 Turbojets



Mar 1959 Archangel 11

2 Turbojets