Air Vehicle Design

AOE 4065 – 4066

II. Air Vehicle Design Fundamentals

Course Module A1

Purpose & Process

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

Overview of AVD Courses

I. Foundational Elements

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

F2. Systems and Systems Thinking

F3. Basics of Systems Engineering

F4. Decision Making with Ethics and Integrity

II. Air Vehicle Design Fundamentals

A1. Purpose & Process

Conceptual Design

A2. Understand the Problem

A3. Solve the Problem

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

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

A6. Cost Considerations

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

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

Conceptual & Preliminary Design

A8. Trade Studies

A9. Use of Software Tools

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

III. Project Management Topics

P1. Basics of Project Management and Project Planning

P2. Project Organization

P3. Roles & Responsibilities of Team Members

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

P5. Project Risk Management

P6. Delivering Effective Oral Presentations

P7. Writing Effective Design Reports

Disclaimer

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

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

CRUCIALLY IMPORTANT

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

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

(*see Appendix in the Overview CM)

The Book of Genesis

~from~

The Aerospace System Designers Bible

By W. Gillette & J.H. McMasters

And on the first day there was gravity and the spirit of Newton said:

$$F = K \frac{m1\,m2}{r^2}$$

and Matters became weighty.

And then there was boundless energy and it was consolidated and Einstein quoth:

$$E = m\,c^2$$

and there was Motion, but it was merely transverse.

And on the third day, from the heavens, a voice cried out:

$$C_L = \iint_{xy} \left(C_{P_L} - C_{P_U} \right) dx\,dy$$

and there was Lift.

Courtesy of McMasters, The Boeing Corp.

But on the fourth day, the Devil said:

$$C_D = C_{D_{P_{min}}} + C_L^2/\pi AR\ e + \Delta C_{D_P} + \Delta C_{D_M} + \Delta C_{D_{P\ bugs}}$$

$$+ (\Delta C_{D_{BOUYANCY}}) + C_L \sin\alpha \quad \text{UPFLOW}$$

$$+ Q_3 \int (erf)^{nerf}\, dz - 2/3\,(\text{Management Requirement})$$

$$+ \Delta C_{D_{TRIM}} - C_{D_{BLOCKAGE}} - C_{D_{TRIP}} + C_{D_{BASE}} + 2\sigma + H.O.T. + C$$

and there was Drag.

On the fifth day a tiny voice from the wilderness cried out:

"... don't forget stability and control."

And this was echoed by various multitudes crying:

"... environmental control systems, ground support equiptment, and etc."

far into the night of the sixth day.

And on the last day, the spirit of Maynard Keynes proclaimed:

"He who controls the purse strings controls the policy."

and there was Economic Reality.

Caveat Emptor. Amen...

Courtesy of McMasters, The Boeing Corp.

Outline

A1. Purpose & Process

A1.1 Purpose of Aircraft Design

A1.2 Process of Aircraft Design

A1.3 Critical Importance of Conceptual Design (CD) Phase

A1.4 Proven CD Process

A1.5 CD Process Implementation & Keys to Success

A1.5.1 Become "Design Smart"

A1.5.2 Innovate

What is the Purpose of Aircraft Design?

Answer: Meet a Need

Need, also termed Operational Capability, may be *Explicit or Perceived*.
Two examples below illustrate this.

"The strategic airlift capability of the armed forces is undergoing considerable modernization ***to extend the life and augment the overall performance of the current fleet***. Just as this modernization has resulted in considerable mission performance improvements over the previous generation of aircraft, it is expected that the next generation will ***provide major improvements over the present one***. This RFP is for the design of a next generation strategic airlift military transport with an assumed 2030 entry into service (EIS)."

- *2014-15 AIAA Undergraduate Team Aircraft Design Competition*

"Researchers have been using Global Hawk-type UAVs to gather data during the hurricane season to improve their computer models. The models predict storm track with accuracy, but they are less accurate in predicting storm formation and intensification behaviors. Those types of predications require long-term observations and measurements. The Global Hawk-type aircraft are limited to 24 hours endurance. This challenge asks students to design a new system of next generation un-crewed aircraft platforms ***with much longer endurance.***"

- *2013-14 NASA ARMD University Engineering Design Challenge*

Meet a Customer Need Which is Typically Non-specific

Customer Needs Generate Requirements

Requirements Typically Spelled Out in a Request for Proposal (RFP)

1st Military Aircraft RFP: 1907

SIGNAL CORPS SPECIFICATION, NO. 486

ADVERTISEMENT AND SPECIFICATION FOR A HEAVIER-THAN-AIR FLYING MACHI

To the Public:

Sealed proposals, in duplicate, will be received at this office until 12 o'clock noon on February 1, 1908, on behalf of the Board of Ordnance and Fortification for furnishing the Signal Corps with a heavier-than-air flying machine. All proposals received will be turned over to the Board of Ordnance and Fortification at its first meeting after February 1 for its official action.

Persons wishing to submit proposals under this specification can obtain the necessary forms and envelopes by application to the Chief Signal Officer, United States Army, War Department, Washington, D. C. The United States reserves the right to reject any and all proposals.

Unless the bidders are also the manufacturers of the flying machine they must state the name and place of the maker.

Preliminary.—This specification covers the construction of a flying machine supported entirely by the dynamic reaction of the atmosphere and having no gas bag.

Acceptance.—The flying machine will be accepted only after a successful trial flight, during which it will comply with all requirements of this specification. No payments on account will be made until after the trial flight and acceptance.

Inspection.—The Government reserves the right to inspect any and all processes of manufacture.

General Requirements.

The general dimensions of the flying machine will be determined by the manufacturer, subject to the following conditions:

1. Bidders must submit with their proposals the following:
   (*a*) Drawings to scale showing the general dimensions and shape of the flying machine which they propose to build under this specification.
   (*b*) Statement of the speed for which it is designed.
   (*c*) Statement of the total surface area of the supporting planes.
   (*d*) Statement of the total weight.
   (*e*) Description of the engine which will be used for motive power.
   (*f*) The material of which the frame, planes, and propellers will be constructed. Plans received will not be shown to other bidders.

2. It is desirable that the flying machine should be designed so that it may be quickly and easily assembled and taken apart and packed for transportation in army wagons. It should be capable of being assembled and put in operating condition in about one hour.

3. The flying machine must be designed to carry two persons having a combined weight of about 350 pounds, also sufficient fuel for a flight of 125 miles.

4. The flying machine should be designed to have a speed of at least forty miles per hour in still air, but bidders must submit quotations in their proposals for cost depending upon the speed attained during the trial flight, according to the following scale:
   40 miles per hour, 100 per cent.
   39 miles per hour, 90 per cent.
   38 miles per hour, 80 per cent.
   37 miles per hour, 70 per cent.
   36 miles per hour, 60 per cent.
   Less than 36 miles per hour rejected.
   41 miles per hour, 110 per cent.
   42 miles per hour, 120 per cent.
   43 miles per hour, 130 per cent.
   44 miles per hour, 140 per cent.

5. The speed accomplished during the trial flight will be determined by taking an average of the time over a measured course of more than five miles, against and with the wind. The time will be taken by a flying start, passing the starting point at full speed at both ends of the course. This test subject to such additional details as the Chief Signal Officer of the Army may prescribe at the time.

6. Before acceptance a trial endurance flight will be required of at least one hour during which time the flying machine must remain continuously in the air without landing. It shall return to the starting point and land without any damage that would prevent it immediately starting upon another flight. During this trial flight of one hour it must be steered in all directions without difficulty and at all times under perfect control and equilibrium.

7. Three trials will be allowed for speed as provided for in paragraphs 4 and 5. Three trials for endurance as provided for in paragraph 6, and both tests must be completed within a period of thirty days from the date of delivery. The expense of the tests to be borne by the manufacturer. The place of delivery to the Government and trial flights will be at Fort Myer, Virginia.

8. It should be so designed as to ascend in any country which may be encountered in field service. The starting device must be simple and transportable. It should also land in a field without requiring a specially prepared spot and without damaging its structure.

9. It should be provided with some device to permit of a safe descent in case of an accident to the propelling machinery.

10. It should be sufficiently simple in its construction and operation to permit an intelligent man to become proficient in its use within a reasonable length of time.

11. Bidders must furnish evidence that the Government of the United States has the lawful right to use all patented devices or appurtenances which may be a part of the flying machine, and that the manufacturers of the flying machine are authorized to convey the same to the Government. This refers to the unrestricted right to use the flying machine sold to the Government, but does not contemplate the exclusive purchase of patent rights for duplicating the flying machine.

12. Bidders will be required to furnish with their proposal a certified check amounting to ten per cent of the price stated for the 40-mile speed. Upon making the award for this flying machine these certified checks will be returned to the bidders, and the successful bidder will be required to furnish a bond, according to Army Regulations, of the amount equal to the price stated for the 40-mile speed.

13. The price quoted in proposals must be understood to include the instruction of two men in the handling and operation of this flying machine. No extra charge for this service will be allowed.

14. Bidders must state the time which will be required for delivery after receipt of order.

JAMES ALLEN,
Brigadier General, Chief Signal Officer of the Army.

Signal Office,
Washington, D. C., *December 23, 1907.*

Key Aspects

- **350 lbs. payload; 40 mph top speed**
- **Easily transportable in army wagon**
- **Cost: $25,000**
- **Schedule: 7 months delivery**
- **“Sole sourced” to Wright Bros.**

Source: Fig. 1.3, Ref. AVD 1 (Nicolai & Carichner)

Wright Bros. Response to RFP:

1907 SIGNAL CORPS SPECIFICATION, NO. 486

An Air Vehicle that Meets ALL Specifications

RFP-based Military Aircraft Procurement Process Has Remained Essentially "Unchanged" Ever Since!

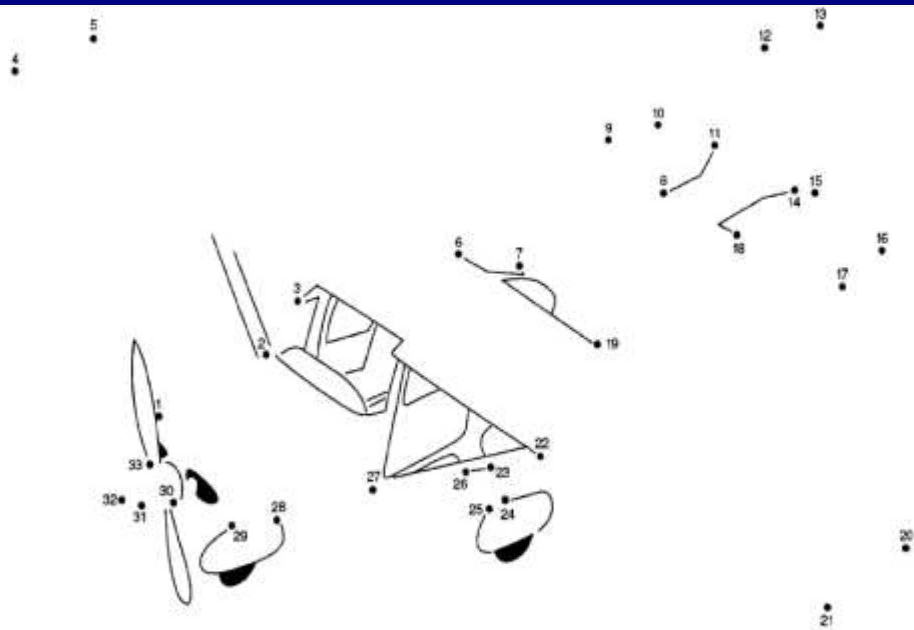
Source: Fig. 1.4, Ref. AVD 1 (Nicolai & Carichner)

Capstone Air Vehicle Design Project

"What have we signed up to do?"

Solve a "Connect-the-Dots" puzzle…

<u>but one created for you, the young adults!</u>



How is it different from a puzzle for kids?

You create the dots yourself (using clues from the RFP) <u>and</u> you connect the dots yourself to create a design!

YOU DO IT ALL!

Capstone Air Vehicle Design Project:
The First Day!

Source: NASA

Supersonic Trans-Pacific Aircraft

Since the demise of Concorde in 2003, there have been no scheduled supersonic passenger services. The market for supersonic civil transport is for a premium-class trans-Pacific service. It is envisaged that the aircraft would carry 50-100 passengers in a first/business class configuration on routes such as Los Angeles (LAX)-Singapore (SIN) or San Francisco (SFO)-Sydney (SYD). These are extremely long-range routes (in excess of 16 hours), and significant time could be saved by supersonic flight. However, it may be impractical for a supersonic aircraft to fly these legs non-stop and it may need to refuel en-route.

Requirements

Although a major task in the first part of the project is to determine customer requirements, some initial performance requirements are:

- Range, at least 6000 nm
- Cruising speed, at least Mach 2.0
- Passengers, at least 50

This project will be completed in collaboration with Virginia Polytechnic Institute and State University (better known as Virginia Tech) in Blacksburg, Virginia, USA. On 22 August 2016, 7 final year students at Virginia Tech started work on this project. Approx. 8 students from AAE will also work independently on the design until November when there will be teleconferences to show progress and plan future work. See the separate documents for this project for the full details.

There may be opportunities to visit and/or host the VT students around Thanksgiving 2016 and/or Easter 2017 respectively.

RFP

Describes the need (among other things)

BSP

To be filled with your design that best meets the need!

The Question is: How?

RFP: Request for Proposal

28 September 2024

BSP: Blank Sheet of Paper

Outline

A1. Purpose & Process

"There's a method to the madness!"

The only way to learn about design is to *do design*. But how to '*do design*'? There is a *process to do design* that produces a quality product, and the process *can be learned.*

- **In engineering design, designer uses *three types of knowledge*:**
  - A. **knowledge to generate ideas**—comes from experience and natural ability
  - B. **knowledge to evaluate ideas**—comes from domain-specific knowledge
  - C. **knowledge to and make decisions and structure the design process**—largely independent of domain-specific knowledge
- **Six basic actions are taken to solve any design problem**
  1) **Establish the need—**what is to be solved
  2) **Plan—**how to solve it
  3) **Understand the problem—**what the requirements are, and what existing solutions for similar problems are
  4) **Generate alternative solutions**
  5) **Evaluate the alternative solutions—**compare them to design requirements and to each other
  6) **Decide on acceptable solutions**

Adapted from "*The Mechanical Design Process*" by David G. Ullman

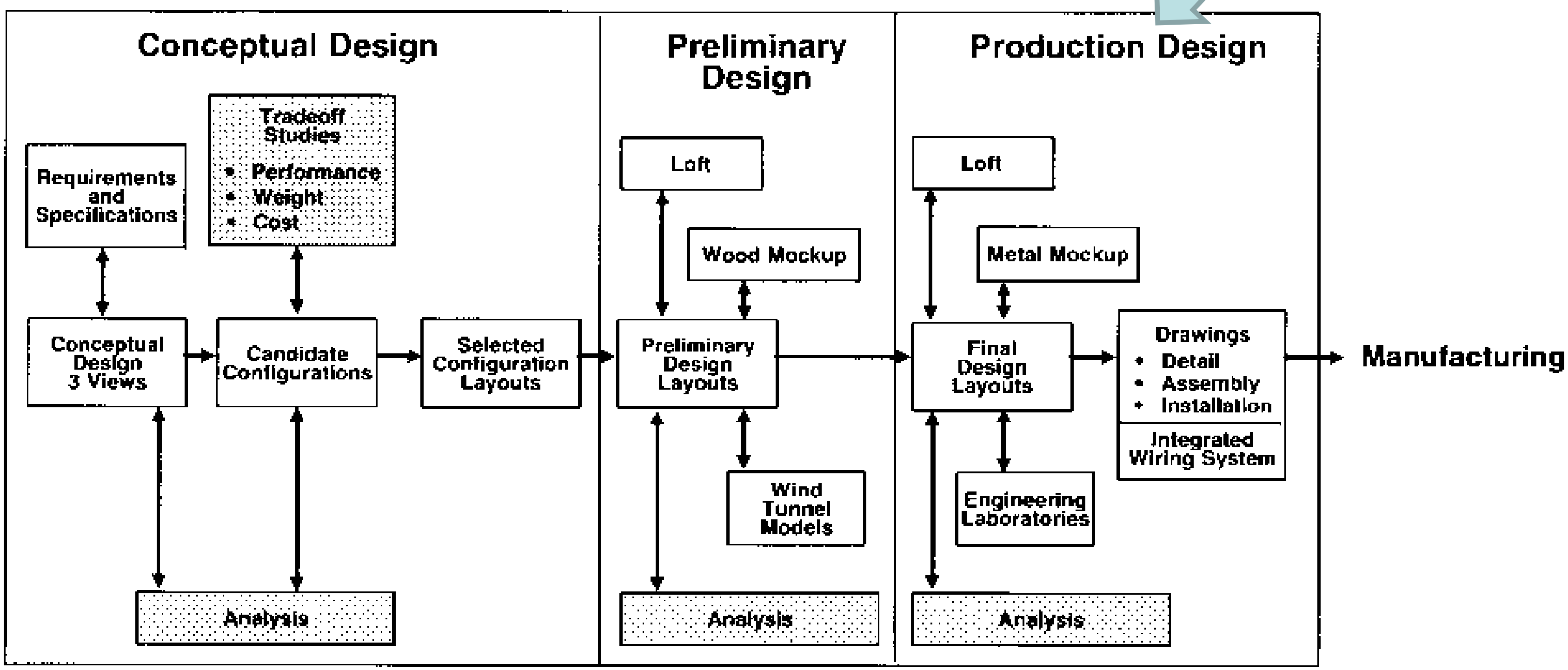
This Model Works for Entire Product or a Small Piece of It

A proven aircraft design process, supported by appropriate tools, exists to help you create innovative air vehicles that best meet all customer needs.

Aircraft Design Process

Three Phases: Conceptual, Preliminary, and Detail (or Production)

aka Detail Design



A schematic of the aircraft design process created in the late 1980s by Sam Smyth, a Highly Experienced Lockheed Designer

Creation and Evaluation of Ideas Drive the Process

Typical Scope of Three Design Phases

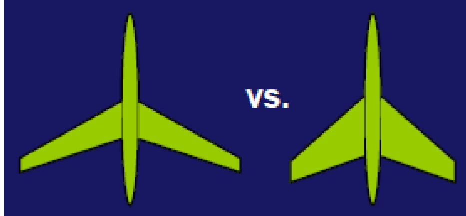
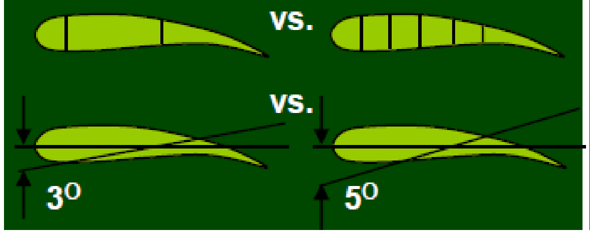
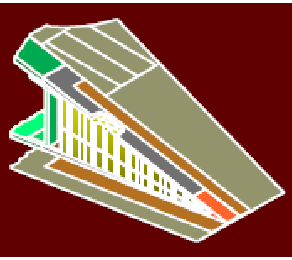
- ***Conceptual Design*** (~1% of the people)
  - Establish performance goals
  - Generate alternative concepts and evaluate
  - Select Preferred concept
  - Define design drivers
  - Ensure concepts are feasible (i.e., meet requirements)
  - Generate 3 views
  - *Limited aerodynamic simulations*

- ***Preliminary Design*** (~9% of the people)
  - Refined sizing of preferred concept
  - Design examined/establish confidence
  - Some changes allowed
  - Start using big computer codes
  - Do serious wind tunnel tests
  - Make actual cost estimate *(you bet your company!)*

- ***Detail Design*** (~90% of the people)
  - Final detail design
  - Drawings released
  - Detailed performance
  - Only "tweaking" of design allowed
  - Certification process
  - Component/systems tests
  - Manufacturing considerations (earlier now)
  - Flight control system design

We 'mimic' the first two in our two courses (4065 & 4066).

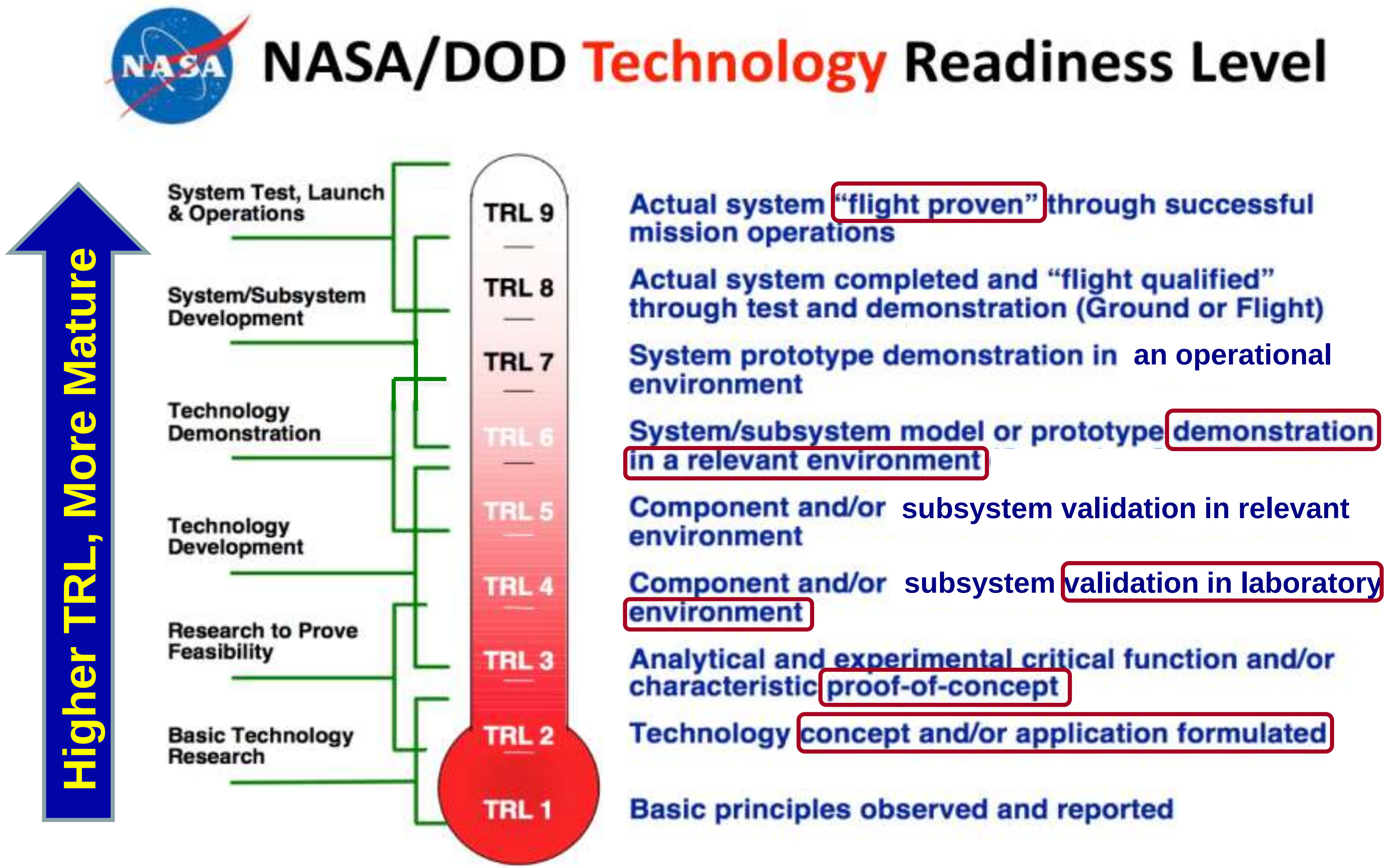
Three-Phase Aircraft Design Process:
Progression from RFP to Shop Drawings!

	Phase I Conceptual Design	Phase II Preliminary Design	Phase III Detail Design
	 	 	
Known	• Basic Mission Requirements • Range, Altitude, Speed • Basic Material Properties σ/ρ E/ρ \$/lb	• Aeroelastic Requirements • Fatigue Requirements • Flutter Requirements • Overall Strength Requirements	• Local Strength Requirements • Producibility • Functional Requirements
Results	**Geometry:** Airfoil Type, AR, t/c, λ, Δ **Design Objectives:** Drag Targets, Weight Targets, Cost Targets, Etc.	• Basic Internal Arrangement • Complete External Configuration – *Camber, Twist Distributions* – *Local Flow Problems Solved* • Major Loads, Stresses, Deflections • Etc.	• Detail Design – *Mechanisms* – *Joints, Fittings & Attachments* • Design Refinements as Results of Test
Output	Feasible Design	Mature Design	Shop Drawings
TRL	2-3	4-5	6-7

Desired output is generated by performing **specific tasks.**

Courtesy of Dr. Lee Nicolai

What is TRL?



Higher TRL > More Mature > Less Risk

Source: Fig. 1.4, Ref. AVD 1 (Nicolai & Carichner)

Outline

A1. Purpose & Process

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

In the Hands of Good Designers, the Design Process has Delivered…

…An Impressive Array of Aircraft With Phenomenal Performance!

Increasing Levels of Performance Achieved with a Dramatic Increase in Cost

Tactical (Combat) Aircraft: *unit cost has increased at a factor of 4 every 10 years since the beginning of the aviation age!*

Source: The Economist, 2010

"In the year 2054, the entire defense budget will purchase just one tactical aircraft… "

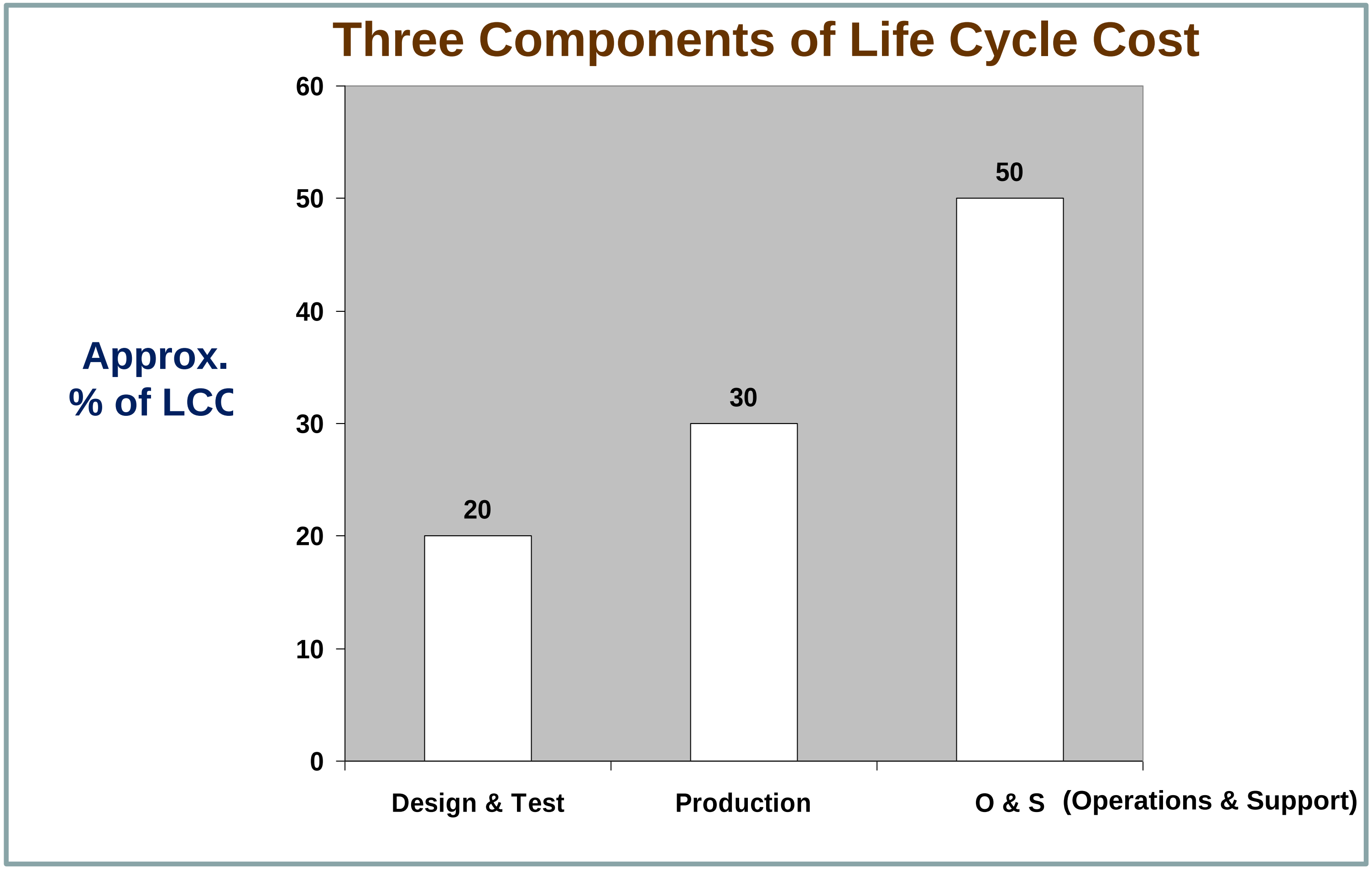
Norm Augustine,
LAW NUMBER IX,
Augustine's Laws, 1983
Published by AIAA

Norm Augustine
Born 1935

Commercial Aircraft: *trend of increasing cost has been basically the same as for military aircraft.*

We Face a Daunting "Affordability Challenge"

Key to Affordability is Reduced Life Cycle Cost (LCC)

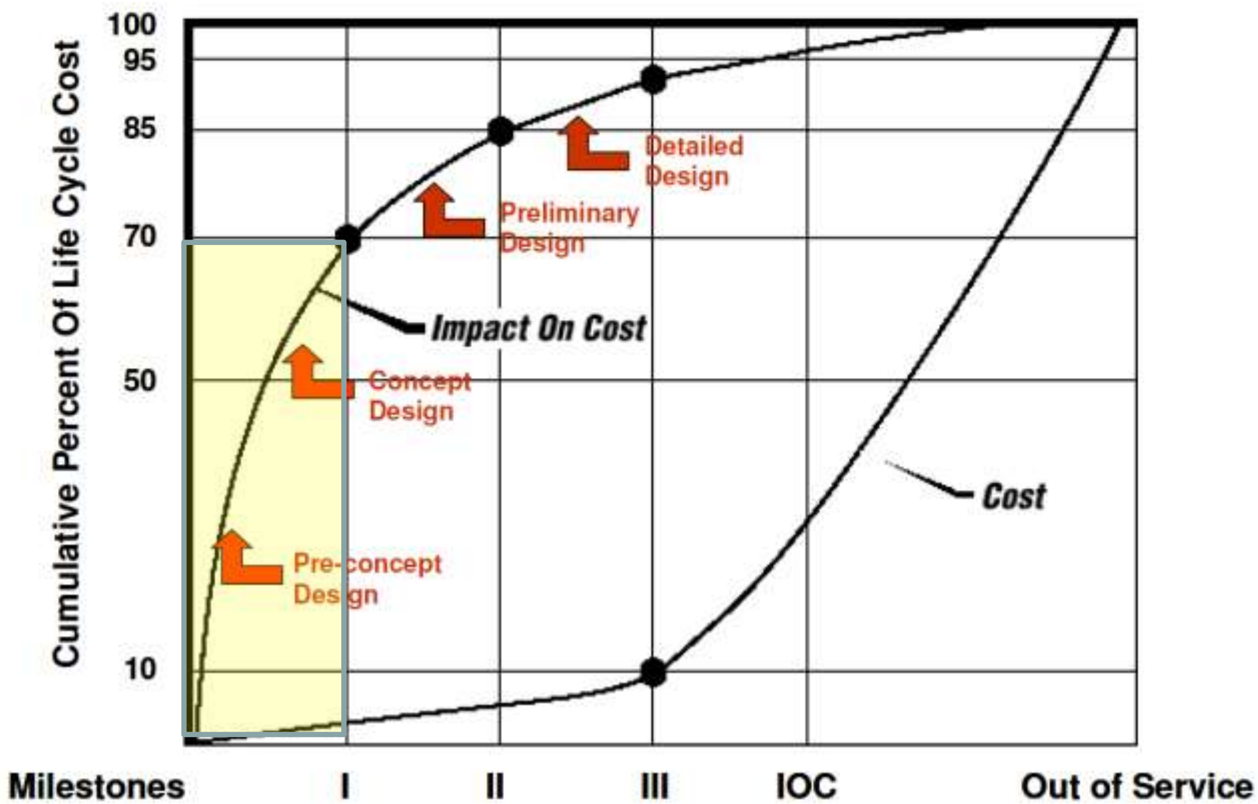


Production + O & S Costs = ~80% of LCC

Design & Test = <u>Only</u> ~20%!

Nearly 70% of Life Cycle Cost (LCC) is *Committed* in Conceptual Design Phase

Cumulative % of LCC *Committed*



Calendar Time (*Not to Scale*)

Source: Defense Systems Management College, 3 Dec 1991

Early Design Decisions Have Disproportionately Large Impact on Life Cycle Cost

Typical Government Acquisition Program

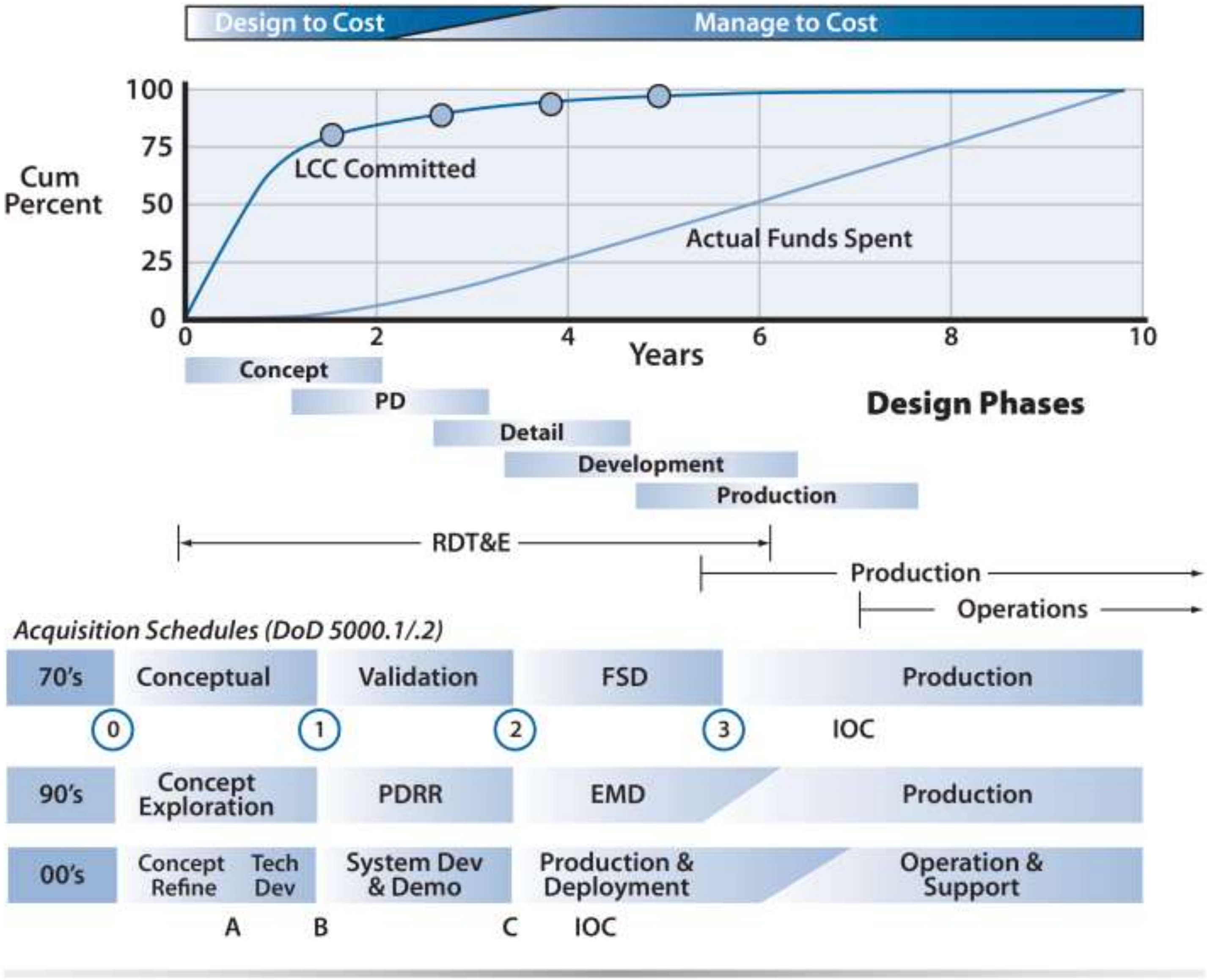


Figure 1.16 Design phases integrated into the entire government program.

Source: Fig. 1.16 Ref. AVD 1 (Nicolai & Carichner)

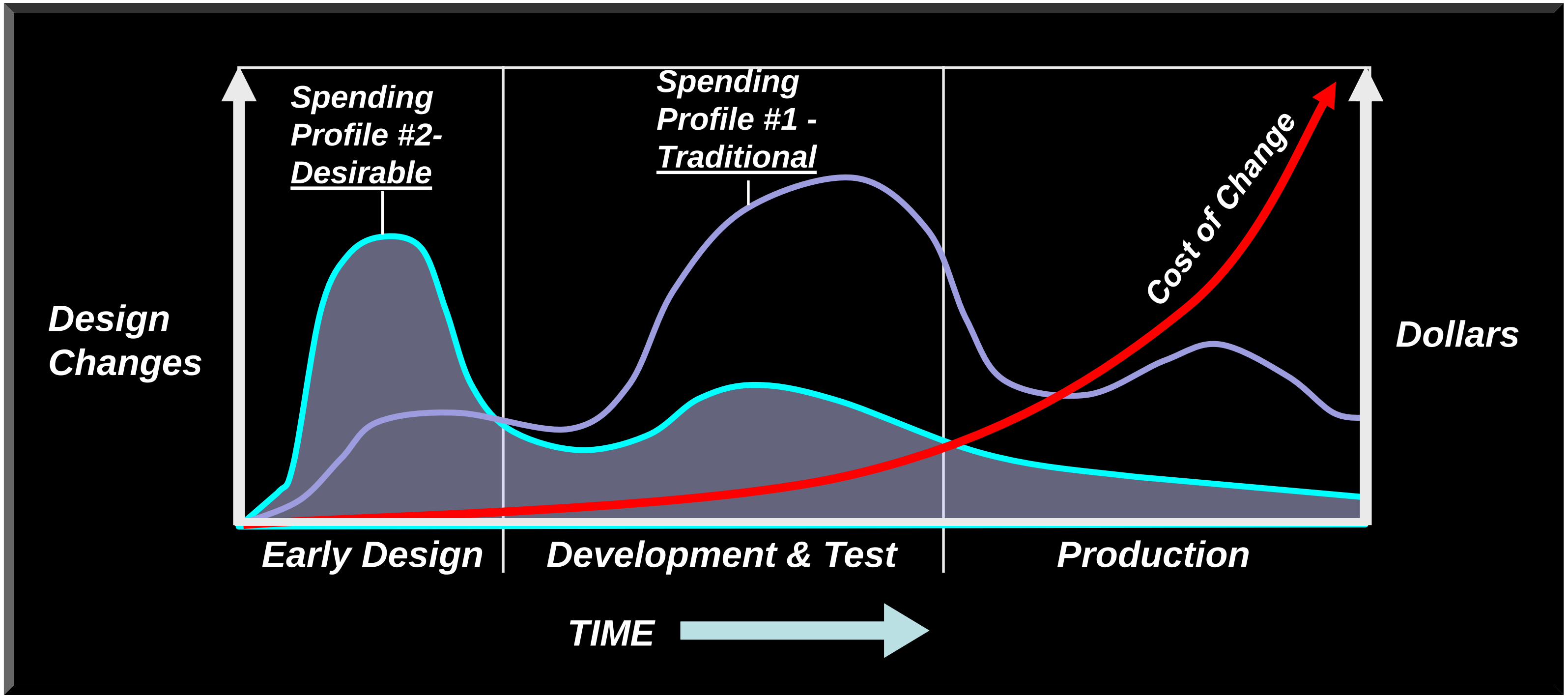
The outcome of the Conceptual Design (CD) Phase essentially determines the Quality and Cost of the aircraft.

Good Decisions Early

↓

Higher Quality and Lower Costs Later

Investing More in *Early Design to Make Good Decisions* is Highly Desirable



Spending Profile #1: Traditional
Spending Profile #2: ~ Three times the Early Design Budget of Spending Profile #1

Dollars spent on trades, iterations and design changes in early stages of design result in reduced program cost downstream

But It's Extremely Difficult to Realize in Practice

Courtesy of Lee Nicolai

Your Challenge in a Nutshell

Successful Designs require Good Decisions [Early]

Good Decisions require Sound Judgment

Sound Judgment requires Extensive Experience

If you have little or no experience, pursue 2 options:

1. Consult with subject matter experts (SMEs)

2. Work with a competent Devil's Advocate*
to increase chances of making Good Decisions!

*someone who is not shy about asking tough questions

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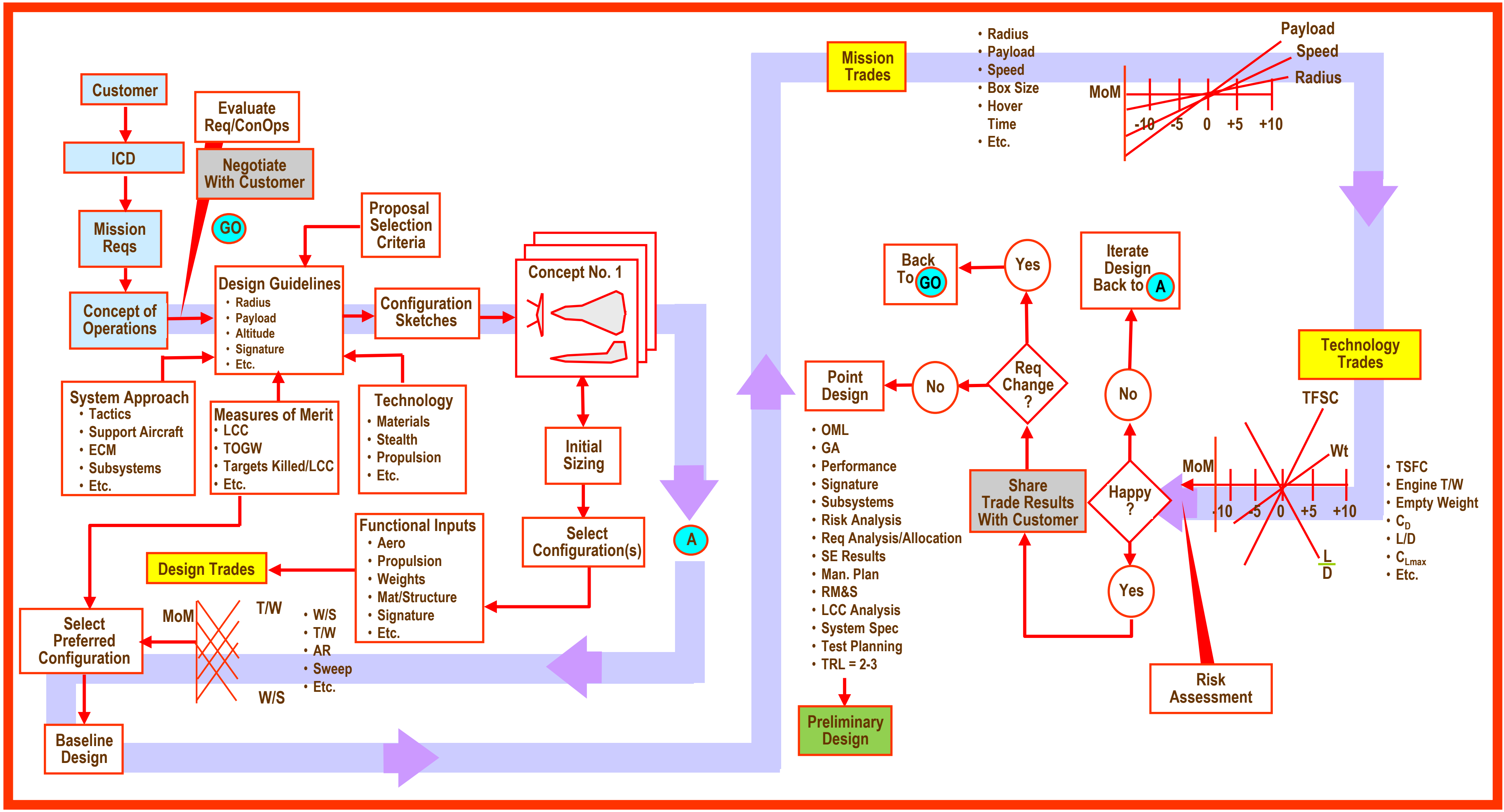
COLLEGE OF ENGINEERING
KEVIN T. CROFTON DEPARTMENT OF AEROSPACE AND OCEAN ENGINEERING
VIRGINIA TECH.

Aircraft Conceptual Design (CD) Process



A Proven and Well Understood Process!

Adapted from Dr. Lee Nicolai's lecture slides

Air Vehicle CD Process: *Three Major Steps*

1. ***Comprehensive Understanding of the Problem* (Initial Step)**
   - Develop a thorough *understanding of the problem* which facilitates, and culminates in, the development of Design Guidelines
2. ***Generation of Feasible Concepts* (Intermediate Step)**
   - Create multiple *viable* concepts based on Design Guidelines
   - Discard the infeasible concepts, and select the *feasible ones* as a set of Preferred System Concepts (PSCs)
3. ***Selection of Best PSC as Baseline Design* (Final Step)**
   - Select the best *PSC as Baseline Design* through comprehensive parametric analyses and trade studies

Note: In this course, we use the following definitions:

- **Viable**—capable of becoming actual: *'we think it should work'*
- **Feasible**—realizable: *'we know it should work'*

Each Step Requires Iterative Decision Making!

Aircraft Conceptual Design Process: *Nature of Decisions*

1. ***Comprehensive Understanding of the Problem* (Initial Step)**
   - ***Define the Need*:** Analyze RFP to determine what must the system do (target capabilities)? How well? Under what conditions? What is the product? When to deliver?
   - ***Determine Requirements and key Design Drivers*:** performance, cost, safety, environment, etc.
   - ***Identify the customer* and *their Measures of Merit* (*MoMs*)**
   - ***Determine Proposal Selection Criteria:*** both technical and programmatic, based on requirements & MoMs
   - ***Develop Design Guidelines***
   - ***Identify competition*:** who/what do we have to beat?

First, Fully Understand the Problem

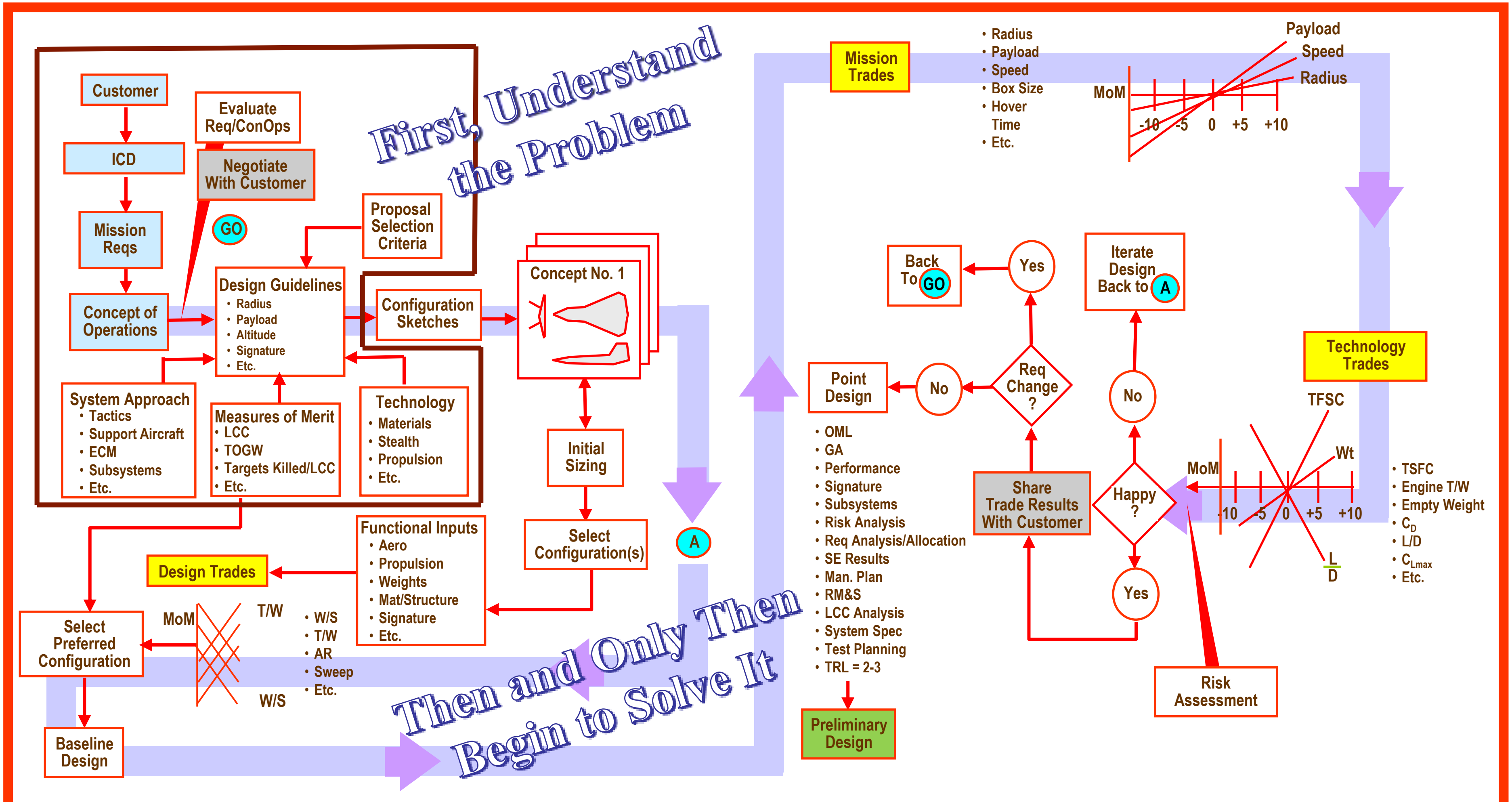
2. ***Generation of Feasible Concepts* (Intermediate Step)**
   - ***Create multiple viable concepts*** that could solve the problem
   - ***Develop feasible concepts*** using engineering analysis, design, and decision-making tools
   - ***Pick a few "good" ones as a set of preferred system concepts (PSCs)*** using appropriate selection criteria

Then and Only Then Begin to Solve it

3. ***Selection of Best PSC as Baseline Design <u>and Quit</u>* (Final Step)**
   - **Select the best PSC as Baseline Design** using results of parametric and trade studies along with customer's MoM's and proposal selection criteria
   - ***<u>There are no right answers, only a best answer at a given point in time!</u>***

Source: Lee Nicolai, Personal communication

Air Vehicle CD Process



NOTE: The Process Only Depicts the WHATs, Not the HOWs. You Choose the HOWs!

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 Choose 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 Create 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"!

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Aircraft CD Process: *Implementation*

- **Define Design Project Scope** **(what tasks the team needs to do)**
  - Using *'The HOWs'*, develop a list of tasks & subtasks that need to be performed (work breakdown structure or WBS)
    - Compile a list of questions that the team needs to answer *for each task and subtask*
    - Once the questions are answered, consider the task or subtask complete!
    - Determine products or results to be delivered (to whom, and when)
- **Develop Design Project Schedule** **(when the team needs to do the tasks)**
  - For each task and subtask, determine when it must be completed so that the project schedule and deliverable requirements can be met
  - Make a **Gantt chart** to show the WBS with milestones and durations
- **Estimate Design Project Cost** **(who on the team will do the tasks)**
  - Allocate available [human] resources to various tasks based on the scope and schedule of each task
- **Develop a Project Organization Chart** **(how to ensure on-time completion)**
  - Organize the team in a way that ensures efficient execution of all tasks
  - Clearly define everyone's roles & responsibilities

See CMs in Part III. Project Management Topics

As you roll up your sleeves to implement the CD process in earnest, let's consider two additional topics that are key to successful outcome:

(1) "Design Smart"

(2) Innovation

Both are essential to ensuring that project scope is accurately defined and associated tasks are properly executed

Source: Fig. 1.11, Ref. AVD 1 (Nicolai & Carichner)

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Become “Design Smart”!

Two Characteristics of “Design Smart” Individuals

1. **They have good understanding of why airplanes—*especially those performing <u>your class of missions</u>*—look the way they do**
2. **They gather lots of sources of information about potential approaches to achieve the desired functionality of the integrated system—*<u>the air vehicle you need to design</u>***

Become “Design Smart”—Your Key to Success!

Image Source: Internet

How to Become "Design Smart"?

Read "Case Studies" that you can find
(some are in primary and supplemental references)

Learn the pros and cons of available options for all elements that are integrated into a full aircraft system.

Keep Your Focus on the INTEGRATED System!

Source: Fig. 1.11, Ref. AVD 1 (Nicolai & Carichner)

How well can you answer two questions?

Why Such Widely Different Air Vehicle Systems?

- ***Perform Desired Mission*: Not all airplanes are well suited for a mission**
  - Shape and size dictated by
    - How far? How fast? How high?
    - What and how much to carry?
    - What are the landing and takeoff requirements?
    - Are there any maneuver/acceleration requirements?
    - What MIL or FAR requirements must be satisfied?

Aircraft designs must meet Mission Performance Requirements

- ***Select Best Configuration Option*: Different design teams make different Design Decisions**
  - Fuselage shape and size: what and how to package “stuff”?
  - Lifting surface size, shape, location: how to best meet RFP requirements?
  - Propulsion system type and location: what best meets RFP requirements?
  - Empennage type and location: what’s the best way to ensure a balanced system?
  - Landing gear type and arrangement: what’s best?
  - Etc.

We have too many choices for each and must decide which one is best for our design!

Different Design Decisions Produce Different Aircraft (Even for the Same Mission!)

Must Create ‘Best’ Airplane to Meet Customer Needs!

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VIRGINIA TECH.

At the End of the Day…

…it's all about the decisions throughout the design process!

Source: Fig. 1.11, Ref. AVD 1 (Nicolai & Carichner)

Airplane Design

“Basic Laws”

- …
- Simplicity is the essence of true elegance—
  - it can also save weight and/or reduce cost.
- If you can't build it, you can’t sell it.
- …

- John McMasters, Boeing

“Good Airplane”

- Aerodynamically efficient, including propulsion integration (streamlining!)
- Must balance near stability level for minimum drag
- Landing gear must be located relative to *cg* to allow rotation at TO
- Adequate control authority must be available throughout flight envelope
- Design to build easily (cheaply) and have low maintenance costs
- Environmentally friendly: quiet, low emissions, sustainable

Source: Adapted from W.H. Mason’s Aircraft Design Lectures

Airplane Design

To Design Good Airplanes, Ask the Type of Questions Listed Below and Find Answers

- **For aerodynamically efficient concepts**
  - **Where do you locate the wing? What shape and size of the wings?**
- **For efficient propulsion integration with the airframe**
  - **What type of engines? How many?**
  - **Where do you locate the engine(s)?**
  - **Meet noise regulations? Low (zero!) emissions? sustainable**
- **For adequate control authority throughout the flight envelope**
  - **Where do you locate the empennage?**
  - **What kind of control surfaces? Where?**
- **For safe ground operations as well as takeoff and landing**
  - **What is the right type of landing gear?**
  - **Where to locate it?**
- **For an airplane that someone is willing to buy**
  - **How to design to build/ manufacture easily and inexpensively?**
  - **How to make it more reliable and have low maintenance costs?**

Some Examples Follow to Get The Ball Rolling

Source: Adapted from W.H. Mason's Aircraft Design Lectures

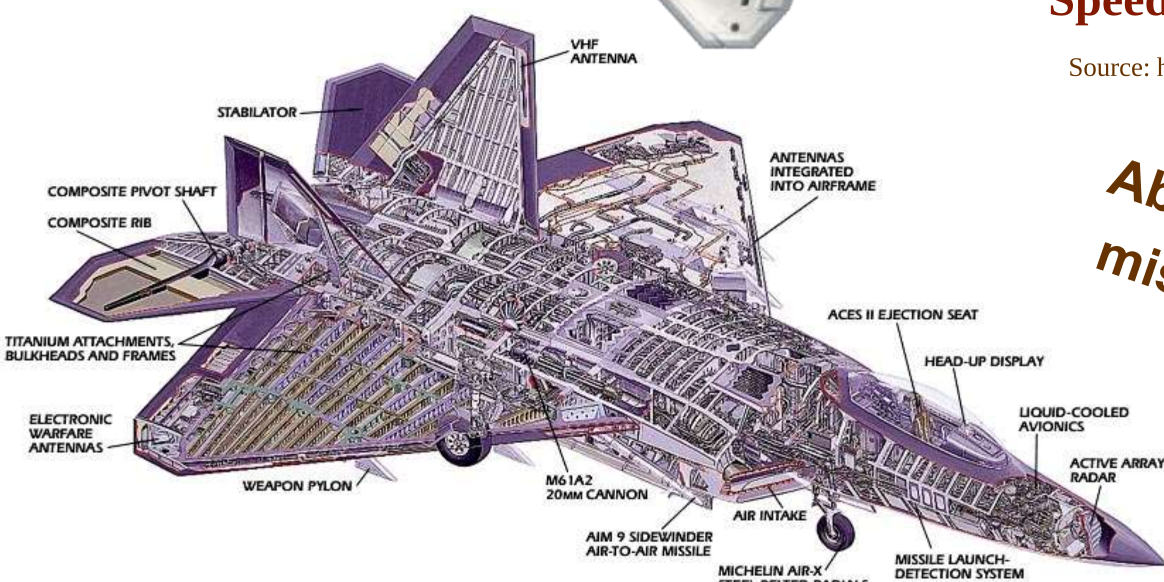
Military Aircraft: F-22

Mission: Air Dominance, Multi-role Fighter

Supermaneuverable
Superstealth
Supercruise

Length	62 ft
Height	16.67 ft
Wingspan	44.5 ft
Wing Area	840 ft^2
Horizontal Tail Span.	29 ft
Engine Thrust Class. . . .	35,000 lb
Max Takeoff Weight. . . .	83,500 lb
Speed	Mach 2 class

Source: https://www.lockheedmartin.com/en-us/products/f-22.html



Source: http://www.f22fighter.com/Specs.htm

Ability to perform the desired mission dictates shape and size

Military Aircraft: F-22

General Characteristics

Contractor: Lockheed-Martin, Boeing
Power plant: two Pratt & Whitney F119-PW-100 turbofan engines with afterburners and two-dimensional thrust vectoring nozzles
Thrust: 35,000-pound class (each engine)
Wingspan: 44 feet, 6 inches **Length:** 62 feet, 1 inch **Height:** 16 feet, 8 inches
Weight: 43,340 pounds
Maximum takeoff weight: 83,500 pounds
Fuel capacity: internal: 18,000 pounds; with 2 external wing fuel tanks: 26,000 pounds
Payload: armament air-to-air or air-to-ground
Speed: Mach 2 class with supercruise capability
Range: more than 1,850 miles ferry range with two external wing fuel tanks (1,600 nautical miles)
Ceiling: above 50,000 feet (15 kilometers)
Armament: one M61A2 20-millimeter cannon with 480 rounds, internal side weapon bays carriage of two AIM-9 infrared (heat seeking) air-to-air missiles and internal main weapon bays carriage of six AIM-120 radar-guided air-to-air missiles (air-to-air loadout) or two 1,000-pound GBU-32 JDAMs and two AIM-120 radar-guided air-to-air missiles (air-to-ground loadout)
Crew: one
Unit cost: $143 million
Initial operating capability: December 2005
Inventory: total force, 183

Source: https://www.af.mil/About-Us/Fact-Sheets/Display/Article/104506/f-22-raptor/

Commercial Aircraft: B-737-800

Mission: Air Transportation (passengers or cargo)

Source: https://www.delta.com/us/en/aircraft/boeing/737-800

Passengers (2 class) 160

Length . . . . 129 ft 6 in

Tail Height . . . . 41 ft 2 in

Wingspan . . . . 117 ft 5 in

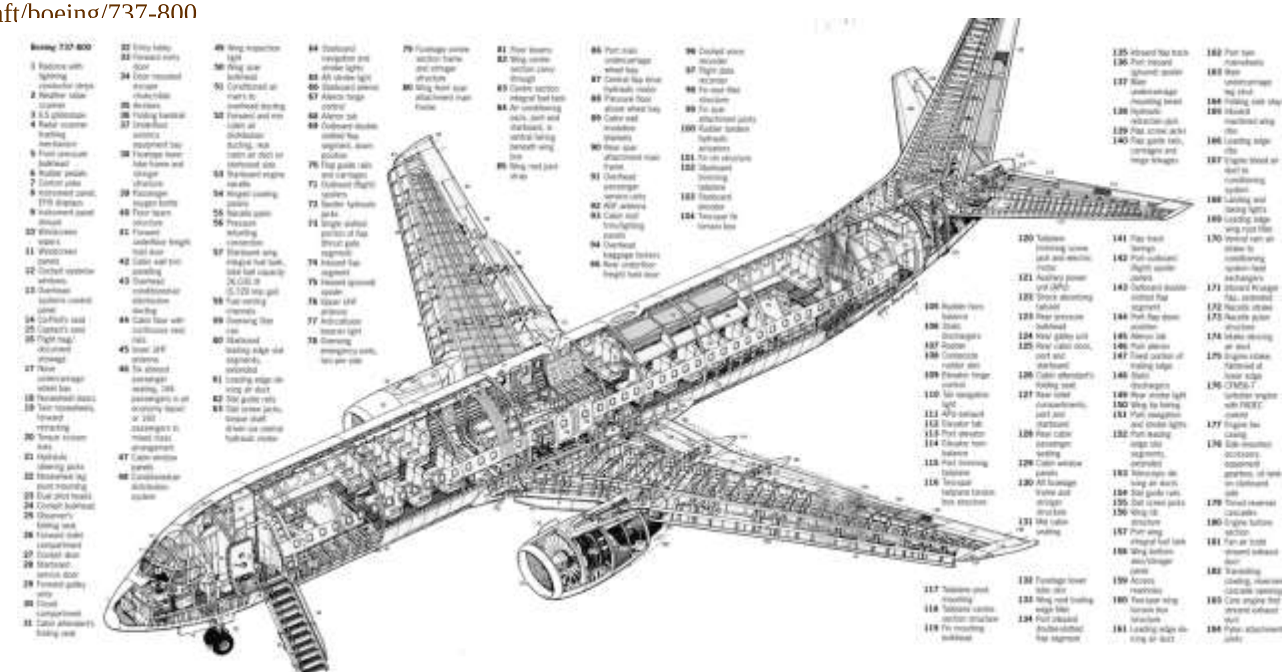
Range . . . . 2,835 miles

Wing area. . . . . 1,341.2 ft^2

Engine Thrust Class. . . . 20,000 to 27,000 lb

Cruising Speed . . . . .525 mph

Ability to perform the desired mission dictates shape and size of the airplane



Source: https://thelexicans.wordpress.com/2013/07/24/cutaway-thursday-boeing-737-800/

A1.5.1.1 Fuselage

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*

Size of weapons bay and embedded engines would have major influence on fuselage shape and size



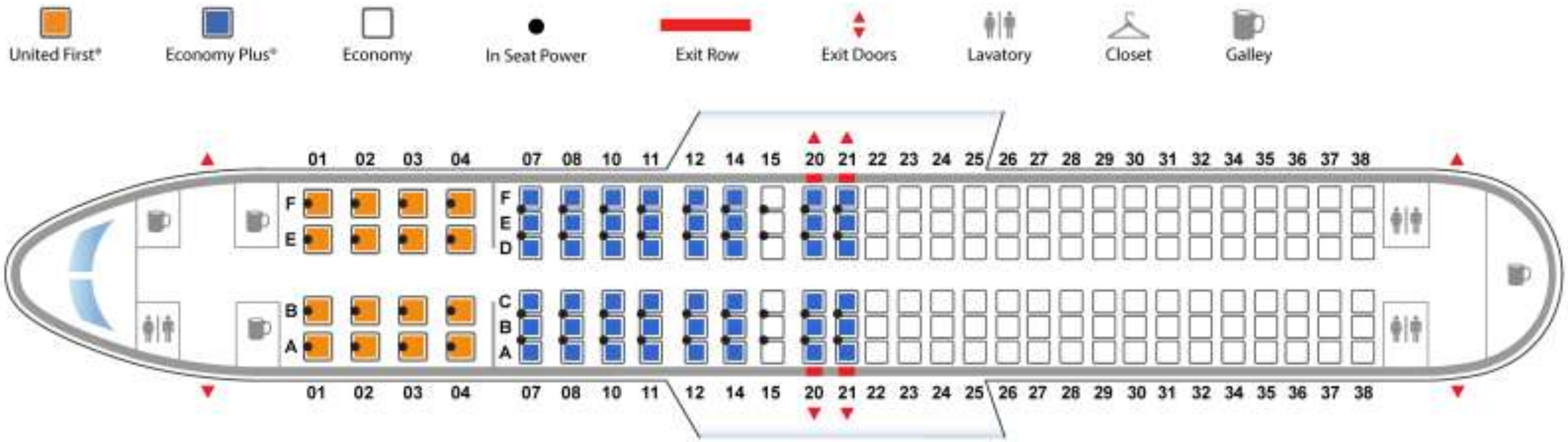





Image Source: Internet

Examples of Fuselage Interiors

Boeing 737-800 Passenger Cabin



C-5M Super Galaxy Cockpit

C-5 Galaxy Main Landing Gear

Stowed inside the LG bay during flight

Image Source: Internet

A1.5.1.2 Wing

Wings (Lifting Surfaces)

What determines wing placement: low, mid or high?

Why sweep the wing? How much?

Why taper the wing? How much?

Focus: Best Integrated Solution to Meet Design Objectives

Image Source: Internet

Wing Size Dilemma

- **Efficient cruise implies C_L close to the C_L for L/D_{max}**

  (if drag rise were not an issue, C_L for max range would be much less than C_L for L/D_{max})
- **Wings sized for efficient cruise require very high max lift coefficient, $C_{L_{max}}$, or long runway to land.**

Source: Adapted from W.H. Mason's Aircraft Design Lectures

Why Sweep the Wing?

Subsonic (usually small sweep)

- **Adjust wing aerodynamic center (AC) relative to *cg***
- **On flying wing, get moment arm length for control**

Transonic (significant, 30° to 35° sweep)

- **Delay drag rise Mach number (compressibility effect)**
  - **What is the drag divergence Mach no.?**

Supersonic (large, 45° to 70° sweep)

- **Wing concept changes from subsonic or transonic designs**
  - **must distribute load longitudinally as well as laterally**
- **Reduce cross-sectional area and area variation of the integrated concept**

Source: Adapted from W.H. Mason's Aircraft Design Lectures

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Why Variable Sweep?

- **Swept back: low supersonic drag, good**
  - **“on-the-deck” ride quality**
- **Unswept position: low landing speed (carrier suit.), *efficient loiter***
- **Optimum sweep back available over transonic speed range**

- **But: adds weight/complexity, currently unfashionable**

Source: Adapted from W.H. Mason’s Aircraft Design Lectures

Why Three Lifting Surfaces?

Piaggio Avanti

- **Can trim with near minimum drag over wide *c.g.* range**
- **But if you can make a design with two surfaces, why use three**
  - **Adds cost, weight, wetted area**
- **Sometimes, efficient component integration leads to three surfaces to save weight**

Source: Adapted from W.H. Mason's Aircraft Design Lectures

Why Winglets?

- **Nearly equivalent to span extension *w/o* increased root bending moment**
- **Used where span limitations are important**
- **Good wingtip flow crucial to low drag**
- **The local flowfield is extremely nonuniform, to work**
- ***Requires advanced computational aerodynamics methods to design***

Source: Adapted from W.H. Mason's Aircraft Design Lectures

Why a Flying Wing?

- **Removing fuselage can improve aerodynamic efficiency**
  - **But, payload volume distribution is still an issue**
- **Synergistic effect with relaxed static stability**
- **Military: low stealth**
- **Commercial: distribute load, reduce weight but, limited *cg* range**

Source: Adapted from W.H. Mason's Aircraft Design Lectures

Options Beyond Cantilever Wings

Truss-braced Wing

Blended Wing-Body

Box Wing

Flying V

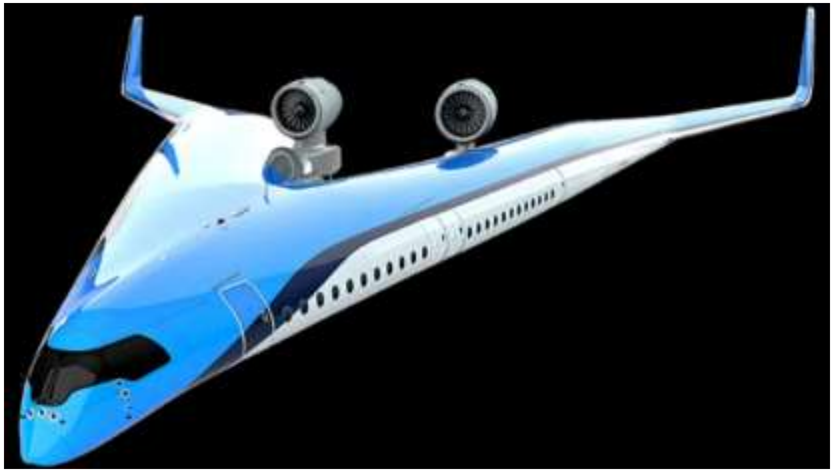


Image Source: Internet

A1.5.1.3 Propulsion

Propulsion System

What Determines Type & Location? Best Way to Meet Design Objectives!








1. Type: jet, propeller, hybrid electric, electric

2. Location: accessibility, efficiency, safety,…

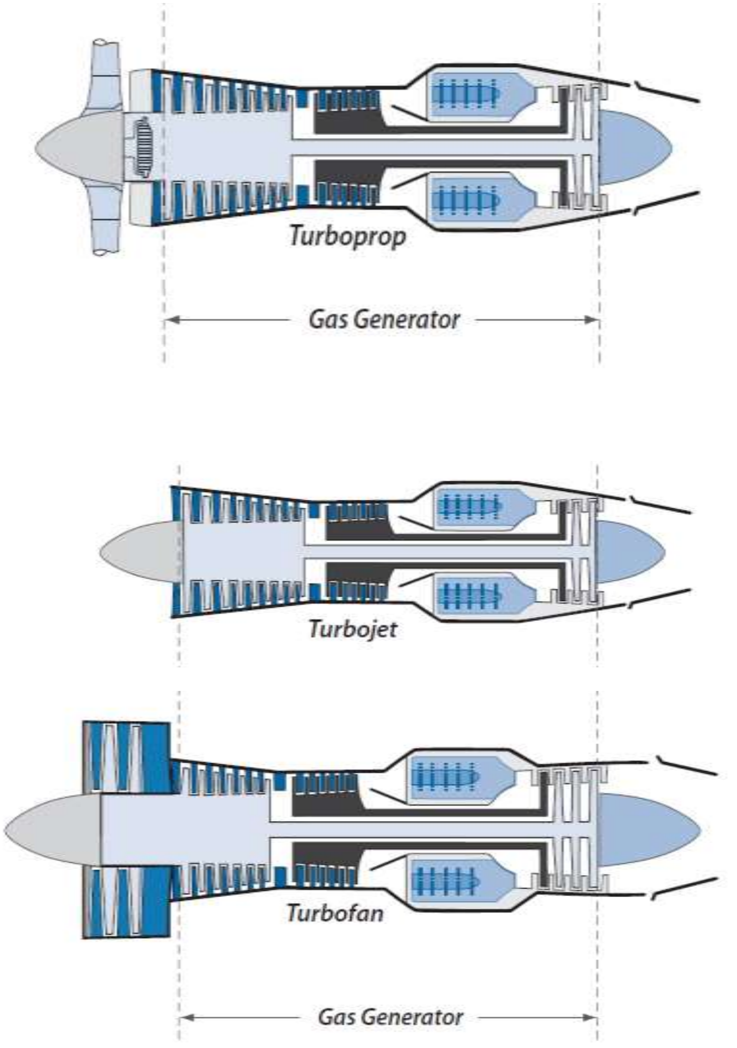
Image Source: Internet

Propulsion System Types

- **Two Main Options to produce forward thrust**

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

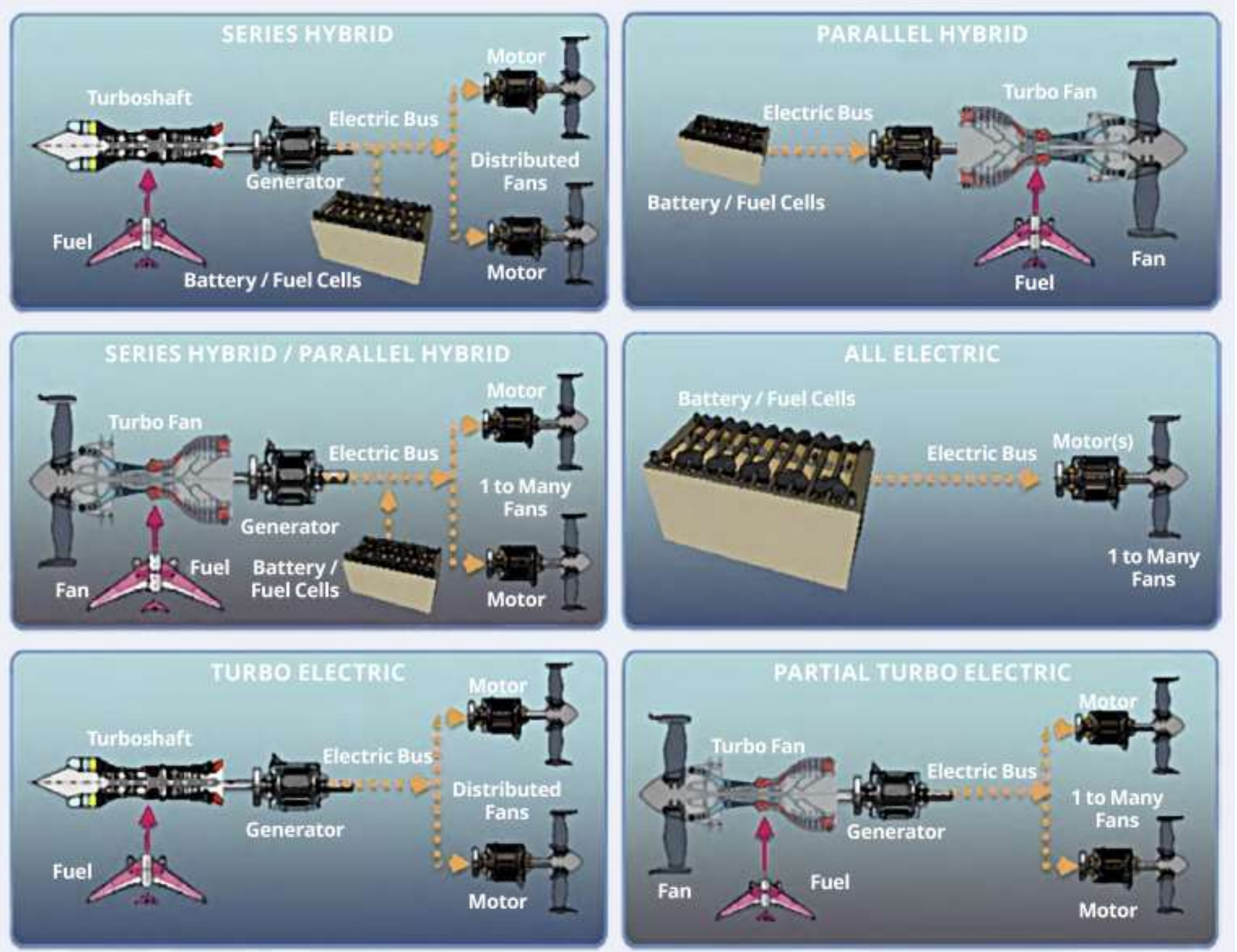
2. **Jet Engines**
   - Variants include turbojets; afterburning turbojets; and turbofans
   - Can operate supersonically to Mach 3.5



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

Hybrid-Electric Power Train

Several Hybridization Options to Integrate IC Engines with Electric Motors



Source: Figure 4.1 https://www.clean-aviation.eu/clean-aviation/our-energy-efficiency-and-emission-reduction/our-strategic-research-innovation-agenda

Propulsion System Location

• Engines in pods on wings

- Load relief on wing: weight savings
- Safety
- Accessibility for service (maybe)
- Can be low drag

• Propulsion for lift control

Image Source: Internet

A1.5.1.4 Empennage

Empennage

Ensure longitudinal and lateral stability, adequate control power, and spin recovery throughout the mission

Many Options!

Choose the Best Option to Keep the Integrated System Balanced Throughout the Mission

Image Source: Internet

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

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

Why Canards?

- **Trim surface carries positive load for positive *g* maneuvers**
- **Reduces subsonic-supersonic *ac* shift**
- **Drawback: downwash from canard unloads wing**
  (for forward swept wing this is good)
- **If balanced stable, C_L on canard is much higher than the wing**
  - **balanced unstable, control system design very expensive**
  - **acceptable high angle of attack lateral/directional characteristics hard to obtain**
  - **When to use? severe supersonic cruise/transonic maneuver requirement**
  - **Not Stealthy**

Source: Adapted from W.H. Mason's Aircraft Design Lectures

A1.5.1.4 Landing Gear

Landing Gear

Numerous considerations in choosing type & arrangement

- *Tip back and turnover*
- *Light weight*
- *Static and dynamic loads*
- *Runway surfaces*
- *Floatation*
- *Stability during taxi and takeoff, and during touchdown and braking*
- *Ground maneuvers*
- *Steering qualities*

Image Source: Internet

Outline

A1. Purpose & Process

What is Innovation?

- **Developing *new value for customers* through *novel solutions* that meet new needs, inarticulate needs, or old needs in *new ways*.**
- **Integrating or applying *better and novel ideas* or methods**
  - It's *not* creation of those ideas or methods—that's Invention
- **Doing something *different***
  - It's *not* doing the same thing better—that's Improvement

Capstone Design Project offers

An Excellent Opportunity to Learn to Innovate

Ability to Innovate:
Your key to "Owning the Future"

Source: Internet

A Few Innovative Aircraft Concepts

https://sacd.larc.nasa.gov/asab/asab-projects-2/x57maxwell/

https://www.boeing.com/features/2019/01/spreading-our-wings-01-19.page

Human Imagination is Limitless!

Driven by Novel Technologies for Sustainable Aviation

https://www.nasa.gov/aero/industry-provides-nasa-with-ideas-for-next-x-plane

How to Innovate?

Don't Just Do It…Ask:
"How might we do it differently?"

An Example of Skunk Works® Innovation

Advanced Composite Cargo Aircraft (ACCA)

Program Manager:
Mr. Mike Swanson

ACCA Genesis

Customer (AFRL) Needs and Wants

- ***Prepare for a Future Cargo Aircraft Paradigm Characterized by***
  - Low Cost / Low Rate Production
  - Manufactured With Composites
  - Large Scale Vehicle
- ***Conduct a Program to Mature Critical Technologies***
  - Advanced Composites
  - Novel Structural Concepts
  - Low Cost Fabrication
  - Rapid Manufacturing
- ***Program Objectives***
  - Design in 5 Months, Build & Fly in 18 Months
  - On Schedule, On Budget
  - *Budget: Not to Exceed (NTE) $50M*

An Impasse!

- Estimated cost to build and fly a new composite airplane: approx. $350M
  - *Not much room to trim the cost of designing, building, and flying a new composite airplane—the traditional way*
- Customer budget: *not to exceed* $50M
- ***How to bridge the large gap?*** ***INNOVATE!***

Break the Impasse by Asking

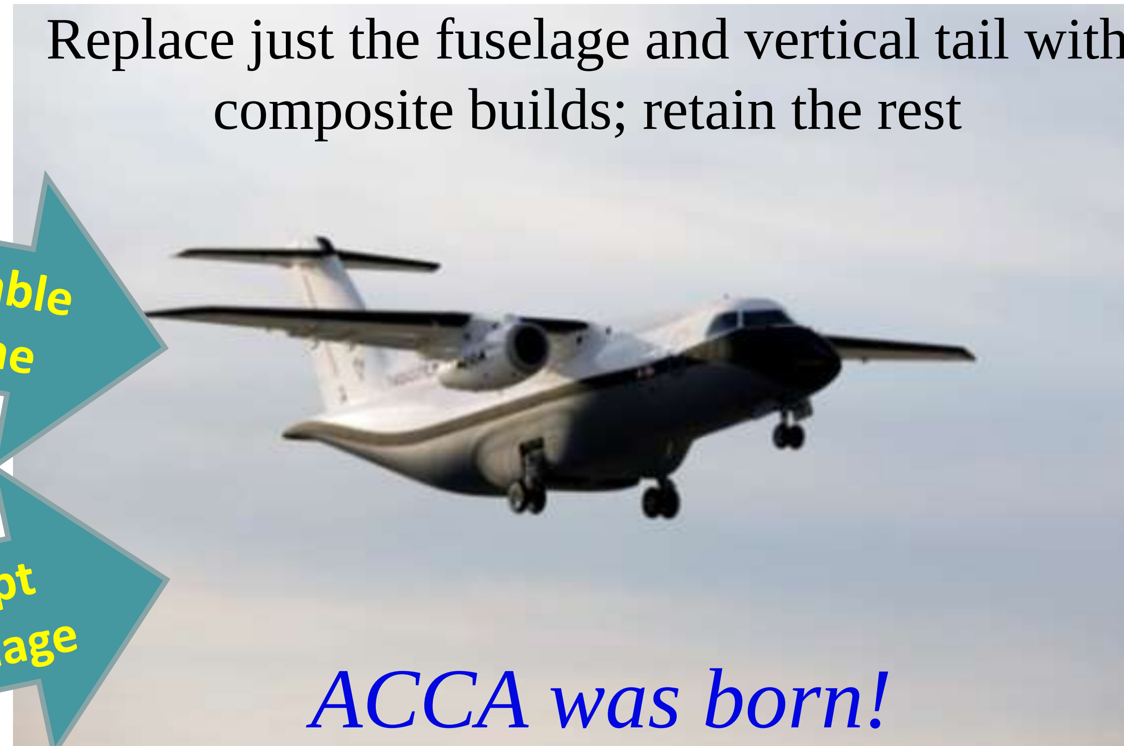
“How might we do it differently?”

Advanced Composite Cargo Aircraft

- **Do we have to build a whole new airplane <u>to meet the needs</u>?**

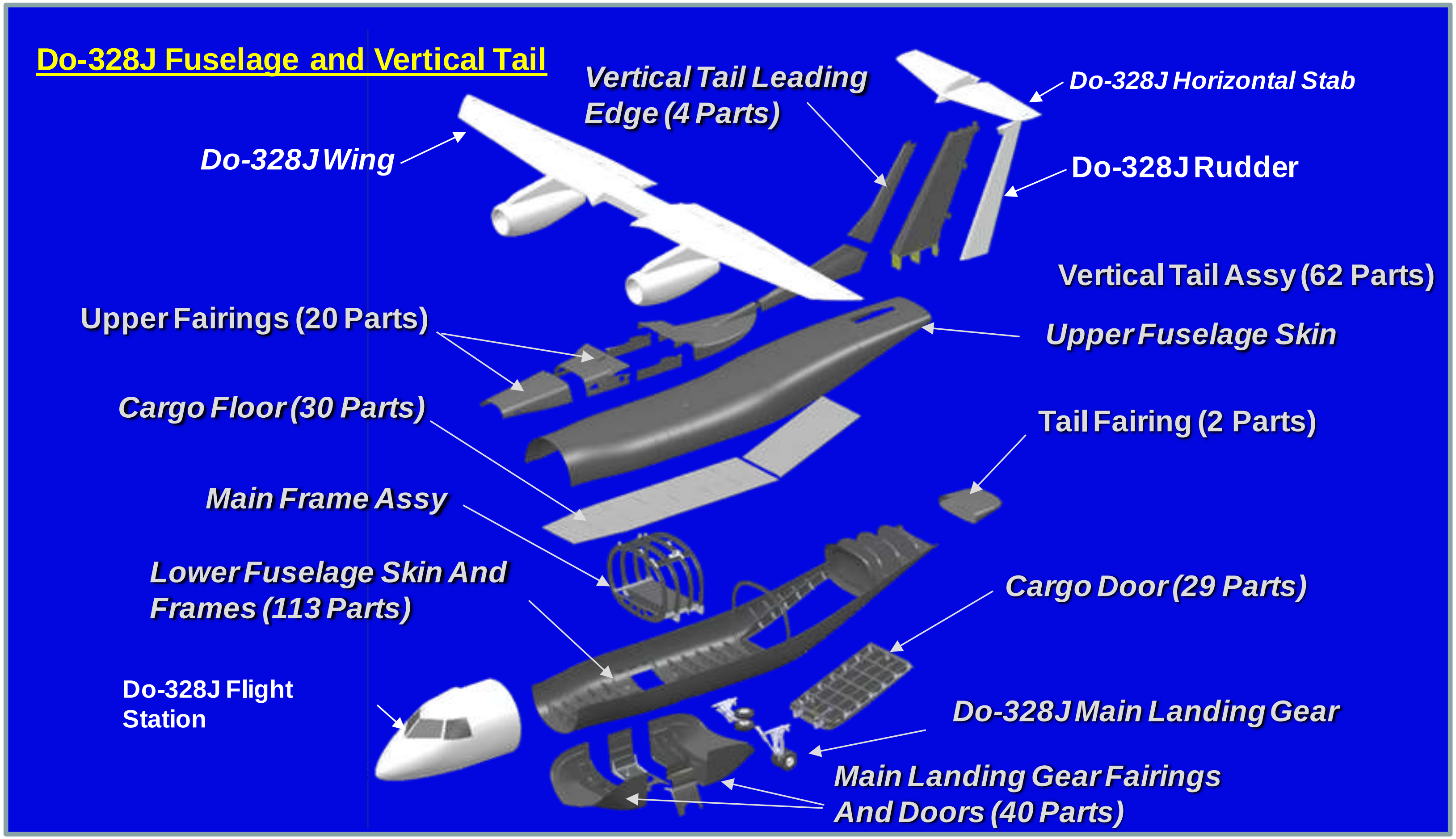
Affordable airplane

Upswept aft fuselage



Innovation at its Best!

ACCA Team Designed and Built Advanced Composite Fuselage and Vertical Tail



Unitized Structure: 90% Reduction in Structural Parts
Elimination of 15,000+ Fasteners

ACCA Key Project Milestones

November 2007: Jet-2 Lands in Palmdale

Fuselage Skin Fabrication

Wind Tunnel Testing

Composite Fuselage Assembly

Mating of Cockpit to Fuselage

Aircraft Re-Assembly

Flight Station Power-On Checks

June 2, 2009: First Flight

20 Months – Landing to Takeoff!

If You Don't Innovate…Someone Will!

The iPhone is commonly referenced as a first-of-its-kind device that revolutionized the way we navigate the world. But in his new book, *The One Device*, Brian Merchant argues that Apple's breakthrough product was less a stroke of genius and more a ***"container ship of [pre-existing] inventions."*** By the time the iPhone debuted, in 2007, Finger Works had figured out multi-touch keyboards, Nokia's phones were playing music and running apps, and IBM had birthed and buried its own smartphone, the Simon.

So what set the iPhone apart? Steve Jobs' insistence on intuitive design was a huge factor. So was timing. In 1992, when IBM unveiled the Simon, hardware was bulky and wifi was essentially nonexistent. By 2007, that landscape had shifted, paving the way for the iPhone's success. "The point isn't that Apple ripped off the Simon," Merchant writes. It's that something like the iPhone was inevitable. Jobs was just the first to make it a mass-market reality.

iPhone was inevitable; Jobs was first to make it!

Note: Highlighting is mine.

Source: http://time.com/4819579/iphone-one-device-review/

Innovative Product Alone Does Not Guarantee Success!

iPhone Launch Video Excerpt (10 mins.)

You Have to Mesmerize the Customers!

https://www.youtube.com/watch?v=-3gw1XddJuc

Epilogue

Get ready to embark on an exciting journey of creating magic by combining your imagination with the aircraft design process!

Recommended Readings

Ref. No.	Chapter	Author(s)	Title
AVD 1	**Chapter 1**	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	**Chapter 2**	Raymer, D.P.	***Aircraft Design* : *A Conceptual Approach ,*** AIAA Education Series, AIAA, Reston, VA, 2012.
AVD 5	**Chapter 1**	Sadrey, M.H.	***Aircraft Design: A Systems Engineering Approach*** , John Wiley & Sons, Inc., 2013.
AVD 8	**Chapter 1 & 2**	Kundu, A.K.	***Aircraft Design*** , Cambridge University Press, 2010.
AVD 9	**Chapter 1**	Torenbeek, E.	***Advanced Aircraft Design: Conceptual Design, Analysis and Optimization of Subsonic Civil Airplanes*** , John Wiley and Sons, Ltd., June 2013.

NOTE: See Appendix in Overview CM