MISSION ADAPTATION & TECHNOLOGY TRENDS IN AERO PROPULSION

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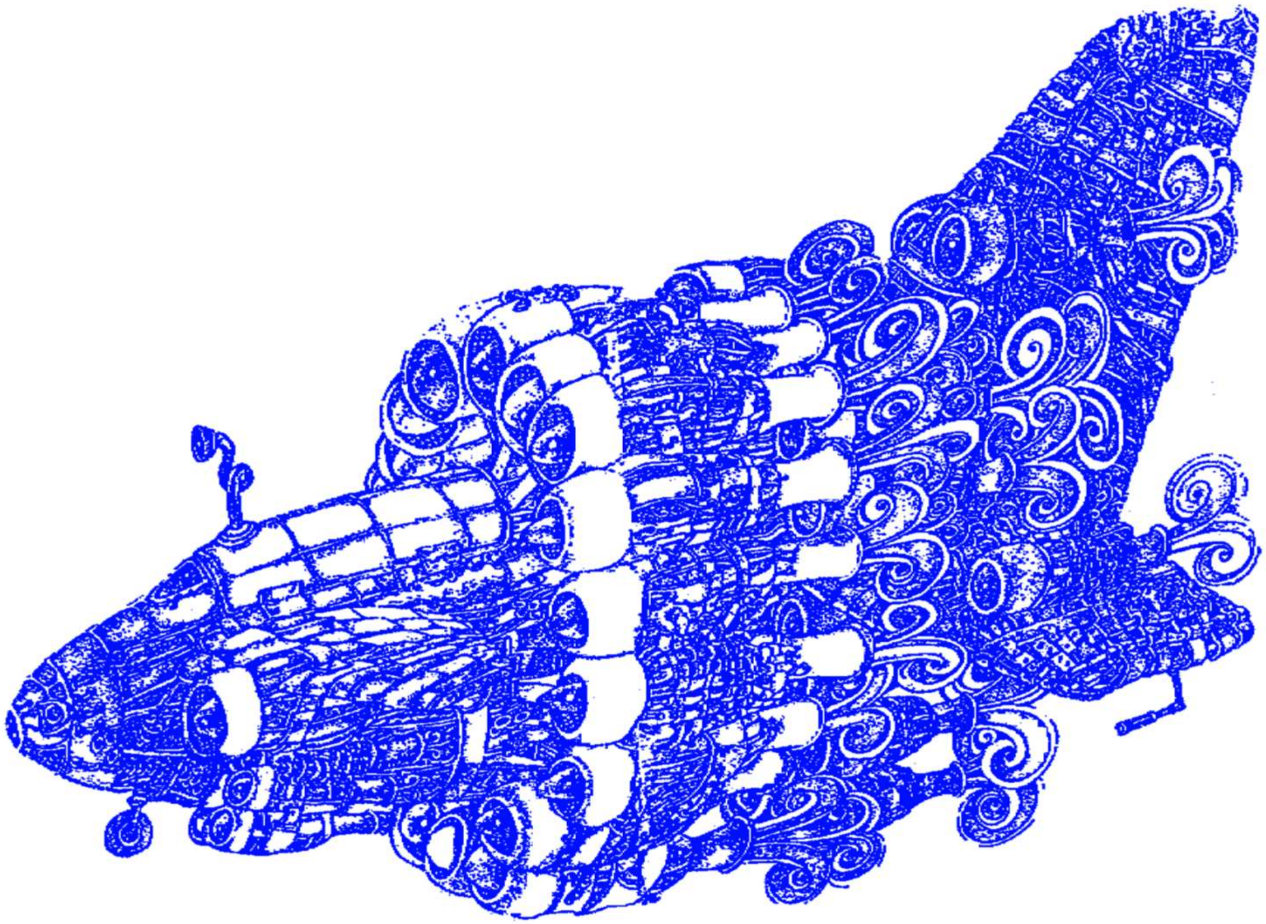
Based on material by Philip Shacter,
Propulsion Systems Analysis

Pratt & Whitney
A United Technologies Company

AN ENGINE MAKER'S DREAM!



Topics

- Flight vehicle characteristics
- Turbine engine characteristics
- Transport engines
- Fighter engines
- Engine technology trends
- Summary

FLIGHT VEHICLE CHARACTERISTICS

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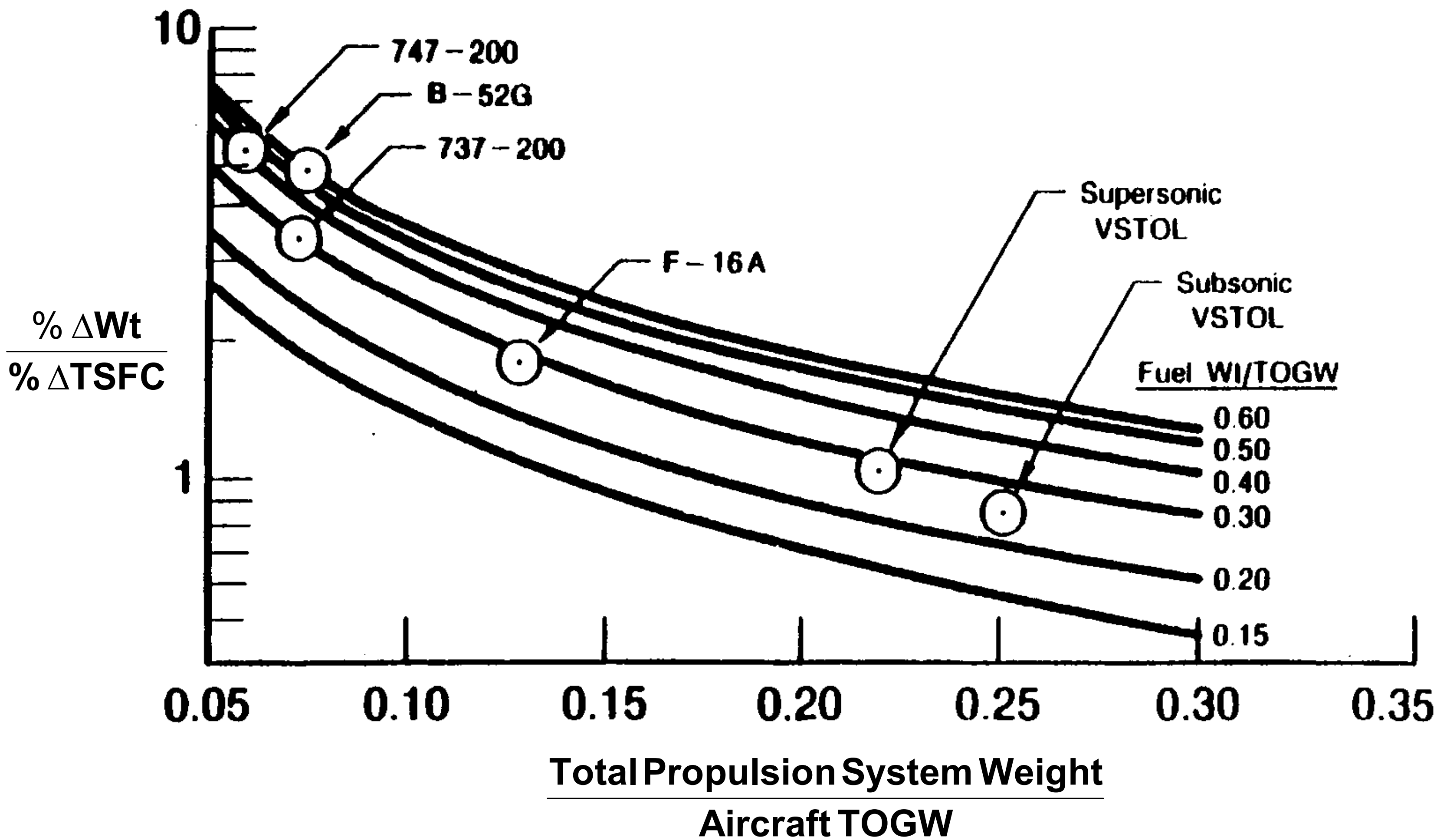
A/C Sensitivity to Engine Fuel Consumption and Weight



Sensitivity to Engine Fuel Consumption and Weight

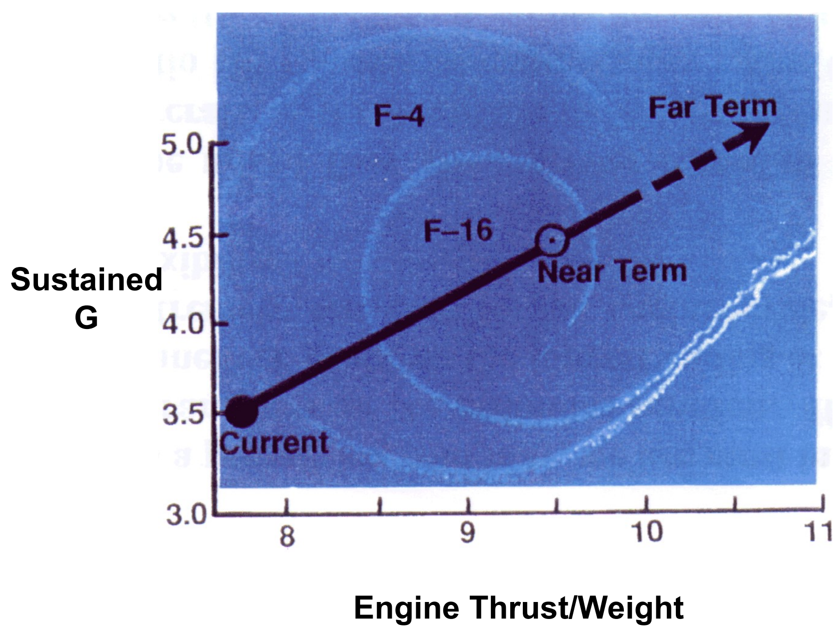
- The previous slide illustrates the relative sensitivities of aircraft gross weight to engine weight and to fuel consumption for both transport and fighter aircraft
- Transport or subsonic bomber aircraft have low ratios of propulsion system weight to aircraft TOGW and high fuel fractions
- These aircraft are therefore **more sensitive to engine fuel consumption than they are to engine weight**
  - For the Boeing 747-200 aircraft, a 1% change in TSFC has the same impact on aircraft TOGW as a 5% change in propulsion system weight

Sensitivity to Engine Fuel Consumption and Weight

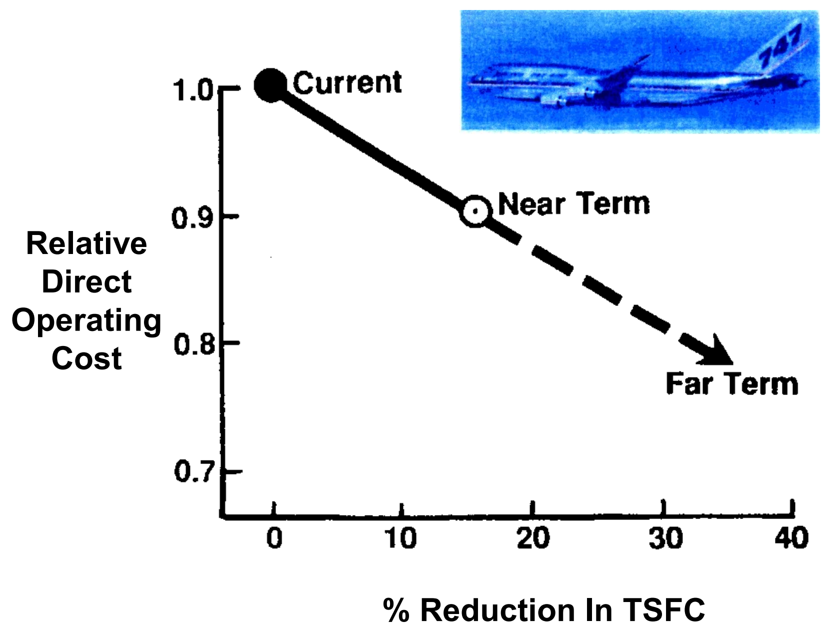
- Fighter aircraft have higher propulsion system weight/TOGW fractions than transport aircraft and are therefore **<u>more sensitive to engine weight</u>**
  - For a subsonic VSTOL fighter which has a propulsion system weight fraction of 25% and a fuel fraction of 25%, a 1% change in engine weight has the same impact on TOGW as a 1% change in TSFC

Aircraft Requirements Establish Propulsion System Requirements

Increased Thrust/Weight Improves Maneuverability



Lower Fuel Consumption Reduces Cost



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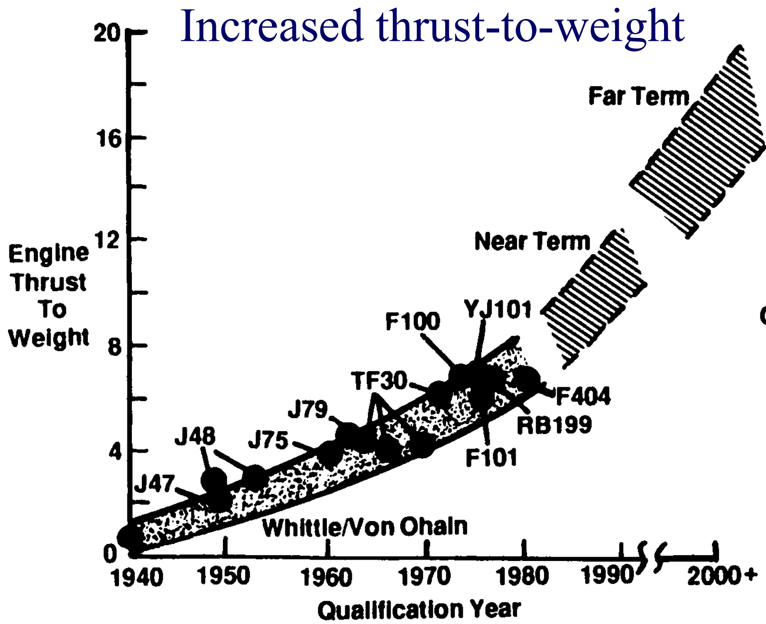
Aircraft Requirements Establish Propulsion System Requirements

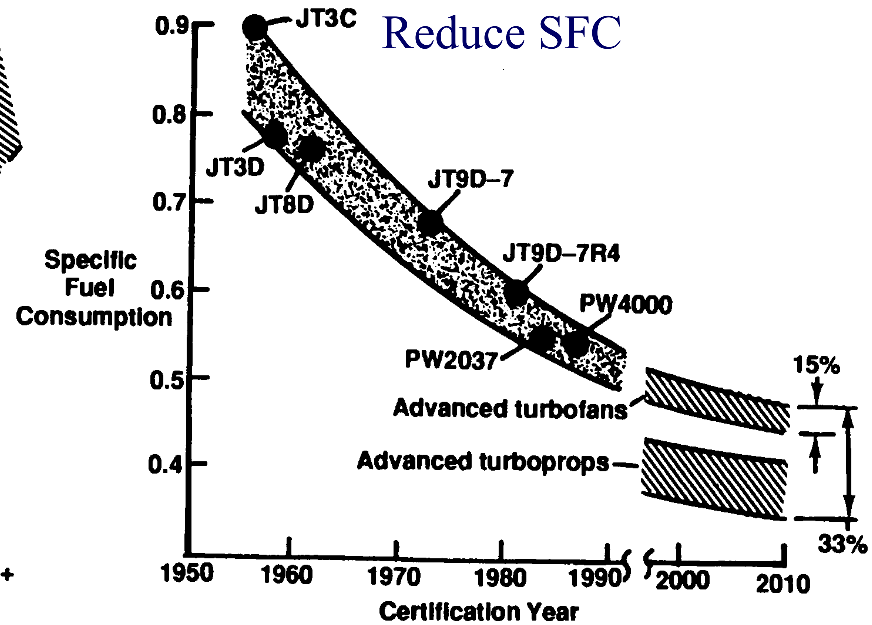
- For a subsonic commercial transport, fuel consumption of the engine is the main driver of the airlines operating cost
  - A 15% reduction in fuel consumption will reduce direct operating cost by 10%
- For fighter/attack aircraft, a high performance, low weight engine is required to achieve high acceleration rates and improved maneuverability
  - Therefore, a high thrust-to-weight engine is a primary requirement for an effective fighter aircraft

Propulsion System Trends

Fighter/Attack



Transport



Other requirements

- Reduced fuel consumption
- Super maneuverability/STOL
- Low observables
- Durability/supportability
- Low cost

Other requirements

- Low emissions
- Low noise
- Durability/supportability
- Low cost

Propulsion System Trends

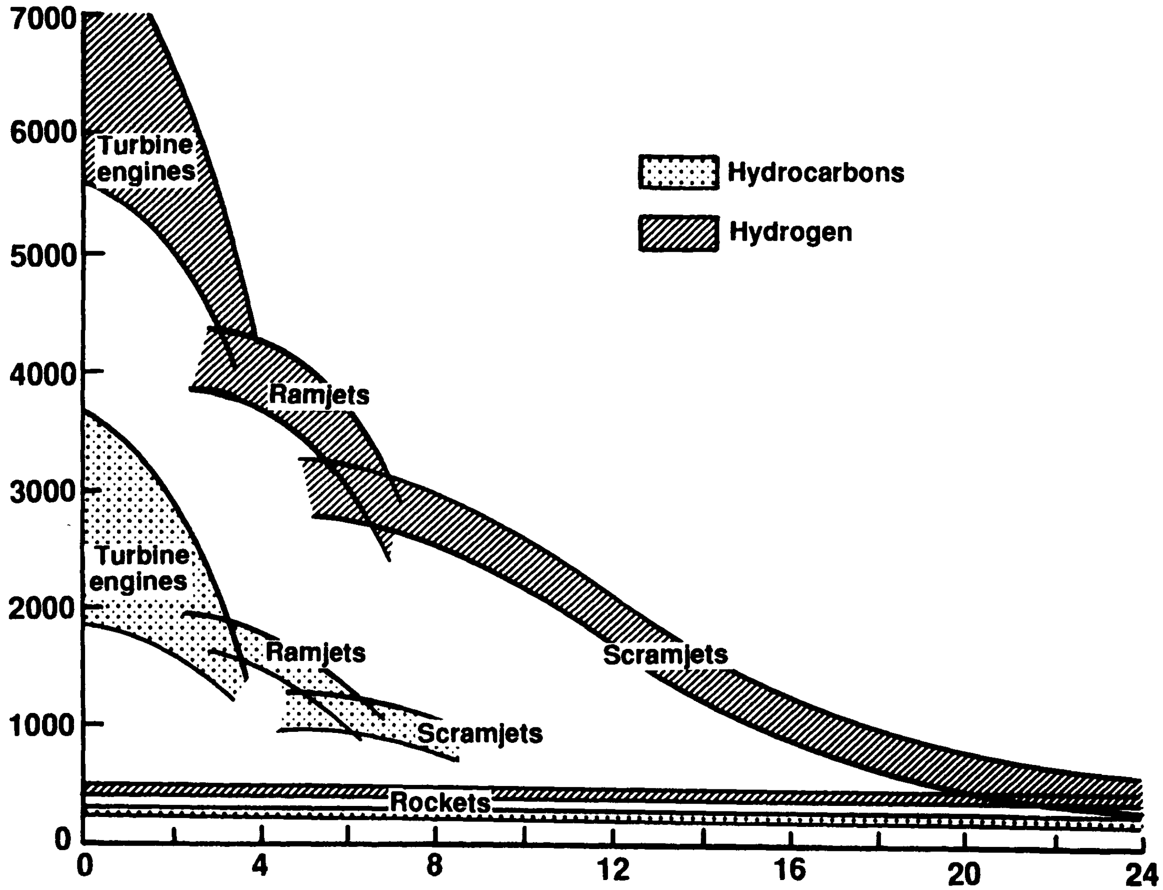
- Fighter/attack aircraft propulsion system thrust-to-weight ratios have been dramatically increased
  - Early afterburning turbojets: 2-3
  - Current afterburning turbofans: 7-8
    - PW F100 and GE F101 engines
- Subsonic commercial transport engine TSFCs at Mach 0.8 have also been significantly reduced:
  - From 0.8 for early low bypass ratio/low OPR turbofans
  - Around 0.6 for current generation high bypass ratio/high OPR turbofans
    - P&W JT9D and PW4000 and GE CF6 and GE90 engines

TURBINE ENGINE CHARACTERISTICS

Propulsion Options

Specific Impulse

$$\frac{1}{TSFC}, \frac{lb_f\ sec}{lb_m}$$



Mach Number

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Propulsion System Options – Performance Envelope

- Typical performance characteristics of different air-breathing propulsion and rocket systems are illustrated
  - The typical Mach operating range for the different air-breathing systems is also indicated
- Specific impulse (I_{sp}) is the inverse of thrust specific fuel consumption ($TSFC$)
  - Hydrogen has approximately 2.7 times the energy per pound compared to hydrocarbon fuels
    - Hydrogen fuel heating value ~ 50,678 Btu/lb vs. ~ 18,400 Btu/lb for hydrocarbon fuel

Propulsion System Options – Performance Envelope

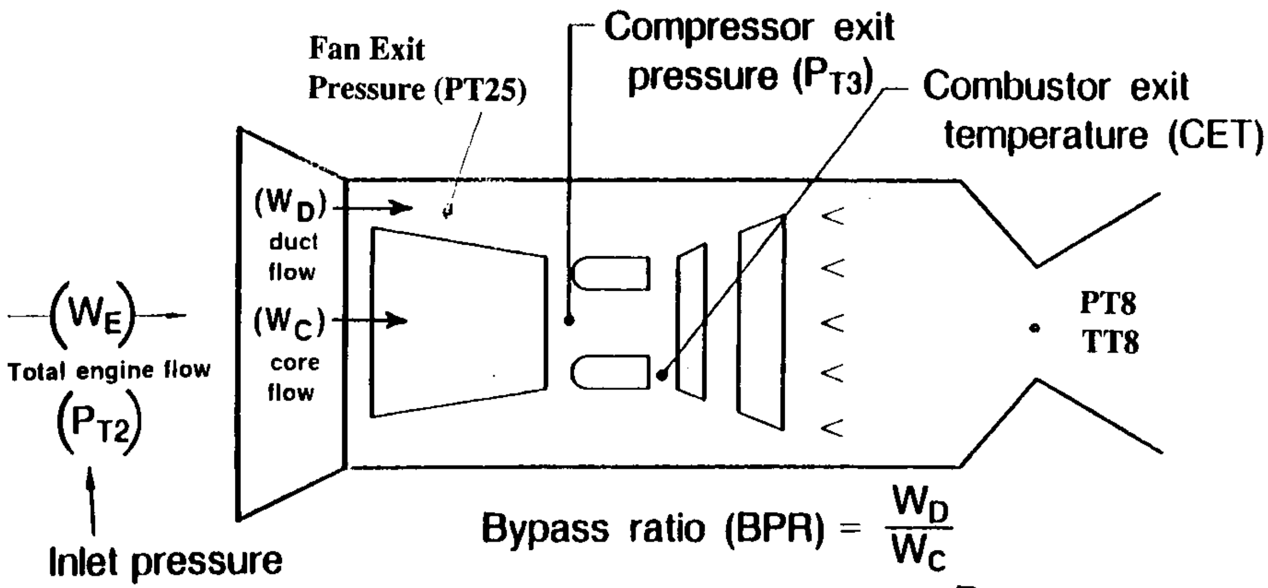
- Specific fuel consumption, or specific impulse is an important parameter in air vehicle performance, as indicated by the Breguet range equation:

$$Range \propto M \frac{L}{D} \frac{1}{TSFC} \ln\left(\frac{W_0}{W_1}\right)$$

$$Range \propto M \frac{L}{D} I_{sp} \ln\left(\frac{W_0}{W_1}\right)$$

Engine Cycle Parameters

- "Cycle" → primary thermodynamic parameters



$$\text{Bypass ratio (BPR)} = \frac{W_D}{W_C}$$

$$\text{Overall pressure ratio (OPR)} = \frac{P_{T3}}{P_{T2}}$$

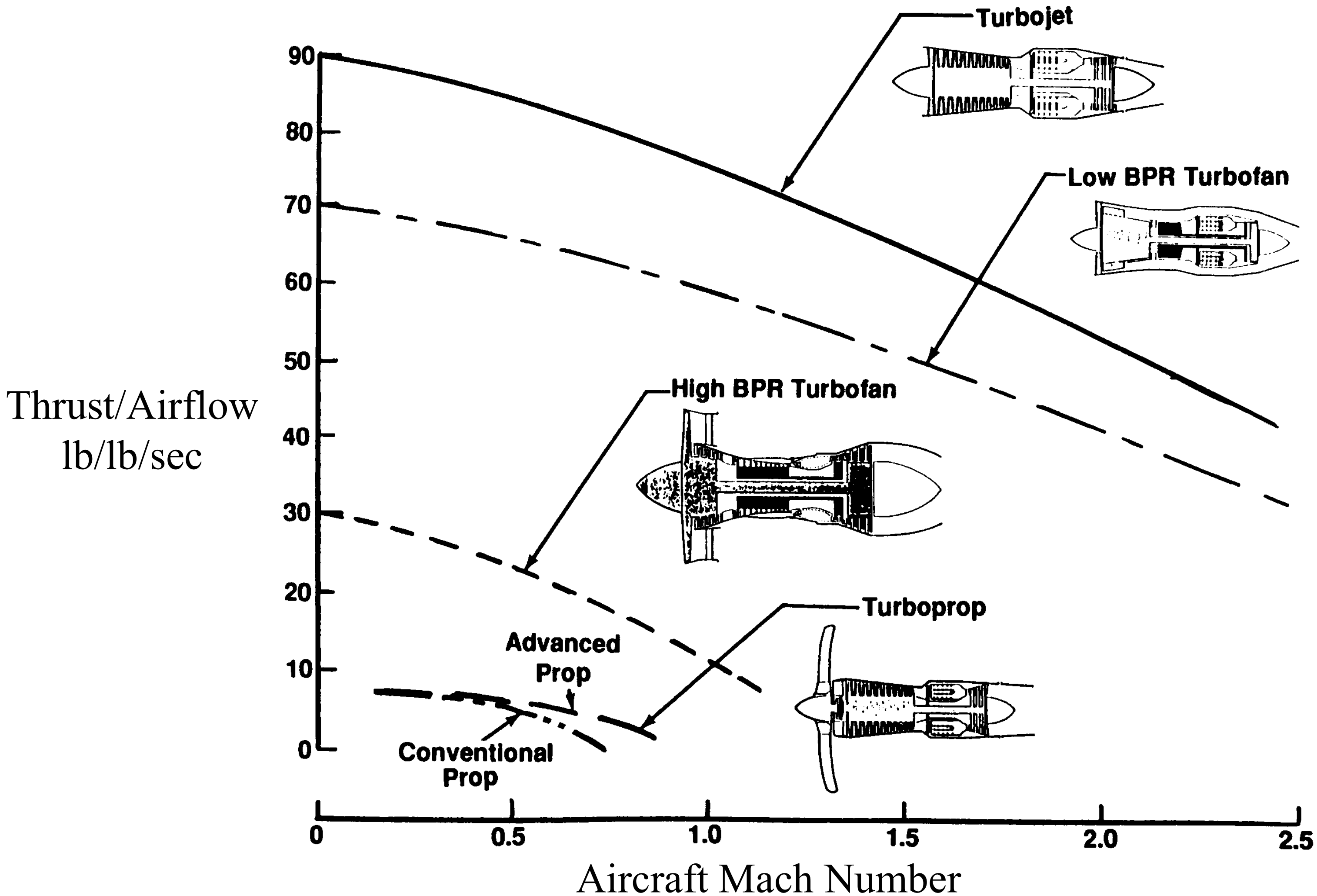
$$\text{Throttle ratio (THTR)} = \frac{(CET)_{MAX}}{(CET)_{SLS}}$$

Fan Pressure Ratio (FPR) = PT25/PT2

Mixed Flow Turbofan Parameters

- Propulsion companies are most interested in seeing the impact of the engine cycle parameters on the optimum solution
  - If the lowest TOGW that meets the radius and maneuver goals, or the longest radius at fixed TOGW that meets maneuver goals is not extremely sensitive to the engine cycle, it affords the engine designer more design flexibility
- The **mixed flow afterburning turbofan** is employed in current and advanced fighter aircraft
- A turbofan allows the system engineer to vary Fan Pressure Ratio (FPR), Overall Pressure Ratio (OPR), Combustor Exit Temperature (CET), and Throttle Ratio (THTR) to produce the best engine for a particular application

Turbine Engine Characteristics



Turbine Engine Specific Thrust Characteristics

- The amount of thrust produced by an engine for every pound of airflow passing through the engine is shown for various types of gas turbine engines
  - Turboprop engines, which increase the pressure of the air going through the propeller by 5 to 10%, produce specific thrust levels at takeoff of 8 lbs of thrust per pound of airflow
  - These engines are used for aircraft flying at Mach Numbers below 0.7

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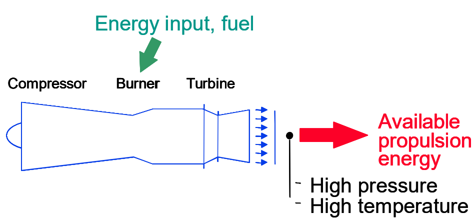
Turbine Engine Specific Thrust Characteristics

- The High bypass ratio turbofans are used in subsonic commercial and military aircraft and produce takeoff specific thrust levels of around 30
  - Examples: P&W JT9D and GE CF6
- Low bypass ratio turbofans are used in supersonic fighter aircraft such as the F-14, F-15, F-16, F-18, and F-22 because they produce high levels of specific thrust, which are required to provide the maneuverability needed by fighter aircraft
- Turbojet engines were used in most of the original jet powered fighter aircraft and produce the highest levels of specific thrust

Reduced Specific Fuel Consumption

Driven By High Thermal and Propulsive Efficiency

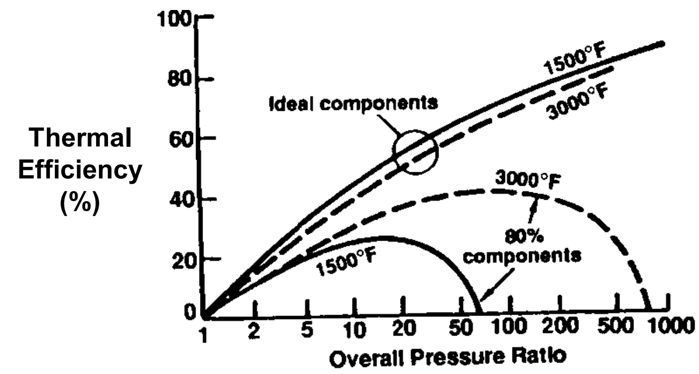
$$\eta_{\text{overall}} = \eta_{\text{thermal}} \times \eta_{\text{propulsive}} \quad \alpha \left(\frac{1}{\text{TSFC}}\right)$$

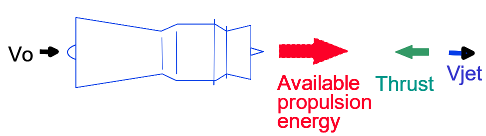


η_{thermal}

$$= \frac{\text{Energy available for propulsion}}{\text{Energy available in fuel}}$$

$$= f(\text{overall pressure ratio, T4, component } \eta, \text{ leakage})$$





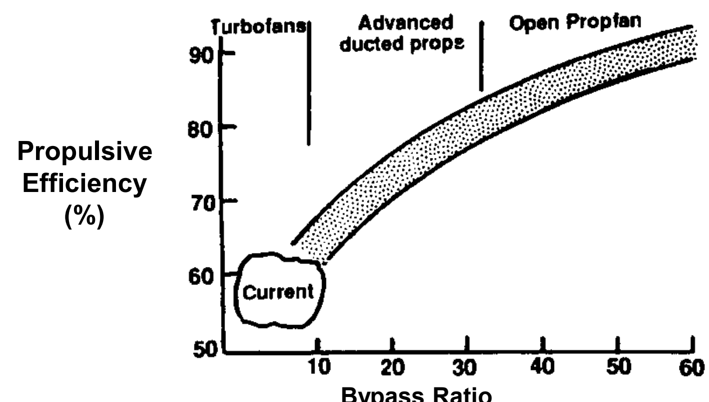
$\eta_{\text{propulsive}}$

$$= \frac{\text{Useful propulsive energy}}{\text{Energy available for propulsion}}$$

$$= \frac{2V_R}{1+V_R} \quad \text{where } V_R = V_0 / V_{jet}$$

$V_R \approx 0.35$ for turbojet

$V_R \approx 0.9$ for propfans



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Reduced Specific Fuel Consumption

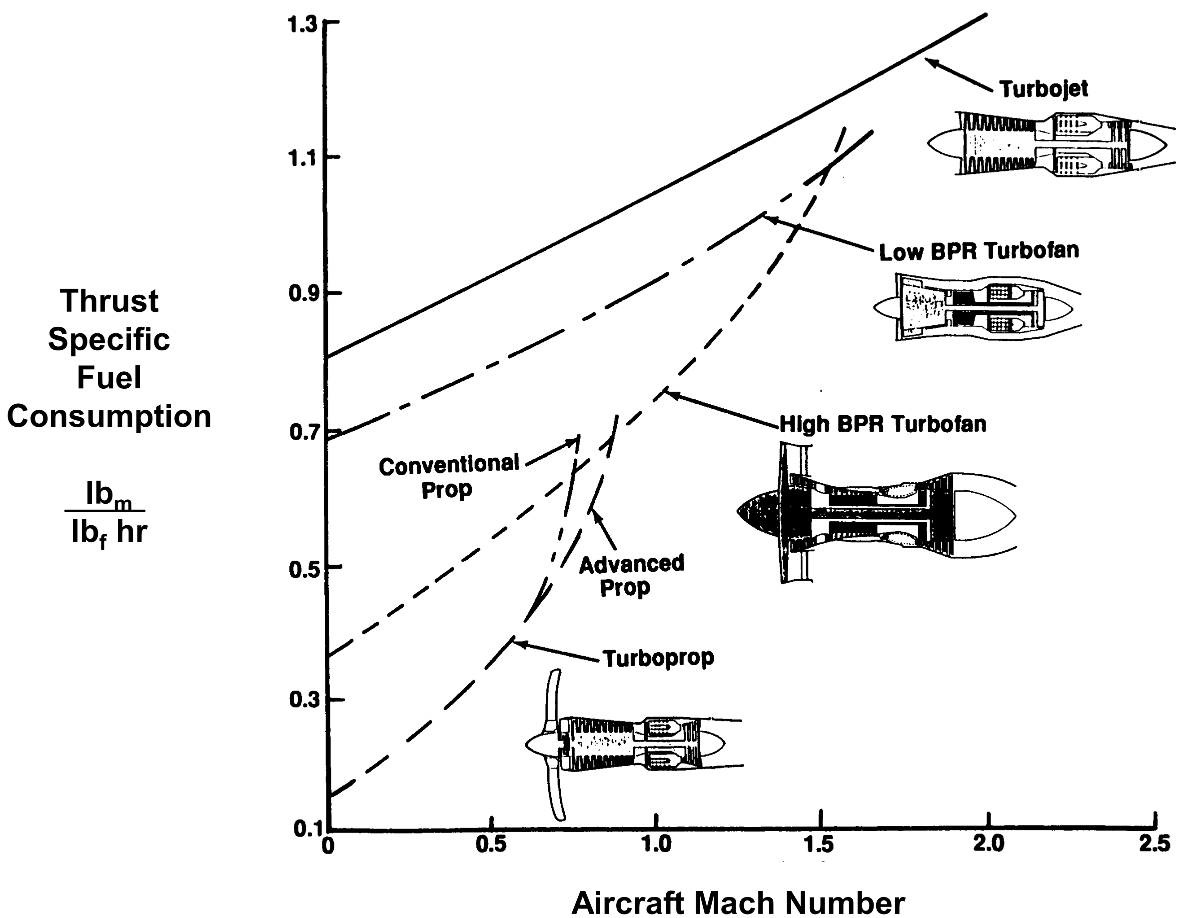
- The overall efficiency of a turbofan engine is a measure of how much useful propulsive energy can be produced for each pound of fuel burned
  - Thus, overall efficiency is inversely proportional to the TSFC, which is the ratio of fuel burned per pound of thrust developed
- Overall efficiency is equal to the product of thermal efficiency and propulsive efficiency of the cycle
  - As shown, the thermal efficiency is a function of combustor exit temperature (T_4), overall compression ratio (OPR), and component efficiencies
  - Early turbofan engines with T4s of 1500°F had OPRs of 15 to 20 to optimize thermal efficiency
  - Future engines with T_4 of 3000°F desire OPRs of 50 to 100

Reduced Specific Fuel Consumption

- Propulsive efficiency is a measure of the useful propulsion and is a function of the ratio of aircraft velocity (V_0) to the velocity of the gas jet as it leaves the engine (V_{jet})
  - A turboprop engine, which has a pressure ratio across the propeller of 1.1, has a V_{jet}/V_0 ratio of about 1.1
  - A turboprop engine has propulsive efficiency of around 95%
- Current turbofans for subsonic transports have Fan Pressure Ratios of around 1.7 and produce propulsive efficiencies of 55 to 60%

Turbine Engine Characteristics

Thrust Specific Fuel Consumption



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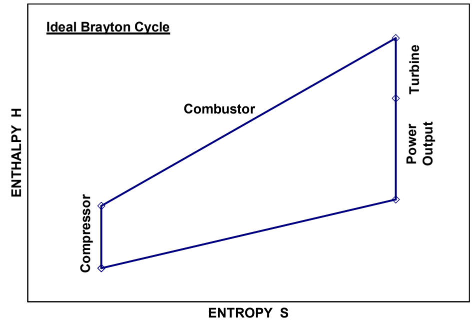
Turbine Engine Specific Fuel Consumption

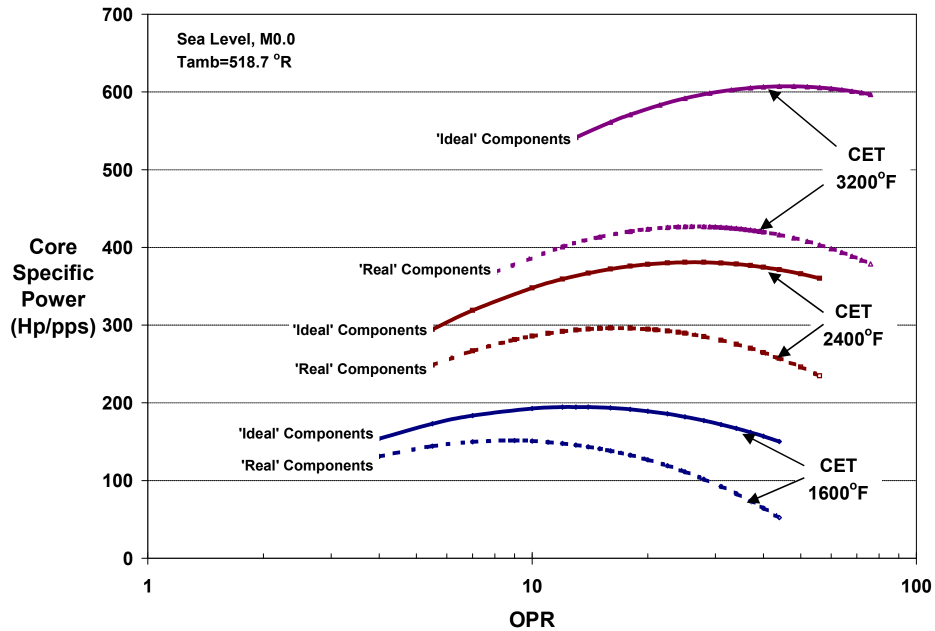
- Thrust specific fuel consumption (*TSFC*) characteristics are presented for various types of turbine engines
  - TSFC is the ratio of fuel burned per hour to the amount of thrust produced by the engines
- Turboprop engines, which have bypass ratios (*BPR*) of around 80 have very low specific fuel consumption
  - However, at a Mach ~ 0.7, *SFC* → 0
  - *TSFC* increases sharply, and becomes worse than the *TSFC* of a high *BPR* turbofan
- High bypass ratio turbofans, which typically have *BPR* greater than 4, are used in subsonic transports that cruise at flight Mach of 0.8 to 0.9, where they have *TSFCs* of around 0.6

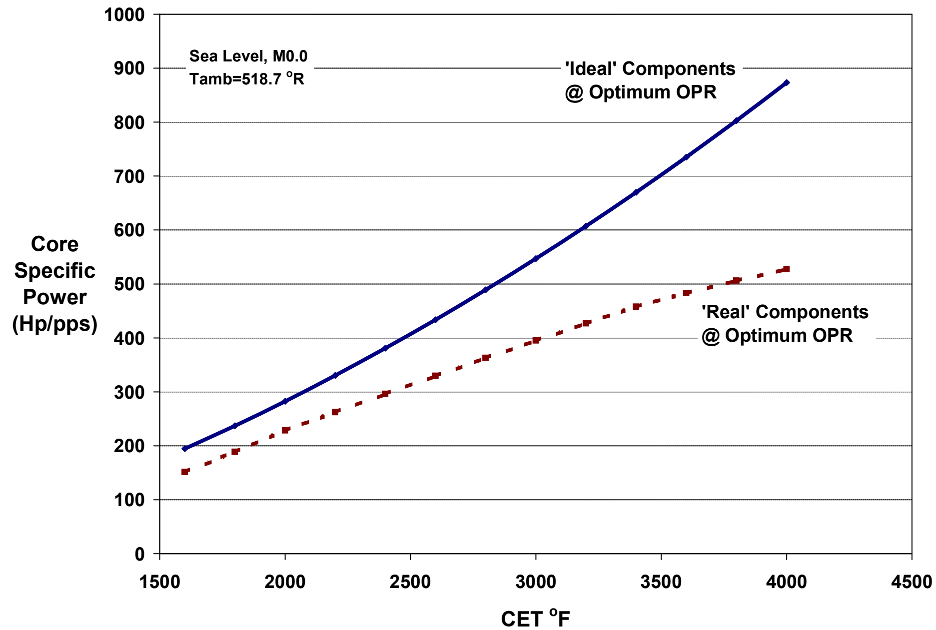
Turbine Engine Characteristics

Specific Power Output

Brayton Cycle
Core Power = *f*(CET, OPR, η)







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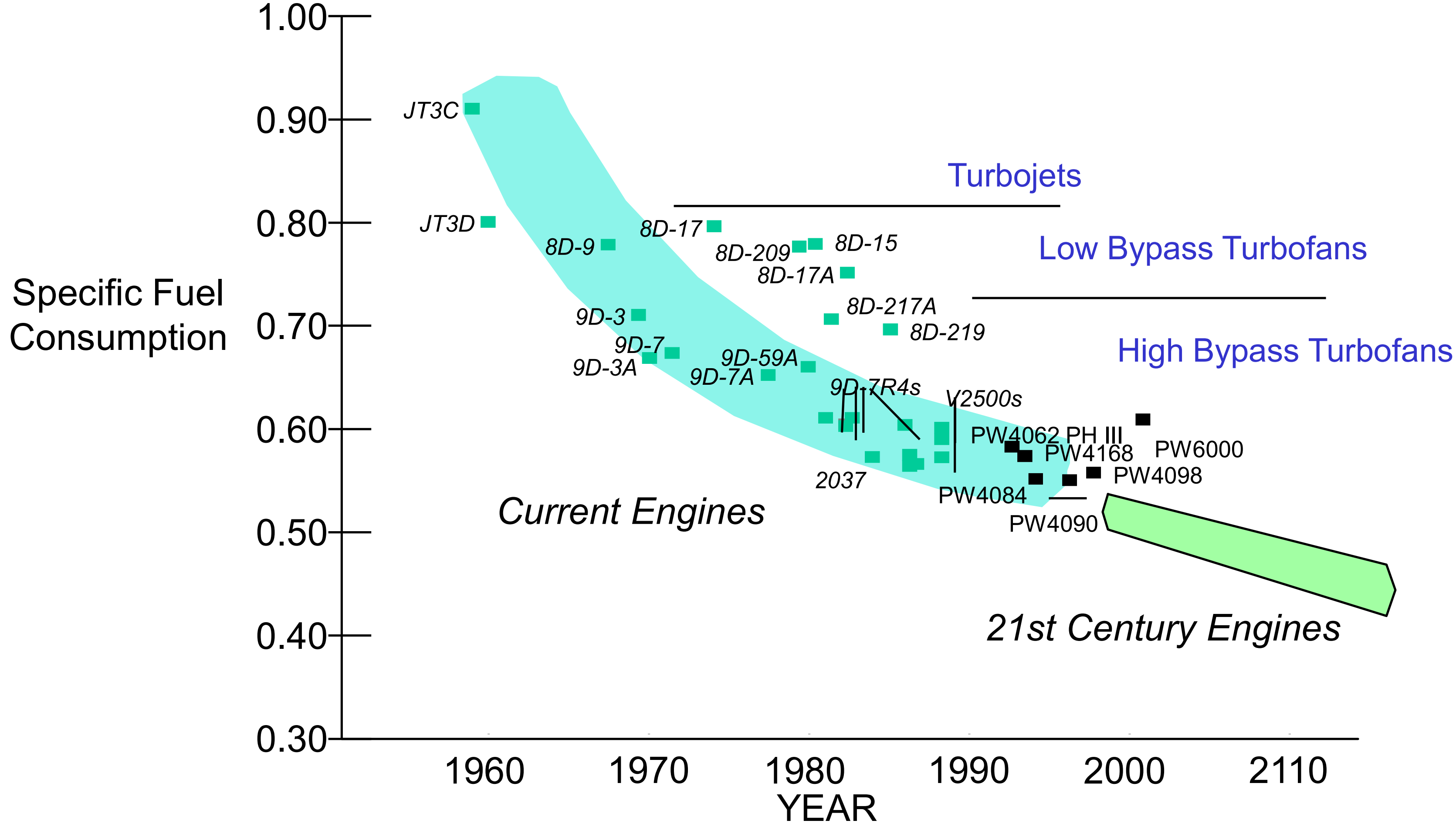
Turbine Engine Core Specific Power

- Turbine core power is the gas horsepower available when expanding isentropically from core exit pressure to core inlet pressure
- Core power is primarily a function of CET
  - There is a cycle OPR providing an optimum power output for a given CET
  - Core power represents the engine thrust potential
- Flow can be expanded through a nozzle to directly produce thrust (i.e. turbojet), extracted by a turbine to produce shaft power (i.e. turboshaft/turboprop application), or 'partially' extracted through a turbine to drive a fan (i.e. turbofan engine)

TRANSPORT ENGINES

Engine Performance Trends

Technology Advances Improve Efficiency



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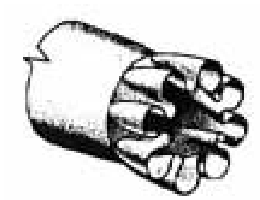
Engine Performance Trends

- Current focus commercial aircraft design and operation is overall economics
  - The primary requirements of transport engine design are to minimize overall 'cost of ownership' and meet increasingly strict noise and emissions regulations
- Thrust requirements generally are set by takeoff requirements at airports significantly above sea level (e.g., Denver) and by desired climb rates
  - Engine size is set by these thrust requirements
  - The engine cycle is chosen to achieve the lowest specific fuel consumption that is achievable by existing technology
- The utilization of technology to achieve reduced specific fuel consumption is illustrated by the performance trend of new engines

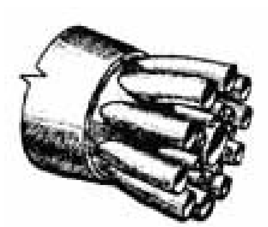
Transport Engines - Noise Reduction

Noise Reduction Advances

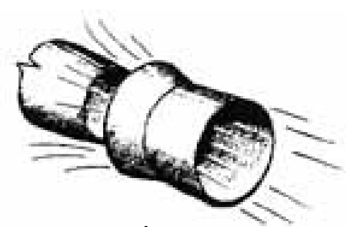
Typical Turbojet
Noise Suppressors



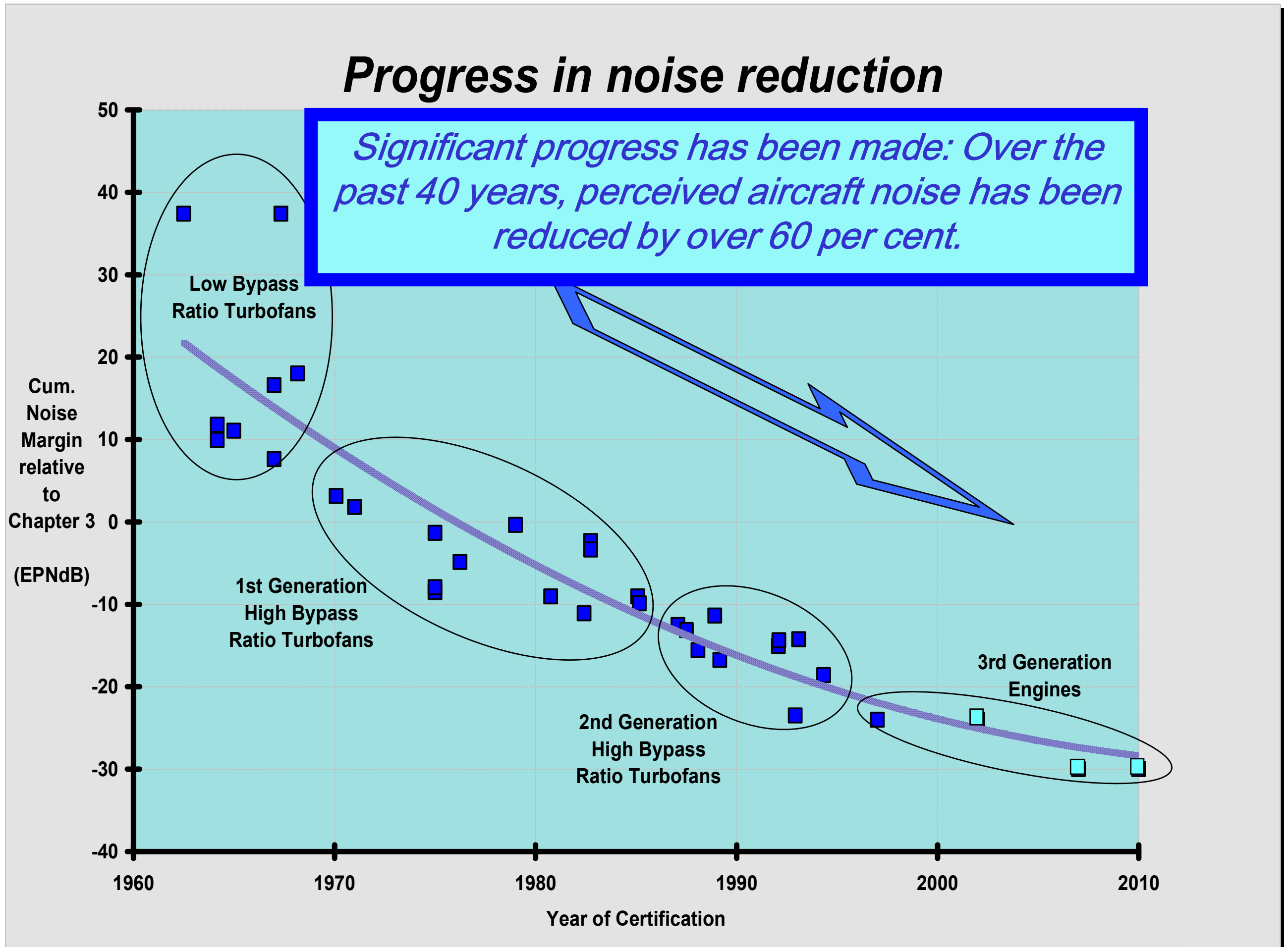
Multi Lobe



Multi Tube



Ejector



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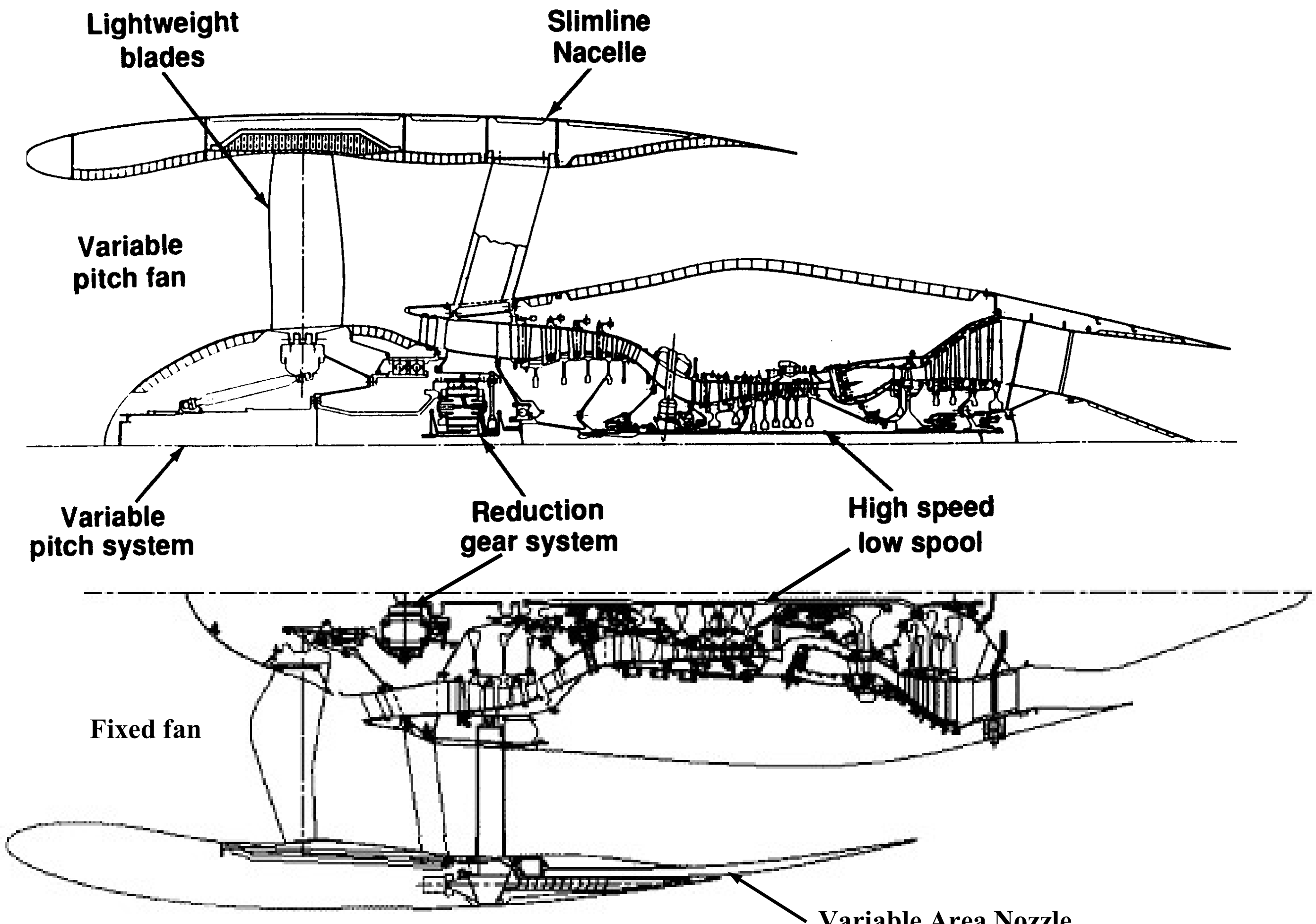
Advanced Transport Engines and Noise

- Overall engine noise has been greatly reduced over the decades
  - Early turbojet engines may have incorporated jet noise suppressors
- The advent of high bypass ratio turbofans has produced lower jet noise due to reduction in overall exhaust jet velocity
  - Advanced turbofan engines are exploring lower fan pressure ratio cycles to achieve further reductions in jet noise
- As the jet noise contribution to total noise is reduced, other noise generating sources such as the fan must be considered
  - Technology focus on detailed engine component design and noise attenuation features will provide a propulsion system with low total noise signature

Advanced Subsonic Propulsion Systems

Ultrahigh Bypass / Geared Fan Turbofan Engine Technologies



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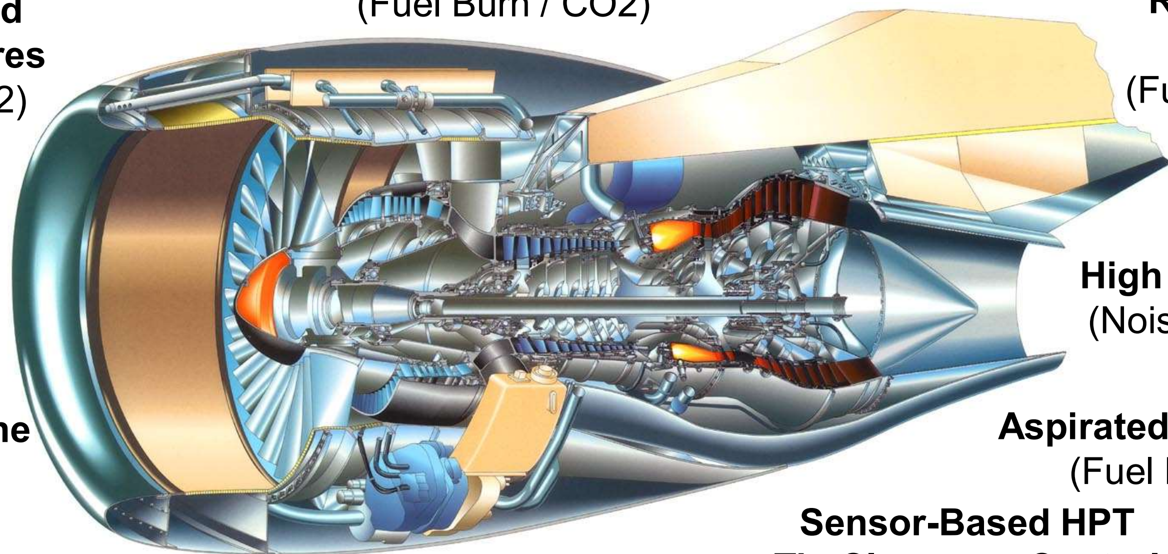
Advanced Subsonic Propulsion Systems

- One approach to solving the technical problems implicit in the continued reduction in Fan Pressure Ratio is the Advanced Ducted Prop (ADP) engine
  - The ADP allows the fan to operate at a lower wheel speed than the fan drive turbine by coupling them through a gear system
  - ADP configurations could incorporate a variable pitch fan, or a fixed fan with a variable area nozzle
  - Both methods allow performance optimization throughout the flight envelope
  - A variable pitch fan system also allows the elimination of the thrust reverser, reducing nacelle diameter and weight

Advanced Turbofan Technology Areas



Low Emissions Combustor
(NOx)

Advanced Thermal Management System
(Fuel Burn / CO2)

Variable Propulsion Cycles
(Fuel Burn/CO2, Emissions / NOx, Affordability)

Composite Cold Section Structures
(Fuel Burn / CO2)

Revolutionary Metallics
(Fuel Burn / CO2)

Common Core
(Affordability)

High BPR Cycles
(Noise, Capacity)

Single Fluid Engine
(Affordability)

Aspirated Aerodynamics
(Fuel Burn / CO2)

Sensor-Based HPT Tip Clearance Control
(Fuel Burn)

Intelligent Controls
(Safety, Affordability)

Ceramic Hot Section Structures
(Fuel Burn / CO2)

All Blisk Compressor
(Affordability)

All-electric Engine
(Fuel Burn / CO2)

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Advanced Technology Concepts

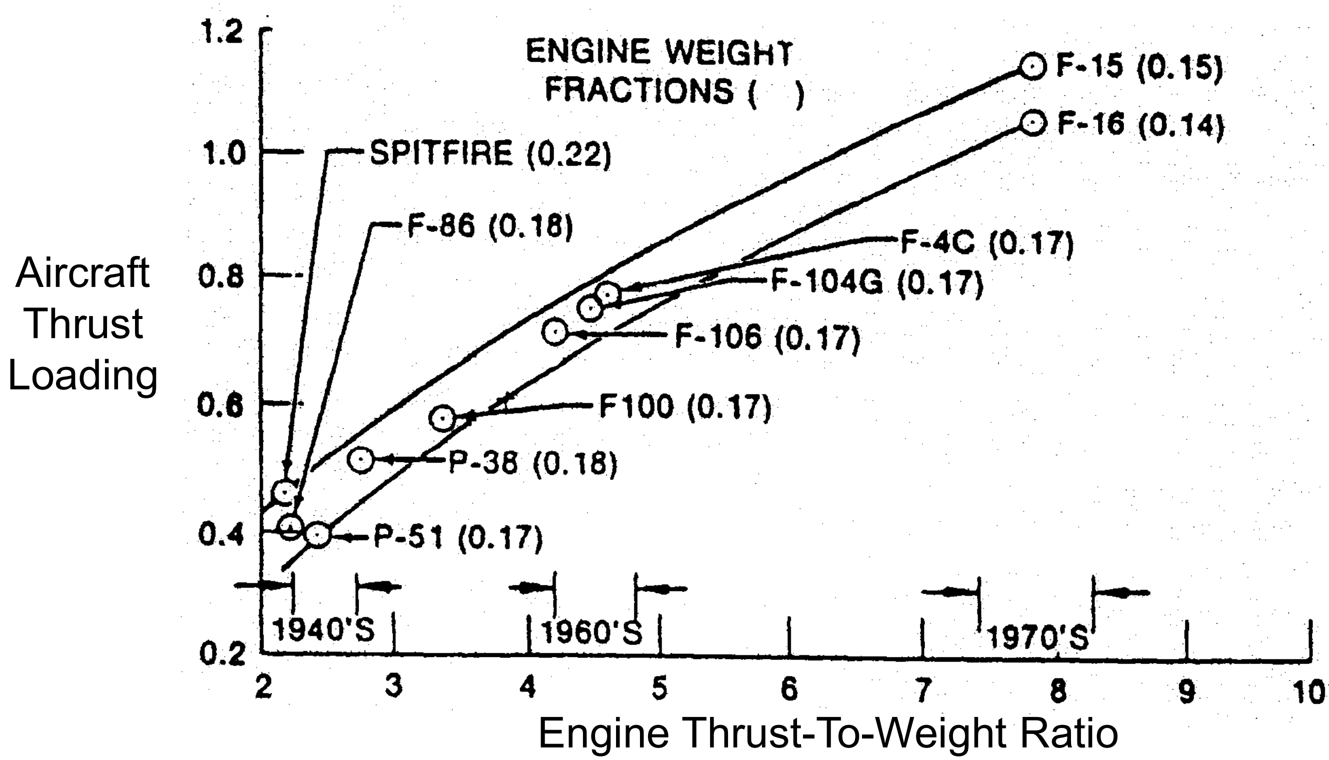
- A broad scope of technology areas are required to develop advanced commercial turbofan engines
- In addition to the continual improvement in turbo-machinery performance, advances in materials, engine controls, and subsystems are necessary

FIGHTER ENGINES

Fighter Aircraft Thrust Loading

- **Increased engine Thrust-to-Weight has provided dramatic improvements in weapon system air combat performance**

$$\text{Aircraft Thrust Loading} = \frac{\text{Engine Thrust}}{\text{Engine Wt}} \times \frac{\text{Engine Wt}}{\text{Aircraft Wt}}$$



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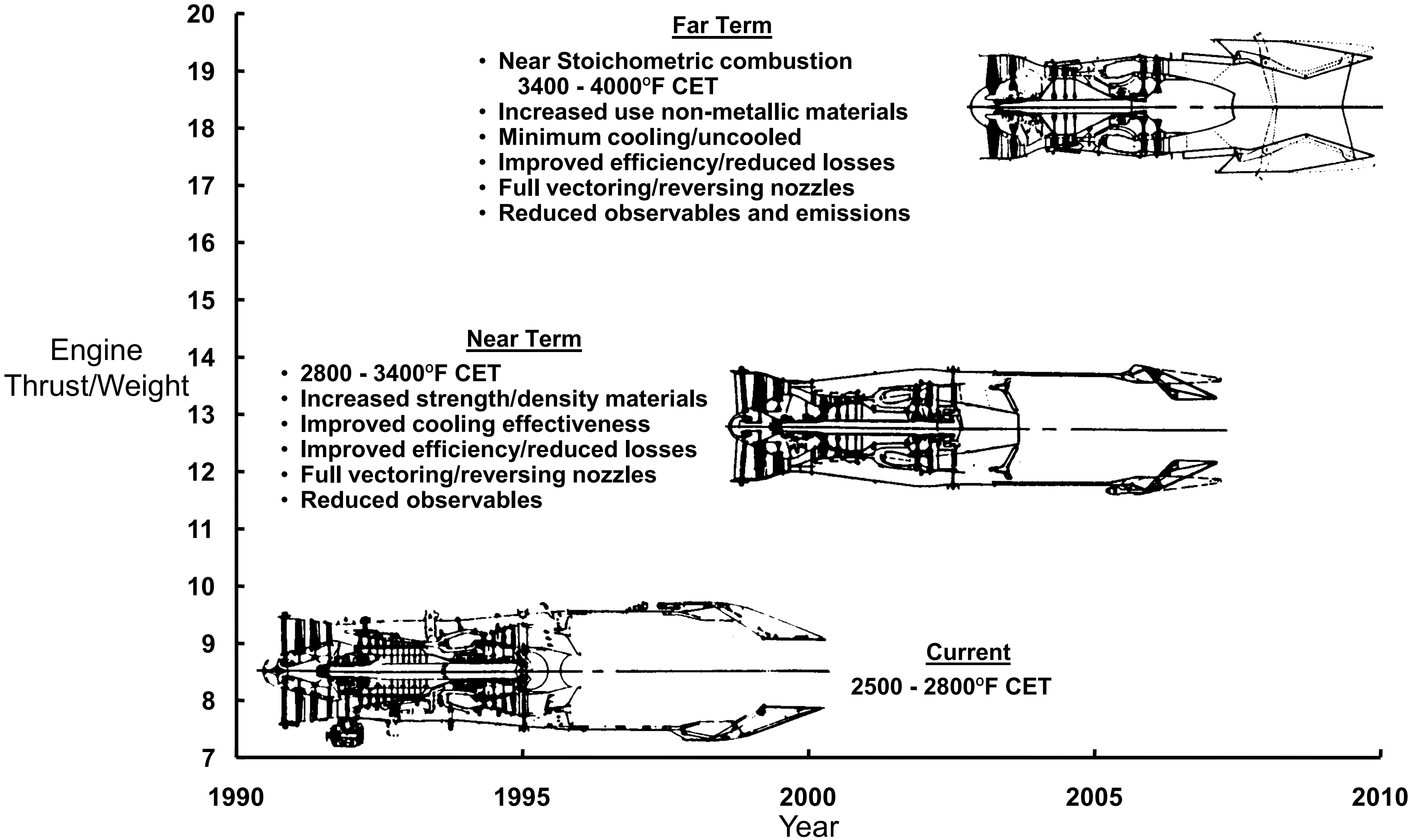
Fighter Aircraft Thrust Loading

- This chart shows how important the engine thrust-to-weight ratio is to aircraft thrust loading
- Aircraft thrust loading is the ratio of the engine's total maximum afterburning takeoff thrust to the takeoff gross weight (TOGW) of the aircraft
  - For example, a 30,000 pound TOGW aircraft with a 30,000 pound thrust engine would have a takeoff thrust loading of 1.0
  - An aircraft with a thrust loading greater than 1.0 could climb vertically after takeoff

Fighter Aircraft Thrust Loading

- The early jet powered aircraft had engines with thrust-to-weight ratios of 2 to 3 and aircraft thrust loadings of 0.4 to 0.5
  - 1960s aircraft such as the F-4 and F-14 had engines with thrust-to-weights of 4 to 5 and achieved aircraft thrust loadings of 0.7 to 0.8
  - 1970s fighters such as the F-15, F-16 and F-18 have engines with thrust-to-weights ratios of 7 to 8 and achieve takeoff thrust loadings of 0.9 to 1.1

Propulsion System Technology Trends



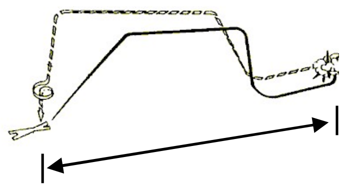
Engine Performance Trends

- The primary goal in fighter engine design is to increase thrust/weight
  - The engine cycle is selected to maximize performance in the vehicle operating envelope which is dependent on the overall mission requirements
- Thrust requirements generally are set by key operating points within the envelope
  - Engine size is set by these thrust requirements
  - The primary technology driver is increasing CET capability

Aircraft Figures Of Merit

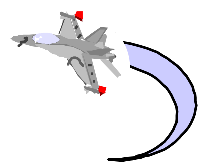
A/C Figure of Merit | ***Engine Driver***

Aircraft Range



– **TSFC**

Aircraft Maneuverability & Performance



Accel time
Turn rate
Rate of climb
Takeoff distance
Hover capability

– **Thrust/Airflow, Weight/Airflow**
⇨ **Thrust/Weight**

Aircraft Weight

$$

"Better" System

$$$ (Lower Weight = Lower Cost)

– **TSFC**
– **Thrust/Airflow, Weight/Airflow**
⇨ **Thrust/Weight**

Aircraft Figures Of Merit

- For current aircraft, the figures of merit to assess the engine benefits are:
  - How far it can fly
  - What is the maneuverability at key flight conditions
- Mission radius may be evaluated on several missions, and each mission probably has its own key maneuver conditions
  - By comparing mission range and maneuverability for different engine options, the relative strengths and weaknesses of each can be identified

Aircraft Figures Of Merit

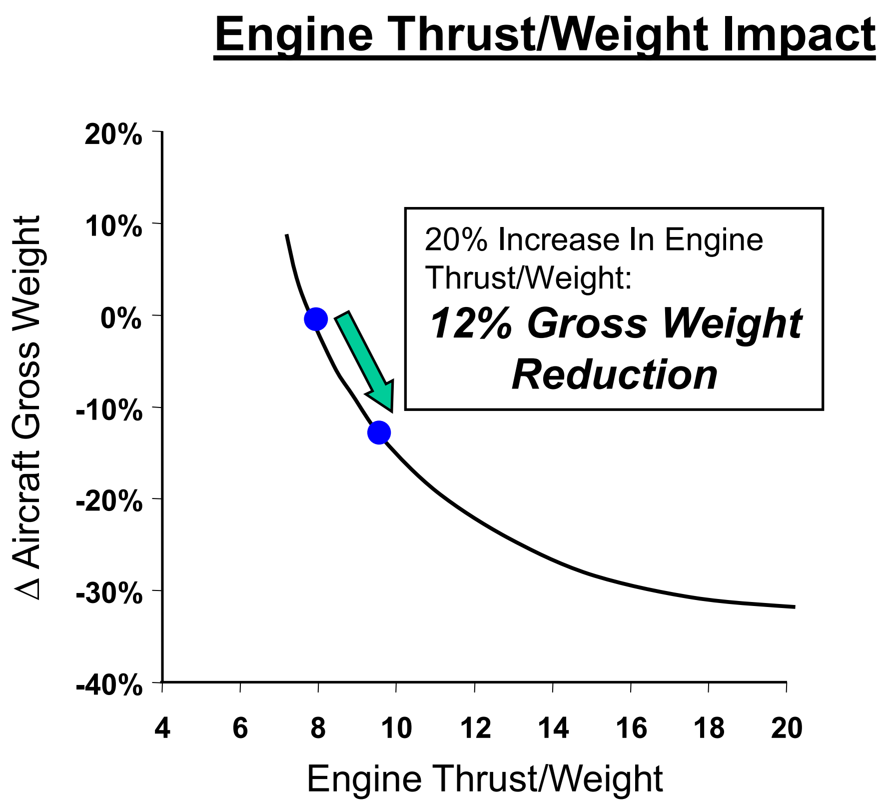
- From the propulsion system standpoint, mission radius is primarily driven by the engine fuel consumption characteristics throughout the mission envelope:
  - High engine thrust/weight is desired to meet military aircraft maneuverability requirements
- Thrust/weight is the specific thrust (thrust/airflow) divided by the specific weight (engine weight/airflow).
  - Therefore an engine with high specific thrust and low specific weight will provide the best maneuverability

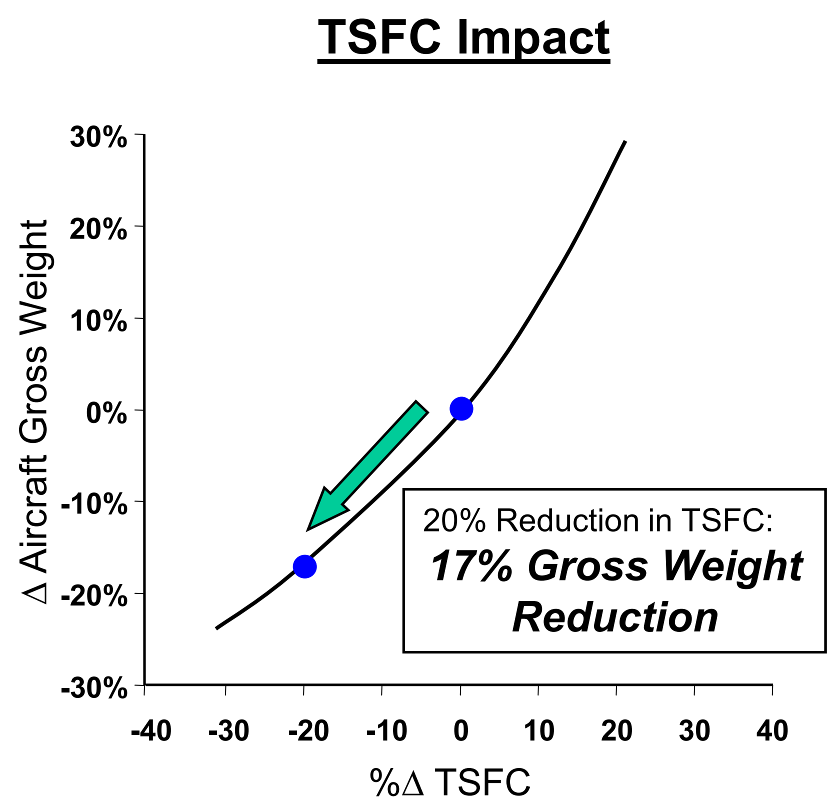
Aircraft Figures Of Merit

- For conceptual aircraft evaluations, the primary figure of merit is usually TOGW which is a good indicator of the relative cost of a system
  - Normally, in a conceptual design, both the aircraft and engine are "rubber", and they can be scaled to provide the smallest aircraft that meets all the aircraft requirements
  - The engine thrust and fuel burn characteristics are both important for reducing TOGW
  - Low TSFC results in reduced mission fuel, and therefore, the aircraft can be smaller and will not need as big an engine
- High engine thrust/weight results in smaller, lighter engines, which will also let the aircraft get smaller, and therefore, need less fuel to fly the mission
  - This synergistic effect from low TSFC and high thrust/weight results in the lowest TOGW

Impact on Aircraft Size

Advanced Fighter Application



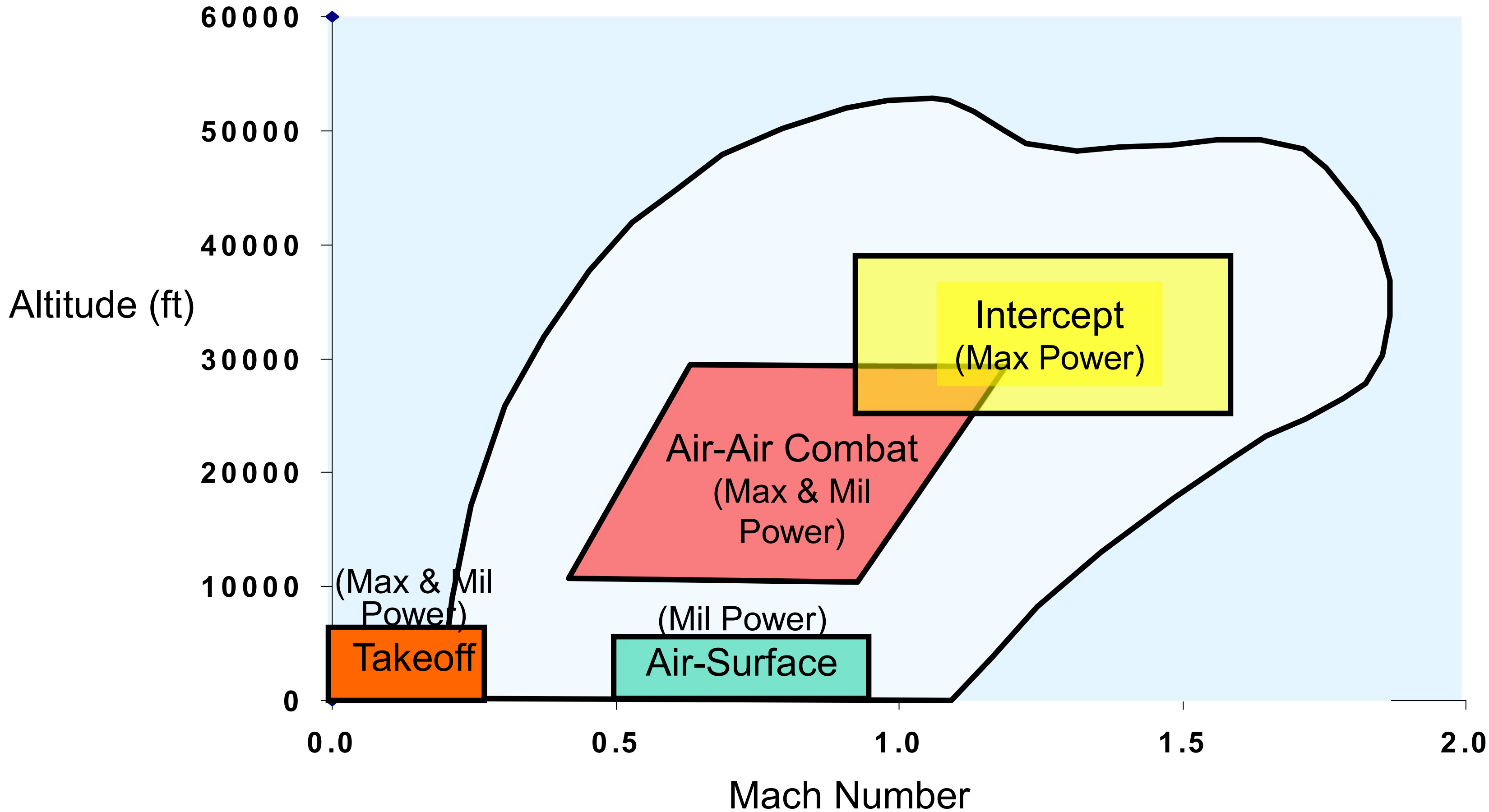


Fighter Aircraft Sensitivities

- The relative sensitivity of an advanced fighter vehicle to engine thrust/weight and TSFC is indicated in the previous figure
- The trend in technology has been to increase CET and FPR to achieve greater thrust/weight with a small improvement in TSFC

Typical Key Mission Areas

Thrust Is Important Here



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Typical Key Mission Areas

- In comparing engines for fighter aircraft evaluation, it is important to recognize the areas of the flight envelope where it is most desired to have superior performance
- The areas illustrated here are generally accepted as the most critical for fighter aircraft
  - Heavily loaded air-to-ground missions are most critical at very low altitudes, especially when the air temperature is high
  - Takeoff distance can be important if the runways have been damaged and/or the need arises to operate out of emergency fields

Typical Key Mission Areas

- The areas illustrated here are generally accepted as the most critical for fighter aircraft
  - During penetration over enemy territory it is important to be able to dash at high speed without the afterburner in order to survive surface-to-air weapons
  - It is also necessary to be able to perform high G maneuvers with minimum speed loss in order to evade missiles and to follow difficult terrain at very low altitudes

Typical Key Mission Areas

- Close-in air-to-air combat (dogfight) with guns and short and medium range missiles will usually occur in the region indicated
  - Here, rapid changes in speed, altitude, and heading are typical, and every second of advantage is important
- High G maneuvers dominate in order to acquire the threat aircraft within the firing cone envelope, followed by rapid accelerations to regain energy
  - Intercept missions require fast acceleration times to high supersonic Mach numbers in order to destroy threat aircraft before they can reach their intended targets
  - Sustained maneuverability is also important at supersonic speeds so that the threat can be acquired within the firing angle without losing speed and becoming vulnerable to other threat aircraft in the vicinity

Specific Excess Power (Ps)

- Ps is measure of the capability of the aircraft to use excess thrust to change its energy state. (i.e.; accelerate, climb or turn). Also known as *Instantaneous Rate of Climb*
  - *NPF* = Net Propulsive Force ("Installed Thrust")

$$P_s = \frac{(NPF) \times Vel}{W_t} \qquad \left(\frac{ft}{sec}\right)$$

- When re-engining an aircraft: $\Delta P_s \approx \dfrac{\Delta NPF \times Vel}{W_t}$

- When comparing two aircraft, +100 ft/sec ΔP_S is considered a significant advantage

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Specific Excess Power (Ps)

- Fighter pilots have always known that management of their aircraft's energy is critical to success. Jet fighter dogfight maneuvers largely rely upon the exchange of potential and kinetic energy to attain a positional advantage
  - The concept of energy management has been analytically developed and applied to aircraft design. Specific excess power (Ps) is one of the most useful figures of merit to be derived from these analyses
- The excess power that the aircraft can use to increase its energy (to climb or accelerate) is the excess thrust (thrust-drag) times the velocity. When divided by the aircraft weight, this becomes the specific excess power

Specific Excess Power (Ps)

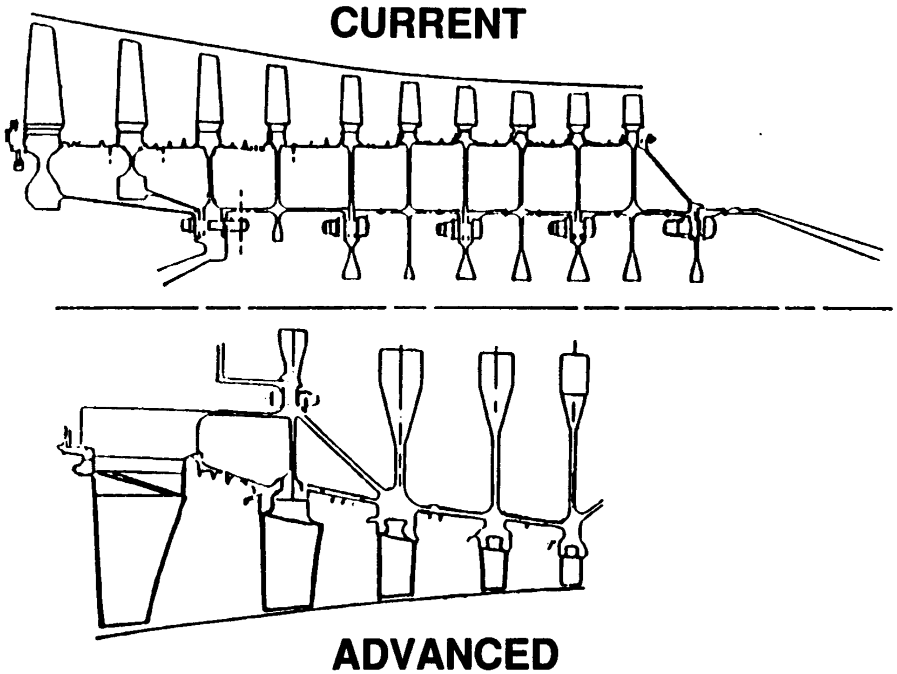
- Ps has the units of feet per second, the same as velocity
  - The Ps at a load factor of one (1 "g") is actually the rate of climb that would be available if the pilot chose to climb at constant velocity
  - Ps = 0 → the engine thrust is equal to the aircraft drag so there is no excess power
    - This means that the aircraft is either flying level at constant speed, climbing and decelerating, or descending and accelerating. In each case the sum of the potential and kinetic energy is a constant
- Ps can also be calculated at a higher load factor than one. The weight term in the Ps equation does not change, but the drag increases as “g” loading increases. The result is a rapid decrease in Ps at high “g”
  - Also, the impact of engine weight on Ps is greater at high "g" loading. The additional lift required to offset an engine weight difference is the load factor ("g") times the delta engine weight. The increased angle of attack required to generate the additional lift can result in large increases in drag

ENGINE TECHNOLOGY TRENDS

Trends in Propulsion System Technologies

Compression System

Requirements	Technologies
High stage loading / fewer airfoils	Low aspect ratio airfoils / increased rotor speeds
Improved efficiency	3D swept airfoils
Reduced weight	High strength-to-density materials / innovative configurations
Reduced observables	RCS technologies



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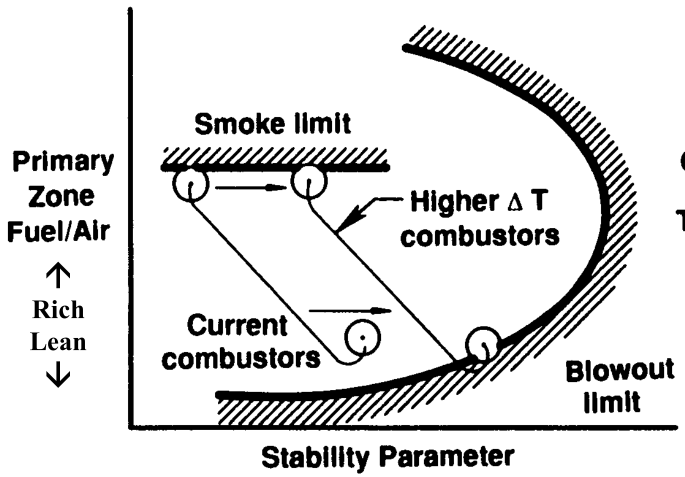
Compression Systems

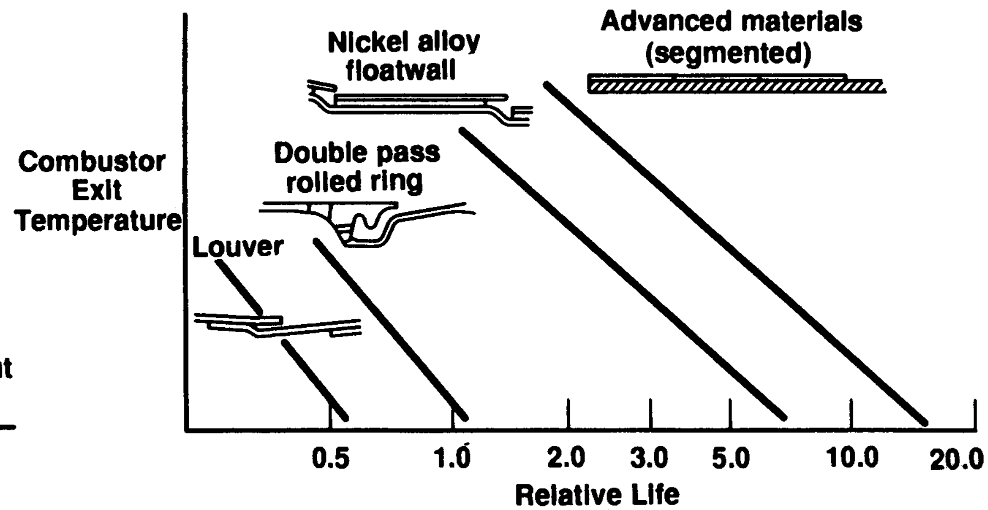
- The trend to increase OPR and thrust/weight requires improvement in fan and compressor systems
  - In addition to advanced airfoil design, the development of integrally bladed rotors (IBR), or BLISKS (bladed disks) can reduce weight & leakage and improve efficiency
  - Similar 3D aero design technology has been applied to large fan design to improve efficiency and reduce noise
  - Advanced materials and hollow-blade design also reduces weight

Trends in Propulsion System Technologies

Combustors

Requirements	Technologies
Reduced section pressure loss	Boundary layer enhancement, improved diffuser design
Improved pattern factor	Improved liner cooling hole design/distribution
Higher temp rise capability	High temp materials for reduced liner cooling
Reduced length & weight	High density fuel injection / advanced materials
Reduced emissions	Innovative combustion chamber design / fuel injection





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Combustors

- Combustors have improved considerably since the early turbines with long individual burner cans, evolving into shorter annular style combustors
- The trend of increasing CET and requirement for reduced emissions to meet current and future standards will require innovative designs

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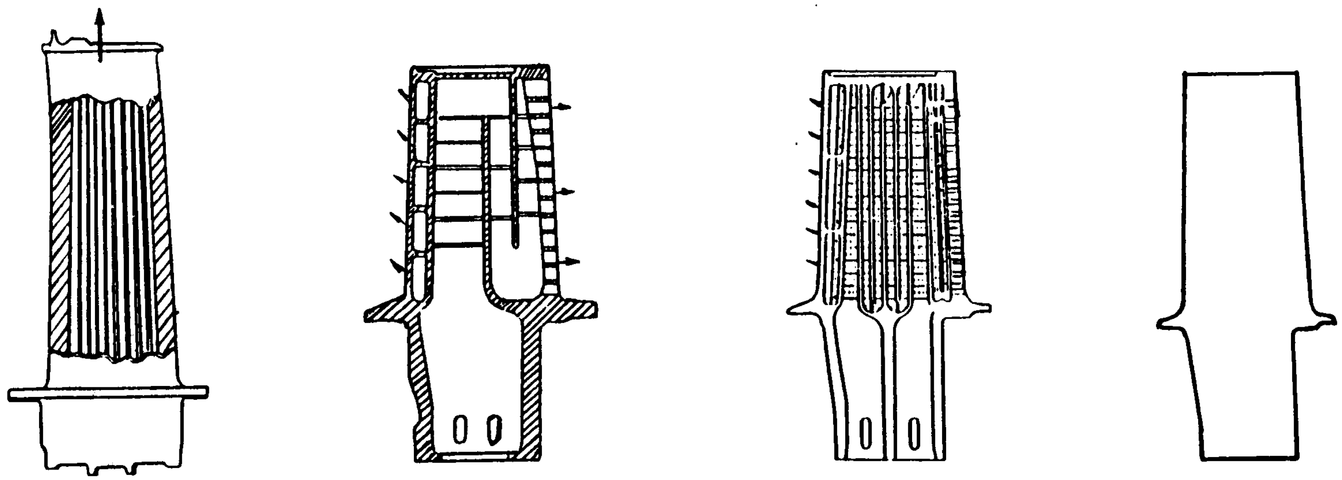
Trends in Propulsion System Technologies

Turbines

Requirements	Technologies
Increased temperature capability	High temp materials / increased cooling effectiveness
High work coefficient	Increased rotor speeds
Improved efficiency	Reduced cooling / 3D swept aero
Reduced weight	High strength-to-density materials / innovative configurations

	1960s	**1970s**	**1980s/1990s**	**Far Term**
Cooling Effectiveness	**Base**	**+130%**	**+150%/190%**	**Uncooled**



1960s	1970s	1980s/1990s	Far Term
• **Simple convection** • **No film**	• **Advanced convection** • **Leading edge film**	• **Multipass convection** • **Full airfoil film** • **Shaped film holes**	• **Nonmetallics** • **High temp materials**

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Advances in Turbine Technologies

- In order to reduce fuel consumption and increase engine thrust-to-weight, higher levels of combustor exit (turbine inlet) temperatures are required
  - Over the last 40 years, improvements in turbine materials and cooling system effectiveness have allowed the high turbine inlet temperature to be increased from 1600°F to 2700°F
  - These increases in turbine temperature provide the core power required to increase bypass ratio for commercial transport engines and to increase fan pressure ratio for military engines
  - In the 1960s simple convection cooling was used and turbine temperatures of 1600°F to 1900°F were used in our engines

Advances in Turbine Technologies

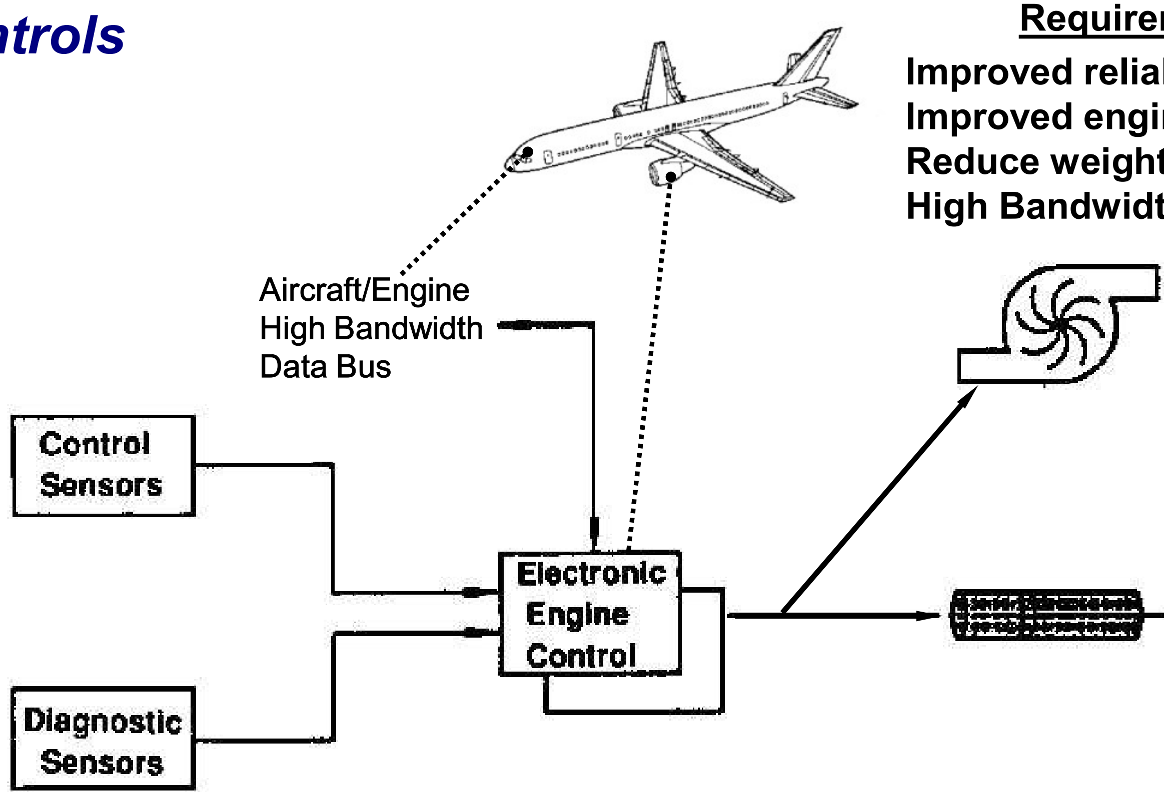
- In the 1970s advanced convection cooling configurations and leading edge film cooling, along with the development of materials with higher metal temperature capabilities, allowed increases of turbine temperatures to 2400°F
- Further improvements in cooling technologies since the 1970s have increased the turbine temperature capability to greater then 3000°F

Trends in Propulsion System Technologies

Controls

Requirements

Improved reliability / cost
Improved engine performance
Reduce weight
High Bandwidth Transmission



Fuel System
- **Centrifugal Pump**
  - **Composites**
  - **High speed**
- **Low Cost Fuel Control**

Actuators
- **Direct drive**
- **High Response**
- **Composites**
- **Electric drive**

Control Electronics
- **High density integrated circuits**
- **Lightweight materials**
- **High Bandwidth Interfaces**
- **Next Generation Digital Electronic Control**
  - **Distributed System**
  - **Smart Sensors/Actuators**

Control Modes and Logic
- **Integrated Subsystems**
- **Expert monitoring**
- **Model Based Control**
- **On-Board Models**
- **Mission Adaptive Modes**

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Engine Control Systems

- Engine control systems have advanced considerably since the early hydro-mechanical devices that used cams and followers
  - Electronic supervisors were added to the hydro-mechanical controllers
  - In the mid-80's, the first digital engine control was introduced, retaining the hydro-mechanical controller as backup
- By the 90's, multiple channel Full Authority Digital Engine Controls (FADEC) were the norm, fully replacing their hydro-mechanical predecessors

Engine Control Systems

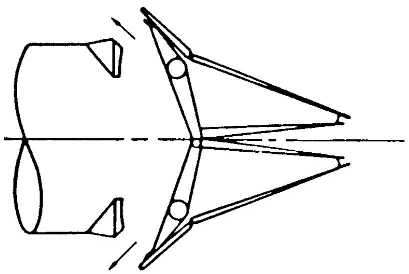
- Future engine control systems are becoming more integrated with the aircraft in terms of both function and information exchanged
  - Advances in computational capability allows sophisticated multi-variable control modes to optimally manage an ever-increasing number engine actuation devices
- High-fidelity engine models and robust sensors are being used to assess engine "health" to identify and isolate problems prior to failure, allowing engine maintenance to be performed based on actual condition rather than by a pre-determined schedule

Trends in Propulsion System Technologies

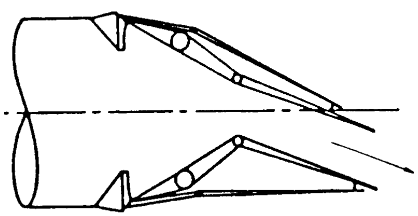
Exhaust Nozzles

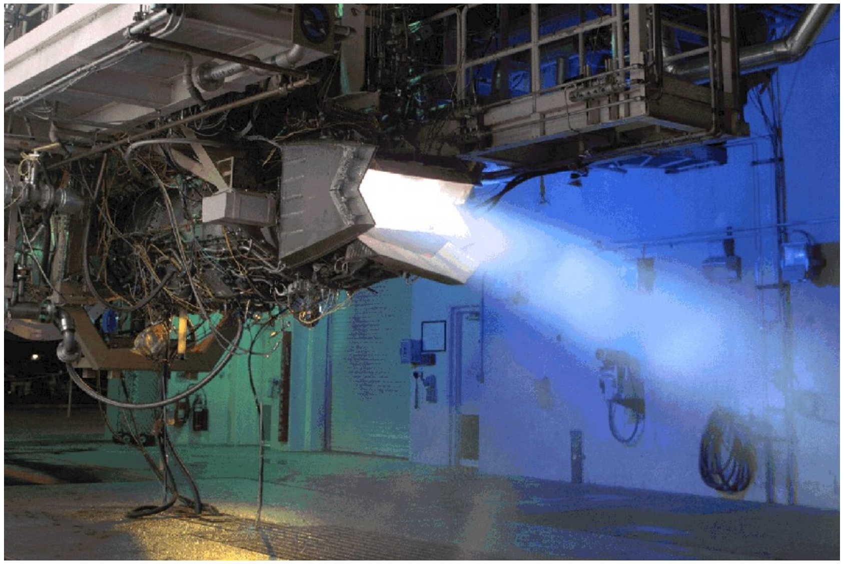
Requirements	Technologies
Multi-function capability	Vectoring / reversing nozzles
Reduced cooling	High temperature materials
Reduced weight	High strength-to-density materials / advanced configurations
Reduced leakage	Improved seal configurations
Reduced Signatures	Unusual geometries / advanced materials

Reverse



Vectored





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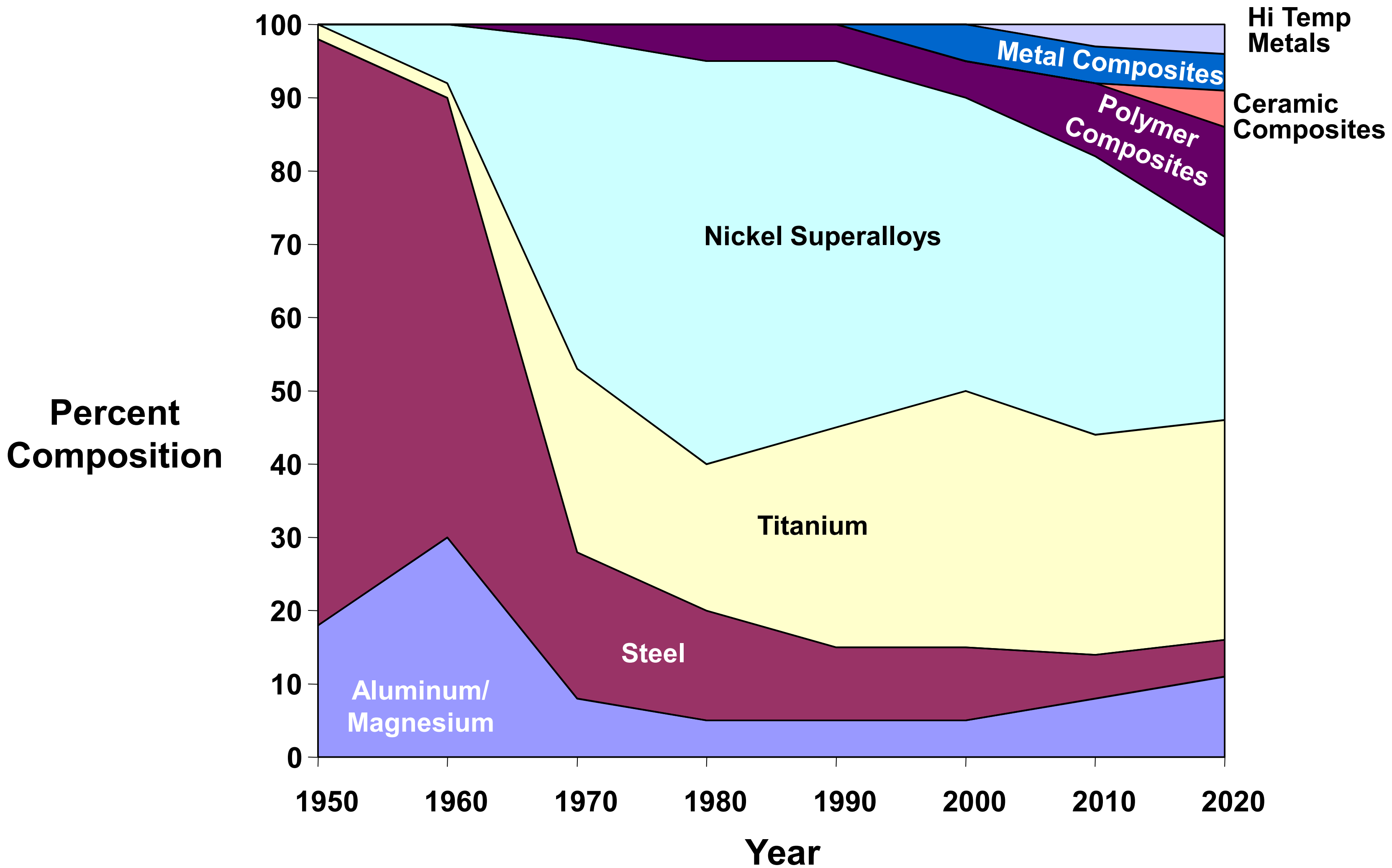
Exhaust Nozzles

- Technology for advanced military engine nozzles has been driven by demand for multi-purpose capability (vectoring, reversing) and reduced signatures (IR & RCS)
- Additionally, vehicle integration and signature requirements have lead to development of non-round exhaust systems

Trends in Material Composition



Engine Materials

- The high temperatures and stresses in turbine engines require capable materials
- Early use of steel alloys gave way to titanium and nickel alloys in the 70s & 80s
- Technology trends indicate continued development of metal alloys and increased use of composites and non-metallics

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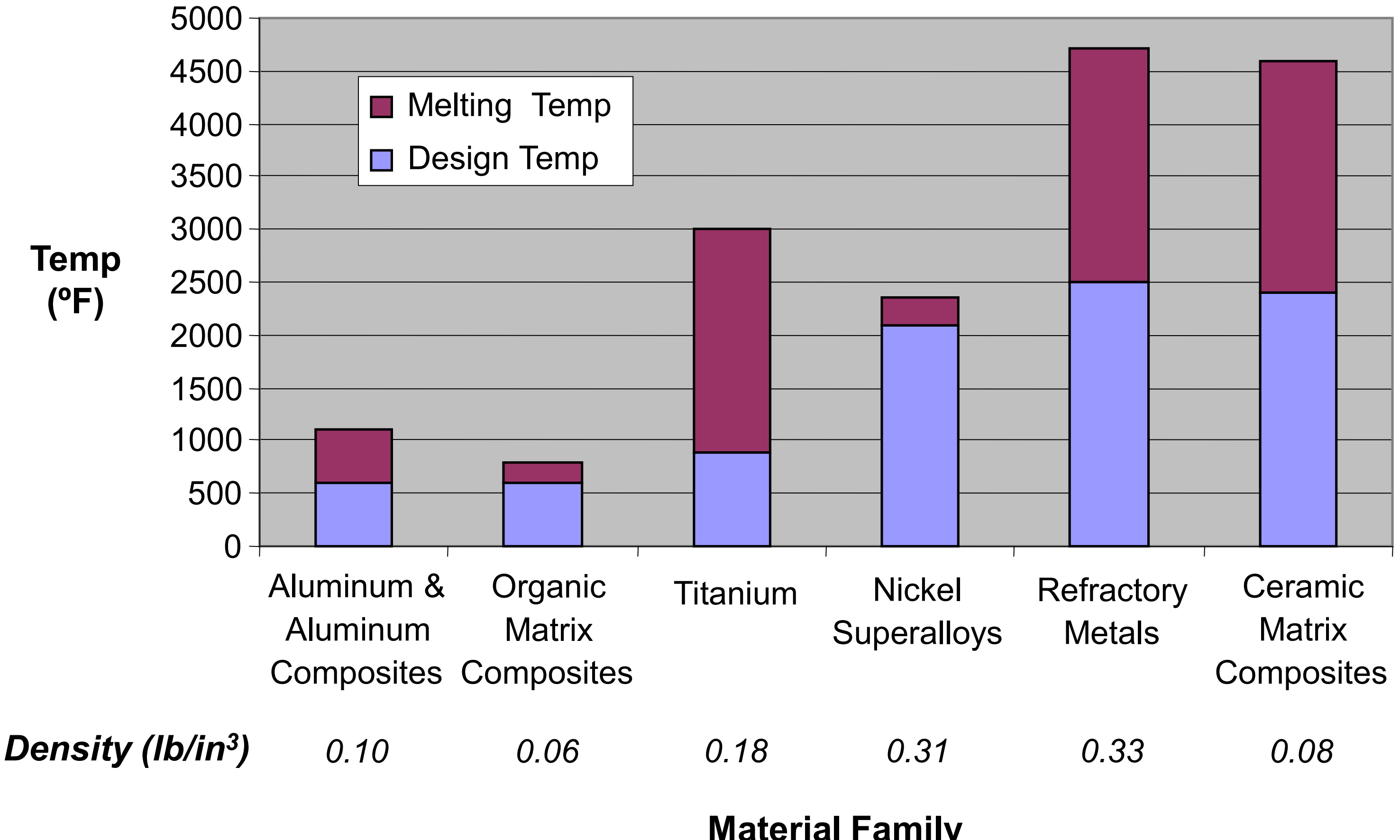
Design Temperature Levels of Jet Engine Materials



Material Properties

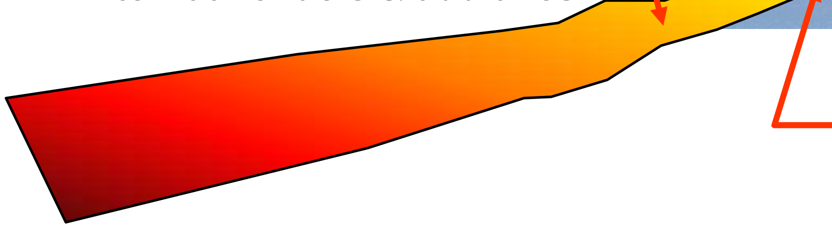
- The high operating temperatures in turbine engines may be above the design temperatures of many materials
- Technology trends are focused on improving metal alloys and developing non-metallics with good structural properties at high operating temperature

Observables - Infrared (IR)

Plume and Hot Parts Drive the IR Signature

Plume
- Temperature (T^4 to T^6)
- Size
- Species concentration
- Visible in both forward & aft hemispheres

Approach to Solution
- Reduce temperatures
- Change species concentration
  - Alternative fuels & additives



Hot Parts
- Skin temperature (T^4 to T^6)
- Skin emissivity
- Species concentration
- Visible in aft hemisphere only

Approach to Solution
- Cooling
- Emissivity coatings
- Masking

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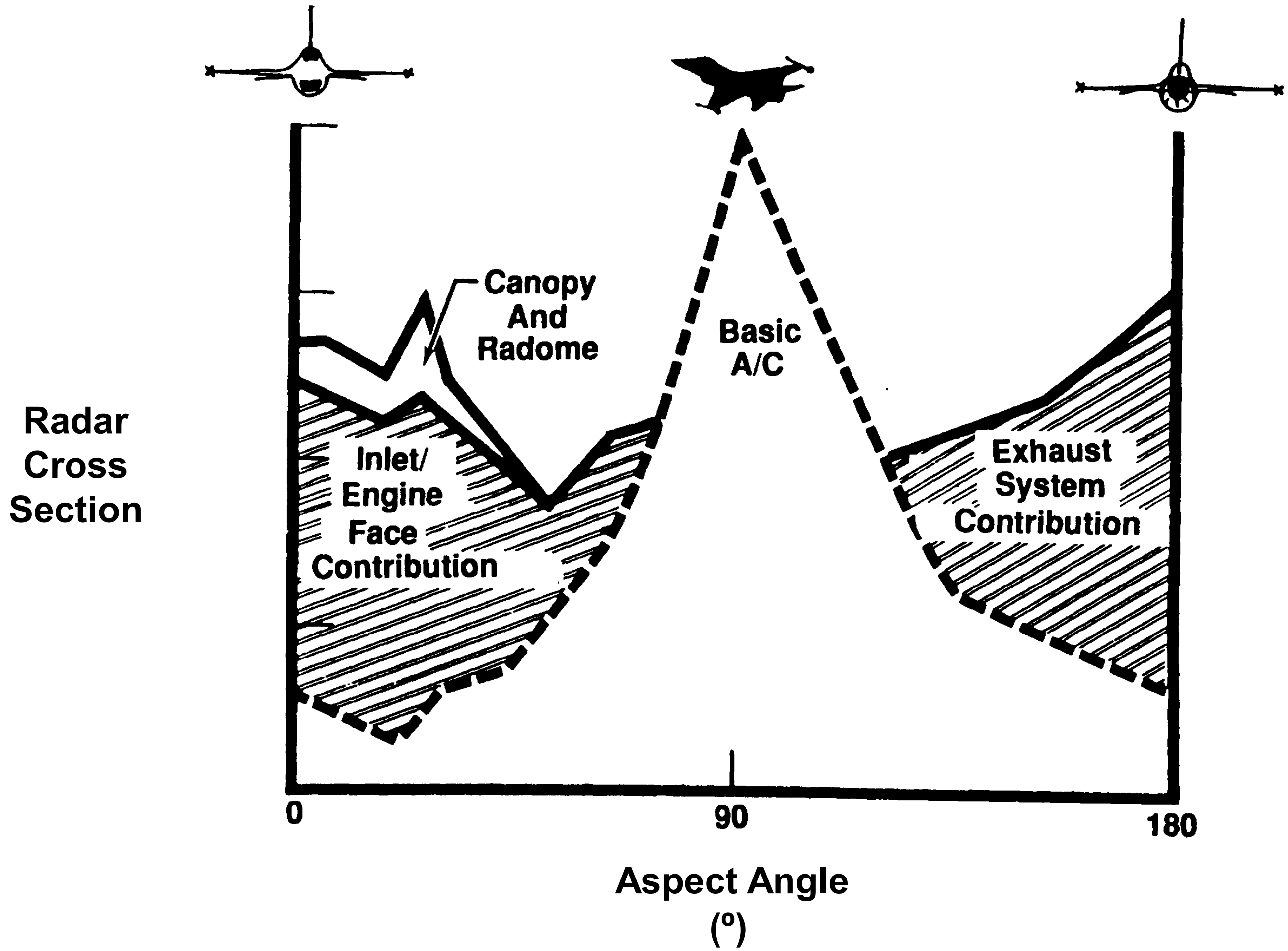
Observables - Infrared (IR)

- Aircraft observables are an increasing concern to military and even commercial operators
- The engine creates a significant infrared signature (IR) from the exhaust plume and hot parts
  - Advanced technology addresses means to reduce or mask IR signature
- An additional consideration is visual signature, i.e. contrails produced by the engine exhaust
  - Technology addresses methods to eliminate or control contrail formation

Observables - Radar Cross Section (RCS)

Propulsion System Is Major RCS Contributor



Observables Consideration - RCS

- Aircraft Radar Cross section (RCS) signature has become an important design consideration for military aircraft
- The engine inlet/fan face and nozzle are significant contributors to overall vehicle RCS
- Reducing vehicle RCS requires a high level of aircraft/propulsion system integration and is a factor affecting engine cycle selection

Summary

Turbine Engine Technology Focus Areas

Commercial Focus

- Noise
- Emissions
- Cost of Ownership
- Fuel Burn

Technology Development Programs - UEET / QAT

Military Focus

- Thrust/Weight
- Observables
- Vehicle Integration
- Supportability

Technology Development Programs - IHPTET & VAATE

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80 Years of Aero Propulsion Progress

Commercial

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80 Years of Aero Propulsion Progress

Military

The National Aeronautic Association's (NAA)
Robert J. Collier Trophy
1952 - P&W J57 turbojet engine
2001 - P&W F135 Integrated Lift Fan Propulsion System

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