Brief Tutorial on Aircraft Propulsion

GMU SYST 460/560

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Overview

- **One of the most sophisticated of modern engineering designs**
- **Requires an understanding of Thermodynamics, Heat Transfer, Fluid Mechanics, Mechanics of Materials**
- **Designs have evolved from Prop to Jet, to Turbojet, Turboprop, High Bypass Ratio Fan Jet engines**

Archimedes of Syracuse (c.287-212 BCE)

- **Sum of the Forces F = 0**
- **Sum of the Moments (F x L) = 0**
- **Buoyancy force = weight of displaced fluid**
- **First Description of the Screw Propeller**
- **Foundation for Lighter than Air Flight in 18th cent.**
- Pi: *"The ratio of the circumference of any circle to its diameter is less than 3 1/7 but greater than 3 10/71."* – calculus like derivation
- **Great Mathematician and Military Engineer killed in 2nd Punic War**

Leonardo da Vinci (c. 1452-1519 CE)

- **Self Educated**
- **Continuity Equation**
  - **$A_1 v_1 = A_2 v_2$.**
- **Precursor to "Conservation of Mass" and Bernoulli Equation in the 18th century**
- **Artist and Military Engineer**
- **Designs poorly documented**
- **Art works better known**
- **Conceptual Designs of Winged Gliders**

Robert Boyle (1627-1691 CE)

- **pV= constant**
- **addition of temperature (T) in Charles's law**
  - **pV/T=constant** (Gas Law)
- **Thermodynamic Equation of State**
  - **Used in Mechanical , Aerospace and Chemical Engineering**
- **Fundamental to understanding Brayton Cycle**
- **Foundation for Lighter than Air flight in 18th century**

Isaac Newton (1642-1727 CE)

- **Great Mathematician, Physicist**
  - **Vector Calculus**
- **Law of Gravity**
- **Vector Relationships**
- **Conservation of Momentum**
- $m\underline{v}$ **= constant**
- $\underline{F} = m\underline{a} = d(m\underline{v})/dt$
- **Sigma** $\underline{F} = 0$
- ***“If I have seen further, it is by standing on the shoulders of Giants”***

Gottfried Wilhelm Leibniz (1646-1716 CE)

- **Great Statesman, Mathematician, Physicist**
  - **Calculus**
- **Altitude + *Vis Viva (mv^2)* = Constant**
- **Today, we state this as the:**
  - **"Law of Conservation of Energy" for solid bodies:**
  - **Potential Energy + Kinetic Energy = Constant**

Daniel Bernoulli (1700-1782 CE)

- **Recognized Leibniz *vis vita* applied to fluid motion as well**
- **Medical experimentalist and Mathematician**
- **Pressure + *rho* v^2 = Constant**
  - **Where *rho* is the fluid density and *v* is the fluid velocity magnitude (along a streamline).**
- **Simple Equation to calculate both Airfoil Lift and Propeller/Fan Thrust**

Rudolf Julius Emanuel Clausius (1822-1888)

- **The net change in the total energy of the universe is zero – 1st Law of Thermodynamics**
- **For a thermodynamic cycle, the net heat supplied to the system equals the net work done by the system.**
- **Carnot efficiency = 1 – Low Absolute Temperature/High Absolute Temperature <100%**
- **The net change in the total entropy of the universe is always greater than zero – 2nd Law of Thermodynamics**
  - **Temperature is a Measure of Entropy in a Heat Engine**
  - **d (Q) = T d(S)**
- ***Perpetual Motion Machine is impossible and the Universe is running down, Information order decays***

John Barber (1734-1801)
George Brayton (1830-1892)
Frank Whittle (1907-1996)

- **John Barber- UK pat. No. 1833 gas turbine engine**
  - **Materials inadequate to construction & operation**
- **George Brayton – US pat. (1872) constant pressure combustion thermodynamic cycle**
  - **Lost ground trans. Competition to Otto Cycle**
- **Air Commodore Sir Frank Whittle (RAF)**
  - **pat. (1930) Turbojet engine**
  - **Ranked by BBC poll #42 of 100 Greatest Britons**

Fundamental Attributes of All Aircraft Designs

- **Aero 101:**
  - **If it Fly's, It weights TOO MUCH!**

- **Wright Bros Major Accomplishment:**
  - **Designed a System with Adequate Thrust to Drag ratio, Low weight with Adequate Structural Strength, Wings with Adequate Lift to Weight ratio and a Stable Flight Control system**

Some Energy Density Comps

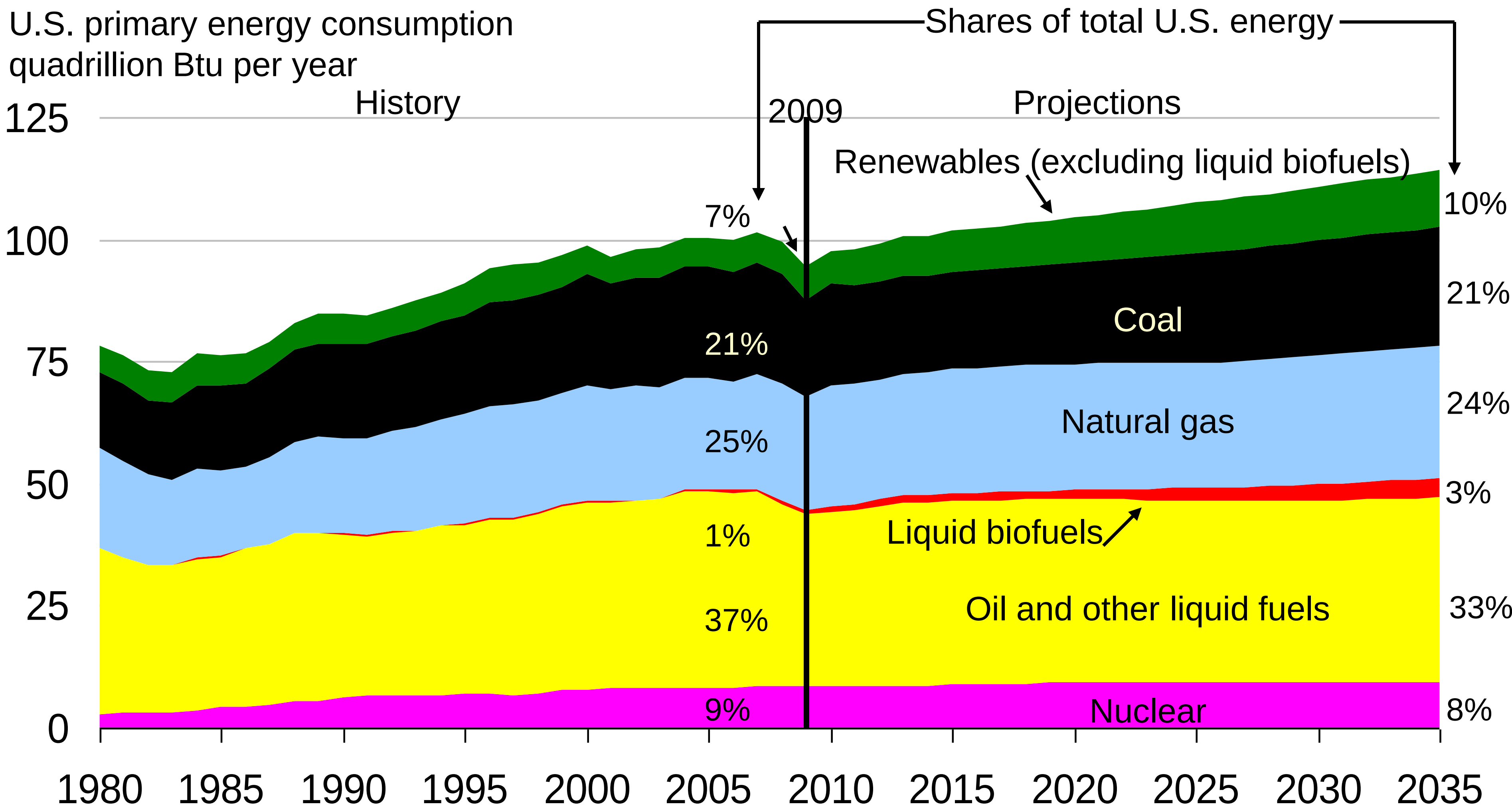
Energy Storage Medium	Energy Density (KW-Hr/Lb)
Lead-acid Auto Battery	0.016
CNG (CH_4)	1.3
Gasoline (C_8H_{18})	5.3
Diesel (Kerosene or JetA) ($C_{12}H_{26}$)	5.8

TNT =0.34

Natural Gas = CH_4 can be chained as (C_nH_{2n+2})

$$2 C_8H_{18} + 25 O_2 = 18 H_2O + 16 CO_2 + \text{ENERGY}$$

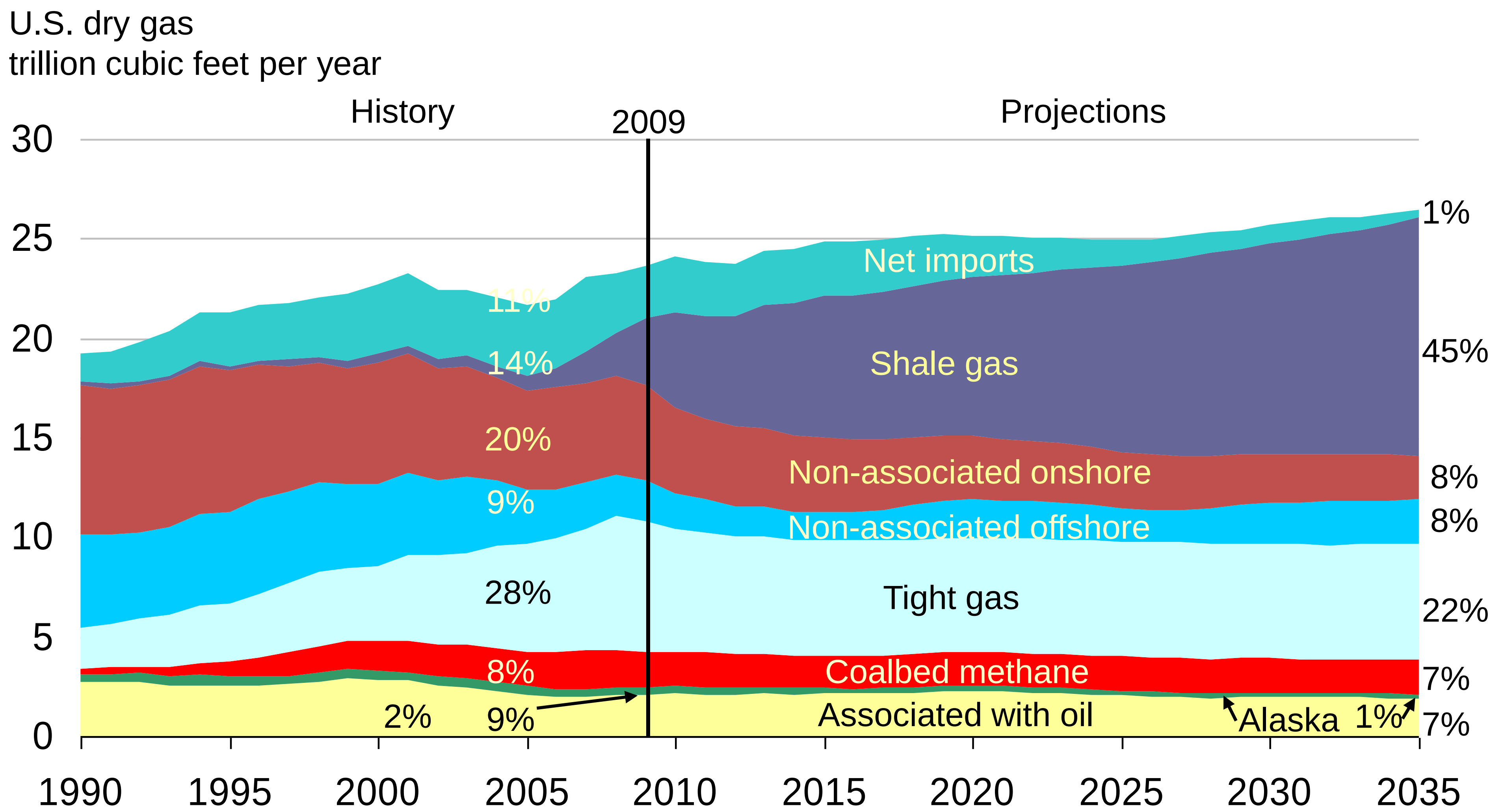
Prediction: Renewables grow rapidly, but under current policies fossil fuels still provide 78% of U.S. energy use in 2035



Richard Newell, December 16, 2010

Source: EIA, *Annual Energy Outlook 2011*

Shale gas offsets declines in other U.S. supply to meet consumption growth and lower import needs



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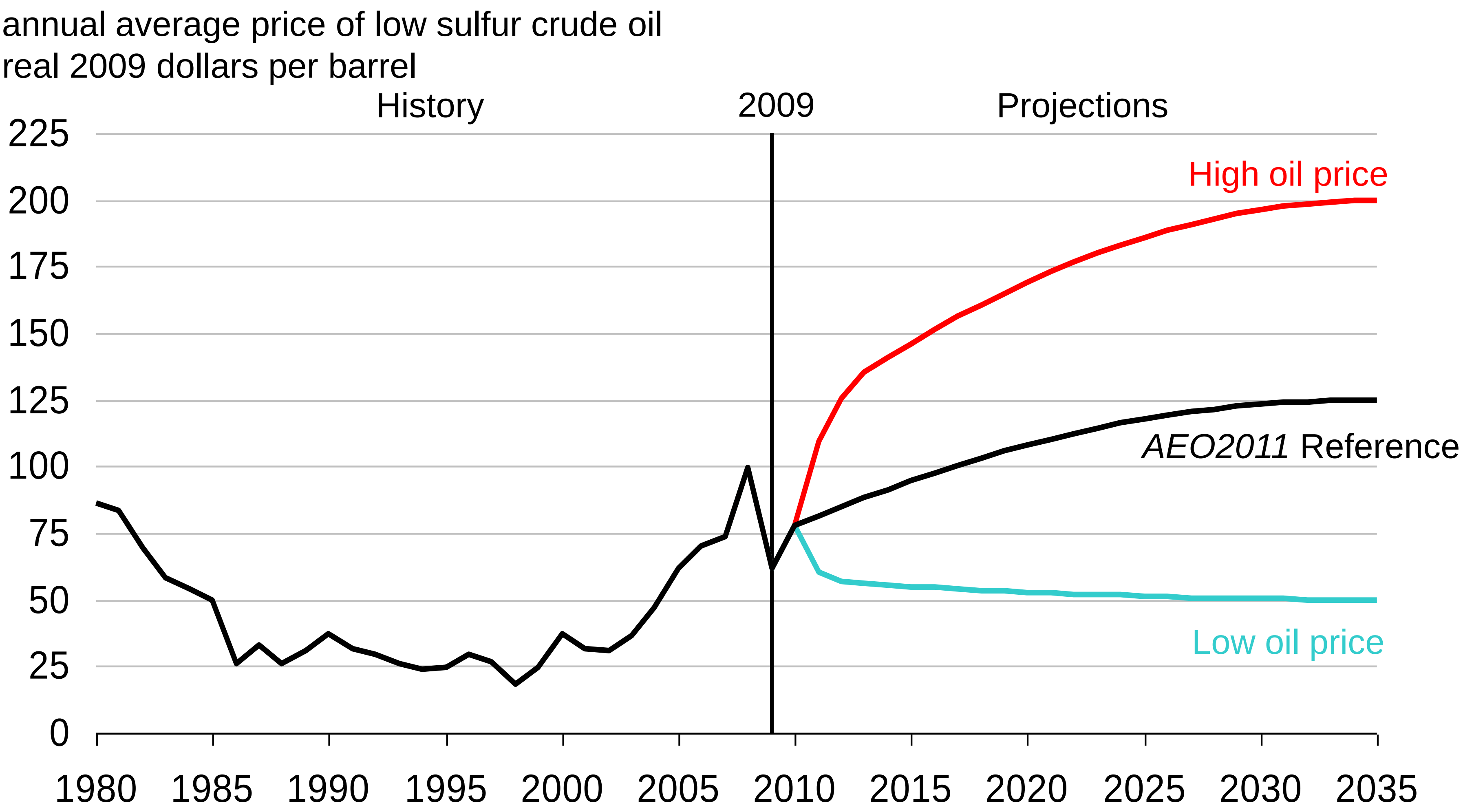
Source: EIA, *Annual Energy Outlook 2011*

Oil prices in the *AEO2011* Report Reference Case rise steadily



Source: EIA, *Annual Energy Outlook 2011*

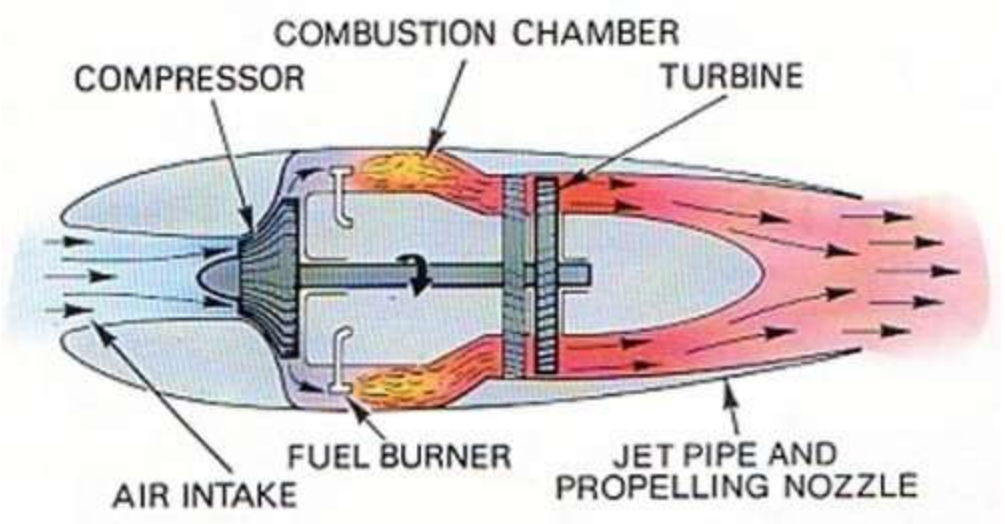
Turbo Jet Fundamental Operating Principles

- **Suck -Air Intake**
- **Squeeze -Cool Axial Compression (Work In)**
- **Bang -Fuel + Combustion (Heat In)**
- **Blow -Hot Turbine to Extract (work Out)**

- **Thrust = $d(m\underline{v})/dt$**

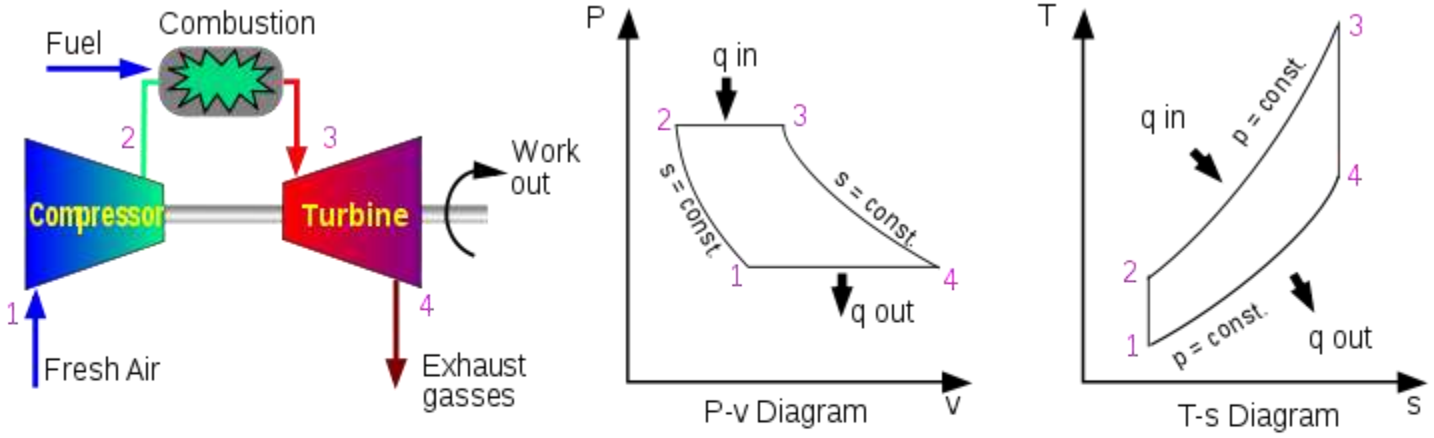
Basic Axial Flow Turbo Jet Engine

- **Low Mass Flow, High Exit velocity (~3:1)**
- **Low Efficiency**



Brayton Cycle Thermodynamics

Actual Brayton cycle:
•adiabatic process - compression.
•isobaric process - heat addition.
•adiabatic process - expansion.
•isobaric process - heat rejection.

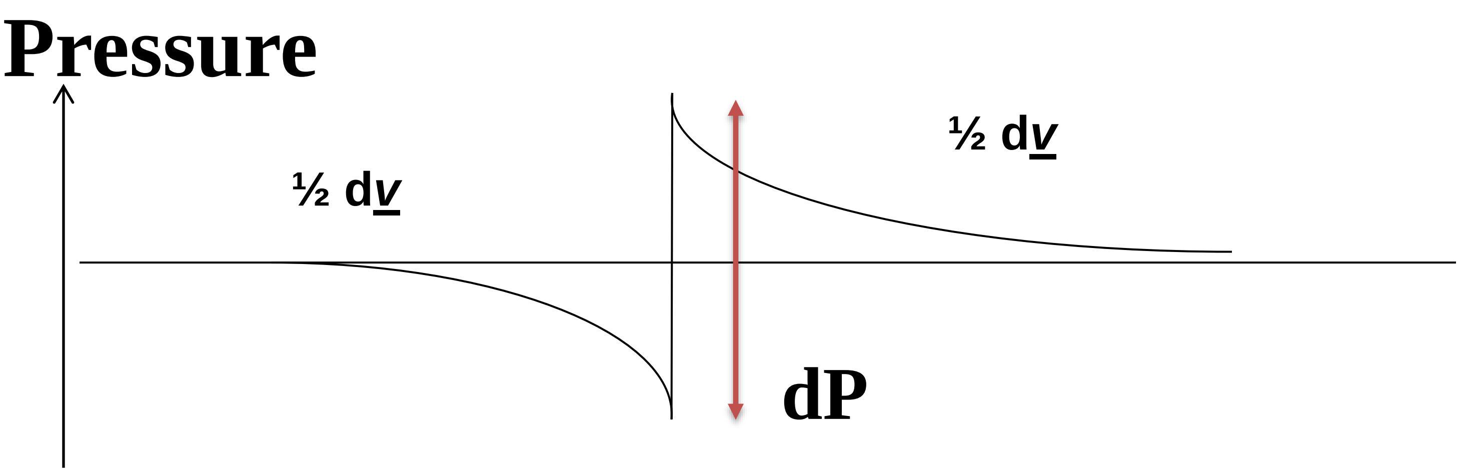


Idealized Brayton cycle

Carnot Eff. = $1 - T_{low} / T_{high}$

Fan/Prop. Thrust & Power

- **Conservation of Energy – Bernoulli Equ. To find Pressure and Velocity Before & After Prop or Fan**
- **Thrust Force = $d(m\underline{v})/dt$**
- **Useful Power = F_{Thrust} * Velocity=$d(m\underline{v})/dt * \underline{v}$**
- **Power Input = $dm/dt*\underline{v}*d\underline{v}\ [\ 1 - d\underline{v}/2\underline{v}\ ]$**



Fuel + Heat = <u>Work</u> + Waste Heat

Est. of Max efficiency

- Brayton Cycle Thermal (Carnot) Efficiency
- $= 1 - T_{low}/T_{high}$ = 1-300K(80F)/1500K(2240F) ~ 80% max
  - Increase Turbine Inlet Temp to Increase efficiency
  - Material Properties Limitation
- Fan (Prop) Propulsive Efficiency = Power Out/Power In

  $= 1 - d\underline{v}/2\underline{v}$ ~ 80% max
  - Where Advance ratio (J) = $\underline{v}/nD$ ~ 0.9
  - D = Prop Disc Diameter
  - Bernoulli Equation (const. energy analysis along an accel. streamline)
- Max Thrust at High d$\underline{v}$
- Max Efficiency at LOW d$\underline{v}$
- Increase Mass Flow at Minimum d$\underline{v}$ to Increase Thrust @ min. Wake Loss
- Combined Efficiency = Prop Eff. X Thermal Eff.

  ~ 0.8 X 0.8 ~ 0.64 MAX

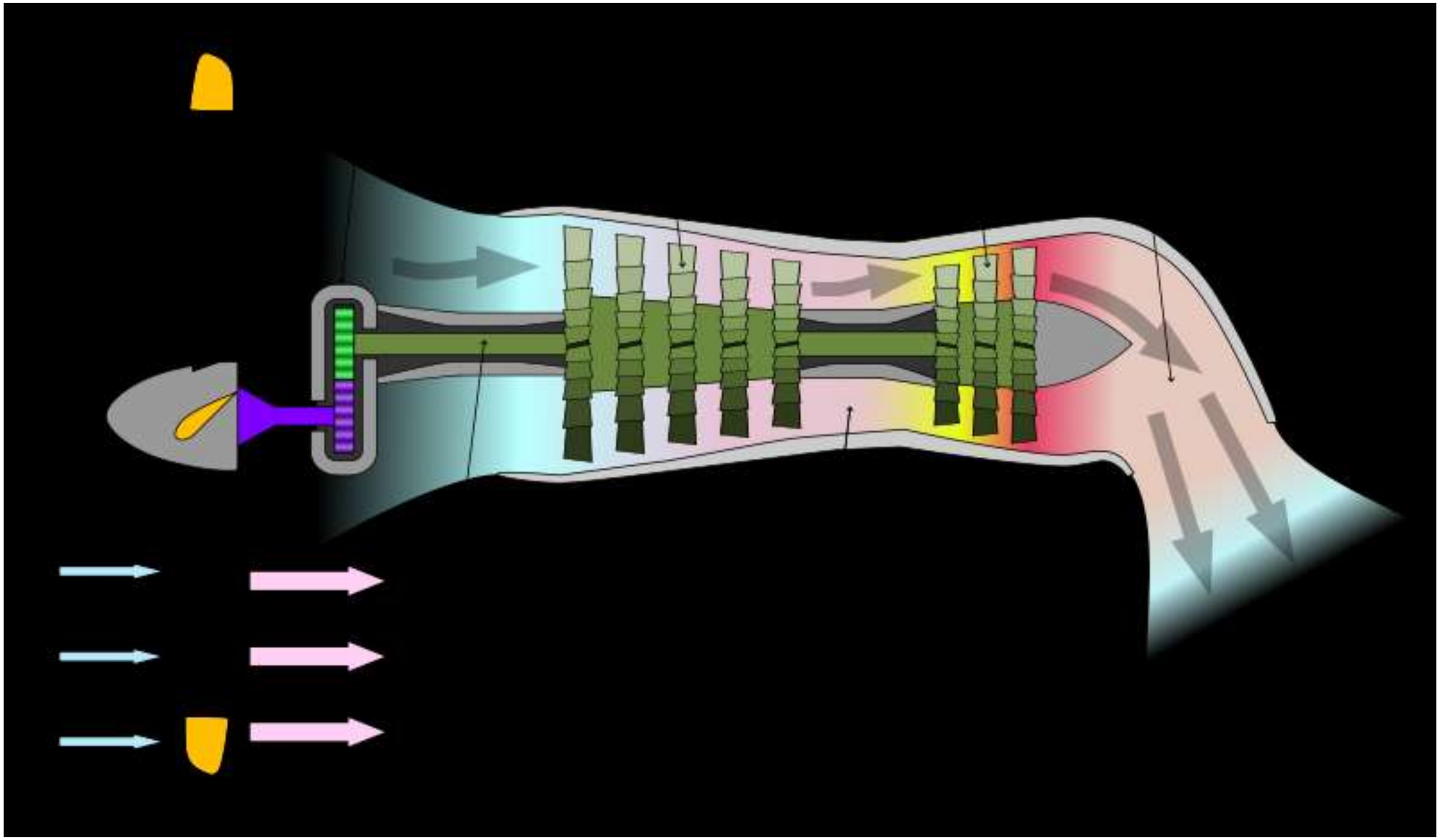
Constraints

- Prop/Fan Diameter
  - Tip Speed less than M1.0 (Noise/Drag)
- Advance Ratio (J)
  - Too High leads to Compressor Blade Stall
- Turbine Inlet Temperature
  - Too high leads to loss of Blade material strength
    - Active Cooling, Titanium, Ceramics

Specific fuel Consumption
Lb Fuel/Hr/ Lb. Thrust

- **Turboprop = SFC ~ 0.5 * *v*/550* prop. Eff (per shp)**
  - **Prop. Eff. ~ 0.8**
  - ***V* (ft/sec)**
  - **d*v*~1.5:1**
  - **SFC @ 550 ft/sec ~ 0.40 / Hr. @~M0.7**
- **Jets @ cruise = SFC ~ 0.9e^(-0.05BPR) : 0 <BPR<6.0**
  - **Turbojet (d*v*~3:1) ~ 0.9 lb fuel/hr / lb Thrust**
  - **LBPR Turbofan (BPR ~6)~ 0.67 lb fuel/hr / lb Thrust**
  - **HBPR Turbofan (~BPR 9:1) ~ 0.57 lb fuel/hr/ lb Thrust**
- **Max Combustion Efficiency @ "stoichiometric"**
  - **Air/fuel 15:1 Turbine Inlet Temp TOO HIGH for Material strength**
  - **Air/fuel @ 60:1 Turbine Inlet temps (2,00 0 to 2,500 deg. F)**

Turbo Prop Vel <M0.75
with Controllable Pitch Propellers



Some Typ. Turboprops

A/C	Engine	TO rating (KW)	Weight (Kg)	Power/Weight
ATR-72-200	PW 127	2,051	481	4.3
C-130J	RR AE 2100	3,424	702	4.9
Dash 8 (Q400)	PW 150A	3,781	690	5.5
Airbus A400M	EU TP-400-D6	8,203	1,900	4.4
TU-95 Bear	NK-12MV	11,033	1,900	5.8

- First applications in 1948

Tu-95 w/ NK-12MV & (2) AV-6H CR Controllable Pitch Props

TU-95 Bear Bomber (1952-present) TU-114 Pax Aircraft (1961-1991)

- **Max Speed = 470 Kn**
- **Cruise Speed = 415 Kn**
- **Range = 3,300 nm**
- **Cruise Altitude = 26,000 ft.**
- **Service Ceiling = 39,000 ft.**
- **High Reliability**
- **224 PAX**
- **Pwr/Wt = 5.8 Kw/Kg**
- **Contra-Rotation Prop ~ 10% increased Efficiency**
- **4 X 4 Props Noisy (5X3 Scimitar would be a better combination)**

Dash 8 (Q400)

- Bombardier Aerospace
- Production (1983-pres)
- 1,054 (Oct. 2011)
- $27M price
- PW 150A engines
- Pwr/Wt = 5.5 Kw/Kg
- 78 PAX
- 360 Knot Cruise
- 27,000 Max Alt.
- 1,500 nmi. Range
- Active Noise& Vibration Reduction (ANVS)

GE-Dowty R391, Prop (Q400)

- P&W150A
- 3,781 KW Take Off Pwr
- Carbon Fiber
- 6 Blade
- Controllable pitch
- Scimitar Propellers

Antonov An-70
Progress D-27 Propfan w/ SV27
Contra-Rotation Scimitar Propellers

- **Dev. ~ 1992 - 1994**
- **14,000 shp**
- **Prop. Dia. 4.2m (165 in.)**
- **Wt. 1,650 Kg (3,600 lb.)**
- **Pwr/Wt = 6.3 Kw/Kg**
- **Never entered production**
- **Competitor to A400M**
- **High efficiency**
- **Noise Concerns**

A400M

- IOC ~ 2012?
- TP400-D6
- CR 8 Bld composite props
- Composite Wings & Emp
- Cruise M0.72 (300Kt)
- Ceiling > 37,000 ft.
- Range ~ 3000 nmi.

TP-400-D6

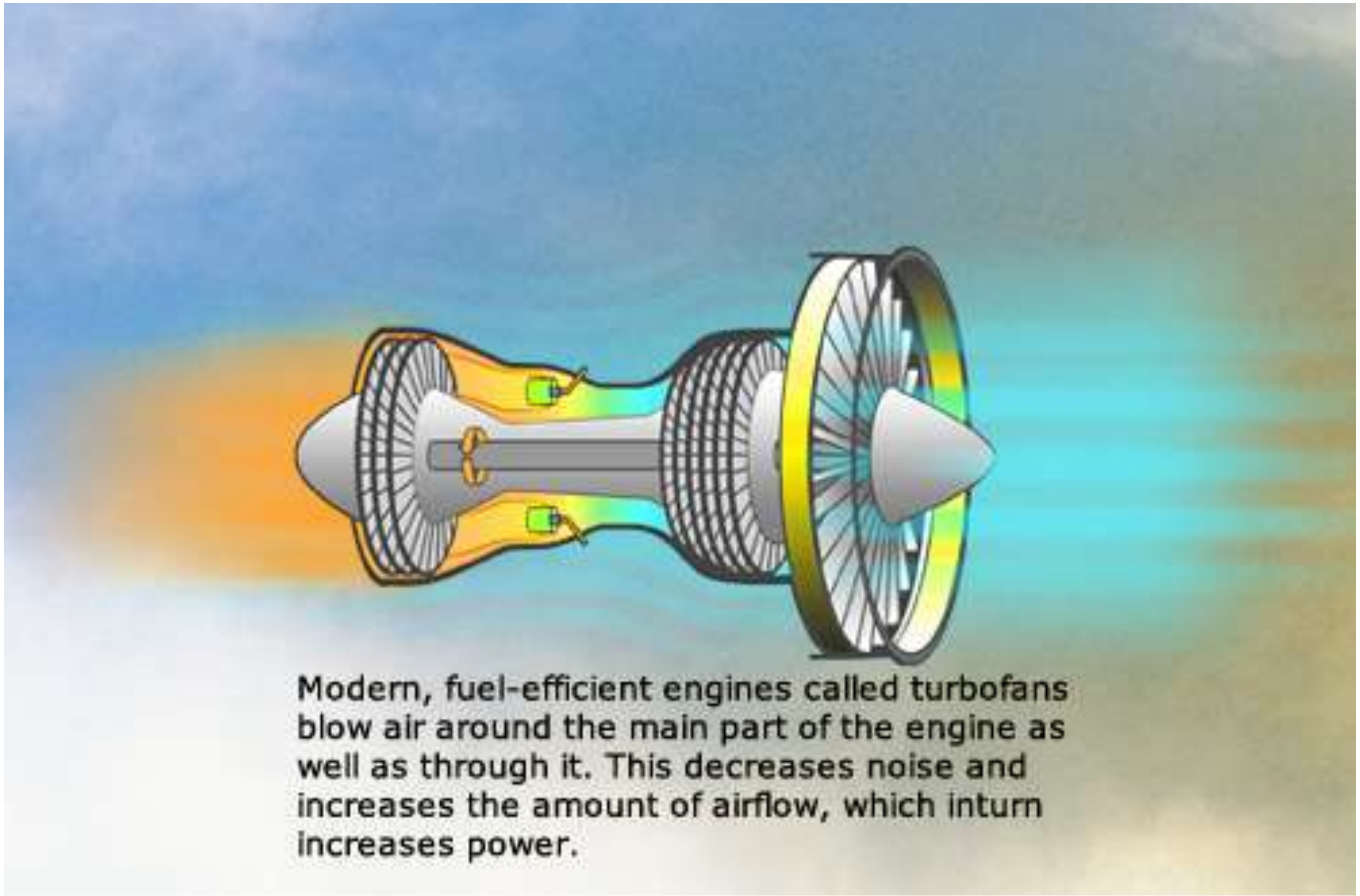
- 11,000 shp (8,200 Kw)
- 1,900 Kg
- TIT = 1500K
- 8 Bld CP composite prop
- Scimitar Propellers
- SFC = 0.4 lb/shp-hr
- Pwr/Wt = 4.4 Kw/Kg
- FADEC to Civil specs
- FOC 2009

FADEC= Full Authority Digital Engine (or Electronic) Control

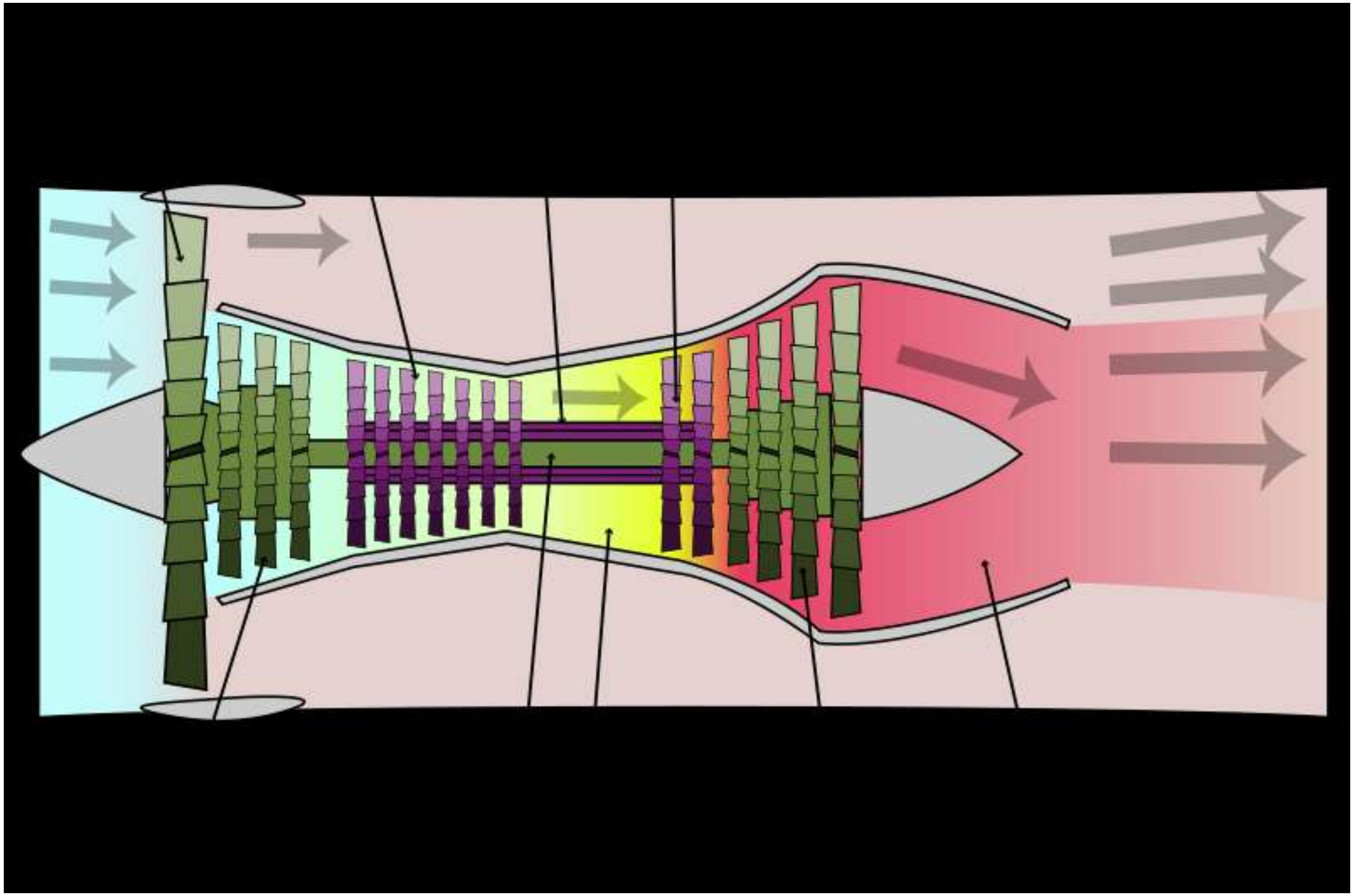
Basic Turbofan Engine

High BPR increases Thrust Efficiency

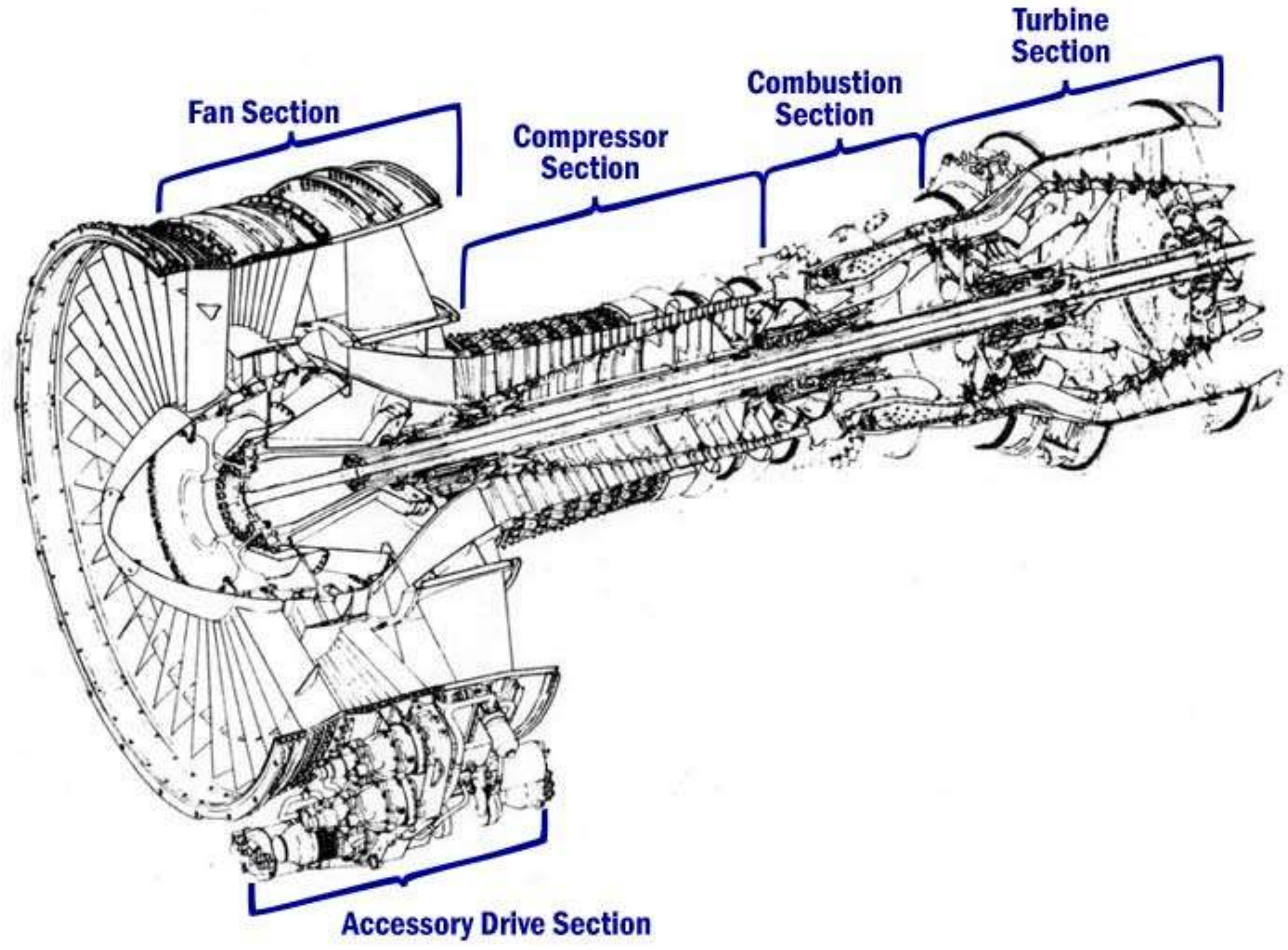
Large Air flow Mass at Low dv



High-bypass Turbofan

- 

GE CF6-6



Fan Section
Compressor Section
Combustion Section
Turbine Section
Accessory Drive Section

Some Typ. Long Range Turbo Fan Jets

A/C	Engine	Thrust (KN)	Weight (Kg)	BPR
B 737-500/A320,A340	CFM 56	100	1,950	6:1
B 777-200LR	GE 90	417	7,550	9:1
B 787,B747-8	GEnx	300	5,816	9.5:1
B787	RR Trent 1000	330	5,765	11:1
B747-400,767,A300,A310	CF6-80C2	280	4,100	5.2

- GE90 has a 128 inch fan diameter

Fanjet Commuter Aircraft

A/C	Engine	Thrust (KN)	Weight (Kg)	BPR
A318	PW6000	100	2,289	5:1
CRJ100/440	GE CF 34-3	41	760	6.2:1
E190/195,ARJ21	GE CF34-10	89	1,700	5.1:1
B717-200	BR 715	83-95	2,800	4:1?
G V	BR 710	66	2,100	?

- BR 715 has a 58 inch fan diameter
- GE CF34-10 has a 57 inch total diameter

Some Final Thoughts

- **BPR on Commuter Jets have been ~ 4 to 6:1**
- **Long Range, high efficiency engines have moved BPR ~ 9 to 11:1**
- **Q400 may be the future of Hub feeder routes**
- **Jet A fuel can be replaced by Synfuel at a cost of over ~$60/bl**
- **Electric Propulsion is not in the future due to low energy density of source and high weight of engines**