Fundamentals of Air-Breathing Propulsion

Presented by:

Dr. Dimitri Mavris
S.P. Langley NIA Distinguished Regents Professor &
Director of the Aerospace Systems Design Laboratory

Georgia Institute of Technology

Module Outline

Thrust vs. Efficiency - basic concepts

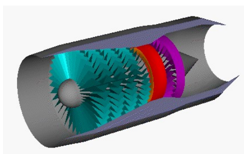
Turbojet Engine
- **How it works**
- **Thrust/SFC varying with Velocity/Altitude**

Turbofan Engine
- **How it works**
- **Thrust/SFC varying with Velocity/Altitude**

Turboprop
- **How it works**
- **Thrust/SFC varying with Velocity/Altitude**

Reciprocating Engines with Prop
- **How it works**
- **Power/SFC varying with Velocity/Altitude**

Trading Thrust and Efficiency

		Thrust	Efficiency
	Propeller/reciprocating engine	Low	High
	Turbojet	Higher	Lower
	Rocket Engine	Substantial	Poor

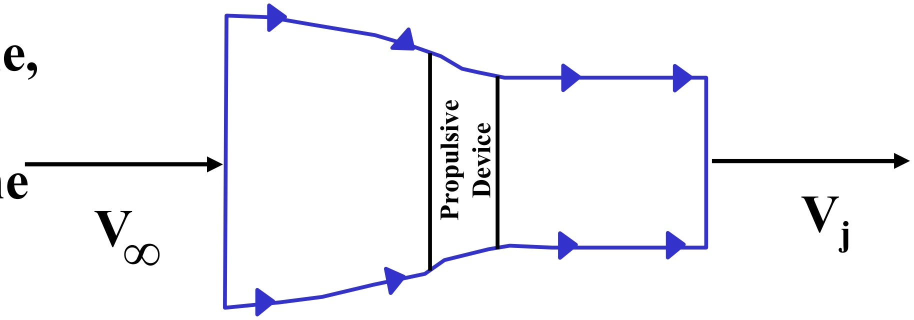
In general, more thrust = less efficiency

This tradeoff helps explain why there are different propulsive devices in use today.

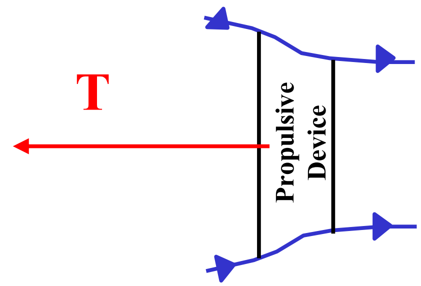
Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

How Thrust is Produced

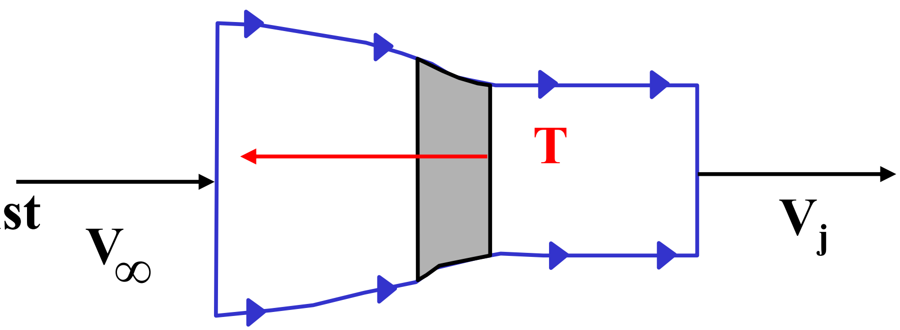
Generic propulsive device (jet engine, propeller, etc.) whose function is to produce thrust, T, acting towards the left



Regardless of type of device, the thrust exerted on the *device* is the net resultant of pressure and shear distributions, at points where air contacts device (internal and external)



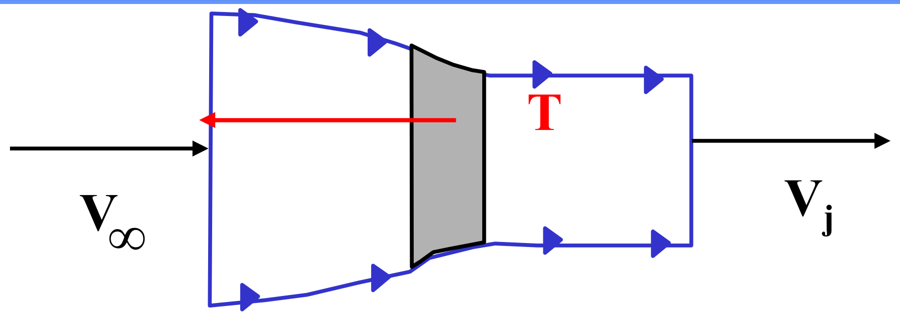
Air experiences equal and opposite reaction (Newton's 3rd Law) to thrust



Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

How Thrust is Produced

Air is accelerated to velocity V_j, called the jet velocity



<u>Newton's 2nd Law</u>: the force on an object is equal to the time rate of change of momentum of that object

$$\boxed{T = \dot{m}\,(V_j - V_\infty)}$$

THRUST EQUATION for generic thrust device

time rate of change of momentum

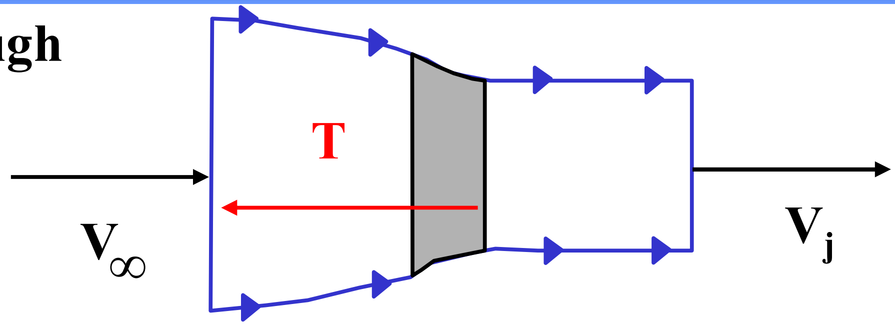
$\dot{m}\, V_j$ → ***momentum per unit time entering stream tube***

$\dot{m}\, V_\infty$ → ***momentum per unit time exiting stream tube***

(Note: we are neglecting the pressure force on the stream tube for this simplified analysis)

Propulsive Efficiency

Instead of considering air moving through device, picture device moving through room of stationary air.



Before device enters the room, air is stationary and has no kinetic energy
After device leaves room, air is moving at velocity $V_j - V_\infty$ and has kinetic energy of

$$\frac{1}{2}(V_j - V_\infty)^2$$

wasted energy-source of inefficiency

Recall: power = force x velocity

$$P_A = T\,V_\infty$$

this is the useful power available

Since power is energy per unit time, the power wasted in the air jet behind the device:

$$\frac{1}{2}\dot{m}(V_j - V_\infty)^2$$

Propulsive Efficiency

Total power generated by device = $TV_\infty + \frac{1}{2}\dot{m}(V_j - V_\infty)^2$

Propulsive efficiency

$$\eta_p = \frac{\textit{useful power available}}{\textit{total power generated}}$$

Substituting in previous expressions,

$$\eta_p = \frac{T V_\infty}{T V_\infty + \frac{1}{2}\dot{m}(V_j - V_\infty)^2}$$

Recall:

$$T = \dot{m}(V_j - V_\infty)$$

and substitute to get...

Propulsive Efficiency

$$\eta_p = \frac{\dot{m}(V_j - V_\infty)V_\infty}{\dot{m}(V_j - V_\infty)V_\infty + \frac{1}{2}\dot{m}(V_j - V_\infty)^2}$$

Divide by:

$\dot{m}(V_j - V_\infty)V_\infty$

$$\eta_p = \frac{1}{1 + \frac{1}{2}(V_j - V_\infty)/V_\infty} = \frac{1}{\frac{1}{2}(1 + V_j/V_\infty)}$$

$$\boxed{\eta_p = \frac{2}{1 + V_j/V_\infty}}$$

$$\boxed{T = \dot{m}(V_j - V_\infty)}$$

Max efficiency occurs when $V_j = V_\infty$ ($\eta_p = 1$) but then T=0 (ultimate efficiency but no propulsive force)

Propulsive Efficiency and Engines

Propeller provides large $\dot{m}$ but small $V_j - V_\infty$ so has high efficiency

low

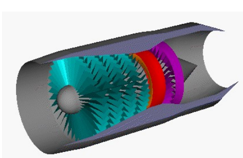
Q: so why don't we use propellers on faster aircraft?

A: as speed increases, the tip speed increases. At high enough speeds, shock waves will form. This increases drag, which increases the torque on the reciprocating engine, which reduces the rotational speed (rpm) of the engine, which reduces power obtained from the engine, which reduces thrust. Also, shock waves on the propeller airfoils increase drag, reducing thrust.

speed

Gas turbine jet engines give a smaller mass of air a larger increase in velocity, but at a lesser efficiency.

high



Turbofans try to combine the thrust generating capabilities of the jet engine with the efficiency of a propeller. Similarly, the turboprop tries to achieve the same.

Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
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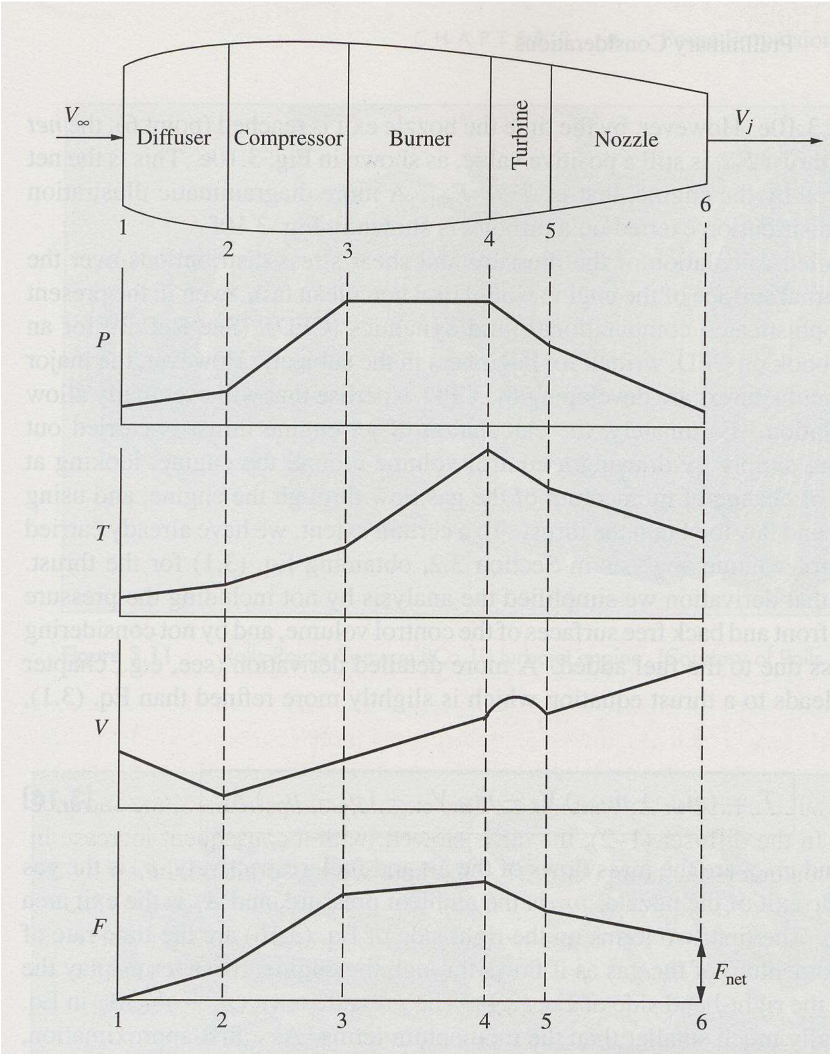
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

The Turbojet Engine



Work is done by the compressor

Work is extracted by the turbine and is transmitted via a shaft to the compressor

Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

Turbojet Engine

Diffuser- slows the air, with increase in pressure and temperature

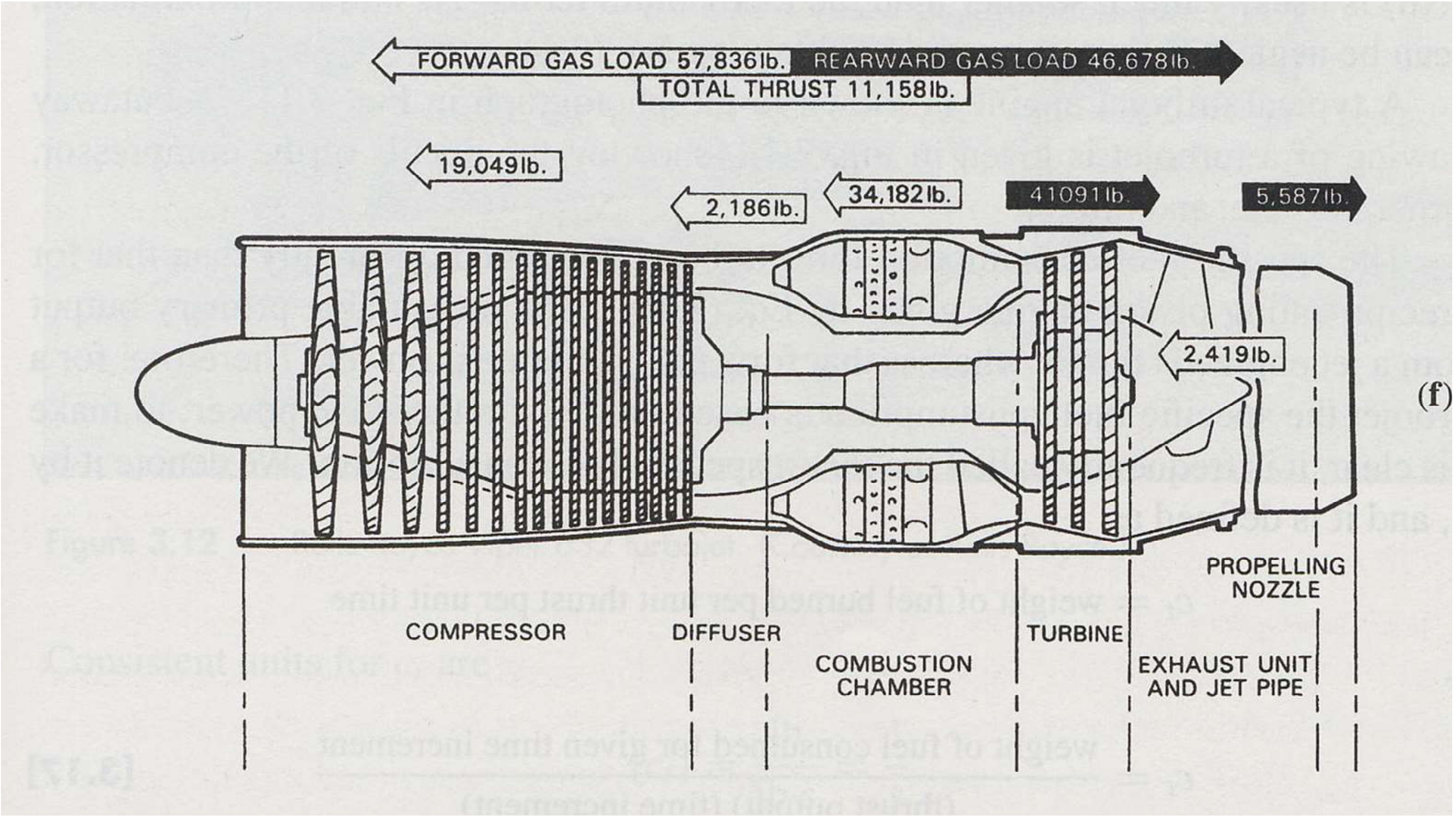
Compressor- work is done on the air by the rotating compressor blades, greatly increasing pressure and temperature

Burner (combustor)- air is mixed with fuel and burned at essentially constant pressure

Turbine- burned air-fuel mixture then expands through a turbine, which extracts work from the gas. The turbine is connected to the compressor by a shaft, and the work extracted by the turbine is thus used to operate the compressor.

Nozzle- the gas expands through a nozzle an is exhausted into the air with velocity V_j.

Generation of Thrust



The thrust generated by the engine is due to the net resultant of the pressure and shear stress distributions acting on the exposed surface areas, external and internal

Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
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dimitri.mavris@ae.gatech.edu

Calculation of Thrust

The detailed calculation of the pressure and shear distribution over the complete internal surface of the engine would be a Herculean task, even in the present day of sophisticated computational fluid dynamics (CFD)

Fortunately, the calculation of jet engine thrust is carried out infinitely more simply by drawing a control volume around the engine, looking at the time rate of change of momentum of the gas flow through the engine, and using Newton's 2nd law to obtain the thrust.

Simplified, this is the result we got earlier: $\boxed{T = \dot{m}\,(V_j - V_\infty)}$

Now, add in pressure acting on the front and back free surfaces, and the extra mass due to the fuel added:

$$\boxed{T = (\dot{m}_{air} + \dot{m}_{fuel})\,V_j - \dot{m}_{air}\,V_\infty + (p_e - p_\infty)A_e}$$

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Turbojet Thrust Equation

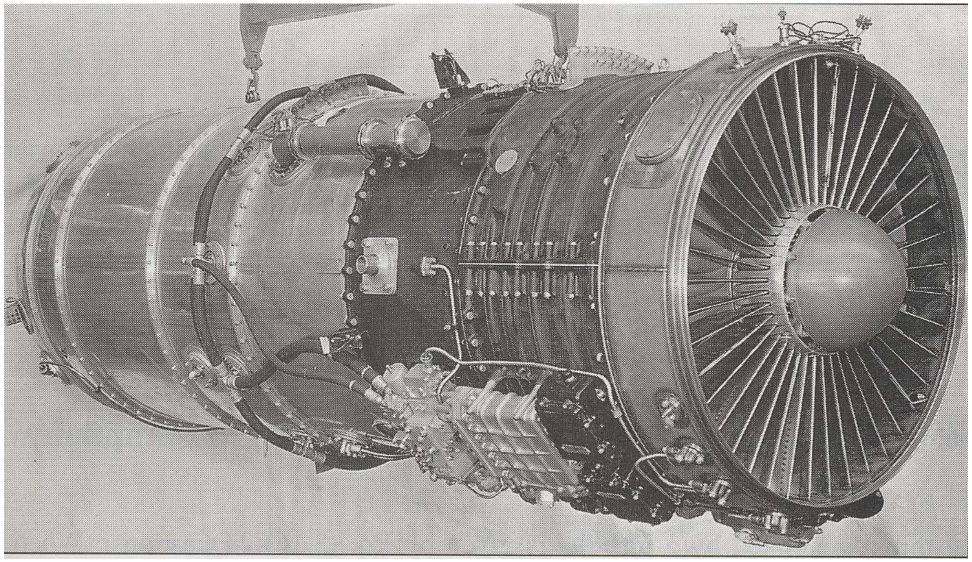
$$T = \underbrace{(\dot{m}_{air} + \dot{m}_{fuel})V_j - \dot{m}_{air}V_\infty}_{\text{time rate of change of momentum of the gas as it flows through the engine}} + \underbrace{(p_e - p_\infty)A_e}_{\text{usually much smaller than momentum terms and can be neglected at times}}$$

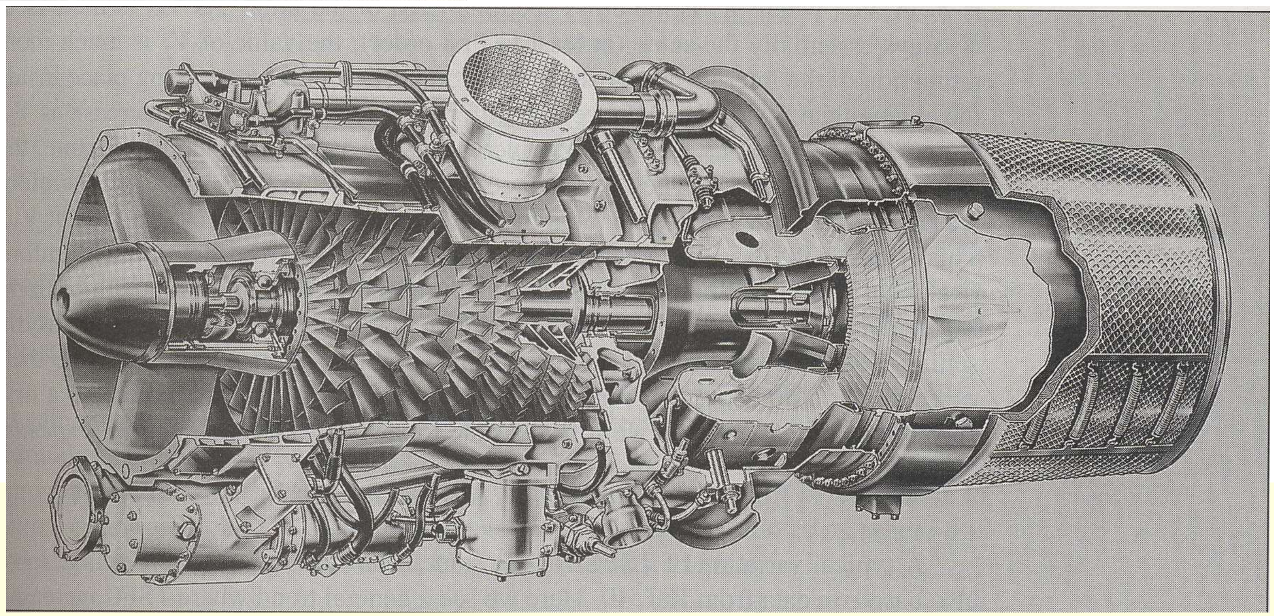
p_e is the gas pressure at the exit of the nozzle

p_∞ is the ambient pressure

A_e is the exit area of the nozzle

Example of a Turbojet





SFC for a Turbojet

SFC for a turbojet is defined differently than for a reciprocating engine

Jet $\longrightarrow$ Thrust **Piston $\longrightarrow$ Power**

To be very clear, we say *thrust* specific fuel consumption

c_t = **weight of fuel burned per unit thrust per unit time**

$$c_t = \frac{\text{weight of fuel consumed for given time increment}}{\text{(thrust output)(time increment)}}$$

$$c_t = \frac{N}{N\text{-}s} = \frac{1}{s}$$

$$\boxed{[\text{TSFC}] = \frac{lb}{lb\text{-}hr} = \frac{1}{h}}$$

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Georgia Institute of Technology
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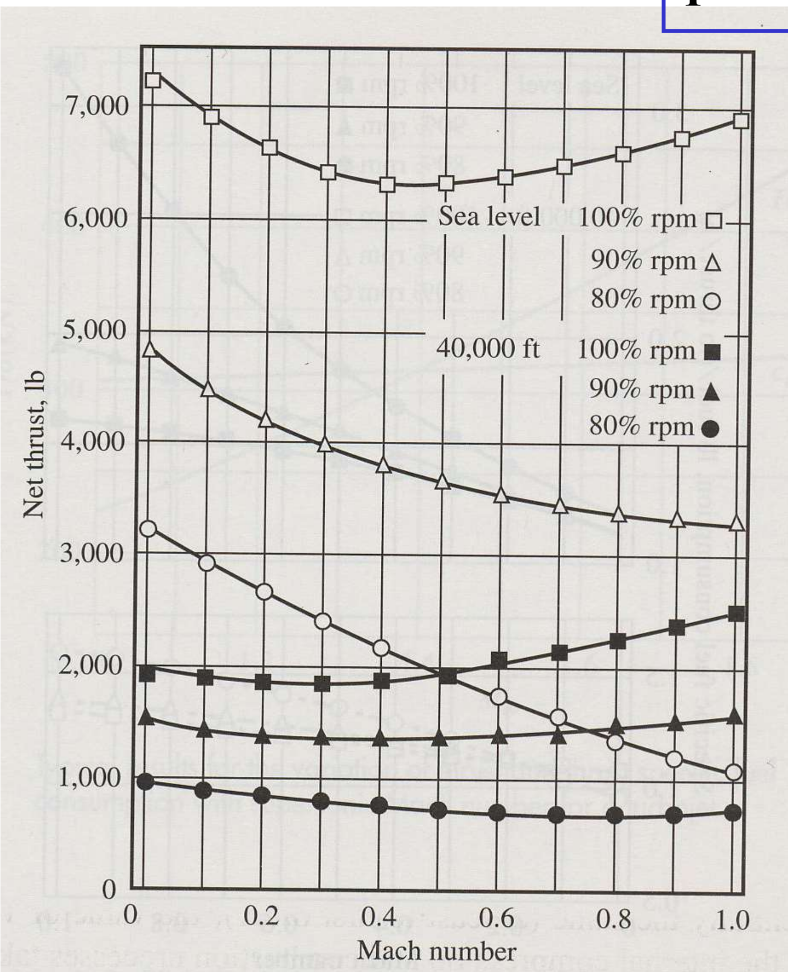
Thrust varying Velocity and Altitude

For subsonic speeds,

$$T = (\dot{m}_{air} + \dot{m}_{fuel}) V_j - \dot{m}_{air} V_\infty + (p_e - p_\infty) A_e$$



Remember $\dot{m}_{air} = \rho_\infty A_1 V_\infty$

so $\dot{m}_{air}$ is directly proportional to ρ. As altitude increases, ρ decreases, $\dot{m}_{air}$ decreases, and from the equation above, T must decrease.

Thrust is strongly degraded as altitude increases

Can approximate thrust changing with altitude by:

$$\frac{T}{T_0} = \frac{\rho}{\rho_0}$$

Note that T is THRUST in this equation, not temperature!

T_0 is sea level thrust

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TSFC varies with Velocity and Altitude

TSFC increases with Mach number

At low speed, can use approximation:

$$\text{TSFC} = 1\frac{\text{lb}}{\text{hp}\cdot\text{h}}$$

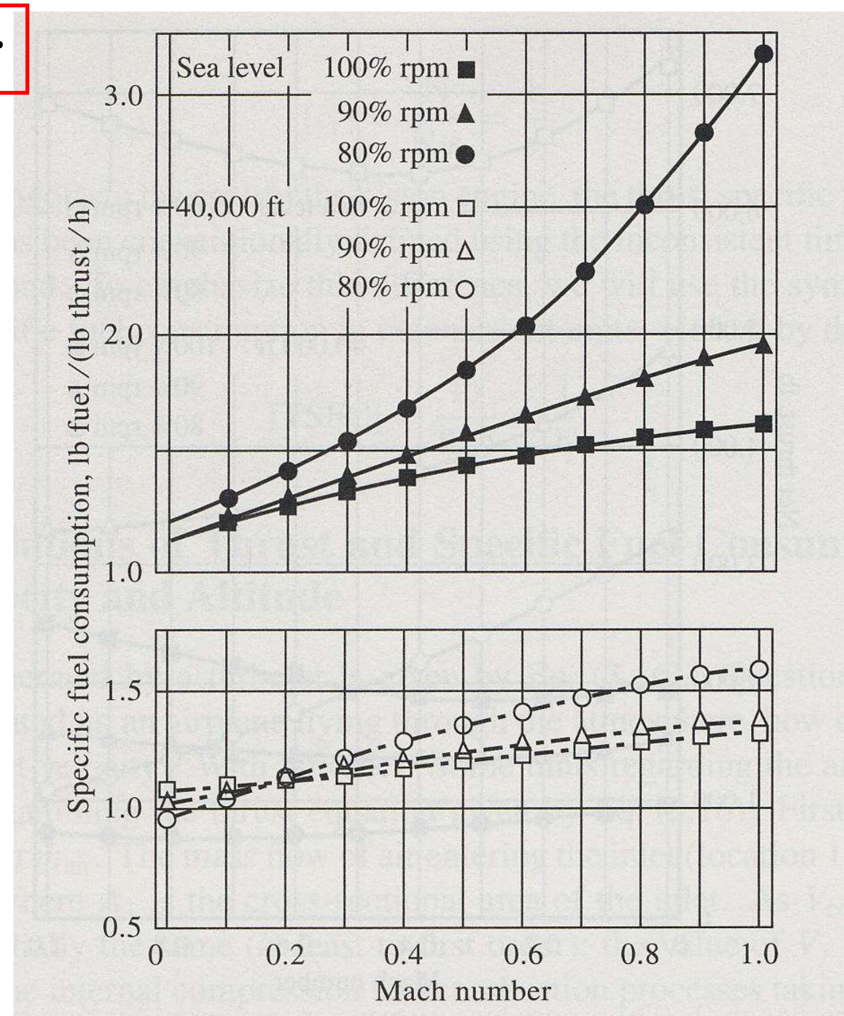
At high speeds, use:

$$\text{TSFC} = 1.0 + k\,M_\infty$$

where k is engine specific, but on the order of 0.5

TSFC is constant with altitude

There is actually a weak effect, but we ignore it for preliminary analysis



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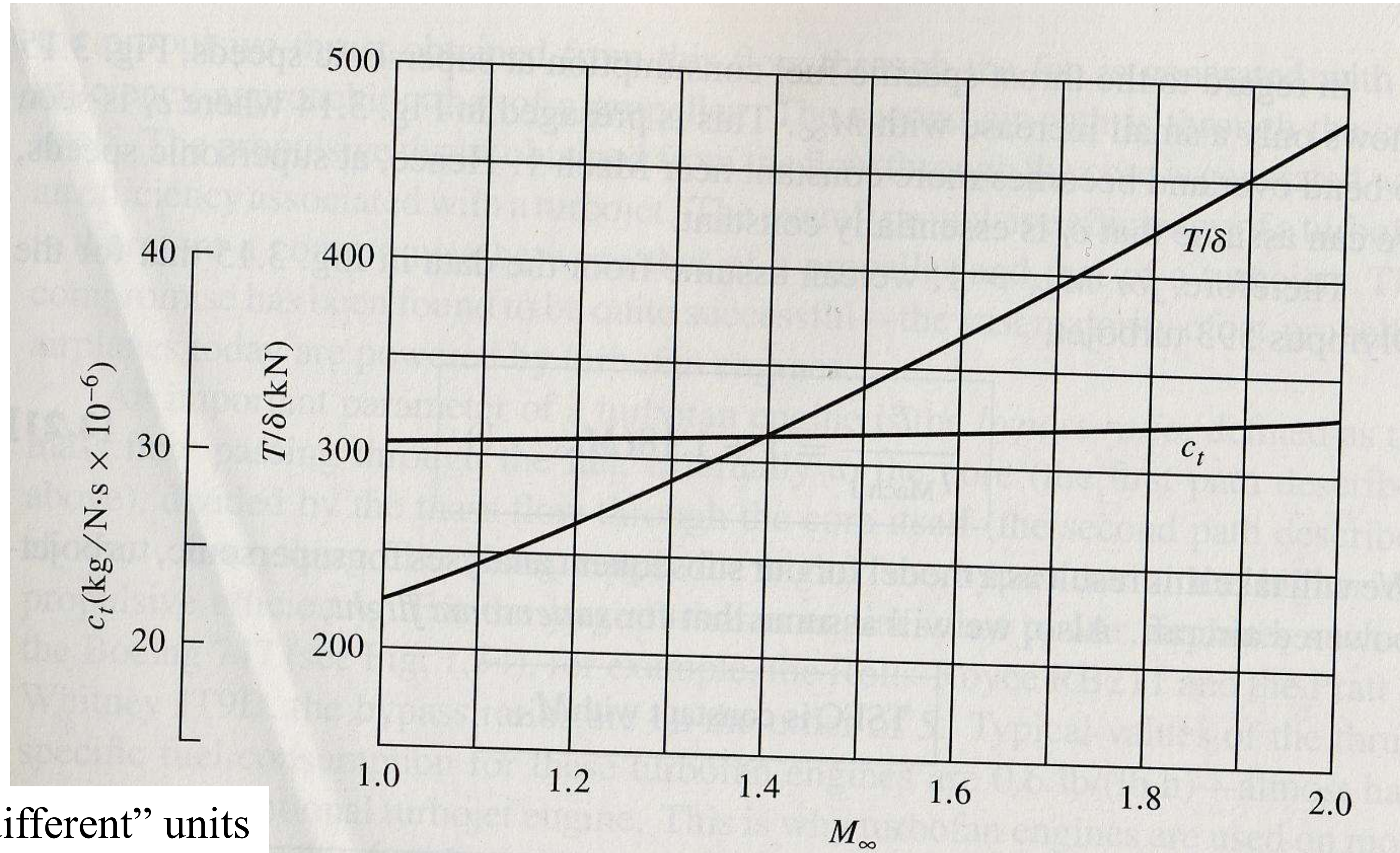
dimitri.mavris@ae.gatech.edu

Supersonic Variations

The Concorde uses turbojets instead of turbofans because of the better supersonic thrust SFC at Mach 2.2, shown below.

$$\delta = \frac{p}{p_0}$$



Note use of "different" units

Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

Supersonic Variation Comments

Why does T increase with M in the supersonic regime, whereas it is relatively constant in the subsonic regime? The answer lies in part in the large total pressures recovered in the supersonic inlet diffuser as M_∞ increases (ram effect).

$$\frac{p_{total}}{p_{static}} = \left[1 + \frac{\gamma - 1}{2} M^2\right]^{\frac{\gamma}{\gamma - 1}}$$

(isentropic)

As M_∞ increases, p_{total} increases dramatically, increasing V_j

Also, $\dot{m}_{air}$ increases. Both of these increase T.

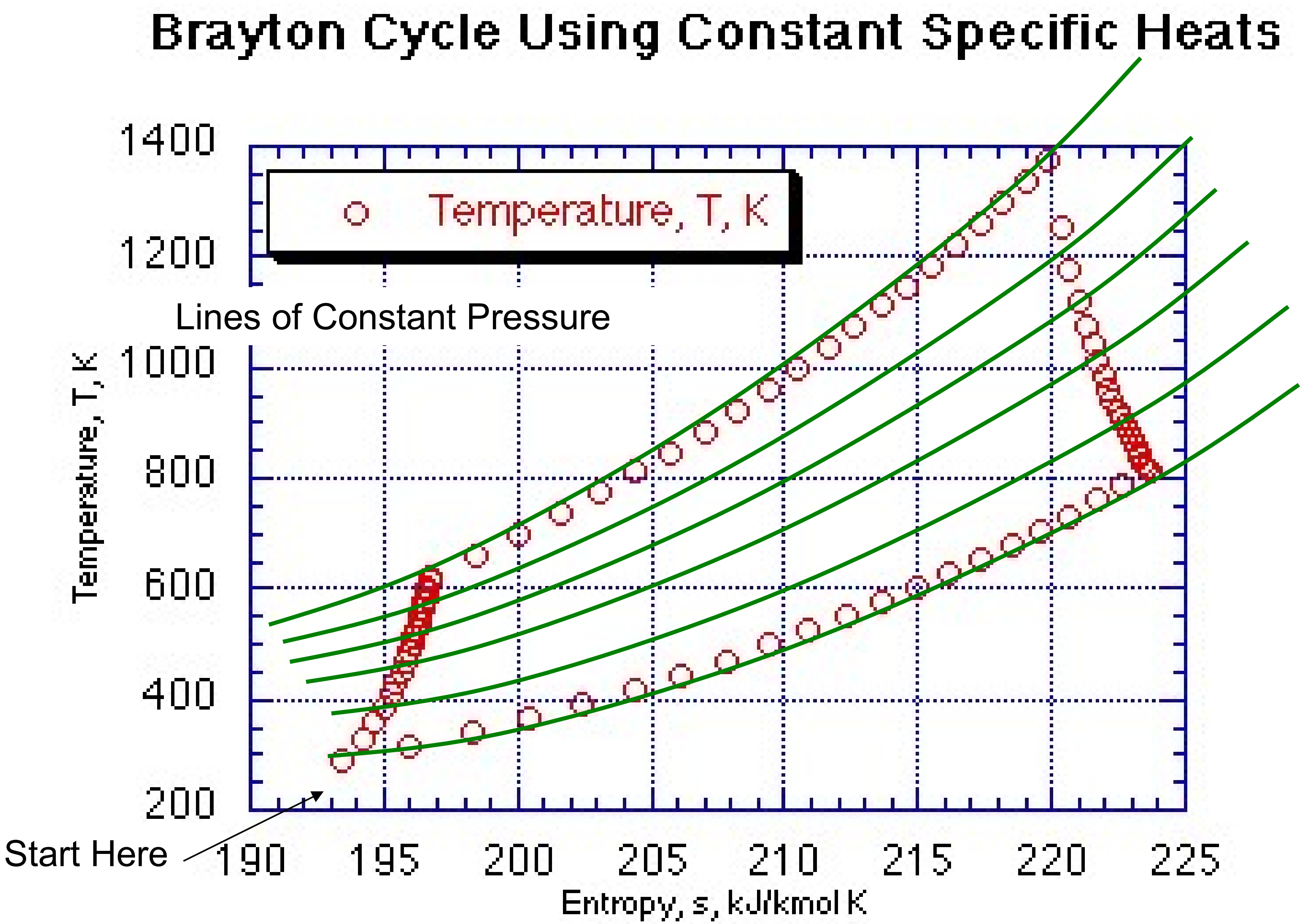
For $M_\infty > 1$, we can use the Concorde turbojet data as a model and approximation:

$$\boxed{\frac{T}{T_{Mach}} = 1 + 1.18\,(M_\infty - 1)}$$

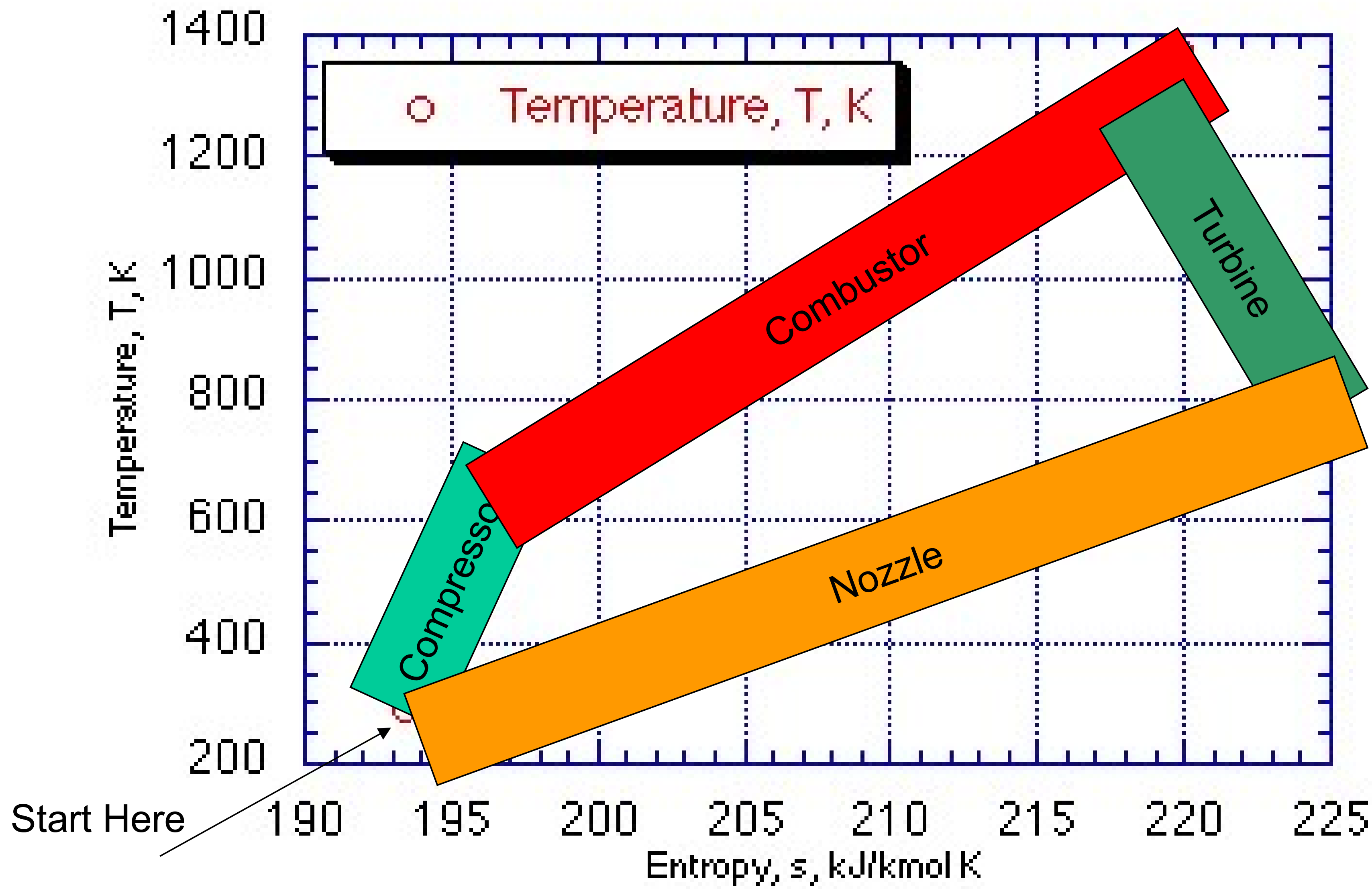
$$\boxed{\text{TSFC is constant with supersonic } M_\infty}$$

Brayton Cycle

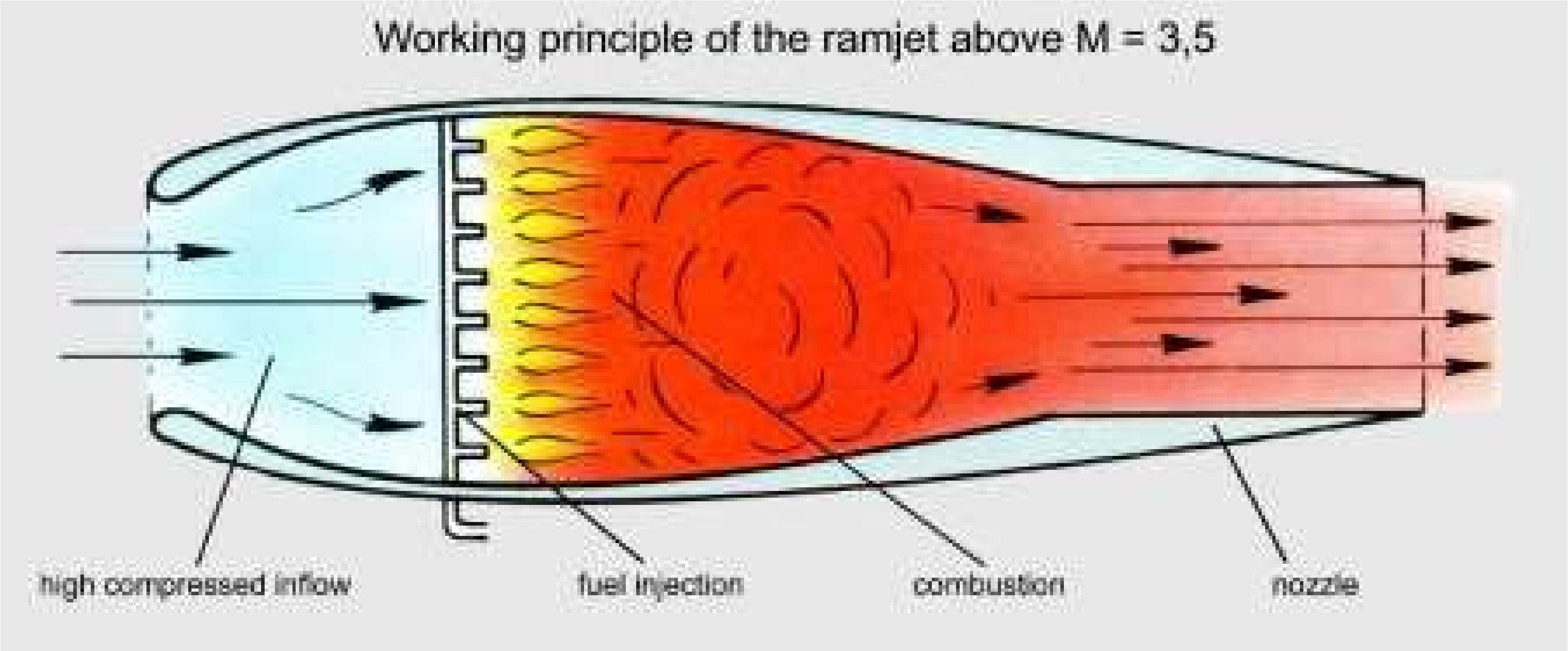
- Four Steps:
  - Compressor working fluid
    - Use a compressor. Adiabatic compression.
  - Heat Added to Fluid
    - Combustion Chamber. Do this at high pressure for increased efficiency.
  - Extract Work from Fluid
    - Use a turbine to do this. Turbine work runs the compressor.
  - Cool the Fluid
    - This usually happens in the atmosphere after the aircraft passes.


Brayton Cycle Using Constant Specific Heats
Temperature, T, K
1400
1200
1000
800
600
400
200
Temperature, T, K
Lines of Constant Pressure
Start Here
190
195
200
205
210
215
220
225
Entropy, s, kJ/kmol K

Brayton Cycle Using Constant Specific Heats

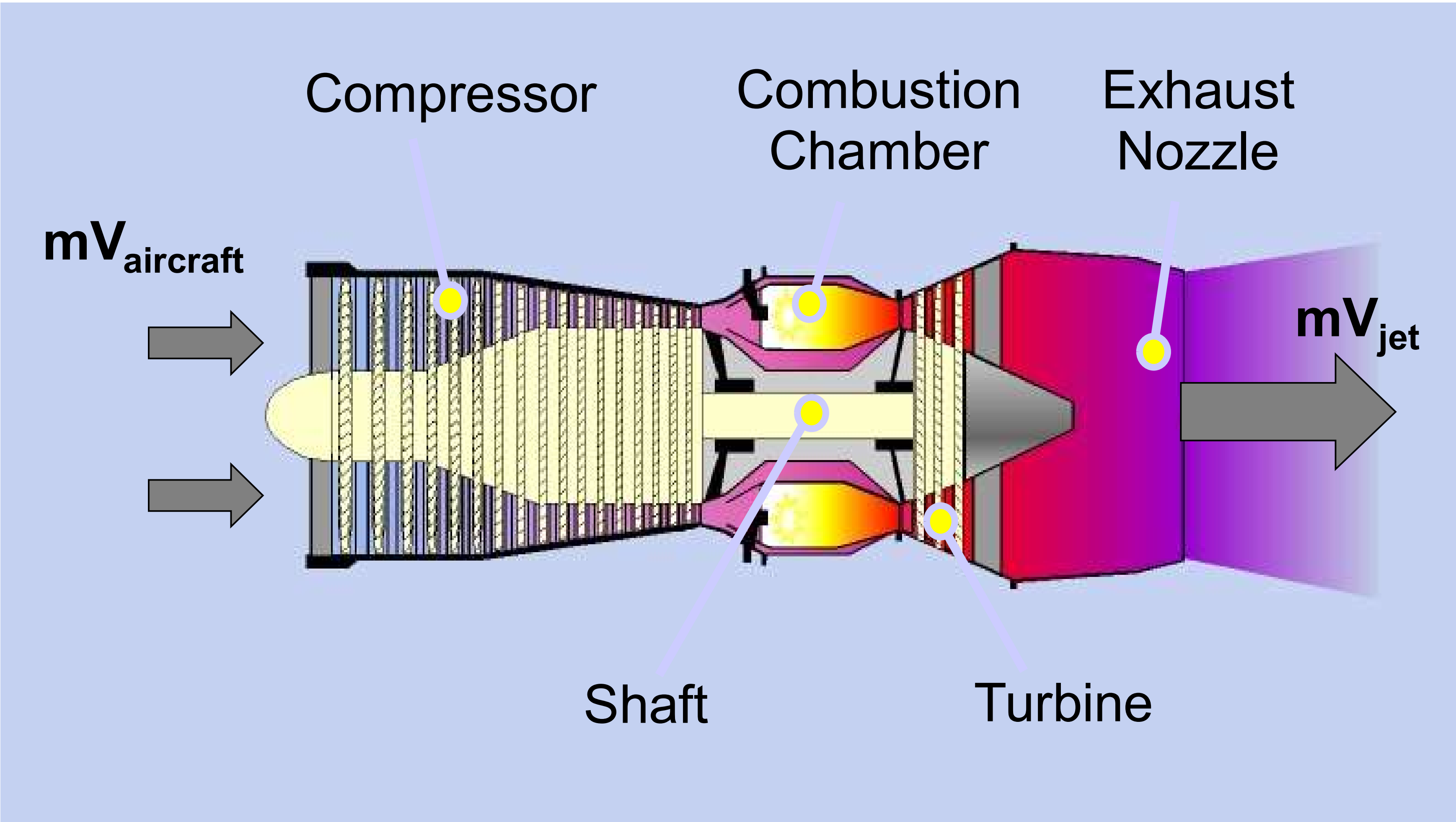


Ideal Engine: Ramjet



- Three Parts: Inlet, Combustor, Nozzle
- Pro: No Moving Parts
- Con: Needs "High Compressed Inflow"

Standard Engine Components: Turbojet



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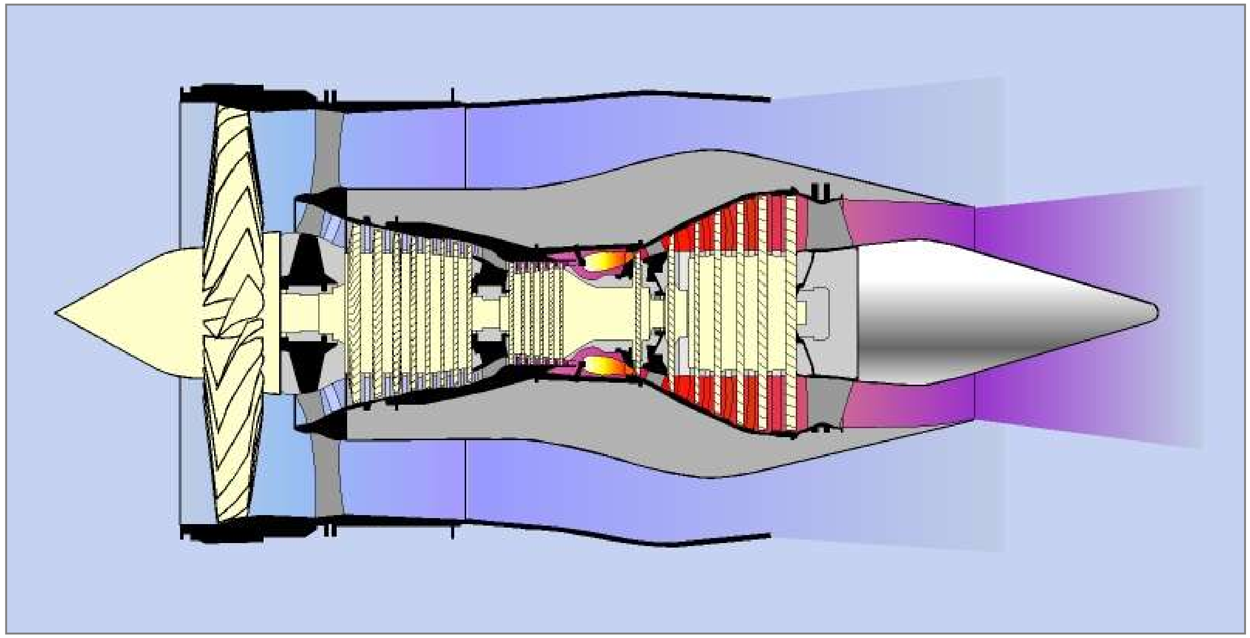
dimitri.mavris@ae.gatech.edu

Modification: Turbofan

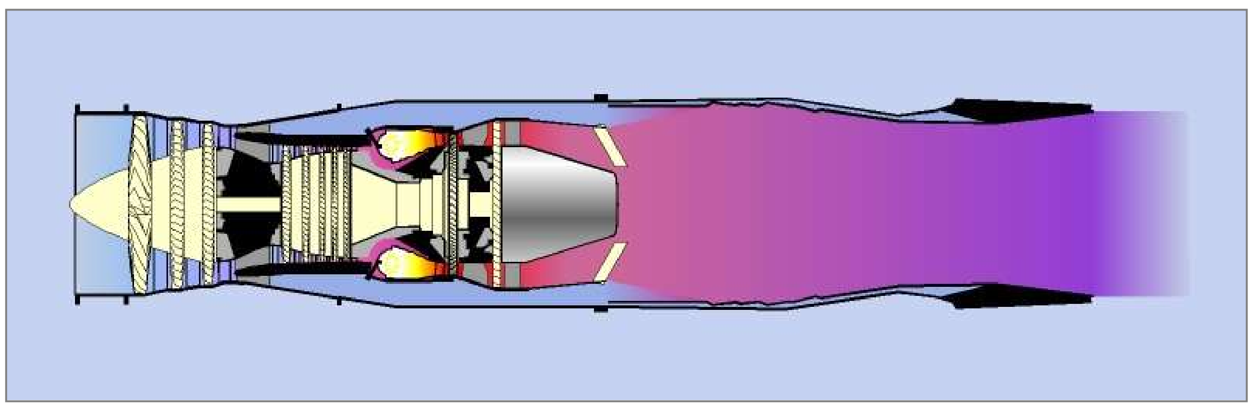
“High Bypass Ratio Turbofan”

300 PAX
RR Trent 800
GE 90



“Low Bypass Ratio Turbofan”

EJ200 (Eurofighter)



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Georgia Institute of Technology
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dimitri.mavris@ae.gatech.edu

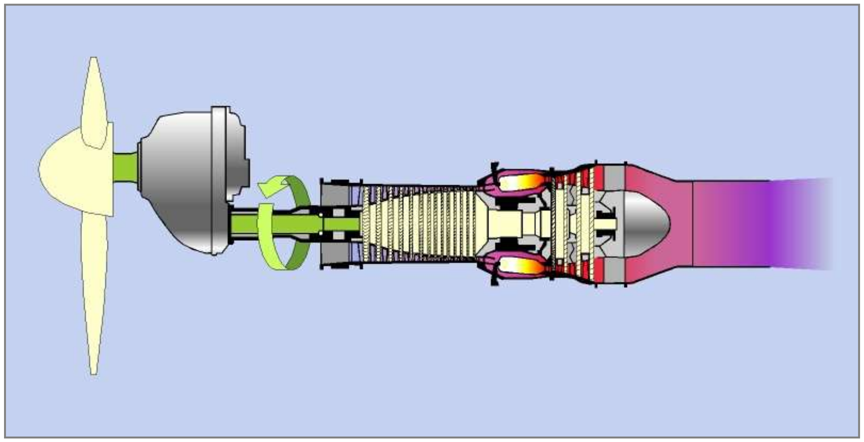
What They Look Like…

EJ200-Eurofighter

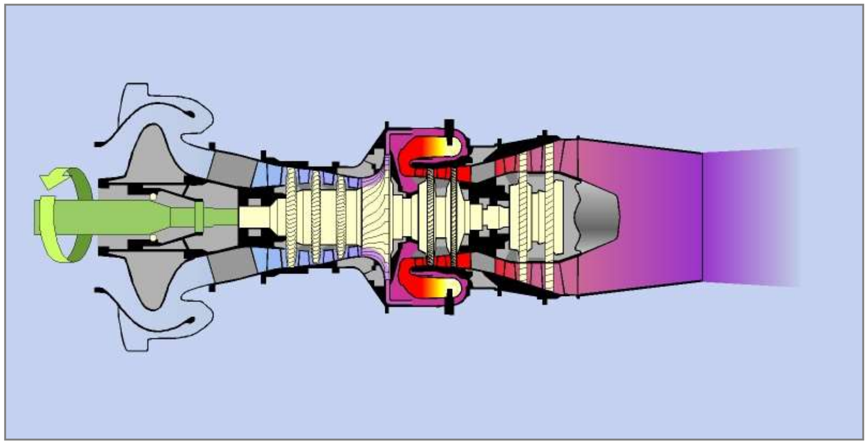
Trent 800
Boeing 777

Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

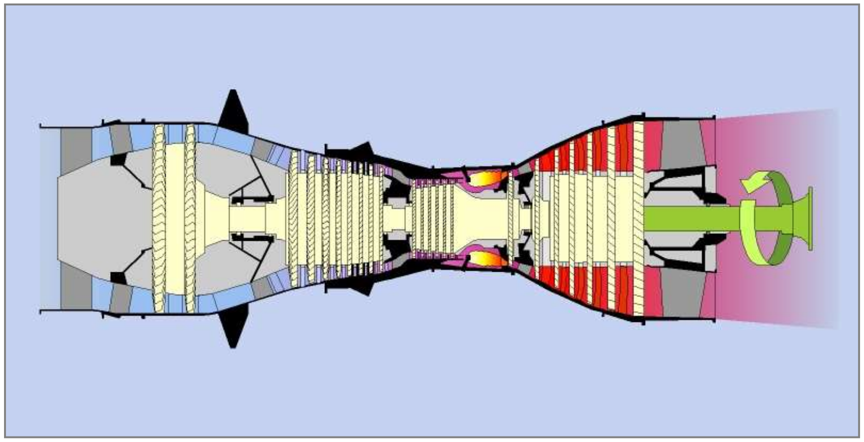
Different Jet Engine Types -



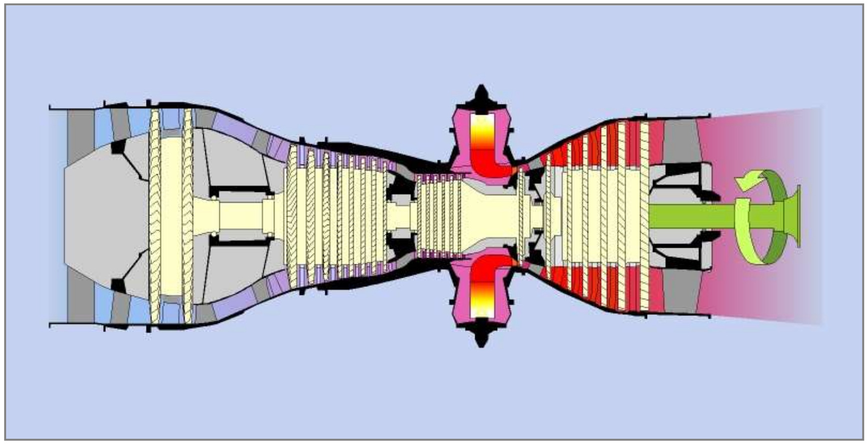
Turboprop - AE 2100



Turboshaft - RTM322



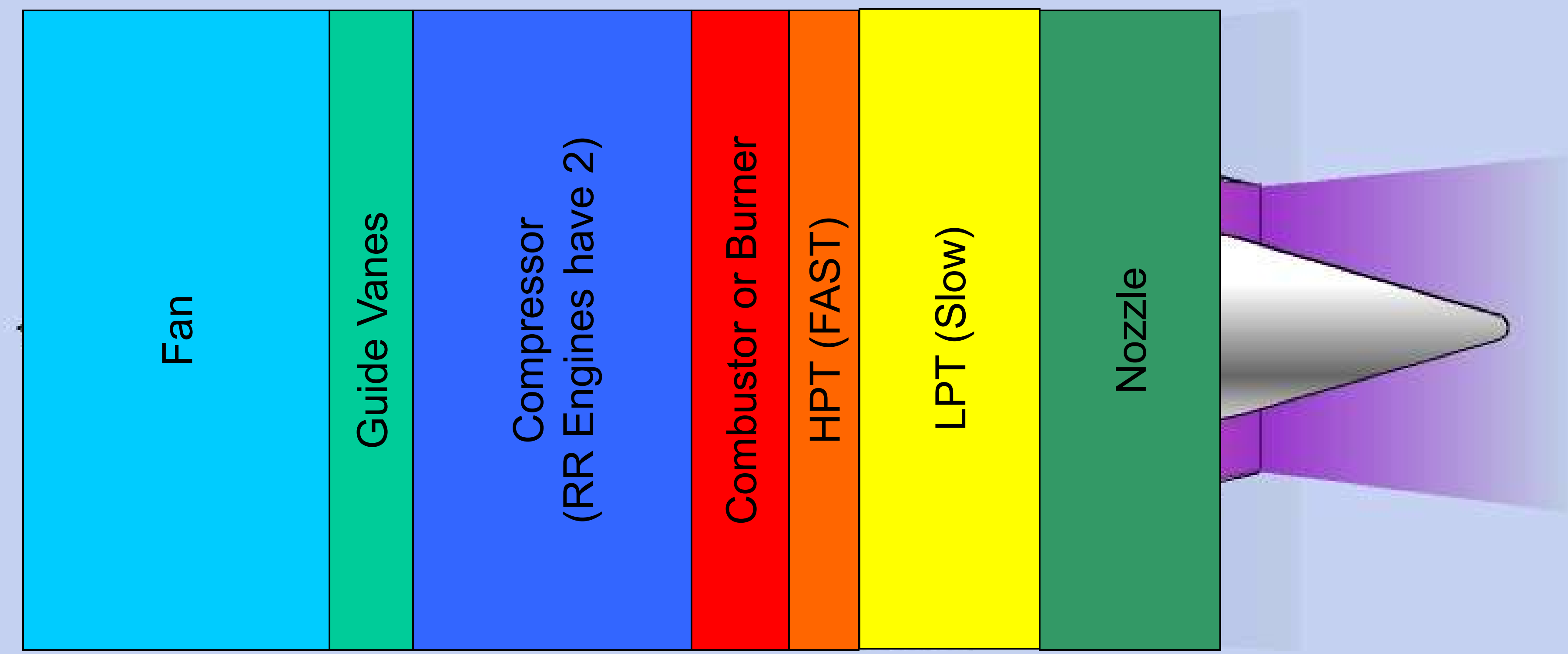
Marine Trent



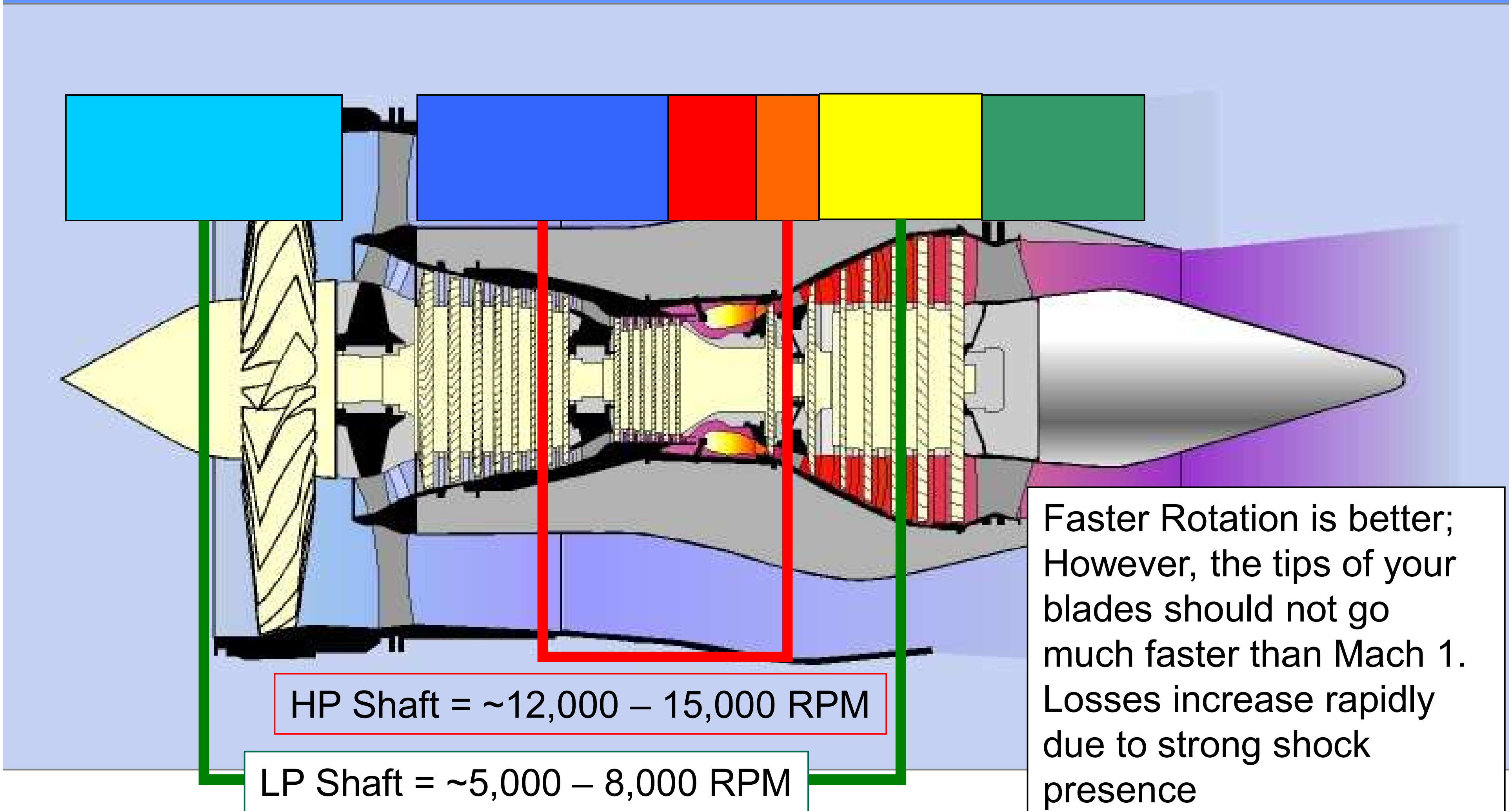
Industrial Trent

Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

Turbofan Engine Components

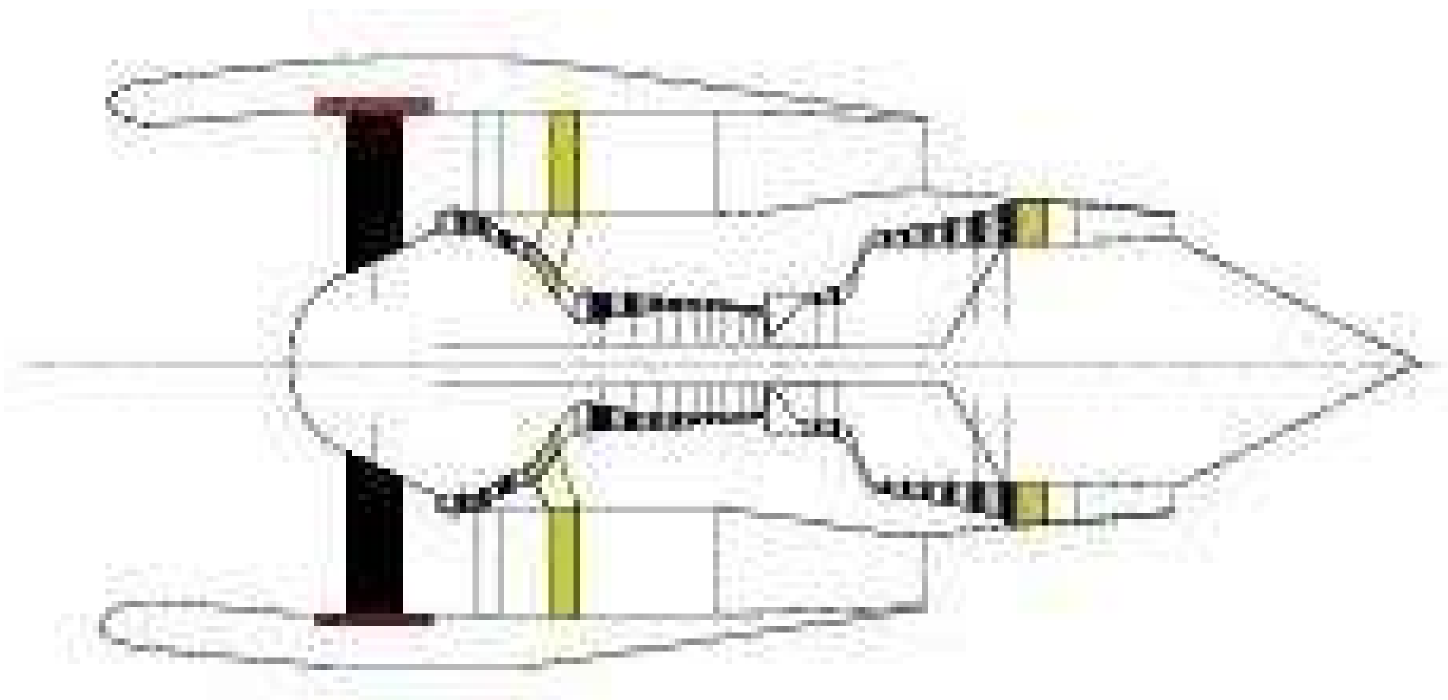


Two Shafts Connect Engine Hardware

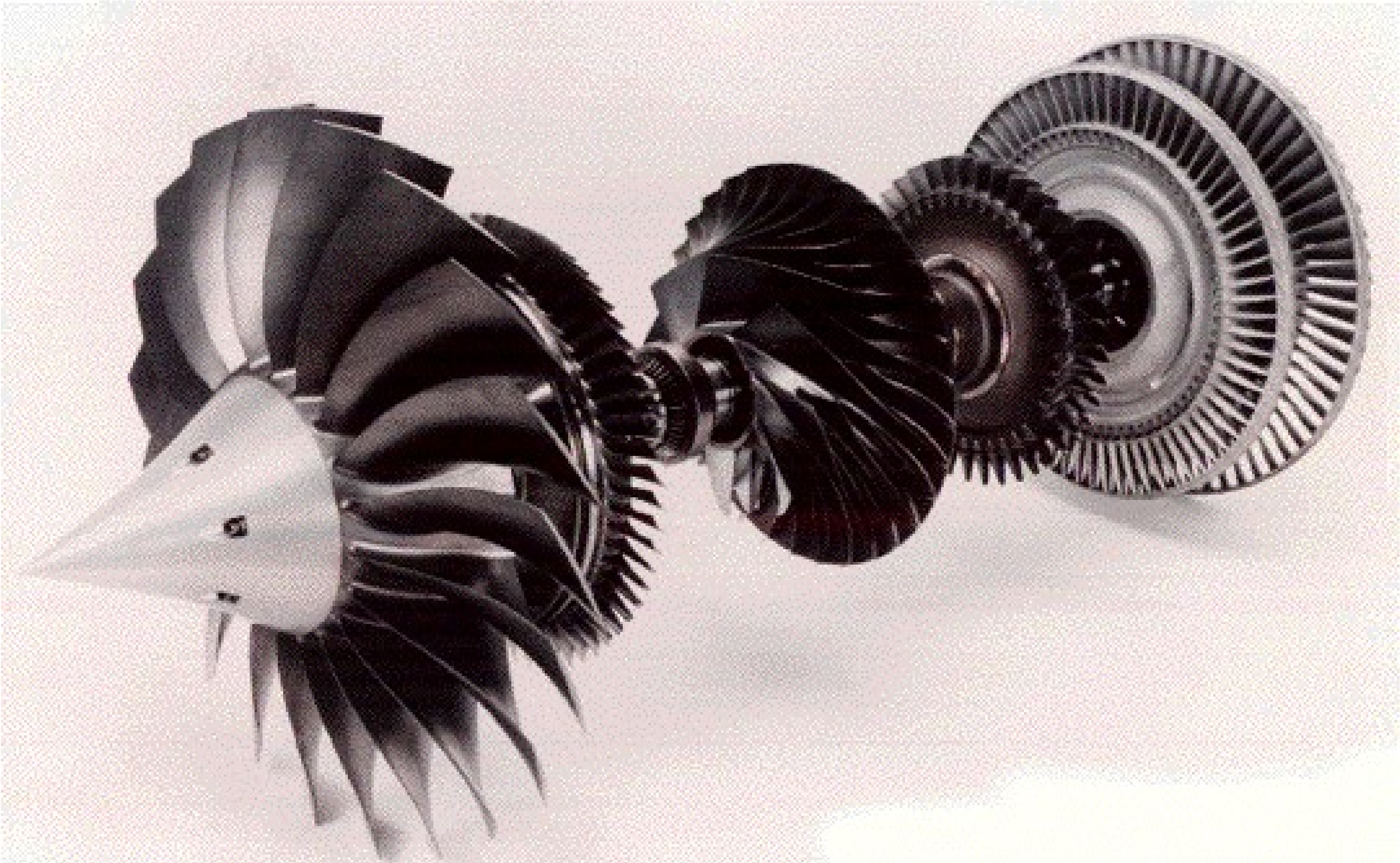


Faster Rotation is better; However, the tips of your blades should not go much faster than Mach 1. Losses increase rapidly due to strong shock presence

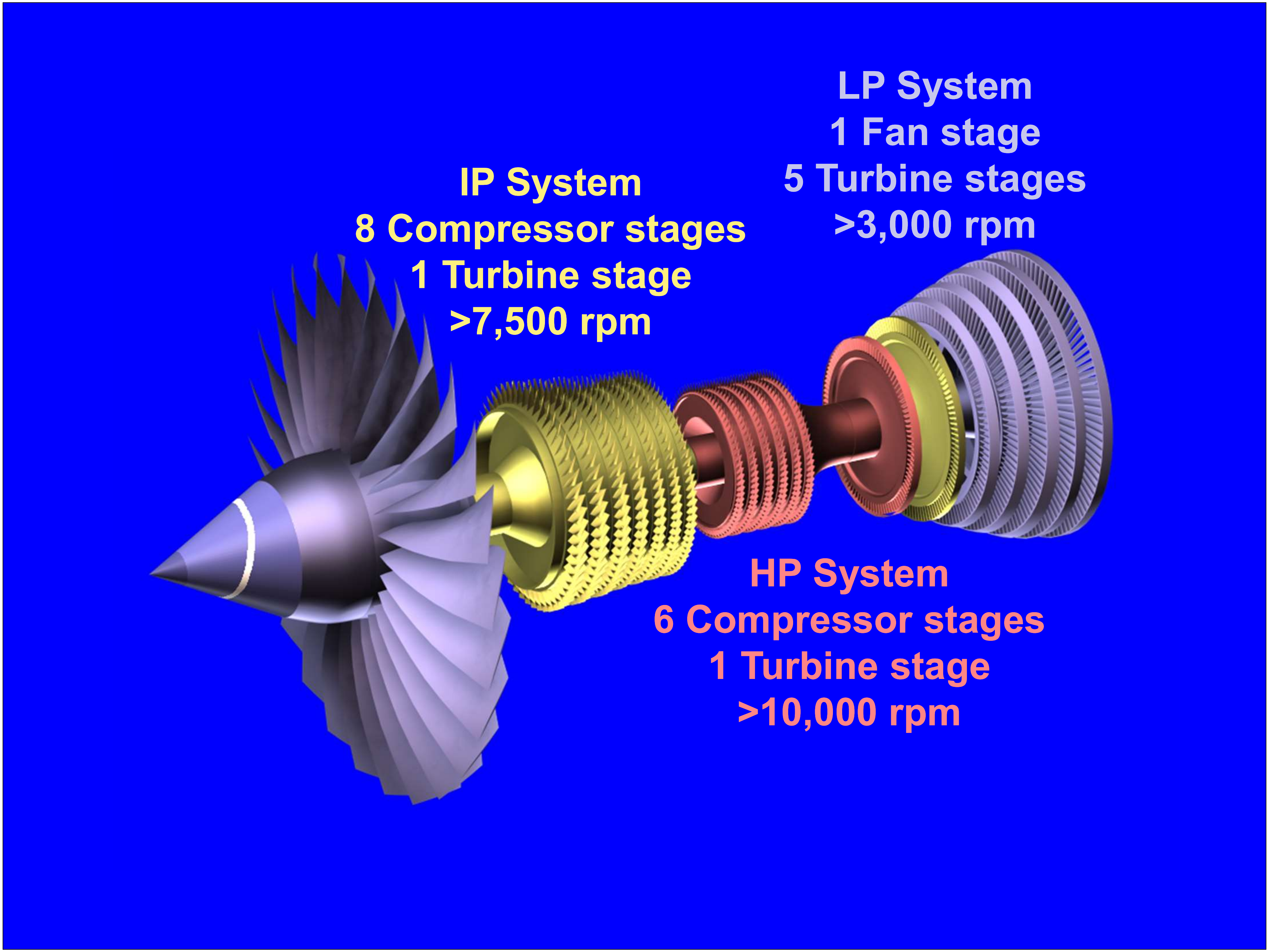
Example: 300 PAX



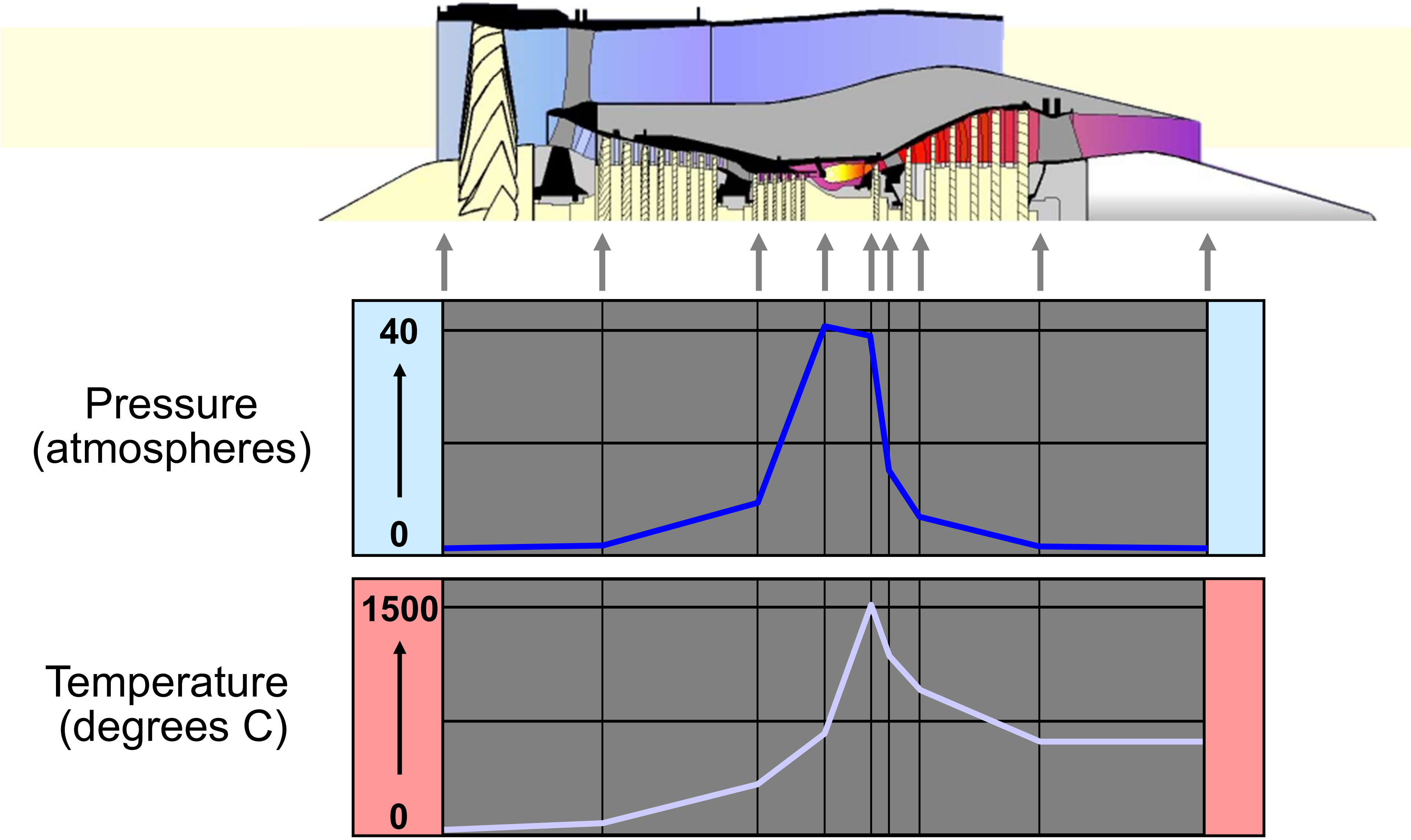
Rotating Machinery



Williams/Rolls FJ-44


LP System
1 Fan stage
5 Turbine stages
>3,000 rpm
IP System
8 Compressor stages
1 Turbine stage
>7,500 rpm
HP System
6 Compressor stages
1 Turbine stage
>10,000 rpm

Pressure and Temperature



Dr. Dimitri N. Mavris, Director ASDL
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Georgia Institute of Technology
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dimitri.mavris@ae.gatech.edu

Fan

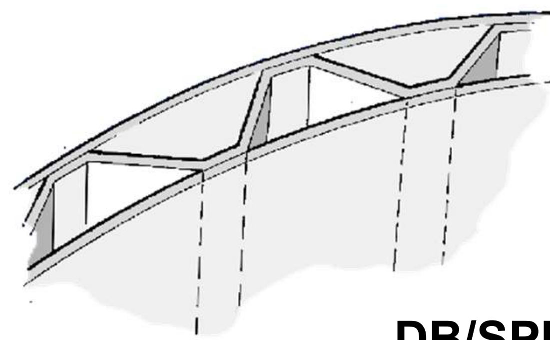
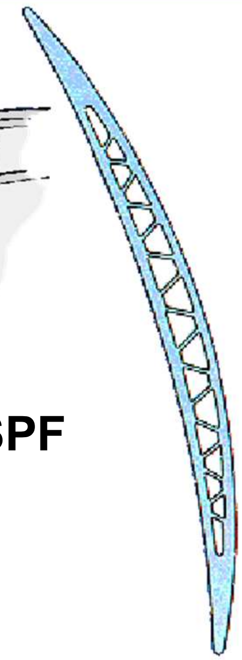
- The fan is the first component of the turbofan engine. It behaves like a propeller

$$F = \dot{m}_e V_e - \dot{m}_0 V_0 + (p_e - p_0) A_e$$

- Thrust is proportional to mass flow and velocity
  – Increasing velocity (turbojet) is noisy
  – Increasing mass flow (turbofan) means a big heavy fan is needed
- Turbofans push more air through the engine, but at a slower velocity

Fan

- Usually 1 or 2 stages
- Blades are very large
- Blades are sometimes hollow
- Root stress on each blade is like having a 747 hanging from the disc!!!

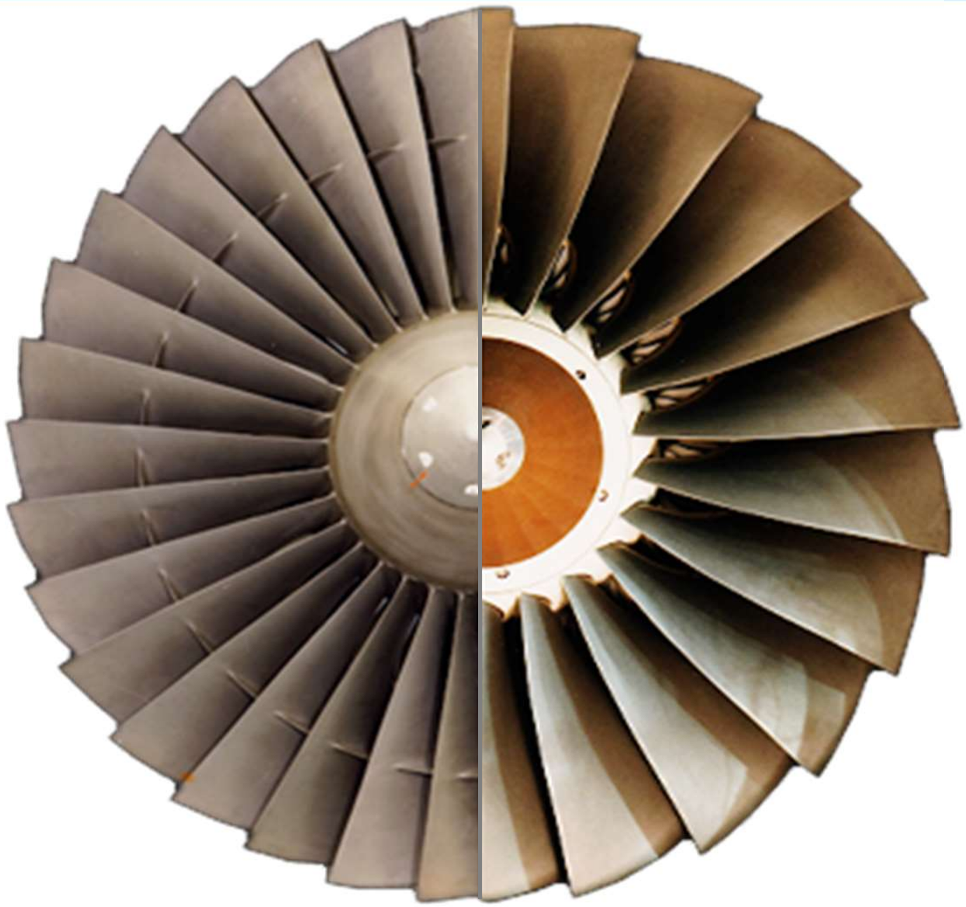



DB/SPF

Wide Chord Blade

Swept Fan Blades

Fan Blade Technology



Clappered

+ 4% efficiency

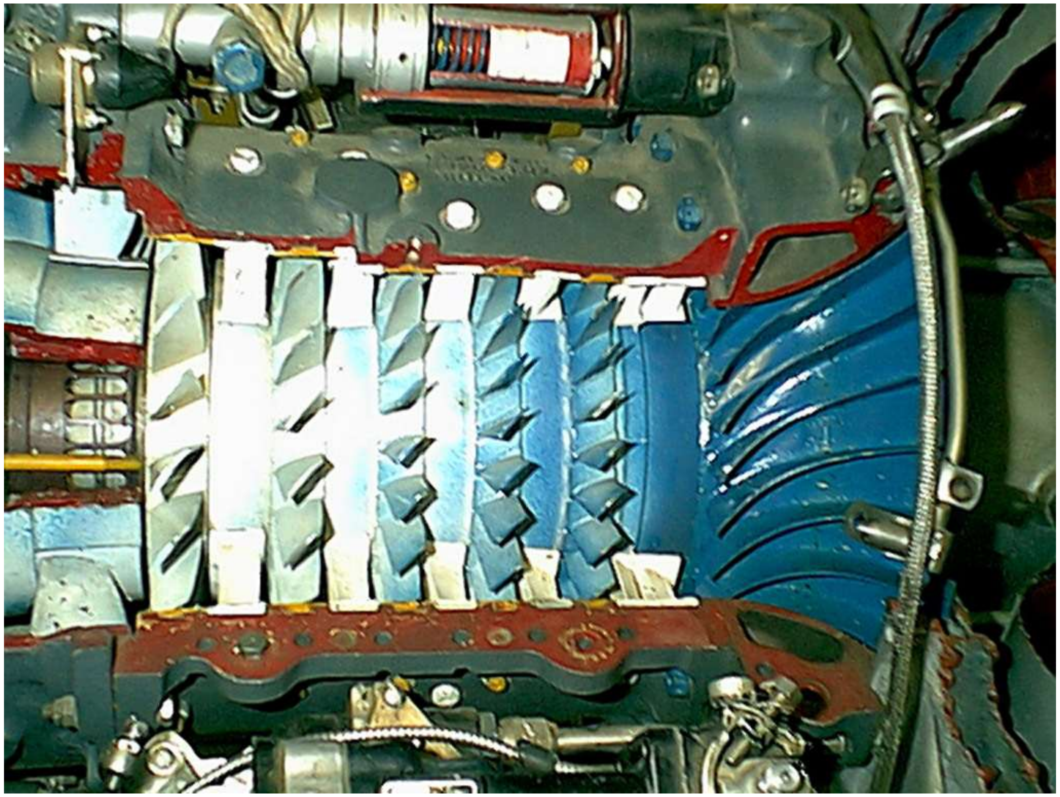
Wide-chord fan

Compressor

- The compressor is made up of many small airfoils called blades.
  - These are attached to discs or “wheels”
  - The discs are attached to shafts which rotate
- There are vanes between each row of blades
  - Spinning metal gives air high vorticity
  - Efficiency is increased by using vanes to “straighten” the flow out
- Compressors are usually the heaviest and most expensive component in an engine

Compressor

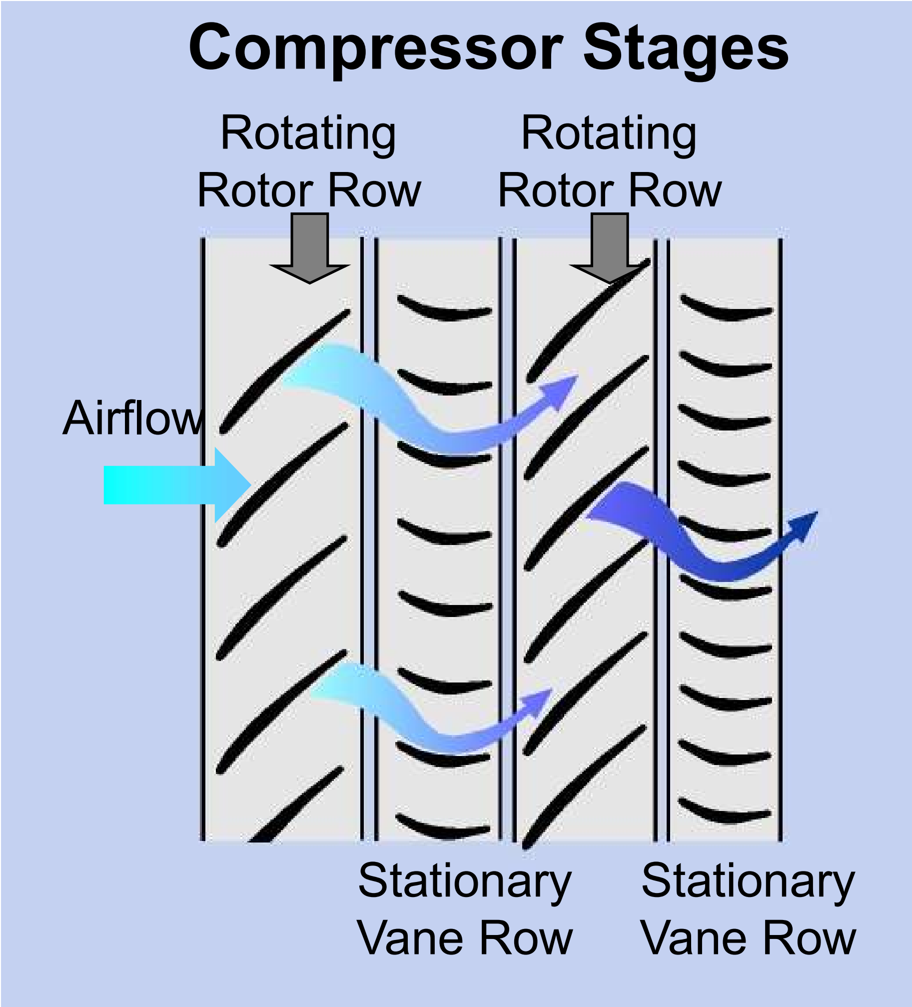
Small Compressor
Disc with Blades

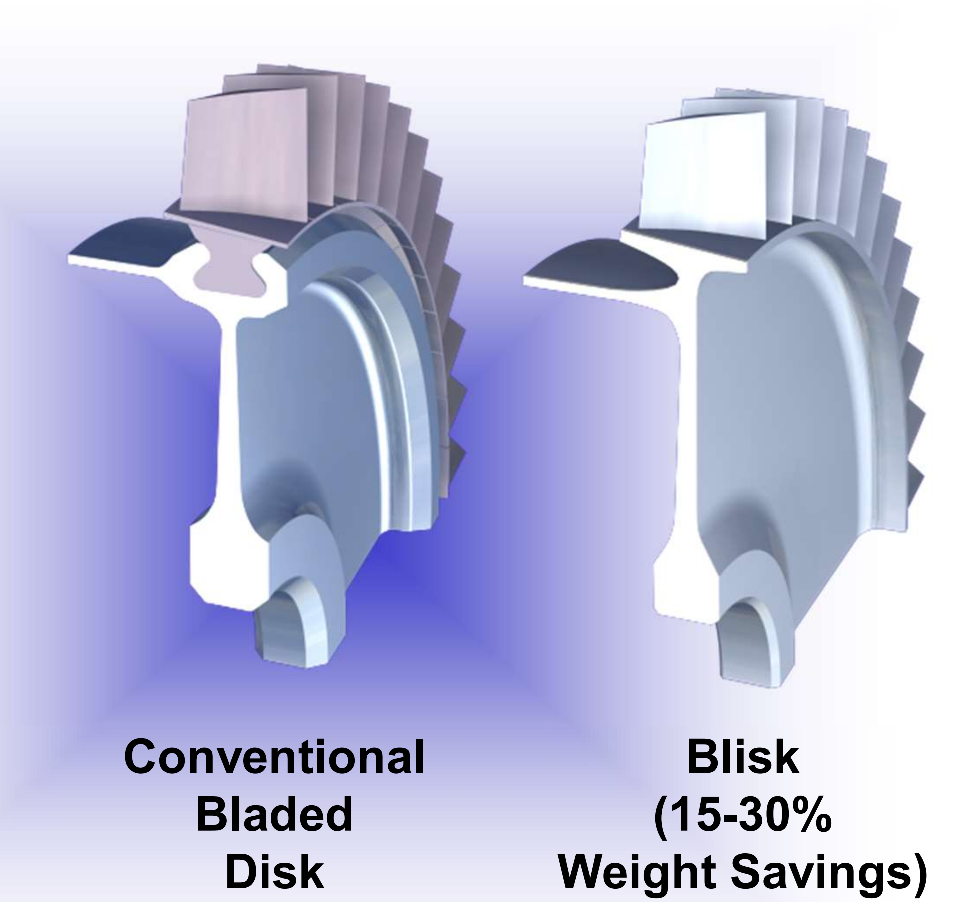


Axial Compressor

Centrifugal
Compressor

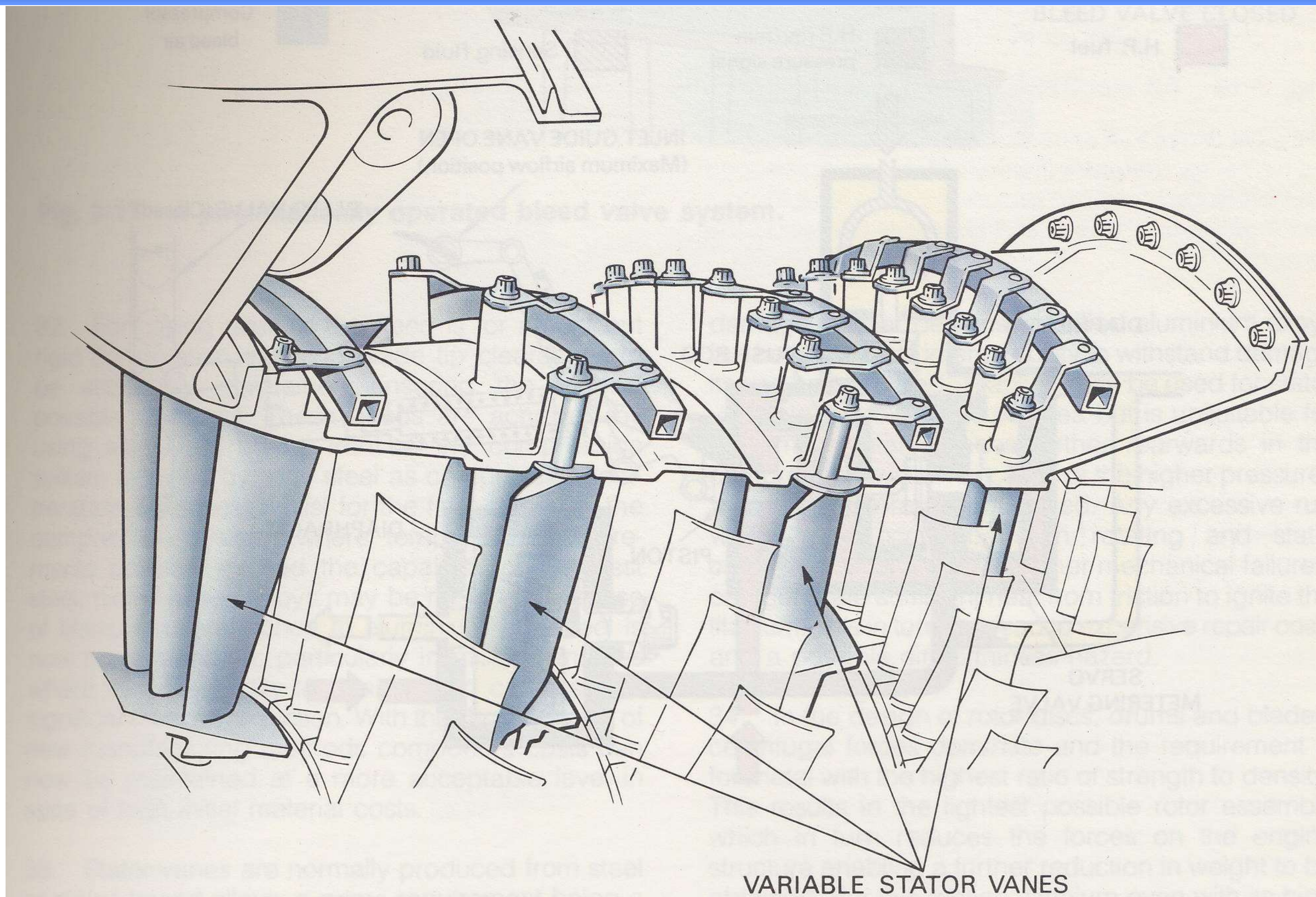
Compressor





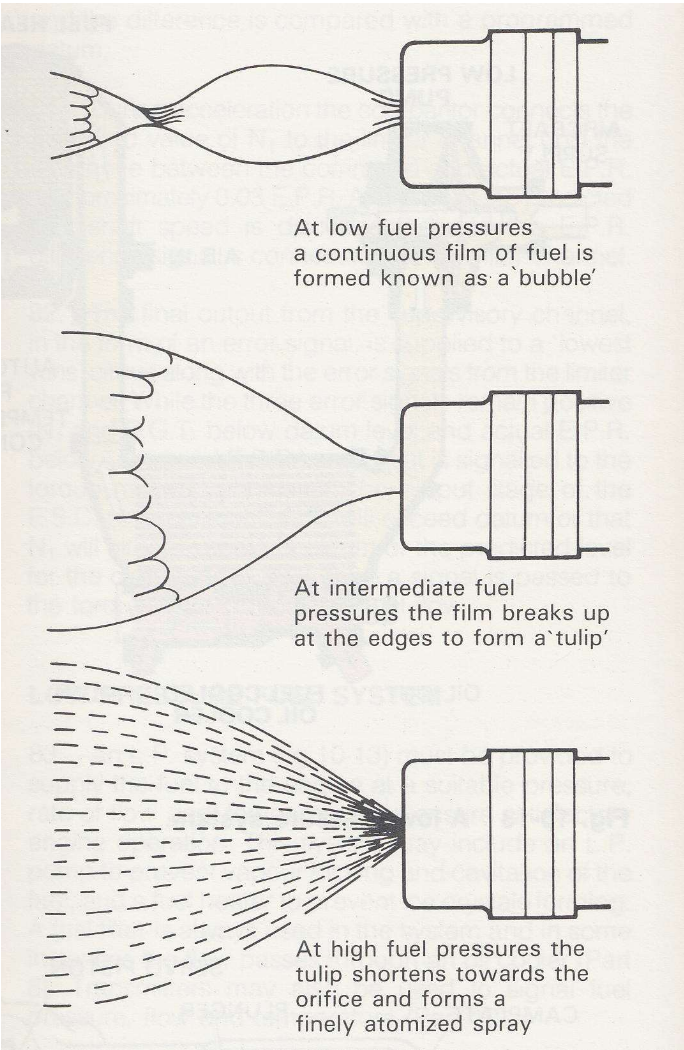
c/o Rolls-Royce

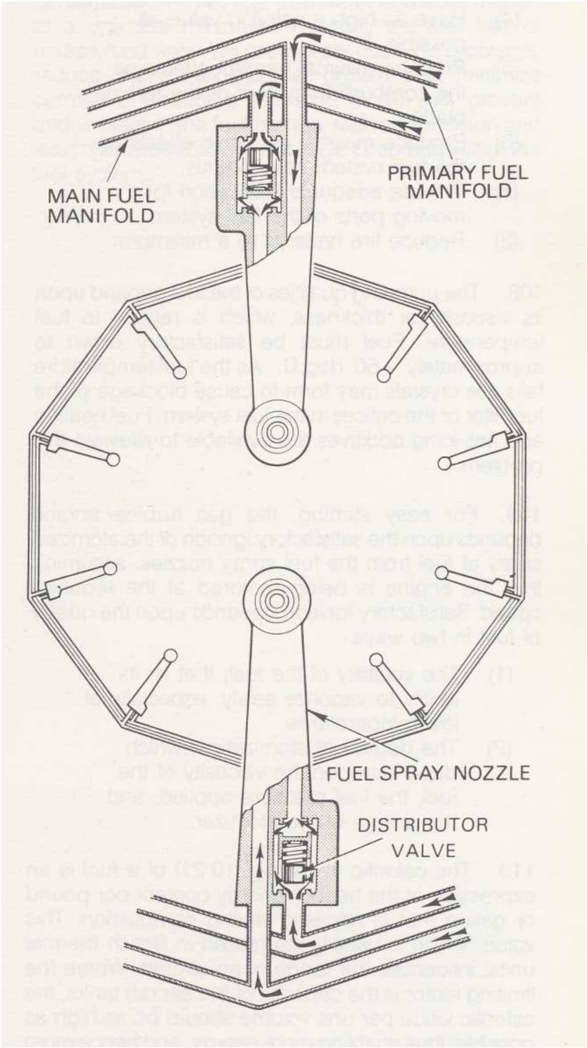
Stators in a Compressor



Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

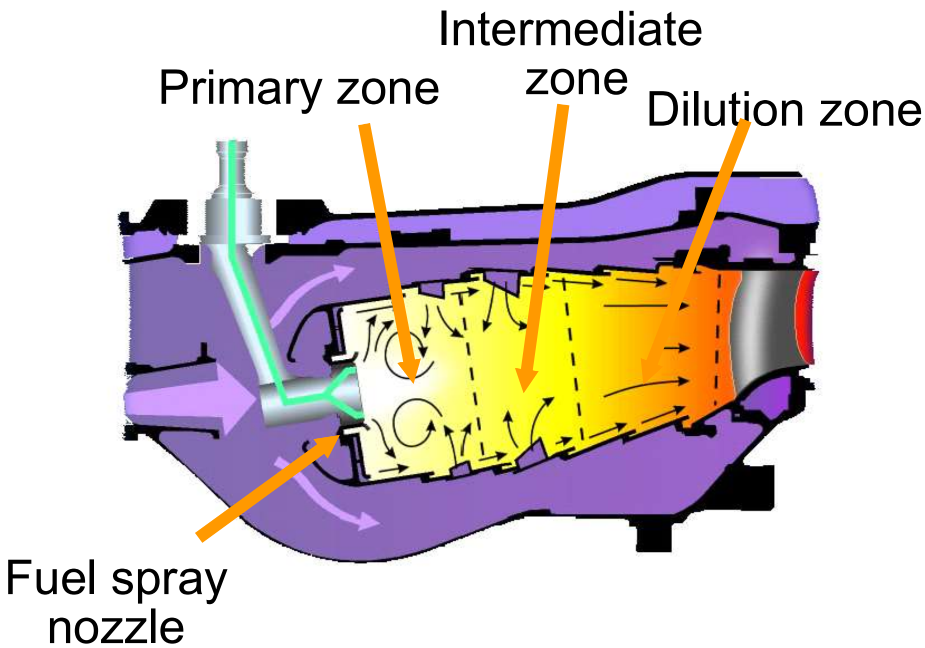
Fuel Injection





Combustor

- Fuel nozzles are like perfume atomizers
- Burn pattern is designed for a certain engine
- Temperature very high. Keep it away from the metal surface.



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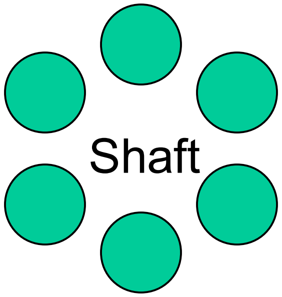
Combustors



NASA's CMC Combustor Liner
2200 F for 9,000 hours

Holes shown are for Cooling Air

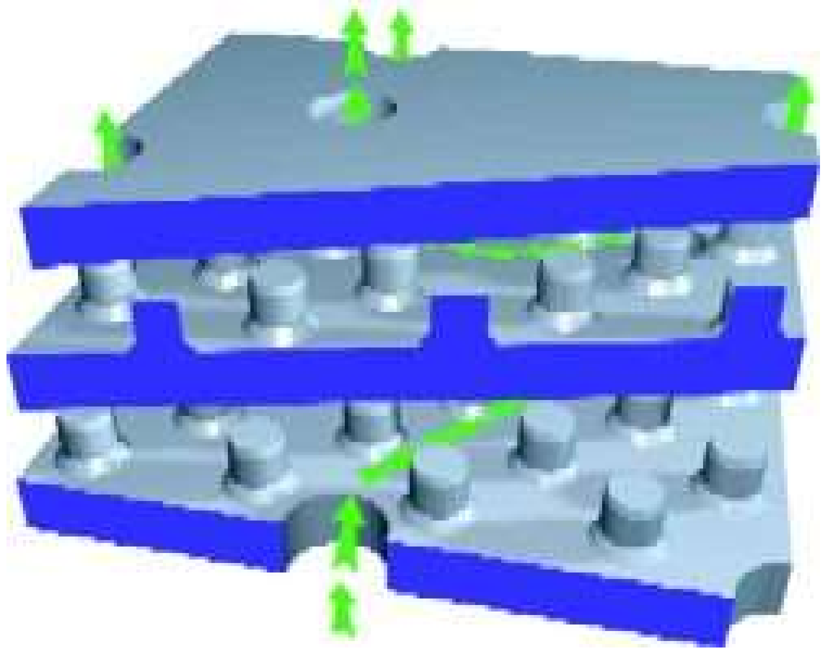
Combustion Liner by AADC
Uses "Lamilloy" cooling.

This is an annular combustor.
One large ring. Shaft in the
Middle of it.

Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

Afterburner/Nozzle

- Lamilloy® is a quasi-transpiration cooling material
- Uses sandwich panels to divert cooling air

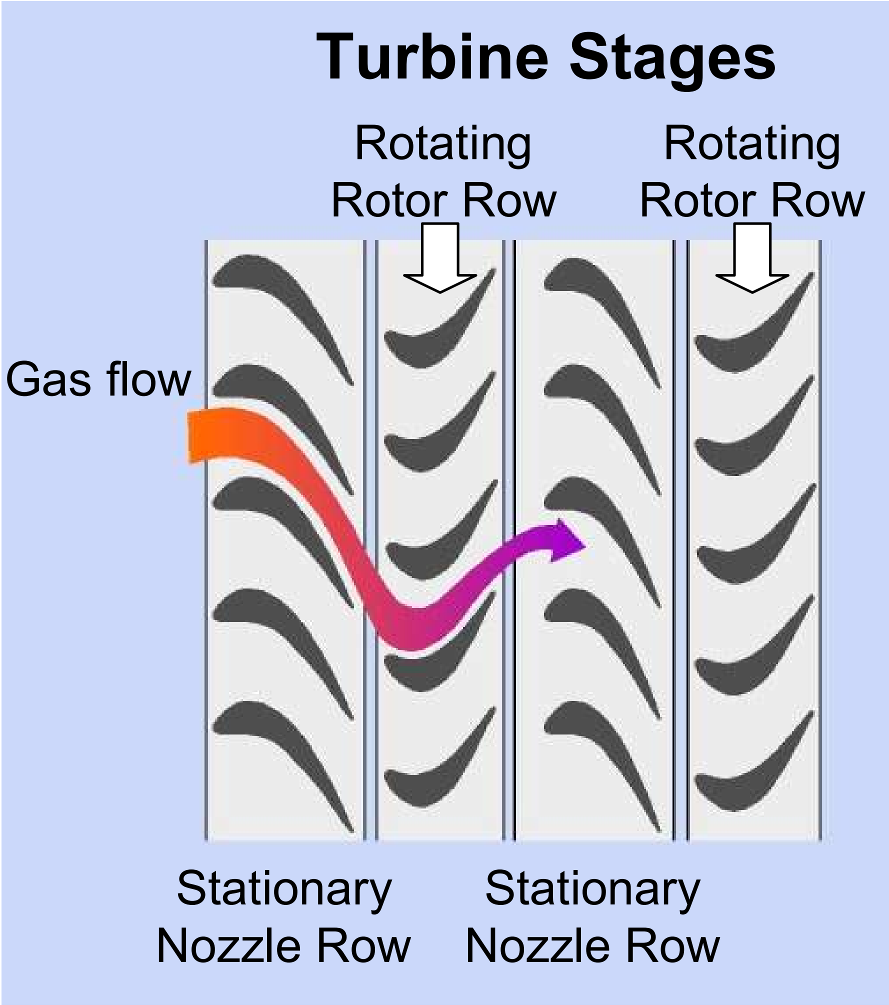


Lamilloy® Sandwich Panels

c/o Rolls-Royce

HP/LP Turbine

- HPT
  - Sometimes Single Stage
  - Efficiency: 90.5%
  - RIT: 2500-3000°F
  - Cooled blades
- LPT
  - Usually Multiple Stages
  - Sometimes uncooled



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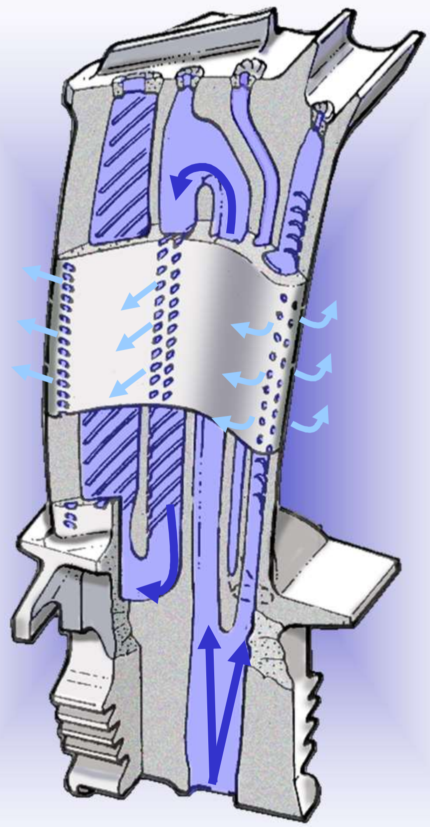
Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

KT40 Turbine Technology

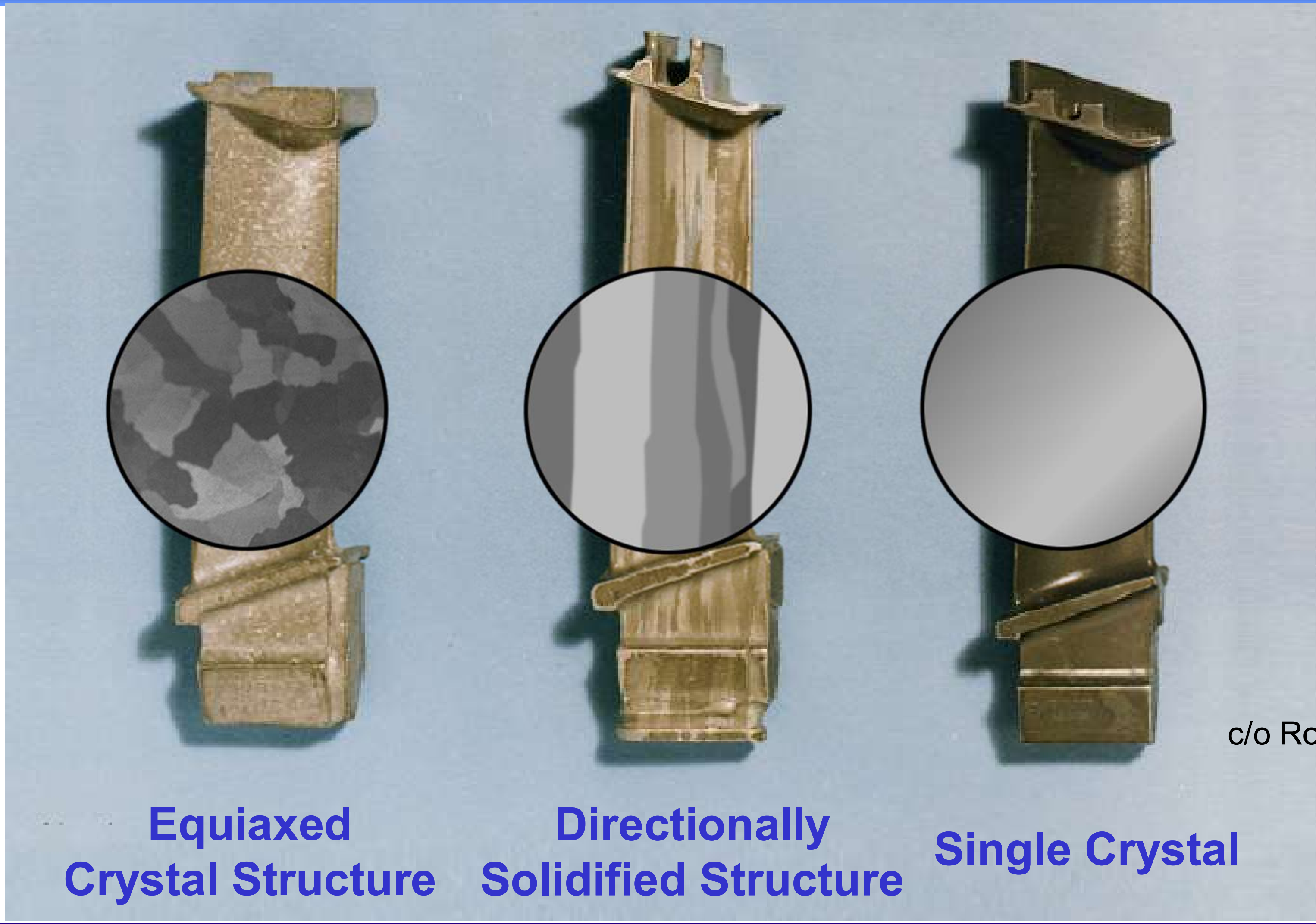
Multi-pass Cooling



Cooling air

Thermal Barrier Coating

KT40 Turbine Technology



c/o Rolls-Royce

Engine Performance

Aerospace Systems Design Laboratory
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150

Engine Performance

- The thermodynamic cycle of the engine can be calculated and used to evaluate the performance of that engine
- This can be easily done by hand, using some given information or assumptions at the beginning of the process

Key Terms

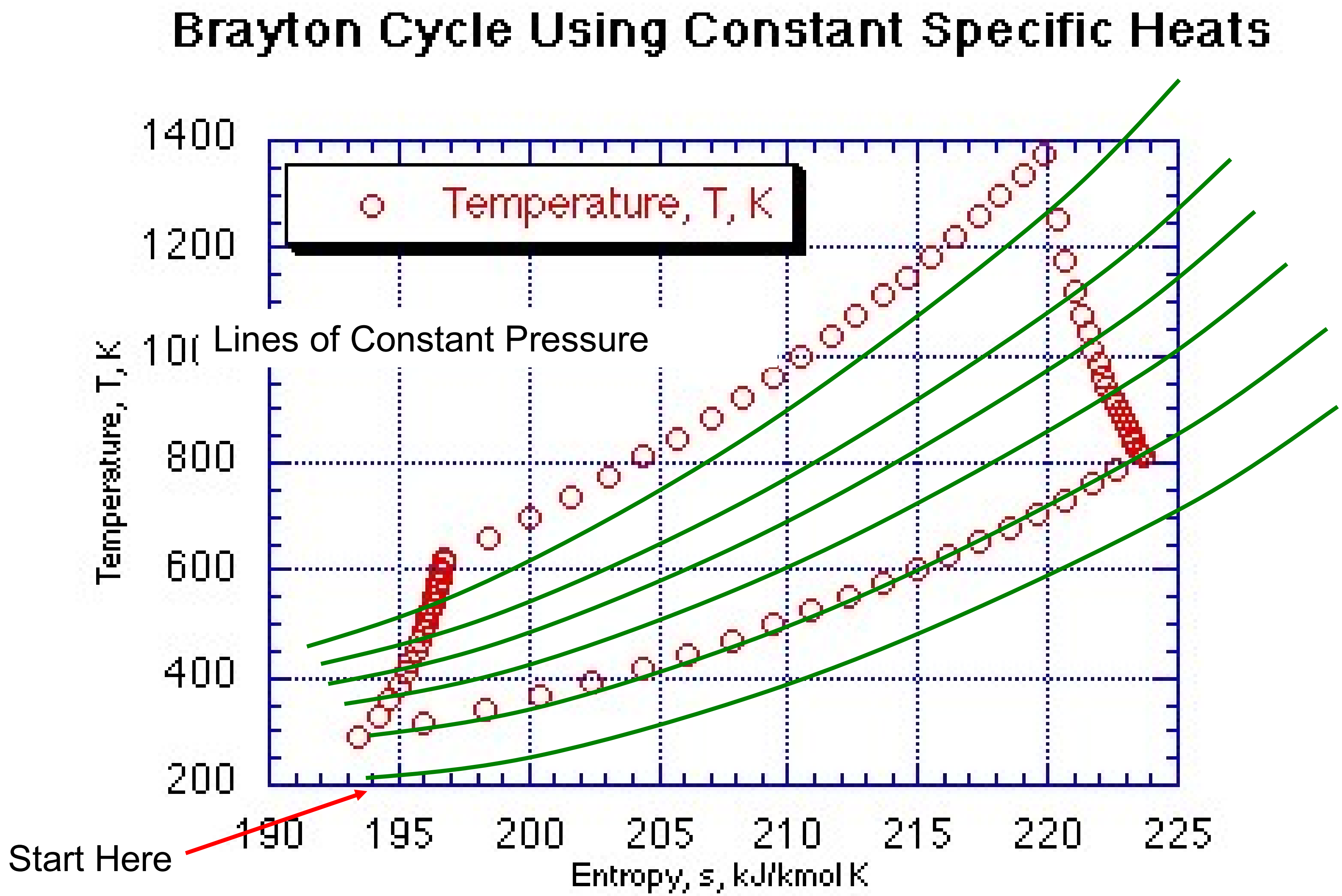
- Adiabatic = no heat loss
- Reversible Process = reactions proceed in either direction
- Isentropic = no increase in entropy
  – If something is isentropic it means it is adiabatic and reversible

- Sometimes, these terms are used interchangeably. Engines usually use the term “adiabatic” to mean no heat losses.

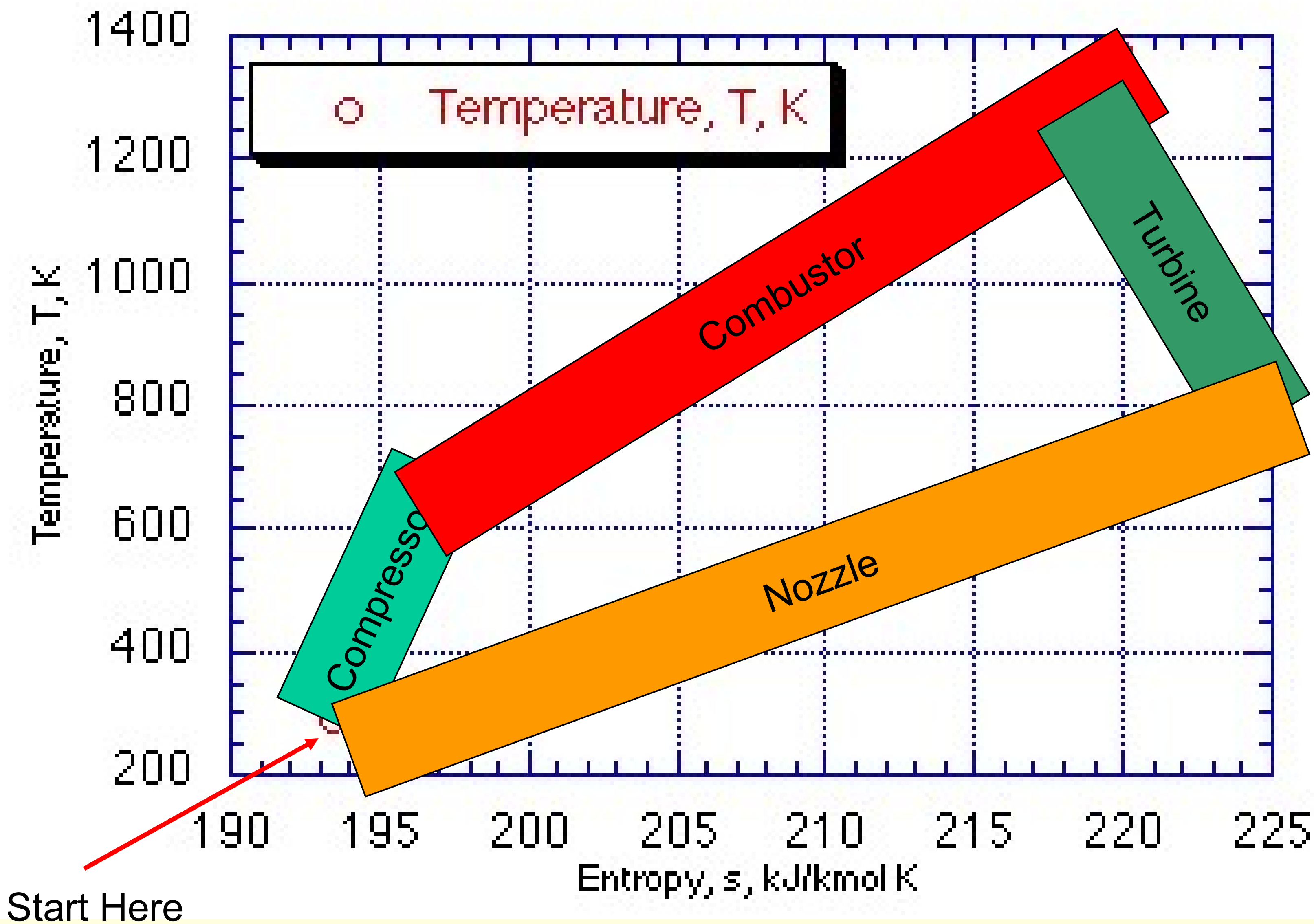
Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

Brayton Cycle

- Four Steps:
  - Compressor working fluid
    - Use a compressor. Adiabatic compression.
  - Heat Added to Fluid
  - Extract Work from Fluid
  - Cool the Fluid


Brayton Cycle Using Constant Specific Heats
Temperature, T, K
Lines of Constant Pressure
1400
1200
800
600
400
200
190
195
200
205
210
215
220
225
Temperature, T, K
Entropy, s, kJ/kmol K
Start Here

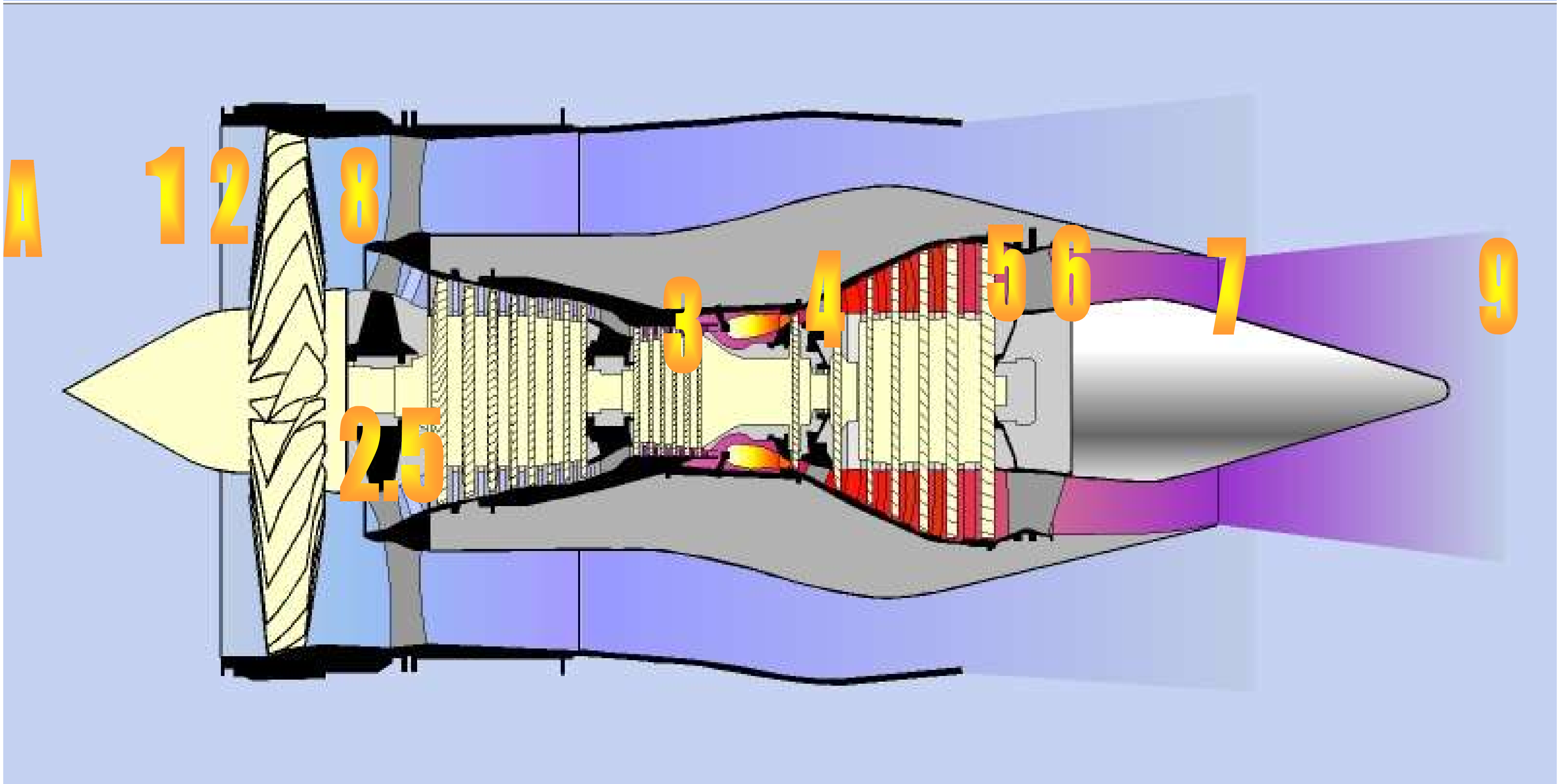
Brayton Cycle Using Constant Specific Heats



What This Tells Us:

- Want to combust at high pressure (higher efficiency)
  - Therefore, need to raise the pressure. Also we raise the temperature when we do this.
- We also want to combust at constant pressure
- We then take pressure or work out using a turbine
- Finally, we blow what is left out the nozzle and try to return to the starting point in a perfect cycle

Station Numbering



Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

Given Information

- Bypass Ratio: BPR = 1.5
  - Turbojet BPR = 0
  - Low BPR = 0-2 or 3
  - High BPR = >4 or 5
  - Ultra High BPR = 10 or 12.
    - These are for a blended wing body or tip driven fan. Not for 777 ish engines.
    - Why? The fan would hit the ground!!!

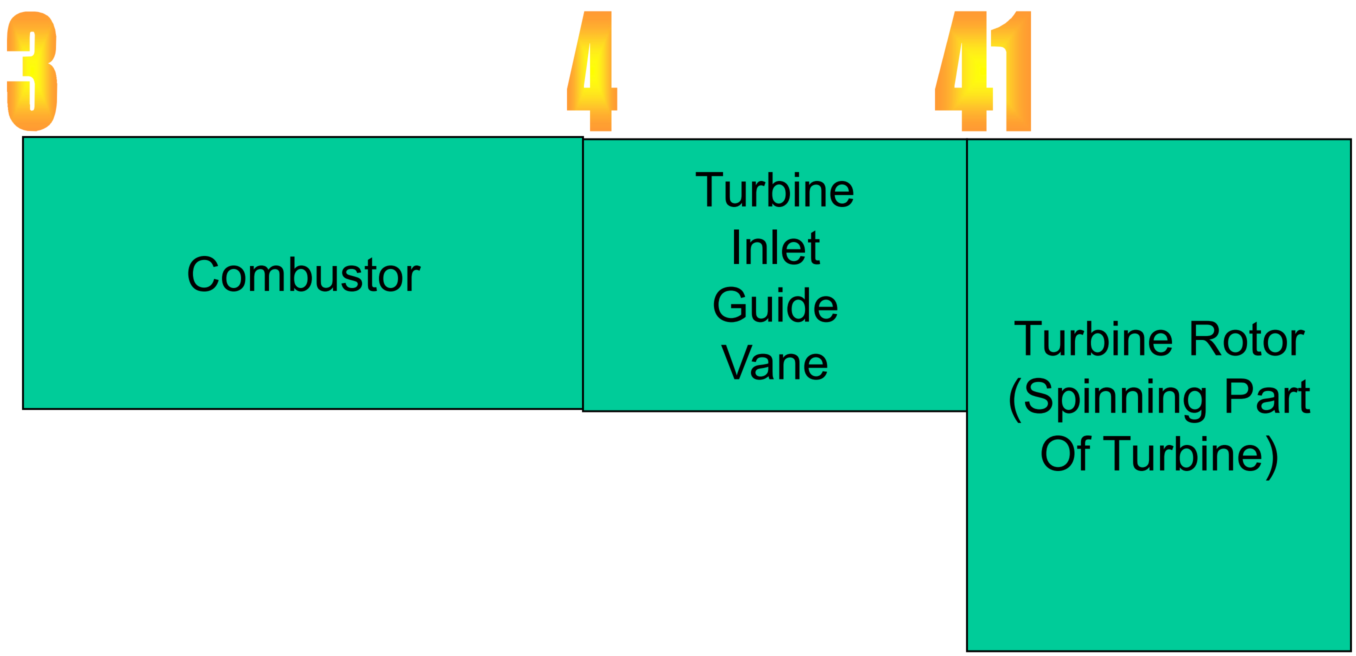
$$BPR = \frac{\dot{m}_{cold}}{\dot{m}_{hot}}$$

Given Information

- Pressure Ratio = How much does the stagnation pressure increase as work is added?
- Compressor (CPR), π_c=10 (typically 10-35)
- Fan (FPR), π_f=2.0 (typically 1.2 – 2.5)
- Fuel Heating Value (q_r=44,194,000 J/kg)
  - This is about right for JP-4 jet fuel
  - This is a measure of how much heat is released (energy, J) for each kg of fuel burned

Given Information

- RIT = 2000°K
  - This is the rotor inlet temperature
  - This is sometimes called “T41”



Given Information- Efficiencies

- Not all components can be 100% efficient
  - In fact, some are not even close!!!
- Efficiencies, η
  - Fan, $\eta_f = 91\%$
  - Compressor, $\eta_c = 88\%$
  - Combustor, η_b (b is for burner) = 98%
    - This can be as high as 99.9%. Often very high.
  - Turbine, $\eta_t = 98\%$
  - Nozzle, $\eta_n = 100\%$

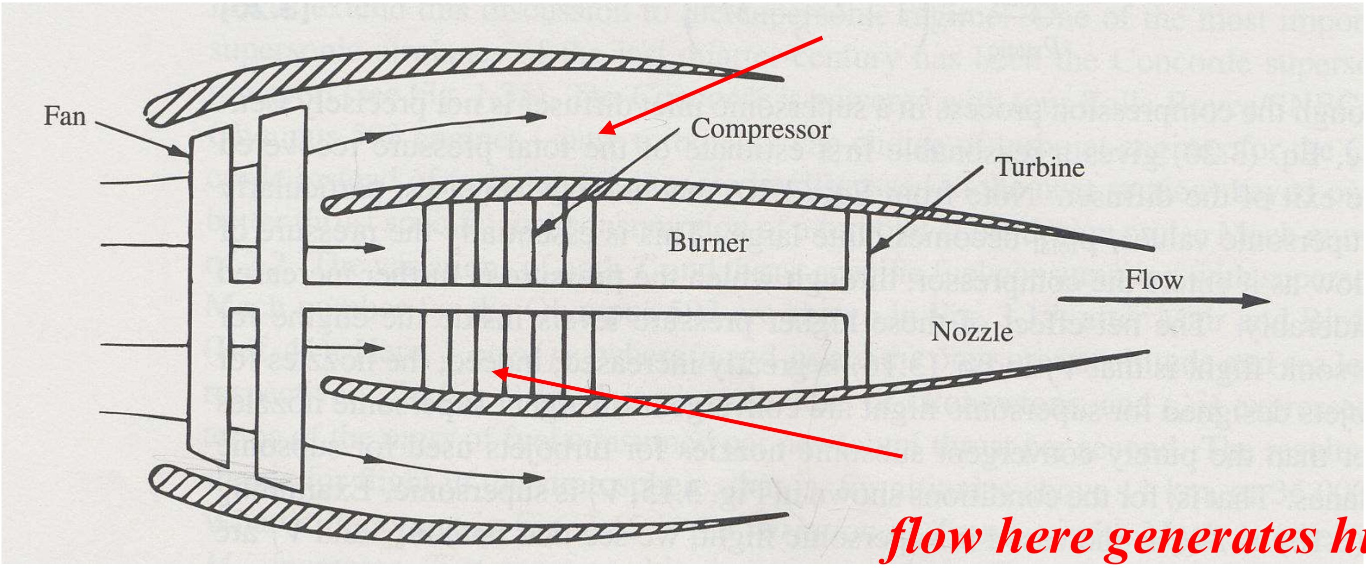
Stagnation Pressure Loss

- As we travel through the engine, we will lose some of the starting stagnation pressure.
- Stagnation pressure translates to work. Taking it away is like throwing away our ability to do work.
- This is also called “pressure recovery, r”
  - Inlet pressure recovery, $r_i = 90\%$
  - Burner Pressure Recovery, $r_b=95\%$
  - The second one is worse because the pressure in the burner is MUCH higher than the inlet pressure!!!

Turbofan Engine

Strives to combine the high thrust of a turbojet with the high efficiency of a propeller

flow here takes advantage of the propeller



flow here generates high thrust

Core of turbofan is a turbojet. However, the turbine drives not only the compressor but a large external fan

Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

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Bypass Ratio

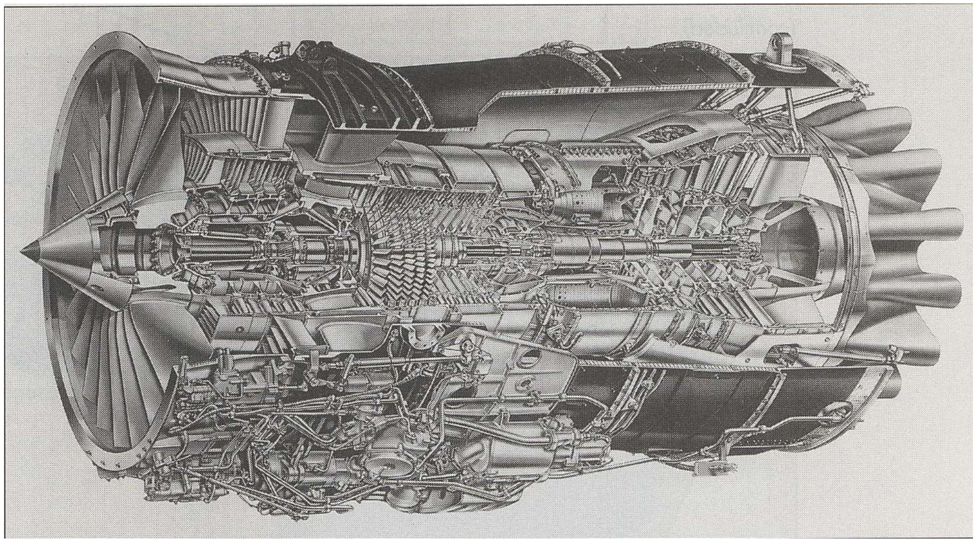
$$\textbf{Bypass ratio} = \frac{\textbf{mass flow through the fan}}{\textbf{mass flow through the core}}$$

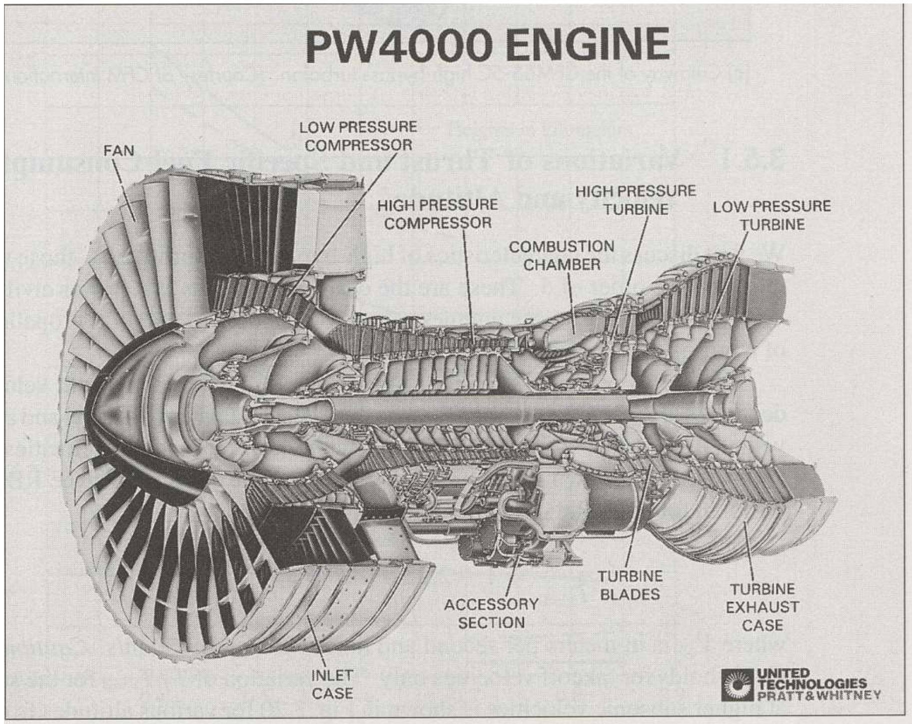
The higher the bypass ratio, the higher the propulsive efficiency

Typical bypass ratios are on the order of 5.

Typical values of TSFC are $\mathbf{0.6}\ \dfrac{\mathbf{lb}}{\mathbf{Hp \cdot {}^* \ h}}$ **(almost half of a conventional turbojet)**

Typical High Bypass Turbofan



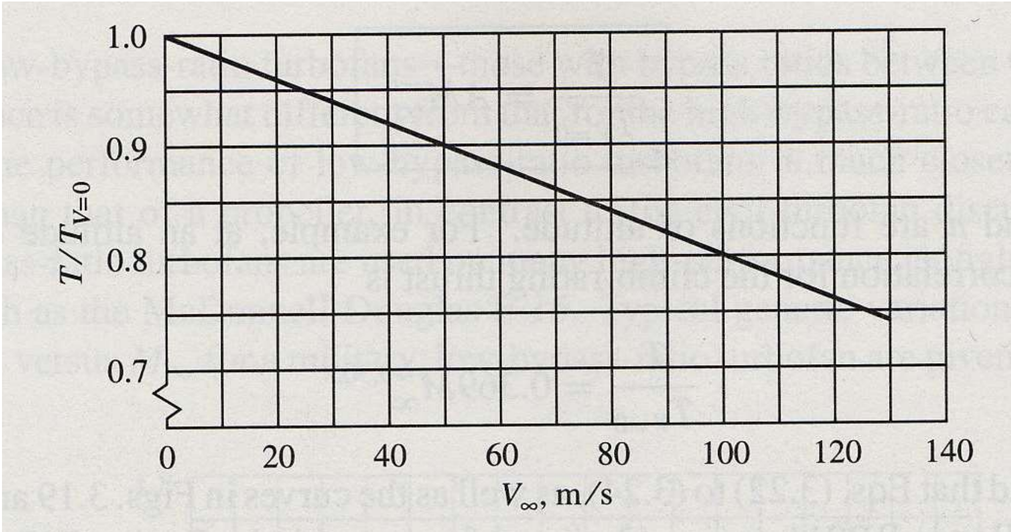


Variation of Thrust with Velocity and Altitude

$\mathbf{T} \downarrow$ **as** $\mathbf{V_\infty} \uparrow$

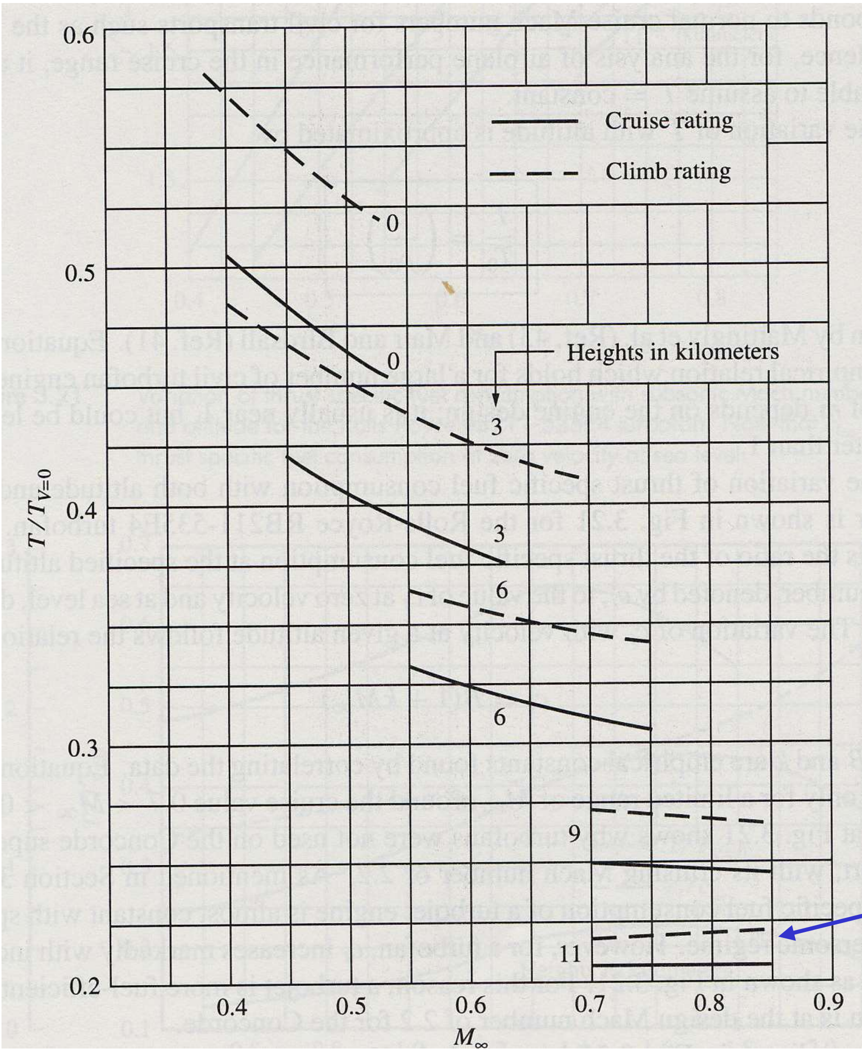
Thrust has strong variation with velocity

Civil Transport Turbofans: bypass ratios of 5+. This is considered "high"



Max Takeoff Thrust as a function of velocity at sea level
Rolls Royce RB211-535E4 Turbofan

Variation of Thrust with Velocity and Altitude



Empirical Relationship for variation of T with altitude:

$$\frac{T}{T_0} = \left[\frac{\rho}{\rho_0}\right]^m$$

(m is function of engine design, usually 1)

Note relatively flat curve at higher altitudes for M=0.70 to M=0.85.

This corresponds to normal cruise Mach numbers, so T can be assumed constant in the cruise range.

TSFC varying with Velocity and Altitude

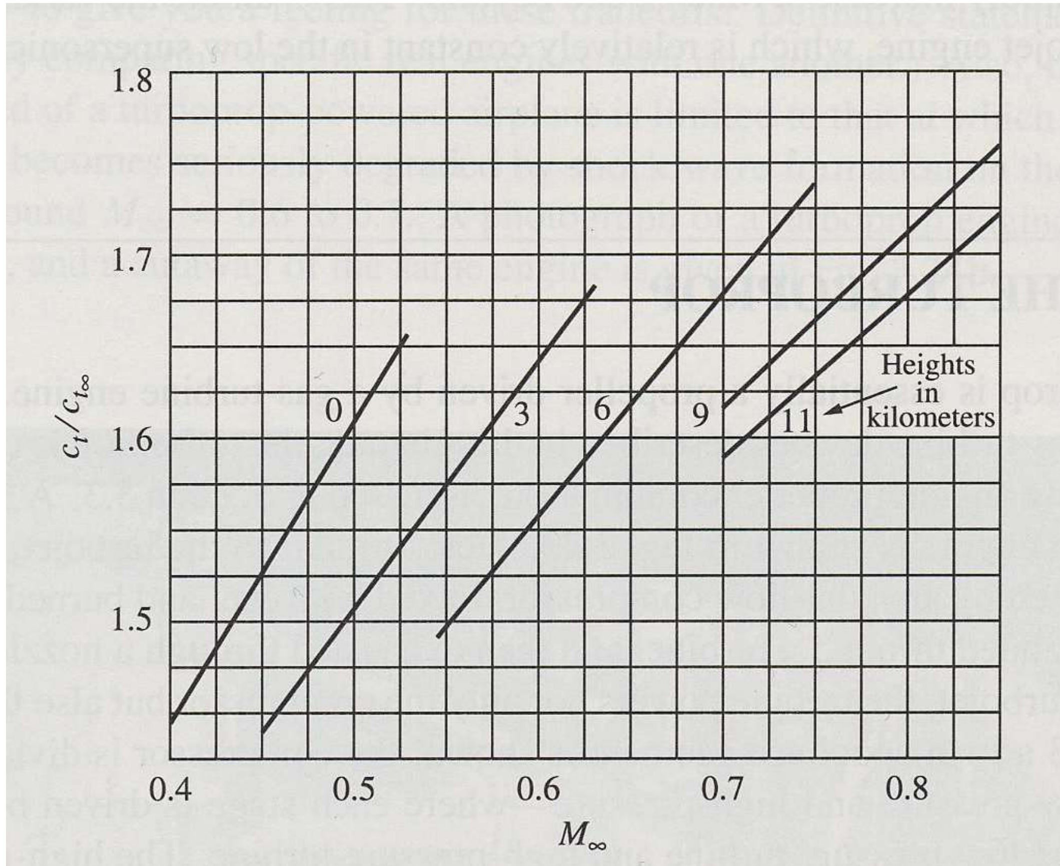
$c_t \uparrow$ as $V_\infty \uparrow$

Follows the relation:

$$c_t = B\,(1 + kM_\infty)$$

where B and k are empirical constants found from correlating engine data

c_t is near constant with altitude



Remember: for a turbojet, TSFC was near constant with speed in supersonic regime. Therefore, turbojet is more **efficient** choice for supersonic cruise aircraft than turbofan.

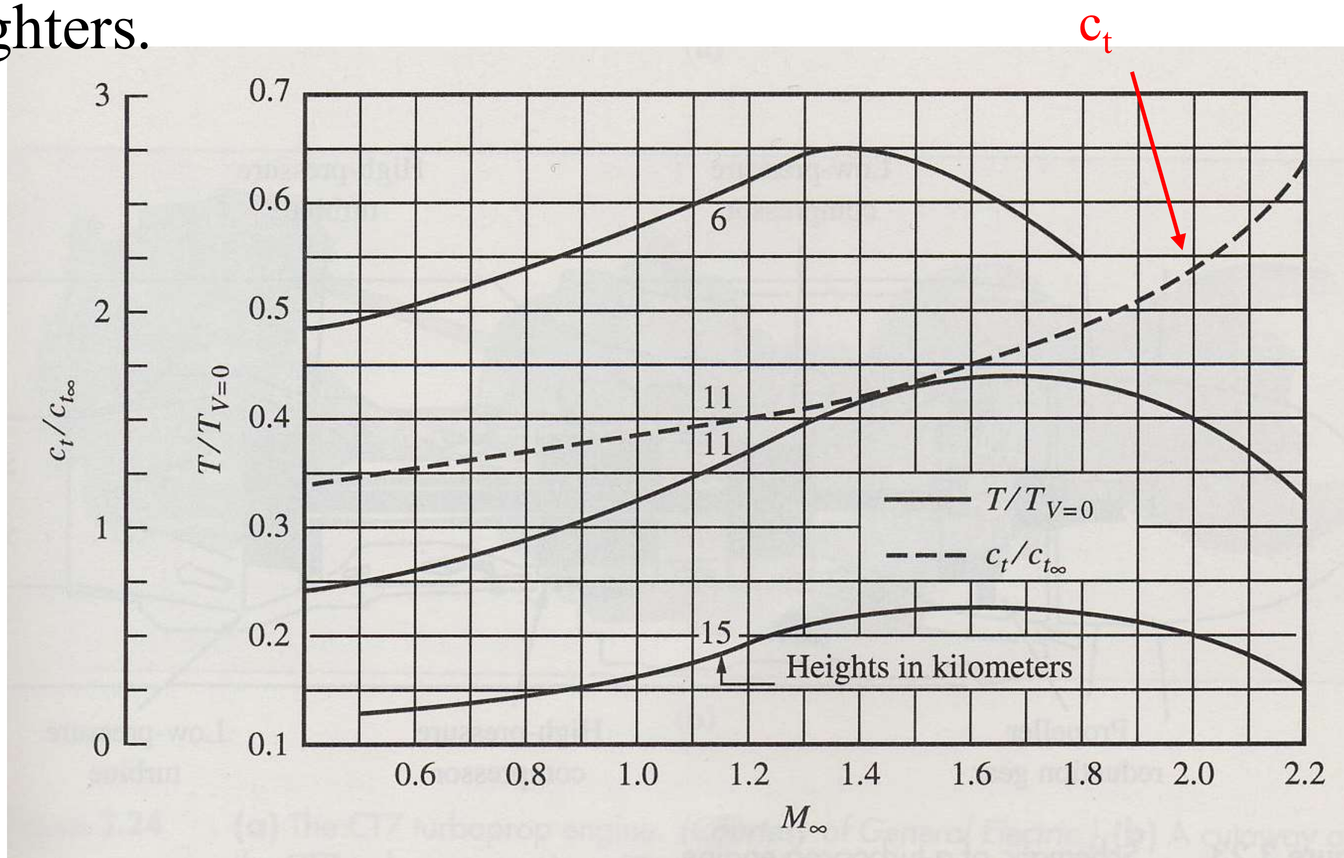
Low Bypass Ratio variations

For low bypass turbofans (between 0 and 1), the performance more closely models a turbojet than a propeller. Generally used on high performance fighters.

T ↑ as M ↑

(at higher M)

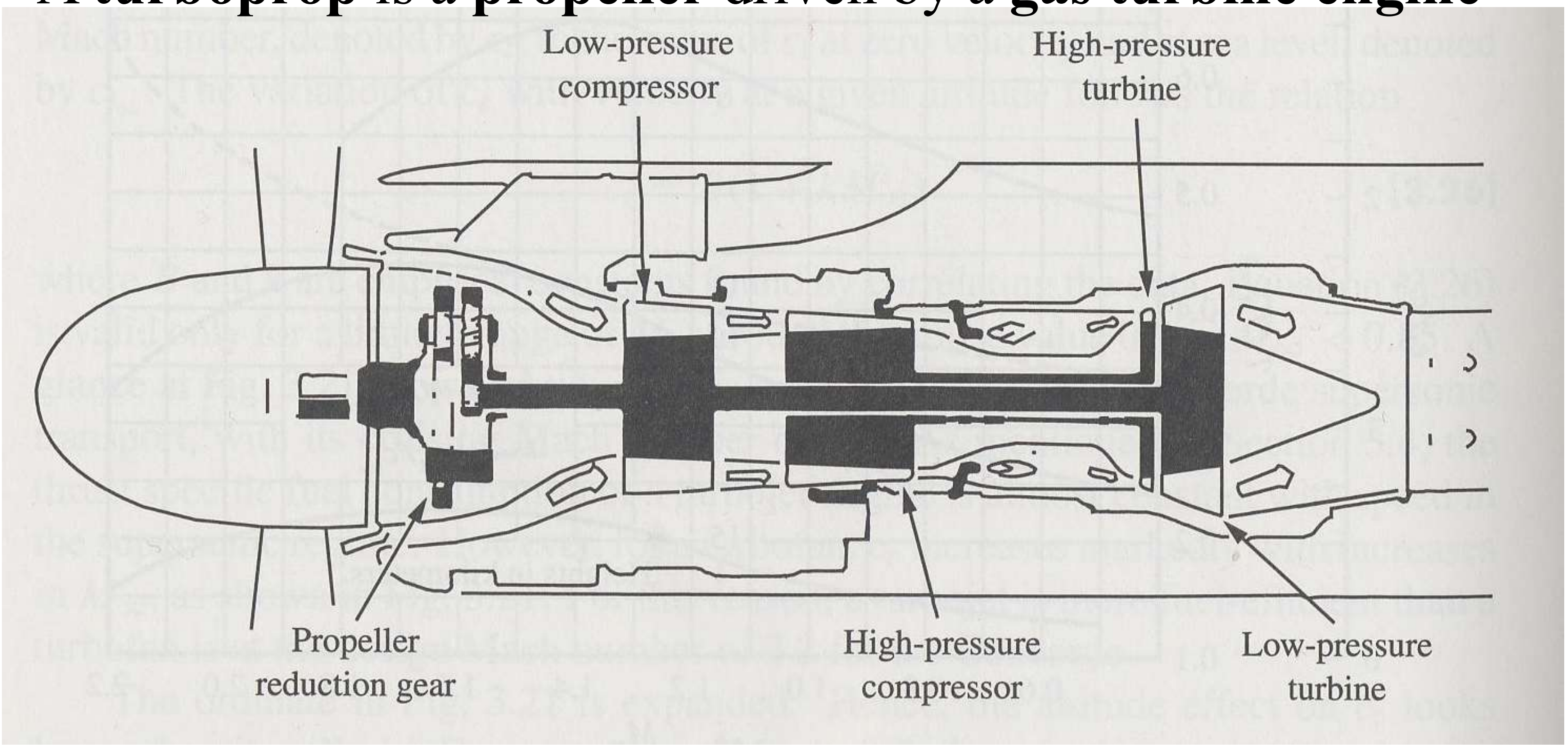
c_t ↑ as M ↑



Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

Turboprop Engines

A **turboprop** is a **propeller** driven by a **gas turbine engine**



The turbine powers both the compressor and the propeller

Most available work is extracted by the turbines, leaving little available for jet thrust. Only ~5% of total thrust is through jet exhaust.

Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

Characteristics of a Turboprop

- Turboprops generate **more thrust** than a reciprocating/propeller combination
- Turboprops generate **less thrust** than turbofans or turbojets
- Turboprops have **higher** SFC than reciprocating/propeller but **lower** than turbofans or turbojets
- Maximum flight speed of turboprop is limited by shock waves (usually M=0.6 to 0.7)

Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

Turboprop Equations

Thrust is sum of propeller thrust and jet thrust. Power available at V_∞ is

$$\boxed{P_A = (T_p + T_j)V_\infty}$$

T_p is propeller thrust
T_j is jet thrust

Due to the propeller aspect of the turboprop, performance is often in terms of power

$$\boxed{P_A = \eta_{pr} P_S + T_j V_\infty}$$

P_S is shaft power

Equivalent shaft power, P_{es}, includes the effect of jet thrust

$$\boxed{P_A = \eta_{pr} P_{es}}$$

This relationship defines P_{es}

Turboprop Equations

Combining above two equations,

$$\boxed{P_{es} = P_S + \frac{T_j V_\infty}{\eta_{pr}}}$$

This relates equivalent shaft power to actual shaft power and jet thrust.

TSFC is defined as

$$\boxed{c_t = \frac{\dot{\omega}_{fuel}}{T}}$$

We don't use power because it could be confusing as to which power we are referring to:

P_s

P_{es}

P_A

Useful approximation: at static conditions (engine operating with airplane at zero velocity on the ground), a turboprop produces 2.5 lb/shp

Variations of Power with Velocity/Altitude for Turboprops

Recall:

$$P_A = T_A V_\infty$$

At $M > \sim 0.7$, $T_A \downarrow$

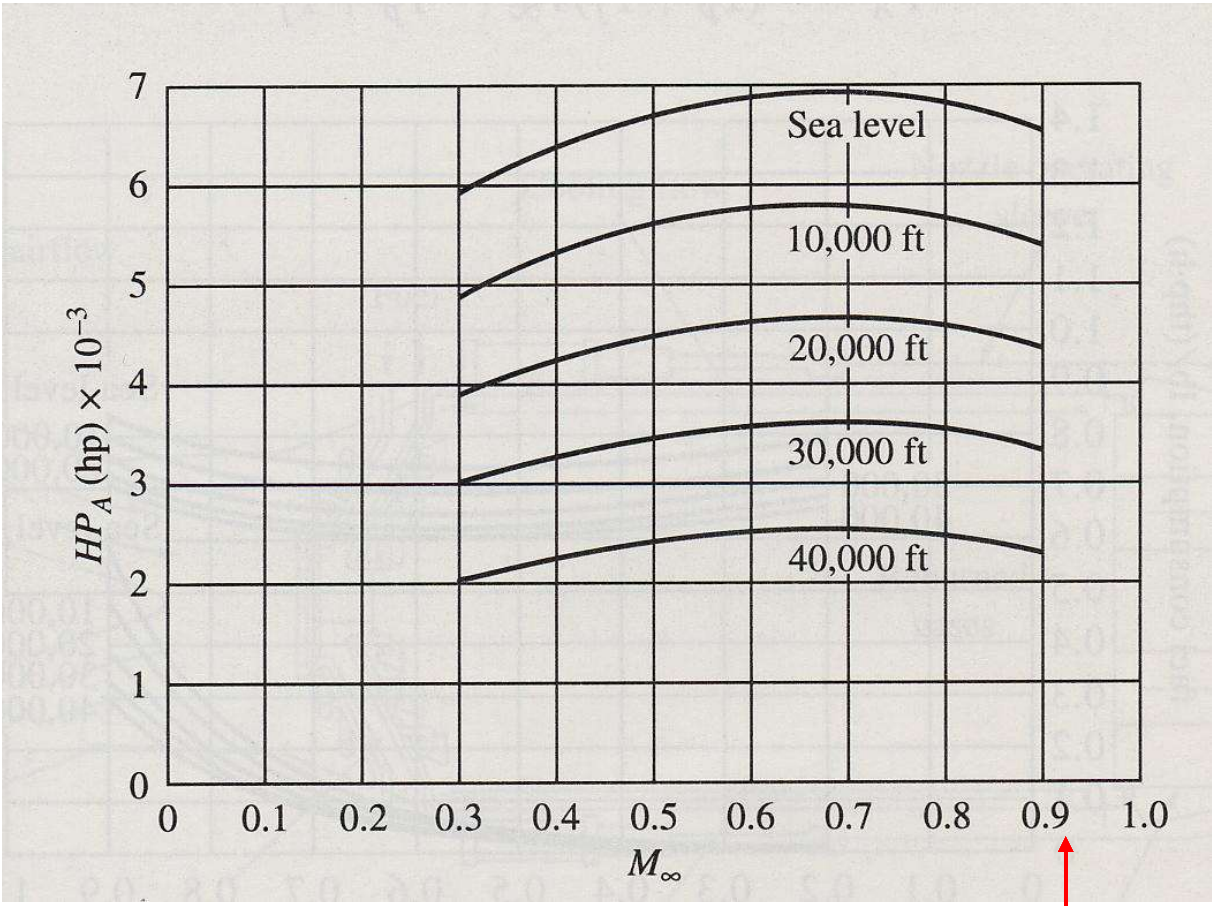
Combined effect of V_∞ and T_A results in

$\boxed{P_A \text{ is constant with } M_\infty}$

For altitude, use

$$\boxed{\frac{P_A}{P_{A,0}} = \left[\frac{\rho}{\rho_0}\right]^n}$$

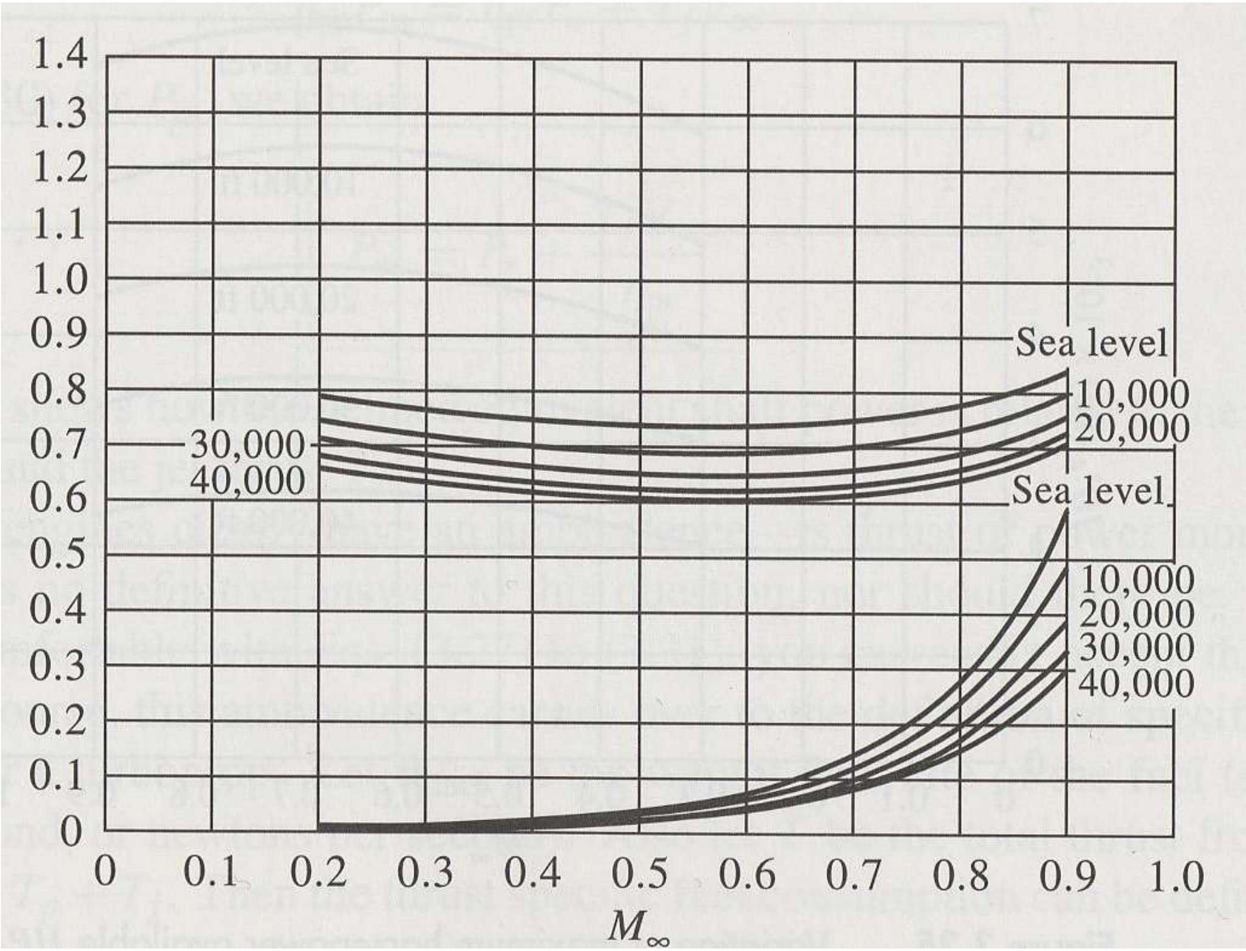
n = depends on engine, use 0.7 for unknown



Shocks form here

Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

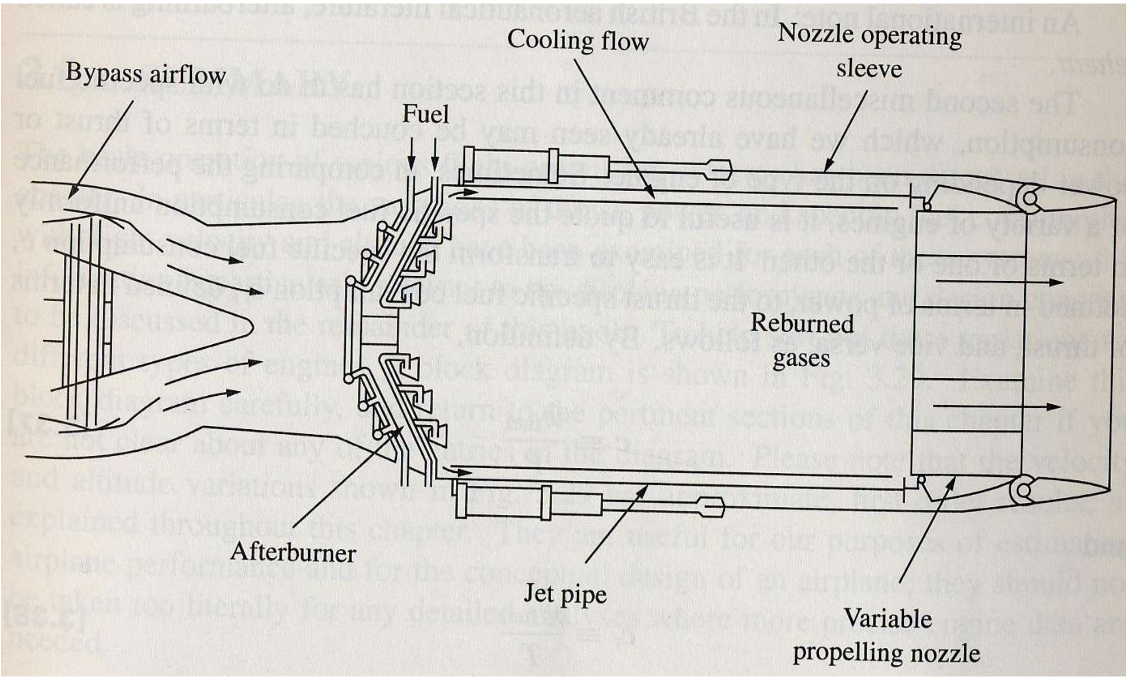
Variations of SFC with Velocity/Altitude for Turboprops



SFC can be assumed constant with velocity and altitude

Afterburners

For a turbojet or turbofan, the fuel-air mixture in the combustion chamber is lean (more oxygen than fuel). Extra fuel is injected into the oxygen-rich exhaust gas and then ignited downstream of the turbine. This is called **afterburning.**



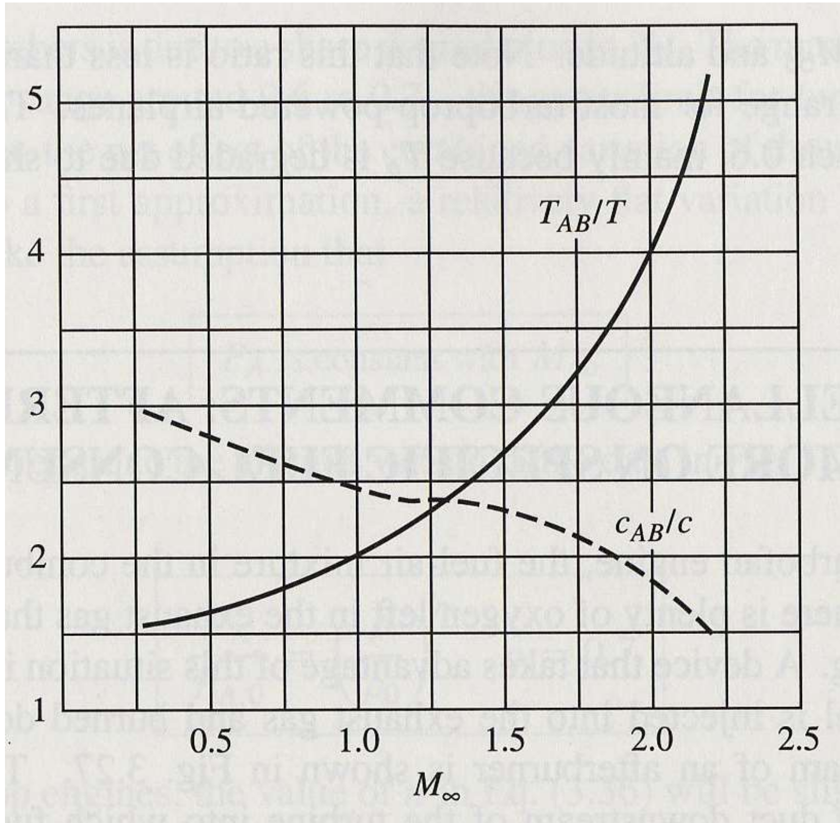
Afterburners are used for short periods of greatly increased thrust, but burns much fuel, so must be used carefully.

Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

Performance of Afterburner

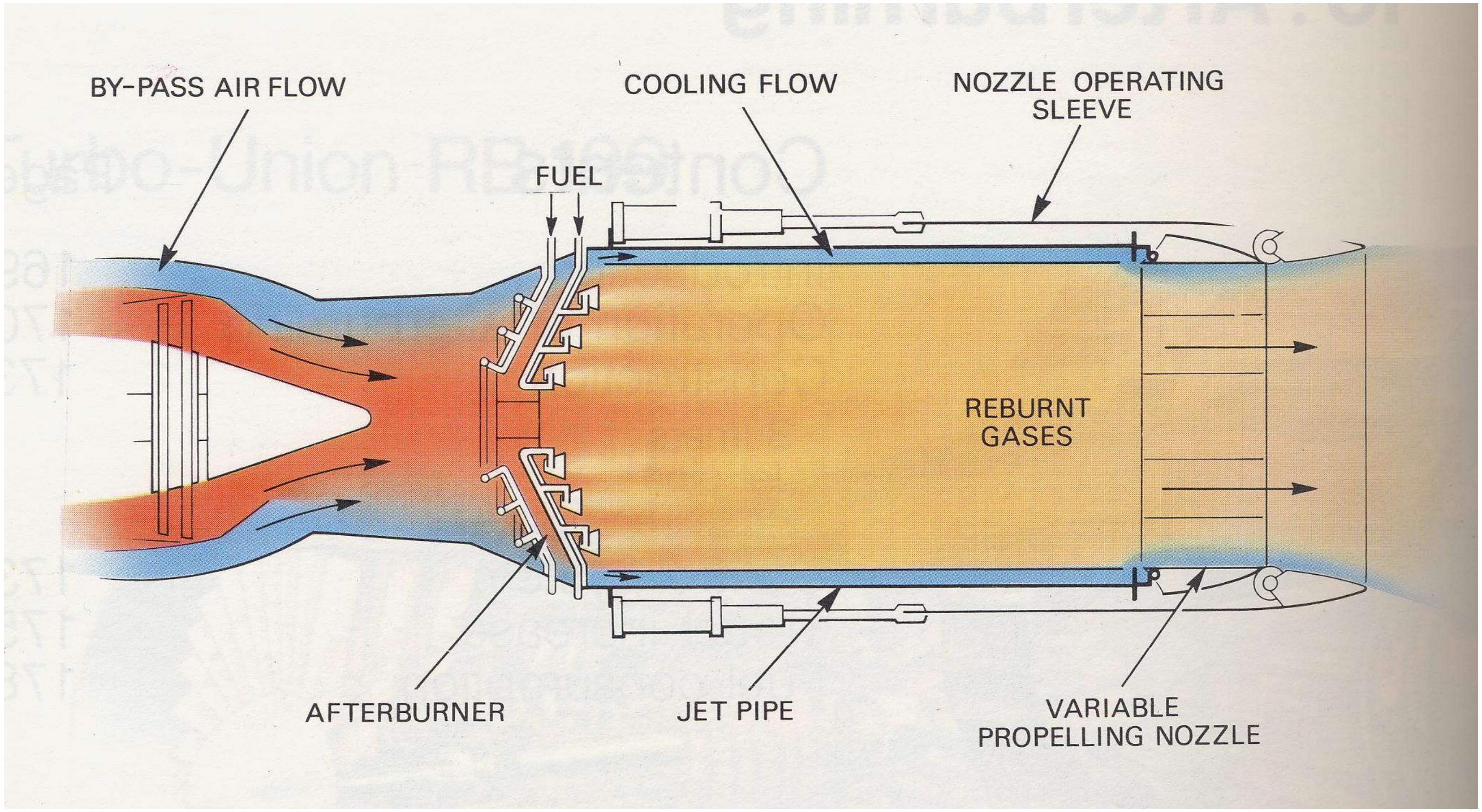
The Concorde uses afterburning for rapid climb and acceleration.

The British call afterburning *reheat*.



Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

Afterburner



Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

Transforming Fuel Consumptions

It is useful to be able to transform specific fuel consumption, c, (which is in terms of power) to thrust specific fuel consumption, c_t, (which is in terms of thrust).

$$c = \frac{\dot{\omega}_{fuel}}{P} \quad \text{and} \quad c = \frac{\dot{\omega}_{fuel}}{T} \quad \text{combine to give} \quad \boxed{c_t = \frac{cP}{T}}$$

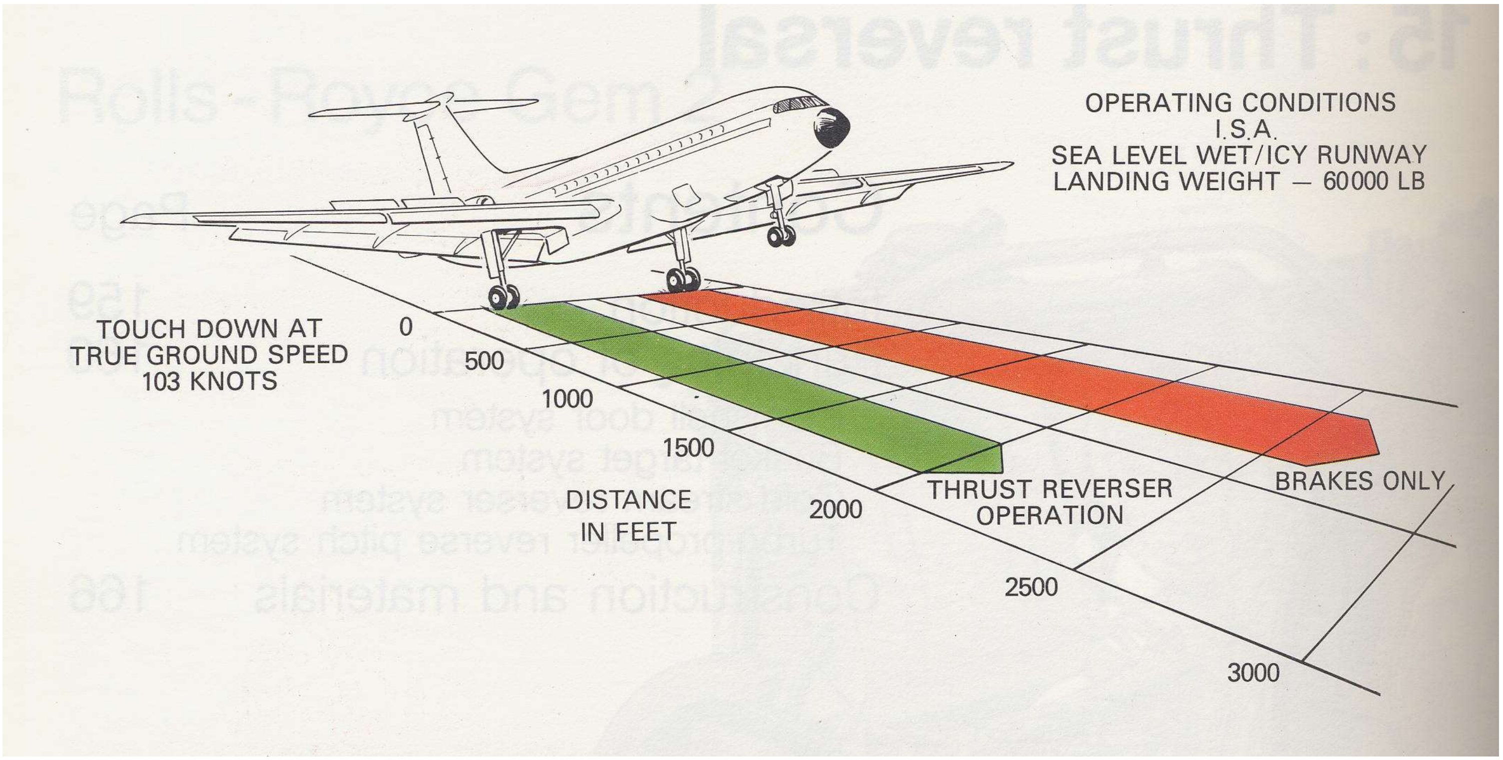
$$P = \frac{P_A}{\eta_{pr}} \quad \text{and} \quad P_A = TV_\infty \quad \text{combine to give} \quad \boxed{P = \frac{TV_\infty}{\eta_{pr}}}$$

Substituting two boxed equations gives:

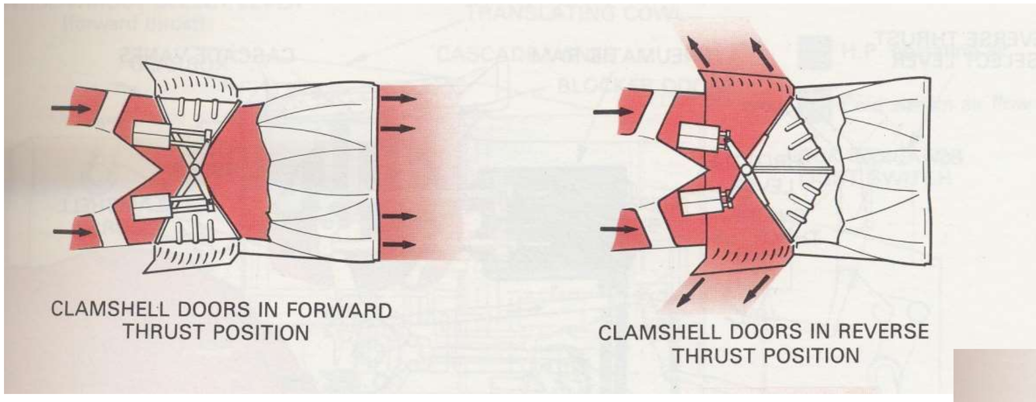
$$\boxed{c_t = \frac{cV_\infty}{\eta_{pr}}}$$

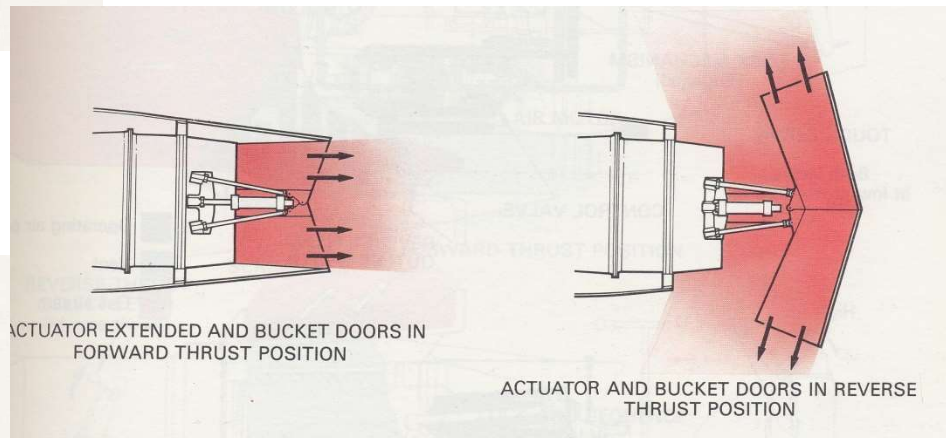
Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

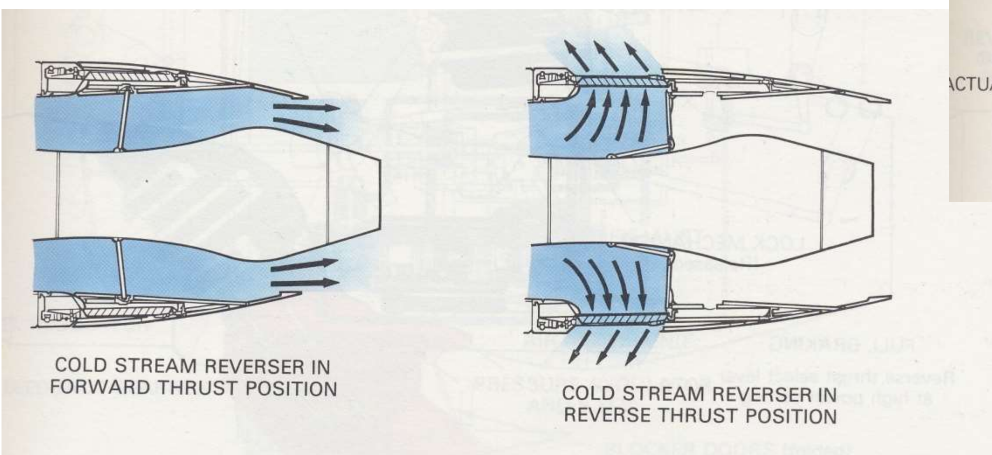
Thrust Reversers



Thrust Reversers







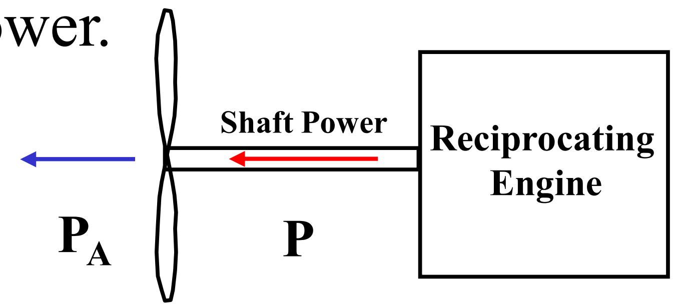
Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

Thrust Reversers

Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

The Propeller

- Realize, like Wilbur Wright did in 1902, that a propeller is nothing more than a twisted wing.
- Like a wing, a propeller produces friction drag, form drag, induced drag, and wave drag. Thus, it is a **loss mechanism** and the power output of the engine/propeller combination will always be less than the shaft power.



$$P_A < P$$

Propeller efficiency is defined as:

$$\boxed{P_A = \eta_{pr} P}$$

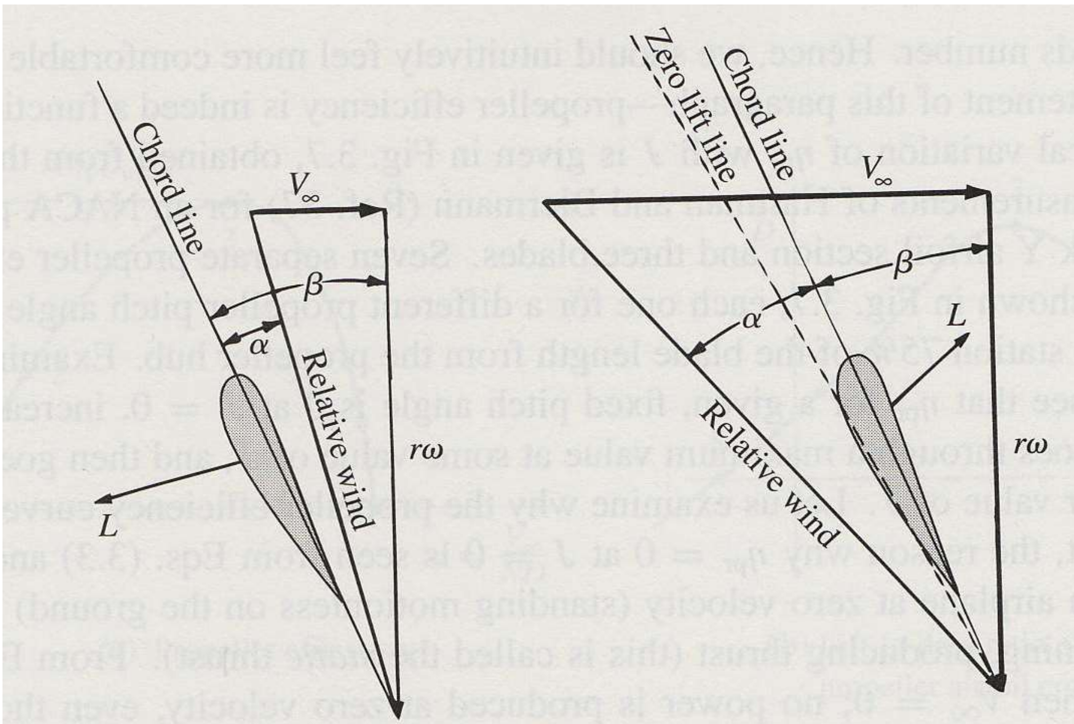
$$\eta_{pr} < 1$$

Propeller efficiency is a function of the *Advance Ratio*

Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

Advance Ratio, J

Local relative wind is the vector sum of V_∞ and the translational motion of the propeller section due to propeller rotation, *rw*.



***pitch angle, β*, between airfoil chord line and plane of rotation**

The ratio $\dfrac{V_\infty}{r\omega}$ sets the direction of the local relative wind

Advance Ratio, J

$$\frac{V_\infty}{r\omega} = \frac{V_\infty}{r(2\pi N)}$$

N is number of propeller revolutions per second

Evaluated at propeller tip:

$$\left(\frac{V_\infty}{r\omega}\right)_{\text{tip}} = \frac{V_\infty}{(D/2)\,(2\pi N)} = \frac{V_\infty}{\pi N D} = \frac{J}{\pi}$$

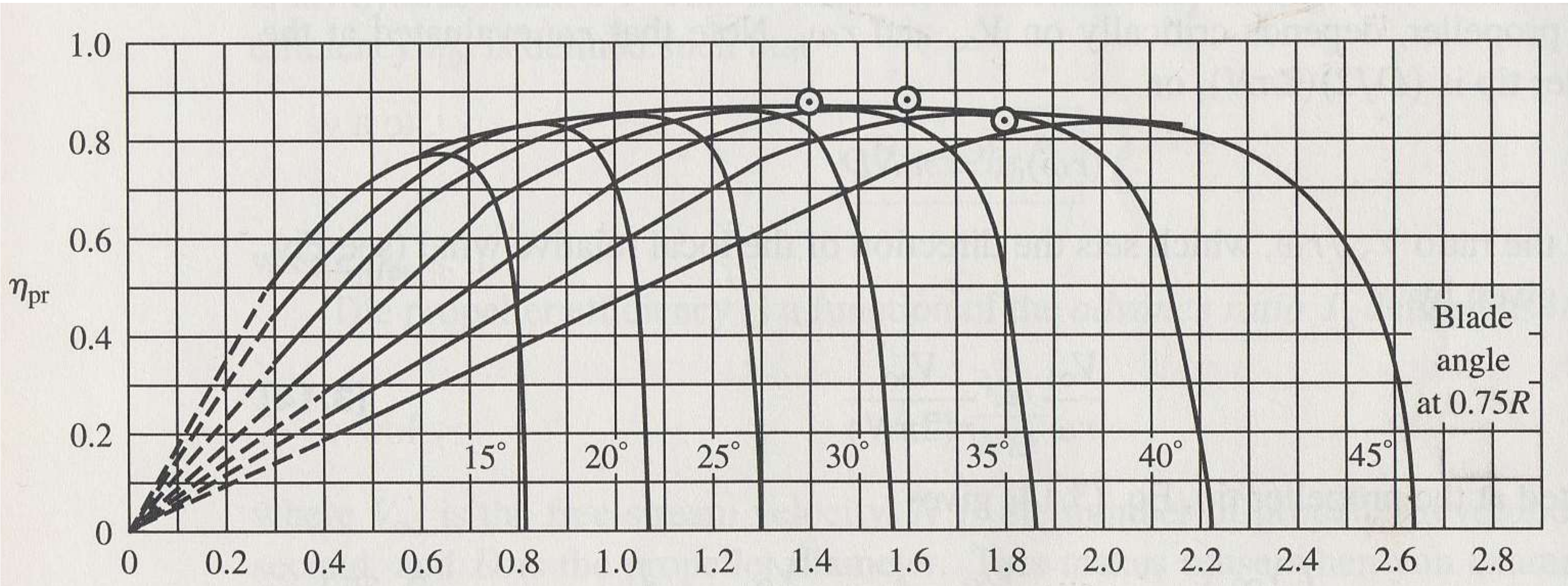
$$\boxed{J = \frac{V_\infty}{ND}}$$

propeller efficiency is a function of J, the advance ratio

J is a similarity parameter for propeller performance, similar to Mach number and Reynolds number

Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

Propeller Efficiency and J

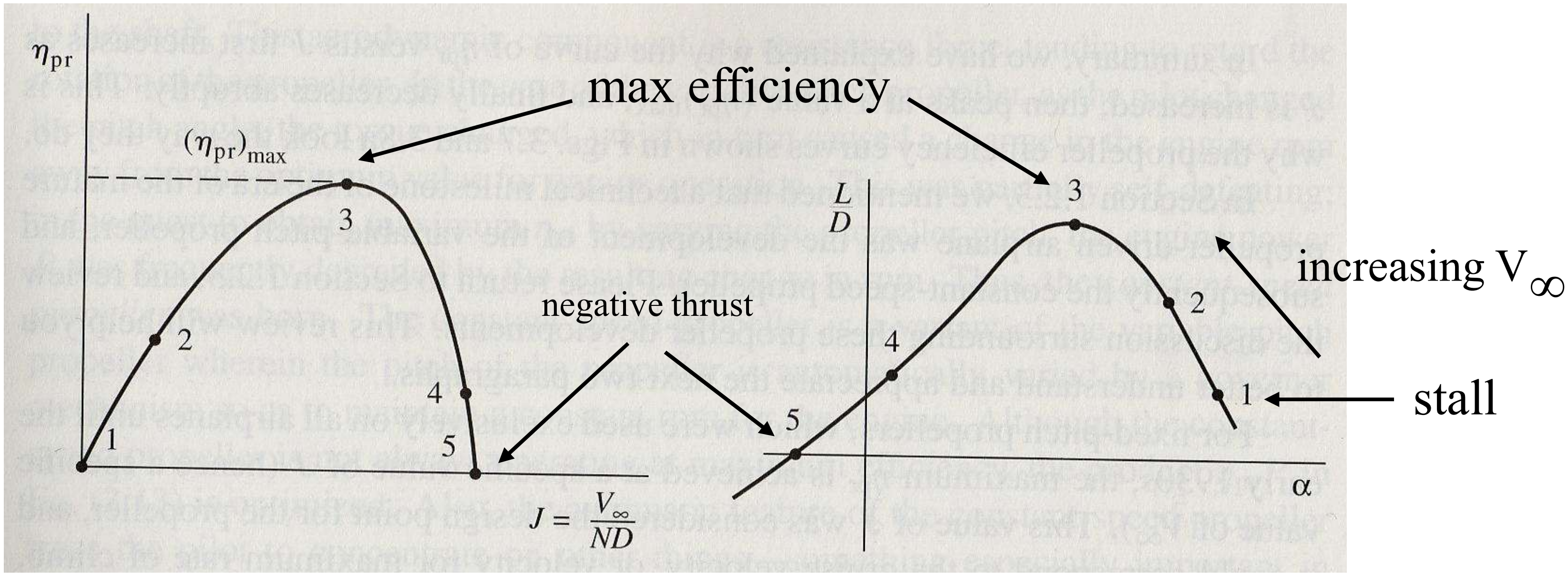


Each curve is for a different pitch angle, β

Remember:

$$P_A = T\,V_\infty = \eta_{pr}\,P \qquad \text{so when } J = 0, \eta_{pr} = 0$$

Shape of Propeller Efficiency Curve



Propeller Efficiency

Lift to Drag Ratio of Airfoil Section

For a fixed pitch propeller, β is constant at any given r. Also, for a given N, rω is constant

However, as V_∞ changes, the angle of attack will change, as will the efficiency.

Feathering

- A propeller is feathered when its pitch is adjusted so that the drag is minimized, and there is little chance of autorotation when the engine is turned off but the aircraft is still moving (the windmill effect).

- Feather the prop when there is an engine failure in midflight, or sometimes on a multi-engine aircraft when one or more engines is turned off and the others are used for taxi.

Rate of Climb and Propellers

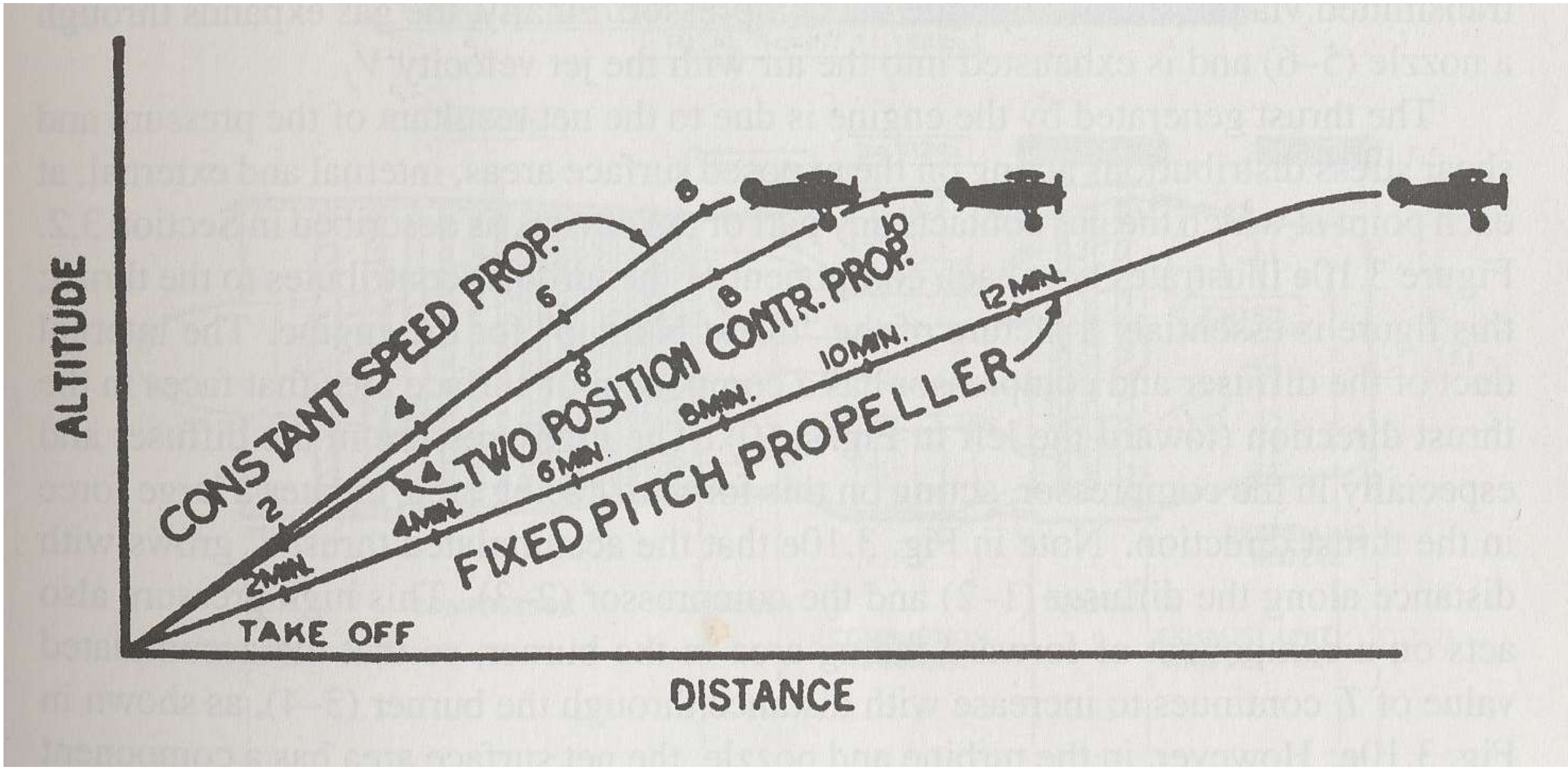


Chart from 1940, the beginning of the mature propeller-driven airplane era