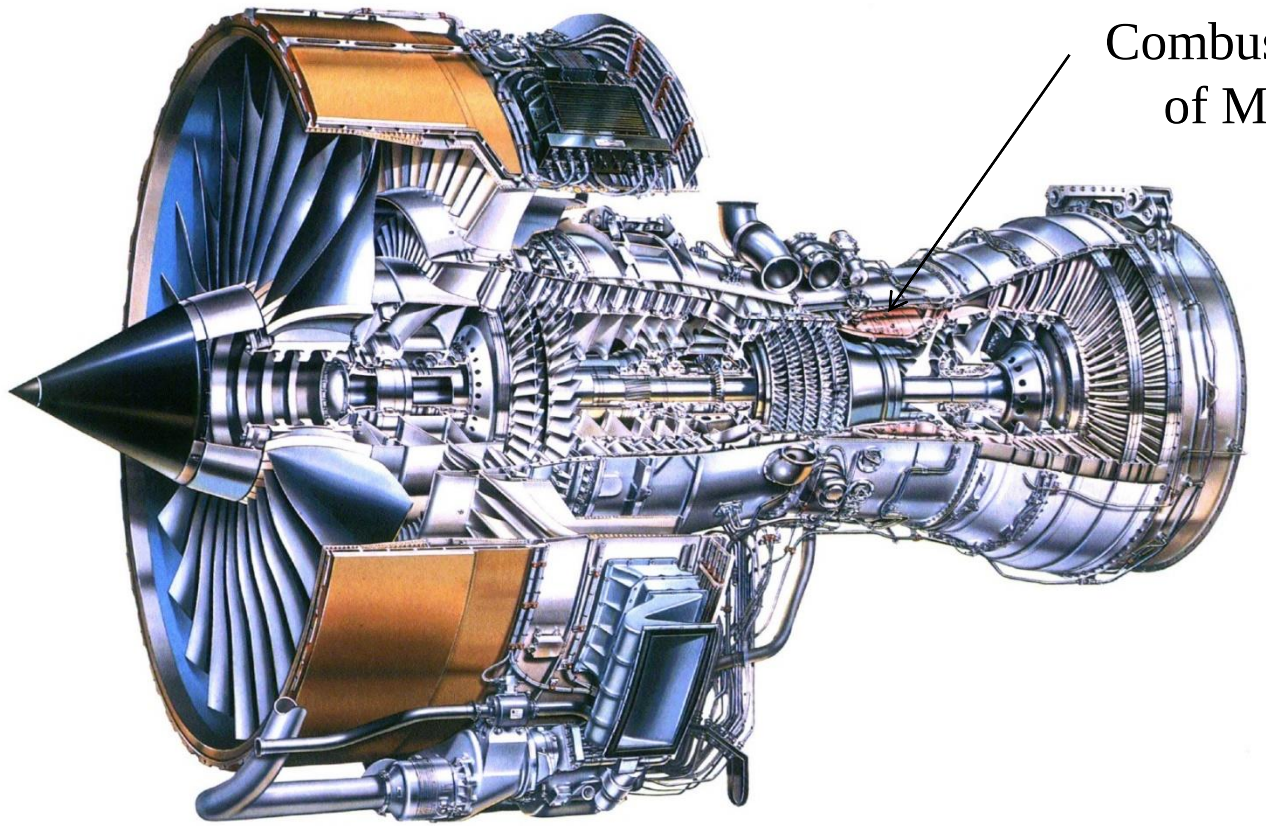
Combustion

Lecture 12



Objective: ***to describe the workings of a Combustion System***

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Combustion Key Issues

- Average temperature rise up to 1000 K;
- Peak gas temperatures 1000K above melting point of walls;
- Energy release at rate of 150 MW enough to:
  - Boil 75000 kettles or
  - Or produce 100,000 Lb of thrust
- Walls glow cheery red
- Must ignite at:
  - - 8 ^{o}C, 0.4 bar for altitude relight
  - - 40 ^{o}C, air & fuel for cold start on ground

COMBUSTION CHARACTERISTICS
Desirable Characteristics

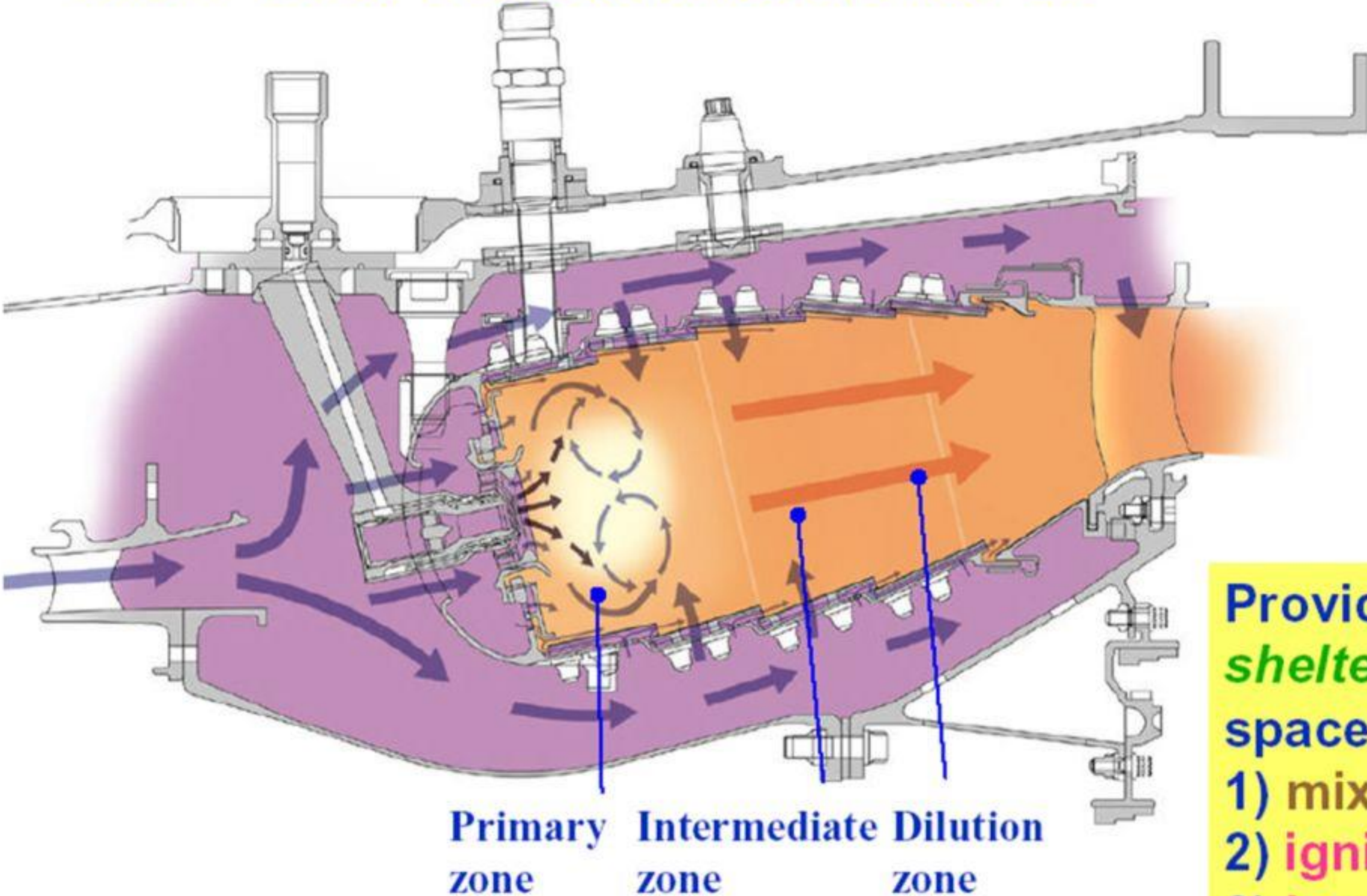
- Complete Combustion for Low emissions & Low smoke
- Low total pressure loss
- Stability of Combustion Process
- Even temperature distribution with no hot spots
- Short length and small cross section
- Freedom from flameout
- Relight ability
- Operation over a wide range of conditions e.g. mass flow rates, pressures and temperatures

Chemistry of Combustion:

$$C_{12}H_{24} + 18O_2 + 67.7N_2 \rightarrow 12CO_2 + 12H_2O + 67.7N_2 + heat$$

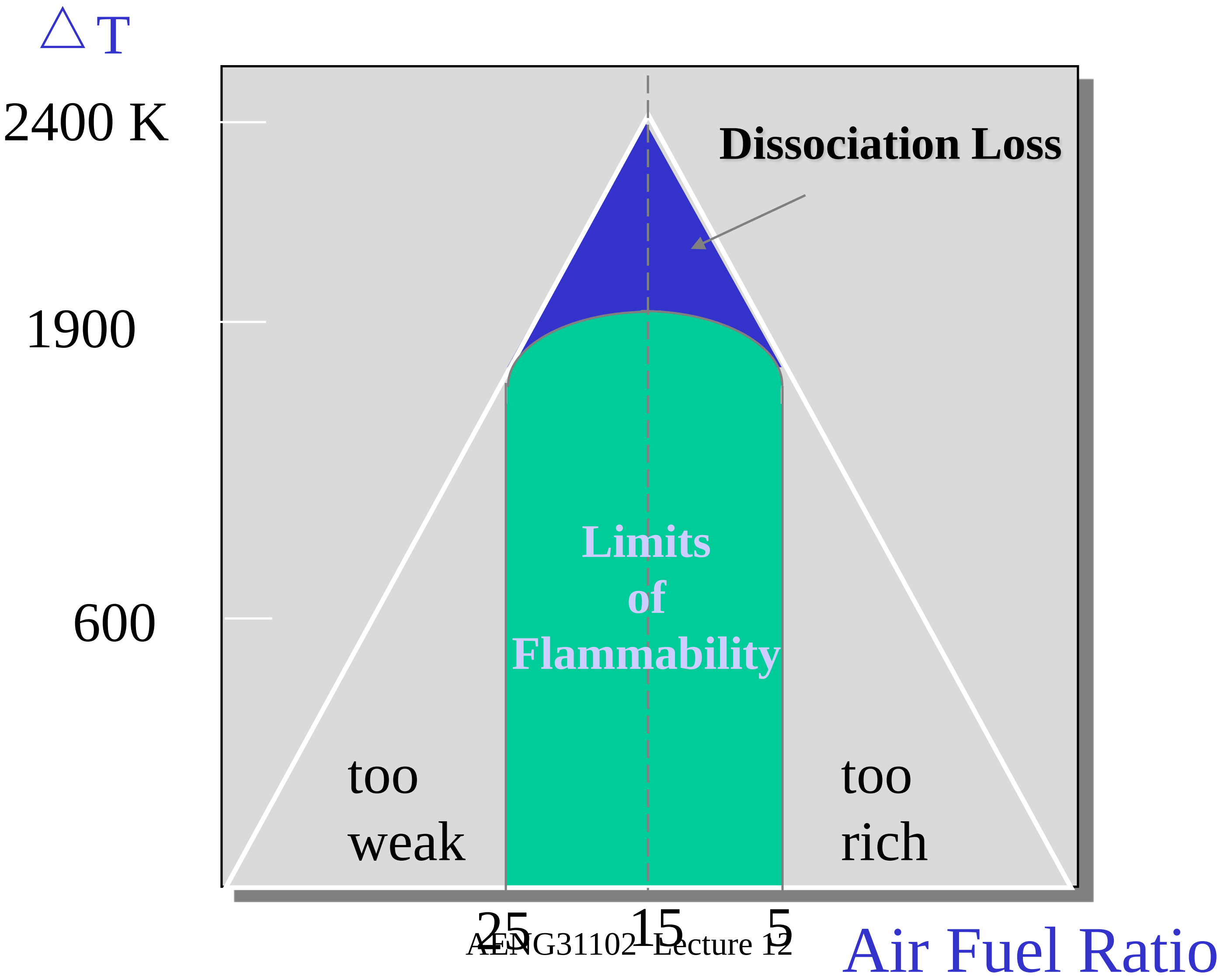
where $C_{12}H_{24}$ is kerosene.

How does the combustor do it?

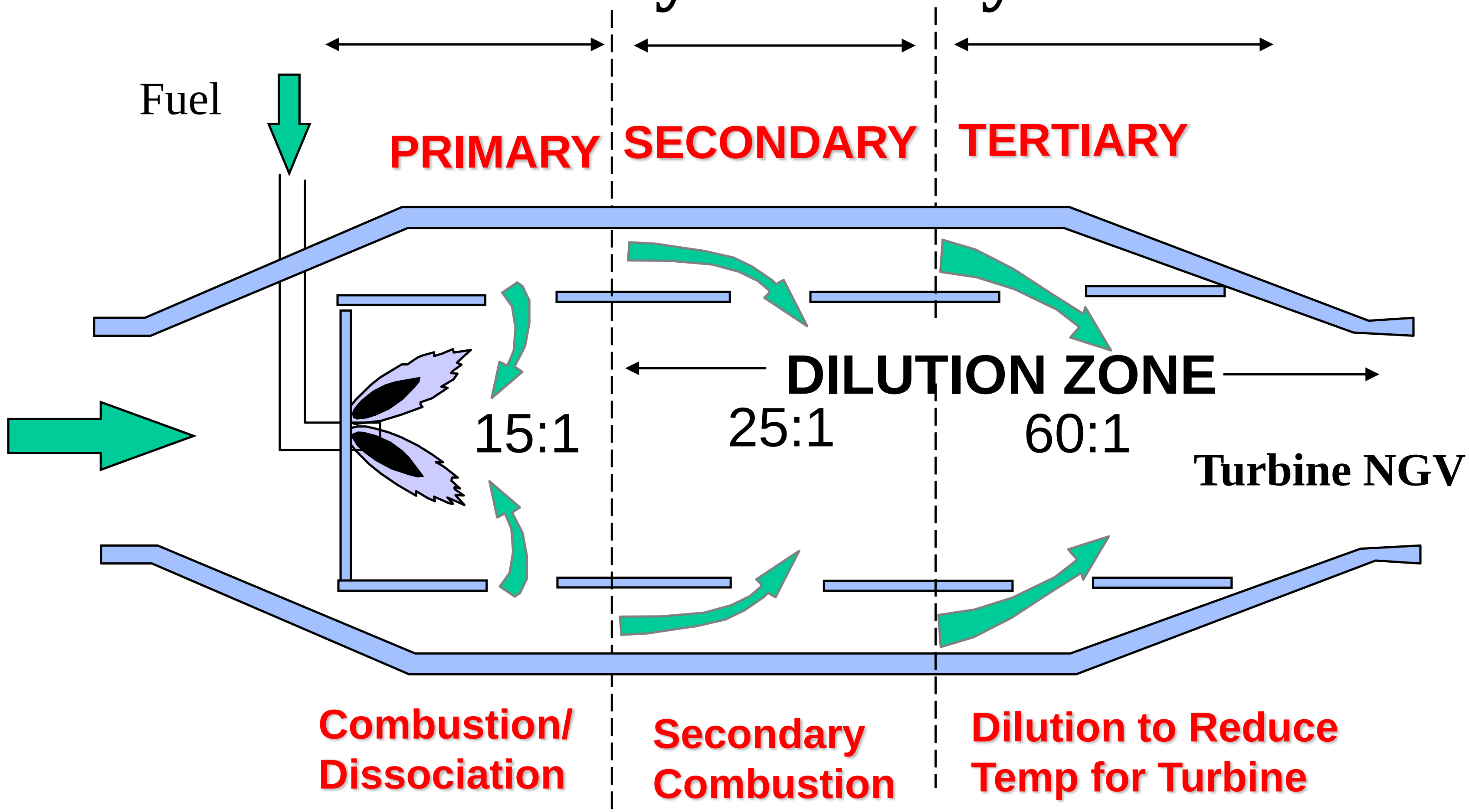


Provides *sheltered* space to
1) mix
2) ignite
3) burn

LIMITS OF COMBUSTION KEROSENE



Combustion System Layout



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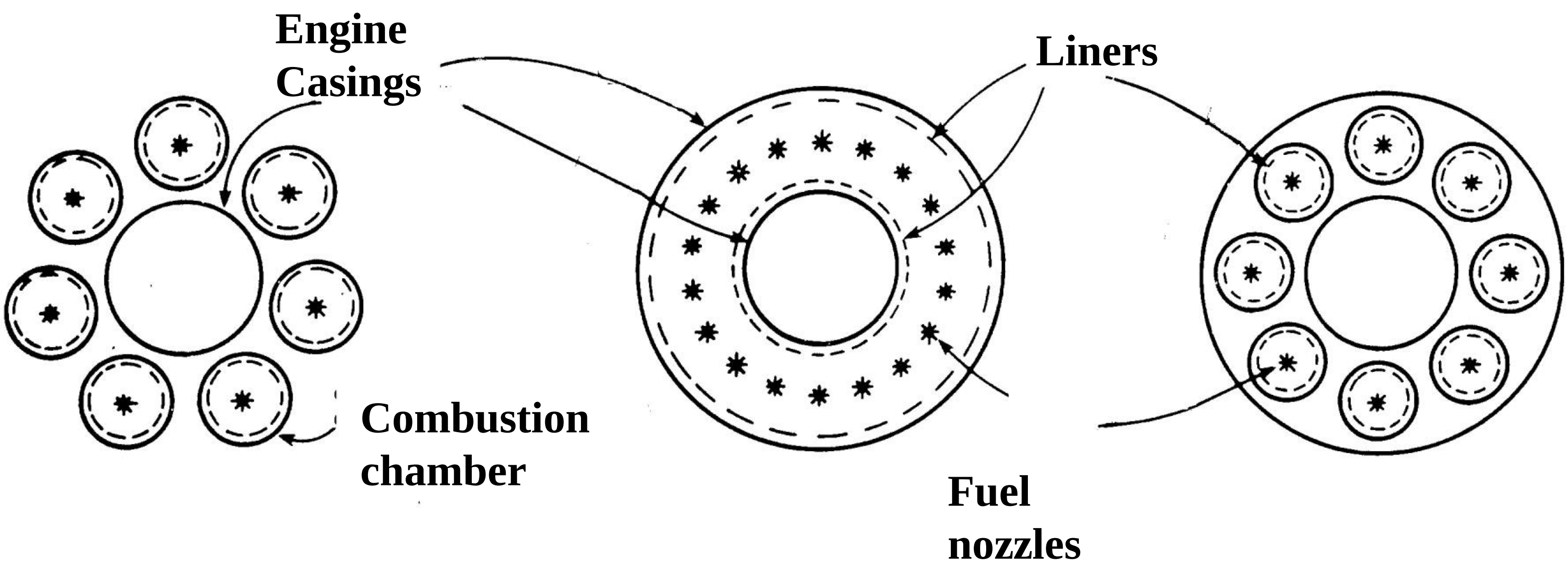
Temp:	800K	2500K	2100K	1800K
Temp Rise:		1700K	1300K	1000K
Velocity m/s	~150	30		Choked in NGV

Types of Combustion System



Tubular
Early Design

Annular
Current Design Style

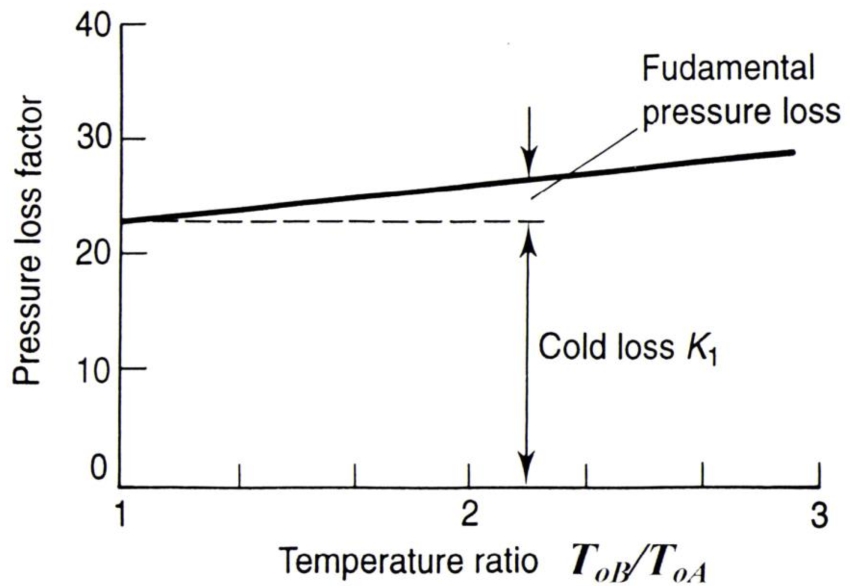
Tubo-annular
Or Cannular

Combustion Chamber Pressure Loss

Caused by:

- **Rise in temperature due to Combustion** ***Fundamental Loss***
- **Skin friction & Turbulence** ***Cold Loss***

Pressure Loss Factor (PLF) = $(P_{oA} - P_{oB}) / \frac{1}{2} \rho C_A^2$

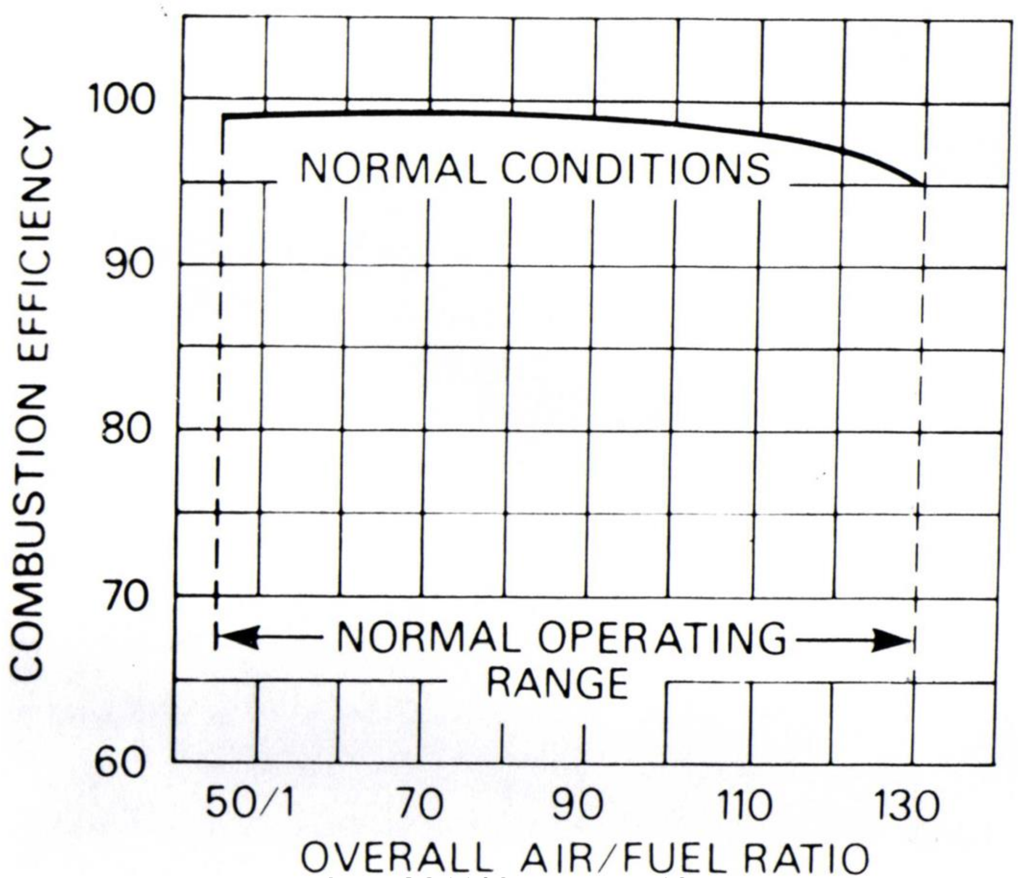


Suffix A refers to Air at inlet to combustion chamber

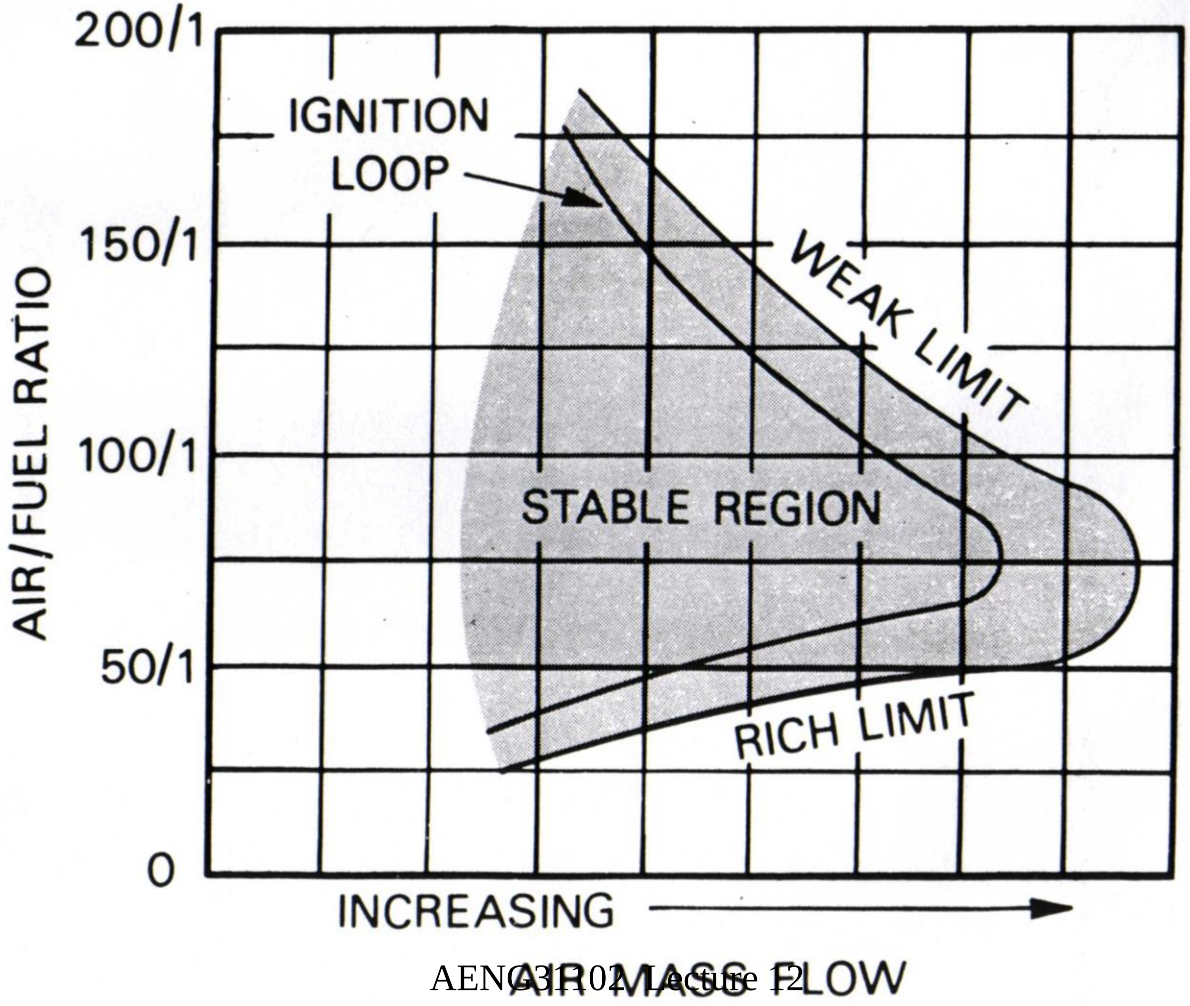
Suffix B refers to products of combustion at exit from the combustion chamber

Combustion Efficiency

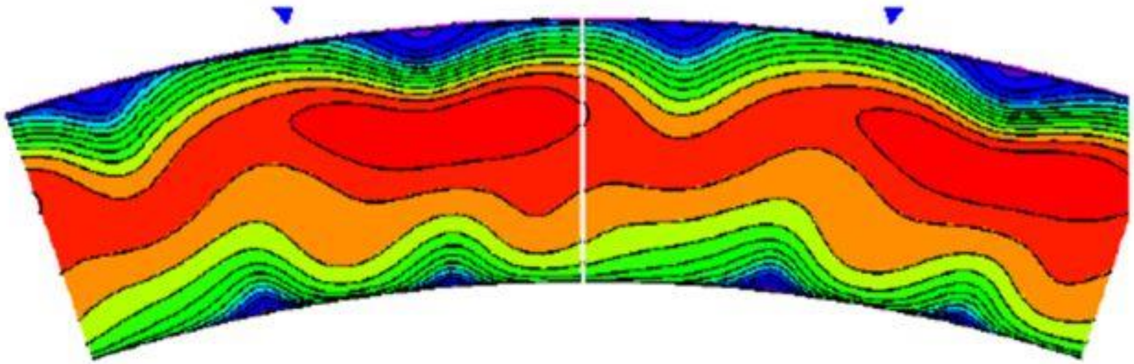
$$\eta_c = \frac{\text{Theoretical Fuel/Air Ratio for actual } \Delta T}{\text{Actual Fuel/Air ratio for actual } \Delta T}$$

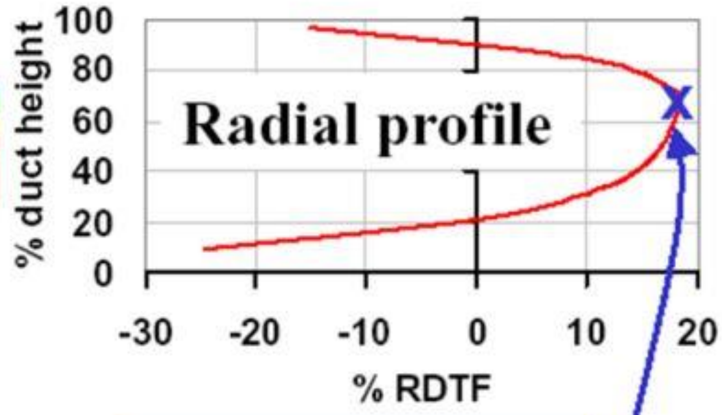


Combustion Stability



Feeding the turbine: 'Temperature traverse'





What stators see

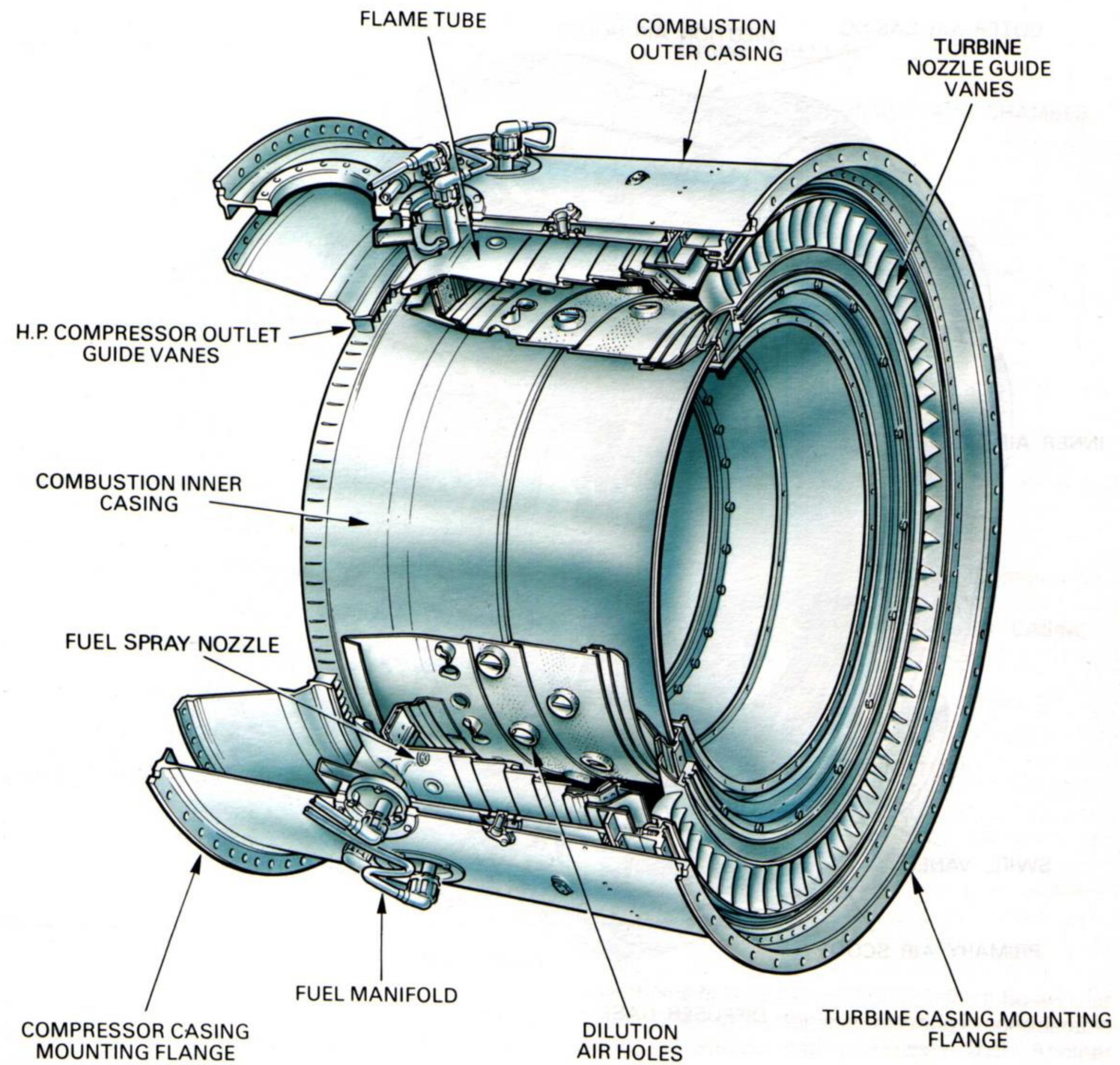
What rotors see

$$OTDF = \frac{T_{PEAK} - T_{INLET}}{T_{MEAN} - T_{INLET}}$$

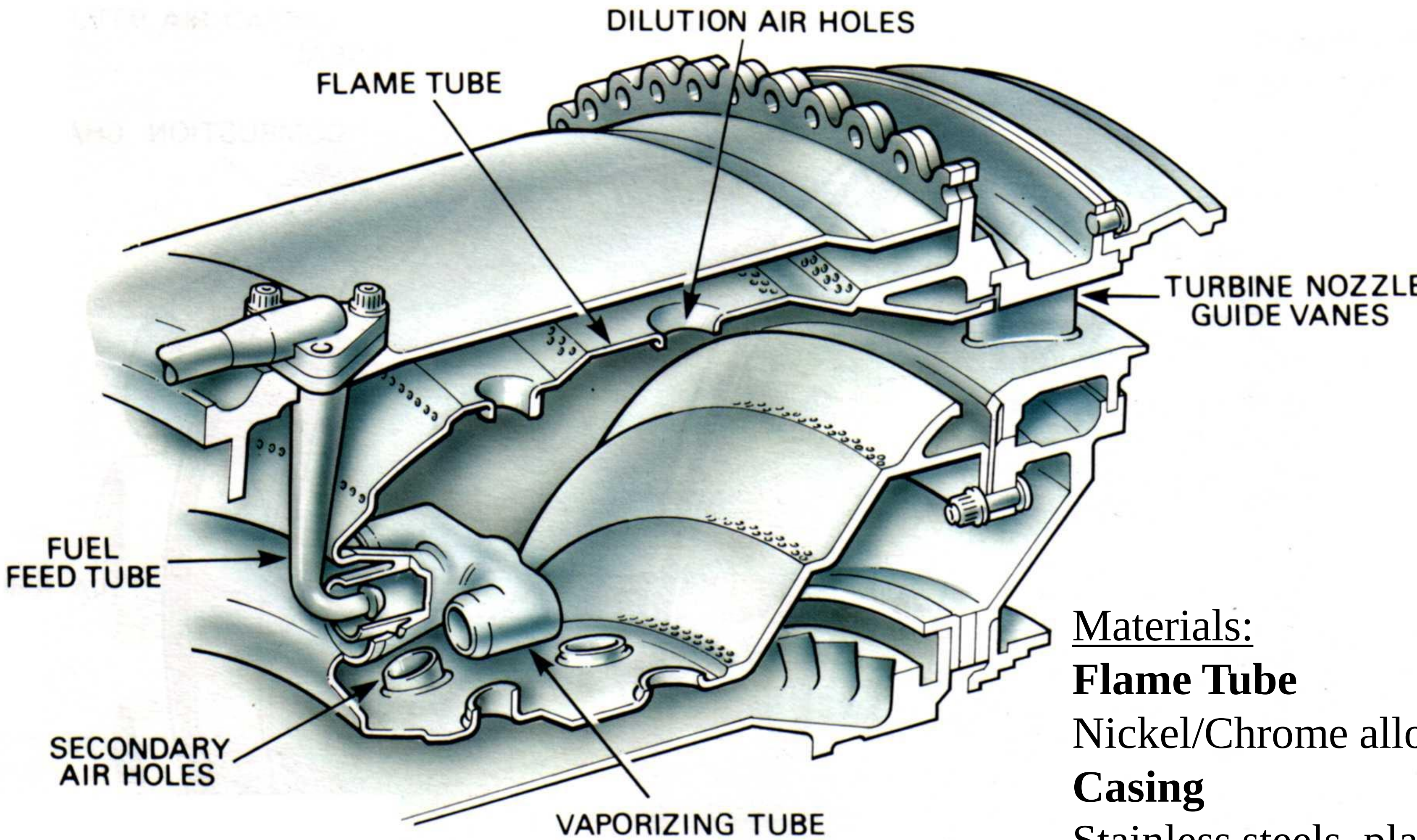
$$RTDF = \frac{T_{MAX\ CIRCUMFERENTIAL\ AVERAGE} - T_{INLET}}{T_{MEAN} - T_{INLET}}$$

- Right temperature distribution vital for life!
  - Overall temperature distribution factor for NGV's
  - Radial temperature distribution factor for rotors
- Use dilution air and rear cooling films to trim traverse

Annular Combustion Chamber



Annular Combustion Chamber



<u>Materials:</u>

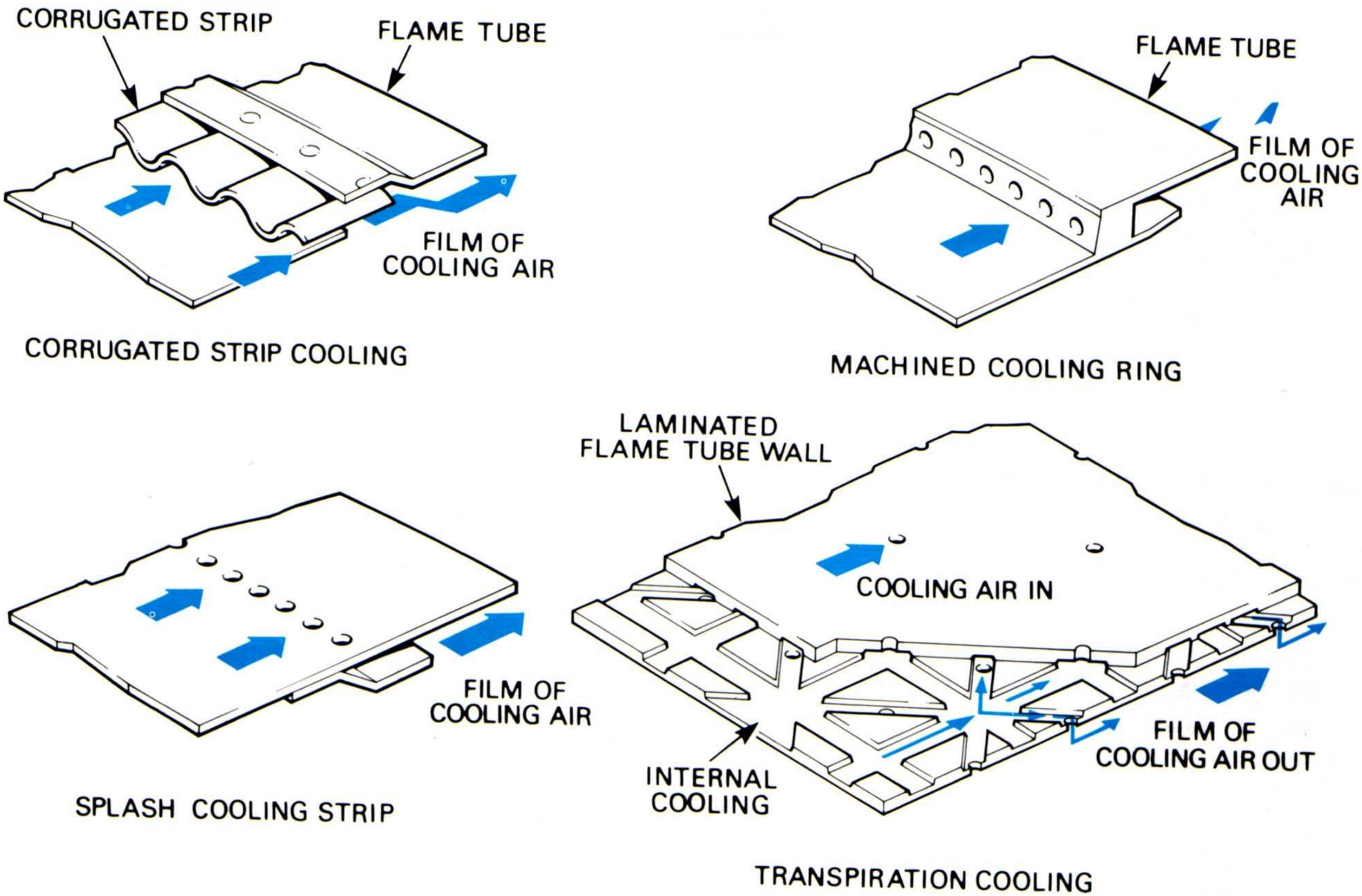
Flame Tube

Nickel/Chrome alloys

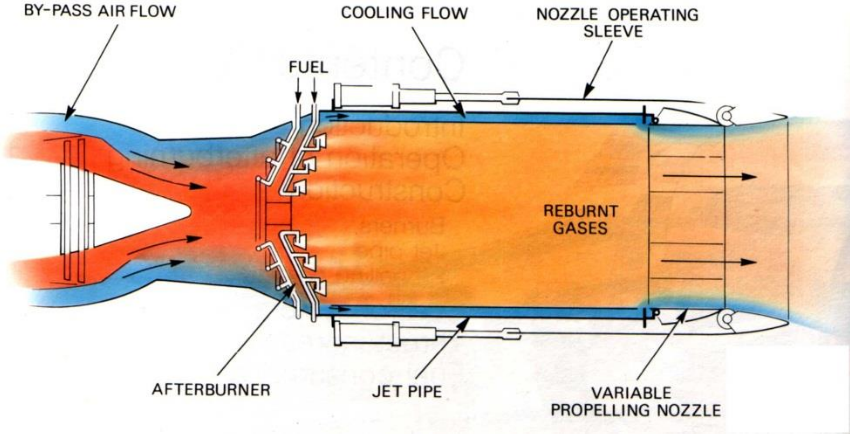
Casing

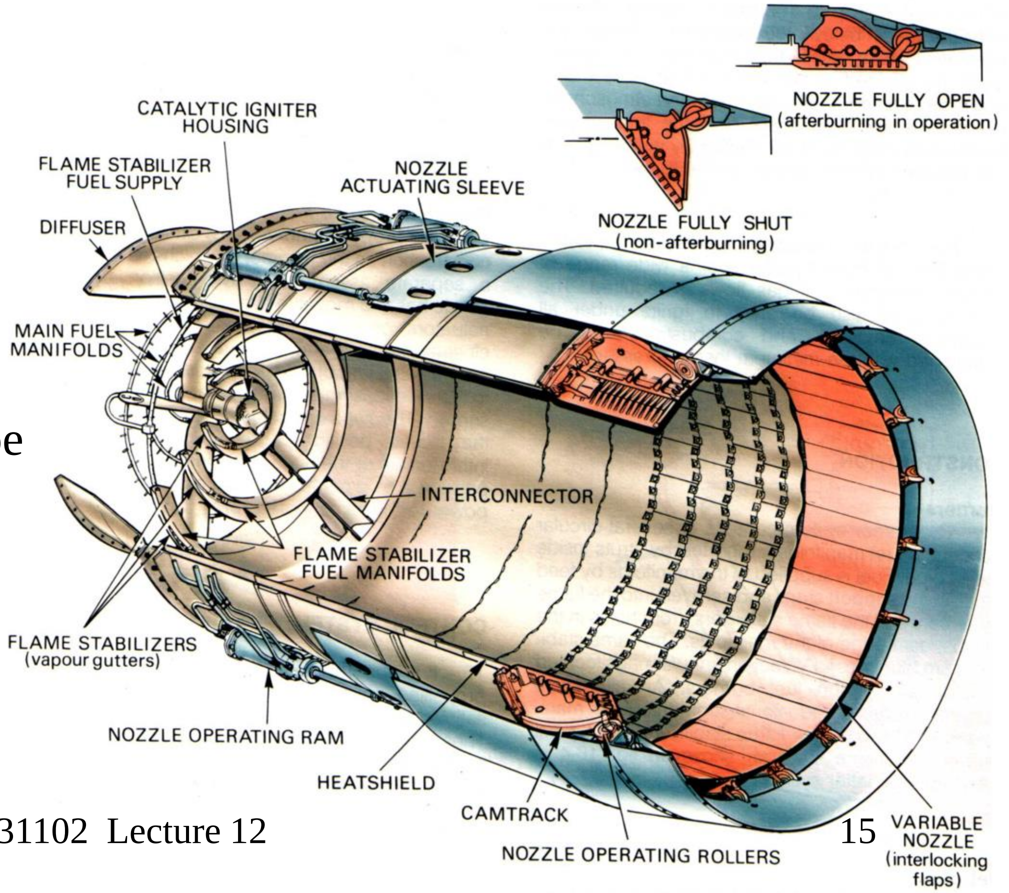
Stainless steels, plated with nickel alloys

Ways of Cooling the Flame Tube



Reheat or Afterburner Systems





Requirements:

- Cool air to keep hot gases off the jet pipe
- Fuel injectors protected from hot gases
- Different fuel flow rates depending on gas temperature
- Sufficient length for stable operation
- Variable Area Nozzle

Environmental Issues

What is the problem?

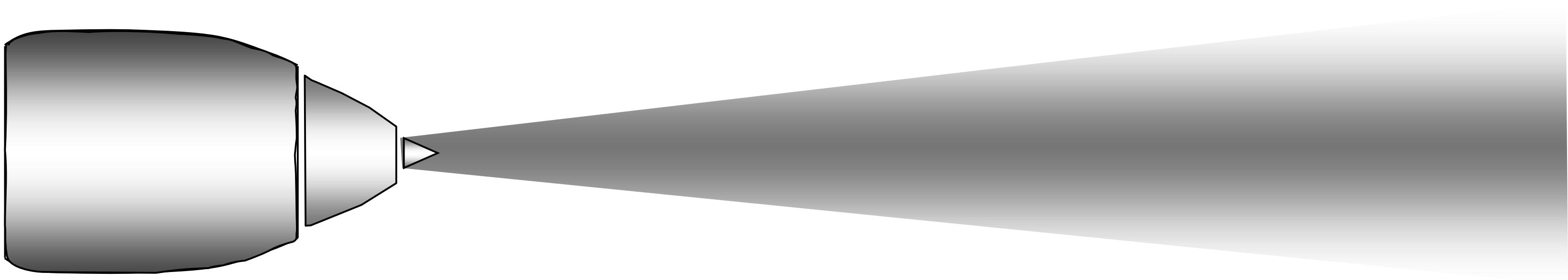
- Civil aviation contributes about 2% of global CO_2…..
- …..about the same as the UK but traffic increasing!!
- Climate science is still in its infancy – much still to be learned

"The absolute emissions by air traffic are small...compared to surface emissions. However, the greenhouse effect of emitted water and of nitrogen oxides at cruise altitude is potentially large compared to that of the same emissions near the earth's surface..."

U. Schumann in Ann. Geophysicae 12, 365-384

Fuel C_nH_m (+S)

Air



$N_2 + O_2$

$$\boxed{CO_2} + \boxed{H_2O} + N_2 + O_2 + \boxed{\boxed{NO_x^*}} + UHC^* + CO^* + \boxed{C_{soot}^*} + \boxed{SO_x}$$

+ + O_3 CH_4 + -

+ -

* Regulated

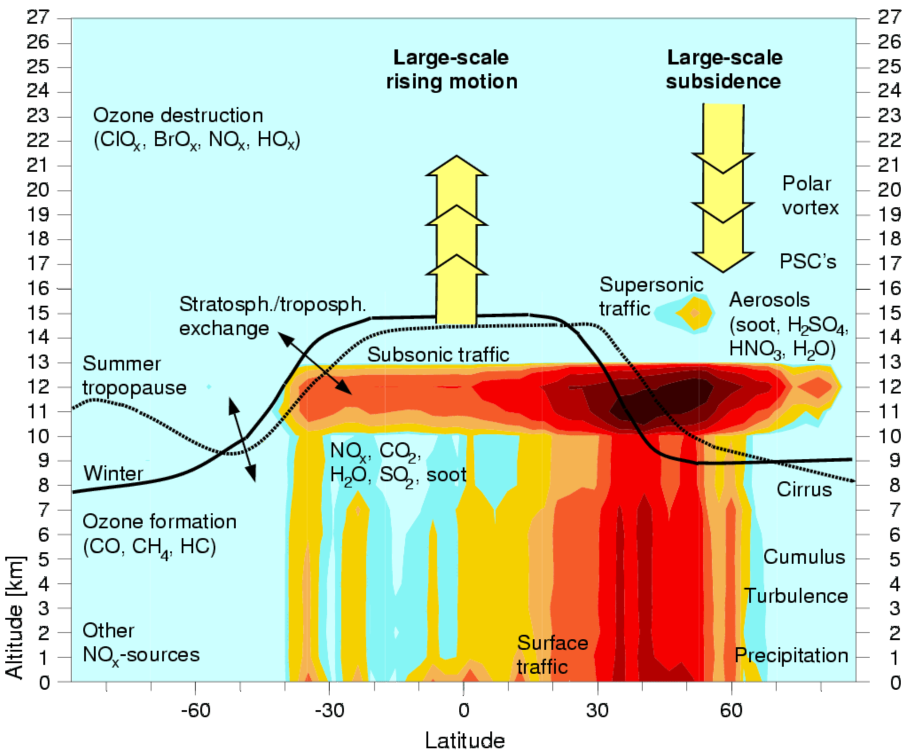
√

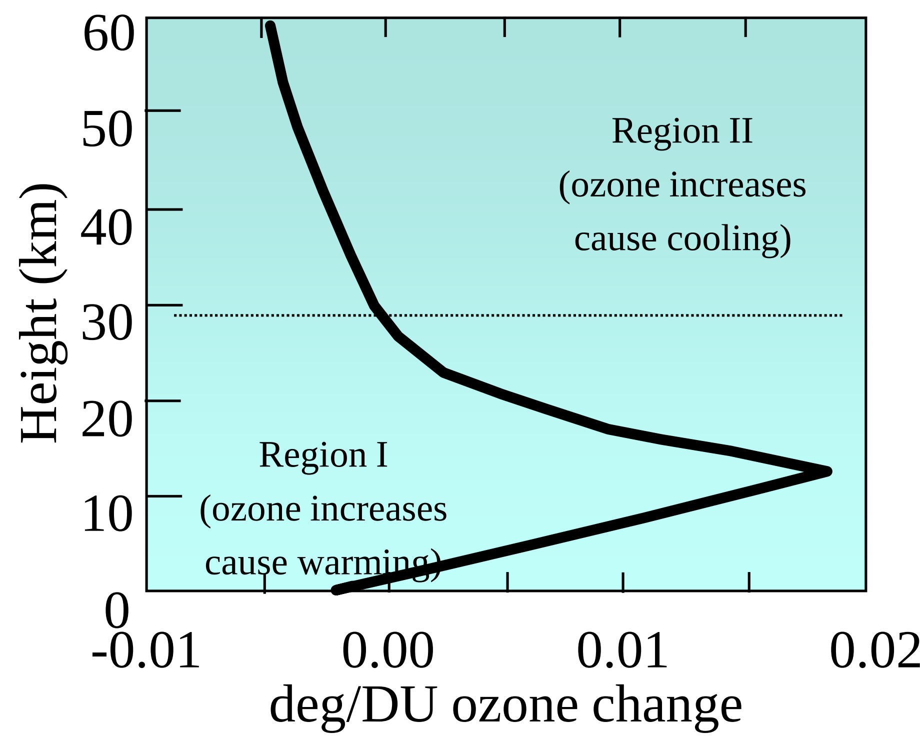
If hydro-carbon is the fuel then reducing fuel burn reduces CO_2

NO_x emissions from aircraft are small, so what is the concern?

- In the boundary layer (<1km)
  - NO_x products are removed by wet and dry deposition to the surface (acid deposition)
- In the upper troposphere (8-12km)
  - NO_x has a longer life-time as these removal processes are not significant
  - O_3 production is more efficient
  - aircraft are cruising in the most sensitive part of the atmosphere to radiative forcing by O_3

The effect of Altitude on Emissions

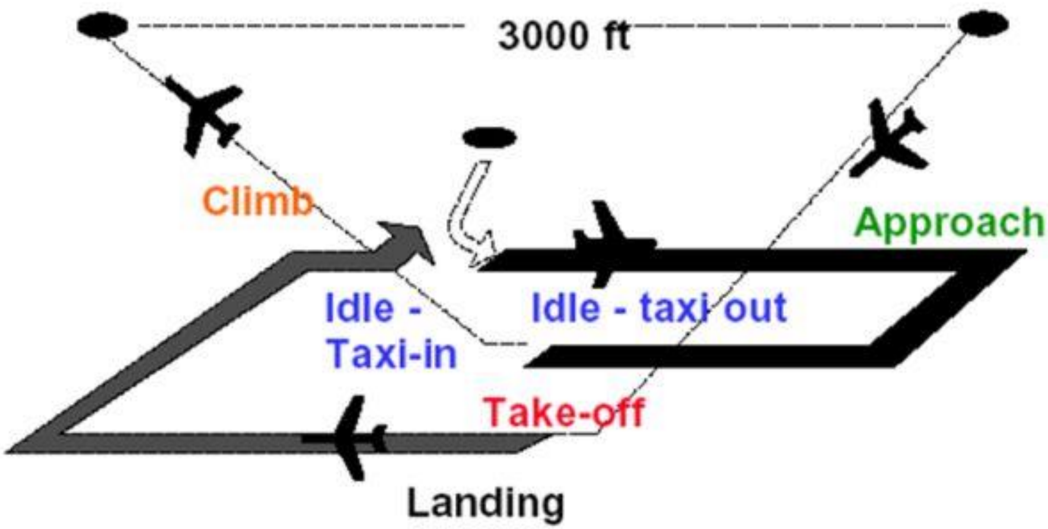




Dobson Unit (DU) - Measurement of ozone density

Emissions Legislation

- Smoke limit to eliminate visible trails
- UHC, CO and NOx limited around LTO cycle:

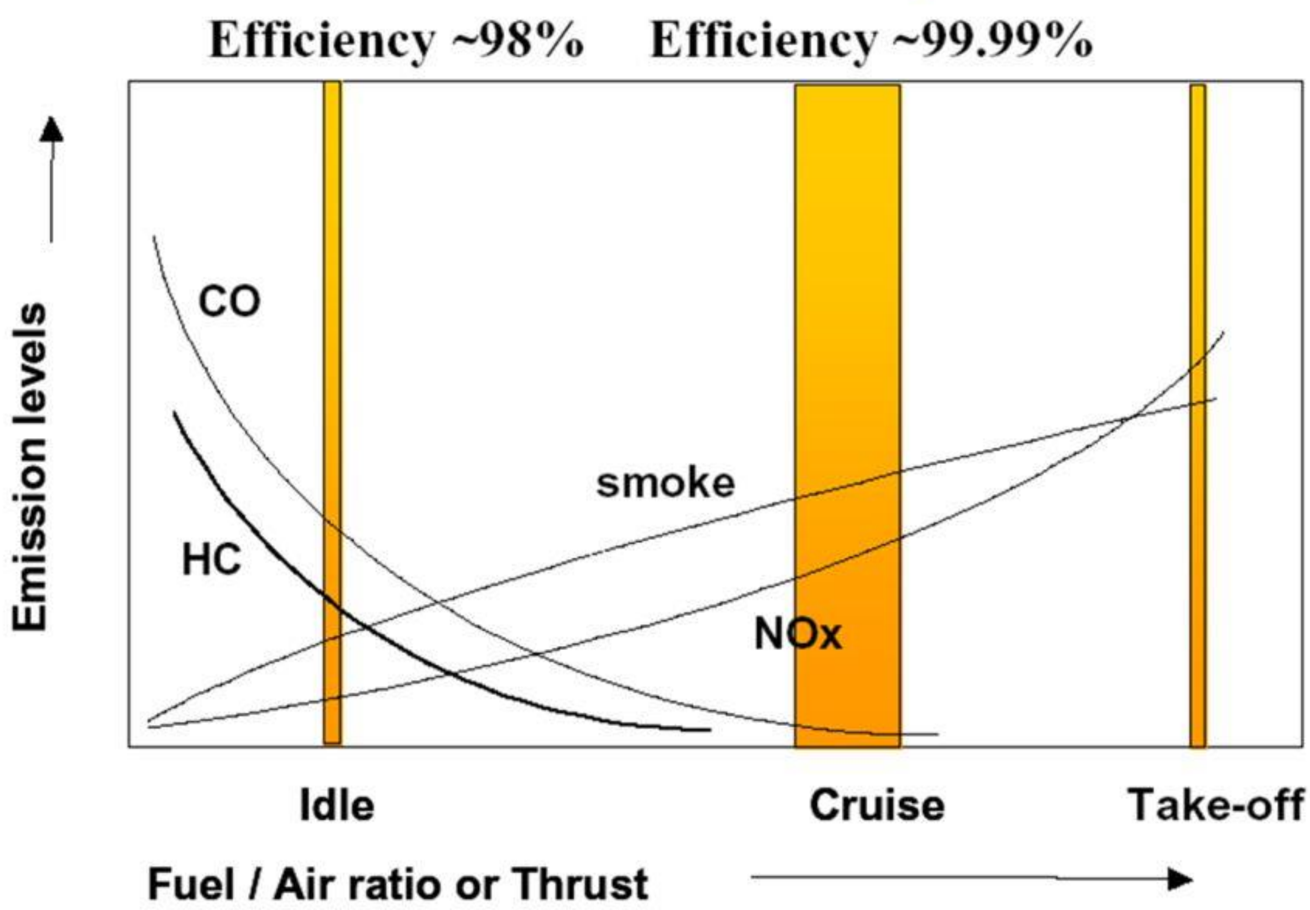


Mode	% Takeoff thrust	Time in mode (min)
Taxi / Idle	7%	26.0
Takeoff	100%	0.7
Climb	85%	2.2
Approach	30%	4.0

- Legislation is being tightened progressively
  - Limits mass of pollutant permitted over LTO cycle
- Driven by local air quality – no cruise limits at present

(LTO: landing and take-off)

Variation of emissions with power

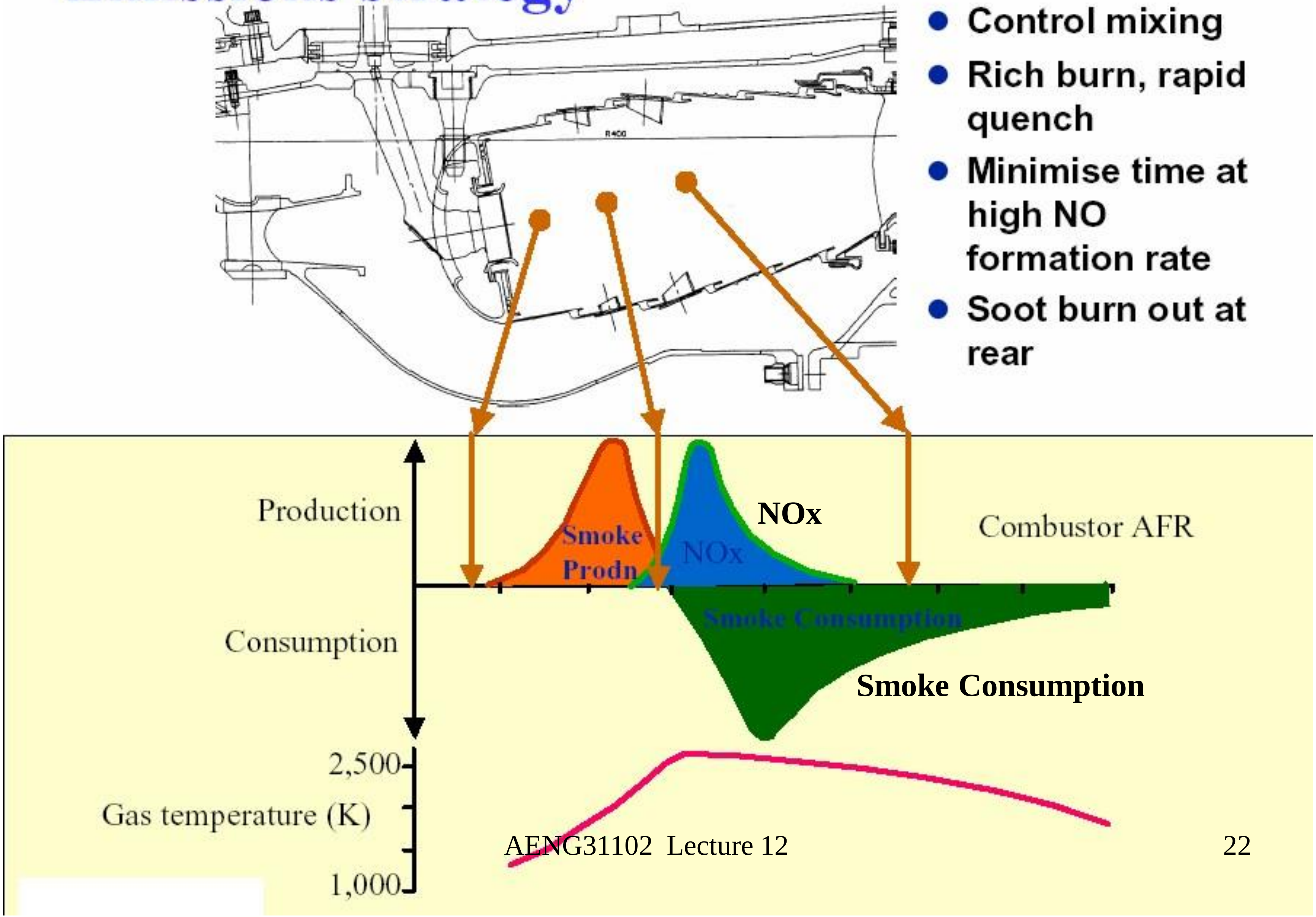


CO_2 *A function of Fuel Burn*

√ NOx *Oxides of Nitrogen* CO *Carbon Monoxide*

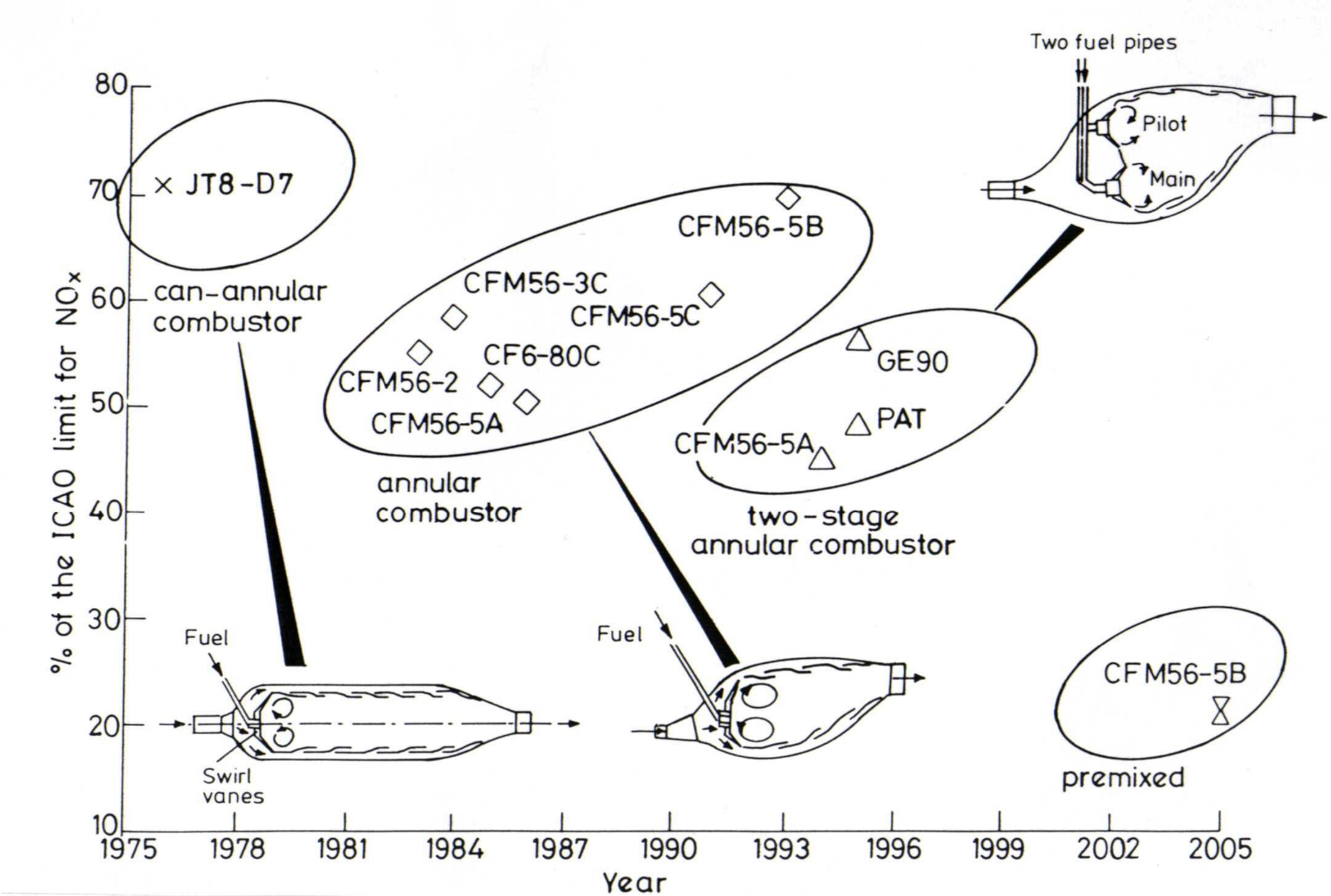
HC *Unburnt Hydrocarbons* Smoke *Carbon particles*

Emissions strategy



- Control mixing
- Rich burn, rapid quench
- Minimise time at high NO formation rate
- Soot burn out at rear

The variation of NO_x with time



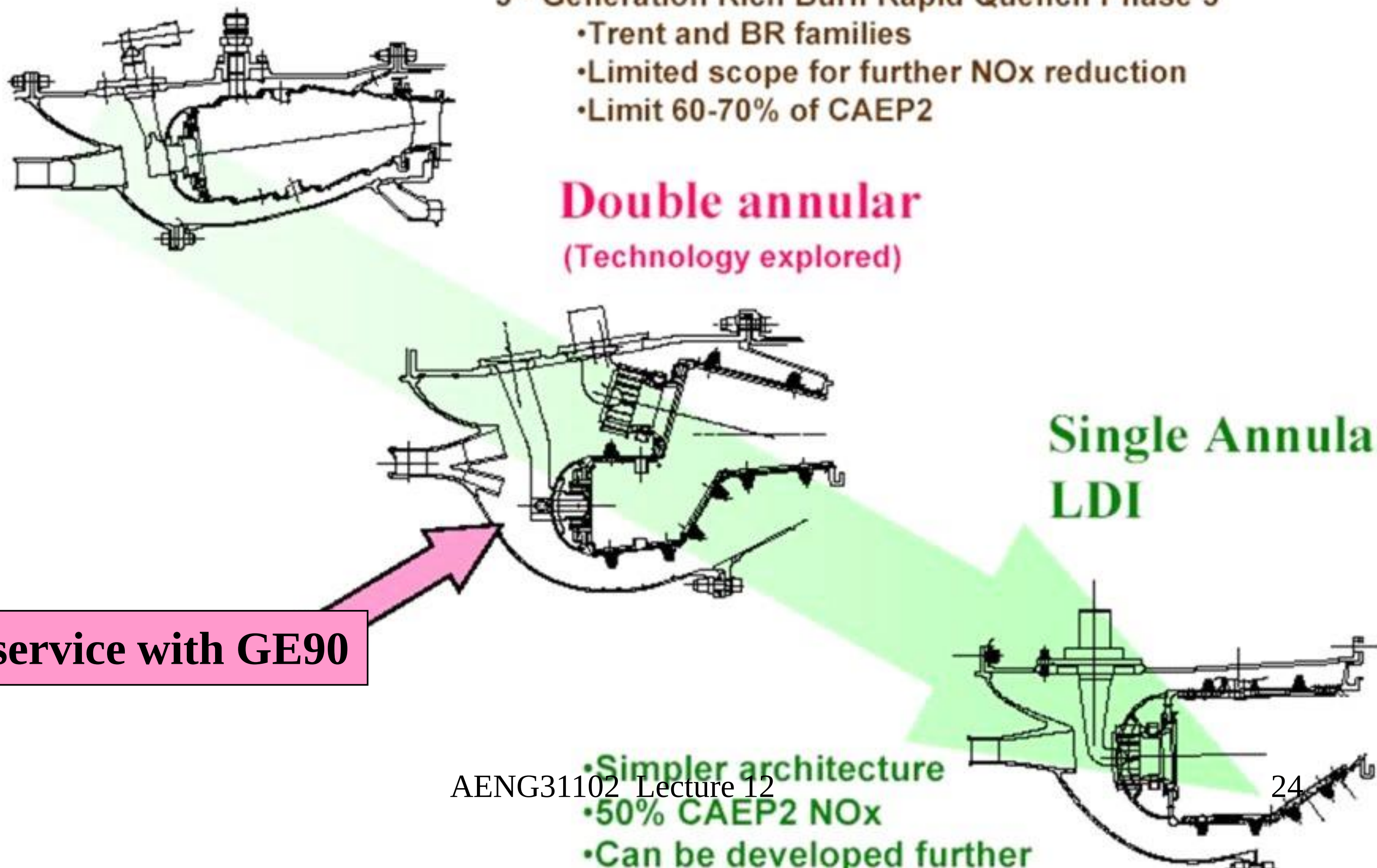
Combustion technology development

Single Annular Conventional

3rd Generation Rich Burn Rapid Quench Phase 5
- Trent and BR families
- Limited scope for further NOx reduction
- Limit 60-70% of CAEP2

Double annular

(Technology explored)

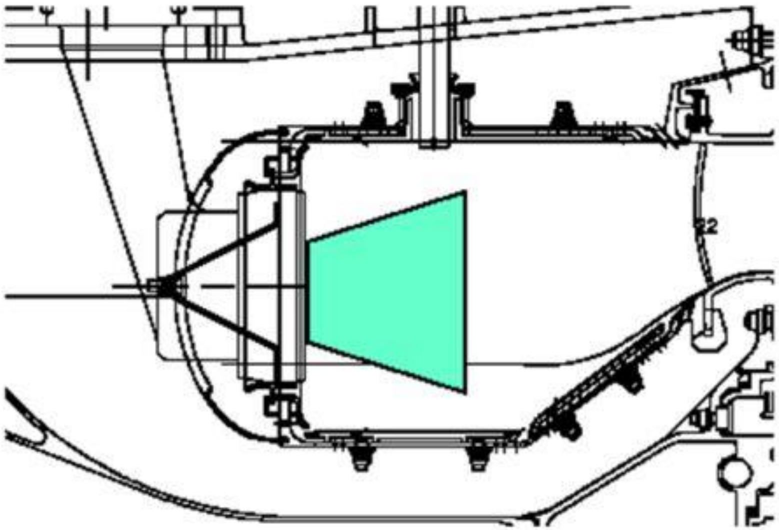


In service with GE90

Single Annular LDI

- Simpler architecture
- 50% CAEP2 NOx
- Can be developed further

Single annular fuel staged LDI concept

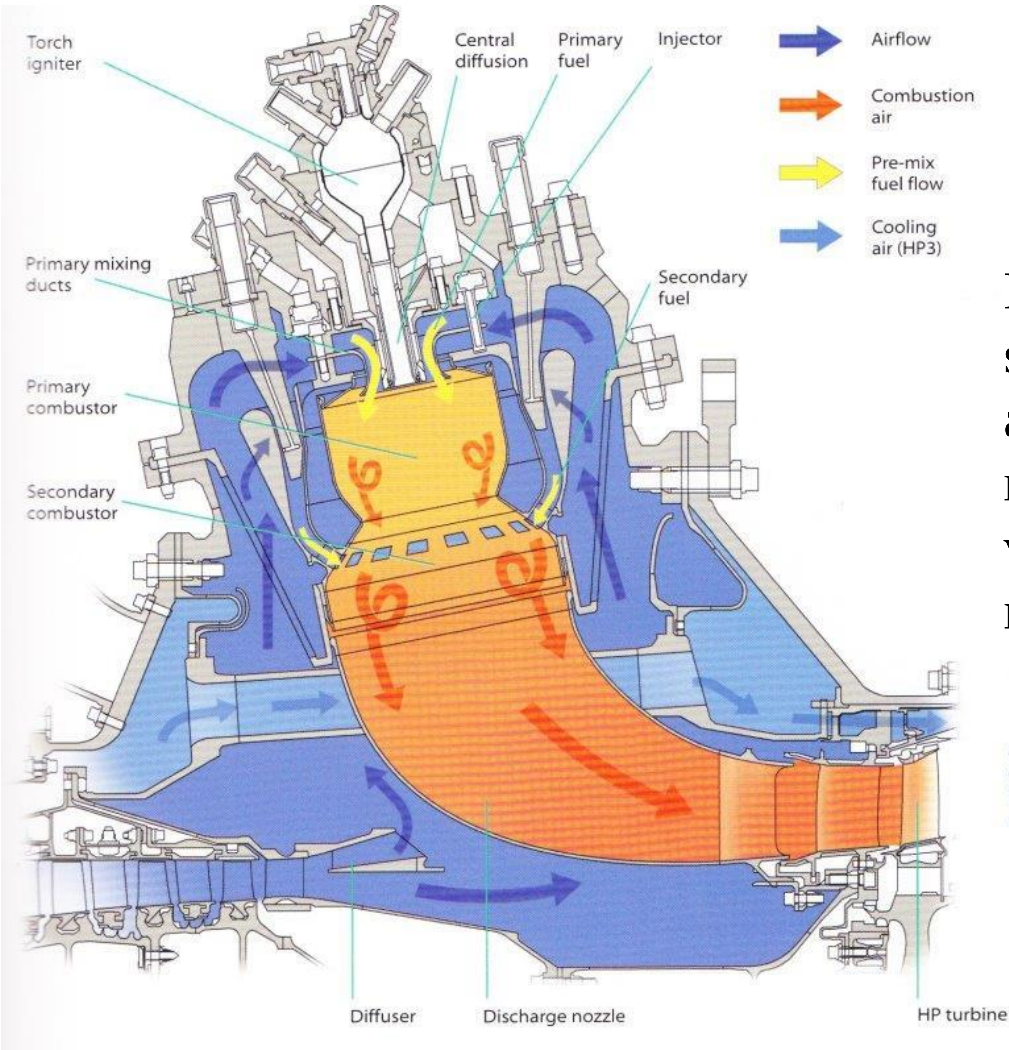


- Nozzle includes pilot spray
- Pilot and main zones within single annular combustor
- No premixing duct
  - No flashback issue

Lean direct injection nozzle – large flow area

Conventional rich burn fuel nozzle

Combustor for a land based system



Emissions regulations for land based systems are more stringent than for aero engines and with no requirements for low weight or volume there is more scope pre-mixing and staging.

RB211 Dry Low Emissions combustor for industrial & marine applications

Ingredients for low NOx

- Control temperature levels & have good mixing
- Fuel staging – keep flame temperatures high at part power
- Minimise cooling flow – to give more for NOx control
- Prevent instabilities
- Must be safe reliable and affordable
- Radical ideas being studied:
  - New architecture
  - More sophisticated controls
  - Must be capable of dealing with rapid manoeuvres (transients)

Issues of policy

- Issue: sustainable development
  - balancing growth and environmental concerns
- Traffic growth – currently about 5% pa
  - ~ doubling in 17 years
  - Fastest growth of all transport modes
  - *"One of nature's biggest forces is exponential growth"*

(Albert Einstein)
- LHR – 3rd runway consultation
  - additional traffic will produce £5bn to UK economy

Key Lessons from Lecture 12

- Chemical reactions forming NO_X are much slower than for CO_2 & H_2O and NO_X formation increases rapidly with temperature. Long time needed to reduce CO & UHC favours formation of NO_X.
- NO_X & smoke are problems @ high thrust settings i.e. high Combustion Temperatures; CO & UHC worst at Taxi & Idle.
- CO & UHC require Combustion process to be prolonged @ high Temperature with ample O_2 to ensure all CO converted to CO_2.
- NO_X formation depends on both Temperature & Residence Time at that temperature. Standard approach is to reduce residence time (to keep NO_X low) keeping in mind other pollutants & efficiency. Hot gases are then quenched to drop temperatures below that at which NO_X formation is significant.
- Staged Combustion has different injectors & different regions for different phases of flight - pilot for idle/taxi and main for high thrust.
- Land based systems use premixing, fuel vaporised & mixed prior to entering Combustion Chamber - avoids stoichiometric burning but difficult to incorporate into an Aero Engine.

Lecture 13

Turbines

Objective: to describe the workings of the Turbine