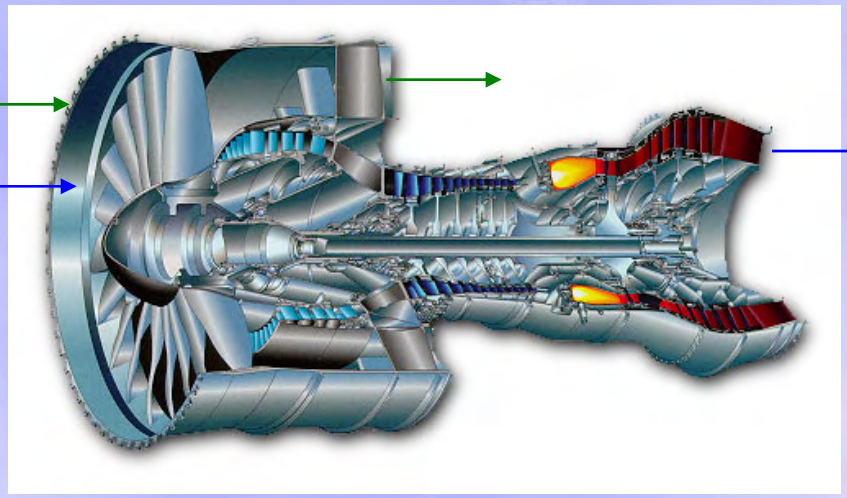
Aircraft Engine Emissions

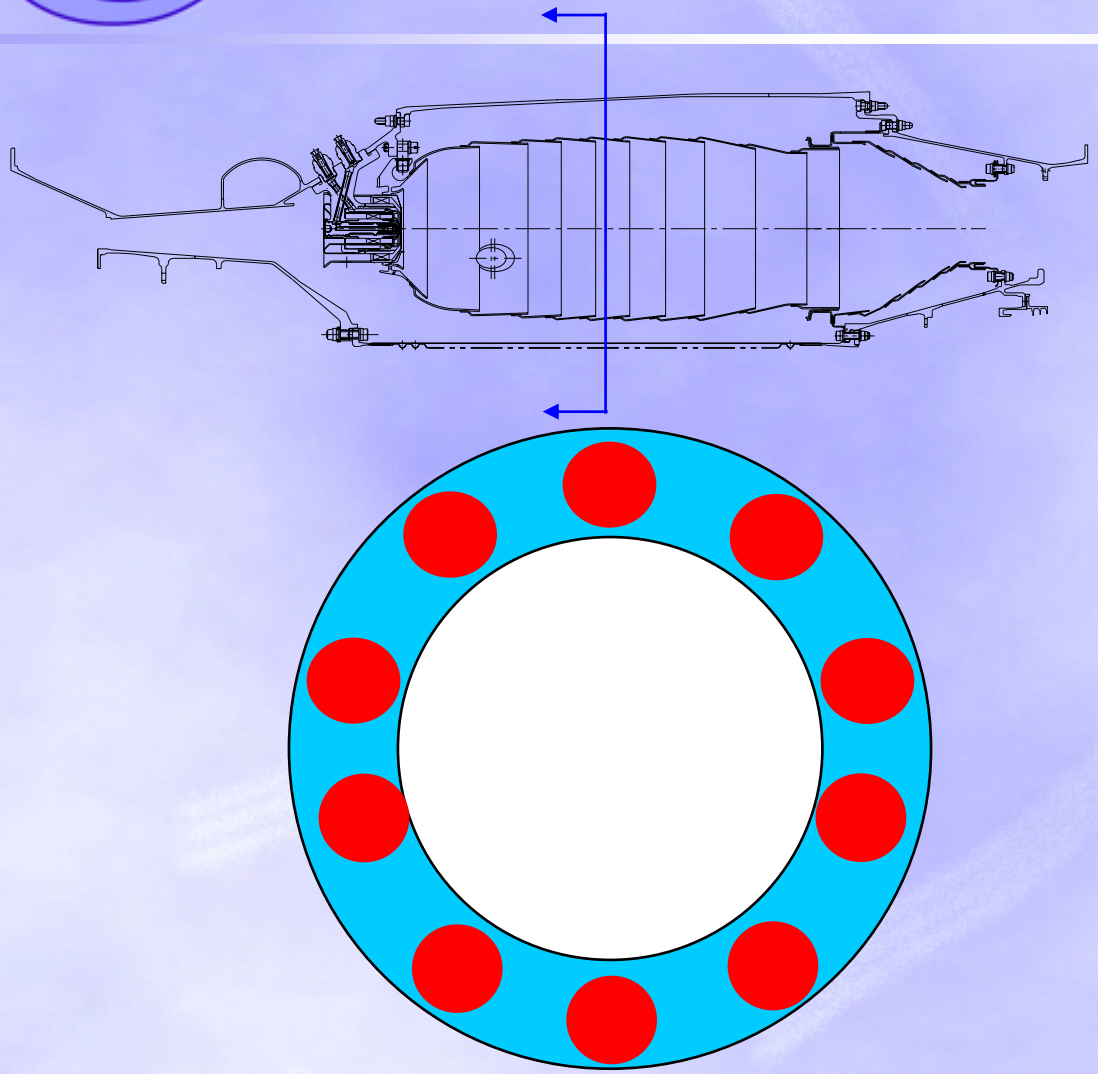
Dr Kenneth Young
Chief of Combustion Research & Technology
Roll-Royce
Representing ICCAIA

The Combustor Adds Heat to the Core Flow of a Gas Turbine



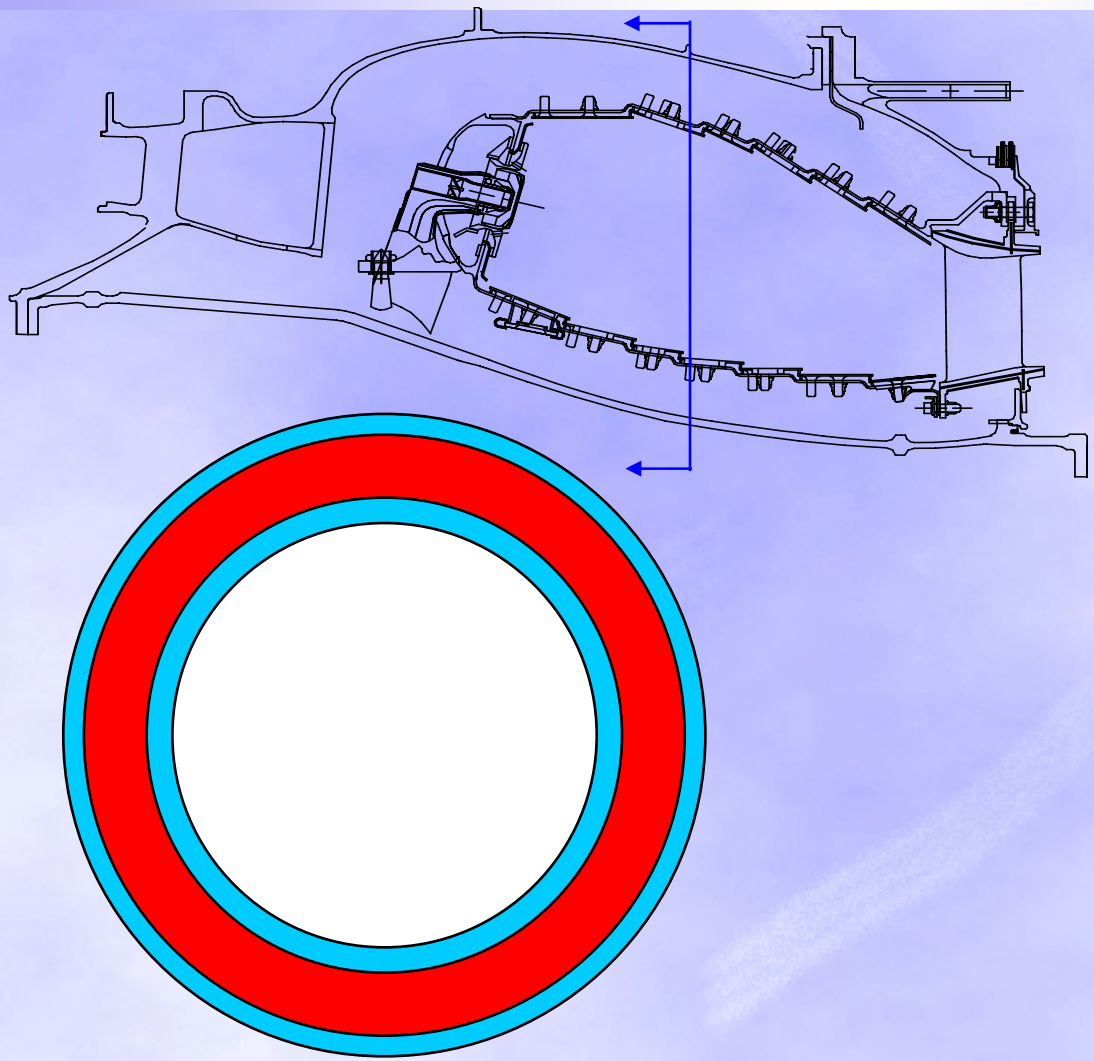
- The combustor is the hottest part of the engine
  - Inlet temperature and pressure can approach 700C (1300F) and 45 atm.
  - Temperature within combustor can exceed 2200C (4000F)
  - Temperature at combustor exit can approach 1650C (3000F)
- Metals melt at ~1350C (2500 F), so making the combustor survive is a major challenge!
- NOx is formed in high temperature regions of the flame

Can Combustor



- **Can Combustors:**
  - Multiple self contained cylindrical combustors
  - Easier to test and develop
  - Longer, heavier designs
  - Large cooling air requirement

Annular Combustor



- **Annular Combustors:**
  - **Compact, light weight design**
  - **Minimizes cooling air requirement for a given combustor volume**

Combustor Performance Requirements

Engine Requirement	Combustor Property
➢ Optimize fuel consumption	➢ High combustion efficiency, Low pressure loss
➢ Meet ICAO and customer emissions requirements	➢ Minimize emissions and smoke
➢ Wide range of thrust	➢ Good combustion stability
➢ Ground start, altitude relight	➢ Ease of ignition
➢ Turbine durability	➢ Good temperature distribution at exit
➢ Combustor and Diffuser Case durability	➢ Low metal temperatures and stresses

Combustion of Jet Fuel - Fundamentals

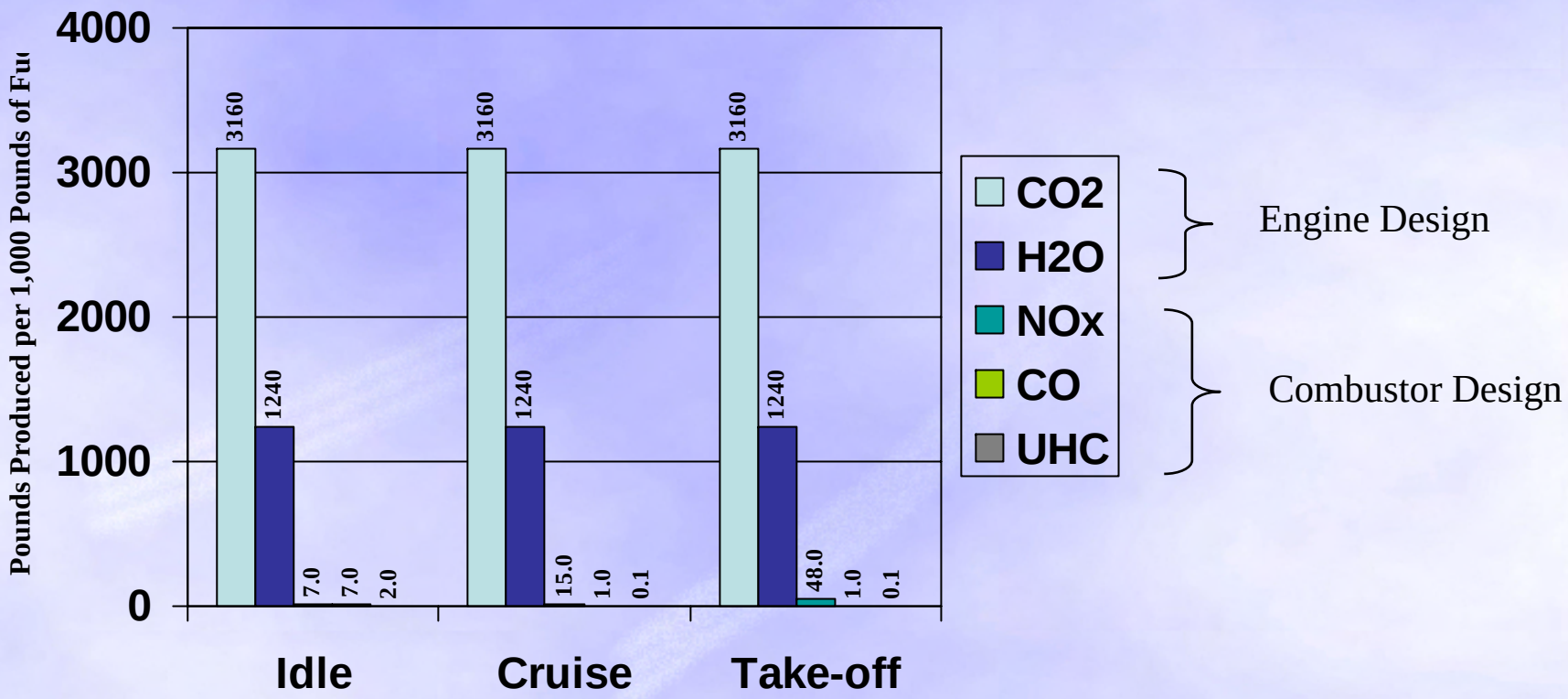
- $C_{12}H_{23} + 17.75O_2 \Longrightarrow 12CO_2 + 11.5\ H_2O$

➢ Fuel + Air ⟹

➢ Excess Oxygen	(O2)	
➢ Excess Nitrogen	(N2)	
➢ Carbon Dioxide	(CO2)	Product of Combustion
➢ Water Vapor	(H2O)	Product of Combustion
➢ Carbon Monoxide	(CO)	Incomplete Combustion
➢ Unburned Hydrocarbons	(HC)	Incomplete Combustion
➢ Oxides of Nitrogen	(NOx)	High Temp. Air Reaction
➢ Smoke		Local High Fuel levels

Combustion of Jet Fuel - Quantified

- For example, a PW4084 Engine produces the following mass of products for each 1,000 pounds of fuel burned:



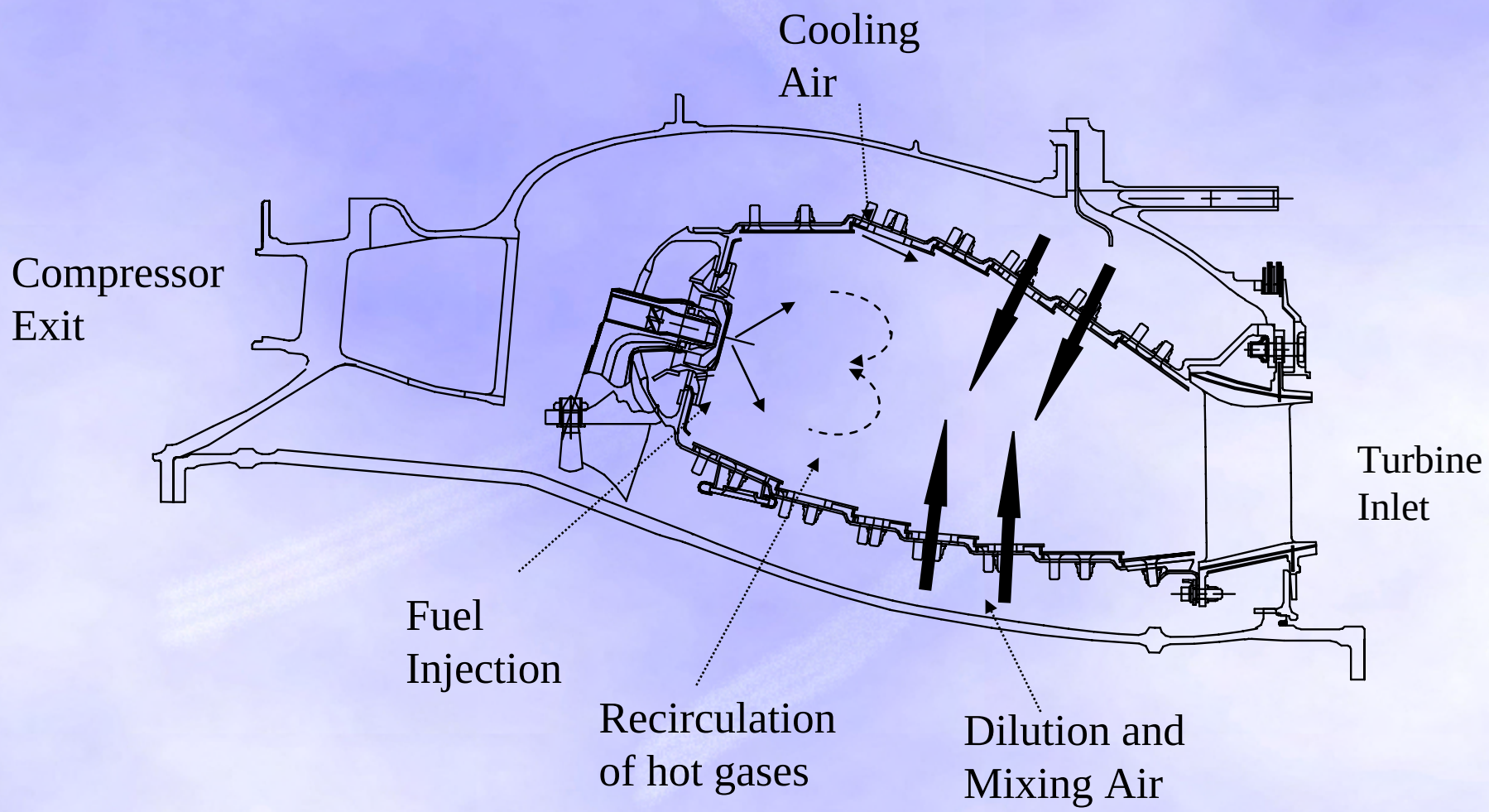
Aircraft Emission Issues - Overview

Emission Category	Primary Issues	
	Local Air Quality (Ground Level)	Climate Change (High Altitude)
Oxides of Nitrogen* (NO_x)	Ozone - Health/Visibility	Ozone - Climate
Unburned Hydrocarbons* (HC/VOC/HAPS-[hazardous air pollutants, e.g. Benzene])	Ozone - Health/Visibility	---
Carbon Monoxide* (CO)	Health	---
Smoke* (Soot, Particulate)	Visible Exhaust Particulate (PM) - Health	Clouds – Climate
Water Vapor (H_2O)	---	Contrails - Climate
Carbon Dioxide (CO_2)	---	Climate
Sulfur Oxides (SO_x)	Acid formation – Health/corrosion	Clouds - Climate

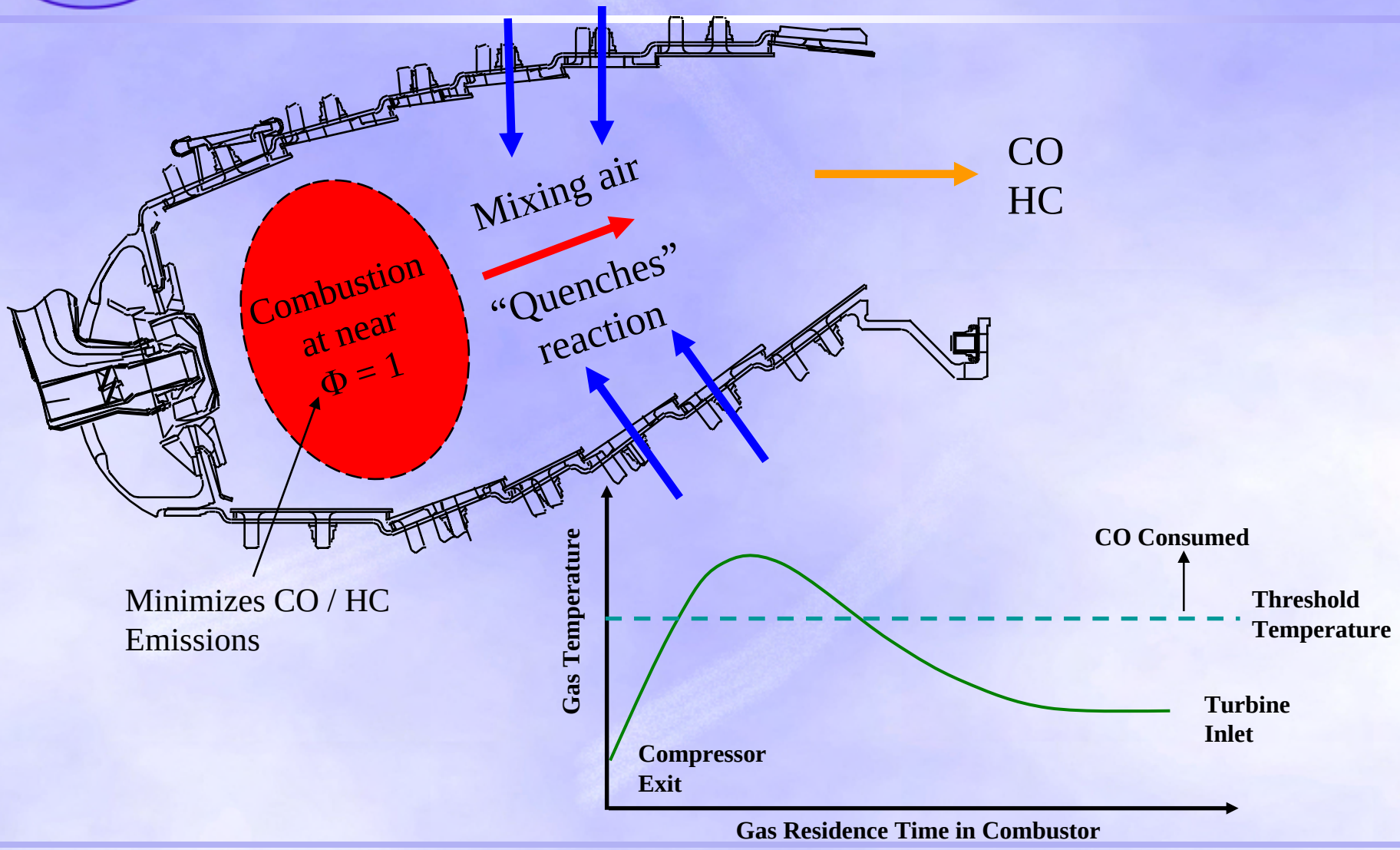
* - Covered by Current ICAO Regulations

Key Issues are Local/Regional Air Quality and Climate

Continuous Flow Combustion with Aerodynamic Stabilization



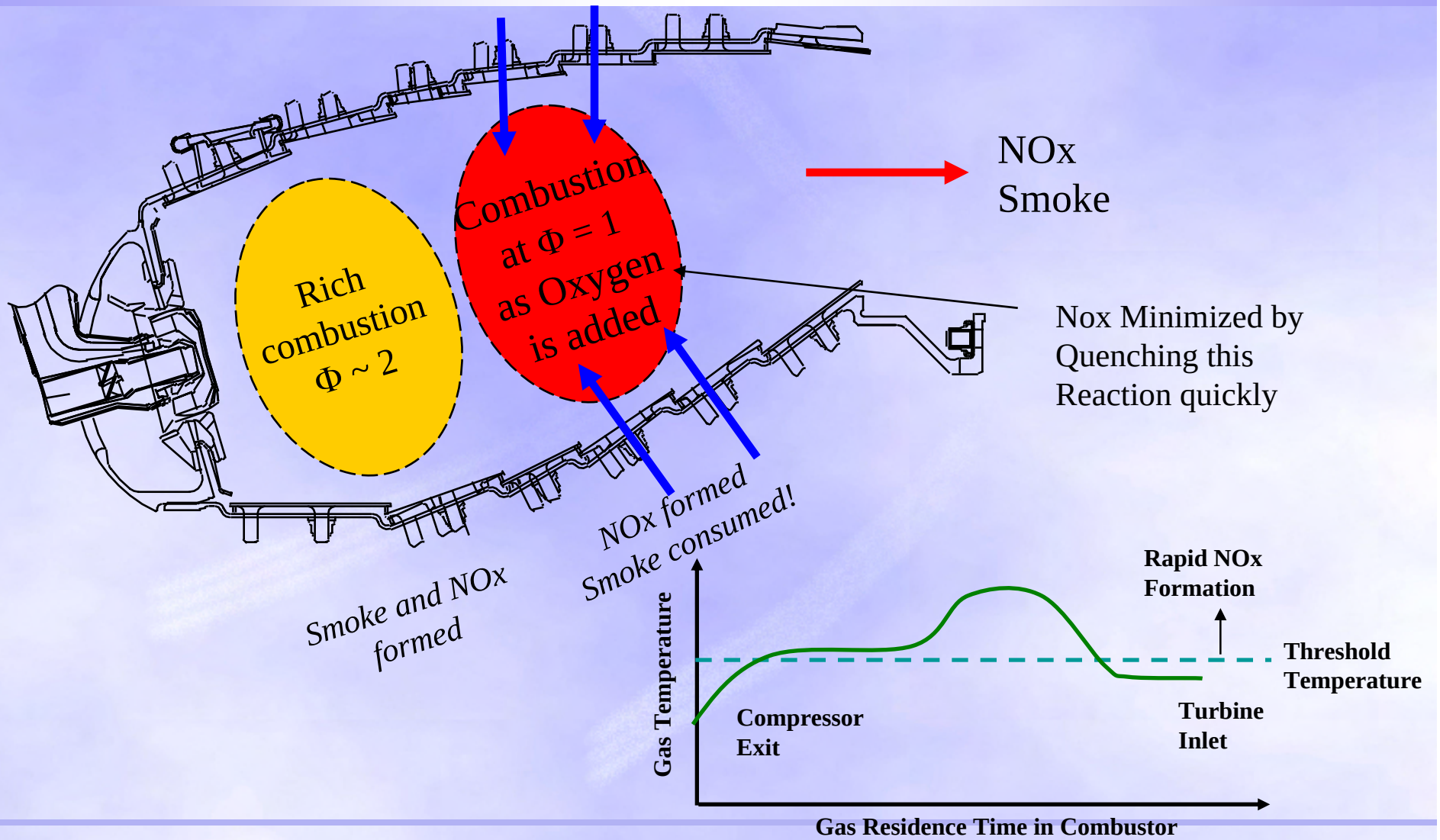
Schematic of Combustor at Low Power



Pollutant Formation - CO & HC

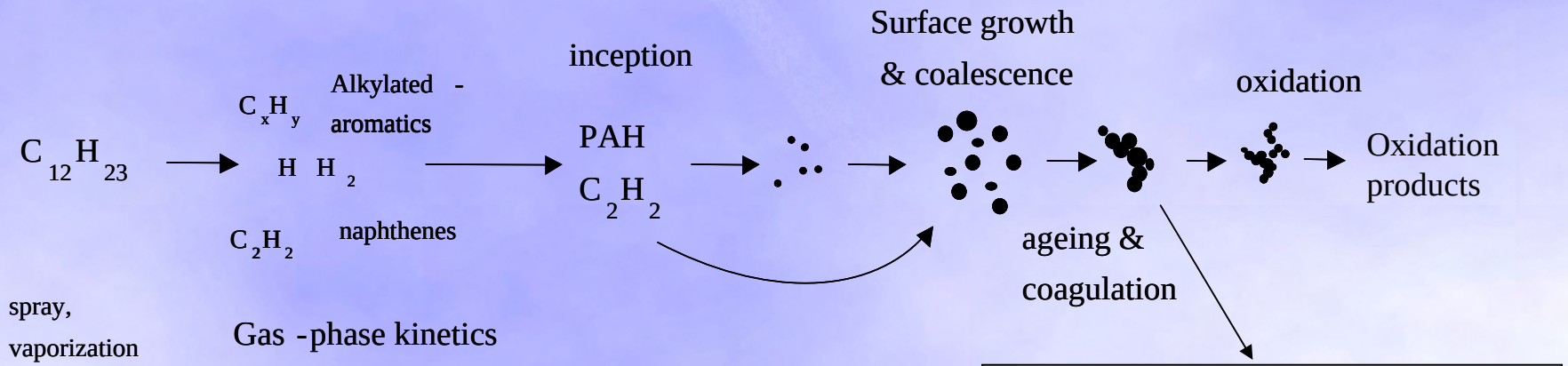
- Inefficient combustion
  - Combustion zone too lean or rich
    - Too much or too little air mixed with fuel.
  - Combustion zone residence time too low
  - Poor atomization of fuel
  - Poor aerodynamic stabilization
- Low temperatures
  - Cool compressor exit temperatures (T3)
  - Quenching of reactions
    - Cooling films
    - Dilution / mixing air

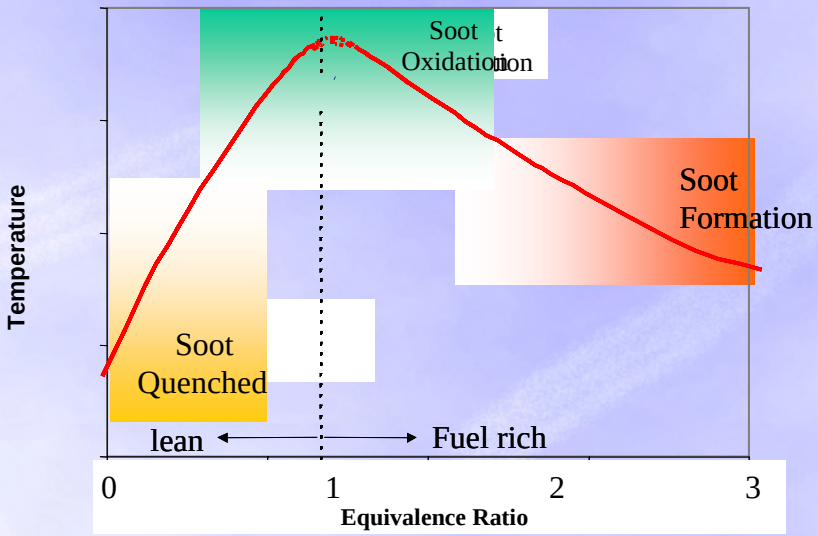
Schematic of Combustor Operating at High Power



Pollutant Formation – Smoke (Soot)

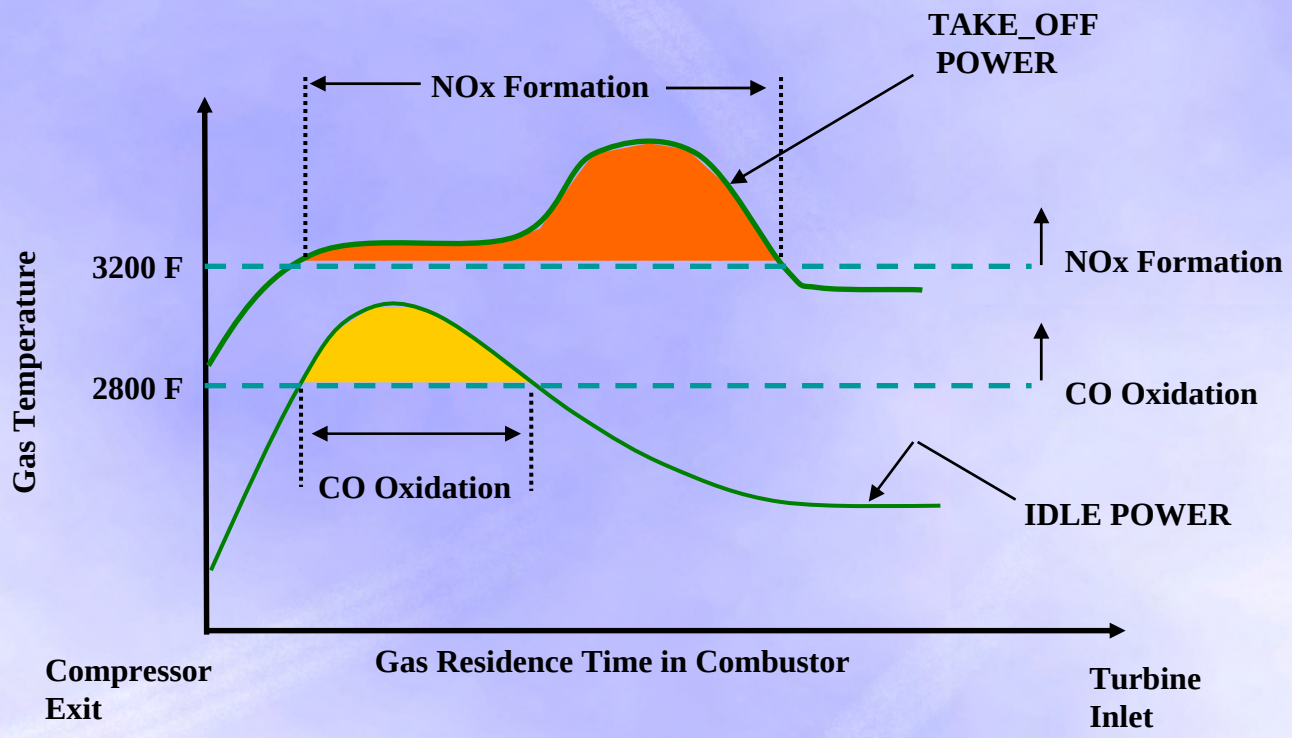
Fuel decomposition => soot formation => soot oxidation





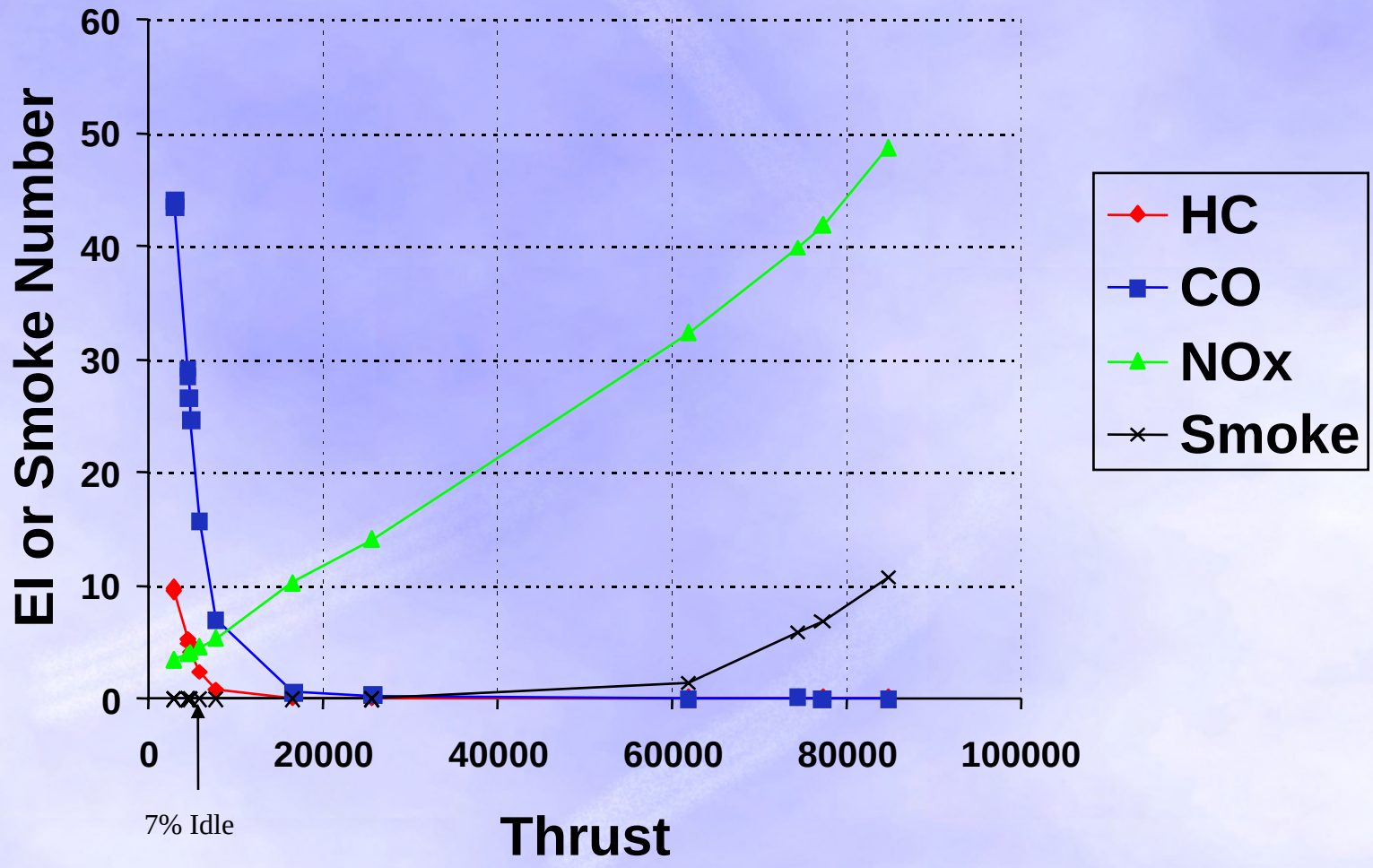
Unoxidized Soot => Visible Smoke Emissions

The Challenge is Good Operation at *BOTH* Low and High Power



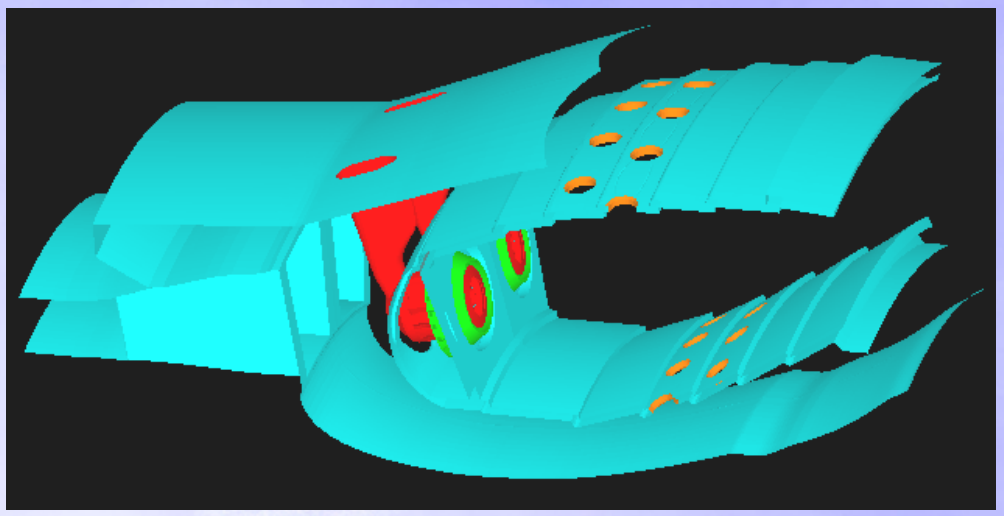
- Combustor temperature distribution can be changed during development by modifying the combustor.
  - but during engine operation it *only* changes as a result of operating condition.

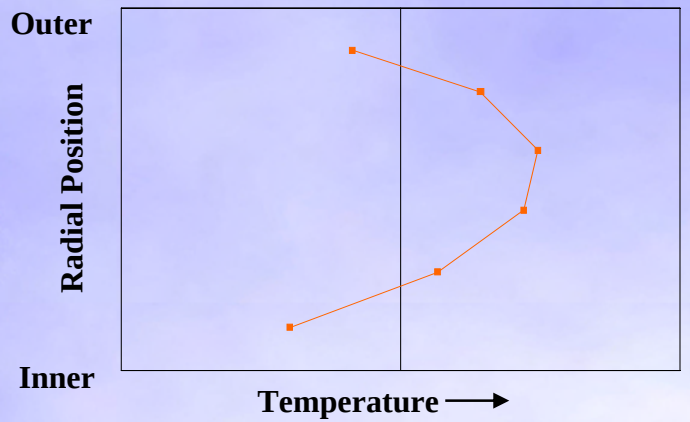
Thrust versus Emissions for the PW4084



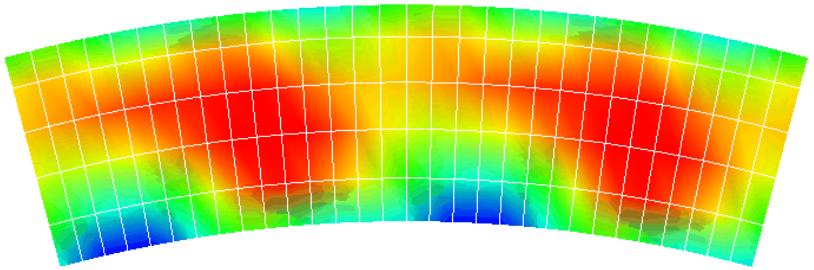
Exit Temperature Requirements Ensure Turbine Durability

Combustor Hole Pattern optimized to meet Exit Temperature Distribution Requirements



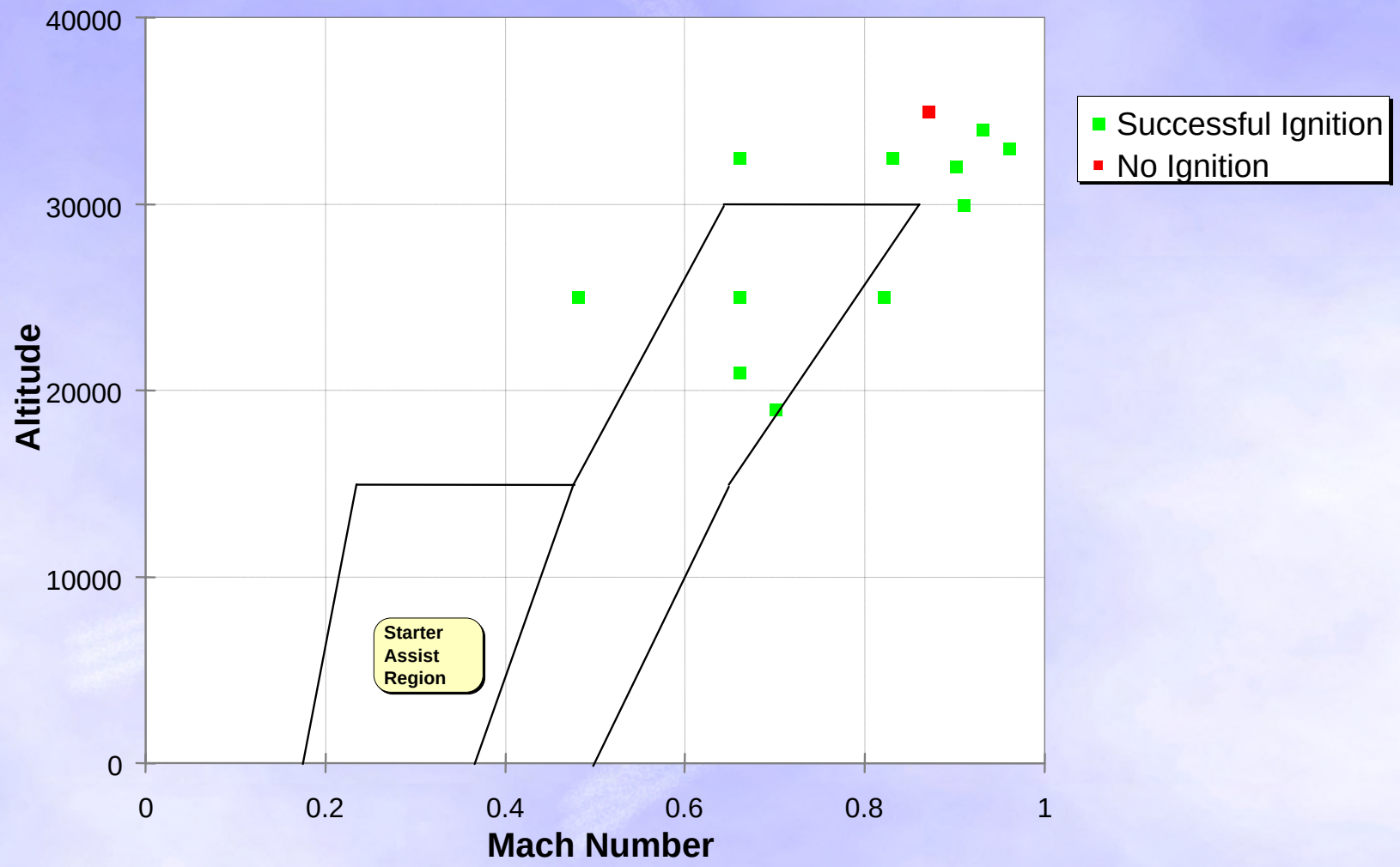


Average Temperature Profile impacts Blade Life



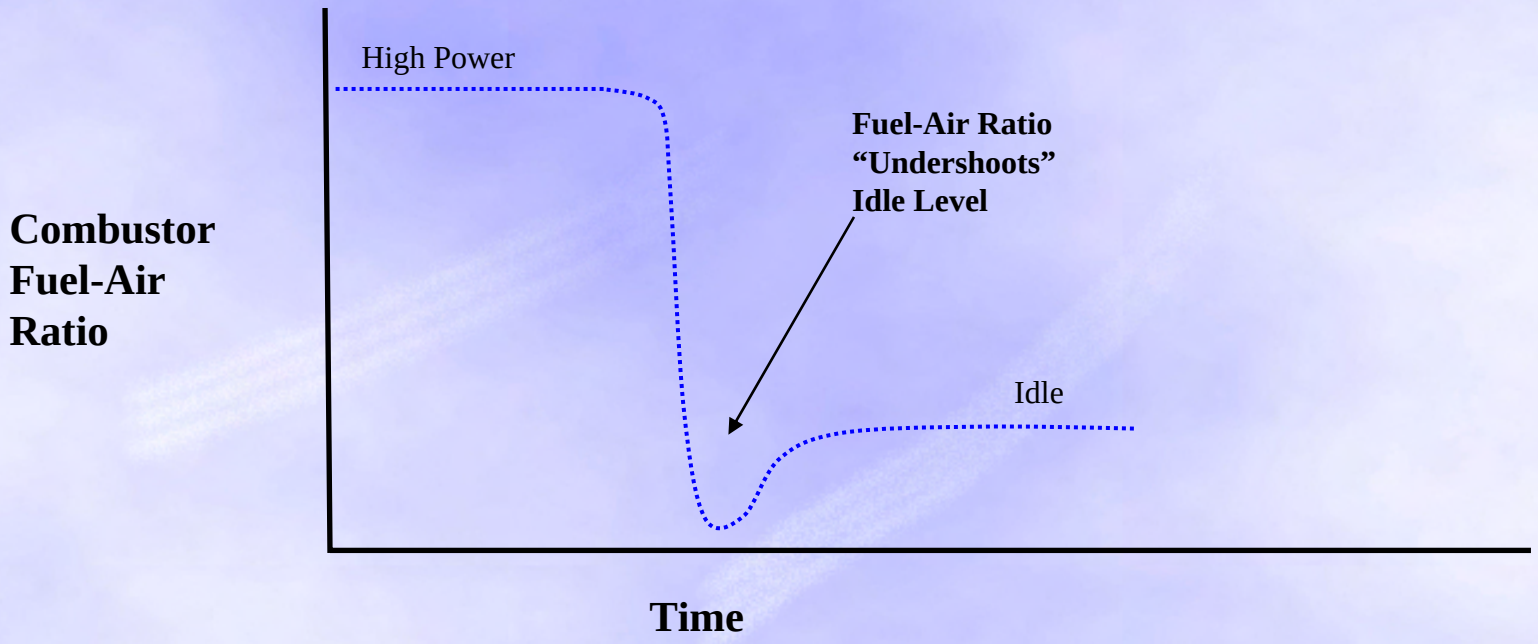
Maximum Local Temperature impacts Vane Life

Typical Altitude Relight Results

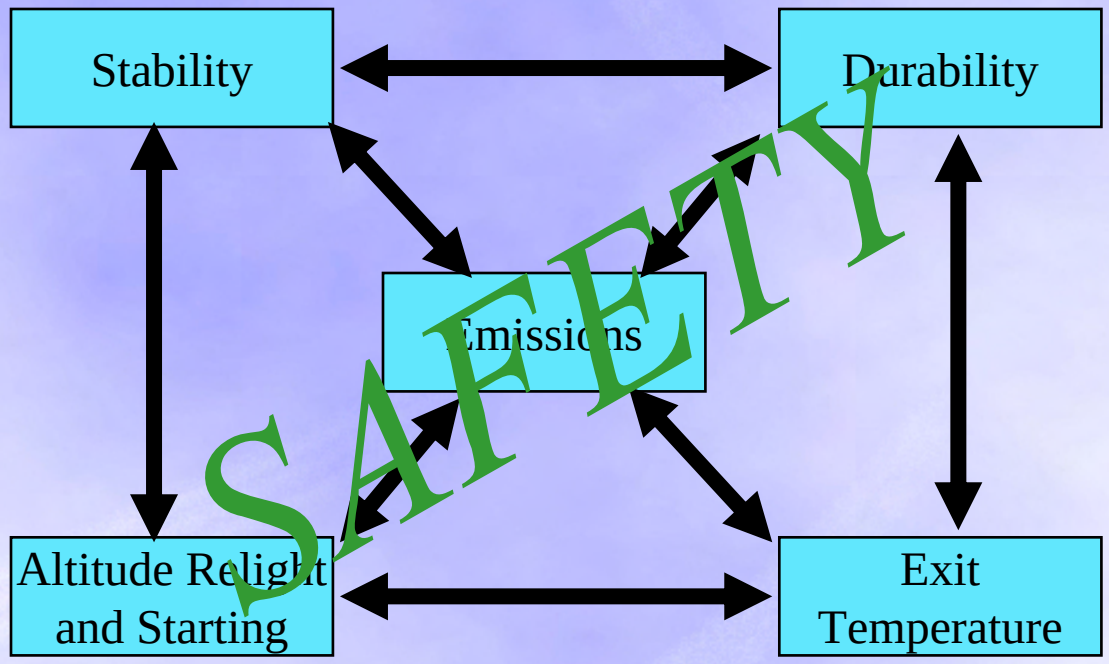


Combustor Stability

- Snap Deceleration of Engine most severe condition
  - Combustor must not “blow out” during these manoeuvres



Combustor Designs Must Satisfy Multiple Requirements



Aircraft Emission Reduction Priorities

	Local/Regional	Climate
Top Priorities*	**NO_x**, CO, HC	**CO_2** & NO_x
Emerging Issues*	Particulate Matter	Particulate Matter

* Research Focal Point Input

Additional Scientific Studies are a Key Need to Address Environmental Tradeoffs in Product Designs