INTERNATIONAL COORDINATING COUNCIL OF AEROSPACE INDUSTRIES ASSOCIATIONS

Engine Technology Development to Address Local Air Quality Concerns

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International Coordinating Council of Aerospace Industries Associations

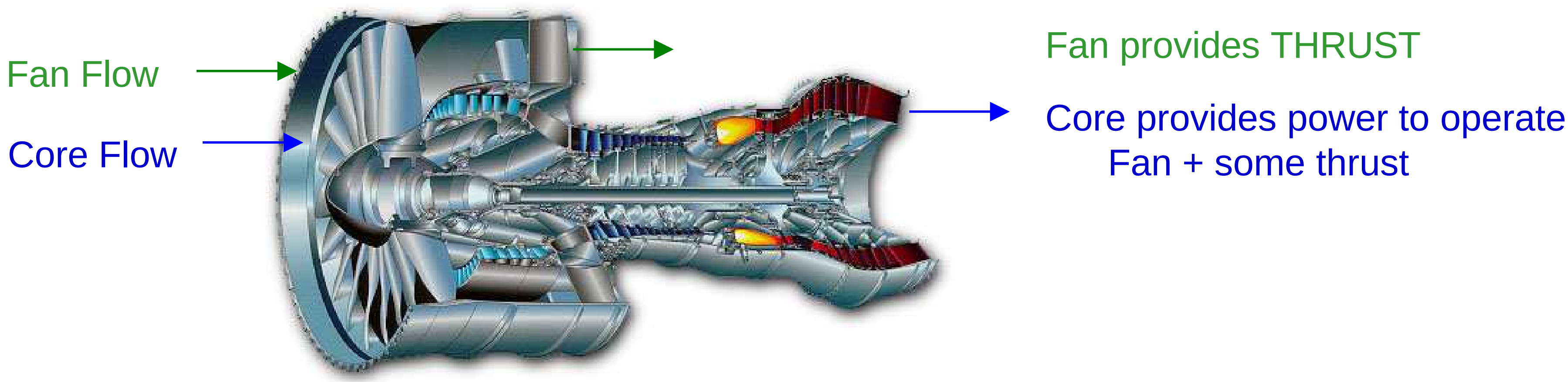
Overview

- Summary of material presented by manufacturers at March 2006 ICAO/CAEP Long Term Technology Goals (LTTG) review – next review will be in 2009
- Complete presentations are available on the CAEP Secure Web Site (WG3 – LTTG):
  - Combustion Fundamentals (R.McKinney - Pratt & Whitney)
  - Recent Engine Certifications (P.Madden - Rolls-Royce, D.Sepulveda - P&W, W.Dodds - GE, D.Allyn - Boeing)
  - Prospects for Middle Term Technology (W.Sowa - P&W, H.Mongia - GE, P.Madden, O.Penanhoat - Snecma, A.Joselzon - Airbus)
  - Emissions Tradeoffs (P.Madden)
  - Technology Transition (W.Dodds)

Technology Focus

- Focus for combustor emissions technology has been NOx
- Recent work by FAA is investigating contribution from PM
  - Primary PM – elemental carbon, organic carbon
  - Secondary PM from NOx
  - Secondary PM from fuel sulfur
- Developing a data base of PM in harsh measurement environment is challenging
  - We are working with PM measurement teams
- With a good data base, we can investigate effective mitigation options
  - Combustor technology for NOx?
  - Alternative fuels for sulfur?
  - Both for primary PM?
- Internationally, ICAO/CAEP is pushing both increased NOx stringency and improved PM measurement capability

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



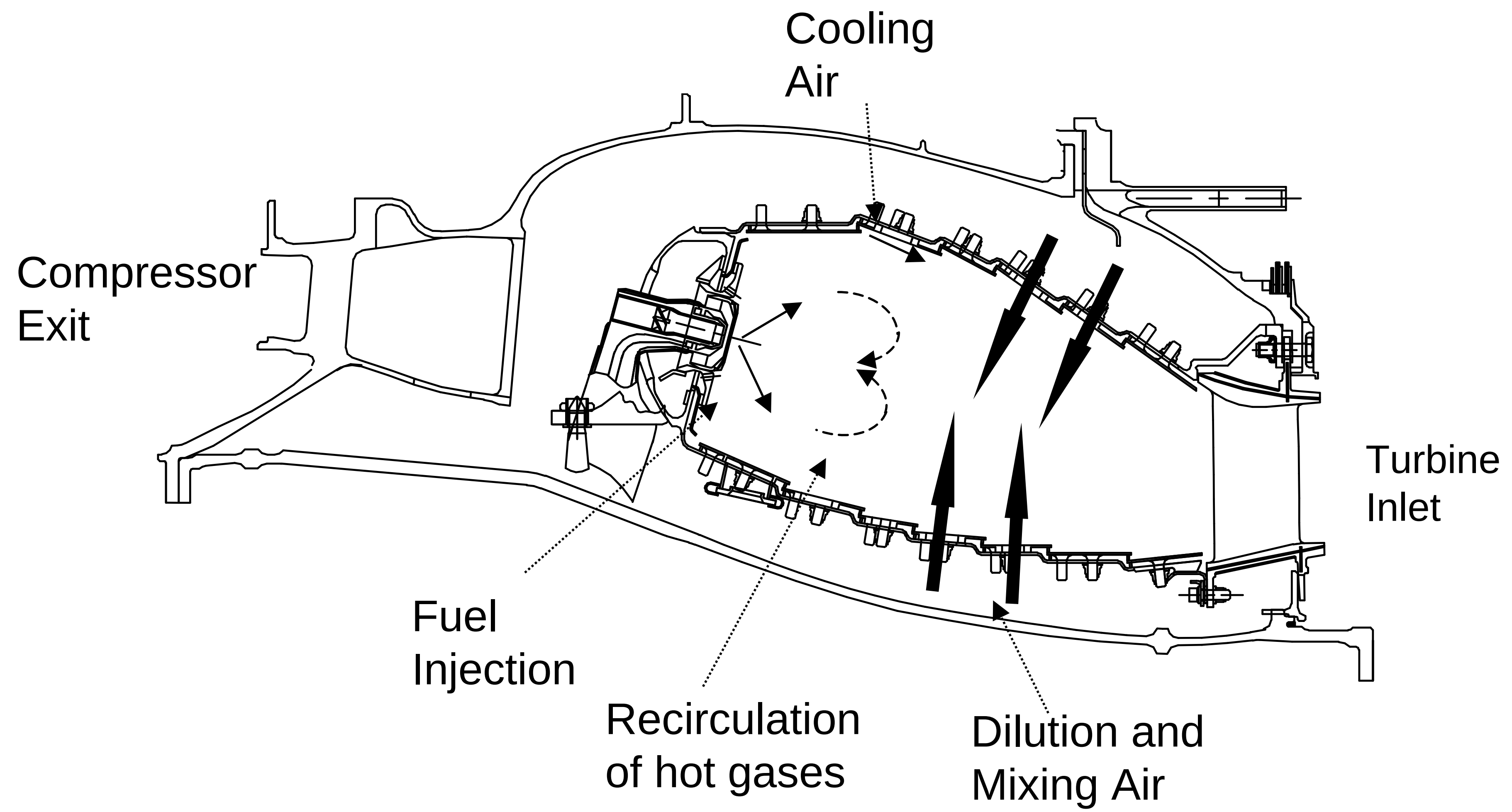
- The combustor is the hottest part of the engine
  - Inlet temperature and pressure can approach 700C (1300F) and 45 atm.
  - Temperature within combustor can exceed 2200C (4000F)
  - Temperature at combustor exit can approach 1650C (3000F)
- Metals melt at ~1350C (2500 F), so making the combustor survive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

Combustor Must Meet Engine Performance, Operability, Weight and Cost Requirements

Engine Requirement	Combustor Property
• Optimize fuel consumption	• High combustion efficiency (>99.9%) and low pressure loss
• Meet ICAO and customer emissions requirements	• Minimize emissions and smoke
• Wide range of thrust, rapid acceleration/deceleration, steady operation in extreme rain and hail	• Wide stability/operability limits • Sustain flame during water and hail ingestion
• Ground start, altitude relight	• Reliable and smooth ignition
• Turbine durability	• Good temperature distribution at exit
• Combustor durability	• Low metal temperatures • Coke-free fuel system
• Low Weight and Cost	• Fit within engine envelope

Safety is the Highest Design Priority!

Continuous Flow Combustion with Aerodynamic Stabilization



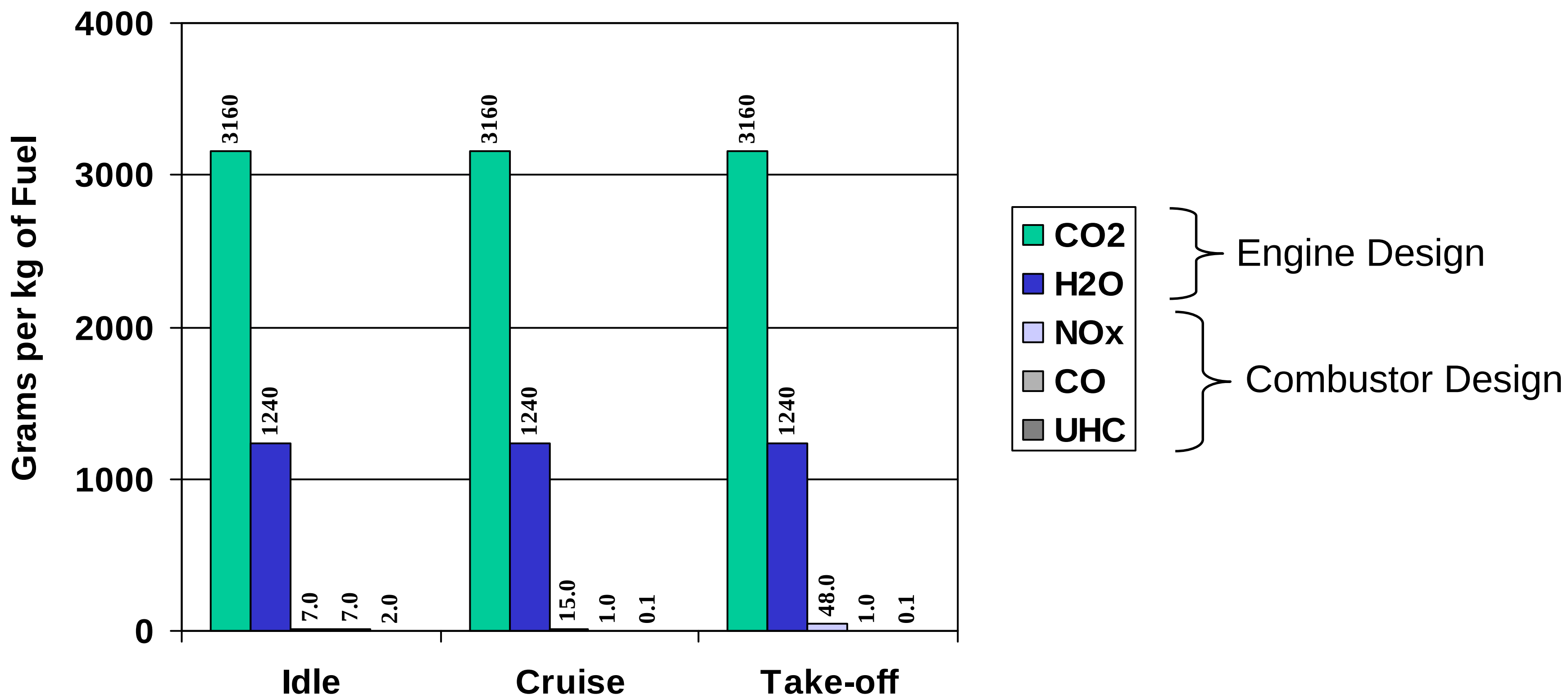
Current Combustor Designs Balance All Requirements

Combustion of Jet Fuel - Fundamentals

- $C_{12}H_{23} + 17.75O_2 \Longrightarrow 12CO_2 + 11.5\ H_2O$
- Fuel + Air react to form:
  - Excess Oxygen (O_2)
  - Excess Nitrogen (N_2)
  - Carbon Dioxide (CO_2) Product of Combustion
  - Water Vapor (H_2O) Product of Combustion
  - Sulfur Oxides (SOx) Sulfur from fuel
  - Carbon Monoxide (CO) Incomplete Combustion
  - Unburned Hydrocarbons (HC) Incomplete Combustion
  - Oxides of Nitrogen (NOx) High Temp. Air Reaction
  - Smoke/Soot PM Local High Fuel levels

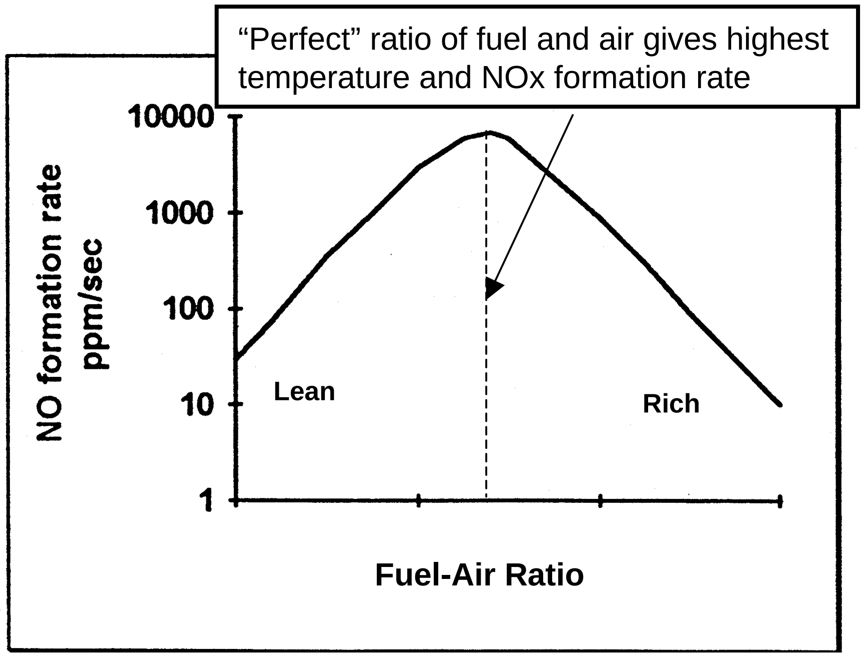
Combustion of Jet Fuel - Quantified

- A typical engine produces the following mass of products for each kilogram of fuel burned:



NOx Formation

- NOx primarily formed through thermal combination of Nitrogen and Oxygen



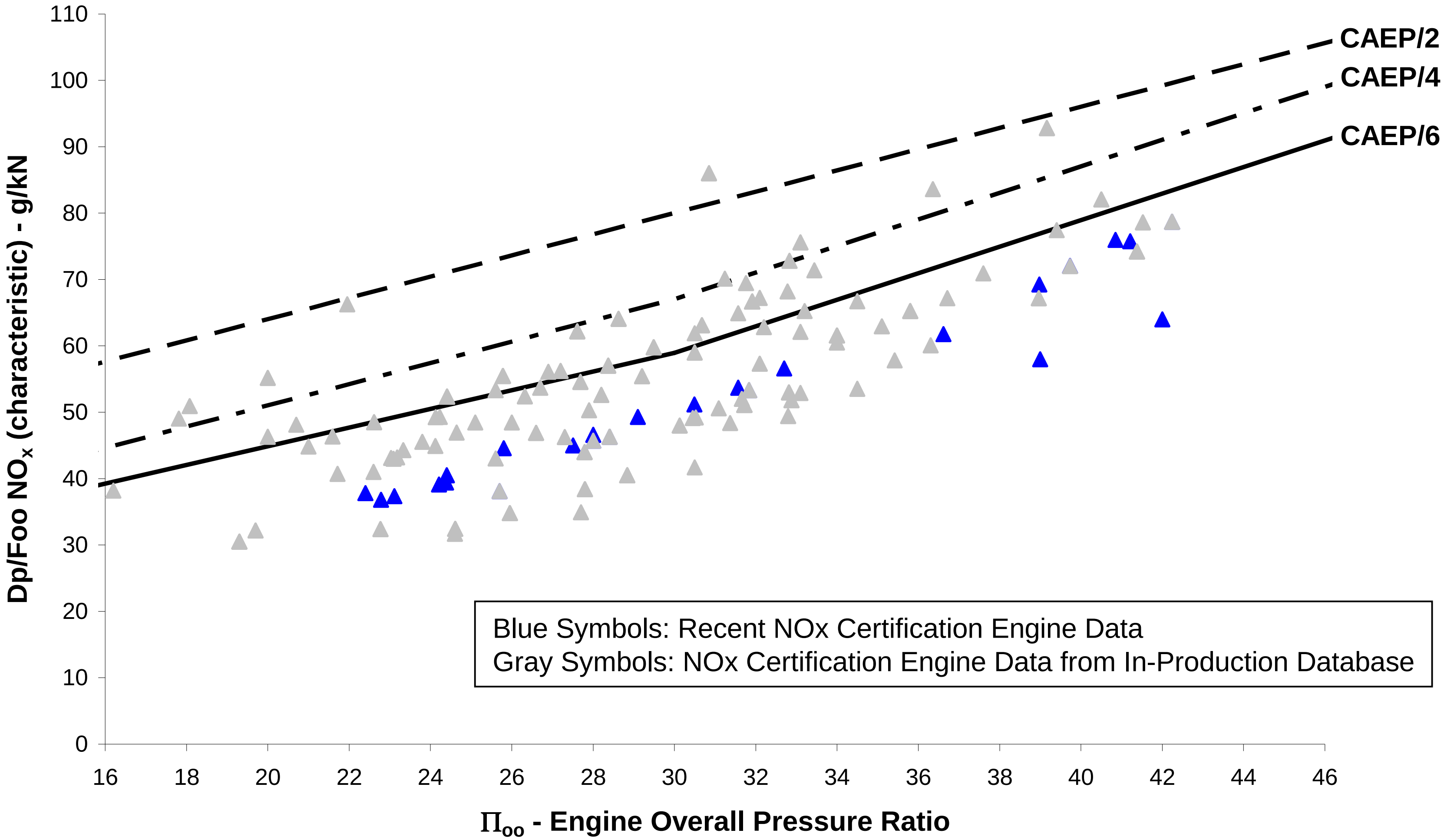
- Formation rate is a function of:
  - Fuel-Air Ratio
  - Temperature & Pressure
- Total NOx formed depends on:
  - Formation rate
  - residence time
- NOx formation can be reduced by:
  - Burning rich (RQL)
  - Burning lean (lean-staged)
  - Reducing combustor volume

Recent Engine Certifications

Recent engine certification results were reviewed to indicate capability of current technology…

- Recent data covers ten engine families that have reached TRL8 or 9 since CAEP/6 "Current Production" emissions data base was published in 2003
  - Thrust: 75 to 514 kN
  - Pressure ratio: 21.4 to 42.9
- All recent combustors use modified RQL combustor NOx reduction technology
- NOx emission reduction may be enhanced due to improved engine performance (lower fuel consumption)

Recent Certification Emissions Relative to Standards



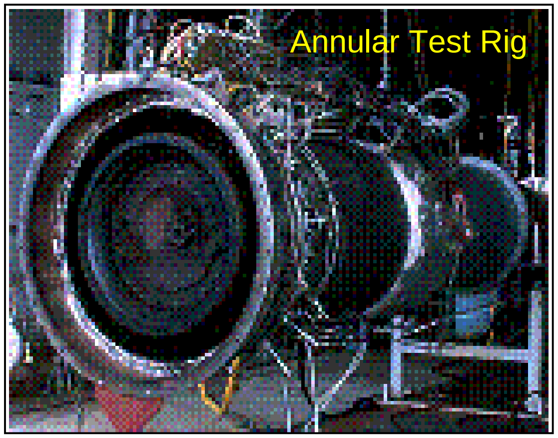
All recent engines meet CAEP/6 requirements with small margin, and are towards lower end of current production

Middle Term Technology Prospects

Current R&D and technology transition projects were reviewed to inform middle term goals…

- Full annular rig and factory engine test data (TRL 5 and 6) on new combustor configurations that are being developed for potential introduction into service within the next ten years

- Middle term approaches include further development of both RQL and Lean-Staged technologies



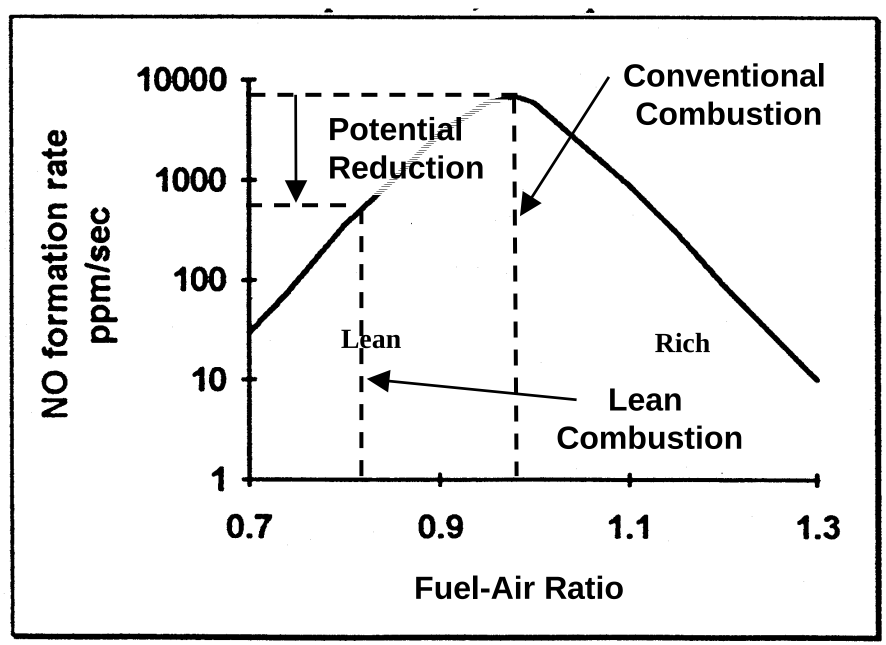
Principles of Lean-Staged Combustion

Principles

- Flame temperature is reduced with lean fuel-air mixture
- Significant theoretical NOx reduction at high power with complete fuel vaporization and uniform fuel-air premixing
- A combustor designed for lean combustion at high power will not light well or burn stably at idle operating conditions:
  - One solution is a “pilot zone” for low power operation. All fuel goes to the pilot zone at low power (fuel staging)

Design challenges:

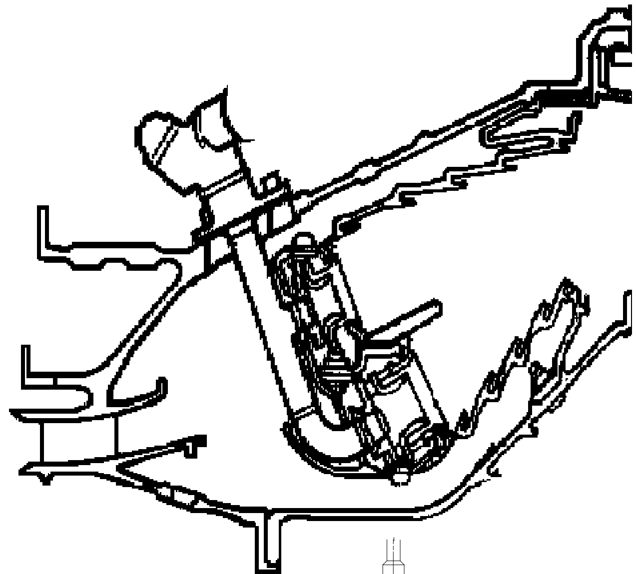
- Smooth control of staging
- Complexity (cost, weight)
- Fuel coking
- Fuel pre-ignition
- Dynamic pressures



Related Background on Lean-Staged Combustion

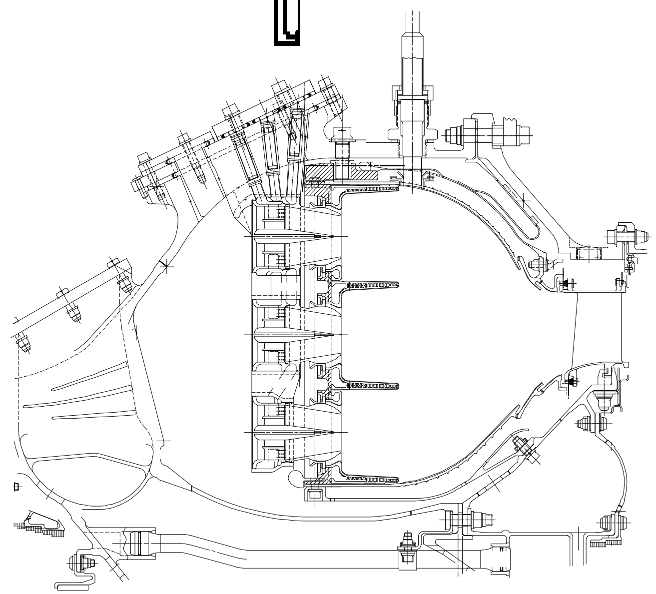
Aviation Engines

- CFM56 DAC:
  - NOx ~30% below baseline combustor
  - ~375 Engines
  - ~5M Flight Hrs.
  - ~3.3M Cycles

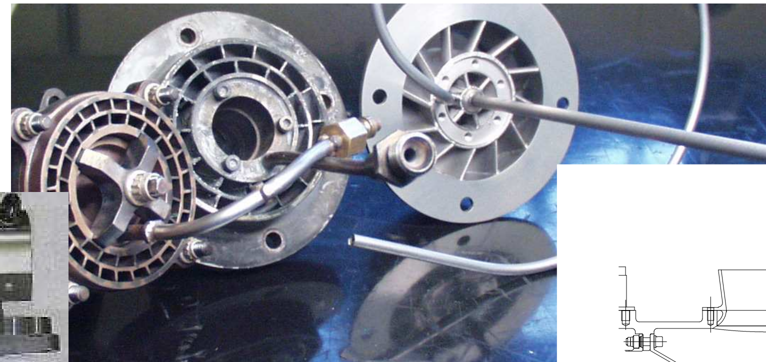


Industrial Engines

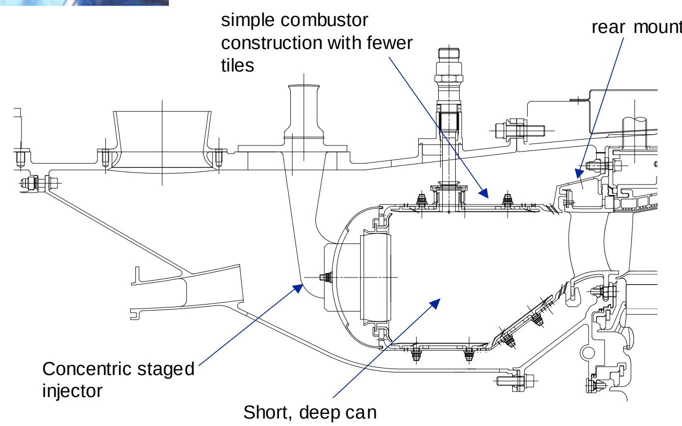
- Lean staged combustors in wide service
- More than 90% NOx reduction capability has been demonstrated in industrial applications
  - Natural gas fuel
  - Slow acceleration and deceleration
  - Expanded combustor envelope
  - No airstart requirement
  - No weight or size limitations
  - No interference with fan stream

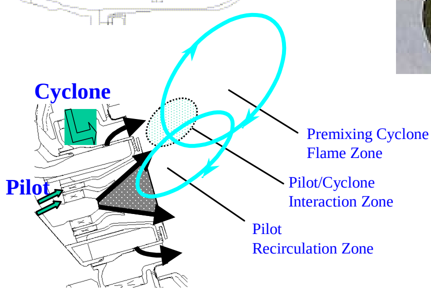


Current Lean Staged Combustor Development



R-R Lean Burn Combustor





GE TAPS Combustor

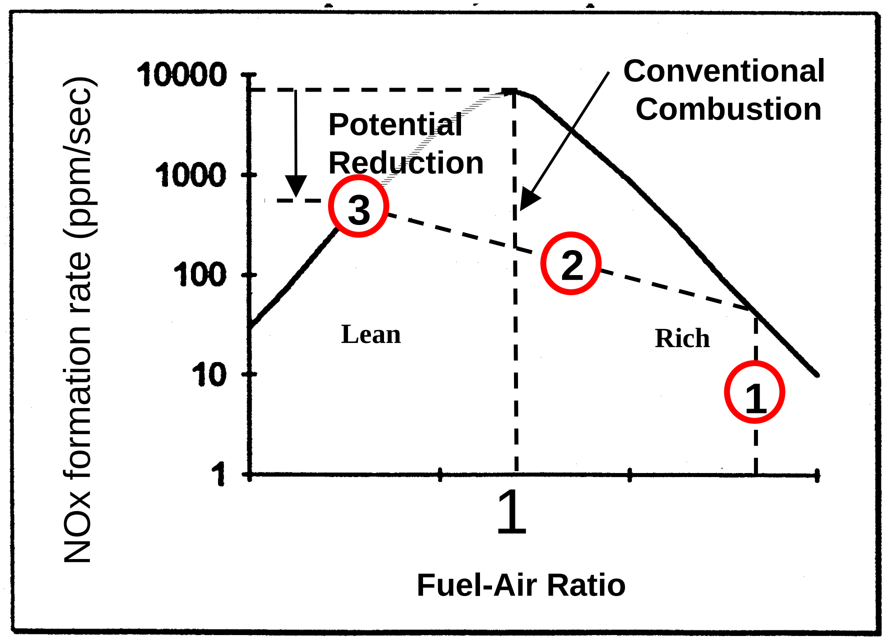
Lean Staged Combustor Development Experience

- ~900 hours factory testing in 30 OPR engine
- 200 hours at the maximum rated thrust
- Performance, Emissions, Noise, Dynamics, Thermal and Mechanical Surveys
- Starts, Throttle Burst-Chop Transients.
- 4,000 LCF cycles
- 2,000 fuel nozzle staging cycles
- Full range ground operation 40 OPR engine

Principles of RQL Combustion

Principles

1. Fuel and small part of air react in rich stage. Mixture reconstituted to CO, H2 and heat. Very low NOx formation rate due to low temperature and low concentrations of oxygen
2. Additional air rapidly added to produce lean mixture. Fast fuel-air mixing is critical to minimize NOx formation
3. Lean mixture reacts at reduced flame temp.



Design challenges

- Avoiding front-end non-uniformities
- Reducing wall cooling
- Rapid quench mixing to minimize NOx production during mixing
- Balancing high/mid/low power emissions

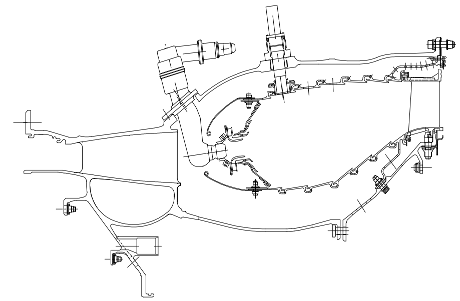
Related Background on RQL Combustion

Aviation Engines

- TALON (PW), Phase 5 (RR) and LEC (GE) combustors in all current products use RQL NOx reduction technology

Advanced Research Programs

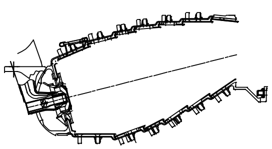
- Significant NOx reductions demonstrated in NASA HSR, AST and QEET Programs



GE "LEC" Combustor

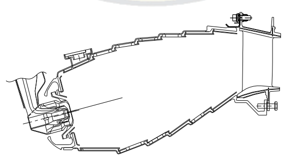
PW RQL Combustor Development (1997-2005)

Conventional Combustor
- PW4090 (EIS 1997)
- Baseline NOx



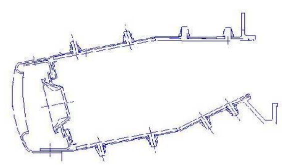
PW4090

TALON I Combustor *(retired)*
- PW4098 (EIS 1999)
- *145,435 hours / 37,761 cycles*
- No unscheduled engine removals
- No in-flight shutdowns
- No delays and cancellations
- Reduced NOx

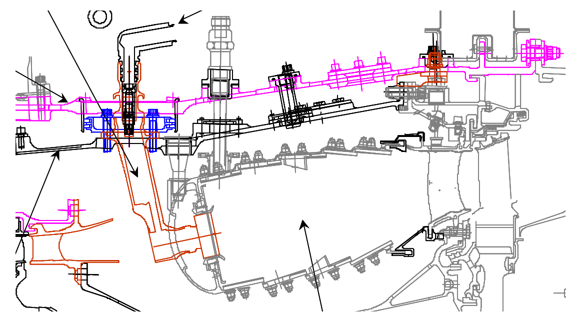


PW4098 TALON I

TALON II Combustor *(through 1/2006)*
- PW4158 (EIS 2000),PW4168 (EIS 2001), PW6000 (EIS 2005)
- *856,378 hours / 286,111 cycles*
- 1 unscheduled engine removals
- No in-flight shutdowns
- No delays and cancellations
- Further Reduced NOx



PW6000 Talon II



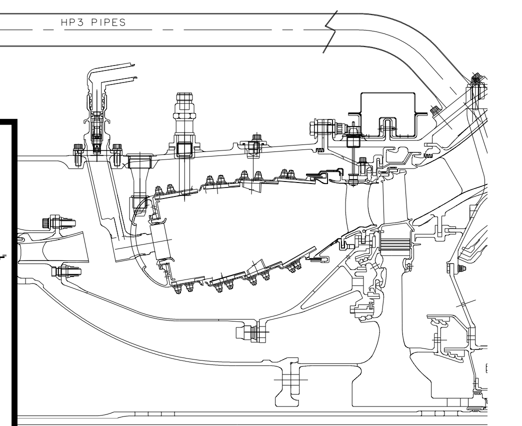
RR "Tiled Phase 5" Combustor

Current RQL Combustor Development

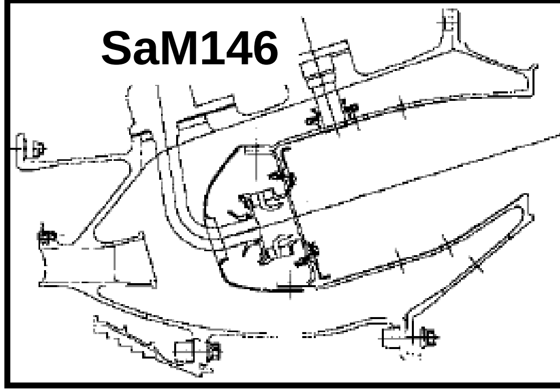
Advanced Trent and SaM146 are expected to achieve significant margin to CAEP/6 in near-term
• Certification planned for 2008

Trent 1000 Combustion System

Derivative low emissions design based on previous Trent experience.



SaM146

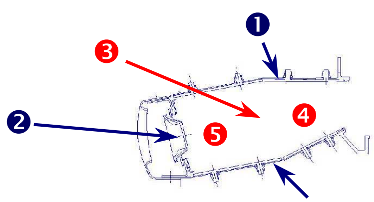


TALON X NOx Reduction Methodologies

Blue parent technologies TRL/6 or higher

❶Advanced Impingement Film Floatwall
- *Equiax cast Floatwall segments*
- *In production*

❷High Shear Fuel Injectors
- *In production*



Talon II cross-section

Red technologies < TRL/5

❸Local Residence Time Adjustments

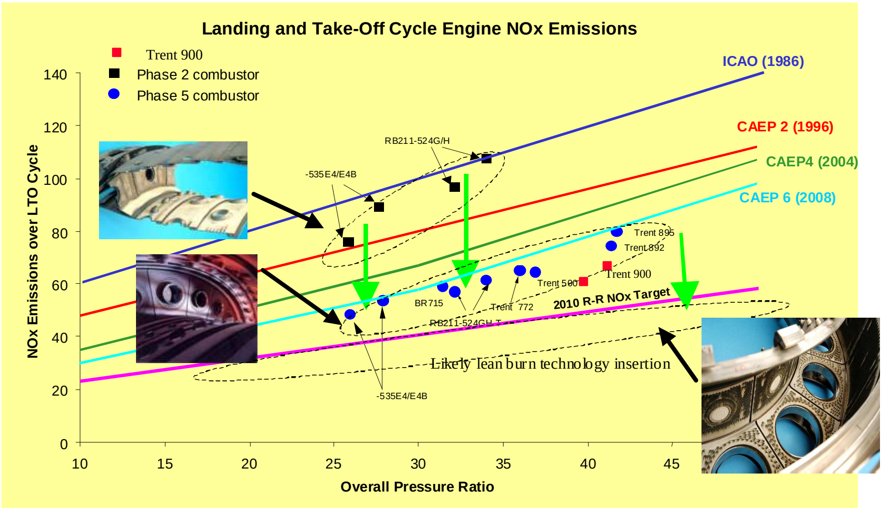
❹Quench (Lean) Zone Mixing Optimization
- *Shaped / directed / tailored quench holes*
- *NOx reduction via reduced mixing scale, elimination of high NOx formation (stoichiometric) zones*

❺Rich Zone Uniformity
- *Fuel injection quality / distribution*
- *Smoke reduction via elimination of fuel-rich pockets*
- *NOx reduction via stoichiometry uniformity*

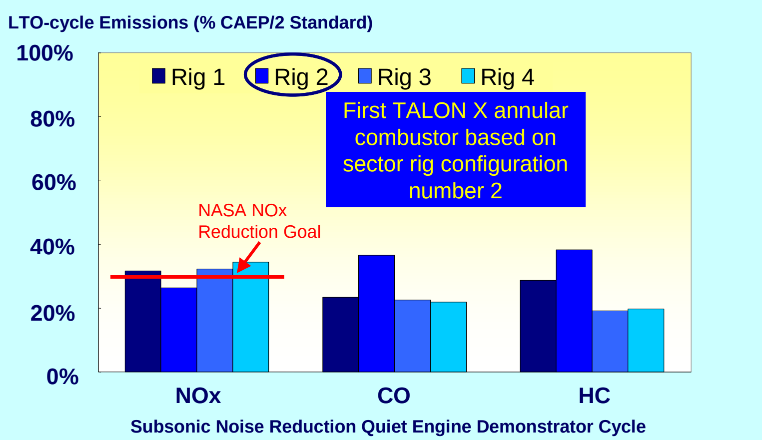
TALON X development aims for substantial NOx reduction in middle term:
• Annular rig test – 2006
• Engine test - 2006
• Potential EIS in 2012-2013

Middle Term Technology Progress

R-R Lean Burn Combustor Emissions Status

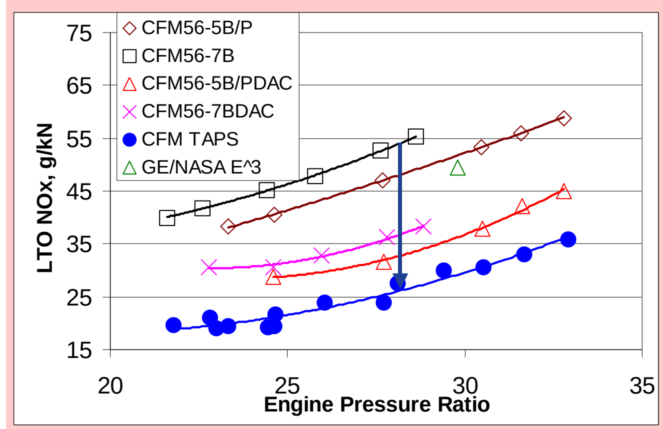


PW TALON X TRL-4 Sector Result Surpasses NOx Goal



Prototype tests of revolutionary RQL and Lean Staged combustors show potential for considerable NOx reduction

GE TAPS NOx



Based on LTTG review, current TRL is 5-6. Flight test data still needed to demonstrate airworthiness

Engine and Combustor Design Tradeoffs

Emissions tradeoffs were considered at length during the LTTG review…

Engine Cycle Trades

- Continuing trend toward higher pressure ratio reduces CO_2, CO, HC and enables noise reduction, but increases NOx.

Combustor Trades

- Rich reaction zone reduces NOx formation but tends to increase soot
- Leaner reaction zone reduces NOx and soot formation, but tends to increase CO and HC. Also reduces combustion stability
- Reduced combustion chamber volume reduces NOx, but tends to increase CO and HC. Also tends to reduce altitude relight capability

Scientific Advice is Needed to Properly Balance Tradeoffs

Overall Summary

- Recent engine certifications demonstrate continuous transition of technology to products – All meet CAEP/6 standards
- All manufacturers have R&D projects aimed at significant middle term NOx reductions with revolutionary RQL and/or Lean-Staged combustor concepts. All projects were considered in setting middle term goals
- Each combustor concept has inherent environmental tradeoffs – scientific understanding is key
- Timely transition of technology from R&D to product without loss of emissions performance will be challenging

Initial CAEP Goals are Consistent with Manufacturers' Aims…
…Future Reviews Will Monitor Progress and Adjust Goals

Questions?