Engine Technology Development to Address Local Air Quality Concerns

John Moran
Corporate Specialist – Combustion
Rolls-Royce Associate Fellow - Combustion

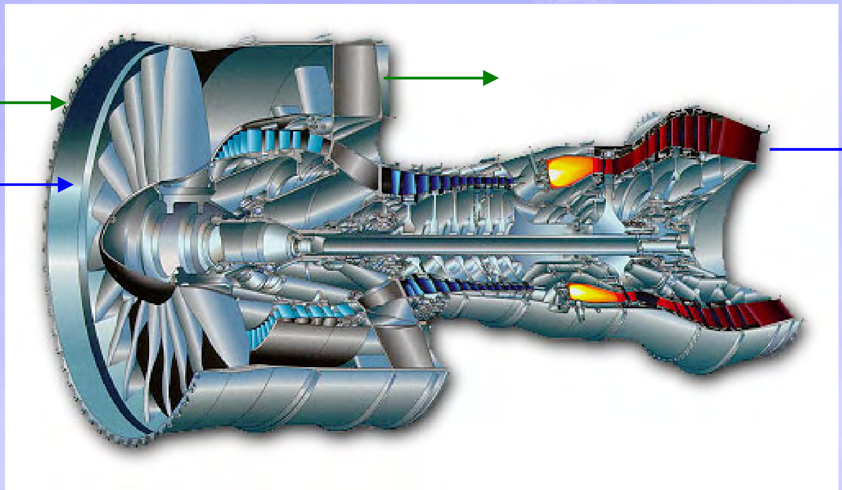
Overview

- This presentation summarizes material presented by manufacturers at the LTTG review
- Complete presentations are available on the CAEP Secure Web Site (WG3 – LTTG):
  - Combustion Fundamentals (R.McKinney)
  - Recent Engine Certifications (P.Madden, D.Sepulveda, W.Dodds, D.Allyn)
  - Prospects for Middle Term Technology (W.Sowa, H.Mongia, P.Madden, O.Penanhoat, A.Joselzon)
  - Emissions Tradeoffs (P.Madden)
  - Technology Transition (W.Dodds)

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

Fan Flow

Core Flow



Fan provides THRUST

Core provides power to operate Fan + some thrust

- 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

NOx Formation

- **NOx primarily formed through thermal combination of Nitrogen and Oxygen**

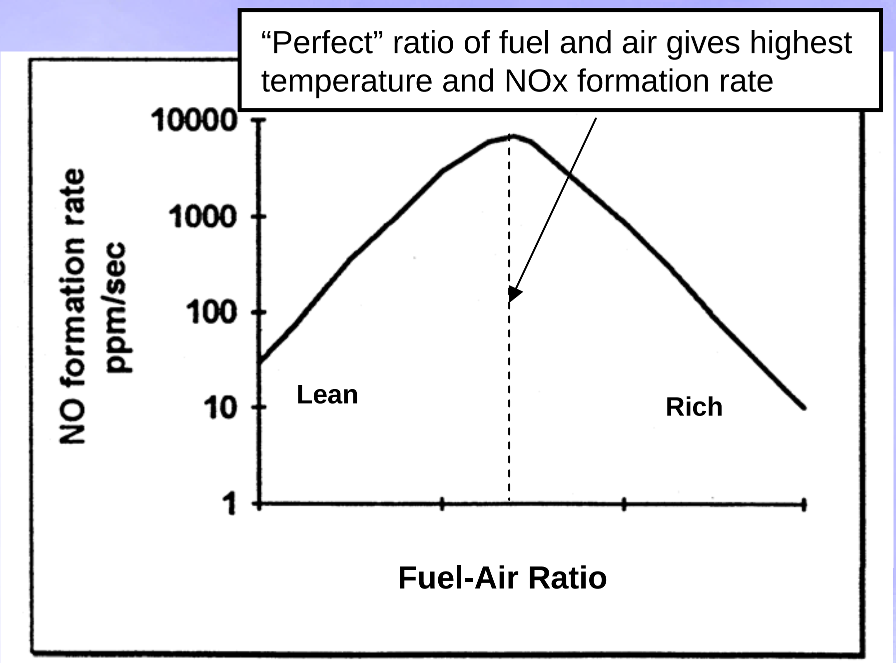


Figure 3-1 Adiabatic Combustion of Kerosene

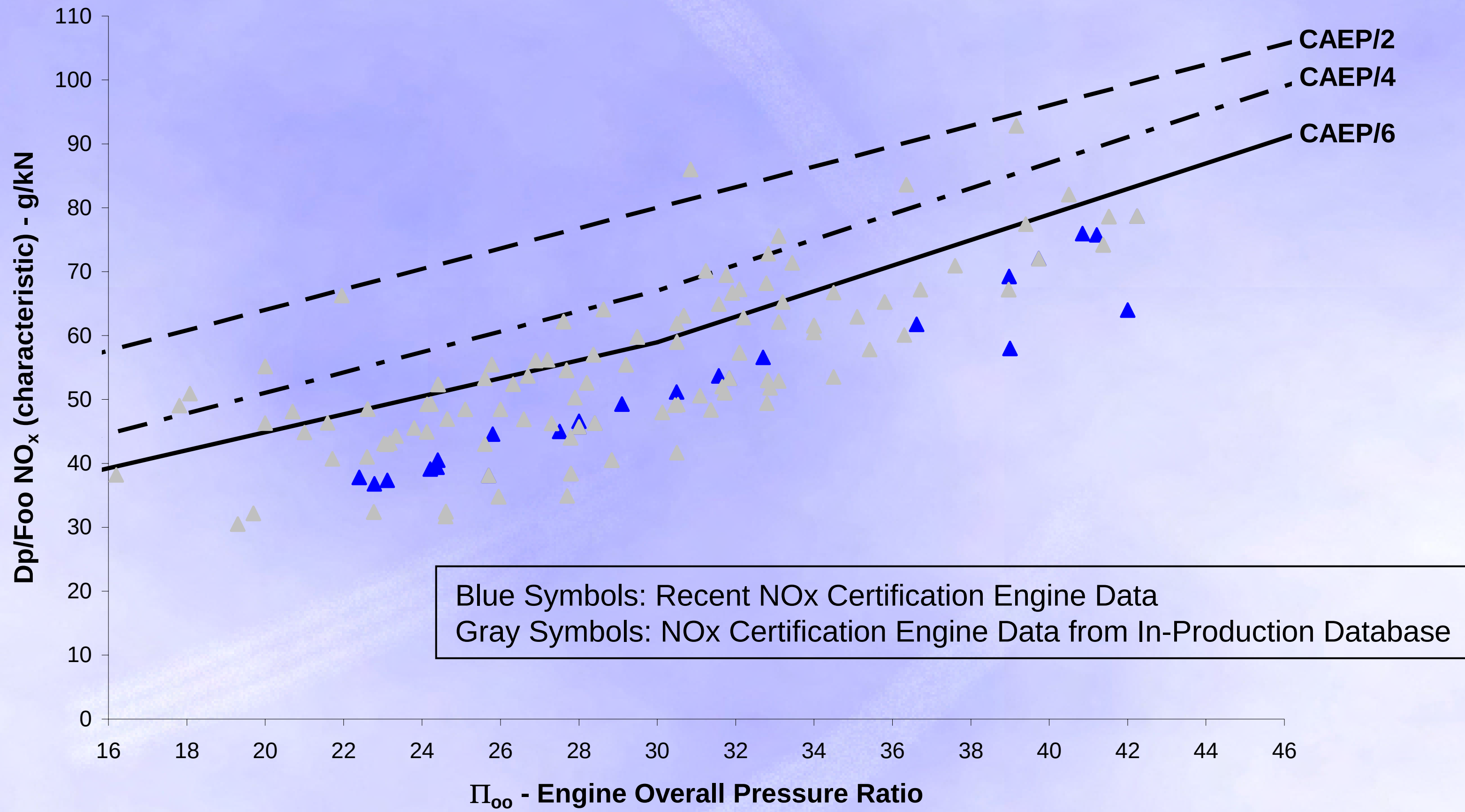
- Formation rate is a function of:
  - Fuel-Air Ratio
  - Temperature & Pressure
- Total NOx formed depends on:
  - Formation rate
  - residence time
- NOx formation can be reduced by:
  - Burning rich (RQL)
  - Burning lean (lean-staged)
  - Reducing combustor volume

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…

Annular Test Rig

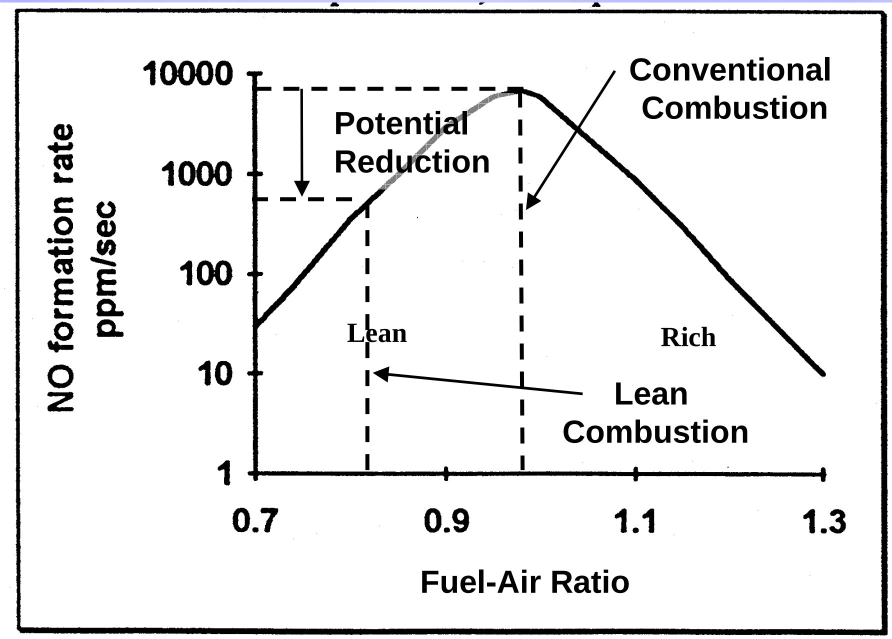
- Full annular rig and factory engine test data (TRL 5 and 6) on new combustor configurations that are being developed for potential introduction into service within the next ten years

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

Principles of Lean-Staged Combustion

Principles

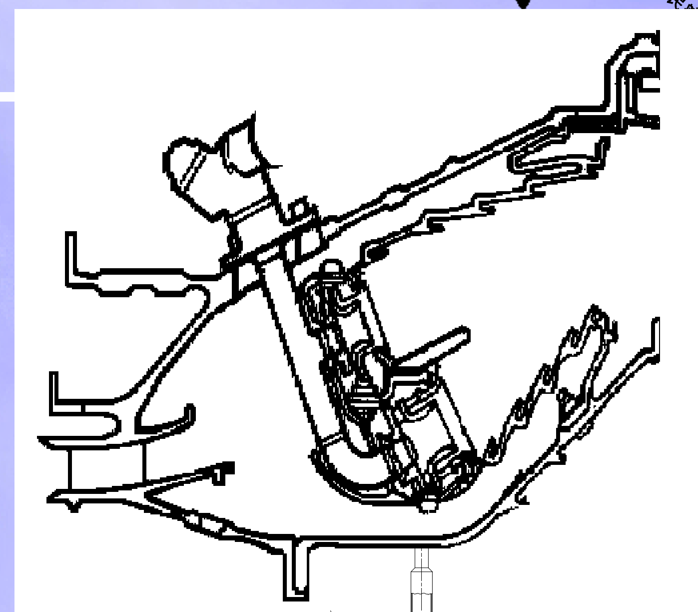
- Flame temperature is reduced with lean fuel-air mixture
- Significant theoretical NOx reduction at high power with complete fuel vaporization and uniform fuel-air premixing
- A combustor designed for lean combustion at high power will not light well or burn stably at idle operating conditions:
  -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

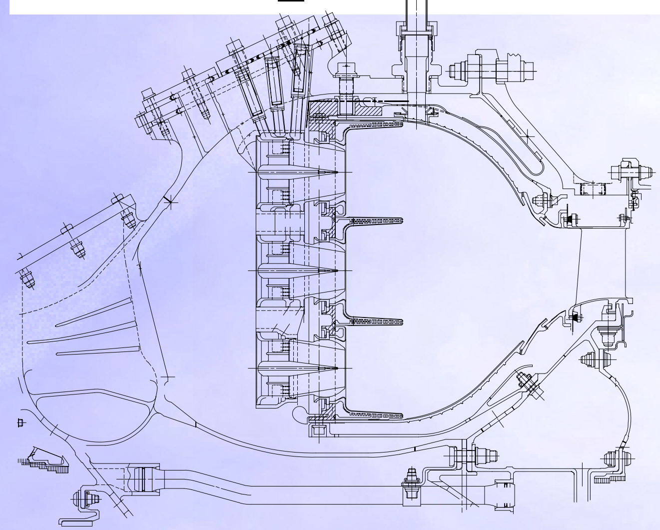


Design challenges:

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

Related Background on Lean-Staged Combustion





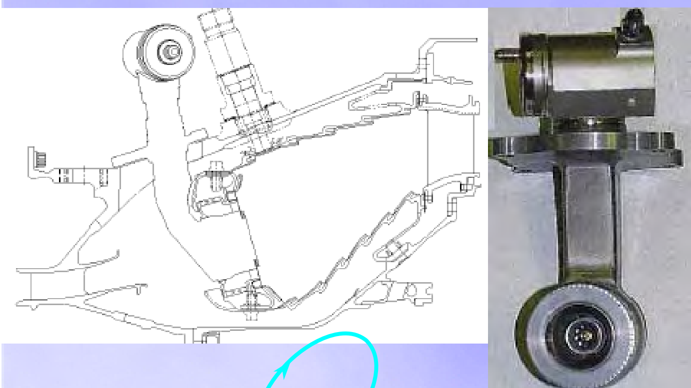
Aviation Engines

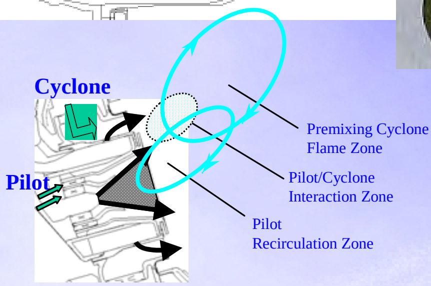
- CFM56 DAC:
  - NOx ~30% below baseline combustor
  - ~375 Engines
  - ~5M Flight Hrs.
  - ~3.3M Cycles

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

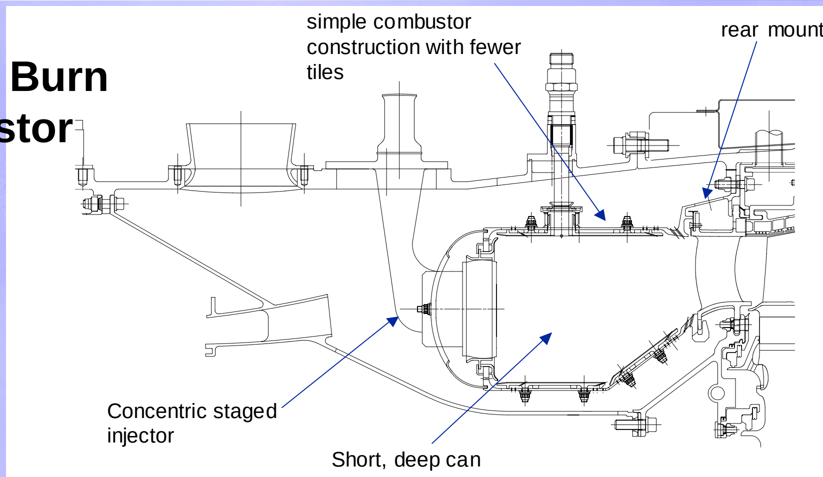
Current Lean Staged Combustor Development





GE TAPS Combustor

R-R Lean Burn 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

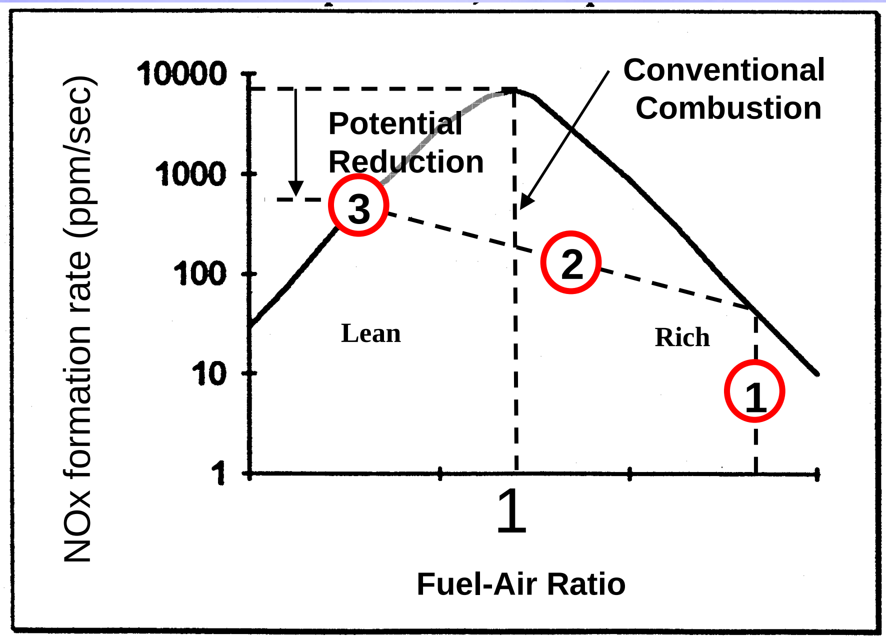
Principles of RQL Combustion

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

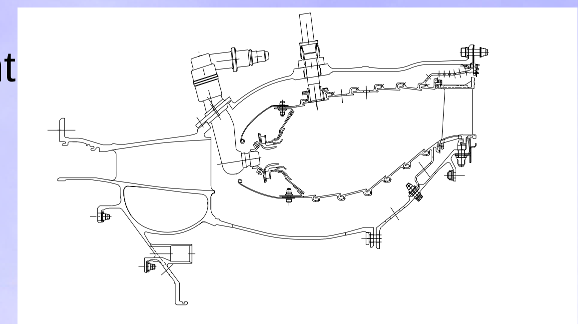
Related Background on RQL Combustion

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

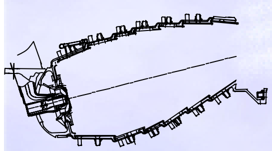


GE "LEC" Combustor

PW RQL Combustor Development (1997-2005)

Conventional Combustor

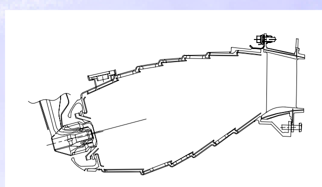
- PW4090 (EIS 1997)
- Baseline NOx



PW4090

TALON I Combustor(retired)

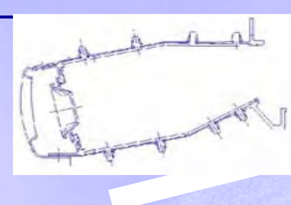
- PW4098 (EIS 1999)
- *145,435 hours / 37,761 cycles*
- No unscheduled engine removals
- No in-flight shutdowns
- No delays and cancellations
- Reduced NOx



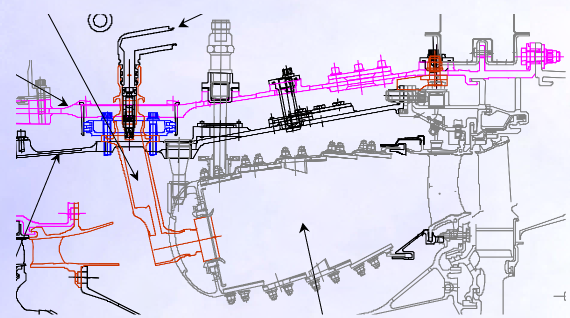
PW4098 TALON I

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

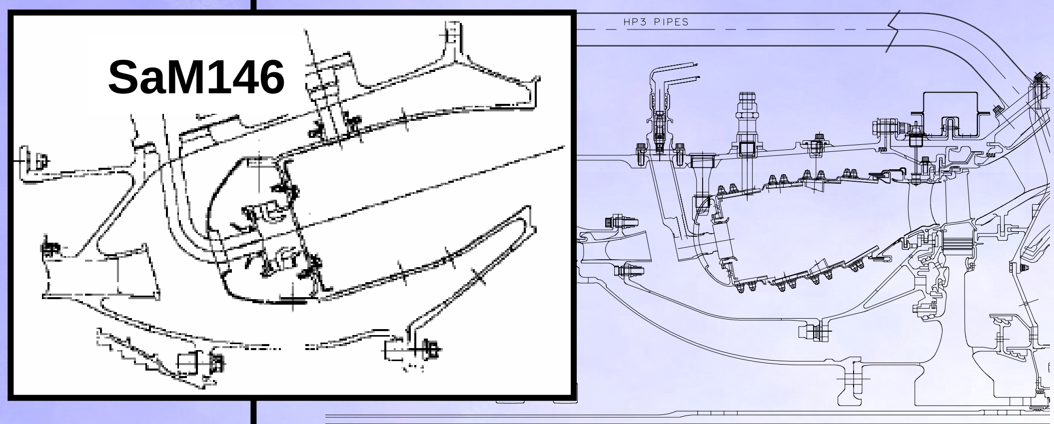
Current RQL Combustor Development

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.



TALON X development aims for substantial NOx reduction in middle term:

- Annular rig test – 2006
- Engine test - 2006
- Potential EIS in 2012-2013

TALON X NOx Reduction Methodologies

Blue parent technologies TRL/6 or higher

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

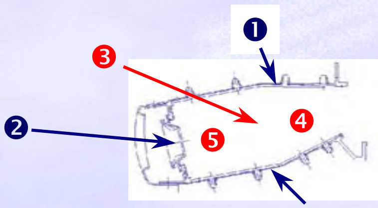
❷High Shear Fuel Injectors
- *In production*

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*

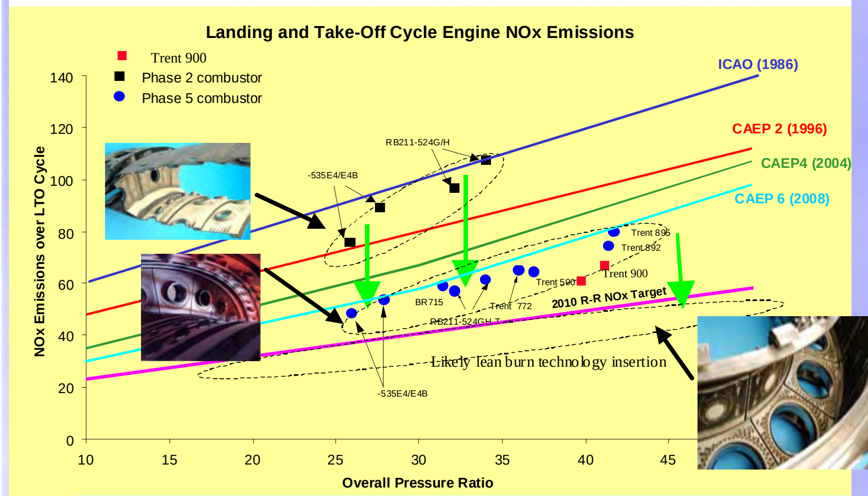
❺Rich Zone Uniformity
- *Fuel injection quality / distribution*
- *Smoke reduction via elimination of fuel-rich pockets*
- *NOx reduction via stoichiometry uniformity*



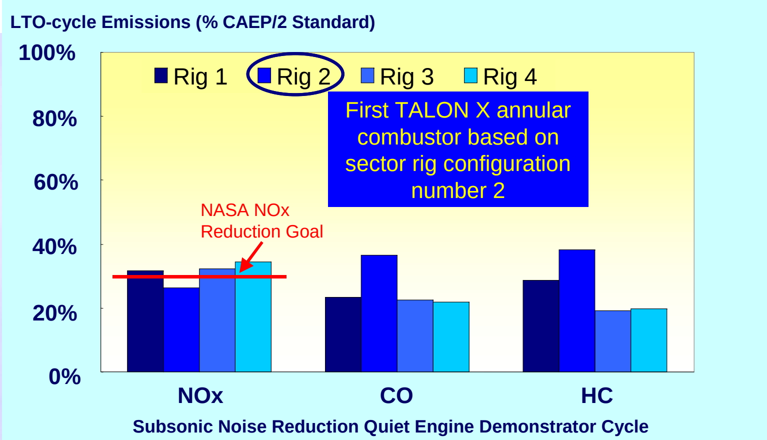
Talon II cross-section

Middle Term Technology Progress

R-R Lean Burn Combustor Emissions Status

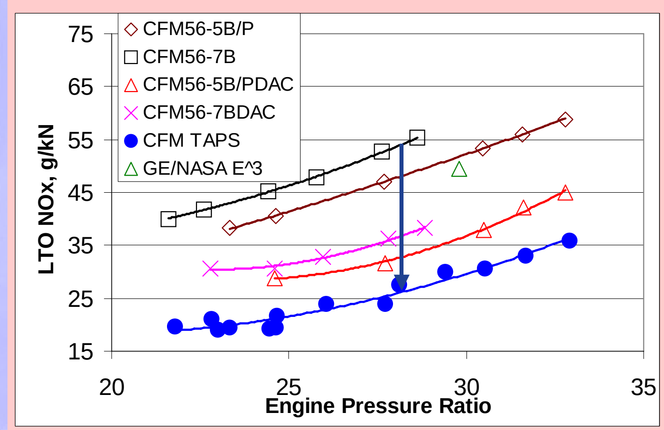


PW TALON X TRL-4 Sector Result Surpasses NOx Goal



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

Technology Transition Issues/Barriers

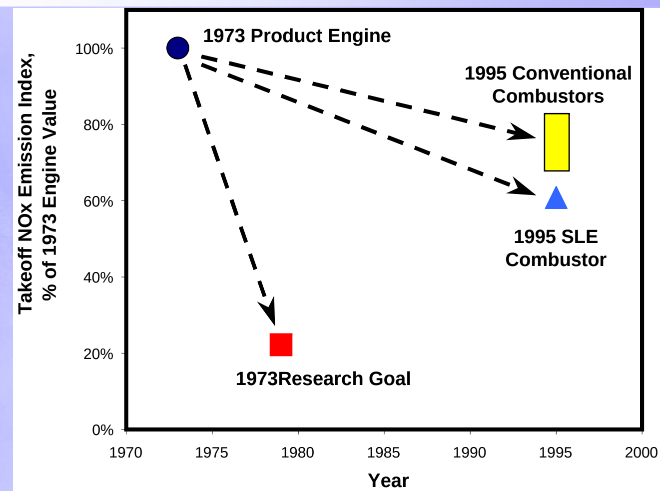
Transition to product was considered during the LTTG review…

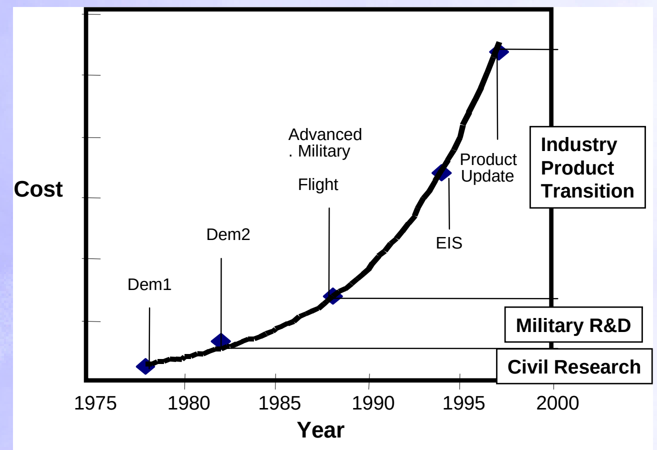
- High development and certification investment with low production volume - Heavily regulated for airworthiness/safety
- Durability, operability, reliability & production cost risks - Critical design requirements - weight, efficiency
- Environmental tradeoffs - Technological and benefits
- Unclear or mixed local/national/regional policies
- Long development and product cycles/uncertain economy

Transition was Considered in Setting the Goals

Staged Low Emission (SLE) Combustor Case Study Findings

- All engine manufacturers began active development efforts in the mid 1970s to meet US EPA promulgated standards
- Combustor development had broad support from commercial and military customers
- ~25 year time to product was much longer than expected
- Benefits were less than expected. In parallel with SLE development, conventional combustor performance was also significantly improved
- Large majority of cost was after TRL6





Goal Setting was Based on Realistic Expectations

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
- Experience indicates significant delay and loss of emissions performance is likely as technology transitions from R&D to product

Initial IE Goals are Consistent with Manufacturers' Aims…
…Future Review Updates Will Monitor Progress and Adjust Goals if Necessary