Engine Technology Development to Address Local Air Quality Concerns

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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

- 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

- 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

Figure 3-1 Adiabatic Combustion of Kerosene

“Perfect” ratio of fuel and air gives highest temperature and NOx formation rate
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)
All recent engines meet CAEP/6 requirements with small margin, and are towards lower end of current production.
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) or max benefit

**Design challenges:**

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

![Graph showing NO formation rate vs. Fuel-Air Ratio for conventional and lean combustion](image)
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

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

**PW RQL Combustor Development (1997-2005)**

**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

**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

**Conventional Combustor**
- PW4090 (EIS 1997)
- Baseline NOx

**GE “LEC” Combustor**

**RR “Tiled Phase 5” Combustor**
Advanced Trent and SaM146 are expected to achieve significant margin to CAEP/6 in near-term
• Certification planned for 2008

TALON X NOx Reduction Methodologies

Blue parent technologies TRL/6 or higher
• Advanced Impingement Film Floatwall
  • Equiax cast Floatwall segments
  • In production
• High Shear Fuel Injectors
  • In production

Red technologies < TRL/5
• Local Residence Time Adjustments
• Quench (Lean) Zone Mixing Optimization
  • Shaped / directed / tailored quench holes
  • NOx reduction via reduced mixing scale, elimination of high NOx formation (stoichiometric) zones
• Rich 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
Prototype tests of revolutionary RQL and Lean Staged combustors show potential for considerable NOx reduction.

Based on LTTTG review, current TRL is 5-6. Flight test data still needed to demonstrate airworthiness.
Emissions tradeoffs were considered at length during the LTTG review…

Engine Cycle Trades
- Continuing trend toward higher pressure ratio reduces CO₂, 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
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
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