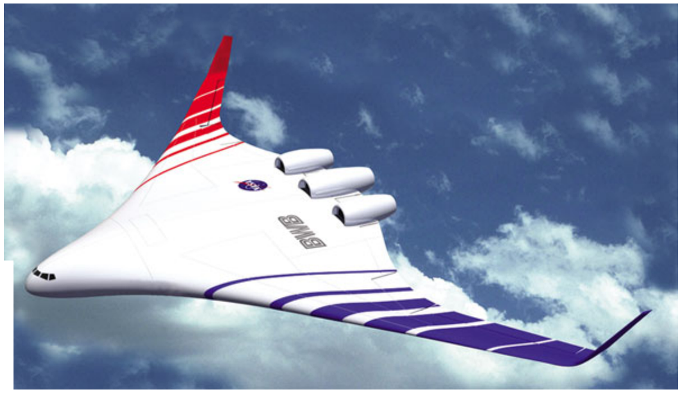
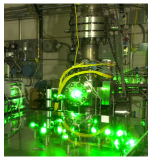
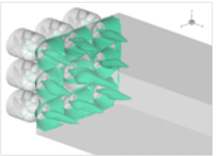
NASA Low NOx Fuel Flexible Combustor Technical Challenges
UTIAS-MITACS 2nd International Workshop on Aviation and Climate Change

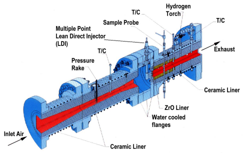


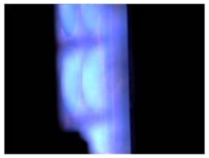
Chi-Ming Lee
Chief of Combustion Branch
NASA Glenn Research Center

May 27,28, 2010
Toronto, Canada









ERA/SFW System Level Metrics

…. technology for improving noise, emissions, & performance

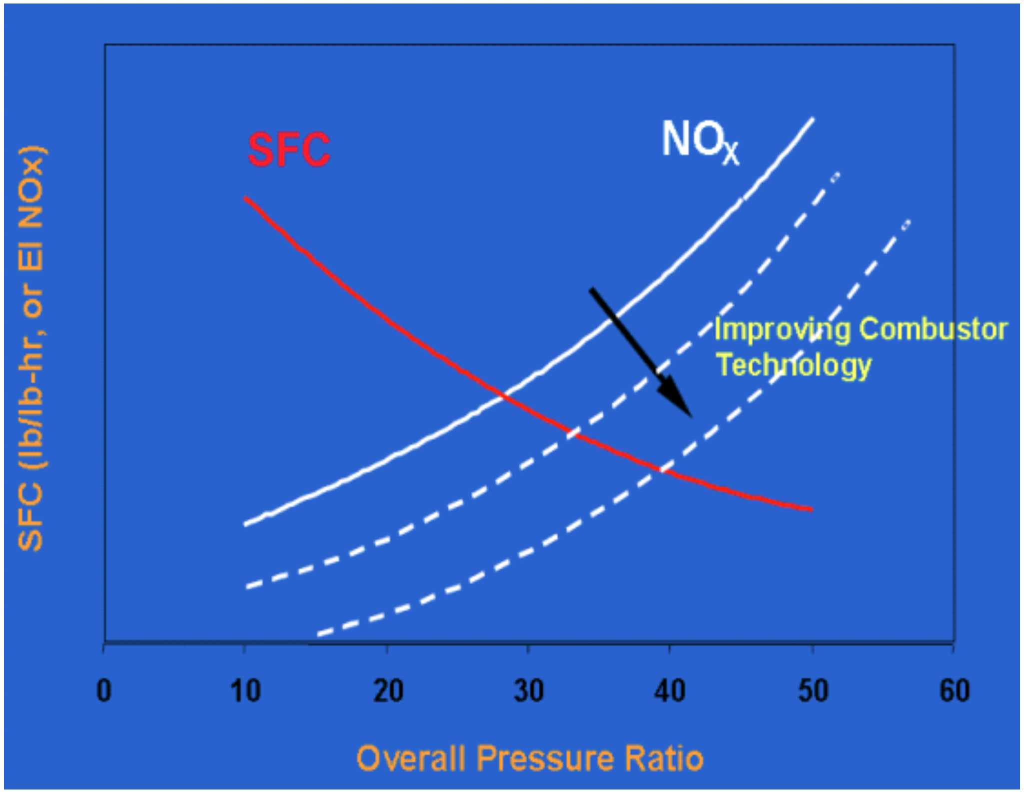
CORNERS OF THE TRADE SPACE	N+1 (2015)*** Generation Conventional Configurations relative to 1998 reference	N+2 (2020)*** Generation Unconventional Configurations relative to 1998 reference	N+3 (2025)*** Generation Advanced Aircraft Concepts relative to user-defined reference
Noise (cum below Stage 4)	-32 dB	-42 dB	-71dB
LTO NOx Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance: Aircraft Fuel Burn	-33%**	-40%**	better than -70%
Performance: Field Length	-33%	-50%	exploit metro-plex* concepts

***Technology Readiness Level for key technologies = 4-6
** Additional gains may be possible through operational improvements
* Concepts that enable optimal use of runways at multiple airports within the metropolitan area

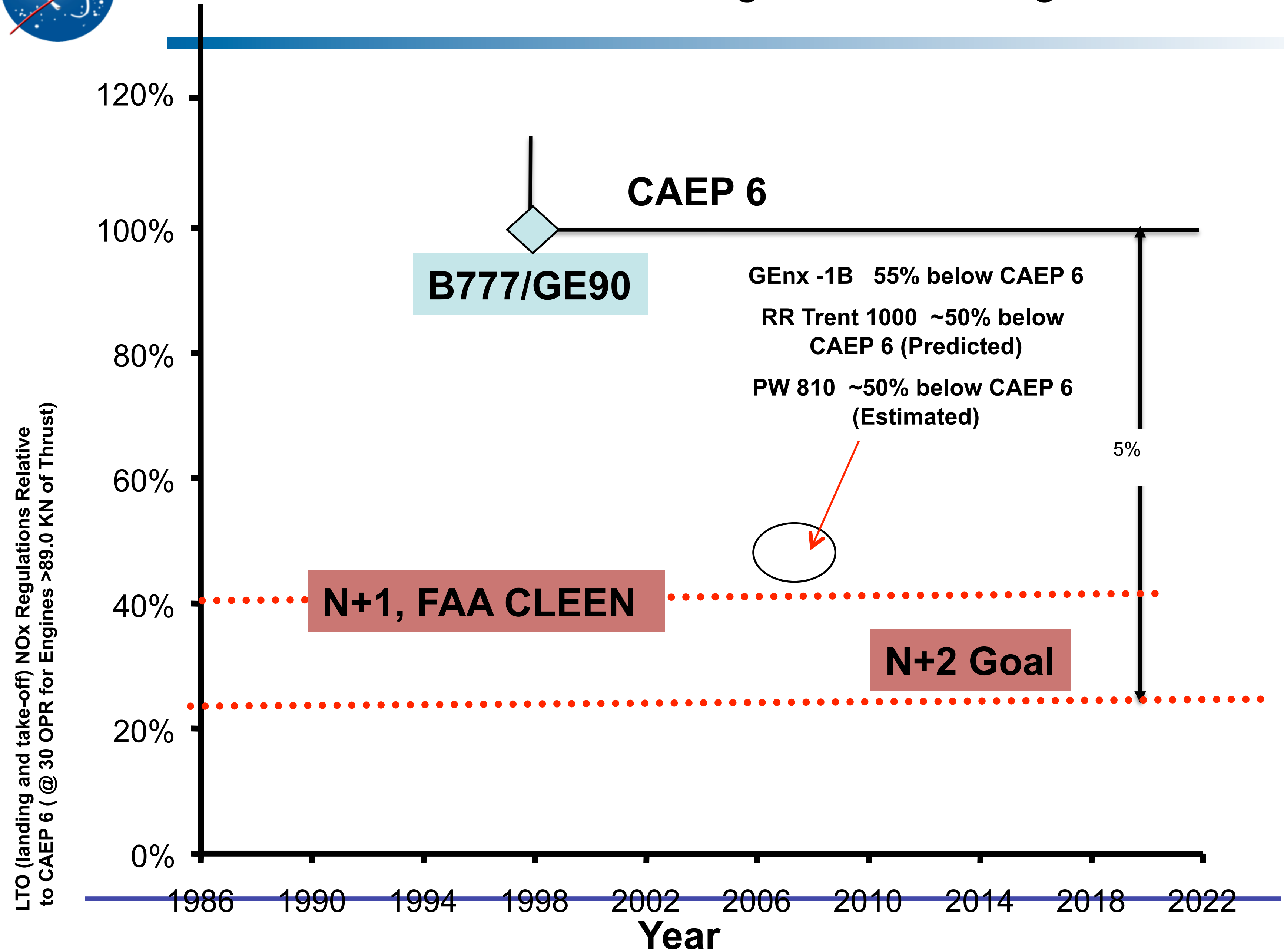
Approach

- *Enable Major Changes in Engine Cycle/Airframe Configurations*
- *Reduce Uncertainty in Multi-Disciplinary Design and Analysis Tools & Processes*
- *Develop/Test/ Analyze Advanced Multi-Discipline Based Concepts & Technologies*

NOx emissions vs. the Overall Pressure Ratio and SFC



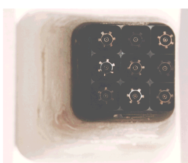
CAEP6 ICAO NOx Regulations for Engines

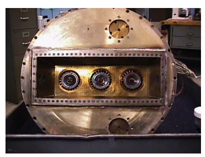


Emissions Reduction - Technology to Product Transition

NASA Program → **Industry Product Integration**

Market conditions and available technology improvements determine opportunity to launch new product engine





Complexity

"Off-Ramp" for Technology

NASA Project will develop and demonstrate low emissions to a technology readiness level (TRL) 6

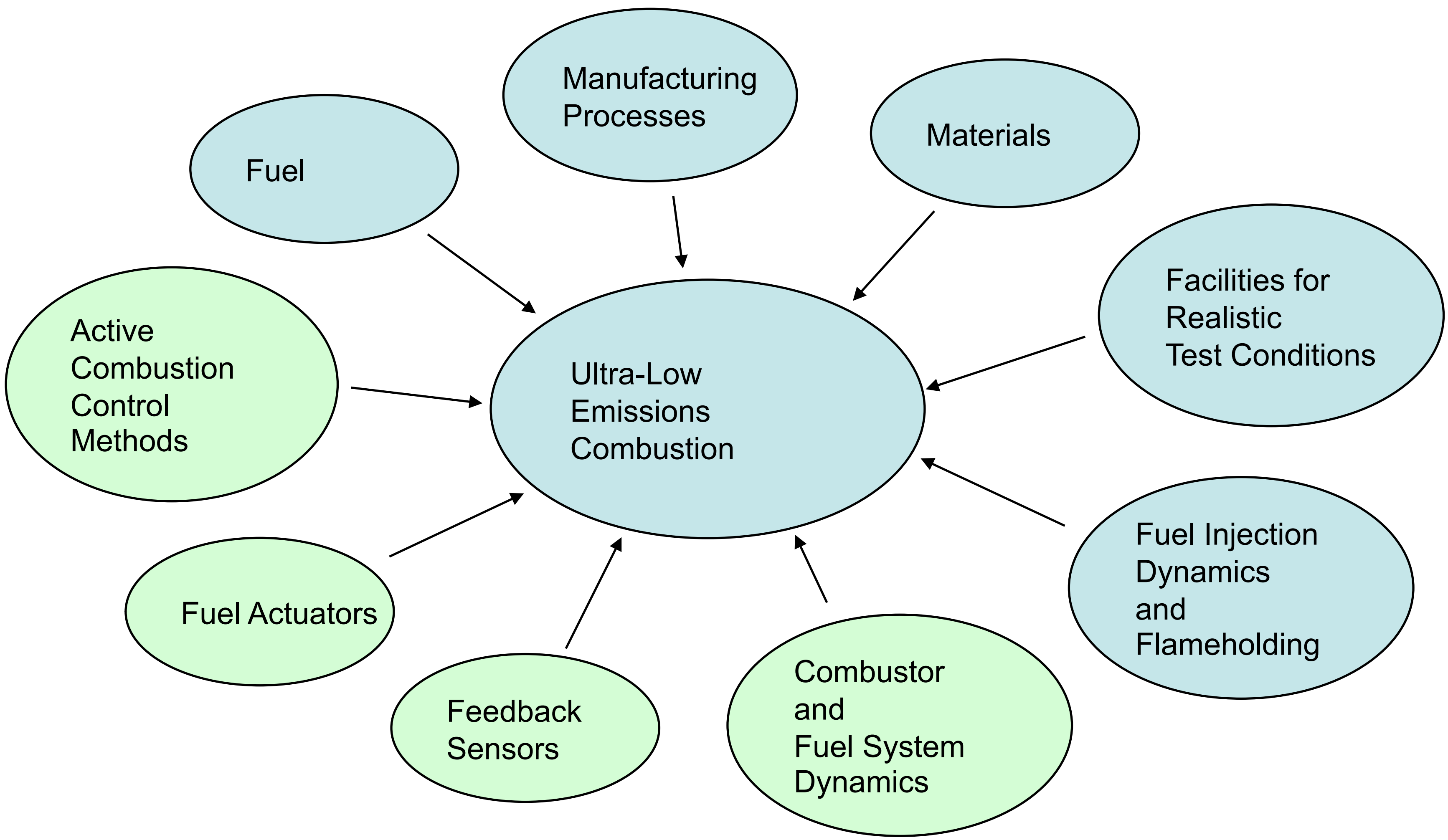
Industry:

- Scaling to product engine size
- Production engine design
- Durability testing
- Transient testing (altitude/flying test-bed)
- Inclement weather testing
- Manufacturing processes and tooling
- Certification
- Product support

Flametube Combustor	Sector Combustor	Full Annular Combustor	Engine Integration	Certification and Entry Into Service
TRL- 3	TRL- 4	TRL- 5	TRL- 6	TRL-9

NASA and Industry Partnership for Low-Emission Combustor Technology Development Followed by Possible Industry Certification and Product Implementation

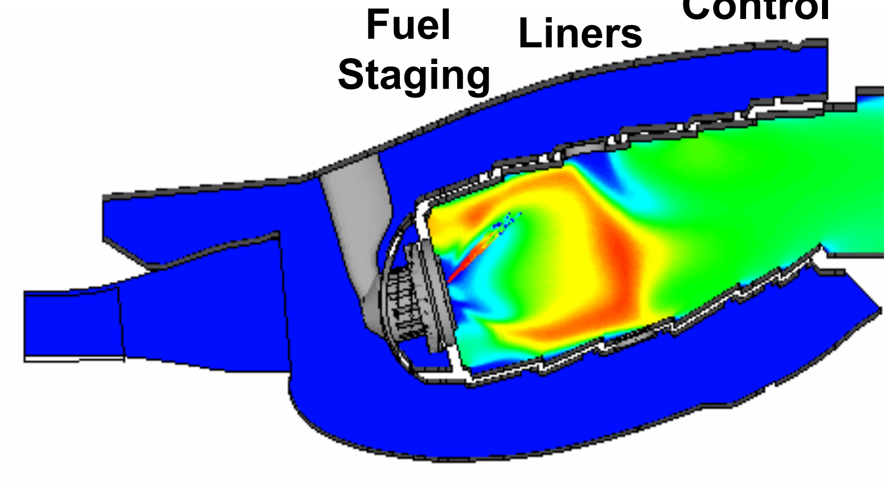
Synergistic Technologies to Enable Ultra-Low Emissions Combustion



Fuel Flexible/Low Emissions

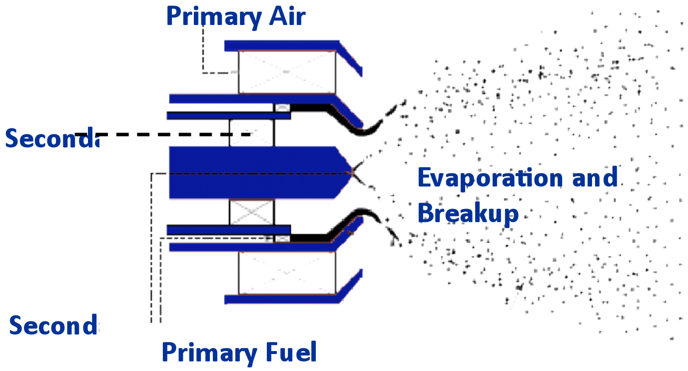
Combustor Technical Challenges

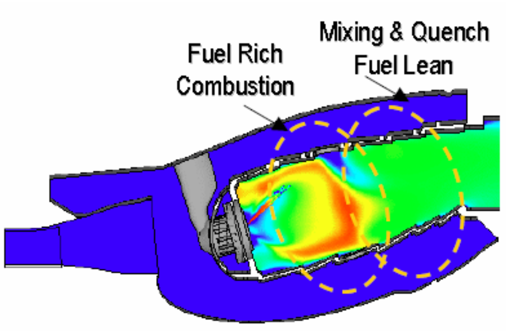
- Injector/Mixer Design
- Active Combustion Control
- High Temperature Combustion Liner

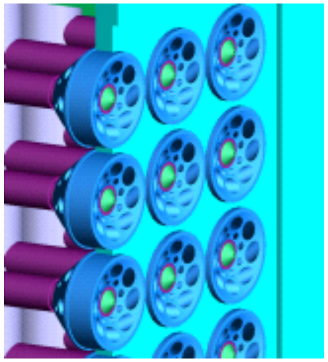


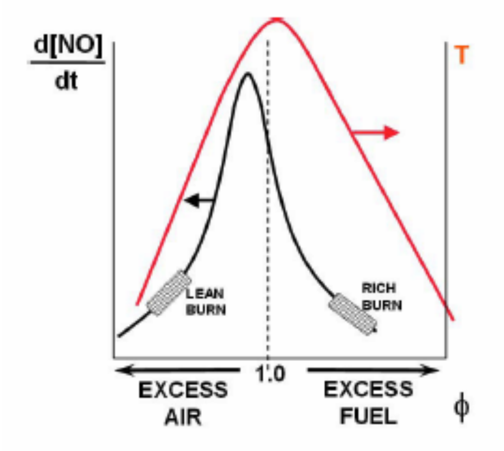
Injector/Mixer Design Challenge

75% Nox Reduction Injector Development









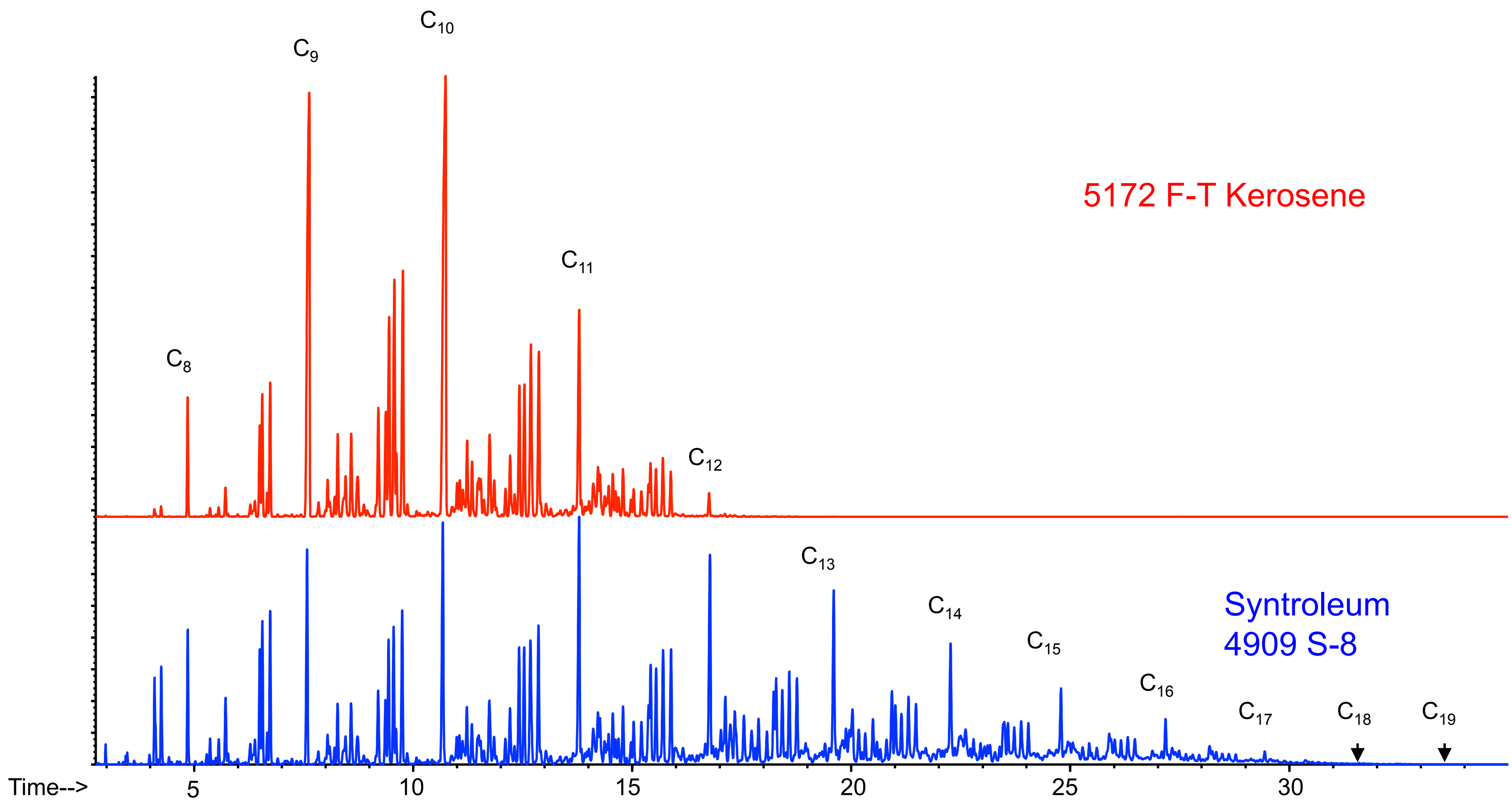
- Advanced Injector Concept
- Fuel/Air Mixing
- Ignition

Fischer-Tropsch & Jet A Fuel Analysis

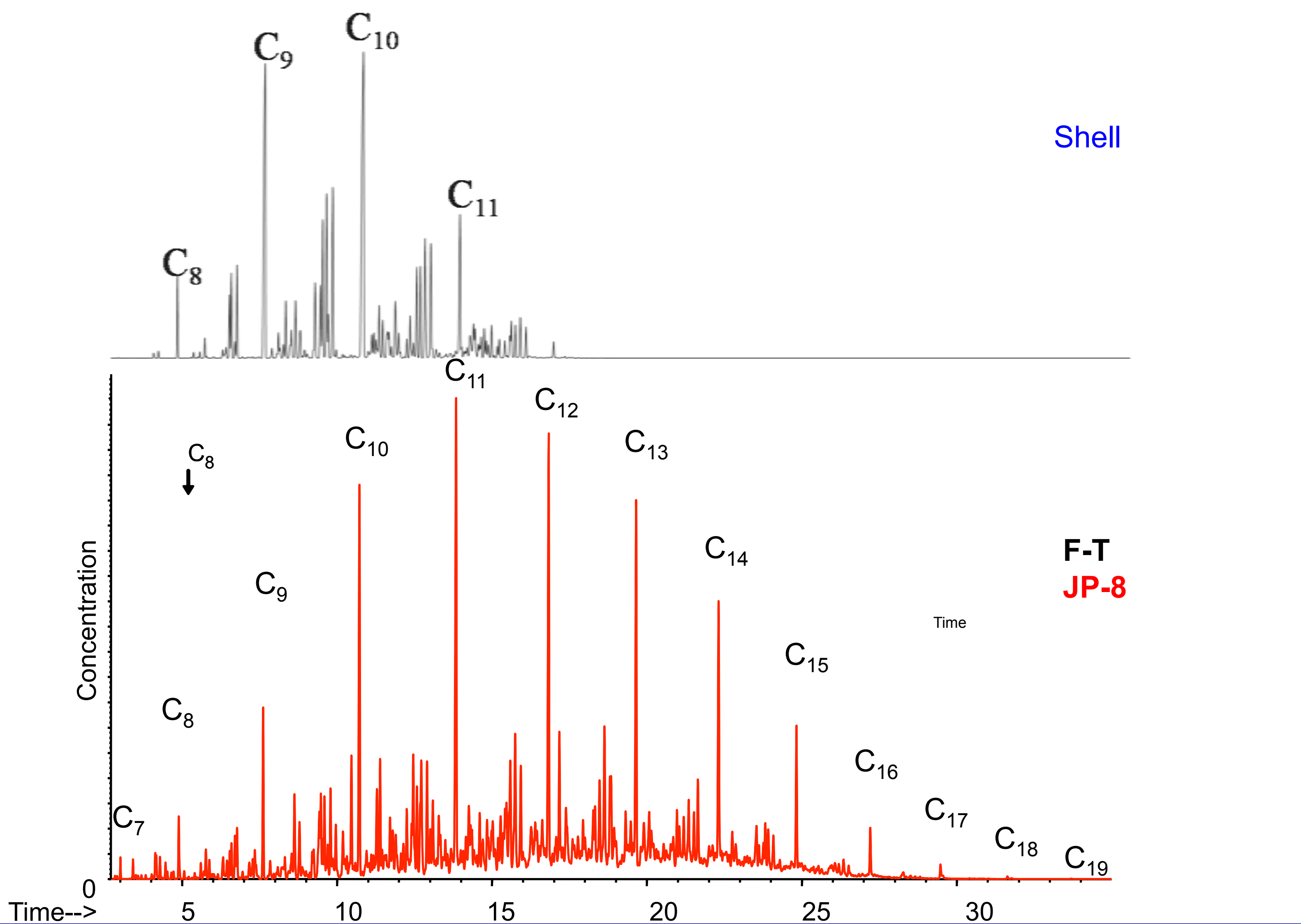
Test	F-T	Jet A
Total Acid Number (mg KOH/g)	0.002	0.00
Aromatics (% vol)	0.0	19
Mercaptan Sulfur (% mass)	0.000	0.000
Total Sulfur (% mass)	0.00	0.0
Distillation		
Initial Boiling Point (°C)	149	
10% Recovered (°C)	162	180
20% Recovered (°C)	163	
50% Recovered (°C)	168	212
90% Recovered (°C)	184	251
End Point (°C)	196	
Residue (% vol)	0.9	1.3
Loss (% vol)	0.4	0.9
Flash Point (°C)	44	51
API Gravity @ 60°F	60.5	
Freezing Point (°C)	-55	-48
Viscosity @ -20°C (mm²/s)	2.6	5.2
Net Heat of Combustion (MJ/kg)	44.2	

Test	F-T	Jet A
Hydrogen Content (% mass)	15.6	
Smoke Point (mm)	40.0	21
Copper Strip Corrosion (2 h @ 100°C)	1a	
Thermal Stability @ 260°C		
Change in Pressure (mmHg)	0	1
Tube Deposit Rating, Visual	1	0
Existent Gum (mg/100 mL)	<1	0.2
Particulate Matter (mg/L)	0.4	0.2
Filtration Time (min)	2	
Water Reaction Interface Rating	1	1
FSII (% vol)	0.00	0.00
Conductivity (pS/m)	217	10
Lubricity Test (BOCLE) Wear Scar (mm)	0.75	
Net Heat of Combustion (MJ/kg)	44.0	43.2
Workmanship	Pass	Pass

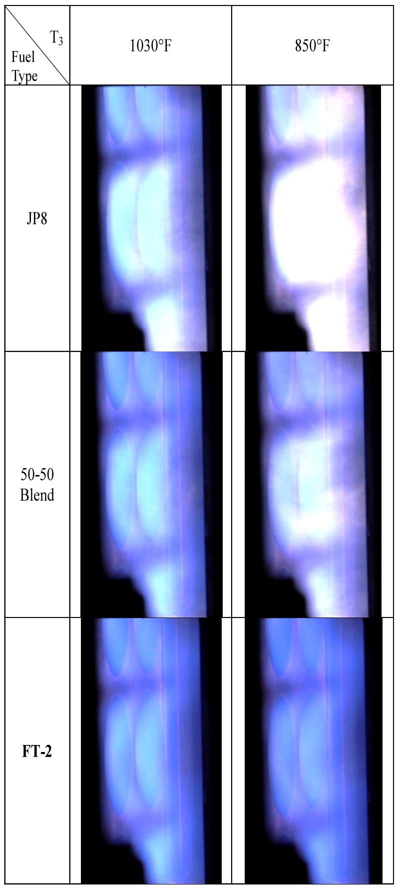
F-T Fuel Analysis



Fischer-Tropsch & JP-8 Fuel Analysis

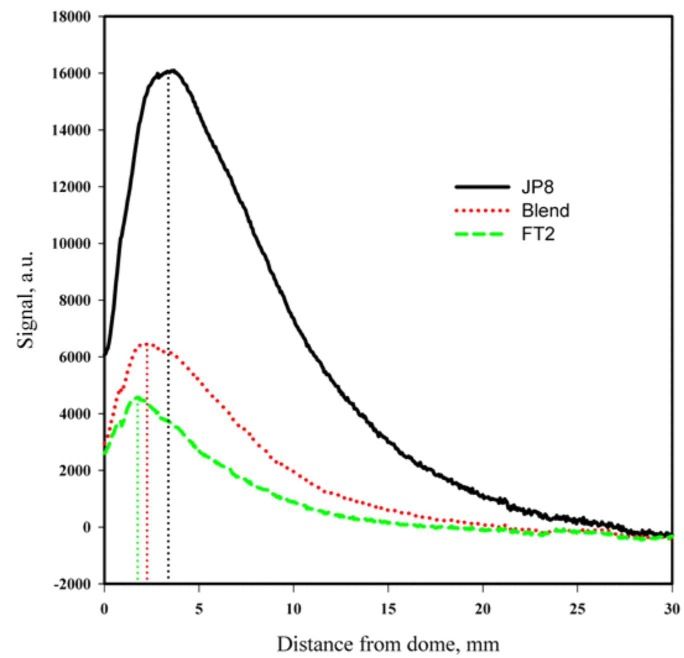


JP8, 50-50 Blend, and FT-2 Comparisons



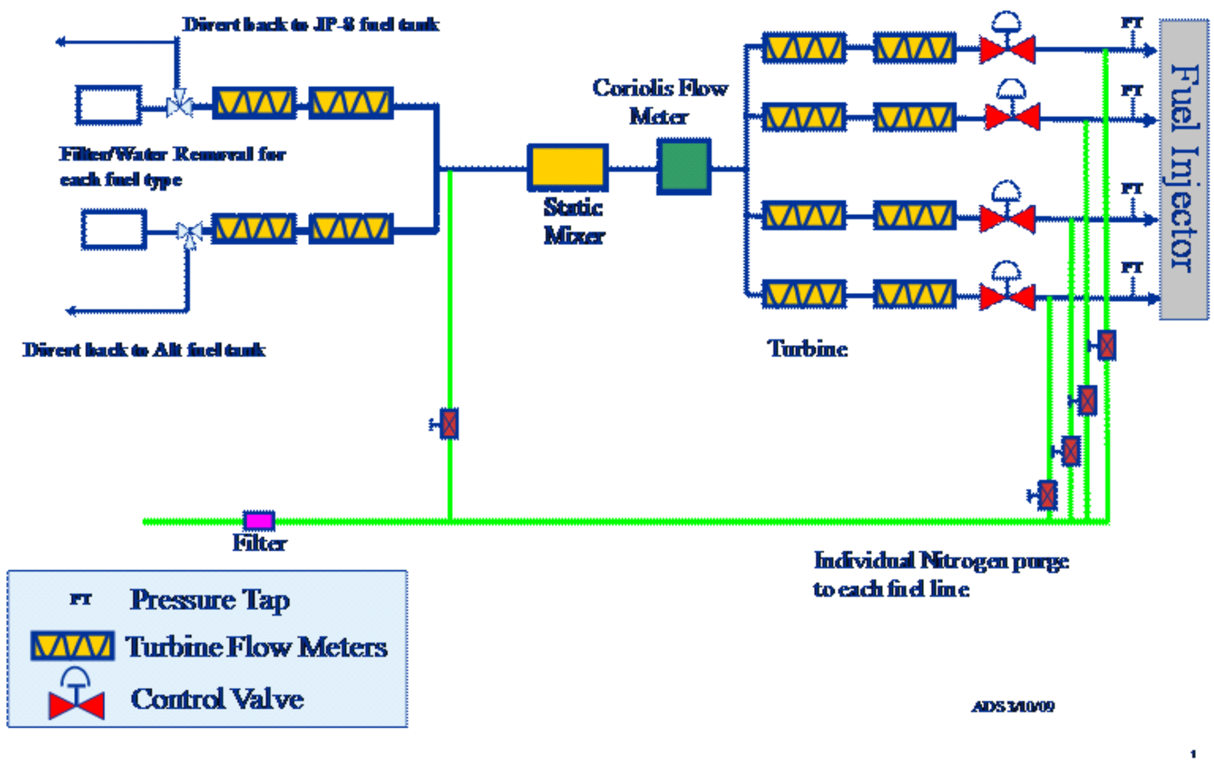
Video Images, with flow from left to right

Comparison showing average flame length and luminous intensity for T3 = 1030°F



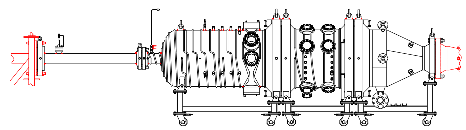
Advanced Subsonic Combustor Rig (ASCR) Alternative Fuels Establishment (cont'd)

Fuel System Configuration



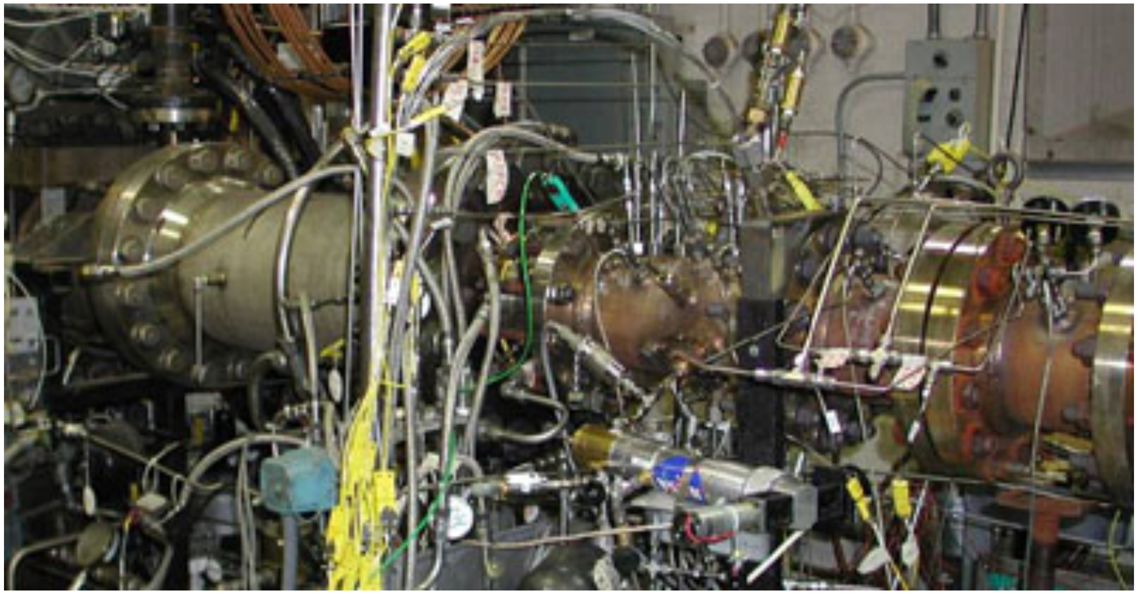
ASCR Plenum Design and Fabrication (cont'd)

EXISTING AND REVISED CONFIGURATIONS

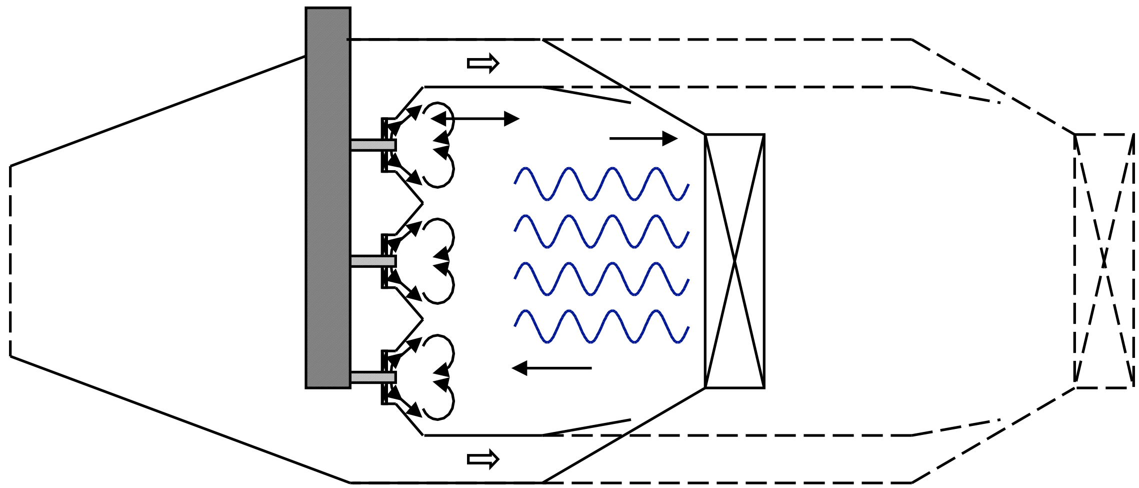


Existing ASCR Sector Rig Assembly 28470M43A000

Active Combustion Control Challenge



Ultra-Lean-Burning Combustors Are More Susceptible to Thermo-Acoustic Instabilities



1. Higher-performance fuel injectors: more turbulence

2. Reduced film cooling: reduced damping

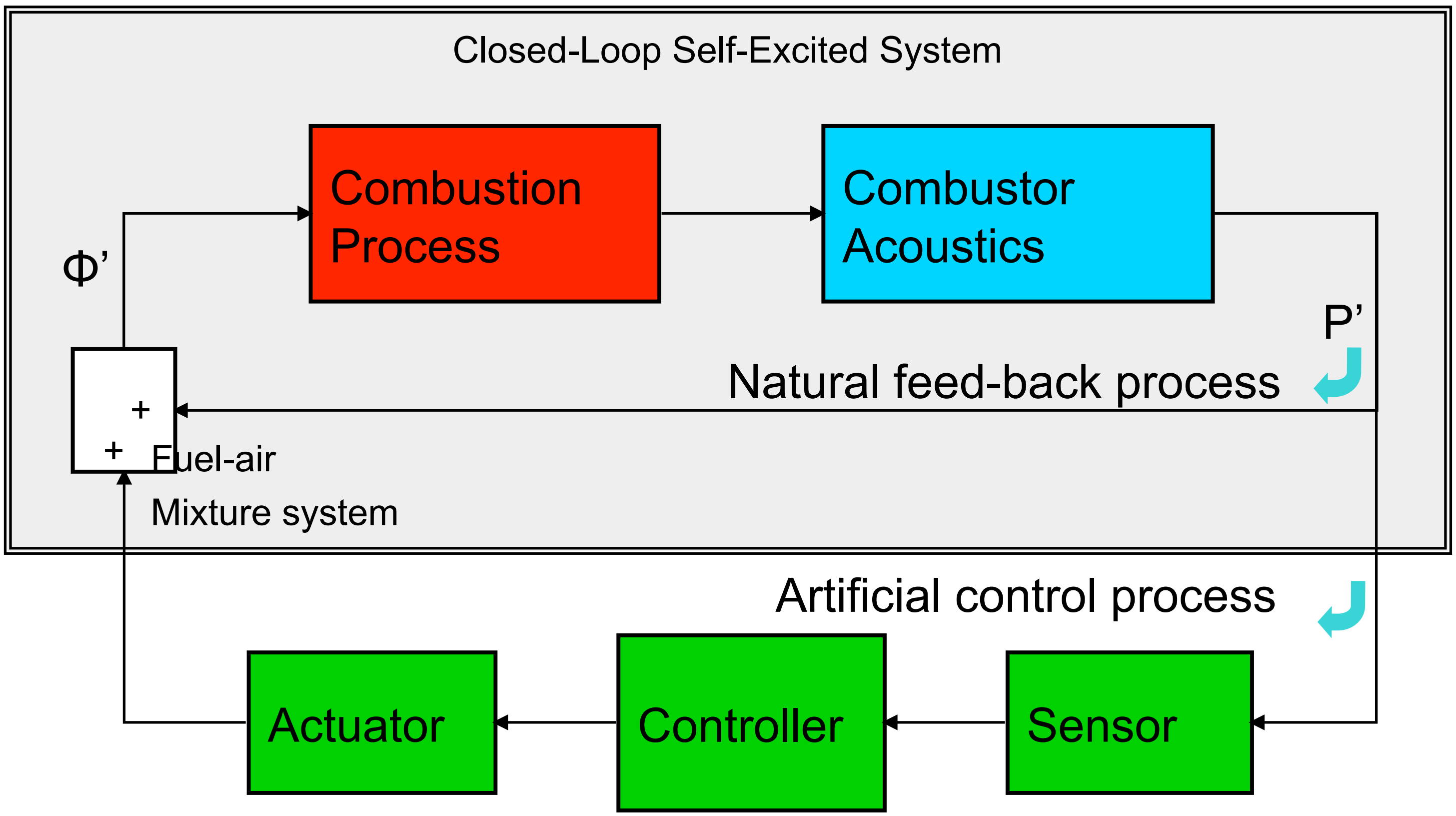
3. More uniform temperature and composition

4. No dilution holes: reduced flame-holding

5. Experience in ground-power gas-turbines

Combustion Instability Control Strategy

Objective: Suppress combustion thermo-acoustic instabilities when they occur



Long Term Goal for Active Combustion Control

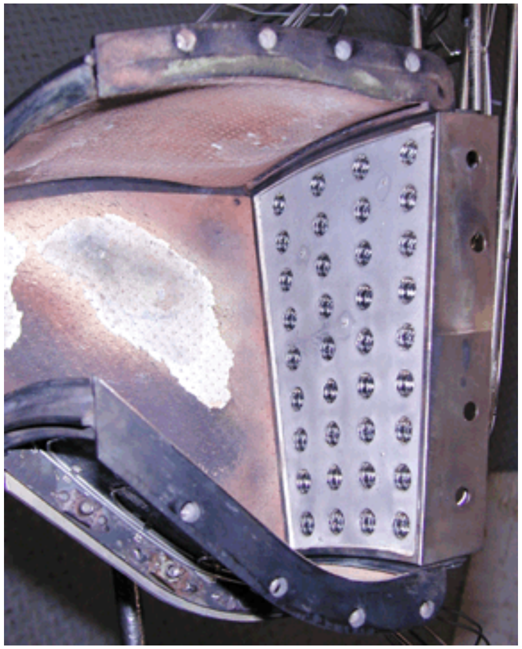
- **Improve fundamental understanding of the combustor processes**

in order to…

- **More effectively integrate multi-point combustor design, controls, sensor, and actuator technologies**

to provide…

  - **An intelligent fuel/air management system with temporal and spatial fuel modulation for**
    - **Instability avoidance/suppression**
      - **Thermoacoustics, blowout**
    - ***Pattern factor control***
    - ***Emissions minimization***



to enable…

- **Combustors with extremely low emissions throughout the engine operating envelope**

Active Combustion Control

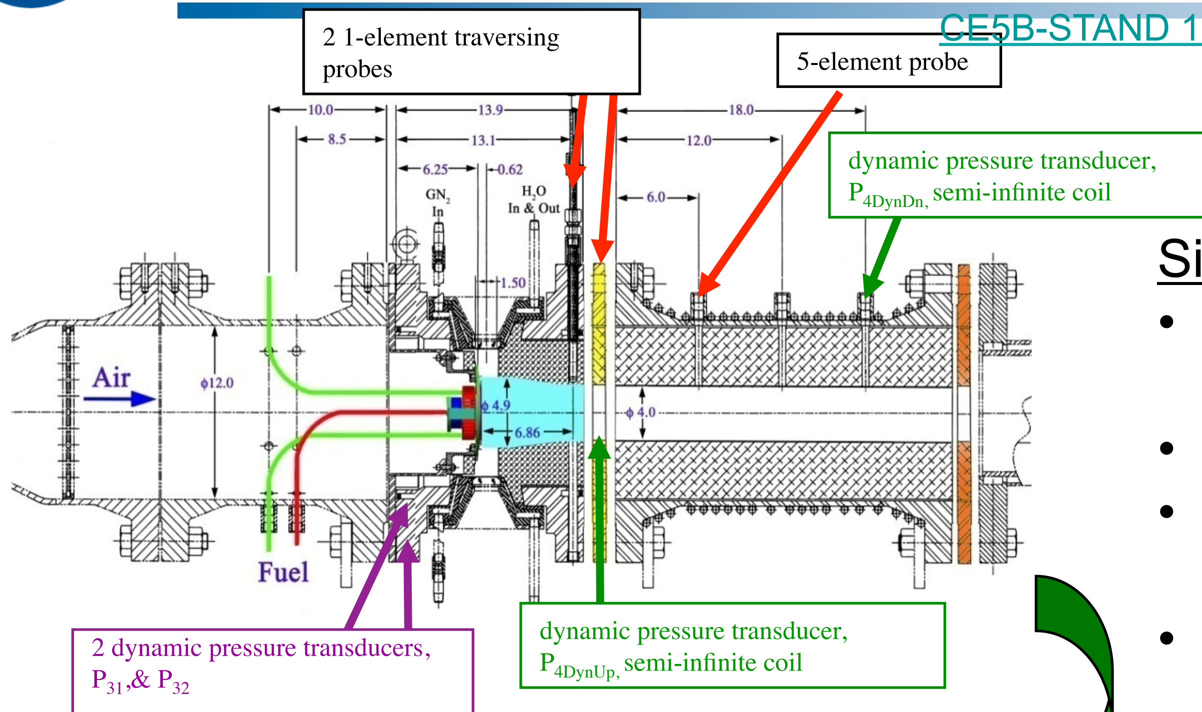
… In order to achieve 75% NOx reduction, it is necessary to demonstrate the capability to detect and suppress combustor instabilities for these very low emission combustors in order to enable efficient combustor operation at all conditions.

- Develop sensor, actuation, high temperature electrical components for processing control signals, and control methodologies for integrated demonstration *with the low emissions concepts*
- Utilize the flametube and sector *combustor test capability*

➢ Goal - Keep pressure oscillation to within 1% of nominal at all power conditions in a sector rig indicative of a 75% NOx reduction combustor (TRL 5).

Active Combustion Control

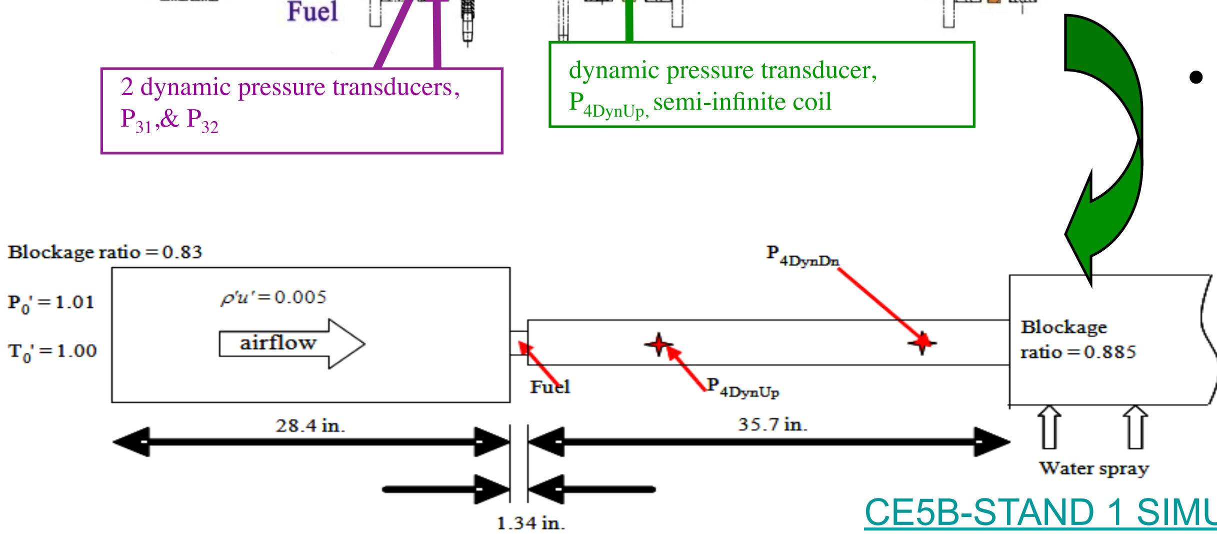
Combustion Instability Dynamics Simulation of an advanced, low-emissions combustor prototype



CE5B-STAND 1 TEST RIG SCHEMATIC

Simulation Features

- Physics-based, Sectored 1-D, reacting
- Time-accurate
- Computationally efficient area transitions
- Upstream and Downstream boundary conditions modeled to match rig



CE5B-STAND 1 SIMULATION LAYOUT

SiC Pressure Sensor Status

- The design, fabrication, and testing of a SiC dynamic pressure sensor is ongoing. These activities include both extending the sensor material structure to higher temperatures as well as characterizing the present pressure sensor structure.
- The work includes sensor fabrication (NASA GRC Microsystems Fabrication Clean Room) and packaging of pressure sensor (Sienna Technologies, Inc.)
- Collaborating with Sienna Technologies, Inc. to develop a high temperature sealing glass with high glass transformation temperature to support pressure sensor operation at 800^oC. A new glass mix was applied on a dummy SiC chip and an old AlN header and both passed the hermiticity and adhesion tests (Figure 1).
- Packaging of several sensors with the modified MEMS-DCA package capable of operating at 800^oC (Figure 2) is underway. These sensors were fabricated with a high temperature metallization approach which is a modified version of the existing metallization scheme (Ti/$TaSi_2$/Pt). The result is a baseline for subsequent tests with sensors fabricated with a next generation metallization scheme.
- Meetings have been held related to testing in the research combustor in CE-5. Required pressure fittings have been ordered and, when they arrive, a temperature gradient test will be conducted to determine how long of a sensor will be needed for the combustor testing. This information will be fed to Sienna Technologies for sensor construction.

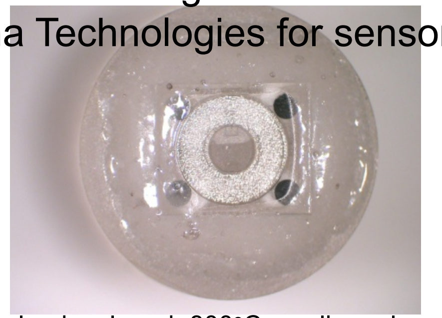


Figure 1 Newly developed 800^oC sealing glass demonstrated on a dummy sensor and AlN package header.

Figure 2: Modified MEMS-DCA package to support 800˚C pressure sensor operation.

SiC Electronics Status

- Building on world-record long-term operation of high temperature SiC electronics circuits (e.g., the differential amplifier in Figs. 1 and 2), we will be fabricating the next generation of SiC electronics with increased complexity and transistor count.
- In-package integration of SiC electronics with pressure sensors allows processing of sensor signals in-situ, improving the accuracy and reliability of the data in harsh environments.
- Test structures are being fabricated in the NASA GRC Microsystems Fabrication Laboratory to verify the newly developed multilevel interconnect process, which will be used to configure tens of SiC transistors in integrated circuits.
- A prototype 500 °C SiC integrated circuit amplifier and analog-to-digital (A/D) converter for use with an SiC dynamic pressure sensor has been designed. Fig. 3 shows the amplifier design. Fabrication of wafers with these electronics will begin in 1 month and should be completed 10 months later, after which the circuits will be packaged and tested.

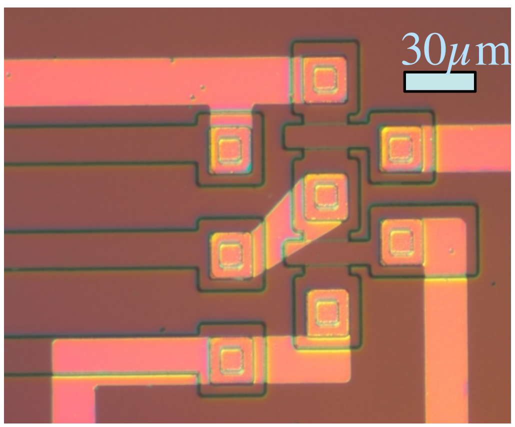


Fig. 1. Differential amplifier circuit using two SiC transistors.

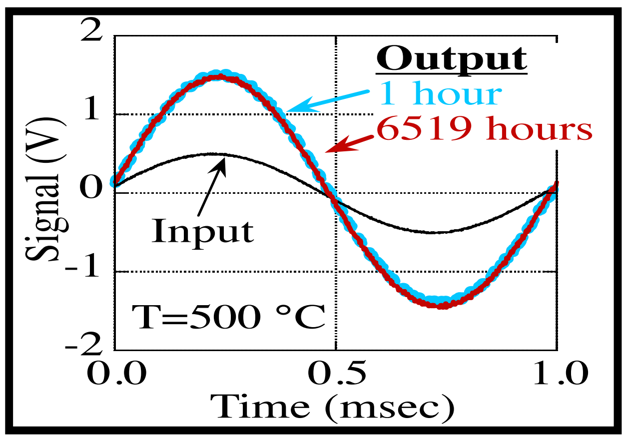


Fig. 2. Diff amp test waveforms showing <5% change despite 6500 hrs at 500 °C.

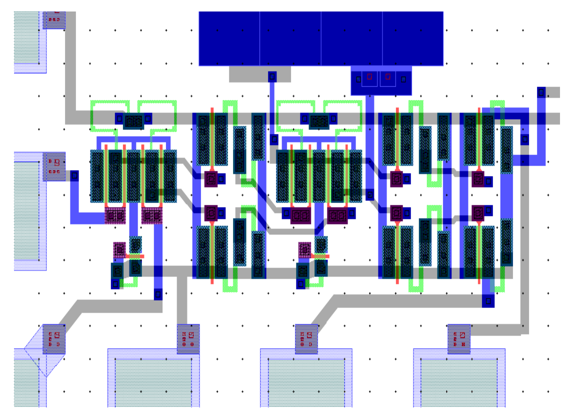
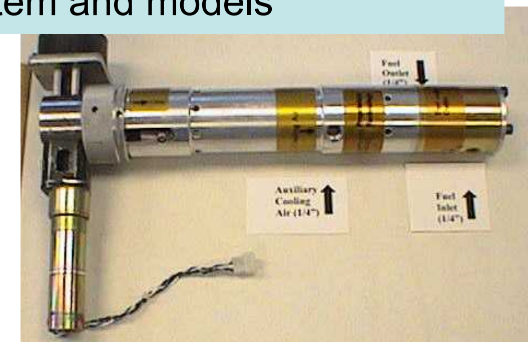


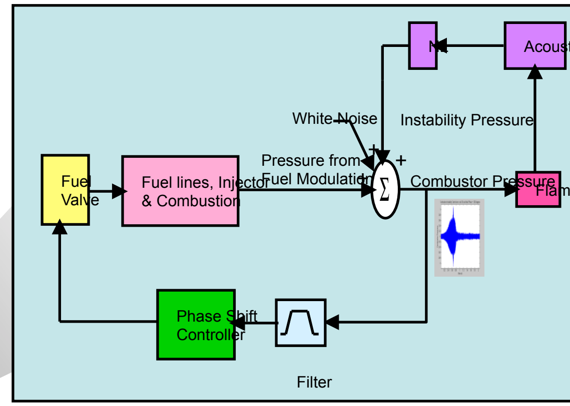
Fig. 3. Design of SiC amplifier for dynamic pressure sensor.

Active Combustion Instability Control Via Fuel Modulation

High-frequency fuel delivery system and models

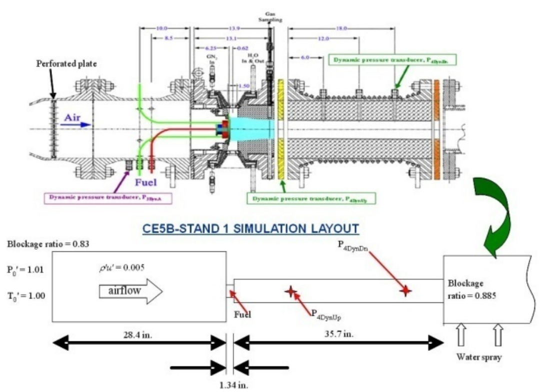


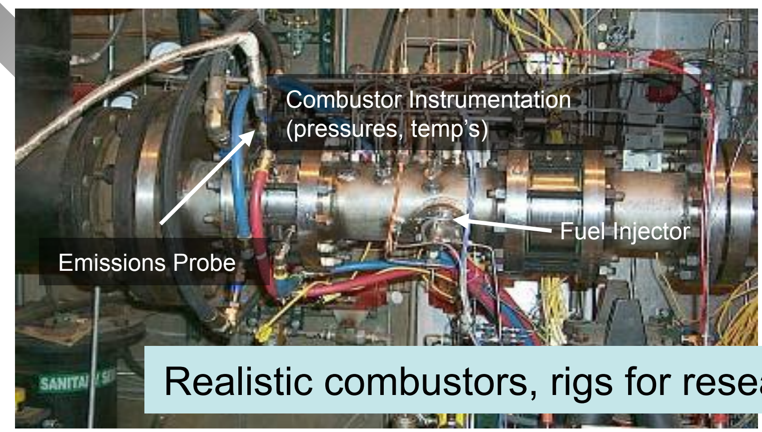
Advanced control methods



High-temperature sensors and electronics

Physics-based instability models





Realistic combustors, rigs for research

SiC Pressure Sensor Status

- The design, fabrication, and testing of a SiC dynamic pressure sensor is ongoing. These activities include both extending the sensor material structure to higher temperatures as well as characterizing the present pressure sensor structure.
- A landmark attempt was made to test the SiC pressure sensor with newly developed higher temperature (> 600 °C) packaging materials. The sensor was pressurized and measurement taken at various temperatures up to 750 C.
- Pressure measurement at 750 °C indicated a net output of approximately 7 mV full-scale at 500 psi. While the observed instability in the device prevented further testing, the result validates the concept of using piezoresistive based SiC pressure sensors for measurement in 750 °C environment.

SiC Electronics Status 03/22/2010

- A wafer of multilevel interconnect test structures is approximately 50% completed and should be finished in about 6 weeks. These test structures will verify the newly developed multilevel interconnect process which will be used to configure tens of SiC transistors in integrated circuits for use at temperatures to 500 °C. Figure 1 shows probe testing of 8-µm-wide vias through the overlying dielectric layer to the SiC substrate of the test wafer. A 4-µm via, at right, is too small to probe test. A via size of 4 µm will enable a transistor gate width of 2 µm for high density integrated circuits. Fabrication of such small features is technically challenging in a class 100 research cleanroom such as ours, yet is important to enable the fabrication of more complex integrated circuits with greater functionality. So far, we have achieved good results with the smallest size test structures.

- Masks for a SiC integrated circuits have been designed. Fabrication of these circuits will begin after the multilevel interconnect test structures successfully pass operational verification testing on a probe station. These circuits should be completed by the end of January, 2011. Circ
SiC integrated … or use with an SiC d

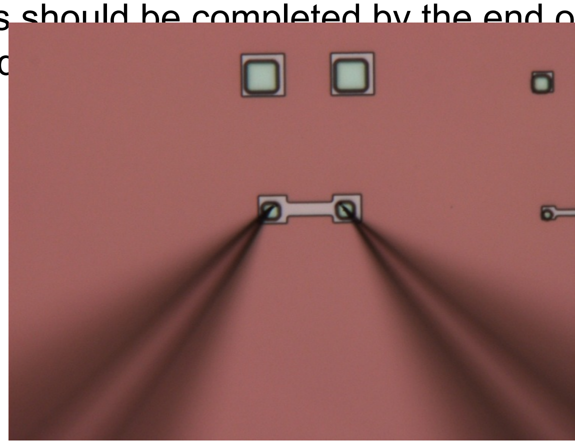


Fig. 1 - Probe testing of 8-µm-wide vias through dielectric layer of interconnect test structure wafer. A 4-µm via is visible at right.

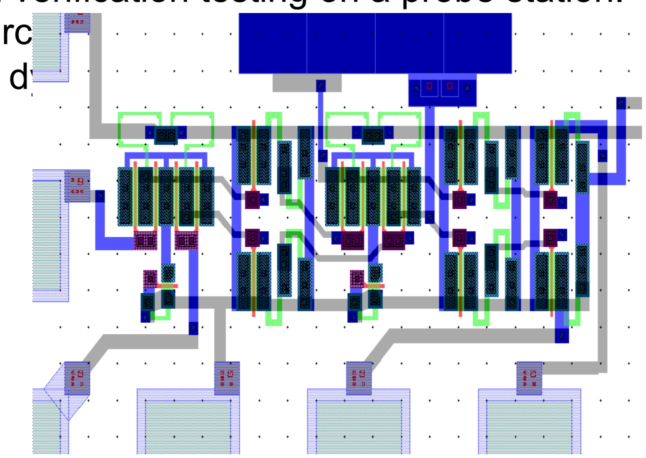


Fig. 2 - Design of SiC amplifier for dynamic pressure sensor.

High Temperature Combustor Liner Challenge

<u>Objectives:</u> **Investigate CMC combustor liner materials, identify issues challenging CMC incorporation into engines, mitigate issues as possible**

Issues for CMC Liner –

Durability –

Insufficient data – both long term coupon and relevant engine environment
Mitigation – In-house durability testing, coupon creep/fatigue/etc testing, HPBR, Subcomponent (NRA) testing.

Advanced Coatings – improved coating compositions, erosion, spallation, *repairability*
Mitigation - **In-house research effort on advanced coatings, HPBR investigations, insuffici**

Integration – Attachment design & fretting coatings
Mitigation - **NRA for attachment design (?), in-house investigation in fretting coatings, coeff f** **etc**

ERA CMC LINER -Overview

Objectives: Investigate CMC combustor liner materials, identify issues challenging CMC incorporation into engines, mitigate issues as possible

Approach:
- Investigate basic properties of relevant CMC
- Develop high coatings
- NRA to obtain subcomponents
- Collaborate extensively with Engine companies
- Test subcomponents in (hot) engine vibratory environment

Benefits:
CMC combustor liner enables new engine designs incorporating higher engine temperatures and reduced cooling air flows

GE 7FA

Status:
- Issues with CMC combustor liner identified with Engine company input
- Basically on schedule – NRA may result in delays
- Task planned, budget allocated
- Selected baseline material
  - HiPerComp Type 2 – procurement
- Plans for Subcomponent delivery via NRA
- Coating systems selected, procurements underway
- Test matrices developed for coupon testing w&w/o coatings

ERA CMC LINER – Subtasks

1. <u>Liner material testing</u>

Issues –

Durability insufficiently understood or proven

Status –

Coupon panels in procurement
Testing procurements underway
Changes to HPBR underway for hot cooling air

2. <u>Advanced Coating Development</u>

Issues –

Temps pushed to 2800F – better coatings needed
NASA coatings compared to GE coating
Repair coatings?

Status-

on track, procurements underway

3. <u>CMC Engine Integration Issues</u>

3a –CMC Attachments

Issues –

CMC attachment design
metal wear /vibratory environment
chemical issues at high temp?

Status -

on track – insufficient bodies?
NRA impact uncertain

3b – Joining

Issues –

thermal expansion mismatch
chemical interaction?

Status – slow start

4. <u>Fuel modulation</u>

Issues –Higher temp piezos – from 250F to 400F

Status –

on track
procurements finished by April 30

ERA CMC Liner
Material Testing

Objectives:

Investigate durability issues for GE HiPerComp Type 2 CMC for high temperature engine environments.

Approach:

Investigate basic durability properties of coupons – 2D uni-layup prepreg Hi-Nic-S, balanced (yr 1).

Develop advanced high temperature coatings

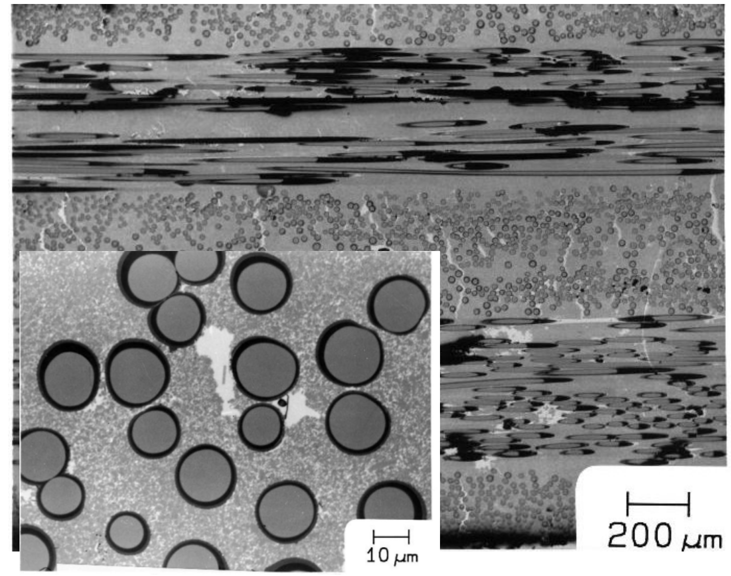
NRA to obtain subcomponents

Collaborate closely with Engine companies

Test subcomponents in simulated engine environment

Benefits:

CMC combustor liner enables higher temp engine, liner surface operating temperature to 2800F



Status:

- Prepreg SiC CMC panels ordered.
- HPBR modifications underway
- Subcomponents obtained by NRA

ERA CMC Liner

Material Testing- Environmental Barrier Coatings

Objective-

Develop and validate advanced 2800°F environmental barrier coating (EBC) systems for SiC/SiC CMC combustors for ERA engine demonstrations.

Status -

- **GE contract plan discussed for combustor EBC testing and development**
- **Quote received from Sulzer for first round of environmental barrier coating powders**
- **Collaborative plan for Dense-Vertical Cracked (DVC) combustor EBC development also discussed with Praxair**
- **Potential trial non-Si bond coats development**
- **High Pressure Burner Rig fixtures designed and fabricated for thermal fatigue and environmental degradation tests of impingement and film-cooled CMC-EBC test coupons**
- **High Pressure Burner Rig Combustor being instrumented for CMC combustor segment rig fixture designs and testing**
- **High pressure burner rig cooling air capability improved (up 600 psi) and fuel is being improved to accommodate planned higher mass-flow rate tests**
- **Simulated thermal gradient fatigue laser rig also ready for 2 inch diameter CMC-EBC specimen thermal fatigue testing**
- **Biaxial stress of heated CMC ring-on-ring test analyzed**

ERA CMC Liner

_Integration Technology - Attachments

Objectives:

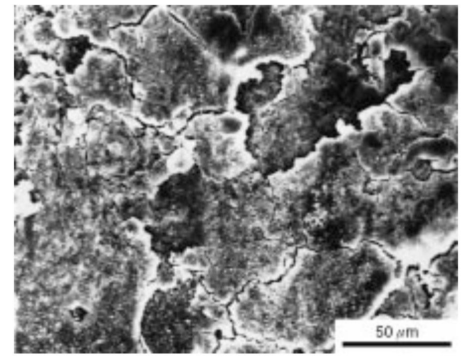
Investigate fretting/wear/erosion issues involved with integrating CMCs into high temperature, dynamic engine environments. High temperature fretting coatings development required to protect metal components

Approach:

- Investigate basic properties of relevant materials
- Develop high temperature fretting coatings
- NRA to obtain subcomponents
- Collaborate with Engine companies
- Test subcomponents in (hot) engine vibratory environment

Benefits:

Enable integrating of critical CMC components



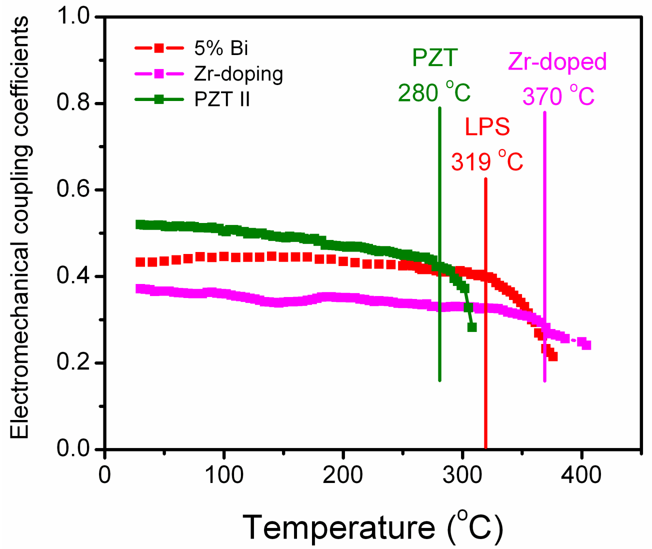
Status:

- Planning meetings with RXC/RXN/GE to identify R&D efforts is on-going. Collaborating with GE to develop needed data.
- Rehabbing a high temperature fretting rig to evaluate samples at up to 1832 F.
- Fretting coatings systems identified

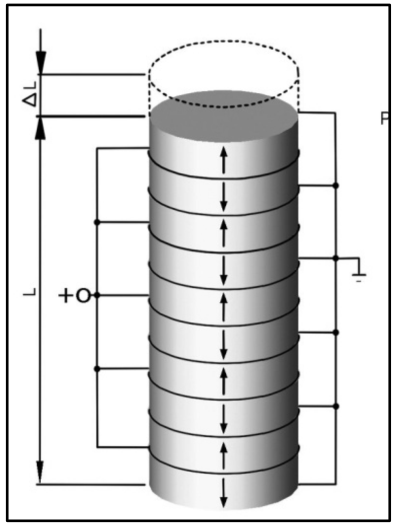
  CMC-Metal oxidation-wear coatings: nitriding surfaces, nitride coatings (TiAlCrTaSiN among others) compared to superalloy substrates
- HVOF nitride-bond coat cermet coatings may also be explored

ERA – CMC Liner - Alp Sehirlioglu
Fuel Modulation with HT Piezos

High Temperature Piezoelectric Material (GRC) + **High Temperature Piezoelectric Actuators** + **Actuator Characterization**



- Improved operating temperature
- Improved coercive field
- Improved remanant polarization



- MTS Dynamic Load Application (up to 2kHz)
- Mitutoyo Laser Micrometer Displacement measurement: 3200 scan per second
- ATS Furnace –with windows for laser access.
- DC power supply, amplifier, Agilent 4294A Impedance Analyzer

Related Publications:

A. Sehirlioglu, A. Sayir, and F. Dynys, J. Am. Ceram. Soc., **91** [9], 2910 (2008).

A. Sehirlioglu, A. Sayir, and F. Dynys, J. Appl. Phys. **106**, 014102 (2009).

A. Sehirlioglu, A. Sayir, and F. Dynys, *in publication,* J. Am. Ceram Soc., (2010).

A. Sehirlioglu, A. Sayir, F. Dynys, K. Nittala, and J. Jones submitted to J. Am. Ceram Soc., (2010).

Conclusion:

Low NO_x, Fuel-Flexible Combustion System

Hybrid Wing-Body Aircraft

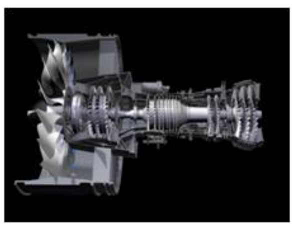
Advanced Aircraft Concept

System Design

Systems modeling
- Flexible fuel staging
- Mission profiling for emissions management

Experimental validation / verification
- Emissions and atmospheric mixing sampling
- In-flight measurement

Multi-Discipline Capabilities

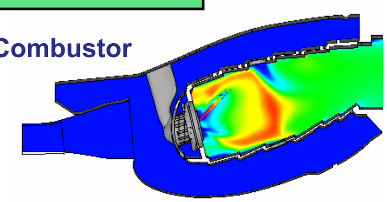


GTF Engine

Propulsion Contributions
- Improved propulsion efficiency
- Higher thermal efficiency

Combustion System Contributions
- Improved thermal mgt
- Light weight structures

Low-NOx Combustor



Discipline Level Capabilities

Combustion Contributions
- Lower NOx Emissions
- Improved fuel-air mixing
- Advanced Active Controls
- Fuel Flexibility

Materials Contributions
- CMC combustor liners with reduced cooling
- Improved high temperature durability

Foundational Physics & Modeling

Fundamental research
CFD modeling; improved diagnostics; experimental techniques; acoustics physics; materials, etc