An Overview of Low-Emissions Combustion Research

NASA Glenn Research Center

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CAEP Review of Advanced Aero-Engine Combustor Designs
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Cornerstones of NASA Combustion Research

1. Combustor concept development

2. Enabling technology research

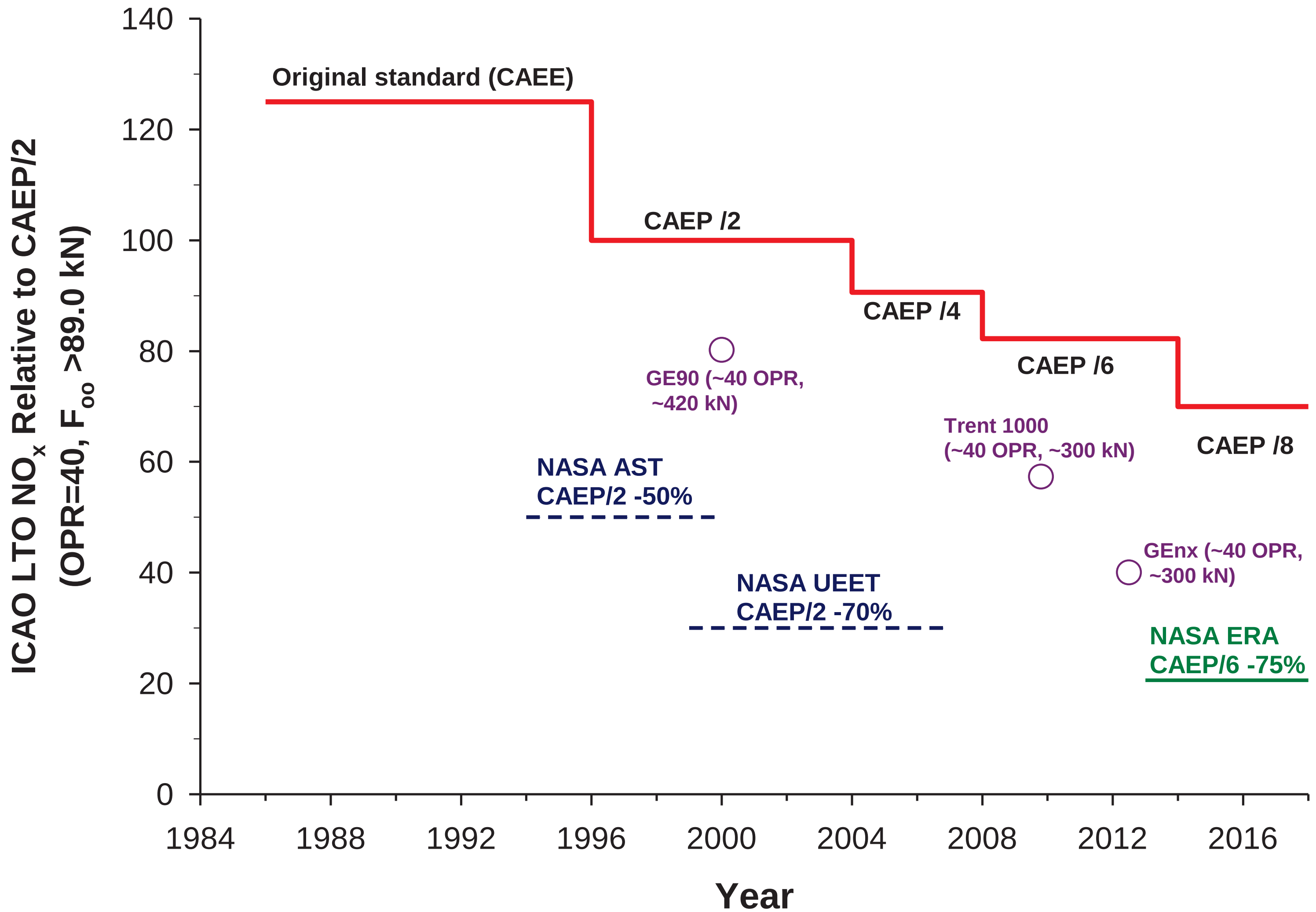
3. Understanding of emissions

4. Challenges of NASA Goals and Metric

5. Cooperative research

NASA Research Leads Product by ~15 Years

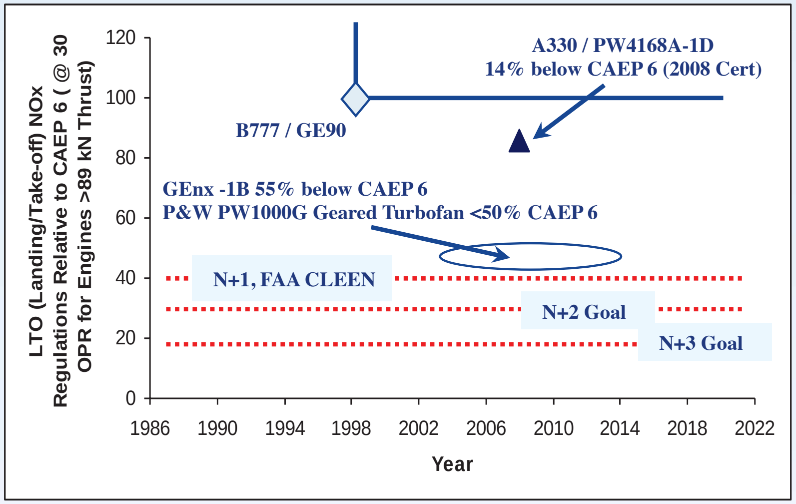
~50% NOx Reduction every 15 yrs

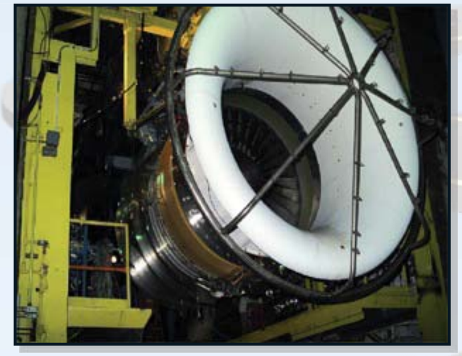


Courtesy of Changlie Wey

Technology for Advanced Low NOx (TALON) Combustor

~ 50% reduction in Nitrogen Oxide emissions





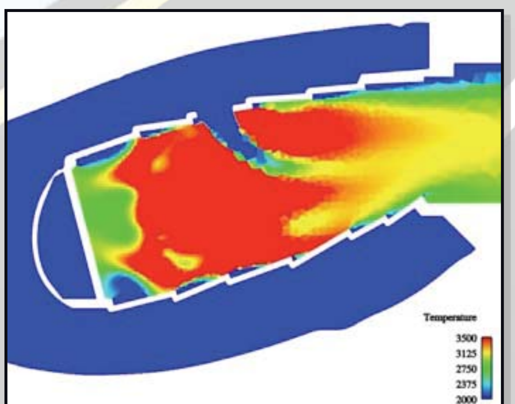
In service on Airbus A330

Systems Assessment: 1999-2008

- *PW4178 Talon II development engine test with NASA PAGEMS particulates van on-site – 1999*
- *PW 4168 Talon II Engine Certification in ground engine test stand – 2000. EIS in 2001*
- *PW 4168 Talon IIB Engine Certification in ground engine test stand – 2008. EIS in 2009*

Fundamental Research: 1995-2010

Development of Rich Quick-Quench Lean Burning
TALON Proof of Concept Sector Demonstration Rig

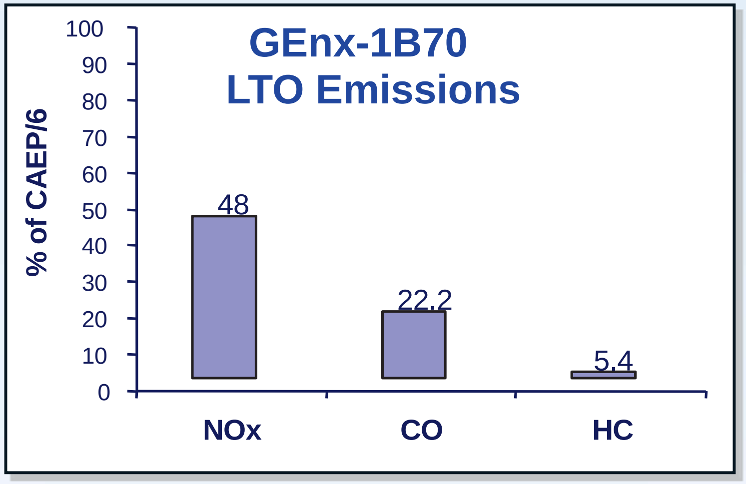


Seedling Idea: mid 1990's

Basic Computational and experimental research to develop a fundamental understanding of Rich Quick-Quench Lean Burning Technology

Twin Annular Premixing Swirler (TAPS) Combustor

~ 50% reduction in Nitrogen Oxide emissions

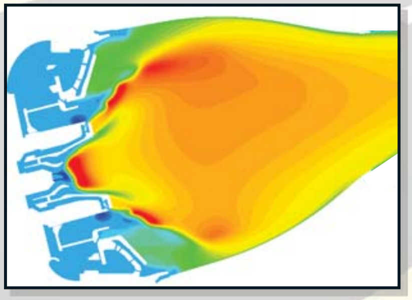


Engine Test

In service in 2011

Systems Assessment: 2005-2009

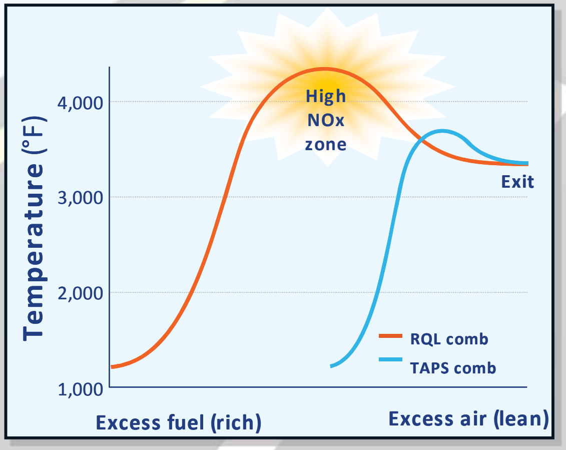
GEnx Engine Certification in ground engine test stands

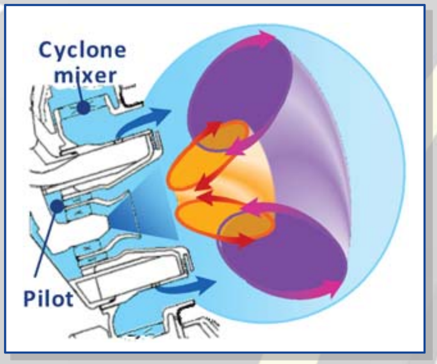


Component Test

Fundamental Research: 1998-2003

Development of Lean Burning TAPS Proof of Concept Sector test at NASA and GE, CFM56 full annular rig and engine demonstration

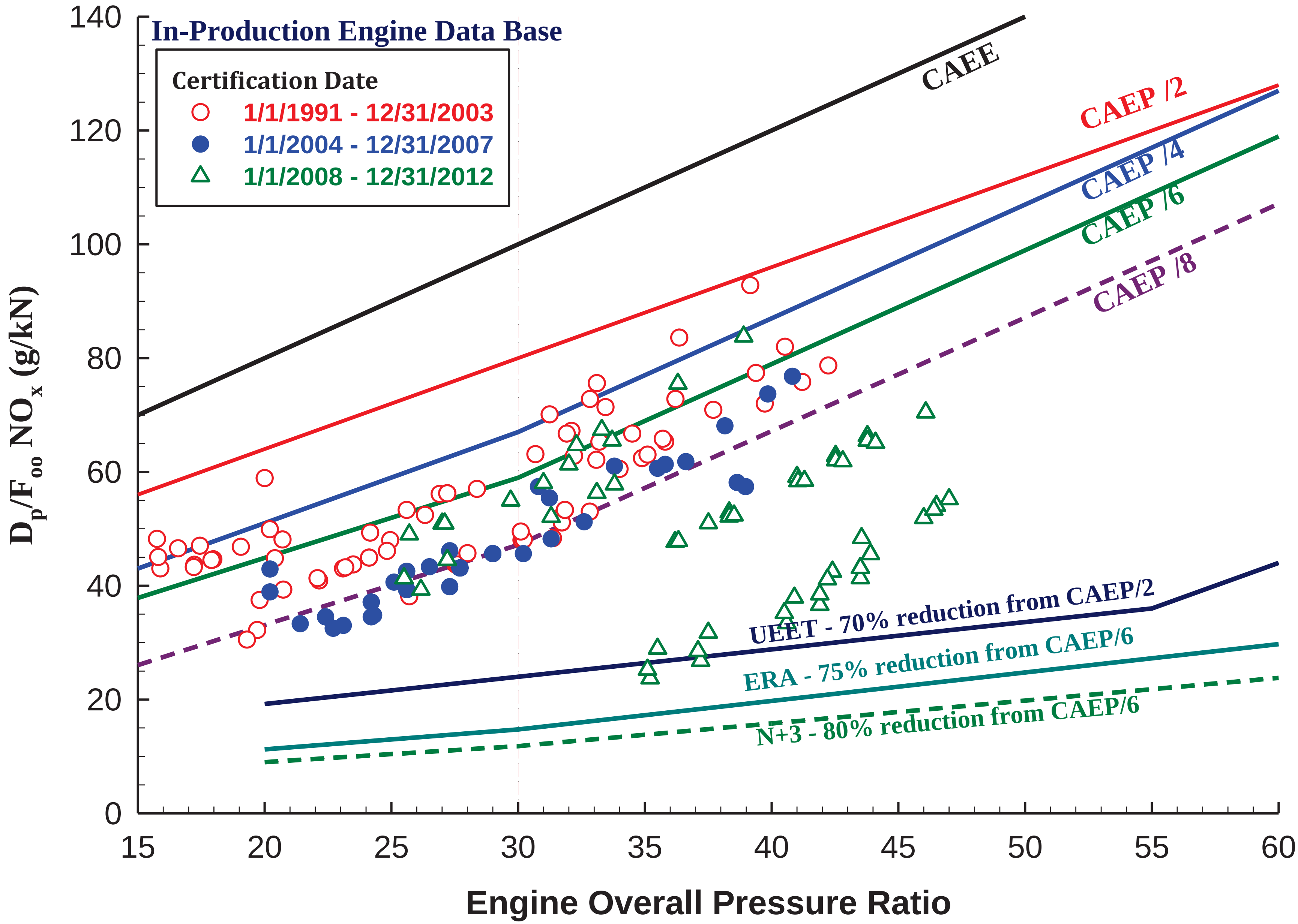




Seedling Idea: 1995

Basic Computational and experimental research to develop fundamental understanding of Lean Burning Technology

Emission Levels of Recently Certified Engines



NASA Subsonic Transport System Level Metrics

Strategic Thrusts

1. Energy Efficiency
2. Environmental Compatibility

v2013.1

TECHNOLOGY BENEFITS*	TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6)		
	N+1 (2015)	N+2 (2020**)	N+3 (2025)
Noise (cum margin rel. to Stage 4)	-32 dB	-42 dB	-52 dB
LTO NOx Emissions (rel. to CAEP 6)	-60%	-75%	-80%
Cruise NOx Emissions (rel. to 2005 best in class)	-55%	-70%	-80%
Aircraft Fuel/Energy Consumption‡ (rel. to 2005 best in class)	-33%	-50%	-60%

* Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines, N+2 values are referenced to a 777-200 with GE90 engines

** ERA's time-phased approach includes advancing "long-pole" technologies to TRL 6 by 2015

‡ CO2 emission benefits dependent on life-cycle CO2e per MJ for fuel and/or energy source used

Research addressing revolutionary far-term goals with opportunities for near-term impact

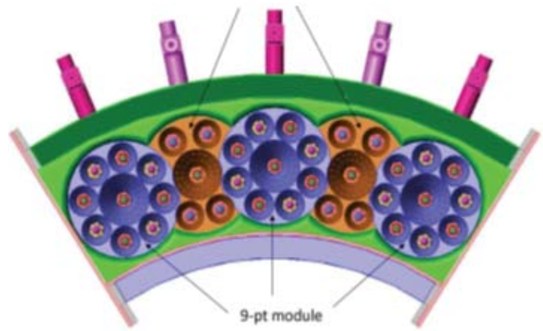
Lean Direct Injector (LDI) Design

Objective

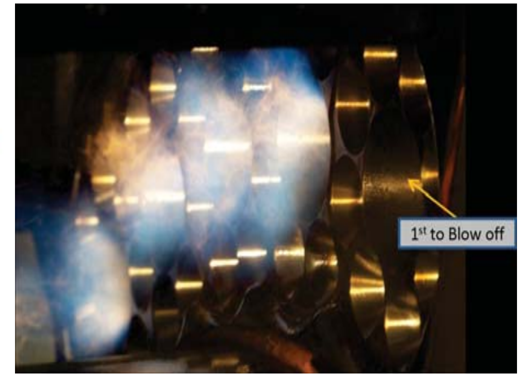
Design, fabricate and test in real engine operating conditions innovative injector concepts that meets N+2 goals.

Accomplishments

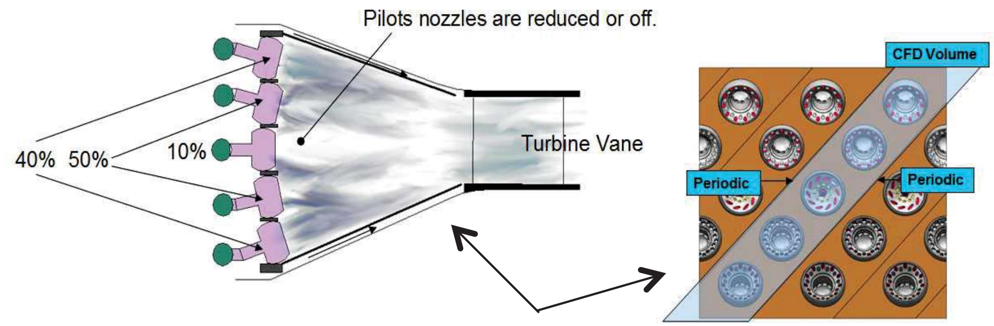
- All concepts designed for high OPR (50-70) engine cycles to meet N+2 emissions goals
- All injectors designed for alternative fuels flexibility (Up to 85% alt fuel blend)
- Goodrich, Woodward, and Parker down-selected most promising LDI concept
- All LDI injectors successfully completed lean blow-off testing
- Testing of the three concepts in NASA's high pressure facility (CE-5) were completed and emissions reduction goals met. Results presented at AIAA 2014 Joint Propulsion Conference.



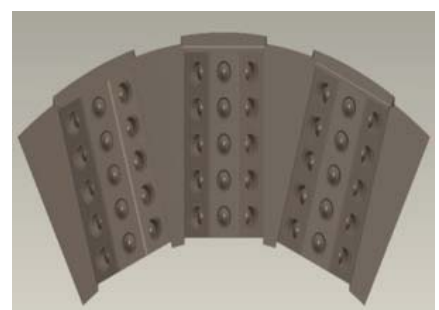
Woodward: 5-cup arc-sector concept



Woodward: Lean-blowout testing



GOODRICH LDI concept



Parker Hannifin: 3-cup arc installation concept

Low NOx, Fuel Flexible Combustor (N+2, ERA)

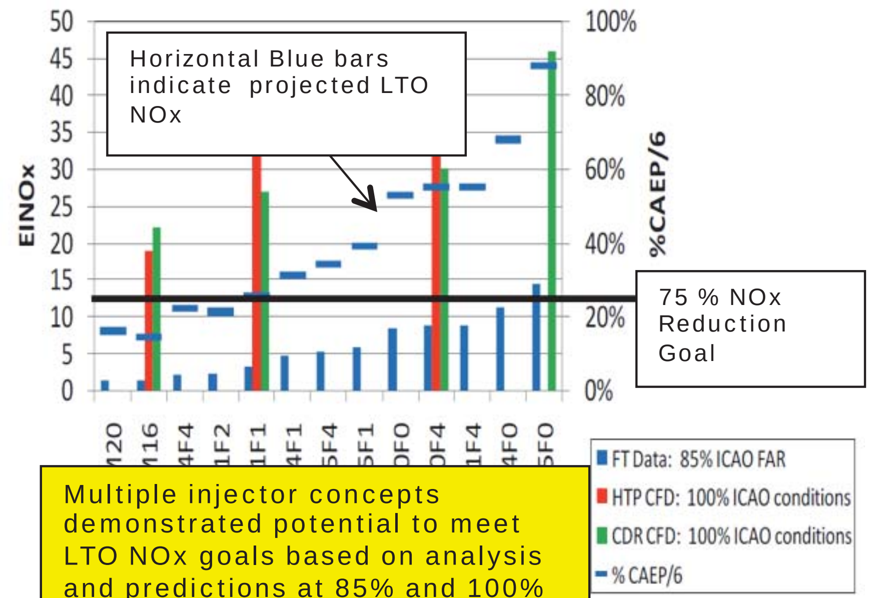
General Electric Phase 1

Objective

- Reduce LTO NOx 75% from CAEP6, while achieving a 50% reduction in fuel burn for the integrated engine/ vehicle.

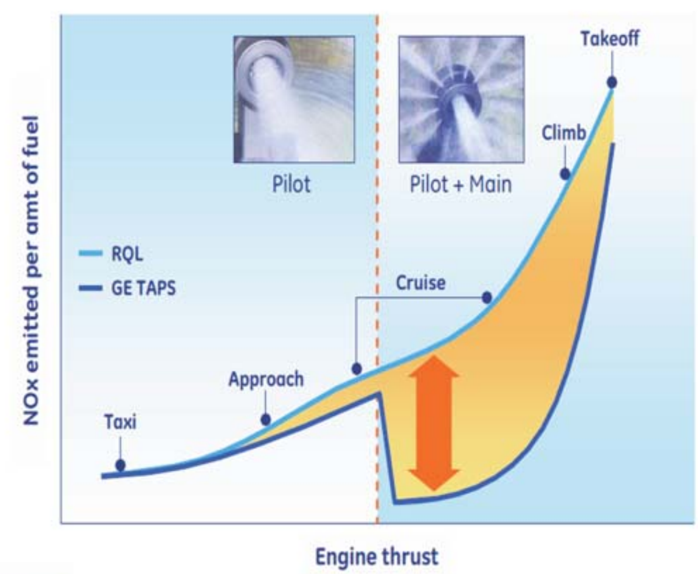
Results and Significance

- Designed and evaluated 13 multiple fuel injector and mixing concepts
- Predicts by CFC that 4 of these configurations could meet the 75% NOx reduction goal
- Demonstrated successful open-loop and closed-loop control of a combustion instability using pilot fuel and an auxiliary fuel injector
- Down-selected one concept for 5-cup sector rig with a CMC liner test at the NASA Advanced Subsonic Combustor Rig.
  - ✓ Lower power and cruise NOx levels low as predicted
  - ✓ NASA and GE Independent analysis indicates performance better than 75% reduction below CAEP/6 standards



Multiple injector concepts demonstrated potential to meet LTO NOx goals based on analysis and predictions at 85% and 100% power.

NOx flight cycle comparison (GE TAPS vs. RQL combustor)



Lean-burn Fuel Staging Enables Significantly Lower NOx Relative to Conventional RQL (Rich Quench Lean) Combustors

Low NOx, Fuel Flexible Combustor (N+2, ERA)

Pratt and Whitney Phase 1

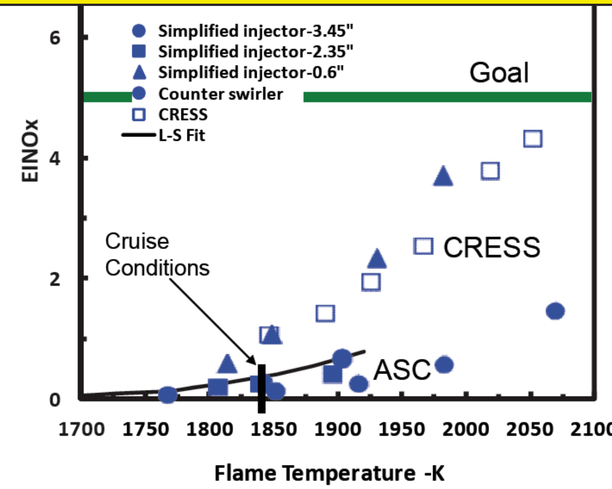
Objective

- Reduce LTO NOx 75% from CAEP6, while achieving a 50% reduction in fuel burn for the integrated engine/ vehicle.

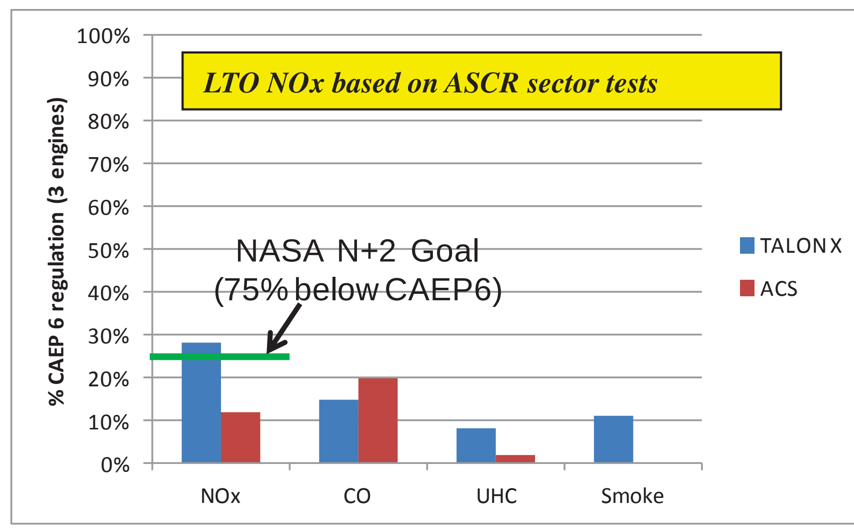
Results and Significance

- Designed and evaluated multiple fuel injector and mixing concepts in flame tube environment
- Down-selected one concept for a 3-cup sector rig test test at the NASA Advanced Subsonic Combustor Rig.
- Tested combustor in ASCR at the LTO NOx conditions as well as cruise condition. (Sept 2012)
- ASCR Sector Rig test results indicated approximately -88% LTO NOx reduction to CAEP 6 and Cruise NOx with margin to 5 EI Nox
- NOx correlation Equation for lean burn and alt fuels testing completed March 2014.

Multiple Concepts meet the goals based on Flame Tube tests simulating 7% and 30% engine power levels.

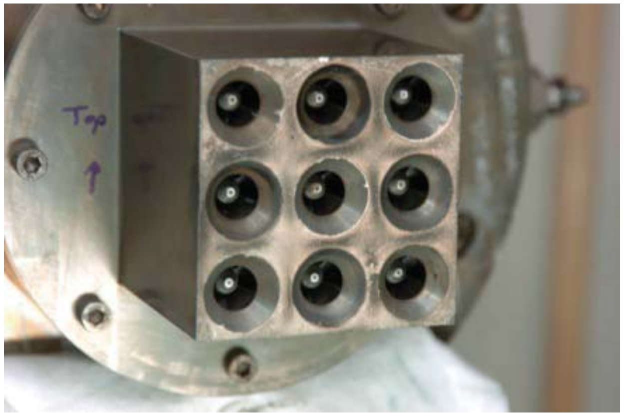


% CAEP6 LTO Emissions in a N+2 Cycle

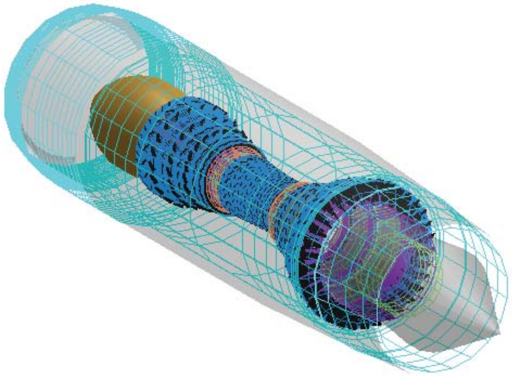


ASCR Sector Rig test results indicated approximately -88% LTO NOx reduction achieved

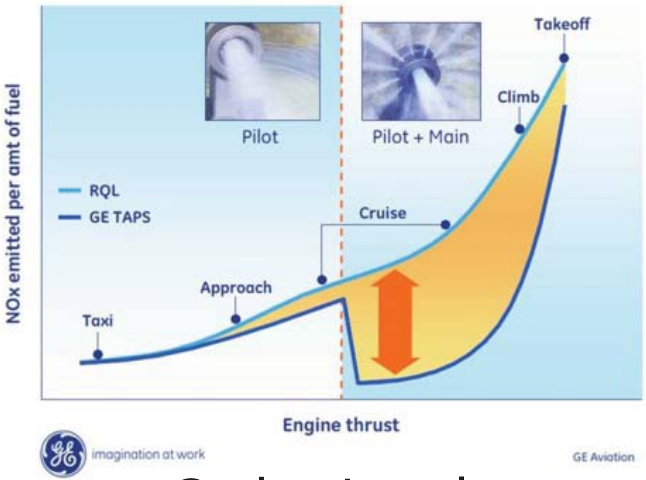
Future Direction



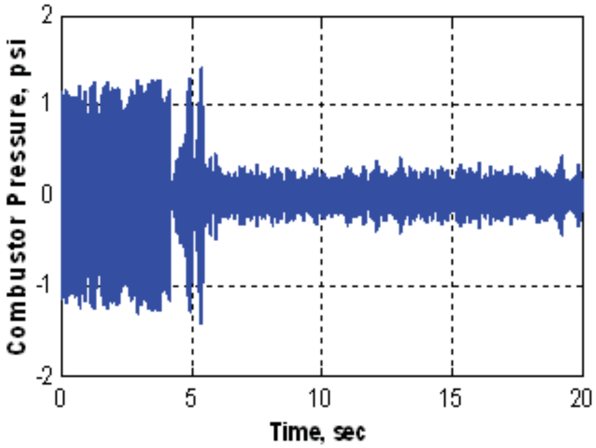
High-pressure
Multi-point LDI



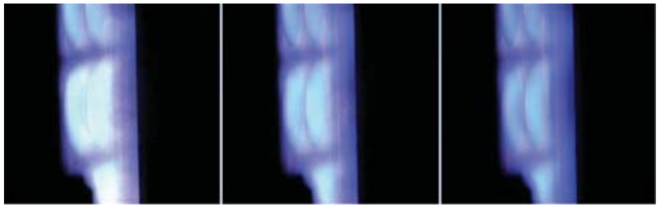
Smaller High
Pressure Engine
Cores



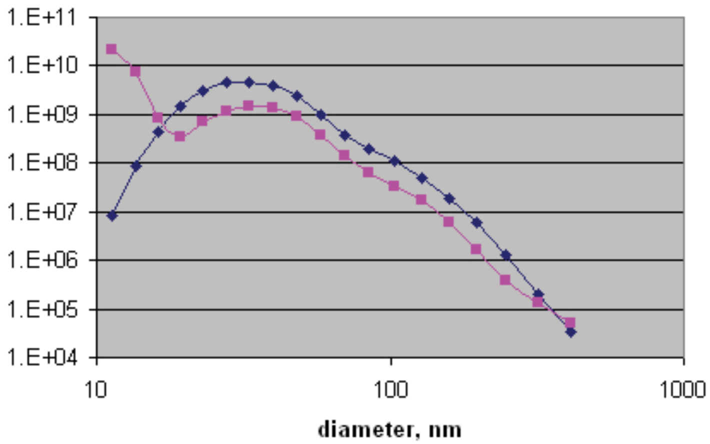
Cruise-Level
NOx Reduction



Dynamics and control



Alt fuel



Particulate Reduction

Low NOx Combustor for High OPR Compact Cores

Objective

Reduce NOx emissions from fuel-flexible combustors to 80% below the CAEP6 standard

Develop design criteria for alternative fuels use in a small core engine to meet high OPR (50+) conditions

Technical Areas and Approaches

Axially Controlled Stoichiometry (ACS) Concepts

- Small core scaling, fuel injection and thermal growth management techniques

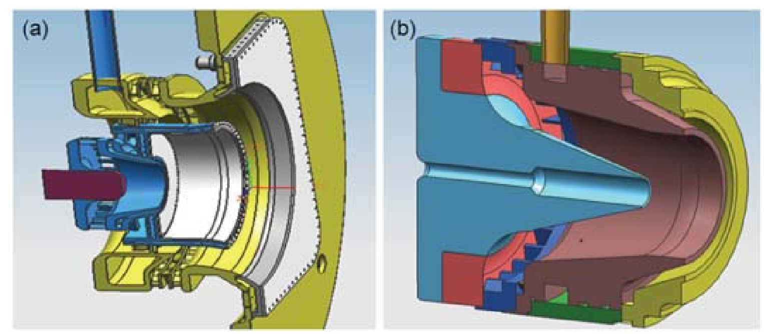
Alternative Fuels Flexibility

- Autoignition, compatibility and blending, and combustion dynamics and stability

Benefit/Pay-off

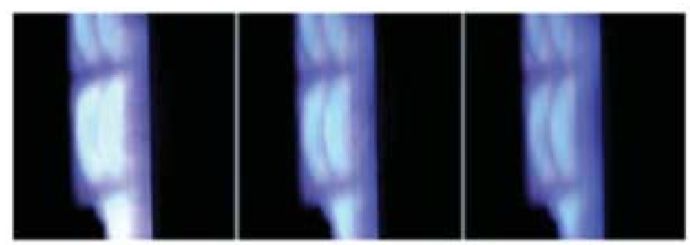
- Achievement of N+3 emission goals for landing LTO conditions including a 80% reduction in NOx emissions lower than CAEP-6 standards for high OPR (50+) for future single-aisle transport aircraft.
- Reduction of particulate formation at LTO conditions
- Compatible for gas-only and hybrid gas-electric architectures and ducted/unducted propulsors
- Compatible with alternative fuel blends
- Reduction of combustion dynamics and instability with alternative fuels

Low emission , fuel flexible concepts



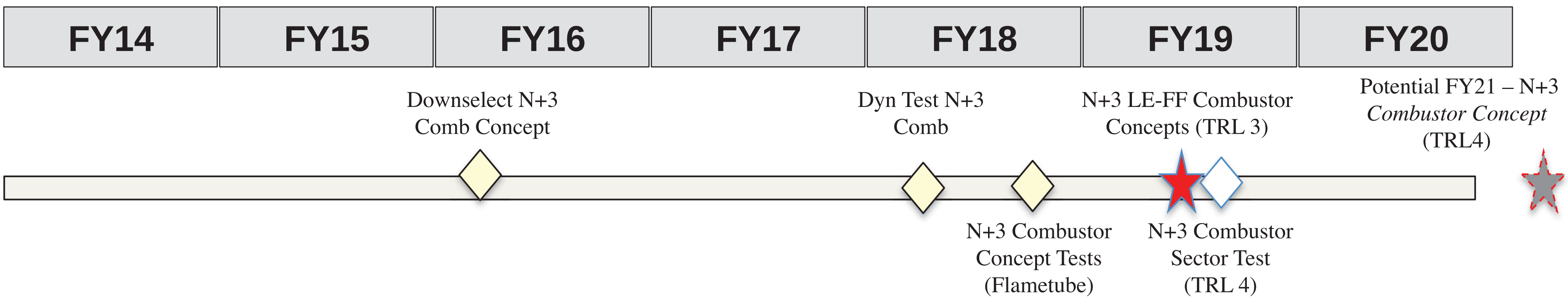
Smith et al., ASME Paper No. GT2012-69078

PLIF



JP-8 | JP-8 / F-T Blend | F-T

Low NOx Combustor for High OPR Compact Cores



Fuel-Flexible Combustor

- Models for high-pressure spray atomization, vaporization, chemical kinetics
- Evaluate combustor dynamics & staging characteristics for N+3 **high power-density** operations
- Explore/develop combustor concepts through flametube tests; sector rig/full annular rig
- Evaluate impacts of **alternative-fuels** and blends on combustion and fuel systems in laboratory, ground-based engine, and in flight
- Combustor-turbine interaction

High Altitude Emissions

- Combustor system dynamics mitigation technology

Fundamental Understanding

- High temperature CMC liner suitable for 3000F flame temperature
- High-pressure spray validation data, identify lean direct injection fundamentals, closed-loop active combustor control strategy
- Improved understanding and modeling of combustion flow physics, including multi-species mixing/dynamics
- Active combustion control components (minature high-freq valves, hi-Temp sensors, CNTL method)

Other Research Theme Investments

- *Understanding combustor-turbine interaction and noise physics*

Combustion Dynamics Test Rig

Objective

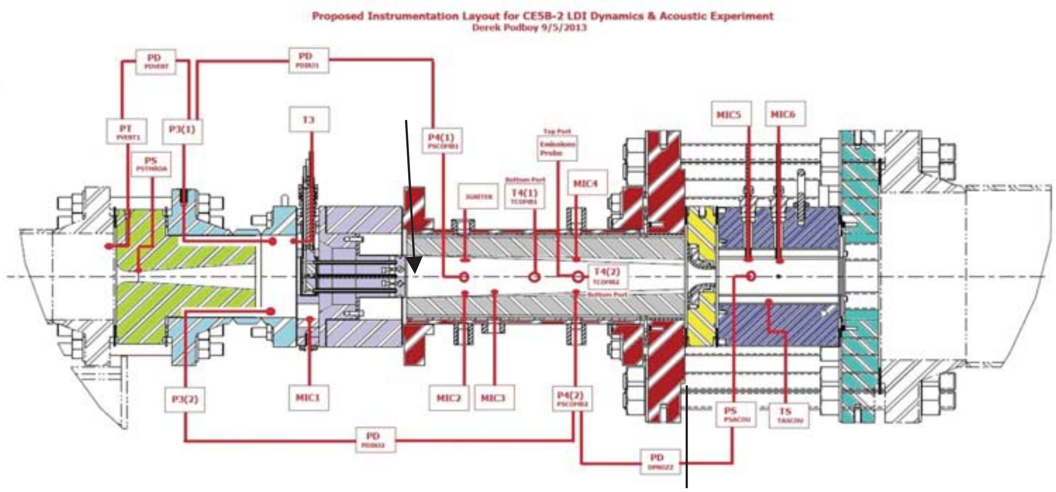
Study combustion dynamics of a typical lean combustion system to improve understanding and provide data for combustion dynamics models.

Approach

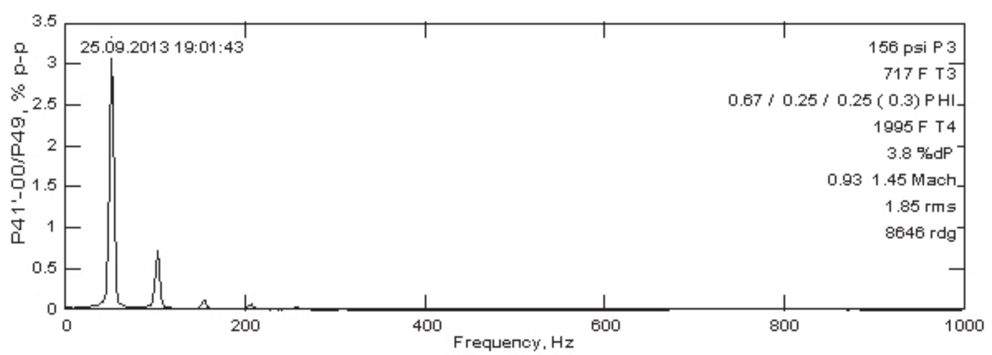
A test rig based on a baseline Lean Direct Injection low-emissions concept has been developed. The rig allows spatial variation in fuel placement with well-defined upstream and downstream boundary conditions.

Results and Significance

- Rig shakedown and initial data tests conducted. Several operating points where combustion dynamics was important identified.
- Test rig supports NASA investigation into combustion dynamics in lean combustion concepts.
- Data of this nature at appropriate gas turbine conditions is not available and will be required for the development of low NOx combustion systems to meet N+3 NOx emissions goals.



Test Rig Schematic



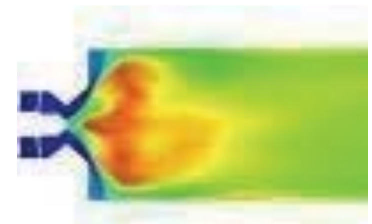
Unsteady pressure data indicating pressure oscillations at several frequencies for a specific operating condition

Fundamental Understanding Efforts

Develop and validate physics-based combustion models, perform fundamental experiments and investigate new combustor technologies

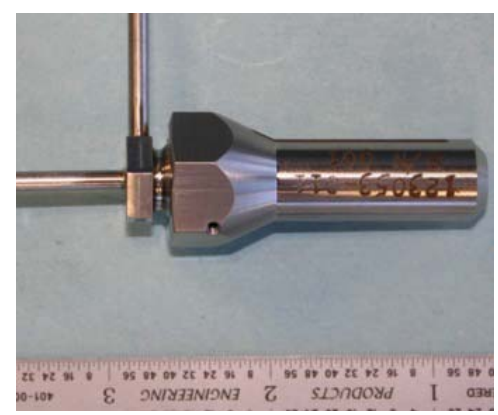
Goal

- Provide improved computational tools and critical technologies to enable combustor concepts that meet NASA fuel burn and emissions goals for future aircraft engines.



Approach

- Develop and validate physics-based combustion models for CFD. Develop capability for tightly coupled combustor-turbine simulations
- Perform experiments to provide high-quality CFD validation data at relevant combustor conditions (fuel, pressure, temperature)
- Perform experiments with detailed diagnostics to provide a fundamental understanding of low-emission systems
- Develop and test critical combustion control technologies (passive and active) for future lean burn combustors
- Explore innovative combustor technologies (such as Pressure Gain Combustion)



Alternative Fuel Emissions at Cruise

Objectives

Explore the potential of alternative fuels to reduce the impact of aviation on air quality and climate, and their impact on performance

Technical Areas & Approaches

Emission & Performance Characterization

- Flight tests
- Ground tests
- Laboratory tests

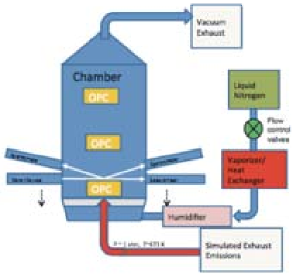
Benefit/Pay-off

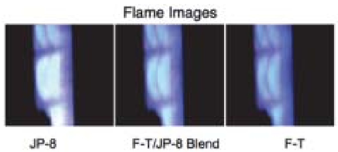
- Will dramatically reduce the impact of aviation on the environment (gaseous, particulates, and contrails)
- Will support standard-setting organizations by providing important and timely data

Alternative-Fuel Effects on Contrails and Cruise EmiSSions (ACCESS)

leverage ground tests from prior years

lab studies



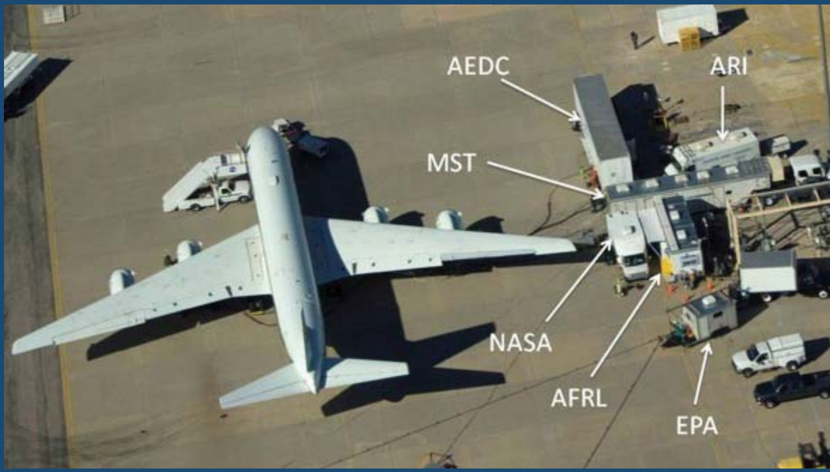


Alternative Fuel Emissions Research

Sample fleet emissions at airports and in the NAS at cruise

ACCESS part of Multi-Tiered Effort to Assess Alt Fuel Performance and Environmental Benefits

Perform detailed ground emissions tests with partners



Assess emissions from a broad range of fuels using APU

Examine fuel effects on contrail formation in altitude test cell

Examine fuel effects on emissions and contrails at cruise

Alternative Aviation Fuel Emissions Research

- **Laboratory tests** to determine alternative fuel combustion and emissions characteristics
  - o High-pressure flame-tube experiments on LDI fuel injectors—ongoing
  - o High-pressure tests on GE & PW sector rig combustors—2013
- **Ground-based engine tests** to evaluate alternative fuel effects on emissions under real-world conditions
  - o PW308—March 2008
  - o AAFEX-I—January 2009
  - o AAFEX-II—March 2011

LaRC, GRC, AFRC, EPA, AFRL, FAA, SAE, Boeing, GE

- **Altitude chamber tests** to examine PM effects on contrail formation
  - o SE-11 facility at GRC: 2010-2012
  - o APU/SE-11 facility at GRC: 2014-2016

GRC, LaRC, FAA ACCRI, SBIR

- **Airborne experiments** to evaluate fuel effects on emissions and contrail formation at cruise
  - o **ACCESS-I: Feb-April, 2013**
  - o **ACCESS-II: May, 2014**

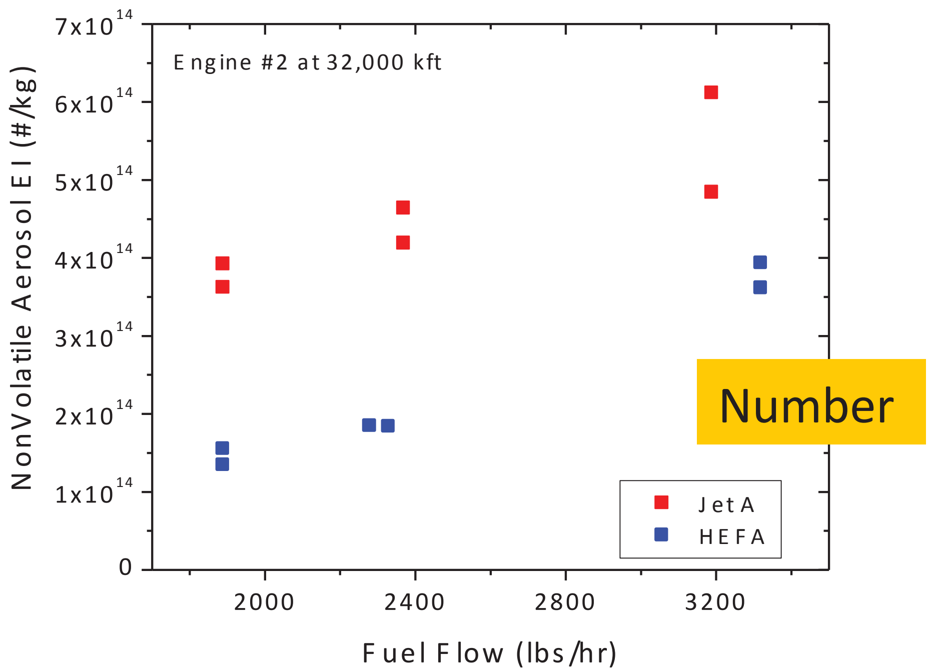
LaRC, GRC, AFRC, DLR, NRC, JAXA, FAA, Boeing, GE

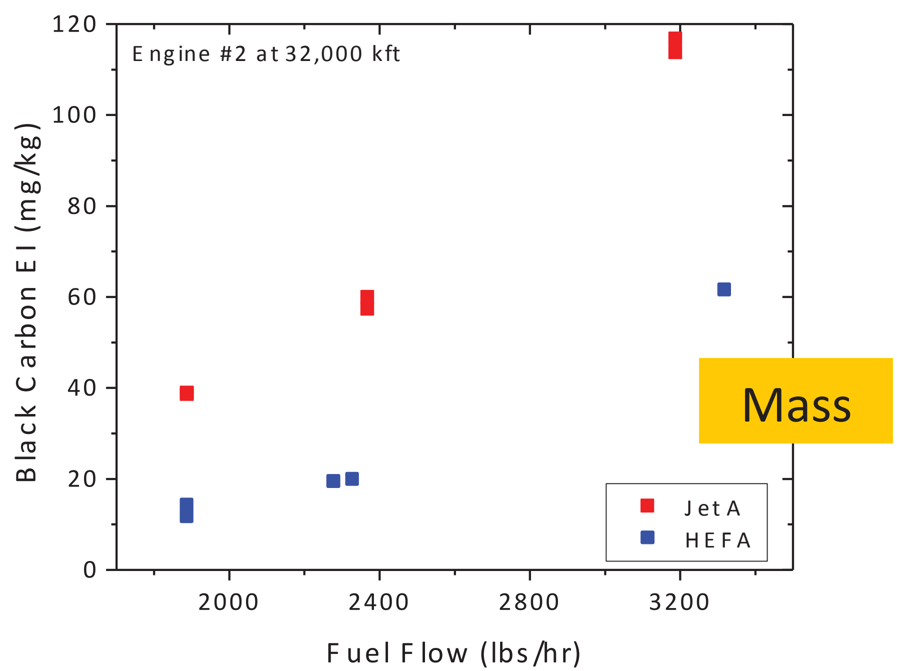
ACCESS: Multi-Platform, Multi-Fuels Sampling

Test	JP-8	JP-8 Hi S	Blend
Sulfur (ppm)	<10 ppm	1000 ppm	<5 ppm
Aromatics (%vol)	18	18	9
Density (kg/L)	0.81	0.81	0.79
End Point (degC)	275	275	279

Preliminary Results from ACCESS II Flight Campaign

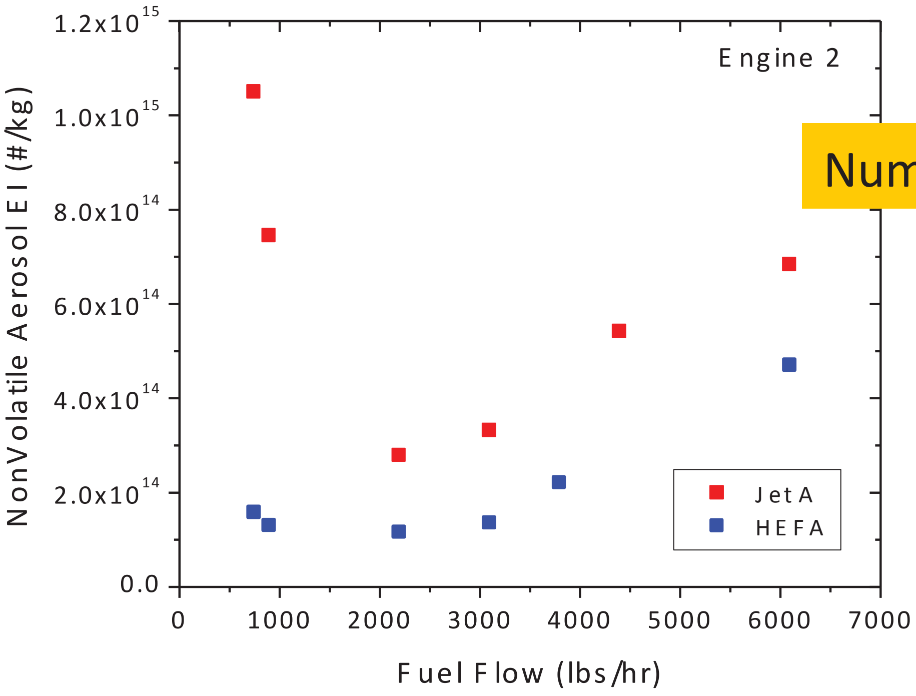
HEFA Blend Reduces Black Carbon Number and Mass Emissions by 30 to 60% at Cruise



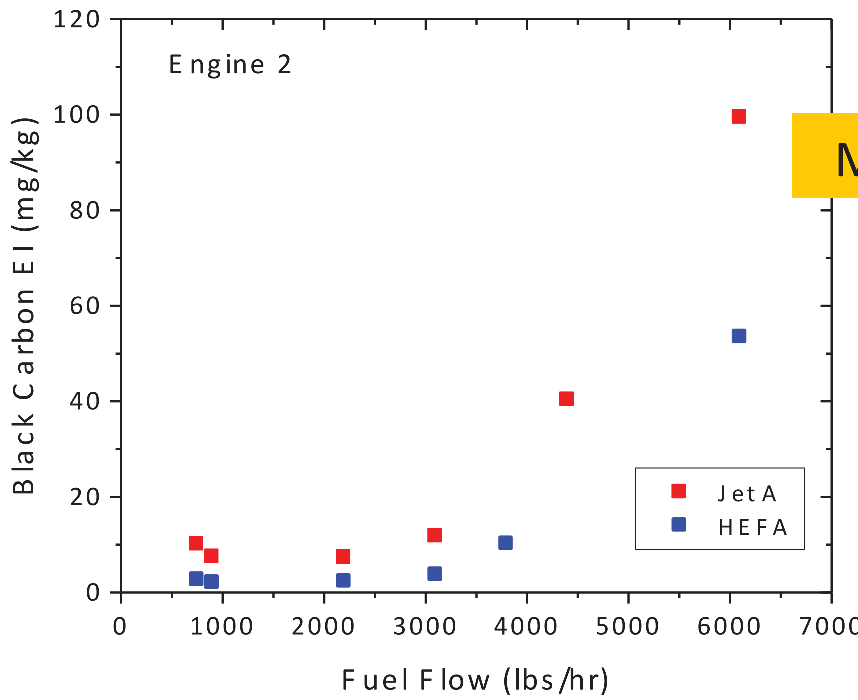


Preliminary Results from ACCESS II Ground Emissions Test

HEFA Blend Reduces Black Carbon Number and Mass Emissions by 30 to 80% during Ground Ops



Number



Mass

Concluding Points

- Rich NASA history in research leading to reduction of LTO NOx emissions
- Strong collaborative efforts with Industry, Academia and Other Government Organization.
- Current research portfolio targeting future generations of commercial transport with goals of reduction of NOx of up to more than 80% below CAEP 6
- Efforts in developing advanced prediction, modeling and simulations tools
- Efforts in understanding the effect on using alternative fuels for aviation and characterizing emissions through ground and flight testing

NASA

Impact of Aviation on The Environment