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# An Overview of Low-Emissions Combustion Research

## NASA Glenn Research Center


Dr. Rubén Del Rosario
Manager, Fixed Wing Project

CAEP Review of Advanced Aero-Engine Combustor Design
Munich, DE
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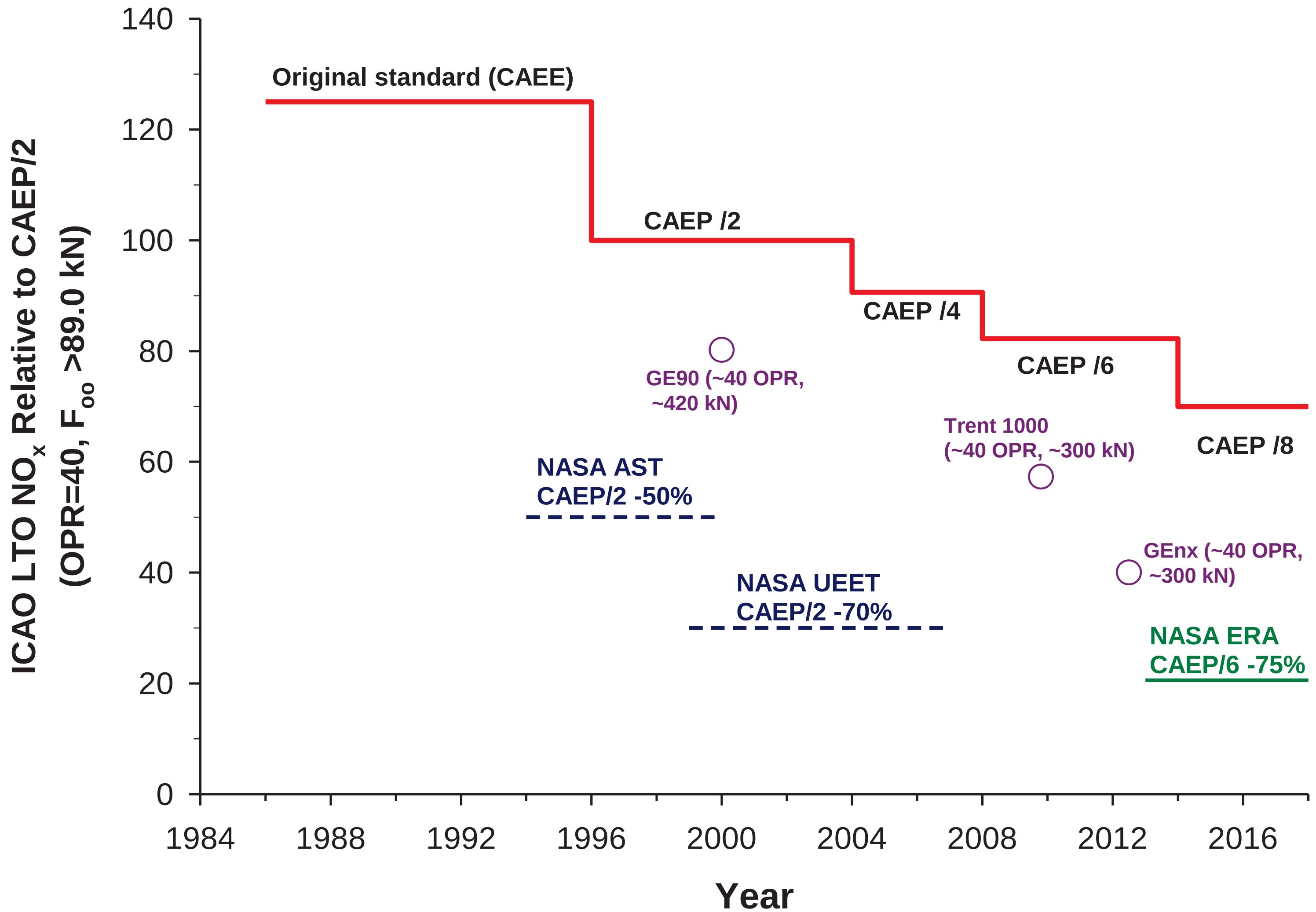
# Cornerstones of NASA Combustion Research

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

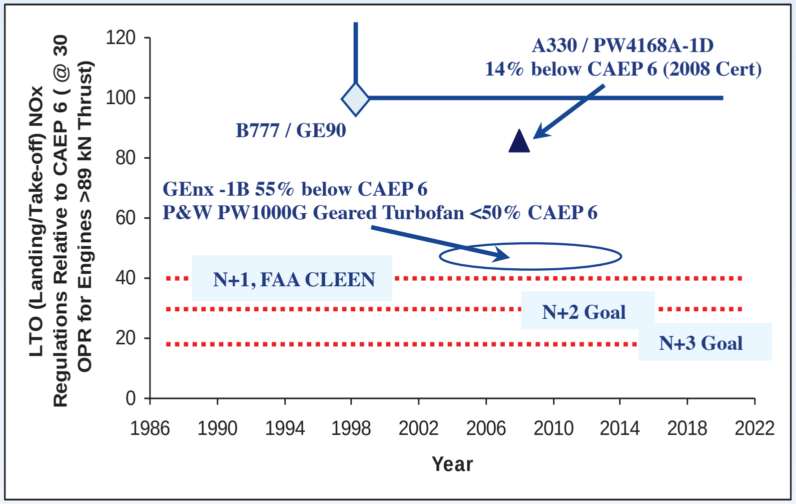
~50% NOx Reduction every 15 yrs

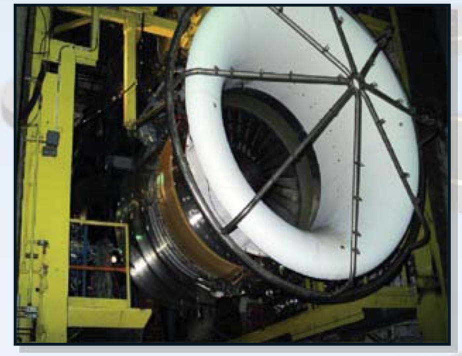



Courtesy of Changlie Wey

# Technology for Advanced Low NOx (TALON) Combustor

***~ 50% reduction in Nitrogen Oxide emissions***



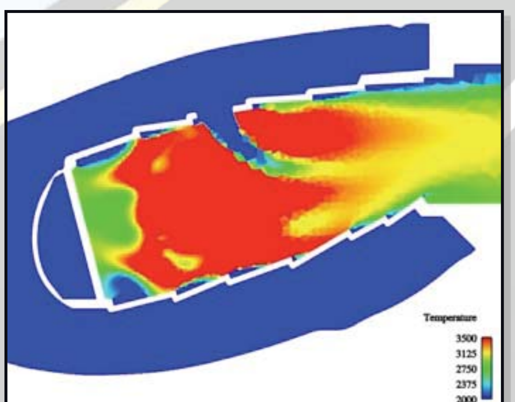

In service on Airbus A330

## 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*

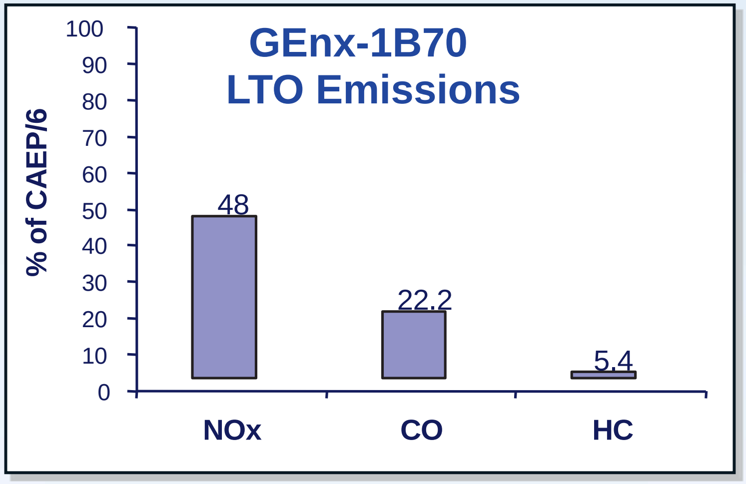



## Seedling Idea: mid 1990's

*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***

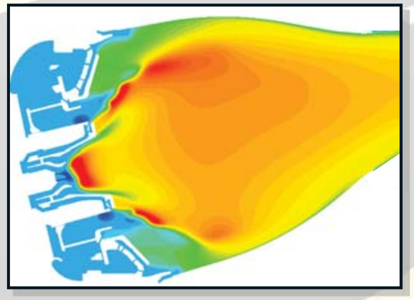



Engine Test


In service in 2011

## Systems Assessment: 2005-2009

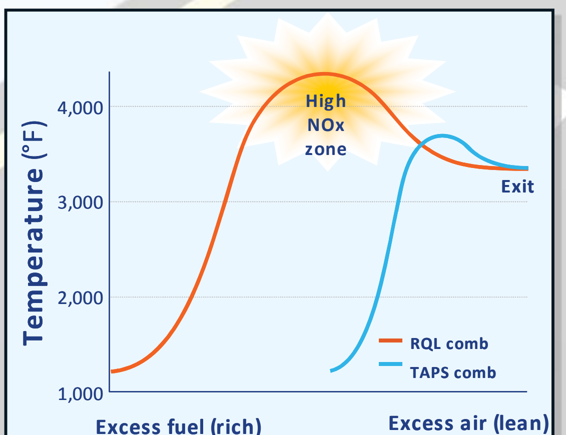
*GEnx Engine Certification in ground engine test stands*

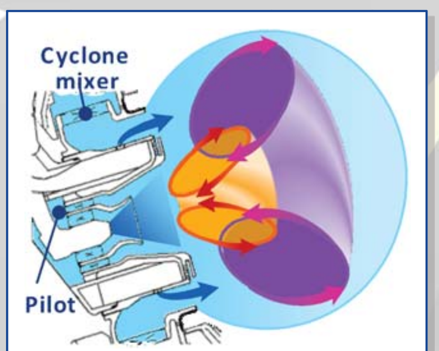


Component Test

## 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*

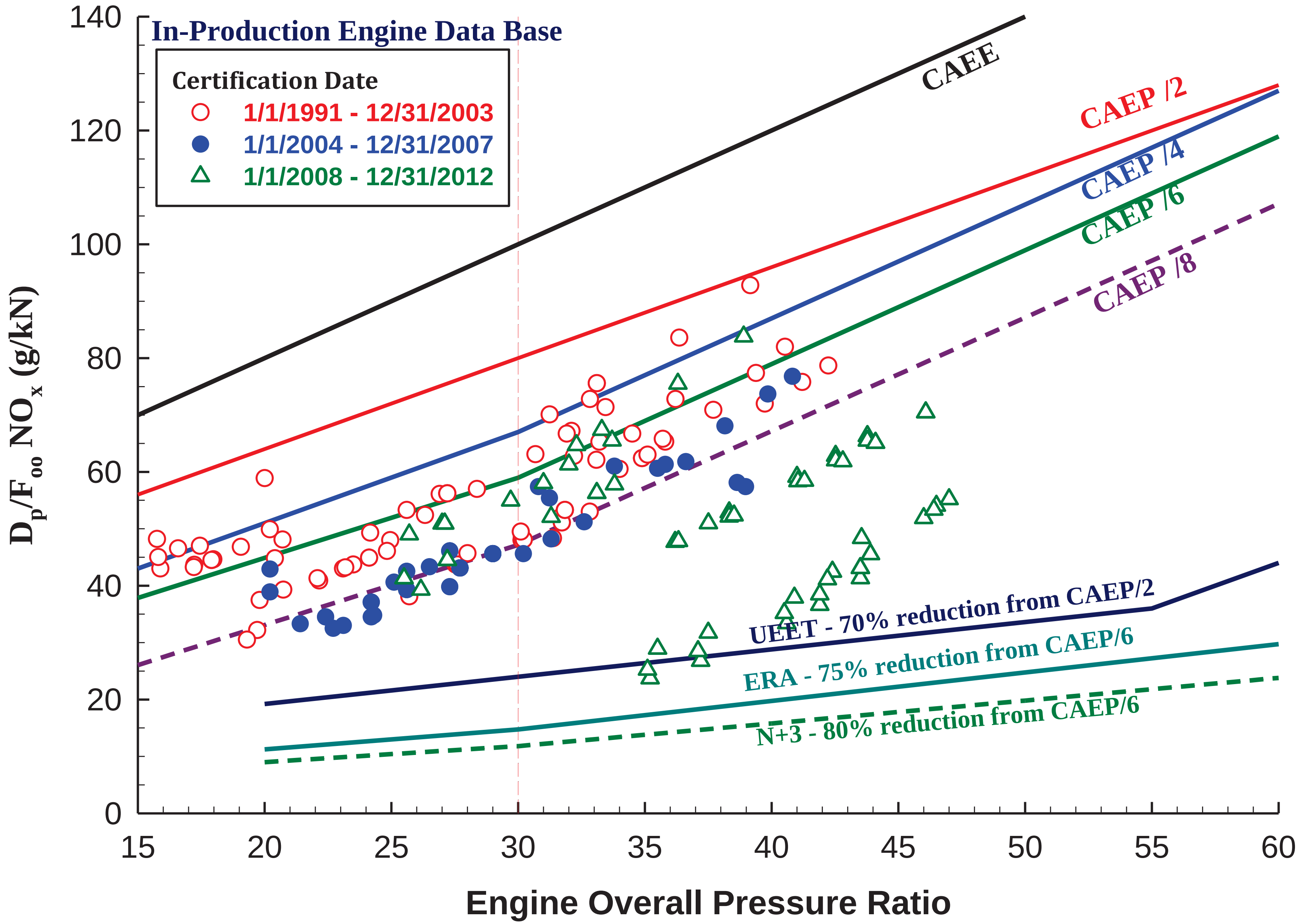



## Seedling Idea: 1995

*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**

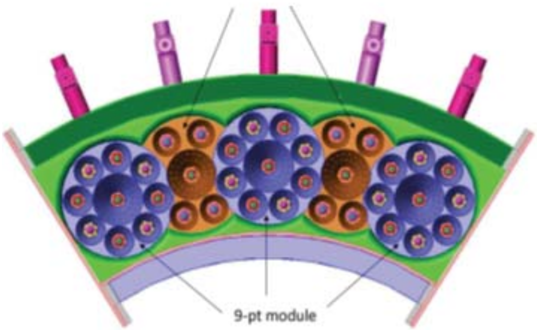
# Lean Direct Injector (LDI) Design

## Objective

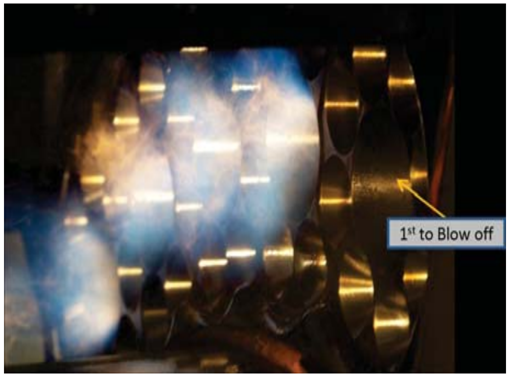
Design, fabricate and test in real engine operating conditions innovative injector concepts that meets N+2 goals.

## Accomplishments

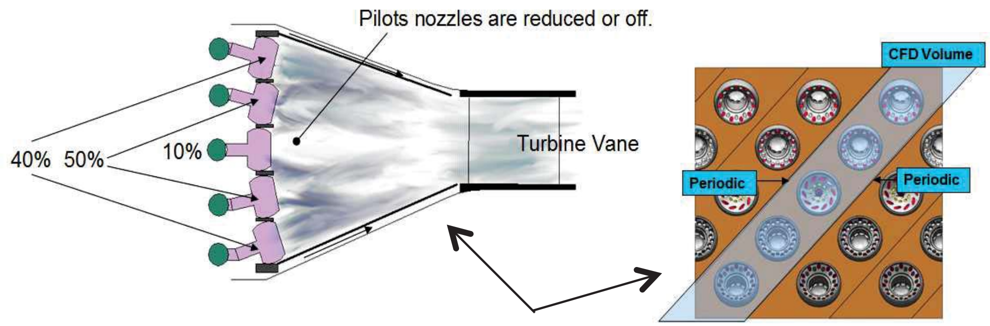
- All concepts designed for high OPR (50-70) engine cycles to meet N+2 emissions goals
- All injectors designed for alternative fuels flexibility (Up to 85% alt fuel blend)
- Goodrich, Woodward, and Parker down-selected most promising LDI concept
- All LDI injectors successfully completed lean blow-off 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.



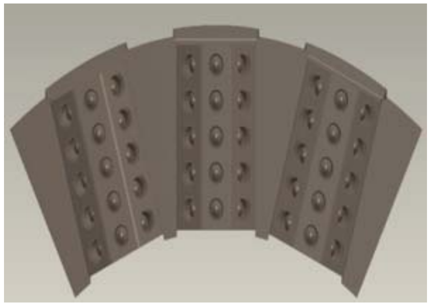
Woodward: 5-cup arc-sector concept



Woodward: Lean-blowout testing



GOODRICH LDI concept


Parker Hannifin: 3-cup arc installation concept

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

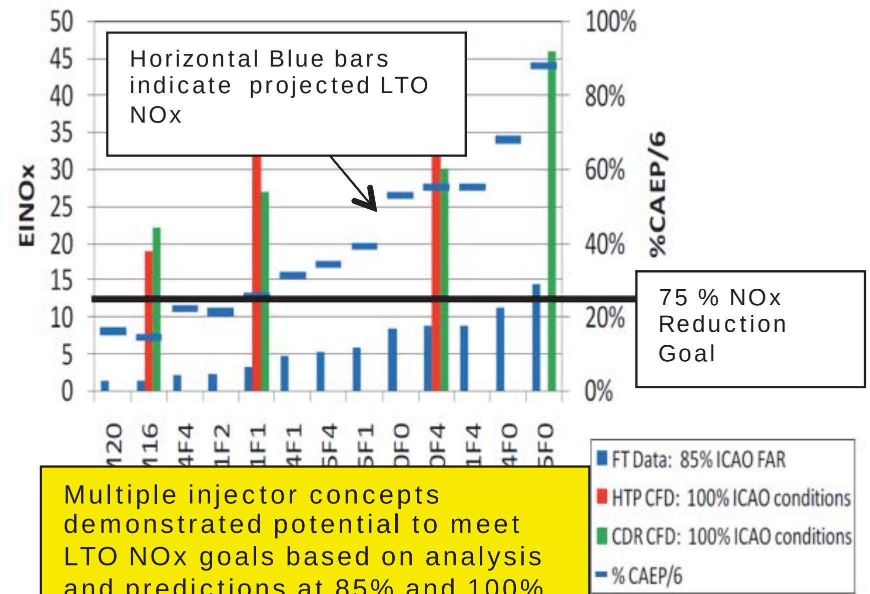
## *General Electric Phase 1*

### Objective

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

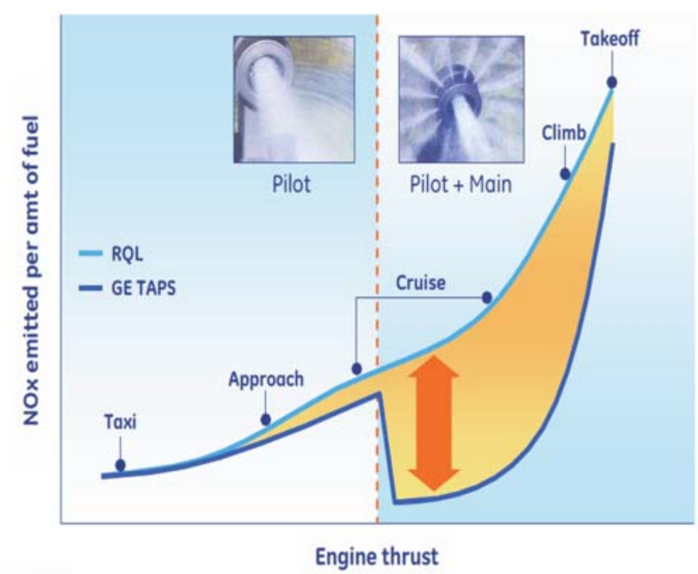
### Results and Significance

- 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*

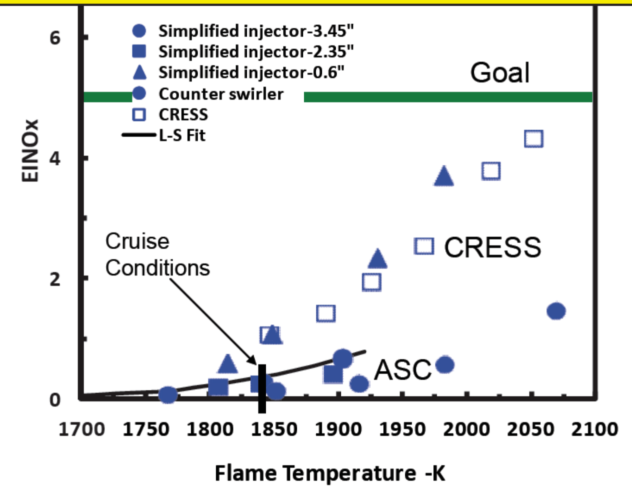
### Objective

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

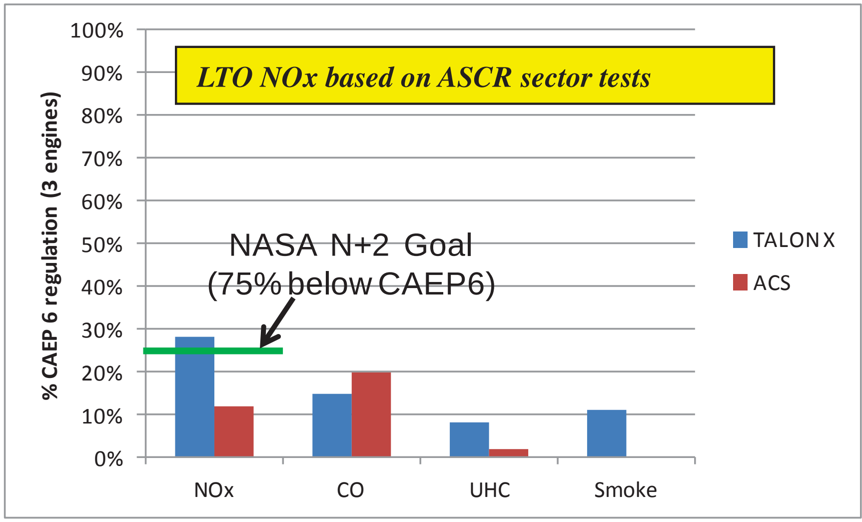
### Results and Significance

- 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.*

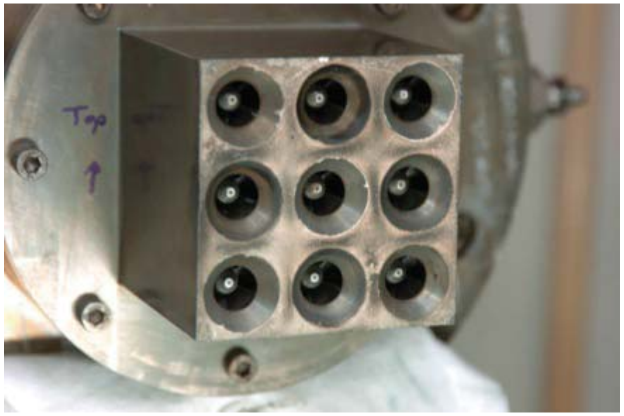



% CAEP6 LTO Emissions in a N+2 Cycle

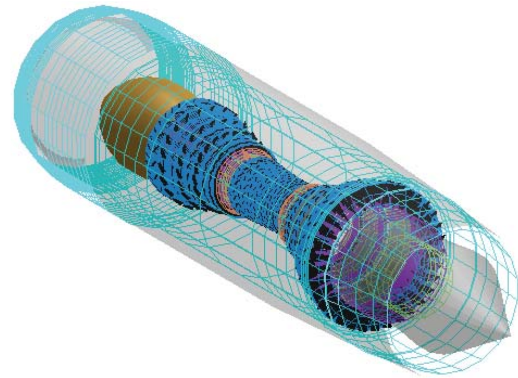



**ASCR Sector Rig test results indicated approximately -88% LTO NOx reduction achieved**

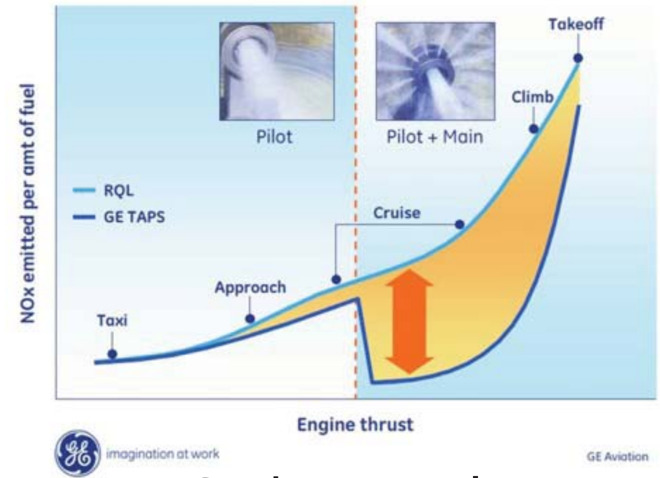
# Future Direction



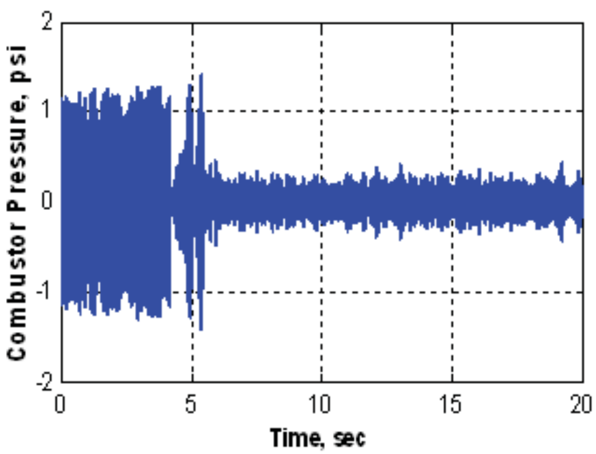

High-pressure
Multi-point LDI



Smaller High
Pressure Engine
Cores

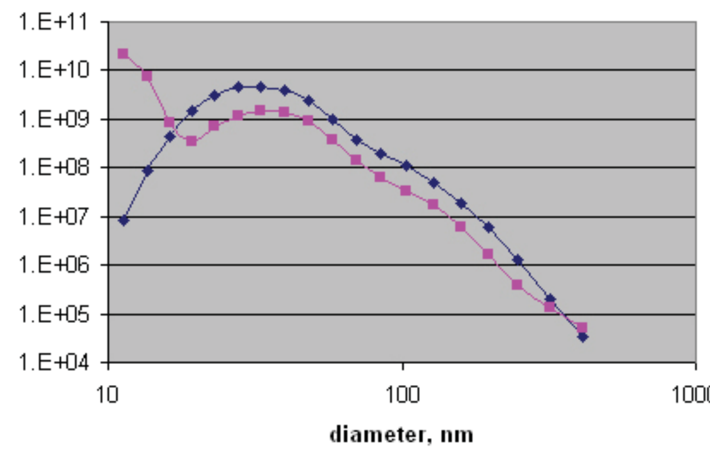



Cruise-Level
NOx Reduction




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

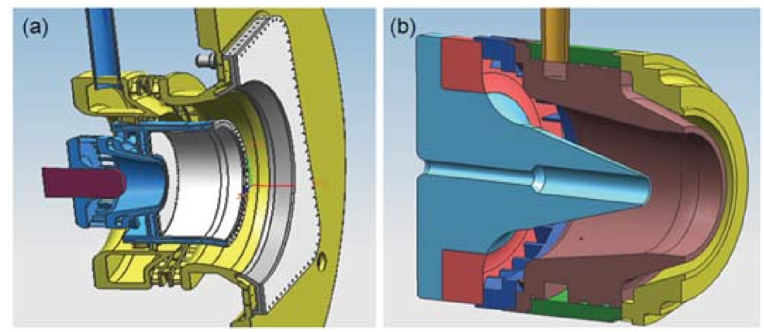
Alternative Fuels Flexibility

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

## Benefit/Pay-off

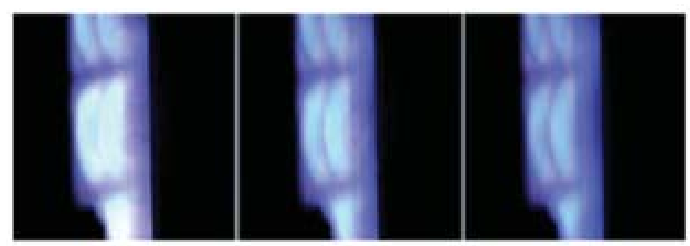
- Achievement of N+3 emission goals for landing LTO conditions including a 80% reduction in NOx emissions lower than CAEP-6 standards for high OPR (50+) for future single-aisle transport aircraft.
- Reduction of particulate formation at LTO conditions
- Compatible for gas-only and hybrid gas-electric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

**Low emission , fuel flexible concepts**



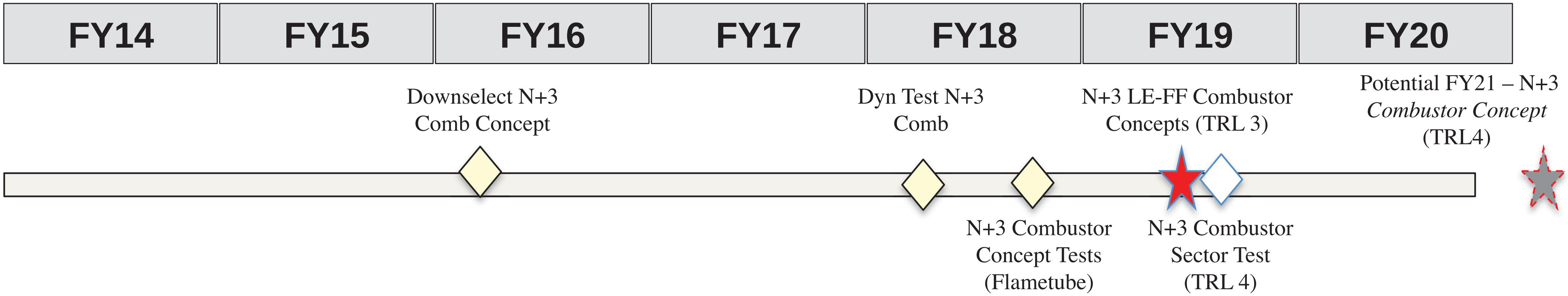

Smith et al., ASME Paper No. GT2012-69078

**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

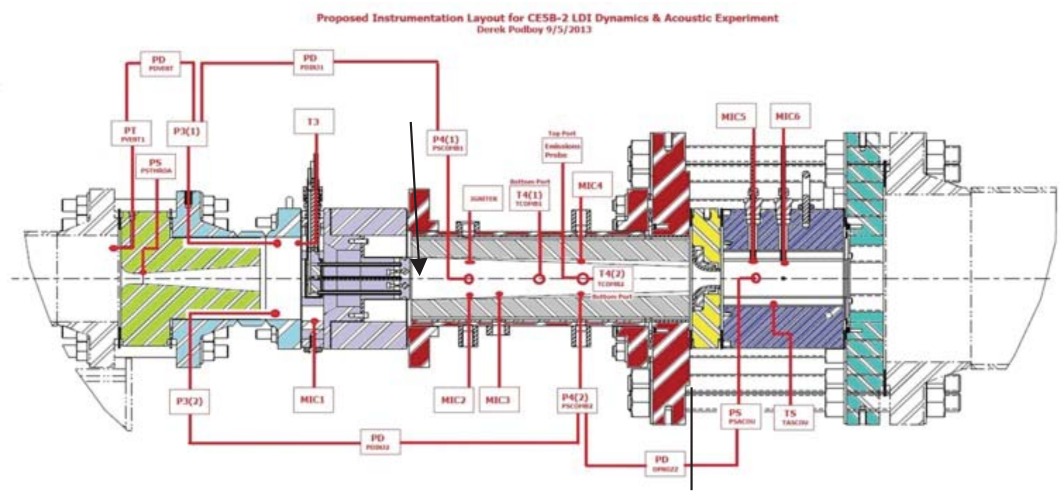
Study combustion dynamics of a typical lean combustion system to improve understanding and provide data for combustion dynamics models.

## Approach

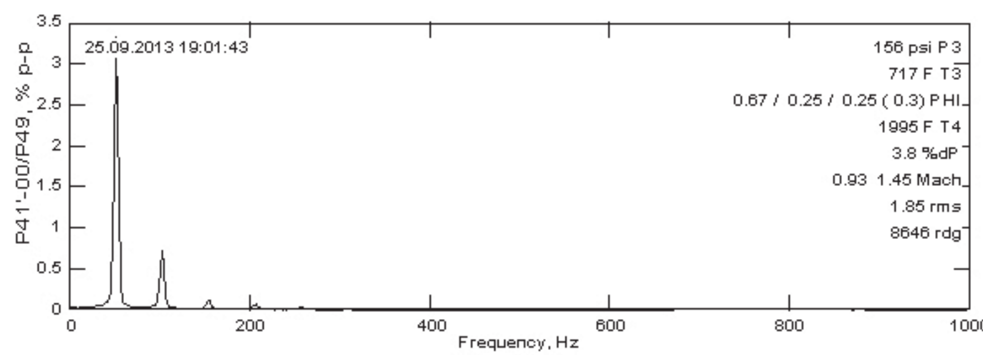
A test rig based on a baseline Lean Direct Injection low-emissions concept has been developed. The rig allows spatial variation in fuel placement with well-defined upstream and downstream boundary conditions.

## 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**



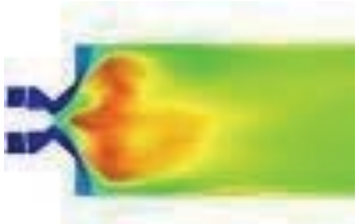

**Unsteady pressure data indicating pressure oscillations at several frequencies for a specific operating condition**

# Fundamental Understanding Efforts

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

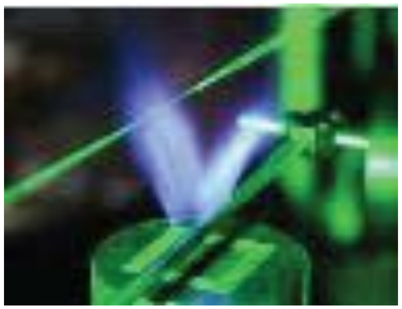
## Goal

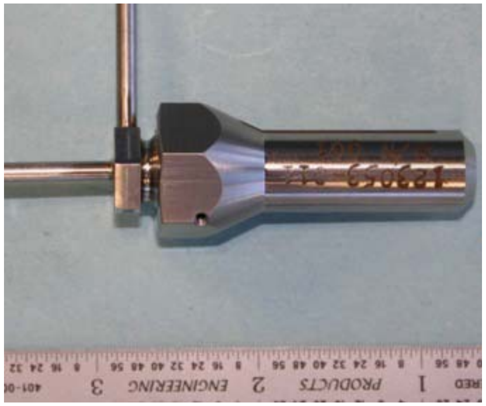
- Provide improved computational tools and critical technologies to enable combustor concepts that meet NASA fuel burn and emissions goals for future aircraft engines.



## 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

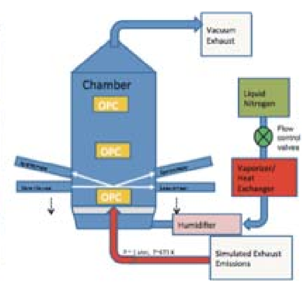
## Benefit/Pay-off

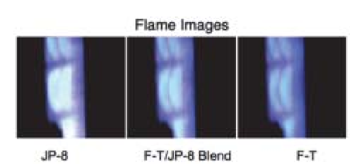
- Will dramatically reduce the impact of aviation on the environment (gaseous, particulates, and contrails)
- Will support standard-setting organizations by providing important and timely data

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**

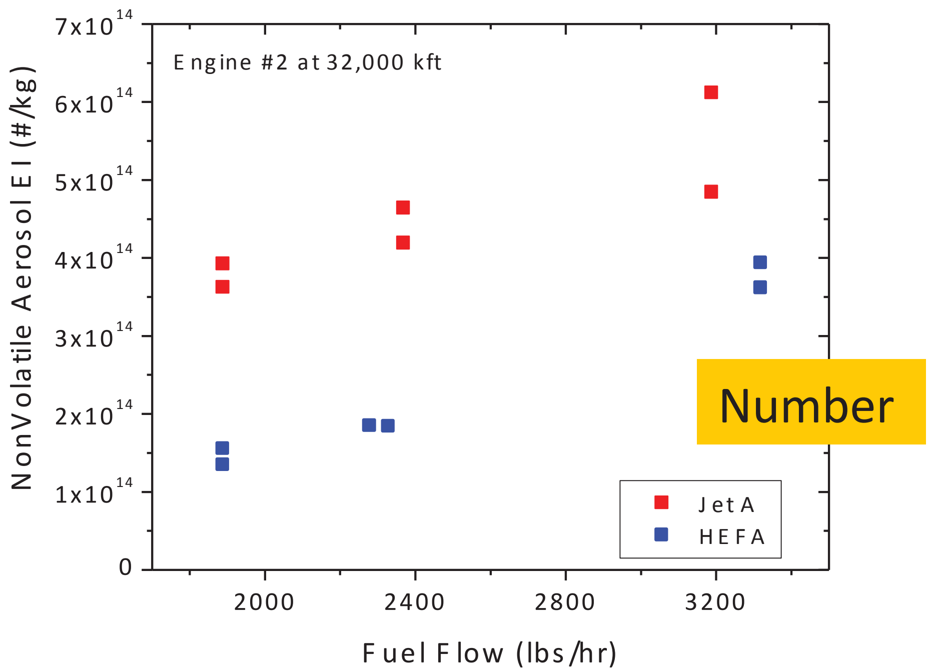
**LaRC, GRC, AFRC, DLR, NRC, JAXA, FAA, Boeing, GE**

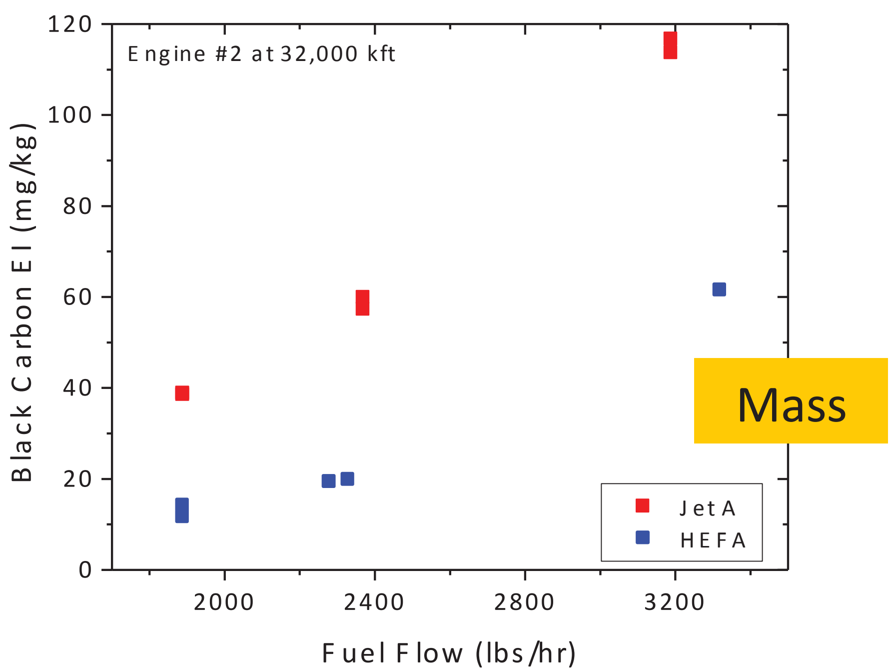
# ACCESS: Multi-Platform, Multi-Fuels Sampling


| 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

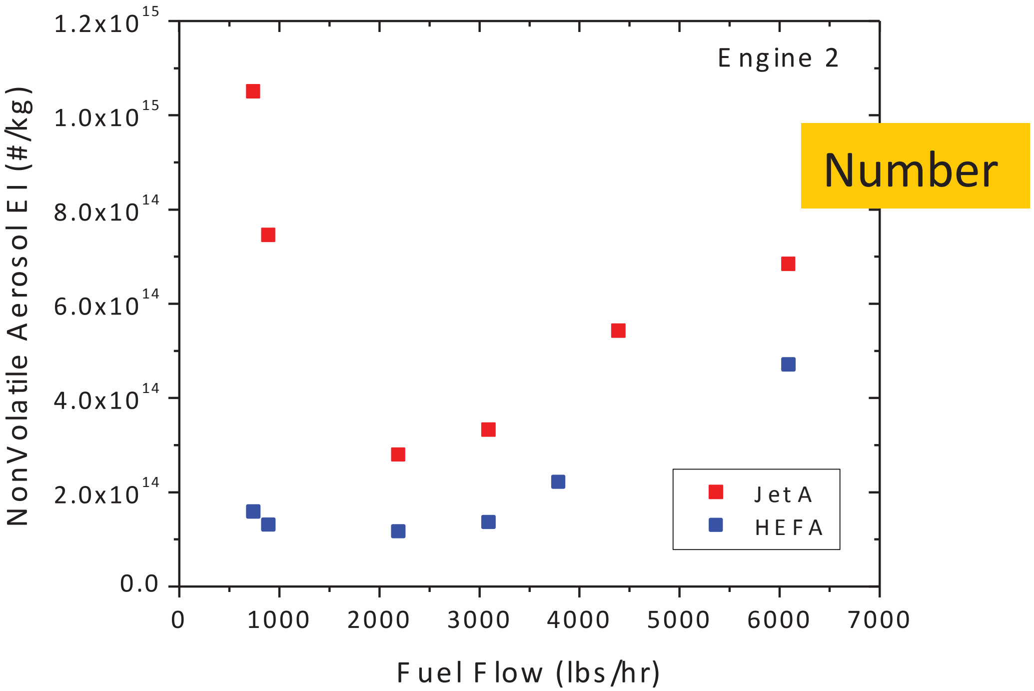
## HEFA Blend Reduces Black Carbon Number and Mass Emissions by 30 to 60% at Cruise

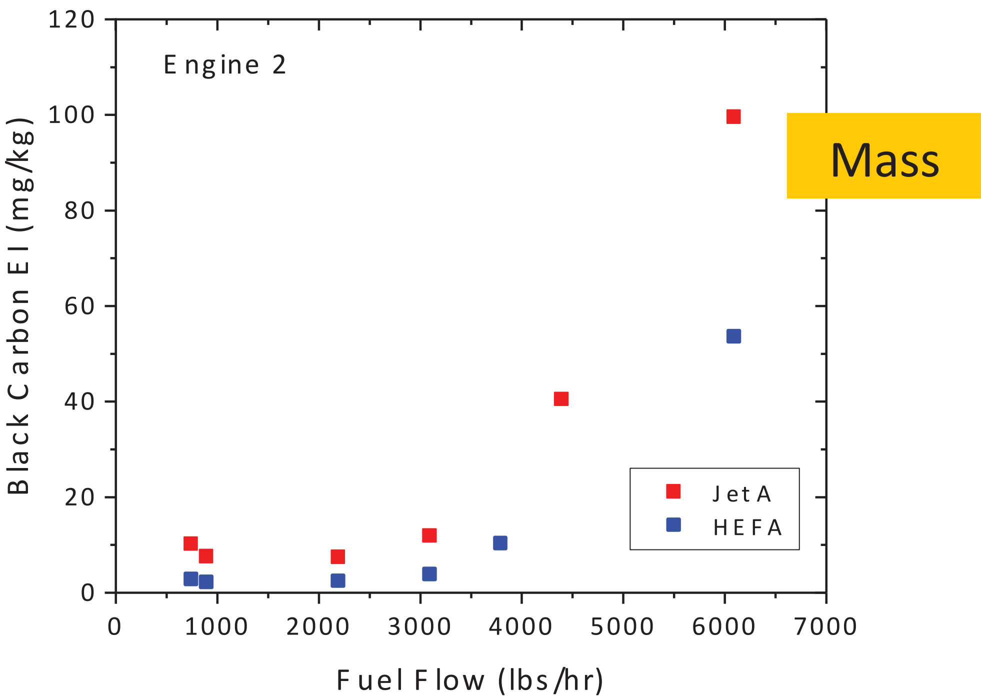


# Preliminary Results from ACCESS II Ground Emissions Test


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



# 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