

# Overview of Low Emission Combustion Research at NASA Glenn

D. R. Reddy

*Deputy Chief, Aeropropulsion Division  
Research and Engineering Directorate  
NASA Glenn Research Center*

ASME TURBO Expo 2016  
Seoul, S. Korea  
June 13 – 17, 2016

# Impacts of Aviation Challenges

***In 2008, U.S. major commercial carriers burned 19.6B gallons of jet fuel, and DOD burned 4.6B gallons. At an average price of \$3.00/gallon, fuel cost was \$73B***

*More than 250 million tons of CO<sub>2</sub> released into the atmosphere each year in U.S.*



*LTO Nox emissions affect local air quality - 40 of the top 50 U.S. airports are in areas that do not meet EPA local air quality standards*

*Aircraft noise continues to be regarded as the most significant hindrance to system growth*



*Since 1980 FAA has invested over \$5B in airport noise abatement programs in homes*

*In 2007, aircraft in the U.S. spent 213 million minutes taxiing and in ground holds – delays cost industry and passengers \$32.9B*



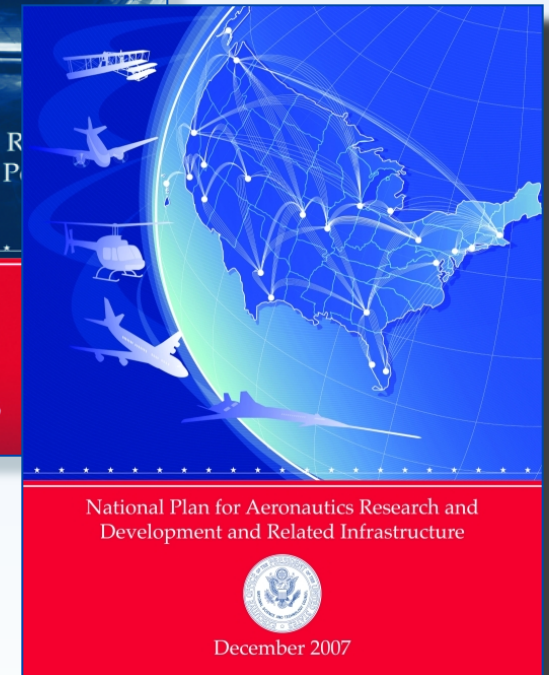
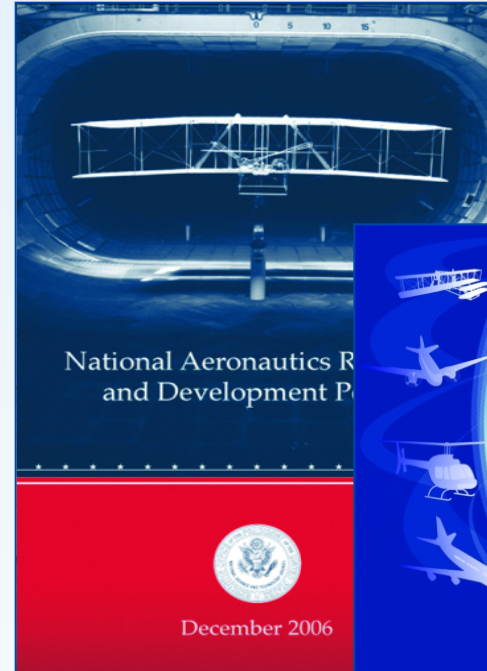
# U.S. Aeronautics Policy and Plan

- Policy

- Executive Order signed December 2006
- Outlines 7 key principles to follow in order for the U.S. to “maintain its technological leadership across the aeronautics enterprise”
- **Mobility**, national security, **aviation safety**, security, workforce, **energy & efficiency**, and **environment**

- Plan (including Related Infrastructure)

- Plan approved by Pres. Bush December 2007
- Goals and Objectives for all basic principles (except Workforce)
- Summary of challenges in each area and the facilities needed to support related R&D
- Specific quantitative targets where appropriate
- Detailed plan published in 2008; to be updated biennially





# NASA Subsonic Transport System Level Metrics

## Strategic Thrusts

1. Energy Efficiency

2. Environmental Compatibility



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	-71 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 <sup>‡</sup> (rel. to 2005 best in class)	-33%	-50%	-60%

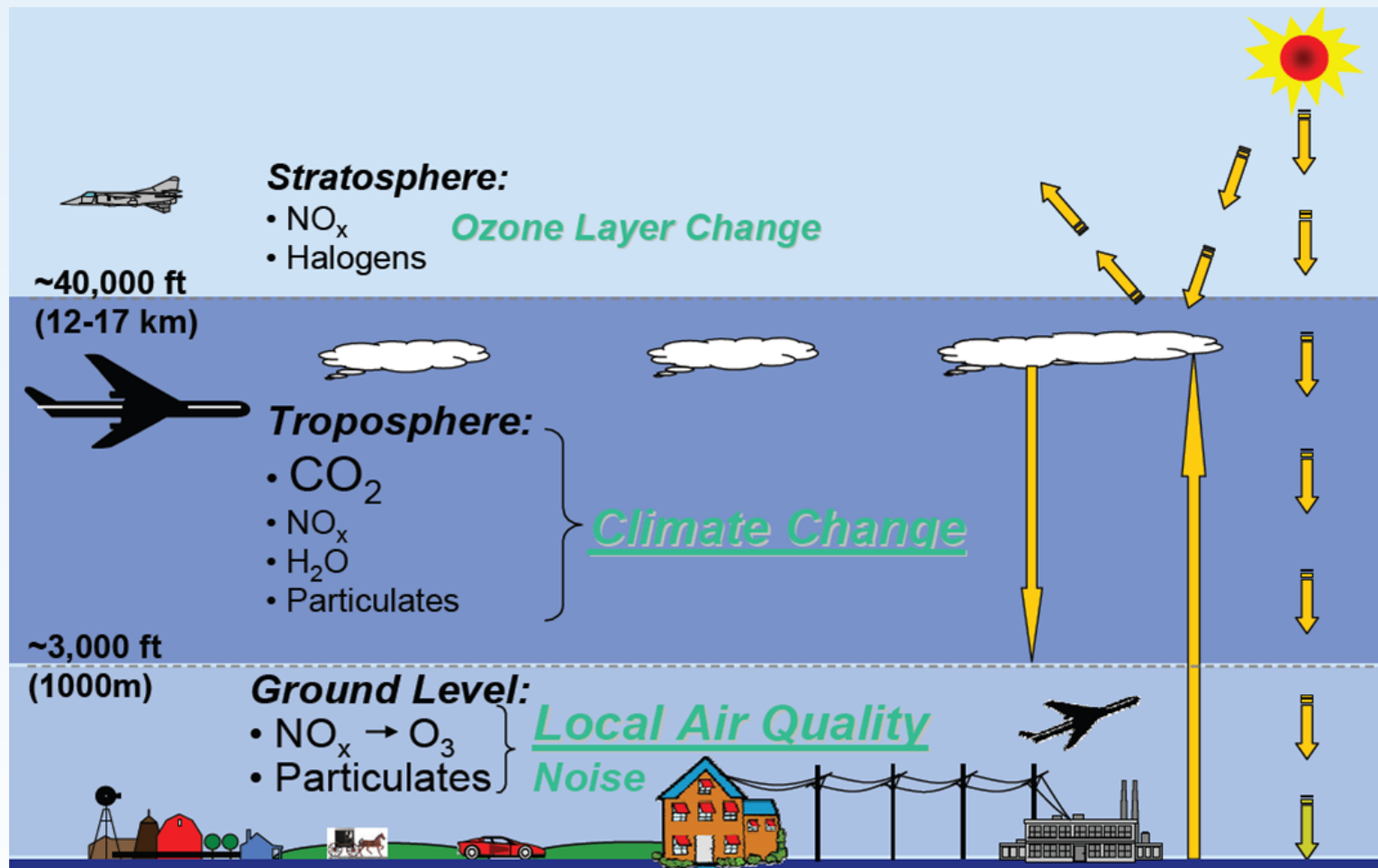
\* Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines, N+2 values are referenced to a 777-200 with GE90 engines

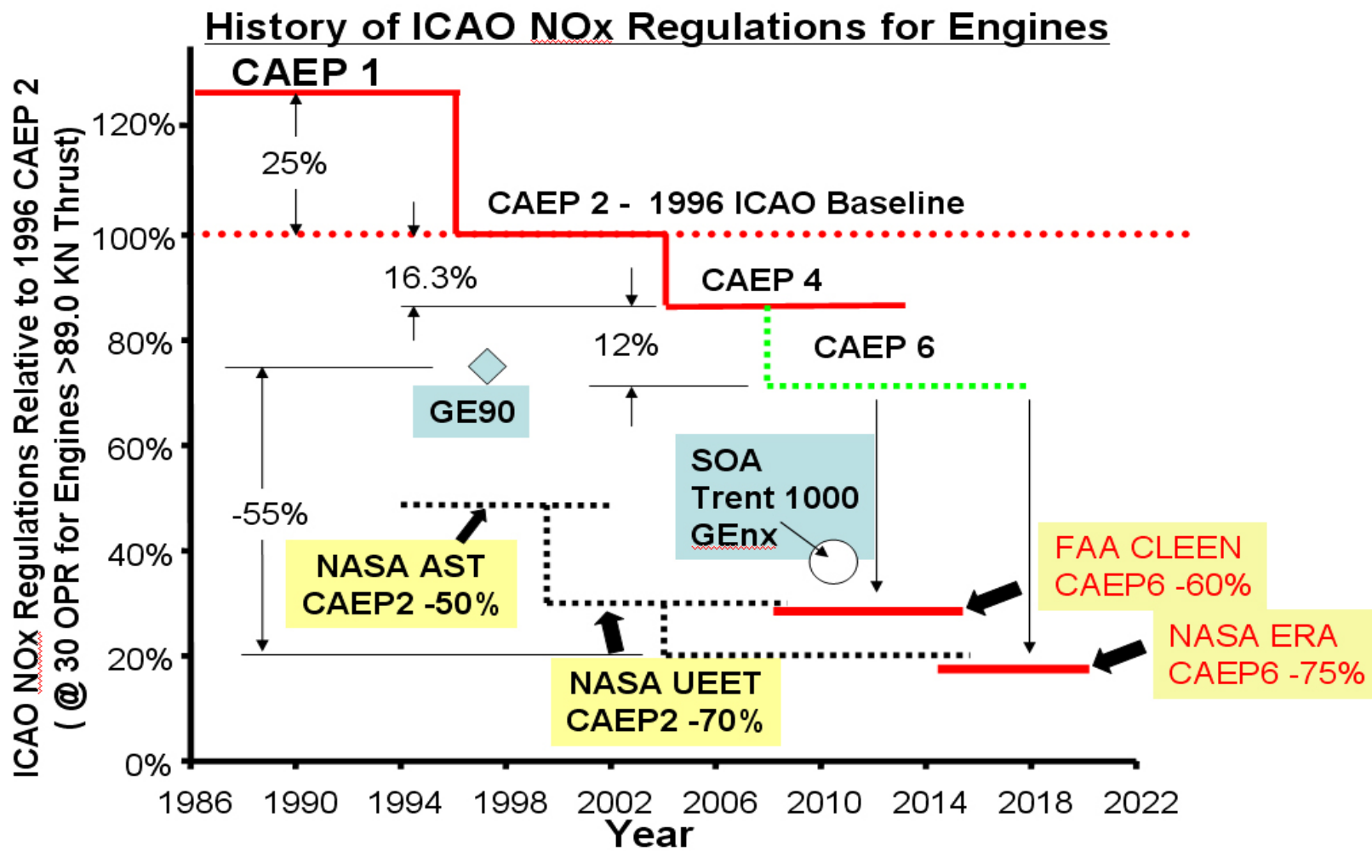
\*\* ERA's time-phased approach includes advancing "long-pole" technologies to TRL 6 by 2015

‡ CO<sub>2</sub> emission benefits dependent on life-cycle CO<sub>2e</sub> per MJ for fuel and/or energy source used

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

# Impact of Aviation on The Environment

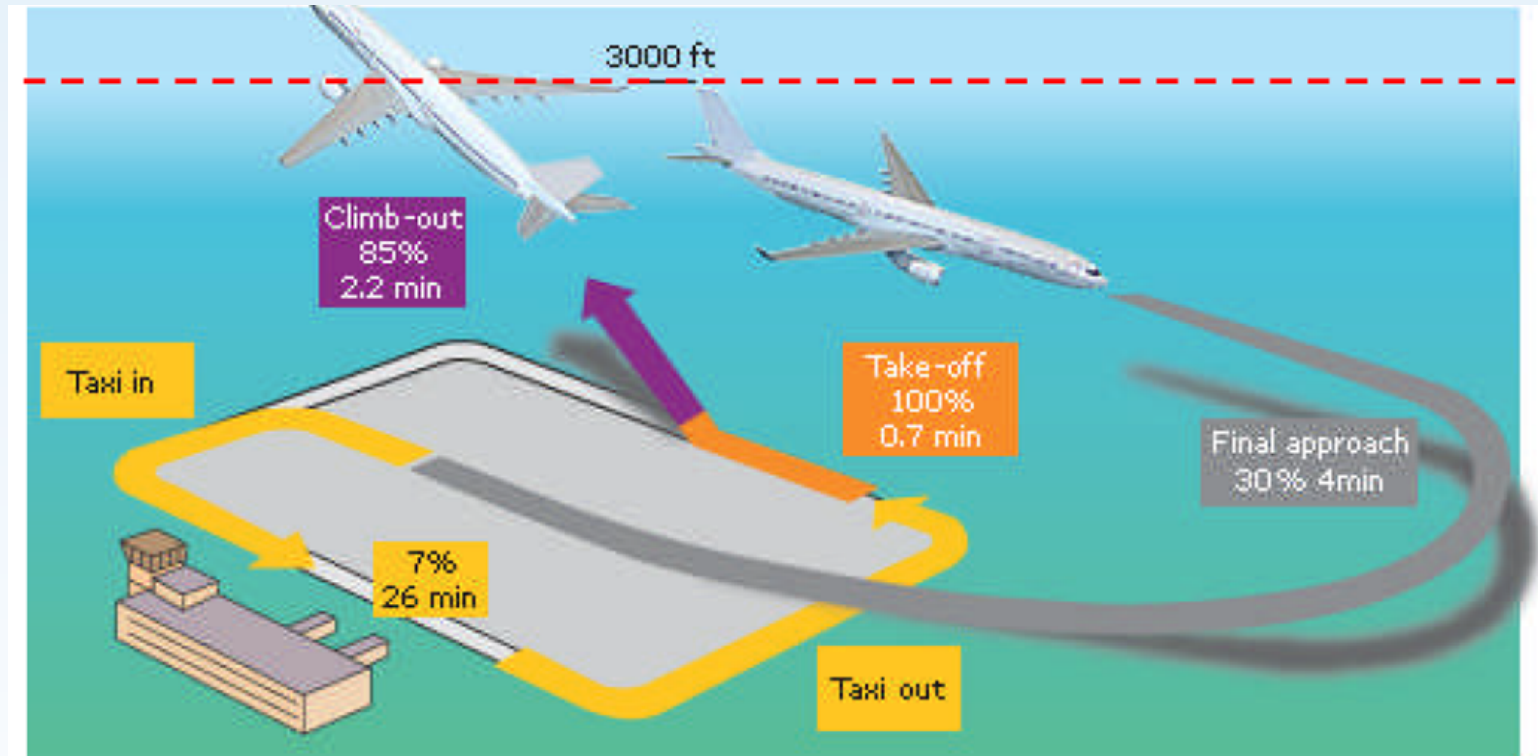




## History of NO<sub>x</sub> Regulations



# Emissions Regulations Driven by LTO Cycle



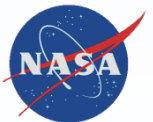
$$\text{LTO Parameter} = \Sigma (\text{Fuel Flow} * \text{EI} * \text{Time}) / \text{Rated Thrust}$$

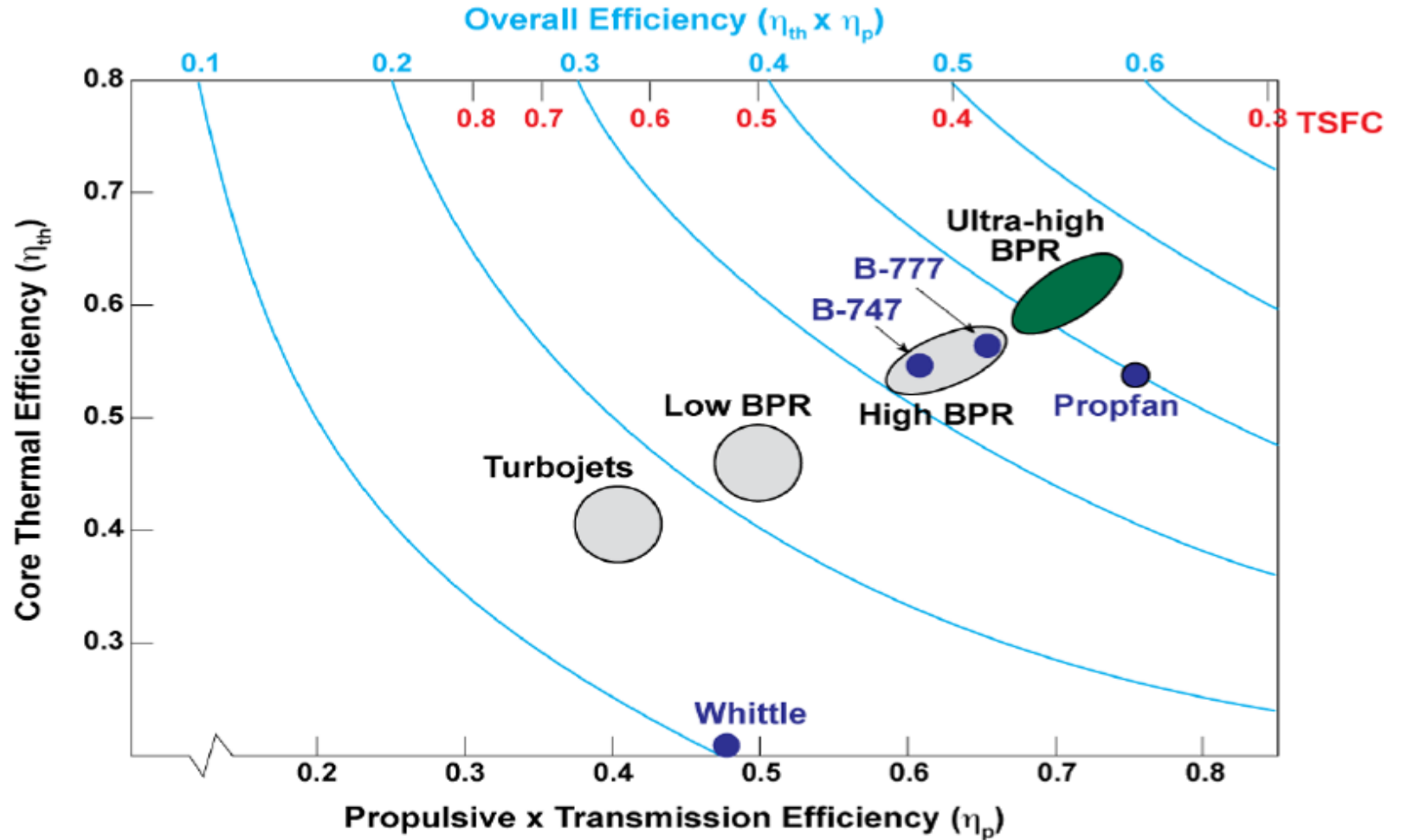
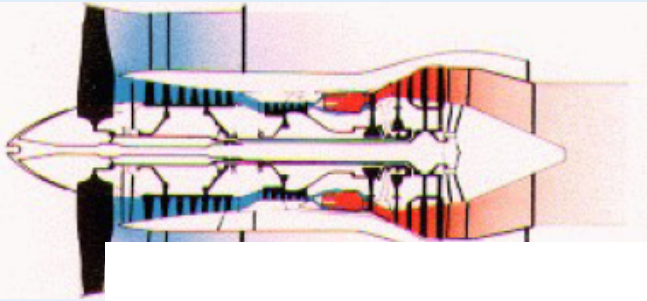
LTO Cycle  
Fuel Burn

Combustor Technology  
and Cycle (T3,P3,f/a)



imagination at work



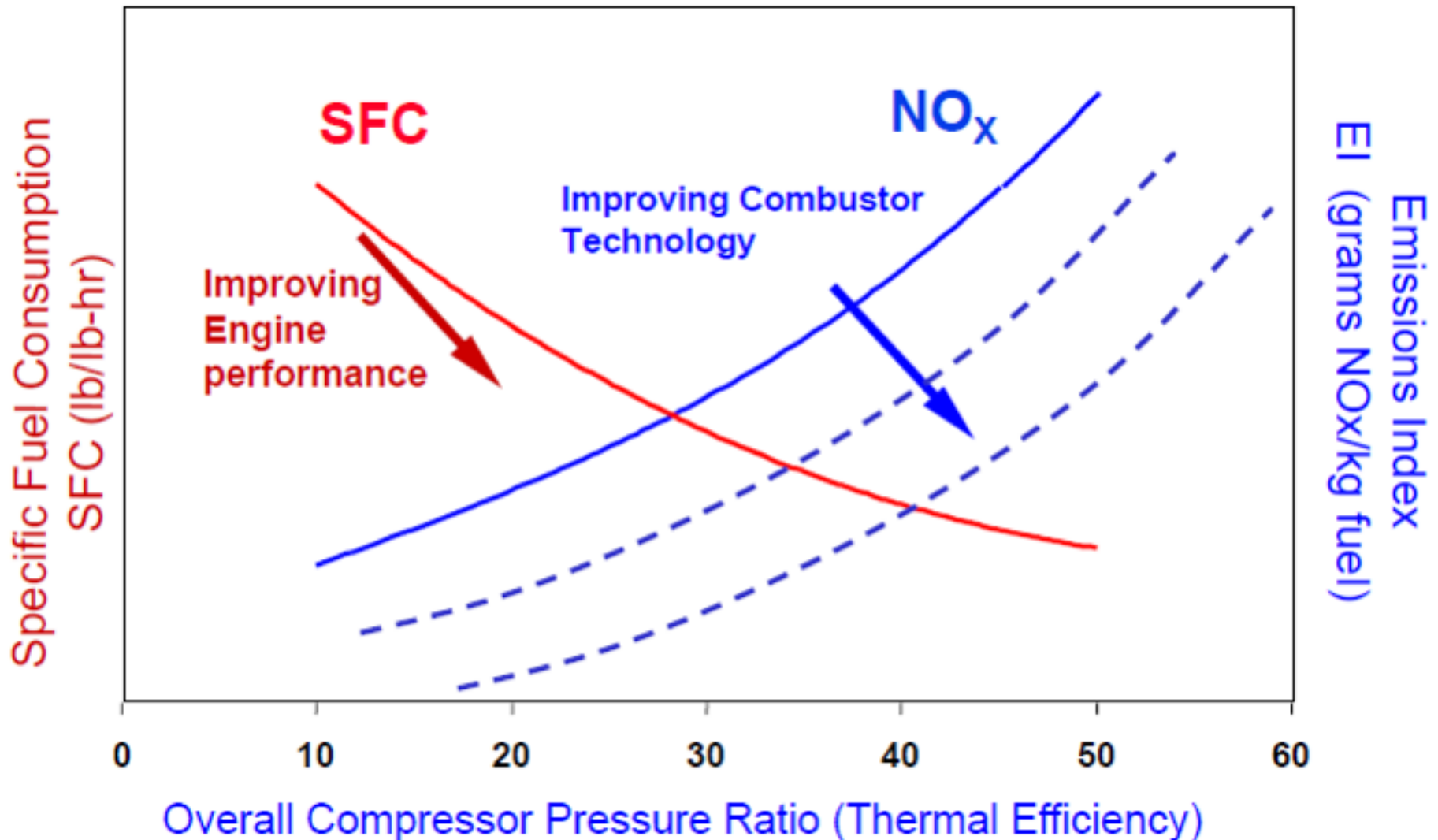


Alan Epstein (P&W)

## Gas Turbine Engine - Historical Efficiency Trends



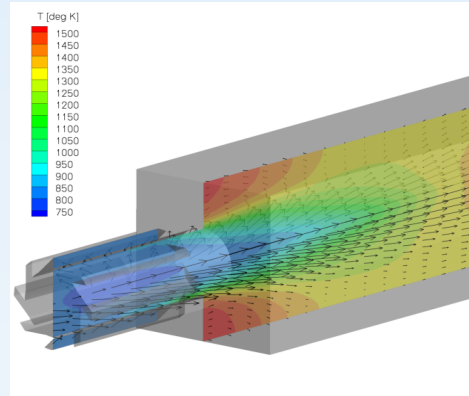
# Trading Performance & NO<sub>x</sub> Reduction



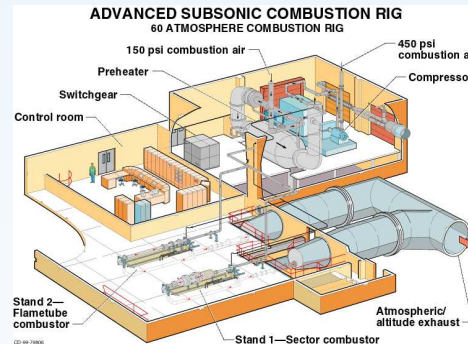
# Combustion Branch (RTB)

## Current Research Areas

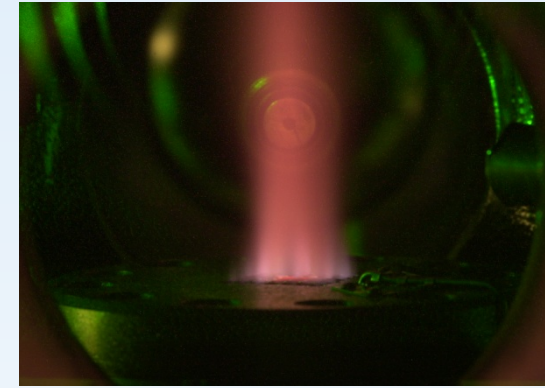
- Low Emissions Combustor Development and Testing
- Alternative Fuel Research
- Combustion Generated Particulate Measurement
- Laser Diagnostics Measurements in Combustion Environments
- National Combustion Code Development and Application
- Active Combustion Control
- Chemical Equilibrium with Applications Code and Thermodynamic Database
- Constant Volume Combustion Cycle Engine



Reacting Flow CFD Predictions



60 atm combustor test facility with laser diagnostics

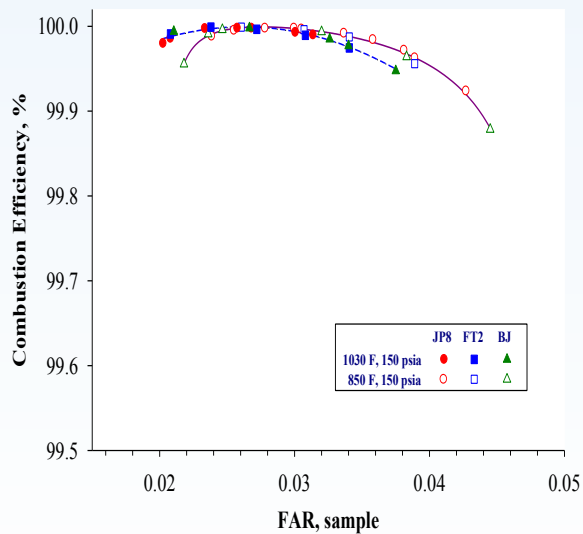
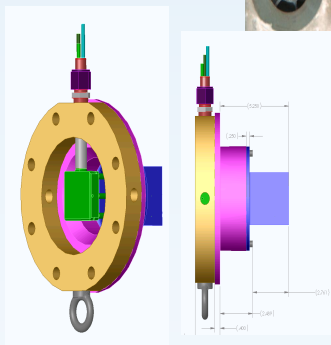
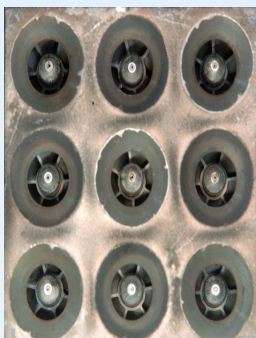


Spontaneous Raman Scattering Laser Diagnostic Development

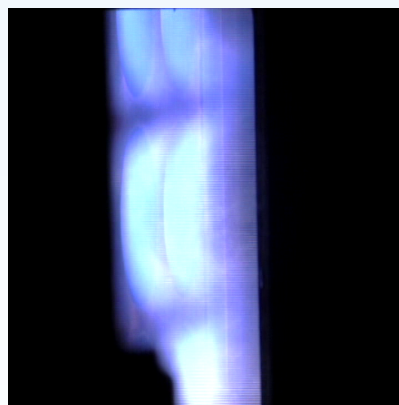
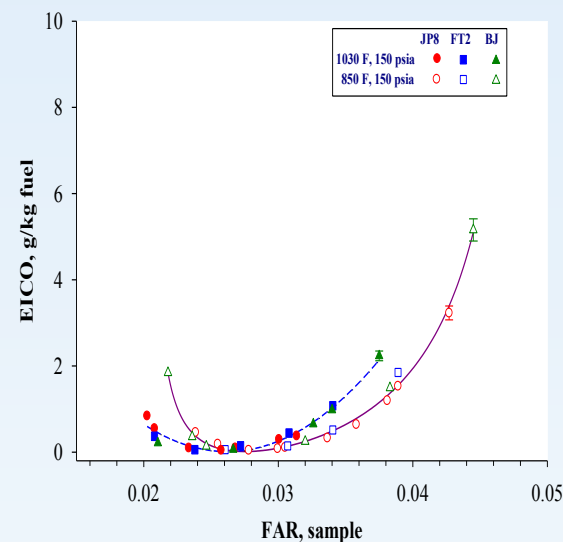
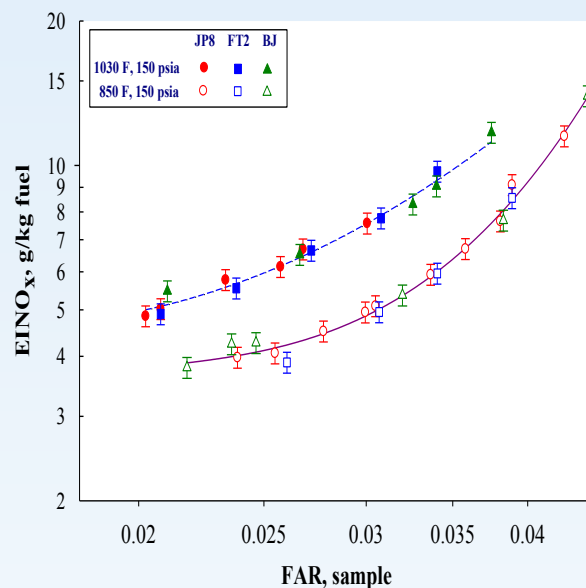


Alternative Fuel Reactor

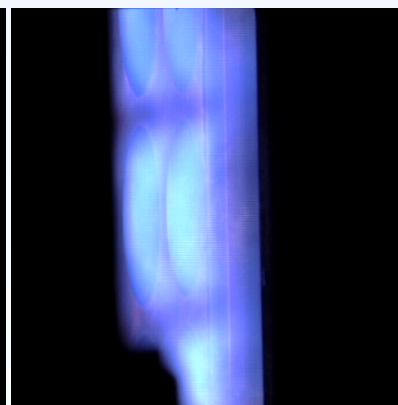
# 9-Pt LDI Injector



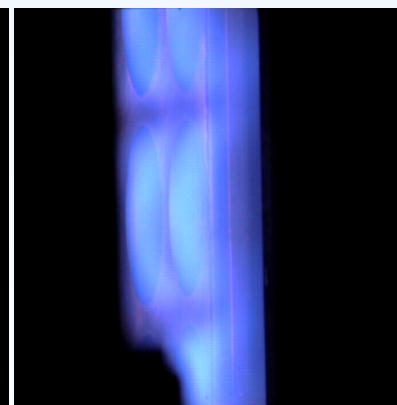
# JP-8 / F-T / Biojet Fuels



JP-8



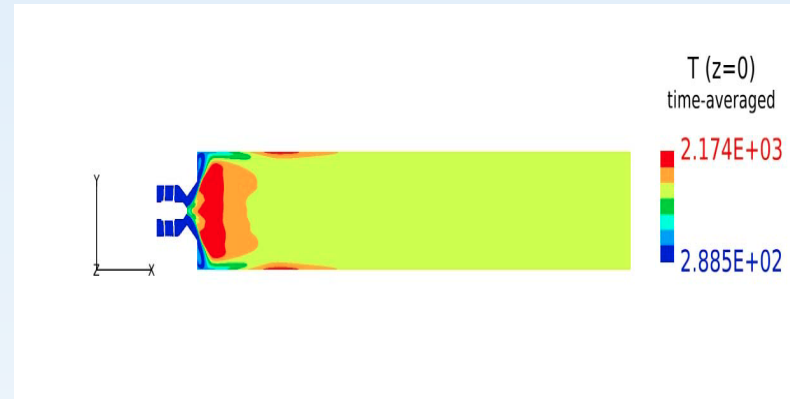
JP-8 / F-T



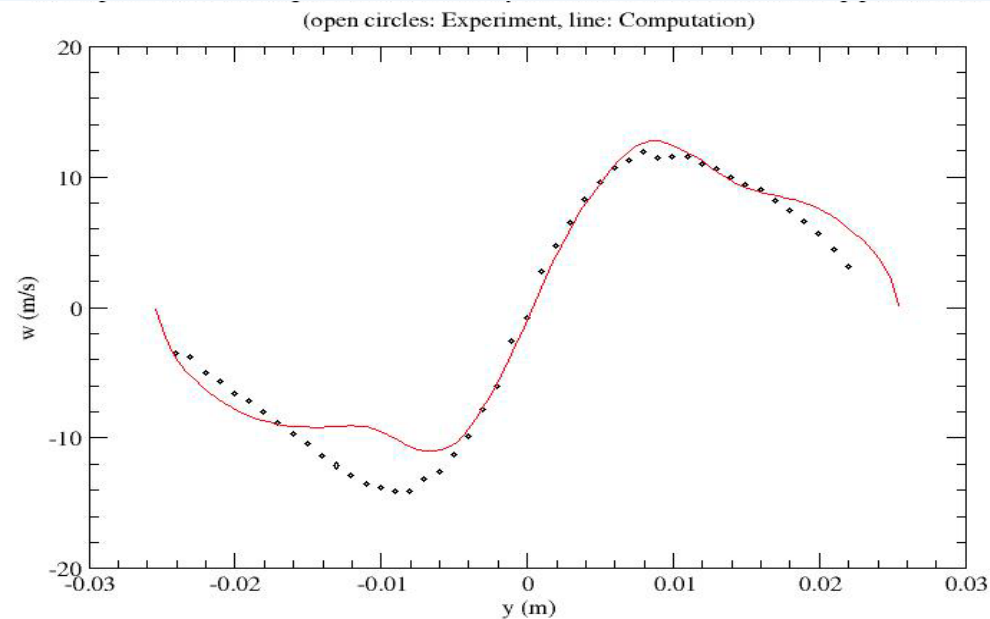
F -T

# CE-5B Medium-Pressure Flametube Testing

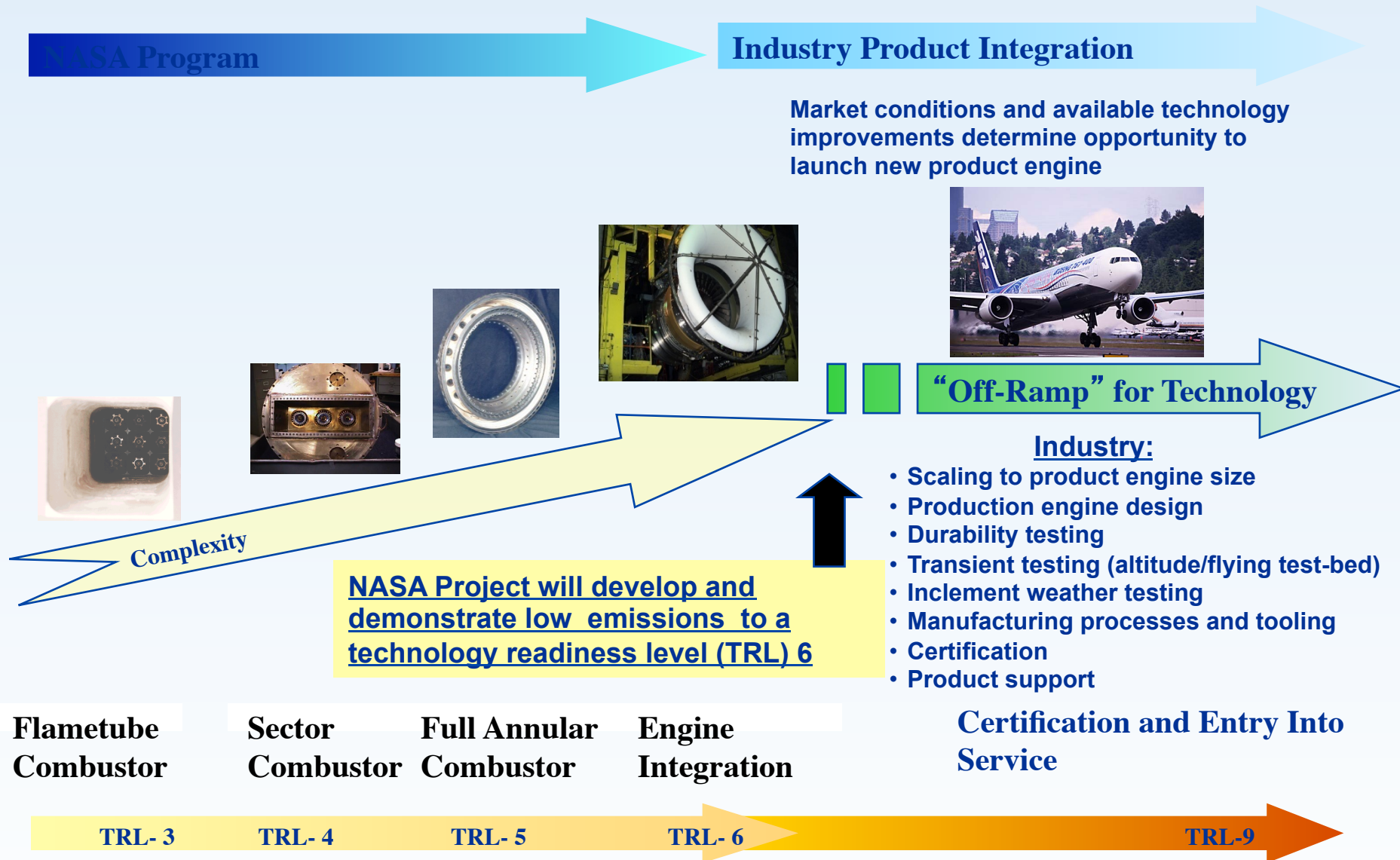
# Computed Temperature Distribution in the Center Plane: Time-Averaged



## Radial Profile of Averaged Azimuthal Velocity (46 mm Downstream of the Dump Plane)

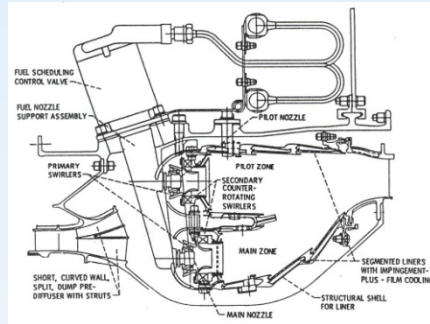
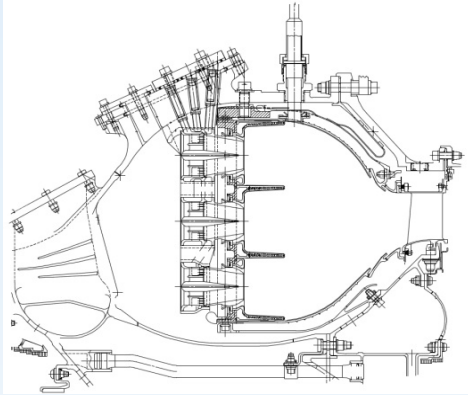


# Emissions Reduction - Technology to Product Transition

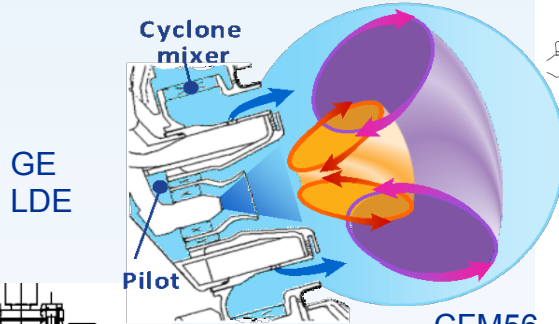
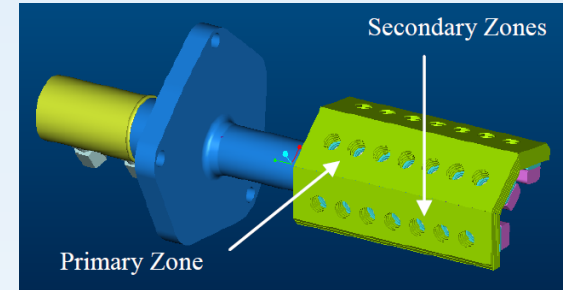


**NASA and Industry Partnership for Low-Emission Combustor Technology Development Followed by Possible Industry Certification and Product Implementation**

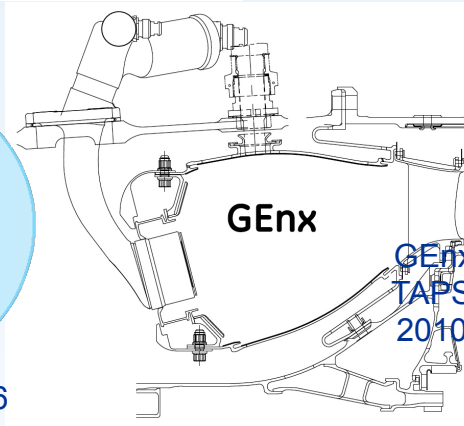
# Limitation of Combustor Pressure on Combustor Concept



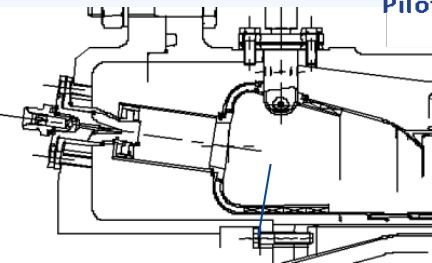
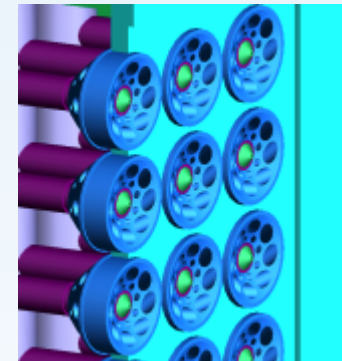
GE90  
DAC  
1995



CFM56  
DAC  
1995



GEnx  
TAPS  
2010



Lean Premixed

NASA  
ECC

Lean Partial-Premixed

NASA AST

NASA  
N+2

Lean Direct Injection

NASA  
N+3

OPR

25

35

45

55

65

75

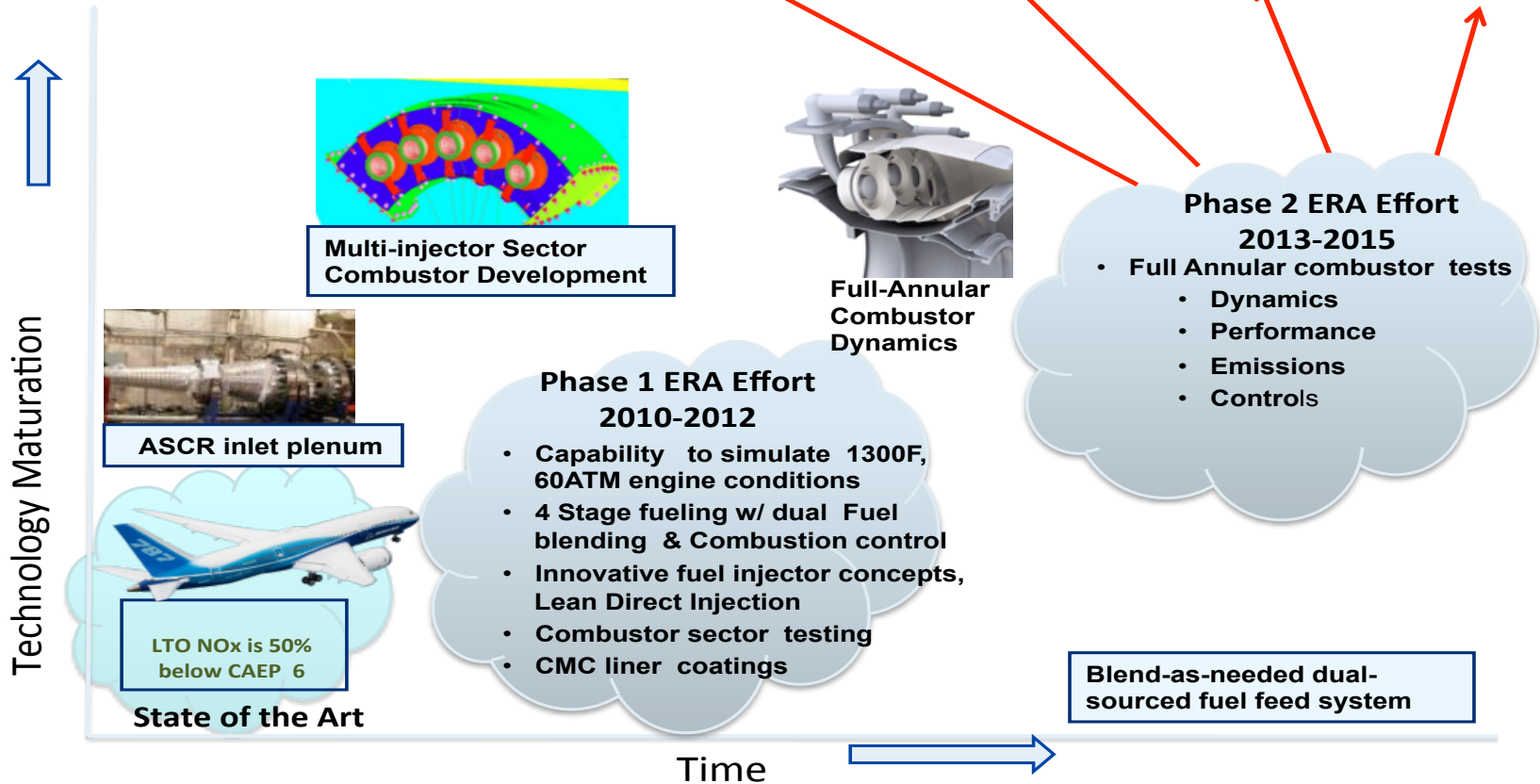


# Technology Transition Map

## Low Nox, Fuel-Flexible Combustor Technology

Objective: Reduce LTO NOx 75% from CAEP6

Potential Engine Product Development opportunities



## NASA ERA Project Combustor Technology Roadmap

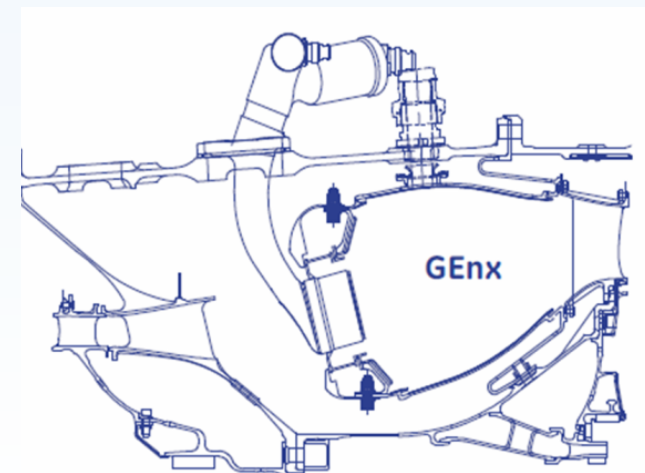
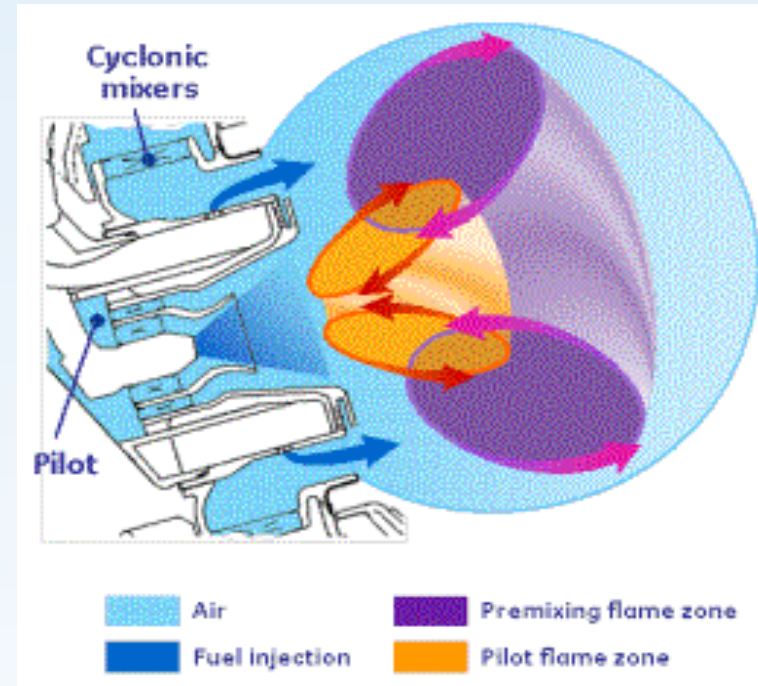
# GE Advanced Low NOx Combustor Technology

## GE combustor concept:

- Advanced TAPS, SAC architecture similar to GENx
- Increased mixer air flow split > GENx (~70%)
- CMC liner materials
- Variety of main fuel injection concepts – improve jet penetration and mixing:
  - Co- and counter-rotating mixer vanes
  - Injection locations
  - Jet penetration improvement via aerodynamic and mechanical means

## GE N+2 program:

- Concept development:
  - CFD analysis leading to multiple single cup test rigs and 5-cup CMC sector testing
- Enabling technology work:
  - Advanced mixer diagnostics
  - Active combustion control
  - Advanced igniter development
  - CMC materials maturation



# Flame tube rig concept evaluation & down select

- Combustion dynamics further assessed in a tunable combustor acoustics rig
- High power emissions & autoignition boundaries assessed in High T/P flame tube rig

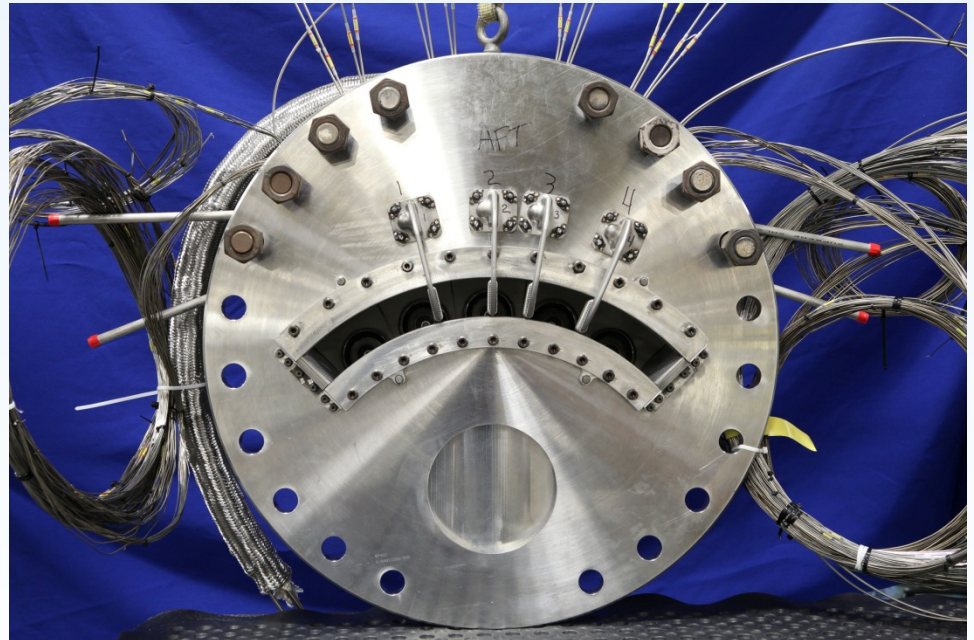
→ M4F1 chosen as best balance between NO<sub>x</sub>, efficiency, autoignition, and dynamics

TCA/HTP Configs	FT Normalized EINO <sub>x</sub>	FT P4' p-p Ranking 1=Best	FT Cruise Eff. Ranking 1=Best	TCA P4' p-p Relative to max limit	HTP Normalized EINO <sub>x</sub>	HTP A/I margin Relative to limit
M6F6	0.512	1	3	-	0.343	-
M1F2	0.8	3	2	>		
M4F2					1.07	-
M4F1	1.509	2	1	<	0.72	+

# Sector rig testing at ASCR

## GE 5-cup sector:

- 1<sup>st</sup> CMC liner sector rig
- 4 sample rakes (16 ganged sample points) on cups 2,3,4
- Data collected at 7%, 30%, Cruise, & near 85 and 100% ICAO points



# GE Low-NOx Combustor achieves <25% CAEP/6 NOx

## GE 5-cup sector results:

- Highest pressure data extrapolated up to 85, 100% ICAO points
- Performance indicates better than 75% reduction below CAEP/6 standards
- Cruise NOx 60-70% reduction below state-of-the-art TAPS combustor
  - >99.9% efficiency at cruise

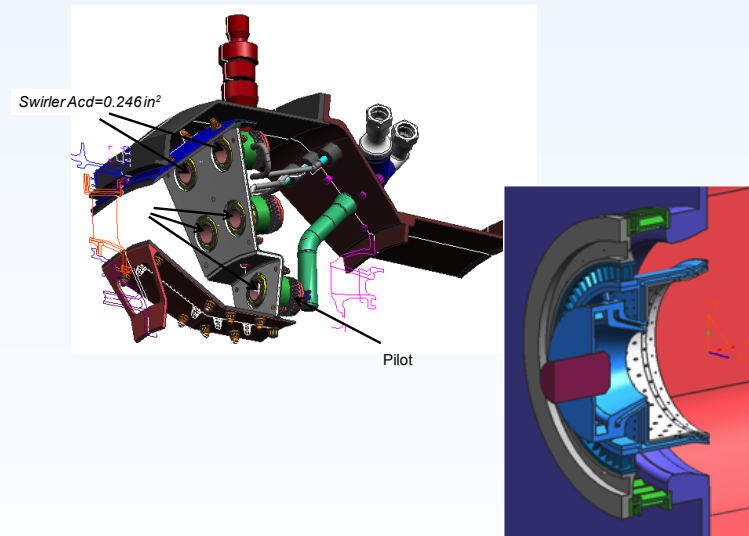
% ICAO	Time [min]	EINOx	dp/Foo	% CAEP/6
100	0.7	17.6	20.6	18.9
85	2.2	7.9		
30	4	13.2		
7	26	5.8		



# PW Conceived Several Concepts to Achieve Low NOx

*Build on significant PW experience*

- Continued development of PW TALON X Combustor Technology
  - Emissions on par with all current technologies
  - Simple, cost effective, low weight design
  - Uniform exit temperature
  - Robust operability
- Investigation of staged technologies
  - Axially Controlled Stoichiometry (ACS) combustor
  - Offers next step reduction in emissions, built on Talon X experience.
  - Demonstrated low acoustic operation

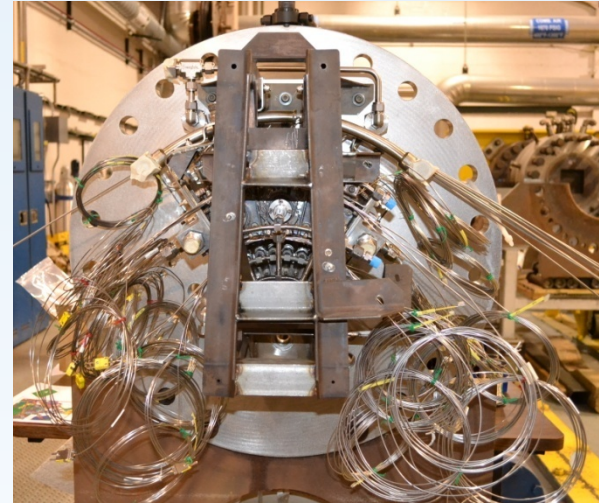




# ACS Development, Advanced Analysis, CFD, and Testing

## *Downselect after Single Nozzle Rig Testing*

- Improvements made to baseline concepts
  - Mixing and piloting emphasized
  - CFD validated as design tool
- Single nozzle rig tests evaluated emissions potential
  - Acoustic characteristics
- Sector rig fabricated for testing at PW/UTRC and NASA
  - Good correlation between UTRC and NASA results

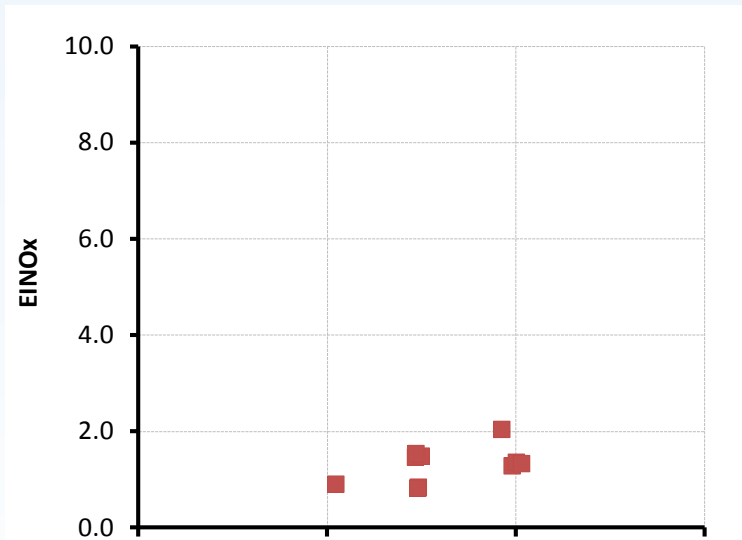


## Combustor Performance at High P,T Met Phase I Goals

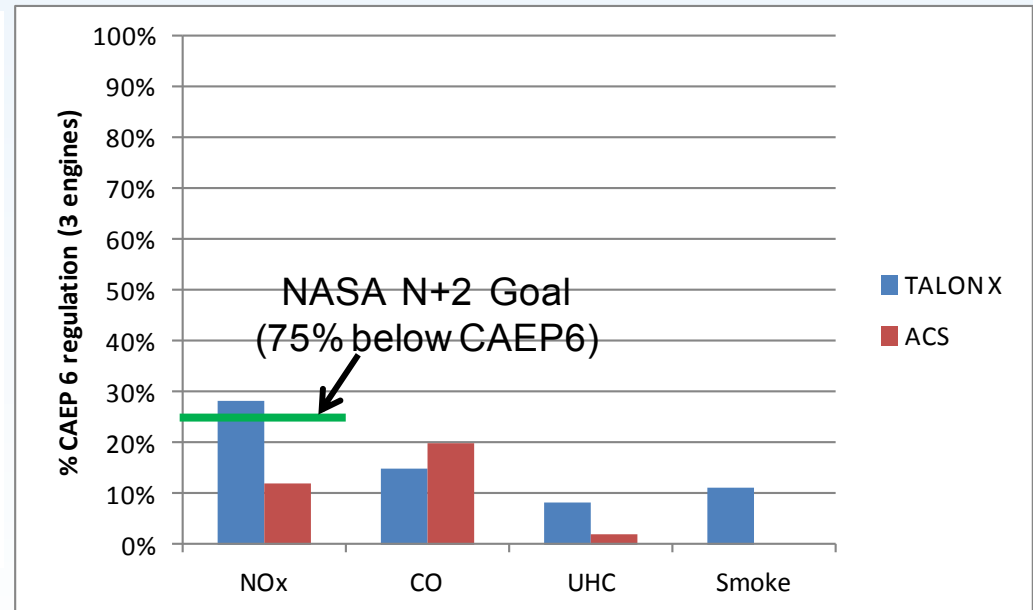
*Significant NOx margin for development – >75% below CAEP6*

- ACS emphasizes PW expertise and experience
  - Packaging allows for potential retrofits
- Testing of 3-sector rig at NASA validated potential
  - 88% Margin to CAEP 6, Cruise NOx with margin to 5 EI
  - Improved TALON X achieves 72% Margin to CAEP6

Cruise NOx in a N+2 Cycle



% CAEP6 LTO Emissions in a N+2 Cycle



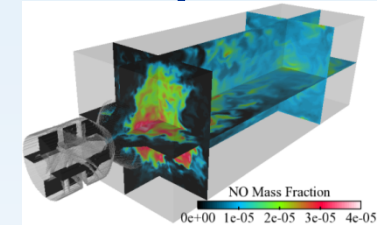
# Combustion – Future Directions

**Low Emissions Fuel Flexible Combustors for Subsonic and Supersonic transport - Particulate, aerosol, contrails in addition to Nox - Need advanced CFD Modeling tools and advanced concept development**



- **Advanced Combustion CFD Model Development**

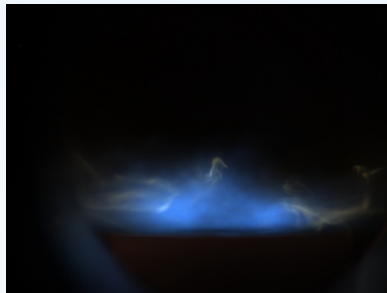
- **CFD Code Validation Experiments**



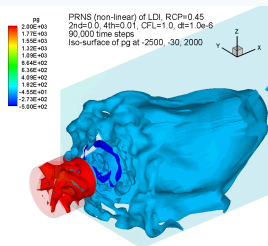
- **Advanced Fuel Flexible Low Emission Combustion Concept Development and Testing**



- **Alternative Fuel Characterization**



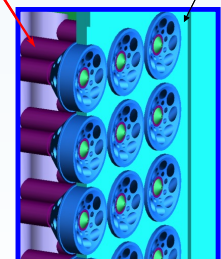
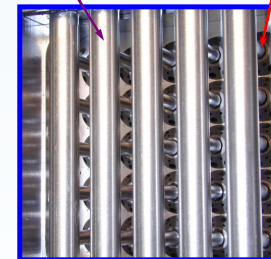
- **Combustion Flameholding for High Speed Applications**



Fuel Manifold with Heat Shield

Fuel Tube with Heat Shield

Face Plate



# Summary

- NASA Played a Significant Role in Advancement of Low Emission Combustion Technology
- Dramatic reduction of emissions achieved through successful partnership with the industry
- Latest effort Demonstrated emissions goals ((75% LTO of CAEP/6 and 70% cruise NOx reduction (2005 state-of-the art)) at the TRL 4 level - sector combustor
- NASA Glenn continues its key role to meet future propulsion performance and increasingly stringent environmental compatibility requirements

