National Aeronautics and Space Administration

# NASA Aircraft Gas Turbine Combustor Emissions Research

## Past, Present, and Future

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With thanks to K Ajmani, C Chang, J Klettlinger, C Lee, J Moder, R Moore, D Reddy, K Tacina

# Motivation

- History of aircraft emissions reduction follows along with the public desire and demand for clean air and water, and low noise around airports, which ultimately led to…

  …Regulations (national and international): EPA, FAA, ICAO CAEP, etc.

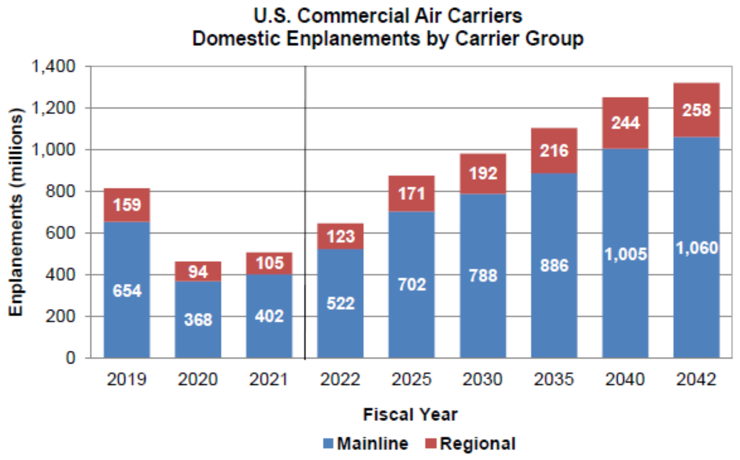
Other factors include:

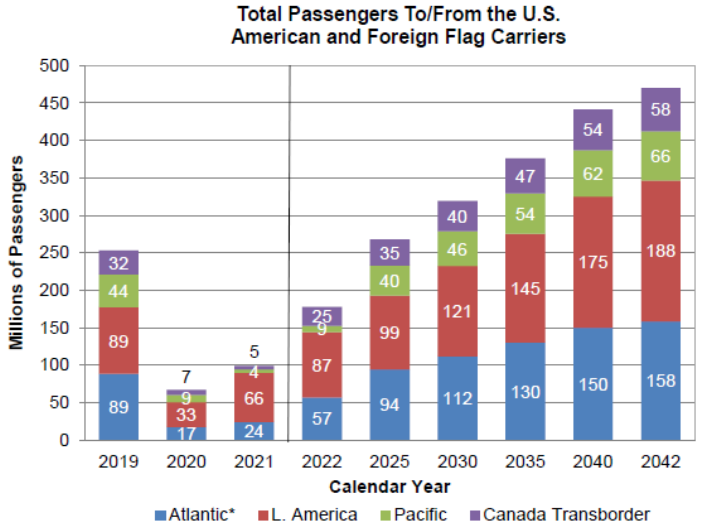
- Airlines, airframer/engine OEMs profitability
- More and more people around the world travel by air, which leads to more flights, therefore more total emissions from aircraft
- NASA is charged with pushing technology development to address national needs—advancing, collaborating, and transferring high-risk technology to the public and industry that are too risky or costly for them to do on their own

# NASA Research Objectives—Emissions

- Meet or exceed noise and **emissions** regulations, fuel burn ($CO_2$) goals for aircraft through the years
- Focus on large aircraft—single aisle with > 90 passengers and twin aisle. These are the planes that most people fly on and would have the greatest environmental impact. Collaborate with airlines, airframe, engine and fuel injector OEMs, other government agencies (OGA), and universities to meet these goals
- Per FAA, System traffic in revenue passenger miles (RPMs) is projected to increase by 5.7 per-cent a year between 2022 and 2042.

From FAA Aerospace Forecast Fiscal Years 2022-2042:



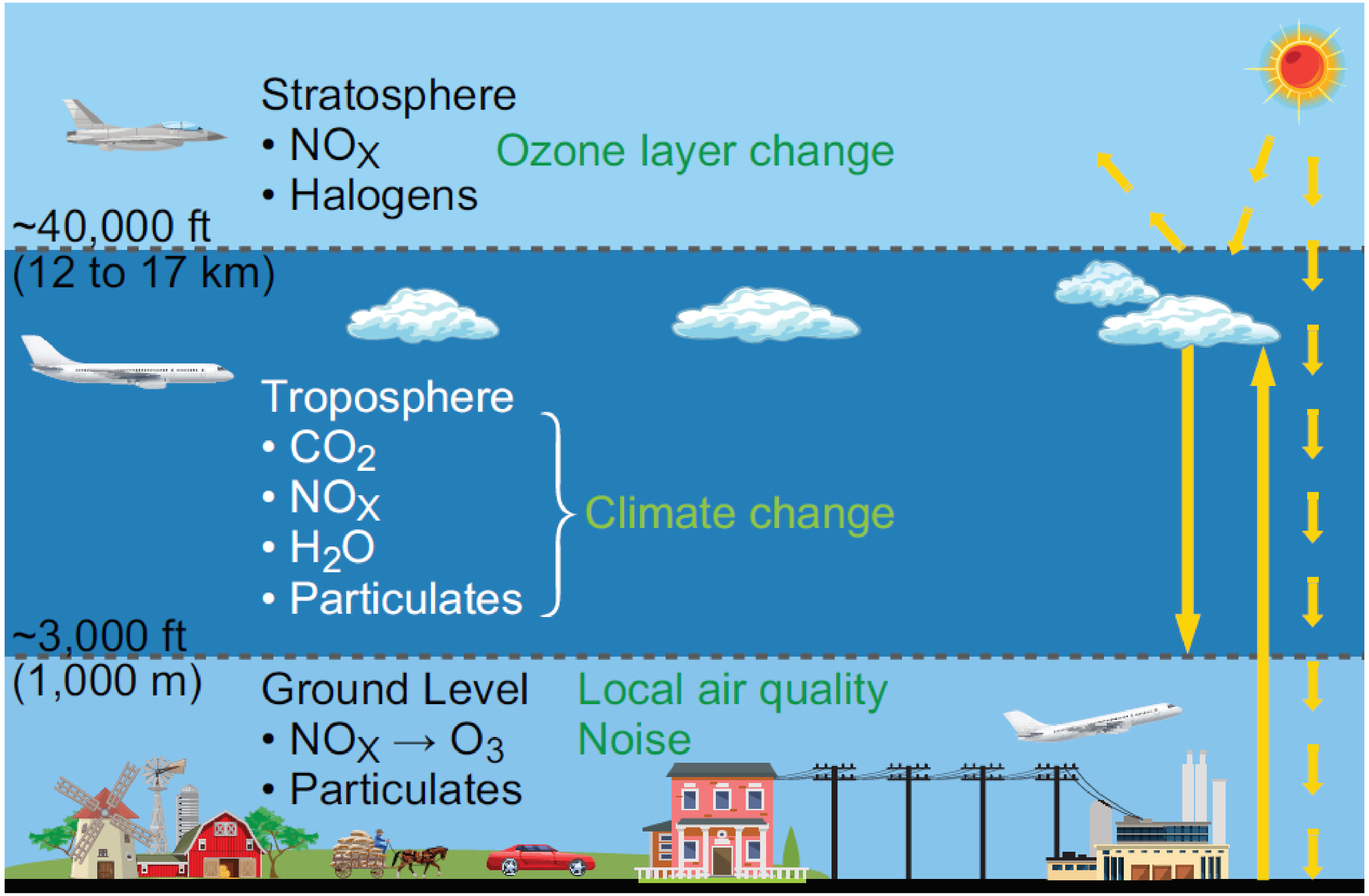




Source: US Customs & Border Protection data processed and released by Department of Commerce; data also received from Transport Canada
* Per past practice, the Mid-East region and Africa are included in the Atlantic category.

# NASA has historically led the effort to reduce aviation environmental effects

***For aircraft gas turbine engines***

- Reduce $NO_x$ emissions from future aircraft engines i.e., the combustors
- $NO_x$ emissions increase smog and ozone in the lower troposphere and decrease the protective ozone layer in the stratosphere.
- More recently, we have added soot and particulate matter to the list of concerning species
- Next generation aircraft will have greater thermal and propulsive efficiency to reduce fuel burn and hence combustion emissions of $CO_2$ , $H_2O$, $NO_x$ and particulates




Lee et al. 2021 notes that exhaust plumes contain gaseous sulfur compounds in addition to the major species and UHC
Aerosol particles serve as nuclei for ice and cloud condensation. Contrails from in low-temperature ice-supersaturated air.

# Outline

- ❖ Part 1. Background. A brief primer on aero engines and annular gas turbine combustors

- ❖ Part 2. Past GT Combustor research for reduced emissions. A historical look back with highlights

  ~ 1970 – 2015

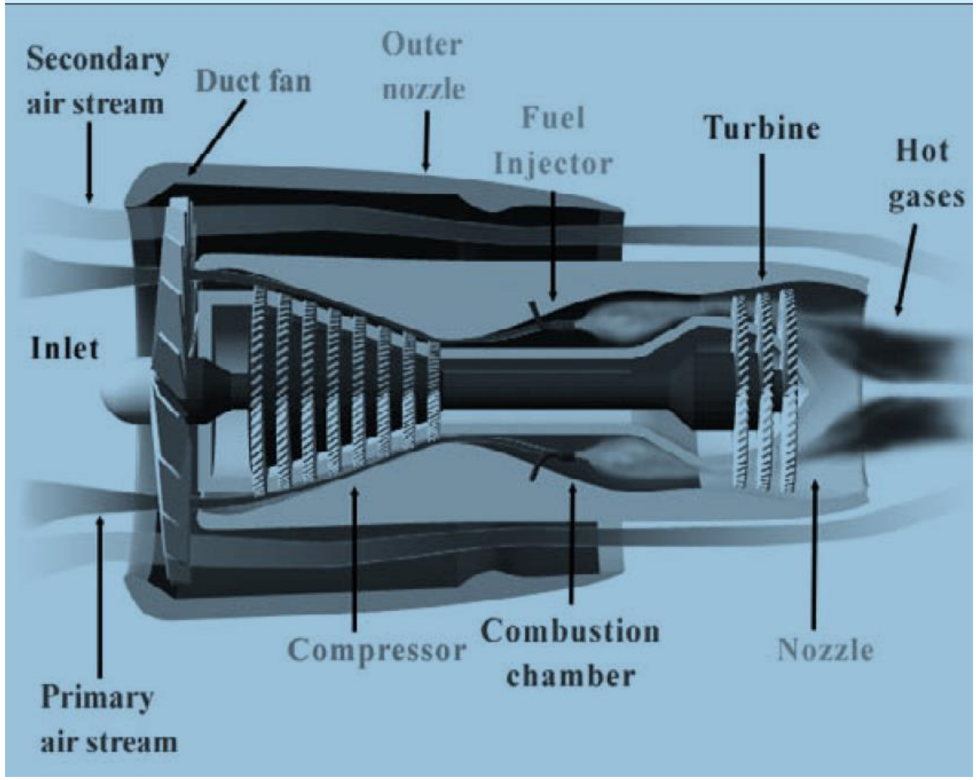
- ❖ Part 3. Present and future GT Combustor emissions-reduction research, from ~ 2015

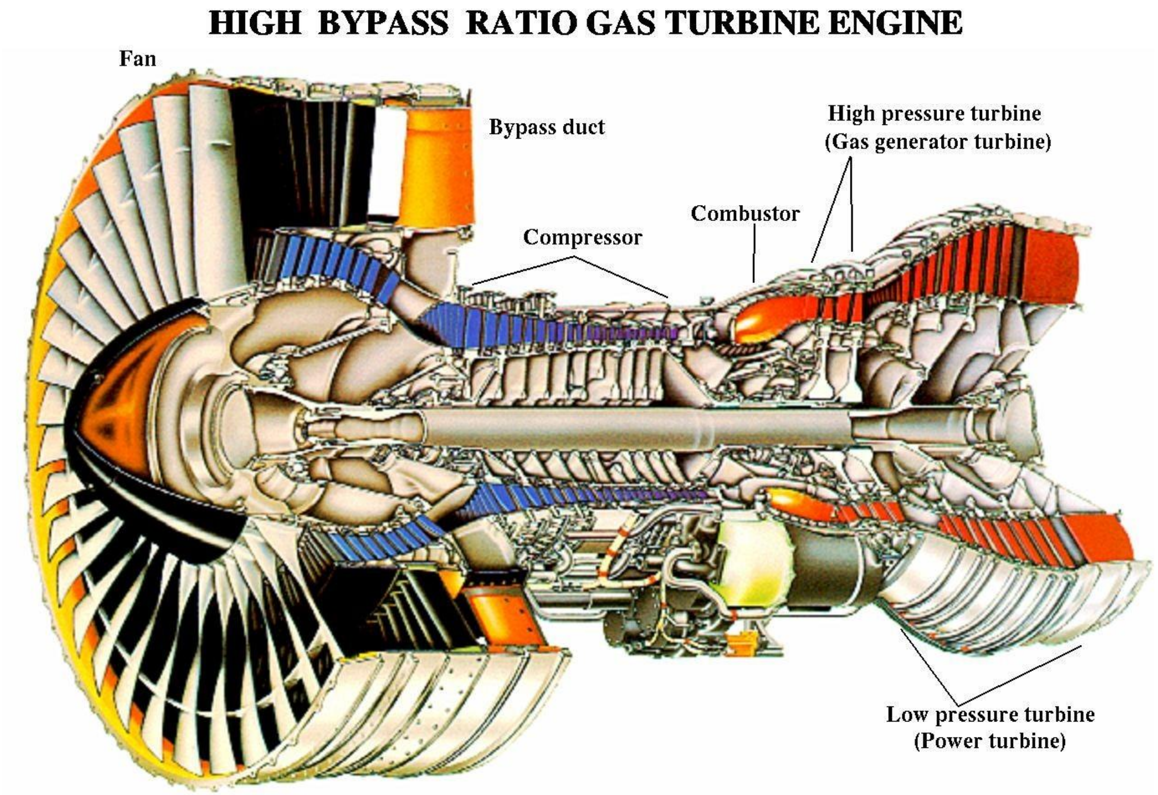
# Part 1  Background information

- Aero engines and annular gas turbine combustors
  - Combustor elements
  - Combustor design requirements
  - Combustor emissions
  - Emissions regulations

# Combustors in Aircraft Gas Turbine Engines

Cutaway view of a turbofan engine*

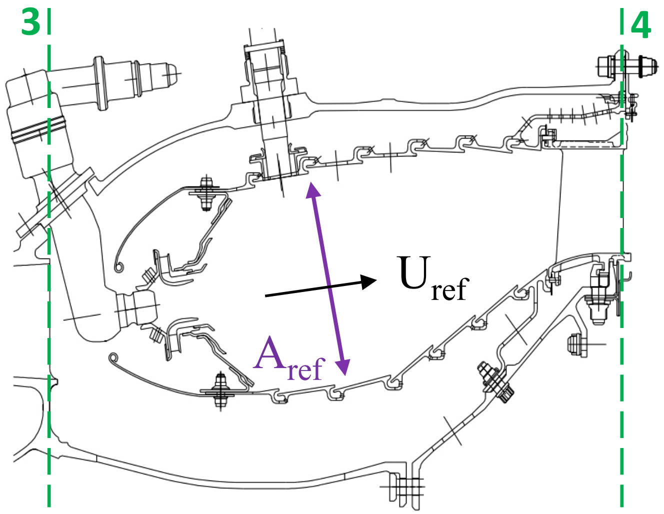


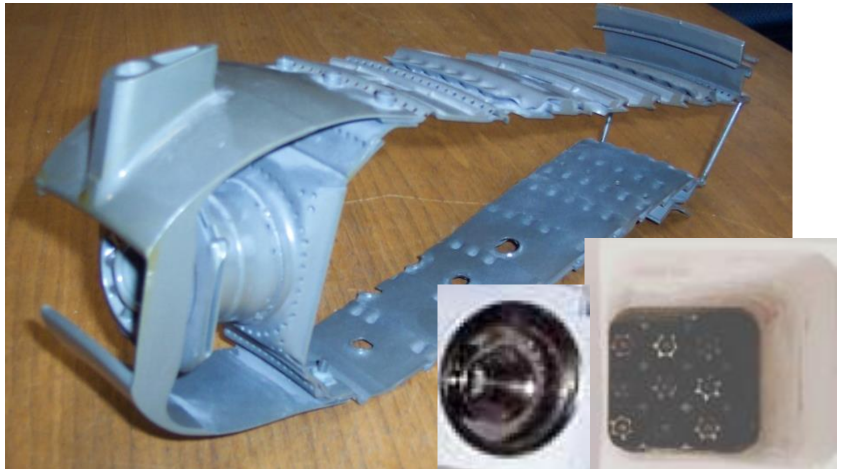




For more on aircraft engines, see

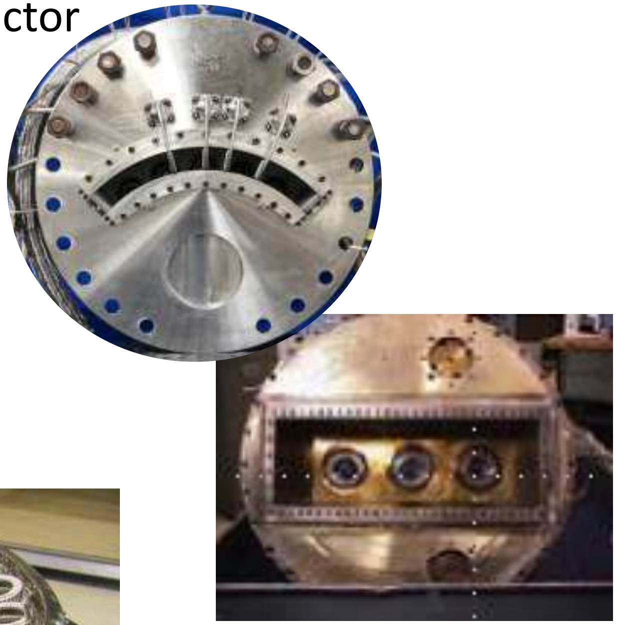
1. * "Pushing the Envelope: A NASA Guide to Engines" (2007). Publication EG-2007-04-013-GRC.
2. Mattingly (1996). *Elements of Gas Turbine Propulsion*, McGraw-Hill, Inc., New York.

# Some combustor terminology





Single cup combustor: flame tube

Multi-cup combustor: sector




A 22-cup full-annular combustor case

There also are dual annular combustors

- Stations 3 (inlet) and 4 (exit) define the combustor control volume for mass, temperature, pressure
- $\Delta P$ = combustor pressure drop = $P_3 - P_4$ ; typical % $\Delta P$ ~ 3 - 5
- Cold flow (unfueled, non-combusting) Reference Velocity $U_{ref}$: ~25-75 ft/s (7.6 – 22.9 m/s)



Upper left illustration from https://www.faa.gov/newsroom/continuous-lower-energy-emissions-and-noise-cleen-program#_Toc80621742

# Combustor Air Flow Parameters

Effective Area: $ACd = m_3 /(2P_3\Delta P/RT_3)^{0.5}$ (station 3 is combustor inlet)

where: $A$ = geometric flow area

$Cd$ = discharge coefficient

$\dot{m}_3, P_3, T_3$ = inlet air mass flow rate, pressure, temperature

$\Delta P$ = combustor pressure drop = $P_3 - P_4$ (station 4 - exit)

$R$ = gas constant

Corrected Flow: $\dot{m}_3^* = \dot{m}_3[(T_3/To)^{0.5}(P_0/P_3)]$

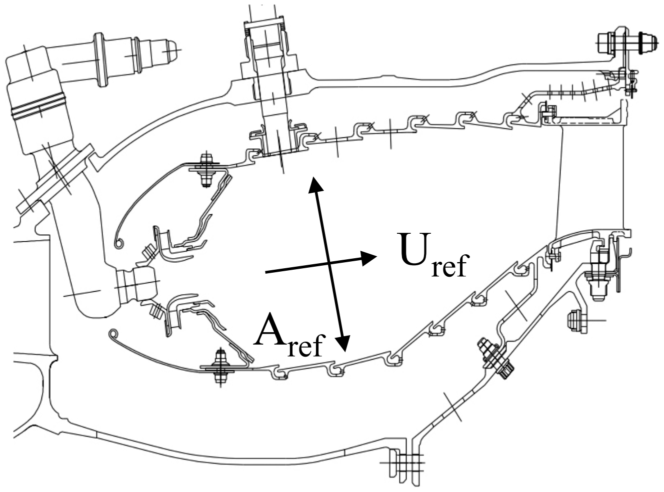
(different definitions on this)

To & Po sea-level static conditions

Reference Quantities:

$U_{ref} = \dot{m}_3 /(\rho_3 A_{ref})$ Reference Velocity ~25-75 ft/s

$M_{ref} = U_{ref}/(\gamma RT_3)^{0.5}$ Reference Mach Number

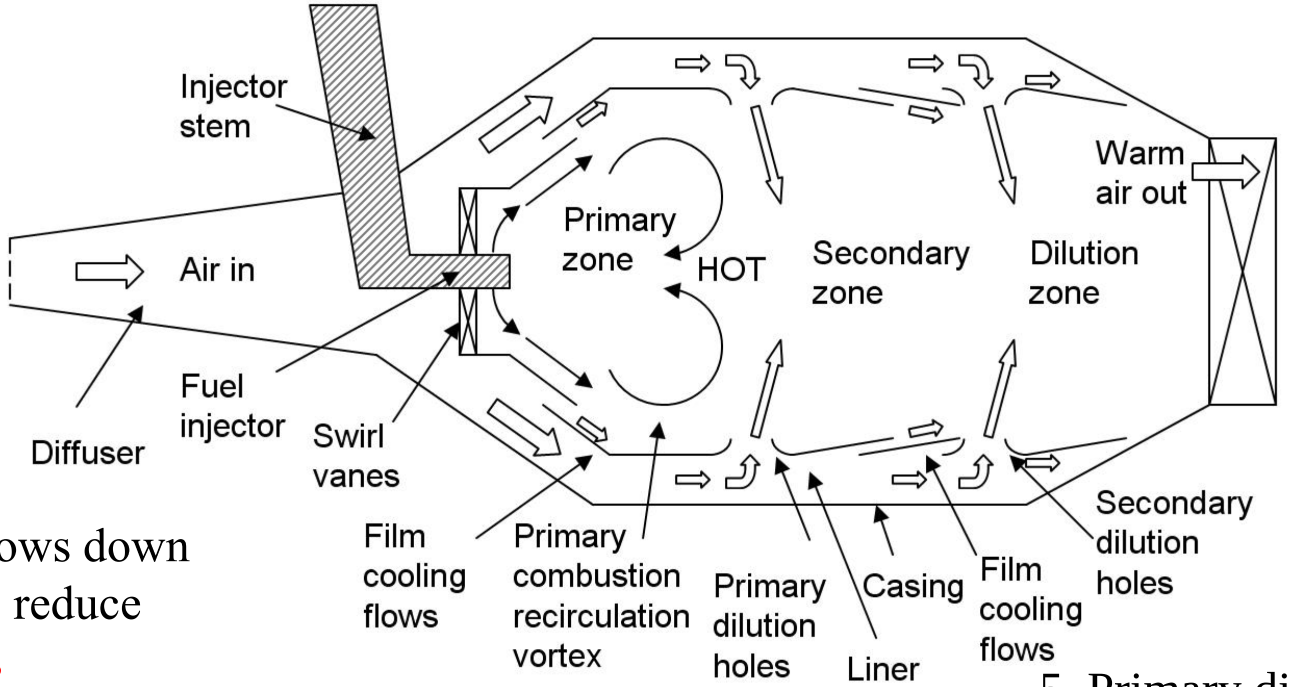


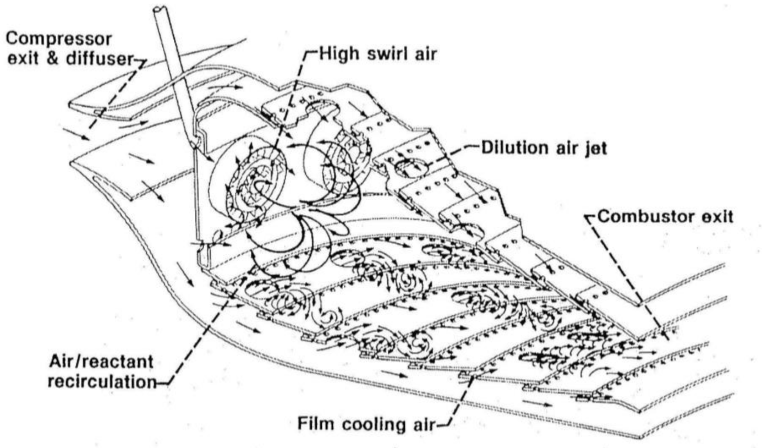

where: $A_{ref}$ = area at plane of maximum cross-section

$\rho_3$ = inlet air density

$\gamma$ = ratio of specific heats = ~1.4

# Legacy Combustor Features (prior to ~1980)




1. Diffuser slows down flow speed to reduce Rayleigh loss

2. Fuel-nozzle turbulence speeds up ***atomization*** by break up liquid into droplets

3. Liner film-cooling decouples thermal loading from pressure casing

4. Swirling flow forms recirculation vortex to provide ***flame-holding***

5. Primary dilution holes provide dilution and vortex anchor

6. Secondary dilution holes add more air to bring T4 down and shape $T_4$ profile

**We focus on fuel atomization/fuel-air mixing and primary zone combustion/flame holding**

# Combustor Design Requirements

## Desired Characteristics

- High Combustion Efficiency at All Conditions
- Reliable and Smooth Ignition at All Conditions, including Altitude Relight
- Wide Stability Limits from idle to cruise, i.e. High Turndown Ratio for fuel injection
- Insensitive to Pressure Perturbations and Acoustic Feedback
- Free From Combustion Induced Instabilities
- Low Pressure Loss
- Exit Temperature Profile Tailored for Life of Turbine (Low Pattern and Profile Factors)
- Low Emissions (CO, UHC, NOx, Smoke, Particulates)
- Minimize Cost, Maximize Durability and Ease of Maintenance
- Size and Shape Compatible with Engine Requirements
- No coking of fuel lines or fuel injectors

# Important Combustor Design Parameters

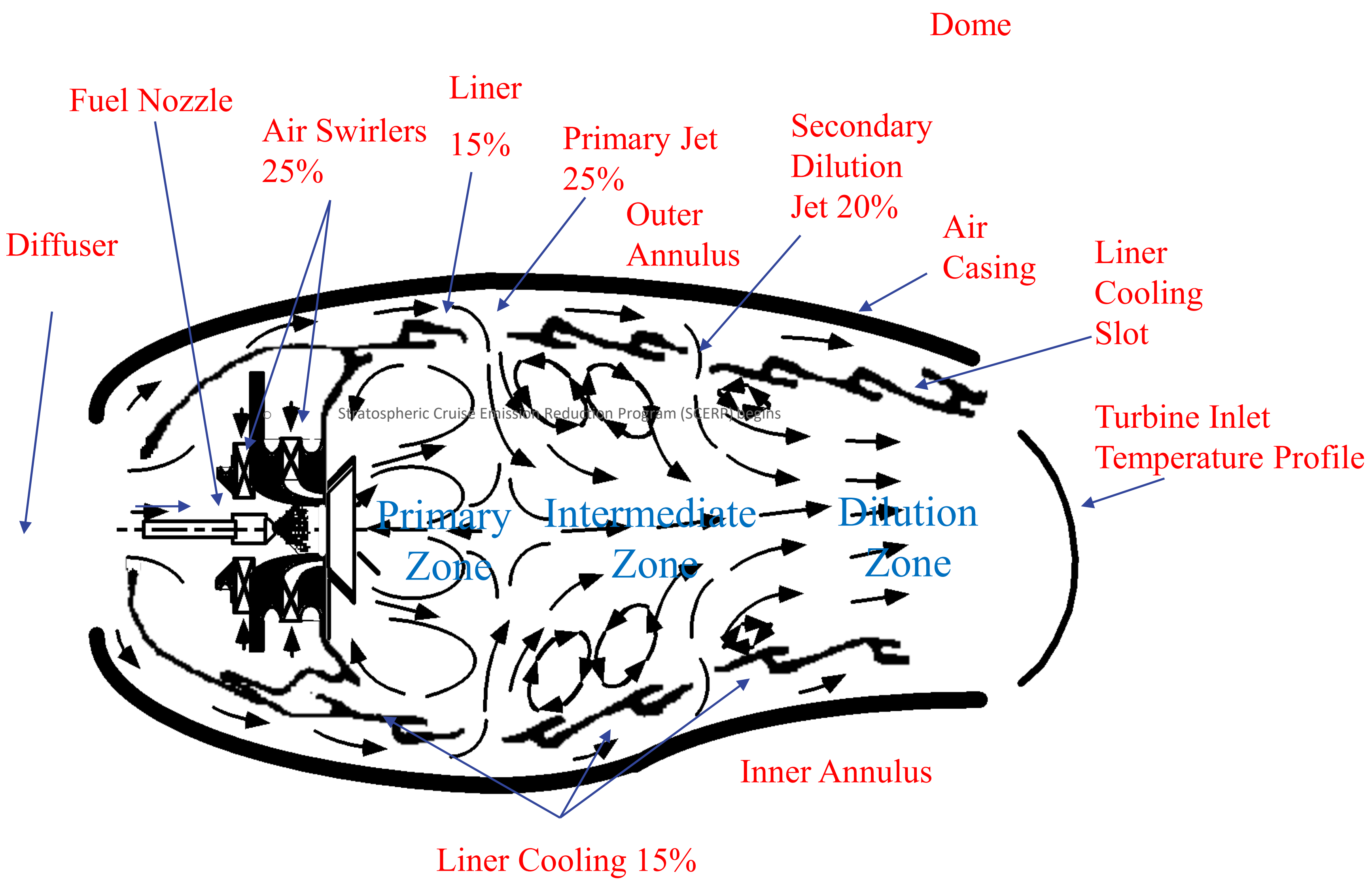
- Combustion Efficiency, $\eta_c$ > 99.9% for all conditions
- Pressure Drop, $(P_3-P_4)/P_3 < 6\%$ (4% – 5% Typical)
- Pattern Factor = $(T_{max} - T_4)/(T_4 - T_3) \leq 0.25$ @ Full Power
- Profile Factor = $(T_{mr} - T_4)/(T_4 - T_3) \leq 0.11$ @ Full Power

Measures of combustor exit temperature variation

- Lean Blow-Out Limit, $\phi \leq 0.1$ Low as Possible f/a ~ 0.005 - 0.008
- Altitude Re-Light $\rightarrow$ 30,000 Ft
- Emissions per the current International Civil Aviation Organization (ICAO) Standards for CO, HC, NOx, smoke or particulate matter (PM)

  "current" applies to entry into service (EIS) for the combustor

# Air-Flow Distribution

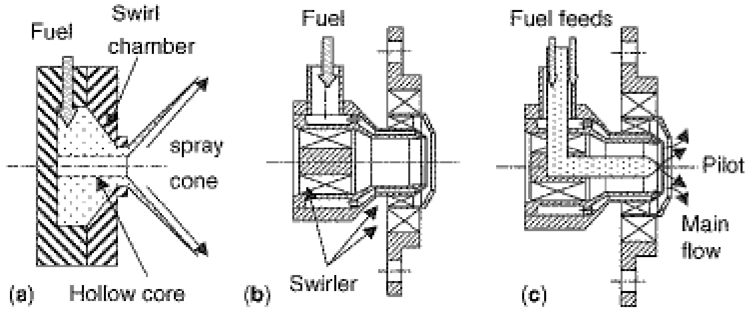


# Fuel injection

How fuel is injected and mixed with the air is critical to keeping emissions low. For aircraft combustors, there are a few common fuel injector (nozzle) types used to achieve the objectives of flame stability, low emissions, engine operability for all parts of the flight envelope from idle to takeoff (turndown), and robustness. These are pressure atomizers and airblast injectors.

- Pressure atomizers rely on fuel pressure drop to achieve good atomization. Quite effective at low engine power, but as power increases, there is less available $\Delta P$ for good atomization
- Airblast nozzles rely on air momentum and shear to atomize fuel. Works great at high power, has relatively poor performance at low power (low air flow)
- These injection schemes are often combined into one fuel injector with more than one fuel circuit

Some fuel nozzle schema




(a) pressure-swirl nozzle, aka simplex

(b) Airblast nozzle with triple swirler

(c) Compound nozzle—pressure and airblast nozzles

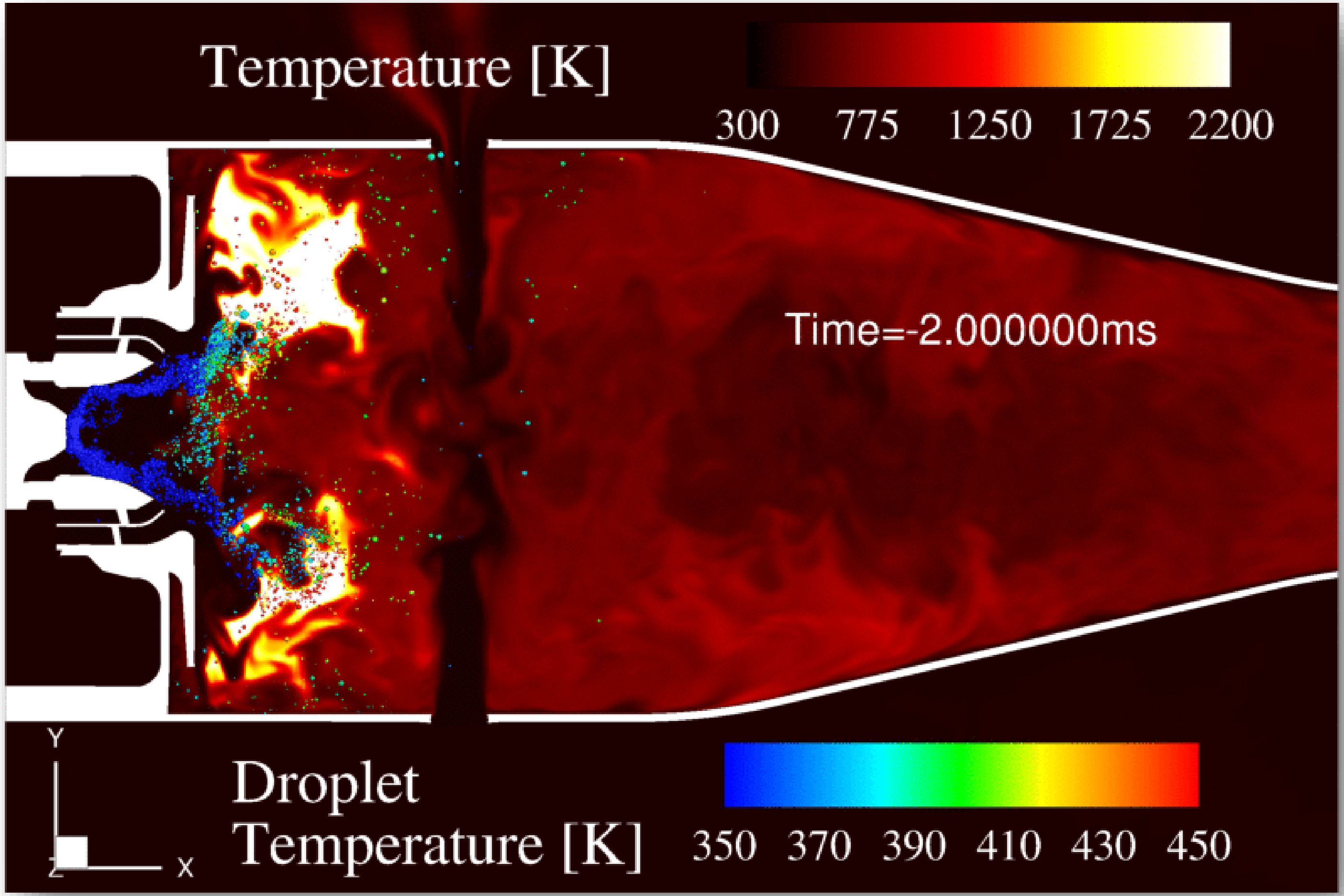
Some representative aircraft fuel nozzles

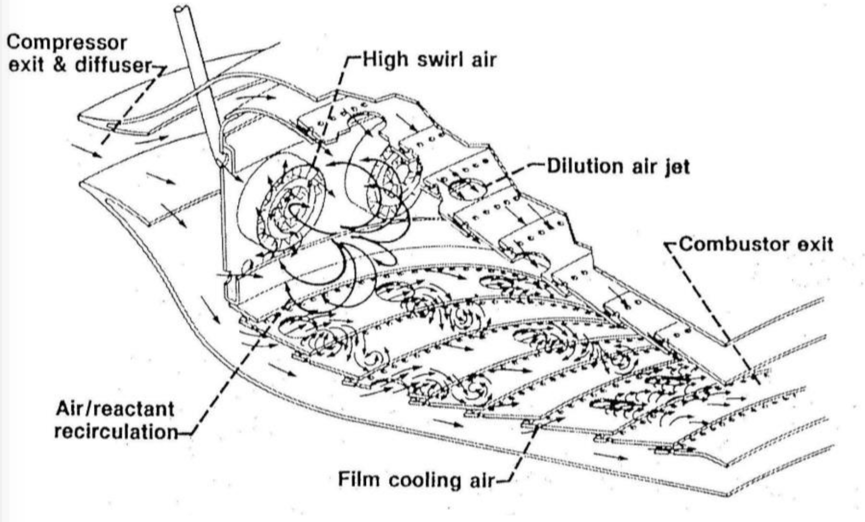
https://www.collinsaerospace.com/what-we-do/Industries/commercial-aviation/power-controls-actuation/turbine-systems/

https://3dprintingindustry.com/news/ge-aviation-celebrates-30000th-3d-printed-fuel-nozzle-141165/

https://ph.parker.com/us/en/product-list/aerospace-engine-fuel-injectors

# Combustor Physics Overview




- Liquid Fuel sprays
- Swirling Flows, recirculating Flows, and jets-in-Crossflows
- Trace Species Emissions: NOx, soot, etc.
- Fuel vaporization and fuel-air mixing
- Chemical Reactions
- Soot, Radiation, Wall Heat Transfer
- Low-Mach Number flows with large T, density gradients
- Turbulence impacts on aerodynamics, spray and chemistry

# Fuel composition and Stoichiometry

Stoichiometric combustion ($\phi = 1$)

$C_{11.4}H_{22.1}$ (~Jet-A*)+ 16.925 ($O_2$ + 3.76$N_2$) →

11.4 $CO_2$ + 11.05 $H_2O$ + 63.638 $N_2$

*1 kg fuel burned → roughly 3.16 kg $CO_2$ and 1.25 kg water*

Equivalence Ratio, $\phi$, is defined using reactant *mass*

$\phi = (f/a)_{actual} \;/\; (f/a)_{\phi=1}$ **$\phi$ > 1: fuel-rich** **$\phi$ < 1: fuel-lean**

Fuel-air mass ratio:

fuel = 11.4 * 12 + 22.1 *1 = 158.9

air = 16.925 * (32 + 3.76 * 28) = 2323.5

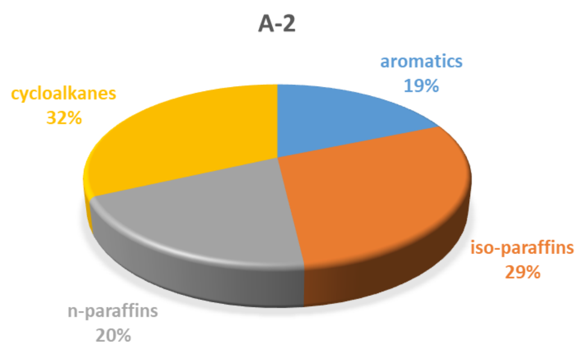
$(f/a)_{\phi=1}$ = 159 / 2324 = *0.0684* or (a/f) = *14.6*

Non-Stoichiometric lean combustion ($\phi < 1$)

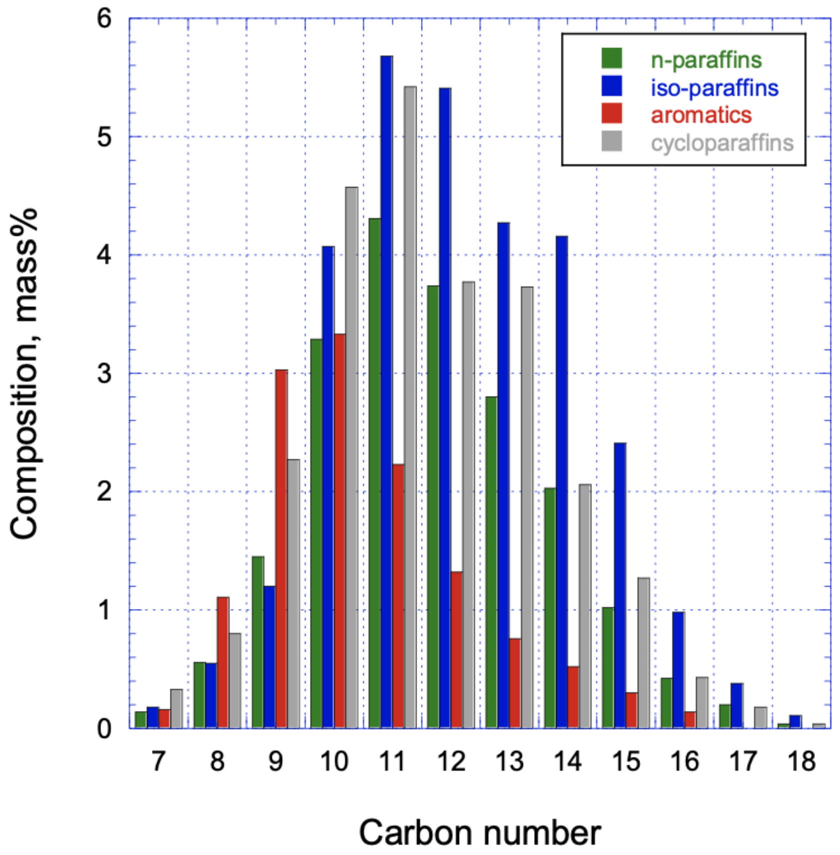
$\phi C_{11.4}H_{22.1}$ + 16.925 ($O_2$ + 3.76$N_2$) →

$\phi$11.4 $CO_2$ + $\phi$ 11.05 $H_2O$ + 63.638 $N_2$ + (1- $\phi$) 11.75 $O_2$

* Jet fuels such as Jet-A and JP-8 are multicomponent, and overall composition depends on from where crude oil comes, time of year originating country federal regulations, etc., so this is an average formula




an Average Jet-A composition

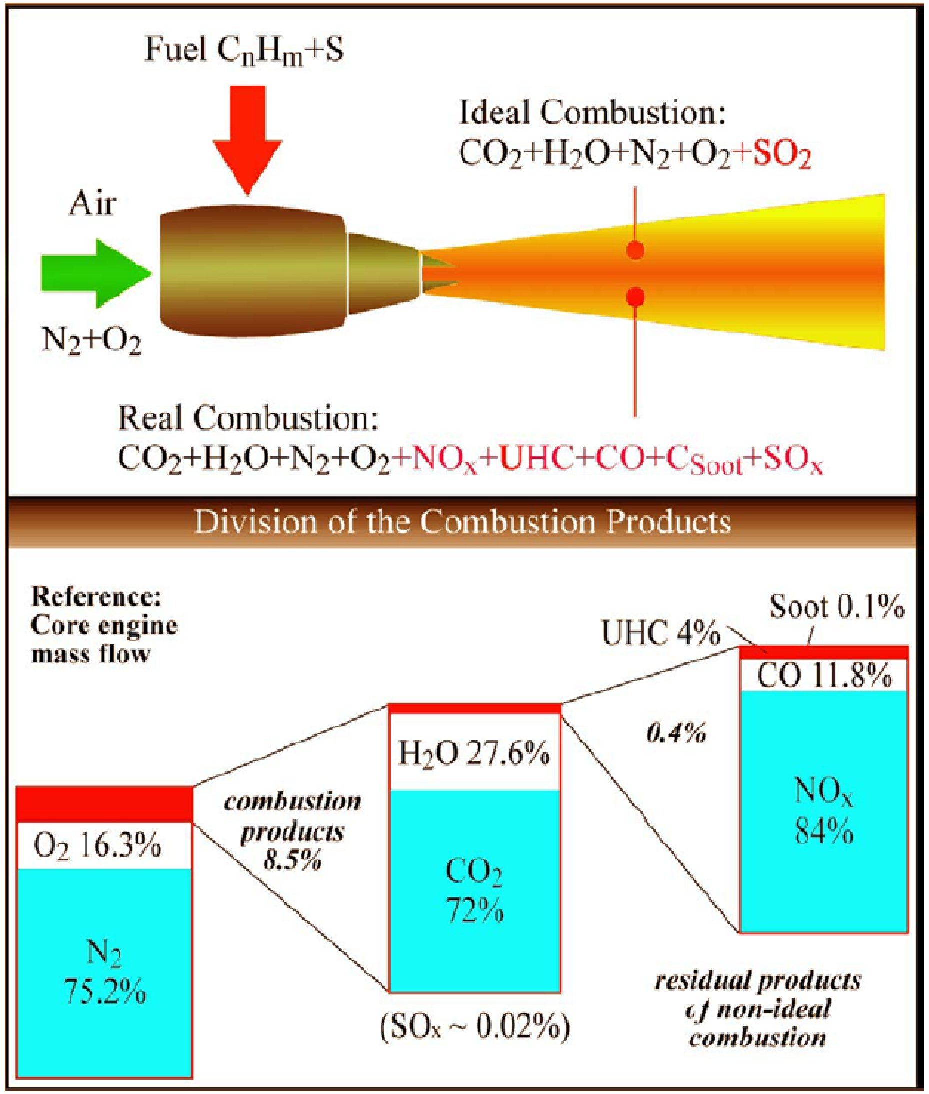



From Edwards, AIAA-2017-0146

# Real Combustion

Jet Fuel: $C_nH_m$ + Sulfur (trace amounts, ~1000 ppm)

Typical subsonic cruise emissions




## Engine Emissions

**Primary constituents:** $H_2O$, $CO_2$, $N_2$, $O_2$

**Secondary products:** NO, $NO_2$, $N_2O$, $SO_2$, CO, stable HC, soot

**Oxidation products of secondary combustion species:** $HNO_2$, $HNO_3$, $SO_3$, $H_2SO_4$, $H_2O_2$, HNO

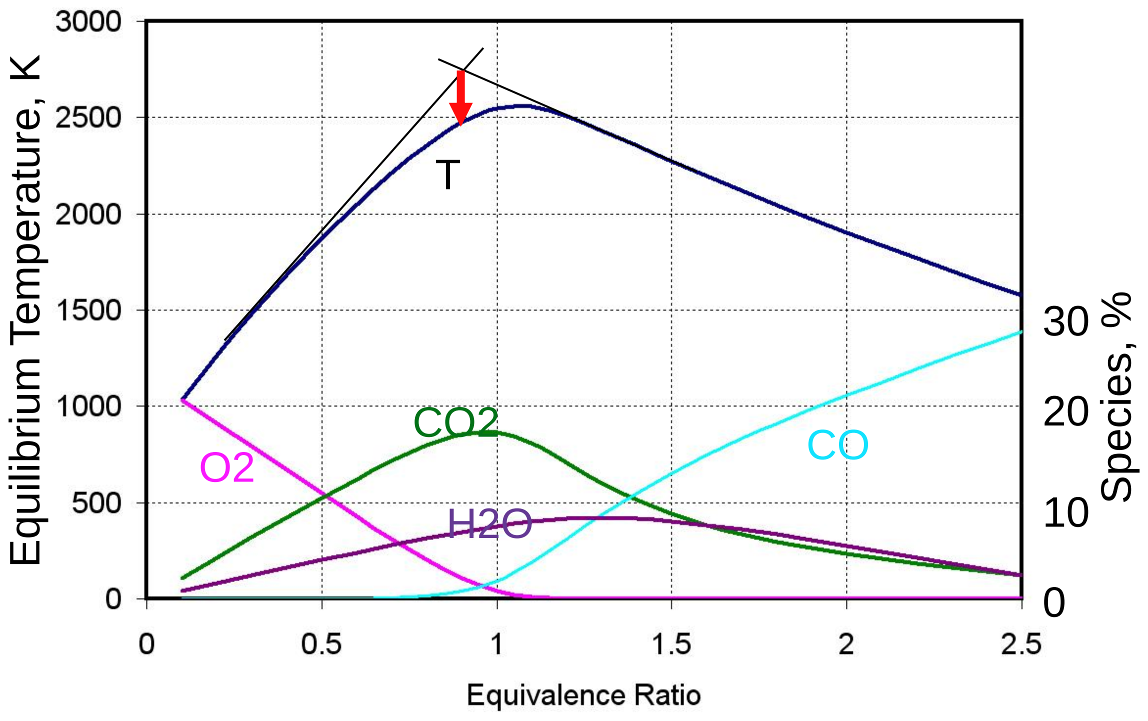
**Reactive species:** O, OH, $HO_2$, SO, $H_2$, H, N, CH

- Pollutant species (CO, HCs, $NO_x$, $SO_x$) measured in ppmV (parts per million by volume).
- $CO_2$, $H_2O$ & $O_2$ in percent
- Required Regulations & Certification : CO, UHCs, NOx, Smoke/Soot

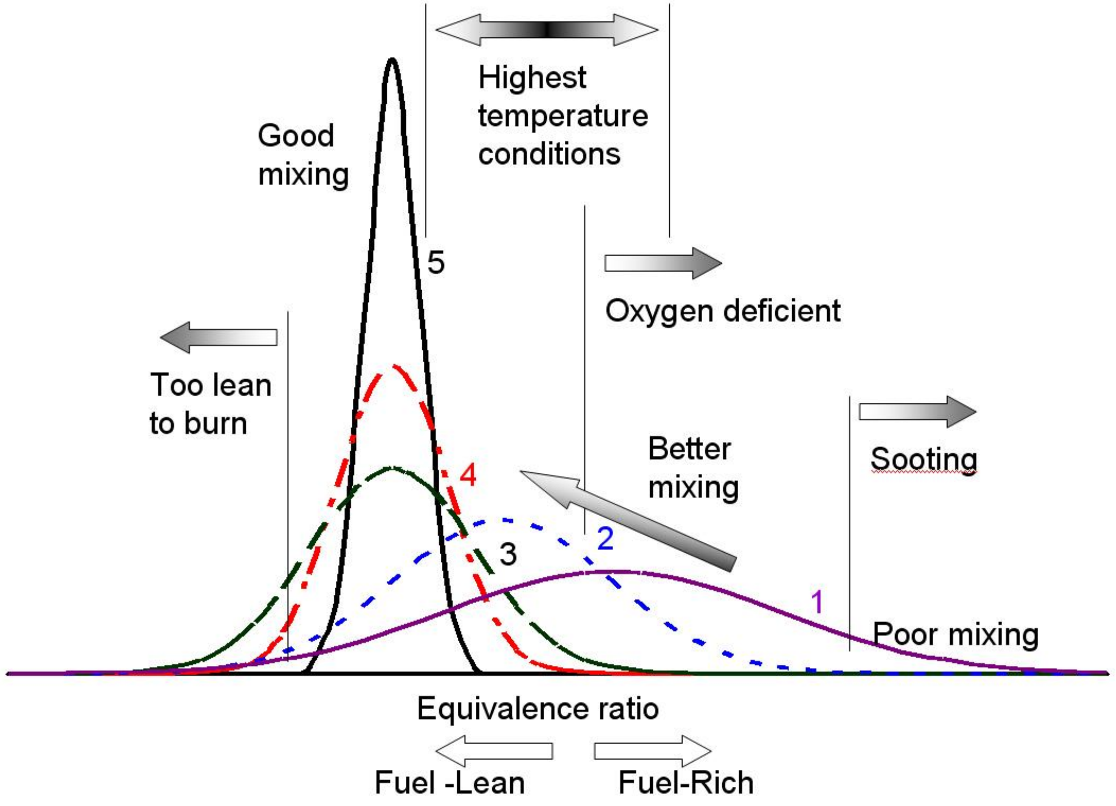
# Influence of Fuel-Air Mixing on Combustor Operation

## Equivalence Ratio and Equilibrium Temperature

What happens when you vary the fuel-air mixture




## Influence of $\phi$ and Fuel-Air Mixing

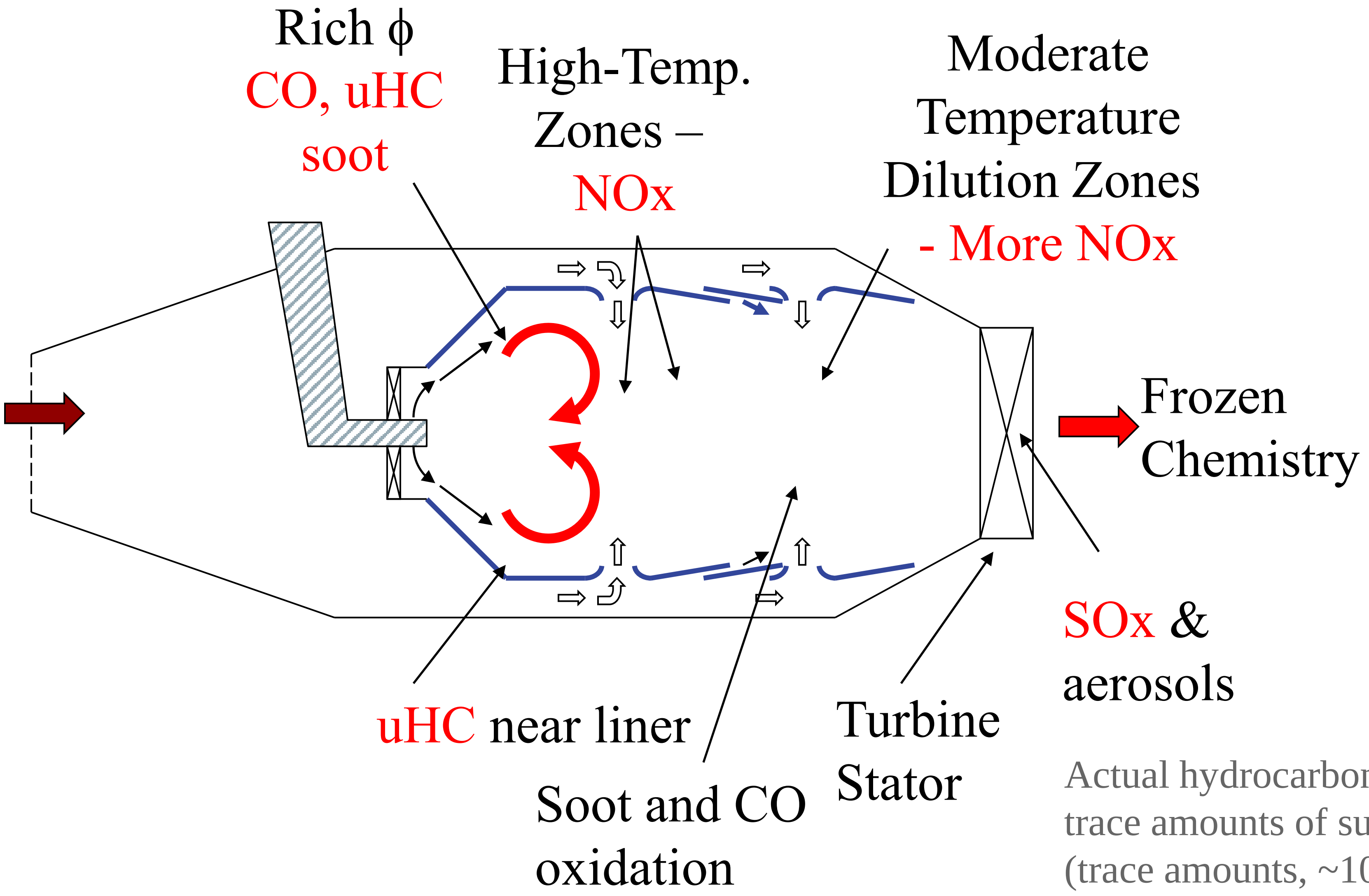



*Key to Low-NOx:*

*1. Avoid high temperature burning*

*2. Keep the exposure time short*

# Pollutant formation




Actual hydrocarbon jet fuel may contain trace amounts of sulfur: CmHn + Sulfur (trace amounts, ~1000 ppm)

# The Emission Index, EI

Calculating the Emission Index (EI) for Specie $X_i$:

$$EIX_i = [\text{Vol Fr}]_i \times [MW_{Xi}/MW_{exh}] \times [(1 + f/a)/(f/a)] \times 1000 \quad \{g\text{-}X_i/kg\text{-fuel}\}$$

where: $[\text{Vol Fr}]_i$ = Volume fraction of specie $X_i$, typically in ppm

$MW_{Xi}$ = Molecular mass of specie $X_i$, kg/kg-mole

$Mw_{exh}$ = Molecular mass of exhaust, kg/kg-mole

f/a = Fuel-to-air ratio, i.e. (mass flow fuel)/(mass flow air)

Calculated for each: CO, NOx, UHC's $\rightarrow$ EICO, EINOx, EIHC

EI normalizes the emissions w.r.t. fuel burned

# Combustion Efficiency

Exhaust-gas analysis to calculate efficiency:

$$\eta_c = 1 - [X_{CO}(\Delta hc)_{CO} + X_{HC}(\Delta hc)_{HC} + X_{H2}(\Delta hc)_{H2}] / [(f/a)(\Delta hc)_f/(1 + f/a)]$$

where: $X_i$ = mass fraction of species *i*

$(\Delta hc)_i$ = the heat-of-combustion for species *i*.

Note: $X_{HC}$ = mass fraction of unburned hydrocarbons

The numerator represents unused chemical energy per mass of exhaust.

The denominator represents the chemical energy per mass of initial fuel-air mixture.

Another common means of expressing the inefficiency is by using the emission index, *EIi*, mass of species *i* per unit mass of fuel burned (g/kgf),

$$\eta_c = 1 - (0.232EICO + EIHC + 2.76EIH_2)/1000$$

Assumes unburned hydrocarbons (HC) come from the fuel.

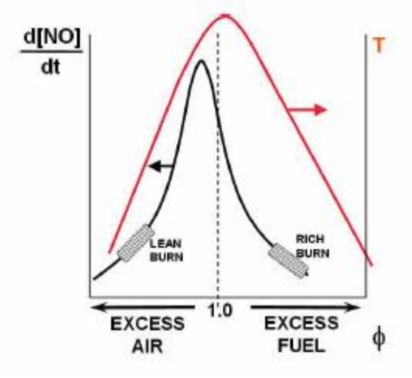
# NOx reduction strategies

Several strategies exist to reduce NOx emissions. All involve staying away from stoichiometric combustion, temporally and spatially. The most common are

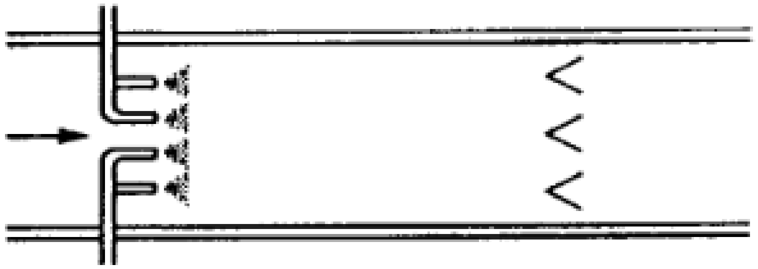
- Lean Premixed, Prevaporized (LPP)—this concept will have a very uniform fuel-lean mixture, to keep emissions of NOx, smoke, and particulate matter (PM) low. A major drawback is susceptibility to combustion instability and flashback. *This makes pure LPP less practical for aircraft combustors*.
- Rich-burn, quick-mix, lean burn (RQL)—RQL has good combustion stability because of its rich front end. The key to avoiding NOx is to rapidly mix in the air to spend as little time as possible near $\phi$=1 and produce a uniform mixture in the lean zone. Many modern engines use this technology because it is simple and robust.
- Lean Direct Injection (LDI)—is a concept that replaces a single fuel cup with several smaller injectors that will enhance fuel-air mixing and fuel vaporization, resulting in smaller and shorter flame zones. The resulting system is partially-premixed, partially-diffusion, and flashback has not been observed. Like LPP, all fuel and air is injected in the front end, and since this concept runs typically fuel-lean, it can also be susceptible to combustion instabilities. There are also concerns about fuel system complexity.
- Staging fuel, air, or both—in this case, separate spatial zones are created to have a primary or pilot stage and a main stage. The pilot stage is primarily used at lower power, but is always fueled to maintain stability. The main stage is fueled at higher power conditions.
  - Axial staging generally involves a pilot stage in the front and a main stage, with fuel injection downstream
  - Radial staging may have the pilot stage closest to the center of the engine and the main stage outside or vice versa.

# NOx reduction strategies, 2

A few concept sketches for LPP, LDI, RQL
For the latter two especially, the key is to keep the residence time short

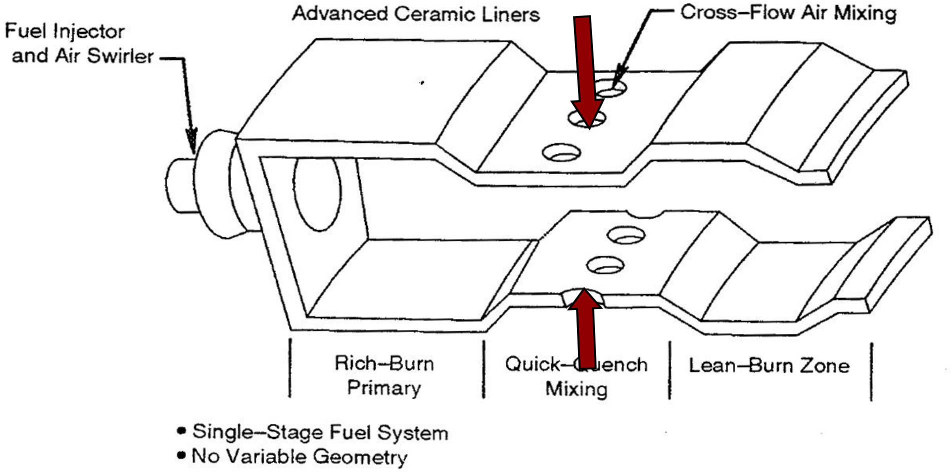



## Lean, premixed, prevaporized



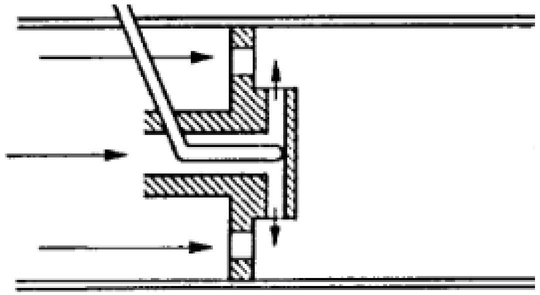
from NASA TM 103268 or AIAA-90-2400

## Rich burn, quick quench, lean burn




from NASA CR-1998-207931 51858

## Lean-Direct Injection



from NASA TM 103268 or AIAA-90-2400

# International regulations

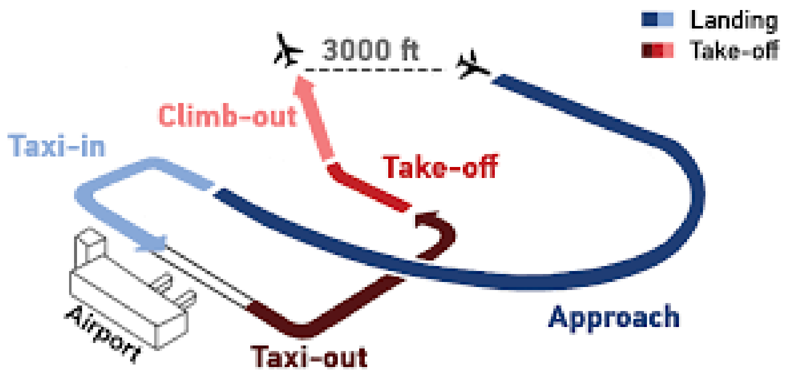
International Civil Aviation Organization (ICAO) established in 1947 and later became a specialized UN agency. The Committee on Aircraft Engine Emissions (CAEE) adopted first Standards and Recommended Practices (SARP) in 1981, adopting HC, CO, and NOx emissions limits. The Committee on Aviation Environmental Protection (CAEP) replaced CAEE. Meetings are triennial and standards are reviewed. These standards generally become more stringent as engine technology, measurement technology improves Typically, new SARPs are adopted then.

The CAEP/11 standard is in effect in 2023 and applies to all subsonic turbofan engines manufactured after 1 Jan 2023 with rated maximum takeoff thrust > 26.7 kN. CAEP/11 includes new rules for Particulate Matter mass

ICAO standards must be adopted into law independently by each country. In the U.S., the FAA is the representative member at annual CAEP steering group meetings and contribute technical expertise to working groups. The EPA serves both as advisor and advisee to the FAA.

# ICAO Landing and Takeoff (LTO) Cycle

- Part of engine certification process, Annex 16, Volume II
- Addresses engine emissions: hydrocarbons, carbon monoxide, oxides of nitrogen, smoke or particulate matter (nvPM) for altitudes below 914m (3000 ft) and engines with rated thrust levels greater than 26.7 kN



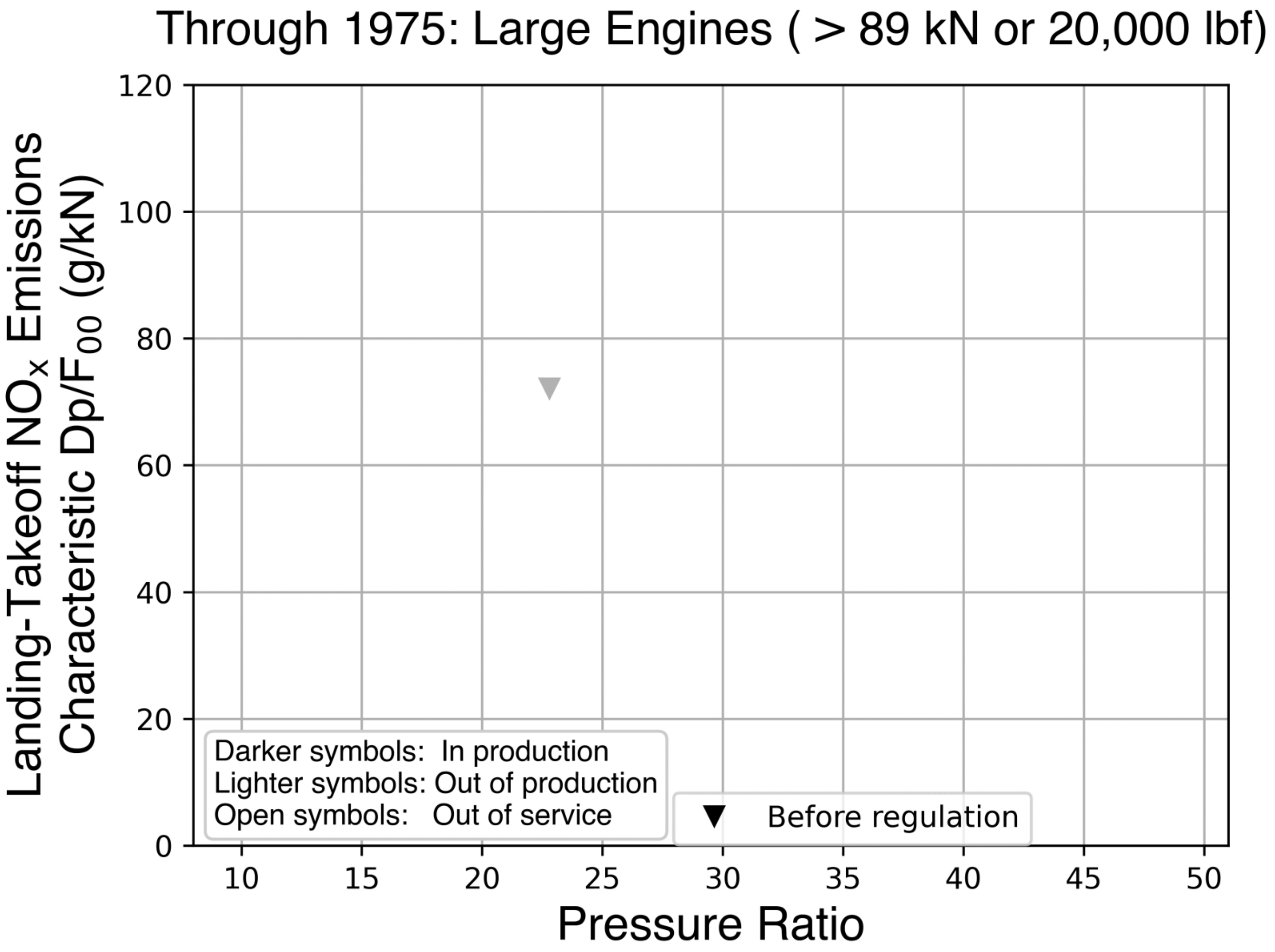

| Mode | Power Setting % takeoff thrust | Time in mode minutes |
|---|---|---|
| Taxi/idle | 7% | 26 |
| Approach | 30% | 4 |
| Climb | 85% | 2.2 |
| Takeoff | 100% | 0.7 |

$$Dp(NOx)/F_{00}\ [g/kN] = (EINOx \times \text{fuel flow} \times \text{time})/F_{00}$$

$F_{00}$ is rated takeoff thrust.

Equation also applies to CO and UHC

# Evolution of ICAO CAEP LTO $NO_x$ regulations through CAEP/8 (latest $NO_x$ reg) and the large engines that fall under those regulations



# Part 2—The Past

History of advancements in emissions reduction via NASA Aeronautics Programs and partnerships with other government agencies (OGA), industry, and academia

This covers a time frame roughly from 1970 to 2015.

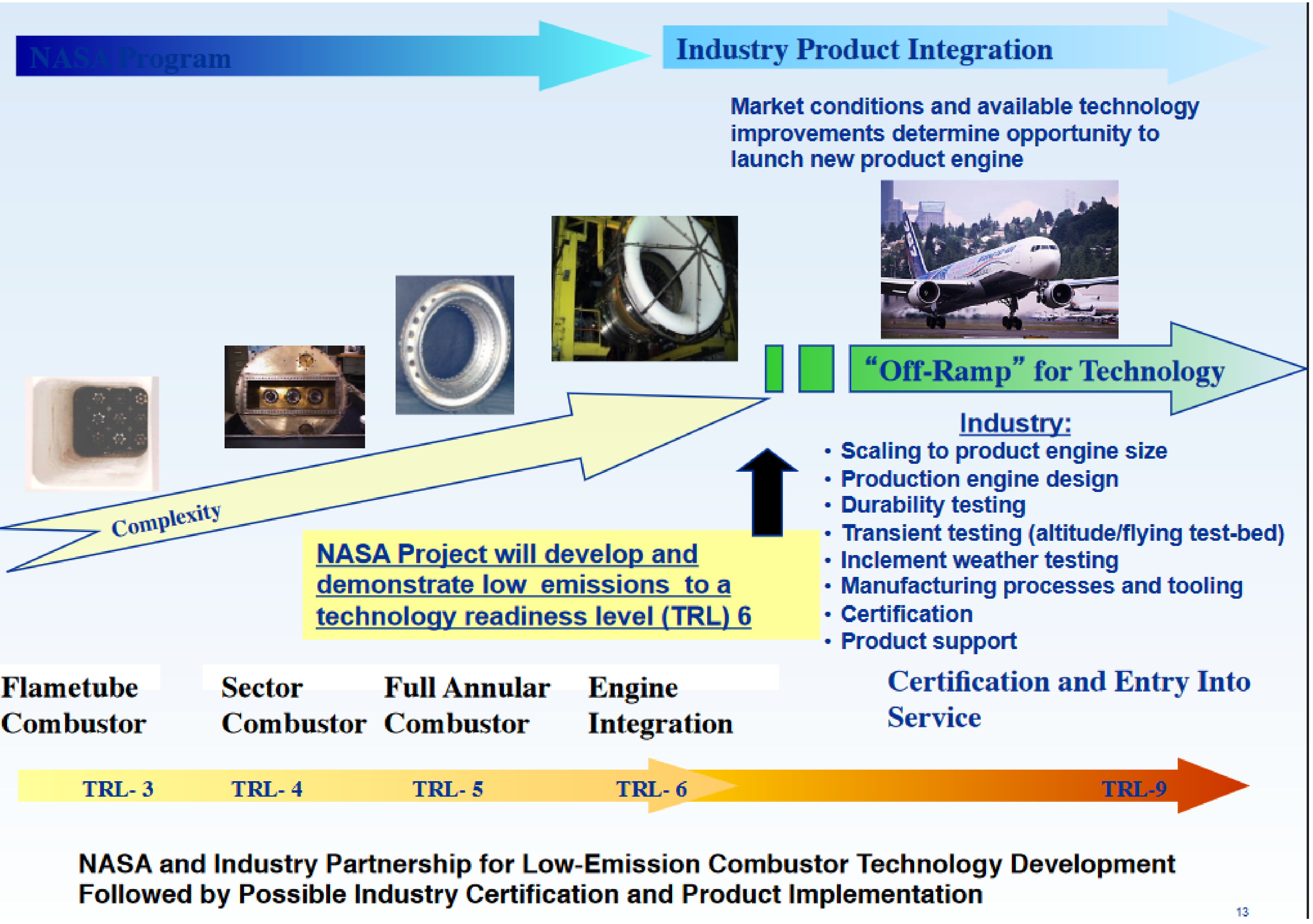
One may notice that some research is cyclical. Ideas that were problematic at first may later advance because of other technology that allowed the old idea to come to fruition. Or a new problem arose that the idea addressed.

# overview of past NASA aero GT combustor research

| Program name | Year | Engine class | Combustor concepts | Legacy |
|---|---|---|---|---|
| Experimental Clean combustor (ECC) | 1973-1978 | Large subsonic | Dual annular combustor (DAC), Vortex burning and mixing (Vorbix) | |
| Pollution Reduction Technology program (PRT) | 1974-1979 | Small to midsize subsonic | Vorbix | |
| Quiet Clean Short-Haul Experimental (QCSEE) | 1974-1975 | short-haul turboshaft | | |
| Stratospheric Cruise Emission Reduction program (SCERP) | 1977-1983 | Supersonic | Lean prevaporized premixed (LPP) | |
| Energy Efficient Engine project (EEE, $E^3$) | 1980-1984 | Large subsonic, high OPR | DAC, axial-staged combustor | CFM56, GE90, V2500-A5 |
| High-Speed Research (HSR) | 1991–1999 | large supersonic | LPP, rich-burn, quick-mixing lean-burn (RQL) | |
| Advanced Subsonic Transport (AST) | 1994–1999 | Large subsonic, 60 OPR | TALON II | PW4100, PW6000, GEnx |
| Ultra-Efficient Engine Technology (UEET) | 1999-2004 | Subsonic, 60 OPR | TALON X, twin annular premixing swirler (TAPS) | GEnx, GTF |
| Fundamental Aeronautics (FA) | 2007-2015 | Various | cutting-edge core comptencies for the long term | |
| Subsonic Fixed Wing (SFW) | | Subsonic | | |
| Subsonic Rotary Wing (SRW) | | | | |
| Supersonics | | Supersonic | | |
| Hypersonics | | | | |
| Environmentally Responsible Aviation (ERA) | 2009-2015 | Large subsonic, 55 OPR | Partially premix, lean direct injection (LDI) | |

Beginning in the mid-1990s, NASA LDI concept has been pursued as a viable alternative to LPP, and has been on-going through the present

# Emissions Reduction – Technology to Product Transition




TRL 3—Flametube Testing:

- Emissions (NOx, CO, HC)
- LBO performance
- Flame Stabilization
- Swirler Fuel Injector Design
- Injector Durability
- Preliminary Acoustics

TRL 4—Sector Combustor Testing

- Emissions (NOx, CO, HC, smoke)
- Liner design and durability
- Wall cooling
- 3d effects
- Combustor/flowpath design
- Injector interactions

TRL5—Full annular combustor testing

- Emissions (NOx, CO, HC, smoke, aerosols)
- LBO performance/Altitude relight
- Ignition/flame propagation
- Possible staging
- Exit profile/pattern factor
- Operability
- Combustion acoustics

# A Brief review of NASA aircraft gas turbine combustor research, synopsized from Chang et al. 2013

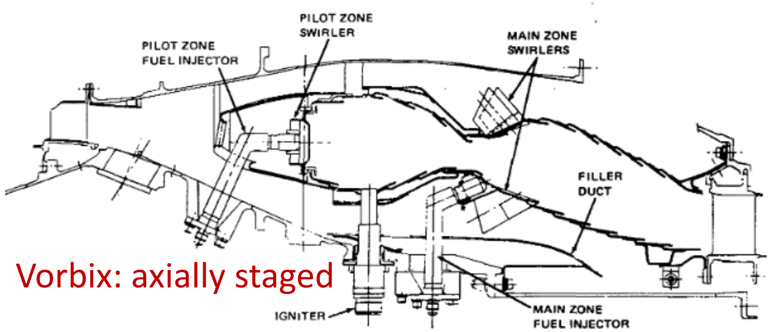
- 1940s – 1950s were devoted to reliability of aero-propulsion systems, primarily for military Late 1960s: *begin energy efficiency + environmental focus for civilian aircraft*
    - civilian engines at the time were based on the existing military engines, which ran fuel rich ($\phi > 1$), as they were designed for stable operation. But along with high $\phi$ comes high smoke count
- 1970 U.S. EPA established. Consolidation of several public health and pollution programs in the federal government. Modern era of consolidated U.S. emissions regulations begins

# Review of NASA aero GT combustor research, cont.

- 1970s: *combustor development programs to reduce NOx, climate impact*
  - efforts to lean out ($\phi < 1$) primary zone to decrease smoke number; reduce high-power NOx and low-power CO and HC.
  - NASA research into fuel scheduling, airblast and air assist fuel nozzles; catalytic, partially premixed, and LPP combustion
  - Industry collaborations to incorporate NASA learnings and to develop low emissions combustor concept retrofits to existing engines (fuel-lean in main zone)
    - Experimental Clean Combustor Program → DAC, Vorbix
    - Pollution Reduction Technology Program → Vorbix
  - Stratospheric Cruise Emission Reduction Program (SCERP)
  - Climate impact studies done by DOT, NAS, NASA. Global Air Sampling Program (GASP) includes air sampling in lower stratosphere, upper troposphere from B-747 aircraft worldwide
  - Research begun for the Rich Burn, Quick-Mix, Lean Burn (RQL) combustor to reduce NOx emissions—Joint DOE/NASA effort (1980)

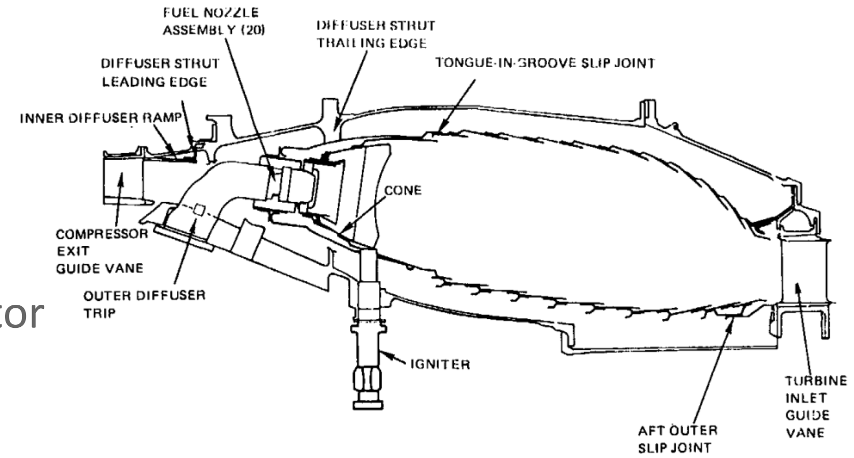
# Experimental Clean Combustor: DAC and Vorbix retrofits

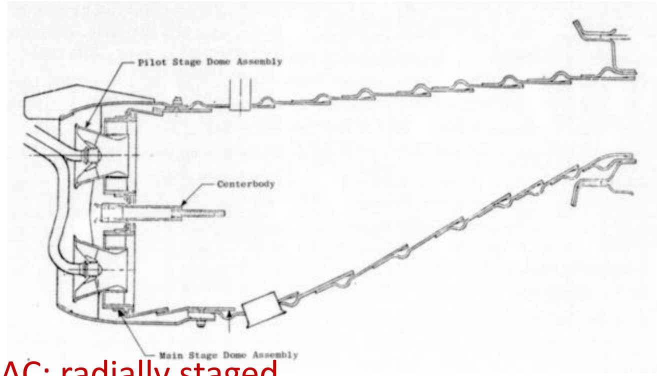
- GE developed the Dual Annual Combustor burner
- PW developed the Vortex Burning and mixing burner




Vorbix: axially staged

into JT9D-7A combustor

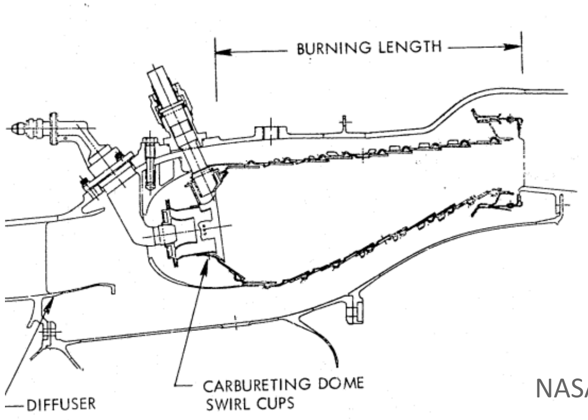



DAC: radially staged

NASA CR-134971

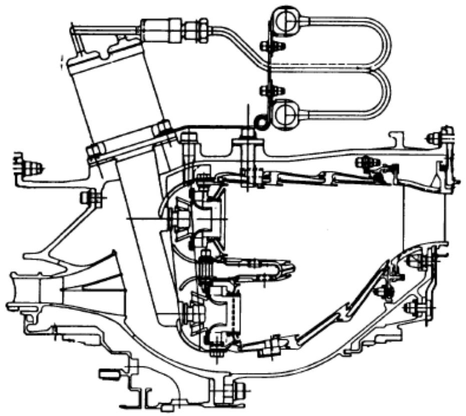
into CF6-50 combustor




NASA CR-168219

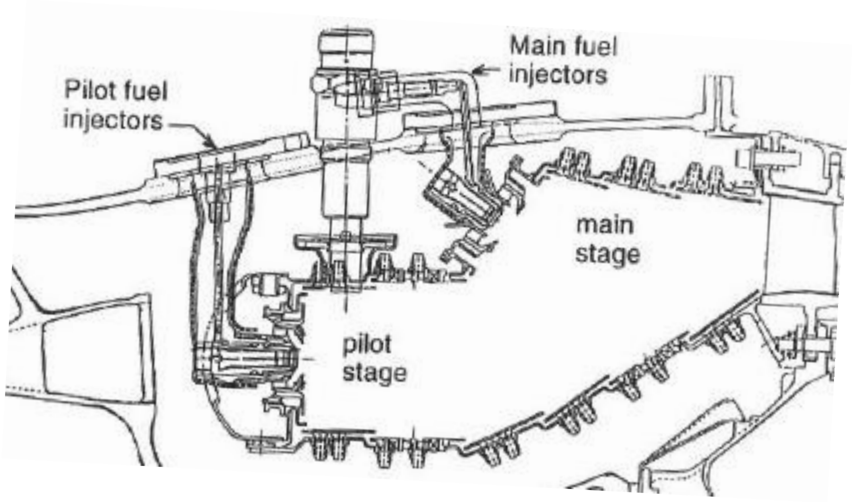
# Review of NASA aero GT combustor research, cont.

- 1980s: *energy efficiency* + *environmental focus for civilian aircraft*
  - NASA studied combustor-diffuser interactions, air dilution, …
  - Energy Efficient Engine (EEE, $E^3$) Project was follow-on to ECCP
    - DAC concept pursued. Pilot outer, Main inner. Provided improved mixing, combustion, lower emissions, more robust liner led to longer maintenance intervals
    - DAC concept on CFM56 and future GE90 engines
    - Vorbix technology was iterated, revised, transformed into a different and better-performing (not named) axially staged combustor and can be found in the V2500 engine, EIS 1989



$E^3$ DAC

NASA CR-168219



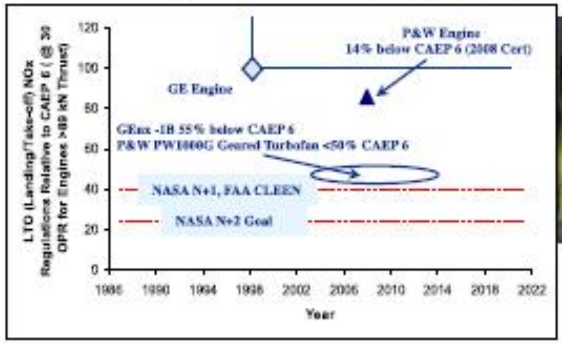

P&W V2500-AS combustor (Lefebvre, 1998; AIAA 2016-2121)

# review of NASA aero GT combustor research, cont.

- 1990s: High Speed Research (HSR), Advanced Subsonic Technology (AST)
  - HSR program for civilian supersonic flight—emissions goal for $EINO_x \leq 5$ to help mitigate concerns for high altitude ozone depletion. RQL and LPP technologies were studied. A modified LPP-type strategy met the goal but had higher sensitivity to combustion instabilities during rapid transients.
  - AST research program had a main driver to improve engine efficiency by increasing the OPR over existing technology from 25 to between 60-75. This reduced fuel burn but increased OPR leads to higher $NO_x$ (higher T3) without new technology in fuel injection and
    - Continued work and refinement of RQL technology led to P&W TALON (Technology for Advanced Low $NO_x$) combustors.
    - GE continued lean-front end technology led to development of the TAPS (Twin Annular Premixing Swirler) combustor, which replaced the lean-burn DAC.

# Advancement of RQL technology to flight: PW Talon

## Technology for Advanced Low NOx (TALON) Combustor



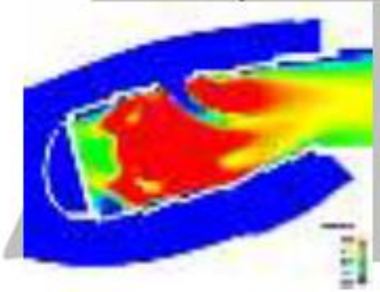


**Systems Assessment: 1999-2008**

- *P&W Talon II development engine test w/ NASA PAGEMS particulates test van on-site – 1999*
- *P&W Talon II Engine Certification in ground engine test stand – 2000. EIS (Entry into Service) in 2001*
- *P&W Talon IIB Engine Certification in ground engine test stand – 2008. EIS in 2009*

**Fundamental Research: 1995-2000**

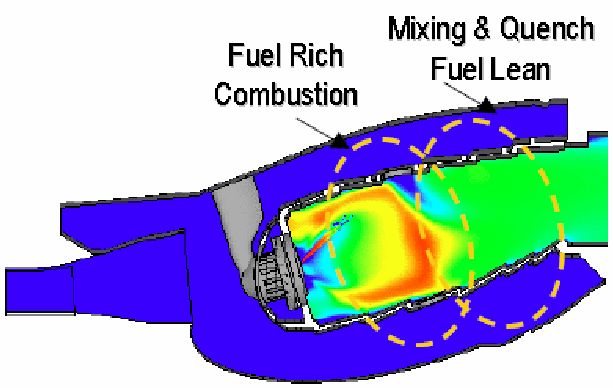
*Development of Rich Quick-Quench Lean Burning, Technology for Advanced Low NOx (TALON) Proof of Concept Sector Demonstration Rig*



**Seedling Idea: mid 1990's**

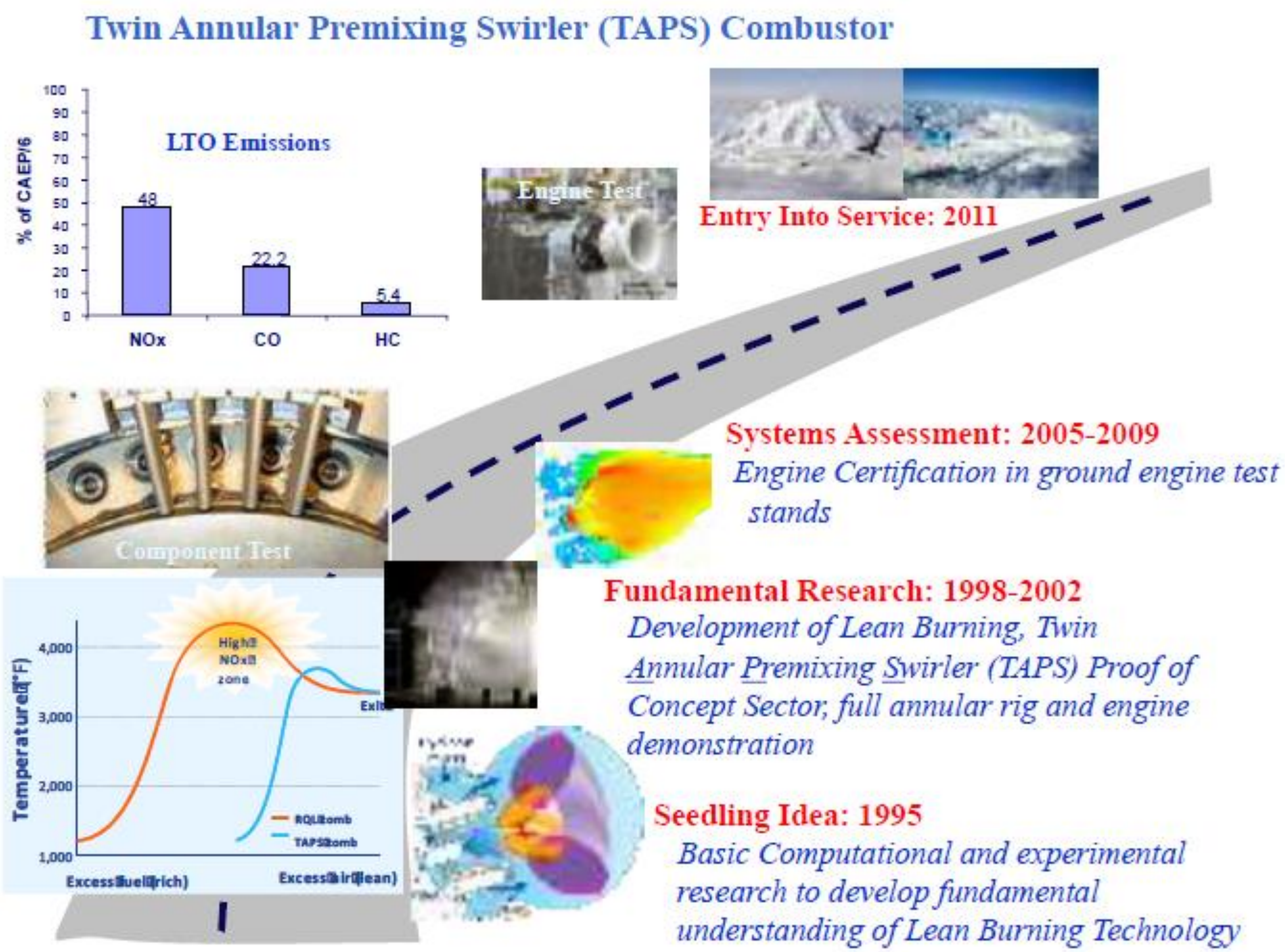
*Basic Computational and experimental research to develop a fundamental understanding of Rich Quick-Quench Lean Burning Technology*

TALON combustors in PW4100, PW6000, Geared Turbofan GTF engines

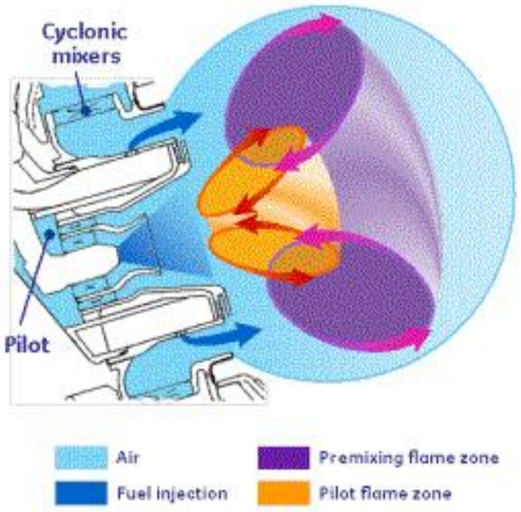



McKinney et al. (2007). The Pratt & Whitney TALON X low emissions combustor: revolutionary results with evolutionary technology. AIAA-2007-386

# Advancement of “LPP” technology to flight: GEA TAPS



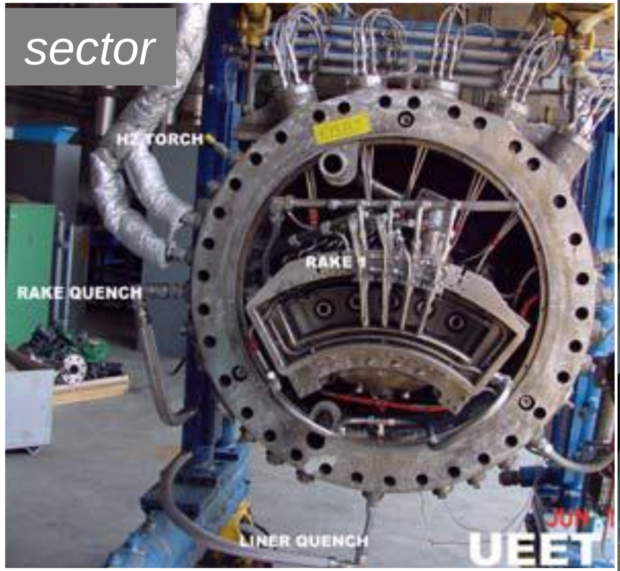

TAPS combustors in CFM LEAP, GEnx, GE9x engines



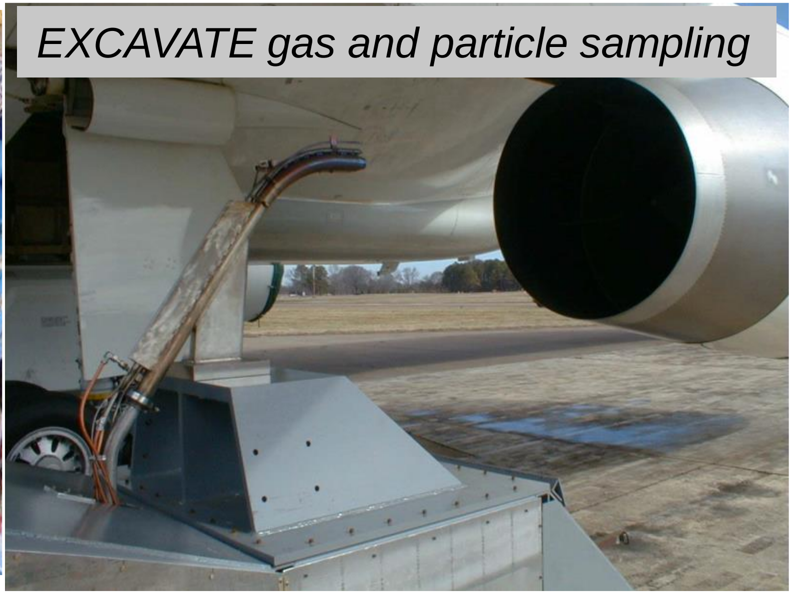

Foust, M.J, et al.(2012). “Development of the GE Aviation Low Emissions TAPS Combustor for Next Generation Aircraft Engines,” AIAA-2012-0936

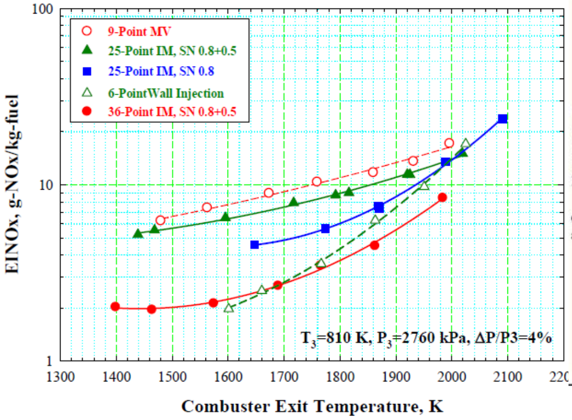
# review of NASA aero GT combustor research, cont.

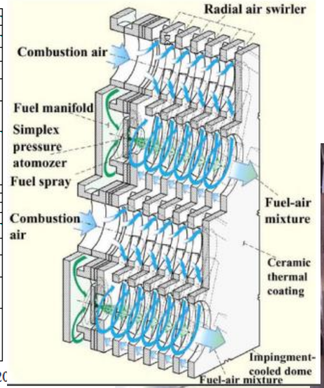
- 2000s: Ultra Efficient Engine Technology Program, UEET
  - Emissions Reduction was one of the UEET Projects. Goal to develop combustor technologies to reduce LTO NOx of 70% relative to 1996 ICAO standards (CAEP/2), applied to large and regional subsonic aircraft. Assess levels of aerosols and particulates. Improve and validate design codes to reduce design and development cycle time by 50%. Studies on LPP, RQL, and LDI technologies continued. Goal for ceramic matrix composite (CMC) material to meet 2700 F (1755 K). Continued work on atmospheric measurements and modeling. Alternative fuels effort.



*sector*


*EXCAVATE gas and particle sampling*




*Analyzing LDI configurations*

# review of NASA aero GT combustor research, cont.

- 2000s: Fundamental Aeronautics Program (FAP)
  - FAP Objective: Develop concepts and technologies to improve energy efficiency and environmental compatibility for sustained growth of commercial aviation
  - FAP has two focus areas of interest for combustion emissions: Subsonic Fixed Wing (SFW) and Supersonics (SUP). These projects took learnings from HSR, AST, and UEET and formulate plans and tasks projected to the future with a particular eye towards meeting the N+3 goals for SFW and for a supersonic business jet under SUP that can meet EINOx emissions goal of < 5.

**NASA Subsonic Transport System Level Metrics**

*.... technology for dramatically improving noise, emissions, & performance*

| 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‡ (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

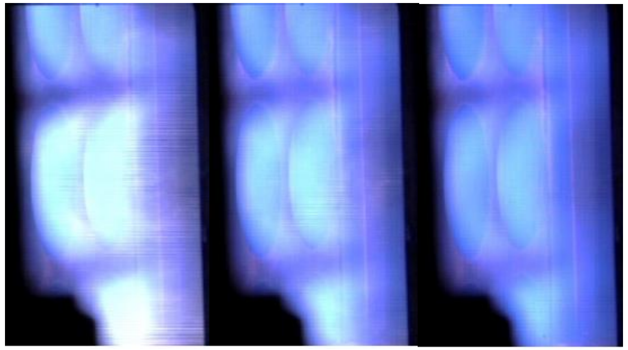
** ERA's time-phased approach includes advancing "long-pole" technologies to TRL 6 by 2015

‡ $CO_2$ emission benefits dependent on life-cycle $CO_{2e}$ per MJ for fuel and/or energy source used

**SFW: Near-term research addressing revolutionary N+3 Goals**



Consideration of alternative fuels was a theme in both projects



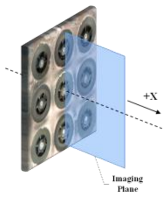
JP-8 50/50 FT

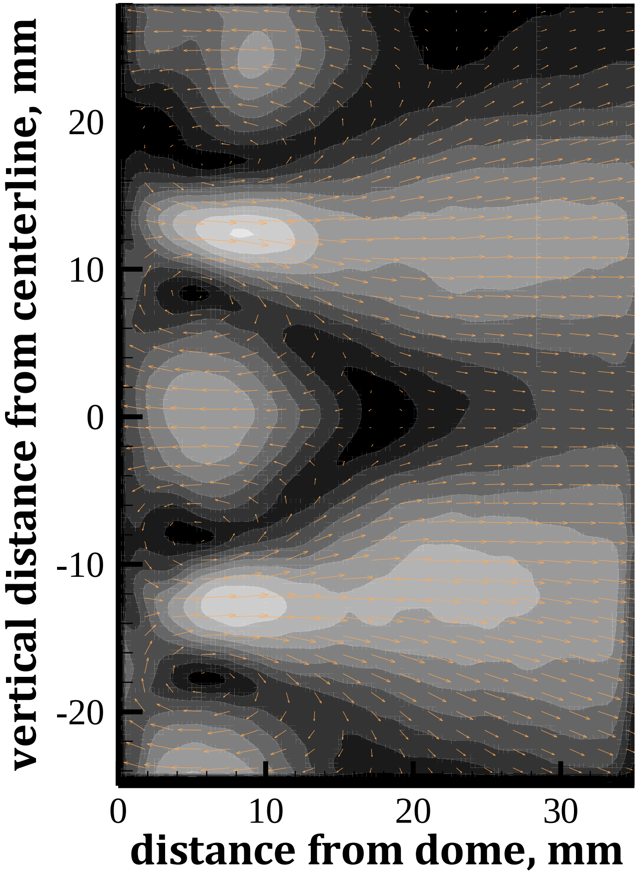
Color video of 9-pt LDI injector showing flame sootiness. From most to least sooty: JP-8/air flame, 50/50 blend, FT/air.

10.2 bar, 4% pressure drop, $T_3$=828 K, $\phi$= 0.44

# review of NASA aero GT combustor research, cont.

- 2000s: FAP SFW, SUP   Characterizing fuel injection from NASA 9-pt LDI

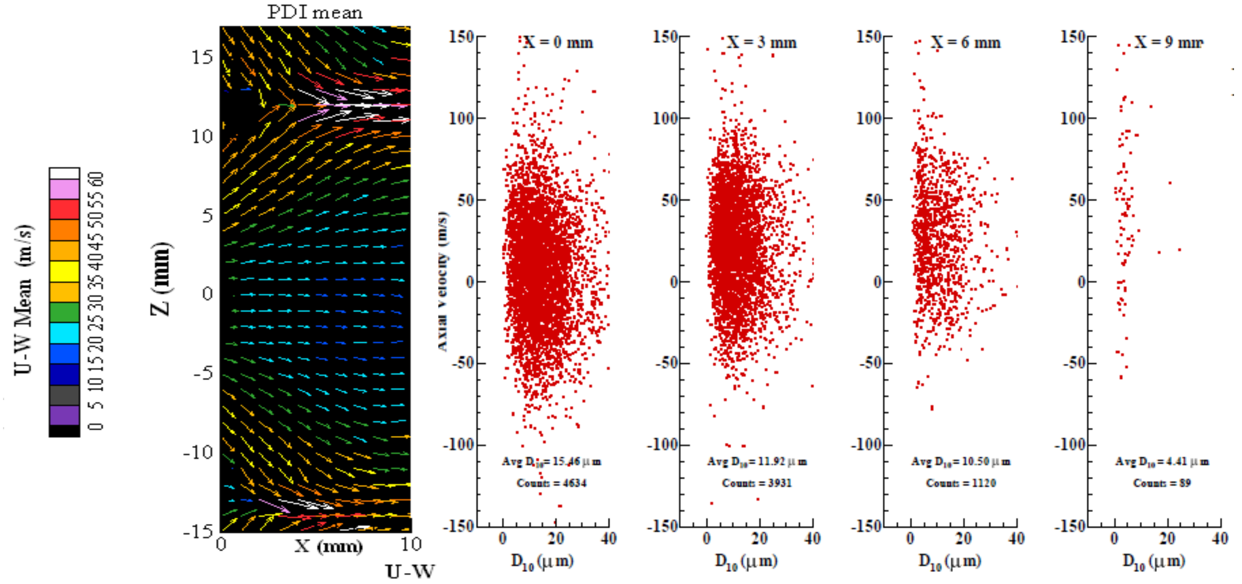



PIV result: Average axial-vertical velocity field of air in vertical center plane, from 500, 2d image pairs.

$T_3$ = 828 K, $P_3$ = 1034 kPa

Hicks et al. ISABE-2011-1106




Phase Doppler interferometry results during combustion around center swirler. Left (contour): Axial-vertical velocity vectors
Right: $D_{10}$ vs Axial velocity

$T_3$ = 738 K, $P_3$ = 1034 kPa, $\phi$ = 0.45

Heath et al. GT2010-22960

# review of NASA aero GT combustor research, cont.

- 2000s: Fundamental Aeronautics Program (FAP)

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

ACCESS objectives were to explore the potential of alternative fuels to
- reduce the impact of aviation on air quality and climate
- reduce impact on performance

Characterization done for flight tests, ground tests, lab tests

ACCESS benefits:
- Dramatically reduce environmental impact
- Support regulating agencies with real data

ACCESS II had two main goals:
- Measure and characterize the amount of soot and other pollutants generated by burning jet fuel (with either high or low sulfur content) that was blended with alternate biofuel.
- Gather basic data on contrail formation in the wake of a jet aircraft and study how or if burning blended fuel altered the contrail formation in any way.

Leverage prior ground tests


Lab studies

ACCESS 2 flight test campaign on-going (May 5-30, 2014)

- Establish effects of alternative fuels on engine emissions and thrust at cruise and examine the impact of aerosols on contrail formation
- In partnership with DLR (Germany), NRC (Canada), FAA (USA)

https://www.nasa.gov/aero/access-ii-confirms-jet-biofuel-burns-cleaner

# review of NASA aero GT combustor research, cont.

- 2000s: Environmentally Responsible Aviation (ERA), a Project within the Integrated Systems Research Program
  - Had a focus on N+3 technology and considered many technical areas to support the objectives for EIS 2030-2035
    - *Hybrid electric and turbo electric*
    - *Truss-braced wing*
    - *Blended wing*
    - Reduced NOx
    - Alternative fuels
    - Ultra high bypass ratio engines with small core

**NASA Subsonic Transport System Level Metrics**

*.... technology for dramatically improving noise, emissions, & performance*

| TECHNOLOGY BENEFITS* | TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6) | | |
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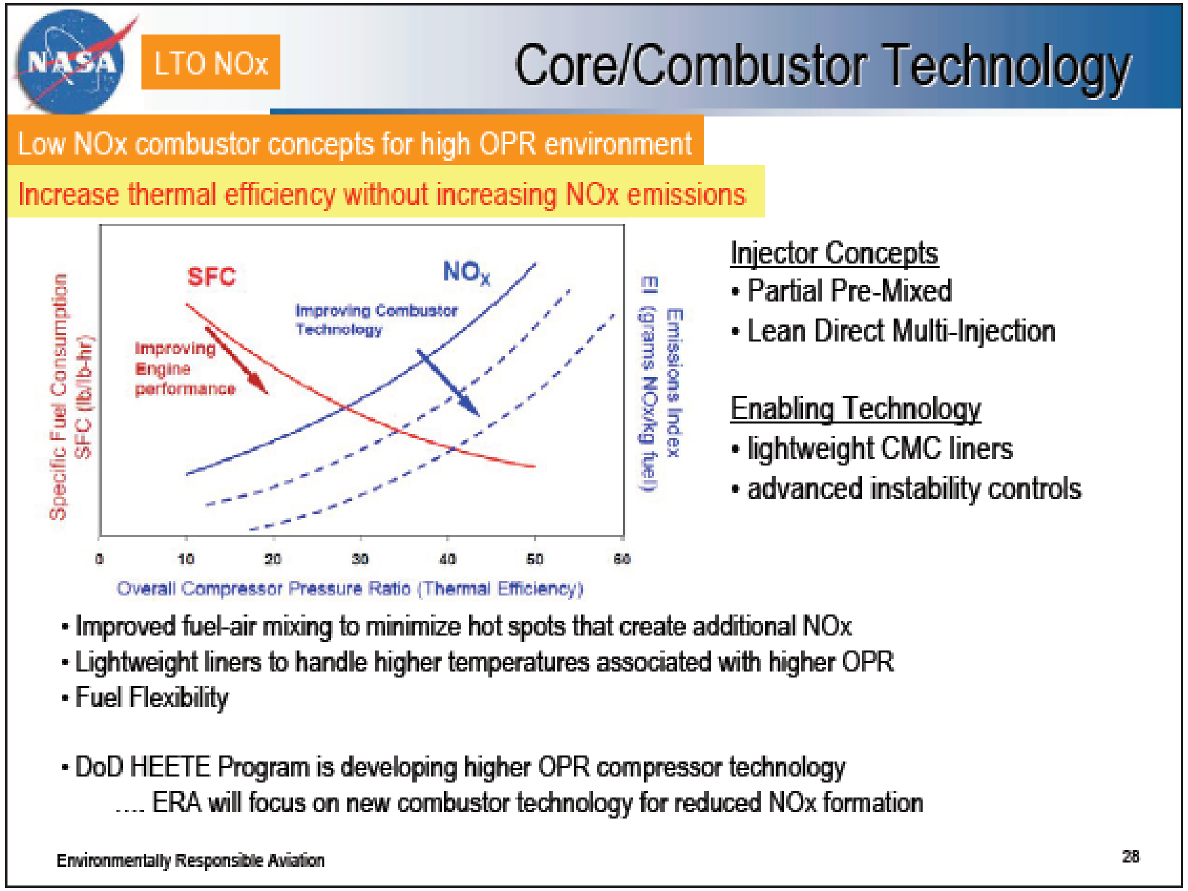
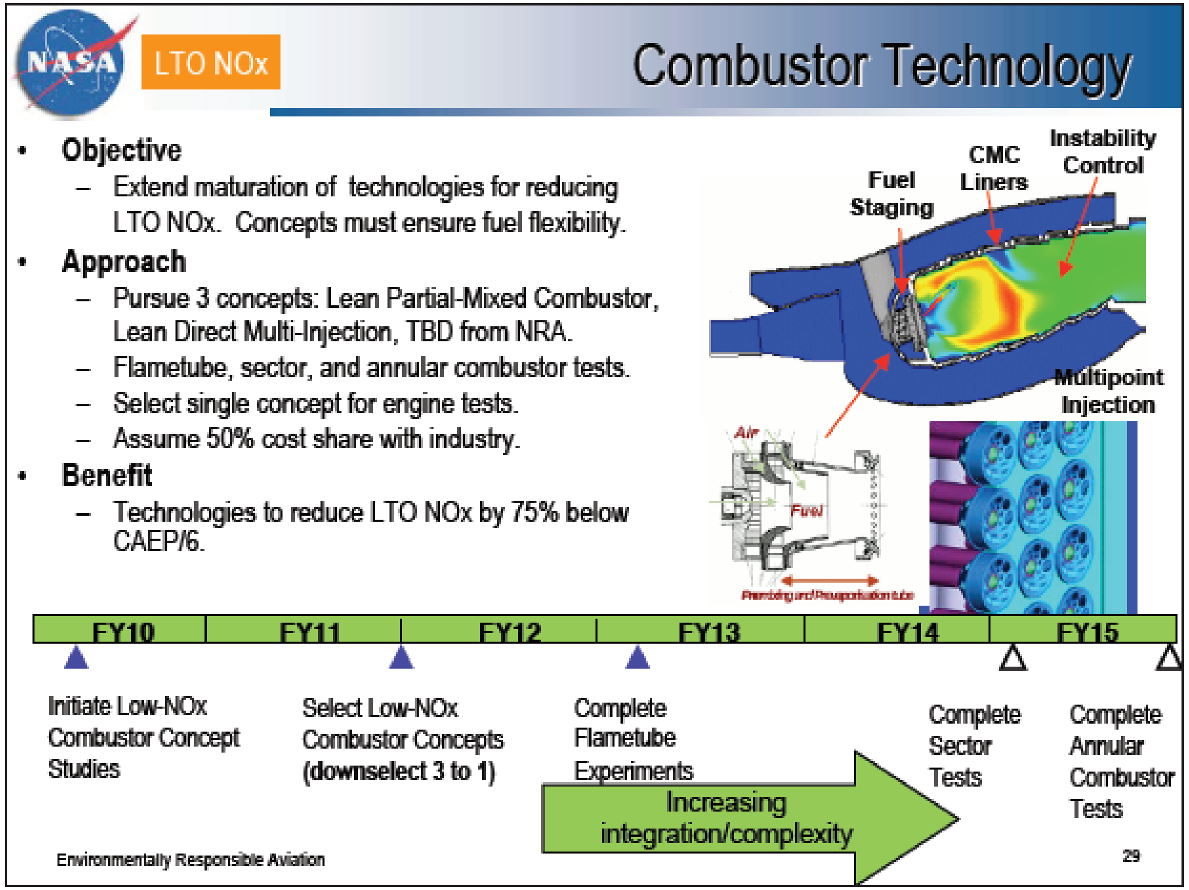
| Cruise NOx Emissions (rel. to 2005 best in class) | -55% | -70% | -80% |
| Aircraft Fuel/Energy Consumption‡ (rel. to 2005 best in class) | -33% | -50% | -60% |

  - ERA phase 1, from FY2010- FY2012 had the objective of meeting N+2 goals (TRL 4-6 by 2020) that included advanced engine combustor development via focused work under National Research Announcement (NRA) awards.
    - Multiple concepts were evaluated during phase 1, and most promising downselected to phase 2

# 2000s: Environmentally Responsible Aviation (ERA) Project

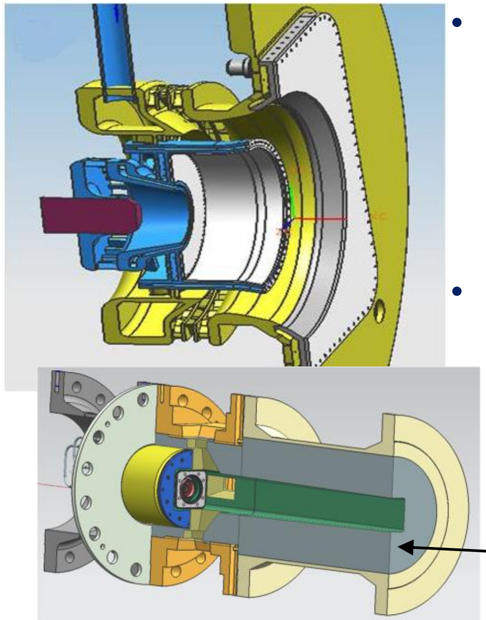



From Merlin (2020) Green light for green flight: NASA's contributions to environmentally responsible aviation
https://www.nasa.gov/connect/ebooks/aeronautics_ebooks_archive_1.html

# 2000s: FAP SUP and ERA subsonic test highlights

## UTRC Pilot in Can Swirler (PICS) injector concept

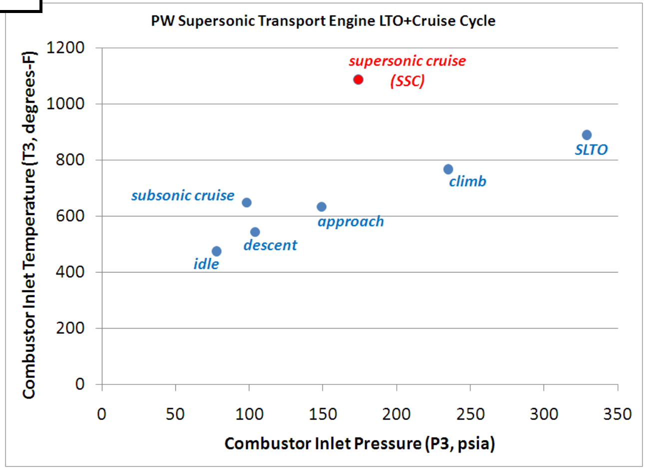


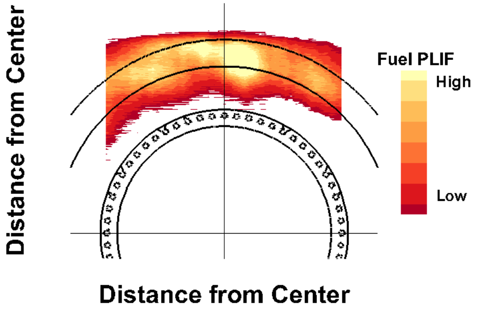
*Castable ceramic liner*

- Pilot
  - Low-power operation
  - Liquid fuel
  - Located in "can" inside the main swirler
  - can isolates pilot from main-stage flame
- Main-stage Supersonic flight
  - fuel used as heat sink
  - Flash vaporizes fuel for main swirler
  - low NOx emissions

| | P3-psi | T3-F | FAR / $FAR_{SLTO}$ |
|---|---|---|---|
| supersonic cruise 50k / M1.8 | 174 | 1087 | 1.10 |
| subsonic cruise 35k / M0.8 | 98 | 648 | 0.77 |
| SLTO | 329 | 890 | 1.00 |
| climb-66% | 235 | 767 | 0.82 |
| appoach-32% | 149 | 634 | 0.66 |
| descent-15% | 104 | 544 | 0.59 |
| idle | 78 | 475 | 0.57 |

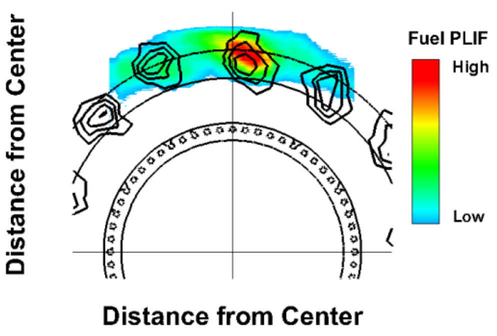
Differences between UTRC/NASA
- Supersonic cruise T3: 1087°F/ 975°F
- Subsonic cruise P3: 329/250 psia
- Fuel: *unheated* JP-5, ~ 70°F (UTRC used vaporized fuel)

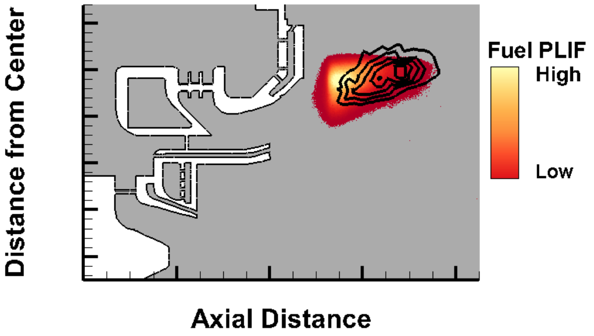



Subsonic Cruise Fuel Pattern

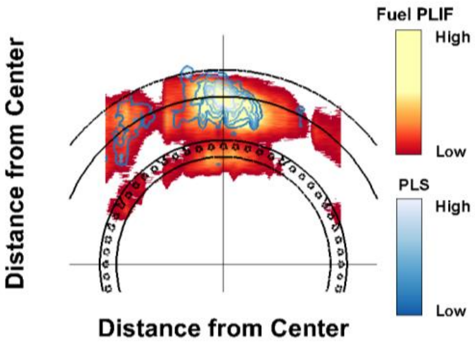
## Results from NASA GRC testing



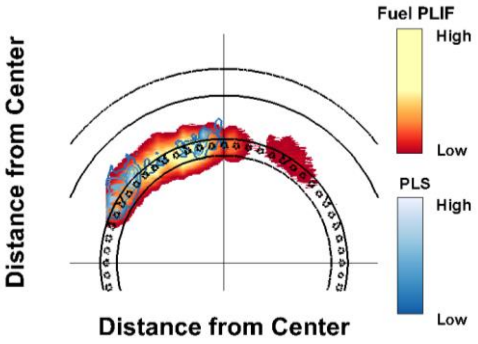




Distribution of Fuel (via PLIF) at N+3 Supersonic Cruise Condition
Line contours CFD; Color contours fuel PLIF
JP-8 enters as liquid at ~ 70°F, T3 = 975°F

Approach-1—Pilot + Main




Approach-2—Pilot Only




Note: UTRC is now RTRC

Hicks et al. AIAA-2014-3627

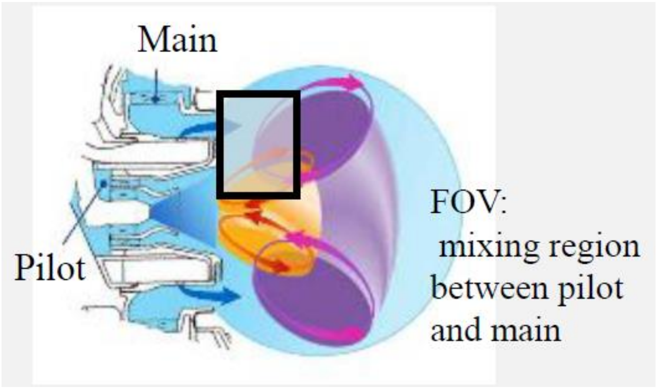
# 2000s: FAP SUP and ERA subsonic test highlights

## Comparing Alternative BioFuel HRJ and JP-8 Fuel: Flame Tube Tests using a GE TAPS Injector Configuration

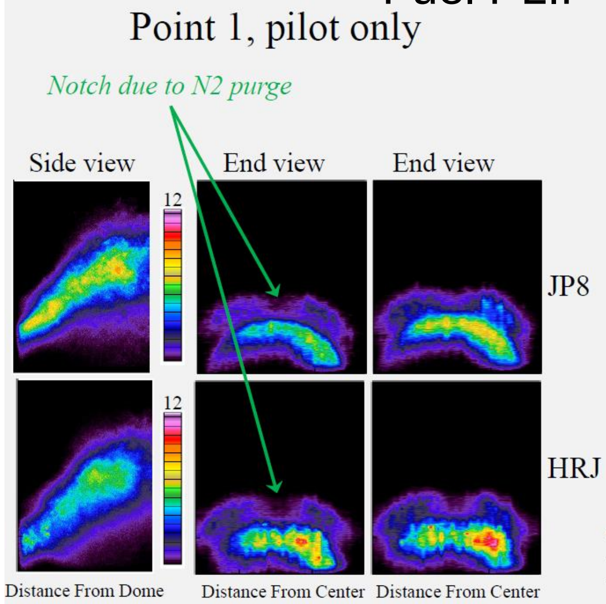
| Test Point | $P_3$ psia | $T_3$ °F | Fuel Split % Pilot/Main | $FAR/FAR_{SLTO}$ |
|---|---|---|---|---|
| 1 | 166 | 650 | 100/0 | 0.48 |
| 2 | 200 | 925 | 10/90 | 0.94 |
| 3 | 200 | 1000 | 20/80 | 0.94 |
| 4 | 200 | 1000 | 10/90 | 0.94 |

Fuel settings:
- 100% HRJ,
- 100% JP8,
- 75% HRJ/25% JP8

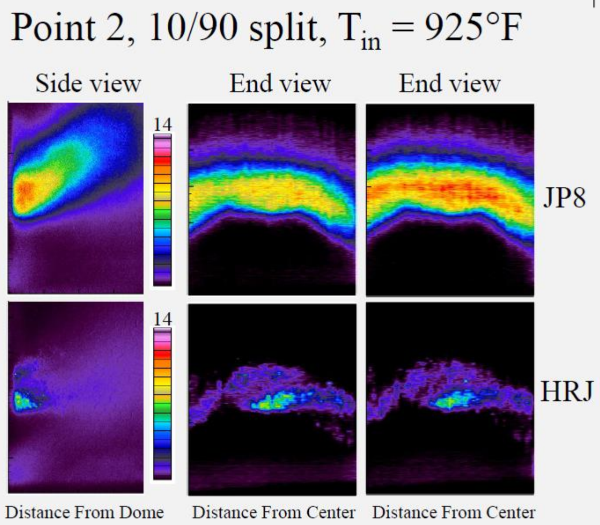
| Fuel | JP-8 | HRJ |
|---|---|---|
| Sulfur (ppm) | 1148 | <3 |
| Olefins (%vol) | 0.9 | 0.4 |
| Aromatics (%vol) | 18.6 | 0.4 |
| Naphthalenes (%vol) | 1.6 | 0 |
| Initial boiling point, ° | 158 | 165 |
| 10% | 176 | 179 |
| 90% | 248 | 243 |
| End Point | 273 | 231 |
| Flash Point °C | 46 | 55 |
| API Gravity | 41.9 | 54 |
| Specific Gravity | 0.816 | 0.758 |
| Freezing Point °C | -50 | -62 |
| Viscosity | 4.7 | 5.3 |
| **Cetane Index** | **41** | **67** |
| H Content (%mass) | 13.6 | 15.3 |
| Heat combustion (MJ/kg) | 43.3 | 44.5 |
| **Fuel H/C ratio** | **1.88** | **2.12** |




Fuel PLIF



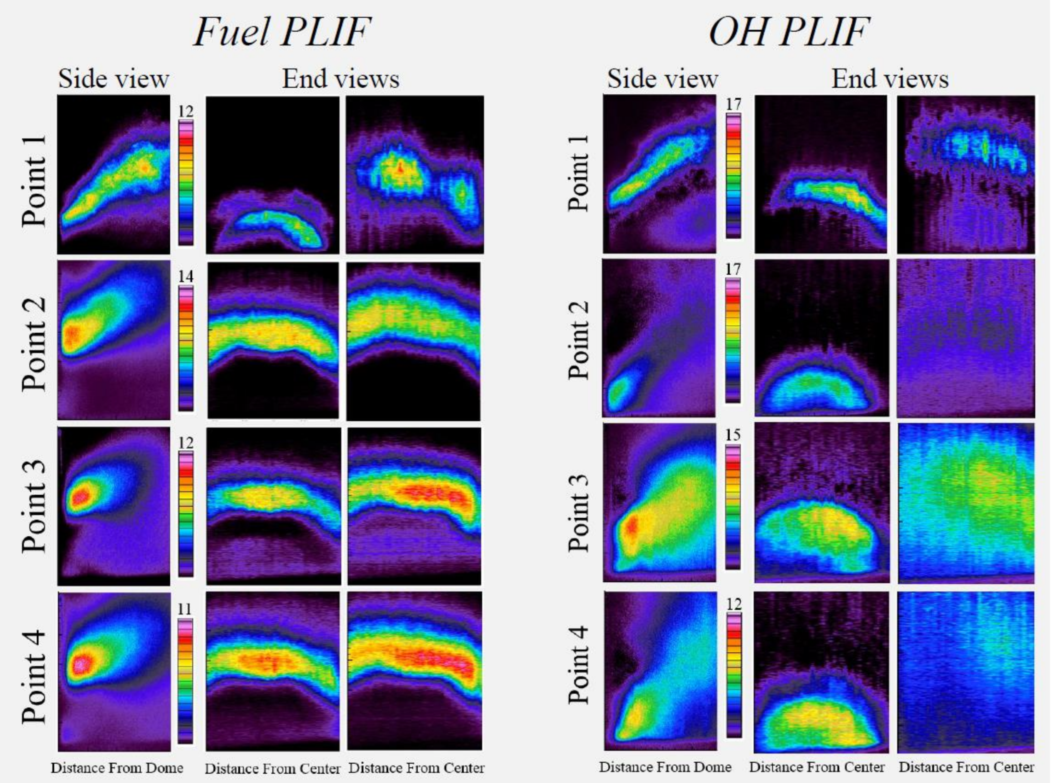

For pilot only, JP8, HRJ have similar spray pattern




JP8: uniform distribution within annulus

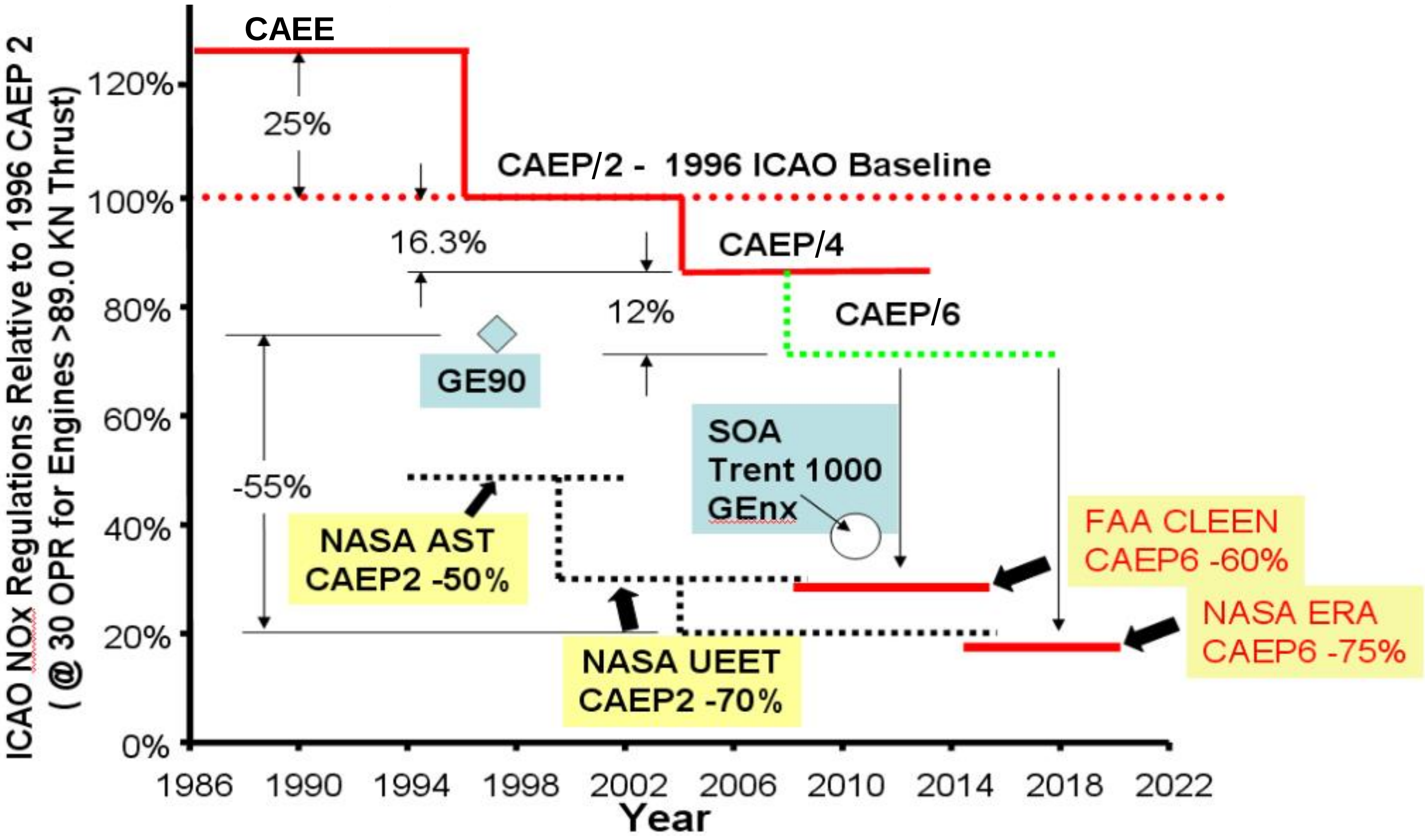
HRJ: Most fuel observed near wetted annular walls

Possibly only HRJ liquid seen because greater number density than in gas phase




Hicks et al. AIAA-2016-4890

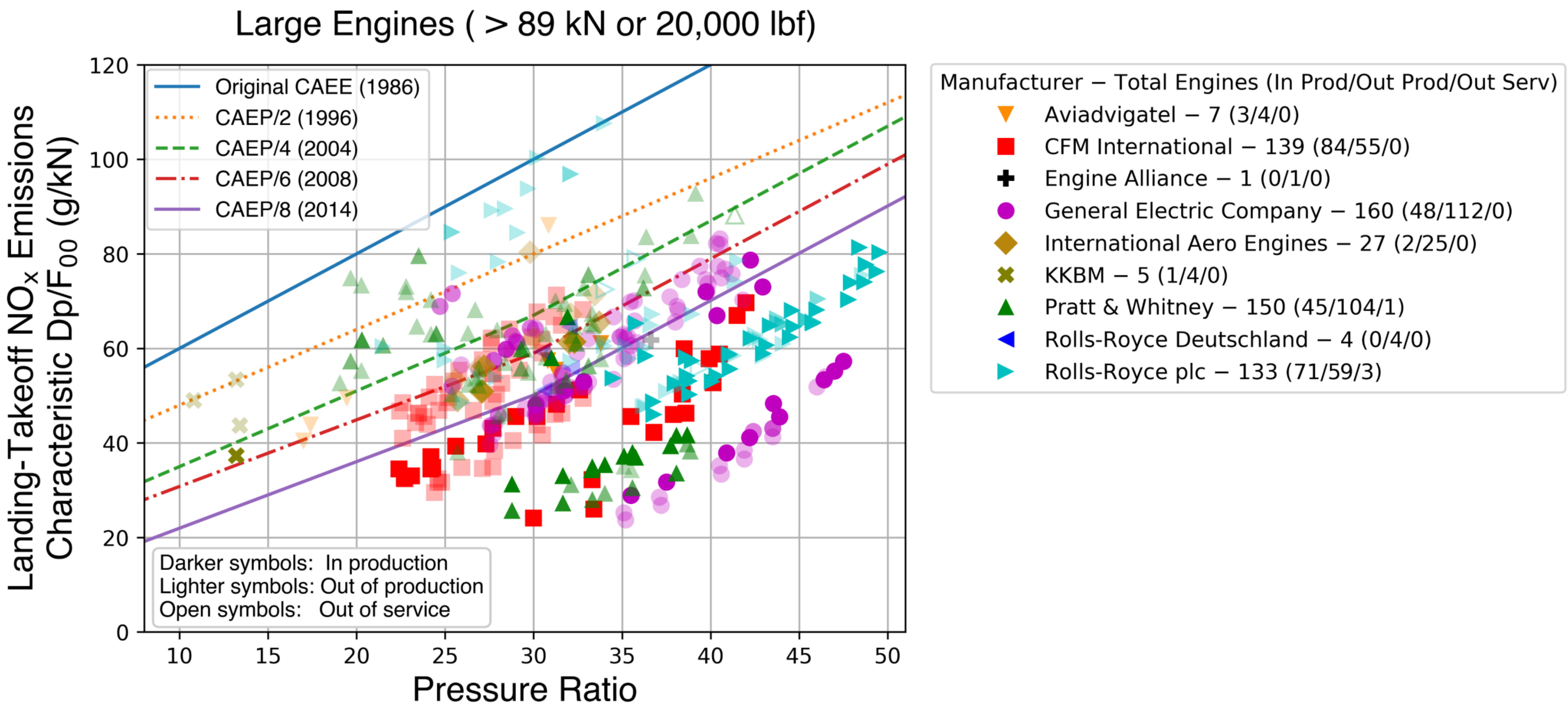
# History of ICAO CAEP regulations for high thrust engine subsonic aircraft from CAEE through CAEP/6






Reddy and Lee GT2016-56100

# Evolution of ICAO CAEP LTO NOx regulations through CAEP/8, along with engines by manufacturer




*Tacina, 2023*

# Part 3: Present and Future, since 2015

Present and future are combined here. One reason is that NASA looks forward to anticipate future needs, as was demonstrated in Part 2 and summarized in the last two slides that show the progress in emissions reduction.

The present comes from the past FAP N+3 and Integrated Systems Research Program ERA goals in other areas (such as for airframe and turbomachinery technologies). These in part led to the current Sustainable Flight National Partnership (SFNP) for subsonic aircraft, which has the objective of achieving net-zero carbon emissions by 2050. A key SFNP activity is the Hybrid Thermally Efficient Core (HyTEC) which will affect work in the Combustion and Emissions area.

The supersonic flight regime presents more Combustion and Emissions challenges to be met.

https://www.nasa.gov/sfnp/ https://www.nasa.gov/aeroresearch/programs/aavp/hytec/technical-portfolio/

# Present → Future: Programs and Projects

Environmentally Responsible Aviation Project (ended 2015)

Advanced Air Vehicles Program (AAVP) began 2016

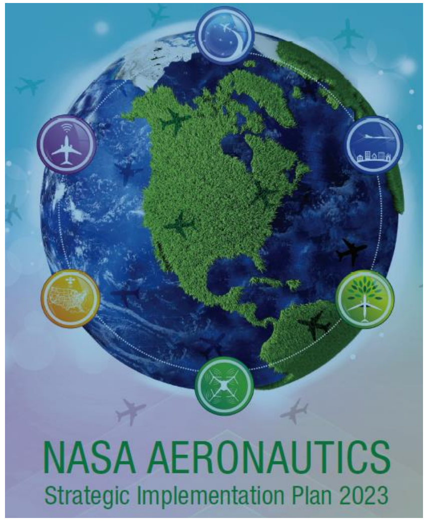
- Advanced Air Transport Technology (AATT)
- Commercial Supersonic Technology (CST)
- Hypersonic Technology (HT)
- Hybrid Thermally-Efficient Core (HyTEC)

Transformative Aeronautics Concepts Program (TACP) began 2015

- Transformative Tools and Technology (TTT, $T^3$)
- Convergent Aeronautics Solutions (CAS)
- University Innovation (UI)

NASA ARMD Strategic Implementation Plan. See Thrusts 2 and 3

https://www.nasa.gov/sites/default/files/atoms/files/sip-2023-final-508.pdf



# Present → Future: AAVP

- AATT project: develop technologies for advanced fixed wing aircraft with high energy efficiency and environmental compatibility. Combustor related technical challenge (TC) is for a fuel-flexible combustor with NOx emissions 80% below CAEP/6 standard with minimal impacts on weight, noise or component life.
  - nvPM extractive & optical measurements
  - N+3 combustor emission measurement and simulations
- CST project: develop technologies that eliminate barriers to commercial supersonic flight. Relevant to combustion are NOx and particulate emissions.
  - Low NOx injector for supersonic cruise
- HyTEC project: develop small core engine tech that enables electrical power extraction (up to 20% at altitude), reduces fuel burn (5% - 10% compared to best-in-class turbofan), and is compatible with 80% - 100% sustainable aviation fuels.
  - Sustainable aviation fuel (SAF) combustor technologies

https://www.nasa.gov/aeroresearch/programs/aavp/aatt
https://www.nasa.gov/aeroresearch/programs/aavp/cs
t
https://www.nasa.gov/aeroresearch/programs/hytec

# Present → Future: TACP

- $T^3$ project: develop state-of-art computational and experimental tools and technologies
  - Soot modeling and experiments
  - Fuel injector: X-ray atomization imaging experiments
  - Transcritical fuel sprays—collaboration with Sandia National Labs
  - Conjugate heat transfer

- UI project: provide opportunities for university-led teams to conduct research into transformative technology to support NASA ARMD goals via NASA Research Announcement awards. These include University Leadership Initiative (ULI), University Students Research Challenge (USRC), and Gateways to Blue Skies Competition (Blue Skies)

https://www.nasa.gov/aeroresearch/programs/tacp/ttt https://www.nasa.gov/aeroresearch/programs/tacp/ui/description/

# Present → Future

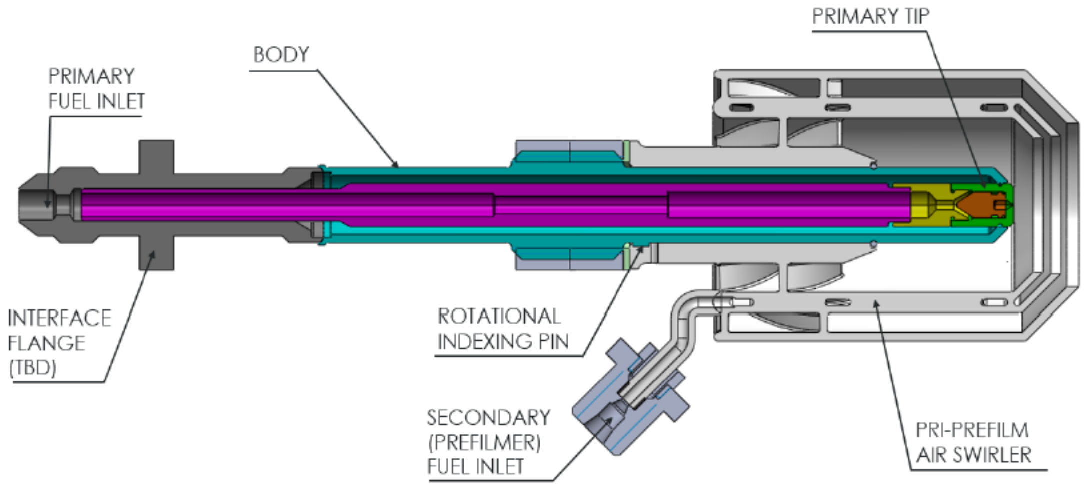
This last section will feature examples in areas not previously highlighted.

- Fuel injection research—Aero Spray Working Group collaboration
- NASA Sustainable Aviation Strategy and Sustainable flight
- Sustainable aviation fuels (SAFs) practicalities
  - Engine emissions
  - Stability: LBO, cold start, altitude relight
- Modeling
  - Fuel injection
  - LBO, ignition
  - Combustors

# Fuel Injector Studies

A non-proprietary prefilming injector is being studied by a consortium called the Aero Spray Working Group (ASWG) that includes the US engine OEMs, AFRL, ARL, ONR, ANL, and NASA to better understand the fuel injection process as it proceeds from inside the injector and into the combustion chamber. X-ray techniques are being conducted by partners at Argonne National Lab that will help to answer these questions. Create detailed measurement database.

Measurement phases
Phase 1: 1 atm, 25°C
Phase 2: 50 atm, 25°C
Phase 3: 50 atm, 700°C




Non-proprietary fuel injector *Woodward FST*

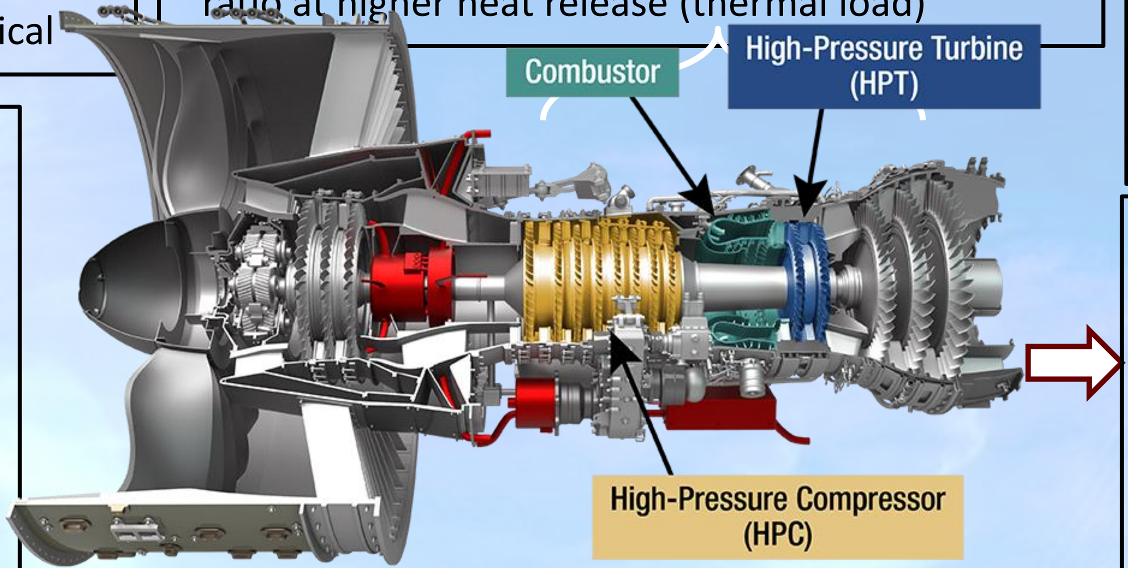
# Combustion and Emissions Challenges for Future Systems

**High OPR**
- Higher P3, T3 air into combustor creates challenges for
  - Low NOx
  - Durability
  - Fuel at trans/supercritical

**Small Core Challenges**
- Scaling combustor to smaller size (residence time, operability, emissions, fuel-nozzle orifice limits)
- Cooling with increased combustor surface/volume ratio at higher heat release (thermal load)

**High-Speed Challenges**
- Long Duration Cruise at harshest thermal condition
- High-altitude required to reduce fuel burn drives need for ultra-low NOx (to minimize ozone depletion)
- Strong drive to quickly get to 100% SAF

**Heated Fuels**
- Thermal management and/or cycle efficiency goals may drive use of fuel as heat sink (small core, high-speed)
- Fuel coking
- Fuel system control, injection, fuel-air mixing if fuel is trans/supercritical




**Emission Challenges**
- New CAEP/11 nvPM standards (LTO)
- More stringent future standards on LTO and potentially cruise (NOx, nvPM)
- Reducing non-CO2 aviation impacts on climate (NOx, particulates, contrail-cirrus formation)
- For Supersonic high-altitude, ultra-low NOx needed to reduce ozone depletion

**Sustainable Aviation Fuels**
- Scaling production of existing and new production pathways is largest challenge
- Further work needed to quantify/maximize SAF benefits (reduced soot, higher thermal stability), and evaluate operability and contrail impact for higher SAF blends

**Hydrogen**
- Different views on degree to which $H_2$ may contribute to meeting net-zero carbon 2050 aviation goals
- Combustion challenges include:
  - Low-NOx while preventing flashback
  - Fuel injection
  - Combustion dynamics

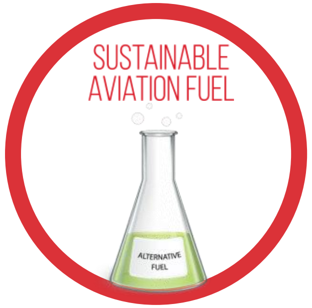
# U.S. Aviation Climate Action Plan

## Global Context for Sustainable Aviation

U.S. aviation goal is to achieve
**net-zero greenhouse gas emissions by 2050.**

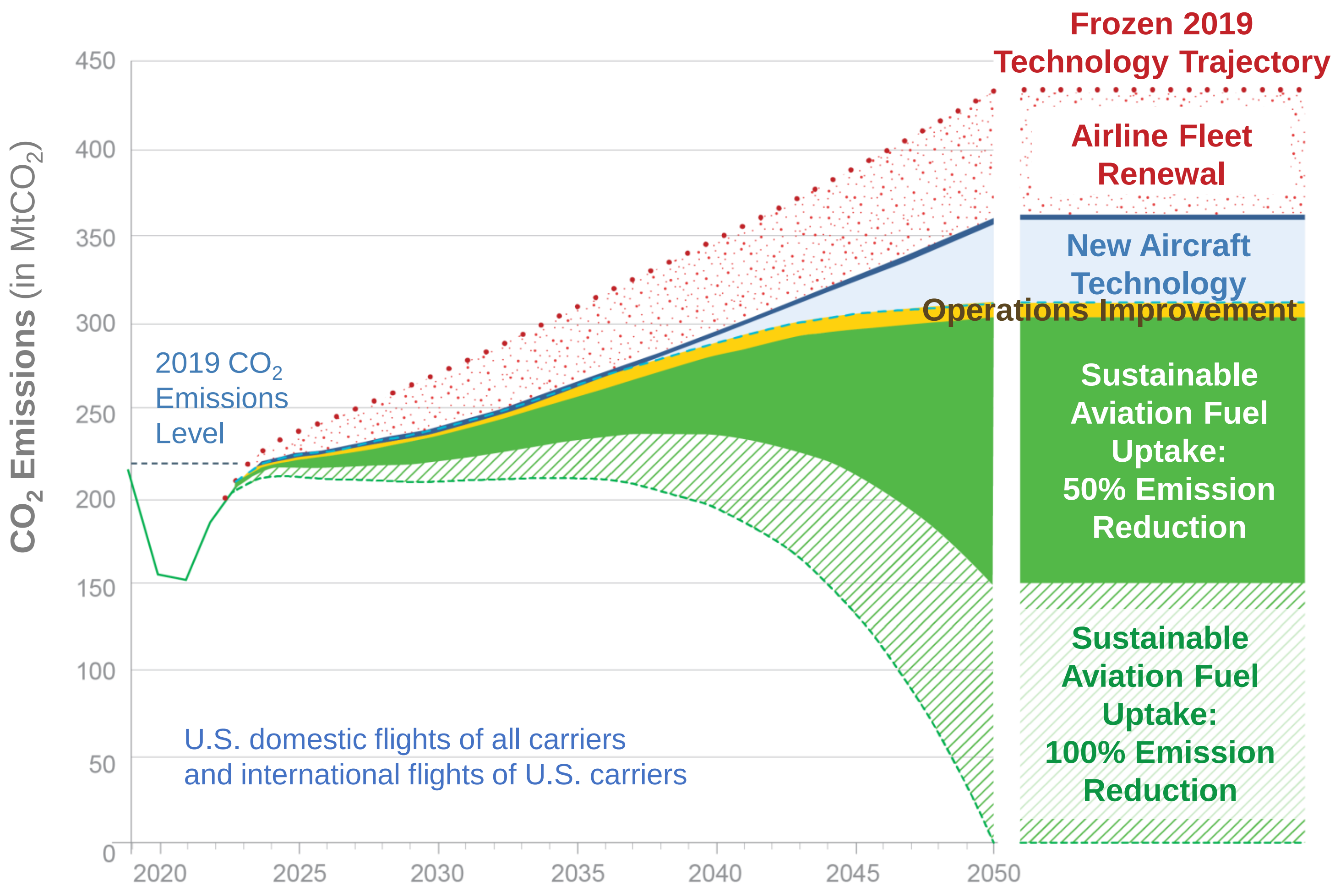
U.S. Aviation Climate Action Plan is aligned with
- U.S. economy-wide goal
- International Civil Aviation Organization
- Air Transport Action Group


NASA = Primary Role




NASA = Supporting Role


NASA = Primary Role




https://www.faa.gov/sites/faa.gov/files/2021-11/Aviation_Climate_Action_Plan.pdf

Klettlinger and Moore, AEC roadmap mtg, May 2023

The U.S. is working with the global community to achieve net-zero greenhouse gas emissions by 2050 using a common basket of measures.

# NASA Sustainable Aviation Strategy

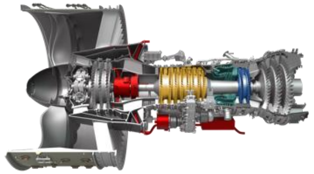
2008-2013 | 2014-2019 | 2020-2025 | 2025-2030 | 2030+

Subsonic Concept/Technology Studies
Electric Aircraft Propulsion,
Transonic Truss-Braced Wing
Blended Wing Body

Environmentally Responsible Aviation Project

Flight Demonstrator Studies

Advanced Composites Project



**SUSTAINABLE FLIGHT NATIONAL PARTNERSHIP**

Sustainable Flight National Partnership to mature and integrate key technologies for next-generation subsonic transports (2030s)

**TODAY**

**ACCELERATING TOWARD NET-ZERO CARBON**

Cast a wide net for zero-emission concepts and technologies

Select and develop promising concepts in partnership with universities, industry

Create a credible mission, architecture, and technologies for beyond next-generation subsonic transports for 2050 horizon

**POWERING AVIATION TO NET-ZERO CARBON AND BEYOND**

Klettlinger and Moore, AEC roadmap mtg, May 2023

Investment in innovation today paves the way
to a net-zero carbon and beyond aviation future.

# Sustainable Aviation Fuels (SAF)

Alternative Jet Fuels (AJF): Fuels produced from **non-petroleum** feedstocks

Sustainable Aviation Fuels (SAF): Fuels produced from **renewable** non-petroleum feedstocks in **sustainable** manner

"**sustainable**" typically includes*:

- Reducing net life-cycle $CO_2$ emissions relative to petroleum-based jet fuel.
- Enhancing the sustainability of aviation by being superior to petroleum-based jet fuel in economic, social and environmental aspects.

SAFs also provide additional health and climate benefits:

- SAFs typically have low (or zero) aromatics content, leading to significant reductions in particulate emissions, which reduces health impacts from engine emissions and reduces contrail formation, a significant non-$CO_2$ contributor to aviation's impact on climate warming.
- SAFs have zero sulfur content, thus removing the formation of sulfur oxides and sulfates resulting from engine emissions, reducing adverse health impacts from aviation

SAF composition and physical properties can vary significantly depending on the feedstock and process for creating a particular synthetic (non-petroleum) jet fuel.



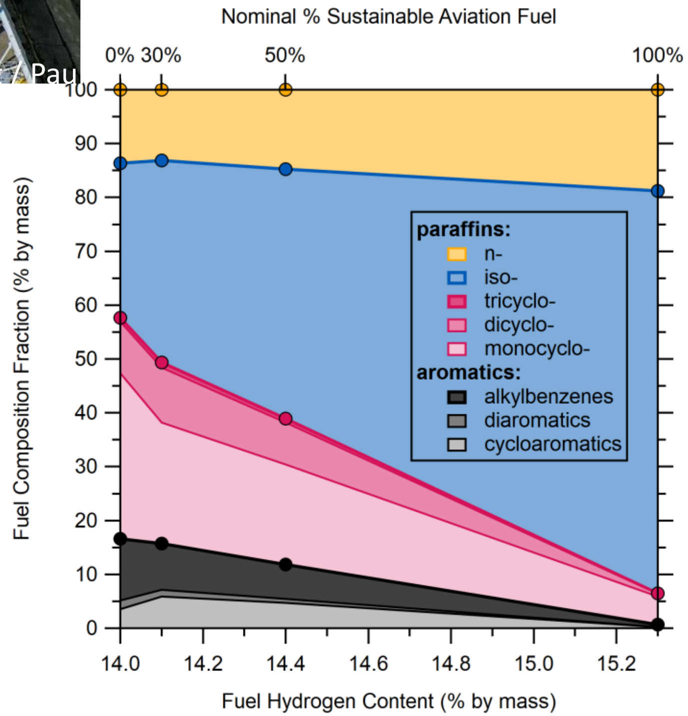
* *CAAFI (Ccommercial Aviation Alternative Fuels Initiative)*: https://caafi.org

# SAF Emissions and Contrails Research

## October 2021 Emissions Ground Test at Boeing Field

- Goal to quantify on-wing emissions relevant for contrails & air quality
- Ultra-low-emitting CFM LEAP-1B engines on the 2021 ecoDemonstrator 737 MAX 9
- Four fuels:
  - 100% SAF HEFA (World Energy)
  - 50-50% SAF-Jet A
  - 30-70% SAF-Jet A
  - 100% Jet A
- Test covers a range of engine thrust conditions from engine idle to takeoff
- Burning 100% SAF in the LEAP-1B engines should give us the lowest possible emissions achievable with in-service technology!

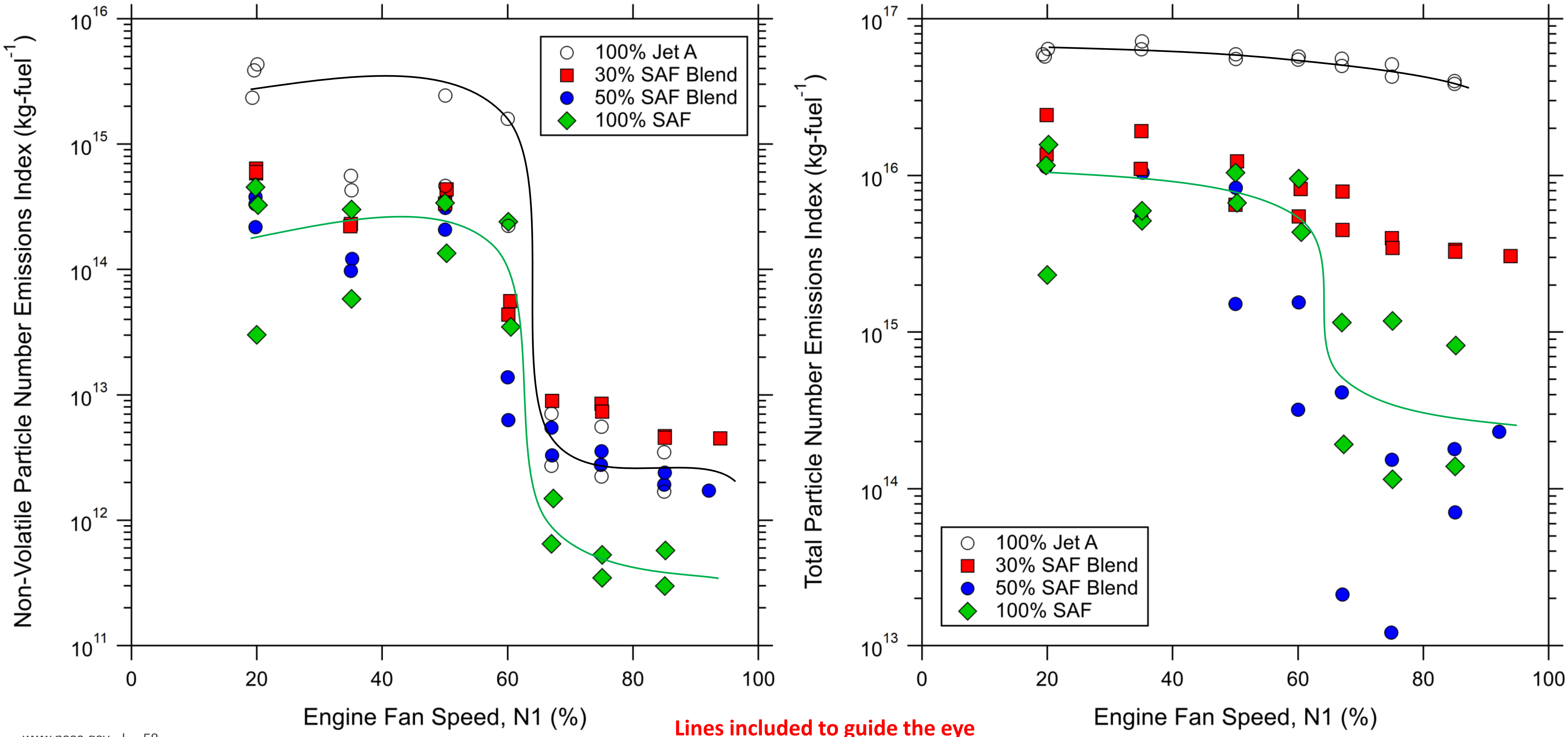

- Good linearity between aromatics and %hydrogen
- 50% SAF tested is NOT halfway between 0% and 100% in terms of aromatics or %hydrogen




https://www.nasa.gov/aeroresearch/nasa-tests-sustainable-aviation-fuel-emissions

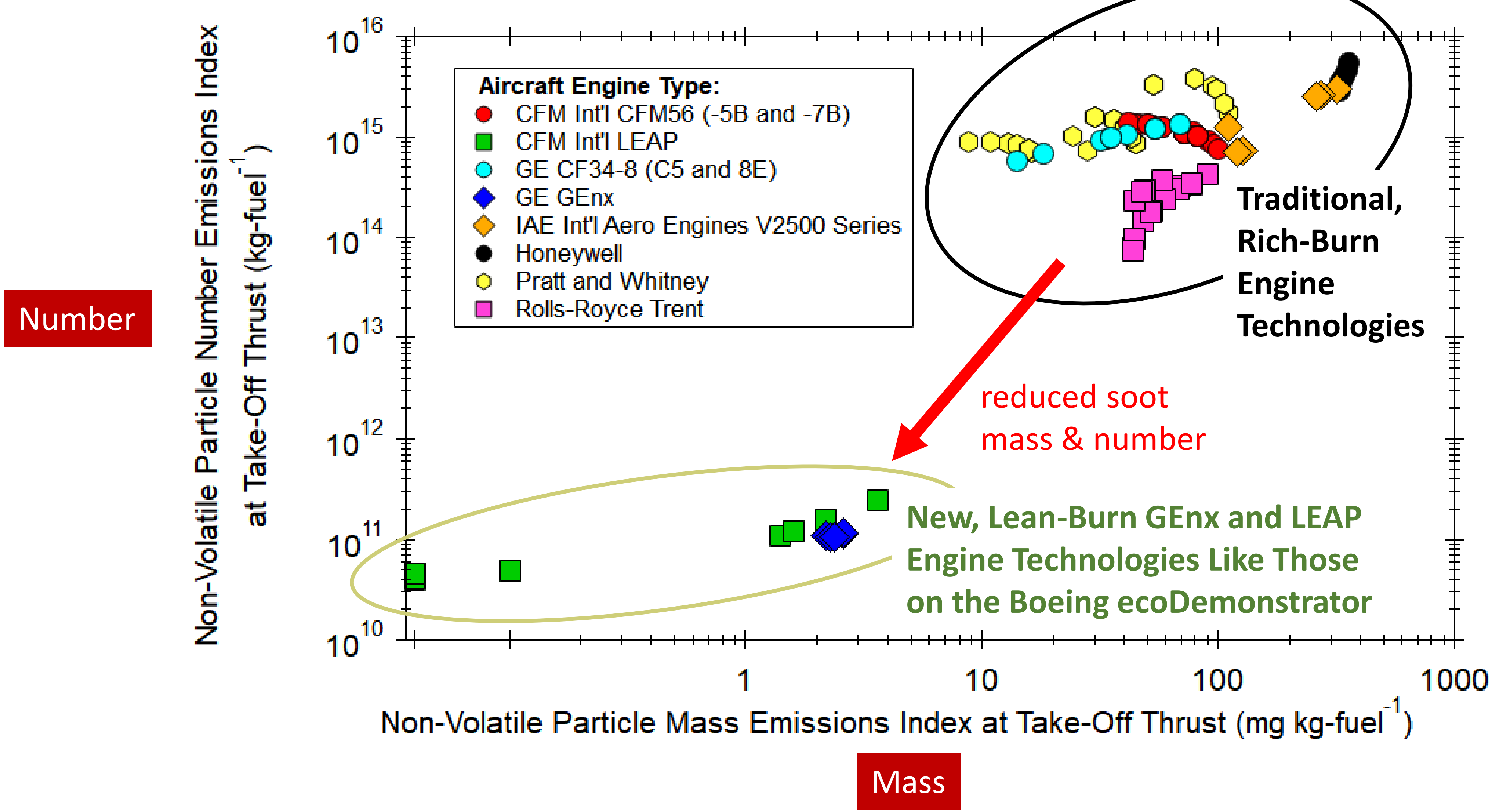
POC: Dr. Rich Moore, LaRC

# Significant Fuel Impacts on Non-Volatile and Total Particle Number




**Lines included to guide the eye**

# Recent ICAO Engine Certification Data (released 12/2020) hint that reductions could be even greater for new combustor technologies!

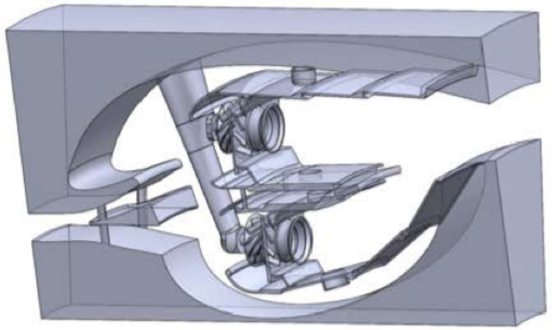


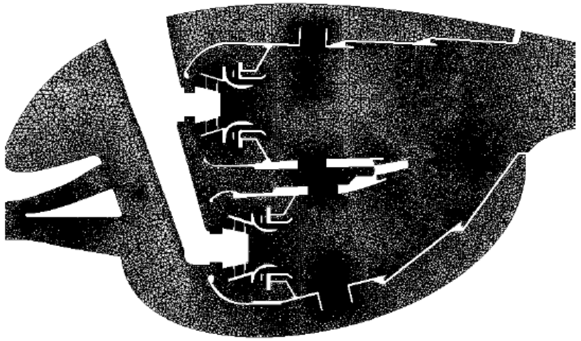
# Combustor modeling examples

- TTT: computational study of combustor-turbine interactions
- CST: modeling of axially-controlled stoichiometry combustor—fuel effects
- CST: evaluation of Woodward FST LDI combustor design variations

# Computational Flow Field in Energy Efficient Engine using OpenNCC

## This work revisited the GE DAC combustor from $E^3$
## Objective: better understand combustor-turbine interactions





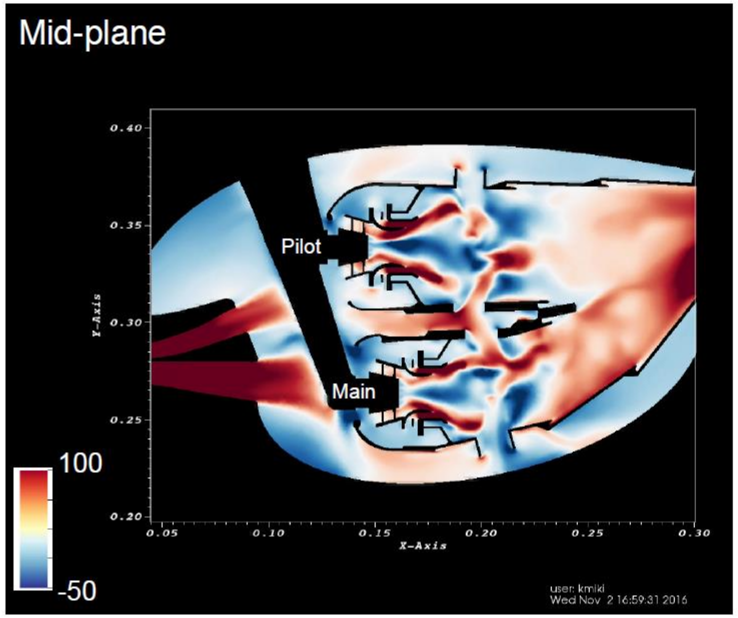
| | Numerics | Steady? | Spray | Fuel | Chemistry |
|---|---|---|---|---|---|
| Case 1 | JST/AUSM | Yes | Gas | C12H23 | one-step |
| Case 2 | JST/AUSM | Yes | Liquid | C11H21 | 14 species-18 reactions |
| Case 3 | JST/AUSM | No | Liquid | C11H21 | 14 species-18 reactions |

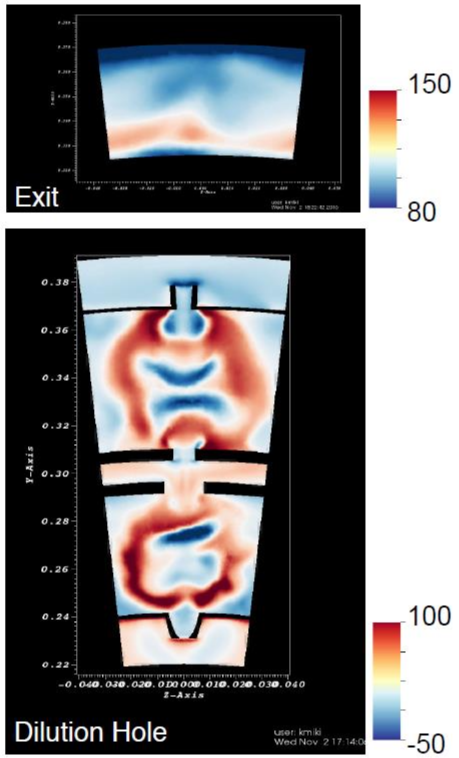
- One-cup (12 degree) $E^3$ geometry(1) is considered
- Tetrahedral mesh (~9.5M) is generated by Cubit (AMR is off)
- Used 960 processors of Pleiades at NASA Advanced Supercomputing facility
- Non-linear k-ε model and finite-rate chemistry
- Taken into consideration is the simulated sea level takeoff condition (SLTO)

| | P3 [atm] | T3 [K] | W3 [kg/s] | $Wf_{total}$ [kg/s] | f/a | $Wf_{pilot}/Wf_{total}$ | $T_{fuel}$ [K] |
|---|---|---|---|---|---|---|---|
| SLTO | 2.52 | 720 | 0.26 | 0.00364 | 0.014 | 0.5 | 520 |

(1) Burrus, D. L., et al, No. NASA/CR-1984-168301, (1984)

### Unsteady flow fields. Contours of axial velocity




- Dilution airflow and swirling airflow interact and oscillate back and forth.
- There is a recirculation zone at the top of the dilution hole, enhancing the oscillation.

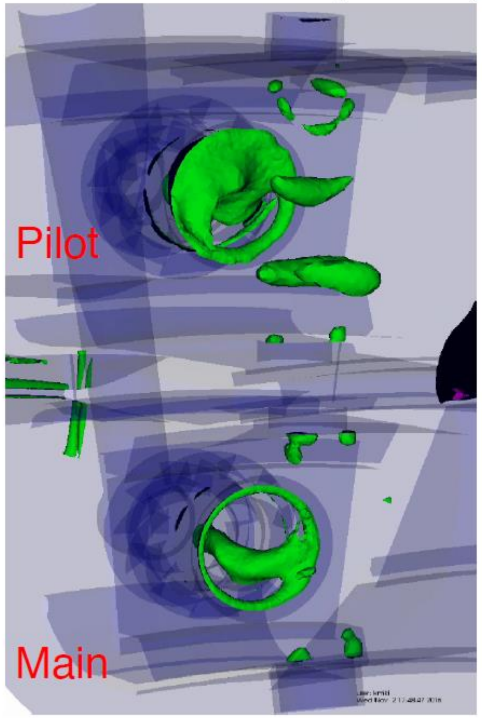
*Miki, Moder, Liou 2016*

One of the issues that greatly affects the blade life and overall gas turbine durability is the existence of hot-streaks. The pronounced non-uniform high temperature spots are often seen on the blade surface. To avoid hot-streaks, the distribution of the cooling air holes needs to be carefully determined. Although the design and investigation of heat transfer of HPT has been done for decades, a full understanding of the formation mechanism of hot-streaks has not yet been achieved

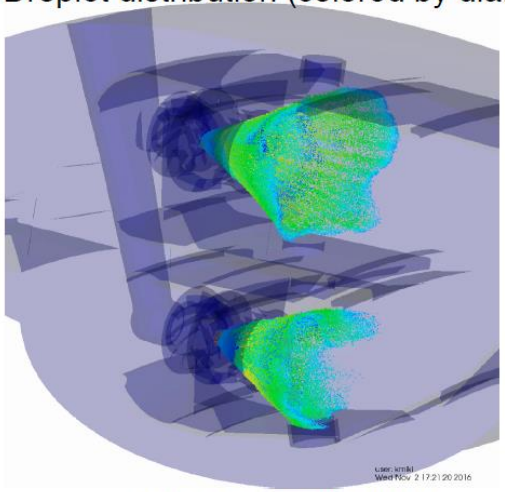
# Computational Flow Field in Energy Efficient Engine using OpenNCC

## Precessing vortex core

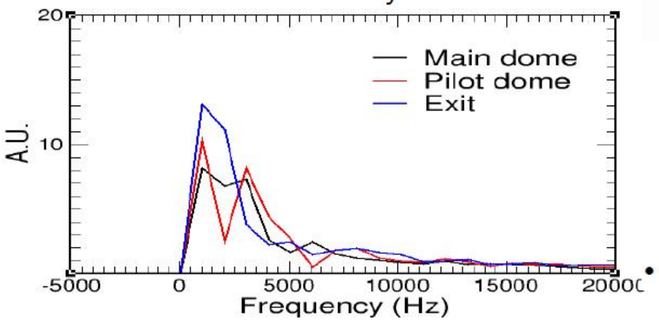
Pressure iso-surface (245K Pa)




Droplet distribution (colored by dia.)

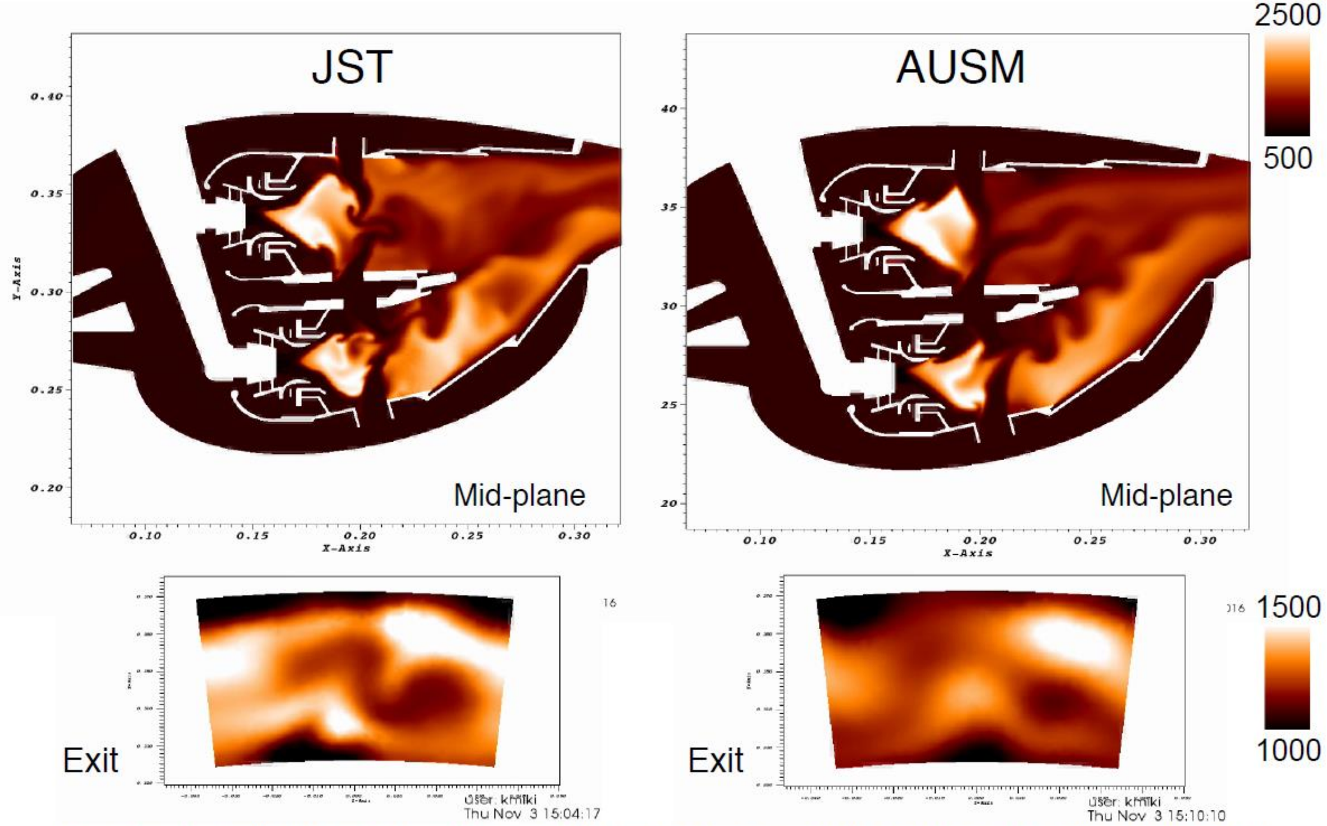


FFT of velocity fields




PVC greatly impacts on the particle motion and the combustion dynamics.

## Temperature fields, time averaged




- Temperature field is not uniform at the combustor exit and lots of hot/cold “spots” .

*Miki, Moder, Liou 2016*

# CST High Altitude Emissions: CFD Evaluation of Advanced Fuel Blends

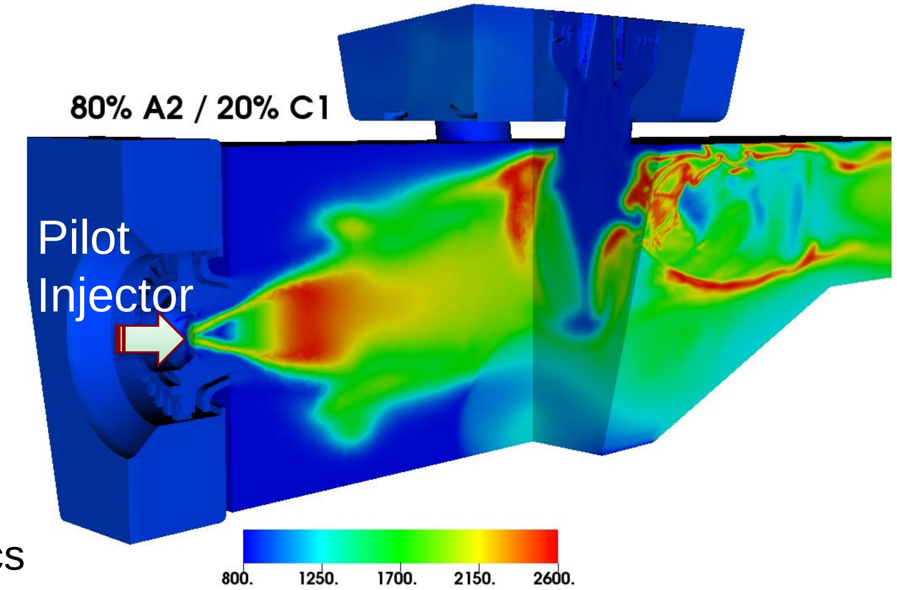
- **OpenNCC CFD Analysis of Fuel Blending. Use Sustainable Aviation Fuels (SAF) for CST**

  **Combine faster-burning Jet-A (A2) with slower-burning SAF (Alcohol-to-Jet or ATJ C1) and assess the effects on Combustor Performance, Flame Stability, Emissions (CO and NOx)**

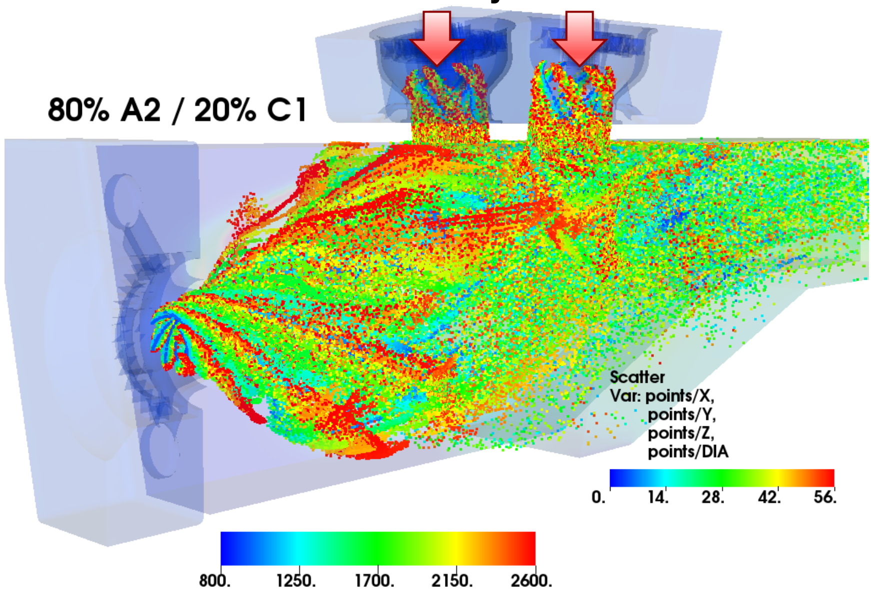
  **Three blending ratios for A2/C1: 80/20, 50/50, 20/80**

| **Composition** | **A2** | **C1** |
|---|---|---|
| aromatics | 20% | |
| iso-paraffin | 20% | 100% |
| n-paraffin | 20% | |
| cyclo-paraffin | 40% | |
| Derived Cetane Number | 49 | 16 |

- Initial Flame w/ 51 Species Kinetics
- Add 30 Species for NOx
- Test and verify multi-component fuel evaporation model
- 1200hrs (1000 NAS cores) for each run




Typical Temperature (K) Contours




Typical Spray Droplet Pattern

Comparable Performance, Flame Stability, EINOx and CO for all three blends. 50/50 Blend shows some advantages.



*POC: Kumud Ajmani, Jeff Moder, Jennifer Klettlinger*

# CST High Altitude Emissions: CFD Evaluation of Advanced Fuel Blends

## Objectives

- CFD assessment of an axially-staged combustor (developed under ERA and AATT N+3 by PW/UTRC) at supersonic cruise with advanced fuel blends to assess fuel impacts on NOx emissions and flame structure

## Summary Findings

- Three Fuel blends: 80/20, 50/50, 20/80 Jet-A (A2)/Gevo Alcohol-to-Jet (C1)

  CFD predictions of flame-structures for all three fuel blend mixtures are similar at CST Cruise conditions with similar flame holding and stability relative to Jet-A

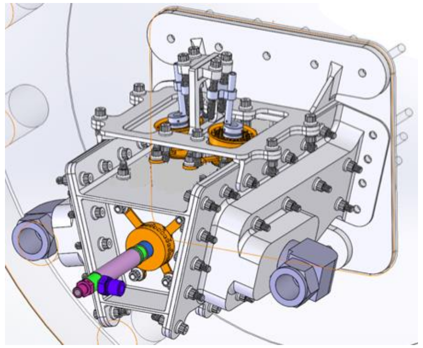
  CFD predictions of NOx emissions for all three fuel blend mixtures are within 10% of each other at CST Cruise conditions.

  CFD predictions of NOx emissions for all three fuel blend mixtures are within 10% of measured experimental values for 100% Jet-A fuel at CST Cruise conditions.

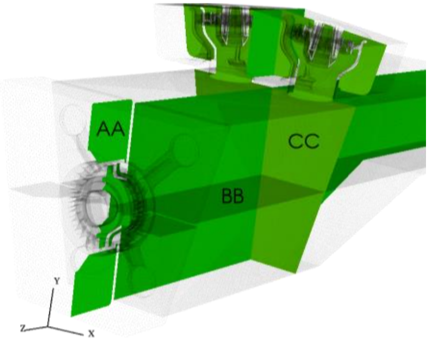
## Significance

***CFD study demonstrated similar flame structures and NOx emissions for fuel blends covering large range of composition and combustion properties variation for a next-generation axially-staged combustor***

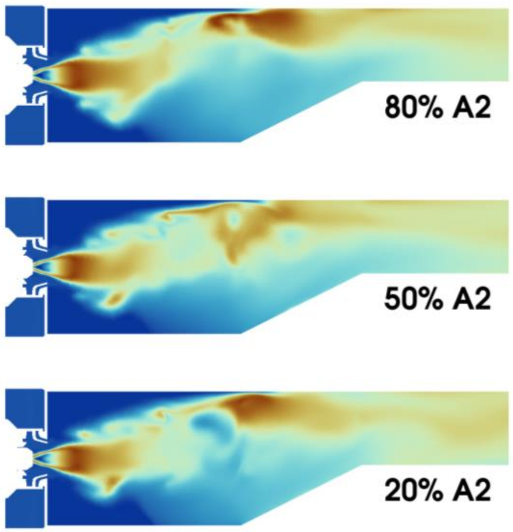
UTRC Hardware



CFD Geometry




**CFD Flame Structure**
(Slice AA)




**Fuel Composition**

| Fuel Composition | A2 (Average Jet-A) | C1 (Gevo ATJ) |
|---|---|---|
| aromatics | 20% | 1% |
| iso-paraffin | 20% | 99% |
| n-paraffin | 20% | |
| cyclo-paraffin | 40% | |

**Predicted Emissions**

| A2 % | C1 % | EINOx |
|---|---|---|
| 80 | 20 | **15.5** |
| 50 | 50 | **14.5** |
| 20 | 80 | **16.0** |

*POC: Kumud Ajmani, Jeff Moder, Jennifer Klettlinger*

# CFD Evaluation of Woodward FST LDI Combustor Design Variations

## Objectives

- CFD assessment of 3rd and 4th generation Lean Direct Injection (LDI) Combustors (Woodward, FST Inc) to predict the effects of injector design changes on NOx emissions and flame structure

## Summary Findings

- Three Designs: Axial Air Swirlers (baseline, 3rd generation LDI-3), Radial Air Swirlers (co-rotating and counter-rotating, 4th generation LDI-4)

  CFD results predicted differences in flame-structures and similar stability between the axial (LDI-3) and radial air swirler (LDI-4) designs at CST Cruise.

  CFD predictions of NOx emissions for all three designs were within 25% of each other at CST cruise.

  CFD predictions of NOx emissions for a radial swirler design (LDI-4) were up to 25% lower than the baseline axial swirler design (LDI-3) at CST cruise.

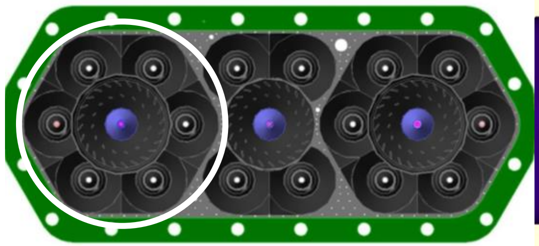
## Significance

***CFD study demonstrated different flame structures and up to 25% lower NOx emissions at CST Cruise conditions with fourth-generation Lean Direct Injection combustor designs***

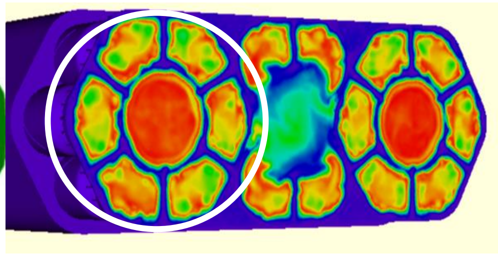
*POC: Kumud Ajmani, Jeff Moder, Jennifer Klettlinger*

**Axial Swirler Design (Baseline, LDI-3)**

Combustor Dome Face
Pilot Injector (Center), 6 Main Injectors



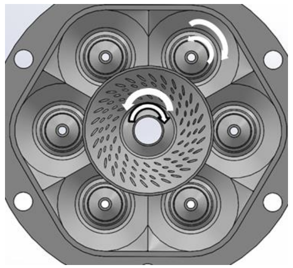
CFD Prediction
(Dome Temperature)



**Radial Swirler Designs (LDI-4)**

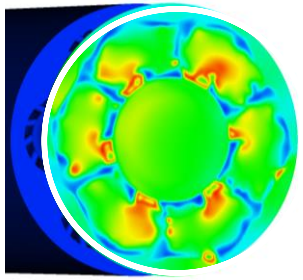
Combustor Dome Face
Pilot Injector (Center), 6 Main Injectors

Co-rotating Swirlers



Counter-rotating Swirlers

CFD Prediction
(Dome Temperature)

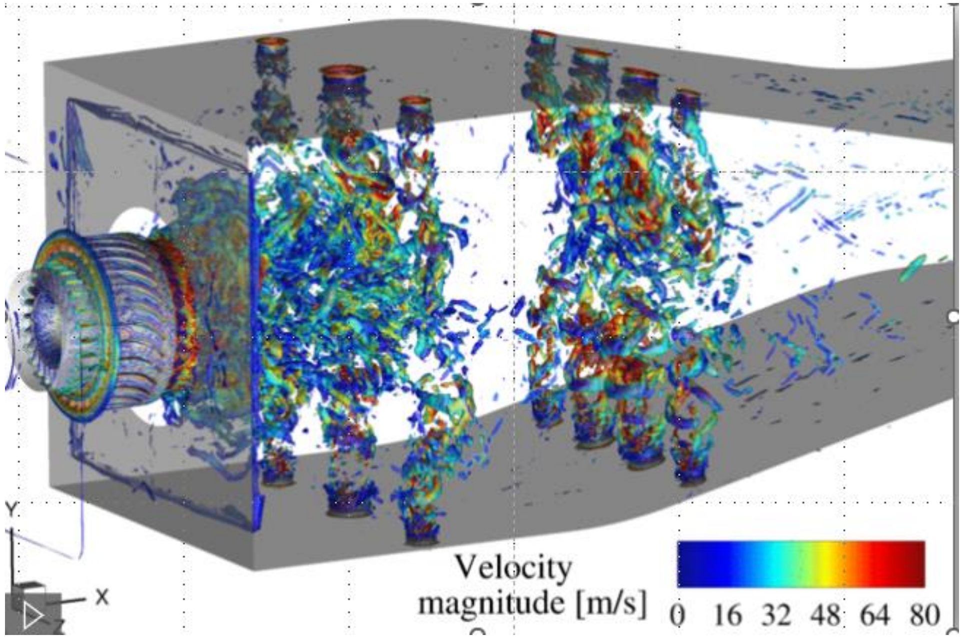


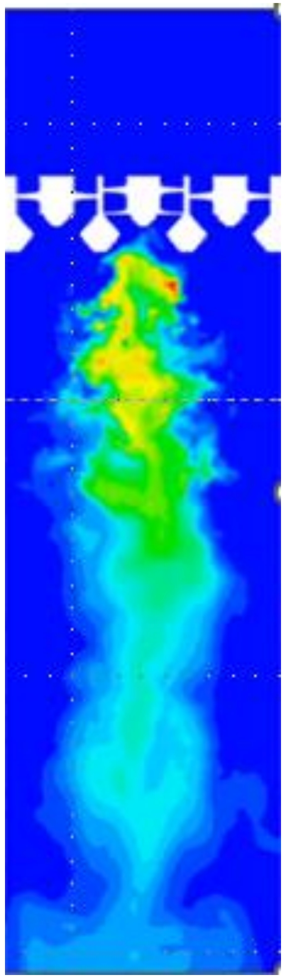
**OpenNCC CFD NOx (CST Cruise)**

| LDI Designs | EINOx (g-NOx/kg-fuel) |
|---|---|
| Axial Swirlers (LDI-3, Baseline) | **16.5** |
| Radial Swirlers (LDI-4, Counter-Rotating) | **15.0** |
| Radial Swirlers (LDI-4, Co-Rotating) | **12.0** |

# Lean Blowout: experiment and CFD examples

- LDI: NASA 7-pt
- RQL: AFRL/UDRI Referee Rig



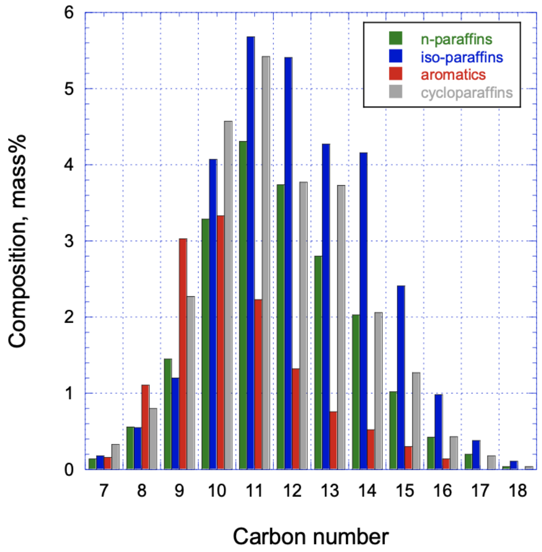



# NASA LBO studies using three National Jet Fuel Combustion Program (NJFCP) fuels

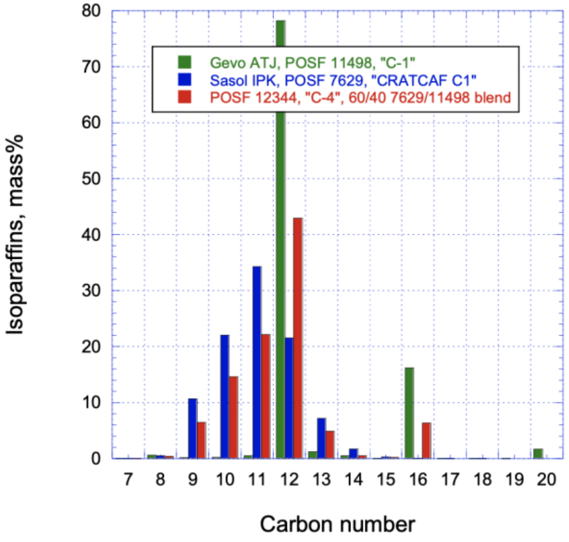
| Fuel | A-2 | C-1 | C-4 |
|---|---|---|---|
| **Composition** | Average Jet-A | GEVO ATJ, highly branched $C_{12}$ and $C_{16}$ iso-paraffins | 60% Sasol IPK (highly branched $C_9$-$C_{13}$ iso-paraffins), 40% C-1 |
| **Description** | Average/ Nominal jet fuel | Very low cetane number with unusual boiling range | Low cetane number with conventional, wide-boiling range |
| **DCN** | 49 | 16 | 28 |
| **Vol % aromatics** | 17 | 1 | 2.3 |
| **Density, 288 K** | 803 | 760 | 760 |
| **Surface Tension, 300 K** | 24.6 | 23.4 | 22.4 |
| **Viscosity, 298 K** | 0.80 | 1.9 | 1.55 |
| **stoichiometric f/a** | 0.0680 | 0.0666 | 0.0665 |

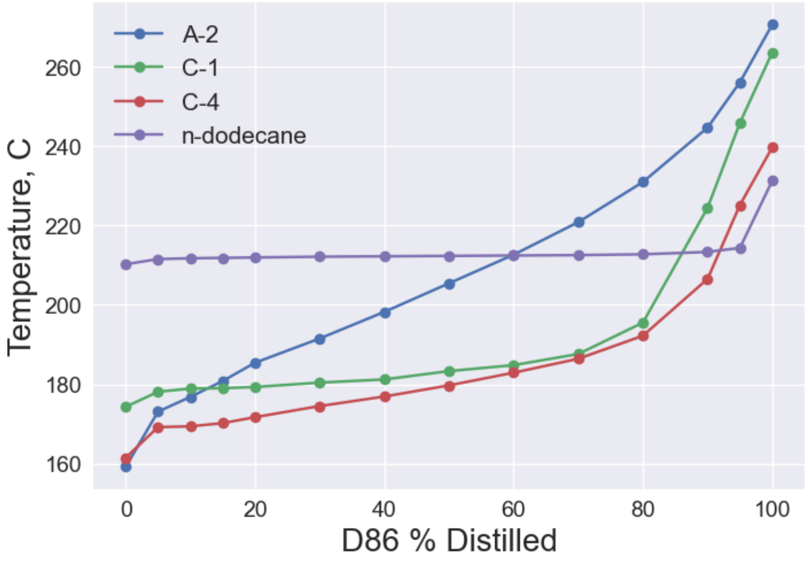
Detailed description of fuels is provided in AIAA-2017-0146, Tim Edwards

A-2, Jet-A composition




C-1 (Gevo), Sasol IPK, C-4 (Gevo/Sasol IPK blend) composition




Experimental LBO measurements conducted for both LDI and RQL
LBO modeling results are compared

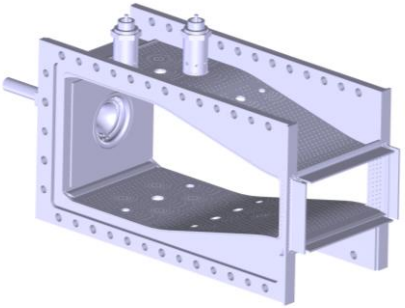
# Rich-Burn and Lean-Burn Combustor LBO Experiments

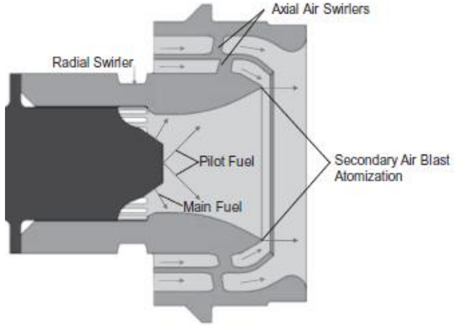
All LBO simulations are Large Eddy Simulations (LES)

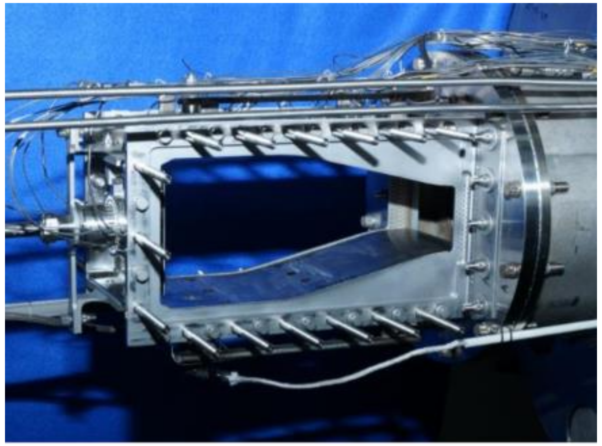
**Rich-Burn**

**AFRL/UDRI Referee Rig**

- Realistic combustor geometry
- Top and bottom liner
- Side windows
- Single cup, three swirler paths





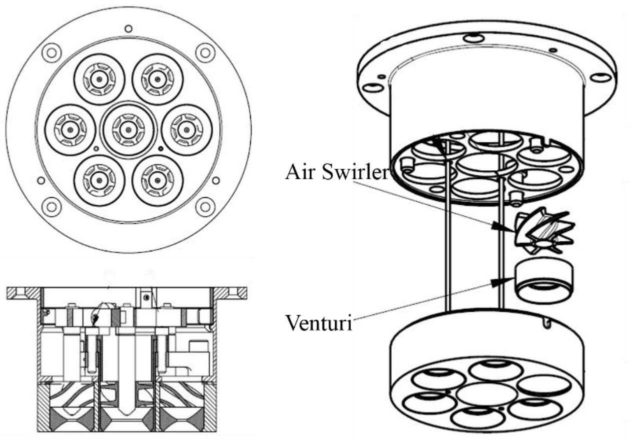
Several NJFCP Fuels are tested in both rigs (including A-2 and C-1)

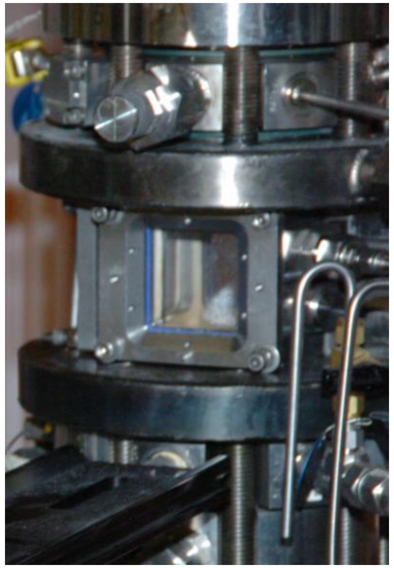
**Lean-Burn**

**NASA GRC CE-13C**

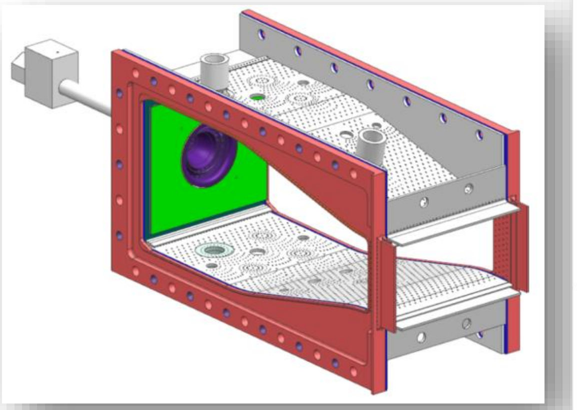
- Circular cross-section
- 3inch diameter
- Flow is downward
- 3 windows

7-point Lean Direct Injection Hardware

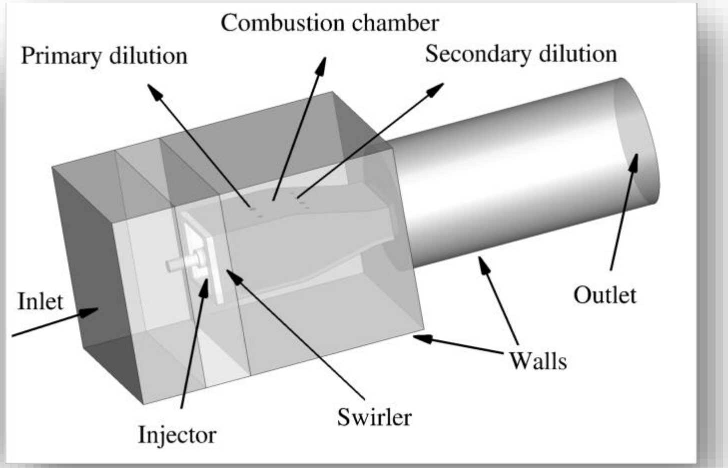


# RQL CFD Domain and Boundary Conditions

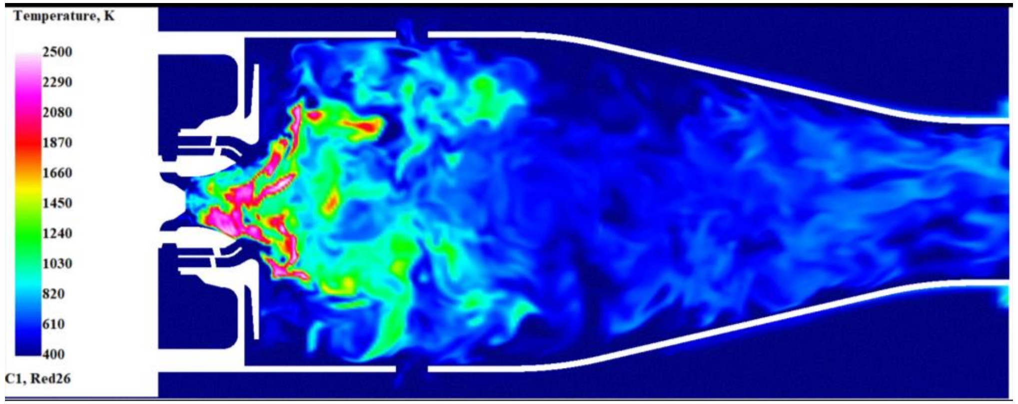


Experimental Combustion Chamber




Full Computation Domain

OpenNCC simulation of approach to LBO for C-1. *Decrease fuel, constant air*

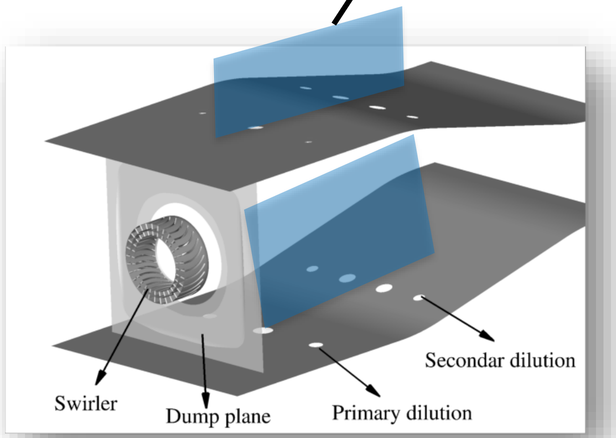



Instantaneous Temperature, K

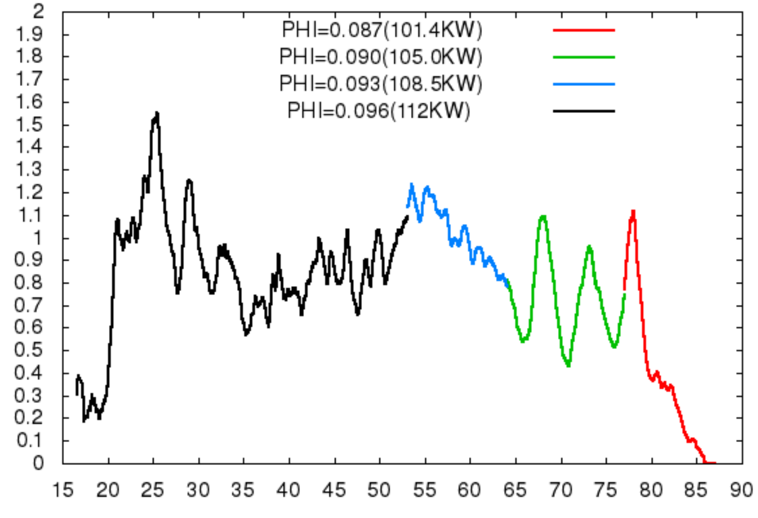
CONVERGE, Fluent, and a second set of OpenNCC simulations gridded all effusion holes

| Parameter | Data |
|---|---|
| Exit pressure | 207 kPa |
| Inlet mass flow rate | 391.4 g/s |
| Inlet temperature | 394 K |
| Effusion mass flow rate | 241 g/s |
| Fuel mass flow rate (At start of LBO exp) | 2.55 g/s (A-2), 2.50 g/s (C-1) |
| Wall temperature | Adiabatic |
| Spray conditions | Based on PDPA data |

Cut Plane




Normalized Global Heat Release Rate




*T. Wey, AIAA-2020-3694*

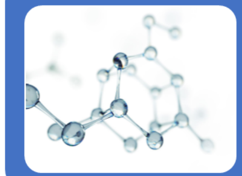
# Lean Blowout CFD Simulations: Predict LBO fuel sensitivity in a lean-burn combustor design.

## Experimental data: 2019 LDI results

- Fuels: A-2 average jet and C-1 Gevo

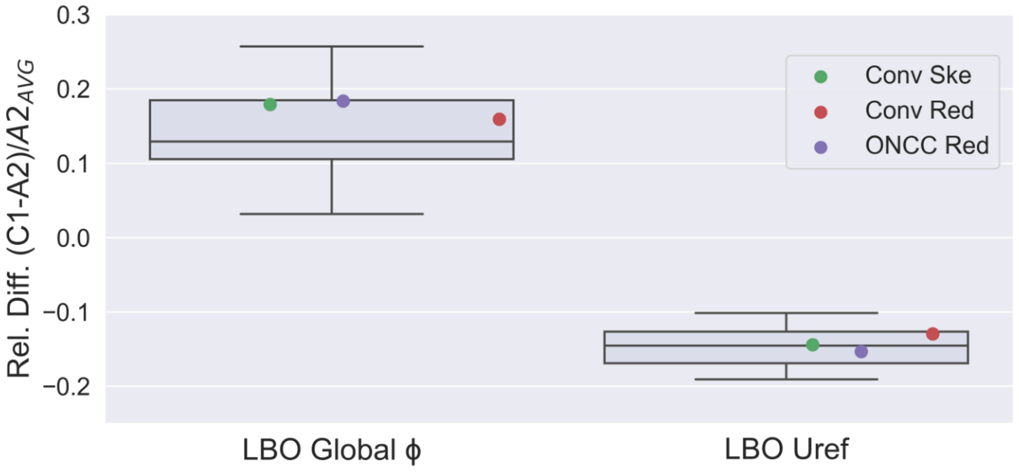
## CFD codes

- **openNCC:** In-house unstructured mesh combustion CFD code
- **Converge:** Commercial combustion code, includes adaptive mesh refinement

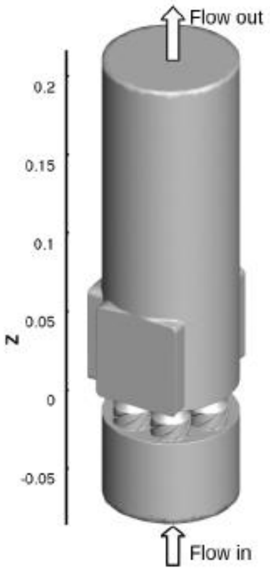


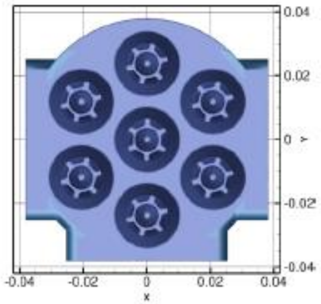
## Chemistry: HyChem mechanisms

- **Skeletal:** based on directed relation graph and sensitivity analysis reduction; 41 species for A-2 **(Converge only)**
- **Reduced:** mechanism includes a second stage reduction using a quasi-stead-state approximization; 31 species for A-2 **(Converge and OpenNCC)**

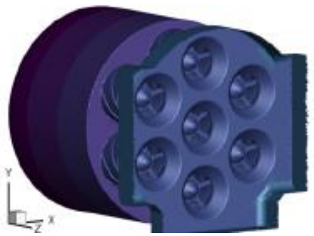



# CFD Domain and Boundary Conditions

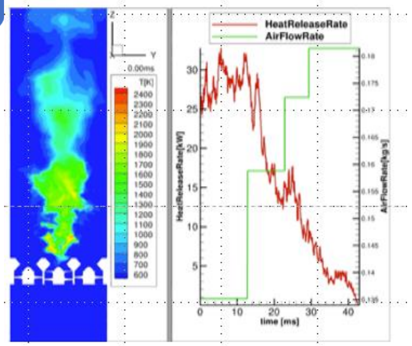



(b)



- CFD boundary conditions are set to match the typical experiment conditions
- All surfaces are adiabatic.
- Swirlers are identical, additively-manufactured right-hand 60 deg
- Only the center injector is fueled at very low equivalence ratio.
- Fuel mass flow rates are fixed and the air mass flow rates are increased in step-wise manner until LBO occurs.
- LBO simulations performed for A-2 and C-1 fuels




Instantaneous Temperature

### Simulation Boundary Conditions

| | Cold Flow | A2 | C1 |
|---|---|---|---|
| Initial Air Flow Rate[kg/s] | 0.2672 | 0.1356 | 0.1352 |
| Fuel Flow Rate[g/s] | N.A. | 1.784 | 1.716 |
| Inlet Temperature(T3)[K] | 700.4 | 506.8 | 503.7 |
| Exit Pressure(P4)[kPa] | 466.8 | 472.6 | 469.1 |

The box plots show range of the experimental results; points are CFD

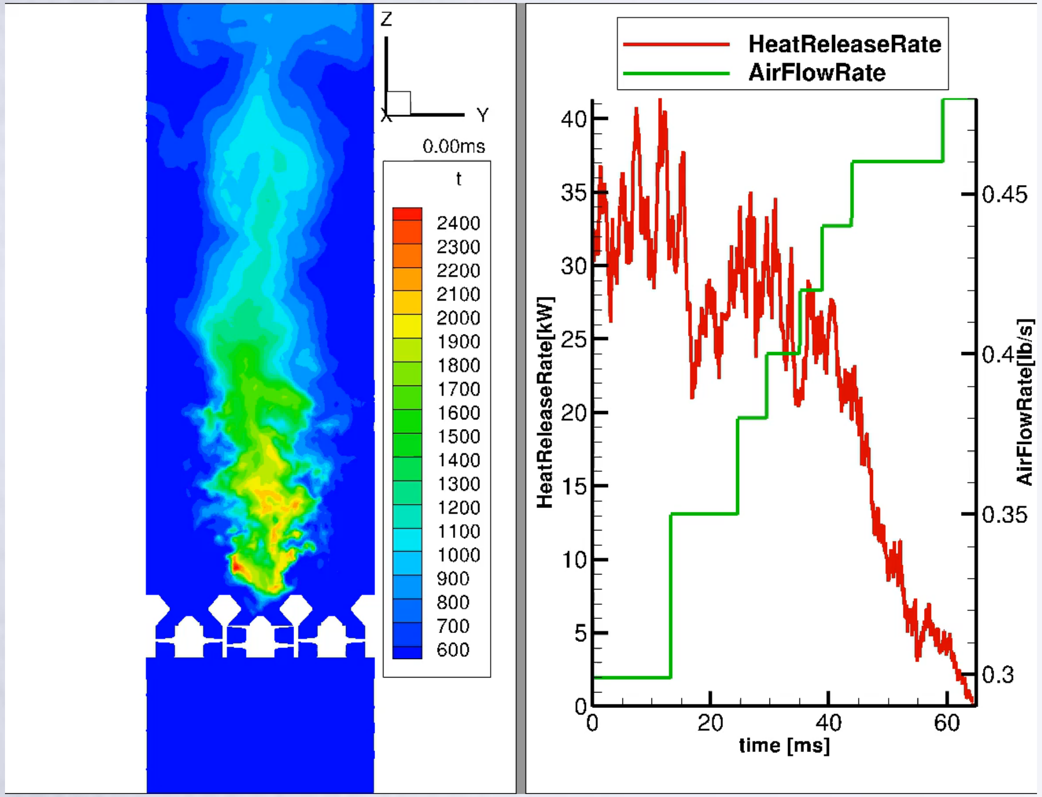
Both the OpenNCC and CONVERGE simulations:

- Predict LBO within the experimental range of fuel relative difference in:
  - Equivalence ratio ($\phi$) : $(\phi_{C-1} - \phi_{A-2}) / \phi_{A-2}$
  - Reference velocity (Uref) : $(Uref_{C-1} - Uref_{A-2})/Uref_{A-2}$

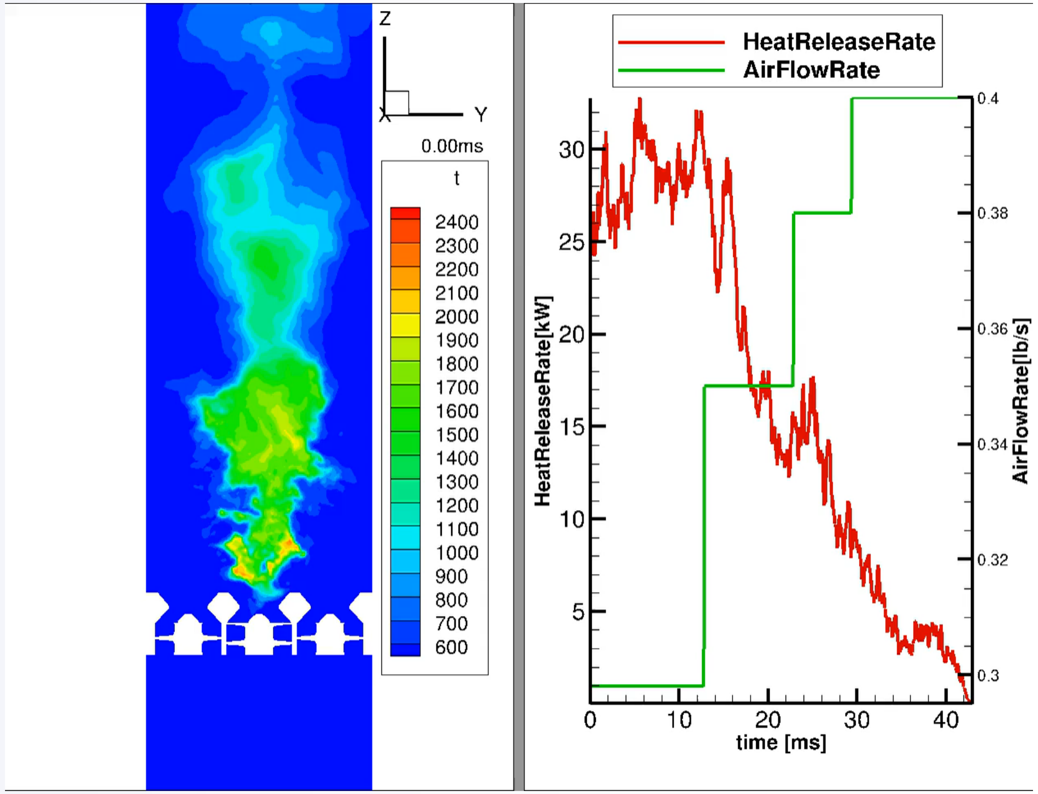
*Endo et al. AIAA 2021-3458*
*Guzman et al. AIAA 2021-3459*

# LDI LBO simulations

## A-2 fuel




## C-1 fuel

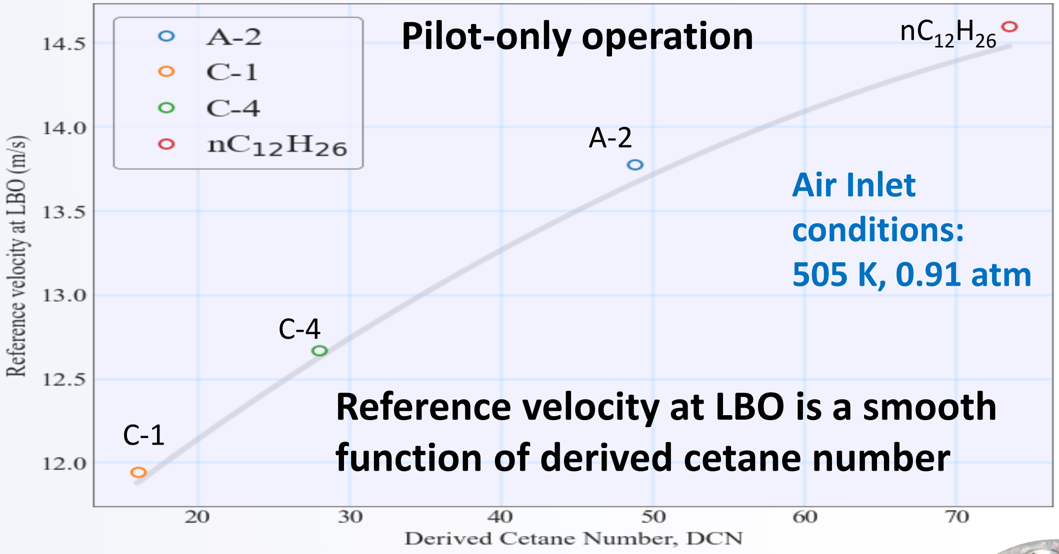


# Fuel Effects on Lean Blowout (LBO) and Flame Structure

- Support SAF certification
- Compare LBO and flame structure using NASA 7-pt LDI injector for 4 National Jet Fuels Combustion Program fuels:
  - A-2: “average” Jet-A
  - C-1: Gevo alcohol-to-jet
  - C-4: isoparaffinic kerosene (Gevo/Sasol blend)
  - n-$C_{12}H_{26}$ (n-dodecane)
- CFD compared well with experimental data†. Predicted the correct trend for fuels A-2 and C-1

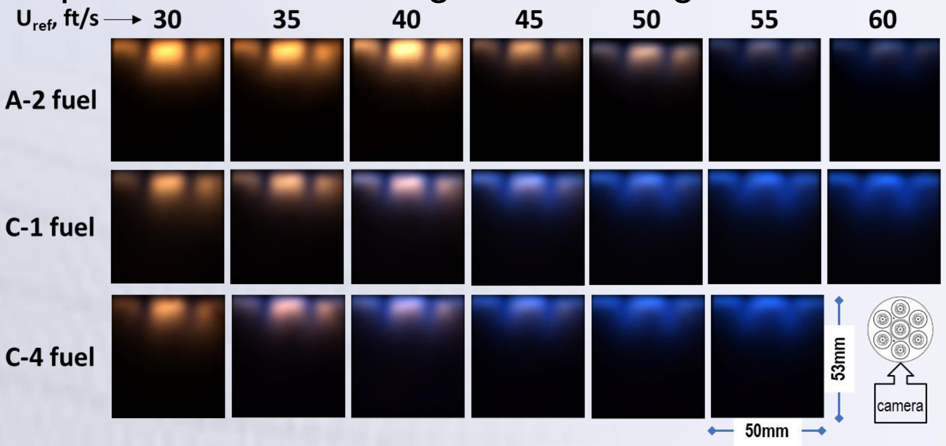
† Endo et al. Numerical simulation of LBO of alternative fuels in 7-element … injector. AIAA 2021-3458
Guzman et al. LBO predictions of a 7-point … array from large eddy simulations. AIAA 2021-3459

*LBO: Increase air flowrate while keeping fuel flow constant*.




## Color high speed camera average flame images, 40-50 kHz

Air Inlet conditions:
$T_3$ = 700 K
$P_3$ = 5 atm
$\phi$ = 0.45
All 7 swirlers fueled

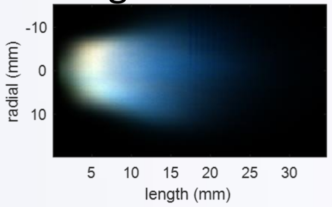



Flow: Top to Bottom

- Overall decreased soot with increased reference velocity for all fuels due to higher turbulence and mixing rates
- A-2 (Jet-A) contains polycyclic aromatic hydrocarbons known to promote soot
- Iso-paraffin fuels C-1 and C-4 have low DCN, where ignition delay and mixing timescales may affect local equivalence ratios and soot

## C-4/air flame example

Average NBO flame

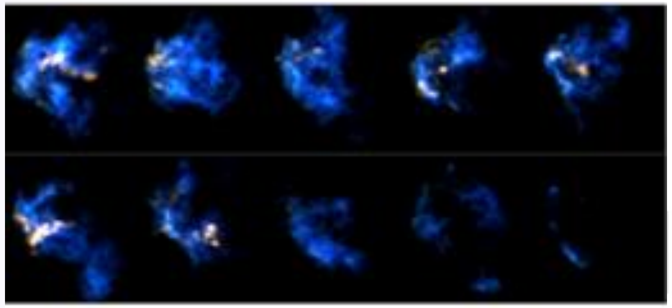



NLBO condition:
505 K, 4.8 bar,
$m_f$ = 5 – 7.1 kg/h
$m_{air}$= 0.14 kg/s

Instantaneous color images, frame rate 40 kHz

At NBO →

Just before LBO →



Tacina, Capil, Hicks

# Summary

- We saw a bit of combustion terminology and technology.
- Emissions
  - There have been tremendous gains over the last 50 years with more still possible
- Hydrocarbon fuels will be with us at least through 2050
  - SAF production is a key driver to achieve carbon neutrality
- Compact core combustors (such as with HyTEC), electrification, and supersonics offer challenges and opportunities.
  - Fuel injection for high OPR: fuel behavior trans to supercritical, effects on operability, measurements
  - Scaling: requires fuel-air mixing development and staging effects on emissions
  - Durability: injector, advanced materials, wall heat transfer tools, advanced liner materials and cooling strategies
  - Particulate measurement capabilities

NASA