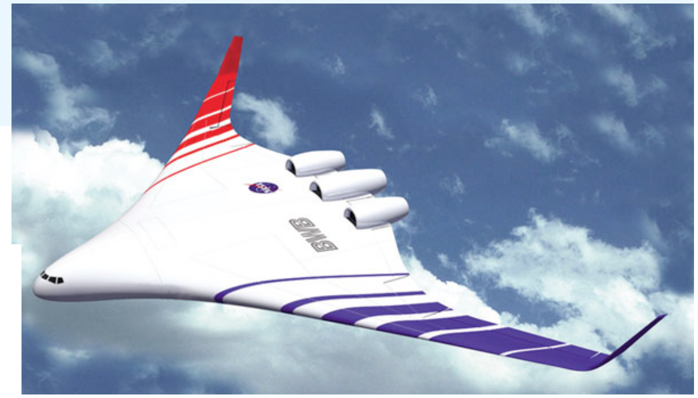
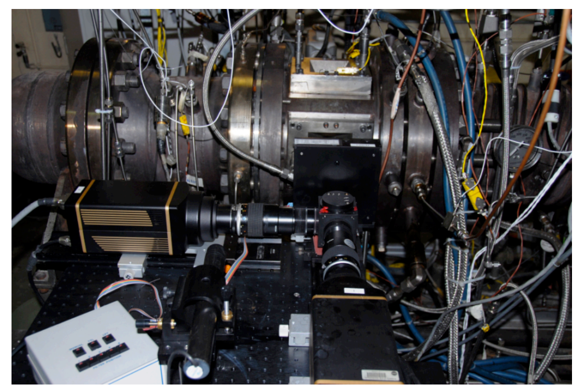
NASA Emissions Reduction and Alternative Fuels Research
UTIAS-MITACS International Workshop on Aviation and Climate Change

Dan Bulzan

Associate Principal Investigator, Subsonics Fixed Wing and Supersonic Projects

NASA Fundamental Aeronautics Program



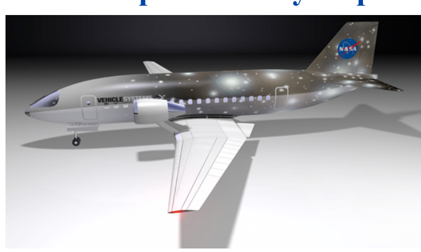


System Level Metrics – Subsonics Fixed Wing ….

technology for dramatically improving noise, emissions, & performance

CORNERS OF THE TRADE SPACE	N+1 (2015 EIS) Generation Conventional Tube and Wing (relative to B737/CFM56)	N+2 (2020 IOC) Generation Unconventional Hybrid Wing Body (relative to B777/GE90)	N+3 (2030-2035 EIS) Advanced Aircraft Concepts (relative to B737/CFM56)
Noise (cum below Stage 3)	- 42 dB	- 52 dB	better than -81 dB (55 LDN at average boundary)
LTO NOx Emissions (below CAEP 2)	-70%	-80%	better than -80% plus mitigate formation of contrails
Performance: Aircraft Fuel Burn	-33%***	-40%***	better than -70% plus non-fossil fuel sources
Performance: Field Length	-33%	-50%	exploit metro-plex concepts

*** An additional reduction of 10 percent may be possible through improved operational capability



?

Supersonics
NASA Developed Systems Level Requirements

	N+1 Supersonic Business Jet Aircraft (2015)	N+2 Small Supersonic Airliner (2020)	N+3 Efficient Multi-Mach Aircraft (2030-2035)
Cruise Speed	Mach 1.6-1.8	Mach 1.6-1.8	Mach 2.0 Unrestricted Flight 1.6-2.0 Low Boom
Range (nmi)	4,000	4,000	6,000
Payload	6-20 pax	35-70 pax	100-200 pax
Sonic Boom	65-70 PLdB	65-70 PLdB	65-70 PLdb low boom flight 75-80 PLdB unrestricted flight
Airport Noise (cum below Stage 3)	10 EPNdB	10-20 EPNdB	20-30 EPNdB
Cruise Emissions Cruise Nox EI	Equivalent to Subsonic	<10	<5
Other		?	?
Fuel Efficiency	Baseline	15% Improvement	25% Improvement

N+1 "Conventional"

N+2 Small Supersonic Airliner

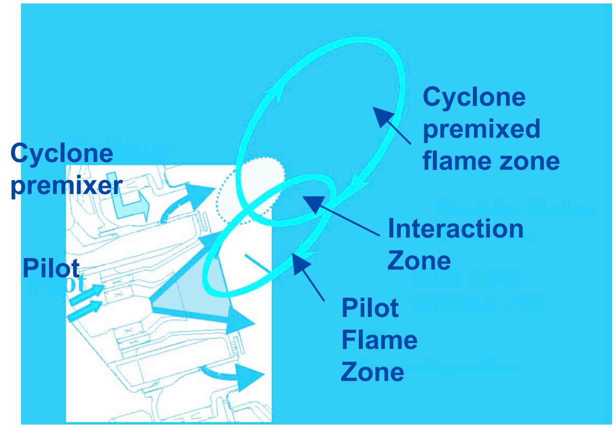
N+3 Efficient Multi-Mach Aircraft

NOx Emissions Reduction

"N + 1" Conventional Small Twin

70% LTO NOx reduction below CAEP/2
Target Next Generation Single Aisle (NGSA)
Annular combustor TAPS (GE)
- **Improved fuel/air mixers**

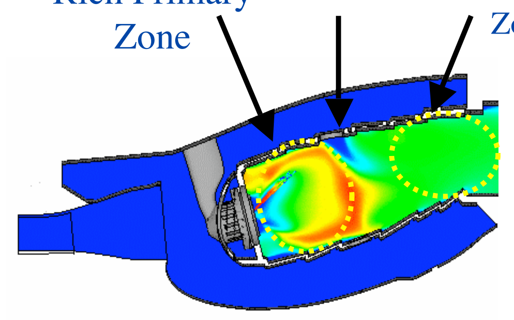
TALON X (P&W)
- **Optimized quench section for improved mixing**
- **Improved fuel/air mixing in rich zone**



Cyclone Main with Pilot Concept

"N + 2" Hybrid Wing/Body

80% LTO NOx reduction below CAEP/2
Improved CFD Modeling
Advanced combustor concepts
Advanced fuel/air mixers
Active combustion control
High temperature liners
Alternative fuels



Rich Burn Quick Quench Lean Burn Concept

Lean Direct Injection Multipoint Concept

Objectives – Subsonics Fixed Wing

- Develop the necessary technologies to enable low emissions (gaseous and particulate) combustion systems to be developed for subsonic engine applications.
- Develop the fundamental technologies to assess the feasibility of alternative fuels in subsonic aircraft applications.
- Develop and validate physics-based models to enable quantitative emissions and performance predictions using Combustion CFD simulations.

Subsonics Fixed Wing Combustion Discipline Technical Approach

- NASA Research Announcement (NRA)
- Combustion Fundamental Research
  - Alternative Fuels
  - Fundamental Experiments
  - Physics-Based Model Development
- Combustion Technologies and Tool Development
  - Combustion CFD Code Development and Application
  - Low-emissions Combustion Concepts
- Multidisciplinary Analysis and Optimization

Supersonics
Technical Challenges

- Environmental impact of supersonic cruise emissions is greater due to higher flight altitudes which makes emissions reduction increasingly important.

- Accurate prediction tools to enable combustor designs that reduce emissions at supersonic cruise are needed as well as intelligent systems to minimize emissions.

- Combustor operating conditions at supersonic cruise are different than at subsonic cruise since inlet fuel and air temperatures are considerably increased.

Supersonics
Technical Approach

- NASA Research Announcement
- Emissions Prediction and Modeling
  - Physics-based model development for combustion CFD codes for improved supersonic cruise emissions predictions
- Diagnostics and Validation Experiments
  - Laser-based diagnostics development for quantitative major species and temperature measurements
  - CFD code validation experiments at supersonic cruise conditions
- Low Emission Concepts
  - Low NOx emission concept development
  - Active combustion control
- High Temperature Sensors
  - High temperature sensor development

Alternative Fuels

- **Major Tasks**
  - **Buildup of Bldg 109 Alternative Fuels Laboratory**
  - **Thermal Stability Measurements of alternative fuels**
  - **Fundamental studies of Fischer-Tropsch Reaction kinetics**
  - **Combustion Testing in laboratory scale burner, flametubes, and engines**
  - **Database of alternative fuel thermochemical and physical properties**
  - **Identification of suitable alternative fuels for use in aeronautics applications including biofuels**
  - **Participate in planning/roadmap meetings with other agencies performing research on alternative fuels**

- **Status of Current Activities**
  - **Alternative Fuels Laboratory buildup completed-checkouts and safety permits underway**
  - **Hot Liquid Process Simulator (HLPS) for thermal stability installed and initial testing is being conducted**
  - **Installation of alternative fuel system in NASA CE-5 combustion flametube facility completed to allow on line fuel blending**
  - **Collaboration with AFRL for alternative fuel properties, combustion testing, and particulates measurements**
  - **Purchased F-T fuel in conjunction with Air Force for combustor flametube and engine tests in FY08**
  - **NRA funded studies for basic studies of F-T Reactor Kinetics (University of Kentucky)**

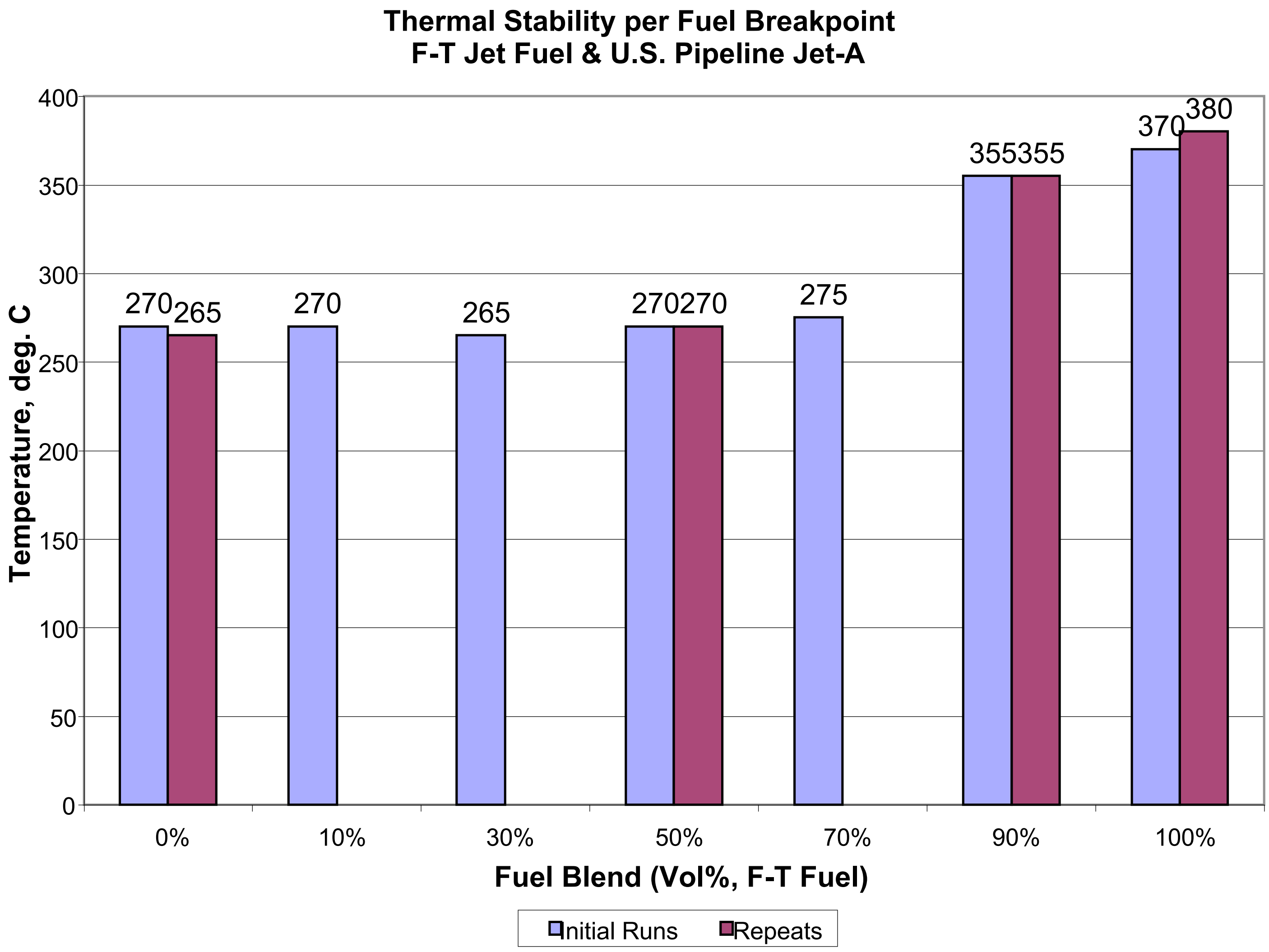
Alternative Fuels

F-T Reactors installed in Alternative Fuel Laboratory

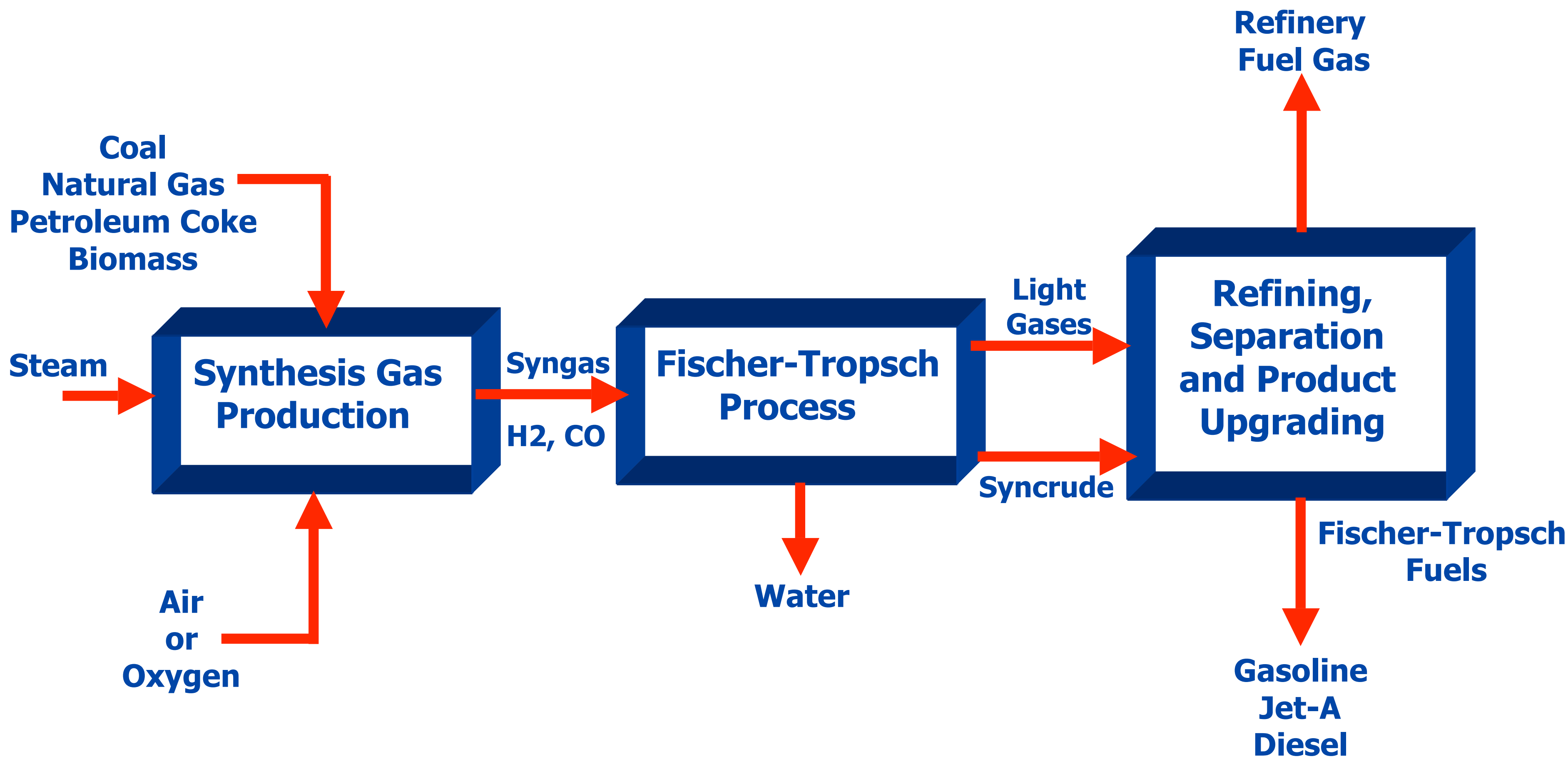
HLPS Instrumentation

- **Planned Activities**
  - **Testing in P&W 308 and UHB engines for F-T fuel/Jet-A blends to measure gaseous and particulate emissions**
  - **Purchase additional alternative fuel - combined with Air Force purchase for F-T fuel**
  - **Alternative fuel testing using NASA DC-8 with CFM56 engines for static ground tests to measure gaseous and particulate emissions to allow complete disclosure of measurements**
  - **Combustion flametube testing in NASA flametube facility of NASA 9-point LDI, Complex Multi-Swirler Mixer from GE, and other industry low emission combustion concepts**
  - **Experiments to study algae and halophytes to measure production rates for Biofuel production**

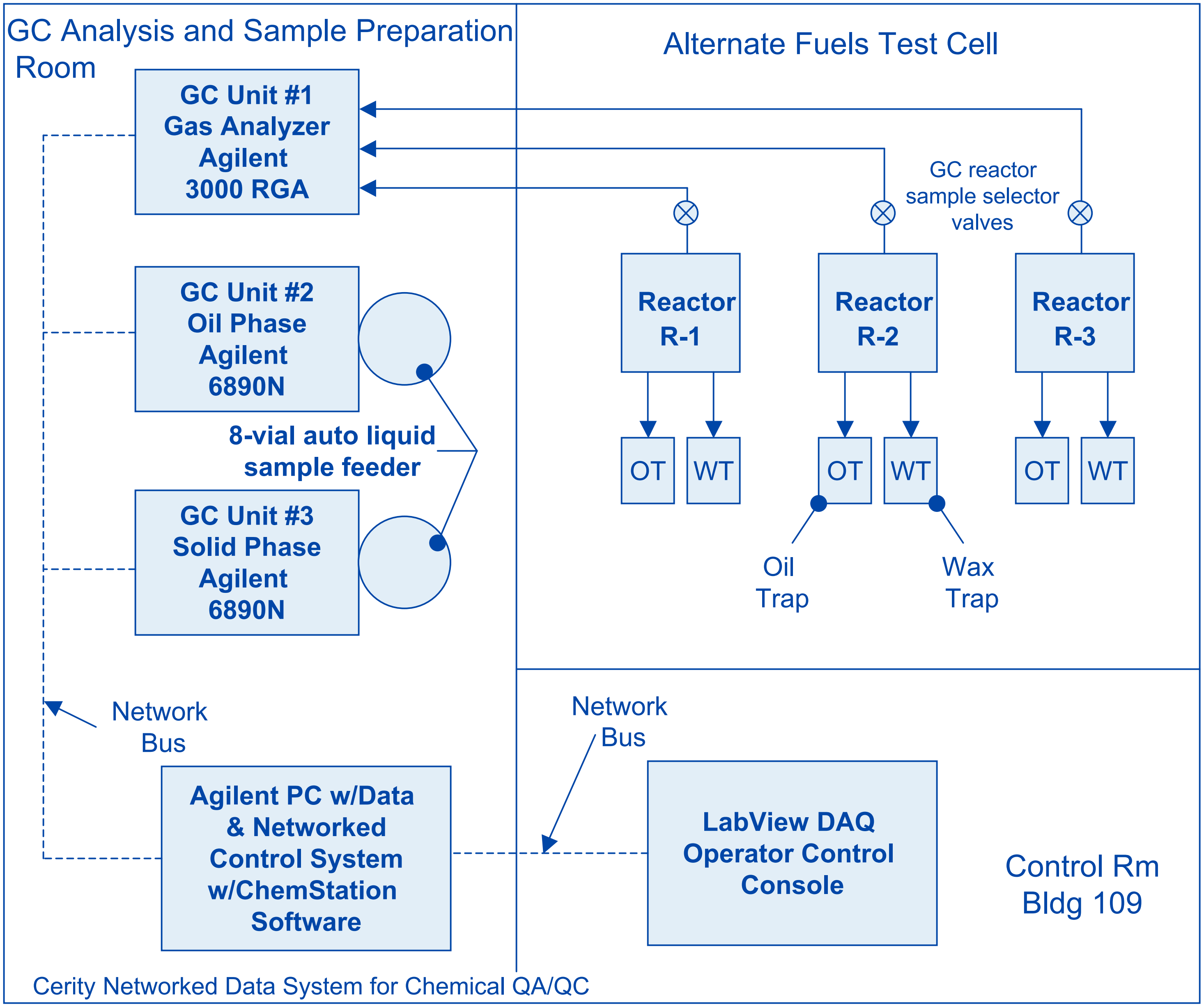
F-T Fuel Characterization



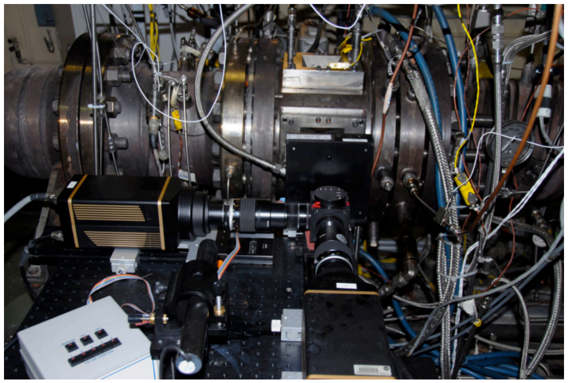
- Fuel breakpoint per ASTM D3241
- F-T jet fuel highly stable
- F-T jet fuel & Jet-A mixture thermal stability is not linearly related to FT fuel content


Refinery
Fuel Gas
Coal
Natural Gas
Petroleum Coke
Biomass
Steam
Synthesis Gas
Production
Syngas
H2, CO
Fischer-Tropsch
Process
Light
Gases
Syncrude
Refining,
Separation
and Product
Upgrading
Fischer-Tropsch
Fuels
Air
or
Oxygen
Water
Gasoline
Jet-A
Diesel

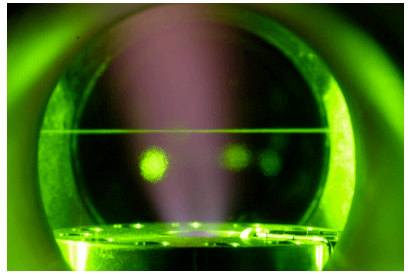
GC Analyzer System Layout / Configuration.

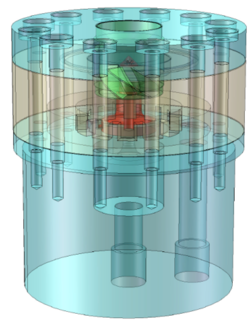


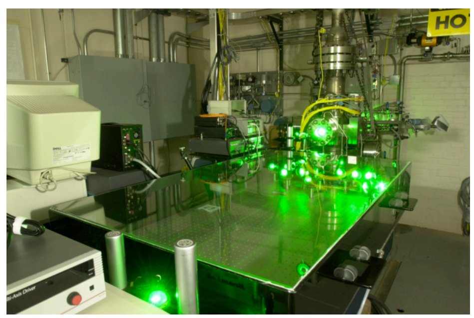
NASA Facilities



CE-5 High Pressure Flametube Stand 2







SE-5 High-Pressure Laboratory Scale Burner

SE-11 Particle Altitude Simulation Laboratory

Ultra High Bypass Engine Testing with F-T Fuel Blend

Intersection of NASA-P&W Goals

UHB Partnership Objectives from Demo Test

- Evaluate alternative fuels
  - Fischer-Tropsch fuel
  - Confirm reduced emissions (particulates)
  - Specific fuel consumption
- Scalability data to confirm subscale model fan results. Validate:
  - NASA codes and systems
  - Reduced noise, higher efficiency
- **NASA supplying probes, emissions measurement equipment and will participate in engine tests at West Palm Beach Facility**
- **Alternative fuel blend will be 50/50 blend of Shell F-T fuel with JP8 or Jet A**

Gaseous and Particle emissions probes

Pratt & Whitney
A United Technologies Company

Ultra High Bypass Engine Testing with F-T Fuel Blend

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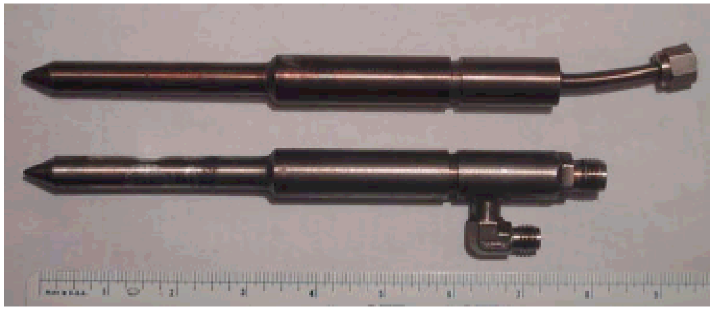

Gaseous and Particle emissions probes

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Pratt & Whitney
A United Technologies Company

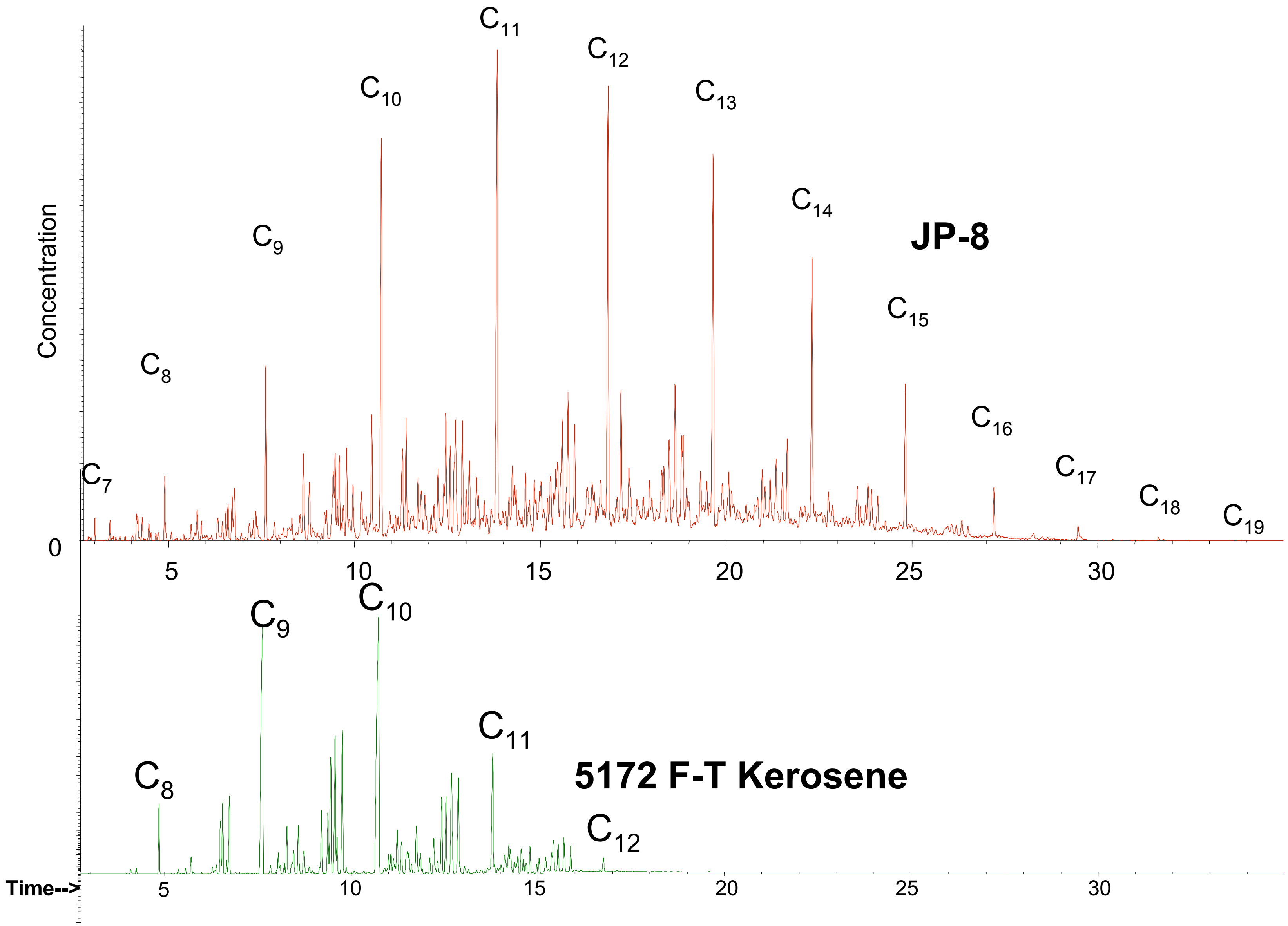
Test Objective

- Evaluate performance of the engine with a blend of 50% synthetic fuel and 50% JP-8
- Determine engine emissions with synthetic fuel blend and JP-8
  - Gaseous emissions
  - Particulate emissions
- Compare engine emissions and general performance with synthetic fuel blend and JP-8

P&W teamed with NASA to perform the test

- Synthetic fuel was supplied by NASA.
  - Certain fuel stabilization and lubricant additives were added to the synthetic blend (50% synthetic fuel and 50% JP-8)
  - The synthetic fuel contains no aromatics or fuel-sulfur
  - Synthetic fuel's chemical composition and physical characteristics meet aviation fuel standards
- NASA researchers made gaseous and particulate measurements
- P&W/UTRC developed the sampling system with NASA's assistance
- Back-to-back tests were performed with the synthetic fuel blend and JP-8

Properties of Synthetic fuel/blend



Fuel analysis performed on the blend and JP-8

Property	Blend	JP-8
Viscosity	1.16 cSt	1.38 cSt
Specific Gravity	0.776	0.8067
Net Heat of Combustion	18,740 Btu/lb	18,546 Btu/lb
Hydrogen % mass	14.72	13.96
H/C ratio	0.17	0.16

Properties of the blend are within the specification of Aviation fuel

Test Matrix developed to ascertain the performance of the blend at different thrusts

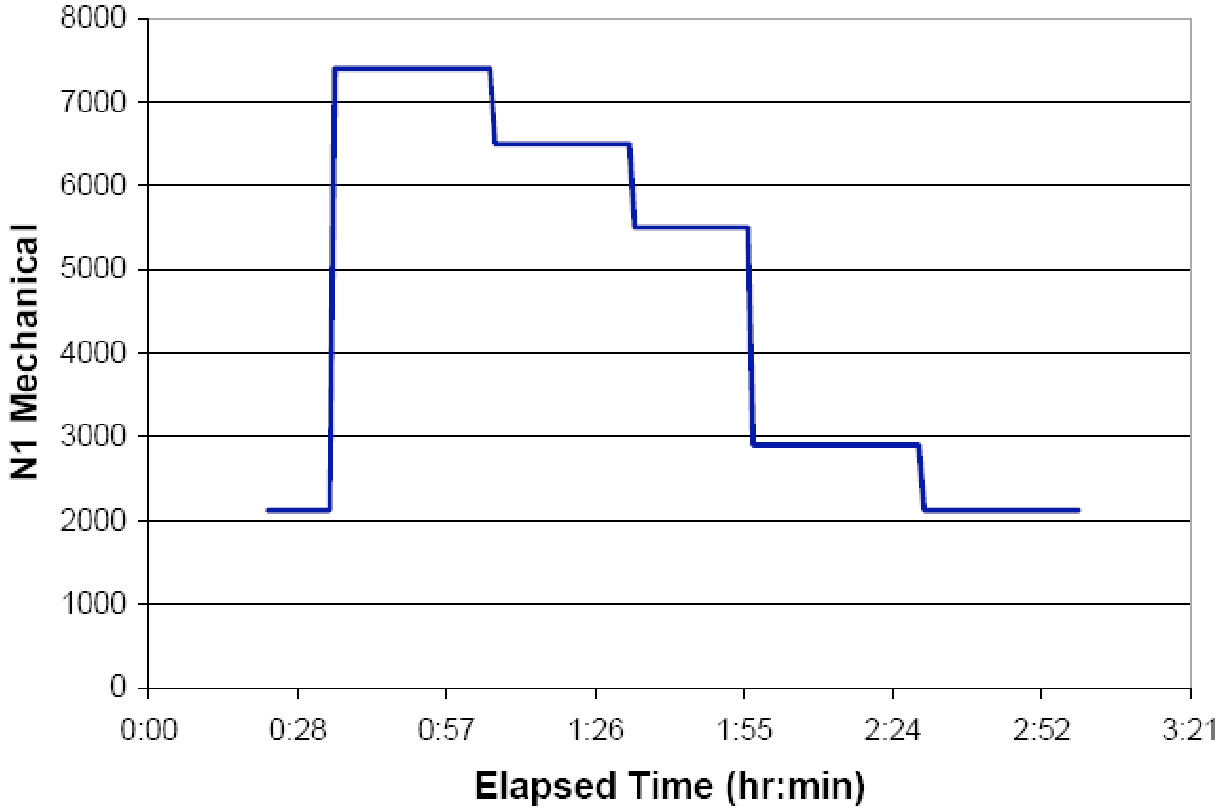


Figure 4: Typical Test Card Timeline (simplified)

Performance data does not indicate major differences between the two fuels

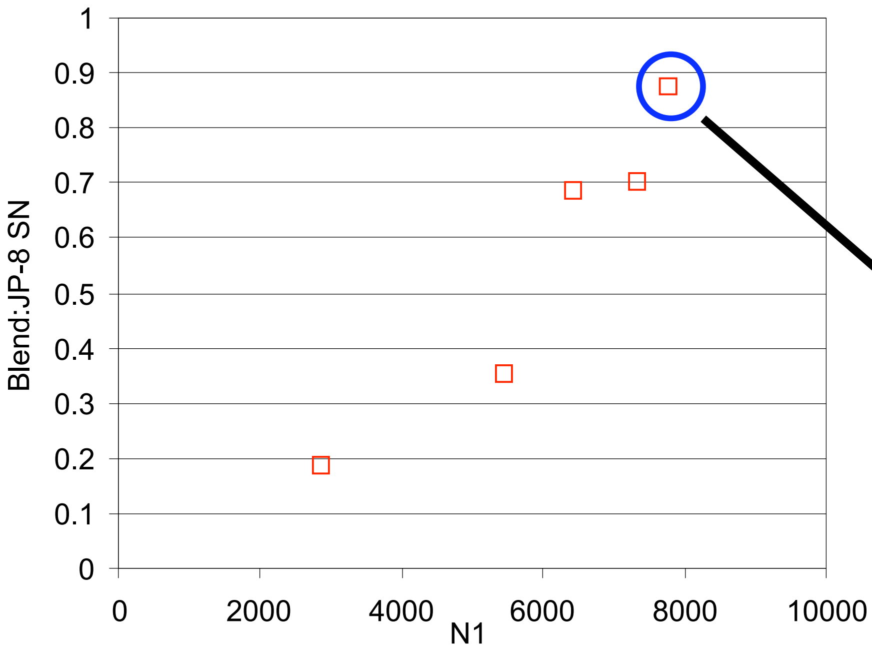
	RATIO - Blend/JP8			
Thrust (Rotor Speed N1)	Fuel flow	NOx	CO	SO_2
LOW (2200)	0.999	NA	0.92	0.55
INTERMEDIATE (6500)	0.990	0.994	NA	0.54
HIGH (7800)	0.995	1.001	NA	0.54

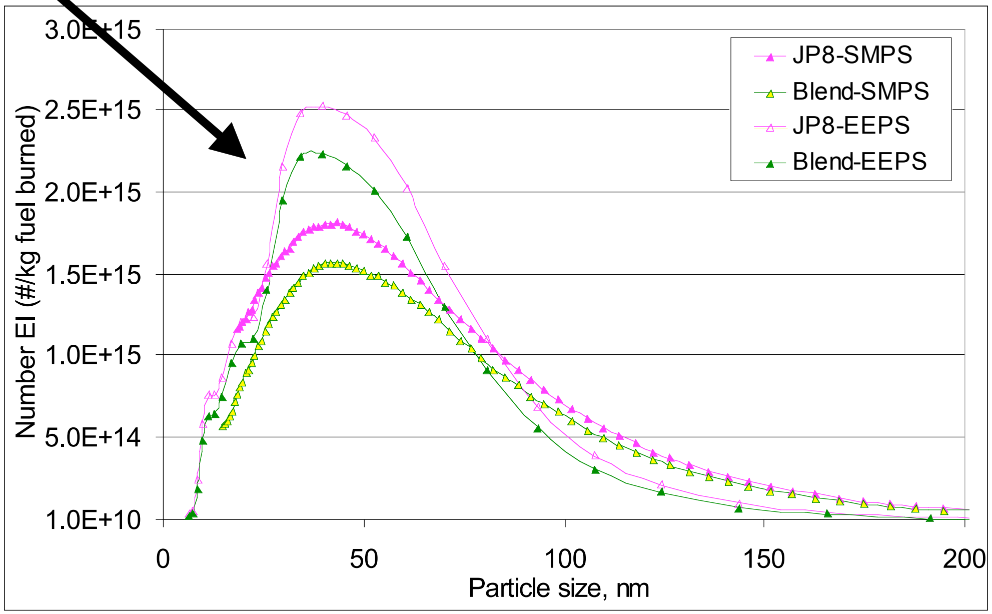
GASEOUS EMISSIONS

- At low power
  - NOx emissions are too low to calculate a ratio
  - Lower CO with blend may be due to higher H/C ratio
- At intermediate/high power
  - Very low CO emissions
  - No difference in NOx emissions
- Negligible UHC at all power conditions for both fuels
- SO_2 emissions indicate Sulfur content of the blend to be around 50% of JP8

Negligible differences in performance as expected due to similarity in the Physical properties of the two fuels (like heating value, specific gravity)

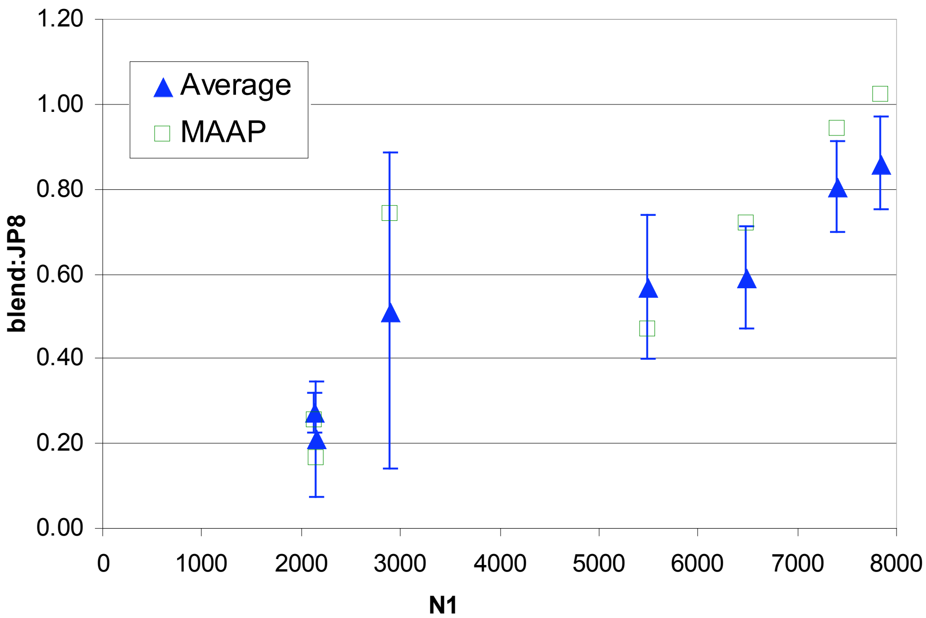
Engine running on Synthetic fuel blend produced lower SN and particles





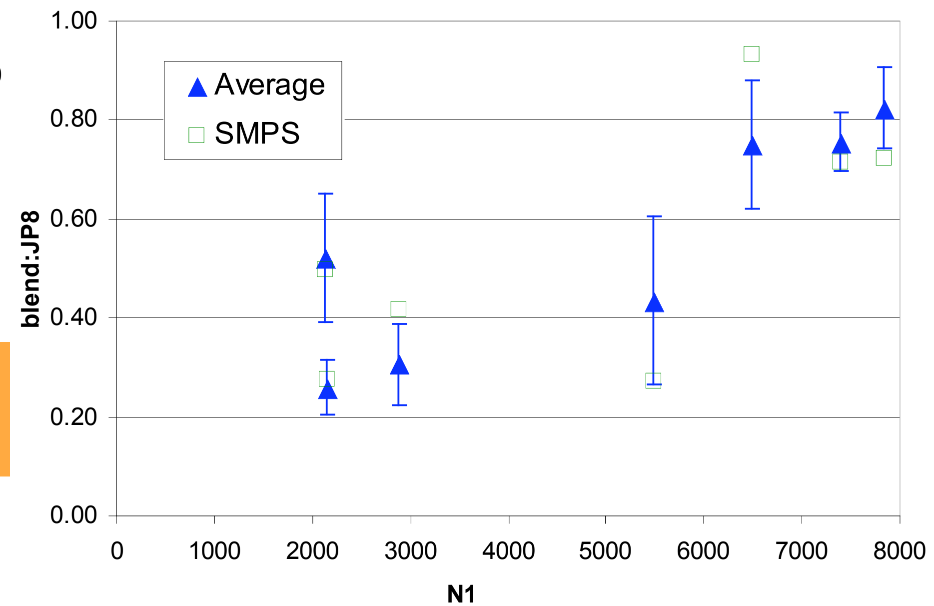
As expected lower PM emissions with synthetic fuel due to its chemical Composition (higher H/C ratio and no aromatics/Sulfur)

Sizing and Mass instruments indicate similar trends as seen with SN data



MASS: Lower mass for synthetic blend

NUMBER: Lower number count for synthetic blend



Observations from Synthetic fuel blend test

- Synthetic blend had negligible Thrust and Fuel Flow impact when compared to JP-8
- Emission performance of the blend indicated positive trends
  - No significant difference in gaseous emissions
  - PM emissions showed a reduction with blend

Selected NRA Summary Slides

- Subsonics Fixed Wing Project
  - 6 Round 1(FY07)
  - 3 Round 2 (FY07)

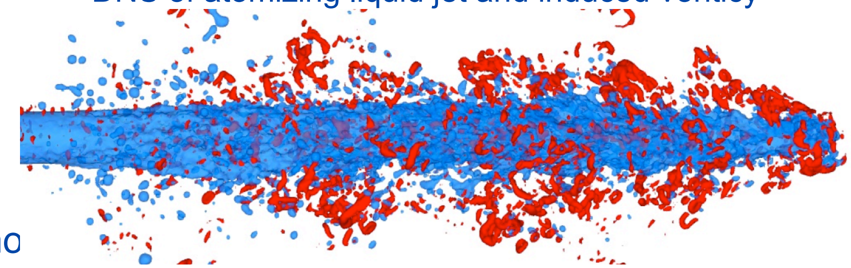
- Supersonics Project
  - 6 Round 1 (FY07)
  - Round 1 (FY08) proposals currently being evaluated

Integrated Large Eddy Simulation of Multi-Phase Turbulent Reacting Flows for Realistic Gas-Turbine Combustors

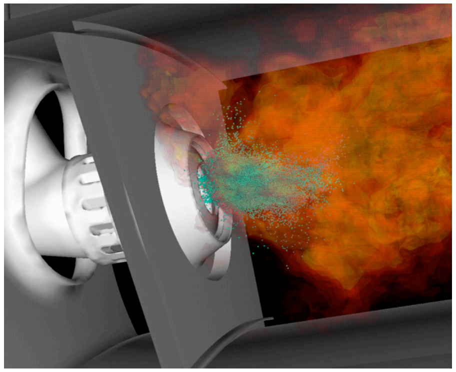
PI: Heinz Pitsch, Stanford University

Modeling issues for predictive simulations of aircraft engine combustion

DNS of atomizing liquid jet and induced voriticy



- Primary breakup process of liquid fuel
  - DNS and modeling
- Combustion modeling
  - Coupled TPDF/Flamelet-Progress Variable mo
  - Joint PDF of mixture fraction and progress variable from TPDF
  - Mixing from flamelet model
- Reduced chemical models for Fischer-Tropsch fuels
  - Detailed and reduced chemical schemes will be developed based on a component library approach
  - Automatic reduction strategies
- Validation with simple experiments and full engine geometries

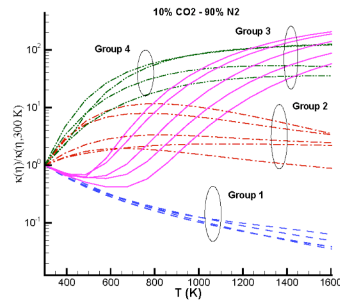


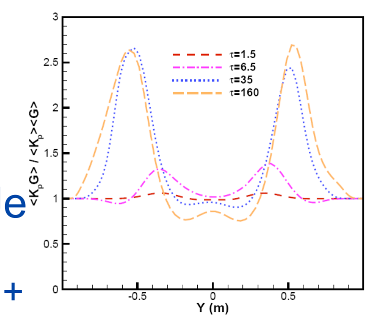
LES Modeling of Spectral Multiphase Radiation and Turbulence/ Chemistry/Radiation Interactions in Reacting Turbulent Flow

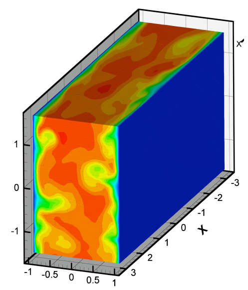
- Spectral Radiation Modeling
  - Hybrid multiscale/multigroup FSK method
  - On-the-fly construction of k-distributions
  - Gas-phase mixtures + soot + hot walls

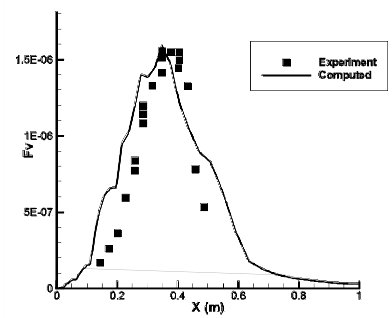
- LES in Canonical Configurations
  - Nonreacting and reacting planar channel flows
  - Systematic variations in optical thickness
  - Isolation of TRI contributions

- PDF-Based Modeling of Laboratory-Scale Nonpremixed Je Flames
  - Detailed gas-phase thermochemistry + detailed soot models + method-of-moments
  - Thermochemistry validation in laminar flames
  - Comparisons with experimental data









NASA Grant # NNX07AB40A

Michael Modest (PI) and Daniel Haworth (coPI)

PENNSTATE

1855

Comprehensive Chemical Kinetics of Conventional and Alternative Jet Fuels for Aeropropulsion Combustion Modeling

PI: Chih-Jen Sung
Case Western Reserve University, Cleveland, Ohio

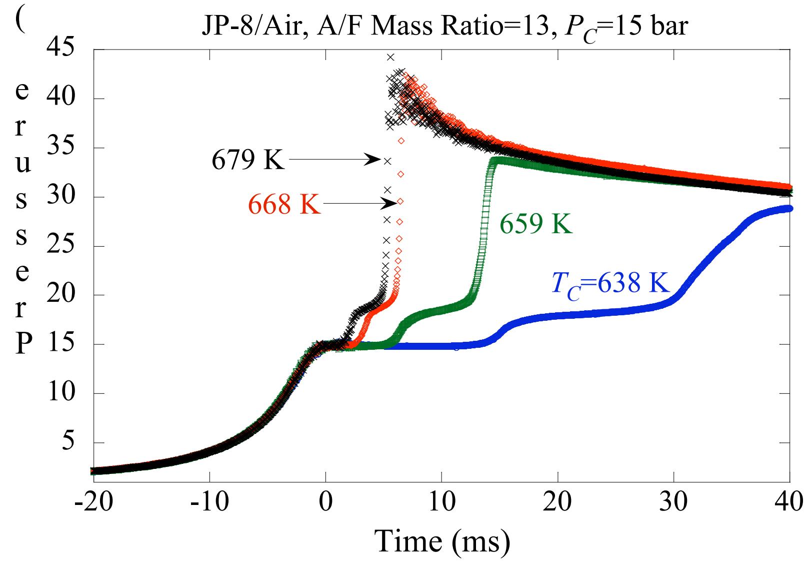
Objective: Development of comprehensive detailed and reduced kinetic mechanisms of jet fuels for chemically-reacting flow modeling.

Scientific Challenges:

• Developing experimental facilities capable of handling higher hydrocarbons and providing benchmark combustion data.

• Determining and understanding ignition and combustion characteristics, such as laminar flame speeds, extinction stretch rates, and autoignition delays, of jet fuels and hydrocarbons relevant to jet surrogates.

• Developing comprehensive kinetic models for jet fuels.



Major Accomplishments – Year 1:

• Developed and characterized experimental facilities for handling high-boiling-point liquid hydrocarbons and real jet fuels.

• Obtained extensive experimental data and assessed model performances for *n*-decane autoignition.

• Obtained experimental data for ignition delays of JP-8, Sasol fuel, and blends of toluene+isooctane and toluene+diisobutylene-1.

• Developed tools for automatic and efficient minimization of detailed kinetic mechanisms.

• Conducted computational fluid dynamics simulation of a rapid compression machine with detailed and reduced chemistry.

Relevance to NASA: Experimental data obtained will be used for development of comprehensive, computationally efficient kinetic models suitable for developing energy efficient aero-combustors with reduced emissions.

Grant #: NNX07AB36A

Program Monitor: Dr. Krishna P. Kundu

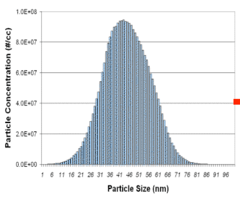
PI Contact information: Dr. Chih-Jen Sung Email: cjs15@case.edu, Ph. #: 216-368-2942

Effect of Particle Sampling Technique & Transport on Particle Penetration at the High Temperature & Pressure Conditions found in Gas Turbine Combustors & Engines- UTRC

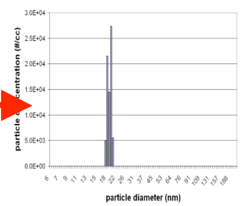
Year 1 Objective:

Develop techniques to quickly & accurately evaluate sampling line size-dependent transmission losses

Approach:
Use laboratory measurements to develop and evaluate low-order modeling



Differential Mobility Sizer

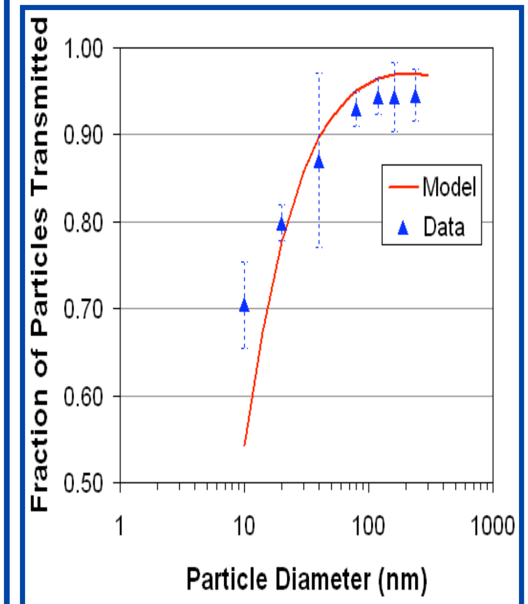


Sample Line Variables:
- Tubing diameter, length, type
- Sample flowrate
- Bends
- Ageing

Up → **Condensation Particle Counter**

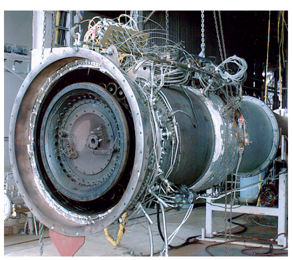
Down → **Condensation Particle Counter**

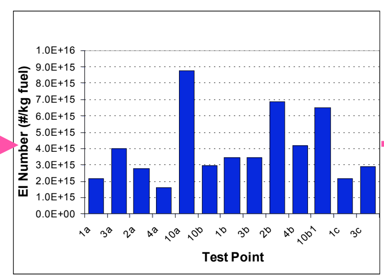
Expected outcome:
Use model to correct engine/combustor emission data for line losses

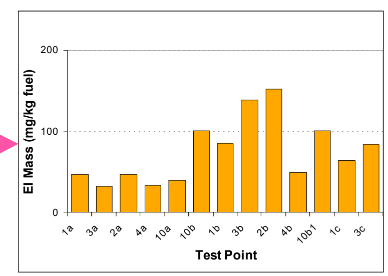


Year 2 Objective:

Acquire particulate measurements in high pressure and high temperature combustion experiments

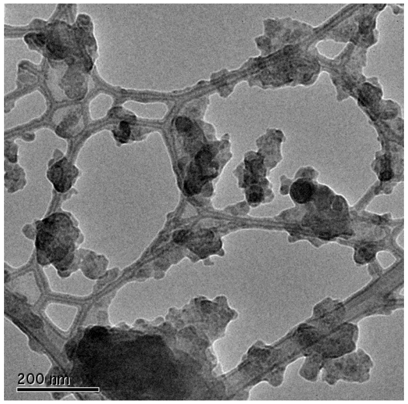






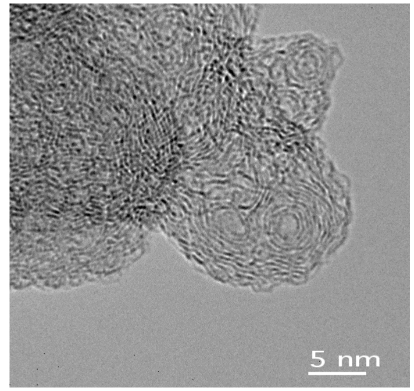
Electron Microscopy, Spectroscopy and Chemical Analysis of Aircraft Engine Particulate

Microstructure - morphology



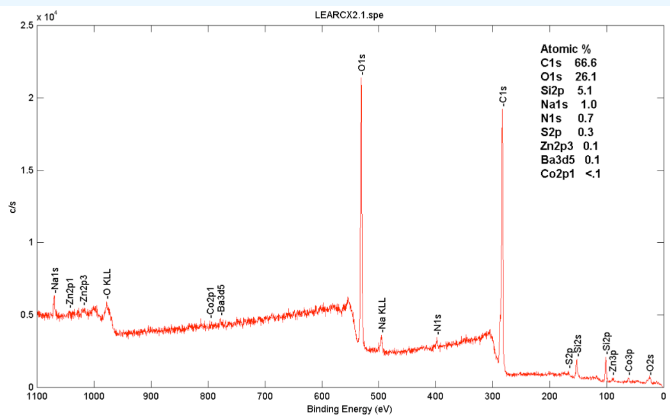
Low resolution TEM provides aggregate size and shape for particles captured on netmesh TEM grids

Nanostructure - carbon organization



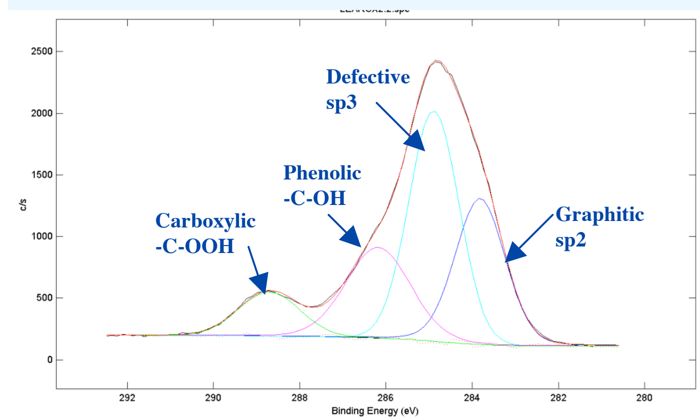
High resolution TEM provides direct visualization of graphitic, fullerenic and amorphous contents of soot.

Chemical Composition



Survey XPS scans provide elemental content

Surface Chemistry



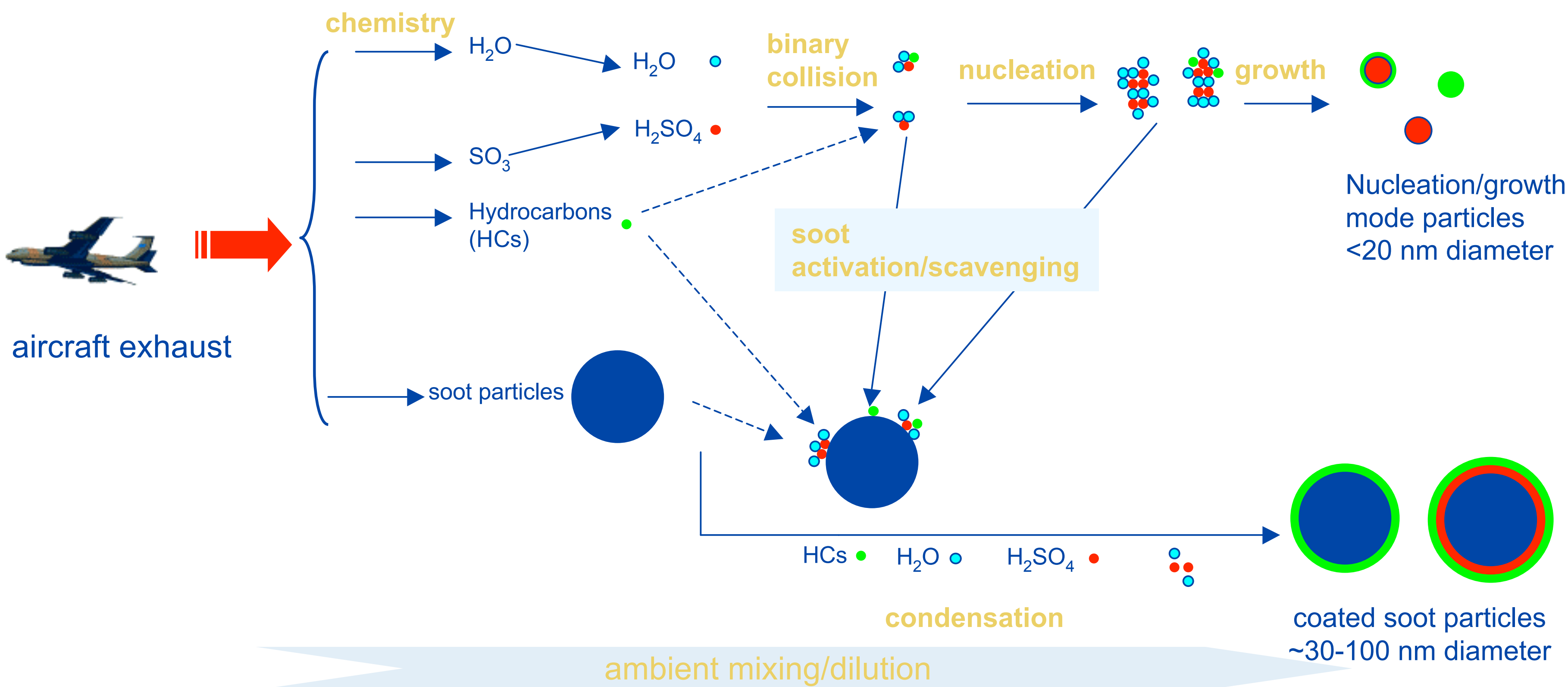
High res. XPS scans provide surface chemistry

PI: Dr. Randy L. Vander Wal (USRA @ NASA-Glenn)

Support: NASA Aero2007 NRA

Experimental Measurements of the Composition of Volatile Particles Present in Aircraft Gas Turbine Engine Exhaust – Aerodyne Research, Inc.

M. T. Timko (PI), R. C. Miake-Lye (Co-I) NASA GRC # NNC07CB57C



Motivation. The potential human health and environmental impacts of aviation pollution, especially particle emissions is poorly understood.

Background. Aircraft engines emit a mixture of soot and volatile gases. As pictured above, these gases cool to ambient temperature by mixing with ambient air and convert to the particle phase by condensation and nucleation/growth. The nucleation/growth mode particles and soot coatings are complex mixtures of sulfuric acid, water, partially burned hydrocarbons, and engine oil.

Objective. This work aims to characterize the composition of aviation particles and their evolution during atmospheric processing and dilution.

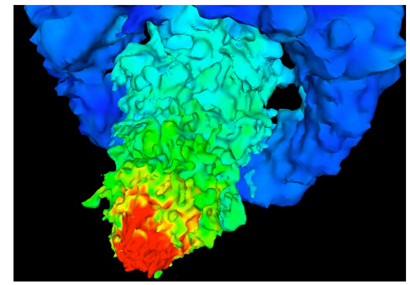
Emissions Prediction and Modeling of Supersonic Vehicle Combustion Systems

PI: Heinz Pitsch, Stanford University

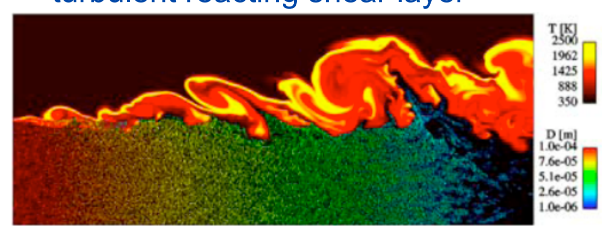
Modeling needs for predictive simulations of pollutant emissions in supersonic aircraft combustors:

- Predictive models for premixed and partially premixed combustion
  - Improvements of level set model
  - Dynamic model for turbulent burning velocity
  - Turbulent flame structure model for level set method
- Specific multi-phase models
  - Superheated evaporation
  - Combustion/evaporation interaction
- Models for soot formation
  - Interaction of soot formation with turbulent flow
  - Multivariate statistical model for soot
- Validation for
  - Well characterized simple experiments
  - Full scale combustor for supersonic aircraft

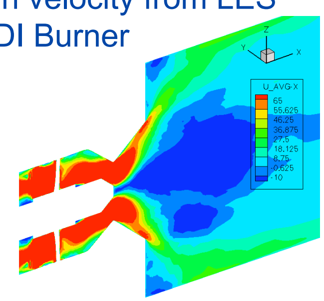
Turbulent partially premixd low-swirl flame



DNS of droplet evaporation in turbulent reacting shear layer



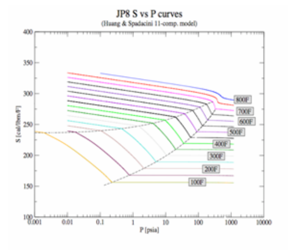
Mean velocity from LES of LDI Burner

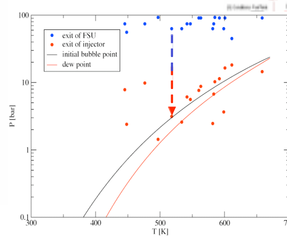


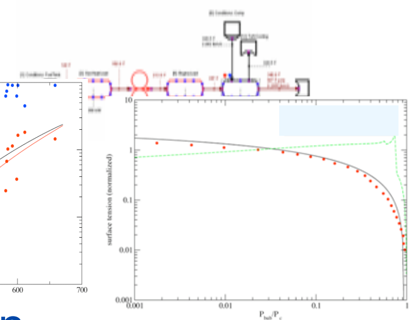
Superheated Fuel Injection and Combustion

Develop high fidelity computational models to enable the controlled use of superheated multicomponent fuel injection to achieve low emissions propulsion for supersonic cruise applications

Year 1 Assess Existing Models and Develop Preliminary Submodels

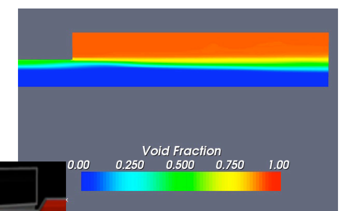






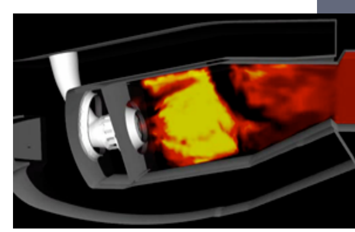
- System level study
- Jet A surrogate thermophysical properties
- Updated Homogeneous Relaxation Model
- Internal flow and liquid spray core

Year 2 Develop Physics-Based Submodels for Superheated Injection

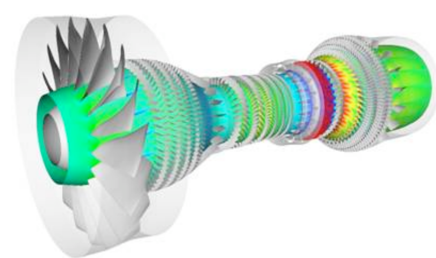


- Nucleation and bubble growth
- Droplet vaporization and transport
- Generalized sheet atomization

Year 3 Combustion Simulations and Emissions Prediction



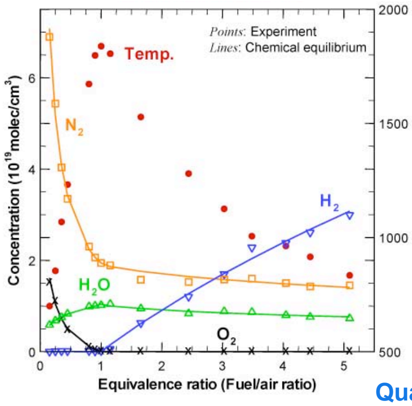
- Integration into commercial CFD
- Emissions model
- Combustor performance and emissions simulation

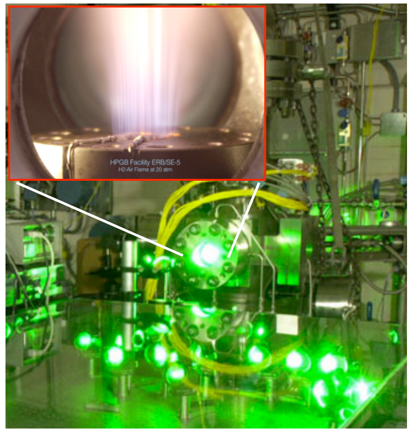


UTRC: Jeremiah Lee, Ravi Madabhushi, Catalin Fotache
UMass Amherst: David Schmidt, S. Gopalakrishnan
NASA: Nan-Suey Liu, Dan Bulzan

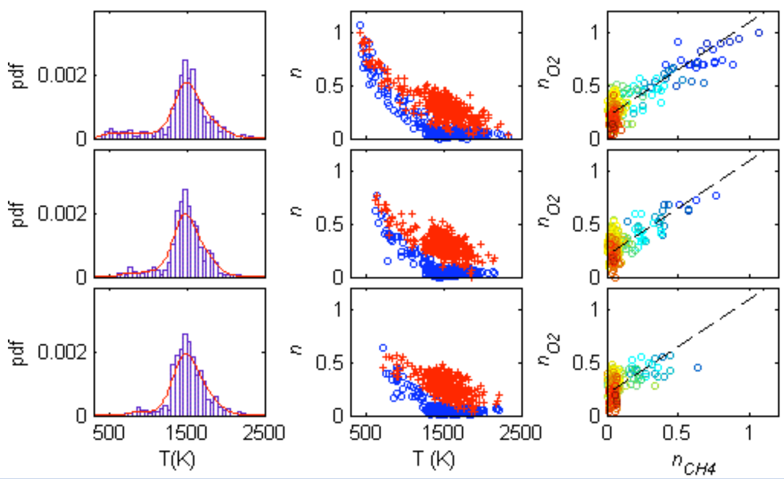
Technical Challenge: Turbulent Combustion Multi-Phase Code Validation Experiments
(Supersonics Program: Combustion Diagnostics subtopic)
PI (NASA NRA): Jun Kojima, Ohio Aerospace Institute

Spatially & Temporally Resolved Multi-Scalar Measurements For Code Validation





High Pressure Combustion Rig with Quantitative Laser Diagnostics (NASA GRC)



Benefits & Gaps: (1) Provide quantitative data in various high-pressure (<30 atm) flames to validate turbulence-chemistry interaction modeling in combustion codes for "Physics-Based Low-Emissions Combustor"

Goals: Provide *critical* chemical species and temperature data in high pressure flames for ***validating predictive low-emissions combustor codes***

Task Description: Perform a series of experiments of increasing flow complexity starting with fully-premixed gaseous burners that approximate chemical equilibrium, to more realistic concept burners (gaseous and liquid fueled) with swirl-effects. Additionally, the effects of chemical complexity will be addressed using different fuels (H_2, H_2/CO, CH_4, n-heptane, jet fuel) in various burners.

Quantitative laser Raman diagnostics is used to measure spatially and temporally-resolved scalar information of major species concentration, and temperature to derive statistical values (mixture fractions and probability density functions) to compare with combustor code predictions of unsteady-effects of turbulence such as NASA's National Combustion Code (NCC).

Validation Requirements (Exit Criteria): Obtain measurements of joint chemical species-temperature-velocity vector fields with < 5% uncertainty in high pressure (<30 atm) multi-phase reacting flows.

Technical Risk: Development of quantitative multi-species chemical concentration and temperature measurements in high temperature/ pressure reacting multi-phase flows; Development of simultaneous temporally and spatially resolved chemical species scalar and velocity vector measurement system capable of working in droplet-laden flows;

Current SOA: Multi-scalar chemical species and temperature measurements in single-phase atmospheric pressure flames. Velocity vector field measurements in high pressure flames; no simultaneous measurements in high pressure flames; multi-phase measurements limited to basic cases with no quantitative data.

Collaborator: Quang-Viet Nguyen, NASA Glenn Research Center, Combustion Branch/RTB

Coherent Anti-Stokes Raman Scattering (CARS) For Quantitative Temperature and Concentration Measurements in a High-Pressure Gas Turbine Combustion Test Rig

Principal Investigators: Robert P. Lucht and Jay P. Gore

Graduate Students: Mathew P. Thariyan and Vijaykumar Ananthanarayanan

Postdoctoral Research Associate: Sergei Filatyev

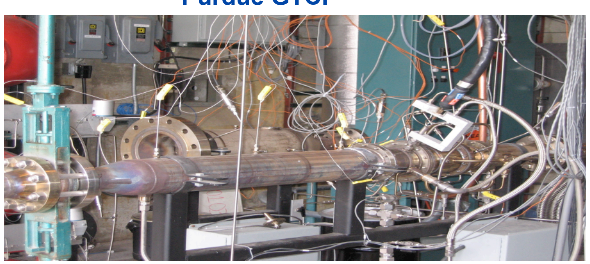
Background and Motivation

- **This work is being performed with support from NASA Glenn under Cooperative Agreement NNX07AC90A. Our primary contact at NASA Glenn is Dr. Yolanda Hicks.**
- The primary objectives of the work are (1) to demonstrate the application of dual-pump CARS for species and temperature measurements at supersonic cruise conditions and (2) acquire data of validation quality for operation with NASA-supplied injectors. The data acquired will be used to validate NASA's National Combustion Code (NCC).

Gas Turbine Combustion Facility

- The Purdue Gas Turbine Combustion Facility (GTCF) has been developed with assistance from Rolls Royce Corporation in Indianapolis, IN.
- Combustion tests conducted up to 270 psia, 2.5 lbm/s air.
- Tests run for varying fuel-air ratios, varying pilot fuel fraction. State-of-the-art gas analysis system installed and tested.
- NASA injector supplied and will be installed in late 2007.

Purdue GTCF

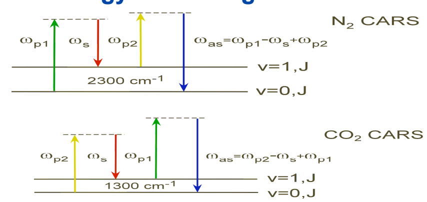


Advanced FT-IR Multi-Gas Analyzer

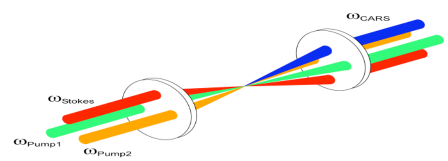
Dual-Pump CARS

- Dual-pump CARS will be used for simultaneous, single-laser-shot measurements of temperature and two species in the high-pressure reacting flow field.

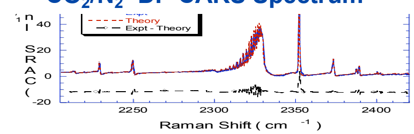
Energy Level Diagrams



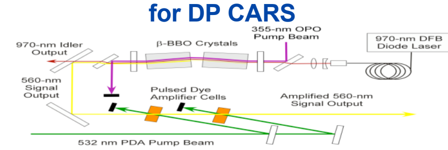
DP CARS Phase-Matching



CO_2/N_2 DP CARS Spectrum



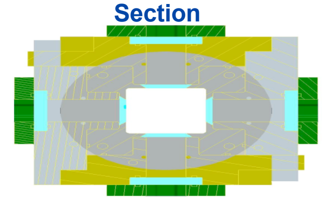
Advanced Laser System for DP CARS



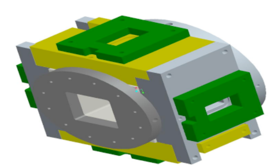
GTCF Optical Access

- The Purdue GTCF is being modified to provide optical access for laser diagnostics. A thin inner window to contain the thermal loading and a thick outer window to hold the pressure will be used.

Window Assembly Cross Section



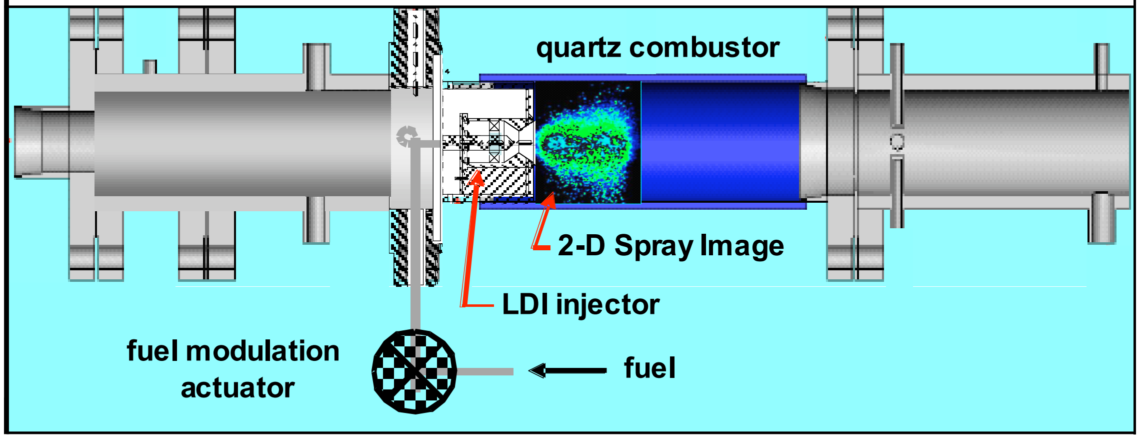
Window Assembly Drawing



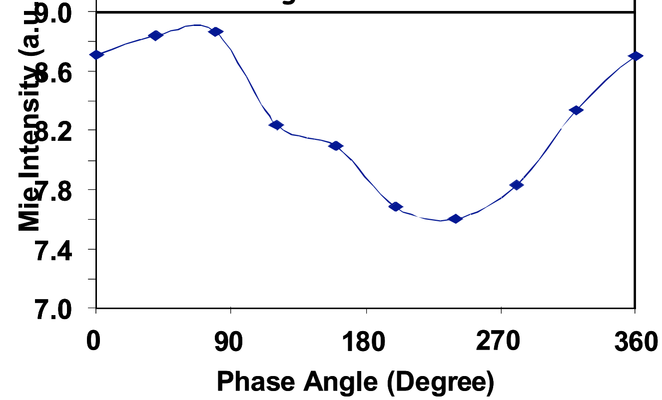
Active Combustion Control for Low Emissions Combustors

NASA Award No: NNX07C98A

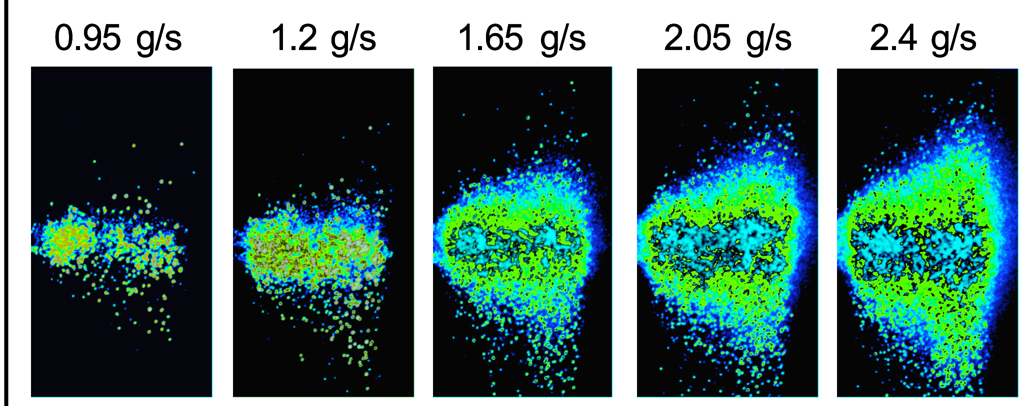
Combustor test rig for flame response measurements



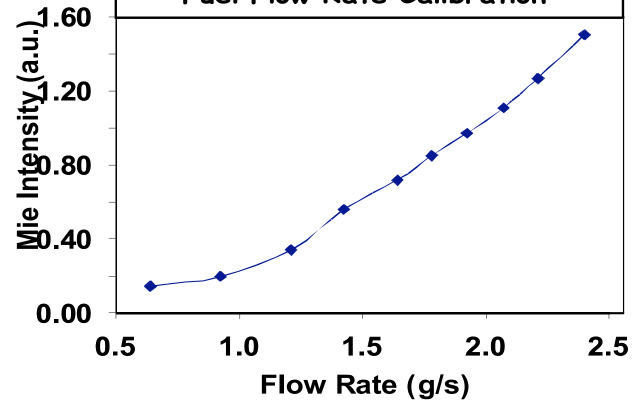
Mie Scattering Intensity Fluctuation During Fuel Modulation



Mie Scattering Calibration Images



Mie Scattering Intensity versus Fuel Flow Rate Calibration



PENN STATE 1855

Virginia Tech 1872