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Turbine Fuel Technologies

Innovative Injection and Mixing Systems for Diesel Fuel Reforming

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Goodrich Turbine Fuel Technologies

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Outline of Presentation

- **Program Goals and Work Scope**
- **Technical Approach**
  - Injector and Mixing Concepts
  - CFD Flow Structure and FE Thermal Analyses
  - Experimental Setup and Equipment
- **Results to Date**
  - Test Rigs
  - Multipoint Impingement Injector and Mixer
  - Single Point Gas-assisted Injector and Mixer
  - High-Energy Piezoelectric Injector
- **Future Plans**

Program Goals and Work Scope

- **Objective – The primary objective is to develop cost-effective injection and mixing concepts to enable development of reliable diesel fuel reforming technology for solid oxide fuel cell power system.**
- **Major Tasks**
  - Task 1- Evaluate Atomization and Injection Concepts
  - Task 2- Develop Effective Mixing Chamber
  - Task 3- Construct Test Rig and Perform Laser Diagnostics
  - Task 4- Investigate Carbon-resistant Coating Materials and Design features

Technical Issues on Liquid Fuel Reforming

- Adequate atomization over the entire operating range
- High flow rate turndown ratio required
- Minimum inlet pressure of steam and airflow
- Uniform distribution of temperature, velocity and fuel mixture at the entrance of the reactor
- Intrinsically unstable flow
- Recirculation and flow reversal inside mixing chamber
- Autoignition
- Droplet impingement on wall surface
- Quick mixing between feed streams

Technical Issues (continued)

- **Thermal management issues (heat shielding, steam condensation and internal coking)**
- **Pressure loss and plugging due to small passage and orifice**
- **Diesel fuel difficult to vaporize and prone to pyrolysis**
- **Coking and metal corrosion problems**
- **Simple and robust injector/mixer design**
- **Cost effective and low power consumption**
- **Easy to integrate with different reactors**
- **Multi-fuel capability**
- **Quick startup and rapid response**

Survey Results for 10-kW Injector/Mixer Operating Parameters

- Reformer Types - ATR, CPOX, ATR/SR
- Fuel Types - Diesel, Jet A, JP8
- Fuel Delivery Requirements - 0.6 to 8 lbs/hr, 50~145 psig inlet pressure
- Fuel Turndown Ratio - 2:1 to 10:1
- Air Delivery Requirement - 6 to 40 lbs/hr; temperature 70 ~950°F; maximum inlet pressure less than 2 psig
- Steam Delivery Requirements -3 to 20 lbs/hr; 500~700°F; maximum inlet pressure 10 to 30 psig
- Packaging Requirements - 0.5 ~ 1 liter
- Steam/Carbon Ratio - 0.5 to 3
- Oxygen/Carbon Ratio - 0.8 to 1.3

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Difficulties Using Conventional Pressure Swirl Injection Technique

1 psig/1 pph

Jet Fuel SMD>120 µm

Diesel SMD>140 µm

5 psig/2.7 pph

Jet Fuel SMD=80 µm

Diesel SMD=90 µm

20 psig/4.8 pph

Jet Fuel SMD=60 µm

Diesel SMD=70 µm

50 psig/7.25 pph

Jet Fuel SMD=45 µm

Diesel SMD=55 µm

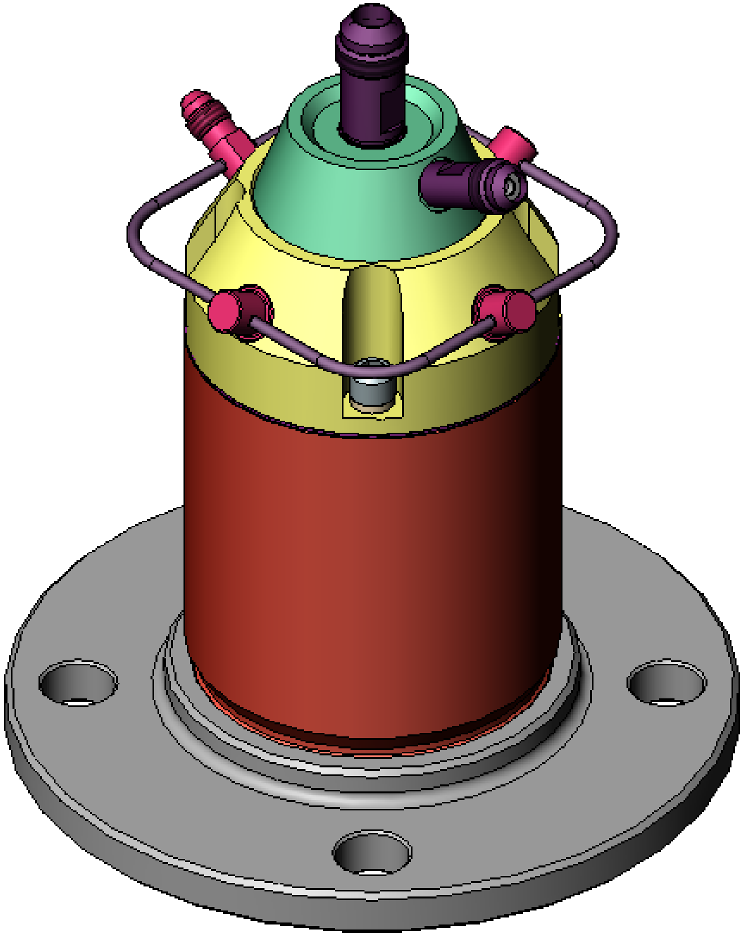
Technical Approach

- Conduct a thorough evaluation of various injection and mixing concepts
- Establish threshold and target performance data
- Perform Design of Experiment (DOE) to map out the operating conditions for the most promising concepts
- Utilize CFD and FEA tools to help predict and understand flow-field structure and injector/mixer performance
- Perform detailed laser diagnostics for performance evaluation and design substantiation
- Incorporate carbon-resistant or coke-tolerant design features

Injection and Mixing Concepts

- Multipoint Impingement Injector
- Single-Point Steam or Air-assisted Simplex Injector
- High-Energy Piezoelectric Simplex Injector
- Preheating Simplex Fuel Injector
- Pulse Modulated Fuel Injection
- Effective Mixing Swirlers and Mesh Screens
- Carbon Tolerant Design Features

Multipoint Impingement Injector Concept



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Gas-Assisted Simplex Injection and Mixing Concept

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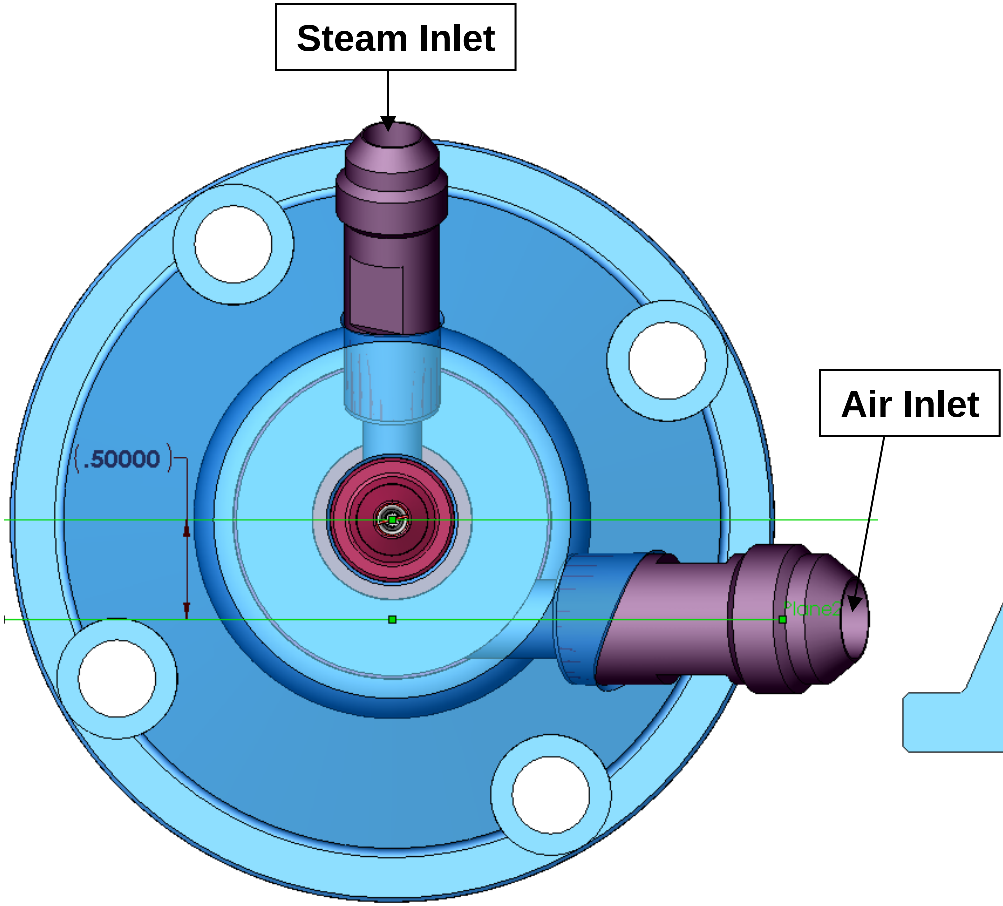

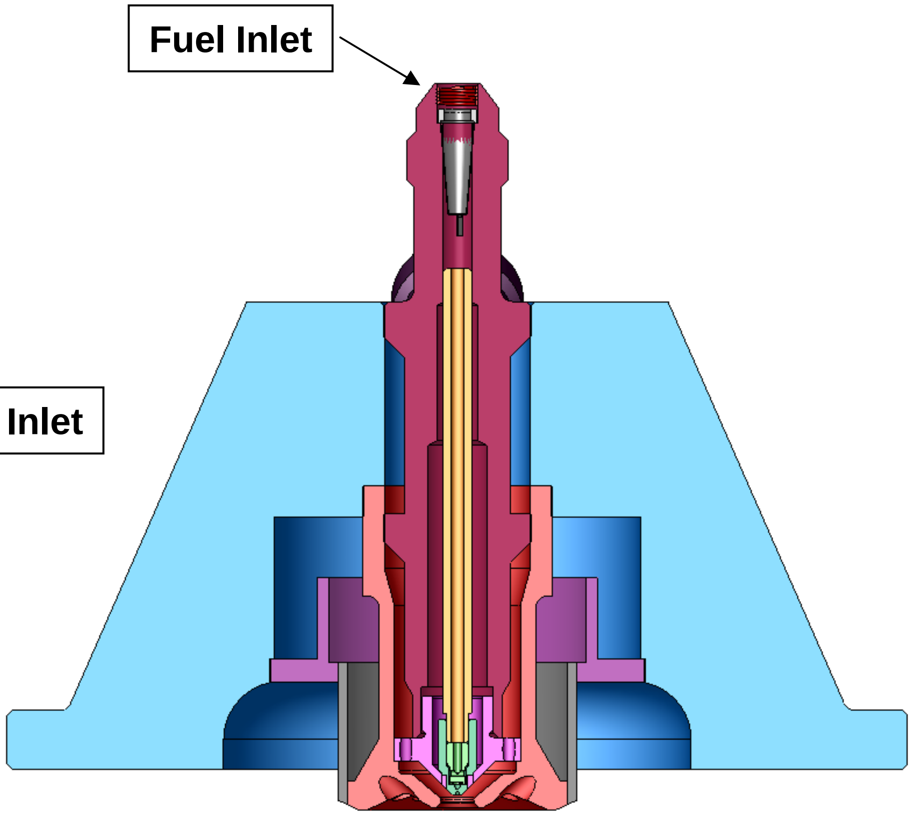

High Energy Piezoelectric Simplex Injector

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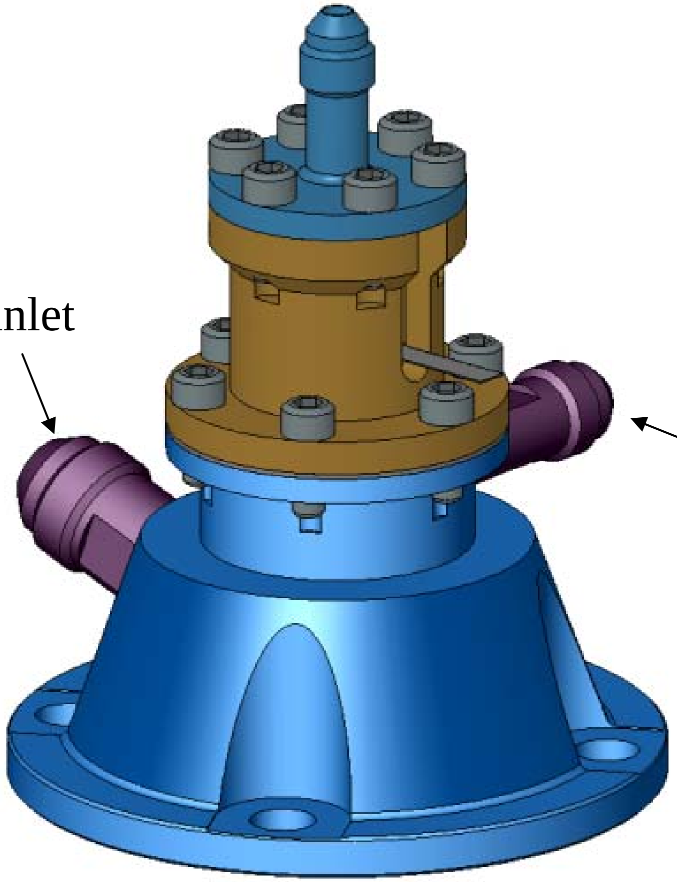

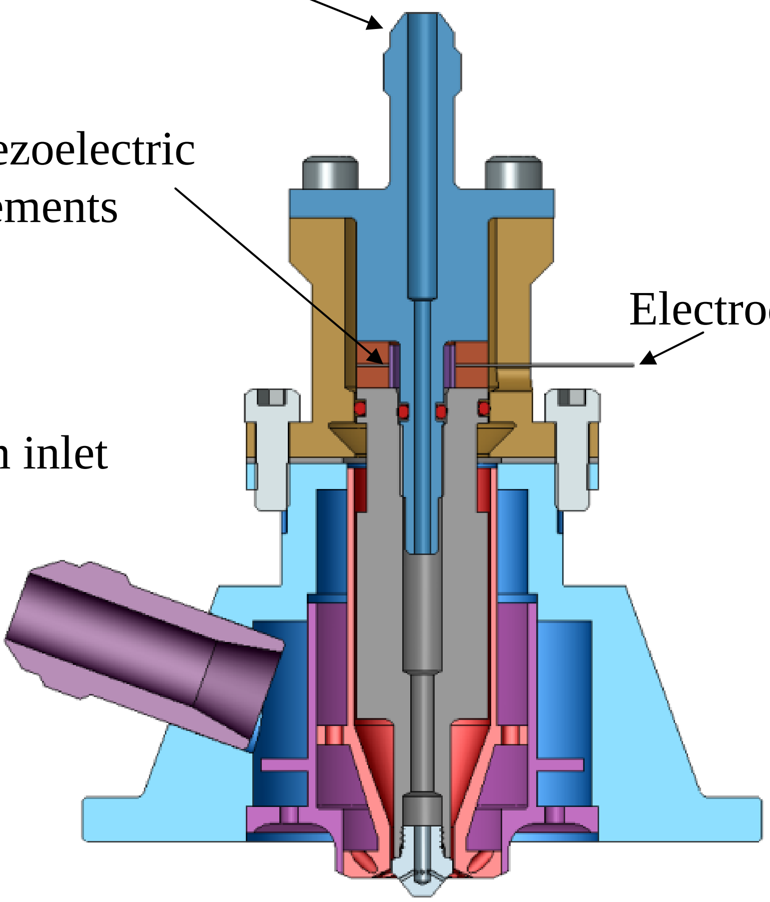

Experimental Capabilities

- **Advanced developmental machine shop**
- **Test rig representative of 3~10 kW reformer operation**
- **Phase Doppler Interferometry**
- **SETscan Optical Patternator**
- **Fuel Reformer Diagnostic Equipment from NASA Glenn**
  - Particle Imaging Velocimetry (PIV)
  - Raman Spectroscopy
  - Gas Chromatography

Injector and Mixer Testing Equipment

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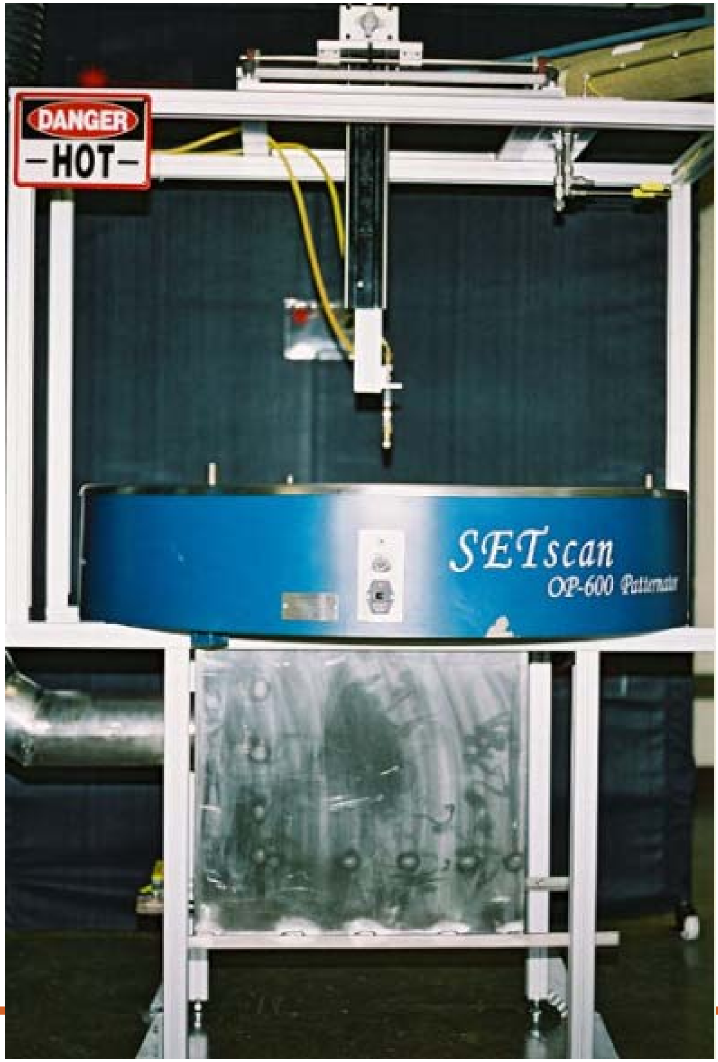
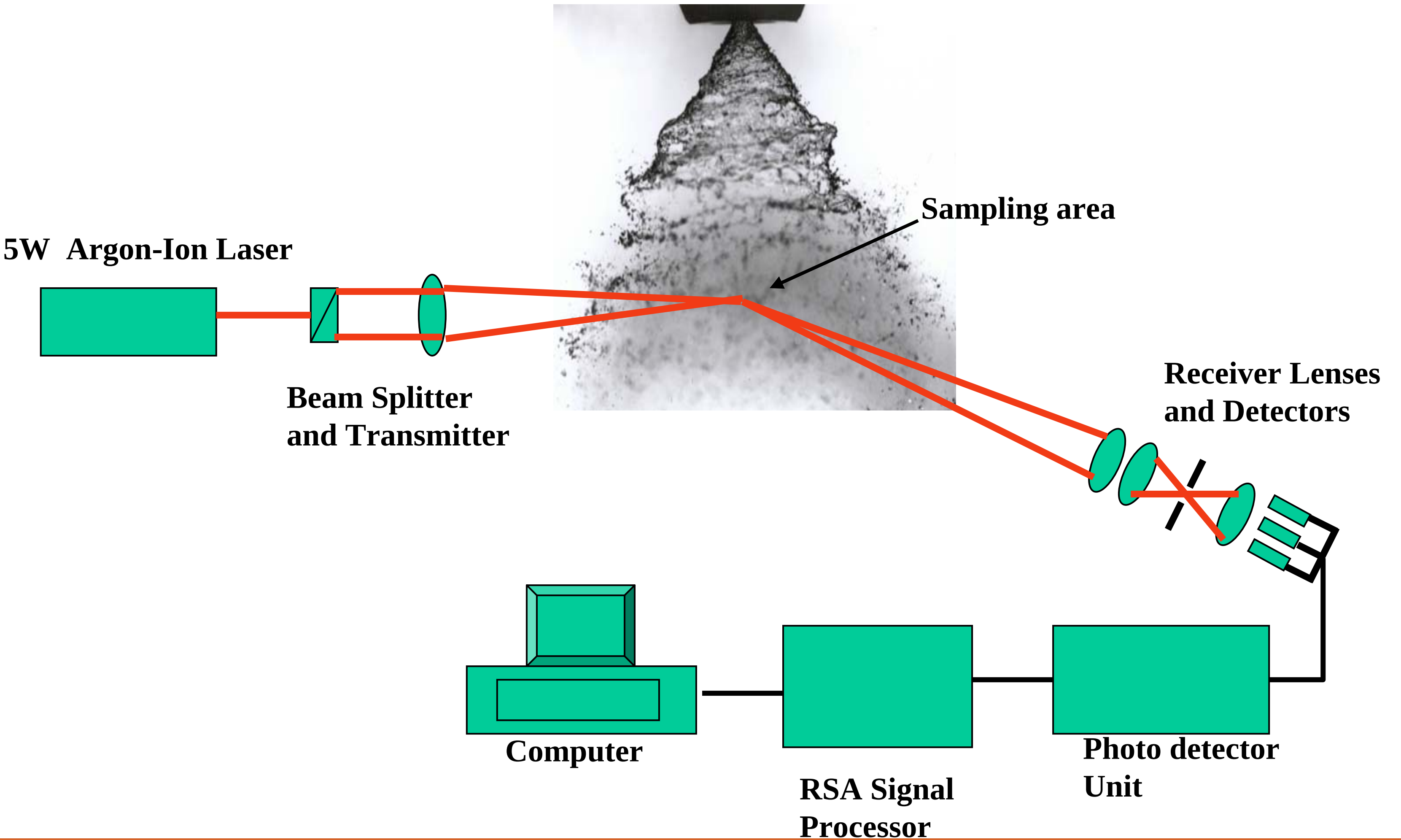
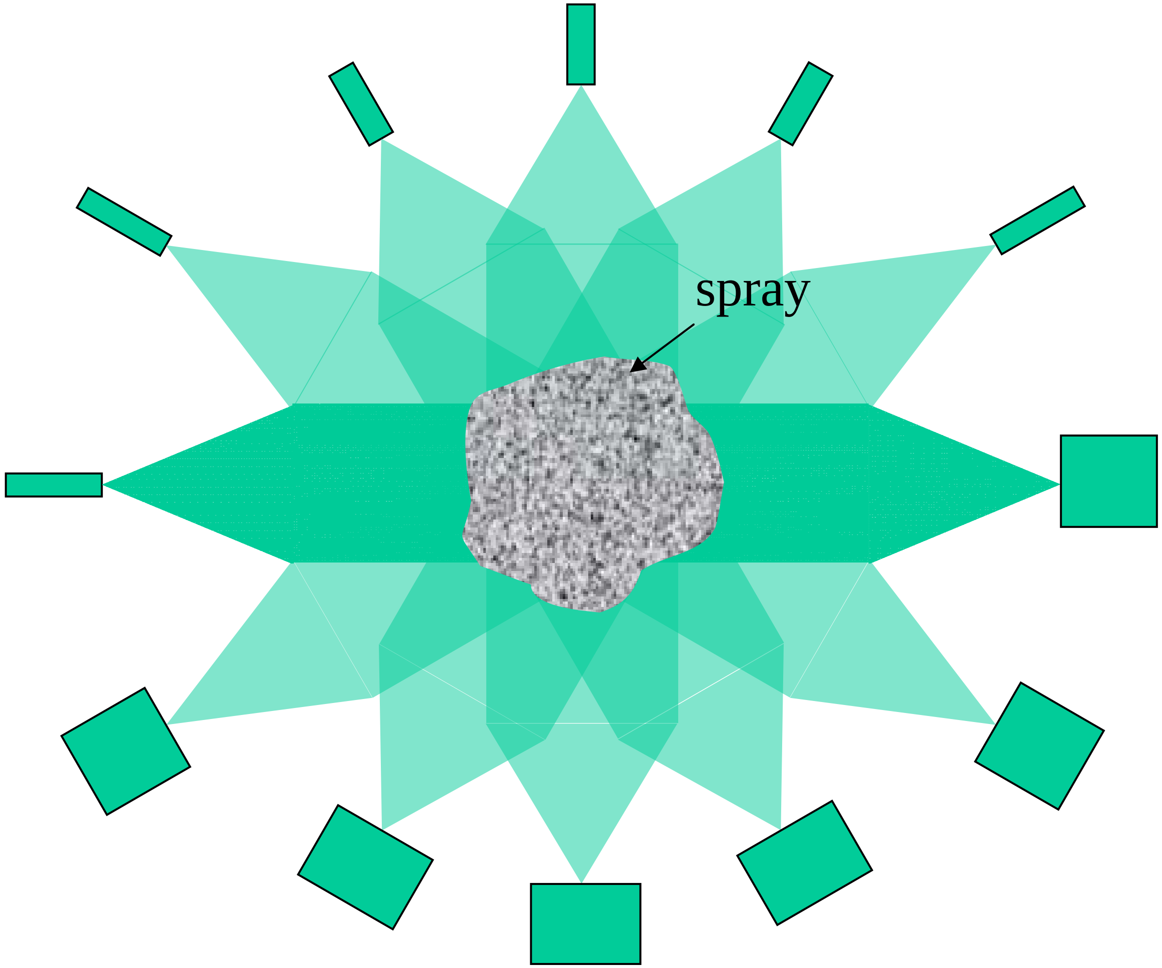
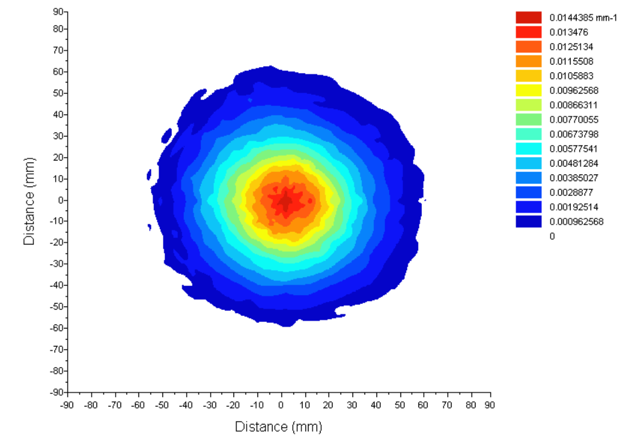


Phase Doppler Particle Analyzer

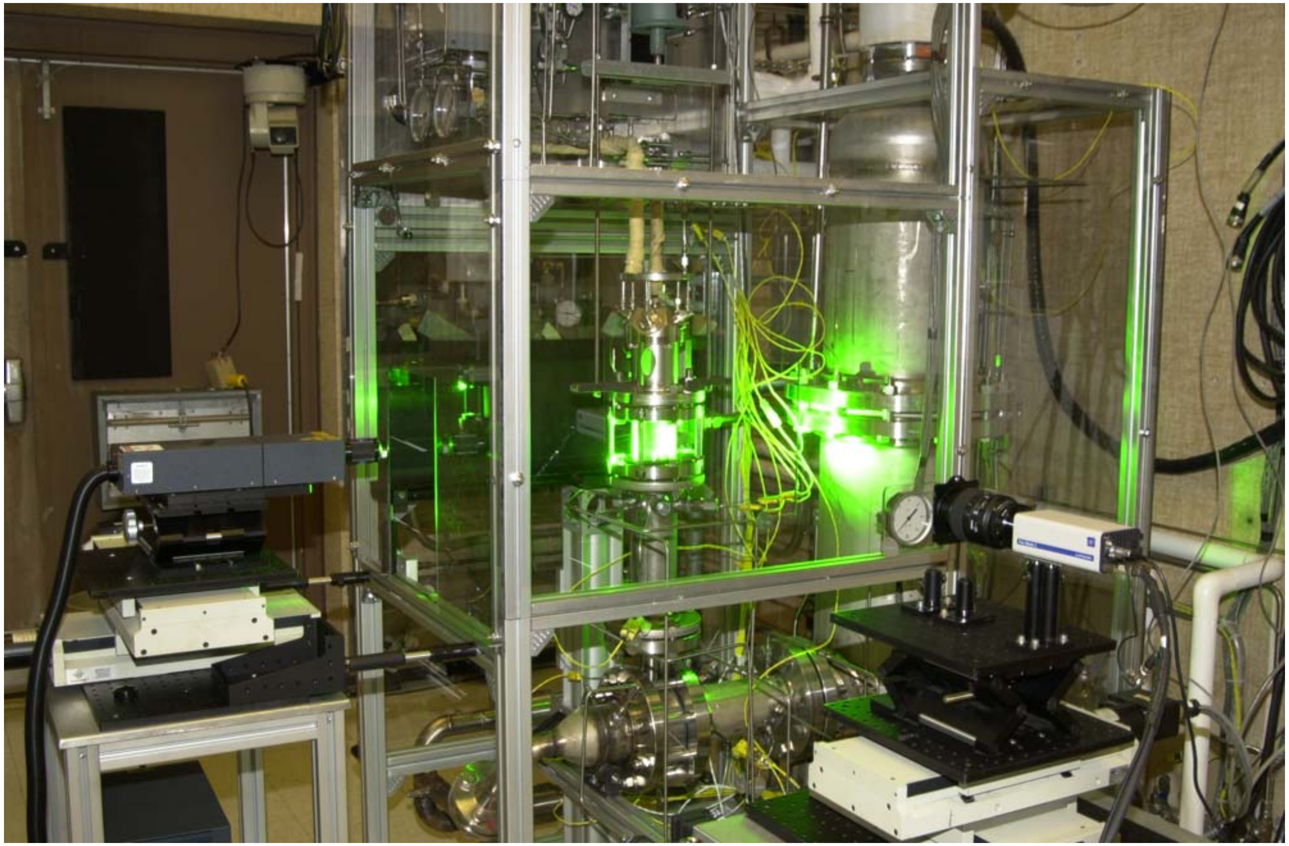


6-Axis *SETscan* Optical Patternator

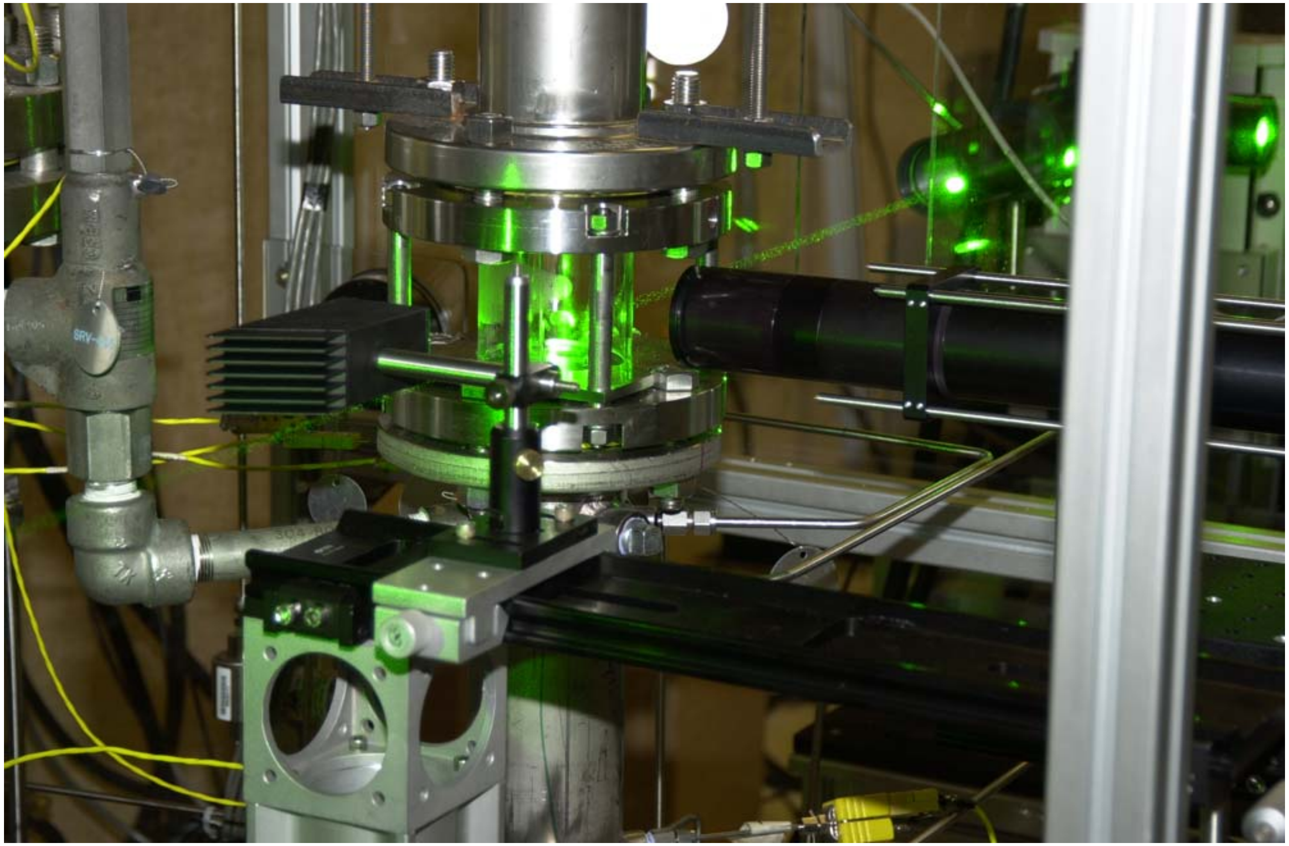




Particle Imaging Velocimetry



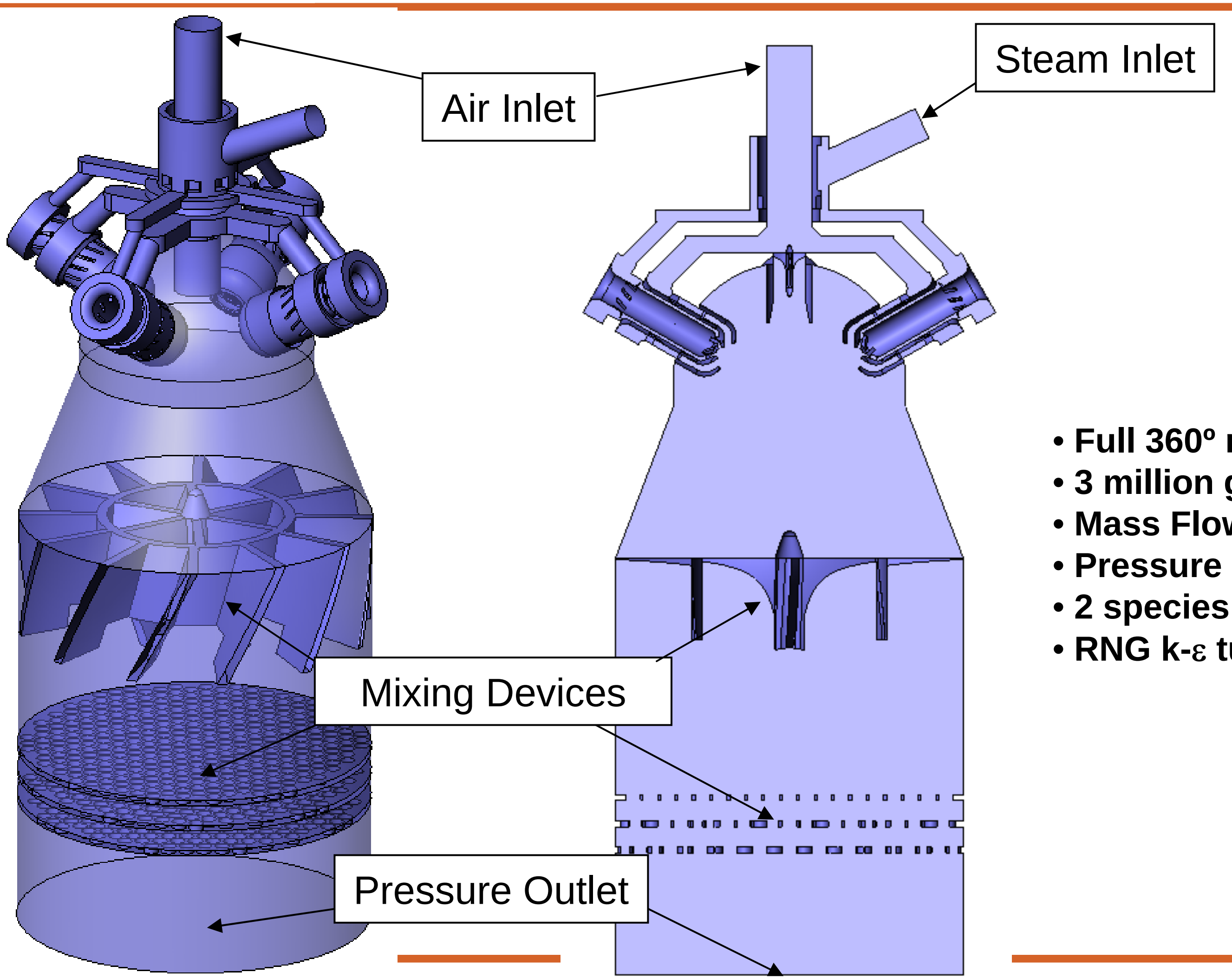
Raman Spectrometer



Results to Date
(from October 2004 through March 2005)

- Constructed a hot flow test rig for performance development and concept screening
- Completed the evaluation of the multipoint impingement injector concept in March 2005
- Assembled a gas-assisted simplex injector for detailed performance evaluation
- Fabricated a prototype piezoelectric injector for evaluation of driver electronics and injector operating parameters
- Analyzed various injector and mixing chamber configurations for improved mixing capability and thermal management
- Conducted detailed flow field measurements using phase Doppler interferometry, SETscan optical patternator, Raman spectrometer and porcupine thermocouples.

Injector/Mixer Flow Field Analysis



- Full 360º model
- 3 million grid cells
- Mass Flow Inlet Boundaries
- Pressure Outflow Boundaries
- 2 species (air, steam)
- RNG k-ε turbulence model

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Multipoint Impingement Injector Flow Field Analysis

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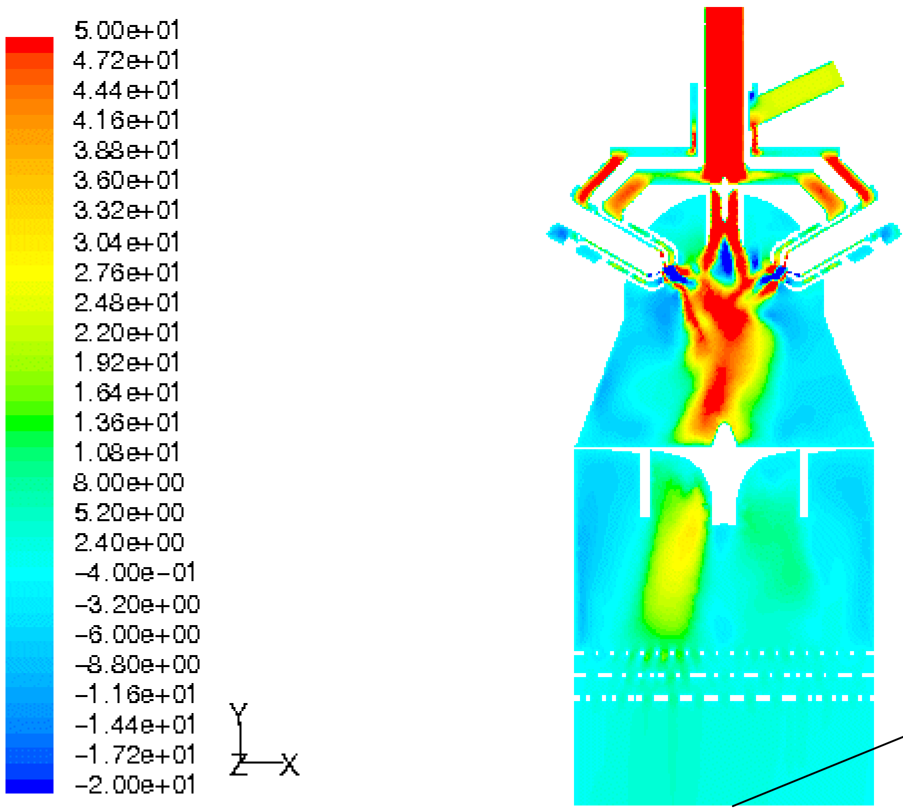
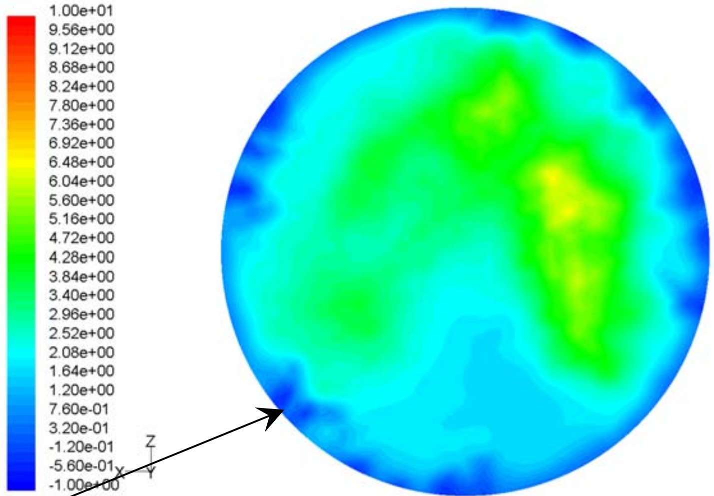
CFD Predicted Axial Velocity Contours (m/s)



Air: 930 ºF, 30 lb_m/hr
Steam: 550 ºF, 12 lb_m/hr



Time-averaged axial velocity contours at the outlet boundary

Thermal Analysis for Multipoint Impingement Injector

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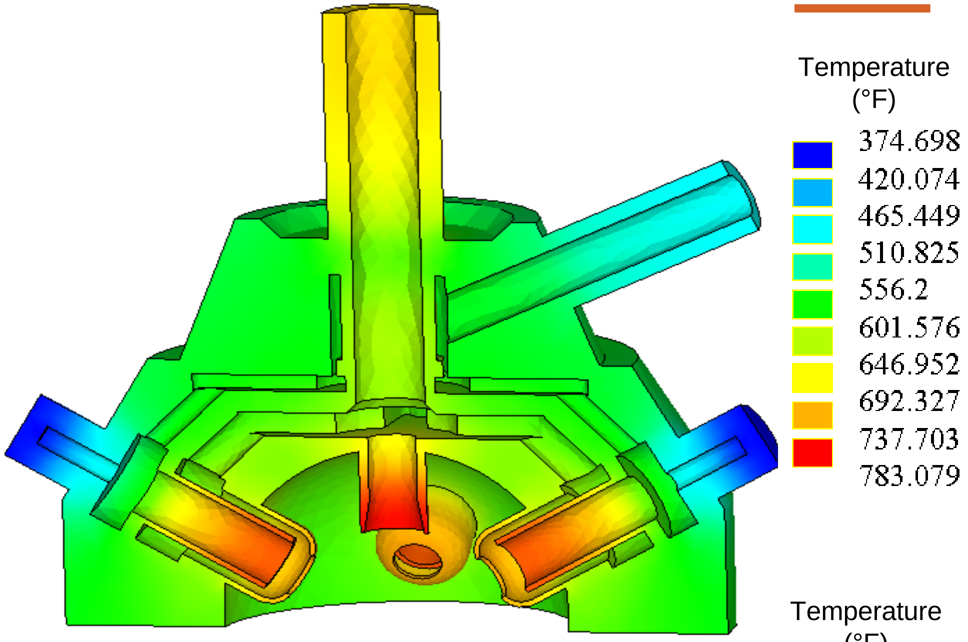
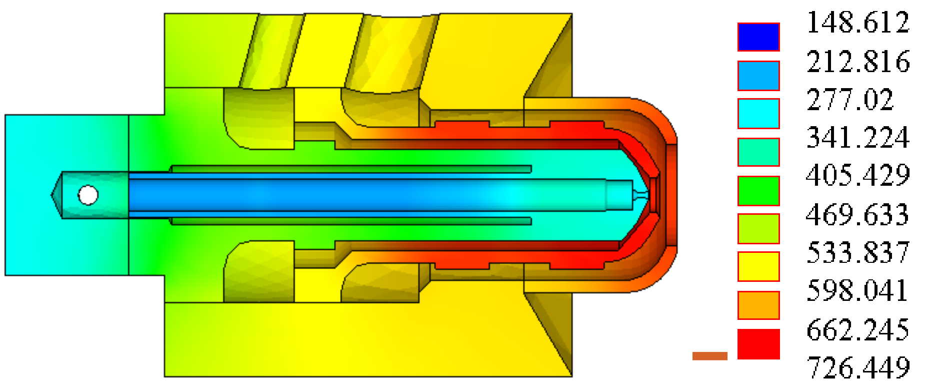
- SolidWorks model directly imported into ANSYS
- Wetted wall temperature of the fuel circuit must not exceed 400°F.
- Internal wall temperature of the steam circuit must be above saturation temperature at the operating pressure.
- Temperature gradients of the metal must be low enough not to cause undesired thermal growth and stresses.





Porcupine Thermocouples for Temperature Measurements

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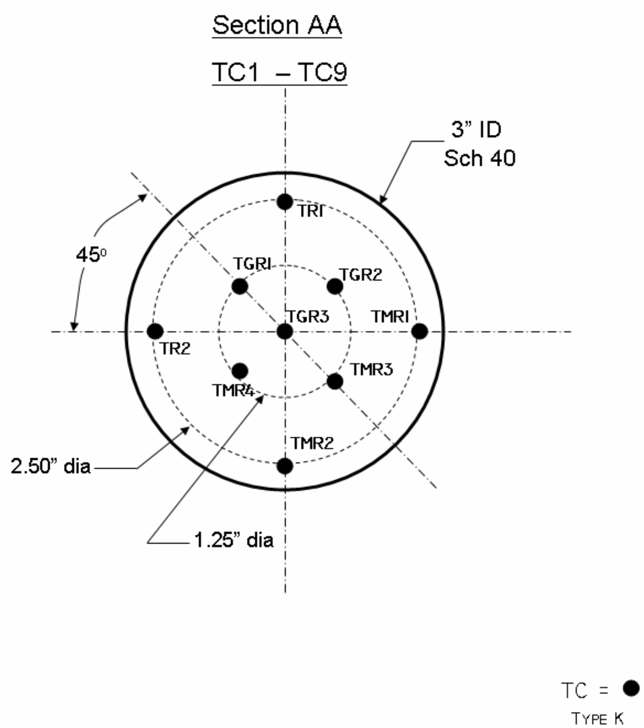
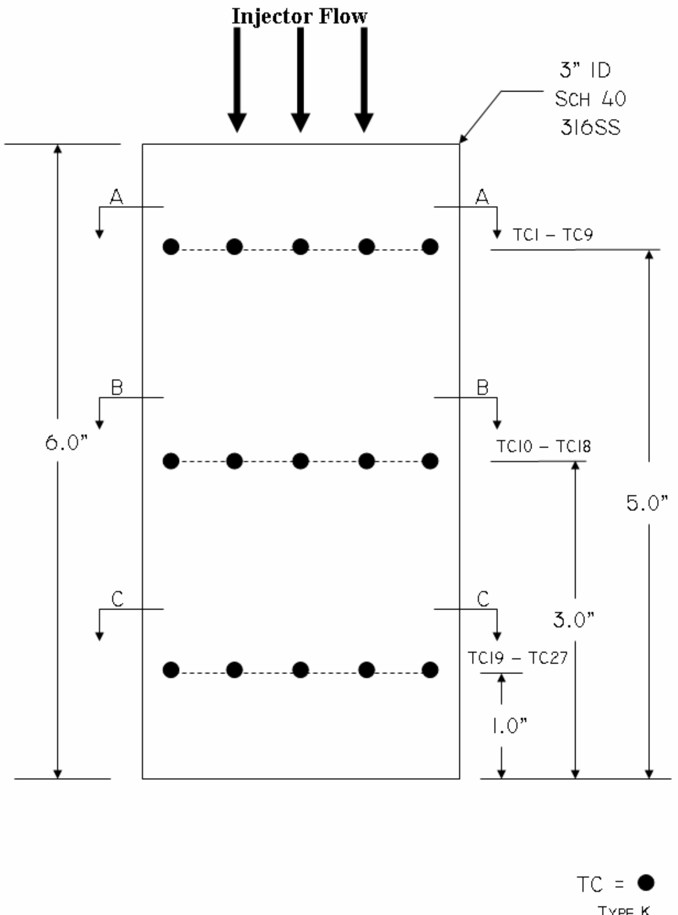
3" Test Section Spool – TC Layout



Note: Spool will use existing TC Input Channels from 10 kW ATR Reactor (30 available)

Scale: 1.0" = 1.0" Flanges Not Shown TMT 3/12/05

3" Test Section Spool – TC Layout (Porcupine)



Total 27 TC's

Scale: 1.0" = 1.0" Flanges Not Shown TMT 3/12/05

Temperature Uniformity at Downstream Locations

	Section A-A (1" downstream)			Section C-C (5" downstream)		
Test Point	**Ave. (°F)**	**Max-Min. (°F)**	**UI(%)**	**Ave. (°F)**	**Max-Min. (°F)**	**UI(%)**
Pt.1 - Fuel 5 pph, Air 25pph/930F, steam 10pph/550F	525	10	1.91	515	30	5.82
Pt.2 - Fuel 5 pph, Air 25 pph/930 F, steam 6.5pph/550F	549	26	4.74	538	34	6.32
Pt.3 - Fuel 5 pph, Air 25 pph/930 F, steam 3 pph/550F	554	21	3.74	545	29	5.32
Pt.4 - Fuel 1.5 pph, Air 7.5 pph/930 F, steam 3 pph/550 F	551	23	4.17	544	25	4.59
Pt.5 - Fuel 2 pph, Air 12 pph/930 F, steam 5 pph/550 F	553	20	3.62	547	23	4.20

Uniformity Index   UI = (Max.-Min.)/Average

Temperature is considered very uniform for UI less than 5% .

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Multipoint Impingement Injector Effect of Steam Pressure

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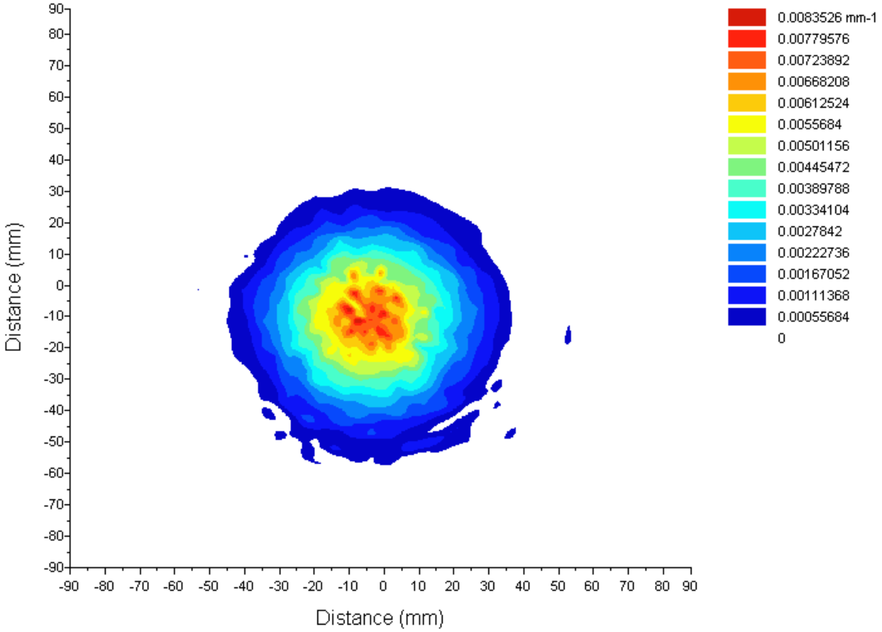
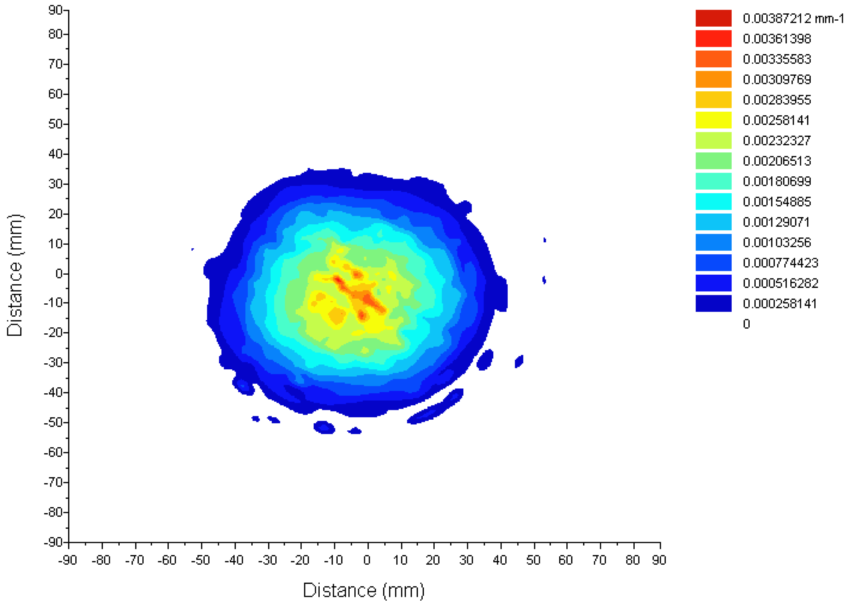
Cold Flow Tests Using SETscan Optical Patternator



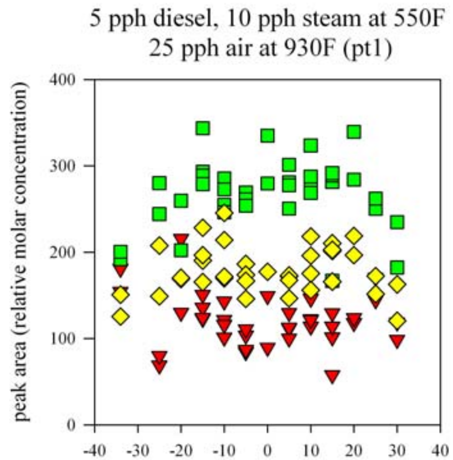


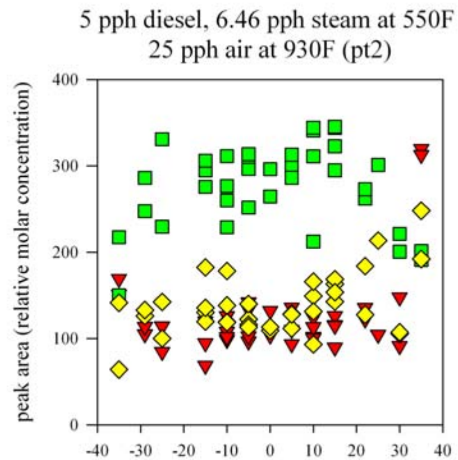
2 pph fuel, 15 pph steam, 15 pph air

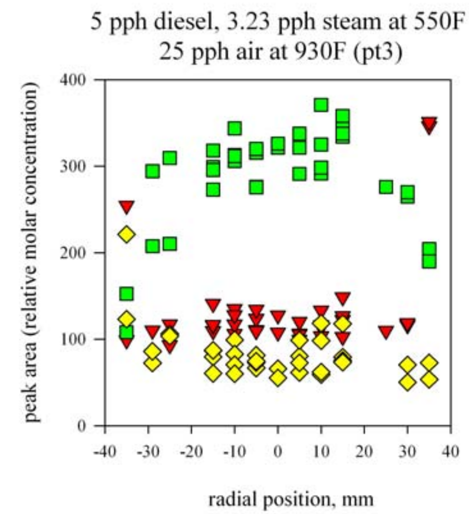
2 pph fuel, 5 pph steam, 15 pph air

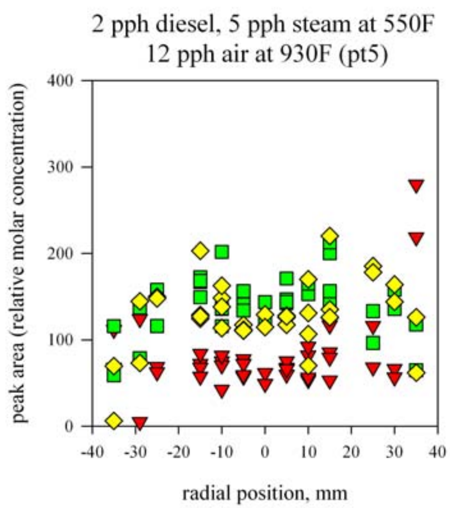
Note: Shop air was used in the steam circuit for cold flow patternation tests.

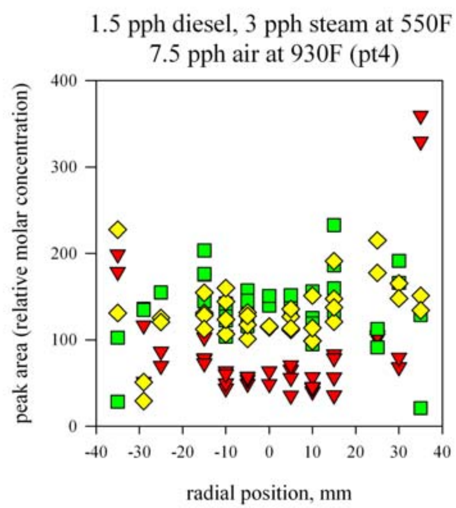
Effect of Operating Conditions on Species Distribution

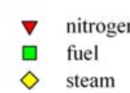












Multipoint impingement injector

-2 mixing chamber without mixing devices

Diesel Fuel

Effect of Fuel Properties on Species Distribution
Top Row: Jet-A; Bottom Row: Diesel

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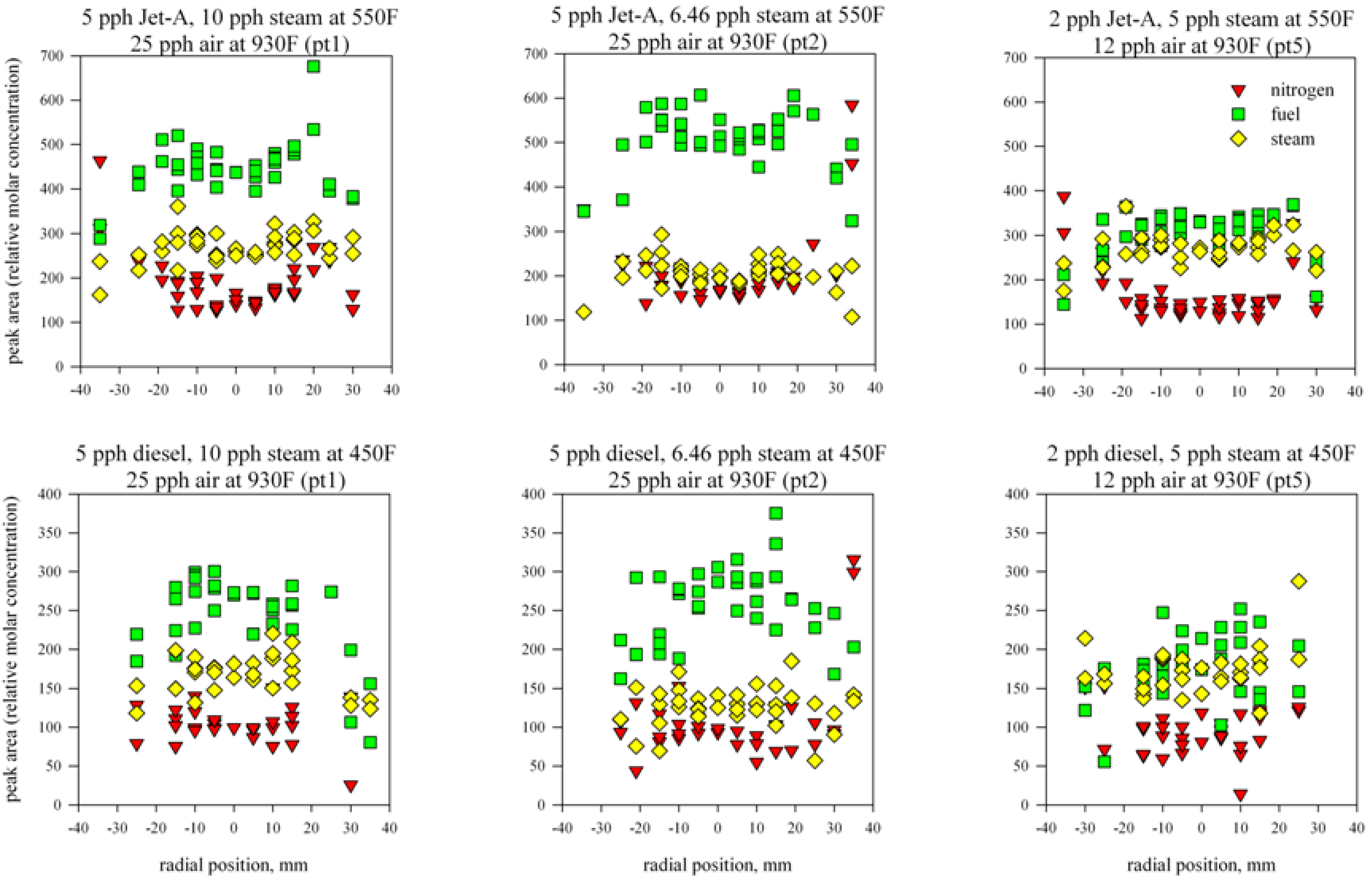

-1 mixing chamber with mixing devices

Effect of Steam Temperature on Species Distribution

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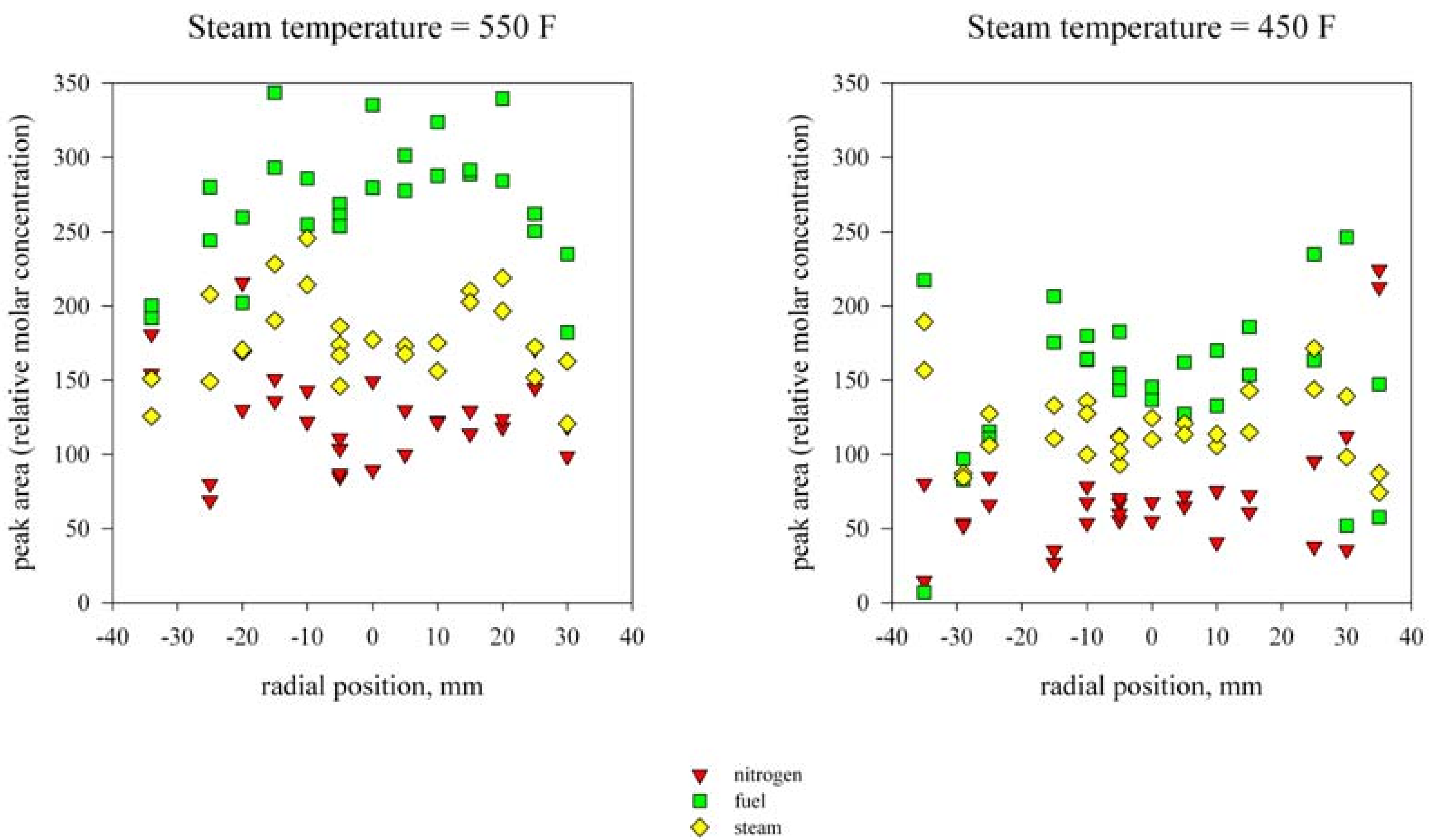
Diesel Fuel: 5 pph, Air Flow: 25 pph at 930°F, Steam Flow: 10 pph



-2 mixing chamber without mixing devices

Effect of Mixing Devices on Species Distribution

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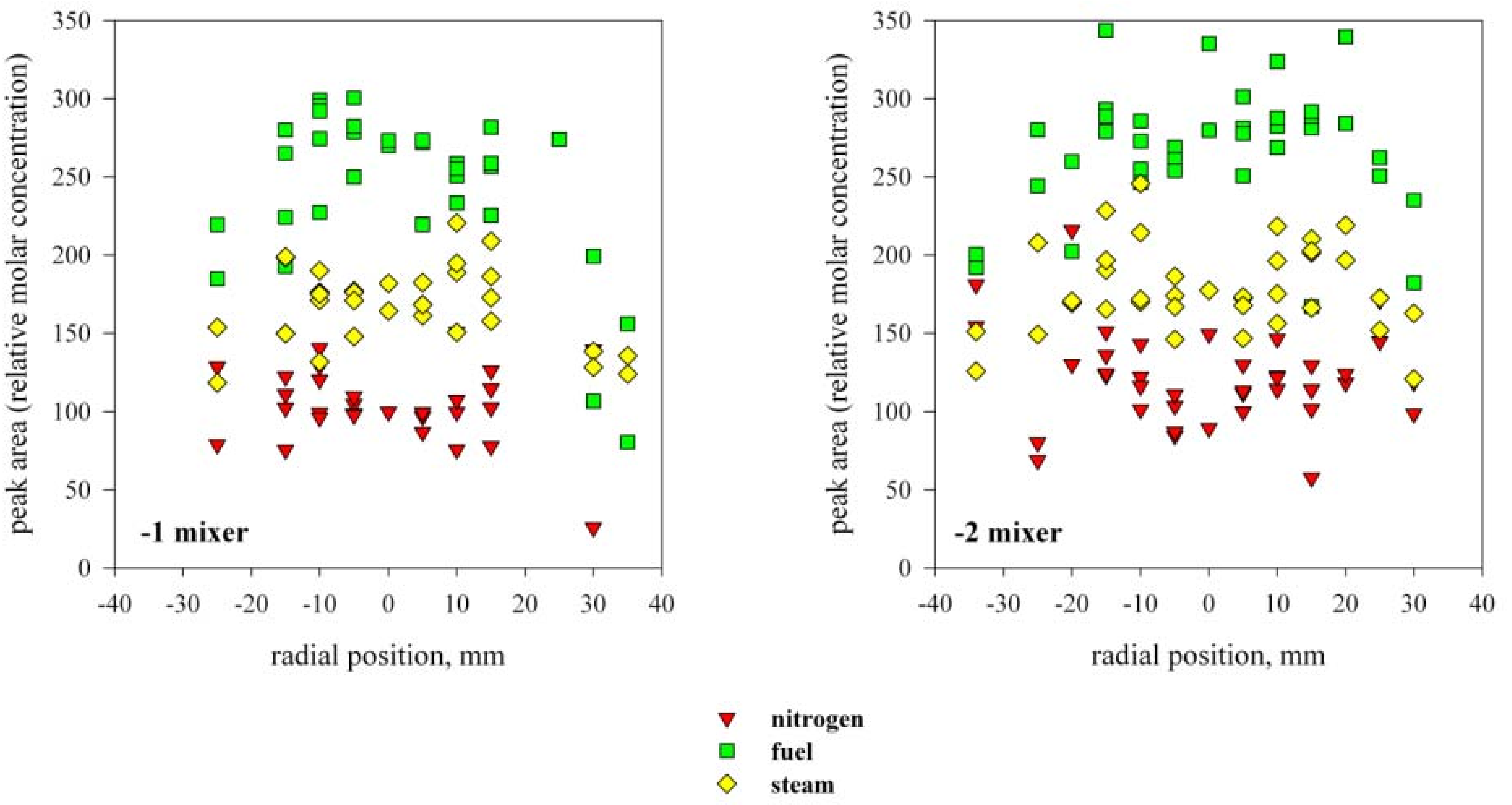
Diesel Fuel: 5 pph, Air Flow: 25 pph at 930°F, Steam Flow: 10 pph at 450°F

-1chamber with mixing devices

-2 chamber without mixing devices

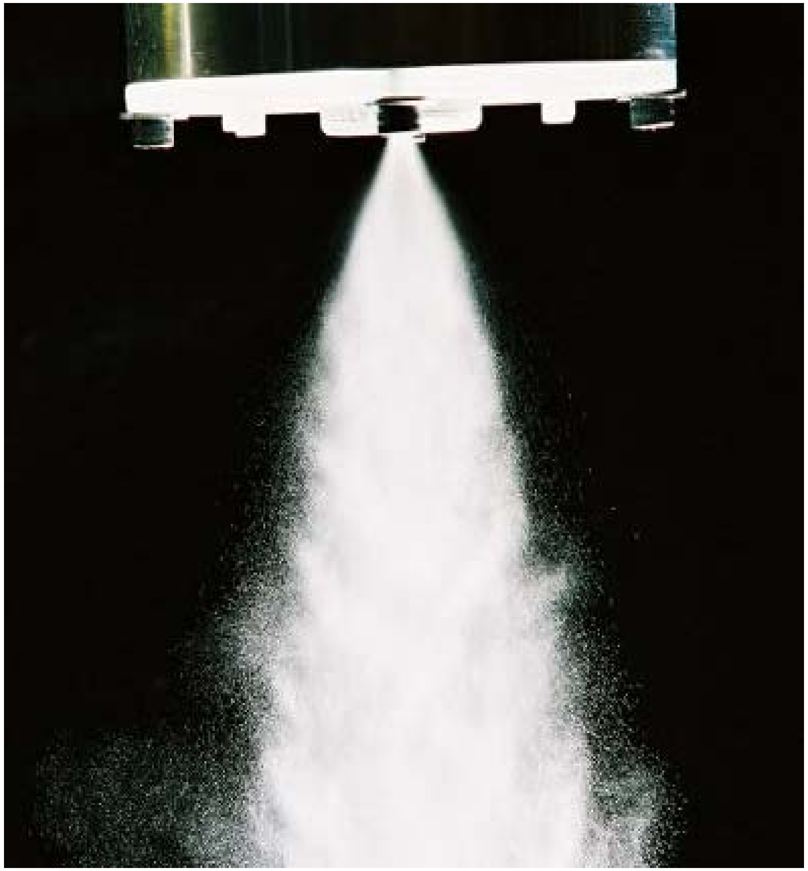


Summary of Test Results for Multipoint Impingement Injector

- **Present investigation allowed us to evaluate the effect of fuel type, mixing chamber configuration, steam temperature and operating conditions on injector performance.**
- **All test conditions exhibited relatively uniform temperature and species distributions.**
- **Higher steam temperature appears to provide stronger Raman signals and more uniform mixture distribution in the central region.**
- **The overall signal strength for diesel fuel is lower than Jet fuel due to different physical properties. Jet fuel distribution also appears to be both more uniform and more repeatable.**
- **Mixing devices do not appear to provide any noticeable benefit to the multipoint impingement injector concept.**
- **Species distribution appears to be more scattered as steam/carbon ratio decreases when using mixing devices.**

Single Point Gas-assisted Simplex Injector and Mixing Concept

- **Simple, more robust design and less prone to internal coking**
- **Easily adaptable to a different reformer**
- **Narrow spray angle to minimize carbon deposition on the chamber wall**
- **Excellent atomization when there is adequate gas inlet pressure**
- **Mixing devices are required for uniform mixture distribution**



Spray Characterization Impingement Injector Versus Gas-assisted Injector

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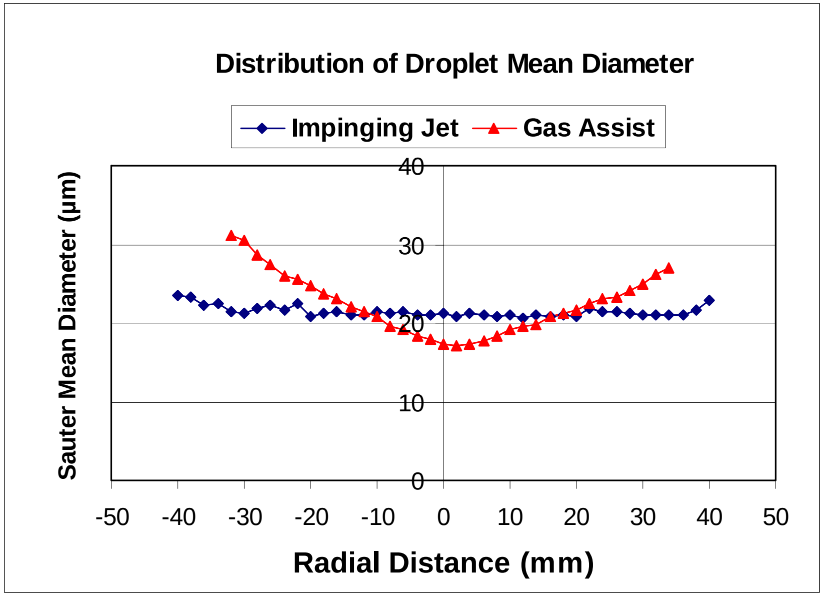
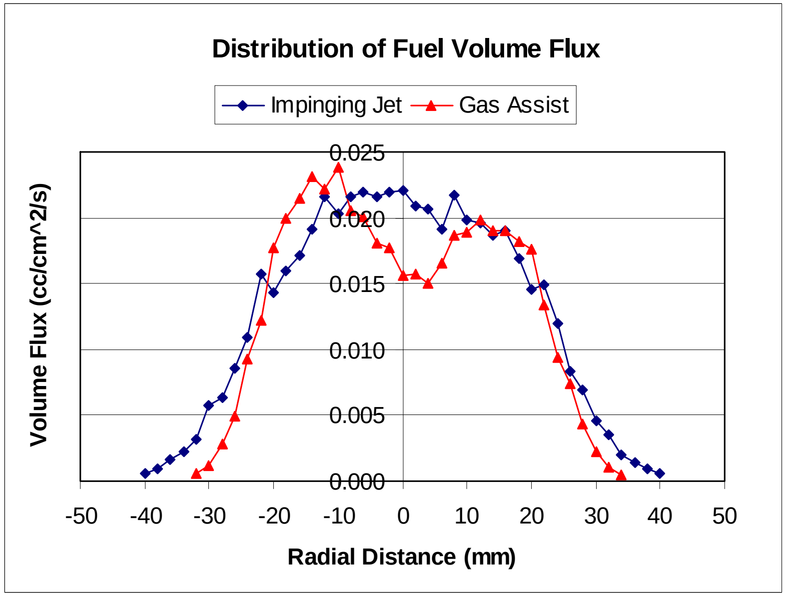
Fuel: 5 pph, Steam: 10 pph (using air), Air: 25 pph

Simulated Cold Flow Tests





Measurement Distance: 3 inches from injector discharge

Spray Characterization Impingement Injector Versus Gas-assisted Injector

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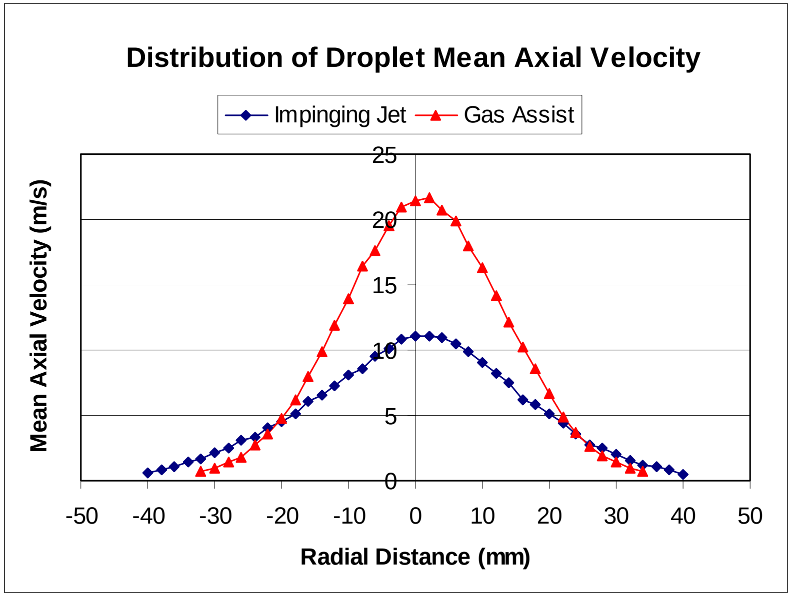
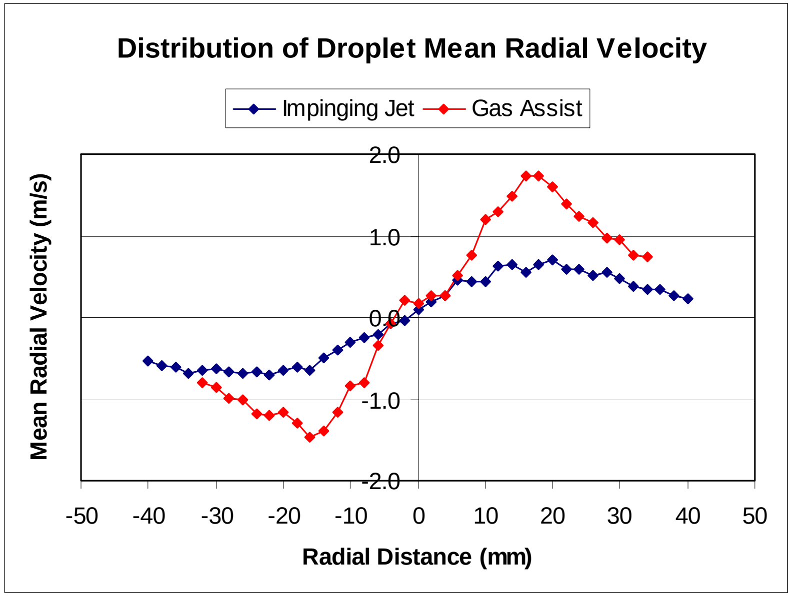
Fuel: 5 pph, Steam: 10 pph, Air: 25 pph

Simulated Cold Flow Tests





Measurement Distance: 3 inches from injector discharge

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Gas-assist CFD Analysis

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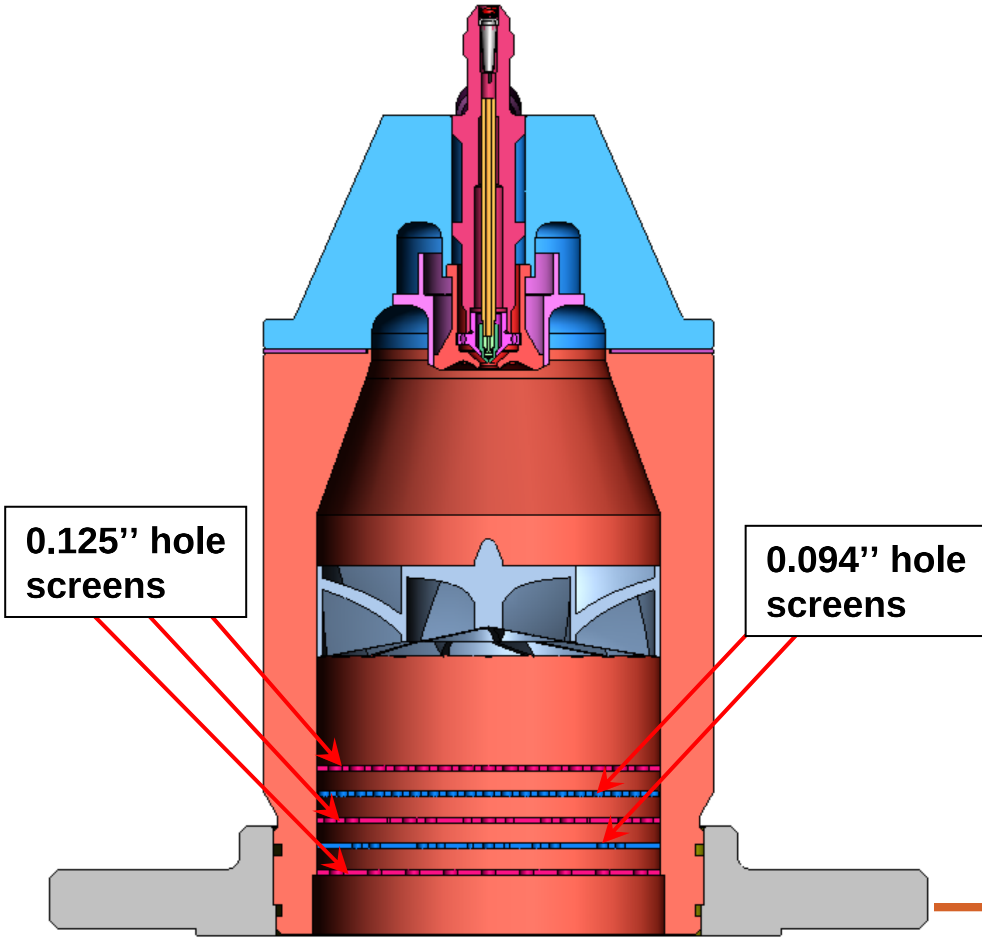

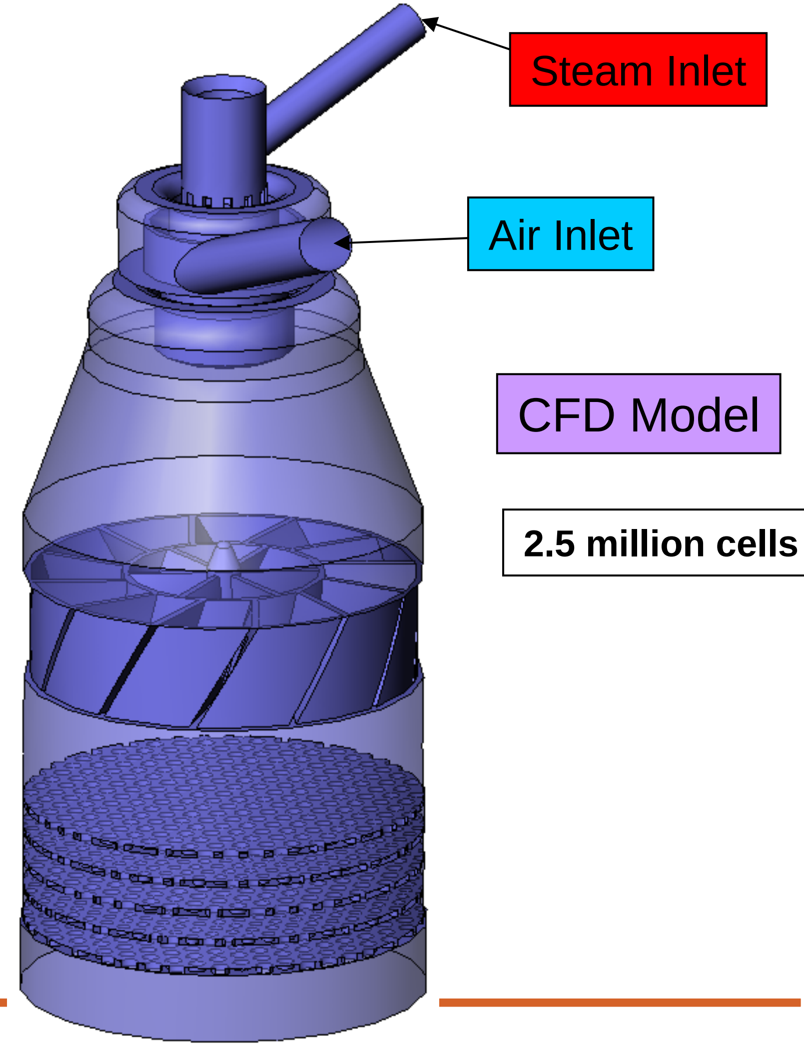

CFD Flow Field Results for Gas Assist Injector/Mixer

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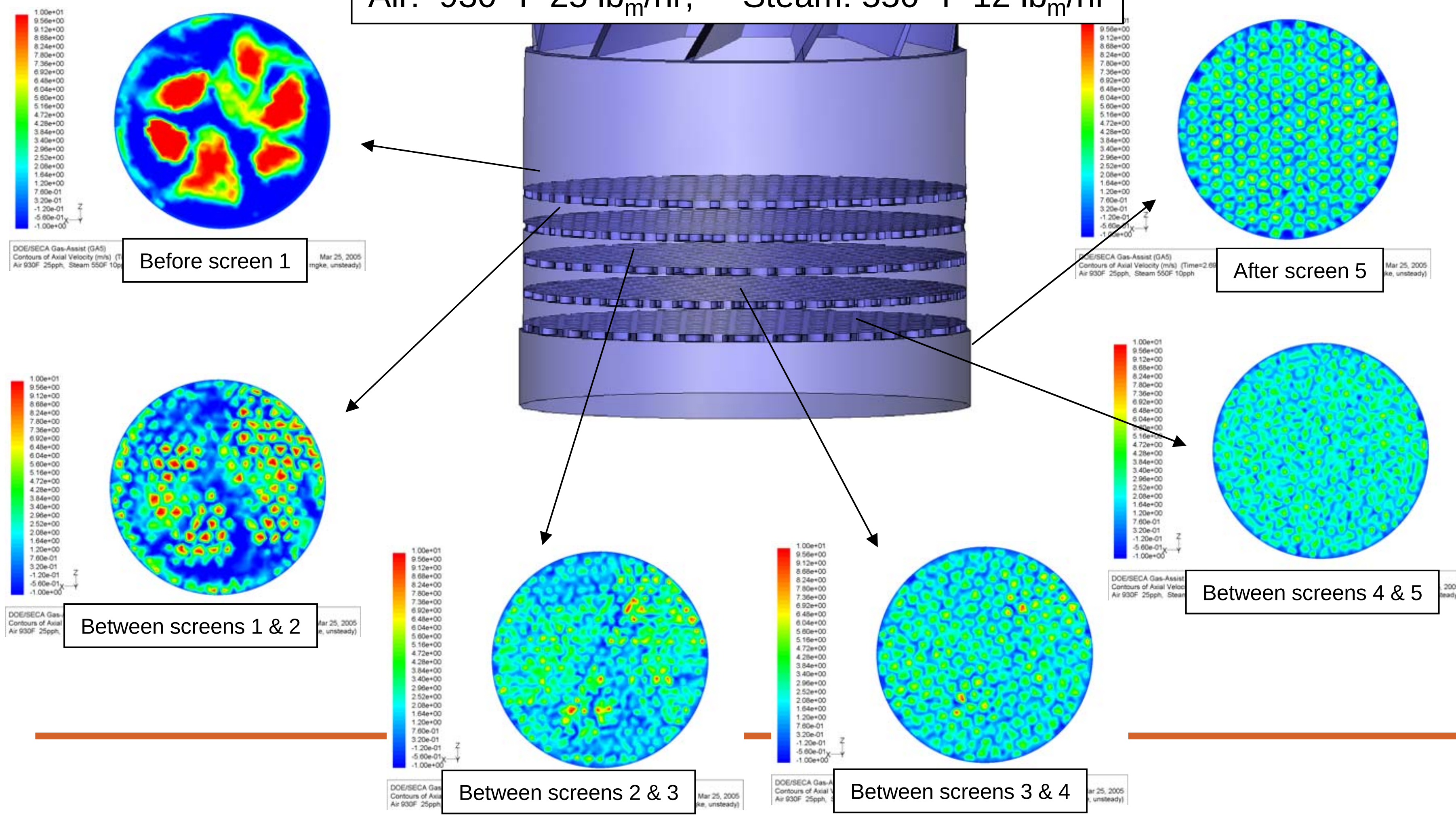
Axial Velocity Contours (range set -1 to 10 m/s)
Air: 930 ºF 25 lb_m/hr, Steam: 550 ºF 12 lb_m/hr



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Prototype High-Energy Piezoelectric Injector Spray

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- Excellent atomization for low flow rate applications
- High turndown ratio possible (>10:1)
- Power consumption needs to be minimized
- Drift of operating frequency and spray quality due to changes of temperature and flow rate
- Great potential for pulse modulated injection

2 pph fuel operated at 46 kHz frequency

Future Plans

- Evaluation of the single-point gas assisted simplex injector/mixer concept will be completed in May 2005.
- The high-energy piezoelectric injector will be constructed to meet the third quarterly milestone in June 2005.
- Evaluation of the preheating simplex injector/mixer concept will be completed in September 2005.
- Laser diagnostics will be performed at NASA Glenn using a reformer test rig for two injector concepts in October 2005.
- The effect of pulse modulated spray will be investigated by December 2005.
- Phase I program will be completed and final report submitted to DOE by March 2006.