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Implementation of Optical Techniques at Large Scale at Sandia National Laboratories

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Sean Kearney
Jill Suo-Anttila
Tim O'Hern
Chris Shaddix

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1st DTRA Instrumentation Workshop

National Nuclear Security Administration

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for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

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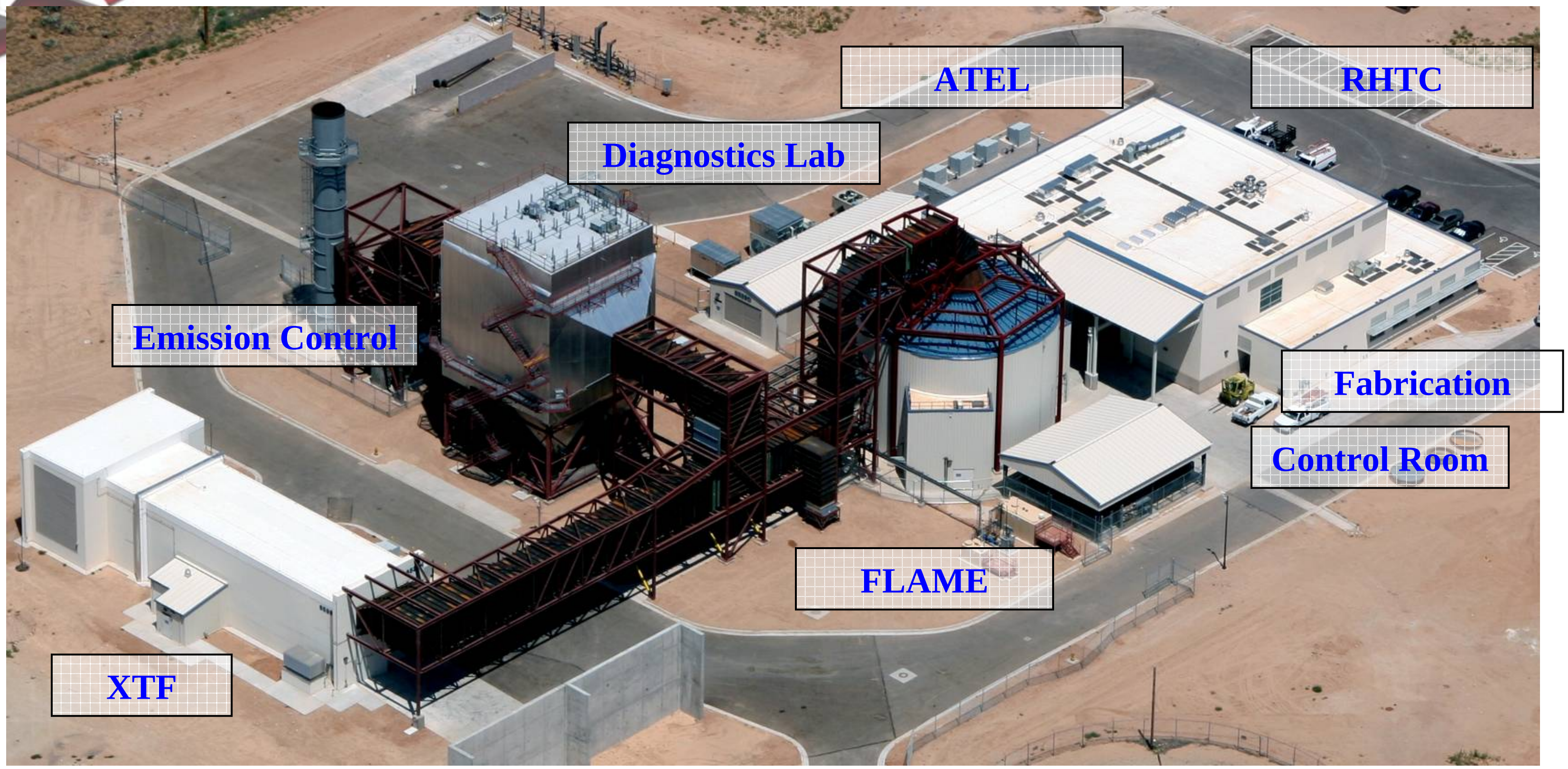
Overview

- Large Scale Experimental Facilities
- Optical Diagnostics and Techniques
  - Particle Image Velocimetry (PIV)
  - Planar Laser Induced Florescence (PLIF)
  - CARS
  - Emission Tomography
  - Emission Spectroscopy
  - 3-Line Soot Concentration and Temperature
  - Tunable Diode Laser Absorption Spectroscopy

Thermal Test Complex



- **XTF – Horizontal Wind Tunnel for Fires in Cross Wind**
- **FLAME – Vertical Wind Tunnel for Fires in Calm Conditions**
- **RHTC – Full Scale Radiant Heat (Fire Loading Simulator) Lab**
- **ATEL – Abnormal Thermal Environment Lab**
- **Supporting infrastructure**
  - **Diagnostics development and instrumentation labs**
  - **Control room**
  - **Fabrication areas**
  - **Emission Control**

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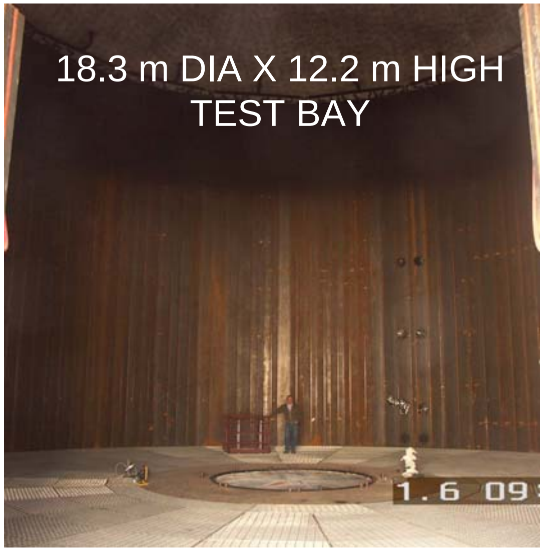
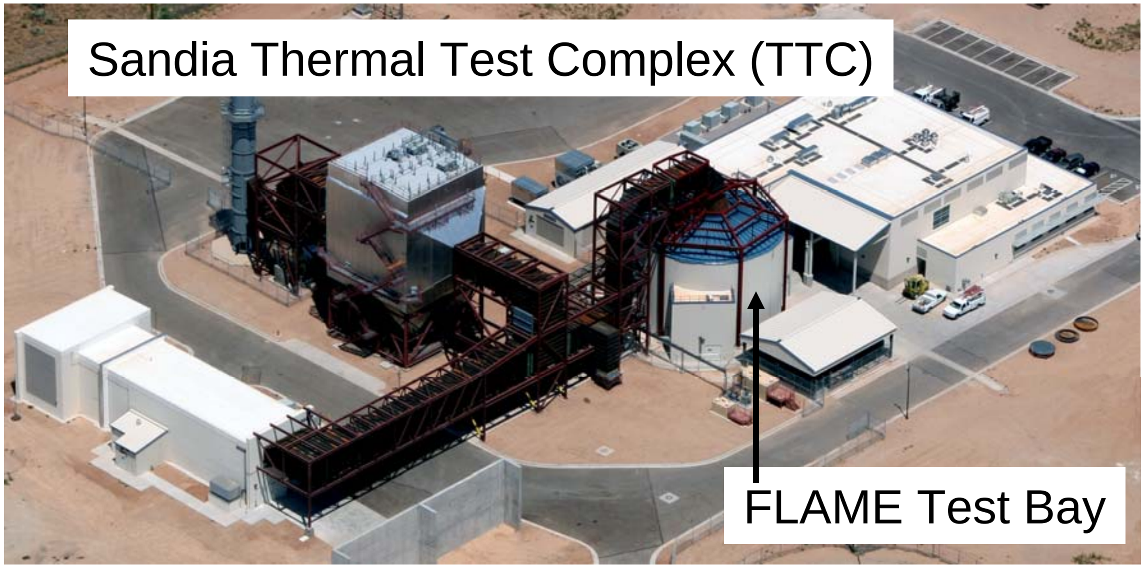
FLAME Facility Enables Full-Scale Testing with High-Fidelity Laser Diagnostics

- Fire Laboratory for Accreditation of Models and Experiments (FLAME) Facility
- Designed to facilitate deployment of optical diagnostics for full meter-scale fire testing
- Optical Access Ports and Adjacent Lab Space at East,West, and South Positions Around Test Cell
- Liquid and Gas-Fueled Fires up to 3-m in Base Dia.
- Brings Laboratory Control to Full Scale Testing





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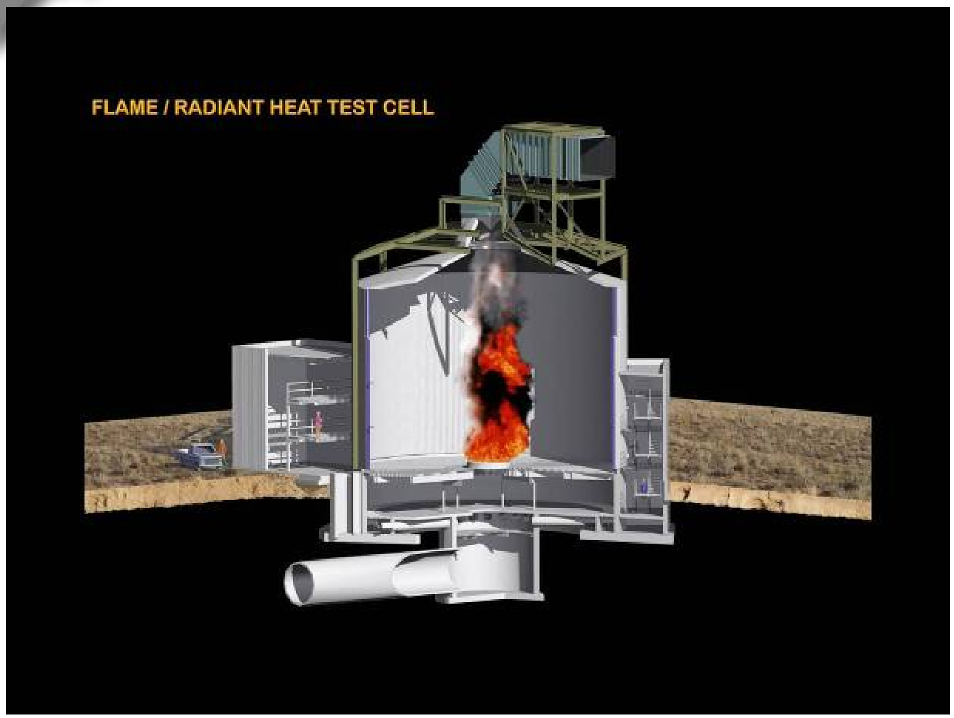
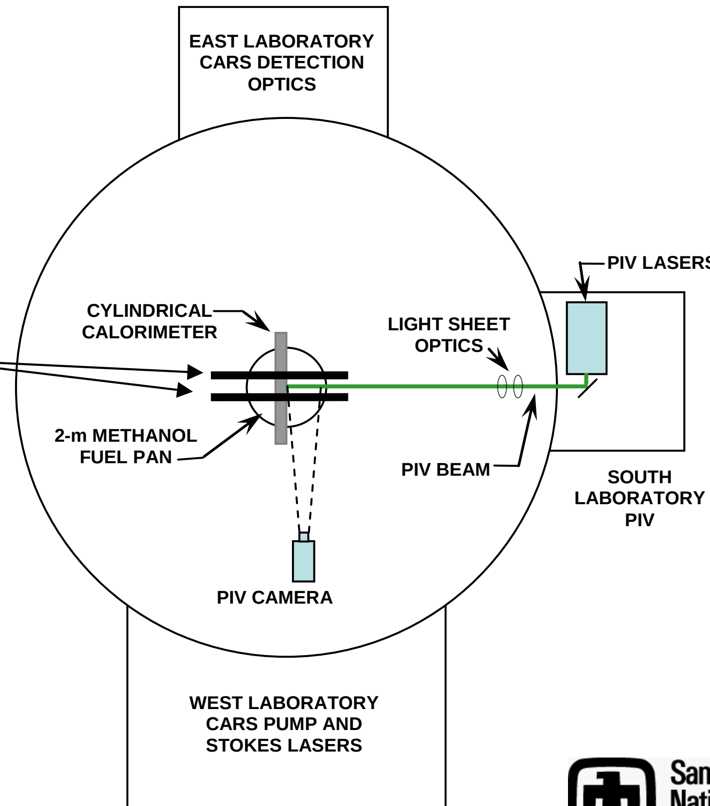
PIV Experimental Setup at FLAME



Seed particle tubes



Principal Investigator: Tim O’Hern (Dept. 1512)

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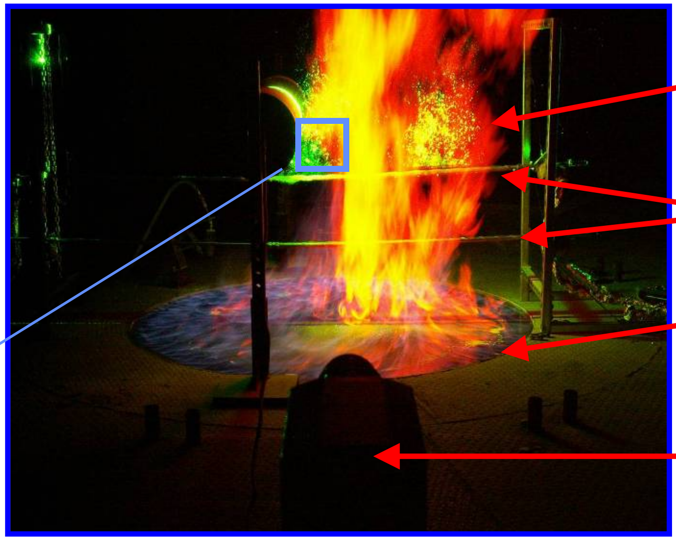
Experimental Setup at FLAME

PIV operation in 2-m diameter methanol pool fire. Blue visible just above the liquid surface is gas band radiation from the methanol fire. Green coming in from the right and striking the calorimeter on the left is due to scattering off of the PIV seed particles and seeders. Yellow and red are the thermal emission of the seed particles entrained in the flame sheets of the methanol fire (acting like artificial soot).

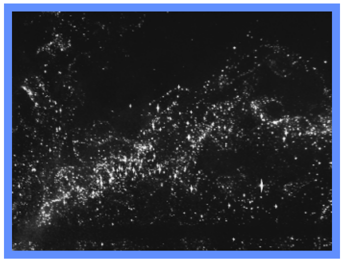


PIV seed particles in YAG light sheet

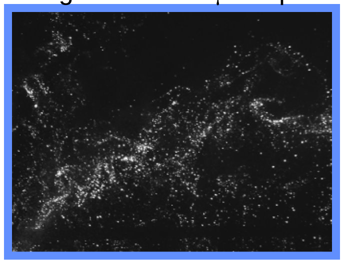
Particle seeding tubes

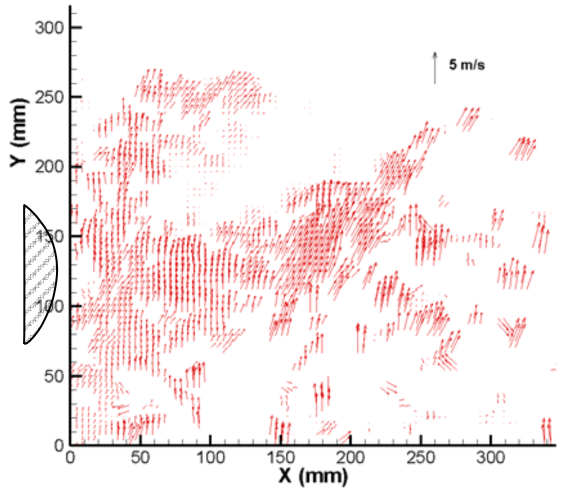
2 m methanol pool

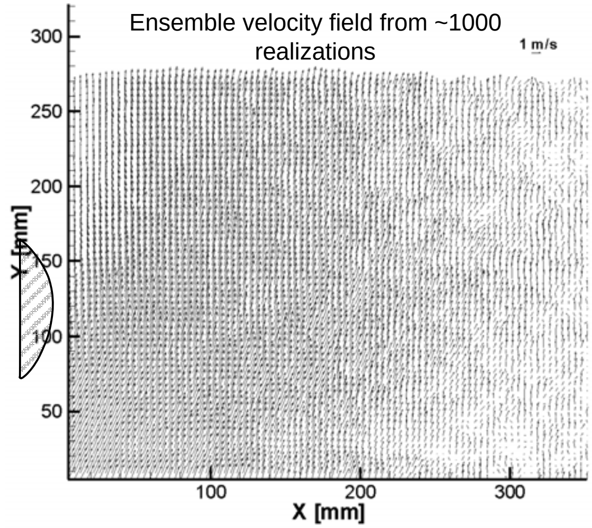
PIV camera (Photometrics CoolSnap)



Images with 700 µs separation







Principal Investigator: Tim O’Hern (Dept. 1512)

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Large Scale FLAME PIV/PLIF

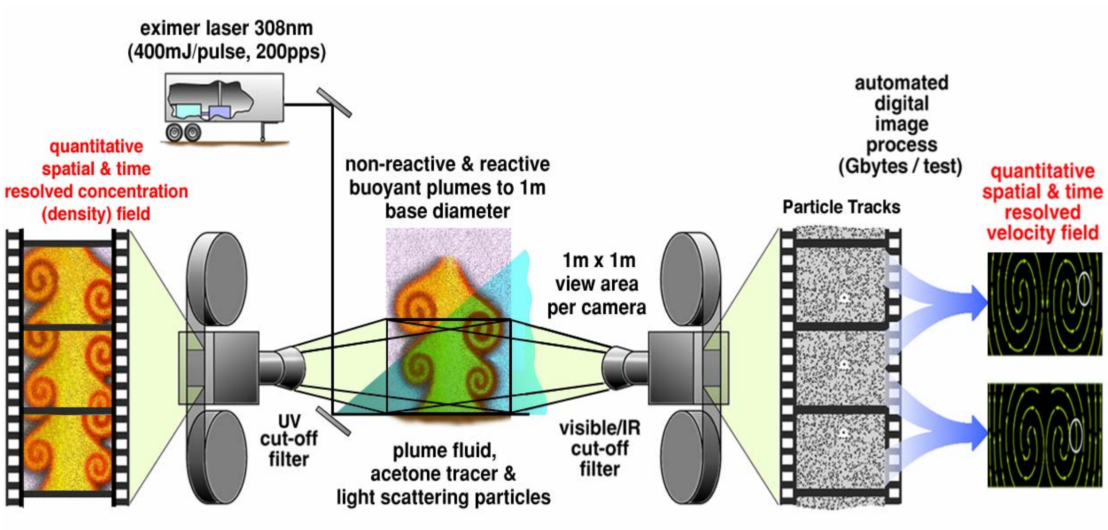
Optical measurements of 1 m diameter plumes and fires

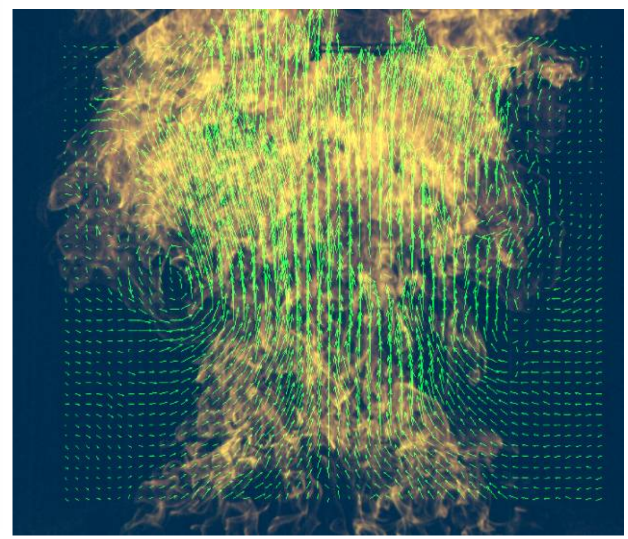
PIV and acetone PLIF for nonreacting helium plume

PIV and visualization for methane and hydrogen fires

System used excimer laser and high-speed 35 mm film cameras

Worked well but camera issues, slow film processing turnaround time, etc. led to desire to use YAG lasers and digital cameras

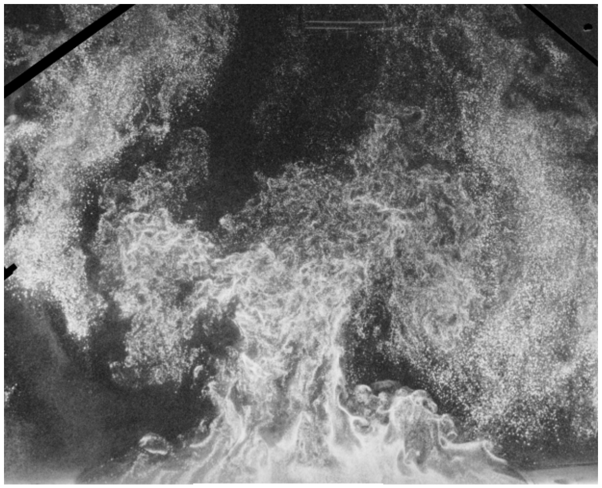




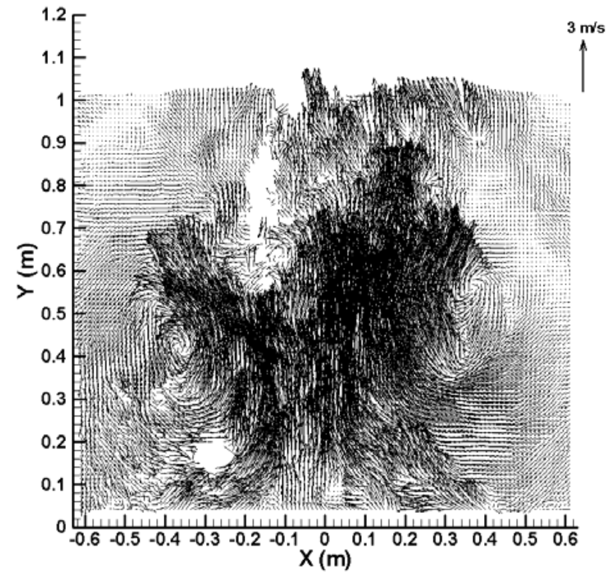
PIV in a 1-meter dia. methane fire

Principal Investigator: Tim O'Hern (Dept. 1512)

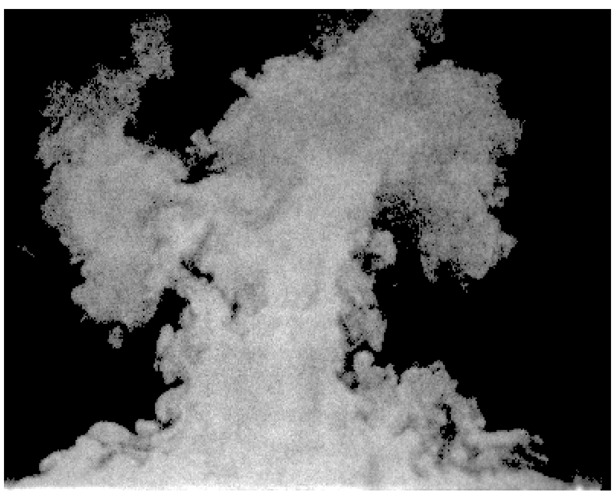
Helium plume PIV/PLIF



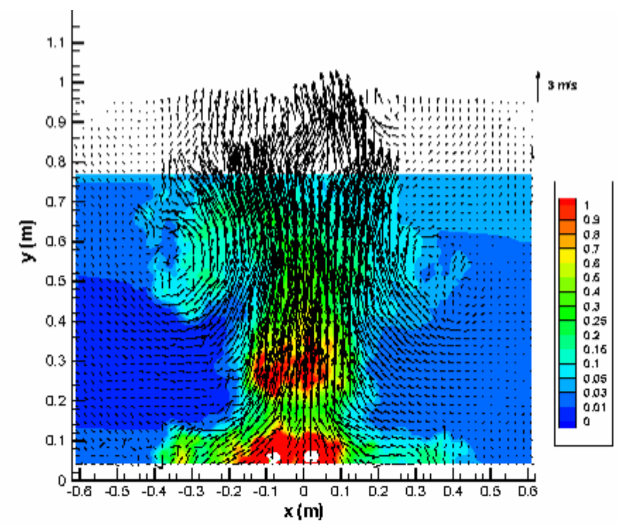
Raw PIV Image



PIV Vector Field



Acetone PLIF Image



Combined helium PLIF concentration and PIV velocity vectors

Principal Investigator: Tim O’Hern (Dept. 1512)

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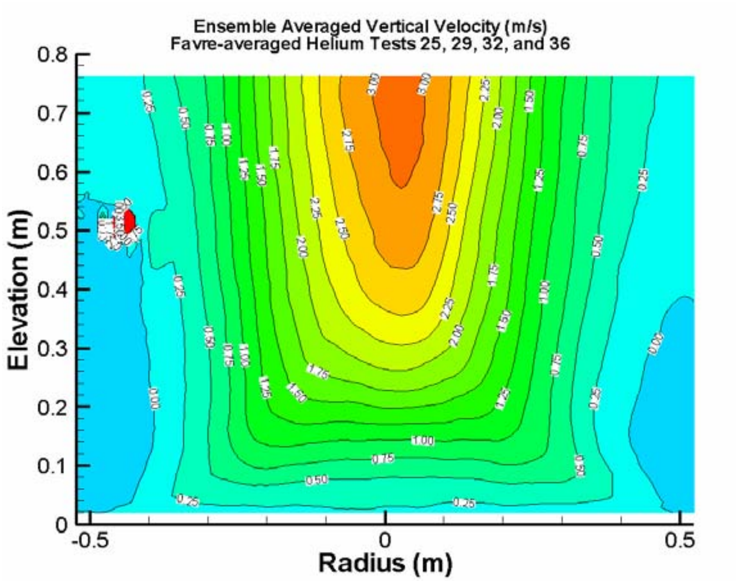
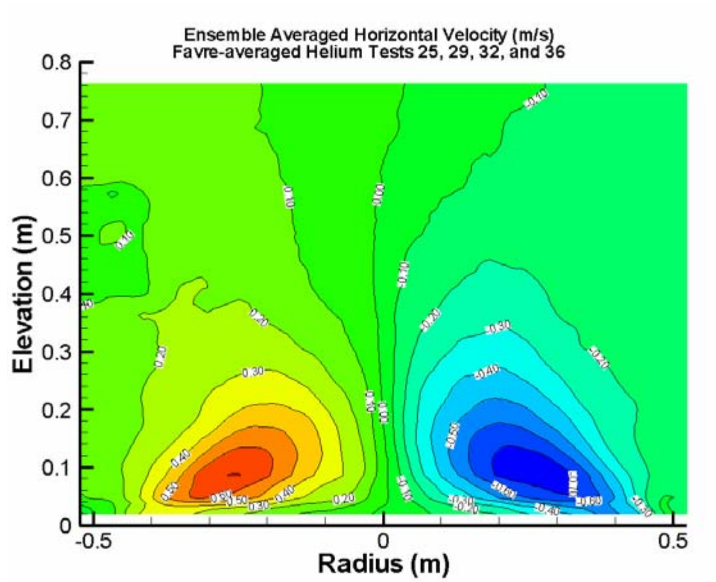
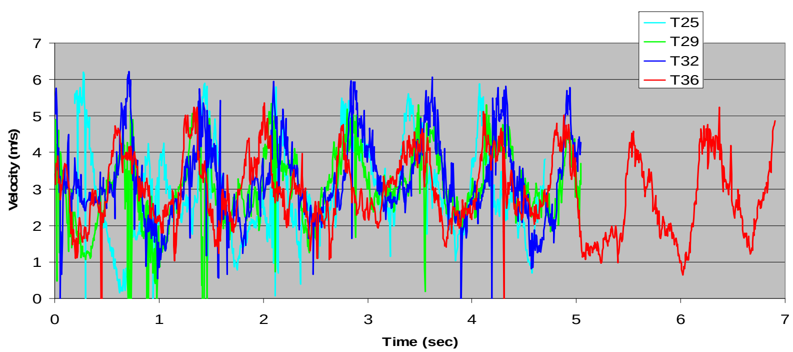
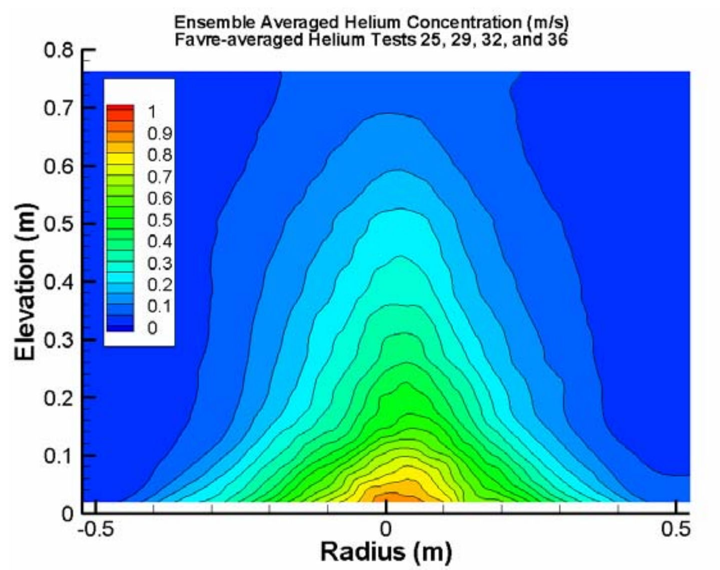
Helium Statistics







Can track instantaneous velocity at any location (200 Hz image acquisition). Can calculate u', v', Reynolds stress, etc.



Principal Investigator: Tim O'Hern (Dept. 1512)

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CARS Diagnostic for Probing Sooting and Particulate-Laden Fire Environments

Mission Driver: Strategic Surety. Probe Hostile Jet-Fuel and Propellant Fire Environments

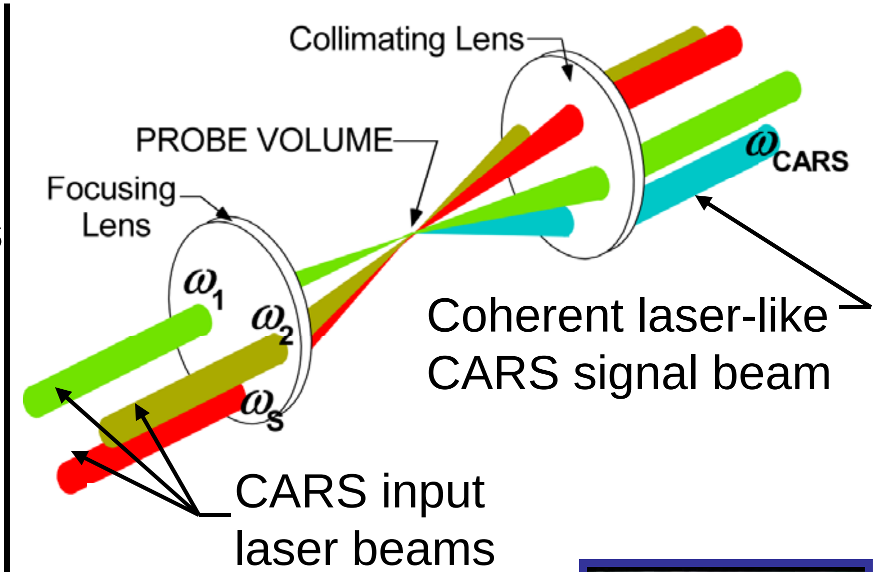
Technical Challenge:

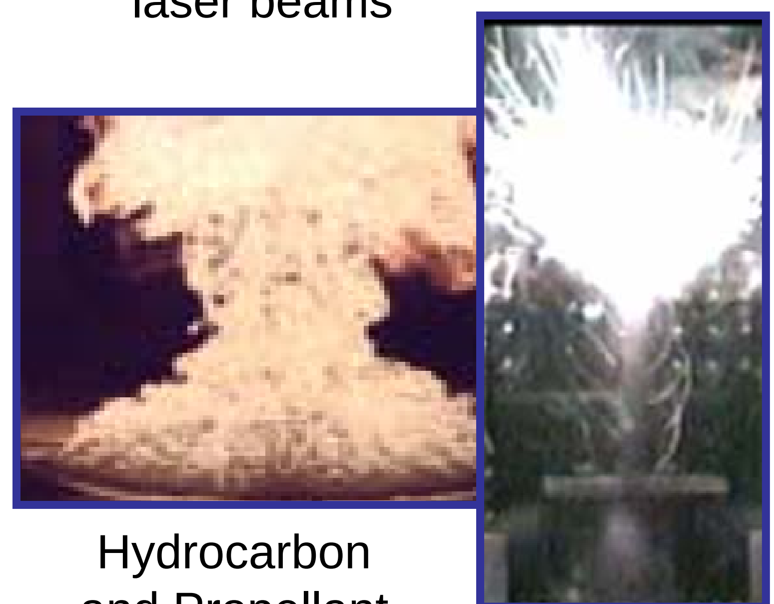
- Measure noninvasively – physical probes too susceptible to bias
- Luminous particulate-laden combustion environments prohibit most optical diagnostic approaches
- Background luminosity, scattering from particles overwhelm diagnostic signatures

Approach/Solution: Coherent anti-Stokes Raman Scattering (CARS)

- Excellent combustion thermometer
- Multi-parameter temp/mole fraction data are possible
- Blue-shifted and laser-like signal
- Efficient spectral and spatial rejection of background interference from flames
- Engineering quantities obtained from the shape of CARS spectrum

Principal Investigator: Sean Kearney (Dept. 1512)





Hydrocarbon and Propellant Fueled Fires

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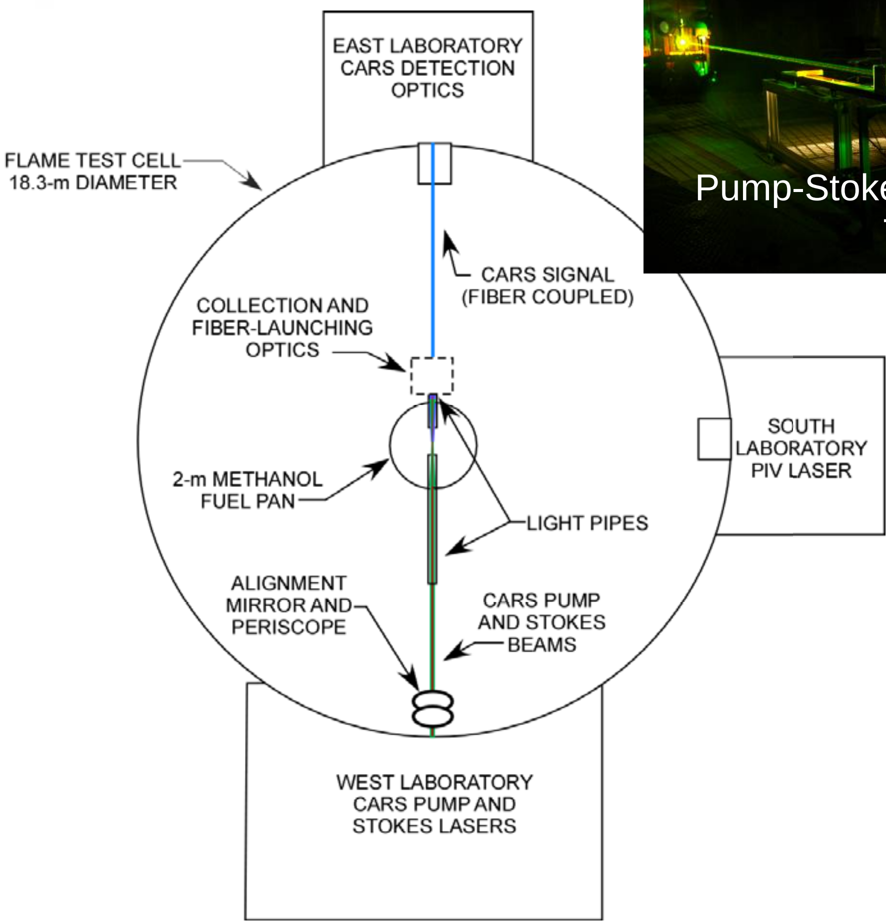
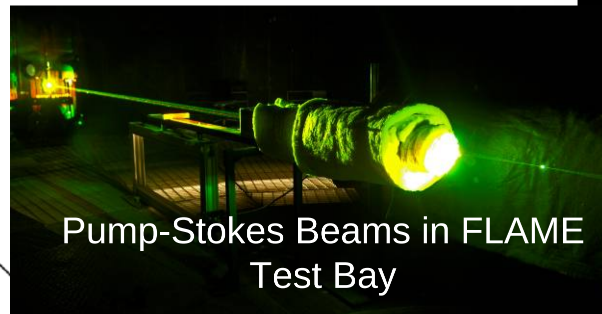
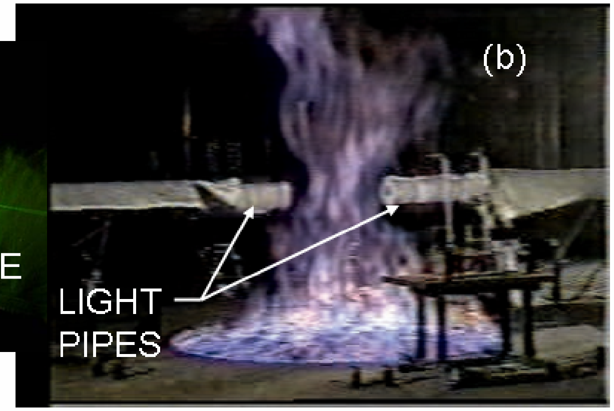
Coupling of CARS Laser Beams to FLAME for 2-m Methanol Fire Testing







Methanol Pool Fire with Laser Light Pipes

- Pump and Stokes beams are mirror coupled to the test bay
- Beams propagate through 100-mm dia. steel pipes
  - Shield beam-crossing lens and collection optics
  - Limit distance for beam steering to 66 cm or 0.33 dia.
- Collection optics and fiber launching of CARS beam provided at exit of 2nd beam tube

Principal Investigator: Sean Kearney (Dept. 1512)

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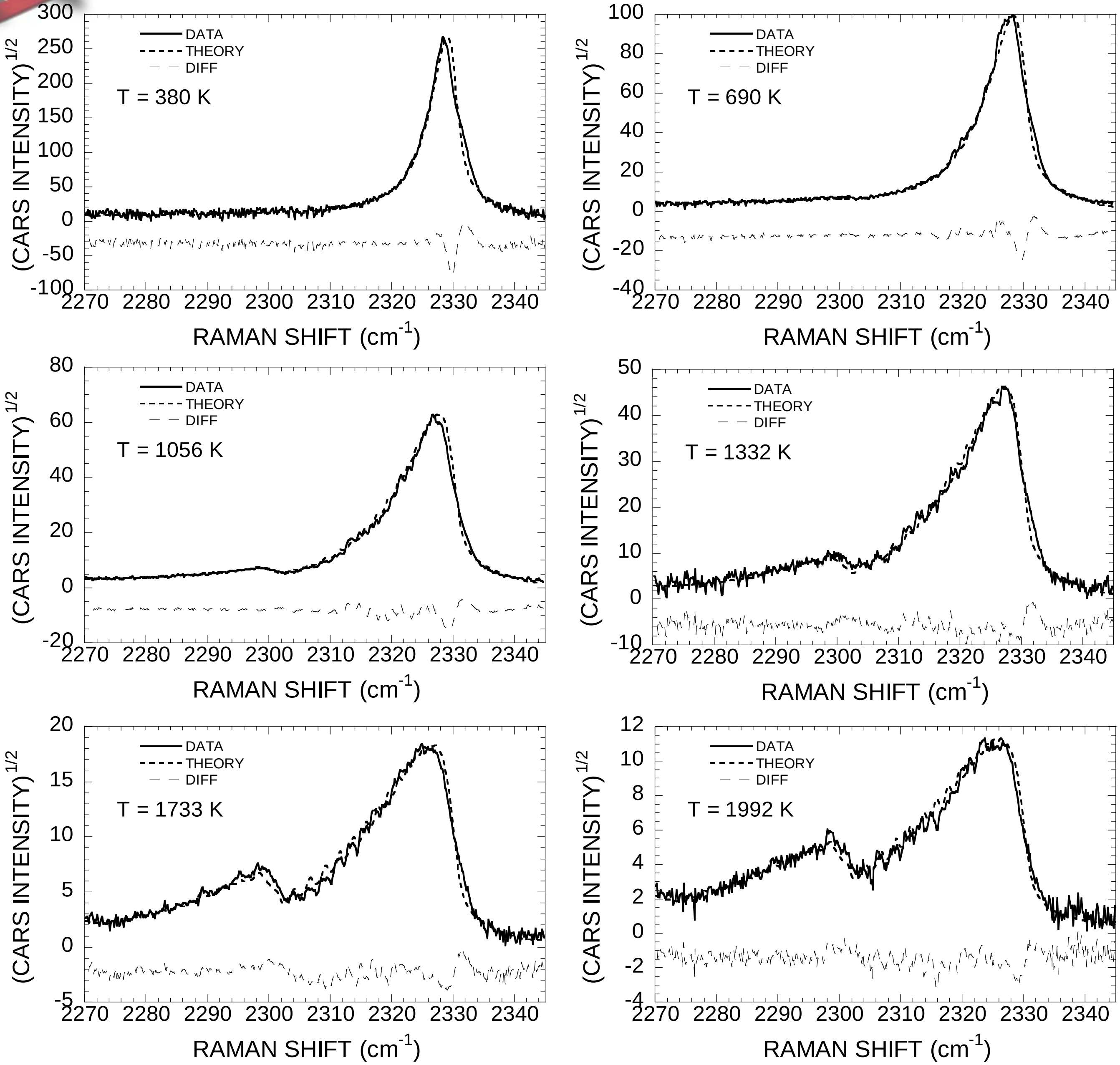
Single-Shot CARS Spectra from a Methanol Pool Fire



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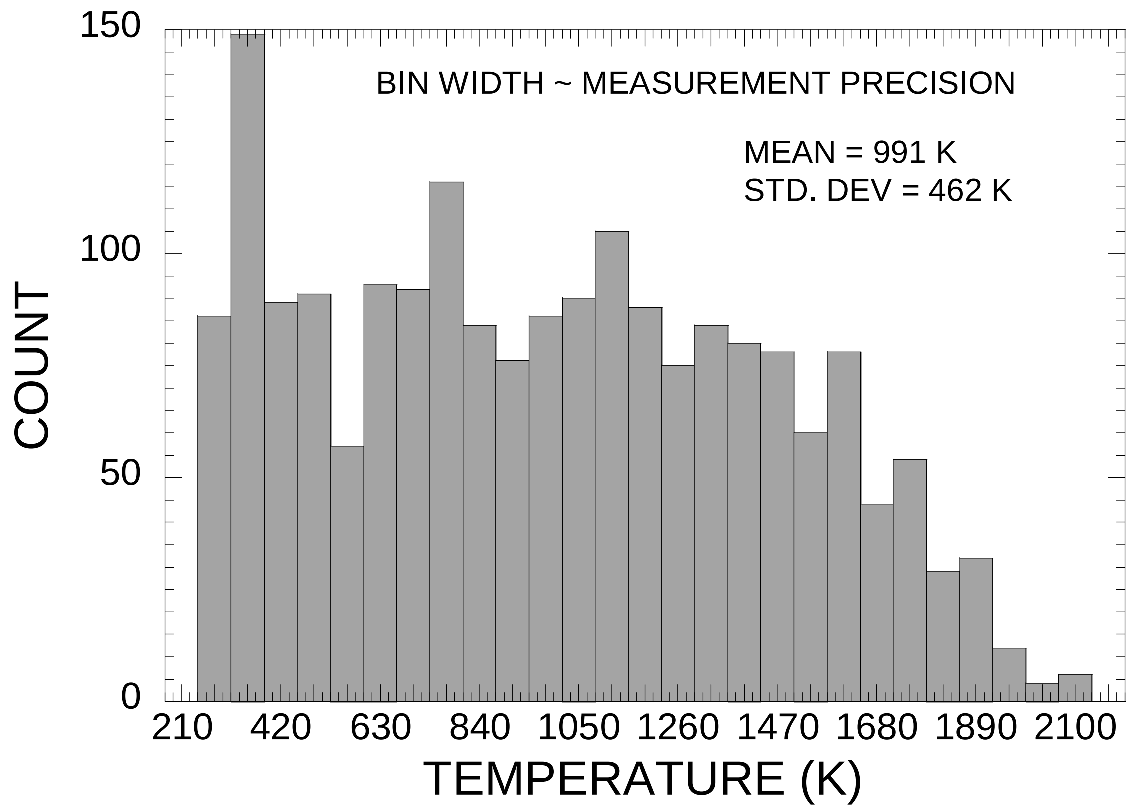
Estimate of Temperature pdf – Methanol Pool Fire

- PDF of the temperature fluctuations at estimated from a histogram of 1000 single-pulse CARS temperatures
- Data from a single point at the center of the 2-m fuel pan and ½ dia. above the fuel surface
- 8 ns temporal resolution
- 100 μm X 10 mm ellipsoidal probe volume
- Upgrade in summer of 2007 will permit simultaneous monitoring of temperature and major species mole fractions and extension to at least moderately <u>sooting fuels</u>

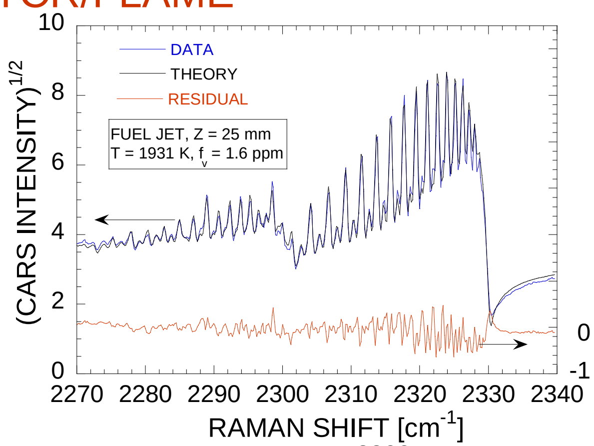


Principal Investigator: Sean Kearney (Dept. 1512)

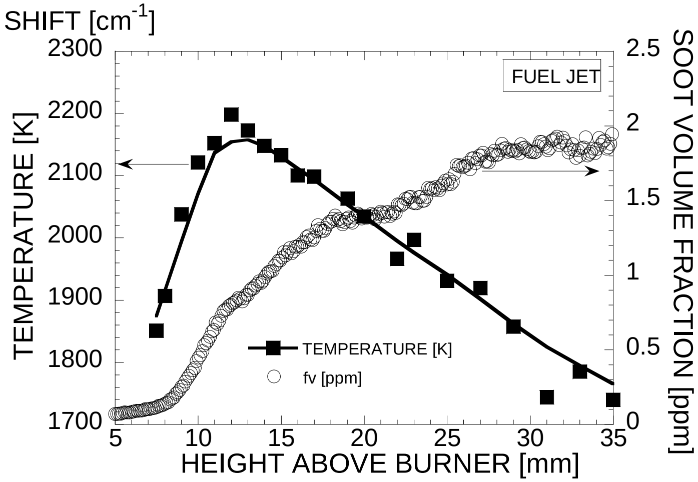
CARS Thermometry in a Heavily Sooting Flame

- We have successfully demonstrated CARS thermometry in heavily sooting acetylene fueled flames
- Valid CARS measurements for soot loadings of at least 2.2 ppm have been demonstrated
- This degree of soot loading is comparable to what is observed in hydrocarbon pool fires
- Next Steps: Propellant combustion, meter-scale pool fires at TCR/FLAME

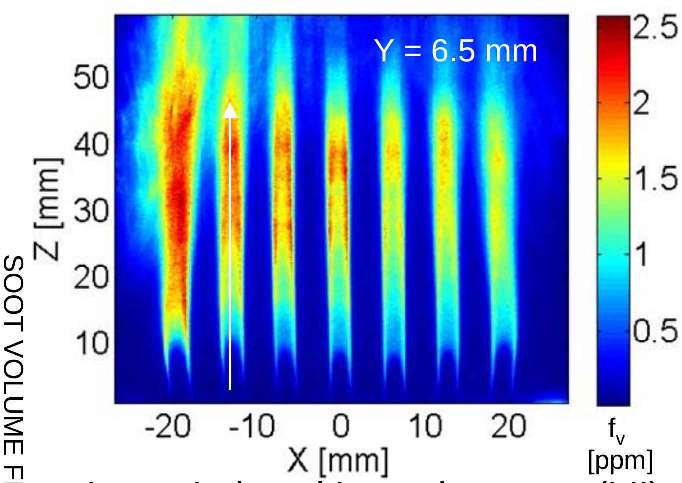
"Propellant Simulating" Burner Provides an Array of Heavily Sooting Fuel Jets



Theoretical Fit to CARS Spectrum from Fuel Jet



Temperature (CARS) and Soot (LII) Profiles Along Fuel-Jet Axis



Laser-Induced Incandescence (LII) Measured Soot Volume Fractions

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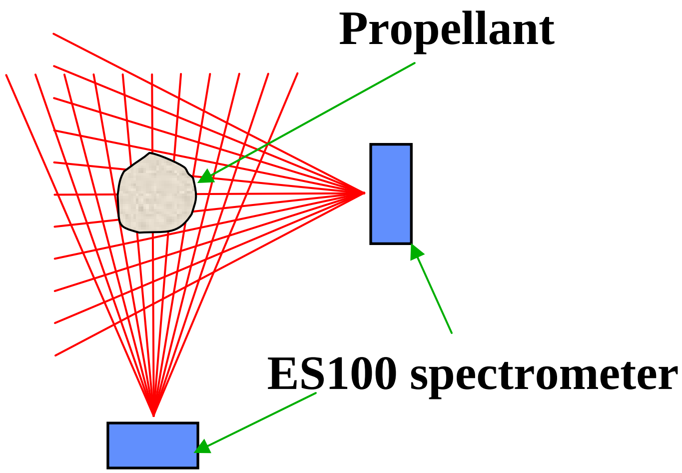
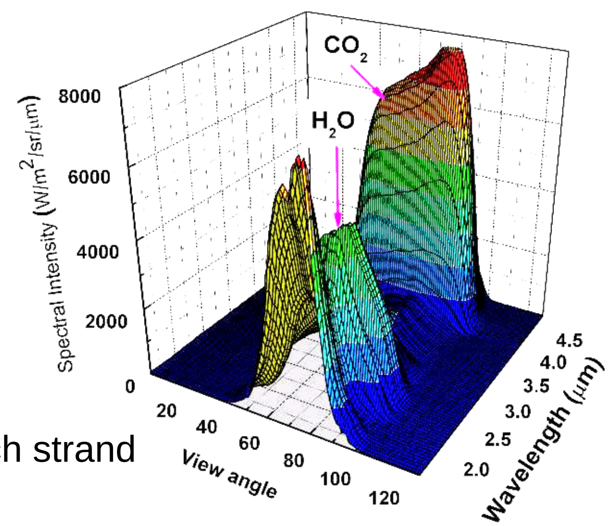
Emission Tomography

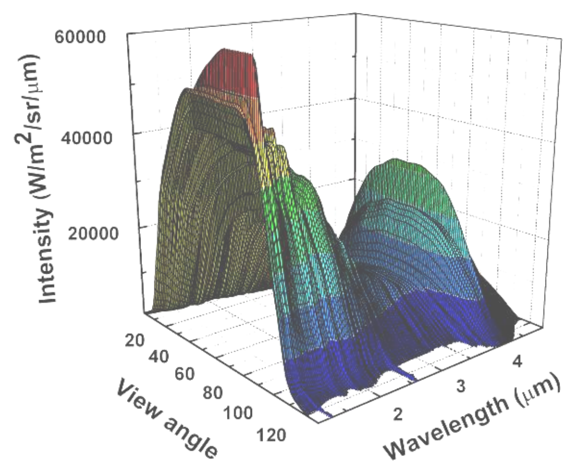
- Utilize spectrally resolved emission tomography to obtain temperatures, gas concentrations, and particulate volume fraction in plume



- **Two orthogonal spectrometers**
- **128 view angles per spectrometer**
- **1.3 to 4.8 microns**
- **1320 Hz for spectra**
- **Full planar measurement at 10.3 Hz**



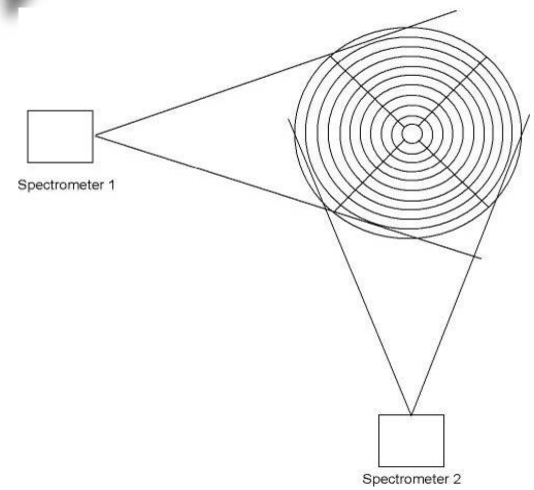
1 inch strand



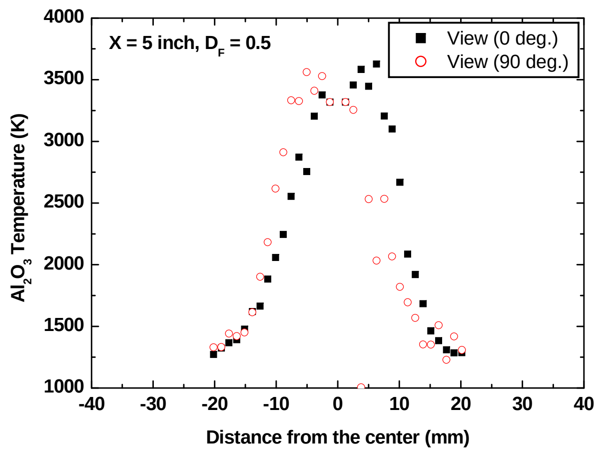
20 inch strand

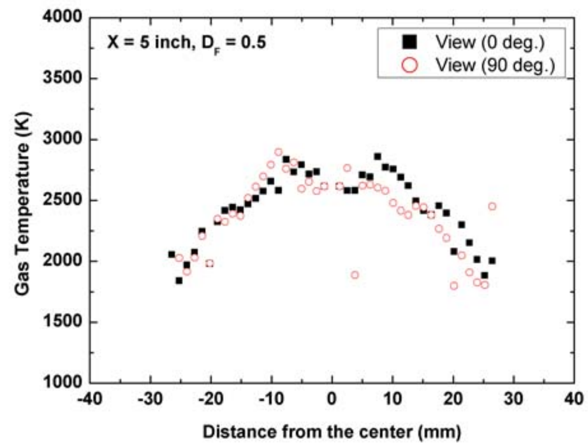
Emission Tomography

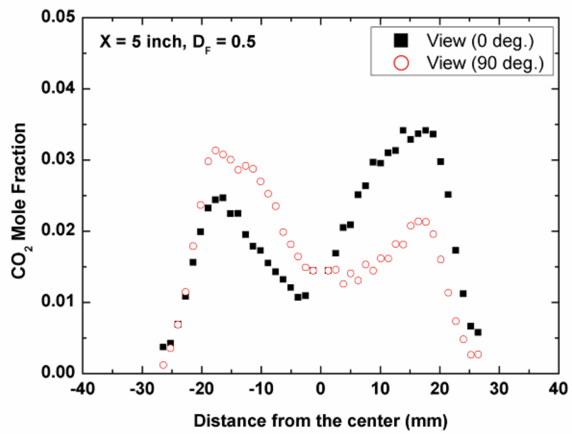
Numerical Approach and Results



- 90 degree angular resolution
- 64 points across width of plume
- Linearized Radiative Transfer Equation
- Maximum likelihood estimation method
- Proven convergence to optimal solution
- Approach demonstrated in small and large scale propellant fires







Strand burner results – particulate temperature, gas temperature, CO_2 concentration

En'Urga Inc.

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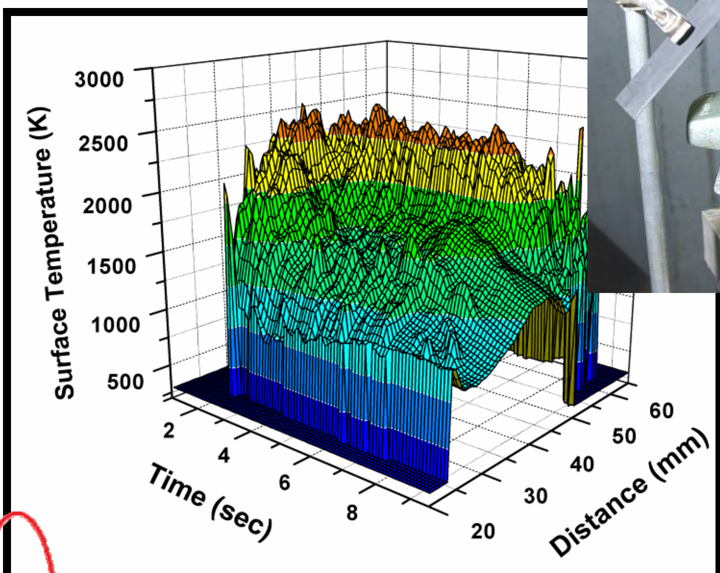
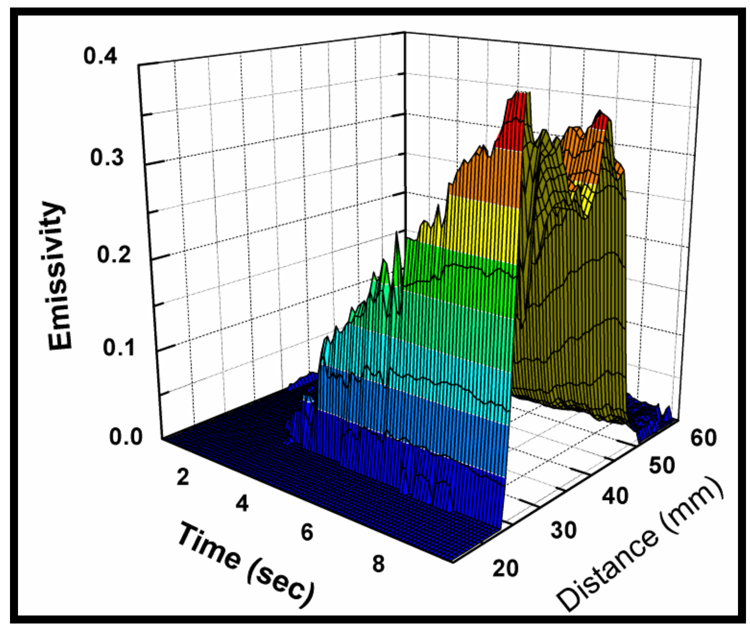
Emission Spectroscopy

• **Utilize emission spectroscopy to obtain surface temperatures and emissivities of objects immersed in plume**

Strand burner surface temperature

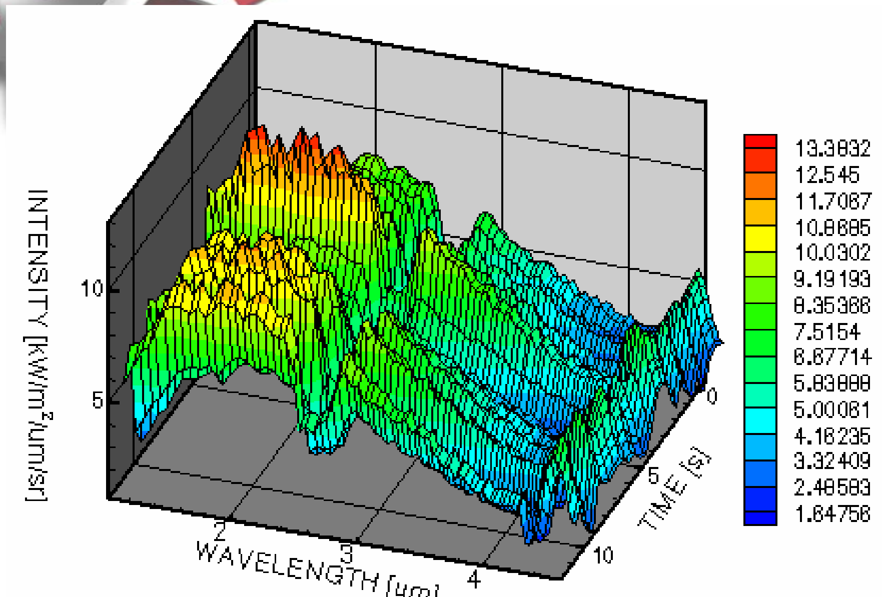


Emissivity of surface deposit

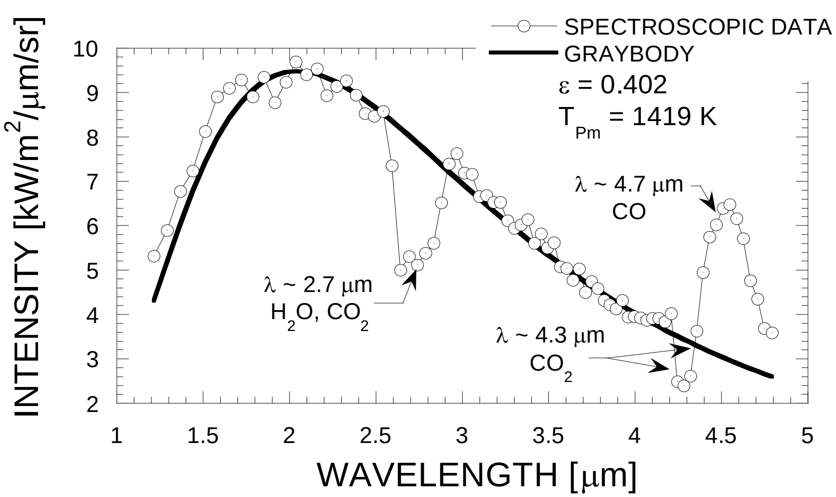


En'Urga Inc.

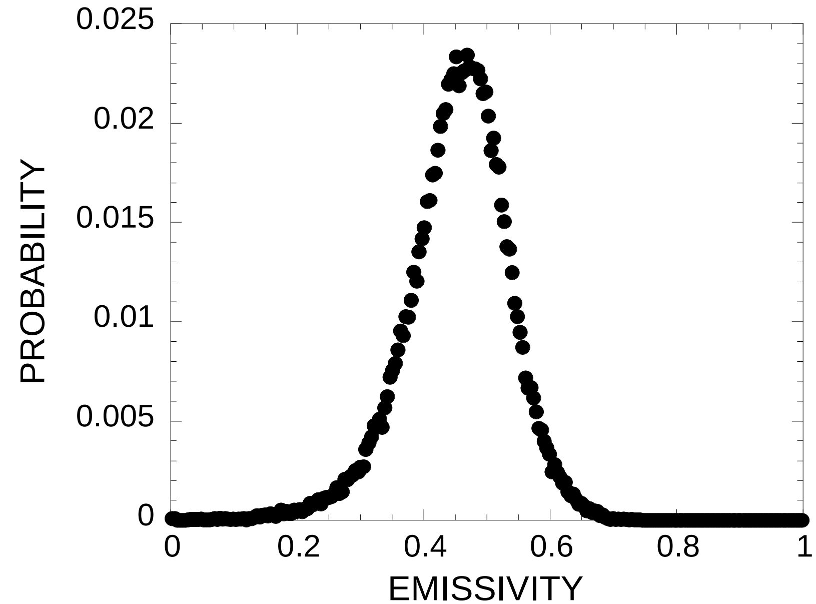
Hydrocarbon Pool-Fire Emission Spectroscopy Studies

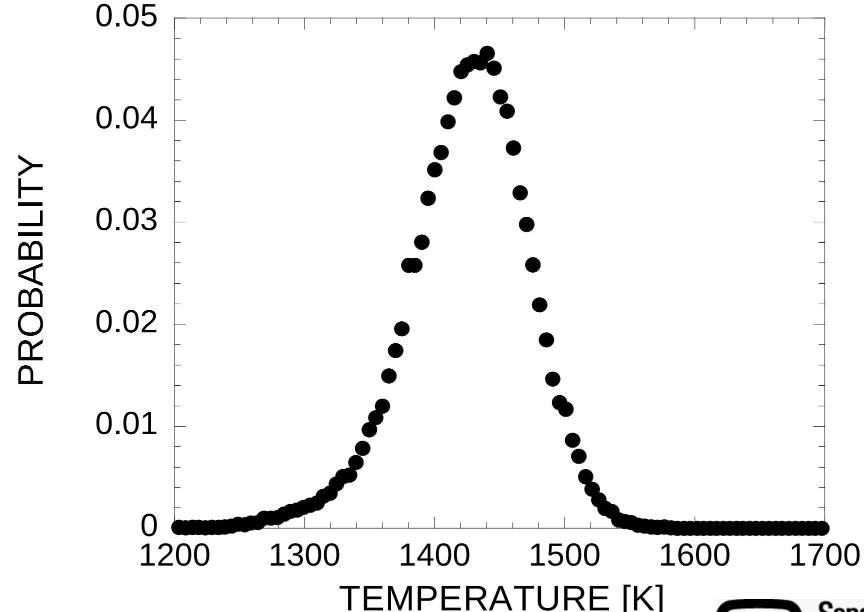


IR Spectral Time Series from 1-m JP-8 Pool fire



Representative Spectrum





Principal Investigator: Sean Kearney (Dept. 1512)

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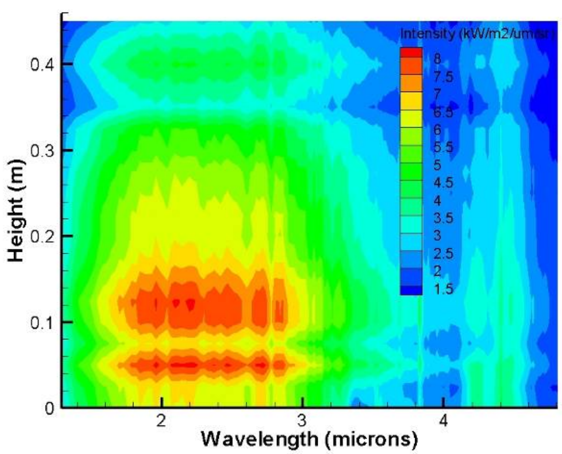
Emission Spectroscopy

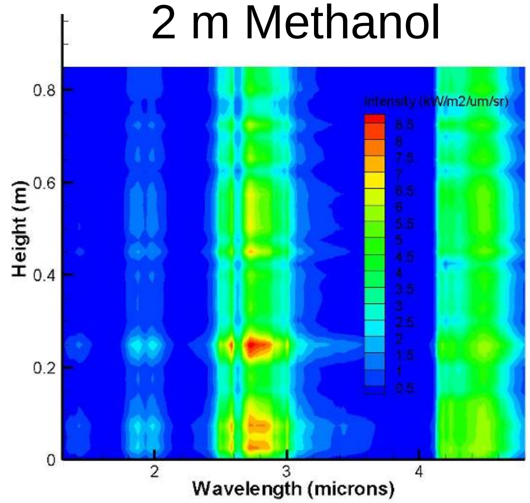
Fuel Radiation Transport

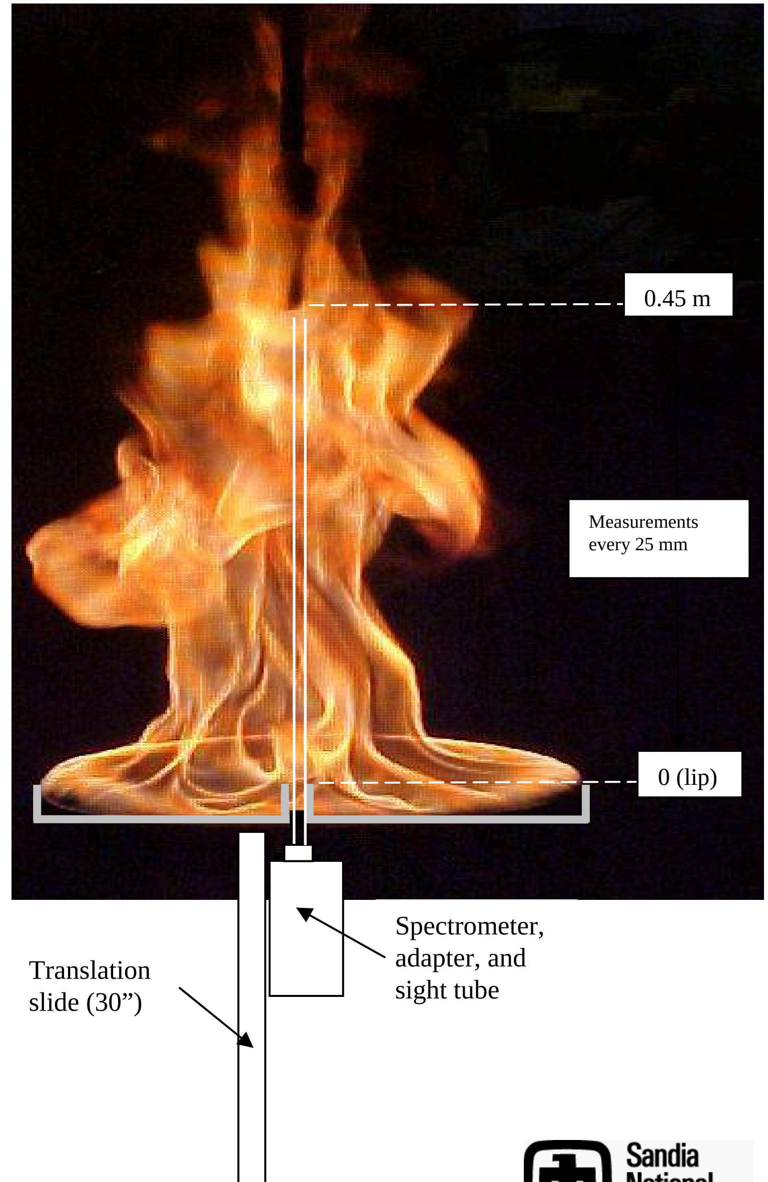
- Evaluate the interaction of thermal radiation with fuel vapor and liquid fuel
- Technique demonstrated in laboratory and large scale pool fires

0.45 m JP-8



2 m Methanol





Principal Investigator: Jill Suo-Anttila (Dept. 1532)

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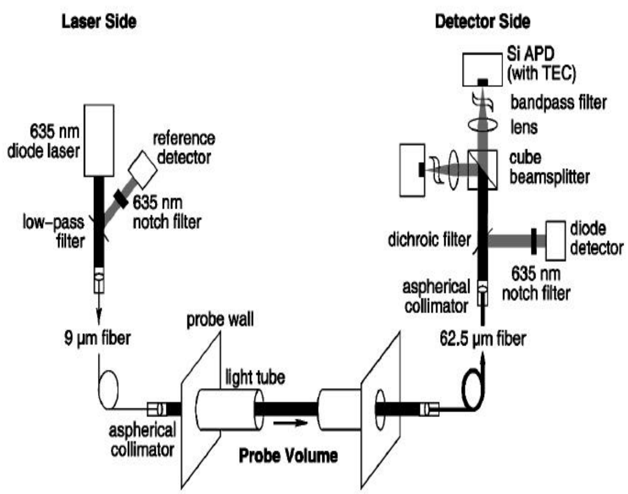
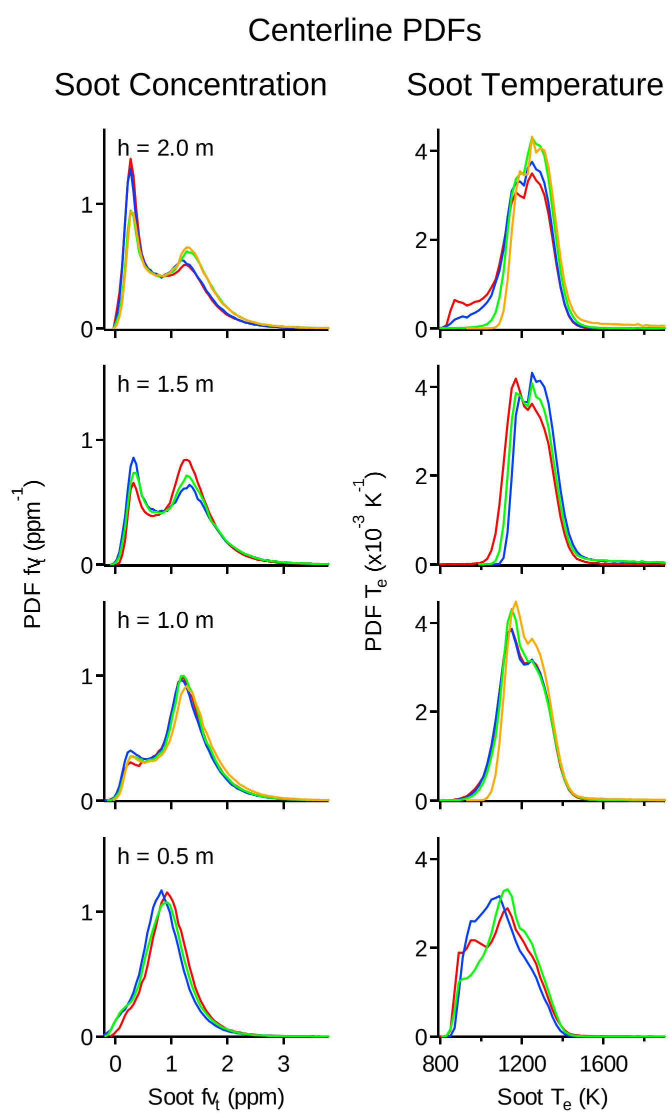
3-Line Soot Concentration and Temperature

- 3-line measurement for soot concentration and temperature using water-jacketed, fiber-coupled probe
- Absorption:
  635 nm laser diode with 50 kHz
  amplitude modulation and lock-in detection (10 kHz bandwidth)
- Emission:
  850 nm and 1000 nm bandpass filters with avalanche photodiodes (5 kHz bandwidth)
- Measurements successfully performed throughout 2-m diameter JP-8 pool fire



layout of laser absorption/emission system

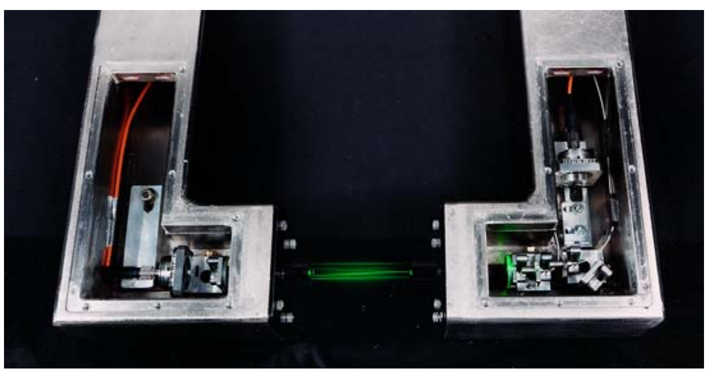


Principal Investigator: Chris Shaddix (Dept. 8367)

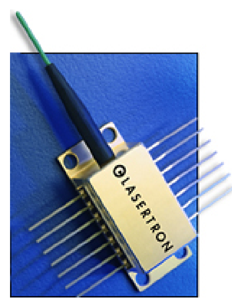
Tunable Diode Laser Absorption Spectroscopy

- Tunable diode laser absorption measurement of gas species concentrations using water-jacketed, fiber-coupled probe
- Use off-the-shelf fiber-coupled telecom lasers near 1.3 μm and 1.55 μm to measure H_2O, CH_4, C_2H_2, CO
- Rapidly tune lasers across absorption features at 1 kHz rate; apply 1 MHz modulation
- Build Herriott cell directly into probe to improve measurement sensitivity
- Status: mean concentrations can be resolved; instantaneous measurements suffer from variations in optical throughput from laser extinction

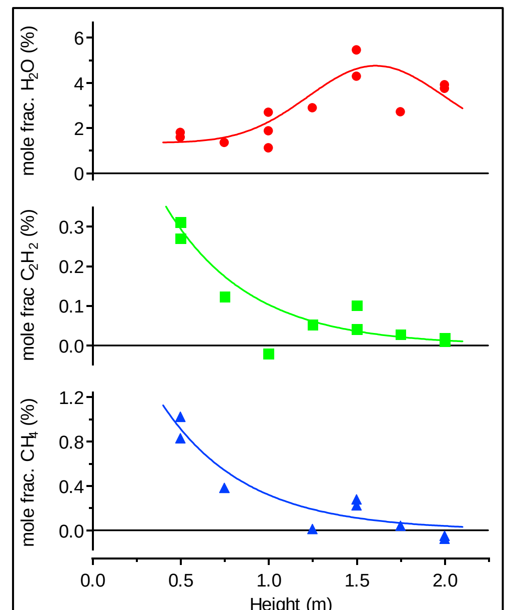
Diode laser diagnostic probe taking measurements in 1-m diameter JP-8 fire
(FLAME facility, SNL/NM, Sept. 2000)



Water-jacketed, fiber-coupled diode laser diagnostic probe



diode laser



Mean centerline concentrations

Principal Investigator: Chris Shaddix (Dept. 8367)

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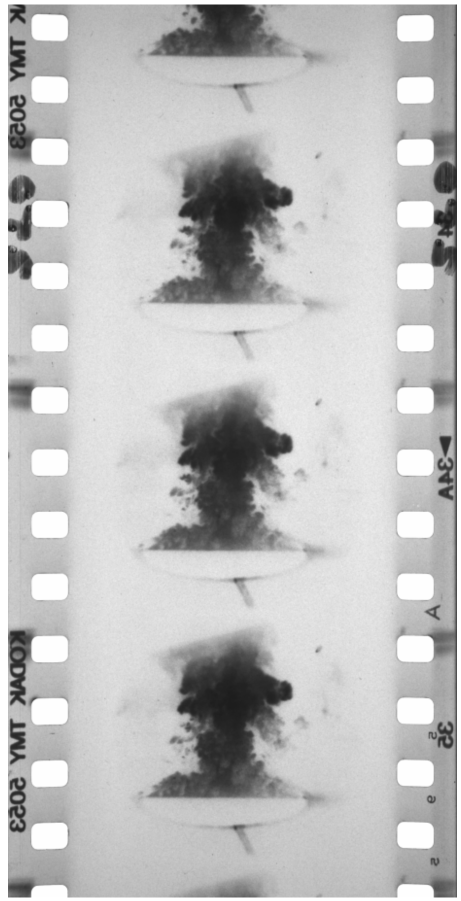
Raw film images (35 mm)

PIV (He, H_2 & CH_4)

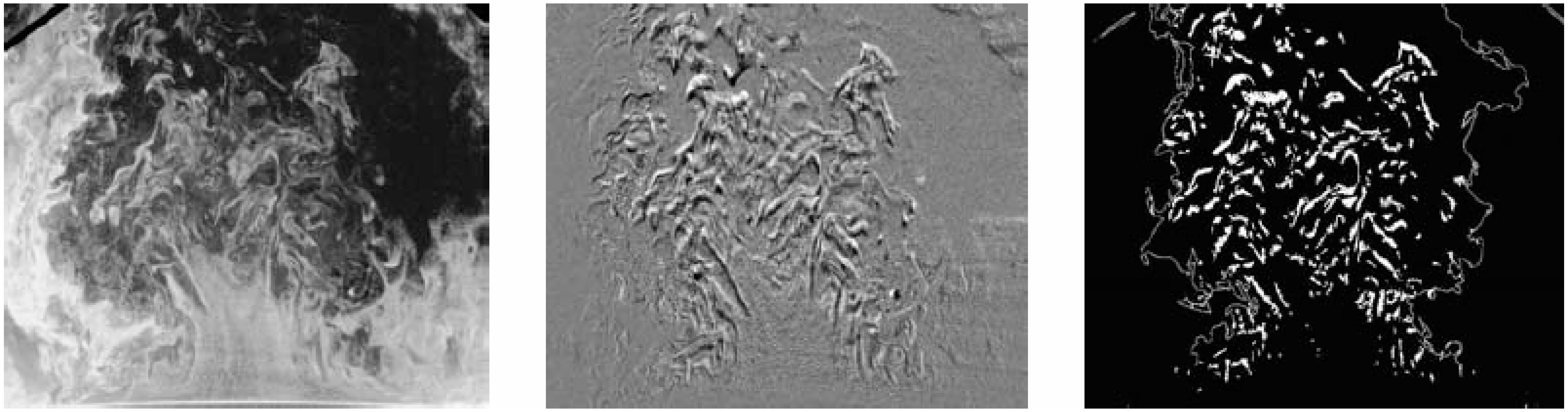


Acetone PLIF
(He Only)

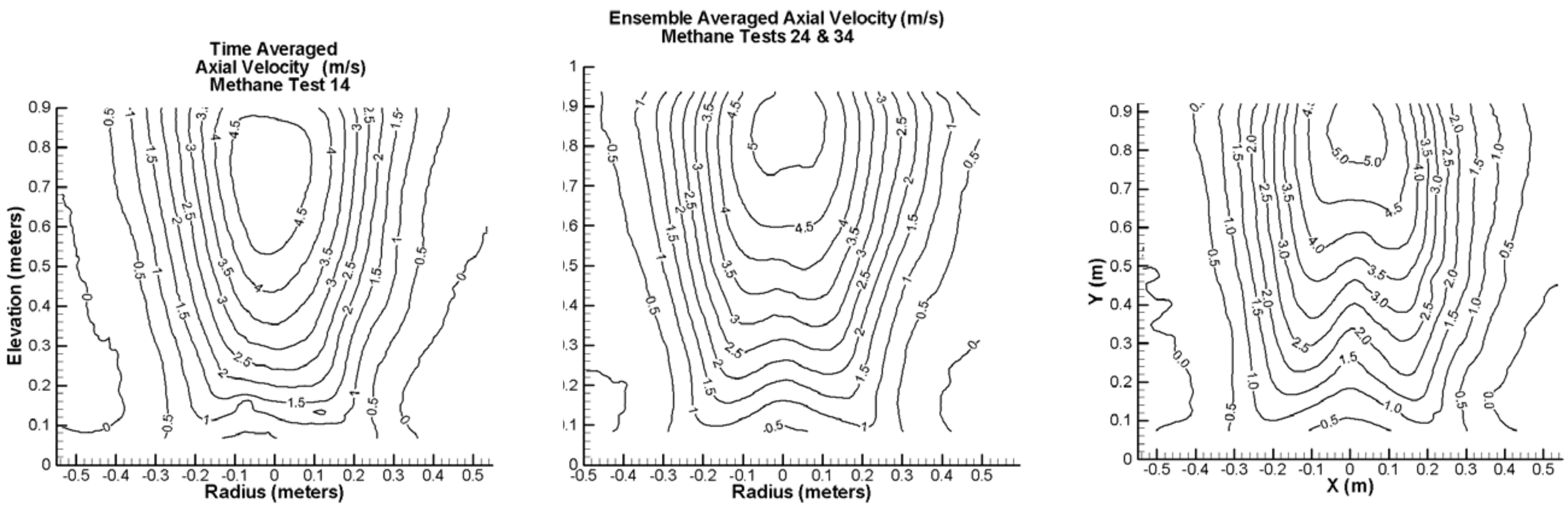
Visible Fire (H2 & CH4)

Principal Investigator: Tim O'Hern (Dept. 1512)

Methane fire



PAH extraction from images



0.032 kg/m²s 0.042 kg/m²s 0.067 kg/m²s

Vertical velocity contours for different gas mass flux values

Principal Investigator: Tim O'Hern (Dept. 1512)

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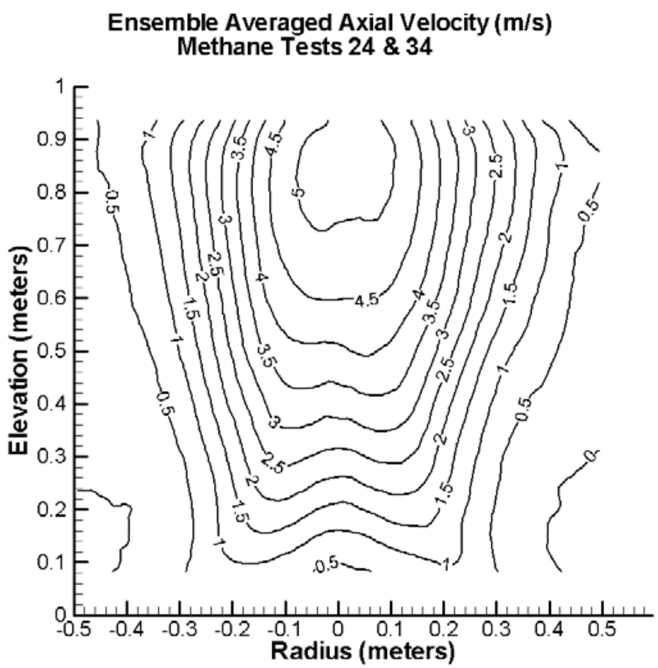
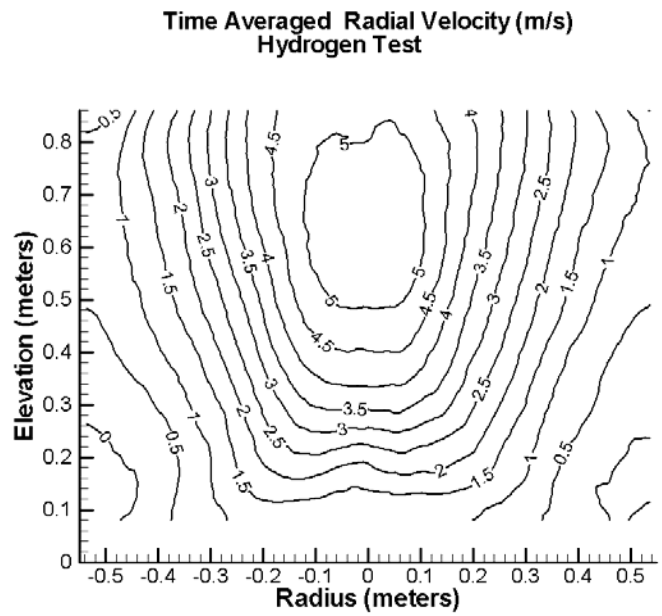
Comparison of methane, hydrogen fires

One test matching energy release rate of methane



2.11 MW Methane Fire



2.12 MW Hydrogen Fire

Analysis of H2 PIV/Visible Data

Principal Investigator: Tim O’Hern (Dept. 1512)

Turbulent statistics derived from PIV data

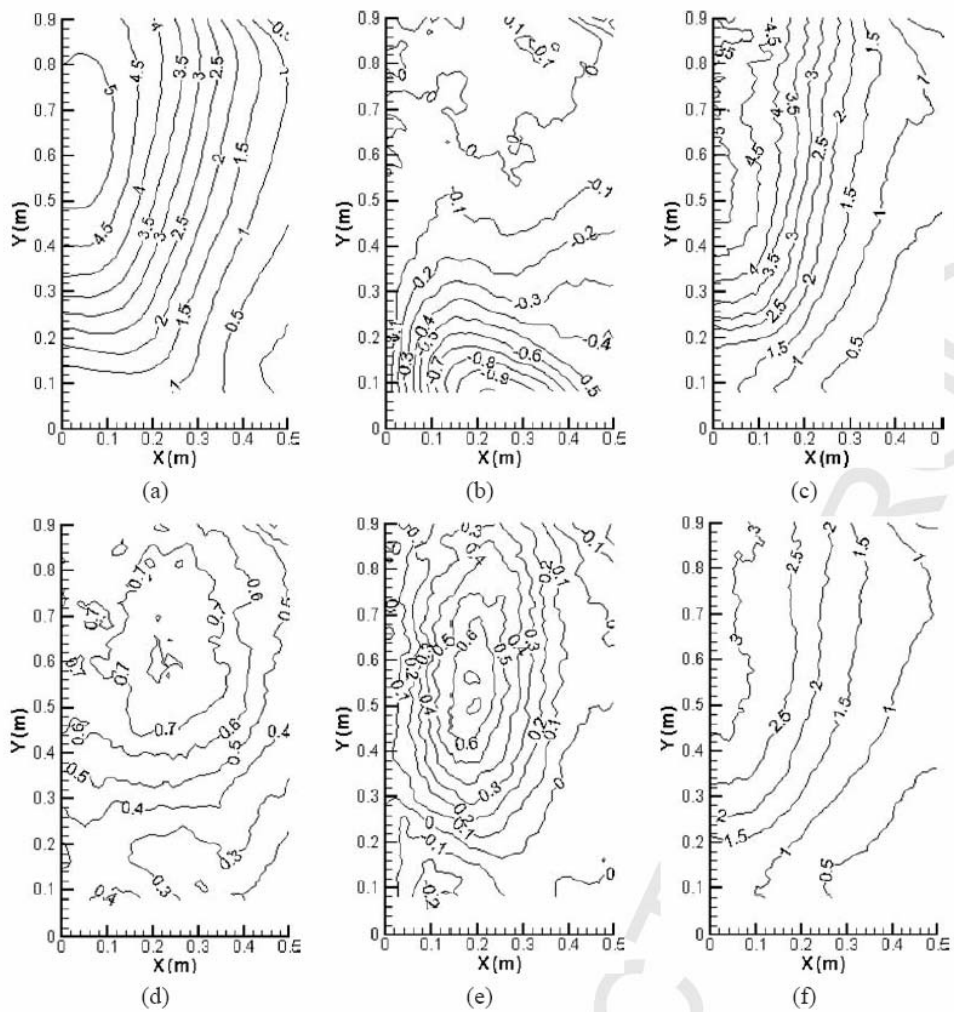


Fig. 13. Time mean statistics for a hydrogen fire. Fuel mass flux = 0.022 kg/m^2 s. (a) Vertical velocity (m/s). (b) Horizontal velocity (m/s). (c) Vertical velocity fluctuations squared (m^2/s^2). (d) Horizontal velocity fluctuations squared (m^2/s^2). (e) Vertical and horizontal fluctuation product (m^2/s^2). (f) Turbulent kinetic energy (estimate $\overline{w'^2} = \overline{u'^2}$) (m^2/s^2).

Similar turbulent statistics (mean vertical and horizontal velocities, velocity fluctuation statistics (u'^2, v'^2, $u'v'$, turbulent kinetic energy) obtained for helium plumes and methane and hydrogen fires.

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