Advanced Sensor Approaches For Monitoring and Control Of Gas Turbine Combustors

Georgia Institute of Technology

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Daniel Guggenheim School of Aerospace Engineering

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SCIES Project 02- 01- SR102

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Project Awarded (5/1/2002, 36 Month Duration)

$337,501 Total Contract Value ($327,501 DOE)

Gas Turbine Need

- **Gas turbines must operate with ultra-low levels of pollutant emissions**
  - *Problem*: lean, premixed operation causes minimal pollutant generation but introduces combustion problems, such as instabilities and blowoff

- **Combustor health and performance information needed to optimize engine across competing demands of emissions levels, power output, and engine life**
  - *Problem*: Hostile combustor environment not amenable to diagnostics

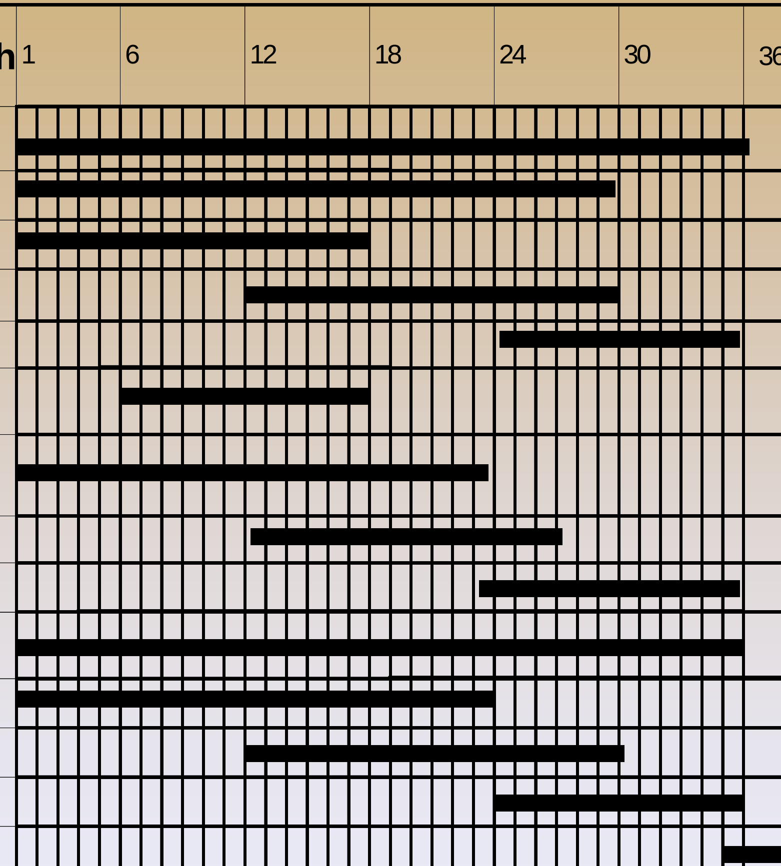
Project Objectives

- Develop real-time sensor methodologies to identify combustor stability margin and performance
  1) **Transient Flame Holding Event Sensors**
  2) **Flame Zone Sensors**
  3) **Combustor Dynamics Stability Margin Sensors**

- Use natural optical and acoustic radiation (light and sound) emitted by the combustion processes

- Characterize these emissions from a number of combustors and correlate to performance and stability

Approach



Task 1. Transient Flame Holding Event Sensor Approaches

1. Acoustic and optical characterization of premixed flames near blowout

-Atmospheric pressure studies

-High pressure studies **+ *Syngas fuels***

2. Test blowoff detection strategy using data from industrial partner

Task 2. Flame Zone Sensor Approaches

1. Spectral characterization of high-pressure, preheated natural-gas chemiluminescence

2. Heat release monitoring

~~*3. Nonuniformity sensing*~~ → ***Syngas fuels***

Task 3. Stability Margin Sensor Approaches

1. Develop stability margin assessment methodology

2. Test methodology on Georgia Tech data

3. Test methodology on data from industrial partner.

Write Final Report

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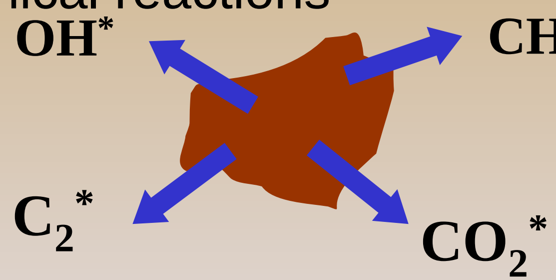
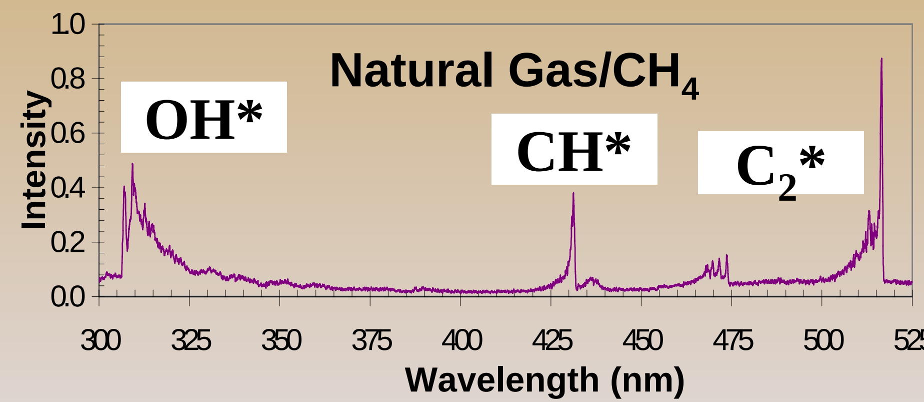
Accomplishments

- **Developed acoustic and optic sensing techniques to monitor combustor stability margins**
  - Blowoff Proximity Sensing: *demonstrated in multiple combustors; in high pressure gas turbine combustor; with multiple fuels (NG, NG+H_2, syngas)*
  - Combustion Dynamics Stability Margin Sensing: *developed approach, licensed technology undergoing field testing; compatible ion probe method tested with industrial partner; extending approach to unstable regime*
- **Developed optical techniques to characterize flame zone characteristics**
  - local flame F/A ratio and heat release for NG combustion
  - F/A for CO/H_2 synthetic gas fuels
- **Enable more reliable, lower NOx gas turbines**

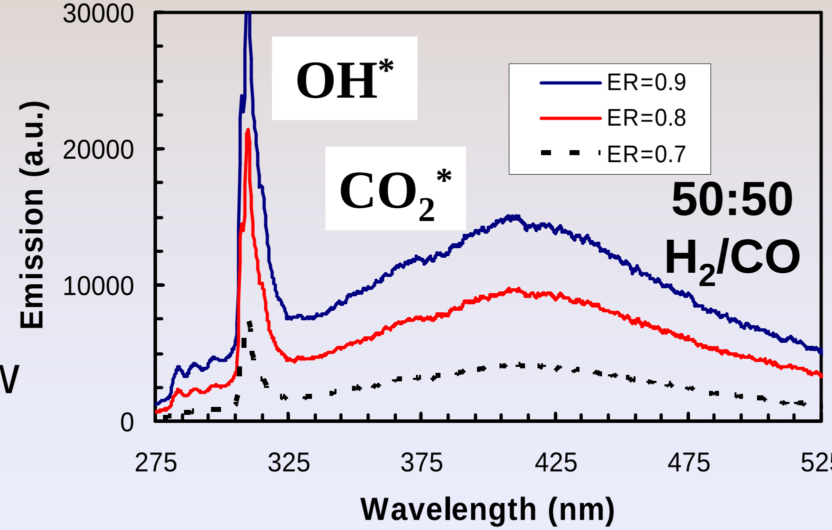
Sensing Strategies - *Optical*

- Chemiluminescence:
  - E-M radiation given off during chemical reactions



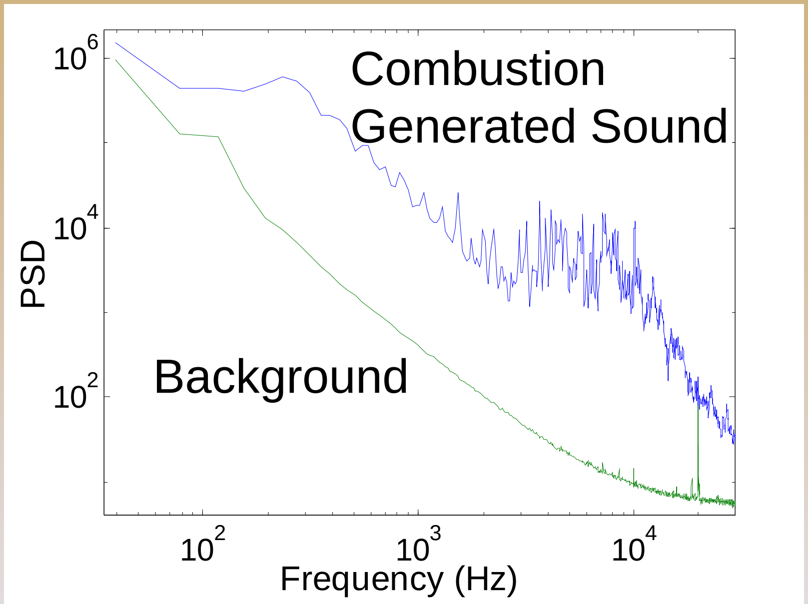


- Sensing issues:
  - Gives state of chemical reaction zone in combustor
  - Detectable with readily available rugged sensors
  - Can view local or global regions
  - Does not require sensor in hot flow
  - Fiber optic access



Sensing Strategies - *Acoustic*

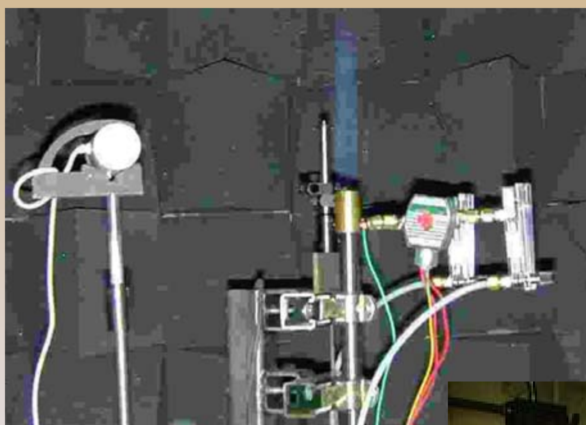
- Acoustic Emission:
  - Unsteady heat release and resulting gas expansion generates sound (acoustic) waves



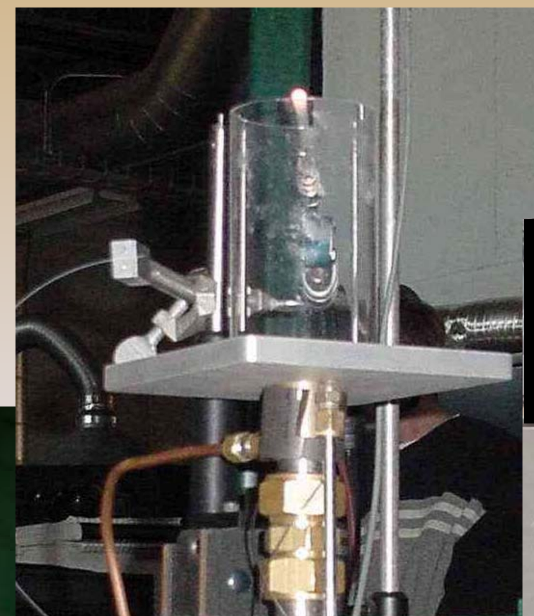
- Sensing issues:
  - Relates to *unsteadiness* of heat release processes
  - Detectable with readily available transducers
  - Does not require sensor in hot flow
  - Global measurement

Experimental Systems

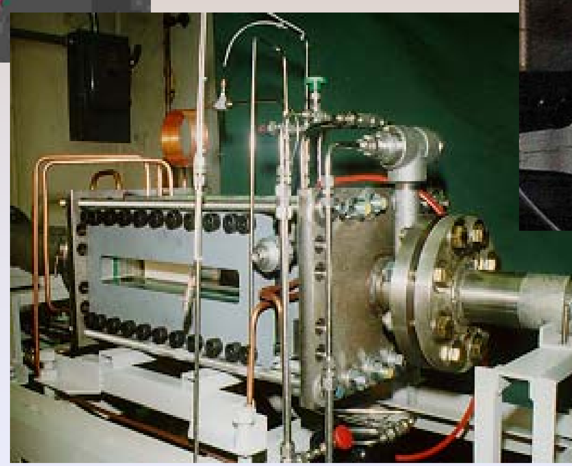
- Measurements of acoustic and optical signatures performed in variety of combustors to ensure robustness



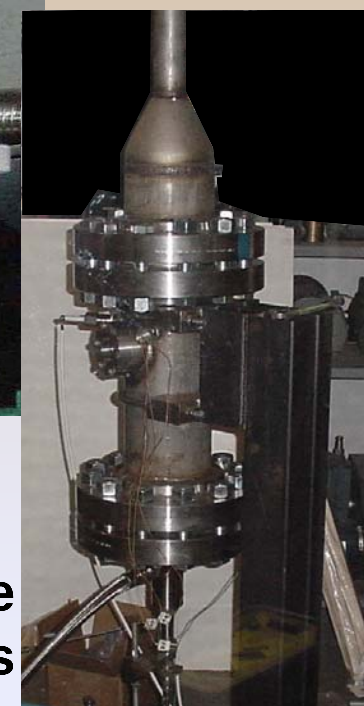
Atmospheric Pressure Jet Flames



Atmospheric Swirl Combustor



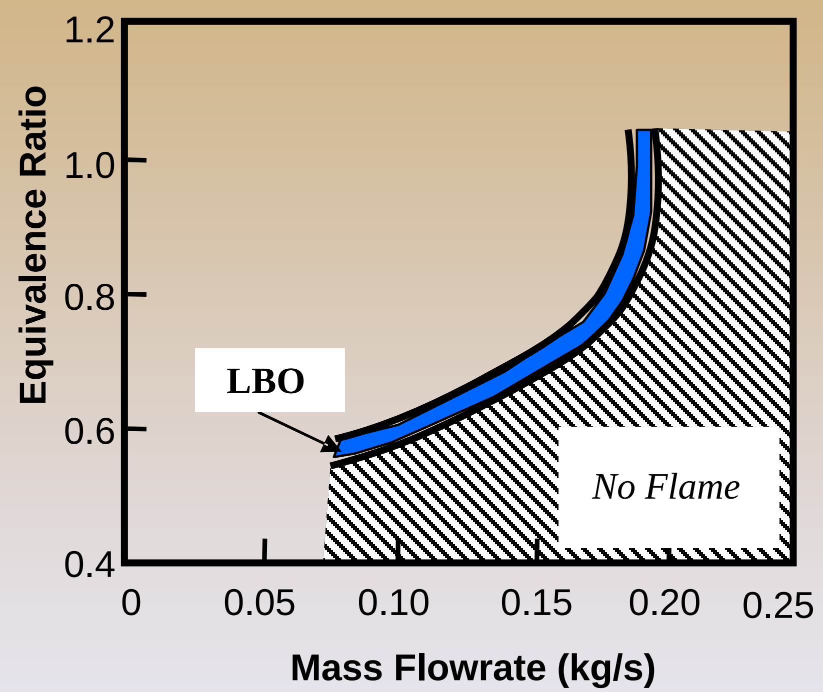
High Pressure Gas Turbine Simulator



High Pressure Syngas Flames

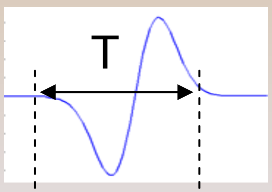
Transient Flame Holding Event Sensors

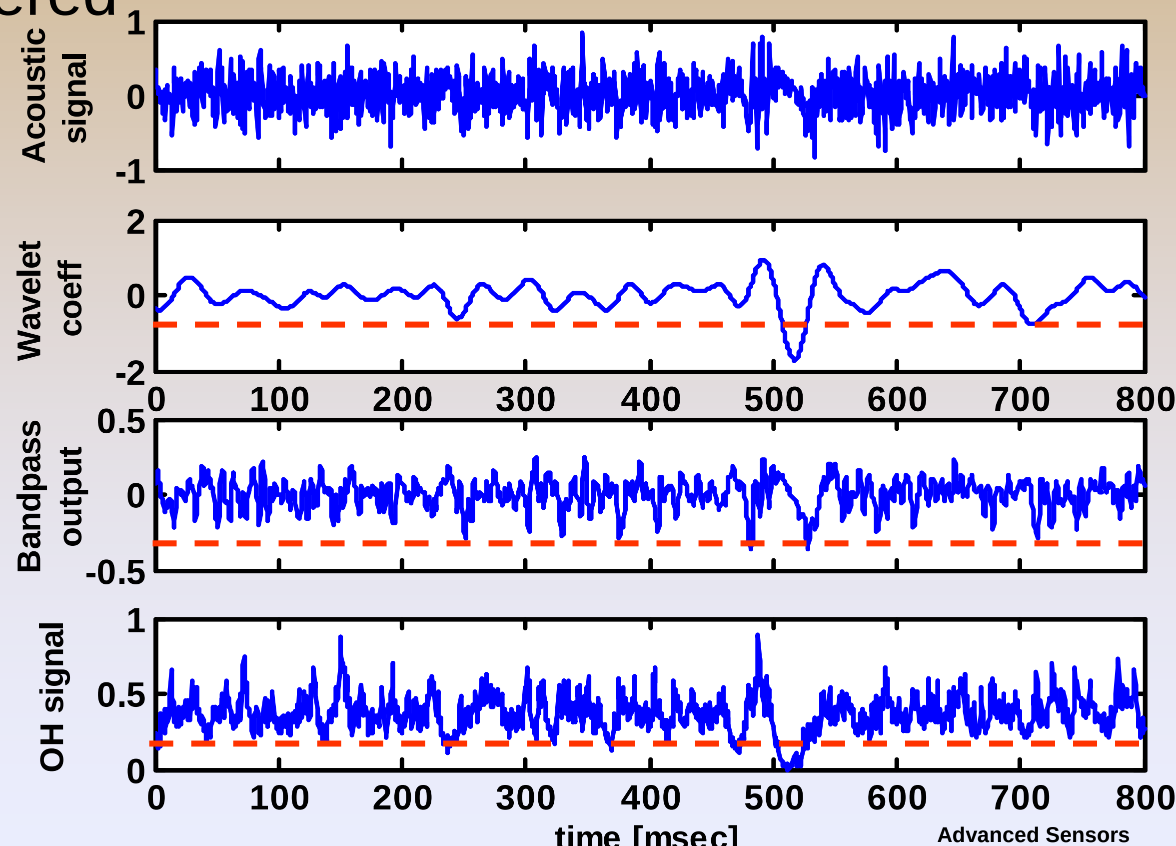
- Develop sensors to detect proximity to lean blow out (LBO) in gas turbine combustors
  1. Characterize acoustic and optical radiation from flames and identify LBO precursors
  2. Extend developed approaches to high pressure combustor
  3. Test and validate developed blowoff prediction strategies on full-scale, fielded turbines
- Previously demonstrated works in various atm. pressure NG combustors



Event Identification

- **Threshold optical signal**
  - threshold: set to a fraction of mean signal (independent of power setting, sensor drift, ...)
- **Acoustic signal** filtered before thresholding



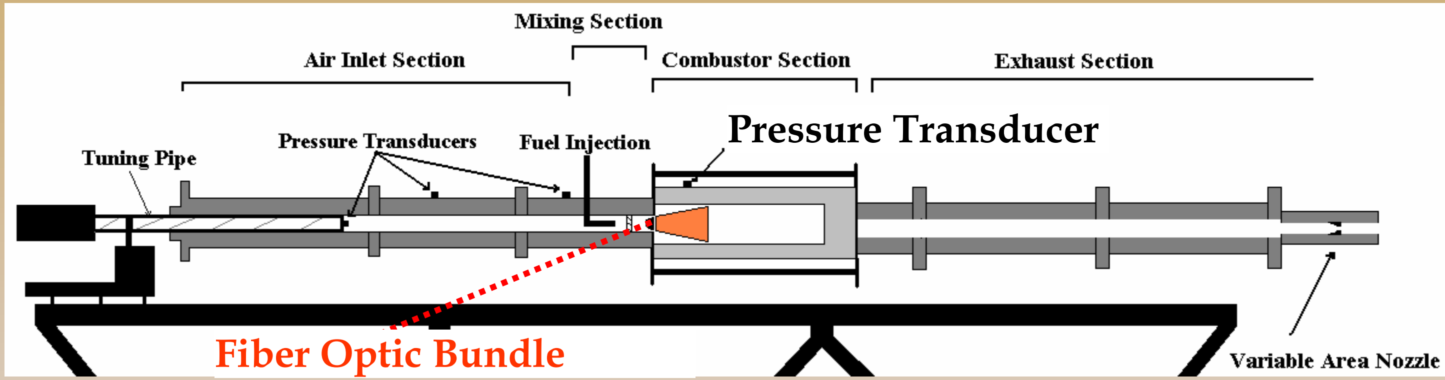


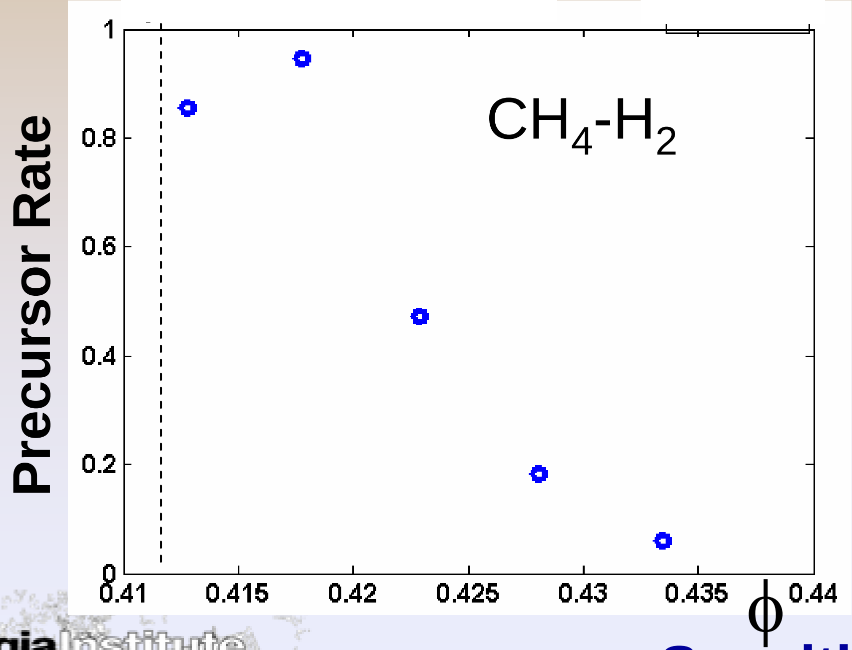
Wavelet Filter
T and threshold

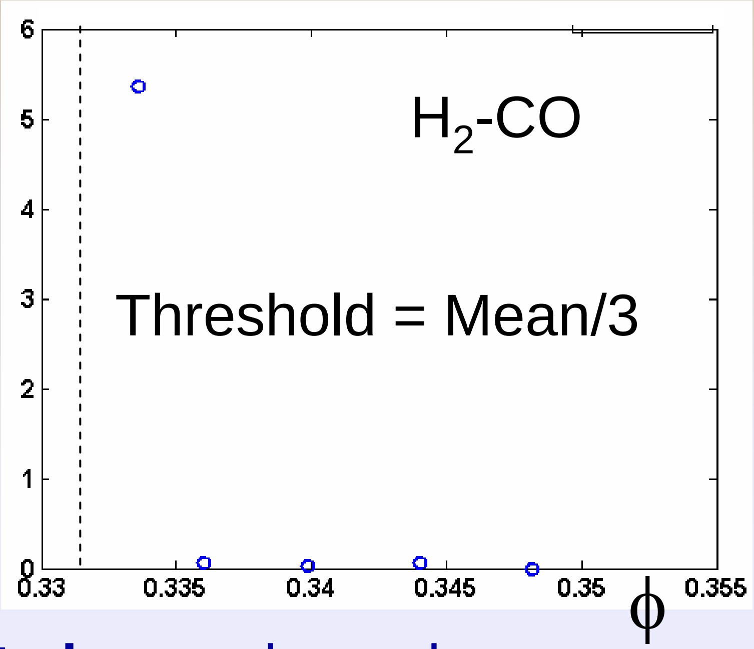
Bandpass Filter
Δf and threshold

LBO Proximity Sensing – Recent Work

- Results from high pressure GT simulator



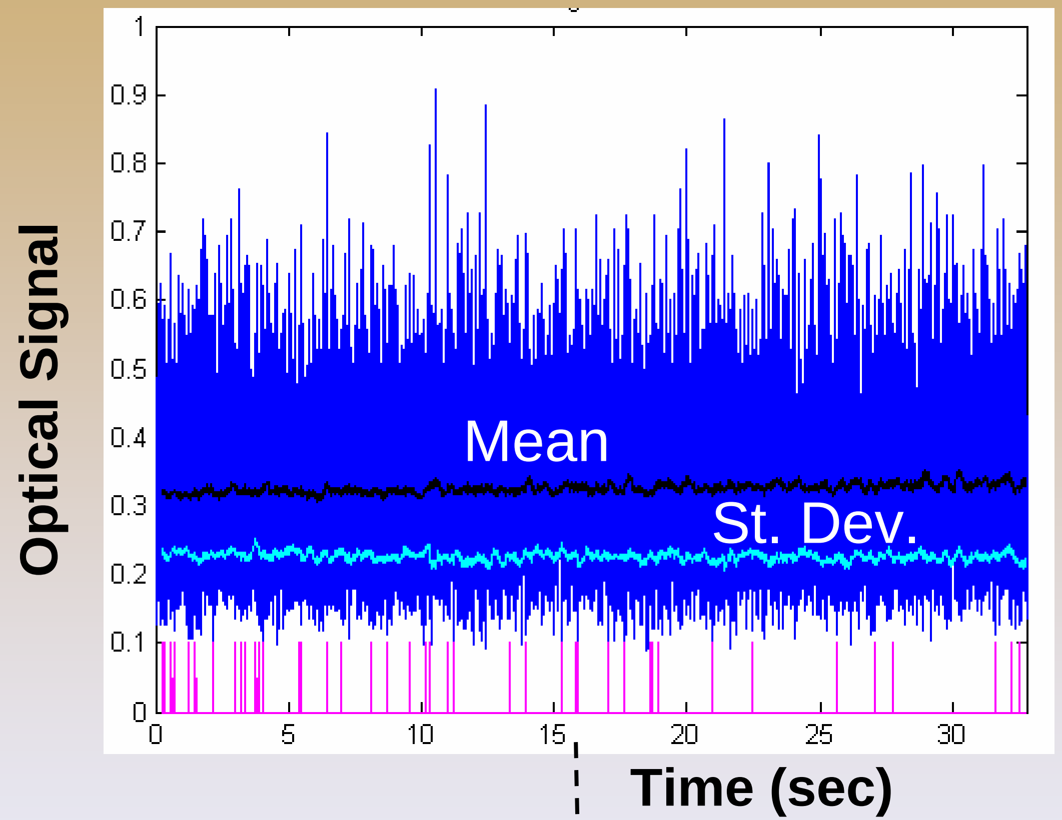


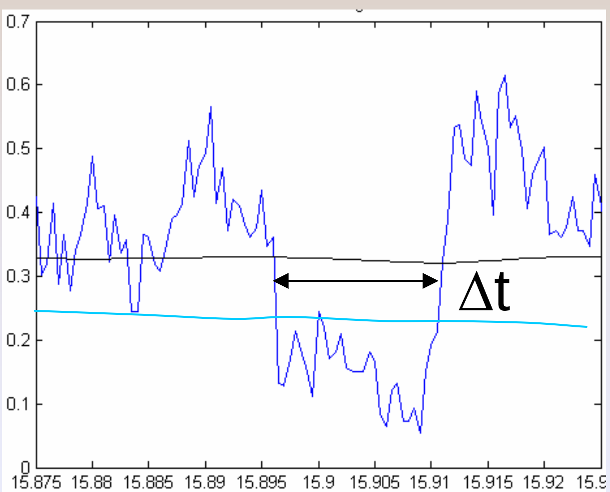


- **Sensitivity issue**: depends on threshold choice

Event Identification Improvements

- Use standard deviation as threshold and min. duration to define events



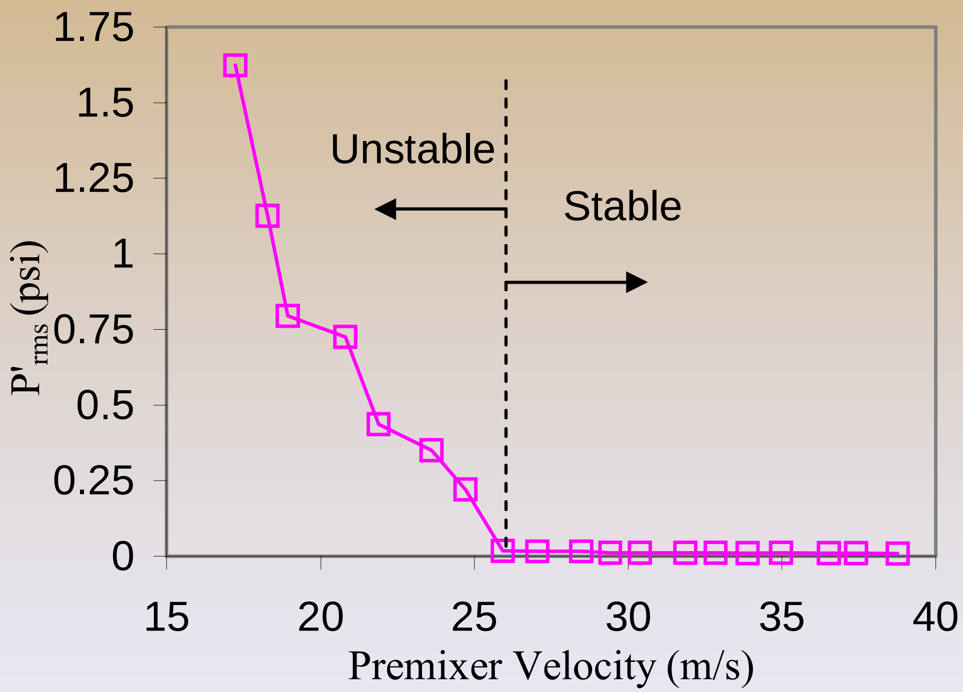


- Reduces noise events and allows increased sensitivity

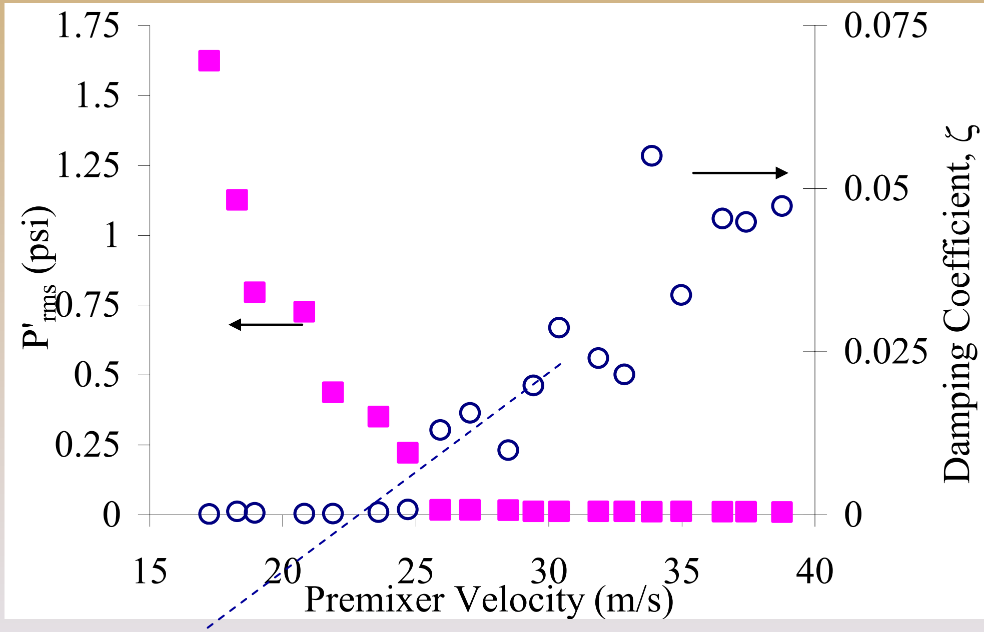
Combustor Dynamics
Stability Margin Sensors

- Develop strategies to determine proximity of combustor to combustion instability
- Demonstrate in fielded engines
  1. Licensed to Alta Solutions
  2. Methodology being tested on four Calpine gas turbines in Texas - working through field issues
- Now extending technique to unstable (nonlinear) regime

  current algorithm provides no useful information once system has gone unstable



Extension of Method to Unstable Regime (Negative Damping)



Previous Approach

- Stability margin quantified through determination of combustor damping
- Decay of correlation of data filtered around unstable mode

Extended Approach

- Work with full nonlinear equations
- Solve Fokker-Planck equation for instability amplitude PDF

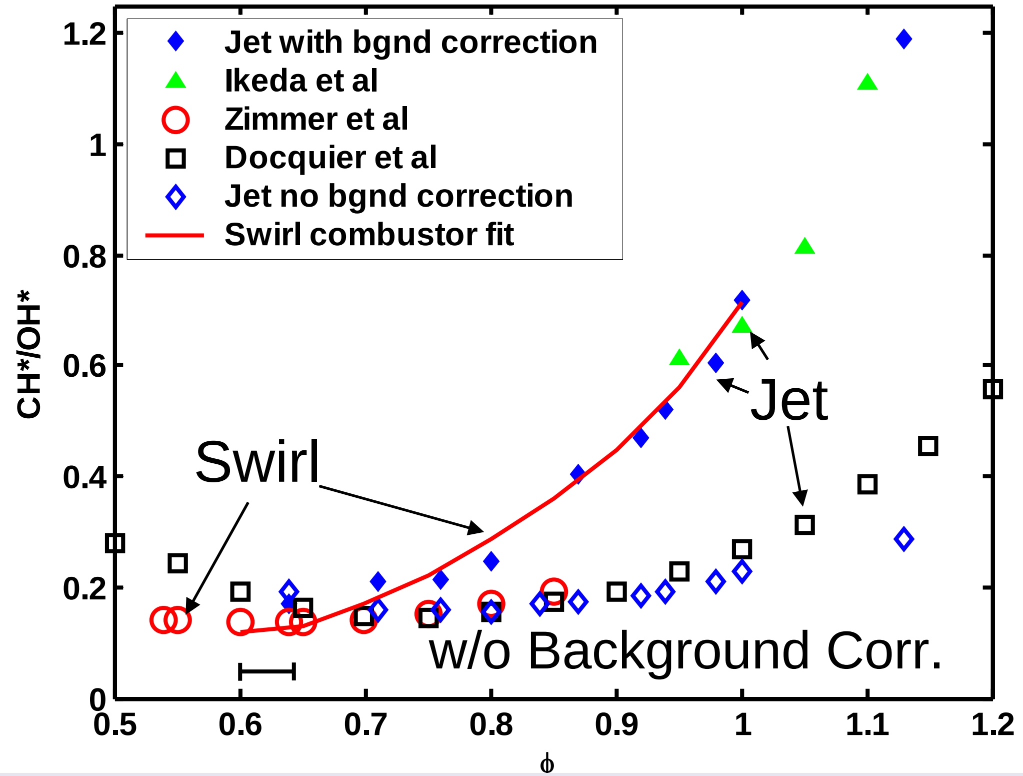
$$W(\tilde{A}) = \frac{4}{\sqrt{\pi}} \frac{e^{-\Omega^2/4}}{1+\operatorname{erf}(\Omega/2)} \tilde{A} e^{\tilde{A}^2(\Omega - \tilde{A}^2)}$$

- Theory shows that damping coefficient directly proportional to parameter Ω
- Theory nearly developed; test on data sets from GT simulator in near future

Flame Zone Sensors

- Develop approaches to sense variations in
  - local fuel-air ratio
  - heat release rate

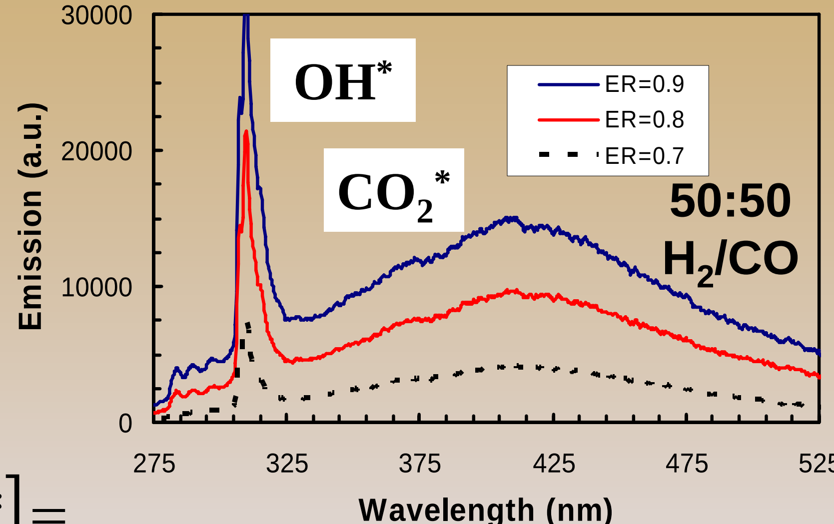
  in flame zone using chemiluminescence
- Previously showed CH/OH ratio monotonically increases with fuel-air ratio in **natural gas combustors**



✓ Good agreement across combustors
✓ Independent of small fuel variations
✓ Background correction important for universality

Syngas Fuel Chemiluminescence

- CO/H_2 flames dominated by CO_2^* and OH^* emission
- Use Chemkin model of laminar flame to predict chemiluminescence signal

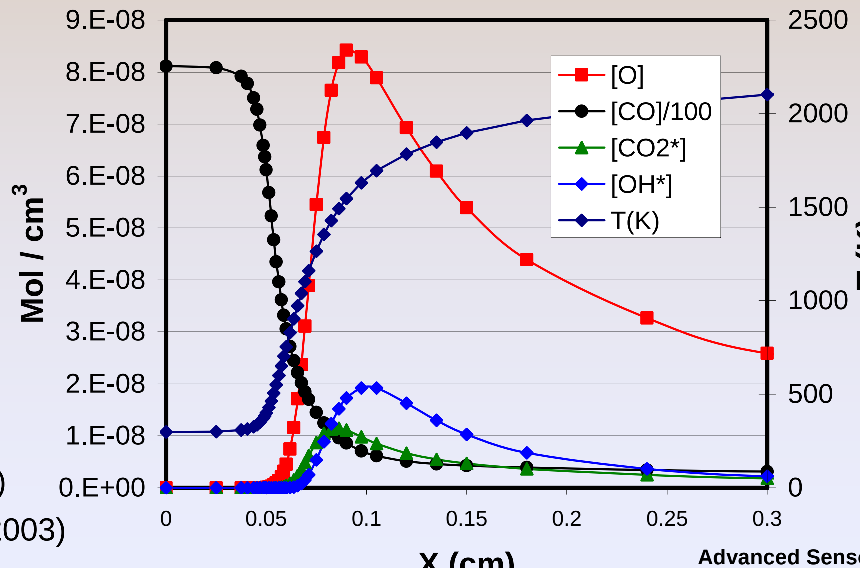


Reactions
$CO + O + M \leftrightarrow CO_2^* + M$
$CO_2^* \rightarrow CO_2 + hv$
$CO_2^* + M \leftrightarrow CO_2 + M$
$H + O + M \leftrightarrow OH^* + M$
$OH^* \rightarrow OH + hv$
$OH^* + Q \leftrightarrow OH + Q$

$$I_{chem} \propto \left[X^*\right] =$$

$$k_{CO_2^*}[CO][O]$$

$$k_{OH^*}\frac{[H][O][M]}{\sum k_Q[Q]}$$



CO_2* - Slack and Grillo, C&F (1985)

OH* - **Petersen *et al.***, 39th JPC (2003)

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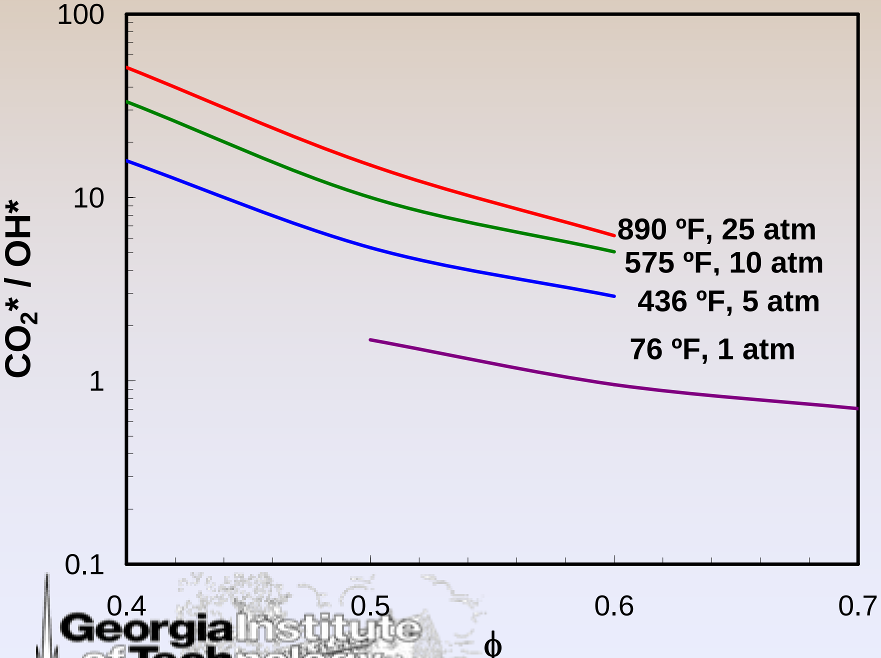
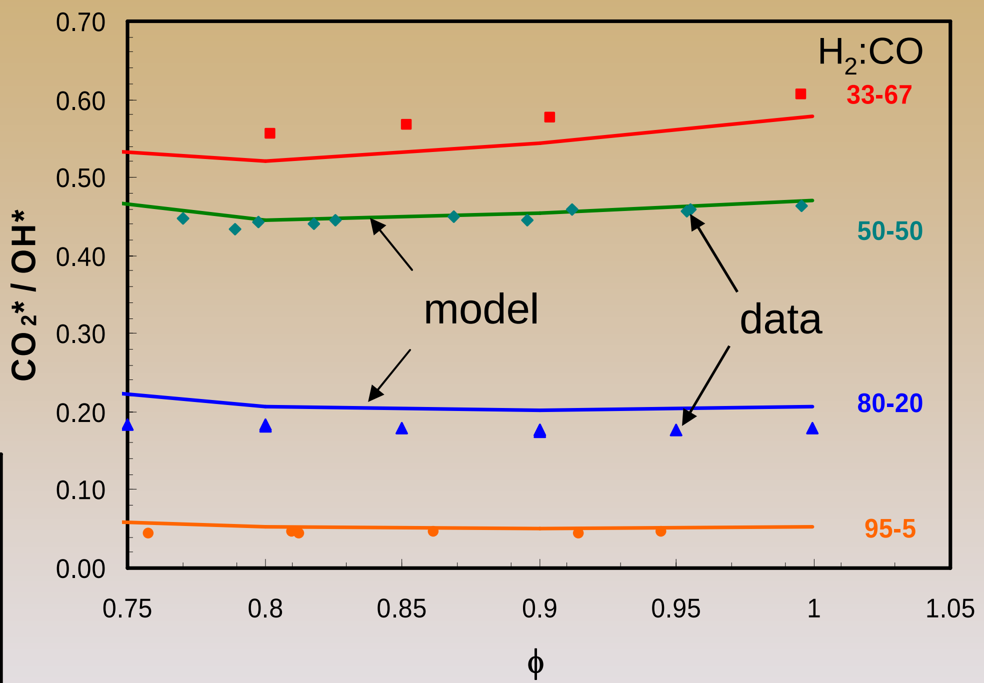
Experiment-Model Ratio Comparison

- Modeling of ratio good match to experimental data in laminar flames
  - little ϕ dependence for near stoichiometric mixtures

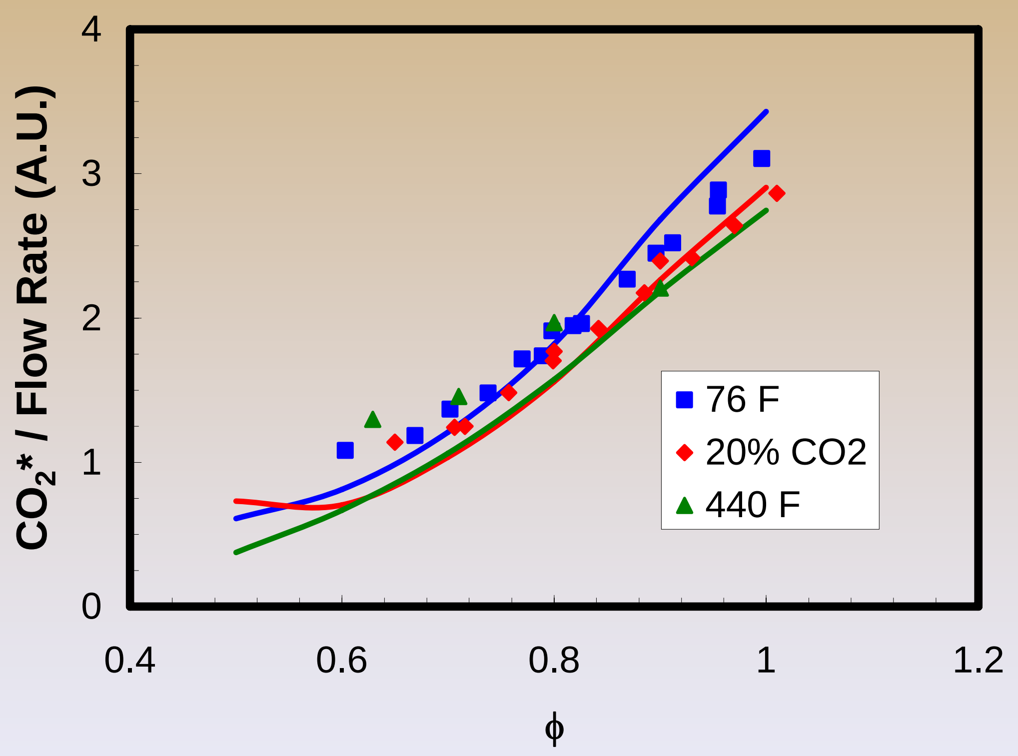




- Modeling for leaner (and compressed) mixtures
  - ratio depends on ϕ

CO_2* Based Approach

- Results also suggest that CO_2* can be used for local fuel-air ratio sensing
  - normalize by total flow rate
  - sensitive over wider (richer) range of F/A
- Potential issue
  - absolute, not ratio approach
  - signals depend on optical efficiency (dirt,…)



Summary

- **Blowout Margin Sensing**
  - Patented acoustic and optical methods shown to give information on proximity to blowoff in range of combustors
  - Demonstrated in high pressure GT combustor for variety of fuels, need to test on data from industrial system
- **Dynamics Stability Margin Sensing**
  - Method based on combustor damping in stable regime patented and licensed – field tests underway
  - Extending approach to unstable regime to provide control system with information needed to return to stable region
- **Flame Zone Sensing**
  - Demonstrated sensing of fuel-air ratio, heat release variations (spatial or temporal) in range of natural gas combustors
  - Approaches developed for syngas fuels – needs testing under GT conditions

Questions?