Understanding Transient Combustion Phenomena in Low-NO_x Gas Turbines

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Overview of presentation

— Project objective

— Technical background

— Technical approach

— Project structure

— Project budget

— Project management plan and risk management

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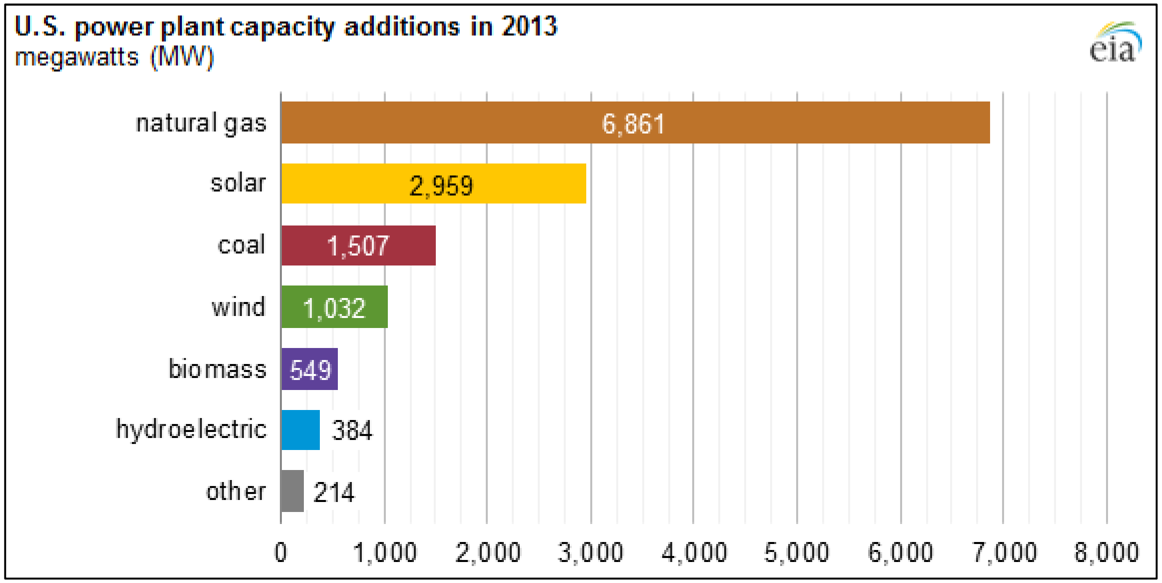
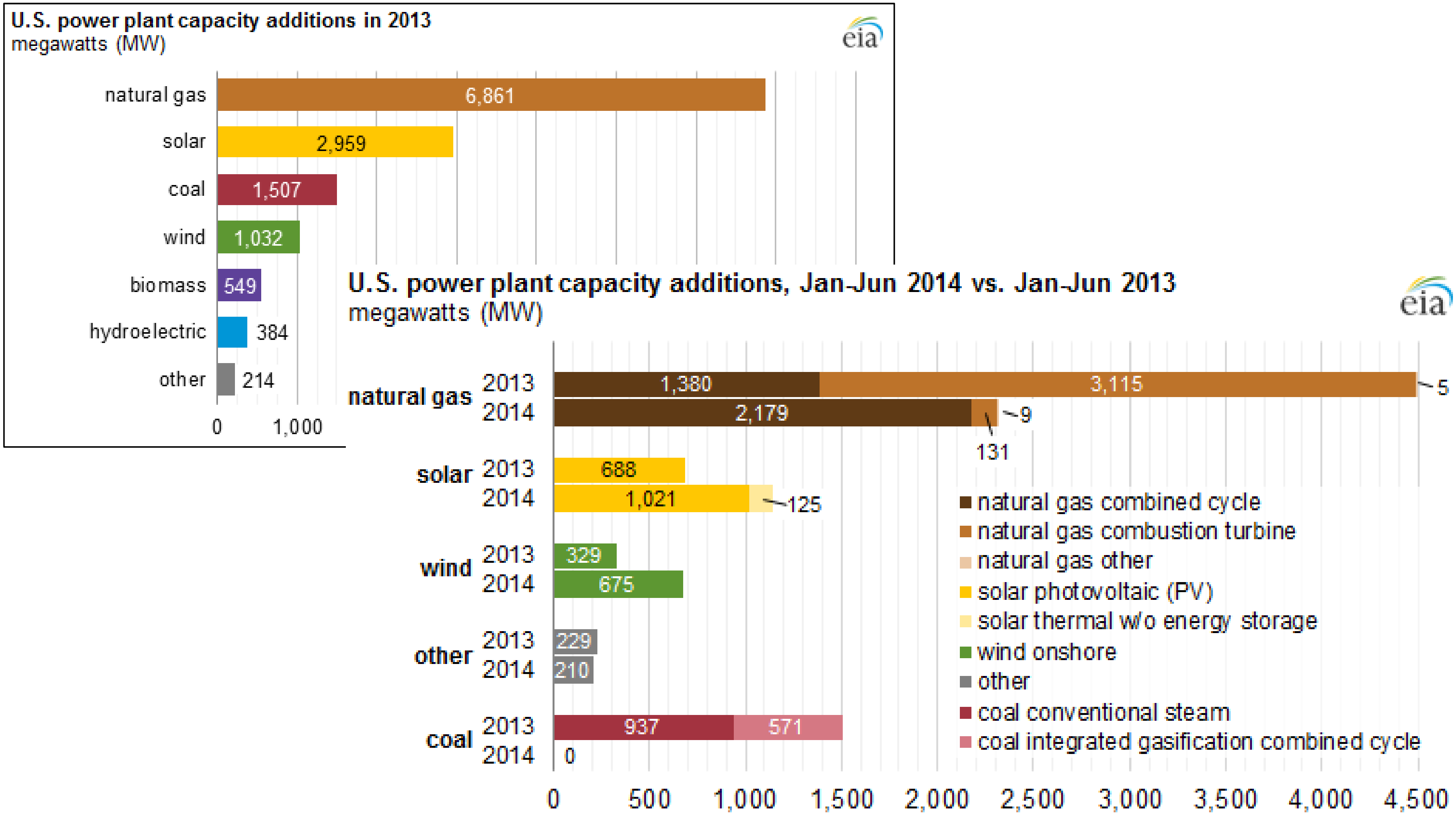
In 2013, 50% of new power generation capability came from natural gas, which was used in gas turbine power plants



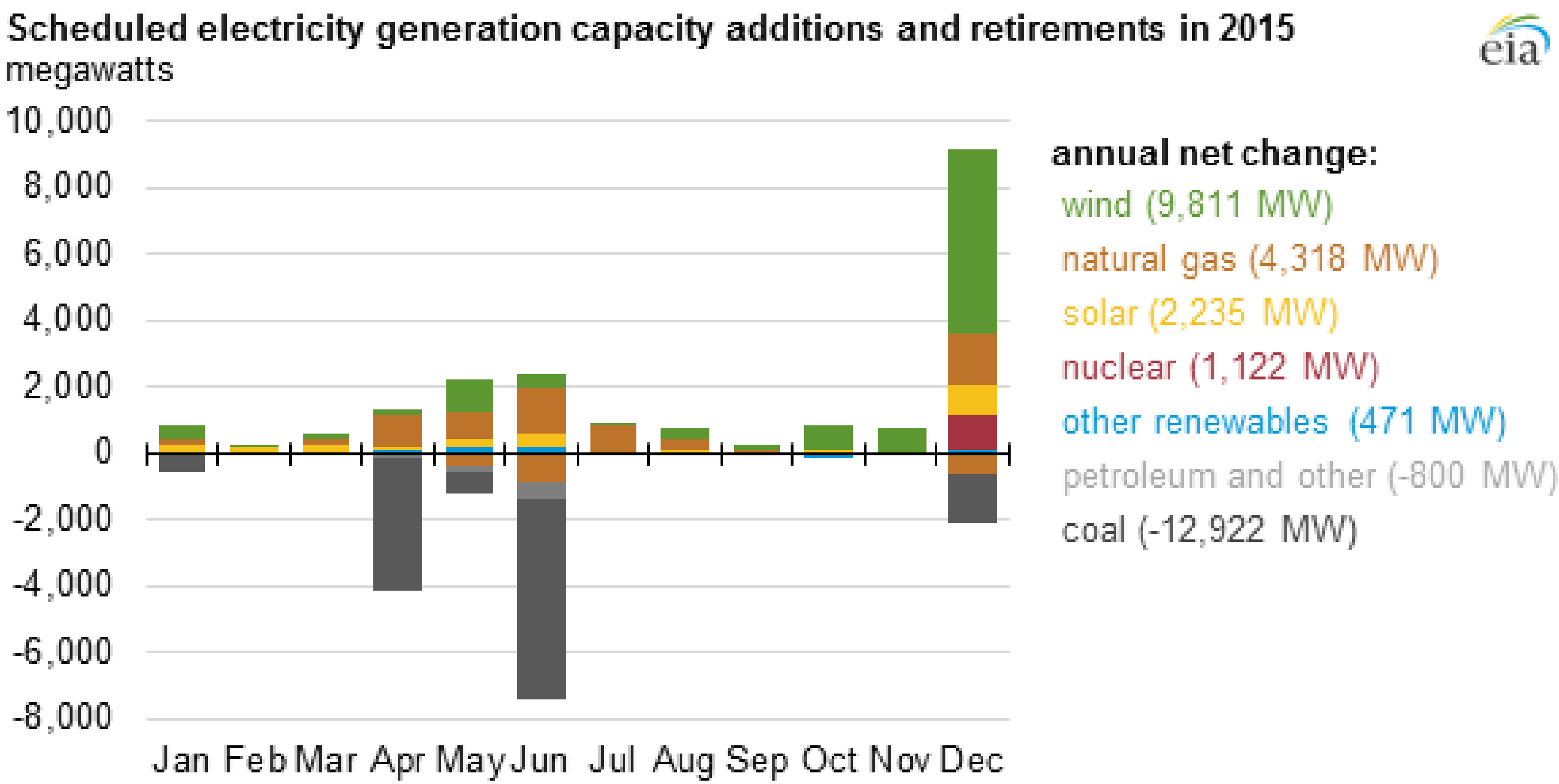
Source: eia.gov

These additions were split between "peaking plants" and combined cycle plants, both of which use gas turbines



Source: eia.gov

Gas turbines, particularly peaking plants, will continue to play an important role in the energy production market



Source: eia.gov

Objective of the program is to *understand, quantify,* and *predict* combustion instability during ***transient operation***

— Two major deliverables for the program:

1. Fundamental understanding of flow and flame behavior during combustion transients and mechanisms for transition to instability

2. Development of a stability prediction or quantification framework

Objective of the program will be achieved through experimental study and close ties with industry

— Experimental program that includes two separate, complementary facilities

— Development of quantification and prediction frameworks will aid in applying the results from this work to other facilities, including industrial hardware

— Cost-share and partnership from GE Global Research will provide industry feedback and internship opportunities for students on project

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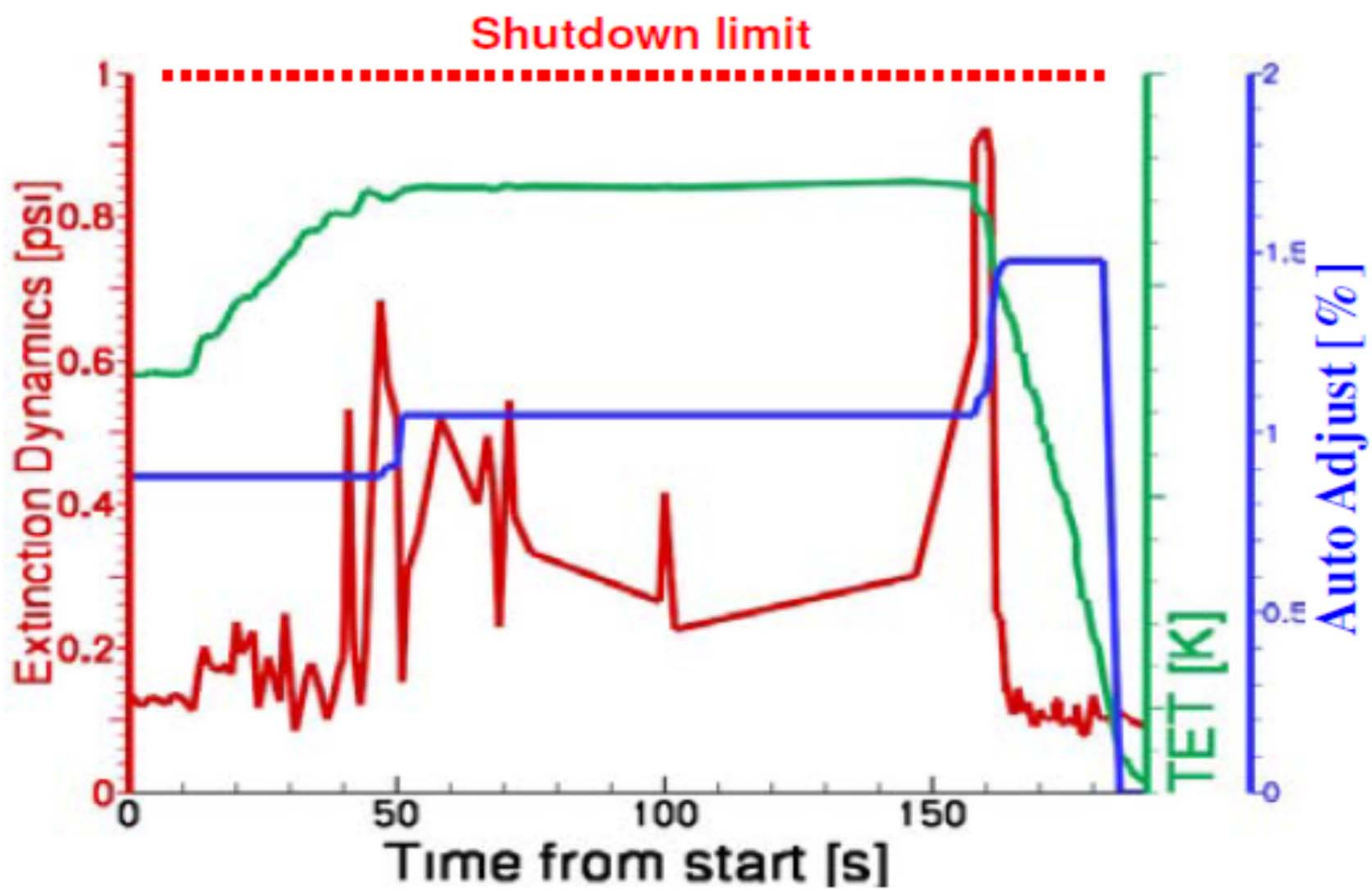
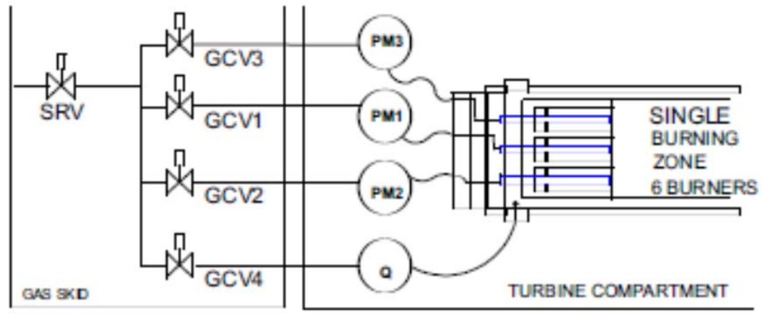
Very few studies have discussed the onset or control of instabilities during transient operation, but it’s a common issue



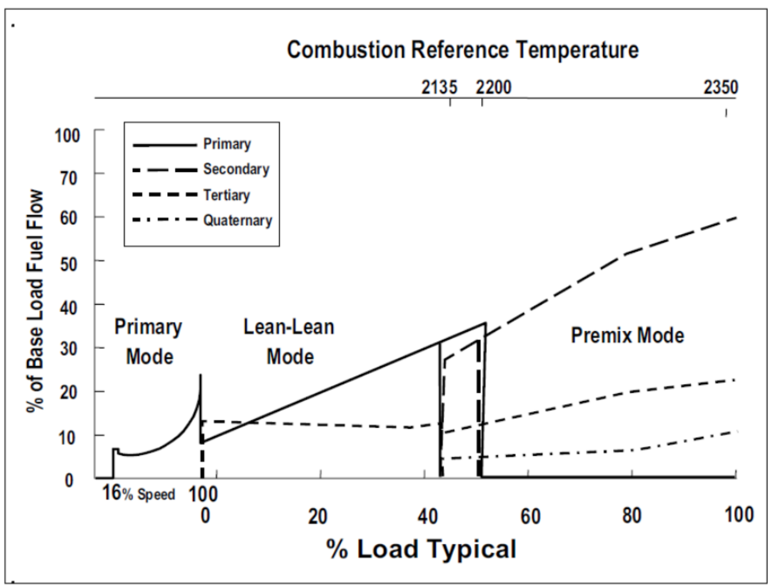
Transient operation of a Siemens SGT-200 (Bulat *et al.* 2007)

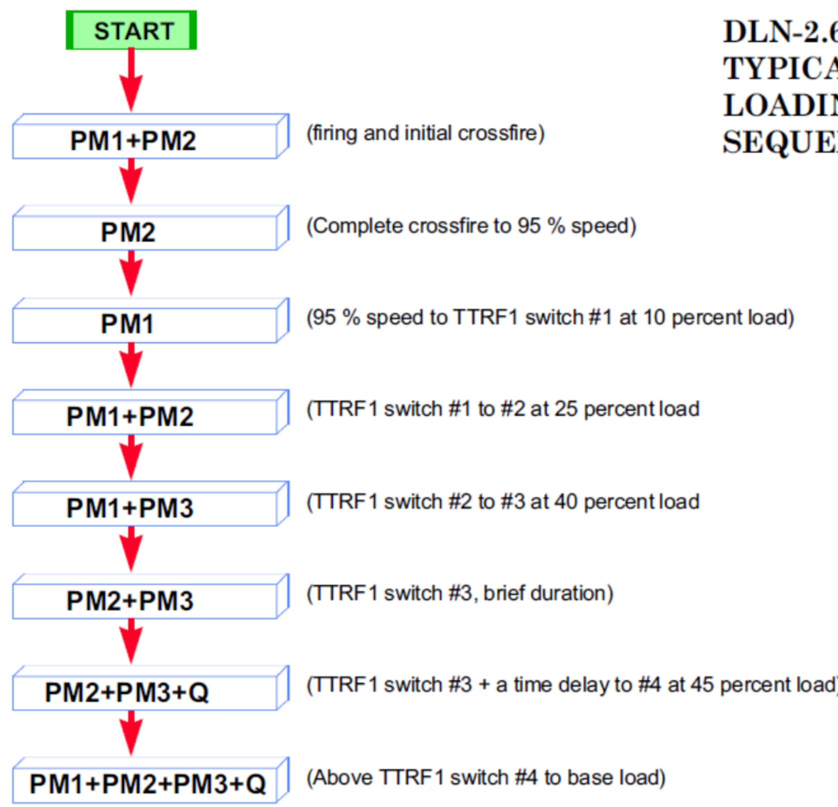
Engine load is typically varied by either varying fuel staging or the equivalence ratio of certain fuel nozzles



SRV SPEED/RATIO VALVE
GCV1 GAS CONTROL PM1
GCV2 GAS CONTROL PM2
GCV3 GAS CONTROL PM3
GCV4 GAS CONTROL Quaternary

PM3 - 3 NOZ. PRE-MIX ONLY
PM2 - 2 NOZ. PRE-MIX ONLY
PM1 - 1 NOZ. PRE-MIX ONLY
Q - QUAT MANIFOLD, CASING, PRE-MIX ONLY

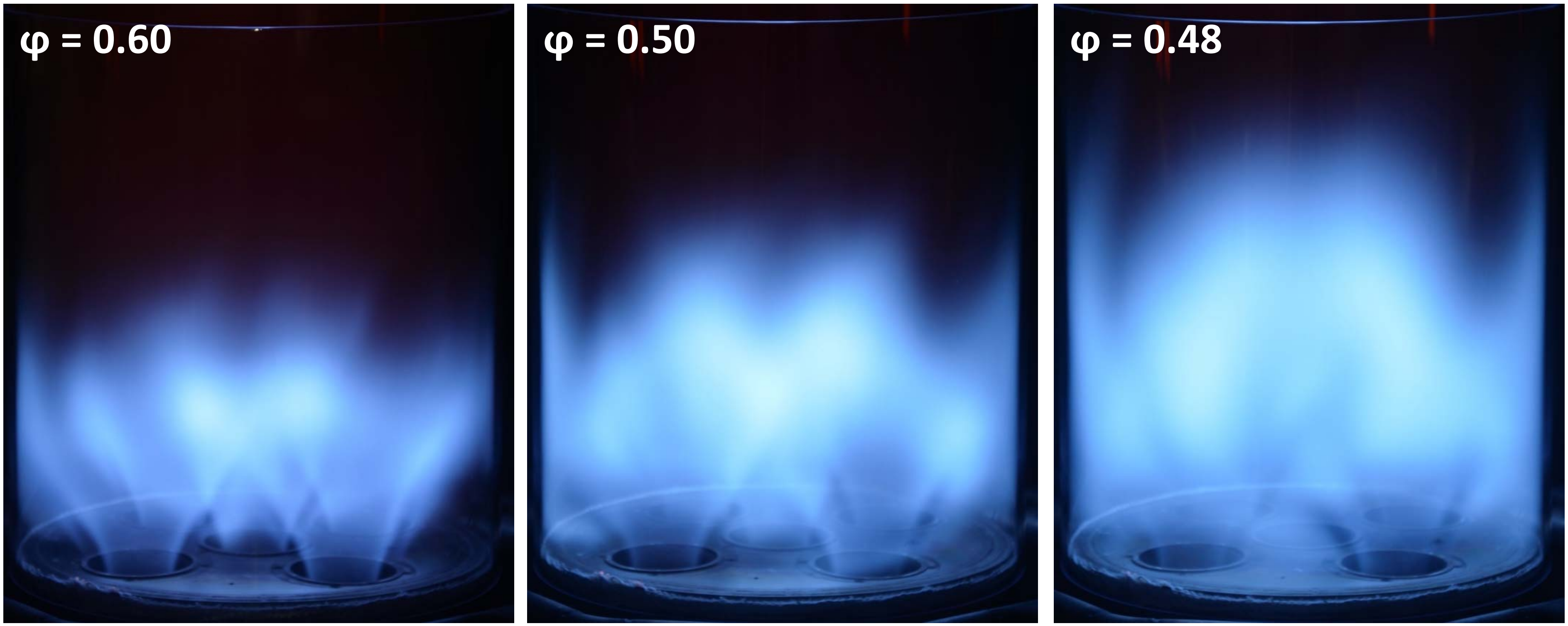




DLN-2.6 TYPICAL LOADING SEQUENCE

Source: Davis and Black, “Dry Low NO_x Combution Systems for GE Heavy-Duty Gas Turbines”

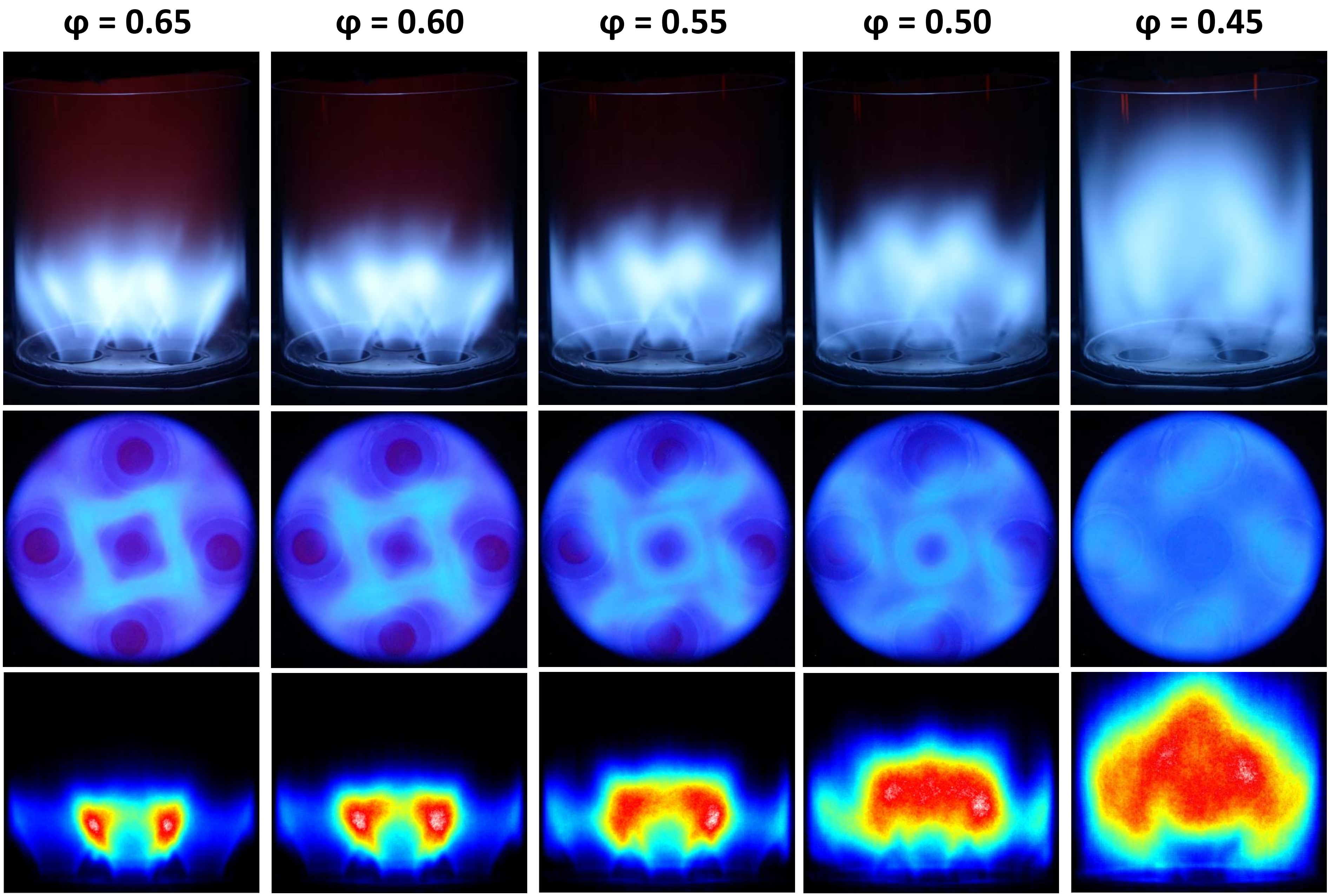
Instabilities may arise as a result of changes in flame shape and flame anchoring that occur with variation in equivalence ratio



Photographs of multi-nozzle flame at U = 25 m/s, T_{in} = 200°C

- **As the equivalence ratio is reduced, the flames get longer and more distributed within the combustor**
- **At φ = 0.48, the middle flame lifts off (picture on far right)**
- **A hysteresis phenomenon is observed with the lift-off of the middle flame**

U = 22.5 m/s, T_{in} = 200°C, fully premixed, unforced



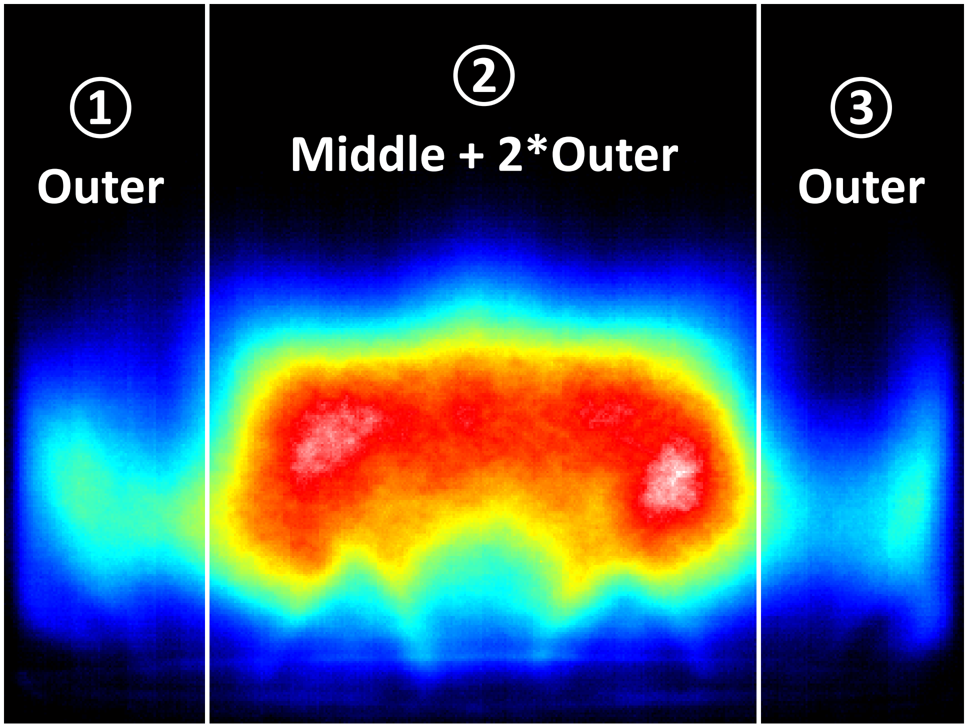
Changes in flame structure observed from photographs and chemiluminescence images of multi-nozzle flame include:

When φ is reduced,

- The flame length increases
- The outer flames become more spread out (move both further upstream and downstream)
- The angle of the middle flame reduces (i.e. it becomes narrower) and eventually lifts off
- The interaction region loses its coherent structure (square shape)
- The CH* chemiluminescence becomes more distributed
- **It appears that a majority of heat release no longer occurs in the interaction region**

Flame-flame and flame-wall regions are separated from the line-of-sight images

The regions are separated based on the locations of the centers of the outer nozzles



Chemiluminescence emission from flame-flame interaction region

$$CH^*_{F\text{-}F} = ② - [①+③]$$

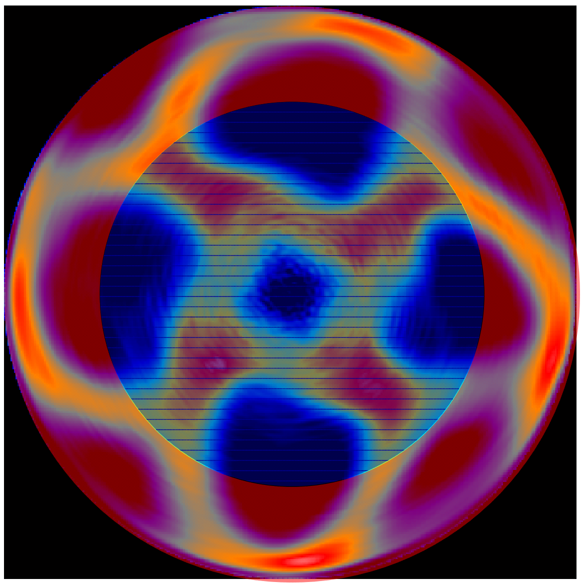
Chemiluminescence emission from flame-wall interaction region

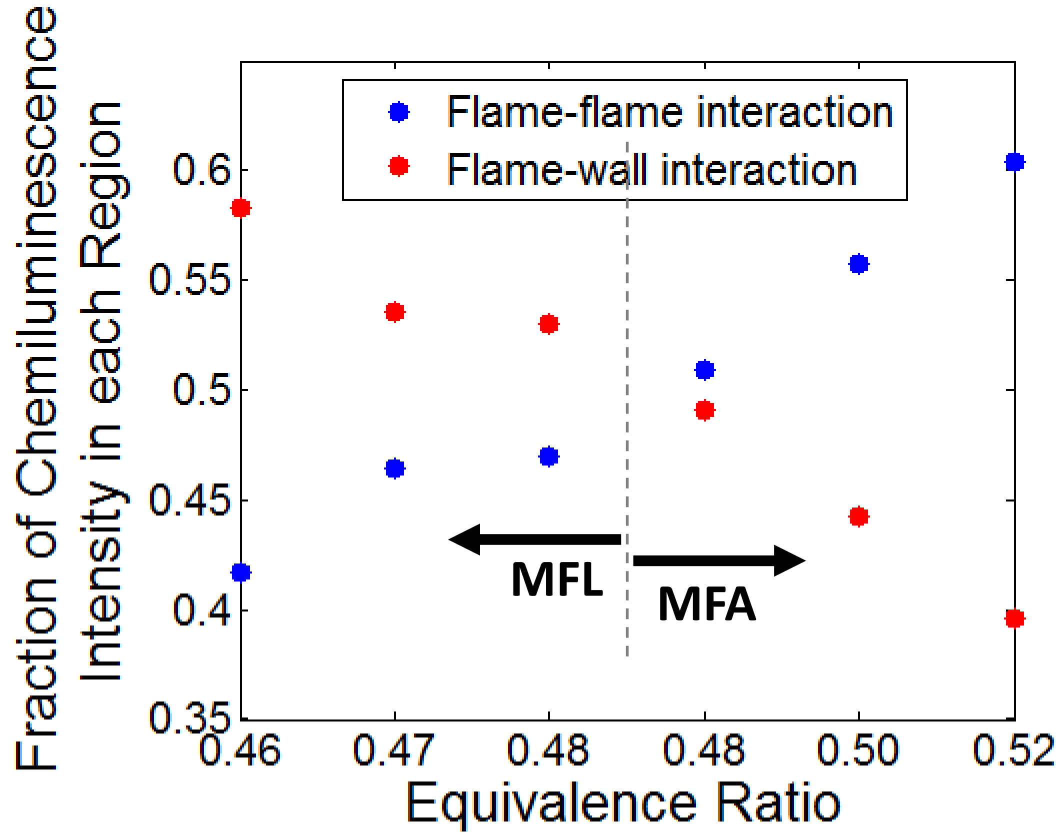
$$CH^*_{F\text{-}W} = CH^*_{Total} - CH^*_{F\text{-}F}$$

This yields reasonable results which may be more physically meaningful since we are isolating parts of the flame that are being subject to very different phenomena

Comparing this to the summed heat release rate of the same regions obtained from a 3-D image yielded differences of only 1%

The majority of heat release rate occurs in the flame-flame interaction region when the middle flame is attached

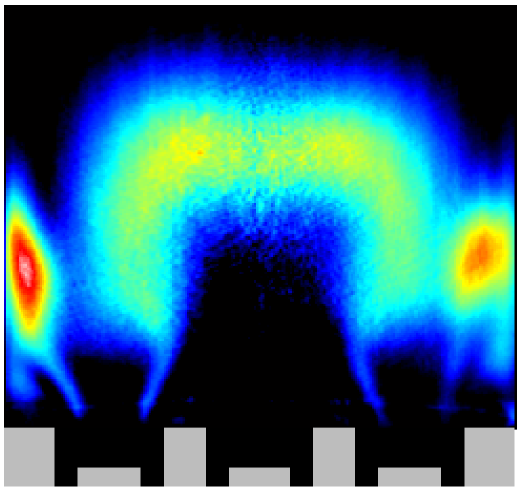




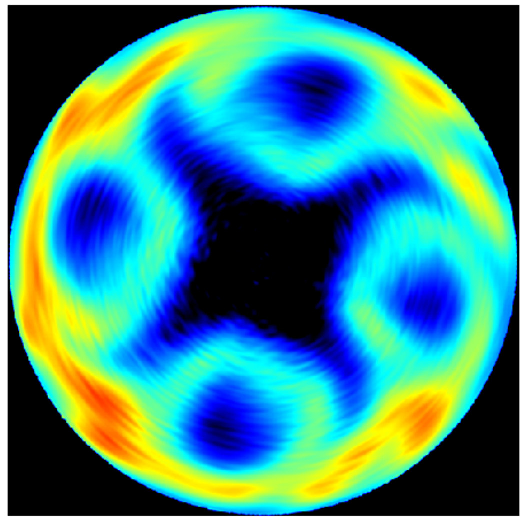
As a result we would expect mechanisms related to flame-wall interaction to dominate the response of the lifted flames and vice versa

To further investigate the structure of the multi-nozzle flame, 3-D image sets were obtained at ϕ = 0.60 and ϕ = 0.48

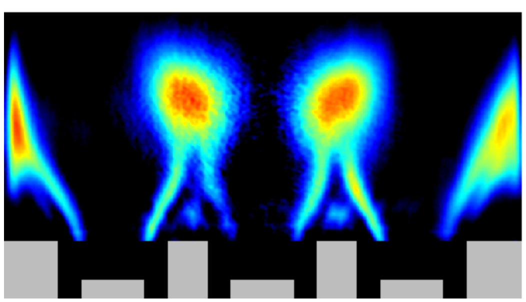
ϕ = 0.48



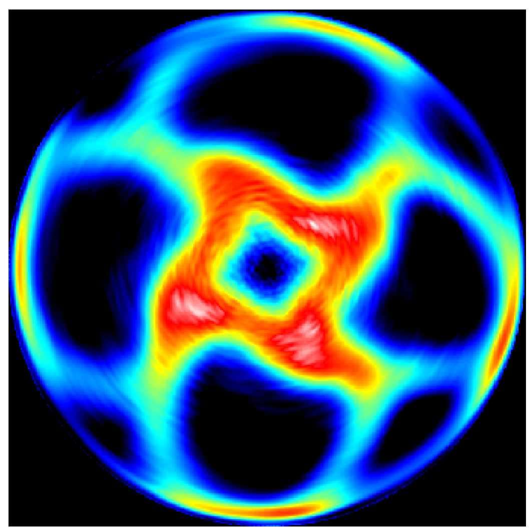
ϕ = 0.48



ϕ = 0.60

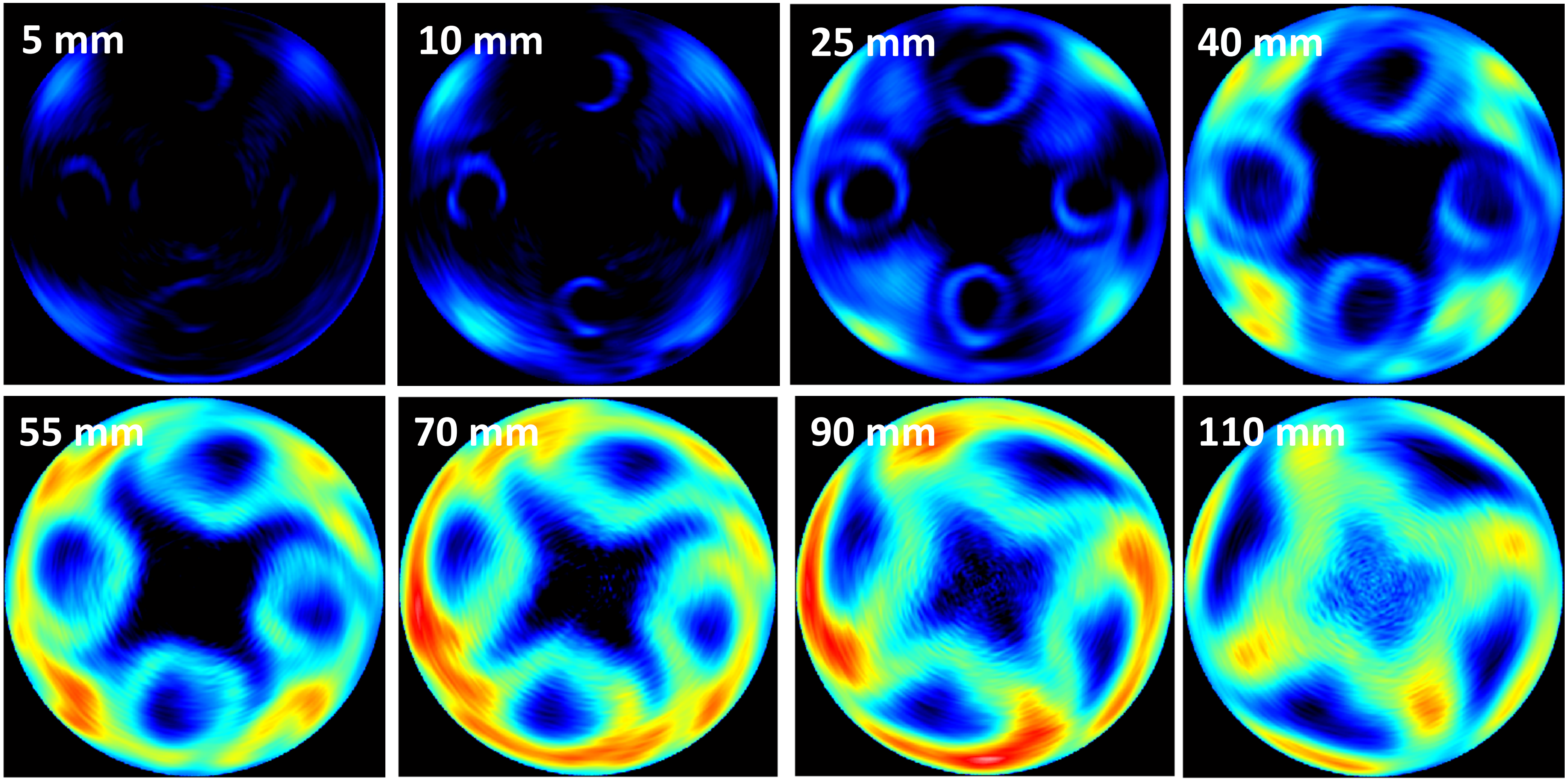


ϕ = 0.60



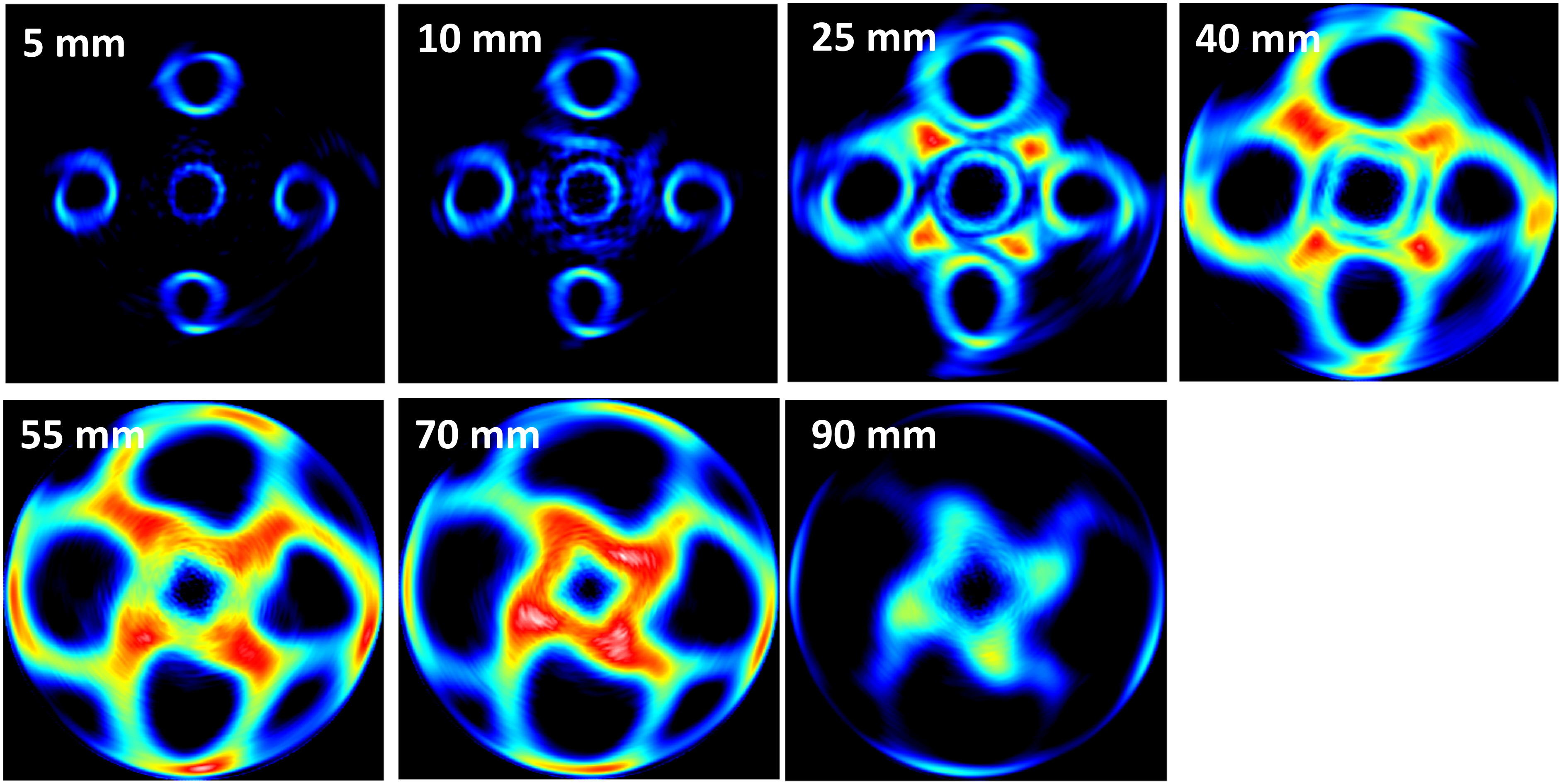
- **As with previous investigations, vertical and horizontal 2-D slices of the 3-D flame image will be analyzed**
- **Middle flame does not exist in the φ = 0.48 case**
- **A single large interaction region is observed downstream**

Analysis of horizontal slices ($\phi = 0.48$)



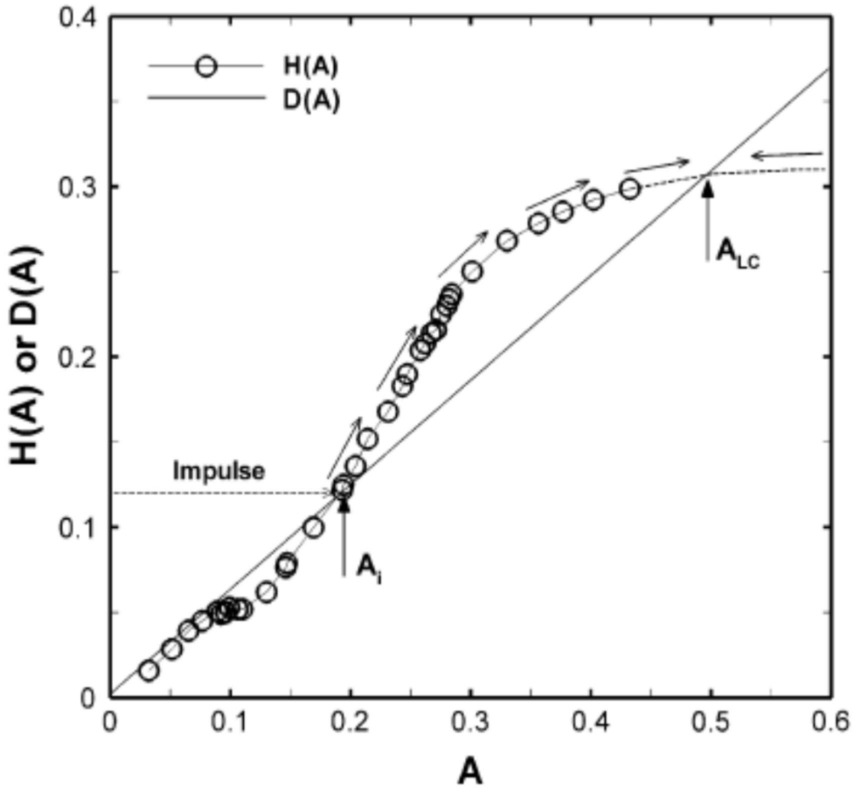
- **Asymmetries in the flame structure are more evident in this case**
- **Areas of large heat release rate near the walls at the base indicative of flame spreading all the way down to the dump plane**
- **A majority of the heat release rate occurs at the flame-wall interaction regions**

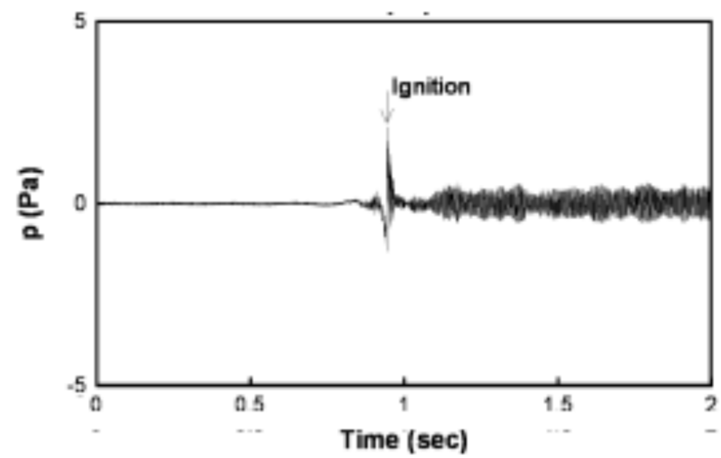
Analysis of horizontal slices (ϕ = 0.60)

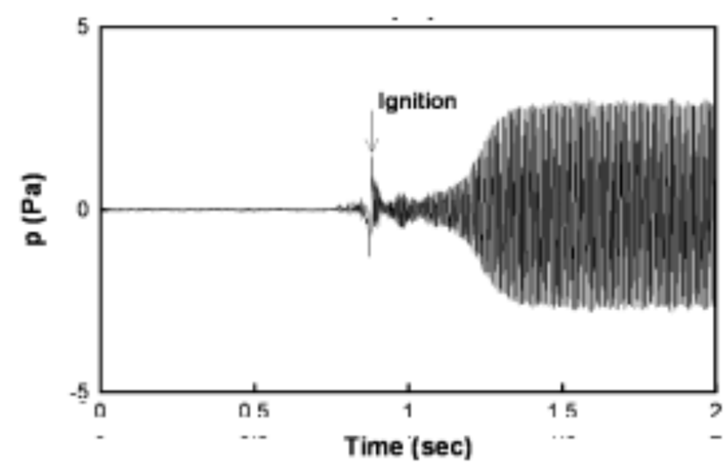


- **A majority of the heat release rate occurs at the flame-flame interaction regions**

The transient timescale, relative to other key timescales, may result in “triggering” of combustion oscillation







Kim and Hochgreb, 2012

Very limited data is available on the behavior of flames at different fuel splits except in the cases of flame piloting

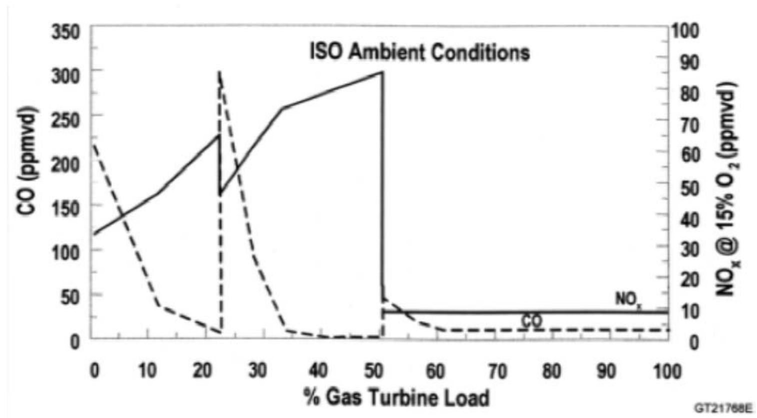


Figure 9. MS7001EA/MS9001E emissions - natural gas fuel

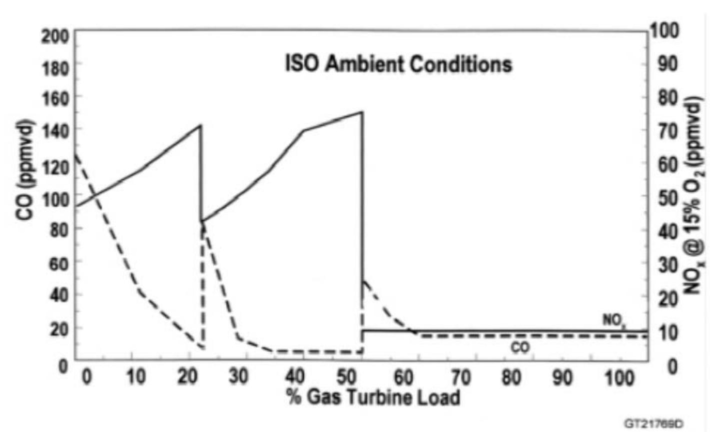
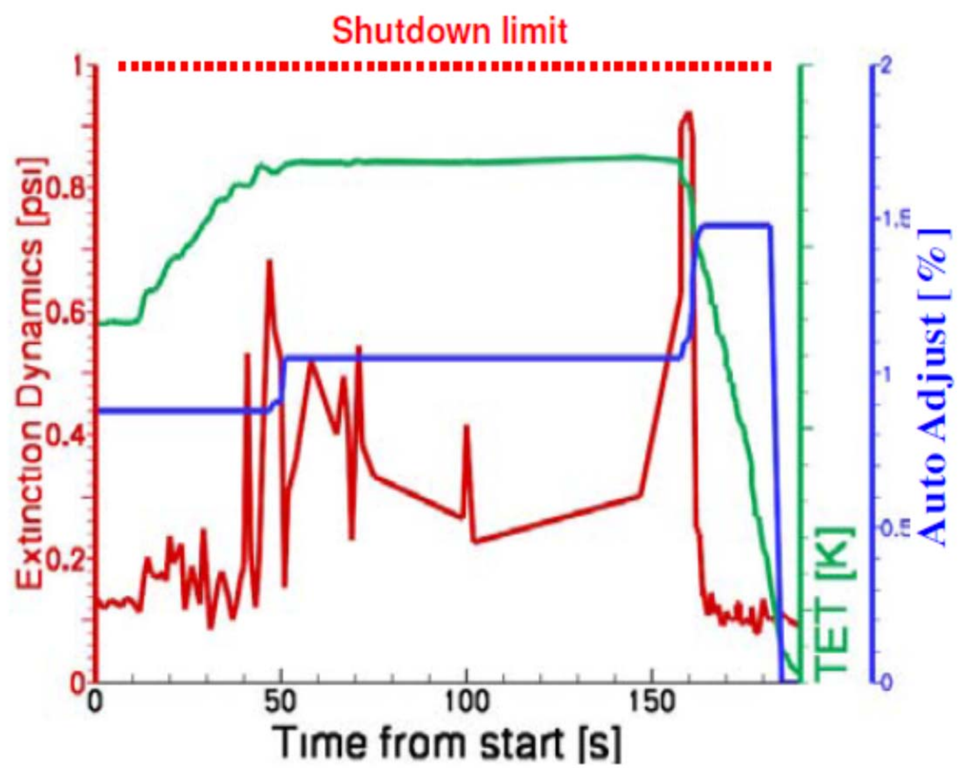


Figure 10. MS6001B emissions - natural gas

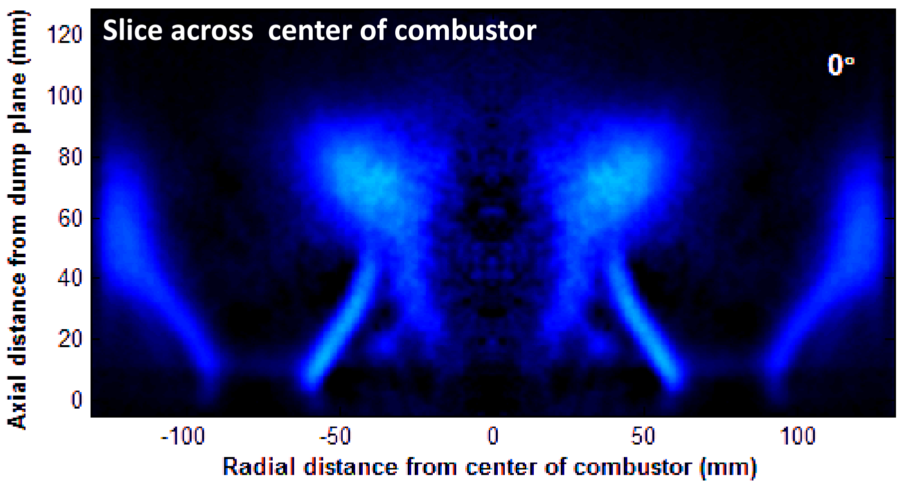


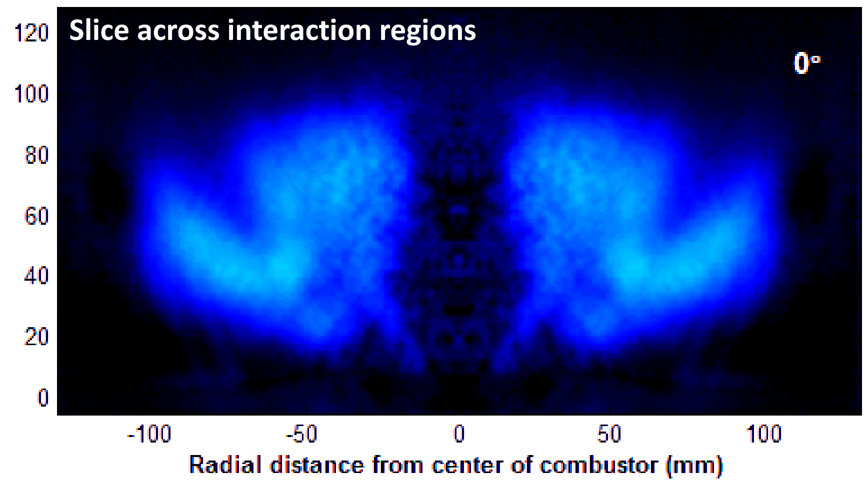
Transient operation of a Siemens SGT-200 (Bulat *et al.* 2007)

Source: Davis and Black, "Dry Low NO_x Combution Systems for GE Heavy-Duty Gas Turbines"

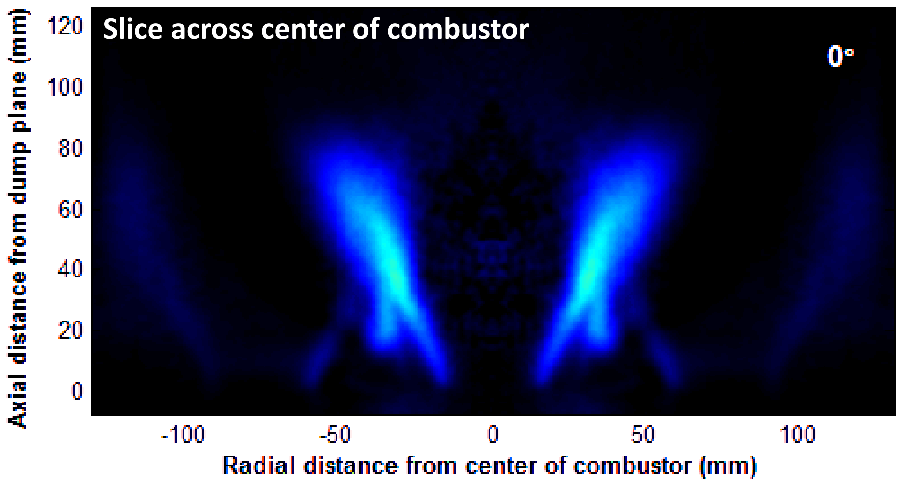
Data from our multi-nozzle combustor shows that fuel splitting changes flame structure and oscillation during instability

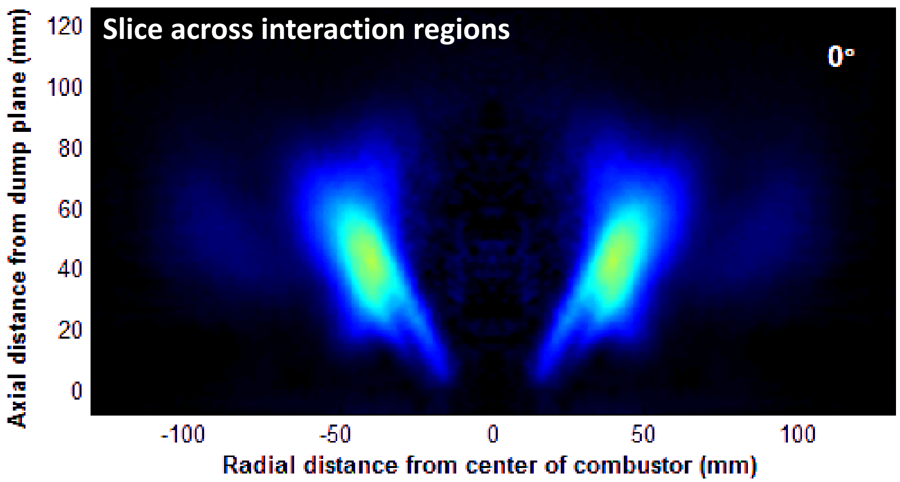
ϕ = 0.6 in all nozzles





ϕ = 0.5 in outer nozzles, ϕ = 0.8 in middle nozzle





The final area of interest is transients in fuel composition from pure methane to higher levels of propane and hydrogen

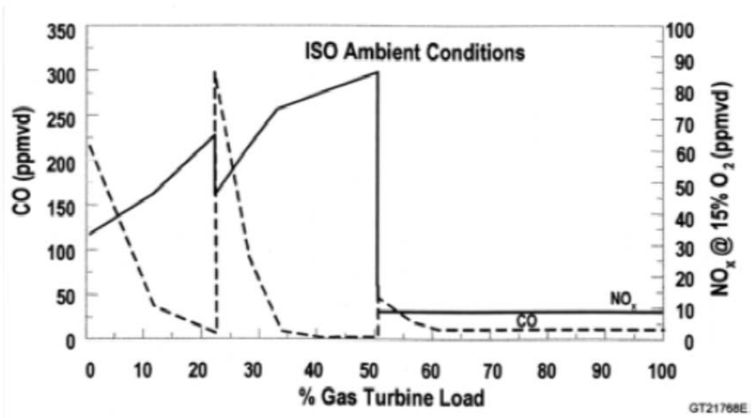


Figure 9. MS7001EA/MS9001E emissions - natural gas fuel

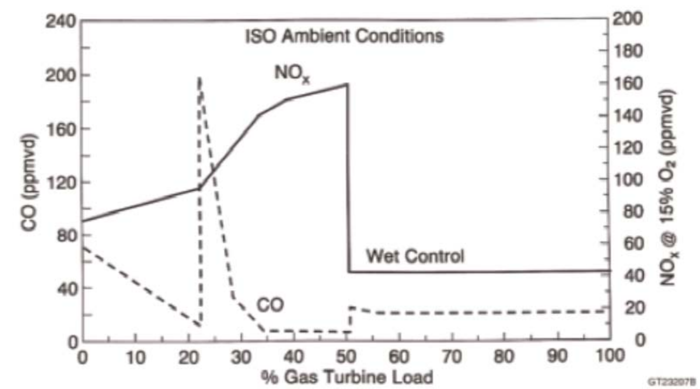


Figure 11. MS7001EA Dry Low NO_X combustion system performance on distillate oil

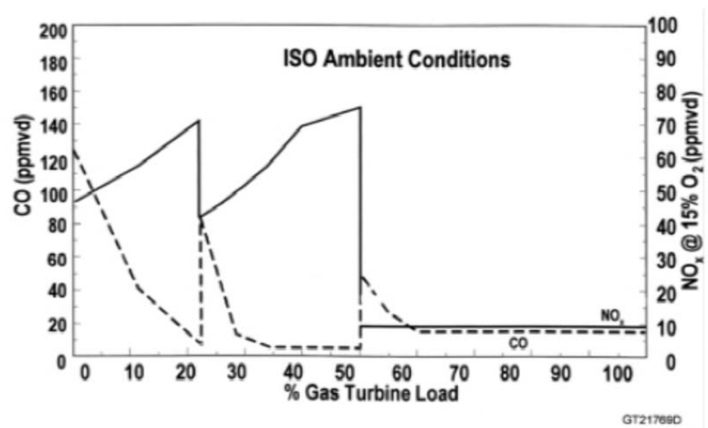


Figure 10. MS6001B emissions - natural gas

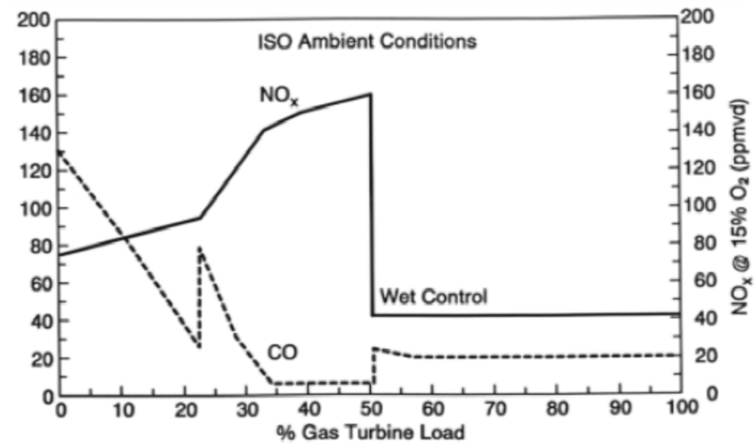


Figure 12. MS6001B emissions distillate oil fuel

Source: Davis and Black, "Dry Low NO_x Combution Systems for GE Heavy-Duty Gas Turbines"

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- —Project objective
- —Technical background
- —Technical approach
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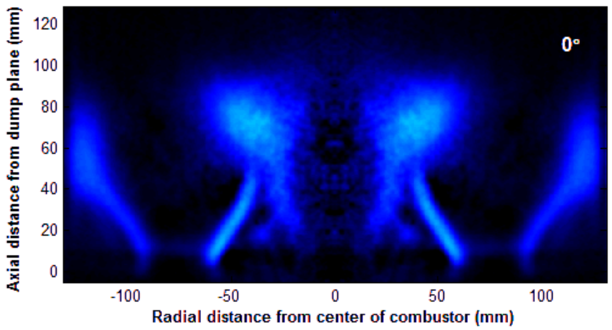
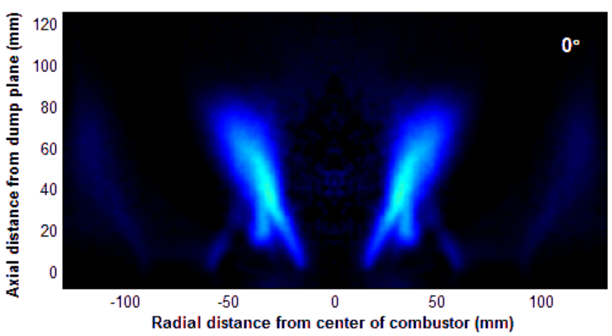
Three types of transients will be considered in the program that mimic the types of transients used in operational turbines

Fuel Splitting

ϕ = 0.6 in all nozzles

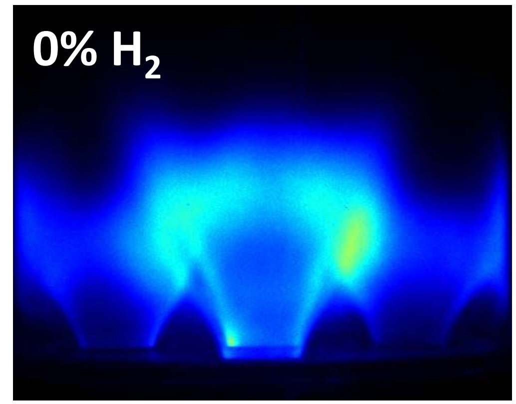


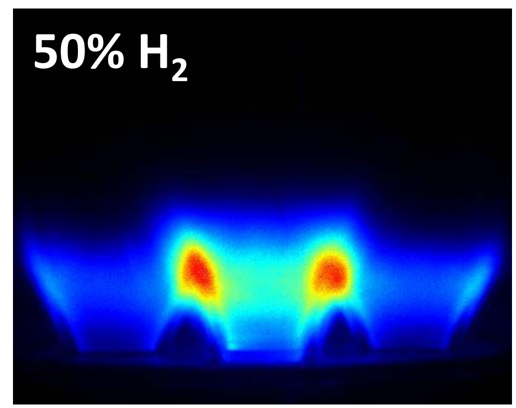
ϕ = 0.5 in outer nozzles,
ϕ = 0.8 in middle nozzle



Equivalence Ratio

Fuel Composition

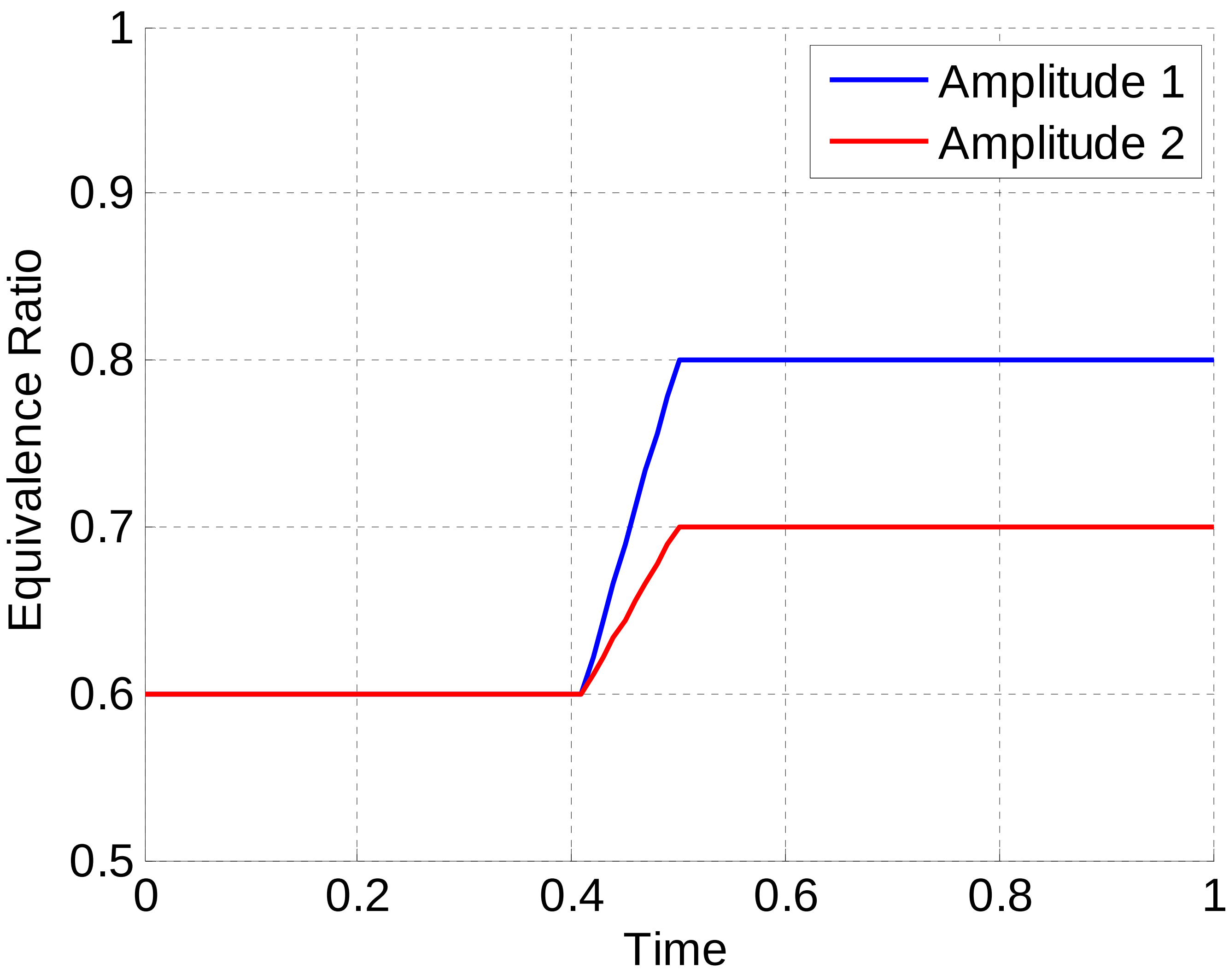




Images obtained from work done by Alex De Rosa (2011)

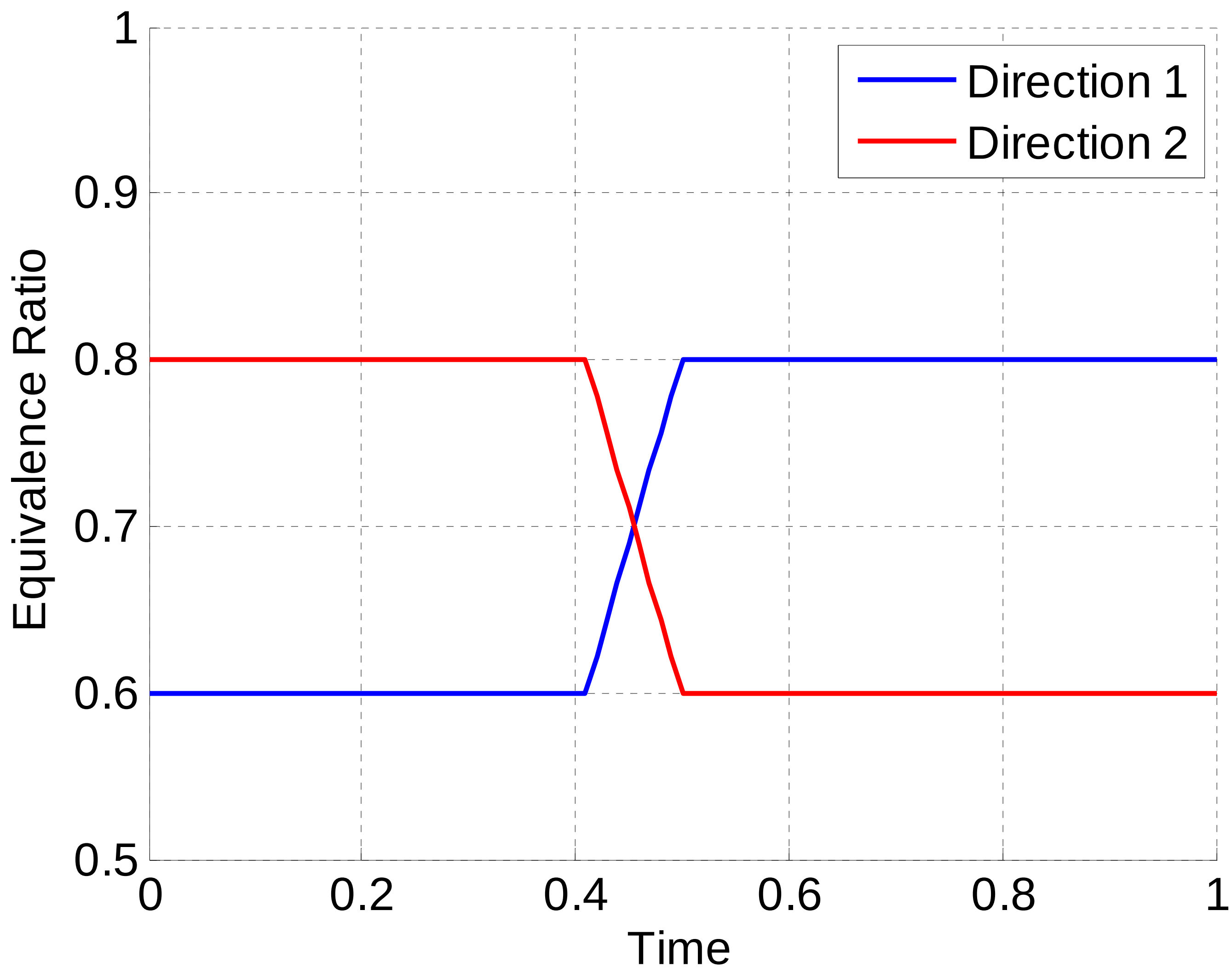
The transients will be quantified using three different metrics: *amplitude*, *timescale*, and *direction*

Amplitude



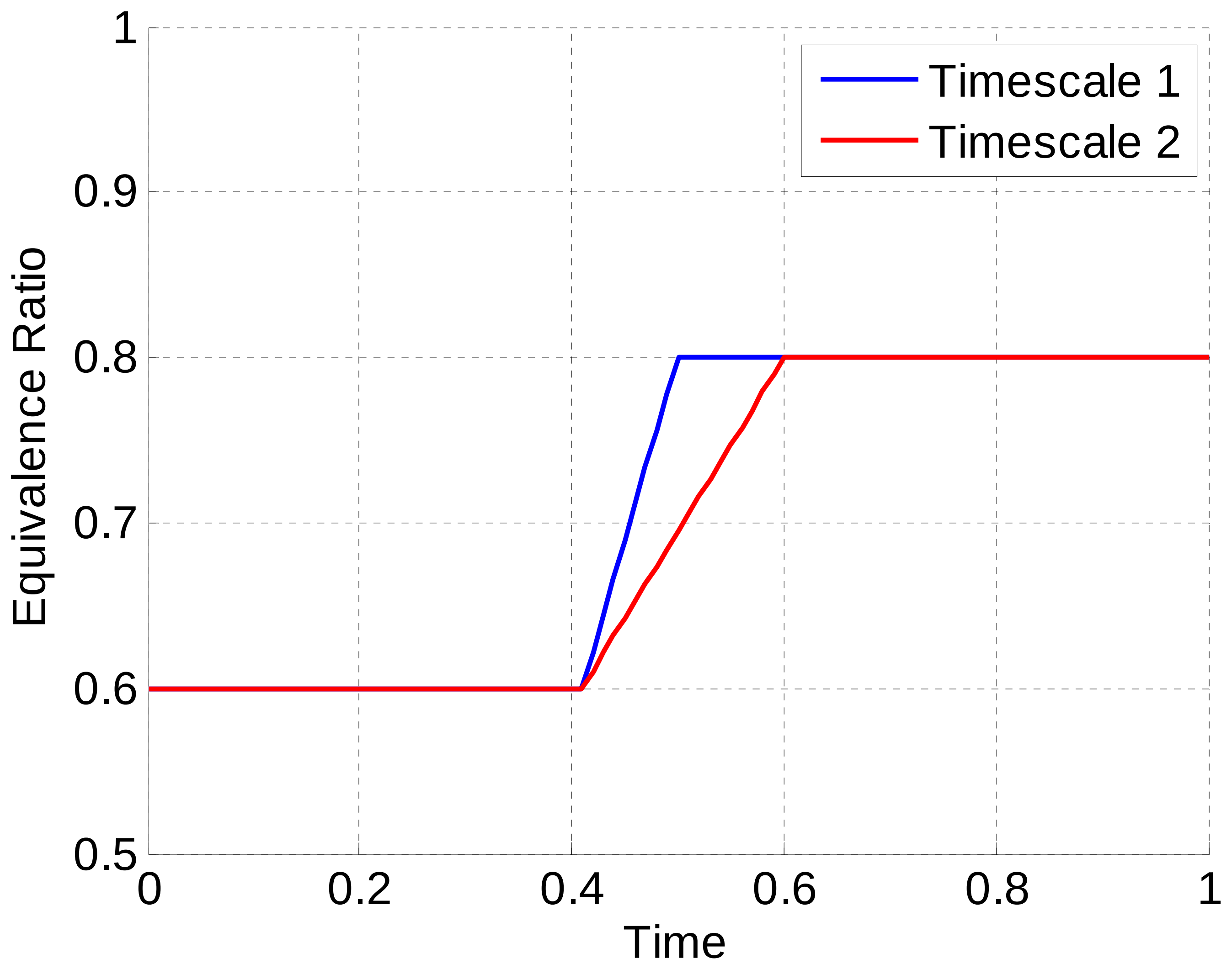
The transients will be quantified using three different metrics: *amplitude*, *timescale*, and *direction*

Direction

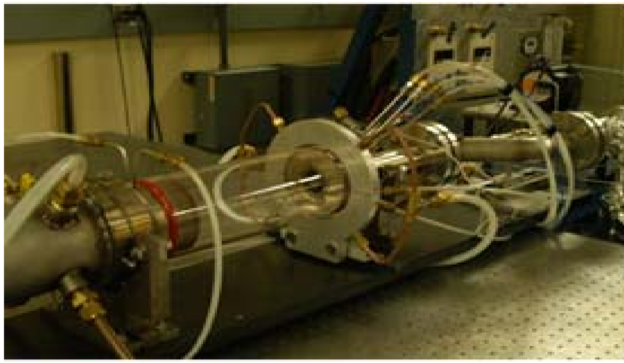


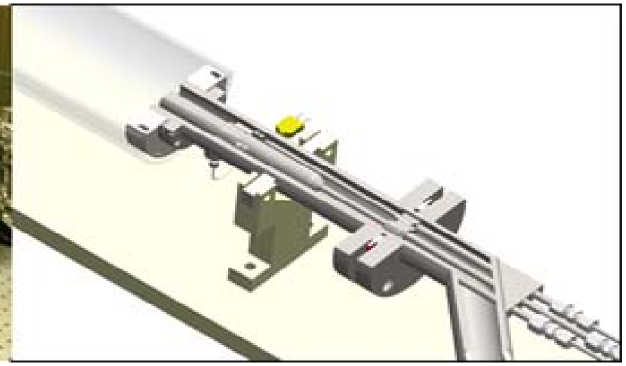
The transients will be quantified using three different metrics: *amplitude*, *timescale*, and *direction*

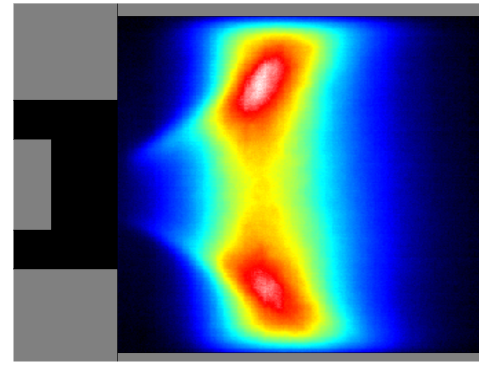
Timescale

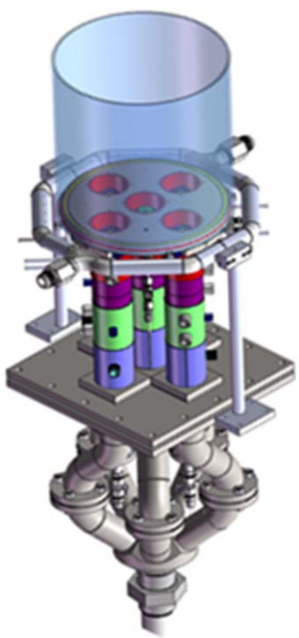


Experimental facilities include both a single-nozzle and multi-nozzle combustor, fuel splitting on multi-nozzle only









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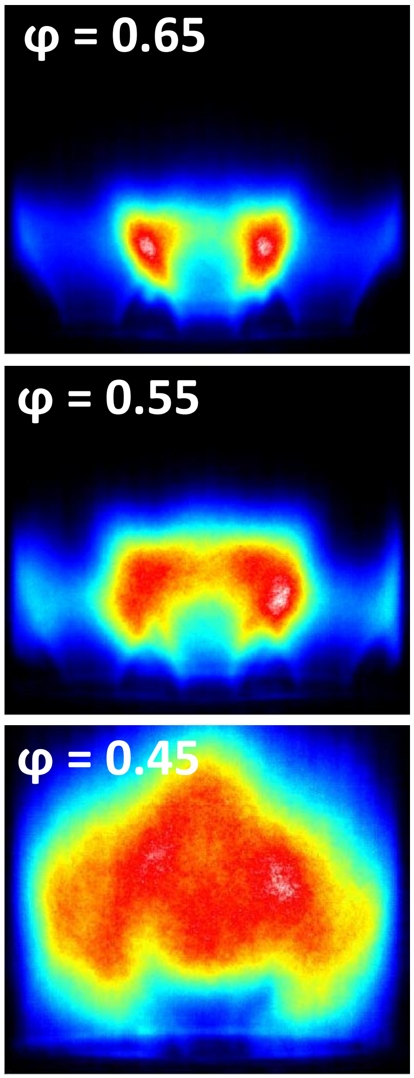
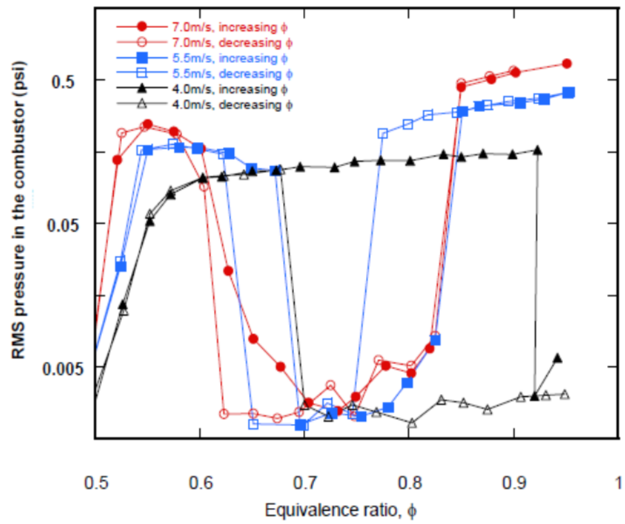
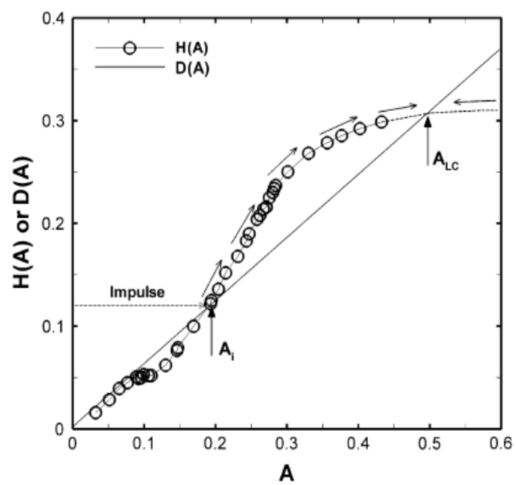
Project structure includes three stages of experimentation: mapping, transients, and quantification

<u>Mapping</u>



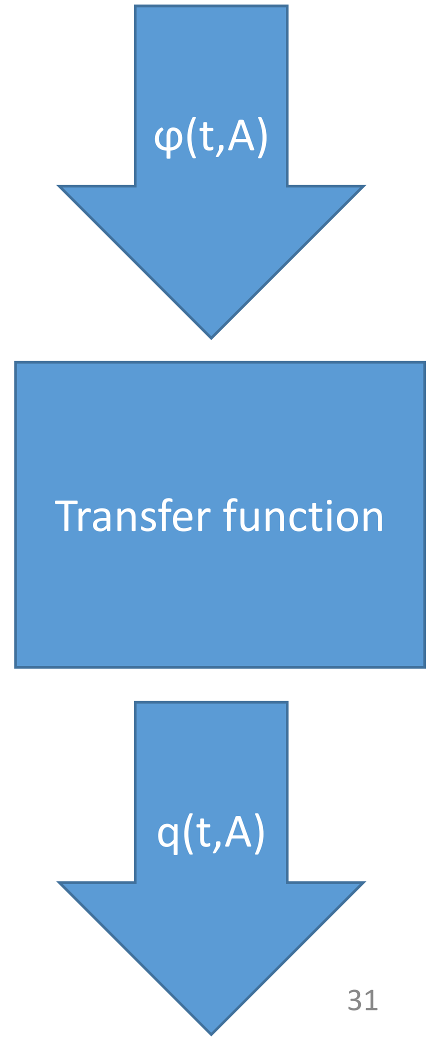
<u>Transients</u>





Kim and Hochgreb, 2012

<u>Quantification</u>



Milestones are distributed over three years with internships for graduate students at GE Global Research in two summers

Milestones	Quarter 1	2	3	4	5	6	7	8	9	10	11	12
Phase 1: Facility upgrades and diagnostic installation												
1. Updated facility design completed	•											
2. Updated facility installation completed		•										
3. Shakedown testing completed		•										
Phase 2: Combustor operational mapping												
4. Test matrix design	•											
5. Single-nozzle combustor map completed			•									
6. Multi-nozzle combustor map completed			•									
Phase 3: Testing of fuel splitting transients												
7. Testing of fuel splitting transients completed				•								
8. Report of fuel splitting transient results					•							
Phase 4: Testing of equivalence ratio transients												
9. Testing of equivalence ratio transients in multi-nozzle combustor completed						•						
10. Testing of equivalence ratio transients in single-nozzle combustor completed							•					
11. Report of equivalence ratio transient results from both combustors with comparison and analysis								•				
Phase 5: Testing of fuel composition transients												
12. Testing of fuel composition transients in multi-nozzle combustor completed									•			
13. Testing of fuel composition transients in single-nozzle combustor completed										•		
14. Report of fuel composition transient results from both combustors with comparison and analysis											•	
Phase 6: Development of prediction framework												
15. Integration of single-nozzle and multi-nozzle results for three transient operation types to identify commonalities in flow/flame results and precursor signals								•			•	
16. Development and implementation of signal processing techniques for utilizing precursors in prediction methods												
Phase 7 (optional): High-pressure testing												
17. Transient tests in high-pressure facility at GE Global Research											•	
18. Implementation of stability prediction framework in high-pressure tests using precursor analysis methods											•	
19. Comparison of high-pressure results with results from Penn State experiments												

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Project budget

CATEGORY	Budget Period 1 Costs	Budget Period 2 Costs	Budget Period 3 Costs	Total Costs	Project Costs %
a. Personnel	$94,641	$97,005	$99,436	$291,082	38.9%
b. Fringe Benefits	$20,281	$20,784	$21,309	$62,373	8.3%
c. Travel	$2,000	$2,000	$2,000	$6,000	0.8%
d. Equipment	$0	$0	$0	$0	0.0%
e. Supplies	$5,000	$2,000	$2,000	$9,000	1.2%
f. Contractual					
Sub-recipient	$0	$0	$0	$0	0.0%
Vendor	$0	$0	$0	$0	0.0%
FFRDC	$0	$0	$0	$0	0.0%
Total Contractual	$0	$0	$0	$0	0.0%
g. Construction	$0	$0	$0	$0	0.0%
h. Other Direct Costs	$33,322	$78,886	$80,272	$192,480	25.7%
Total Direct Costs	$155,244	$200,675	$205,017	$560,936	$1
i. Indirect Charges	$61,813	$61,748	$63,248	$186,809	25.0%
Total Project Costs	$217,057	$262,423	$268,265	$747,745	$1

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Project Management Plan

- Task 1 – Project management and planning
- Task 2 – Modification of current experimental facility with monitoring diagnostics and new hardware for transient control
- Task 3 – Map combustor timescales at target operating points
- Task 4 – Design of transient experiments
- Task 5 – Fuel split transients
- Task 6 – Equivalence ratio transients
- Task 7 – Fuel composition transients
- Task 8 – Data analysis and determination of prediction/quantification framework

Risk Management Plan

- Risk 1 – Test matrix repeatability
  - Randomized test matrix and baselining methodologies
- Risk 2 – Combustor stability and safety
  - Close coordination with PSU safety office and combustor monitoring
- Risk 3 – Flame flashback
  - Combustor monitoring and test matrix design for H_2 addition in small increments
- Risk 4 – Programmatic risks
  - PI coordination on shared resources and project timeline
- Risk 5 – Cost-share implementation
  - Continual coordination with GE Global Research throughout duration of project will keep work at PSU tied to GE, making internships more fruitful

Questions?