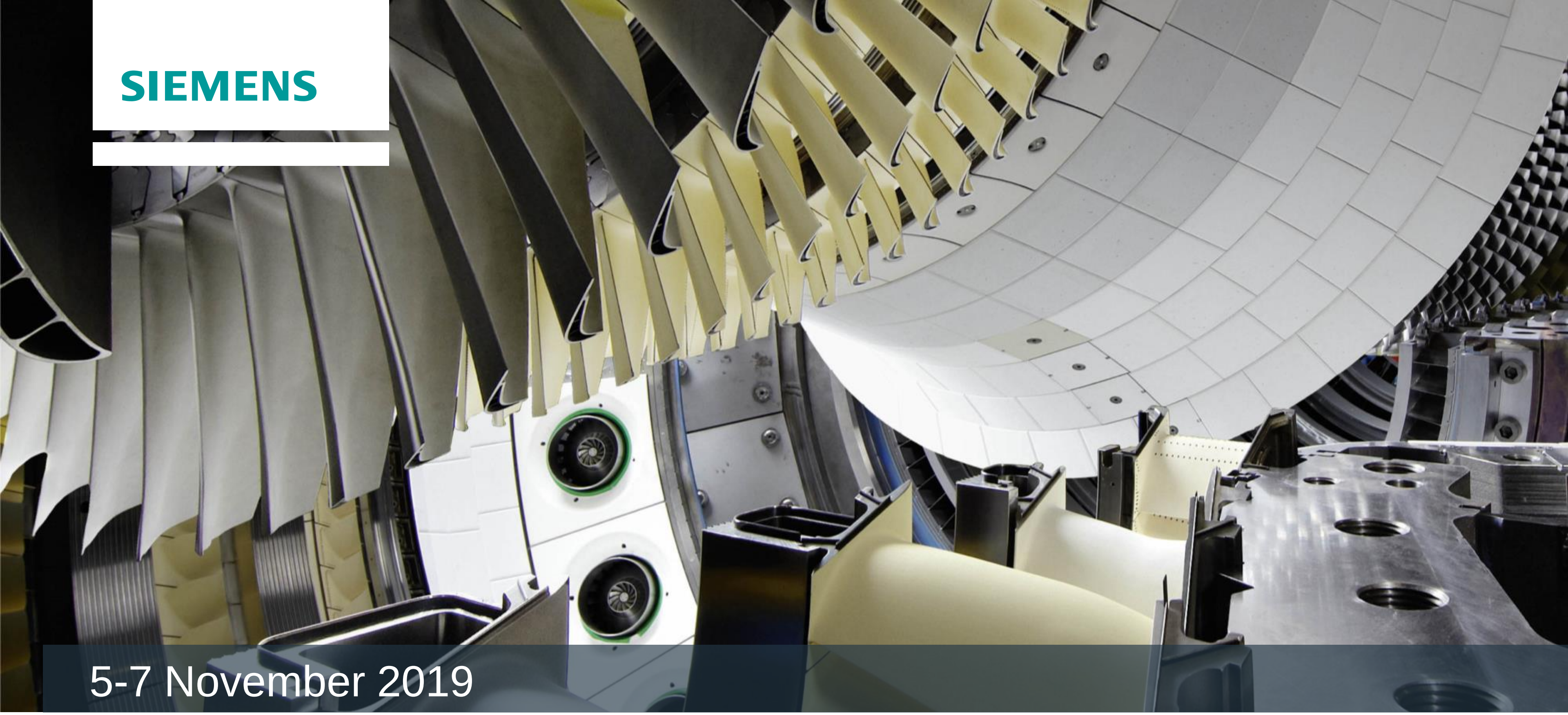

5-7 November 2019

Extremely Low NOx Axial Stage Combustion System

Andrew North

http://siemens.com/energy/power-generation/gas-turbines

Extremely Low NOx Axial Stage Combustion System

Presentation Outline

1. Technology Background
2. NOx reduction enablers
3. Obstacles/hurdles
4. Co-axial stage technology introduction
5. Combining co-axial staging with the extremely low NOx axial stage
6. Overheating risk mitigation
7. Small gas turbine engine testing plan
8. Thermoacoustics risk mitigation plan
9. Conclusions

Extremely Low NOx Axial Stage Combustion System

Background – Technology Introduction and Current Development Status

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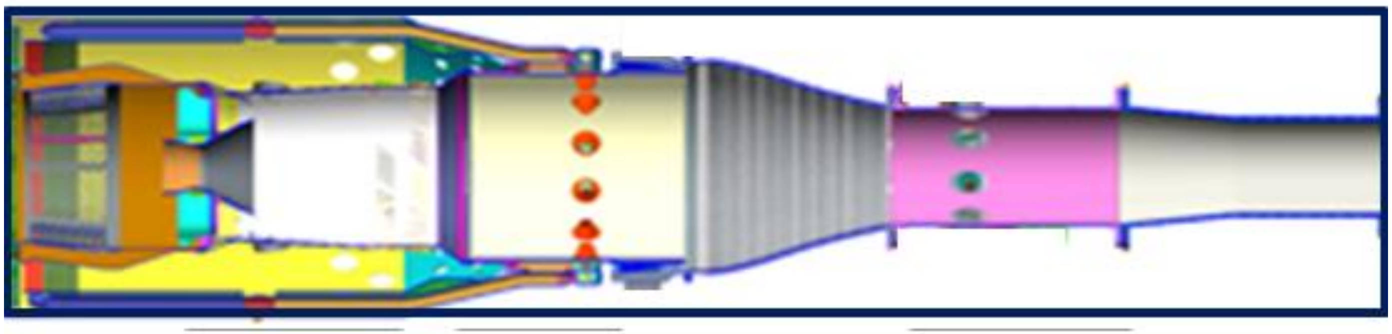
Proof of Concept Hardware



Head End

Standard Residence Time Axial Stage

Ultra Low Residence Time Axial Stage

Accelerated cross flow enables:

- Shortened flame
- Further reduced residence time
- Increased pre-flame mixing

- **Proof of concept hardware demonstrated potential for high efficiency GT with low NOx emissions through ultra low residence time secondary stage**
- **Enabler for 65% efficiency**

Substantial improvement in NOx emissions demonstrated

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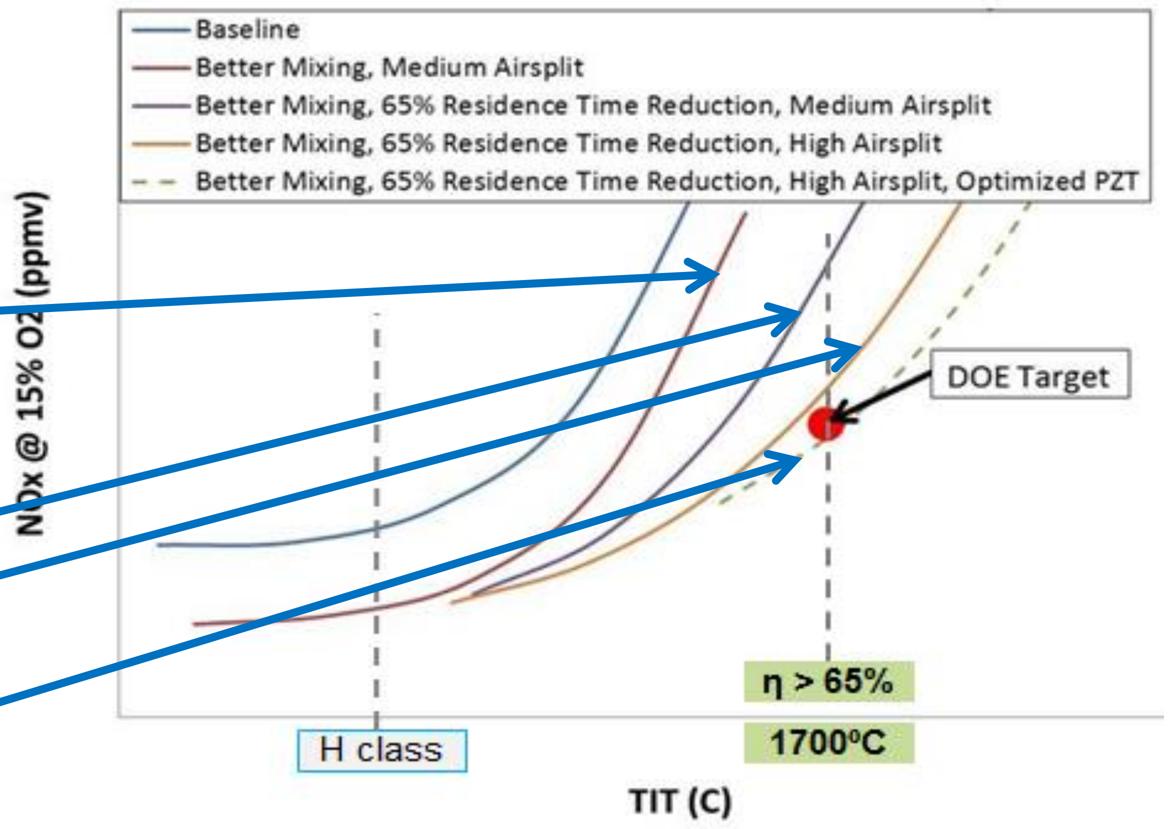
Background – Levers for Increased Firing Temperature with Low NOx

NOx Reduction Enablers:

1. **High rate of entrainment of dilution gases into axial stage flame**
2. **Minimal axial stage residence time**
3. **High air-split**
4. **High performance primary zone combustor**



Combined approach puts 65% CC efficiency target within reach

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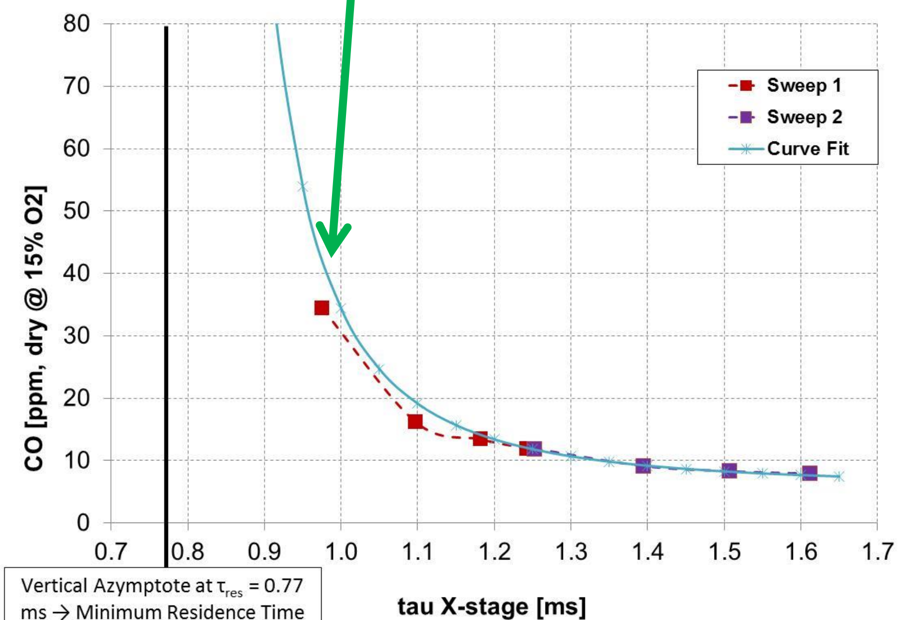
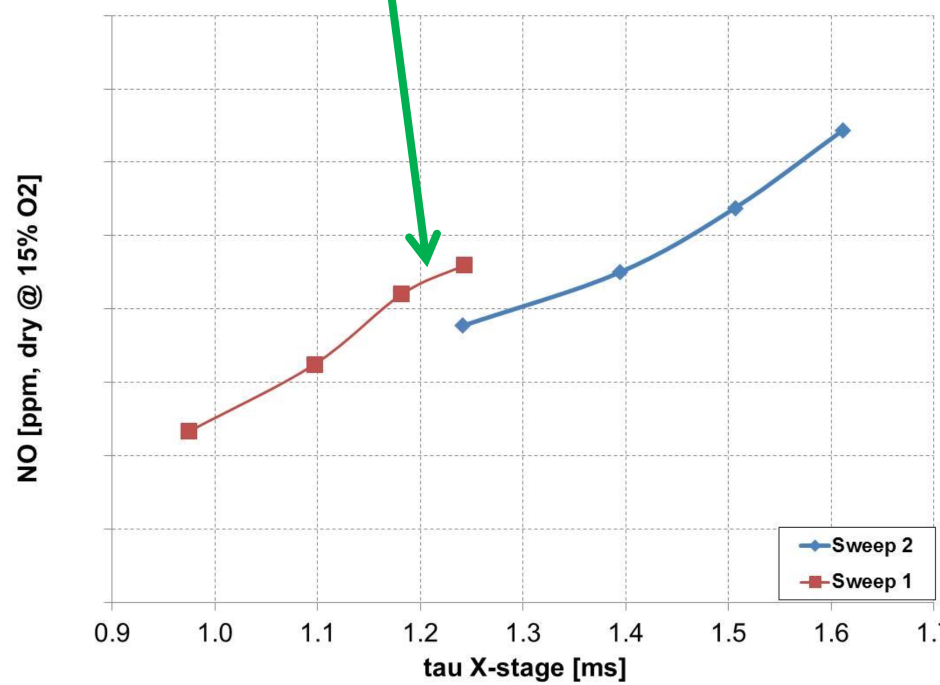
NOx Reduction Phenomena Utilized

CO increases with decreasing residence time while NOx decreases → critical to identify minimum residence time



Vertical Azymptote at τ_{res} = 0.77 ms → Minimum Residence Time Limit for complete Burnout



A key enabler for low NOx emissions at high firing temperatures is to minimize the X-stage residence time – CO trend versus residence time used to determine residence time limit

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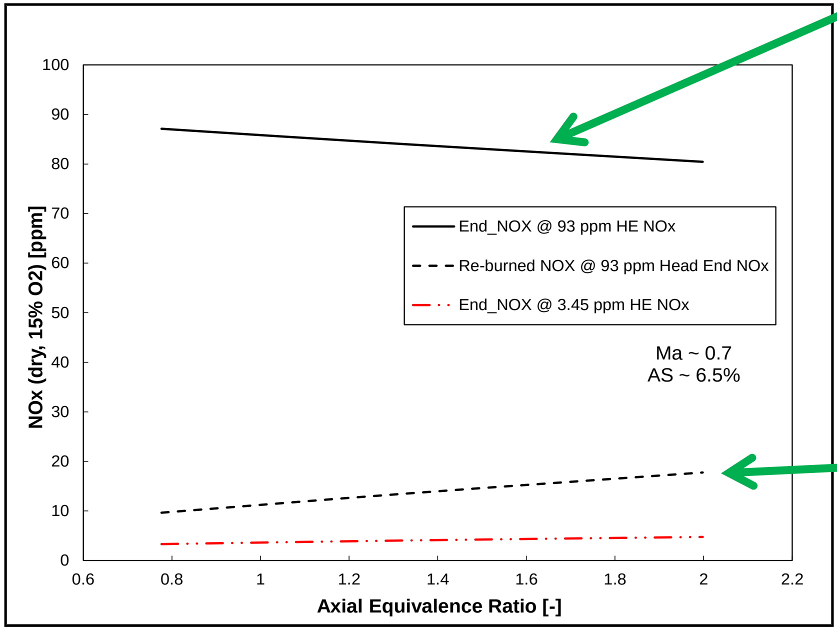
NOx Reduction Phenomena Utilized – NOx Re-burning

The new Glarborg mechanism was used to computed NOx as a function of axial stage equivalence ratio showing the NOx re-burning phenamena



Total NOx is going down as the fuel flow to the axial stage increases and the turbine inlet temperature increases

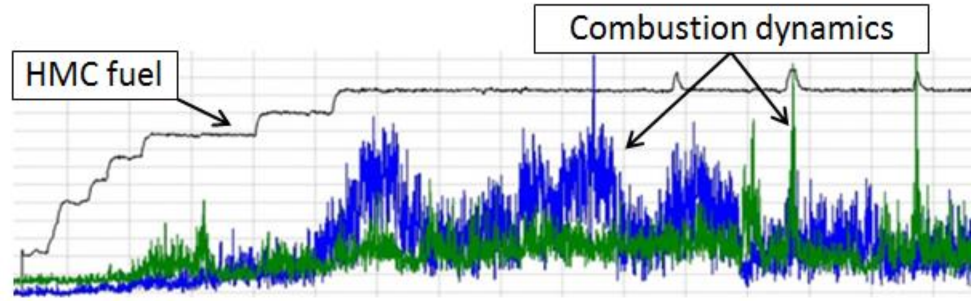
Amount of NOx which was chemically removed, originally produced in the primary zone, by the axial stage

NOx re-burning is believed to be one of the key phenomenon contributing to the demonstrated extremely low NOx emissions

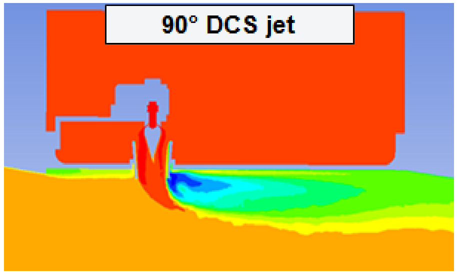
Extremely Low NOx Axial Stage Combustion System
Obstacles Tackled in DOE Phase I Work

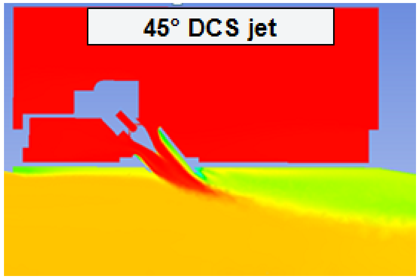
Upcoming Milestones Prior to Engine Readiness:

1. **High combustion dynamics when axial stage fuel nears optimum level**
2. **High pressure loss across axial stage flame**



	90˚ Injectors	45˚ Injectors
Total Pressure Drop	10.5%	7.9%
Static Pressure Drop	30%	27.2%

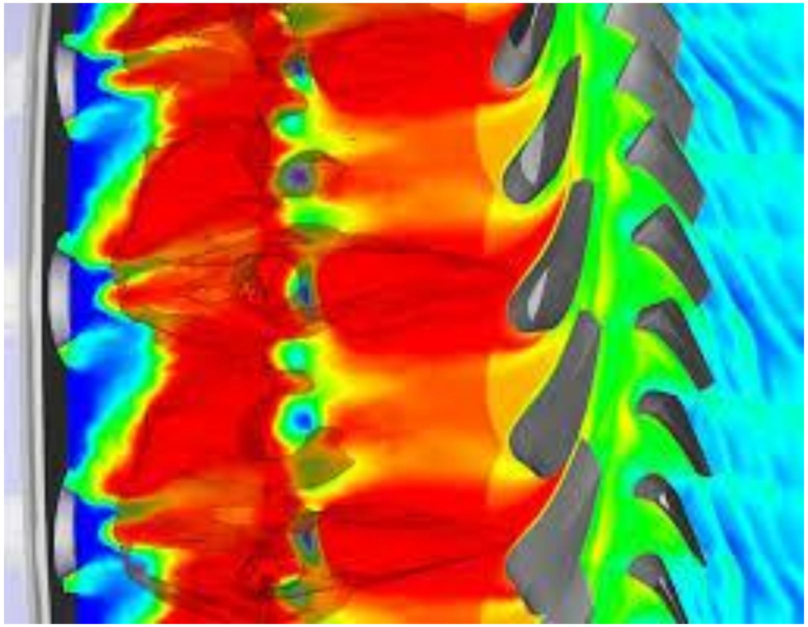




Remaining obstacles necessitate additional design variants for mitigation while maintaining high performance characteristics

Extremely Low NOx Axial Stage Combustion System
Obstacles Tackled in DOE Phase I Work

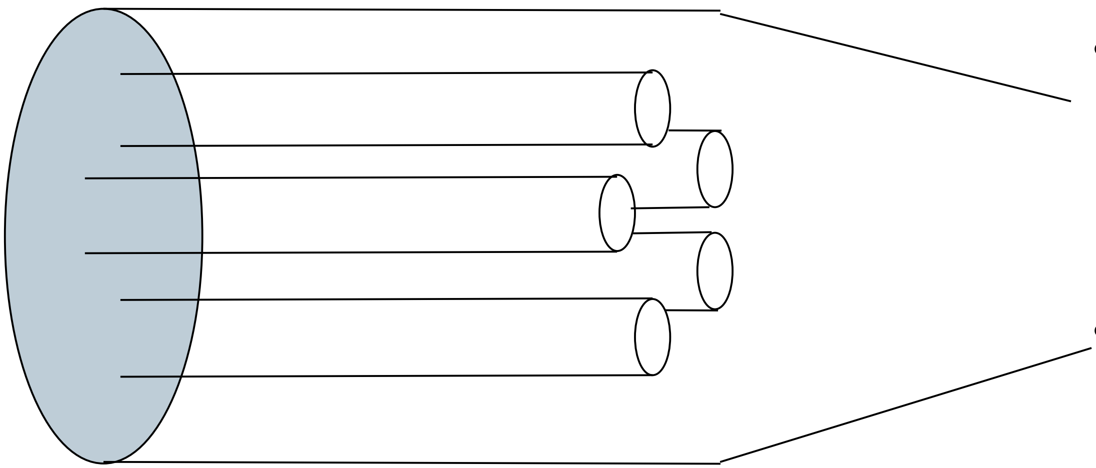
- It is difficult to route liquid fuel to the axial stage when it is positioned so far downstream
- Injection so late could lead to aeromechanical risks in exciting harmonic frequencies of the first turbine blade section
- The significant amount of risks and hurdles leads to a potentially long time to market for the technology



CFD Result of Oscillating Temperatures Contacting the Turbine Blade

Modifications to the implementation of the technology concept are needed for engine realization

Extremely Low NOx Axial Stage Combustion System
Introduction of the Co-Axial Stage



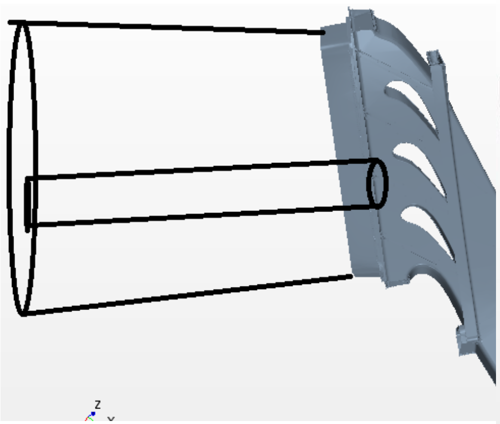
Modular head end combustor with 5 co-axial stage tubes added

- Has the benefits of the axial stage in a simpler package that will lead to a faster time to market
- Thermoacoustics will be reduced due to reduced oscillations of the flame near the axial stage tube exit
- Fuel source near the head end facilitates liquid fuel operation

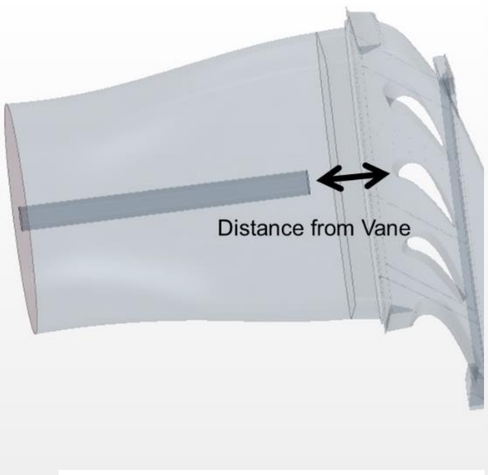
The co-axial stage technology mitigates many of the risks and hurdles central to the original low residence time axial stage technology

Extremely Low NOx Axial Stage Combustion System

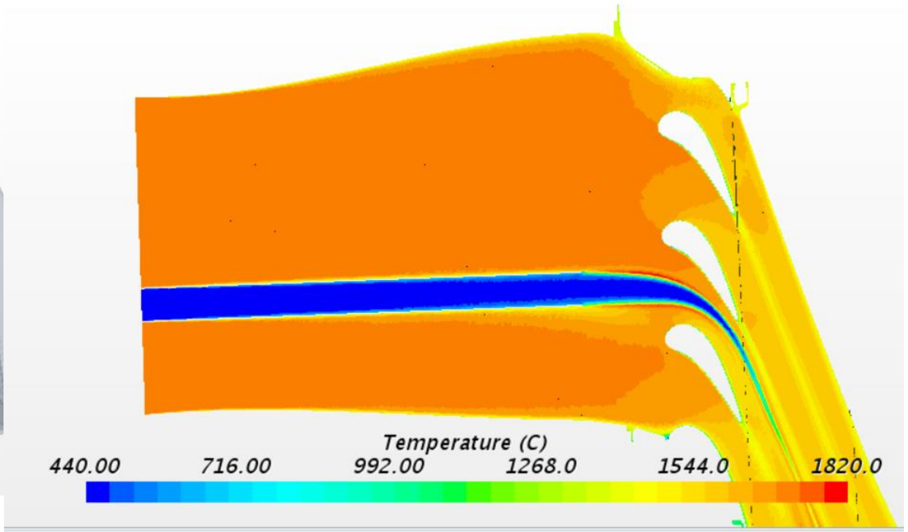
Combining Co-Axial Stage and Low NOx Axial Stage Technologies



Injection Just Upstream of Vane



CFD Study Parameterized Distance From Vane



Combustion Occurs Primarily Downstream of the Vane

- Late injection achieves similar NOx performance as previously demonstrated, but with additional advantages of co-axial staging
- CFD study looks at how late injection can be achieved with acceptably low CO emissions

This unique new technology realizes the best advantages from co-axial staging and the extremely low NOx axial stage technologies

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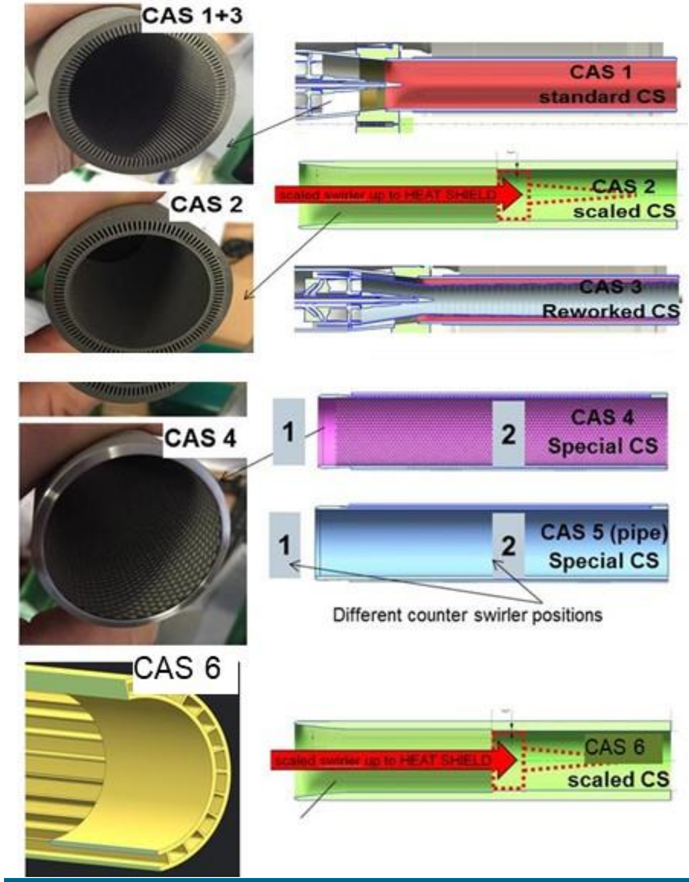
Extremely Low NOx Axial Stage Combustion System

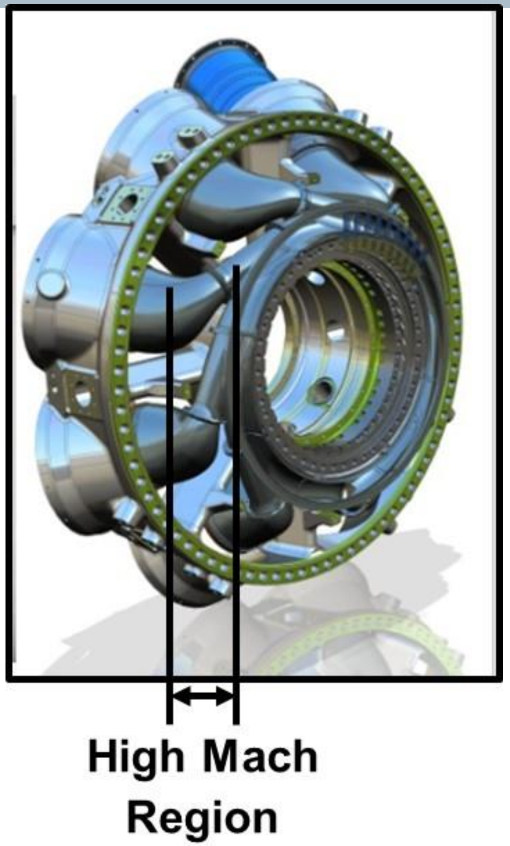
Resolving the Risk of Overheating Co-Axial Stage Tube



- The long tube surrounded by hot combustion gases from the primary zone poses the risk of overheating and potentially causing flashback
- Several cooling design concepts were devised and subsequently compared via low order modeling tools and CFD to determine the best designs to use for testing
- Many of the designs proved viable and resolved the overheating risk

By resolving the overheating risk via advanced wall cooling designs, we were able to make the co-axial stage a viable technology

Extremely Low NOx Axial Stage Combustion System
Accelerated Full Engine Testing Plan



- The SIEMENS advanced transition has been redesigned for inclusion into one of SIEMENS small gas turbines
- The extremely low NOx axial stage injectors can now be included in a full engine testing environment in an accelerated fashion
- Full engine testing will be conducted for validation of the whole engine system

The strategy to conduct testing in a small gas turbine environment allows the technology to be tested and validated in a full engine setting early in the development process

Combustion Dynamics at High Power Density

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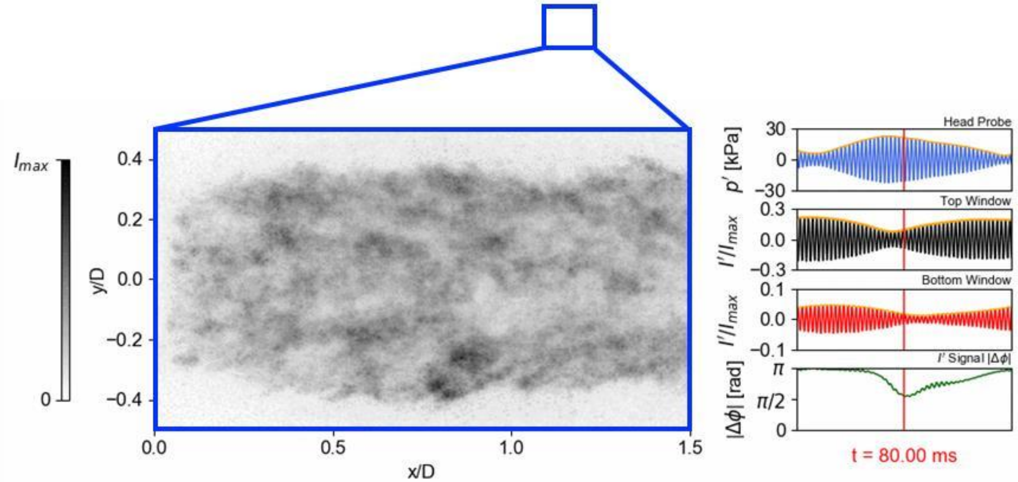
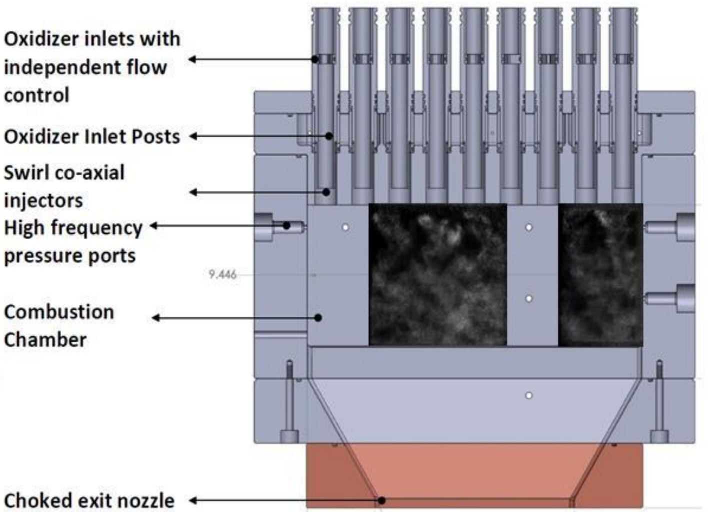
Self-Excited Instability Experiments at Purdue



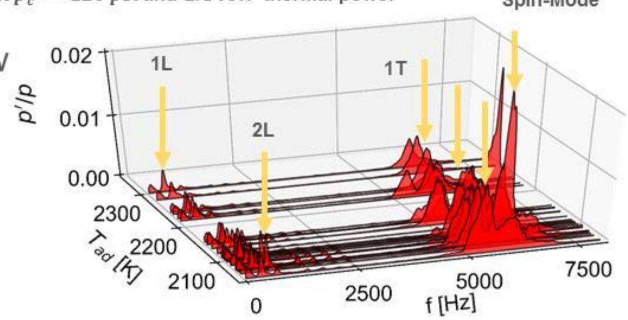
Single element, fully-premixed, air/methane flame at $p_c = 120\ psi$ and $1.5\ MW$ thermal power

- ○ Multi-element rocket combustors have exhibited self-excited instabilities in array configurations
- ○ Wide range of propellants, injector configurations, geometries, chamber pressures, instability amplitudes, and frequencies



9 element, O2/methane, swirl co-axial combustor ($p_C \approx$ 145 psi, 1T ≈ 2.6 kHz)

- ○ Single-element combustors show three distinct instability regimes:
  - 1L instability ~370 Hz [p' = 0.8-1.3%]
  - Intermittent 1L and 1T instability behavior [p' = 2-6%]
  - Spinning instability [p' = 7-10%]



Planned Thermoacoustics Mitigation Testing Approach

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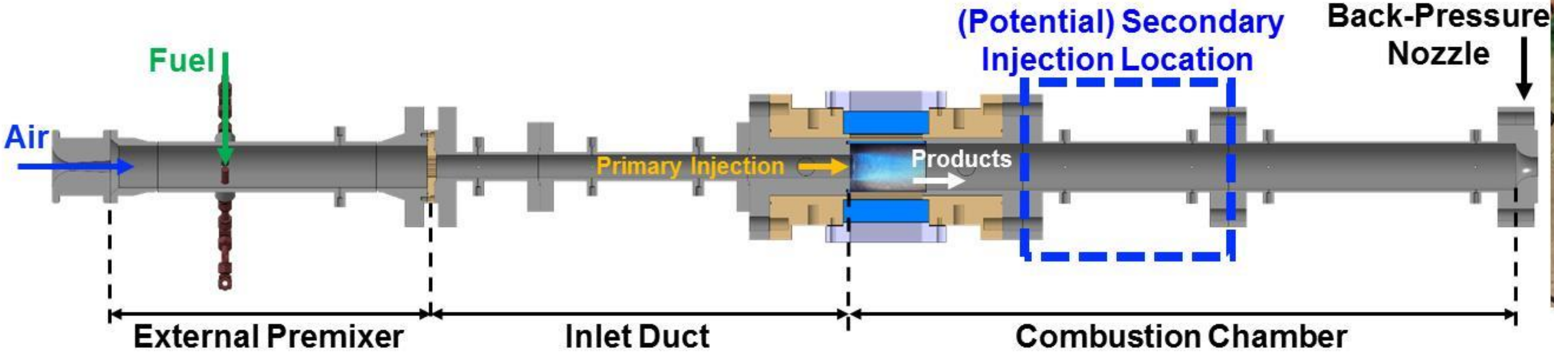
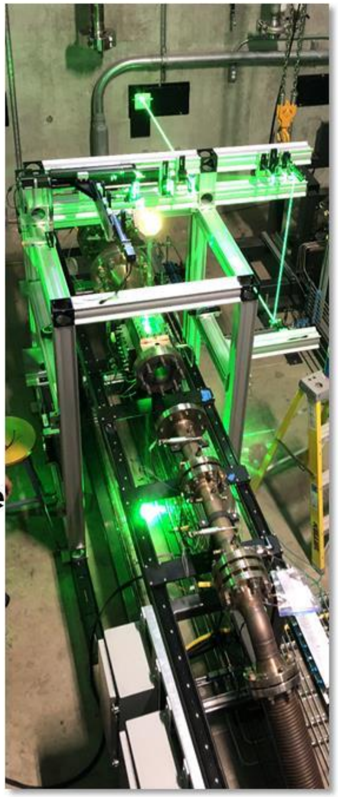
Axially-Staged, High-Pressure Combustion Dynamics Experiment

- Objectives:
  - Develop an experiment to study combustion dynamics in a canonical staged combustion system, at engine-relevant flame conditions.
  - Replicate the complex instability coupling mechanisms that manifest intermediate and high-frequency dynamics with realistic acoustic and hydrodynamic scales
- Requirements:
  - 10 bar mean chamber pressure and 1-2 MW thermal power.
  - Hardware modularity to accommodate variation in 1) cross-flow Mach number at secondary injection, 2) Axial location of secondary injection, and 3) flow angle of secondary injection.
  - Diagnostics: dense array of high-frequency pressure transducers, high-speed chemiluminescence imaging (20-100 kHz), high-speed PIV (10-100 kHz), and high-speed PLIF (10-40 kHz)





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Conclusions

1. The next generation axially staged combustion system has demonstrated the potential to enable 65% CC efficiency with < 25 ppm Nox
2. This technology has now been modified to include the co-axial stage concept in resolving many of the risks identified during testing
3. Future testing will include small gas turbine tests for faster iterations
4. Thermoacoustics risks will be mitigated by studying the problem in lab scale at Purdue University

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Thank You