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Investigation of Ammonia for Combustion Turbines (IACT) - Summary DE-FE0032172

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Investigation of Ammonia for Combustion Turbines (IACT)

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- Goal - develop advanced combustor technology to utilize ammonia as a zero-carbon fuel for power generation applying an iterative physics, computational, and experimental approach resulting in a pilot combustor design validated through tests
- Testing Scaled Combustor
  - Design using updated mechanism/ validated model
  - NOX Target: 20 ppm at 15% O_2
  - High combustion efficiency
  - Stable flame (no blowoff)
- Challenges with ammonia
  - Safety considerations with ammonia
  - Ammonia ignition and flameholding
  - NOx generation

	Methane	Hydrogen	Ammonia
Lower Heating Value (LHV)	Mass: 50 MJ/kg (21,500 BTU/lb) Volume: 915 BTU/scf	Mass: 120 MJ/kg (51,600 BTU/lb) Volume: 275 BTU/scf	Mass: 18.6MJ/kg (8,000 BTU/lb) Volume: 365 BTU/scf
Flame Speed (S_L)	37 cm/s (1.2 ft/s)	291 cm/s (9.5 ft/s)	7 cm/s (0.23 ft/s)
Flame Temperature (T_{ad})	1950°C (3542°F)	2110°C (3830°F)	1800°C (3272°F)

Comparison of fuel characteristics

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ELECTRIC POWER RESEARCH INSTITUTE
UCF UNIVERSITY OF CENTRAL FLORIDA
Georgia Tech
CRAFT Tech
LCRI LOW-CARBON RESOURCES INITIATIVE

IACT Plan & Key Roles

Schedule: 9/2022-1/2026; Funding: $4.2M

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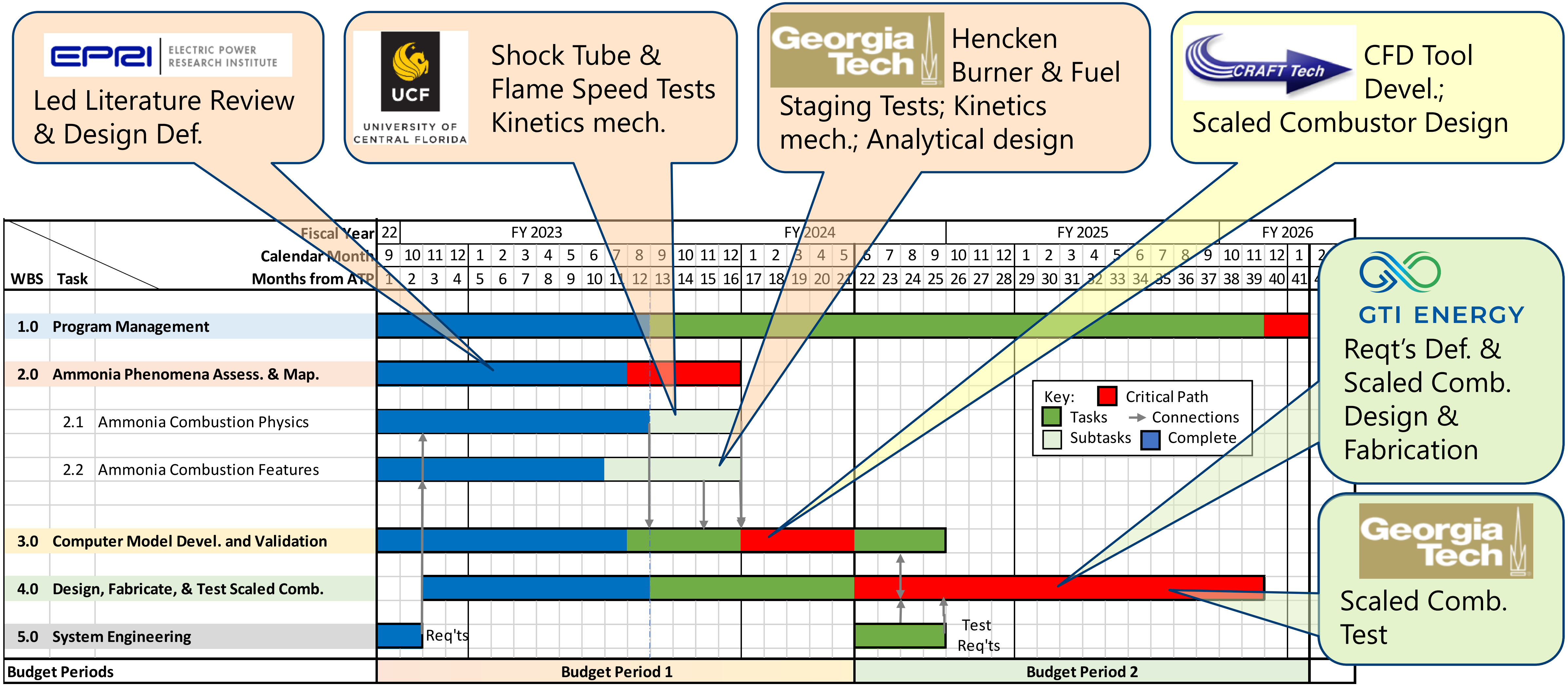
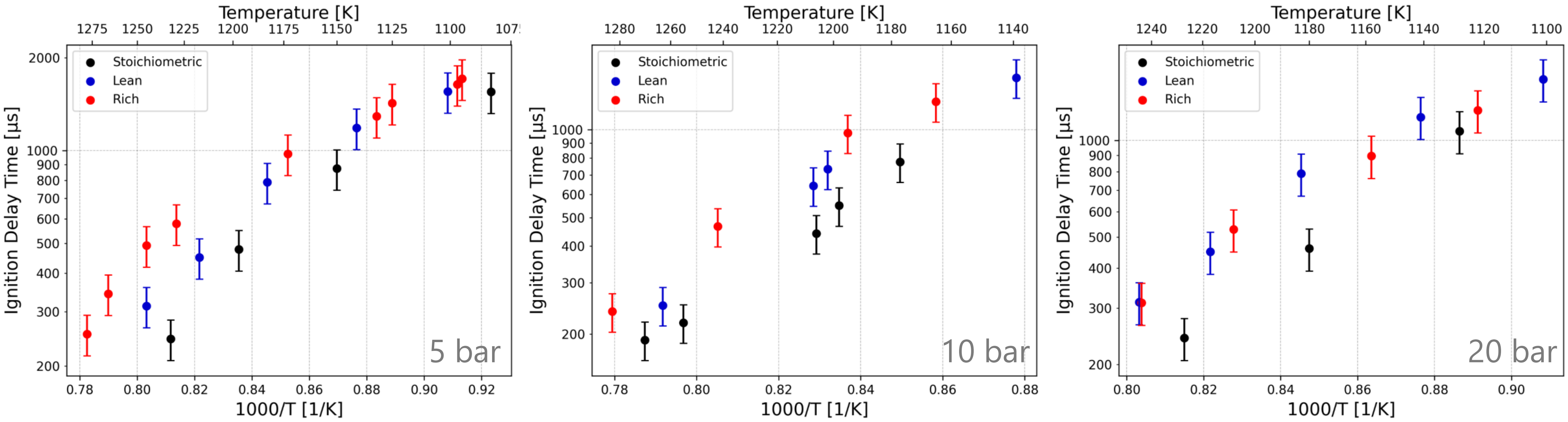


IACT Project Flow

- Literature search to understand SOA and identify knowledge gaps
  - *Define test conditions to fill gaps*
- Fundamental NH_3 & NH_3+H_2 combustion physics testing
  - *Generate improved detailed and reduced kinetics*
- Develop computational CFD design tool implementing updated mechanisms
  - *Apply combustion physics knowledge and design tool*
- Design and test scaled combustor

70/30 NH_3/H_2 IDTs
Also Pure Ammonia and 50/50 Mix

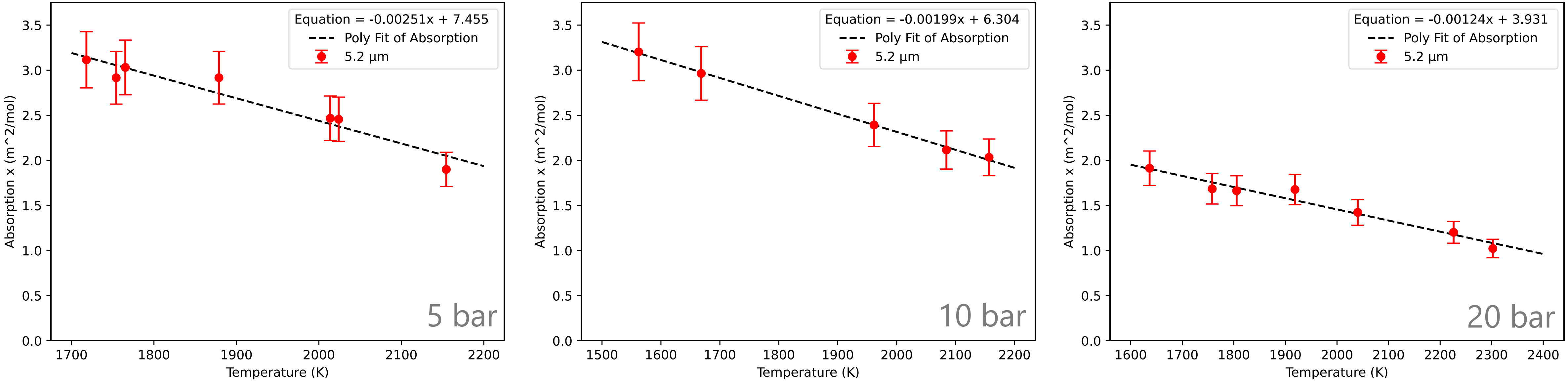


- At 5 bar and 10 bar, ignition order follows rich<lean<stoichiometric. However, at lower temperatures, all mixtures ignite nearly at same time.
- At 20 bar, lean and rich mixtures ignite slower than stoichiometric mixtures.

- IDT data new and will be utilized to develop a **validated ammonia/hydrogen chemical kinetic model for gas turbine operating conditions**

NO Cross Sections

- For measuring species time histories, individual species absorption needs to be characterized.
- **Plan to measure NO, NO2, NH_3 and H_2O species time histories during NH_3/H_2 combustion at 5, 10 and 20 bar.**
- NO absorption characterization results are shown below:



- NO absorption cross-section is found to decrease with increase in temperature.
- NO absorption cross-section is found to decrease with pressure.
- A linear fit was developed at 5, 10 and 20 bar to fit experimental data.

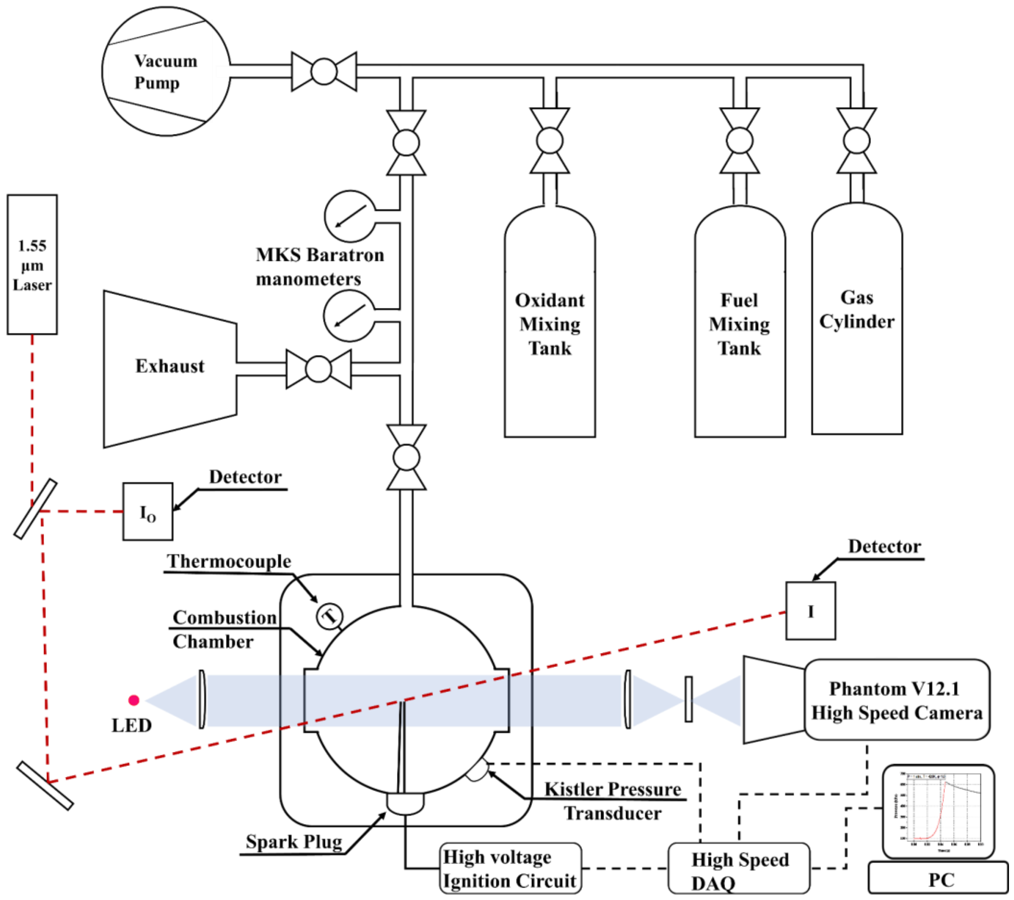
Flame speed measurements - Test matrix

- Conduct flame speed measurements to acquire flame speed data at 10 and 20 bar for pure ammonia and ammonia/hydrogen blends

Mixture	NH3 in fuel (%)	Oxidant[1]				Phi	Temp. (K)	Pressures (atm)
		O_2	N_2	Ar	He			
H_2-NH_3	50	1	1	0	3	07 – 1.2	296	10
	70	1	1	0	3			
	100	1	2	0	1			
H_2-NH_3	50	2	1	0	3			20
	70	2	1	0	3			
	100	2	1	0	3			

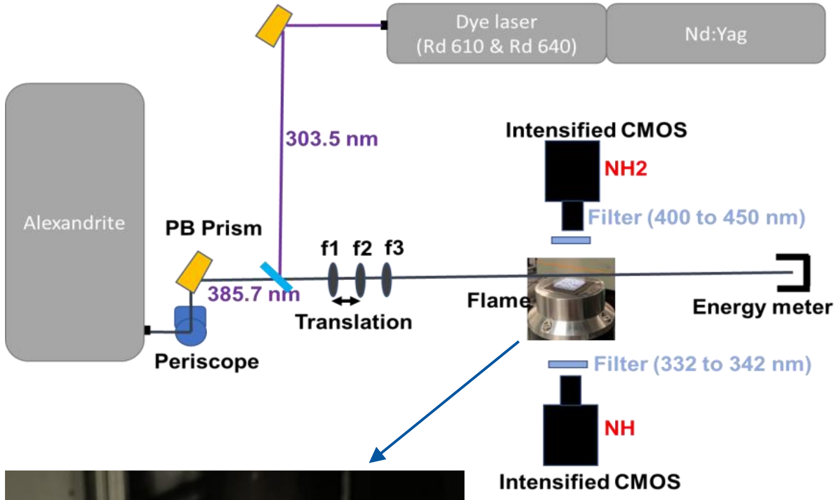
1. Oxidant ratio will be determined during experiments to get laminar flame speed.

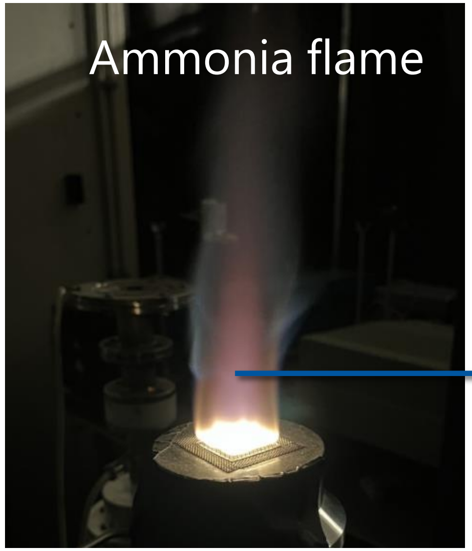
- Utilize shock tube IDTs, speciation and flame speed experimental data to develop/improve chemical kinetic model for ammonia/hydrogen blends



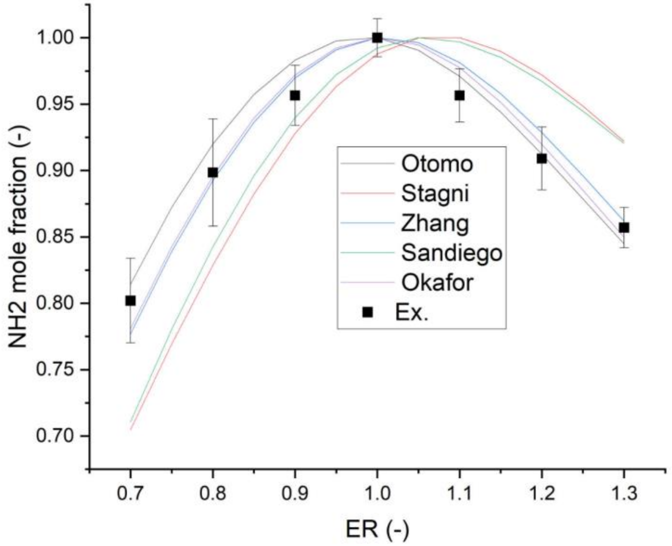
Hencken Burner Test Setup

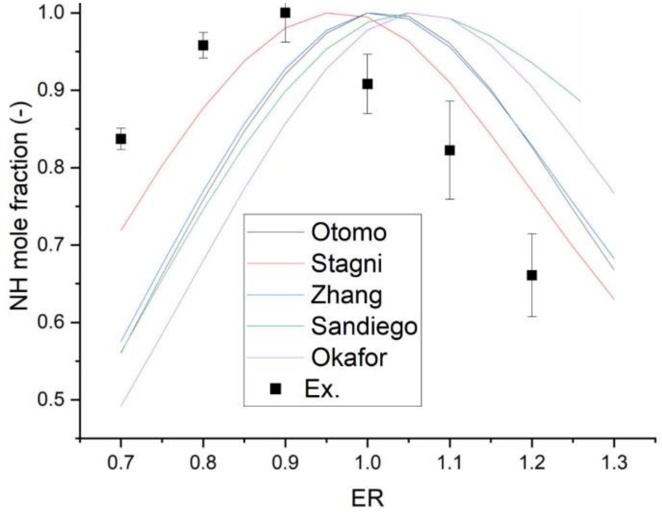
- Investigation of NH_2/NH laser-induced fluorescence (LIF)
  - Pure ammonia-air cases, O_2 enriched air (50% O_2/50% N_2) to help stabilize flame
  - Models seem to predict NH_2 trend vs ER well
  - NH trend vs ER is noticeably different
  - Work in progress
- New CAI Gas Analyzer commissioned and will measure NO, NO_2 N_2O, and NH_3 at various equivalence ratios





Water cooled Sample Line



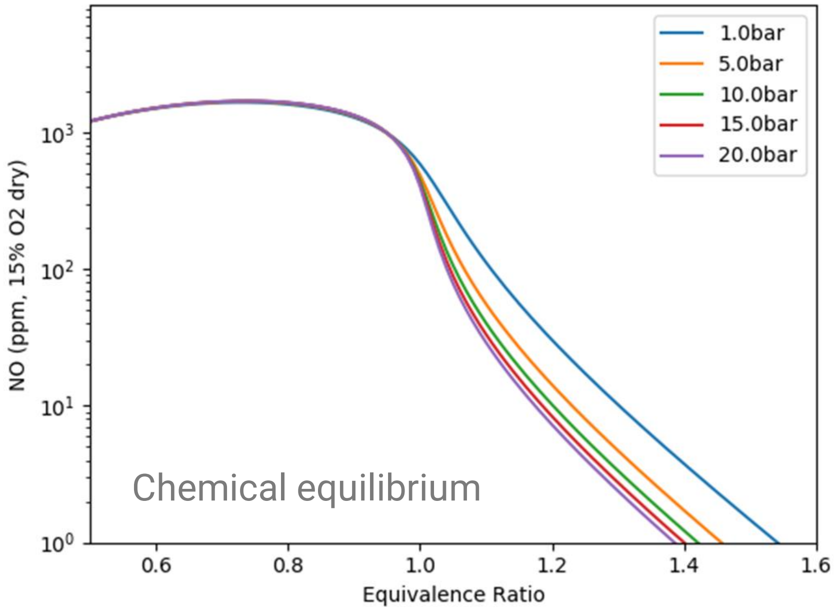


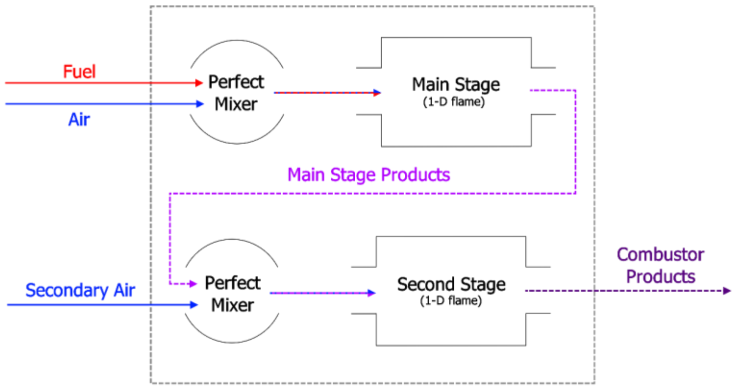
Theoretical Minimum NOx for Ammonia Combustion

- A useful benchmark: what is the theoretical minimum possible NOx emission from ammonia combustion?
  - Not simulating a specific combustor, but rather what is possible with technology development

- Reactor network modeling (kinetic model from Mei et al. 2019)

- Acceptable NO_x ($O(10)$ ppm) possible
  - Rich front end, relaxation zone, lean zone
  - i.e., more than just RQL





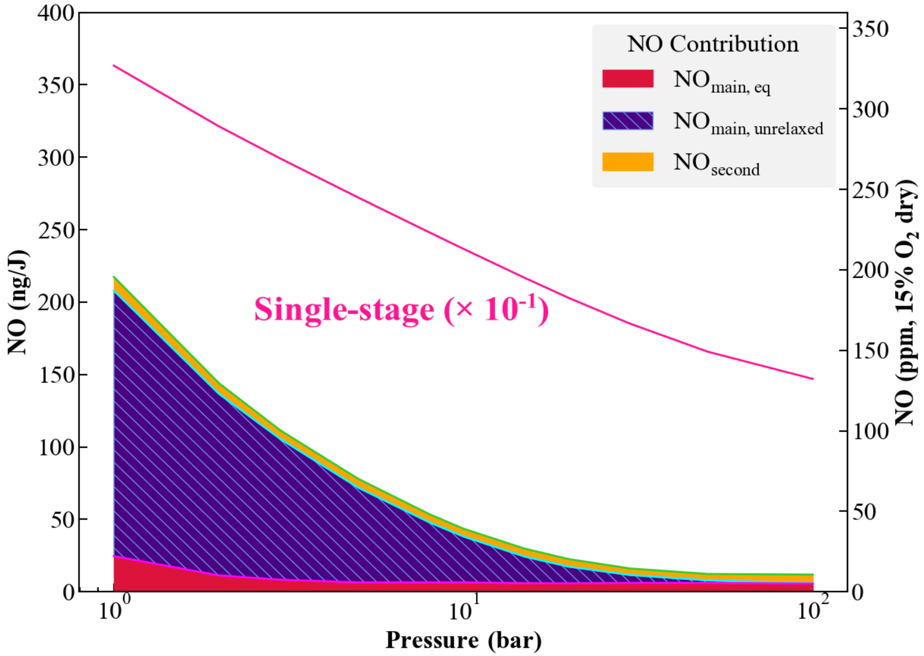
Schematic of staged combustor reactor network model

Gubbi, S., Cole, R., Emerson, B., Noble, D., Steele, R., Sun, W., & Lieuwen, T. (2023). Air Quality Implications of Using Ammonia as a Renewable Fuel: How Low Can NO x Emissions Go?. *ACS Energy Letters*, *8*, 4421-4426.

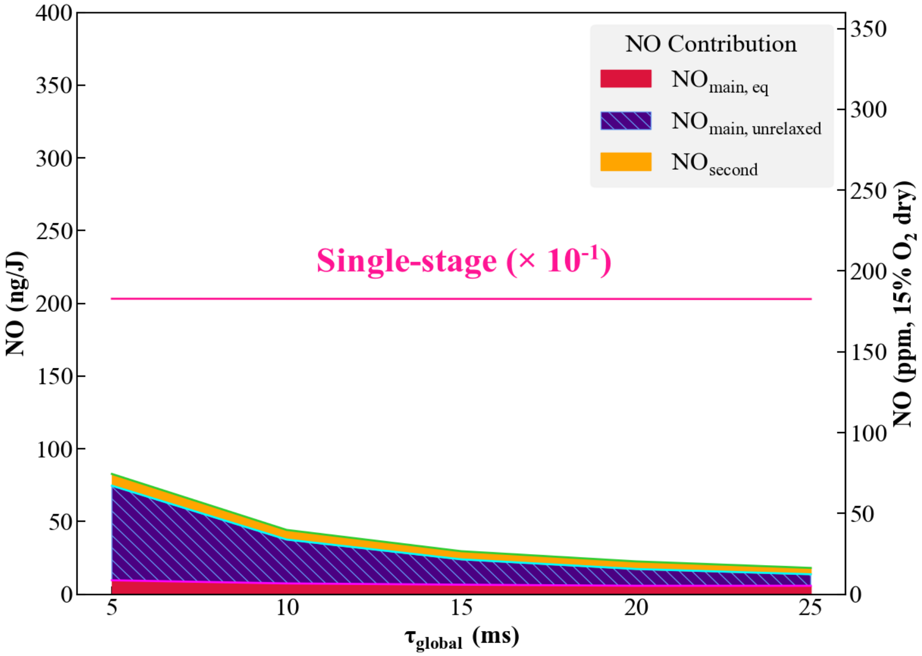
Optimized NO Emissions

- “Unrelaxed” NO dominates, manage by:
  - Increasing pressure (reduces equilibrium NO, increases relaxation rates)
  - Increasing temperature (increasing relaxation rates)
  - Increasing residence time
- Sensitivities are flipped for current DLN technologies!
- Theoretically, it is possible to be EPA compliant without SCR for ammonia combustion

Pressure and residence time dependence of NOx emission breakdown

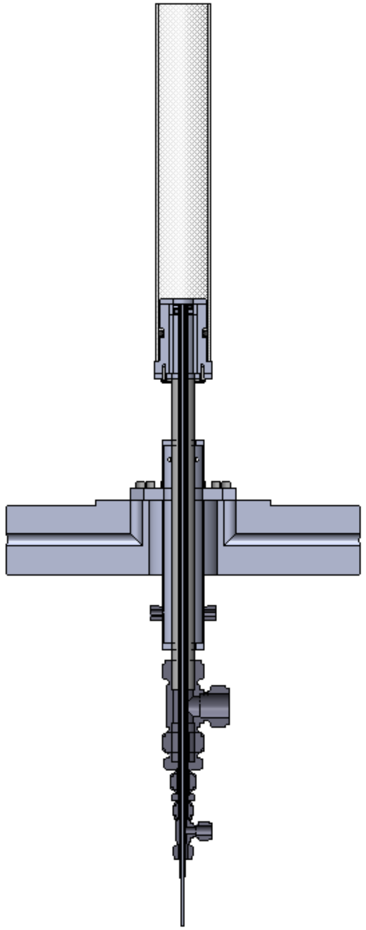


Minimum NO at various combustor pressures (T_{exit} = 1900 K, τ_{global} = 20 ms)

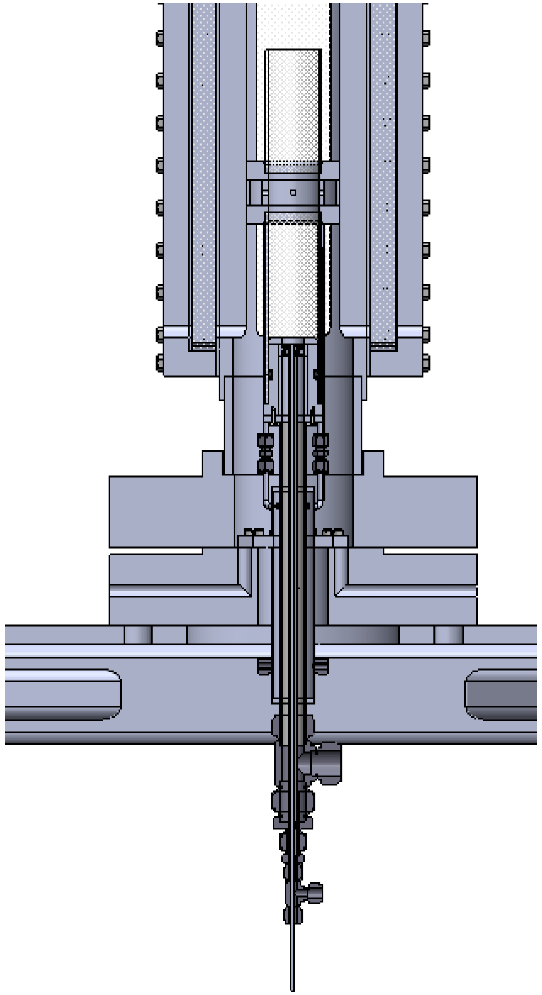


Minimum NO at various global residence times (T_{exit} = 1900 K, P = 20 bar)

Atmospheric/Pressurized Tests
Staging Tests



Atmospheric burner design



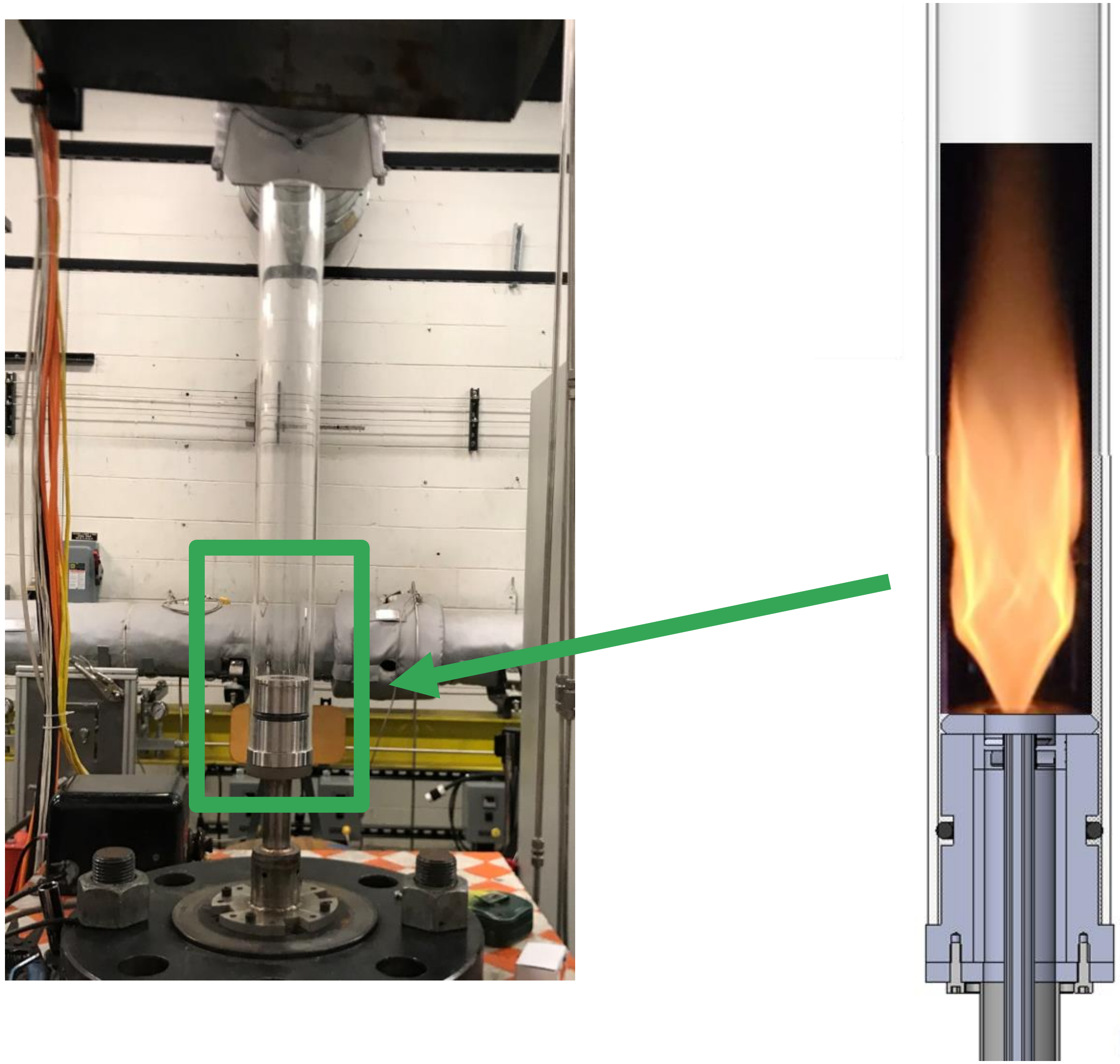
Pressurized burner design

- Design for atmospheric and pressurized ammonia testing is complete
  - Tests will share the burner
- Experiments will investigate flame stability, blow-off, and emissions
  - Various swirl configurations
- Atmospheric tests will characterize the emissions profiles in the primary zone at various residence times
  - Investigate the NO relaxation vs. theoretical minimum NOx calculations

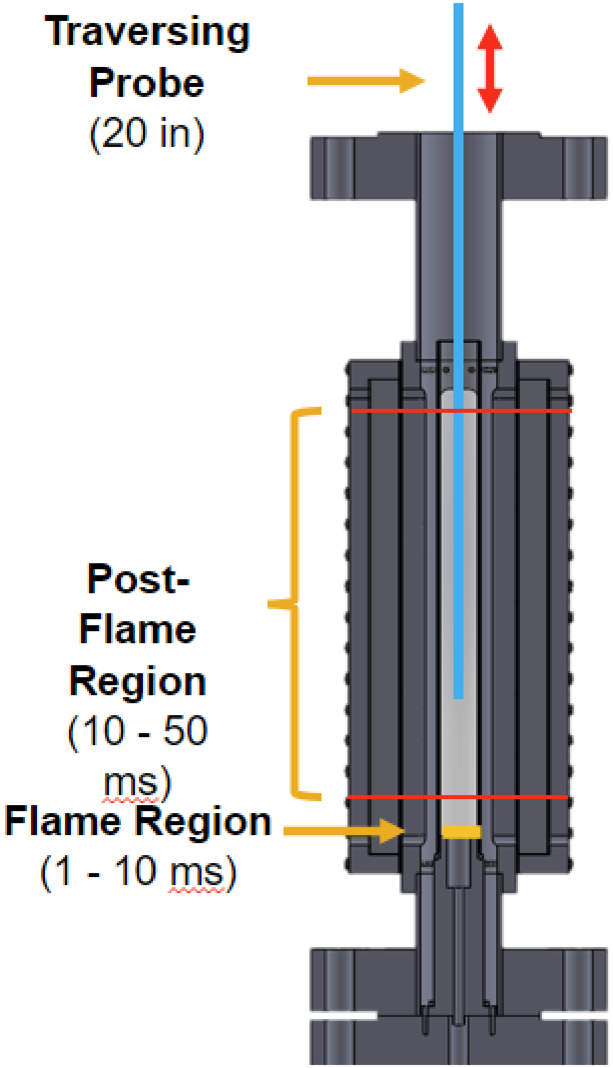
Atmospheric/Pressurized Tests
Staging Tests

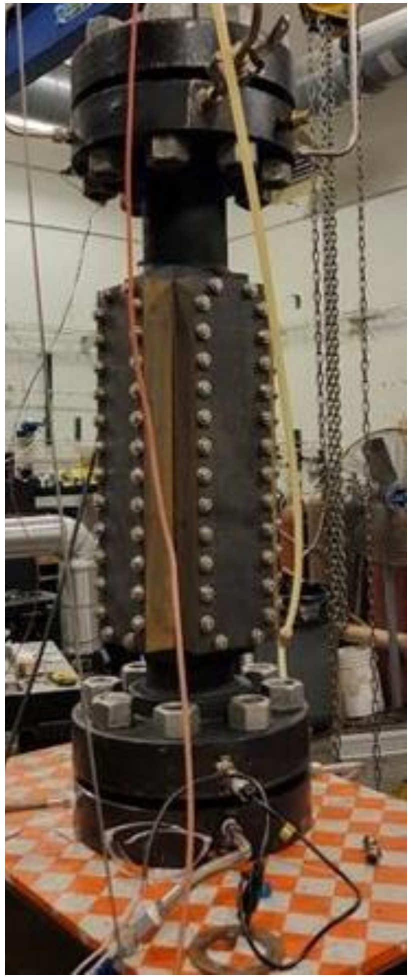
- Burner manufactured, passed safety review, shakedown, and first fire
- Planning atmospheric and 6 bar tests

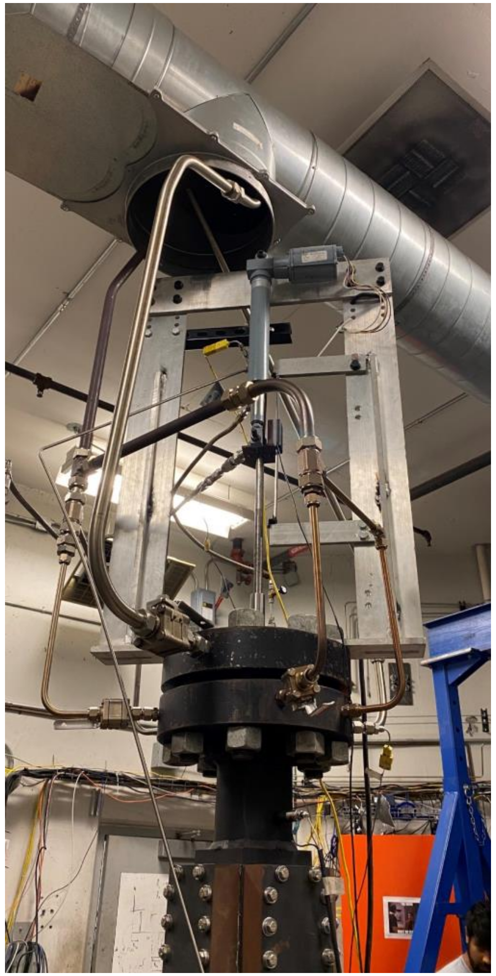
Modular Swirler Burner (Swirl numbers 1.1, 0.7, 0.4)



Scaled Combustor Test Planning





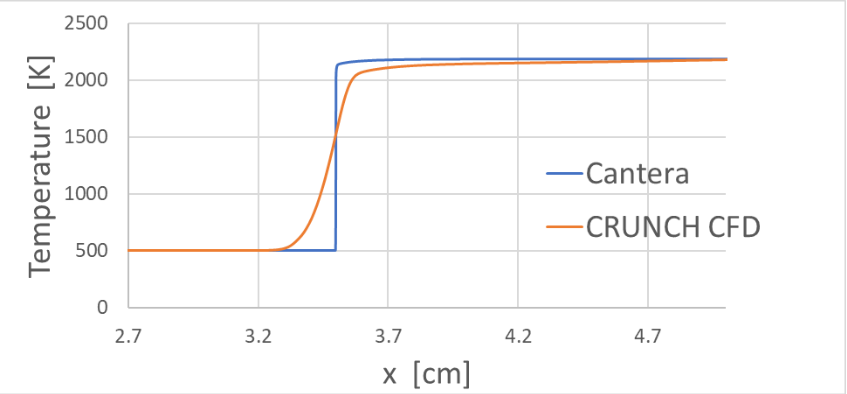


- 20 bar experiments planned for 2024

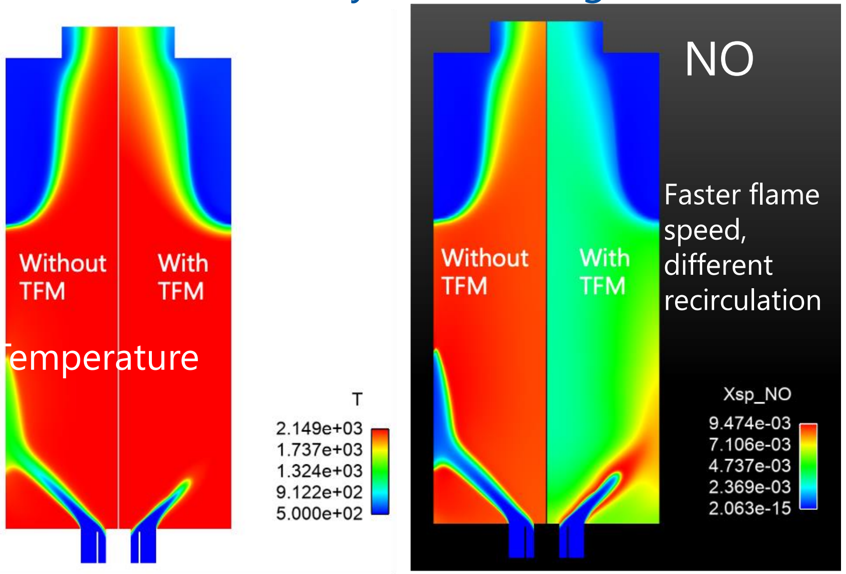
Modeling Upgrades for Turbulent Premixed Flames

- CRAFT Tech completed code development related to Thickened Flame Model (TFM) implementation in CRUNCH CFD
- TFM: Well-established turbulent combustion model for application to premixed flows using finite-rate chemistry
  - "Flame front" artificially thickened to be properly resolved locally on computational grid
  - Effects of turbulent flame interactions and flame stretch included by modifying flame speed of thickened flame front
- Initial TFM evaluation complete (operation/robustness):
  - 2-D Laminar freely-propagating flame
  - 2-D Tohoku University/AIST configuration
- Application to GA Tech test configuration in progress
- Leveraging on MTS-FPV tabulated chemistry capabilities to reduce computation cost and turn-around time of simulations

2-D Laminar Flame



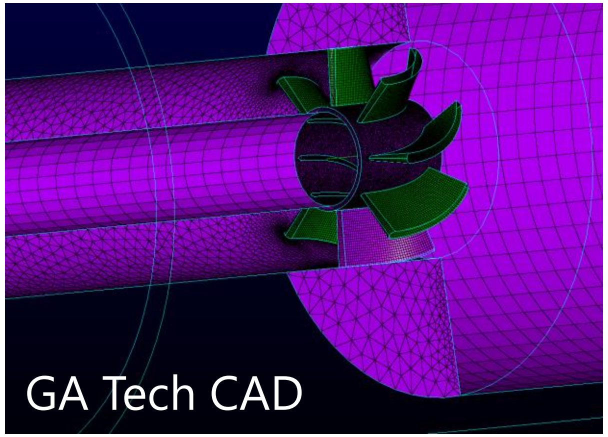
Tohoku University/AIST Configuration



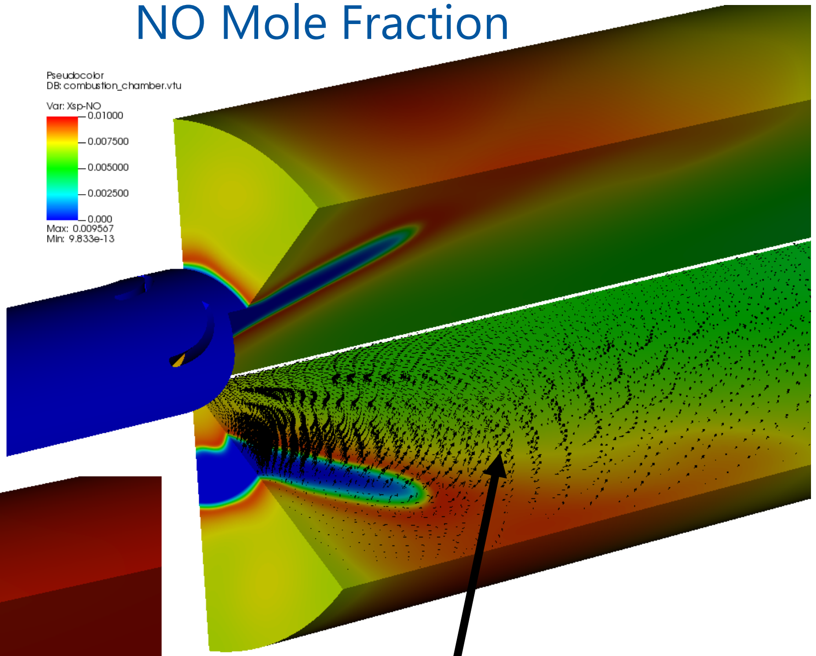
Strong effects of kinetics and turbulence

Modeling of GA Tech Test Configuration

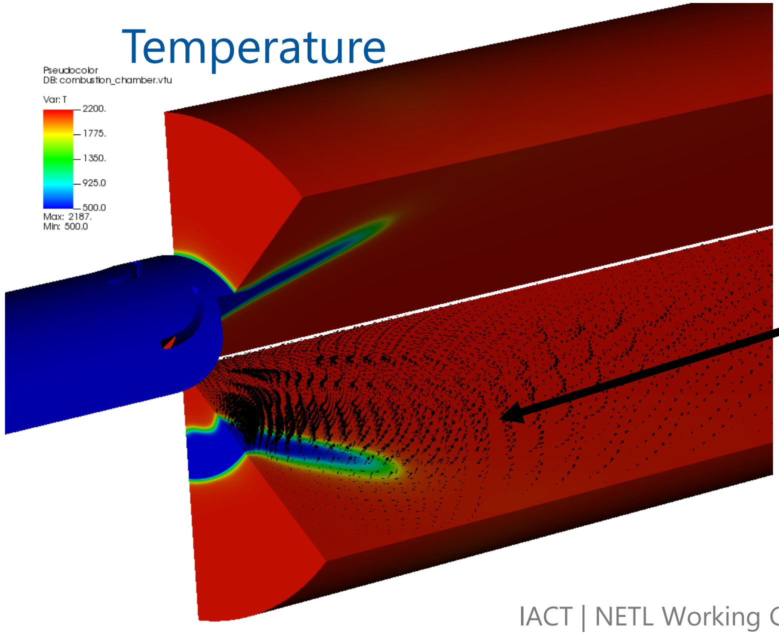
- Completed calculation setup on HPC systems:
  - Leveraged on periodicity: 45 degree wedge (one vane)
  - Used placeholder chemistry model
- Established **computationally efficient** procedure for steady-state solution:
  - Non-reacting swirl flowfield with FPV approach
  - Ignition in combustor via FPV table lookup (detailed species mapping and temperature field initialization)
  - Reacting flowfield with TFM approach
- Next: Test planning calculations



NO Mole Fraction



Temperature



Velocity vectors

- Swirl number of 1.1
- Stoichiometric NH_3-air mixture (premixed) at 1 atm pressure

Summary/Next Steps

- Selected for 41 month, $4.2M project to advance NH_3 combustion technology
  - Ammonia is an alternative low-carbon energy carrier
- Completed detailed Literature Review and analyses indicating a preferred path forward
- Ammonia combustion physics testing is ongoing (UCF) over a range of relevant gas turbine conditions to fill in high pressure data
- Hencken Burner and staged fuel tests ongoing (GTRC)
- Initial CFD model updates ongoing and analysis of configurations ongoing
- Ongoing preparations for higher pressure Scaled Combustor tests at GTRC
- Thanks to DOE NETL for supporting this work