Ammonia GT Combustor

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UCI Combustion Laboratory
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AGENDA

Ammonia Gas Turbine Combustor

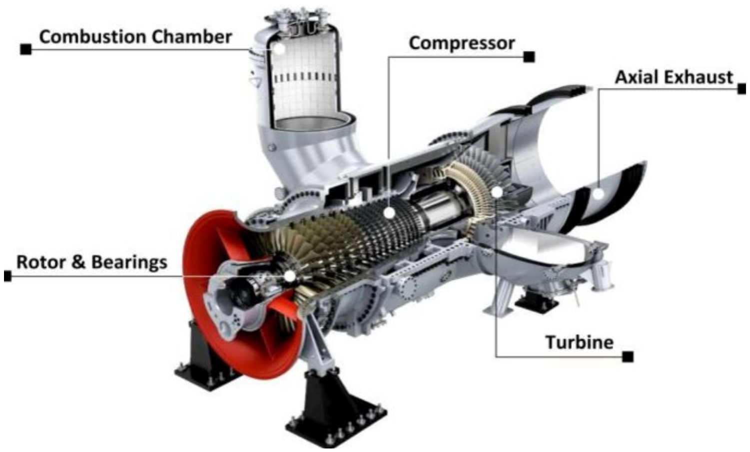
- Introduction
- NH_3 Chemistry and Chemical Kinetics Simulations
- 3D CFD Modeling
- Experimental Results
  - Atmospheric Combustion Tests
  - High Pressure Combustion Tests
- Summary & Next Steps

Introduction

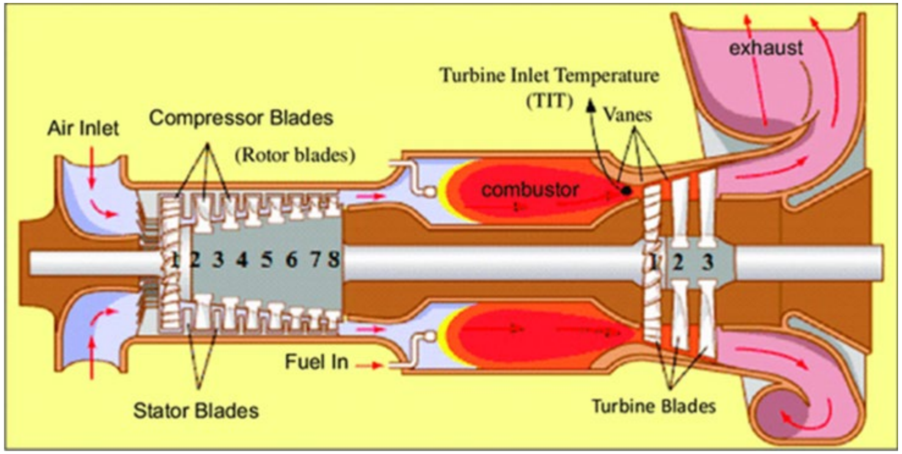
INTRODUCTION

Objectives

- Objective – Define optimum operating conditions for the design of an Ammonia Combustor that is most competitive and provides a stable combustion environment



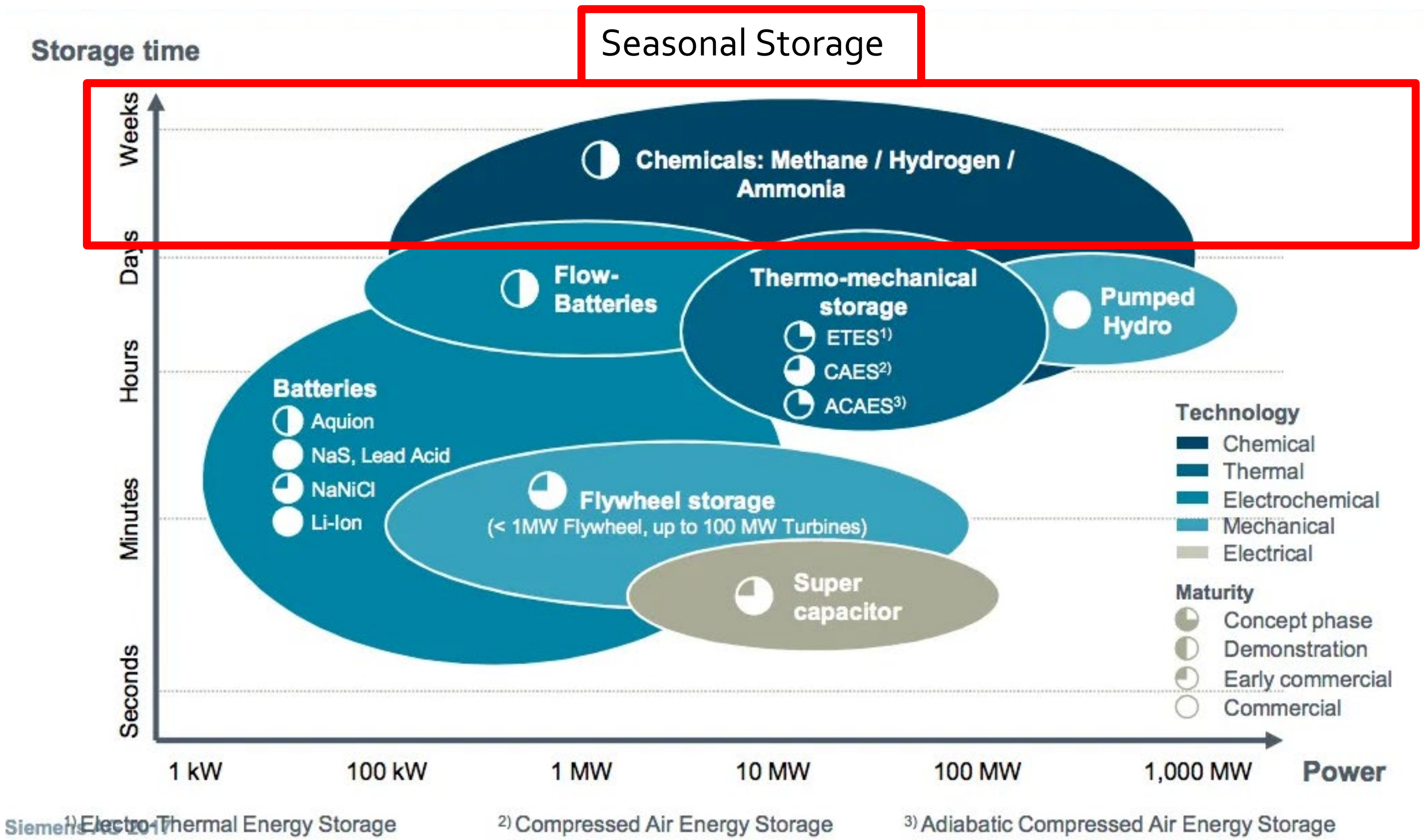
- Design goals and criteria
  - Complete burnout of fuel
  - Minimize NO_x emissions at combustor exit
  - Stable conditions – Low thermoacoustic vibrations
  - Reduced cost (capital cost, operating costs, maintenance, etc..)



Problem

Limited & Costly Long Term Energy Storage

- Chemical Energy Storage (Power to Gas), offers long-term large-scale energy storage independent from geographical and geological constrains



Source: Valera-Medina, Agustin, et al. "Ammonia for Power." Progress in Energy and Combustion Science [2018]: 63-102

Ammonia for Power

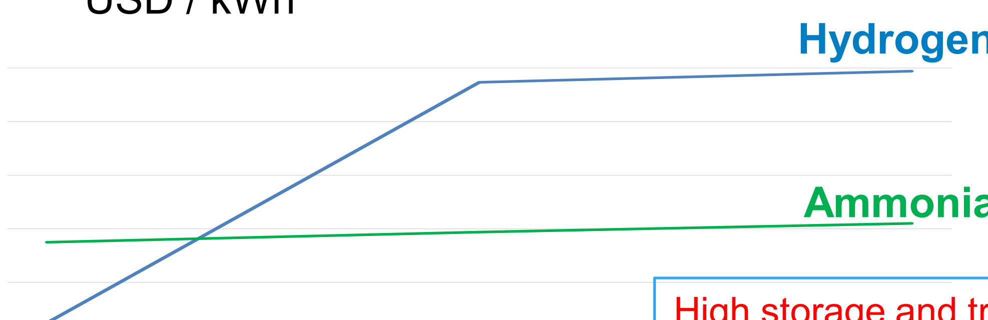
Potential Solution?

Advantages	Problem
The advantages for ammonia.. Storage and transportation ▪ Liquefies at much warmer temperatures than hydrogen and LNG ▪ Ammonia infrastructure already exists for agricultural sector	Challenges for ammonia.. Combustion ▪ Less reactive than conventional fuels ▪ Low energy content ▪ Nitrogen-bound Fuel leading to high NO_x emissions

H_2 → High Costs

NH_3 → Difficult to Burn

Energy Costs
USD / kWh



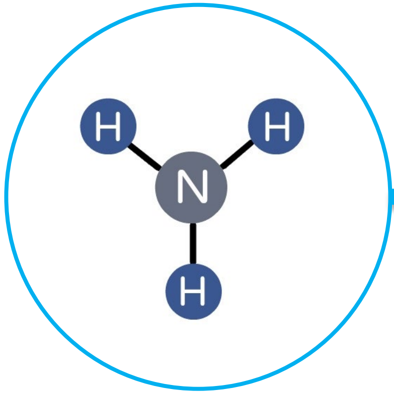
High storage and transport costs hinder Hydrogen's use as an alternative fuel

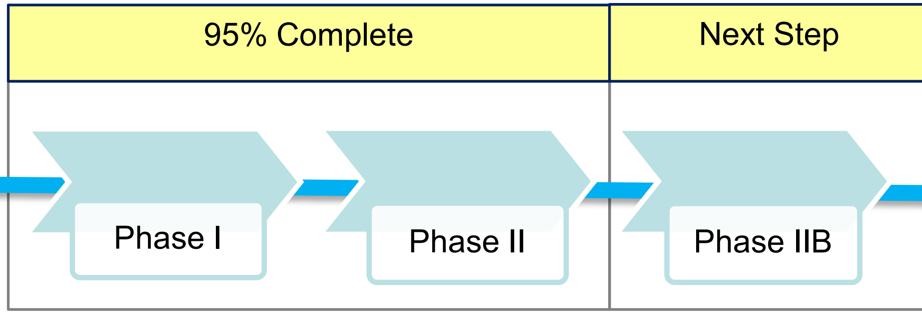
Ammonia Combustion
Challenges

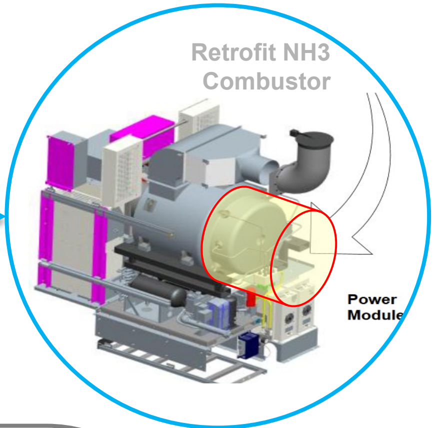
Challenges for Ammonia Combustor	Parameters analyzed to address challenges
❑ Ignition	❑ Burner Stabilization Method
❑ Flame Stability	❑ Equivalence Ratio
❑ Low Emissions	❑ Air Inlet Temperature
❑ Translation to physical design	❑ Pressure
	❑ Residence Time

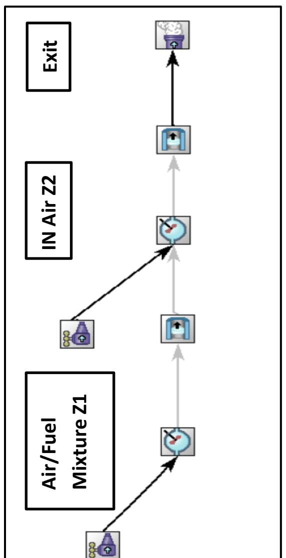
Prototype Engine

NH3 Chemistry → Industrial GT Combustor

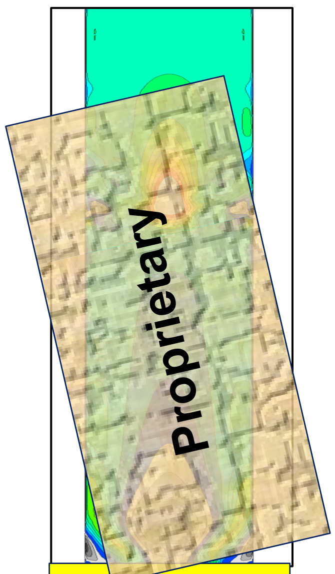






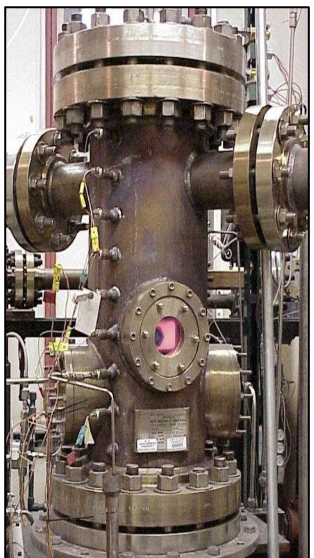


1D Chemical kinetics simulations



3D CFD simulations

Lab-scale NH3 combustion tests at 1 atm

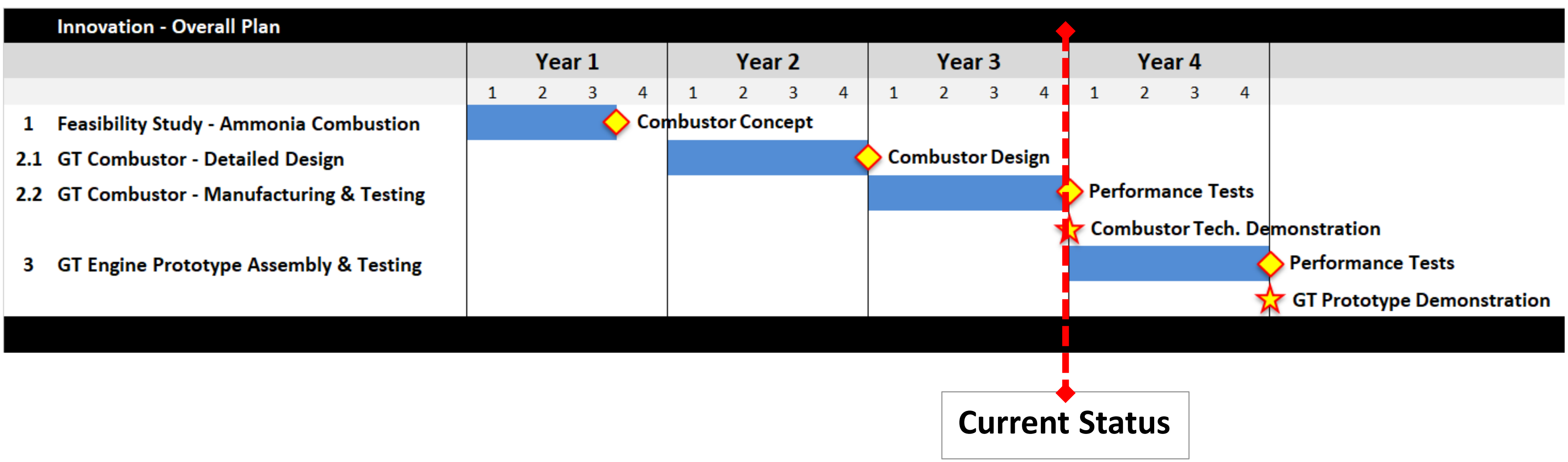


NH3 combustion tests at GT operating Conditions

SCOPE

Ammonia Combustion

- Stable ammonia flames
  - Reactants' ignition method
  - Flame equivalence ratios
  - Hydrogen mass fraction if any?
- Burner and Combustor Concept
  - One or two combustor zones
  - Aero concept designs
  - Fuel and air flows
- Pollutants' emission levels
  - NH_3 < 1 ppm
  - NOx < 20 ppm (15% Excess O_2)
- Combustor outlet conditions (mass flow and temperatures) to drive GT cycle
- Down-selection industrial Gas Turbine



Prototype Engine Selection

- Relatively Small Engine Size (Advantageous for Decentralized Power).
- GT design should allow for easy modification/extension of the combustor section.
- Ideally the engine will be designed for external firing.
- Combustor inlet air temperature should be as high as possible to facilitate ammonia ignition and flame stability.

Ammonia Chemistry

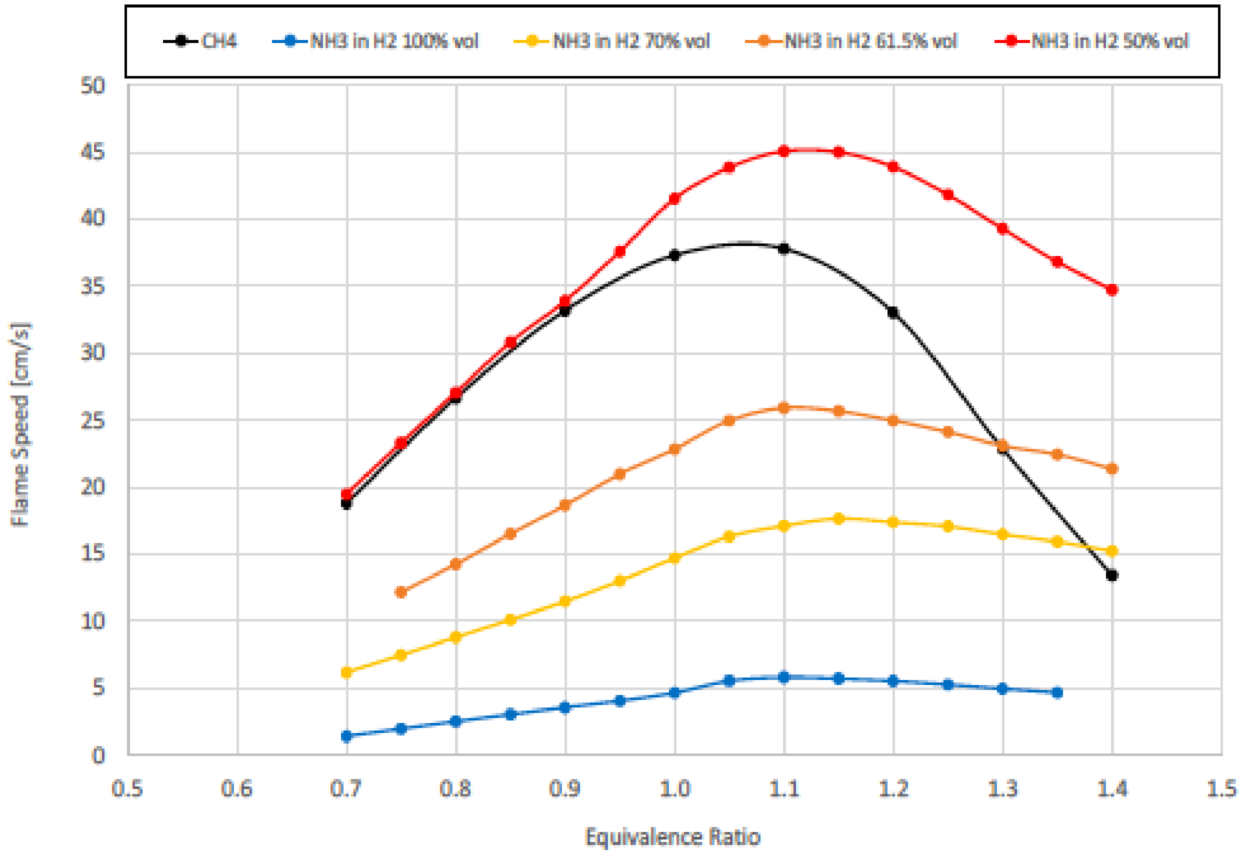
&

Chemical Kinetics Calculations

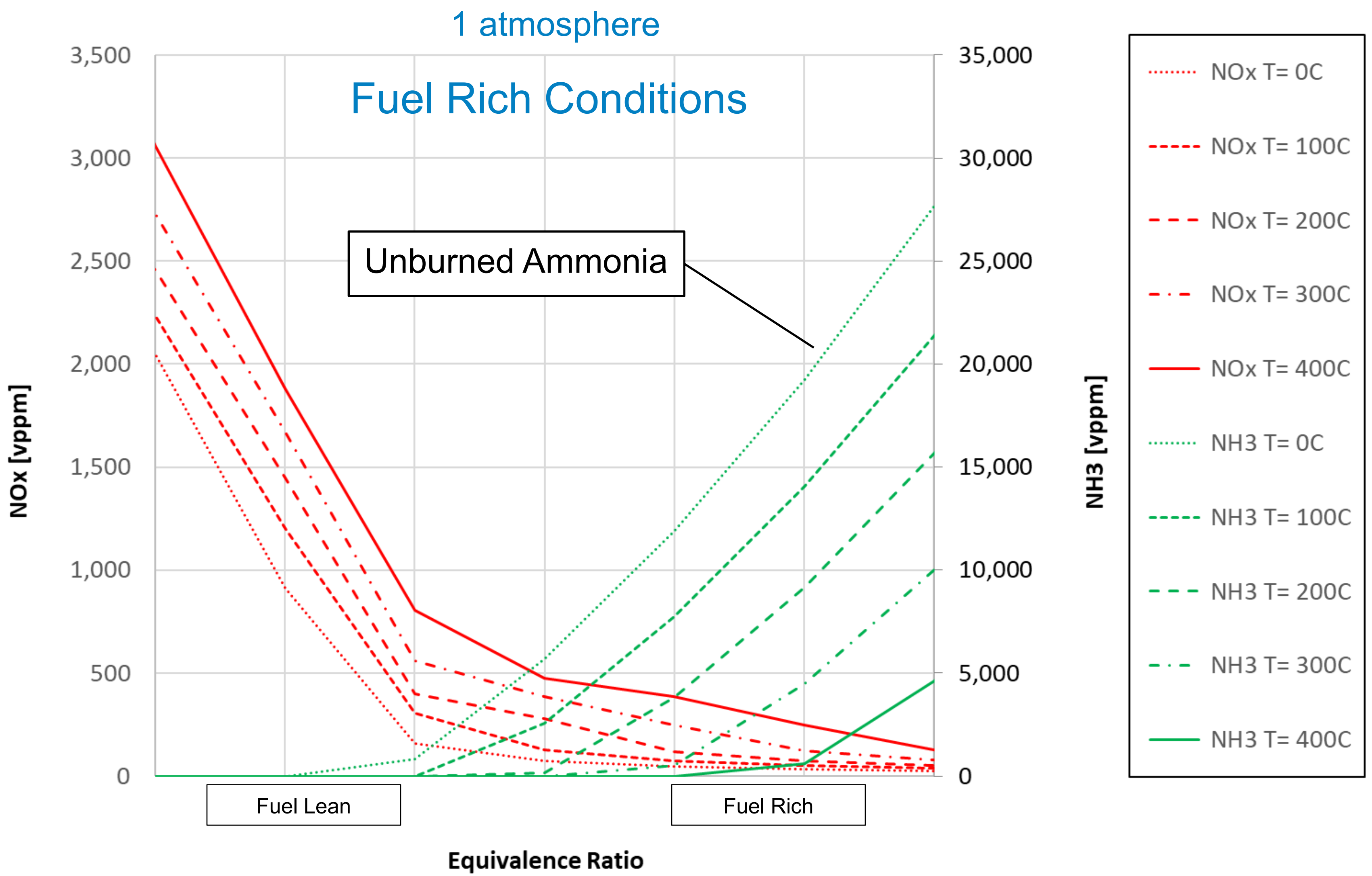
Laminar Flame Speed

1D Ammonia Combustion Simulations

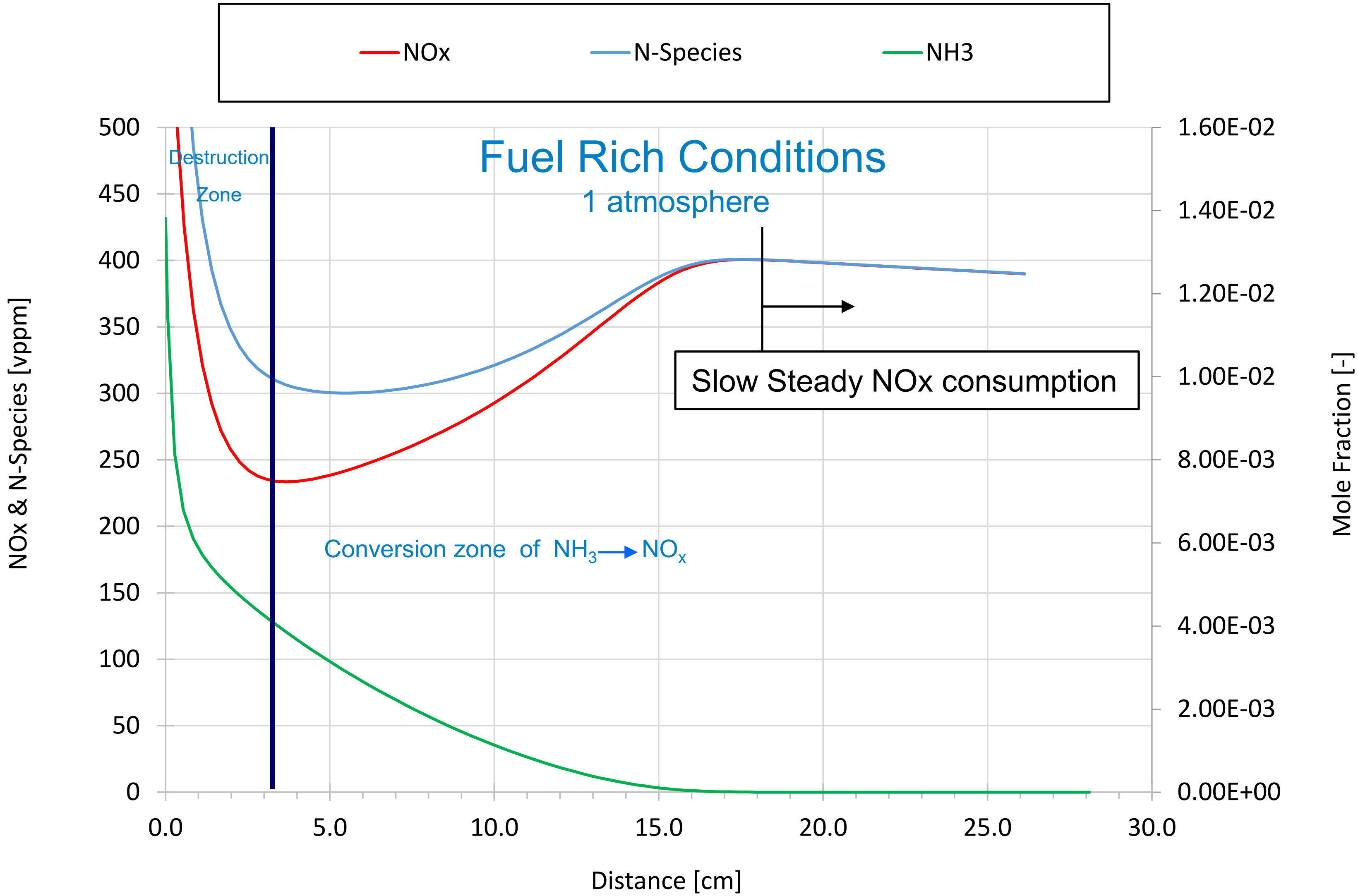
Flame Speeds of ammonia (blue curve) are about one order of magnitude lower than that of methane (black curve)



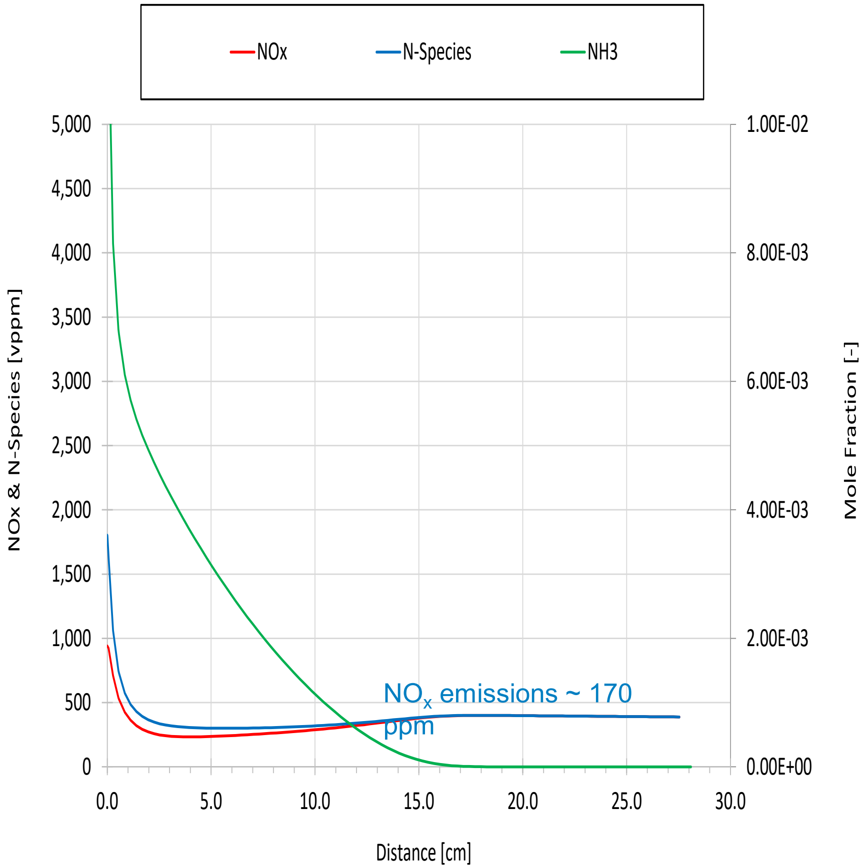
Influence of Preheat Temperature on NH_3 Burnout and NOx Formation



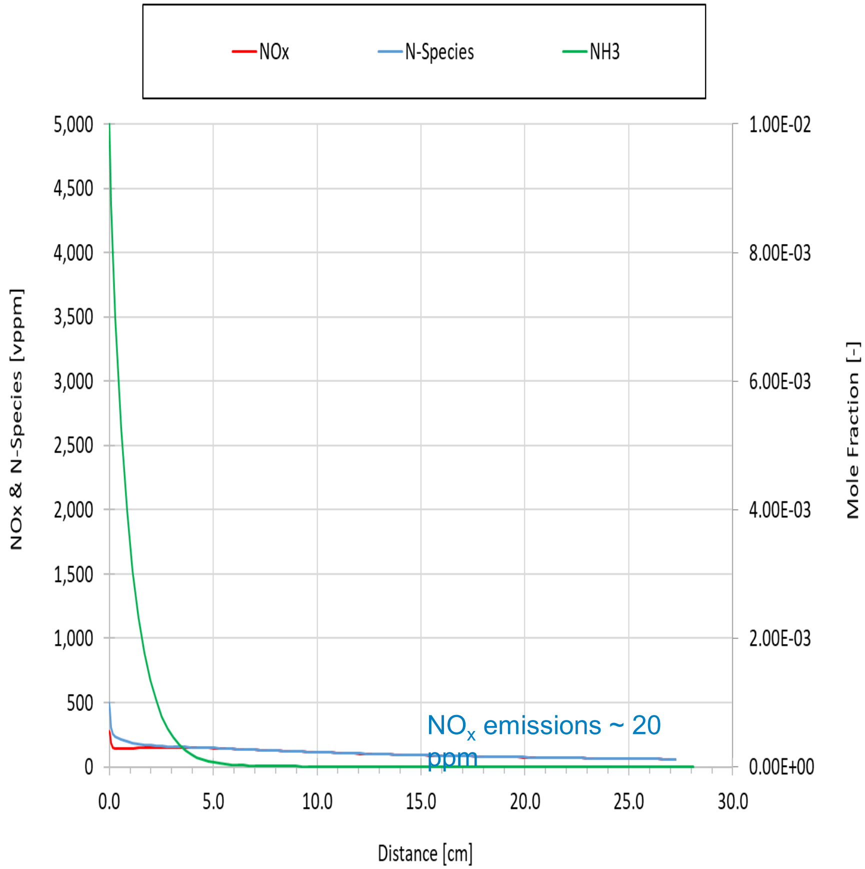
NH_3 and NO_x Formation/Reduction along the Path of a Well Stirred/Plug Flow in Series Reactors



Influence of Pressure on the Formation/Destruction of NH_3 and NO_x Under Fuel Rich Conditions



p = 1 atm



p = 20 atm

1D Chemical Kinetics Simulations

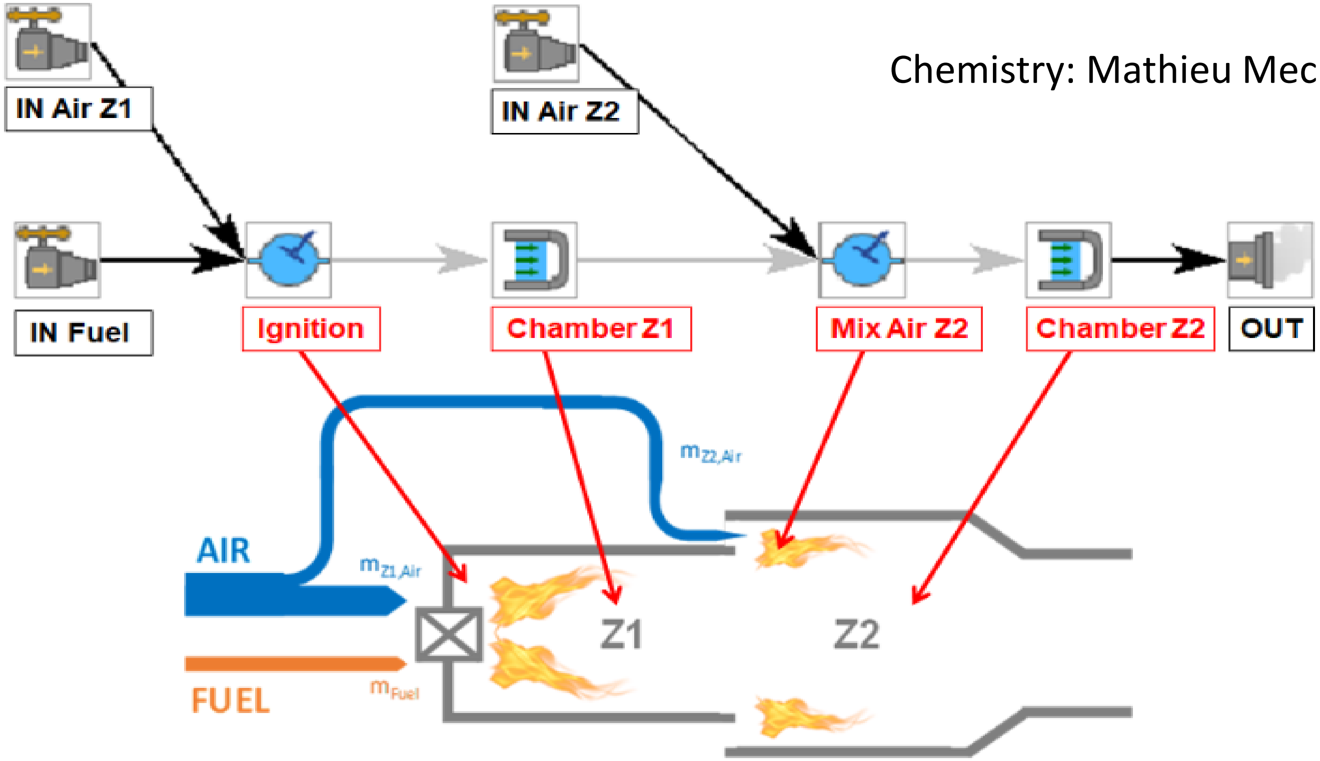
UCICL Rig Modelling

Two Stage Combustion used for decades as a strategy to address NO_X emissions from fuel bound nitrogen

Rich Quench Lean Combustion Configuration

Code: ANSYS Chemkin

Chemistry: Mathieu Mechanism



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CONCLUSIONS

1-D Chemical Kinetics

- For **adiabatic conditions**, fuel rich equivalence ratios result in low NH_3 and NO_x emissions for Z1 and Z2.

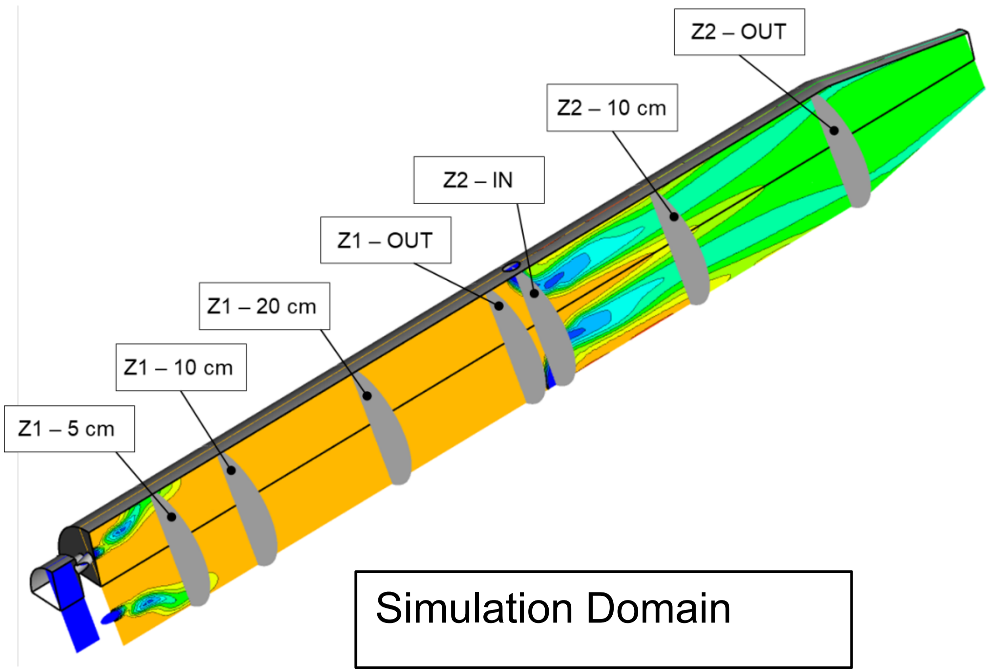
- Inlet air temperatures have a relatively big influence on the combustion
  - In Zone 1, with decreasing inlet air temperatures: Ammonia conversion becomes slower, which could be attributed to lower radical pool (O, H, OH)

- With increasing pressure:
  - Chemistry becomes faster end reach earlier steady state.
  - Less fuel-bound nitrogen is converted to NOx.
  - Less radicals are present (H, O, OH).
  - Optimum ϕ shift to richer conditions

CFD Simulations

CFD Model

- Solver: ANSYS Fluent 2020 R1
- Viscous Model: k-omega
- Chemistry: Mathieu Mechanism*
- Species Model: Partially Premixed Combustion
  C Equation
- Flamelet Generated Manifold
  (Premixed Flamelet)

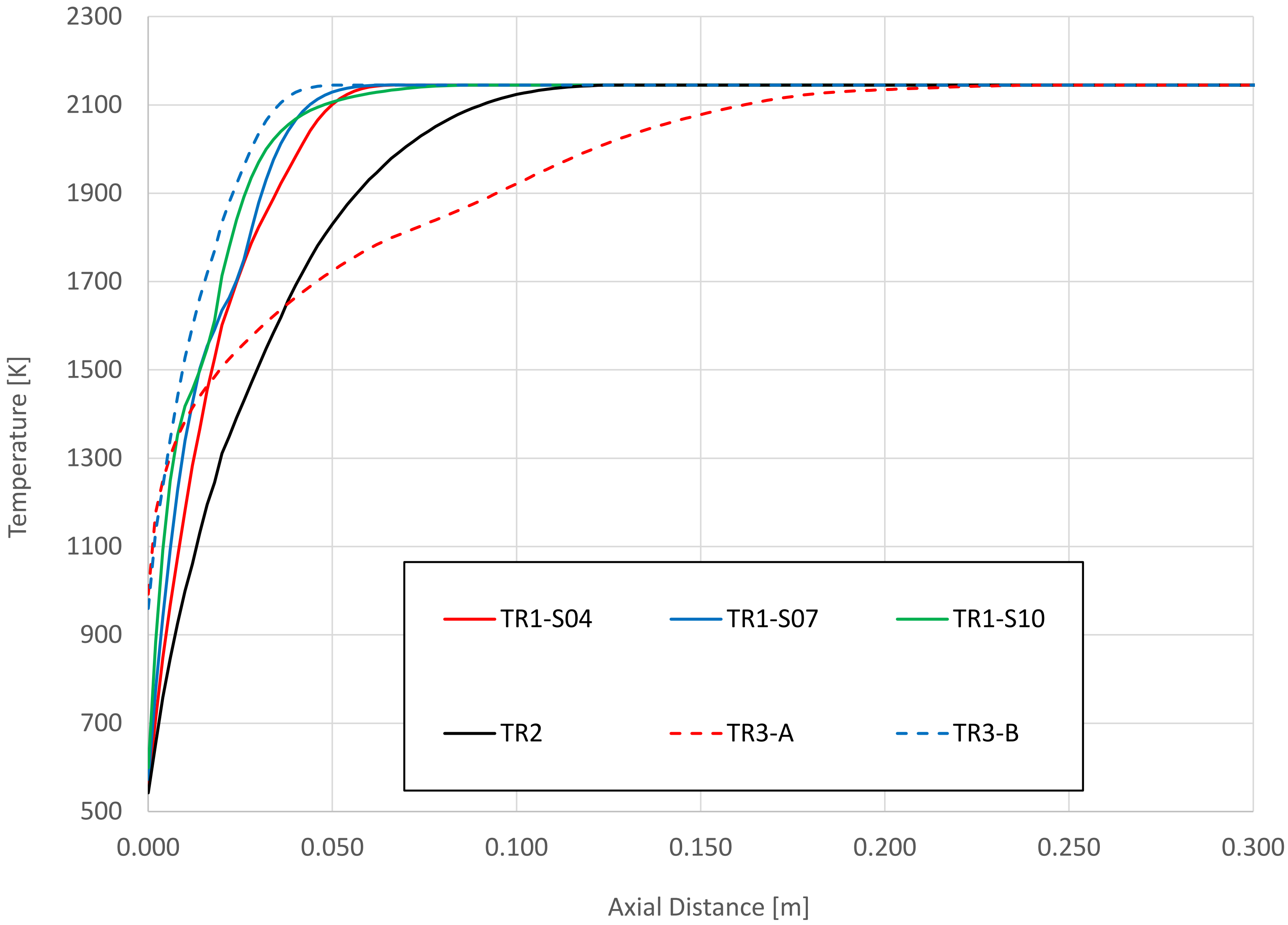


Simulation Domain

* Mathieu, O., and Petersen, E. L., 2015, "Experimental and Modeling Study on the High-Temperature Oxidation of Ammonia and Related NOx Chemistry," Combust. Flame, 162(3), pp. 554–570.

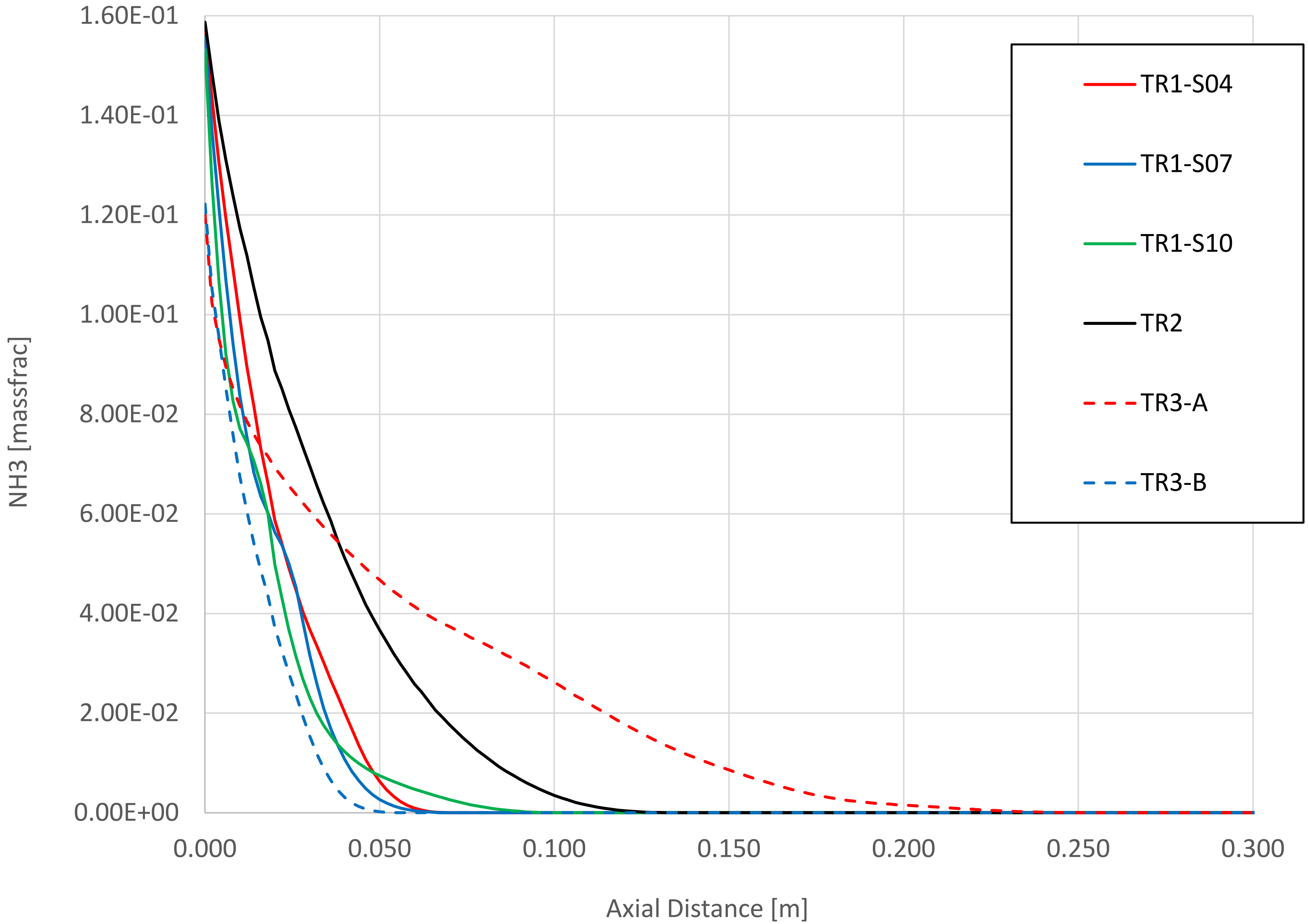
CFD Ammonia Combustion Modelling

Primary Zone Temperature



CFD Ammonia Combustion Modelling

Primary Zone NH_3 Destruction



CONCLUSIONS

CFD Ammonia Combustion Modelling

- 3D CFD modeling was conducted using commercial code ANSYS FLUENT in order to assess the design of the 6 different burner configurations.

- All Test Rig configurations show stable flames with complete combustion in Zone 1 and Zone 2.

- Newly-developed burner design (TR-03B) achieves the best results among all modelled configurations. This could be attributed to the rapid mixing next to the fuel air mixture injection point which is critical in achieving rapid ignition, rapid temperature rise and as a result near full reduction of NH_3.

- Certain burners show risk of flame impingement to the combustor wall.

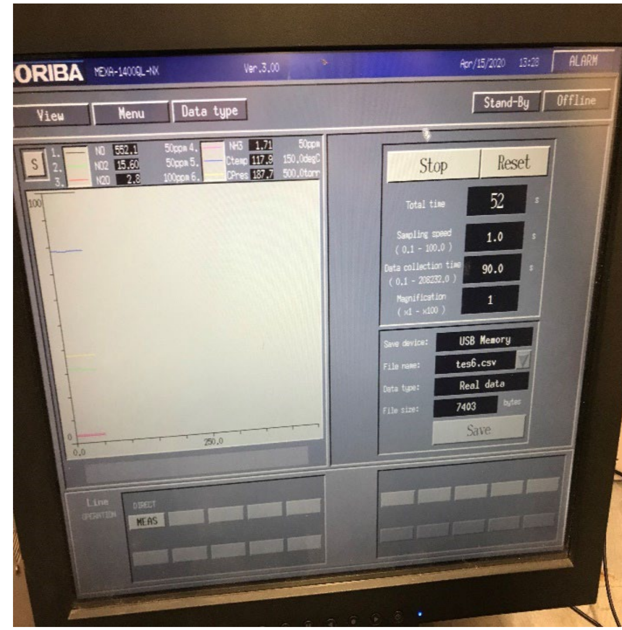
- The three best performing burner designs based on the CFD results where then tested in the UCICL test rig.

Atmospheric Combustion Tests at UCICL

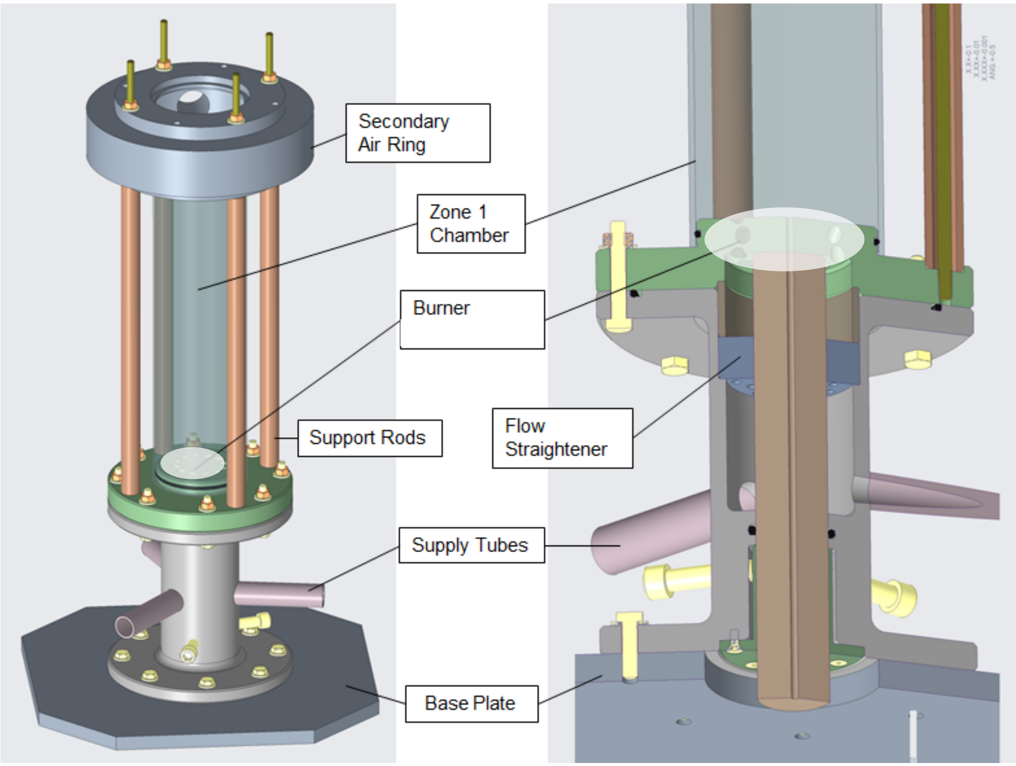
Diagnostics

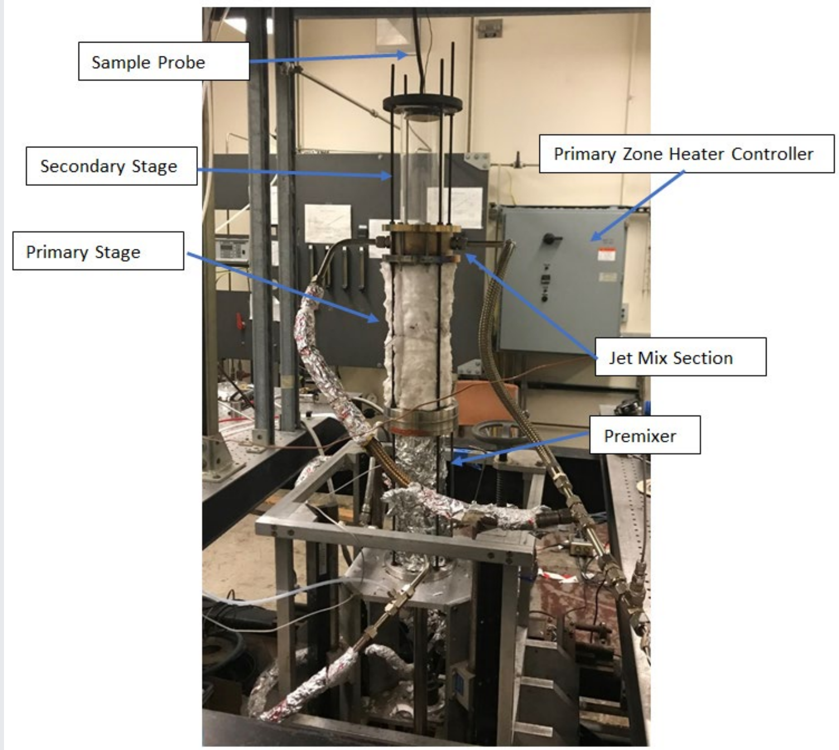
CFD Ammonia Combustion Modelling

- Horiba PG-250/PG-235
  - Primarily for O_2 measurement
- Horiba MEXA QCL-1400-NX
  - NO, NO_2, N_2O, NH_3
- Phase II: AVL FTIR DEMO SESAM SN 3853
  - NO, NO_2, N_2O, NH_3, H_2O
- Water cooled 0.25” extractive probe located at exit of the 2nd stage
  - Corrected to 15% O_2 (measured O_2 levels)



Experimental Setup at UCICL





NH_3 Combustion Flames at 1 atm

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- Observed Stable Combustion Flames

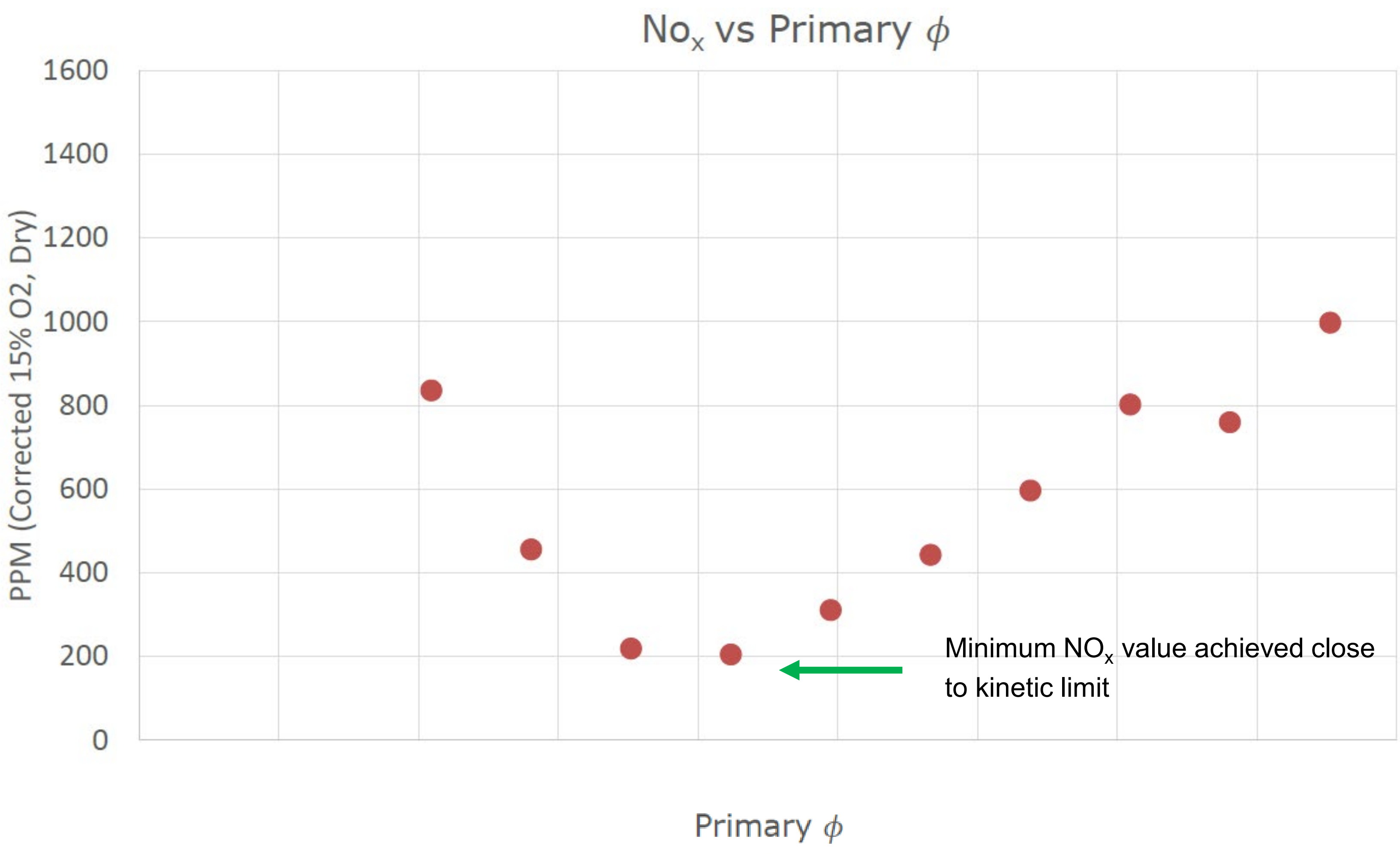
Lean PZ

~ Stoichiometric PZ

Stable Operation attained approaching LFL for NH_3/Air
Allowed focus on 100% NH_3 rather than NH_3/H_2 mixtures

NOx Emission Levels from Ammonia Flames at One Atmosphere

Measured NO_x emissions from the atmospheric laboratory scale experiment



High Pressure Combustion Tests at UCICL

(Towards NH3 mGT)

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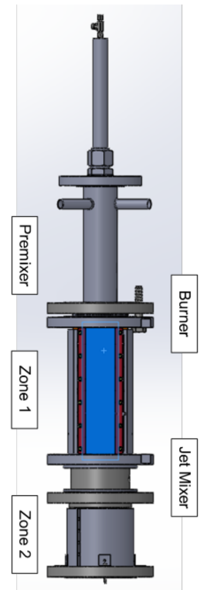
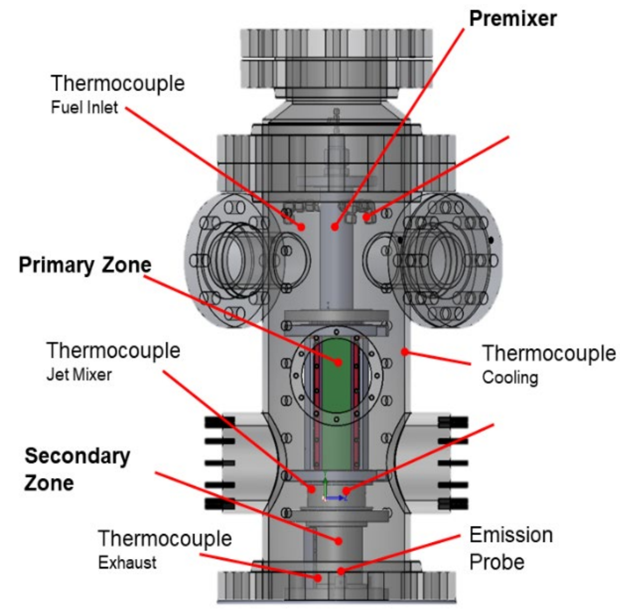
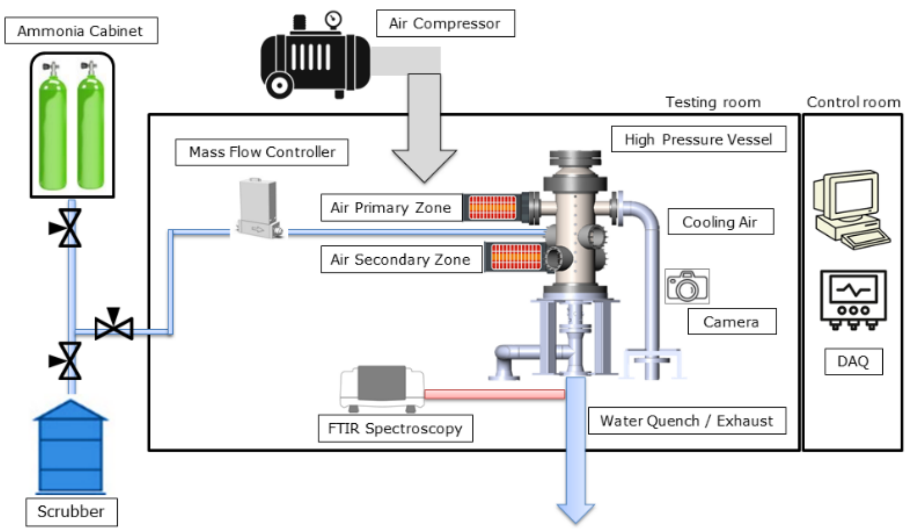
UCICL High Pressure Combustion Test Rig

- Rig Designed to simulate ~1/2 engine cycle conditions:
  - 100 kW steady-state thermal power
  - 4 bar
  - 1200 K
  - Emissions sampling
- Concept built around standard 150 lb schedule 40 pipe and flanges
  - Optical access to the flame zone (zone 1)
  - Zone 2 is customizable modified for standard flanges
  - Exit/Cooling sleeve allows rig preheating and partial quench
- Modular Sections
  - Changeable burner plate
  - Changeable jet ring
  - Separate feed for zone 1 and zone 2
  - Separate heat for zone 1 and zone 2



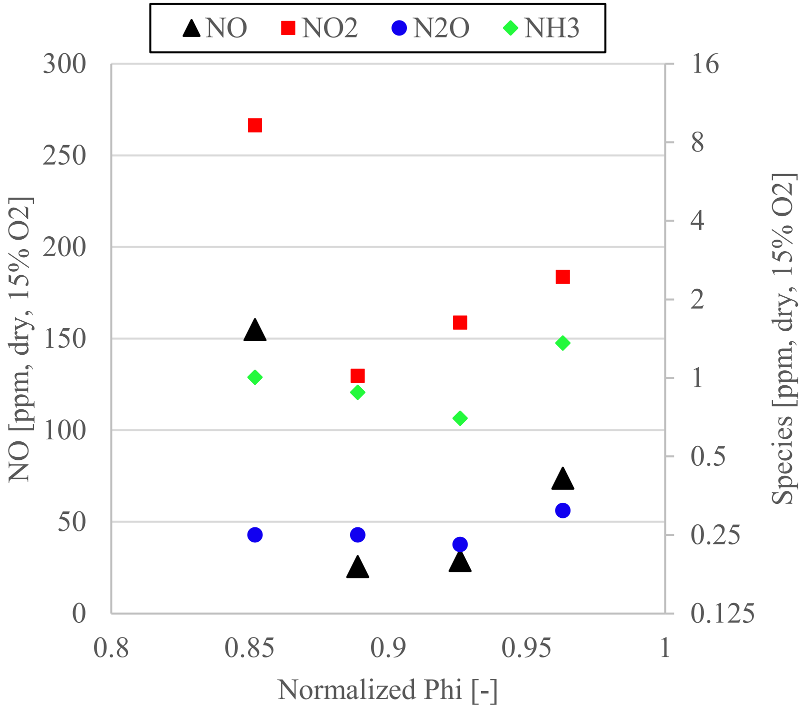




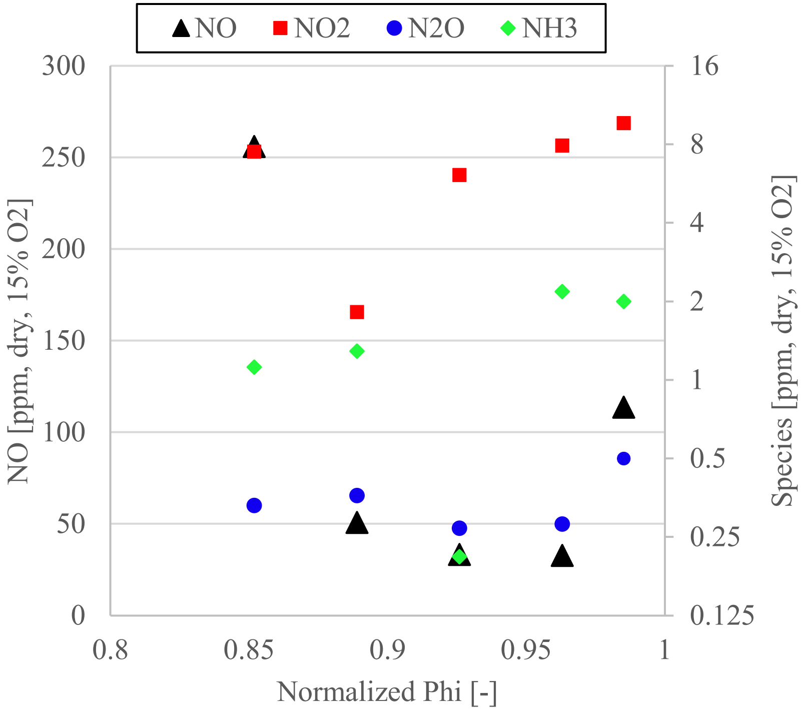
Pressure effect is significant on NO and unburnt NH_3 emissions reduction

Measured the effects of pressure on NOx emissions

- Up to 4 atm conditions (microGT conditions)
  - Limitation on fuel flow due to ammonia suppliers
  - Safety quantity on university campus



p = 1 atm



p = 4 atm

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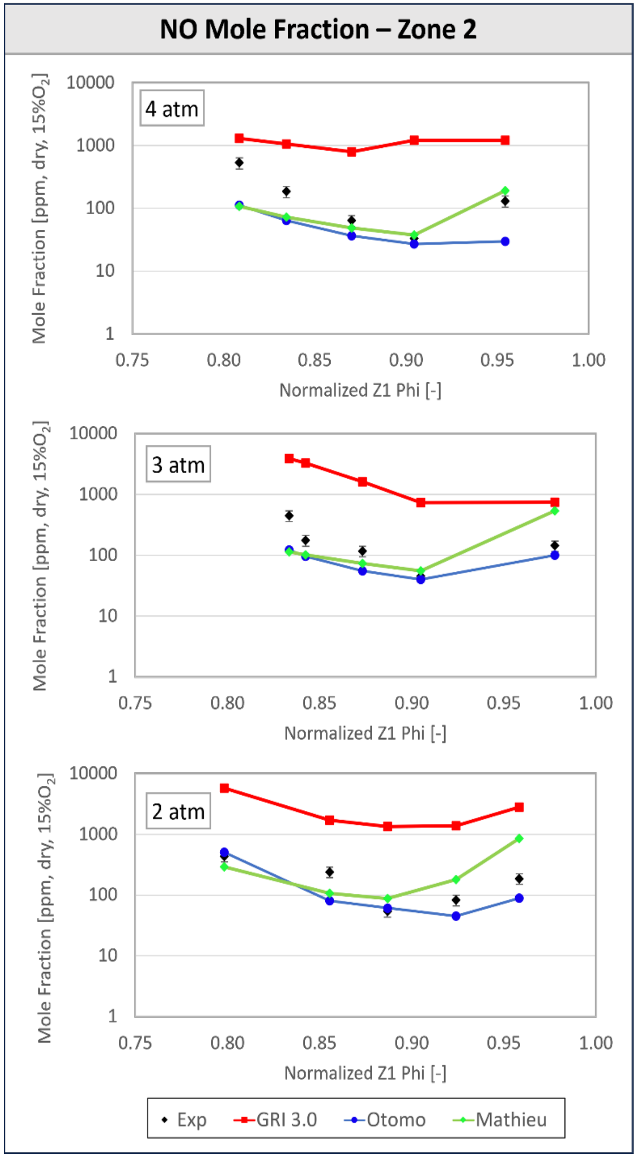
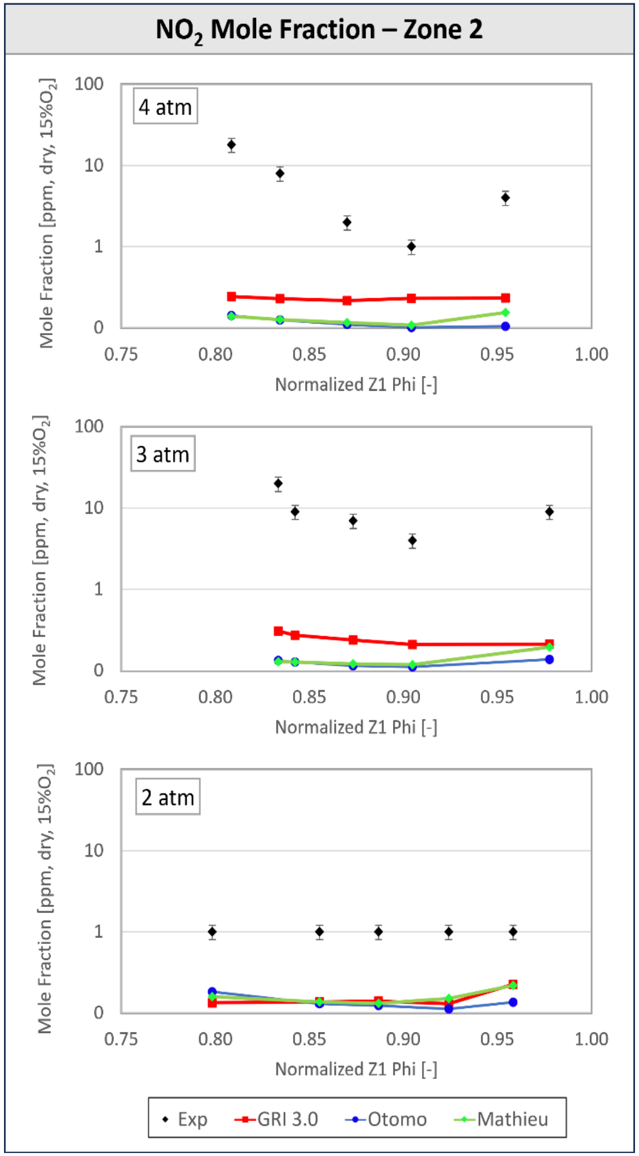
Phase II Combustion Tests

Pressure effect on NOx emissions

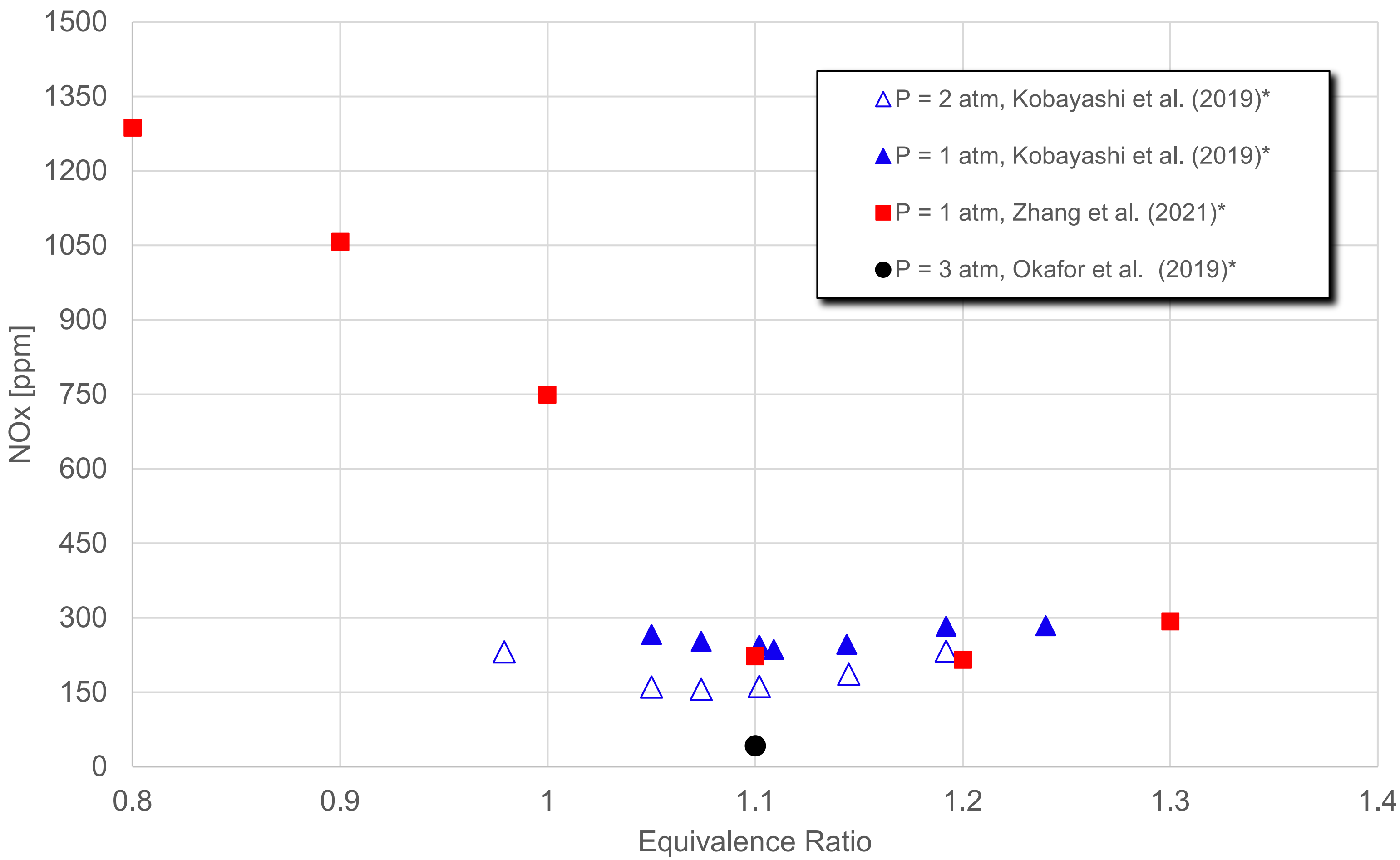
- NOx emissions significantly reduced
  - TBN_4atm = 36ppm
  - TBN_3atm = 50 ppm
  - TBN_2atm = 90 ppm
- Optimum equivalence ratio shifts to richer conditions
- Chemical kinetics calculations using Mathieu Mechanism validated against experimental measurements





Phase II Combustion Tests
Comparison with Literature

The lowest NO_x emission reported in the literature is from Okafor with 42 ppm at 3 atm



High Pressure Combustion Tests

Conclusions

- A Rich-Quench-Lean Combustor can be used to achieve low NO_x emissions while maintaining complete combustion of ammonia.

- Burner technology that allows for a quick mixing of ammonia/air flows and that introduces the reactants at velocities that enable stable flames could also achieve low NOx emissions when operating conditions are optimized.

- At elevated pressures, NOx emissions can be reduced significantly in premixed ammonia/air combustion. In this study, the lowest NO_x of 36 ppmv, corrected for 15% O_2 and dry basis, was recorded at 4 atm.

Summary

Ammonia GT Combustor

Summary

- The study conducted in Phase I demonstrated that although NH_3 has very low flame speeds, it can be burned successfully.
- DOE awarded the second phase of the program to Creative Power Solutions to continue developing the ammonia gas turbine; this phase included the design and testing of the combustor under real engine conditions
- NO_x emission levels from the tests show that they approach very closely what has been achieved in the kinetic modeling studies
- High Pressures have very positive effect on reducing NO_x emission levels in ammonia combustion systems
- High temperatures as well accelerate the preferential conversion of ammonia to N_2 under fuel rich conditions
- Several challenges need to be overcome when using ammonia as a fuel in gas turbine applications; these include the following:
    - Reliable startup of the engine
    - Running up the engine while achieving low NO_x and NH_3 emission levels (prevention of the brown plume phenomenon)
    - Reliability of cycling the engine between full and part load operation
    - Proper cooling management of the combustor liners especially under high load conditions
- The results of phase II show that the new ammonia combustion system is able achieve very high flame stability across a wide range of air to fuel ratios ($0.7 < \Phi < 1.45$) as well as very low NO_x and ammonia emissions.
- In this study, the lowest NOx of 36 ppmv, corrected for 15% O2 and dry basis, was recorded at 4 atm.

Ammonia GT Combustor

Next Steps

- Numerical simulation studies to explore options for further reduction of NOx emissions (< 20 ppm target)

- Operating regime of the combustor is defined:

    - Finalize mechanical design & build combustor prototype

    - Retrofit a microturbine package with the ammonia combustion module

    - Commission engine and conduct in-field engine demonstration tests from ignition to baseload at an agricultural site

Acknowledgements

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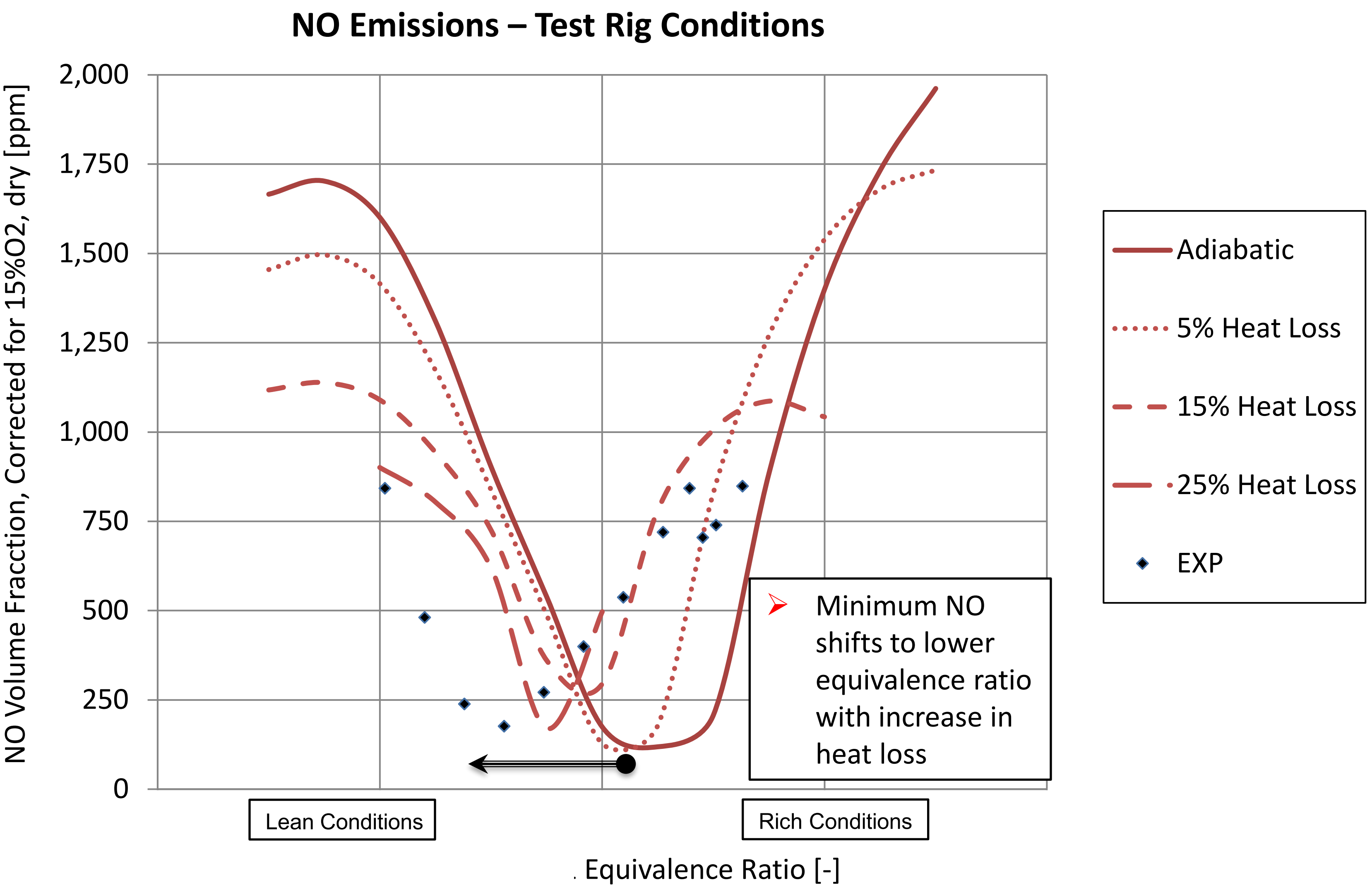
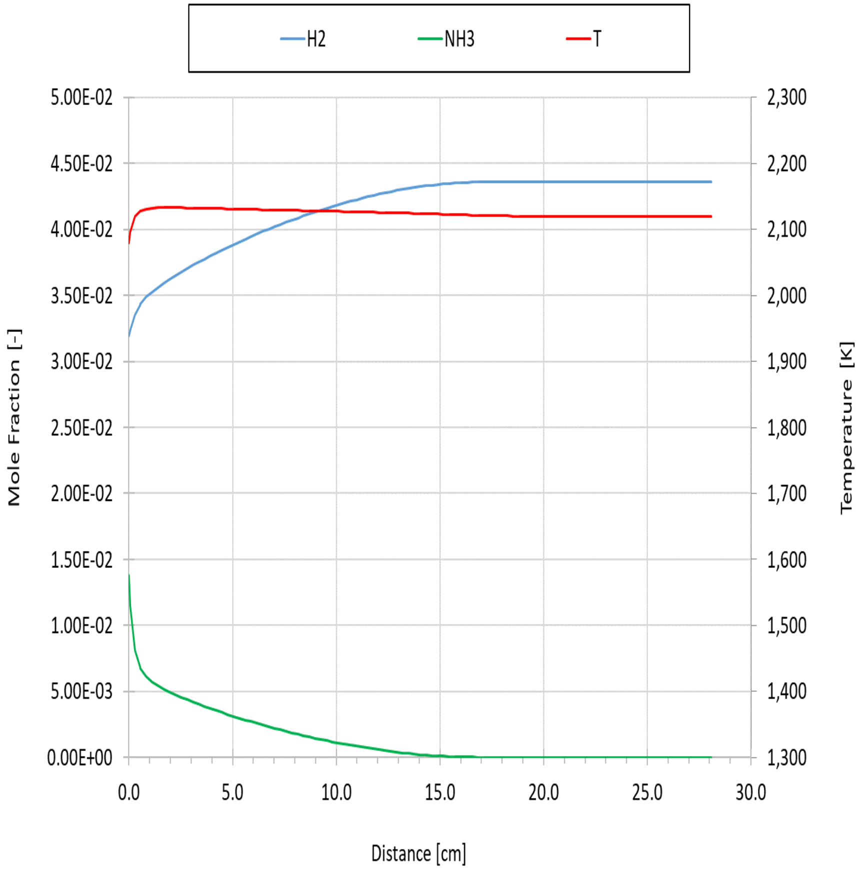
Appendix

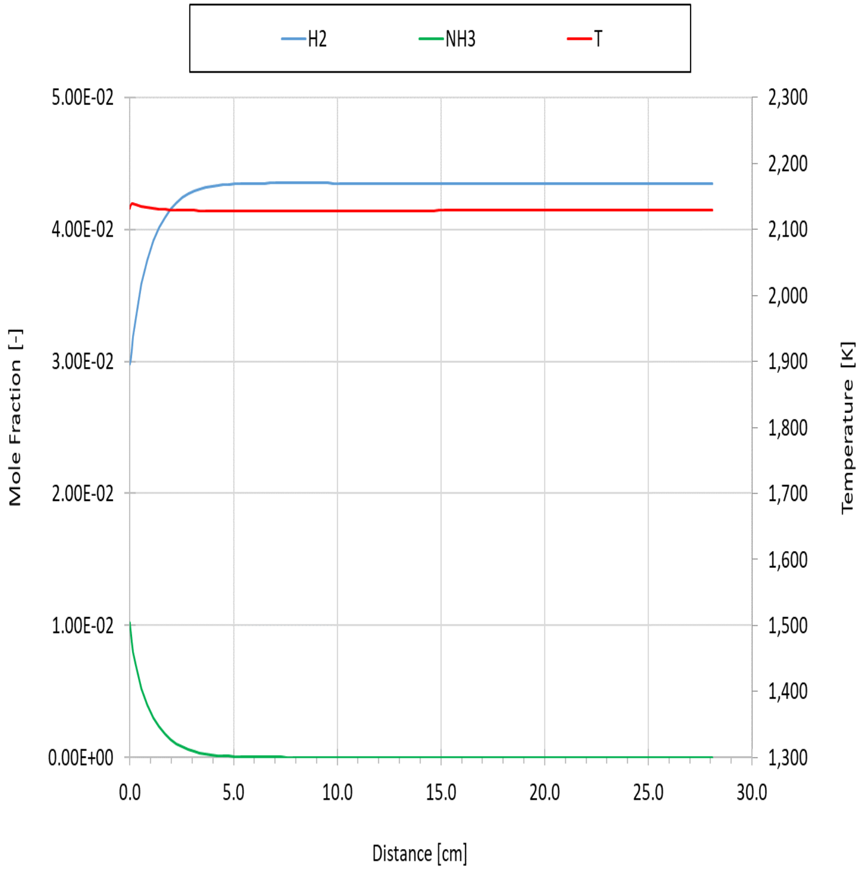
Kinetic Modeling Results Vs. Experimental Heat Loss



Influence of Pressure on the formation of Hydrogen from NH_3 under Fuel Rich Conditions



p = 1 atm



p = 20 atm