Ammonia GT Combustor

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Presenter: Hassan Abdul Sater

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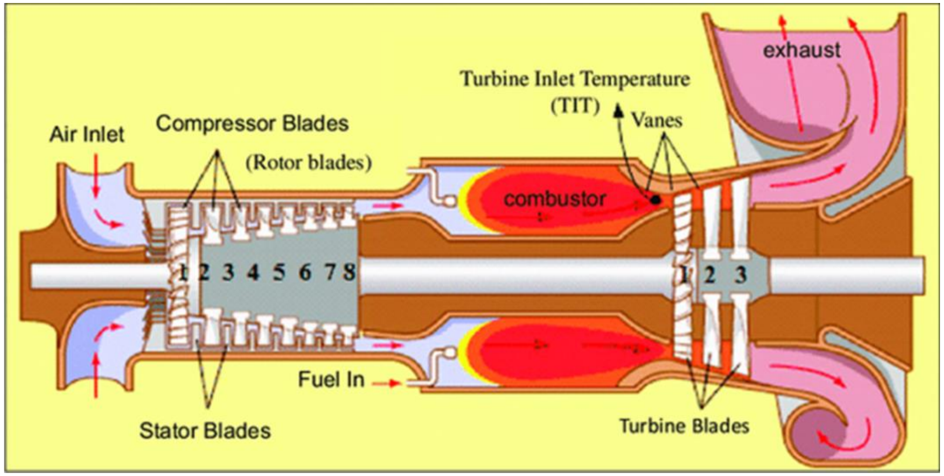
DOE SBIR Phase I Award **DE–SC0020903**

AGENDA

SBIR Phase 1: Feasibility Study

- Introduction
- NH3 Chemistry and Chemical Kinetics Simulations
- 3D CFD Modeling
- Experimental Results
- Phase II - Outlook
- Summary

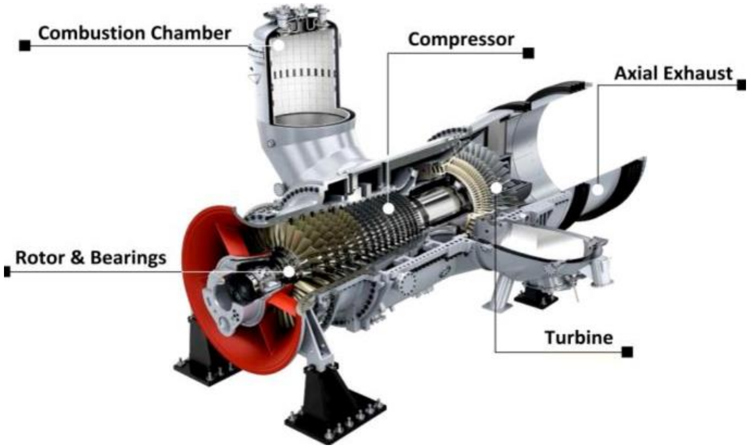


Introduction

INTRODUCTION

Objectives

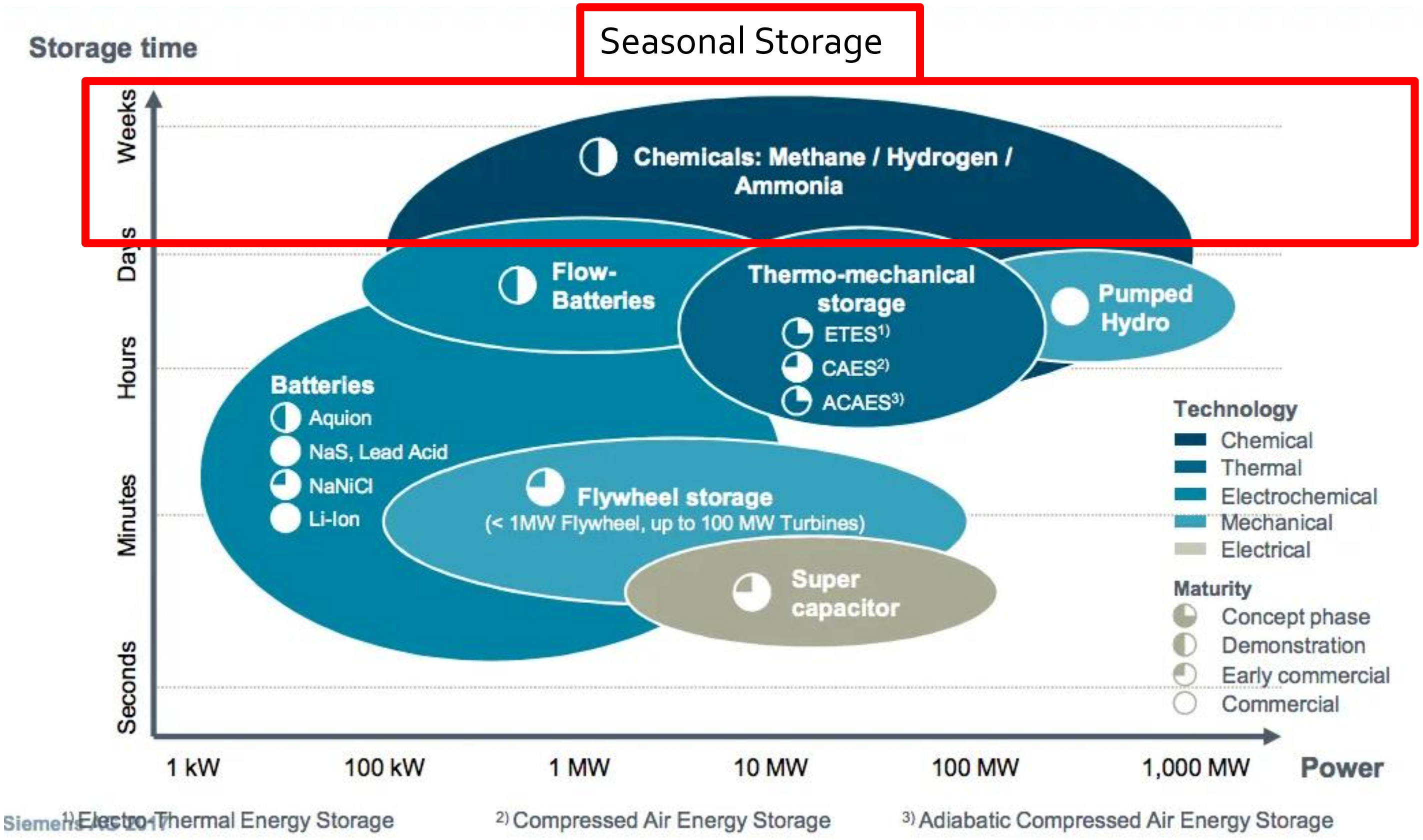
- Objective – Define optimum operating conditions for the design of an Ammonia Combustor that is most competitive and provides a stable combustion environment
- Design goals and criteria
  - Complete burnout of fuel
  - Minimize NO_x emissions at combustor exit
  - Stable conditions – Low thermoacoustic 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

The advantages for ammonia.. Storage and transportation

- Liquefies at much warmer temperatures than hydrogen and LNG
- Ammonia infrastructure already exists for agricultural sector

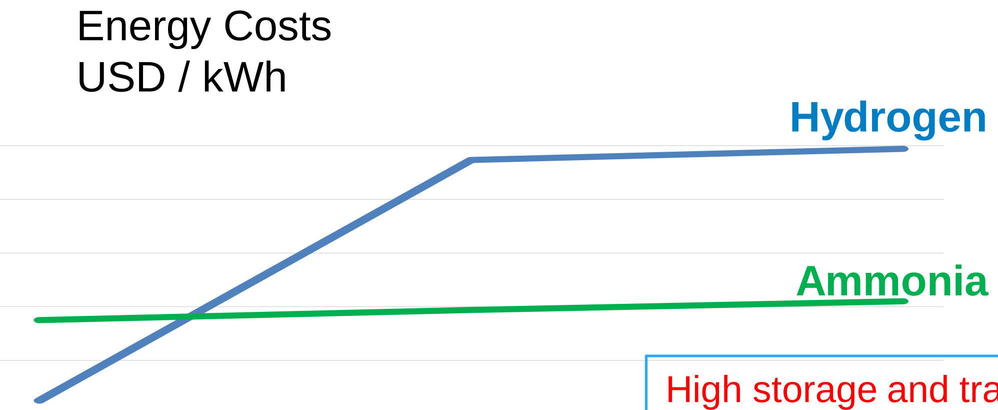
Problem

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



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

Ammonia Combustion

Challenges

Challenges for Ammonia Combustor

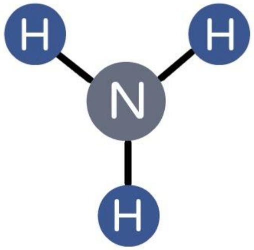
- Ignition
- Flame Stability
- Low Emissions
- Translation to physical design

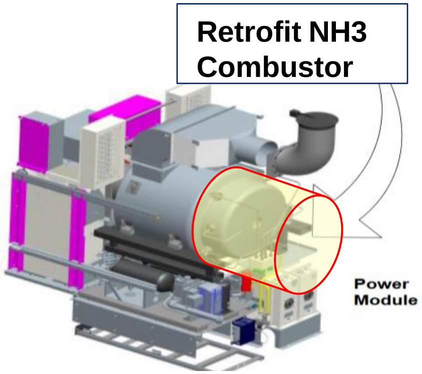
Parameters analyzed to address challenges

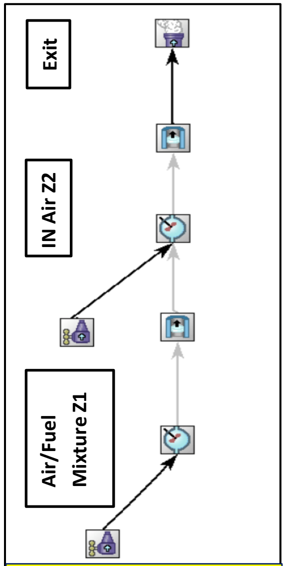
- Burner Stabilization Method
- Equivalence Ratio
- Air Inlet Temperature
- Pressure
- Residence Time

Prototype Engine

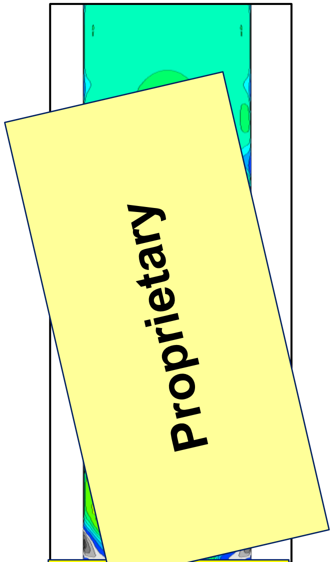
NH3 Chemistry → Industrial GT Combustor




Retrofit NH3 Combustor

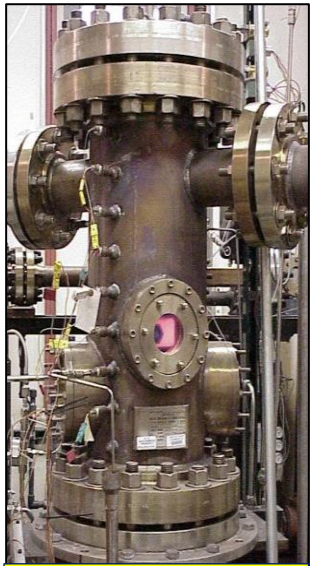


1D Chemical kinetics simulations


Proprietary

3D CFD simulations

Lab-scale NH3 combustion tests at 1 atm

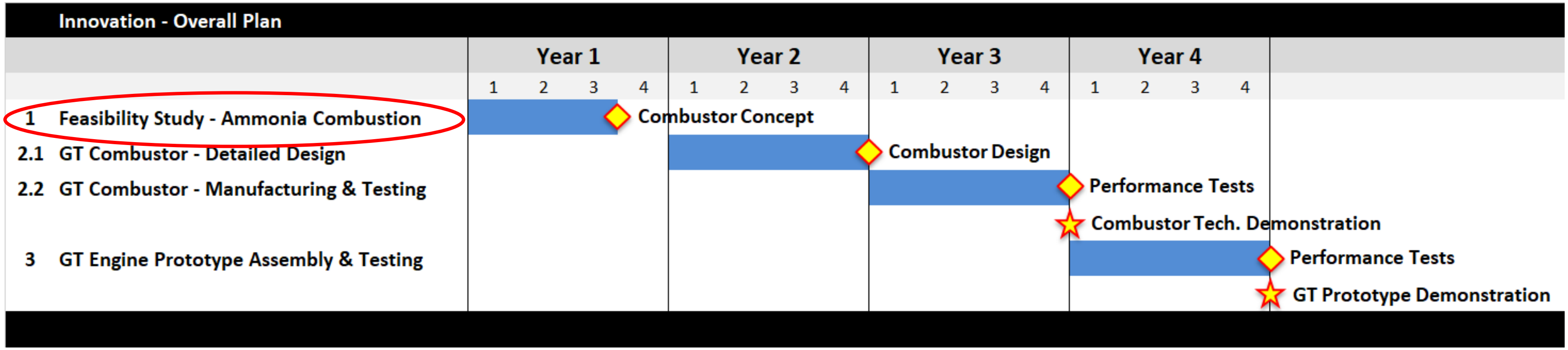


NH3 combustion tests at GT operating Conditions

SCOPE

Phase 1: Feasibility Study - 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
  - NH3 < 1 ppm
  - NOx < 20 ppm (15% Excess O2)
- Combustor outlet conditions (mass flow and temperatures) to drive GT cycle
- Down-selection industrial Gas Turbine



Ammonia Chemistry

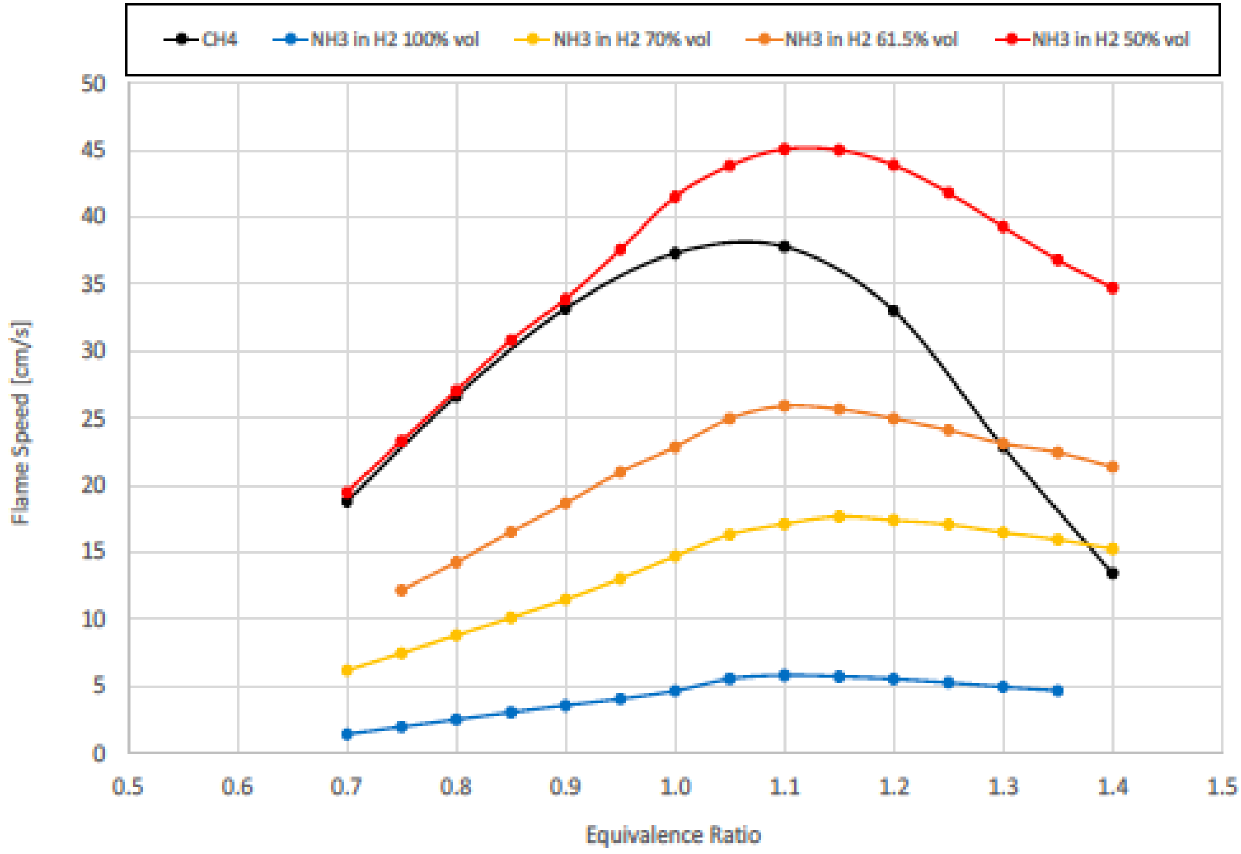
&

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)

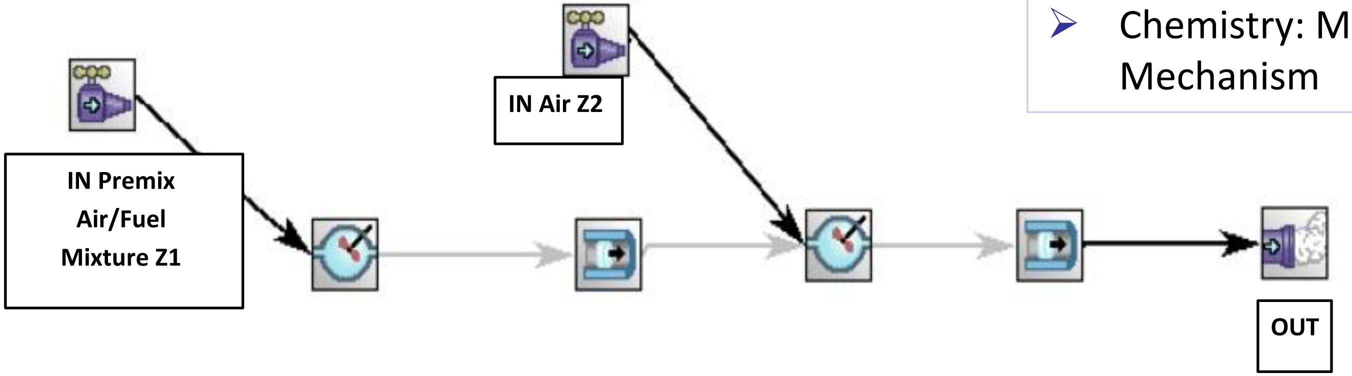


1D Chemical Kinetics Simulations

UCICL Rig Modelling

Radial Swirler Configuration:

- Code: ANSYS Chemkin
- Chemistry: Mathieu Mechanism

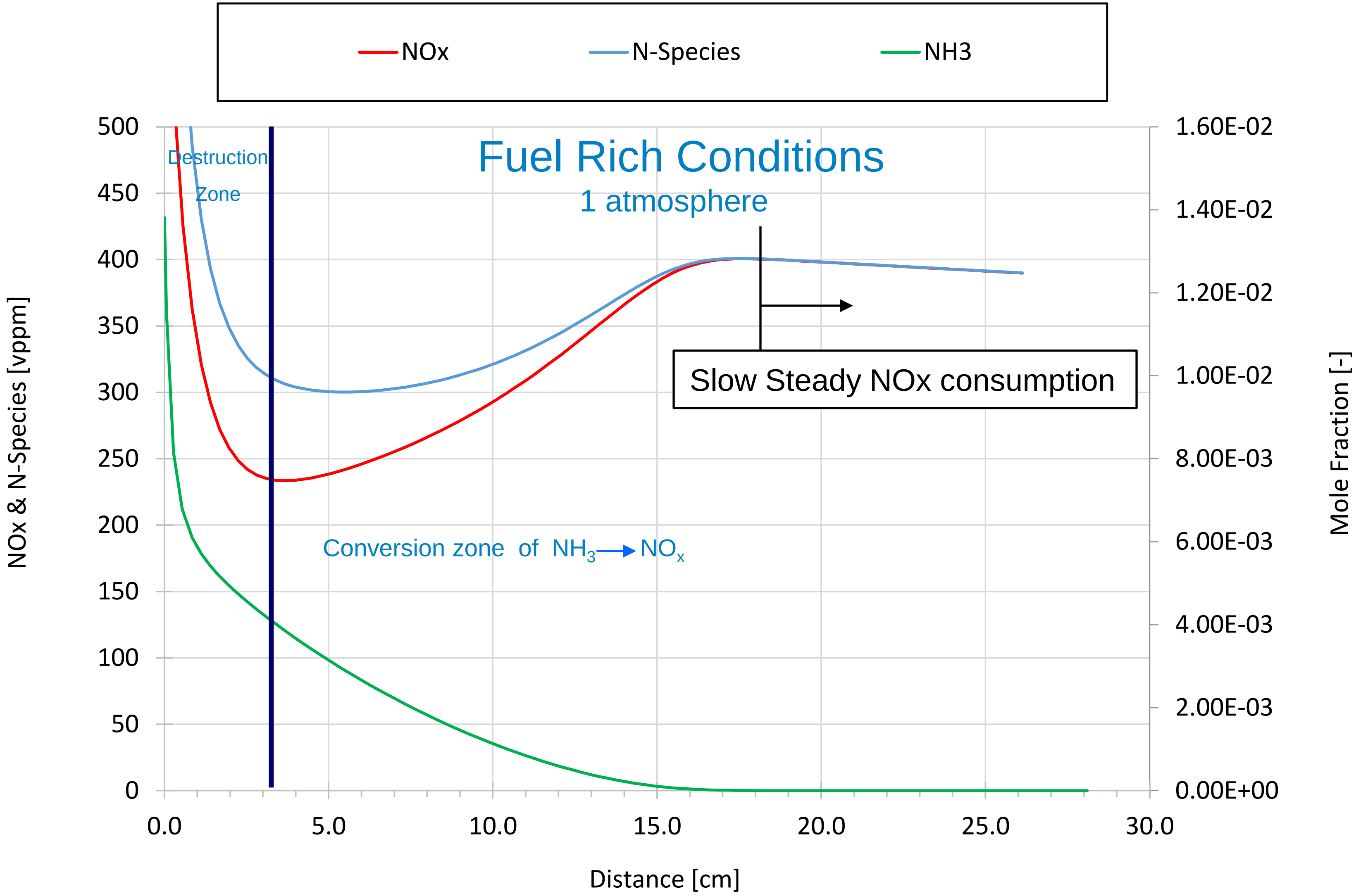


IN Premix Air/Fuel Mixture Z1

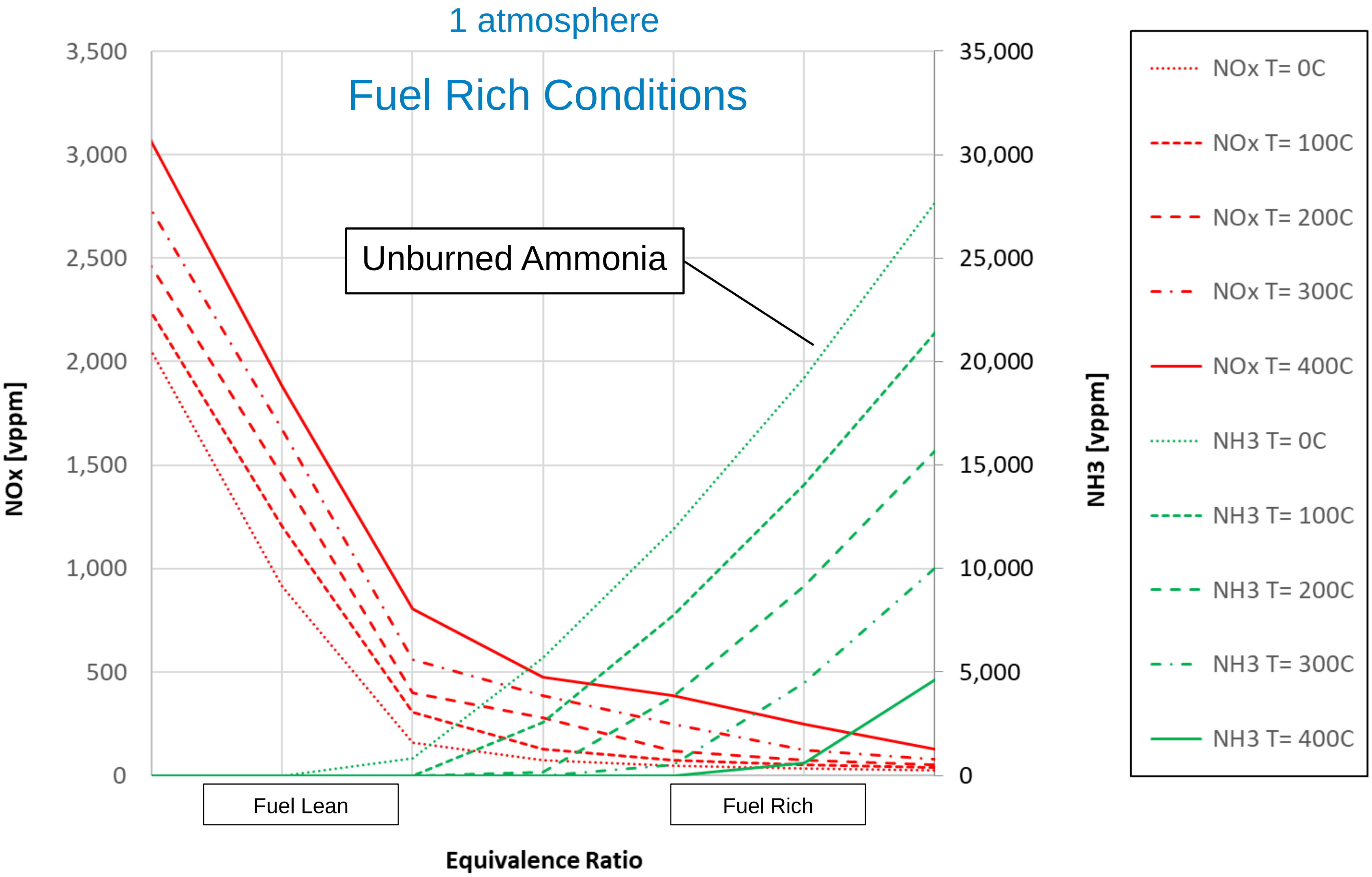
IN Air Z2

OUT

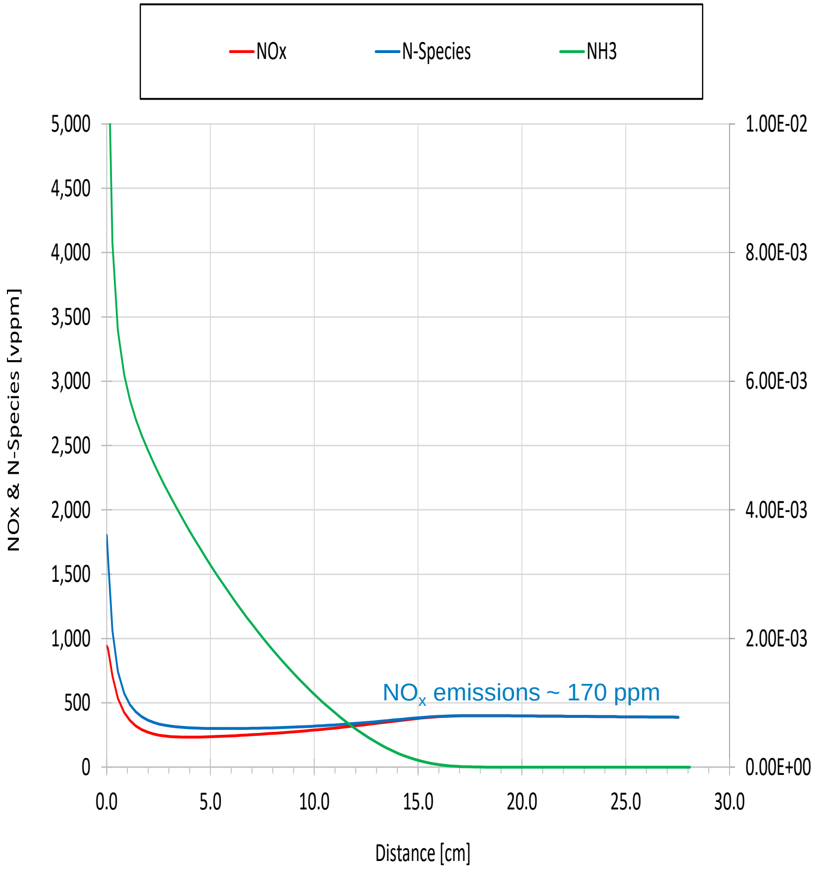
NH_3 and NO_X Formation/Reduction along the Path of a Well Stirred/Plug Flow in Series Reactors



Influence of Preheat Temperature on NH3 Burnout and NOx Formation

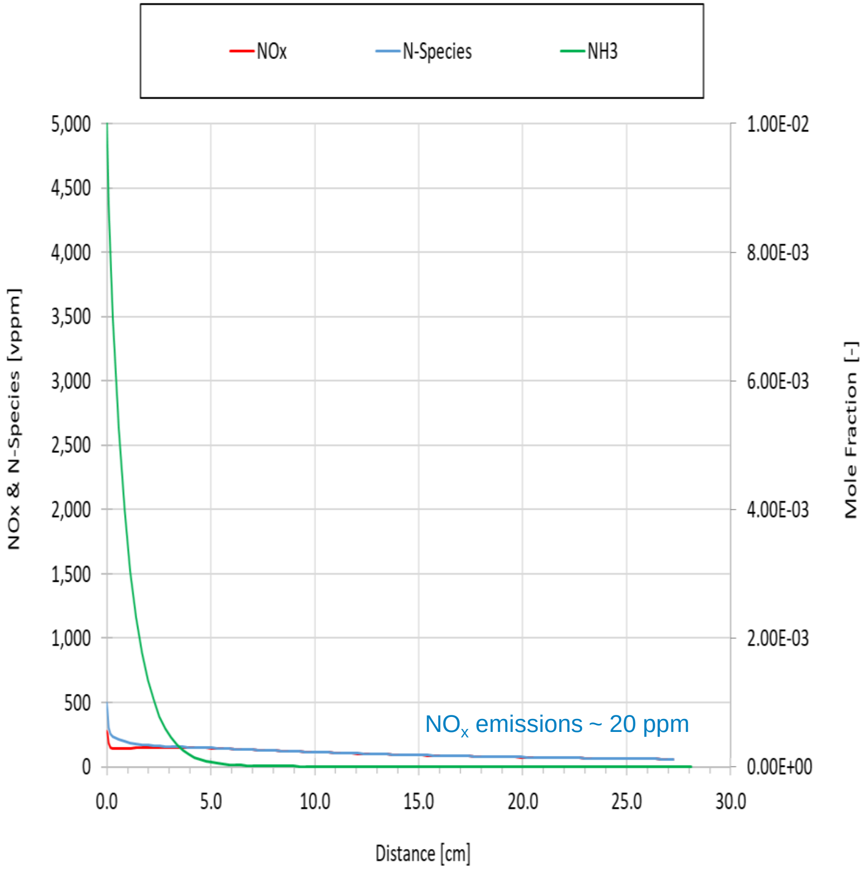


Influence of Pressure on the Formation/Destruction of NH_3 and NO_x Under Fuel Rich Conditions



NO_x emissions ~ 170 ppm

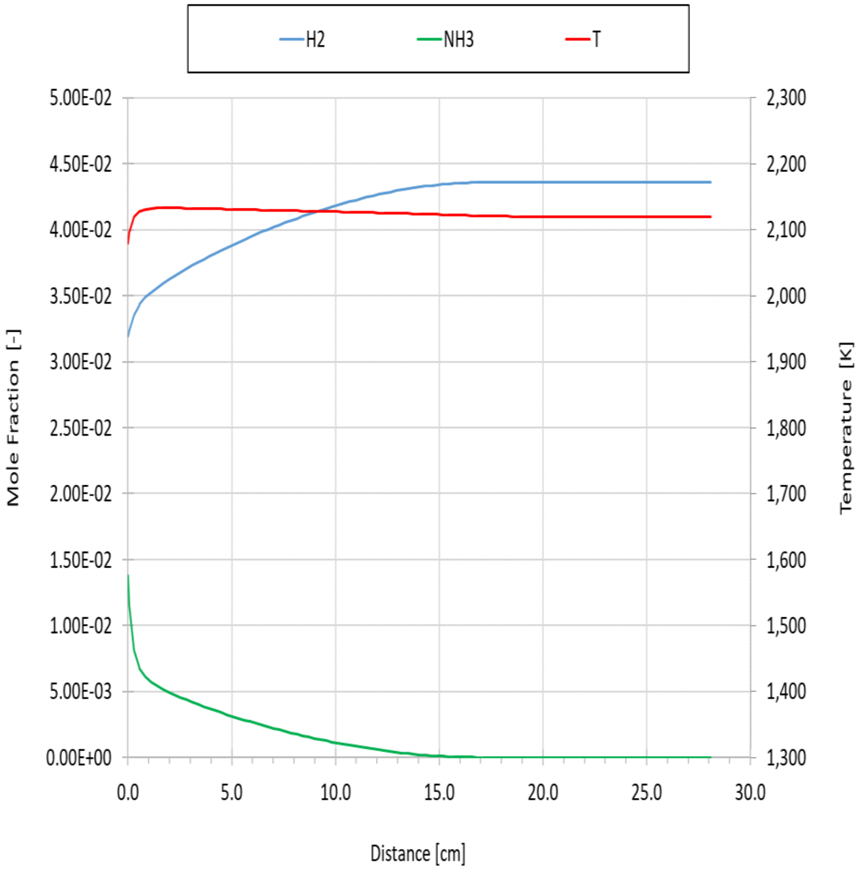
p = 1 atm



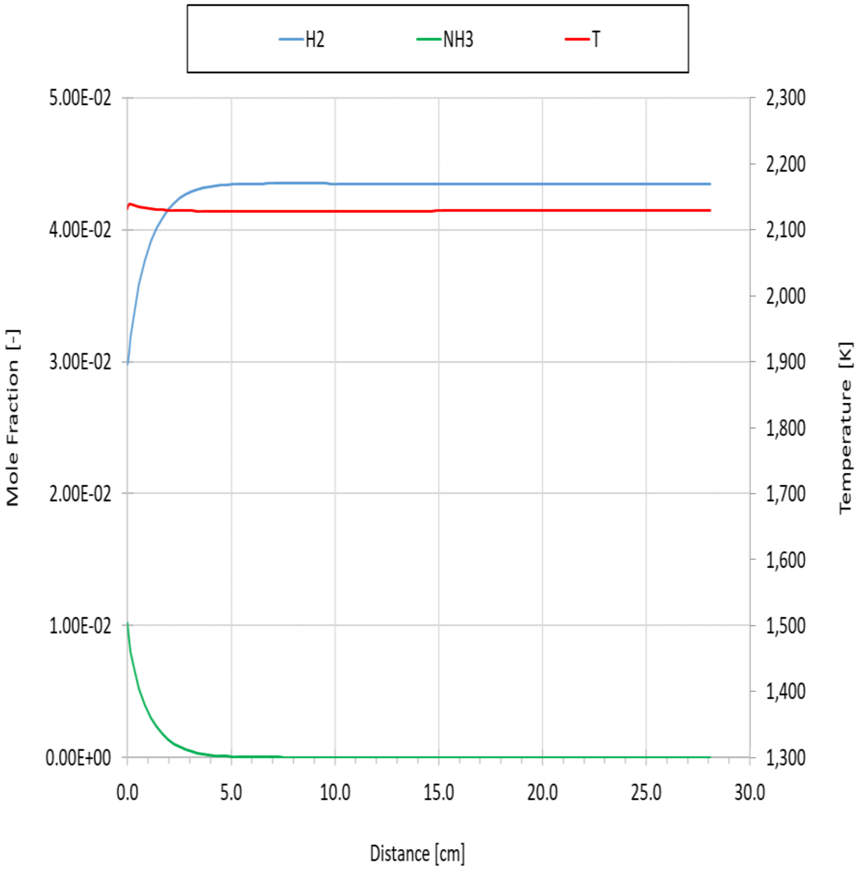
NO_x emissions ~ 20 ppm

p = 20 atm

Influence of Pressure on the formation of Hydrogen from NH3 under Fuel Rich Conditions



p = 1 atm



p = 20 atm

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 Ammonia Combustion Modelling

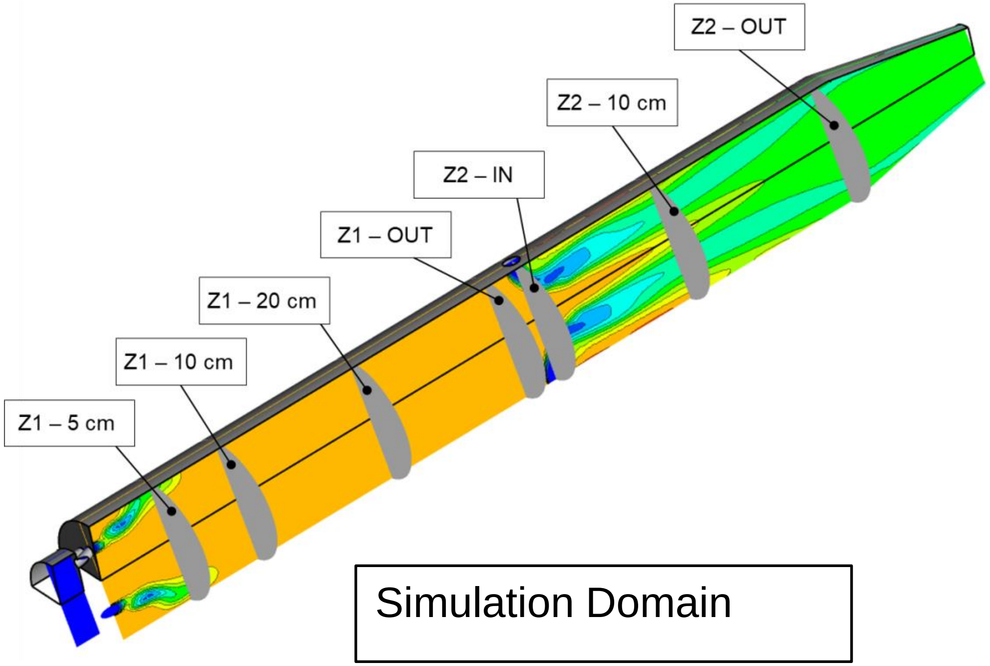
Methodology

CFD Model

Solver:	ANSYS Fluent 2020 R1
Viscous Model:	k-omega
Chemistry:	Mathieu Mechanism
Species Model:	Partially Premixed Combustion C Equation

- Flamelet Generated Manifold

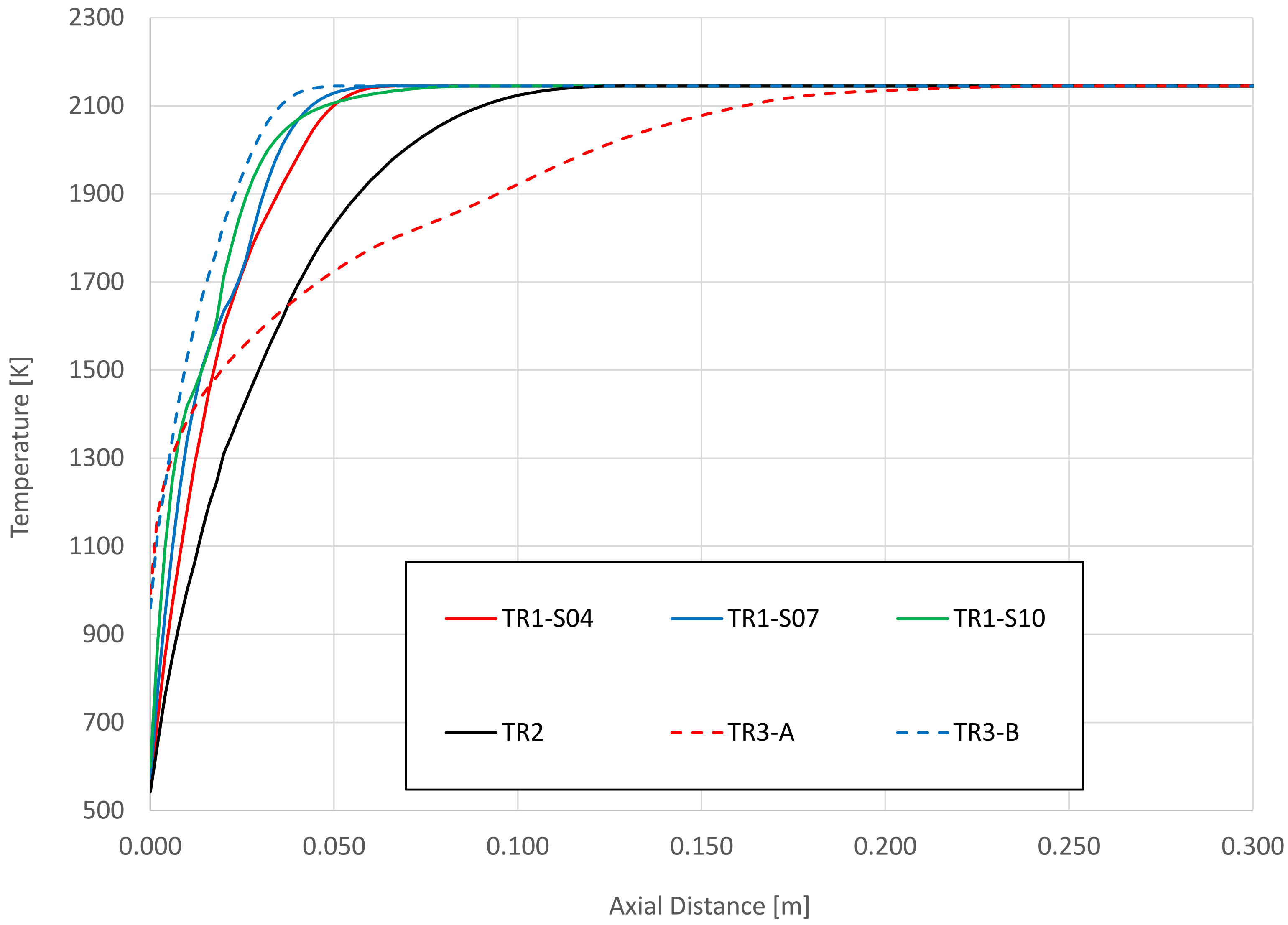
  (Premixed Flamelet)



Simulation Domain

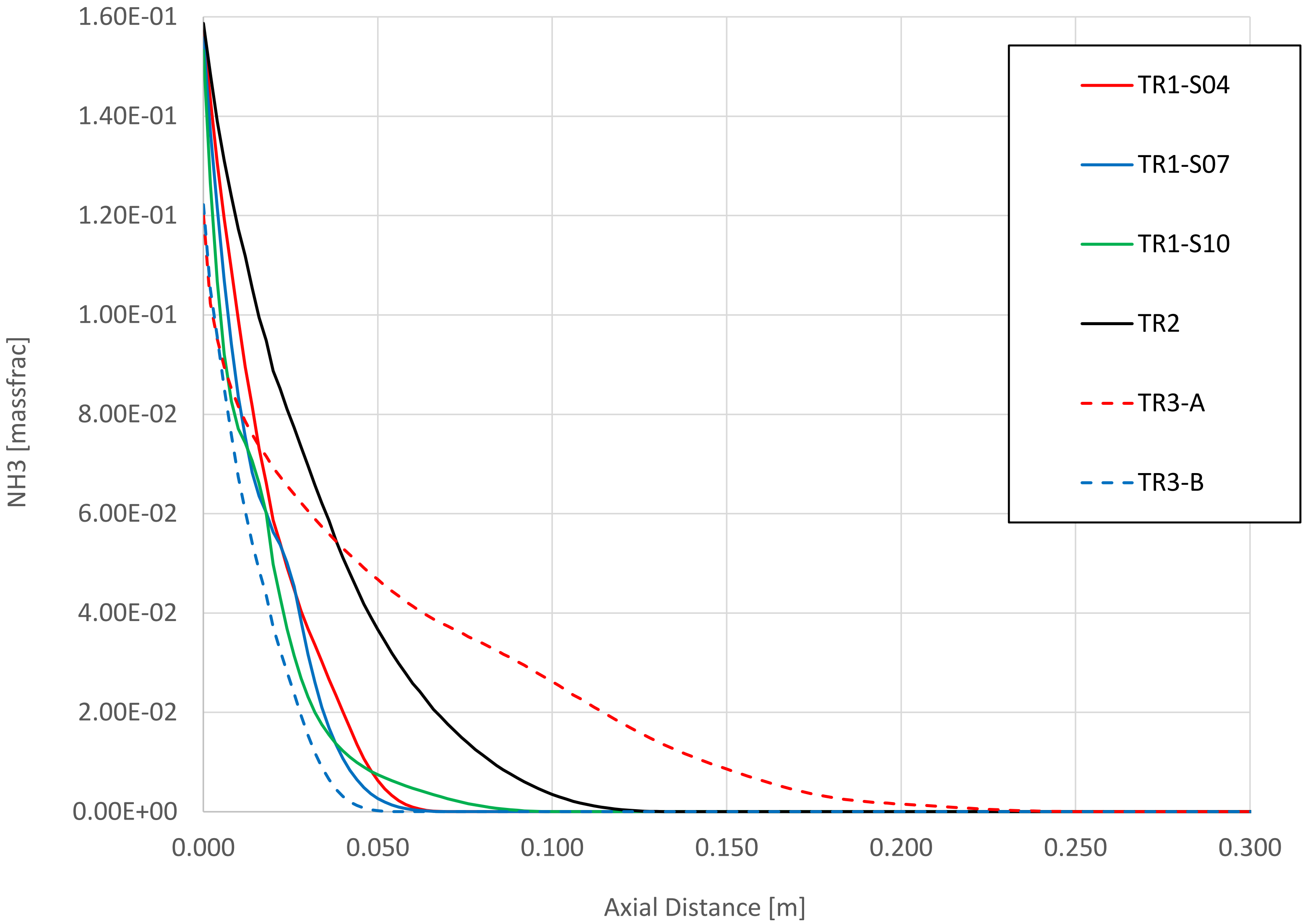
CFD Ammonia Combustion Modelling

Primary Zone Temperature



CFD Ammonia Combustion Modelling

Primary Zone NH3 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 (TR) 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.

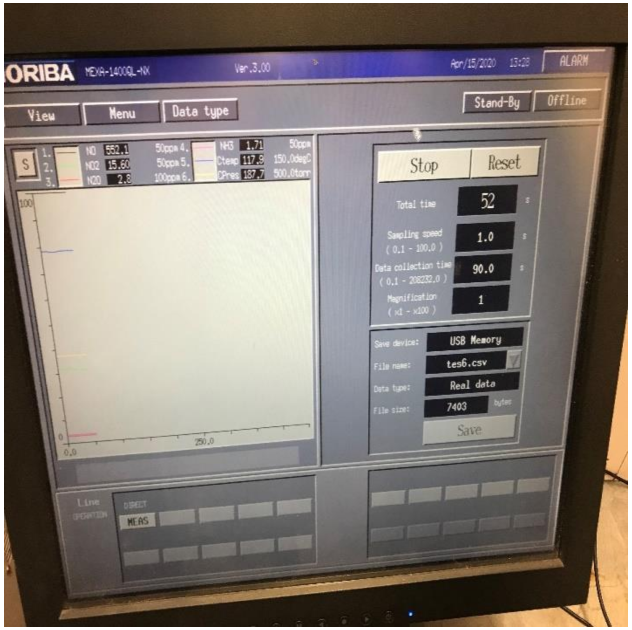
- The three best performing burner designs based on the CFD results where then tested in the UCICL test rig.

Lab-Scale Combustion Tests at UCICL

Diagnostics

CFD Ammonia Combustion Modelling

- Emissions
  - Horiba PG-250/PG-235
    - Primarily for O2 measurement
  - Horiba MEXA QCL-1400-NX
    - NO, NO2, N2O, NH3
  - Water cooled 0.25” extractive probe located at exit of the 2nd stage
    - Water dropout system
    - Samples are on a dry basis
    - Corrected to 15% O2 (measured O2 levels)

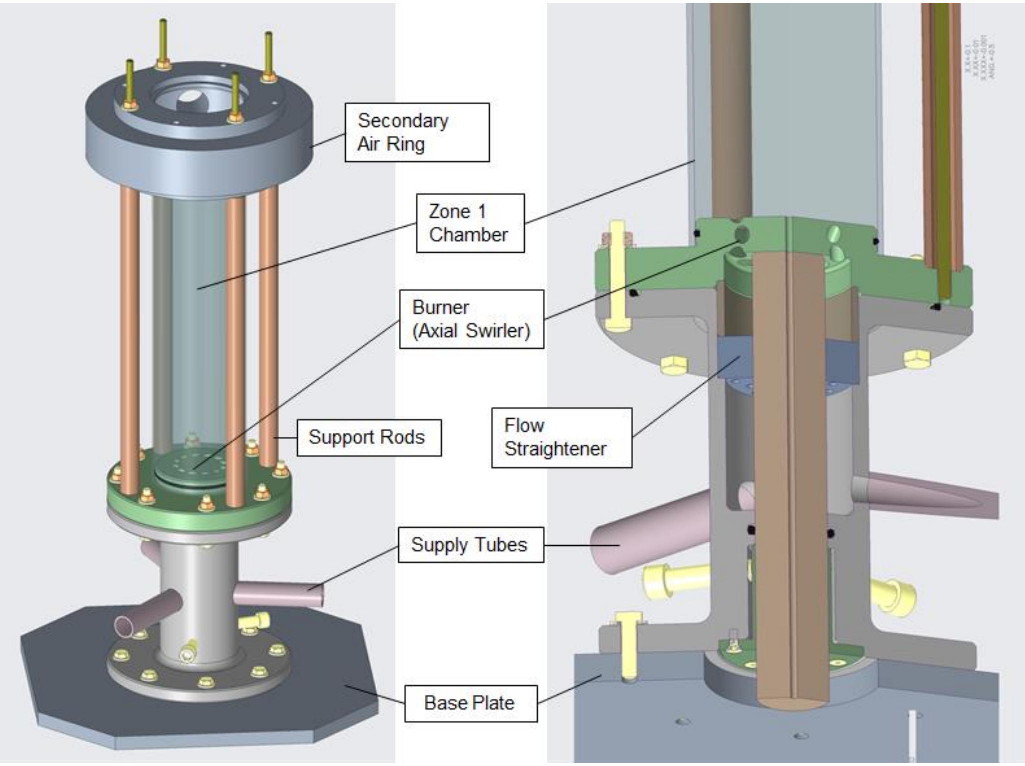

ORIBA MEXA-1400QL-NX Ver.3.00 Apr/15/2020 13:28

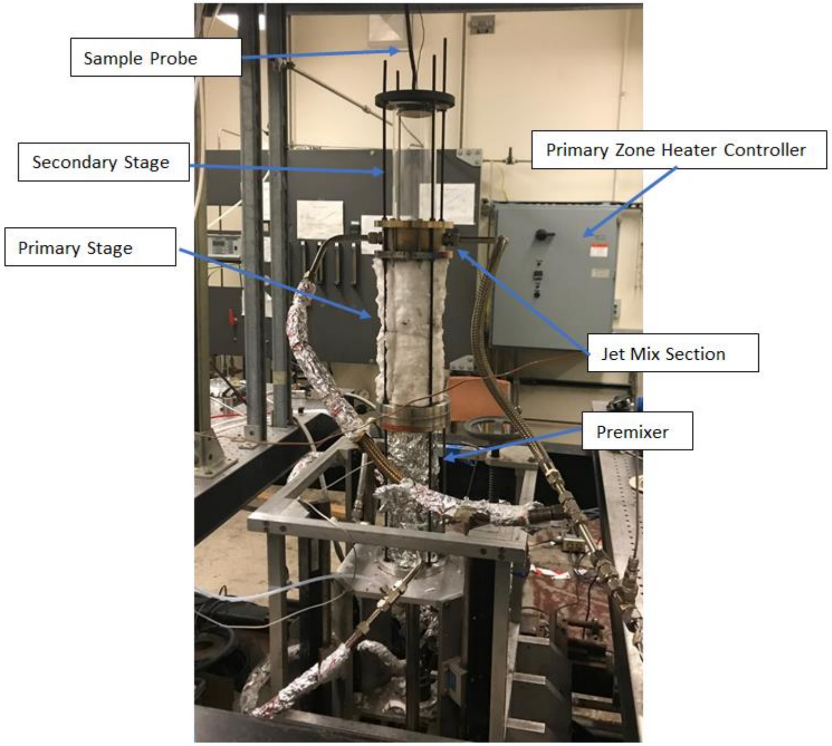
NO 552.1 50ppm
NO2 15.60 50ppm
N2O 2.8 100ppm
NH3 1.71 50ppm
Ctemp 117.9 150.0degC
CPres 187.7 500.0torr

Total time 52 s
Sampling speed (0.1 - 100.0) 1.0 s
Data collection time (0.1 - 208232.0) 90.0 s
Magnification (x1 - x100) 1

Save device: USB Memory
File name: tes6.csv
Data type: Real data
File size: 7403 bytes

Experimental Setup at UCICL





NH3 Combustion Flames at 1 atm

- Observed Stable Combustion Flames

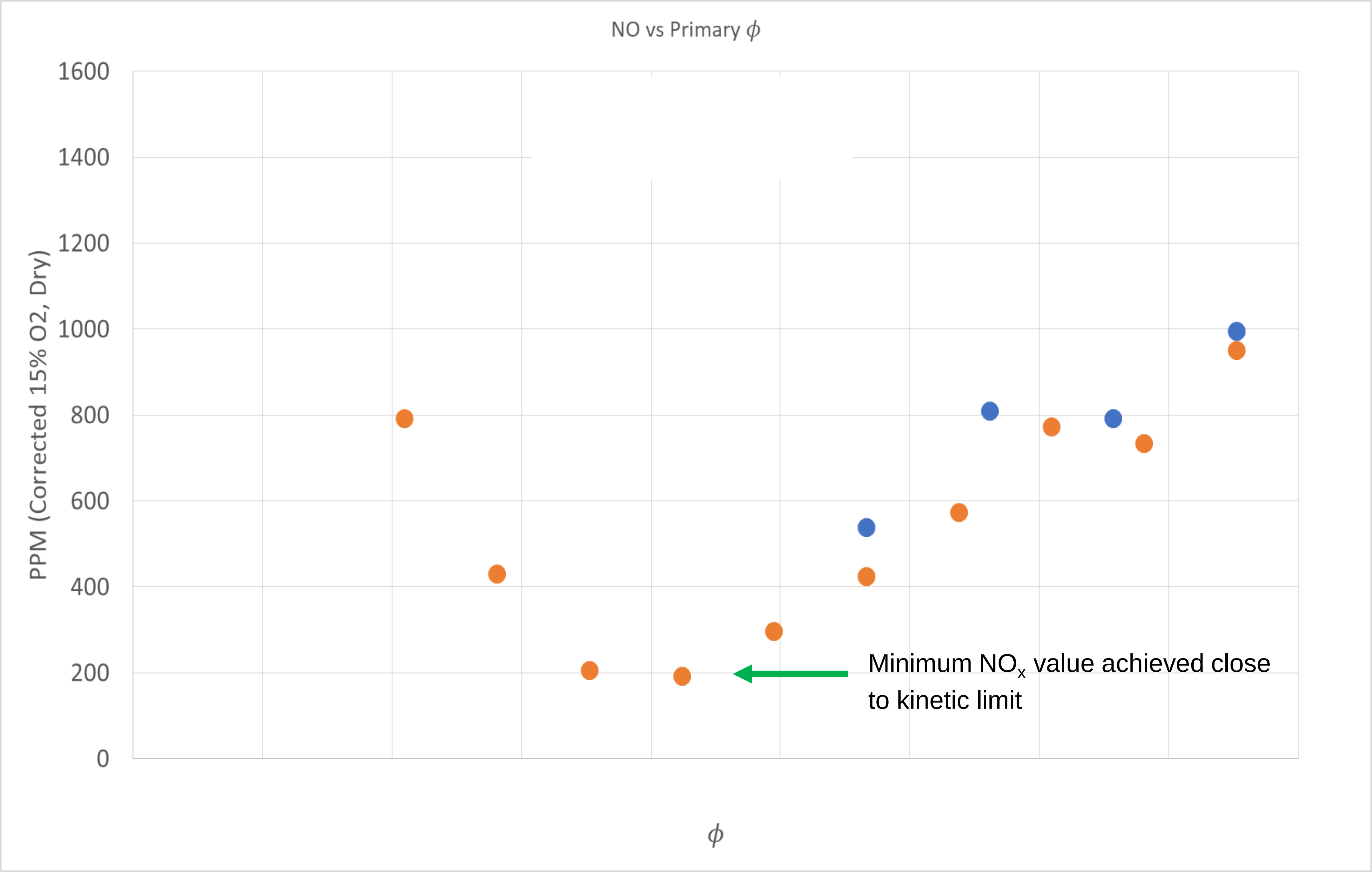
Lean PZ

~ Stoichiometric PZ

Stable Operation attained approaching LFL for NH3/Air
Allowed focus on 100% NH3 rather than NH3/H2 mixtures

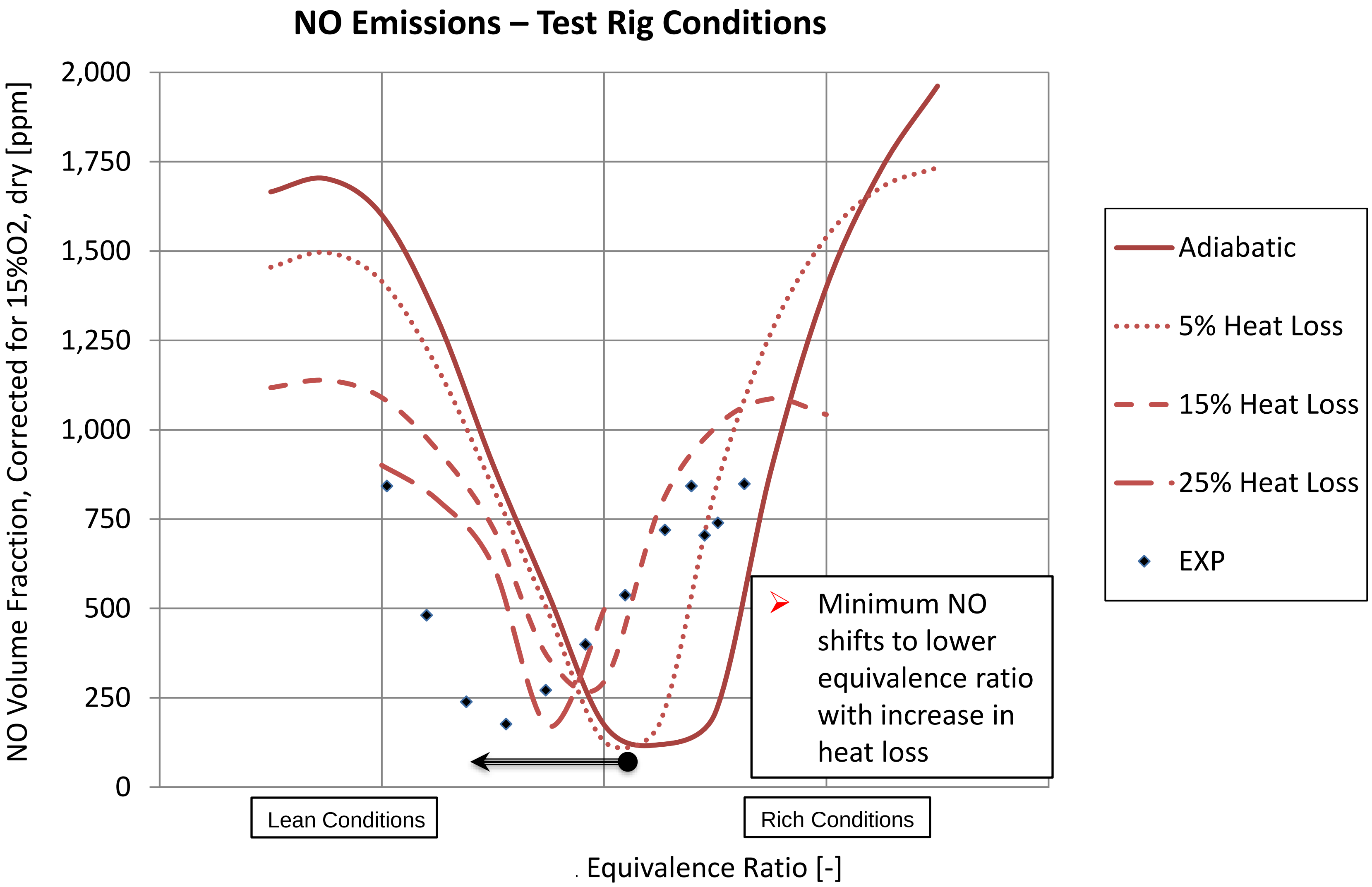
NOx Emission Levels from Ammonia Flames at One Atmosphere

Measured NO_x emissions from the atmospheric laboratory scale experiment



Minimum NO_x value achieved close to kinetic limit

Kinetic Modeling Results Vs. Experimental Heat Loss



- Minimum NO shifts to lower equivalence ratio with increase in heat loss

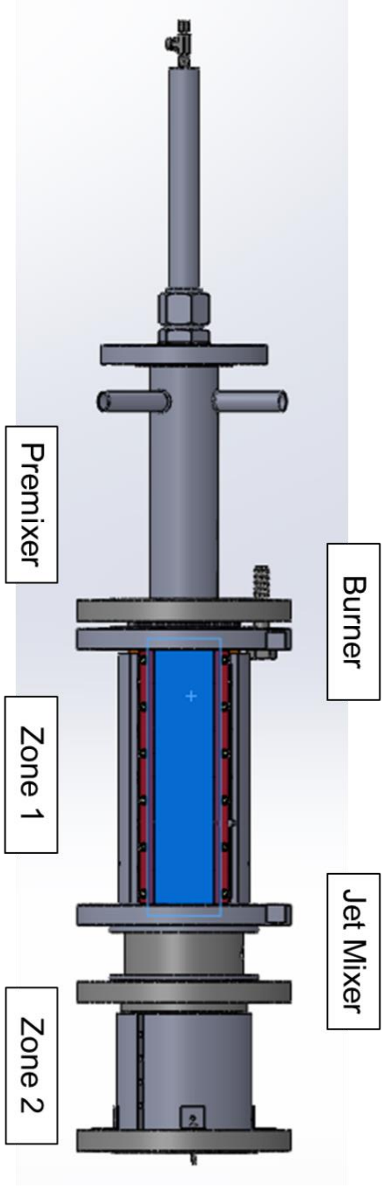
Phase II

High Pressure Combustion Tests

(Towards NH3 mGT)

UCICL High Pressure Combustion Test Rig

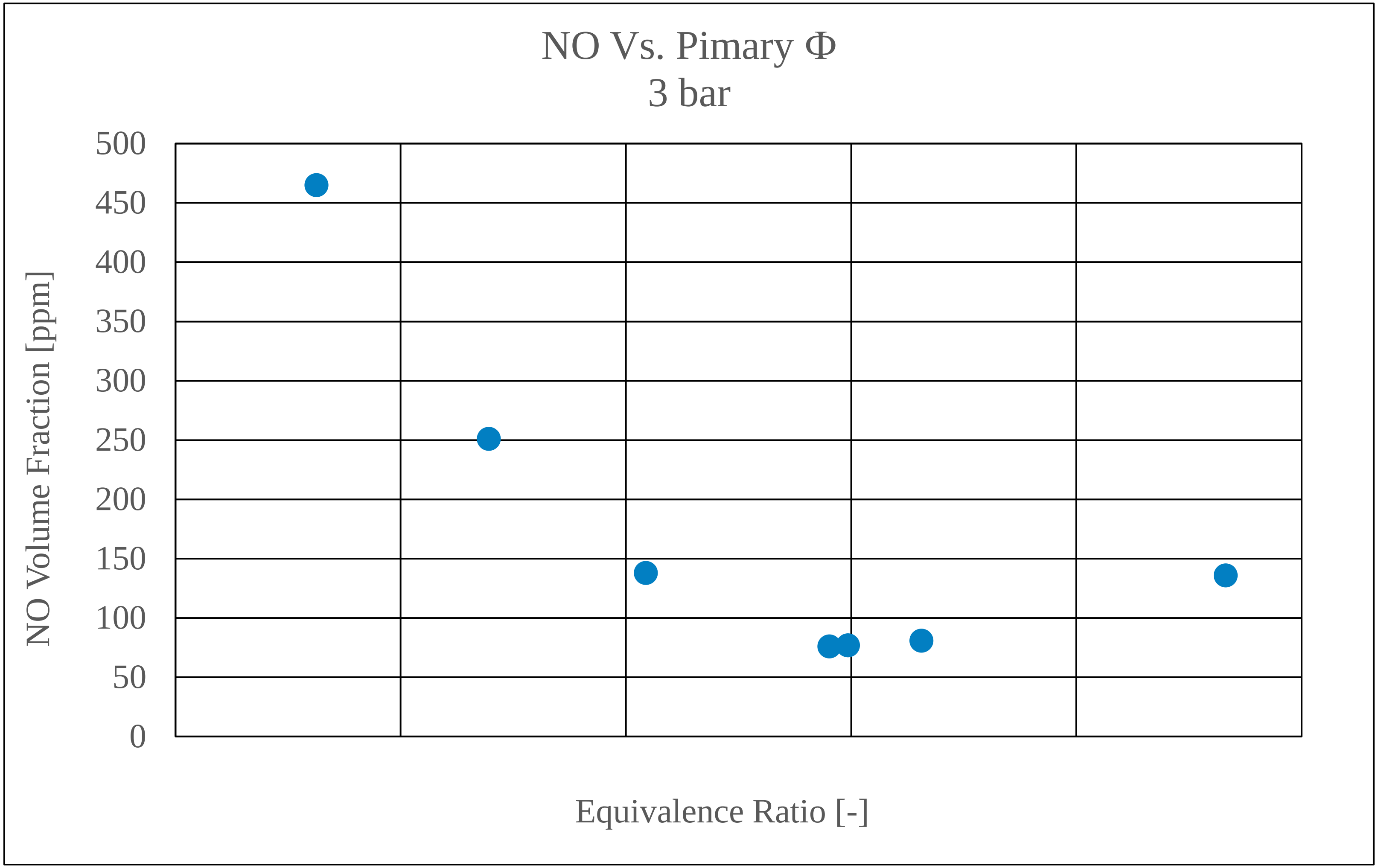
- Rig Designed to simulate ~1/2 engine cycle conditions:
  - 100 kW steady-state thermal power
  - 4 bar P3
  - 1200 K T3
  - Emissions sampling
  - Acoustics probe
- Concept built around standard 150 lb schedule 40 pipe and flanges
  - Excellent optical access to the flame zone (zone 1)
  - Zone 2 is 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



Phase II Combustion Tests

Preliminary Results

Phase II results for NO emissions at higher pressures are very encouraging



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 or has a single silo combustor.
- Combustor inlet air temperature should be as high as possible to facilitate ammonia ignition and flame stability.

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

- NO_x emission levels from the experiment 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

- The results show that it is highly feasible to burn NH_3 in gas turbine applications

- 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

- DOE awarded the second phase of the program to Creative Power Solutions to continue developing the ammonia gas turbine; this phase includes the design and testing of the combustor under real engine conditions
    - The most recent results of phase II show that the new ammonia combustion system is able achieve very high flame stability as well as very low NO_x and ammonia emissions.

Acknowledgements

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