AMMONIA GAS TURBINE COMBUSTOR

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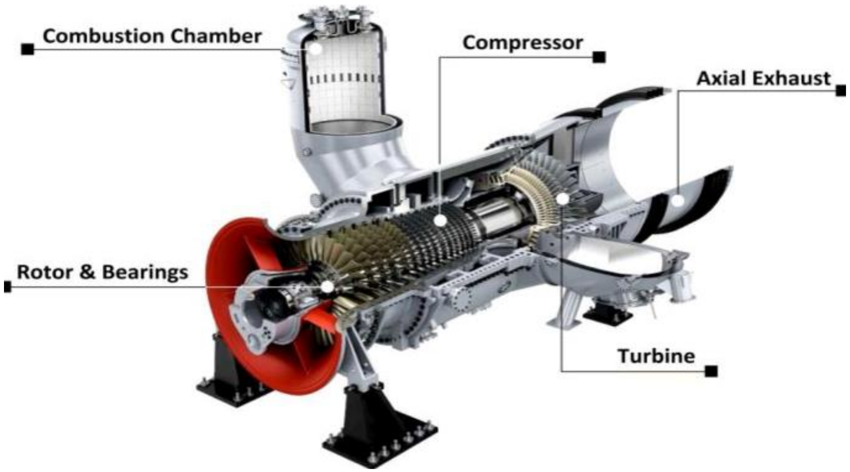
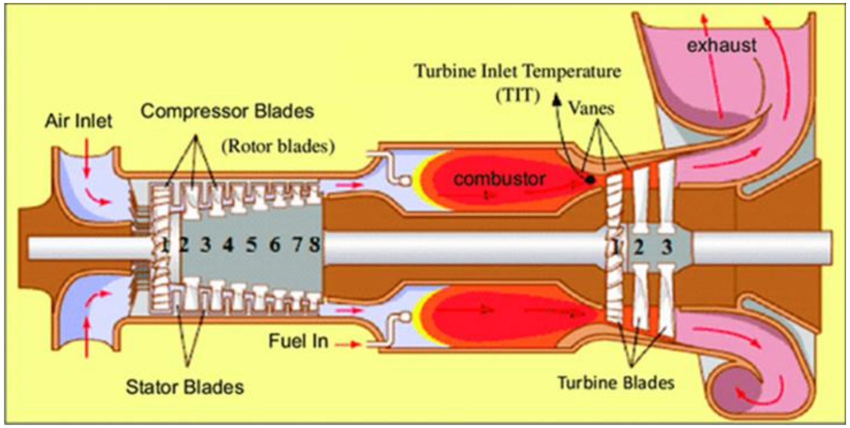
Introduction

INTRODUCTION
Objectives

- Objective – Develop an ammonia combustor that will be retrofitted into a gas turbine and operate the engine across all load levels.

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





Prototype Engine

NH_3 Chemistry → Industrial GT Combustor

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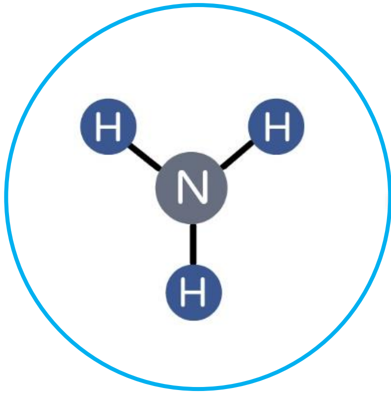
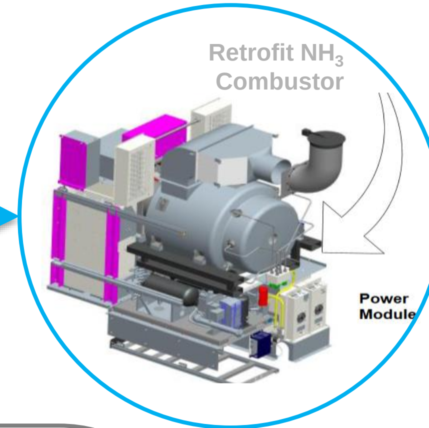
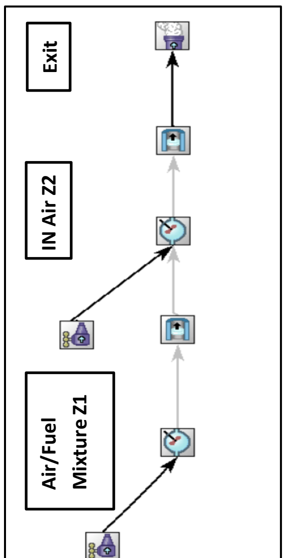
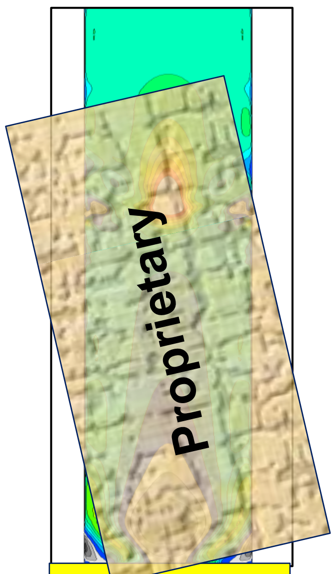


Complete		Next Step
Phase I (2020)	Phase II (2021-2024)	Phase IIB (2024-2026)



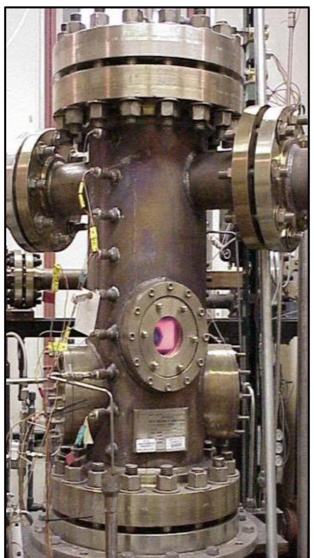


1D Chemical kinetics simulations



3D CFD simulations

Lab-scale NH3 combustion tests at 1 atm

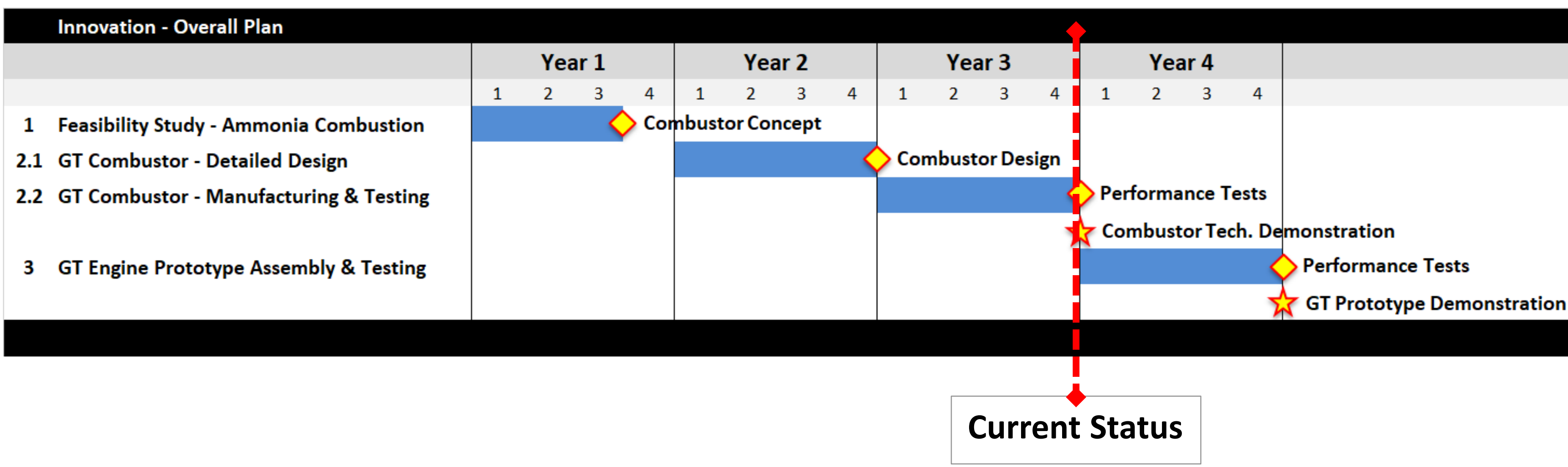


NH3 combustion tests at GT operating Conditions

Technology Development

Ammonia Combustion Innovation Plan

- 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 at combustor exit ✓
  - NH_3 < 1 ppm
  - NOx < 100 ppm (15% Excess O_2)
- Combustor outlet conditions (mass flow and temperatures) to drive GT cycle ✓
- Down-selection industrial Gas Turbine ✓



Ammonia Combustion
Challenges

Challenges for Ammonia Combustor	Parameters analyzed to address challenges
❑ Ignition on 100% NH_3	❑ Burner Stabilization Method
❑ Flame Stability	❑ Equivalence Ratio
❑ Low Emissions across all engine load levels	❑ Air Inlet Temperature
❑ Translation to physical design	❑ Pressure
	❑ Residence Time

- Microturbine Engine Selection criteria:
  - Relatively small engine size with a recuperative capability (Advantageous for Decentralized Power).
  - Combustor inlet air temperature should be as high as possible to facilitate ammonia ignition and flame stability.
  - Easy modification of the combustor section

Current State-of-the-Art Natural Gas Combustion Systems

All state-of-the-art gas turbines natural gas combustion systems are characterized by the following:

- They are based on **premix combustion** concept at full engine loads
- **Combustion temperatures** are maintained below the threshold of high rates of formation of thermal NO
- The burners rely primary on **swirling flows** that maintain internal recirculation zone close to burner exit to stabilize the combustion process.
- The burners operate under **mixed operation conditions** (premix/diffusion) at engine medium load levels.
- The burners operate under **diffusion combustion conditions at low loads.**
- Burner startup is managed under diffusion mode of operation.

Limitation of current technologies:

- Management of thermoacoustic vibrations due to flame instabilities
- High emissions at medium and low load levels, NO_x, CO
- No possibility to startup the burners under premix mode of operation
- Combustor outlet temperature Spread (TAT spread); overheating of combustor liners and stage 1 vanes

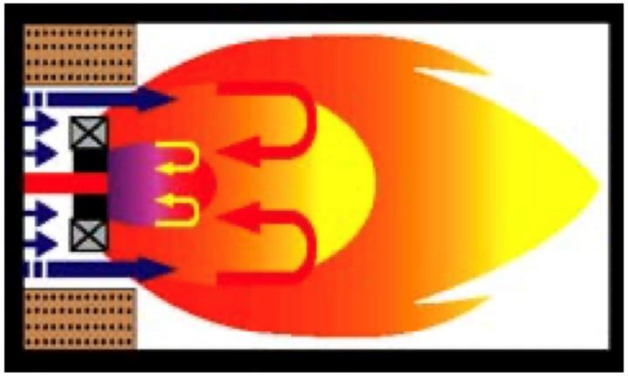


Fig. 1. Non -TVC Swirl Stabilized Combustion (Courtesy of National Combustion Equipment, Inc.)

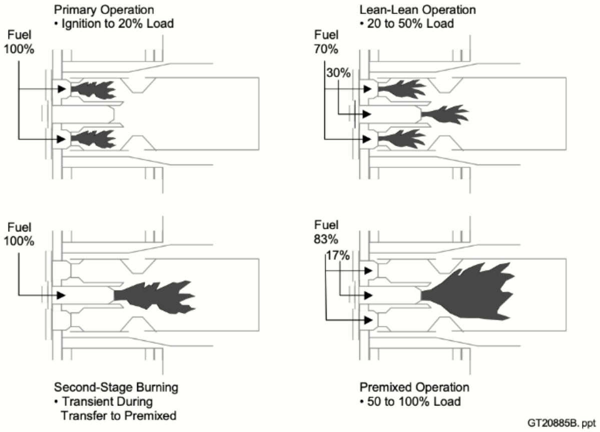
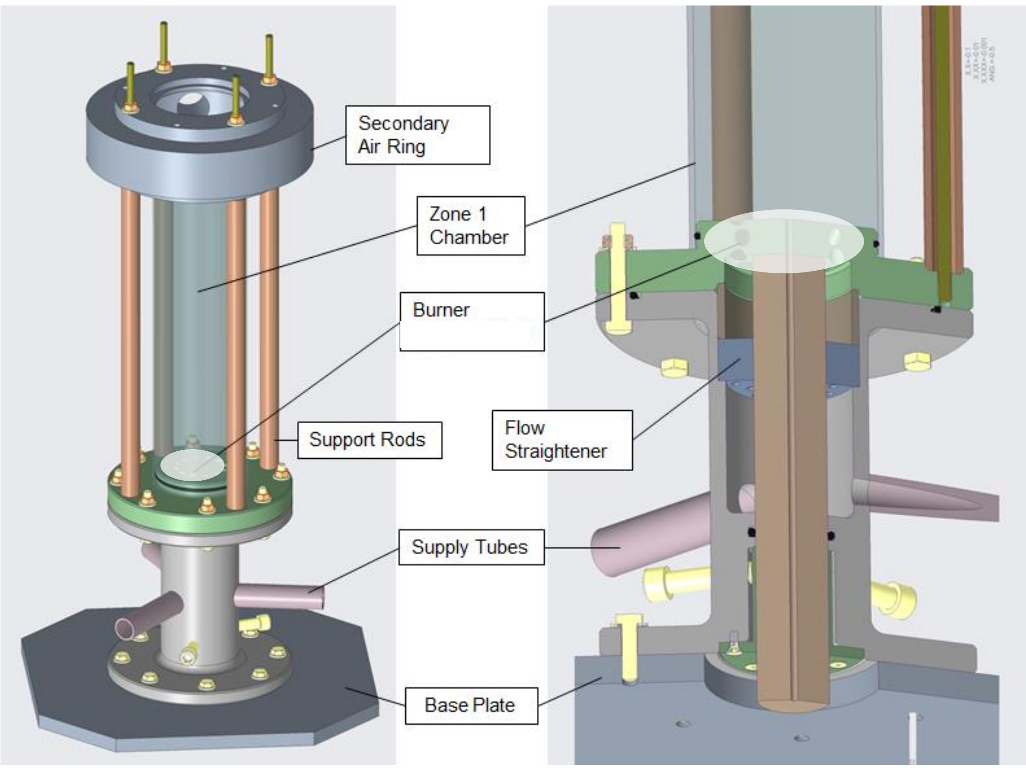
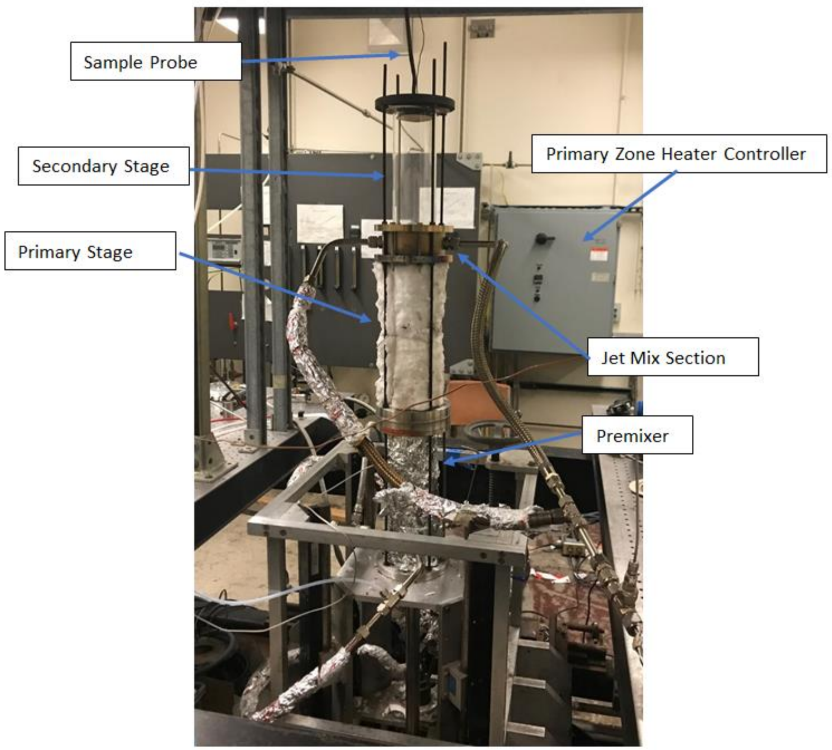


Fig 2. GE's DLN Burner System

Atmospheric and High-Pressure Experimental Set-up at UCICL

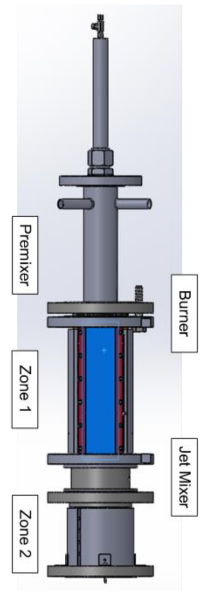
Experimental Setup at UCICL

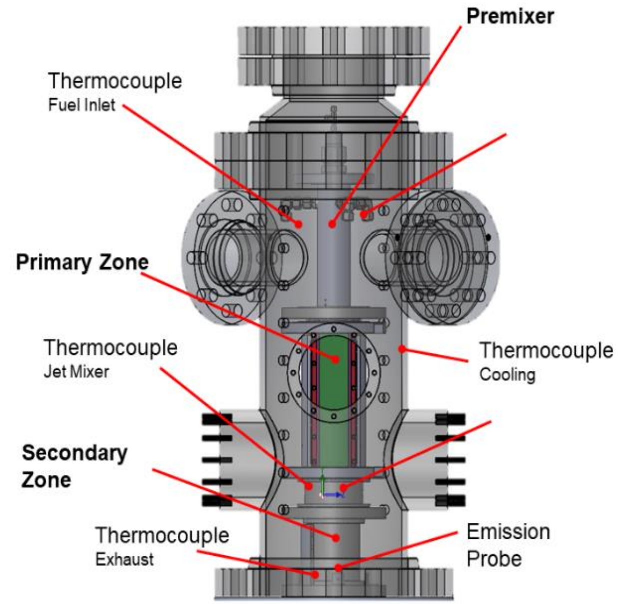


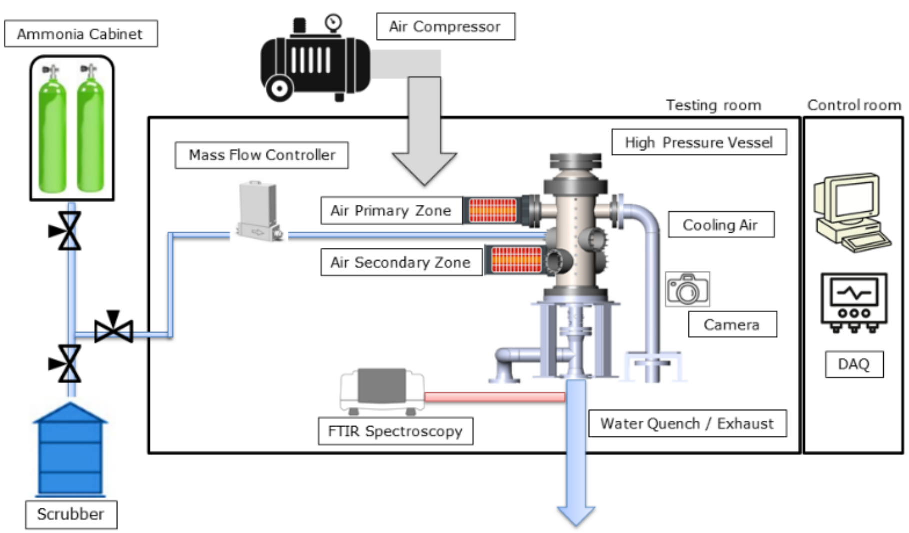


UCICL High Pressure Combustion Test Rig

- 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







Safety Precautions
Ammonia Gas Cabinet

Emergency Shutdown Controller

Sensor #1

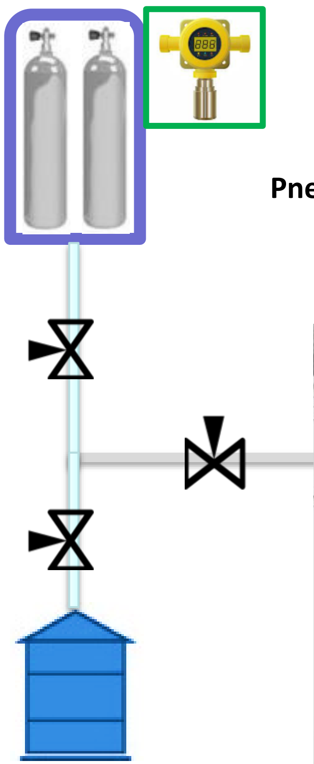
Air Blower

Nitrogen Tank

For Purging

Pneumatic Valve

Scrubber Water tanks



Scrubber
- 280 gallons of water

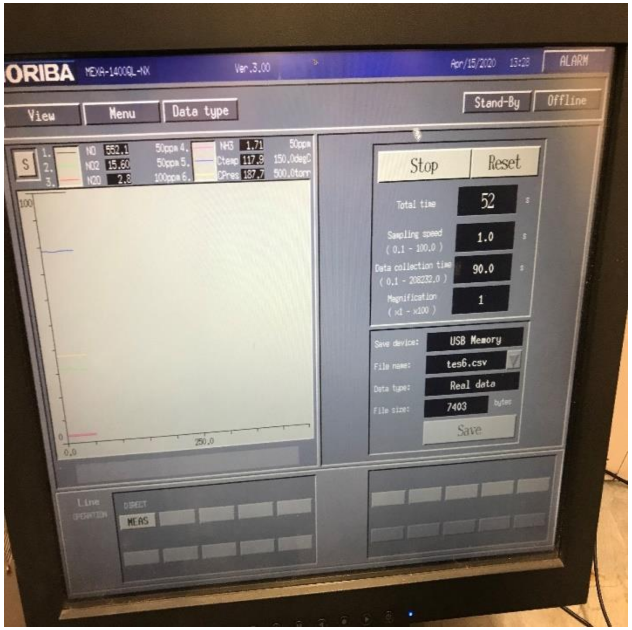
Anhydrous ammonia
- Highly irritating gas
- Colorless
- Suffocating odor

Ammonia Tank

Heater Blanket 2 kW

Ammonia resistant Materials
- Stainless Steel
- Kalrez
- EDPM
- Teflon
- ~~Viton~~

- 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)

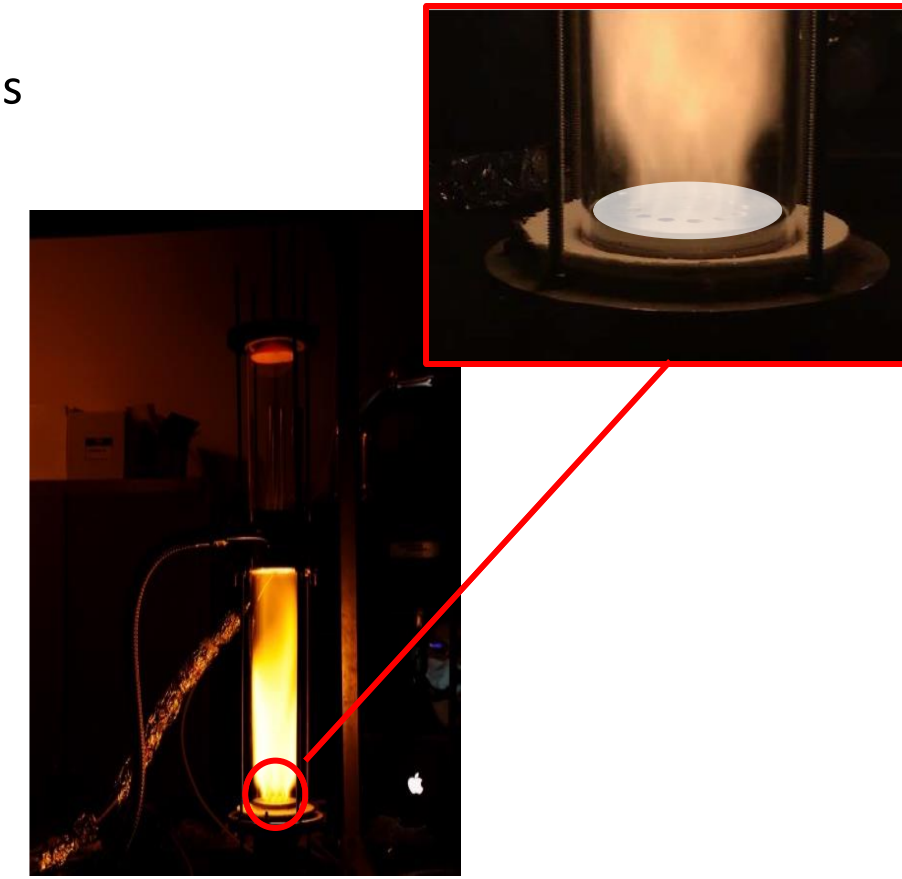


Ammonia Atmospheric Combustion

NH_3 Combustion Flames at 1 atm

- Observed Stable Combustion Flames

Lean PZ

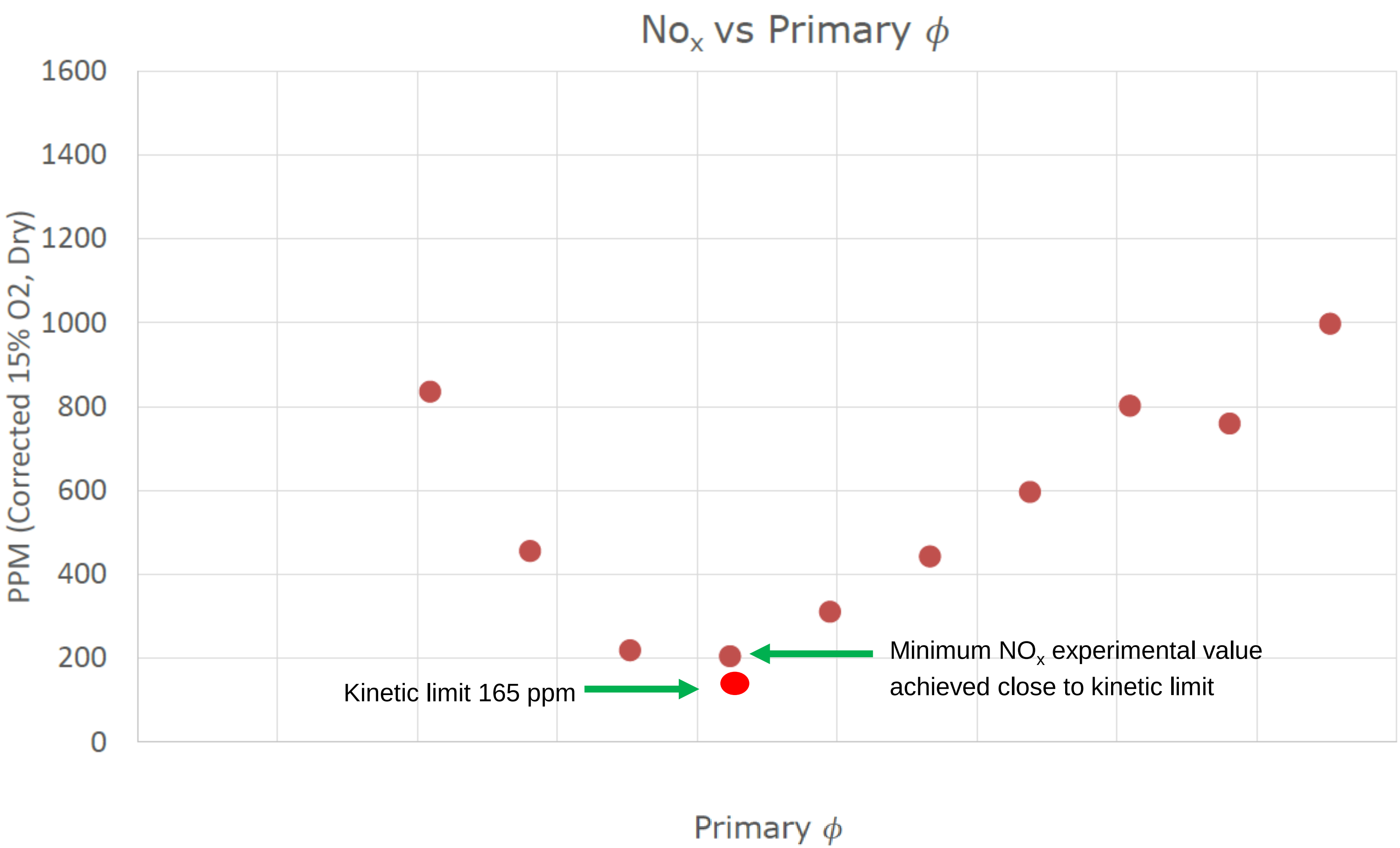


~ Stoichiometric PZ

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



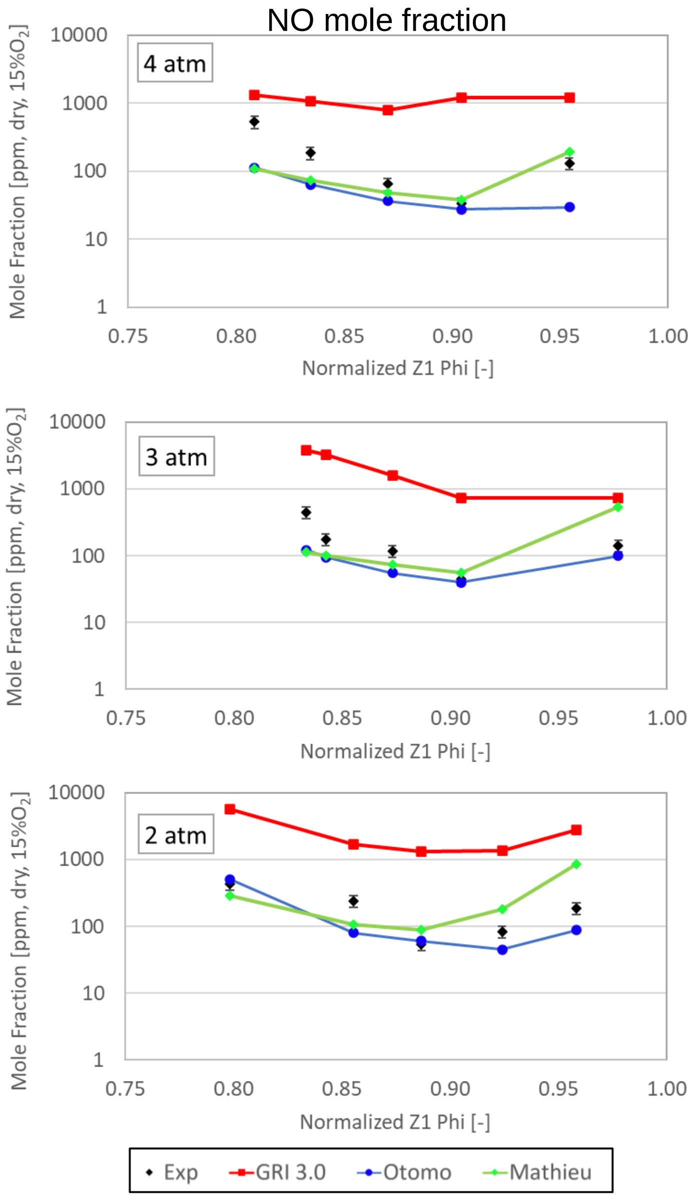
High Pressure Ammonia Combustion Tests at UCICL

Combustion Test Results

NO Mole Fraction – Zone 2

- Chemical kinetics calculations validated against experimental measurements.
- Optimum equivalence ratio shifts to richer conditions with increasing pressure.
- NOx emissions significantly reduced with increasing pressure conditions:
  - TBN_4atm = 36ppm
  - TBN_3atm = 50 ppm
  - TBN_2atm = 90 ppm

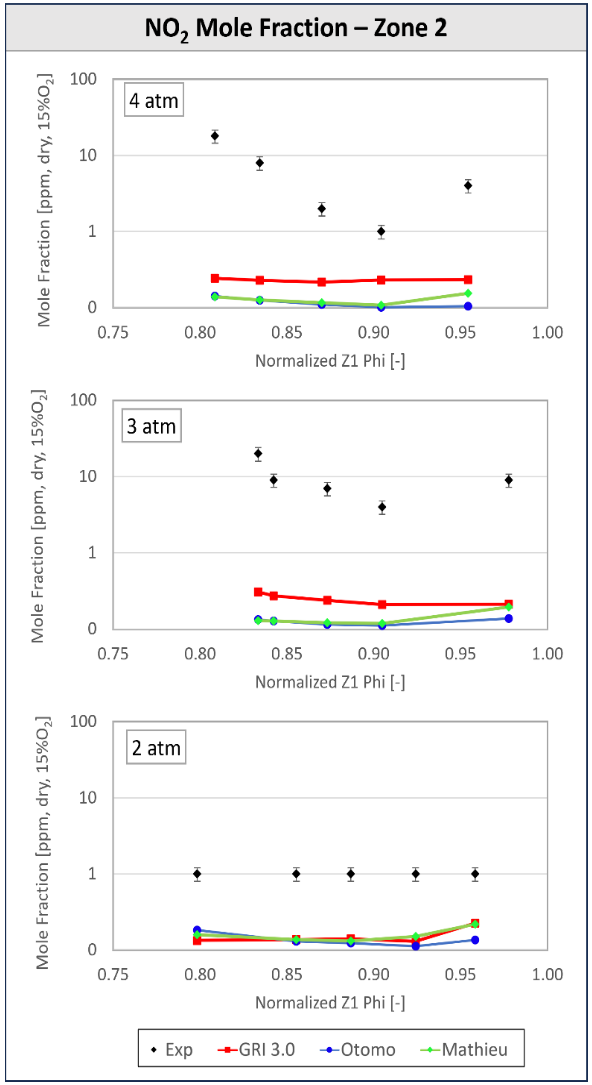
(Total Bound Nitrogen (TBN): is the sum of $NO+NO_2+N_2O+NH_3$)

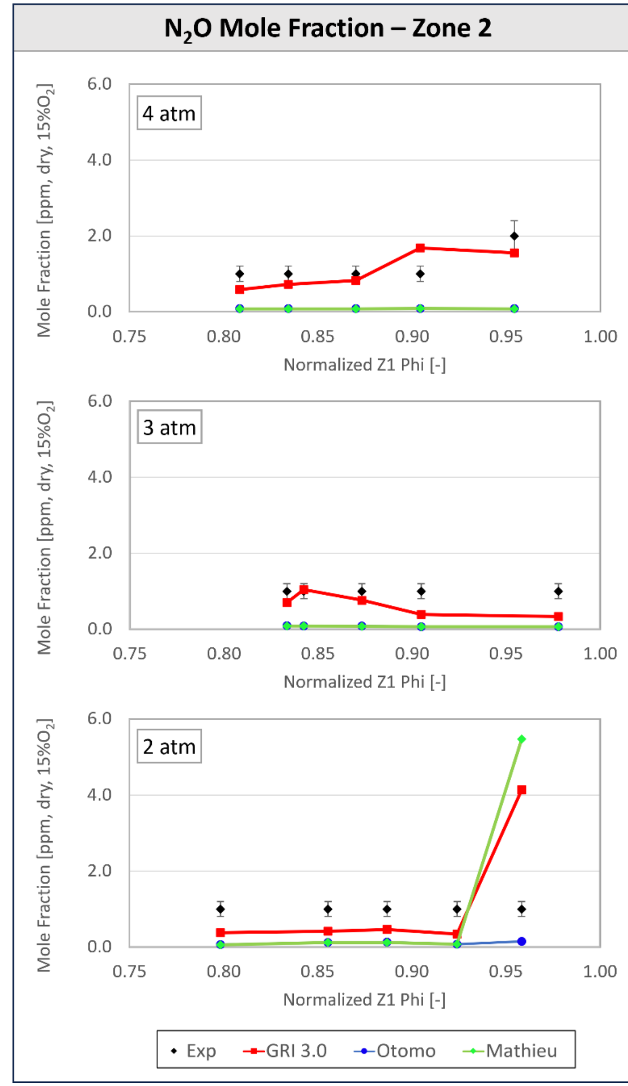


Combustion Test Results

NO_2 and N_2O emissions – Zone 2

- Mole Fraction of NO_2:
  - Experimental data shows that NO_2 follows a similar trend as NO.
  - Chemical mechanisms employed underpredicted NO_2 concentrations at the end of the secondary zone.
- Mole fraction of N_2O:
  - Experimental data shows that higher pressures has no significant impact on N_2O concentrations.
  - Chemical mechanisms employed slightly underpredicted NO_2 concentrations.

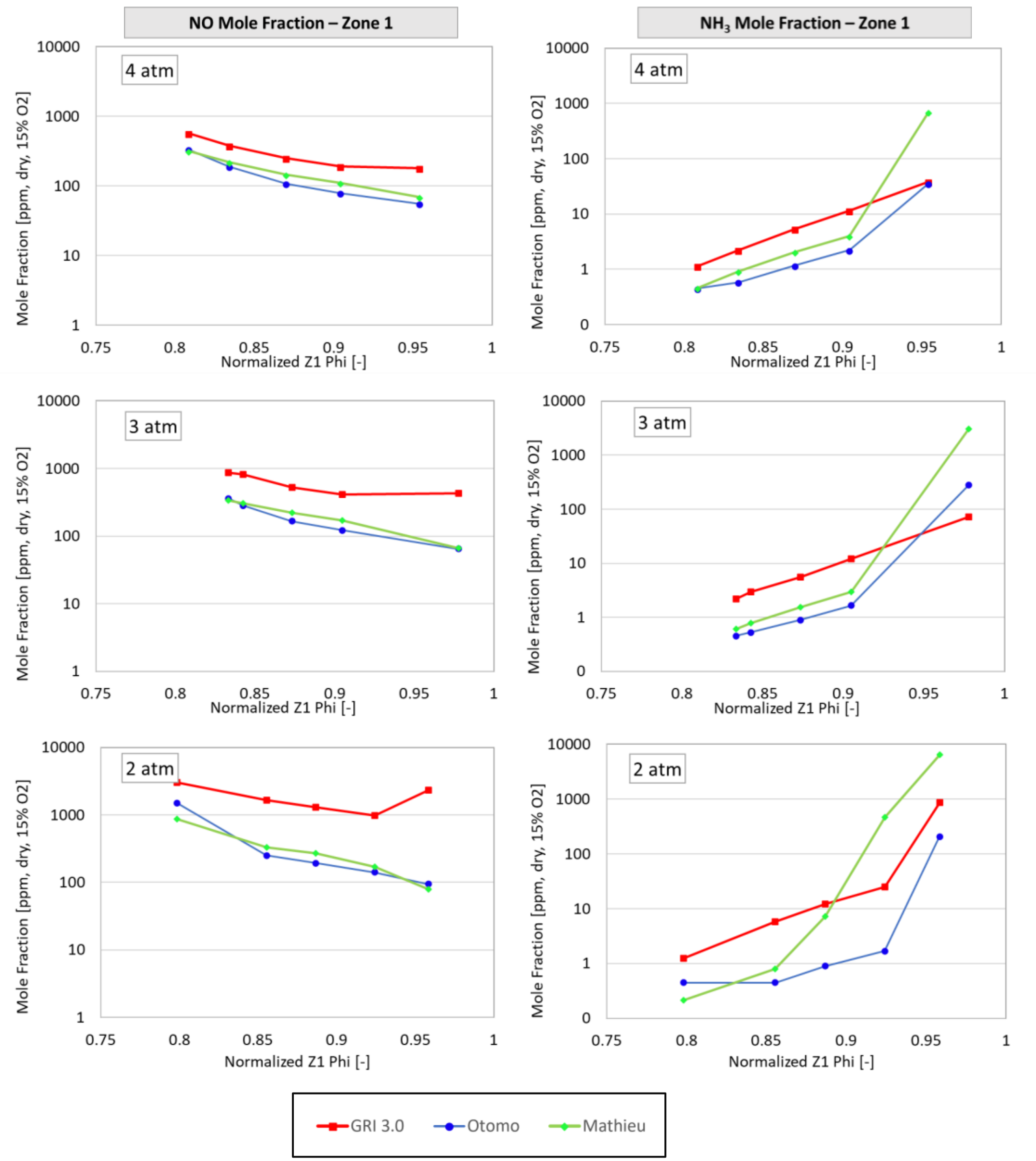




Combustion Test Results

Predictions of NO & NH_3 – Zone 1

- Mole Fraction of NO:
  - Modeling predictions at the end of Zone 1 show that higher pressure leads to lower NO.
- Mole fraction of NH_3:
  - The NH_3 plots confirm that unburned NH_3 quickly rises at higher equivalence ratios.
  - With an increase in pressure, unburned NH_3 levels decrease.
- Other comments:
  - Predictions of species concentrations are generally within the same range across the three chemical mechanisms used. However, under high fuel-rich conditions, the models' predictions become less consistent. The GRI mechanism shows maximum deviations from the other two.



Experimental Measurements Vs. Chemical Kinetics Predictions for NOx Emissions

- Modeling results show that minimum NO_x emission levels rest within a narrow temperature band.
- Experimental results compare well with modelling predictions. Variations could be attributed to the non-ideal rig conditions (Heat Losses) as well as gas analyzer measurement uncertainties.

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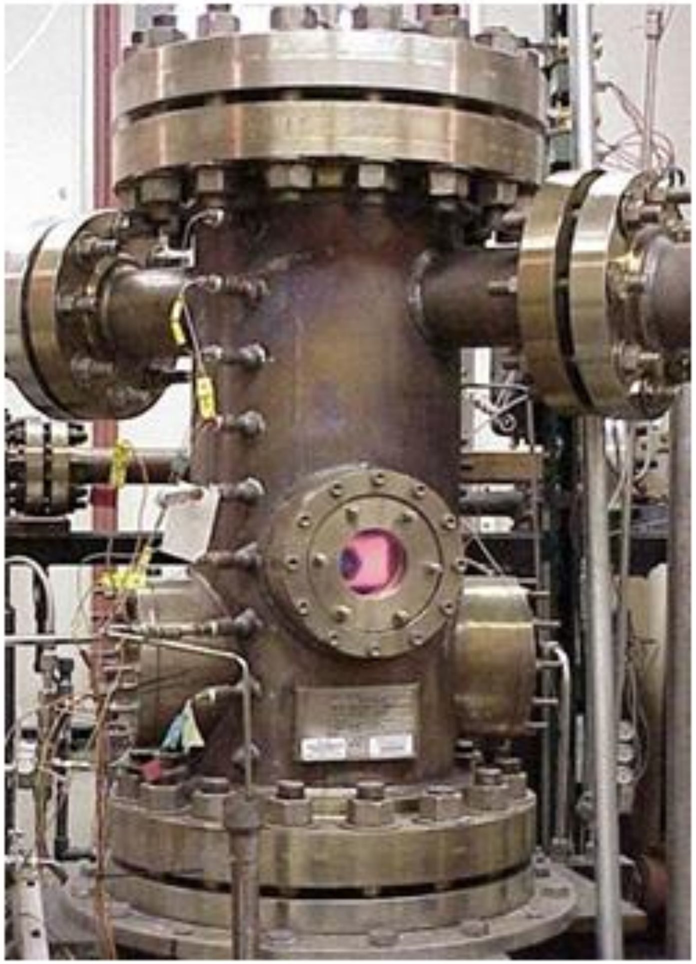
Natural Gas Validation Testing at UCICL

Testing Under Atmospheric and High-Pressure Conditions

- To establish a frame of reference, CPS tested the new burner using natural gas as a fuel in the high-pressure combustion facility at UCICL.
- Pressure was varied between 1-4 bars within the rig.
- Combustion air was preheated to 170 C.
- Combustion tests were carried out using natural gas as a fuel.
- Residence time in the reactor was varied to investigate the impact of short residence time on CO and NO_x emission levels.
- Burner stability was tested under a wide range of relatively low to high combustion temperatures to determine the lean blowoff limit of the new combustion system.



Testing Results Under Atmospheric and High-Pressure Conditions

- Results demonstrate very low NO_X emissions achieved under a wide range of combustion conditions. NO_x emission levels hovered between 2 - 4 ppm.
- Moreover, the new design achieved very low CO emissions, 4 - 34 ppm, under a wide range of temperatures demonstrating the superiority of the new design over existing ones.
- The lean blowoff limit of the new combustion system is extended drastically relative to state-of-the art commercial combustion systems.
- It is noteworthy to mention that heating the combustion air to temperatures typical for gas turbines (400 °C or higher), in comparison to what was done in this program (170 °C), would lead to higher stability making this technology a big disruptor once it is commercially rolled out.
- Moreover, ignition of the burner for ammonia and natural gas cases was achieved in a premix mode of operation.

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Testing Results Under Atmospheric and High-Pressure Conditions

- The new combustion system demonstrates very weak correlation between residence time and CO and NO_x emission levels for the natural gas case across all tested pressures.
- NO_x emission levels increase from 2 ppm for short residence times to 6 ppm for long residence times.
- CO emissions increase from 4 ppm to 34 ppm when the residence time is reduced to 5 millisecond.
- This demonstrates that the combustion process is completed quickly.
- The experimental results support the conclusion of our modelling studies that the new design complete the combustion process in a very short time.
- These results demonstrate the new combustor is superior to current commercial ones.

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Natural Gas Testing – Experimental Results Very Similar to Kinetic Model Predictions

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The experimental program results also show that our kinetic model can provide accurate predictions of the performance of the new combustion system.

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Natural Gas Testing – Experimental Results Very Similar to Kinetic Model Predictions

Our kinetic model exhibits very weak functionality between NO_X and CO emissions and residence time like what was observed experimentally

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Key Conclusions Regarding the New Combustion System Design

Testing the burner using ammonia and natural gas as fuels provided us with the following conclusions:

- Fast combustion achieved in the natural gas case indicating that the new design would achieve similar results for the ammonia case.

- Very low emissions achieved in both cases.
  - Natural Gas NO_x 2-4 ppm CO < 10 ppm
  - Ammonia NO_x <35ppm NH_3 < 1 ppm

- High burner stability demonstrated across both fuels.

- Igniting both fuels in a premix mode of operation were possible without facing any technical obstacles. This is very important for engine startup and engine part load operation.

- Uniform TAT spread; elimination of combustor and 1st stage vane over heating problem

Our New Combustor Technology Outperforms Current Technologies

- The new combustor is a disruptive technology platform … not just an incremental change.
- This disruptive technology has the potential to transform the gas turbine industry.
- The new combustor technology can be used in:
  - Different GT combustor platforms; annular, can annular and silo type combustors
  - The technology is scalable to Gas turbine engines of different sizes
- Experimental results demonstrate very high combustion stability achieved over a wide range of combustion conditions rendering the new design superior to current conventional ones.
- Experimental and modelling results demonstrate that CO and NO_x emissions of the new design can be predicted via modelling.
- The new design has the advantage of increasing the life of the hot gas path components.

NH_3 GT Combustor Demonstration

Phase IIB Activities

Proposed Ammonia Engine Tests for Phase IIB

DOE Phase IIB SBIR is awarded to CPS – expected to start in October 2024

- Partnering organization – UND EERC

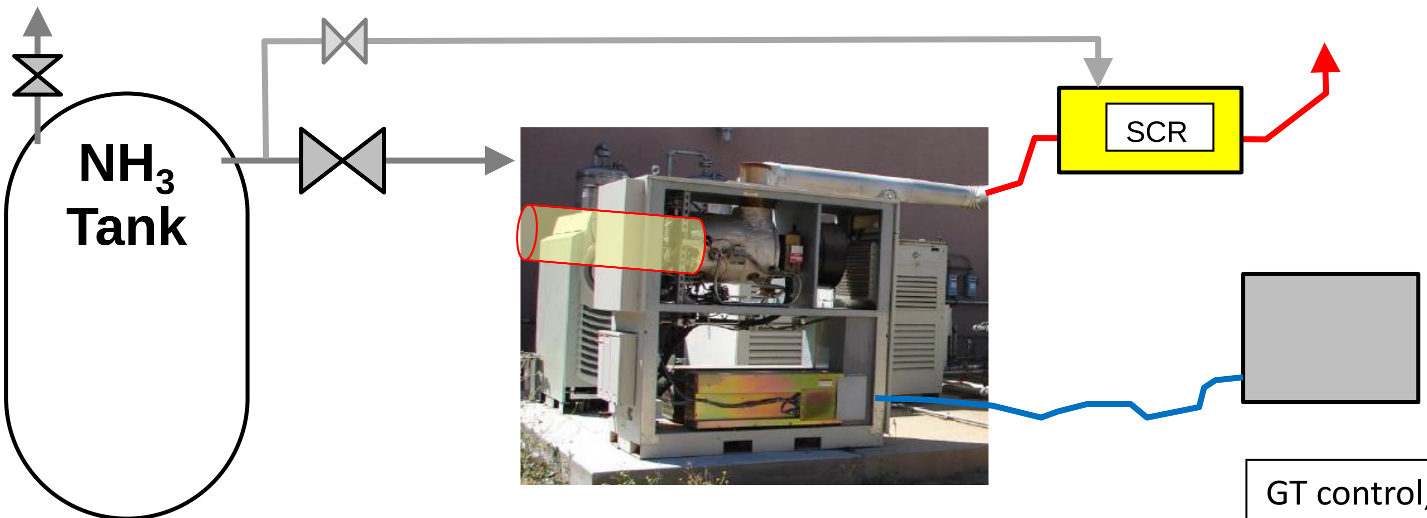
	Cost (USD)	Duration	Comments
Feasibility Study (Phase I - DOE SBIR)	$250,000	9 months	Completed successfully (June 2020)
Pilot-Scale Study (Phase II – DOE SBIR)	$1,600,000	34 months	Completed Successfully (August 2024)
Engine Demonstration (Phase IIB – DOE SBIR	$1,150,000	20 months	Awarded in August 2024

Proposed Tasks & Activities for Phase IIB

- Finalize NH_3 combustor detailed mechanical design
- Fabricate combustor parts and retrofitting kit
- Commission GT engine with NH_3 combustor
- Run Performance tests from ignition to baseload conditions
- Utilize existing Selective Catalytic Reactor to further reduce engine emissions (if needed)

Proposed Ammonia Engine Tests for Phase IIB

- The tests to be run on a demonstrator set up, the equipment is arranged for ease of access.
- We intend to focus in a first test phase on the GT without Selective Catalytic Reduction System (SCR). The results will inform the requirements and the design of the SCR, which can be added for a second test phase, if needed.
- The commercial package will include commercial ammonia validated components in a compact Form.



NH_3 tank with required systems for fuel supply, protection etc

Microturbine with new combustor and modified controls, instrumented for tests. Connected to the grid to enable power tests.

GT control, test supervision and data acquisition/storage system

NH_3 GT Combustor Operation

- The combustor will be operated in a **fully premix mode of operation** from startup to full load operation.
- Emission data will be collected throughout the whole load range.
- The designated tests will determine all limitations of the new technology, if any, across the engine operating conditions.

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Summary

Ammonia GT Combustor

Summary

- Burner technology that allows for 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.

- 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

- The results show that tested 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.
  - The lowest NOx of 36 ppmv, corrected for 15% O_2 and dry basis, was recorded at 4 atm.

- 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

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

Acknowledgements

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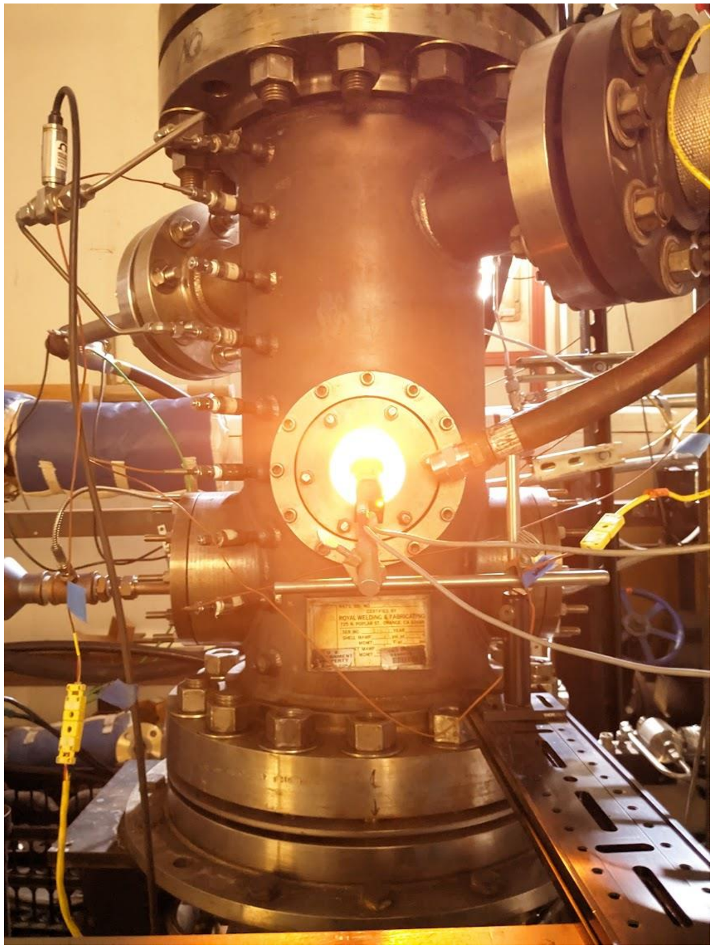

Thank you!

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Appendix