Investigation of Flame Structure for Hydrogen Gas Turbine Combustion

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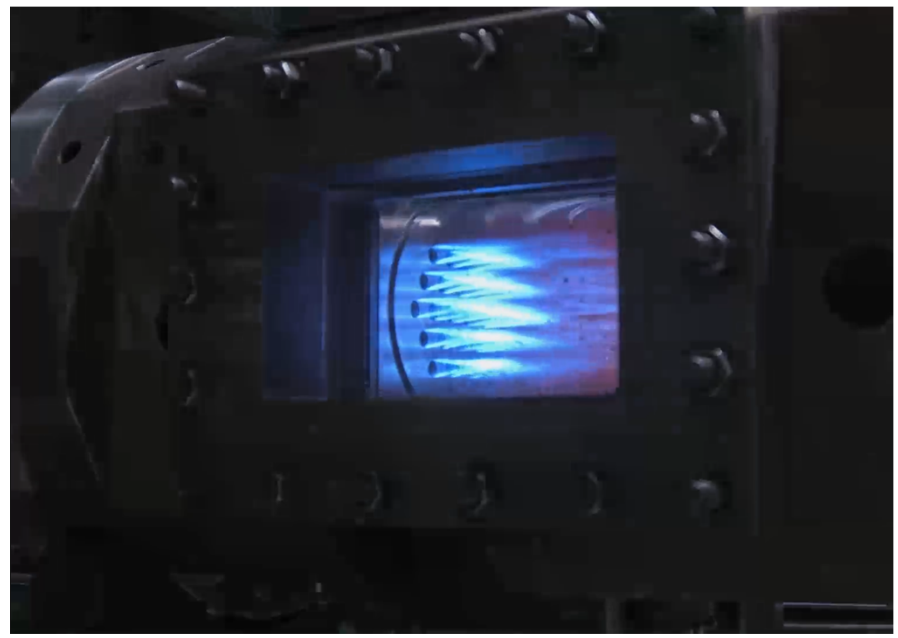


Investigation of Flame Structure for H_2 Gas Turbine Combustion

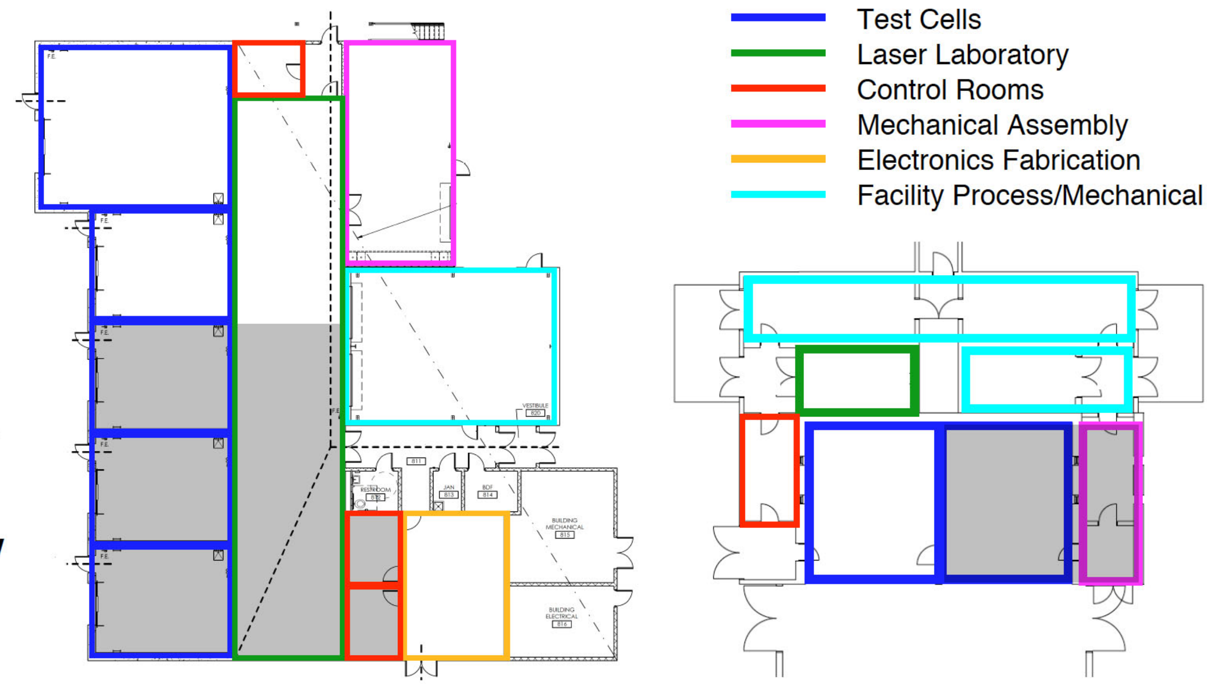
Advance hydrogen combustion technology from the current technology concept and/or application formulated stage (TRL 2) to a component and/or system validation in laboratory environment (TRL 4)

- Explore flame structure and dynamics for gas turbine combustion with hydrogen, ammonia, and mixtures of these fuels with natural gas
- Research focus on multi-stage, multi-tube, micromix (M^3) injectors
- Leverage the Combustor Rig for Advanced Diagnostics (COMRAD) experiment designed to operate at pressures up to 40 bar and inlet air temperatures up to 1080 K. Two test article configurations will be developed:
    - Steady-state configuration for emissions, LBO, flashback.
    - Unsteady configuration for studies of self-excited combustion instabilities.
    - Conditions characteristic of commercial aeroderivative and heavy-duty F- and H-class gas-turbine systems
- Application of advanced diagnostic methods will be used to study flame structure and dynamics.
    - High-speed particle imaging velocimetry (PIV), dual-pump coherent anti-Stokes Raman scattering (CARS) for T, species, and planar laser-induced fluorescence (PLIF) imaging for OH, NO, and NH concentrations.

High Pressure Combustion Laboratory

- Experiment is housed within the Zucrow Laboratory Complex, in the high pressure facilities.
- The High Pressure Combustion Laboratory was constructed specifically for high pressure gas turbine combustion testing and for the application of advanced laser diagnostics for measurements in high-pressure optical rigs.
- The facility is capable of supplying heated air at pressures up to 880 psia (60 bar), temperatures up to 1500°F (1100 K), and a flow rate of 8 lbm/s (4 kg/s).

Aerial View



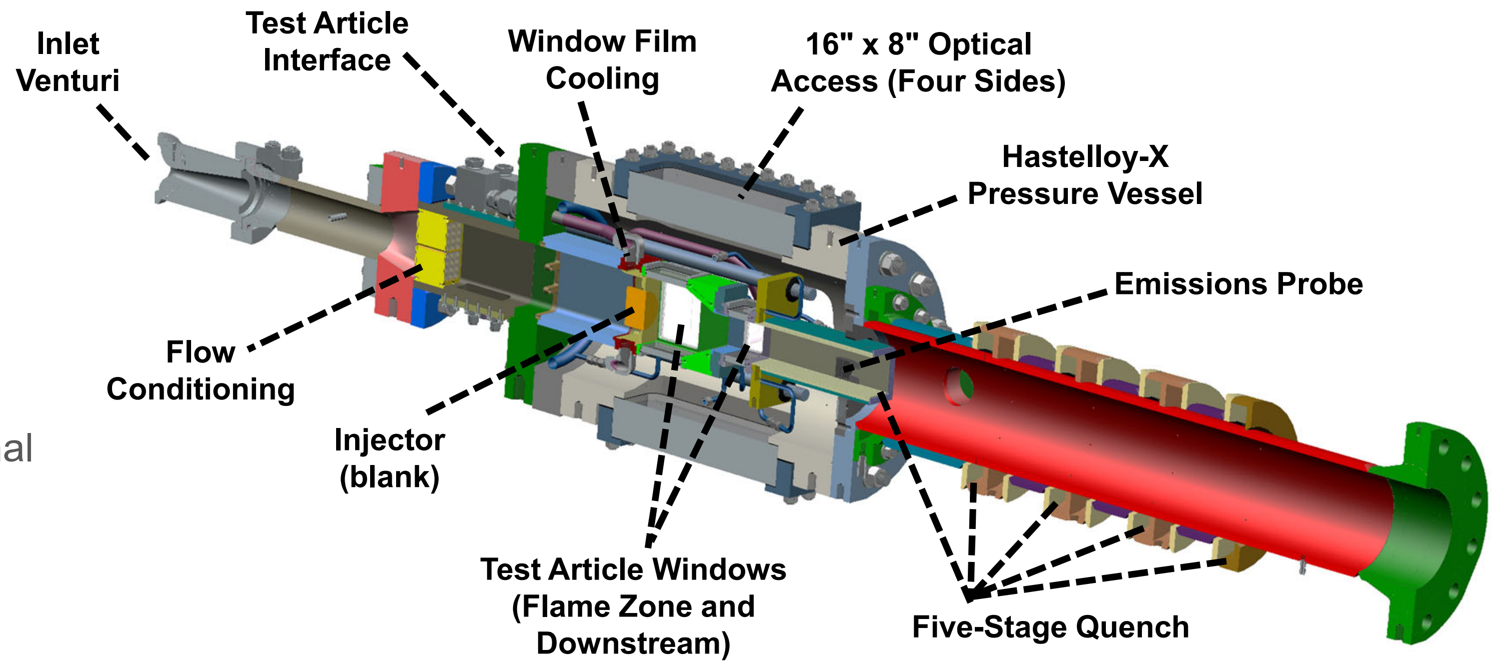
Fluid System Summary

Airbreathing Combustion and Propulsion Lab

Operational Parameters	Maximum Operation (Steady State)
Heated air (or N2) supply 1	5 kg/s at 58 bar and 820ºC (7 kg/s at 450ºC)
Heated air (or N2) supply 2	3.6 kg/s at 41 bar and 540ºC
Heated air (or N2) supply 3	0.75 kg/s at 41 bar and 540ºC
Unheated air	0.45 kg/s (compressor discharge) with 9000 kg storage at 150 bar
Oxygen	2 kg/s and 8 kg/s at 150 bar
Bottled oxidizers	2 circuits at 1 kg/s and 150 bar
Nitrogen	0.05 kg/s (pump discharge) with 9000 kg storage at 400 bar
Bottled inert gases	2 circuits at 1 kg/s and 150 bar
Bulk fuel	Natural gas, hydrogen, and liquid fuels to support >10 MW (steady)
Bottled fuels	4 circuits at 1 kg/s and 150 bar
Water	5 kg/s at 83 bar (pump discharge) with 350 L reserve

Advanced Gas Turbine Combustion Test Rig

- Rig designed to simulate engine cycle conditions
  - 8MW steady-state thermal power
  - 40 bar P3
  - 1000 K T3
  - Water-cooled
  - Film-cooled windows
- Excellent optical access to the flow, including flame zone and boundary conditions
- Will also accommodate traditional probe-type instrumentation
  - Emissions sampling
  - Acoustics



Summary

- Completed development of a modular multi-stage, multi-tube, micromix (M^3) injector
- Developed high-pressure modular combustor to characterize combustion dynamics with variation in fuel composition
- Designed and developed high-pressure gaseous and liquid ammonia delivery system to the experiment
    - High pressure hydrogen and natural gas systems in place for experiments
- Demonstrated self-excited combustion instabilities with high H2 content fuels (with natural gas) to evaluate effect of fuel composition on combustion instabilities
    - High amplitude longitudinal instability observed with NG and low hydrogen fuel content (30% H2/N2 in fuel)
    - Instability amplitude reduced at high H_2 levels – but flashback concerns at 100% H_2/N_2
    - Addition of ammonia to fuel mix in near term plans

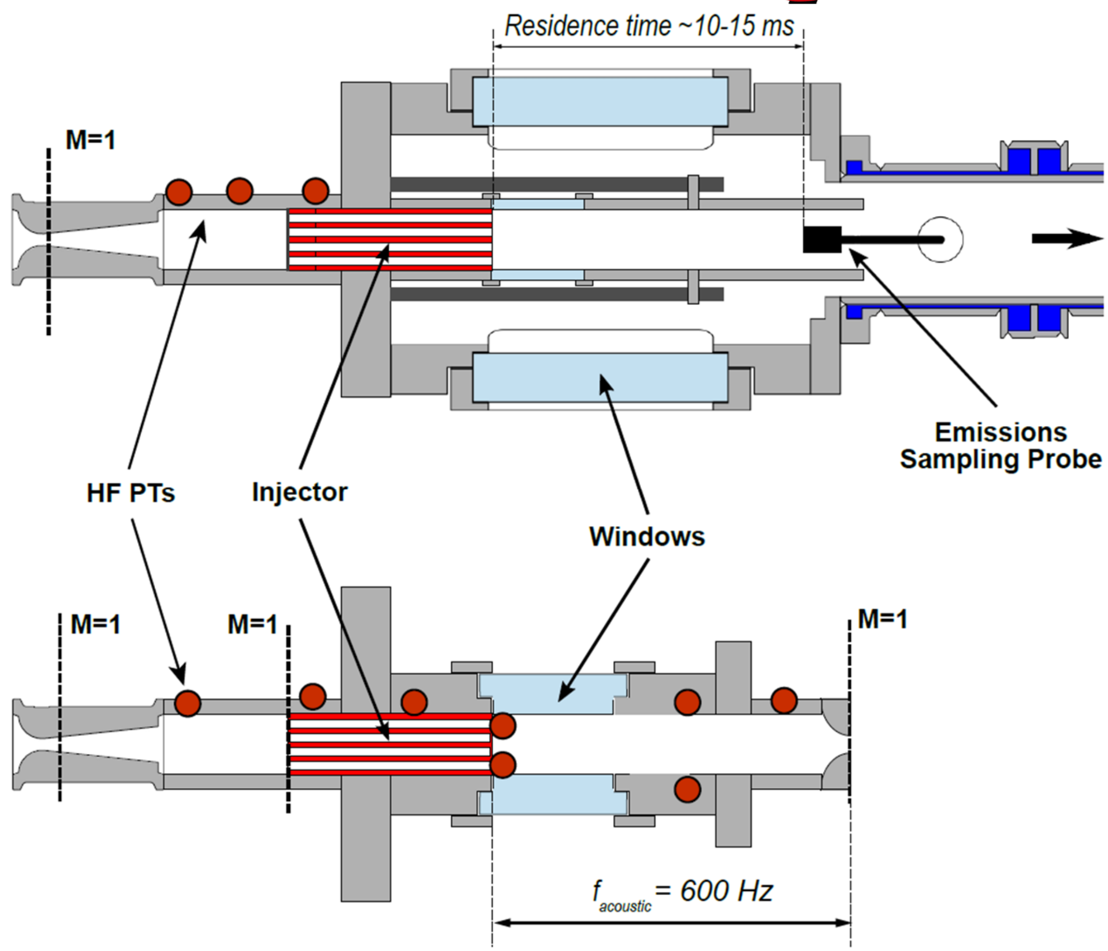
Experiment Configurations

Emissions Configuration

- Steady-state operation for emissions and flame structure characterization with target fuels and operating conditions
  - Large optical access for application of laser-based diagnostics
  - FTIR/FID emission characterization system

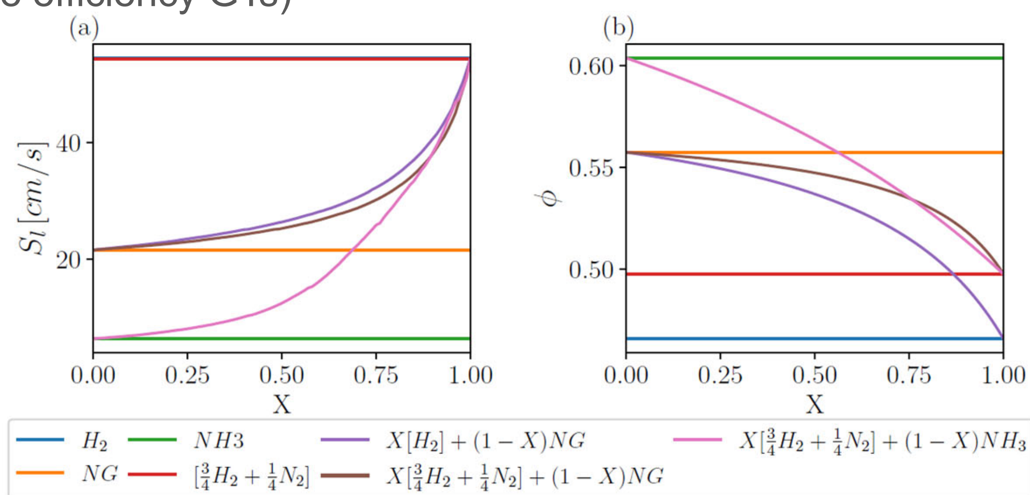
Dynamics Configuration

- Modular geometry to tune frequency and amplitude of dynamics with fuels of largely varying HRR and flame temperatures
  - Well-defined acoustic boundary conditions
  - Large optical access for application of laser-based diagnostics



Design Envelope: Dynamics Configuration

- Investigation of H_2 and NH_3 (H_2 carrier), and mixtures of these fuels with natural gas
- Hydrogen assumed to be derived from ammonia decomposition
- Ammonia decomposition efficiency (η) sweep from 0.4 to 0.9
  - Rate of ignition delay increase requires unreasonable combustor lengths at $\eta < 0.4$
  - Combustor length sized for ~14.5 ms residence time
- Fuel fraction (X) sweep from 0.5 to 0.9
- Equivalence ratio determined at a fixed adiabatic flame temperature of 1980 K (DOE target for 65% combined cycle efficiency GTs)



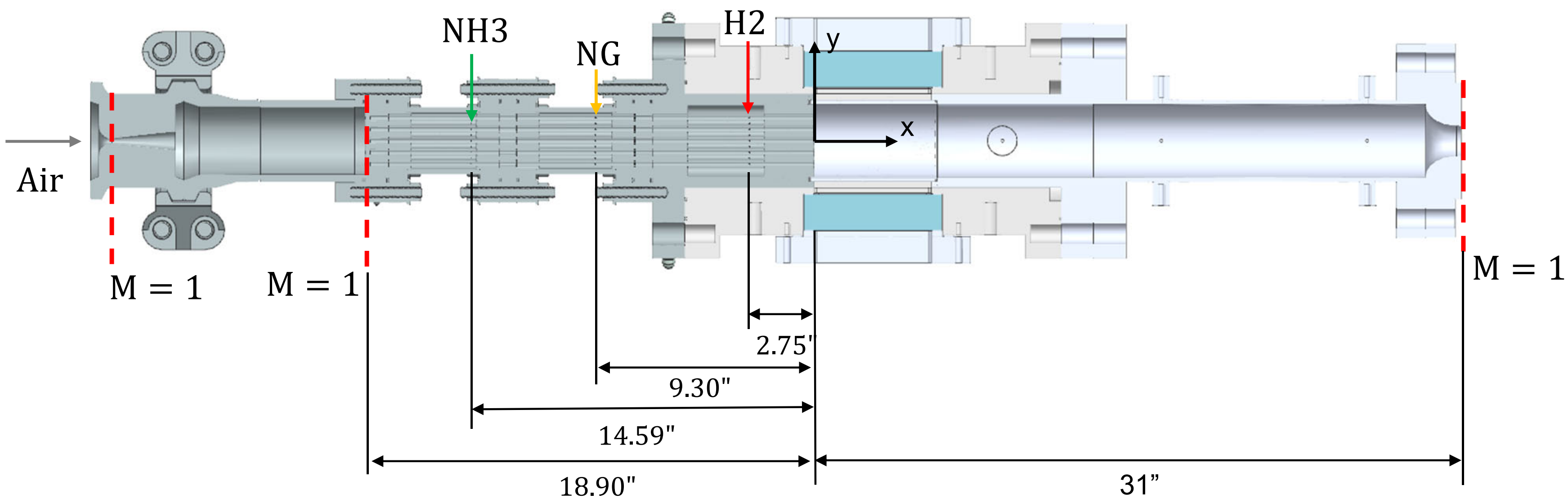
Premixed laminar flame speed (a) and variation in equivalence ratio for an adiabatic flame temperature of 1980 K (b).

$$X\left[\eta\left(\frac{3}{2}H_2+\frac{1}{2}N_2\right)+(1-\eta)NH_3\right]+(1-X)NG$$

Fluid	X	η	$\dot{m}_{max}\ [lb/s]$
H_2	0.9	0.9	0.01
N_2	0.9	0.9	0.05
NG	0.5	N/A	0.02
NH_3	0.9	0.4	0.04
Air	N/A	N/A	1

Combustor Development

- Year 1 efforts focused on experiment development and demonstration of dynamics configuration
- Combustor developed to promote combustion instabilities at frequencies typical of power-gen gas-turbine combustors
  - Fundamental longitudinal mode frequency ~550 Hz
- M^3 injector with discrete modular sections for NH3, NG and H2 injection
- Large optical access for diagnostics and instrumentation to characterize high-frequency dynamics
- Well-defined flow and acoustic boundaries



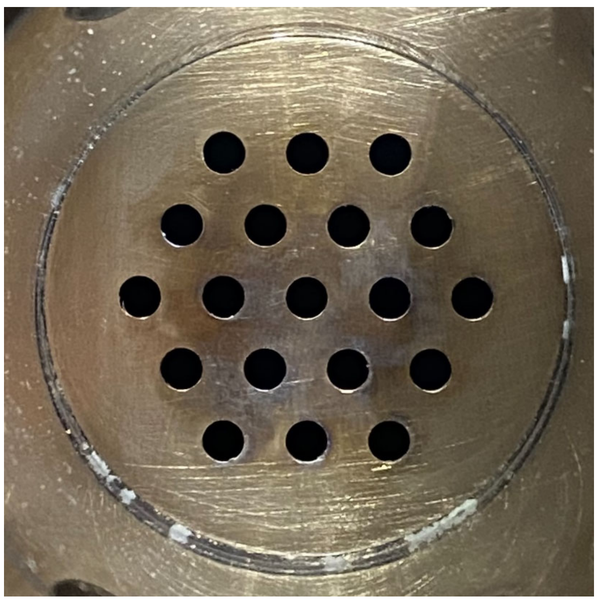
Injector Sizing

- Premixed injectors distributed in an uniform array in cylindrical combustion chamber
  - Inter-element separation maintained between injectors
  - Injector Mach number between 0.15-0.2 at typical flow conditions

Injector Geometry	
$\emptyset_{element}$	0.245 [in]
Velocity	300 – 400 [ft/s]

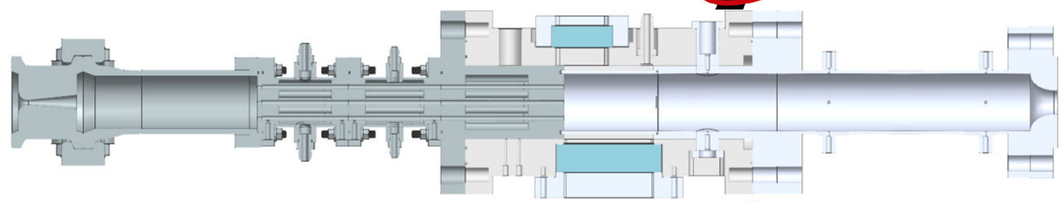
Mach Number		η	
		0.4	0.9
X	0.5	0.25	0.25
	0.9	0.27	0.28

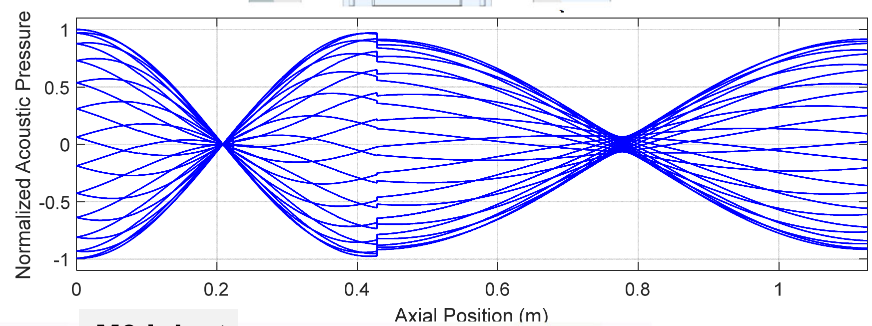
Velocity		η	
		0.4	0.9
X	0.5	432 [ft/s]	439 [ft/s]
	0.9	490 [ft/s]	514 [ft/s]

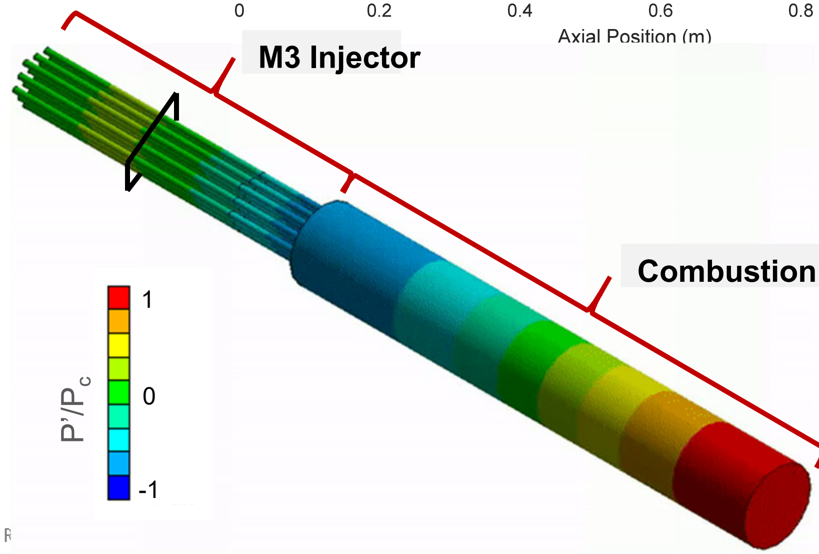


Injector Sizing

- Acoustic design based on linearized Euler equations using the Generalized Instability Model (GIM)
- Combustor dimensions designed to promote combustion instability at 540 Hz
    - Combustor residence time ~14.5 ms
- Combustor divided into domains representing NH_3, NG, H_2 injection regions and combustor
- Mean flow effects considered
- Choked inlet and exit boundaries
- Injector designed as a ½ wave resonator at chamber acoustic frequency



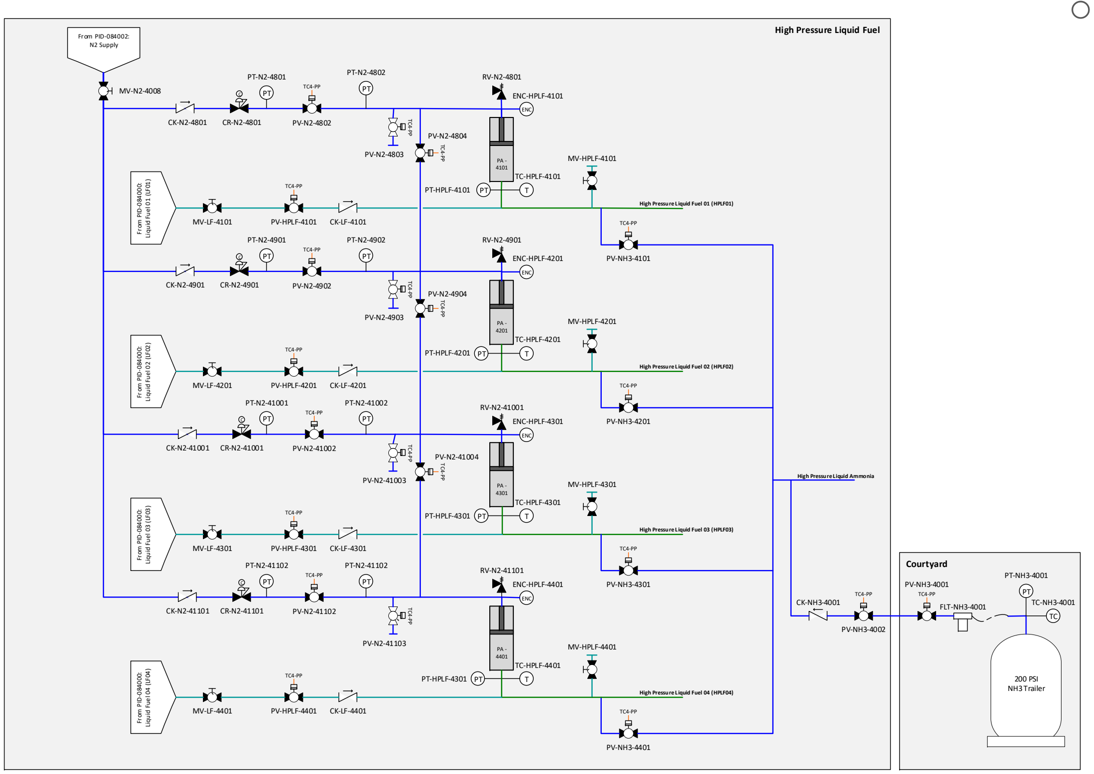




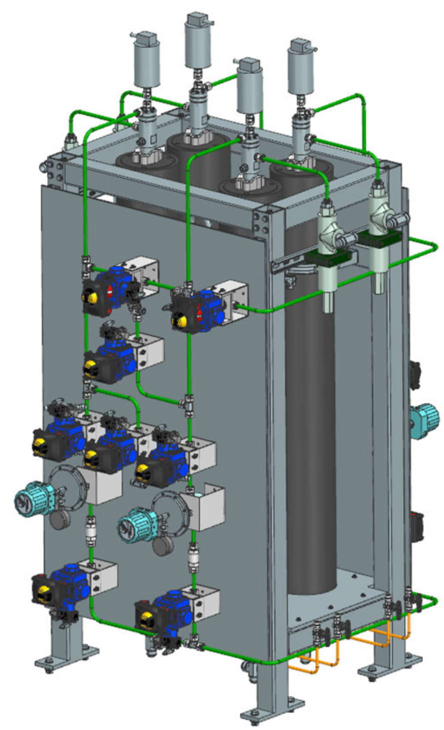
Domain Lengths [in]	
Air	4.31
NH3/Air	5.30
NG/NH3/Air	6.55
H2/N2/NG/NH3/Air	2.75
Combustor	31.00

Ammonia System Design

- Ammonia delivered in saturated state pressurized to target conditions in a piston tank
  - 70 kg of ammonia available per test
  - Maximum supply pressure of 345 bar



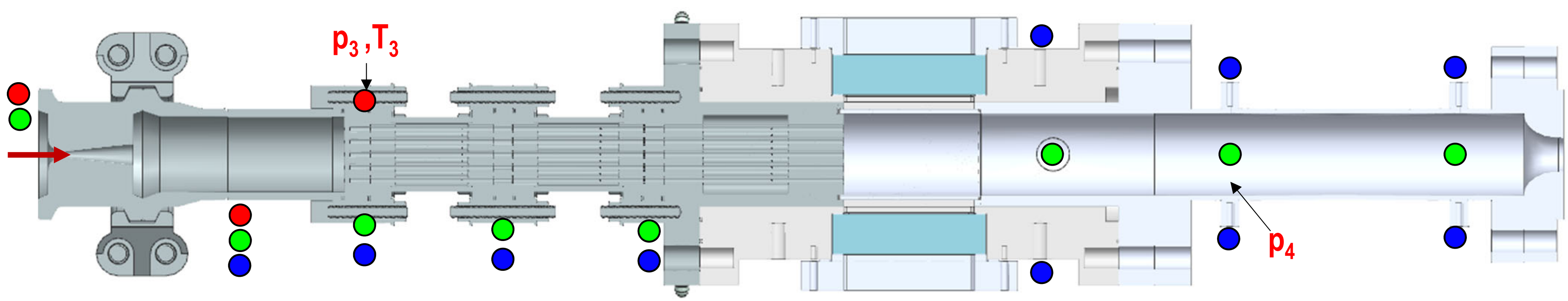
- Ammonia delivered to 85 kW electrical heater prior to injection
  - NH3 heated to high T at high P, then vaporizes as pressure decreases to injection pressure
  - System can also be used for liquid NH3 injection



Instrumentation Layout

Measurement	Instrumentation	Range	Accuracy
LF Pressure	GE Sensing UNIK50E6	35 bar (test article), 70 bar (feed system)	0.04% FSO
HF Pressure	Kulite WCT-312M-35BARA	35 bar	0.1% FSO
Temperature	K-type thermocouple (GKMQIN-062G-06)	< 1250°C	2.2°C or 0.75%

Diagnostic	Equipment
Chemiluminescence Imaging	Phantom V2512 + Lambert HiCATT25

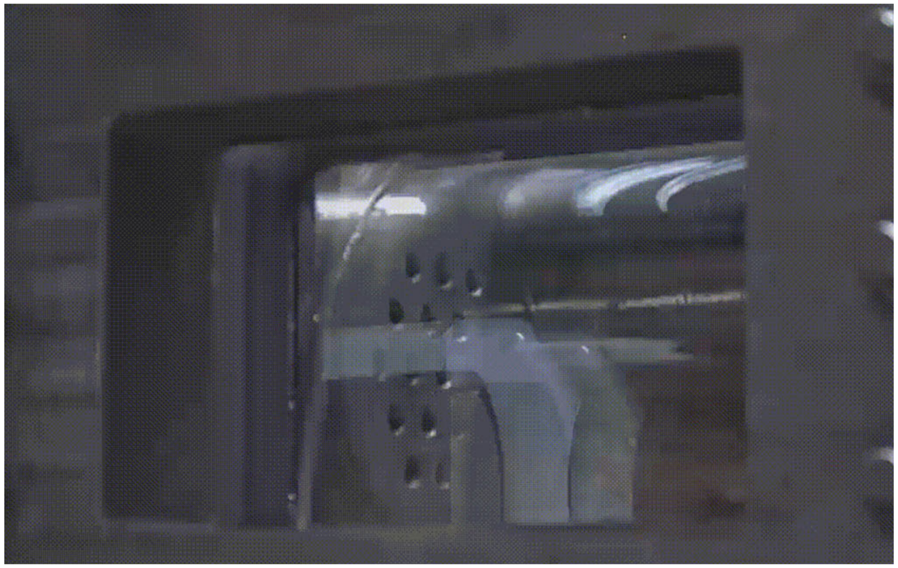


Results

- Experiments performed with dynamics configuration to illustrate influence of fuel composition
- Preliminary investigation with hydrogen (with nitrogen addition to simulate ammonia decomposition) and natural gas fuels
  - X : 0-100 %
  - η : 100% for all tests
- Ignition achieved using laser induced spark with a single-element operating with premixed hydrogen-air

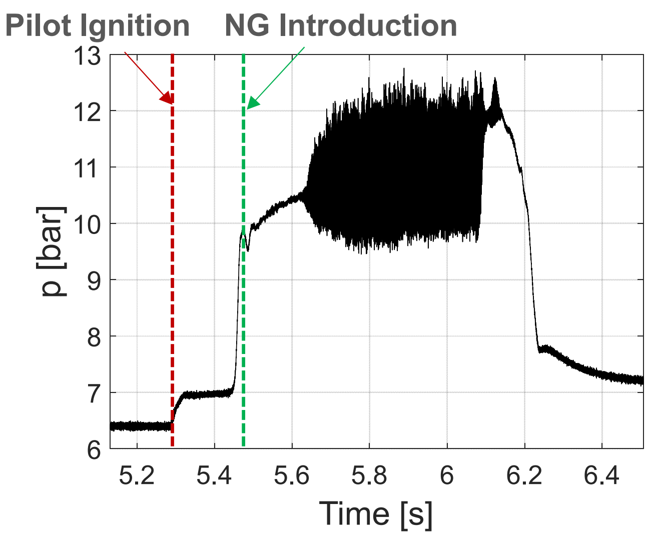
Fuel Composition:

$$X\left[\eta\left(\frac{3}{2}H_2+\frac{1}{2}N_2\right)+(1-\eta)NH_3\right]+(1-X)NG$$

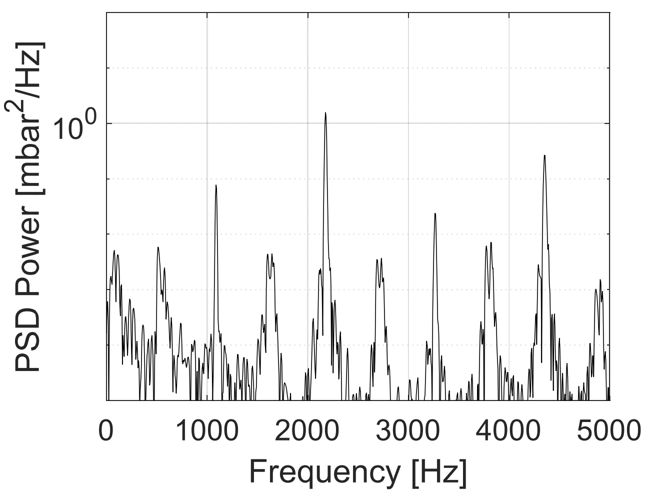


Results: NG only (X: 0 ; η: NA)

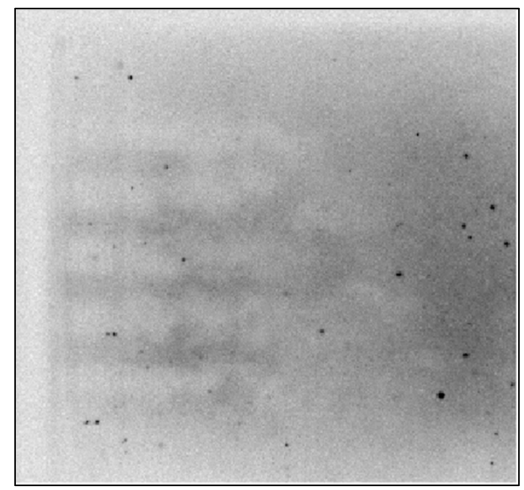
- High amplitude self-excited instabilities present with natural gas operation with the M3 injector
- Mean chamber pressure (p_c) ~ 11 bar with p'/p_c 30%
- Longitudinal mode instability at 1L frequency 510 Hz



Raw Pressure Trace (CC-01)



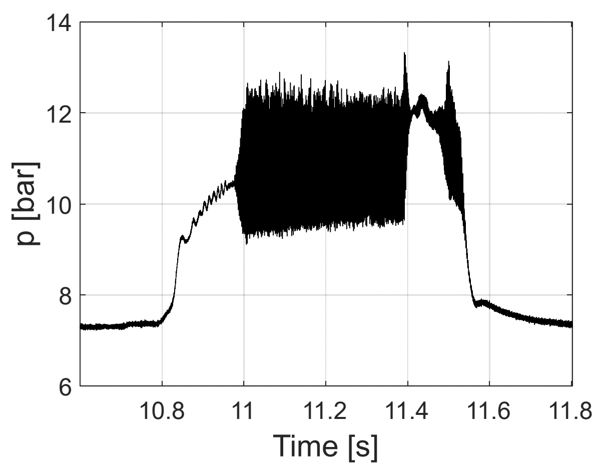
Power Spectral Density (CC-01)



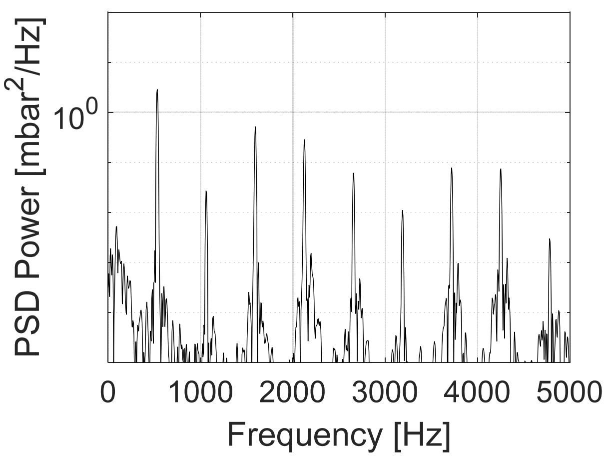
Chemiluminescence (20 kHz)

Results: 30% H2/N2 (X: 0.3 ; η: 1.0)

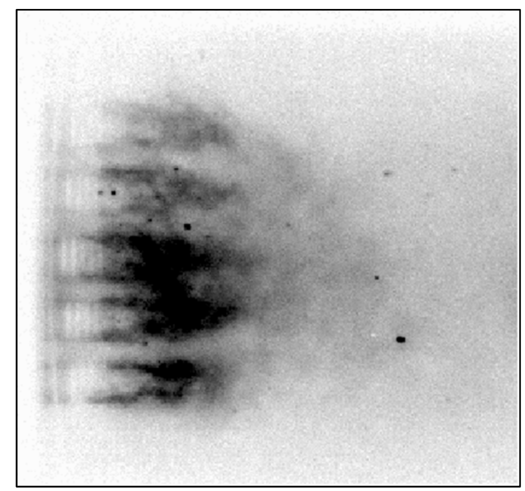
- High amplitude self-excited instabilities with 30% H2/N2 fuel mass fraction
- Mean chamber pressure (p_c) ~ 11 bar with p'/p_c 30%
  - Instability amplitude similar to that of the NG case
- Longitudinal mode instability at 1L frequency 530 Hz



Raw Pressure Trace (CC-01)



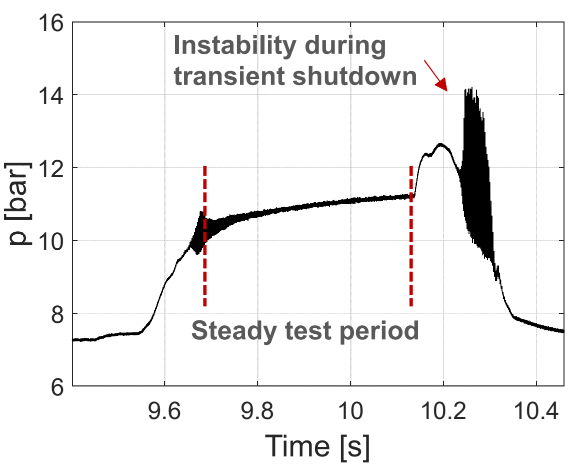
Power Spectral Density (CC-01)



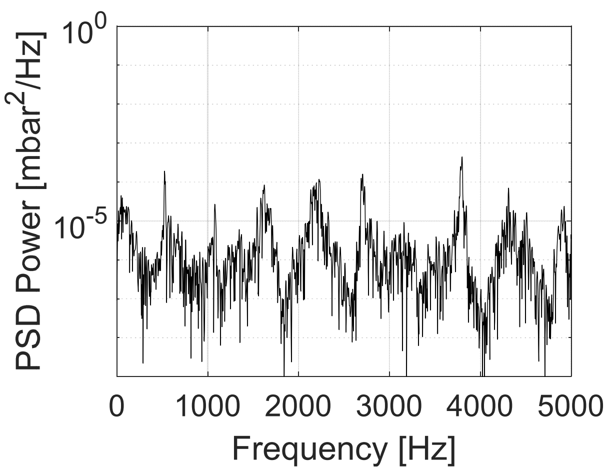
Chemiluminescence (20 kHz)

Results: 70% H2/N2 (X: 0.7 ; η: 1.0)

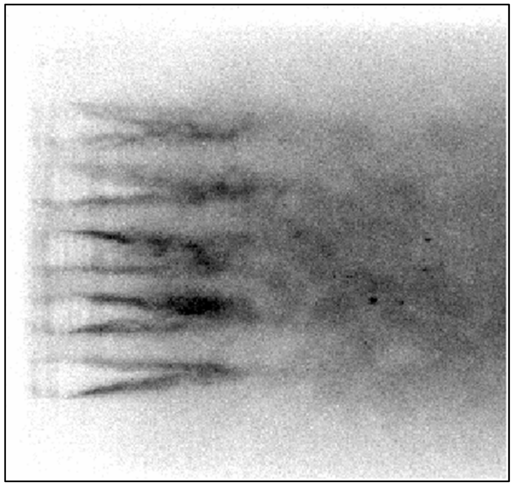
- Combustion instability amplitude significantly damped with further addition of hydrogen
- Mean chamber pressure (p_c) ~ 11 bar with p'/p_c ~1%
  - Instability amplitude significantly compared to NG and 30% H2/N2 cases
- Longitudinal mode instability at 1L frequency 525 Hz



Raw Pressure Trace (CC-01)



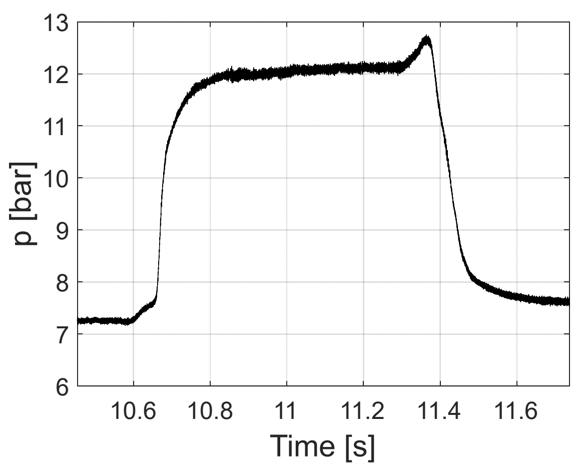
Power Spectral Density (CC-01)



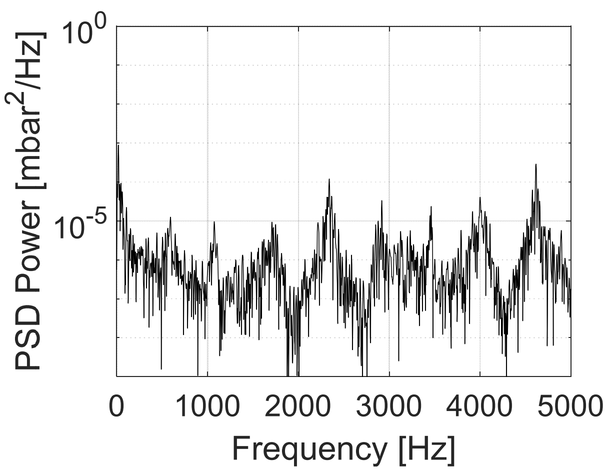
Chemiluminescence (20 kHz)

Results: 100% H2/N2 (X: 1.0 ; η: 1.0)

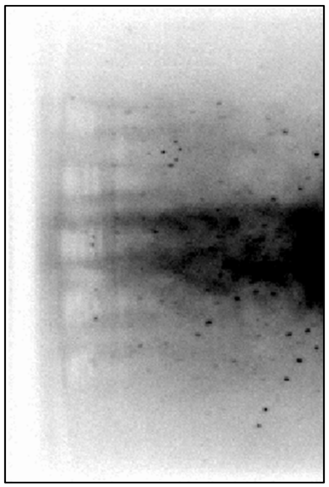
- Combustion instability amplitude significantly damped with hydrogen combustion
- Some flame attachment observed with NG addition to the fuel stream
  - No evidence of flashback into the feed system
  - Further investigation of near flashback conditions necessary
- Mean chamber pressure (p_c) ~12 bar with p'/p_c ~2%



Raw Pressure Trace (CC-01)



Power Spectral Density (CC-01)



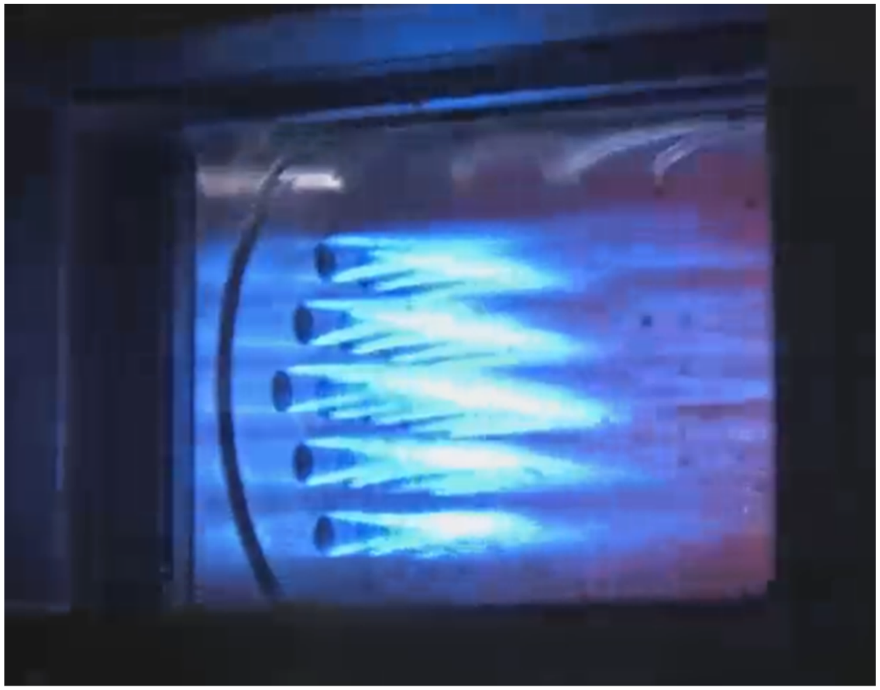
Chemiluminescence (20 kHz)

Summary

- Complete design and development of a multi-tube, multi-stage, micromix injector for ammonia, hydrogen and natural gas
- Characterized influence of fuel composition on self-excited combustion dynamics in a high-pressure experiment
  - Significant combustion instability amplitudes observed with natural gas and low hydrogen content fuel
  - Stability improves with higher hydrogen content but flame flashback remains a concern
- Developed infrastructure for high-pressure ammonia injection

Next Steps:

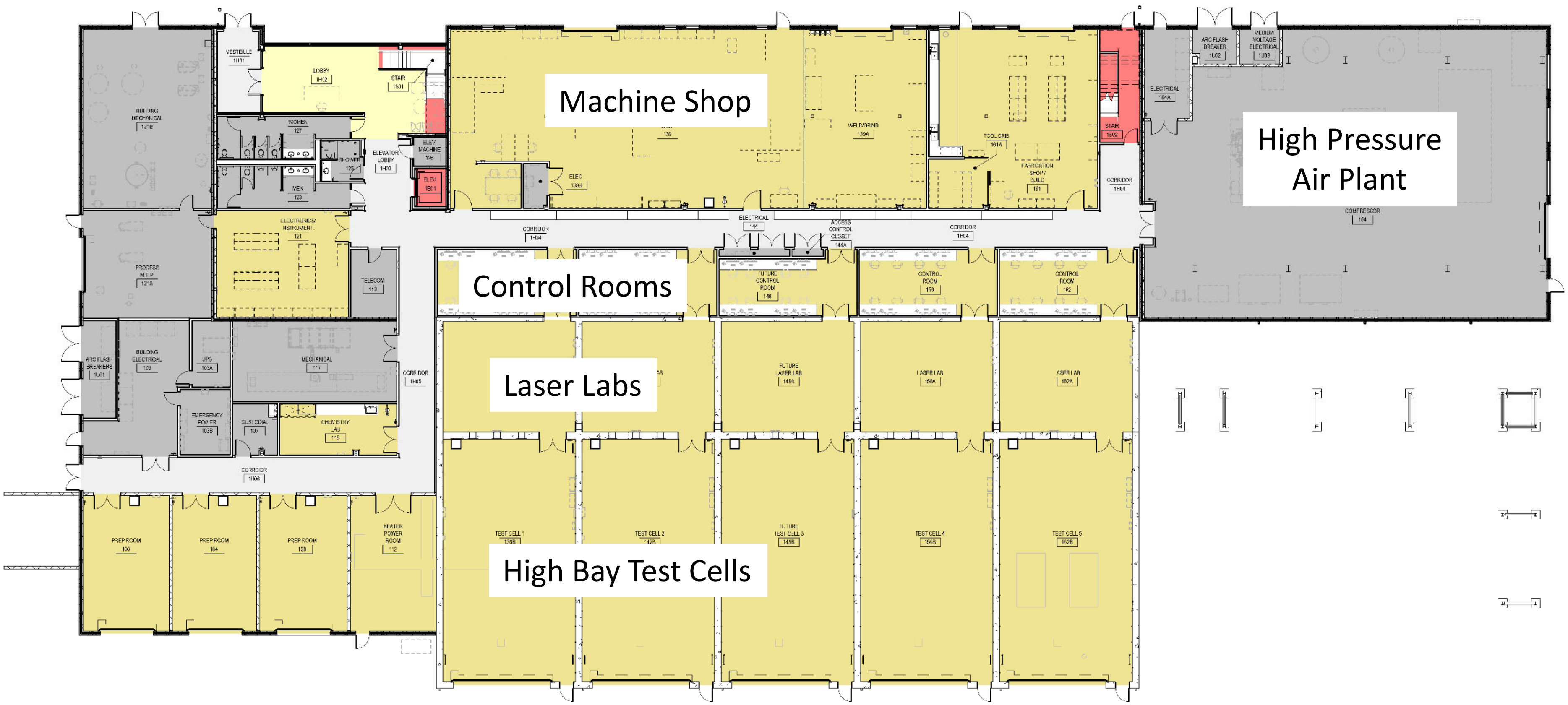
- Detailed characterization of dynamics configuration with variation in fuel composition (including ammonia), injector geometry and operating conditions
  - Application of advanced diagnostics to characterize flame dynamics
- Development of steady-state configuration based on down selected injector design from dynamics study
- Global emissions characterization using FTIR based extractive product gas sampling



Zucrow Labs Overall Site Expansion Plans

- New test cell facility will have with 5 test cells
- Each test cell will have a dedicated laser lab, control room and fabrication room
- New high pressure air plant will supply 5 lbm/s (up from 0.8 lbm/s) at 3400 psia, air storage will increase from 20,000 to 70,000 lbm
- Two new air heaters capable of heating 15 lbm/s to 1500°F
- Groundbreaking in December 2022 for 55,000 sq ft facility

New Test Cell Facility (ZL9) and New High Pressure Air Plant



Second Floor Office Complex

High Bay Test Cells

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