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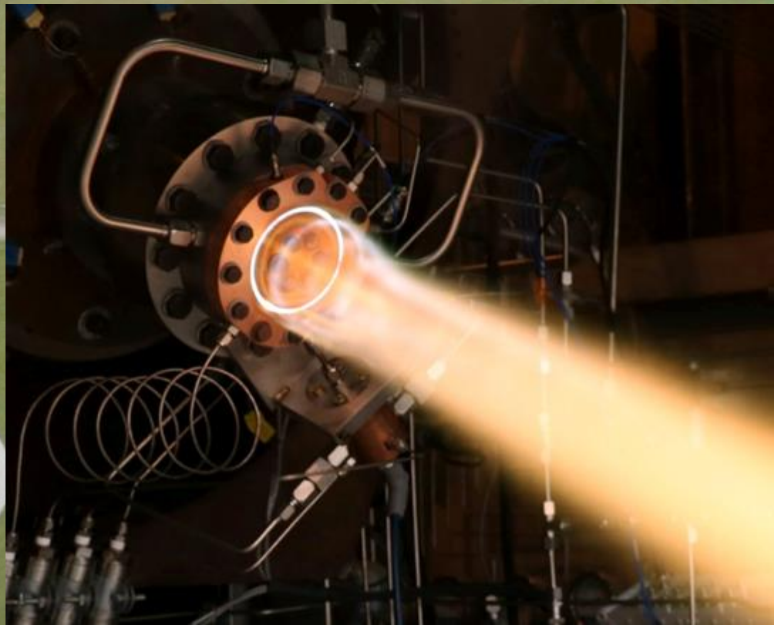
Advancing Pressure Gain Combustion in Terrestrial Turbine Systems

S. Heister & C. Slabaugh
School of Aeronautics & Astronautics

UTSR Kickoff Meeting, 6 October, 2015



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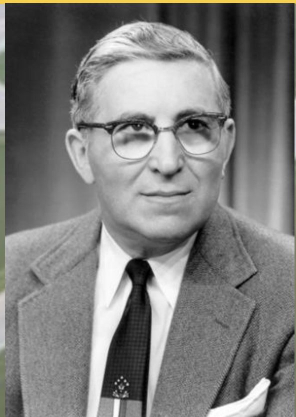
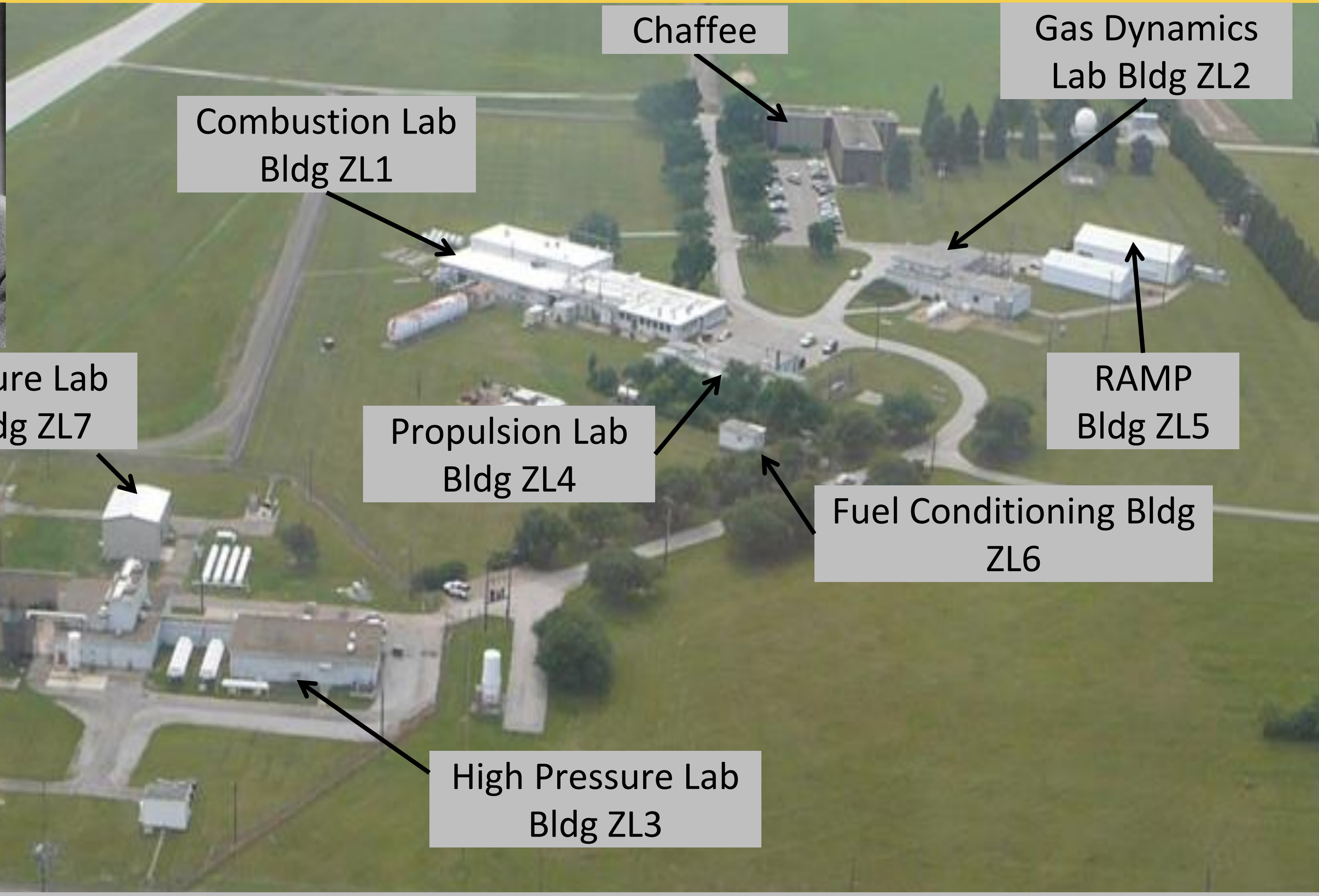
Agenda

- Introduction/Overview of Facilities
- Background and Current Efforts in Rocket-Based RDE
- Summary of Proposed Efforts on UTSR Project
  - Details on Unwrapped RDE Rig
  - Modeling Efforts
  - High Pressure Rig
- Wrap-up/Discussion

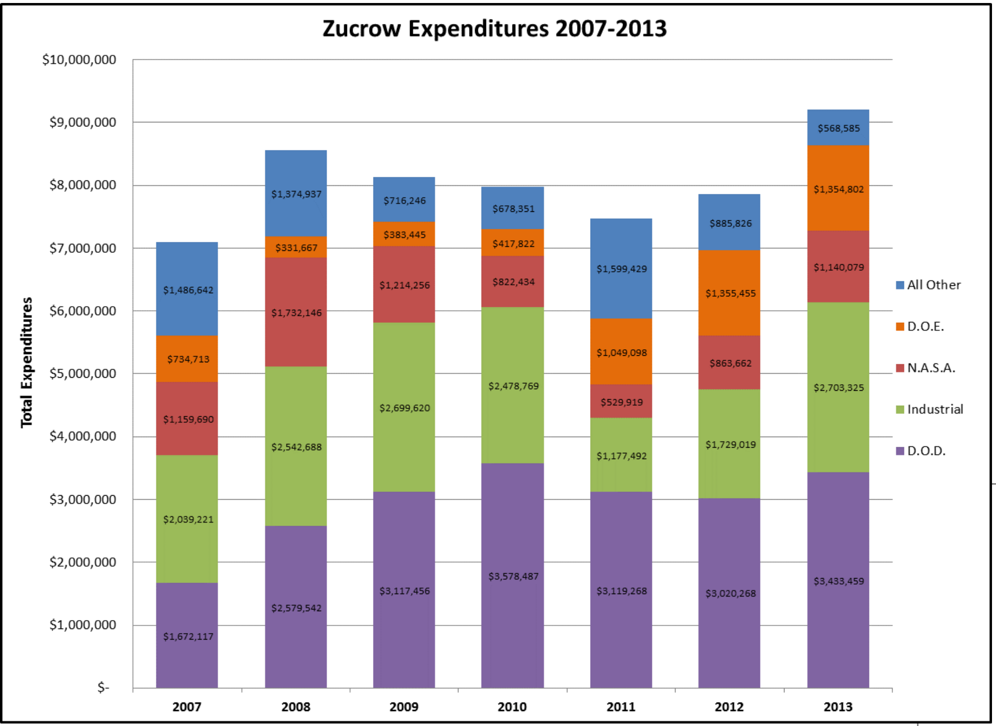
24 Acre MZL Campus



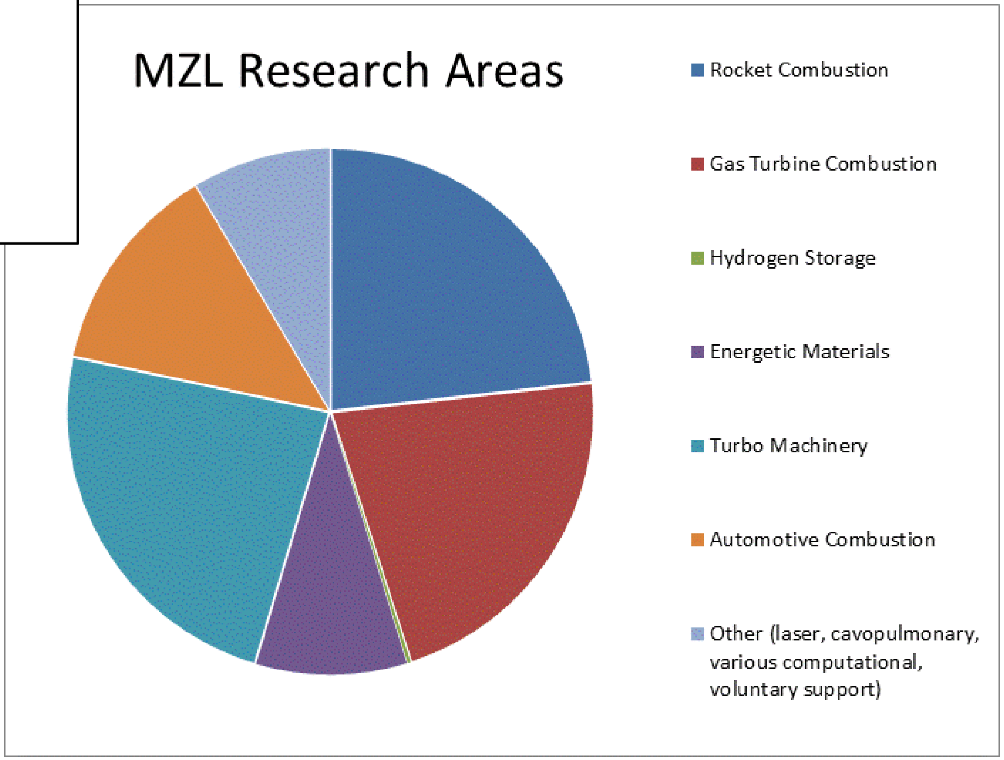


28,000 ft^2 of lab space and 12,000 ft^2 of office space on MZL campus

MZL Sponsored Research



- Roughly 90 graduate students, over 1000 Alums from AAE and ME Schools
- 14 Faculty, 15 Affiliated faculty from 9 different STEM programs on campus
- 8 Staff Members



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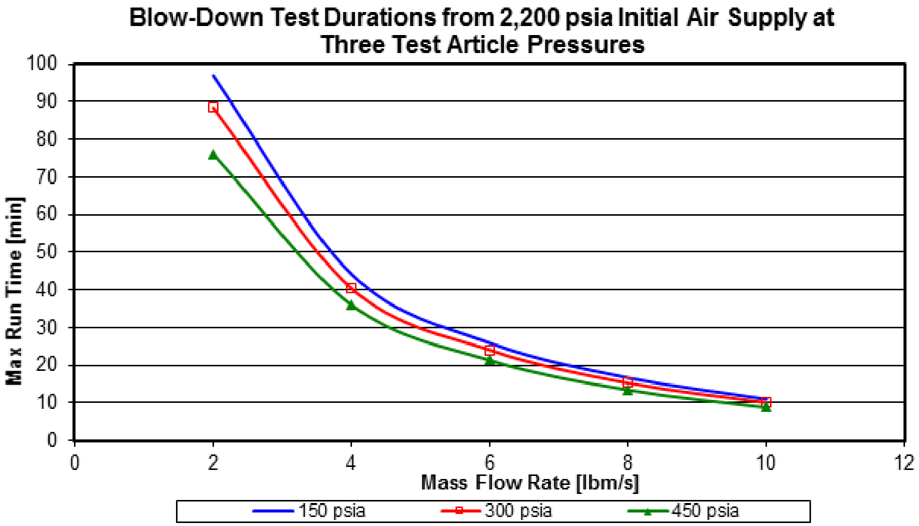
MZL Air System Supply

- Air system came on line in 1976 ($400K at that time)
- Two Ingersoll Rand ESH-2 125 HP compressors
  - 0.45 lb/s each with 300 psi output and 650 cu. ft storage
- Ingersoll Rand TVH 250 HP compressor
  - 500 psi discharge at 0.85 lb/s
- Ingersoll Rand ESH-2 150 HP booster
  - 2200 psi discharge at 0.68 lb/s and 950/1074 ft^3 storage at ZL-1/ZL-3

MZL Large Heated Air System

- Natural gas fired clean-air heater ($2M investment by Purdue)
  - 1,500 degF maximum discharge temperature (maintained at up to 8 lbm/sec)
  - 850 psi maximum operating pressure
  - On-Line June 2015
- 2,000 ft^3 actual volume total air storage at 2,200 psi (1,100 at ZL3, 900 at ZL1)

Aerial Photo of the Zucrow Laboratories Air Heater Taken During Installation Jan 2015

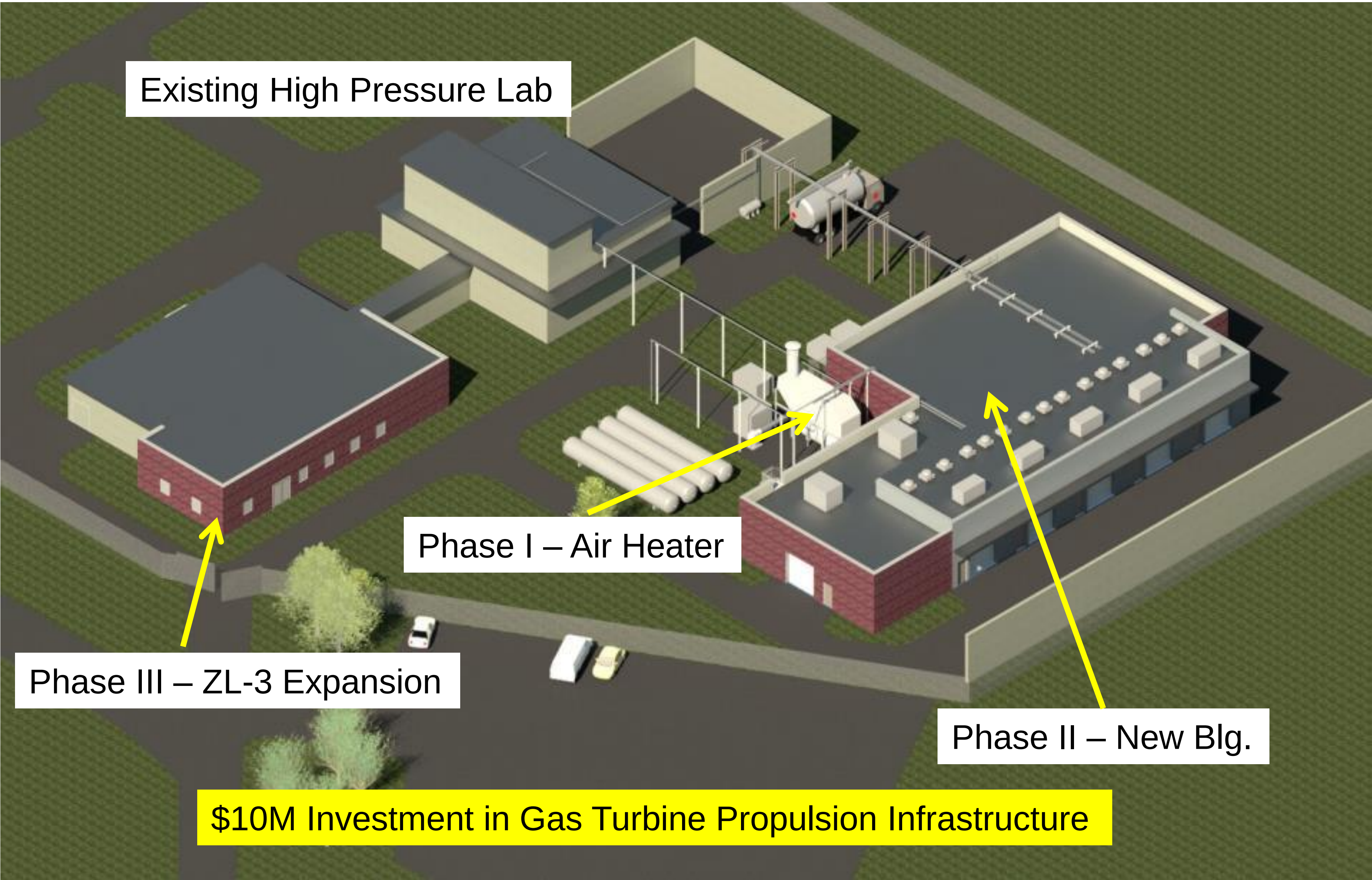


Air System Blow-Down Flow Durations as a Function of Test Article Operating Pressure and Flow Rate

Current MZL Flow Capabilities

Propellant	Test Cell	Maximum Flow Capacity	Max. Operating Condition
Heated High Pressure Air	Rocket & Gas Turbine	7 lb_m/sec	600 psi / 1500 deg F
High Pressure Air	HPL Annex	50 lb_m/sec	1,500 psi / ambient
Electric Heated Air or Nitrogen	Gas Turbine	0.5 lb_m/sec	600 psi / 1,200 deg F
Nitrogen	Rocket / Gas Turbine	5 / 2 lb_m/sec	5,000 psi
Nitrogen	HPL Annex	2 lb_m/sec	5,000 psi
Liquid Aviation Fuel (kerosene)	Rocket / Gas Turbine	22 / 0.2 lb_m/sec/tank	5,000 / 1,500 psi
Liquid Aviation Fuel (kerosene)	HPL Annex	0.2 lb_m/sec	1,000 psi
Cooling Water	Rocket / Gas Turbine	600 / 16 gpm	5,000 / 1,500 psi
Liquid Oxygen	Rocket	15 lb_m/sec	5,000 psi
Rocket Grade Hydrogen Peroxide	Rocket	100 lb_m/sec	5,000 psi
Gaseous and Liquid Methane	Rocket	1.0 lb_m/sec	5,000 psi
Natural Gas	Gas Turbine / Rocket	1.0 lbm/sec	3600 psi
Gaseous Hydrogen	Rocket / Gas Turbine	3 / 0.5 lb_m/sec	5,000 psi
Gaseous Heated Propane	HPL Annex	1 lb_m/sec	300 psi

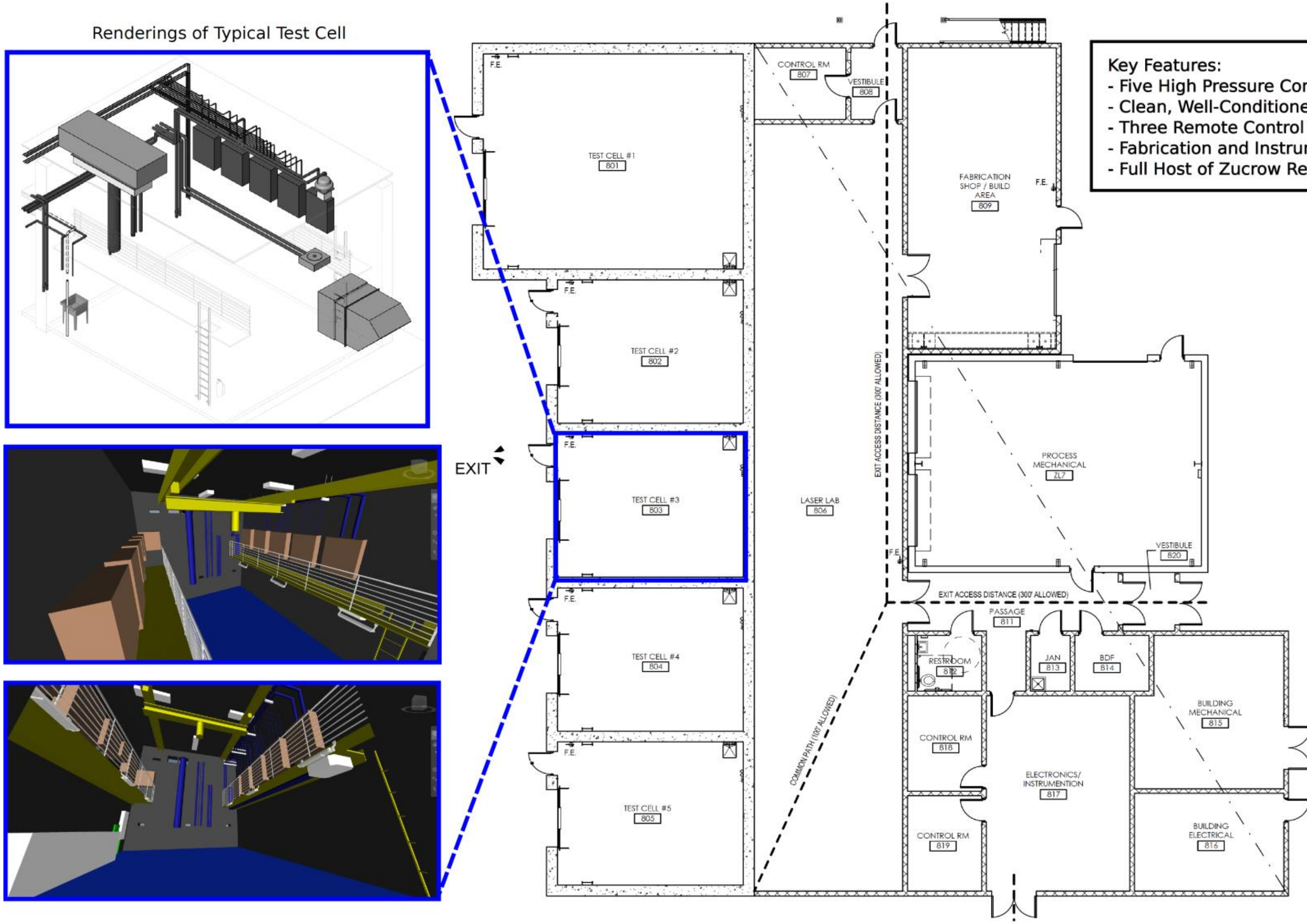
Future of High Pressure Lab Site



New Building Layout

Lab space shown…

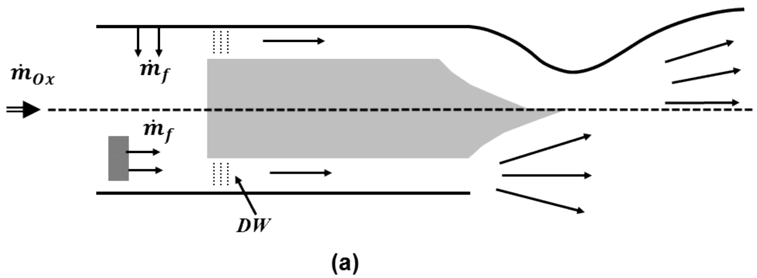
Renderings of Typical Test Cell



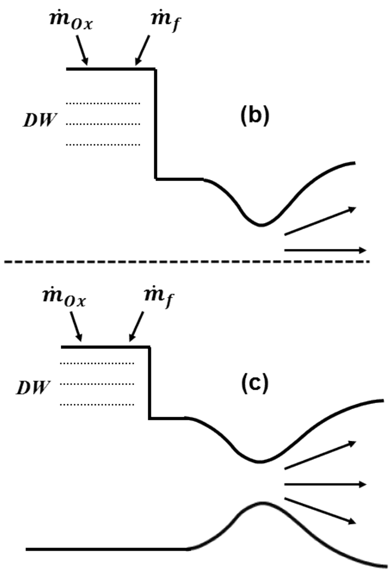
Key Features:
- Five High Pressure Combustion Test Cells
- Clean, Well-Conditioned Laser Laboratory
- Three Remote Control Rooms
- Fabrication and Instrumentation Rooms
- Full Host of Zucrow Research Fluid Services

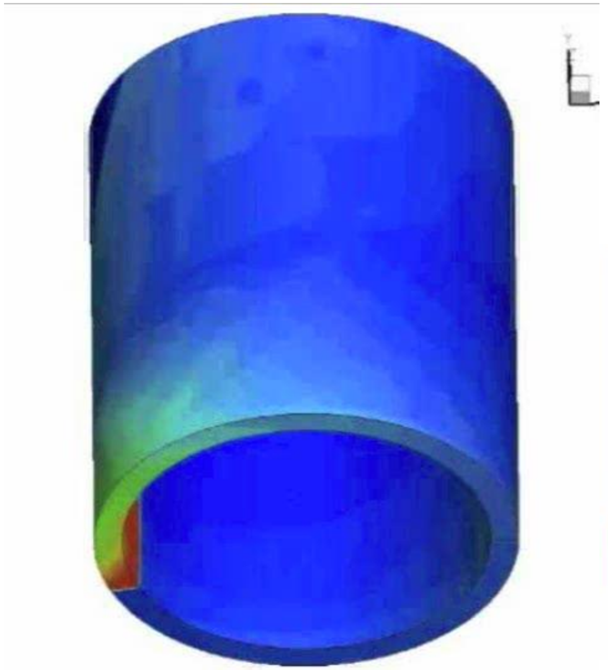
The Rotating Detonation Engine (RDE) Topologies & Cross-section

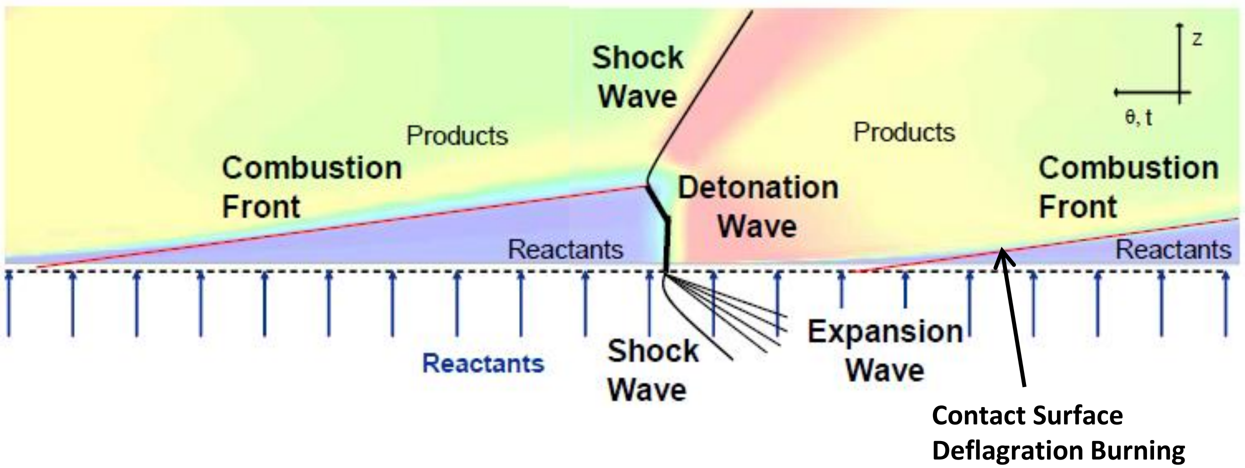
Axial Topology



Radial Topologies



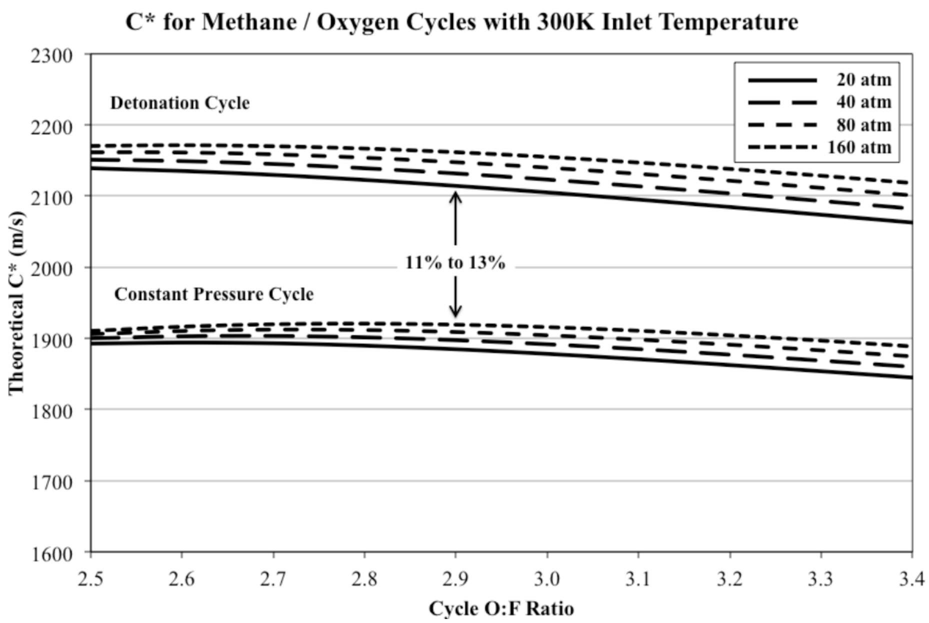


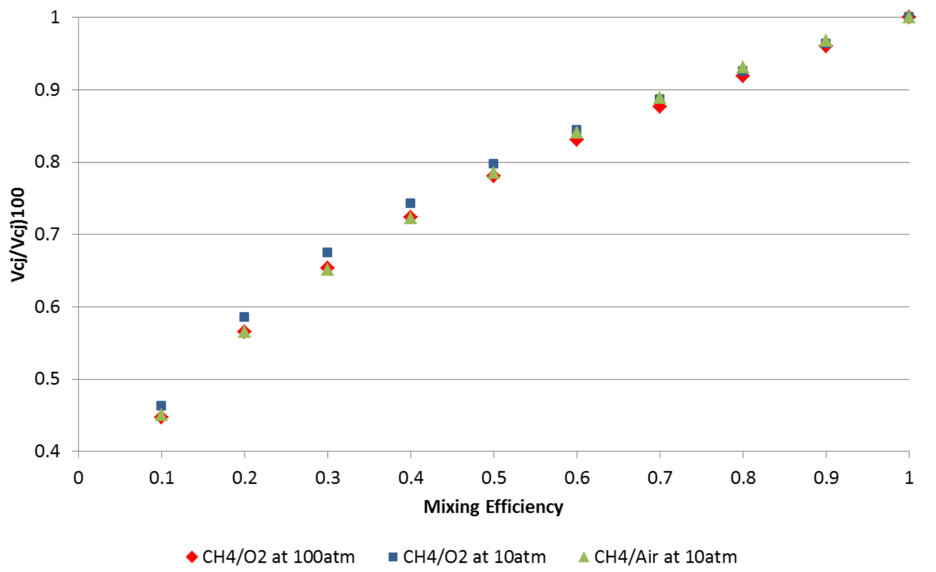


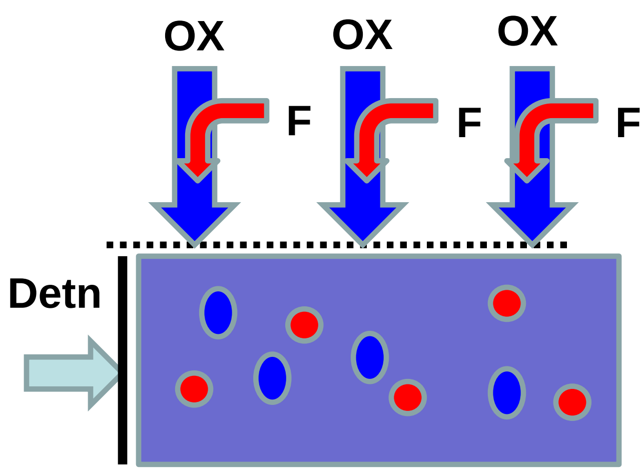
Schwer, D., and Kailasanath, K., "Numerical Investigation of Rotating Detonation Engines," AIAA 2010-6880, 2010.

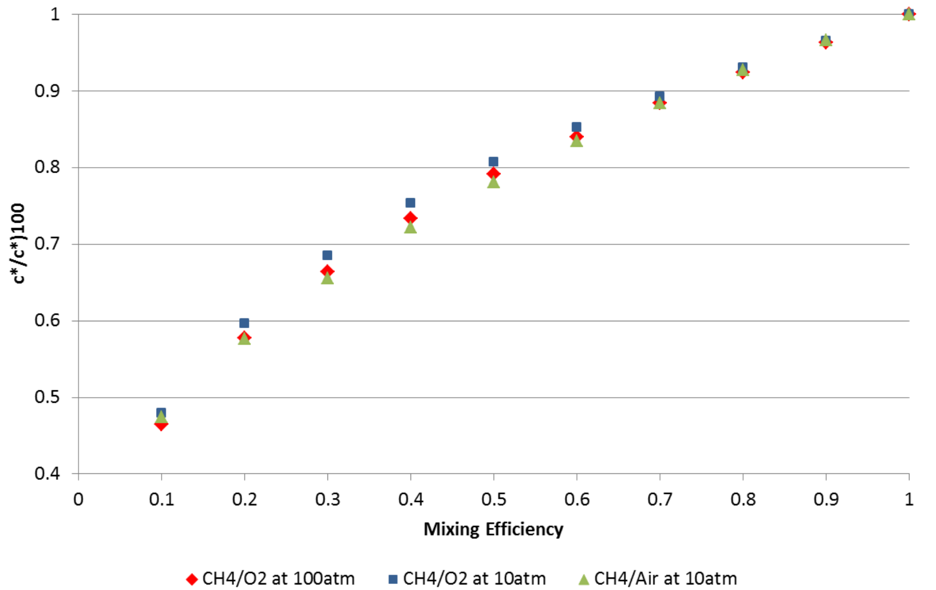
Shank, J., King, P., Darnesky, J., Schauer, F. and Hoke, J., AIAA 2012-0120, 2012.

Performance Benefit of RDE and Price of 'Unmixedness'









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Objectives – AFOSR Sponsored High Pressure Rocket RDE Work

- **Advance understanding of continuous detonation engine physics *as fast as possible* to support development of high pressure flight systems**
  - Develop understanding/capability to exploit dynamic injection environments at realistic operating conditions
  - Control of combustion chemistry to maximize performance

H2 / O2 Test Campaign (5-15 to Present)

- Rig fabrication & initial test ops completed
- Alternate injector designs in fabrication
- Supports schedule and comparison to others

CH4 / O2 Test Campaign (2016)

- Assess performance vis-à-vis H2 results
- Validate liquid/supercritical orifice response codes
- Assess combustion characteristics for various injector configurations

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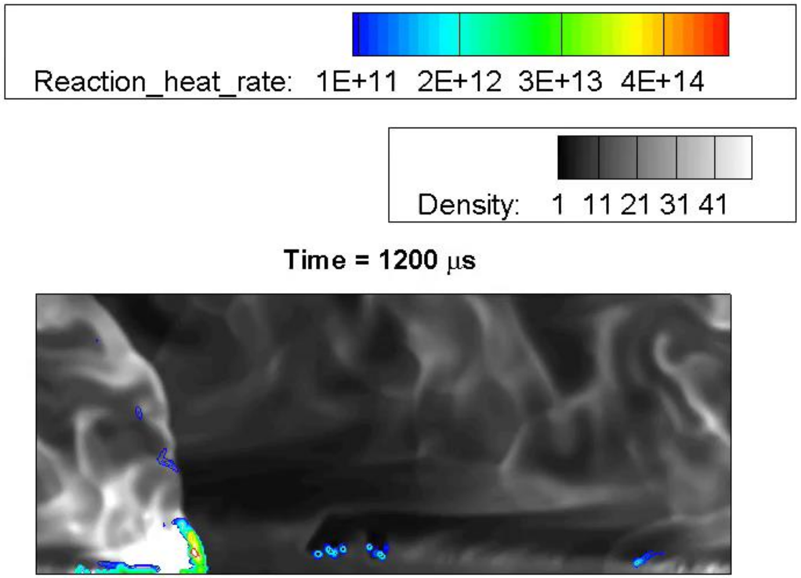
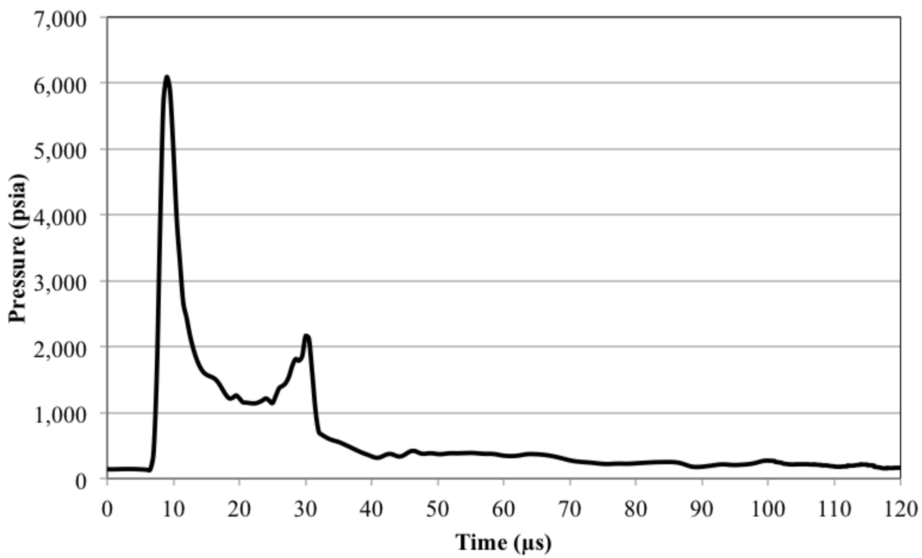
Summary of Accomplishments: High Pressure Rocket RDE Work

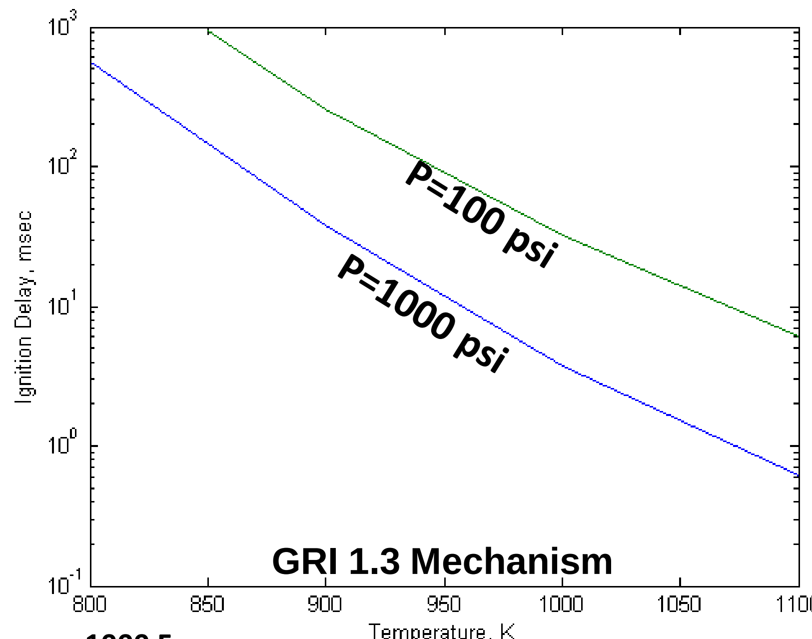
- Project initiated in Summer, 2014
- Completed literature review (ongoing effort)
- Developed design tools
  - 1-D transient orifice injector dynamic response codes
  - 2-D wave-based combustion simulation
  - Hardware thermostructural analysis
- Completed facility development
  - Injection dynamics rig for looking at liquid injection transient response
  - High pressure combustion rig integrated into existing H_2/O_2 preburner
  - Initial H_2/O_2 test campaign
- Completed hardware revisions for second test campaign
  - Hardware being integrated on to stand next week

Computed Detonation Wave Structure & Kinetics (GOX/CH_4 Propellants)





- Slow kinetics advantageous to avoid preignition
- Even at preburner exit conditions, ignition delays of 10's of millisec are readily attainable
- At 1000 psi 800K preburner outflow, ignition delay behind the C-J shock is 3 nanosec!



1000 F

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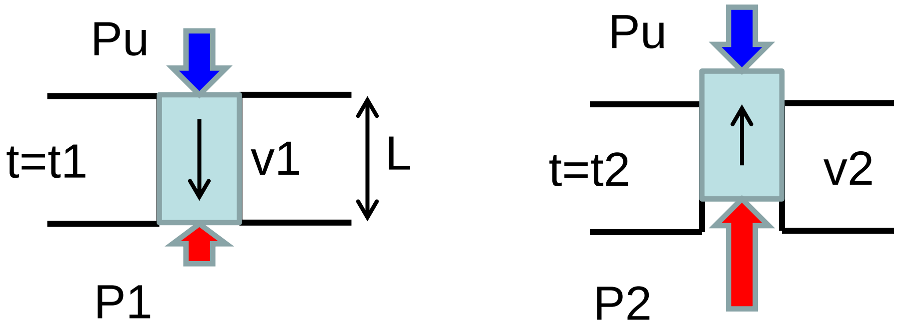
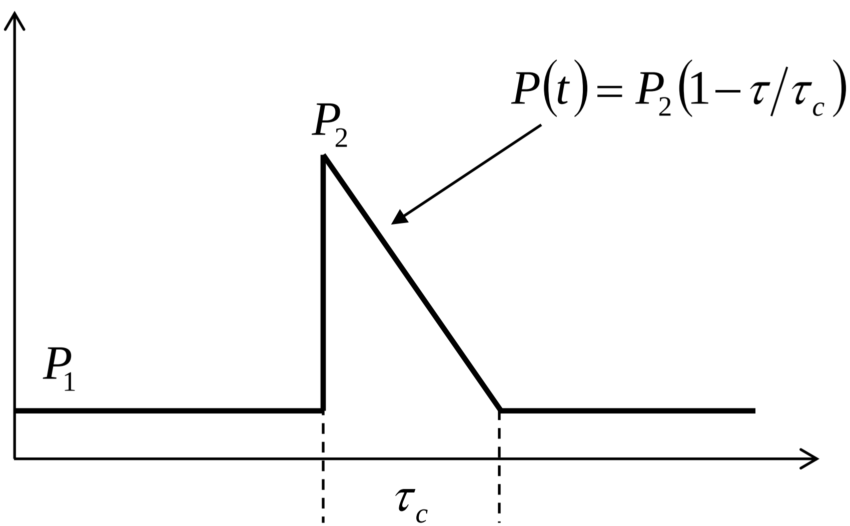
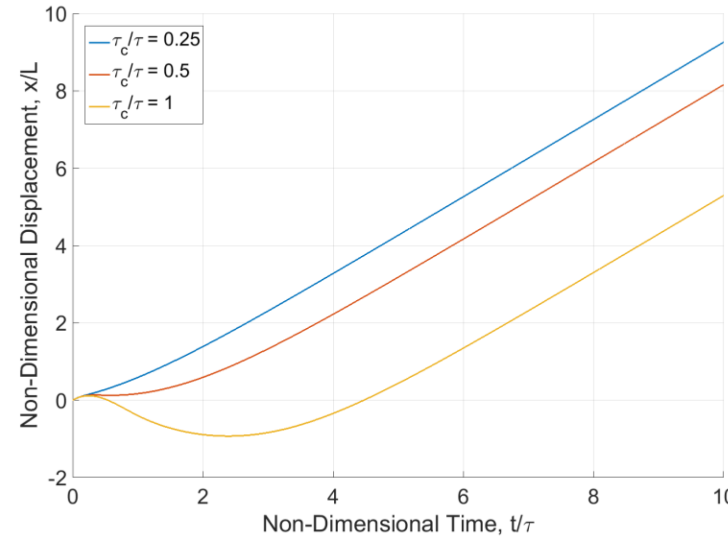
Simple Model of Injection Response

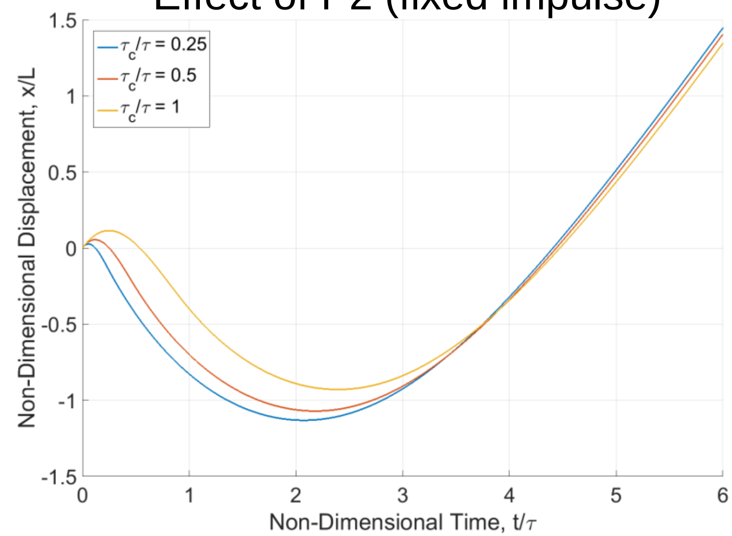




Effect of Pulse Duration (fixed P2)



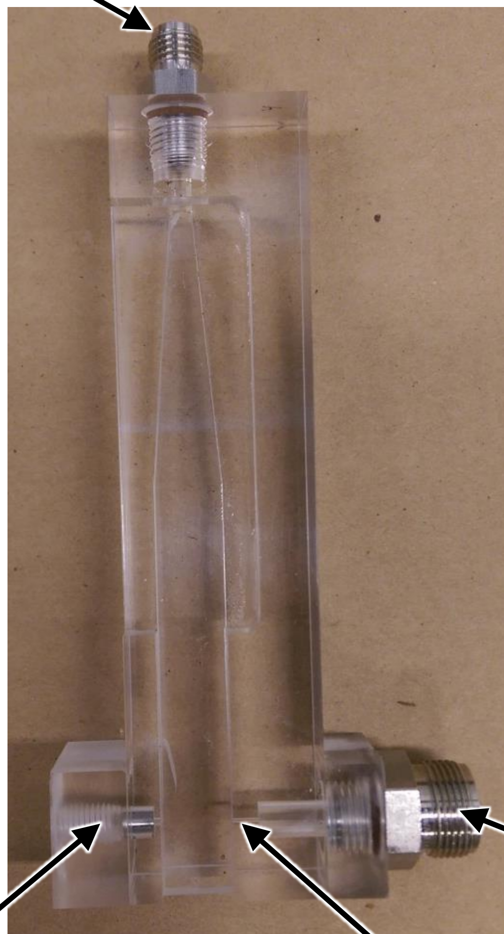
Effect of P2 (fixed impulse)



- For a typical pulse $1 < \tau_c < 50$ microseconds so fluid injection is highly dynamic
- Pulse shape is unimportant – impulse governs overall response

Injection Dynamics Visualization

Connection to pre-detonator



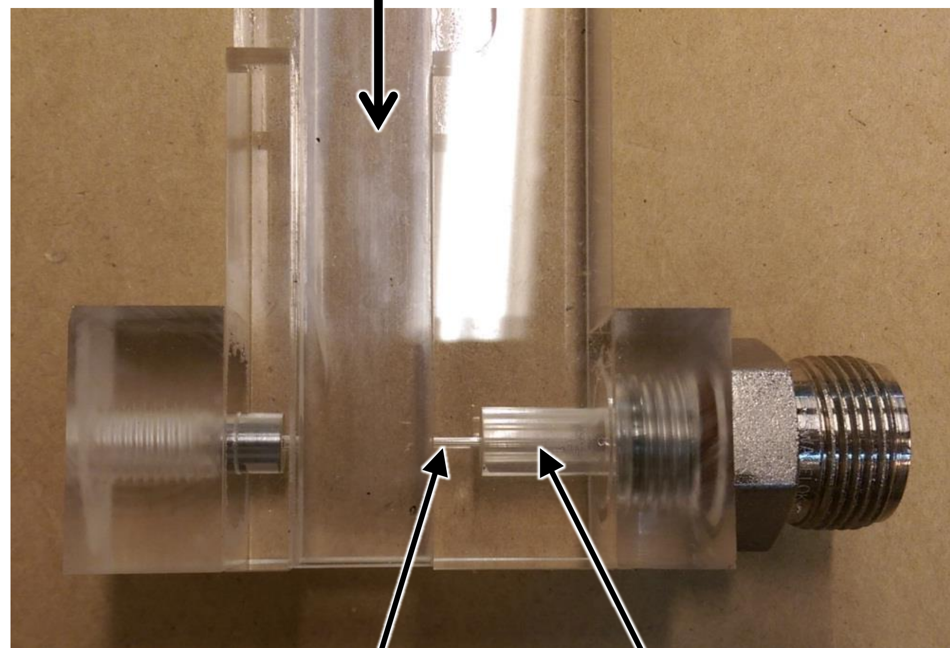
5.25”

Water Inlet

Pressure Port

Injector Orifice

H_2/O_2 Detonation wave



0.033”IDx0.3”L Orifice

Inlet Plenum

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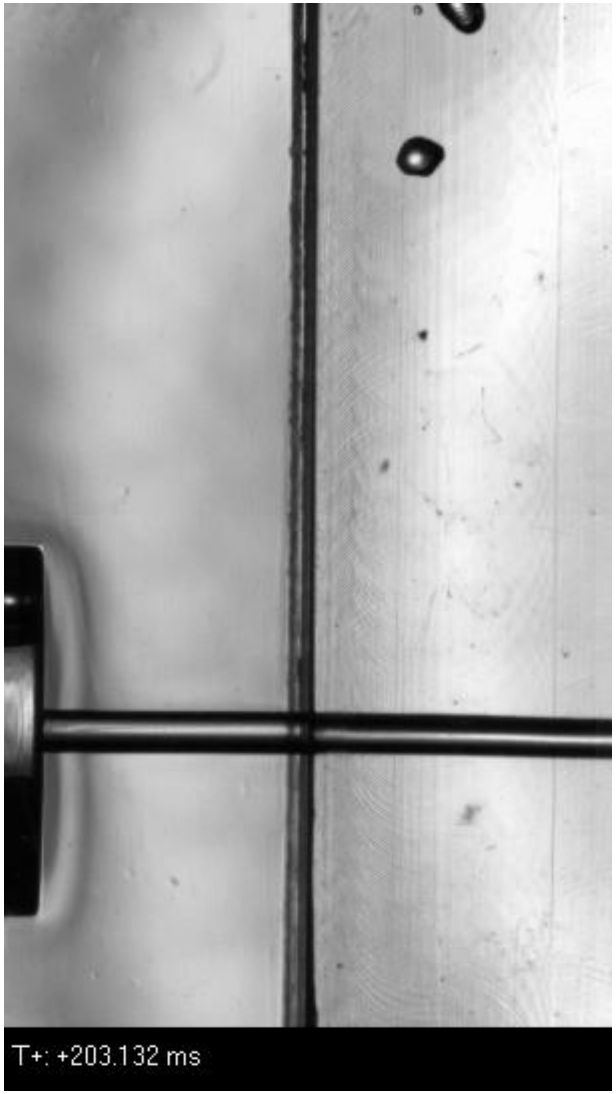
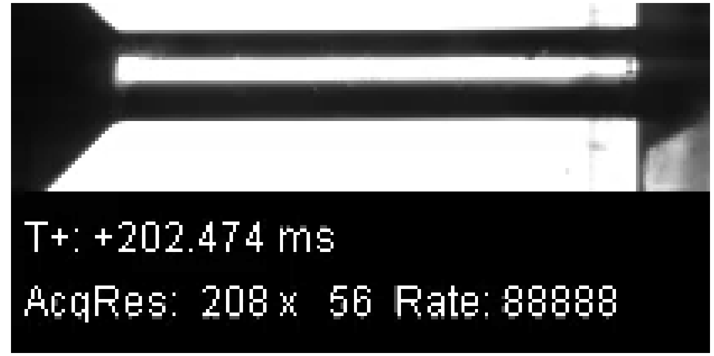
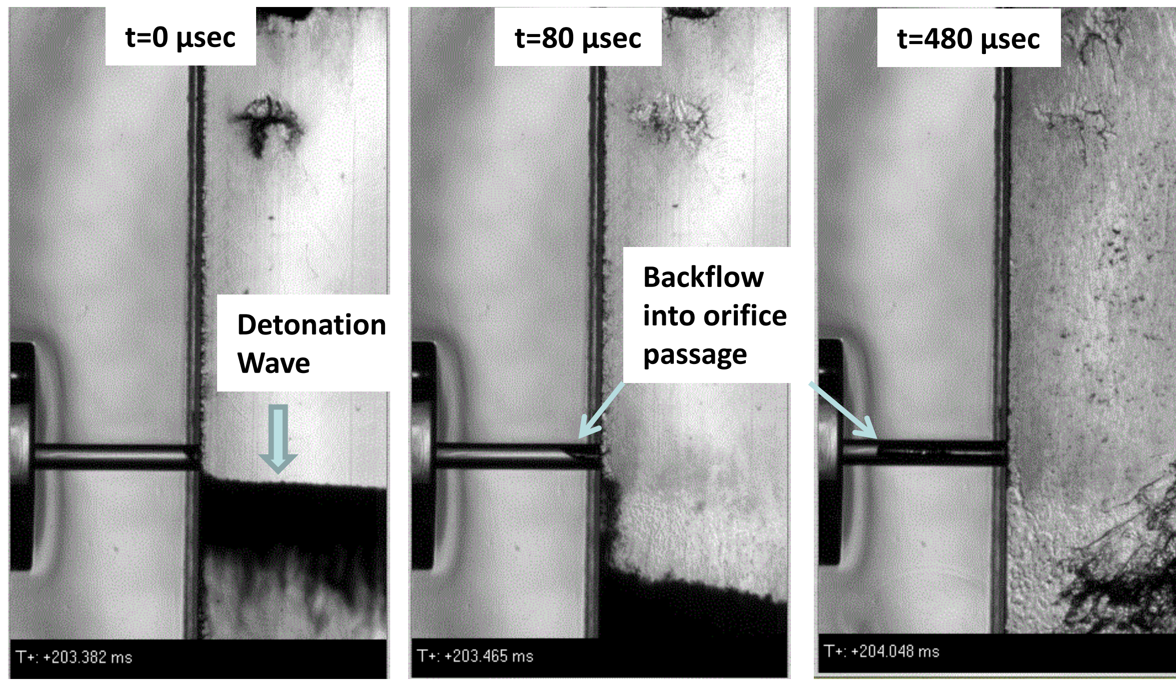
High-speed Movies

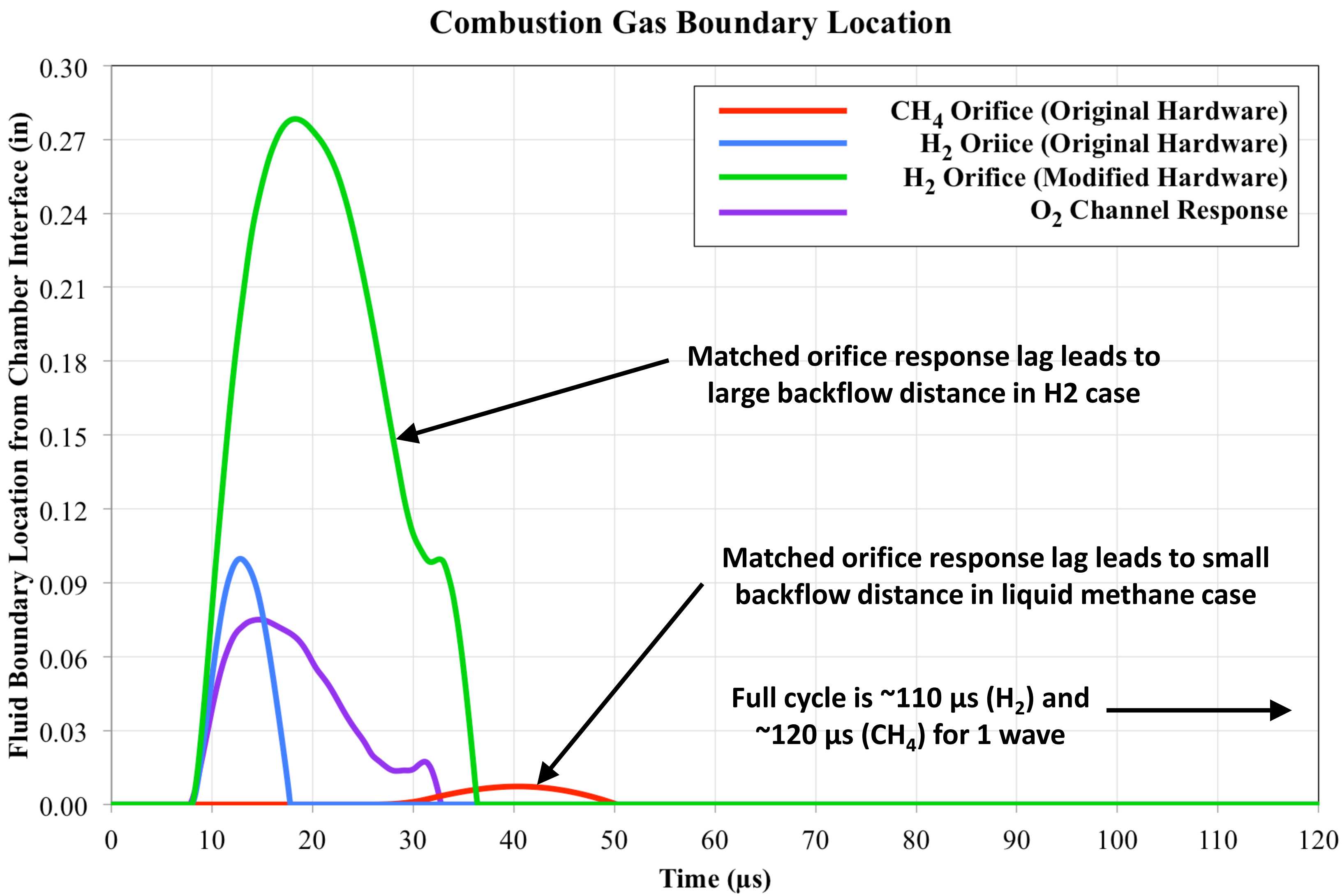


12,000 fps



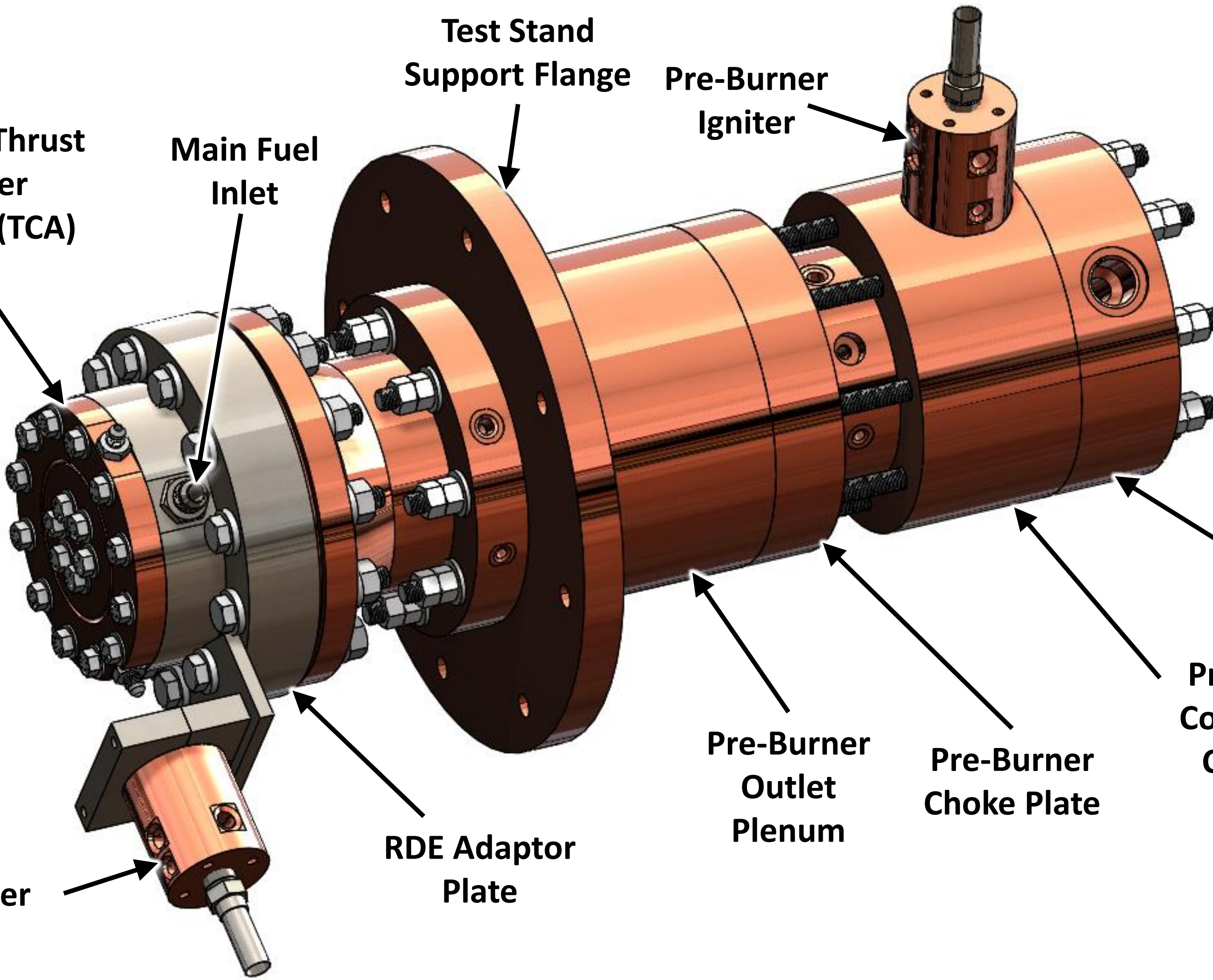


Injection Dynamic Response



Note: The modified hardware includes larger fuel orifices, lower manifold pressure
Methane simulation uses a lumped-parameter model
Hydrogen simulation uses a 1D compressible CFD model

High Pressure RDE Test Article



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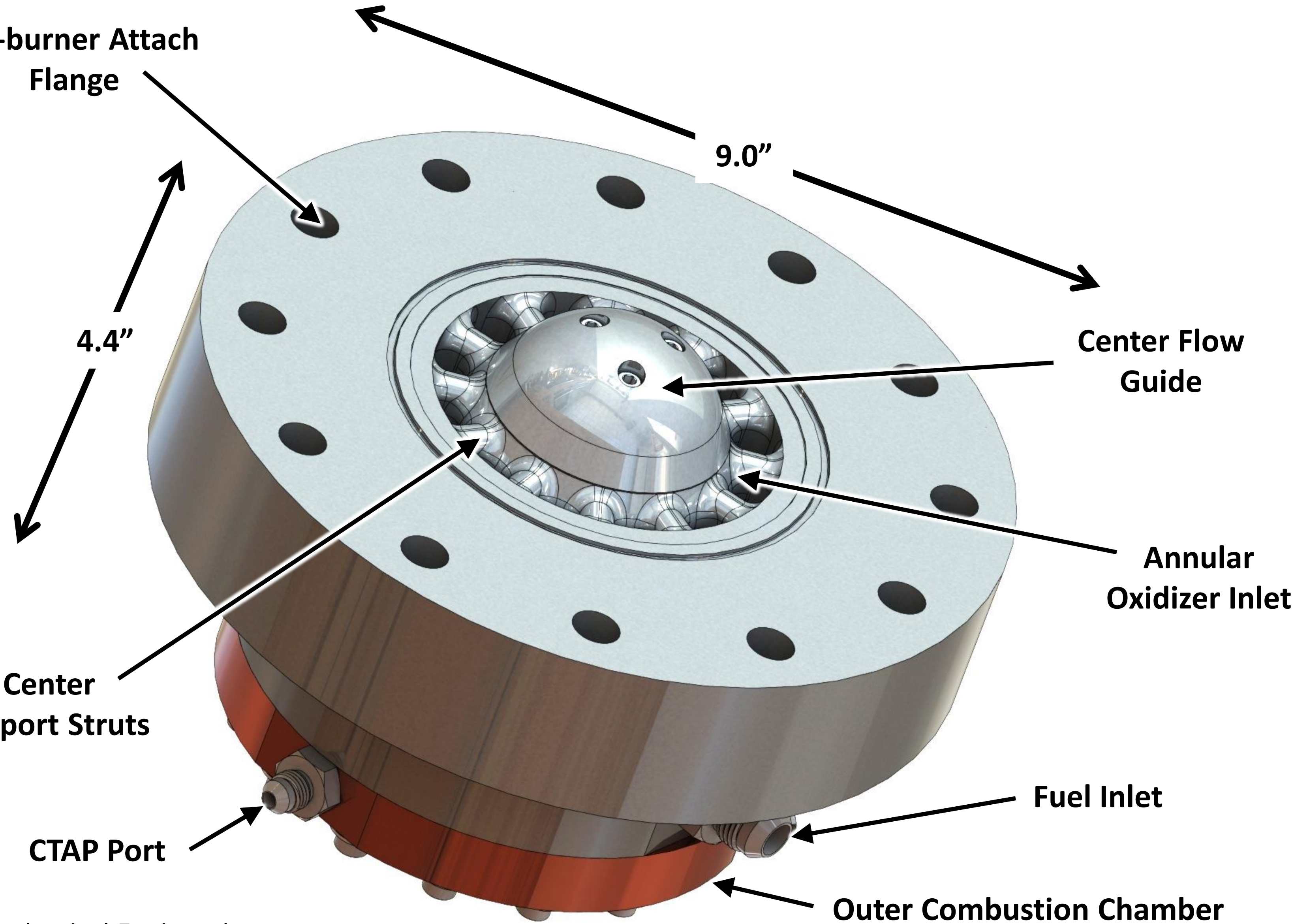
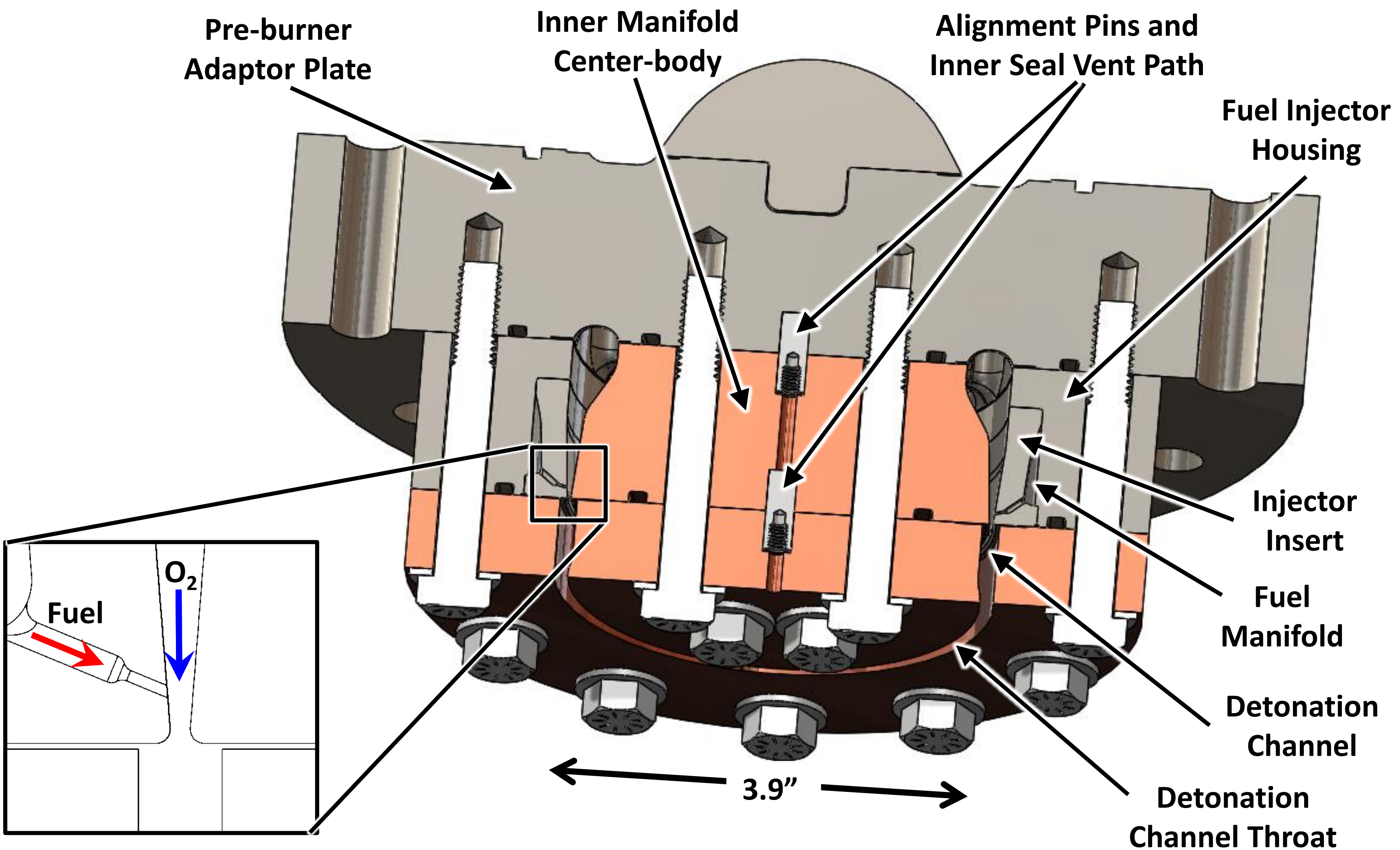
Length: 26”

Weight: 350 lb

High Pressure RDE Test Article



High Pressure RDE Test Article



Predicted Conditions at Full Power:
P_c = 1200 psi, f = 8.1 KHz, F = 2300 lbf, mdot = 8.8 lbm/s, O/F = 2.7

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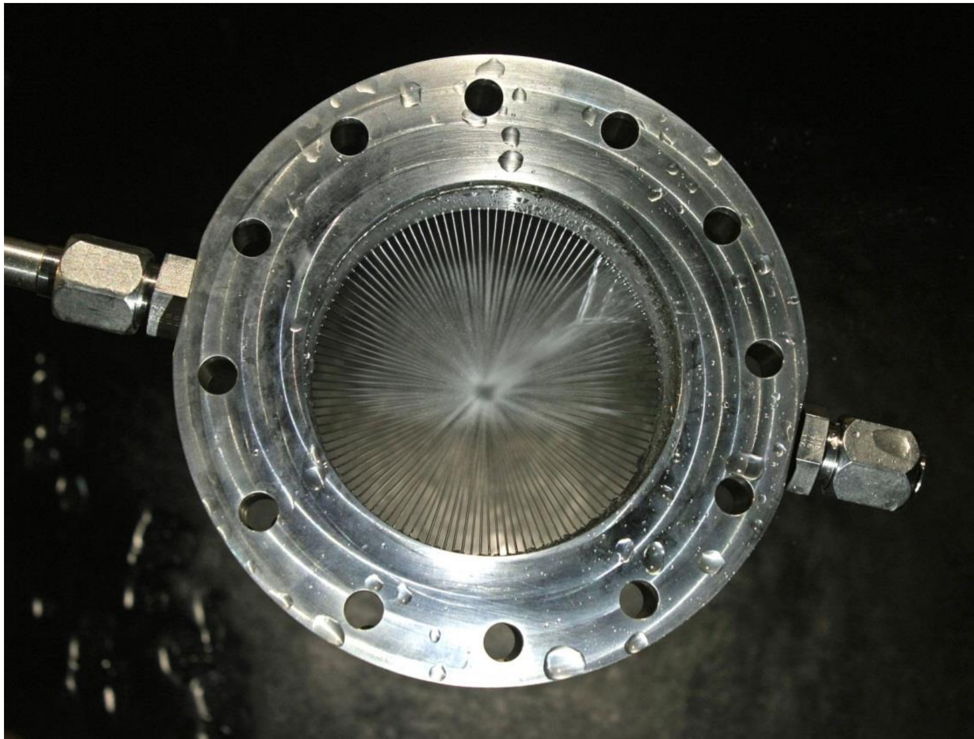
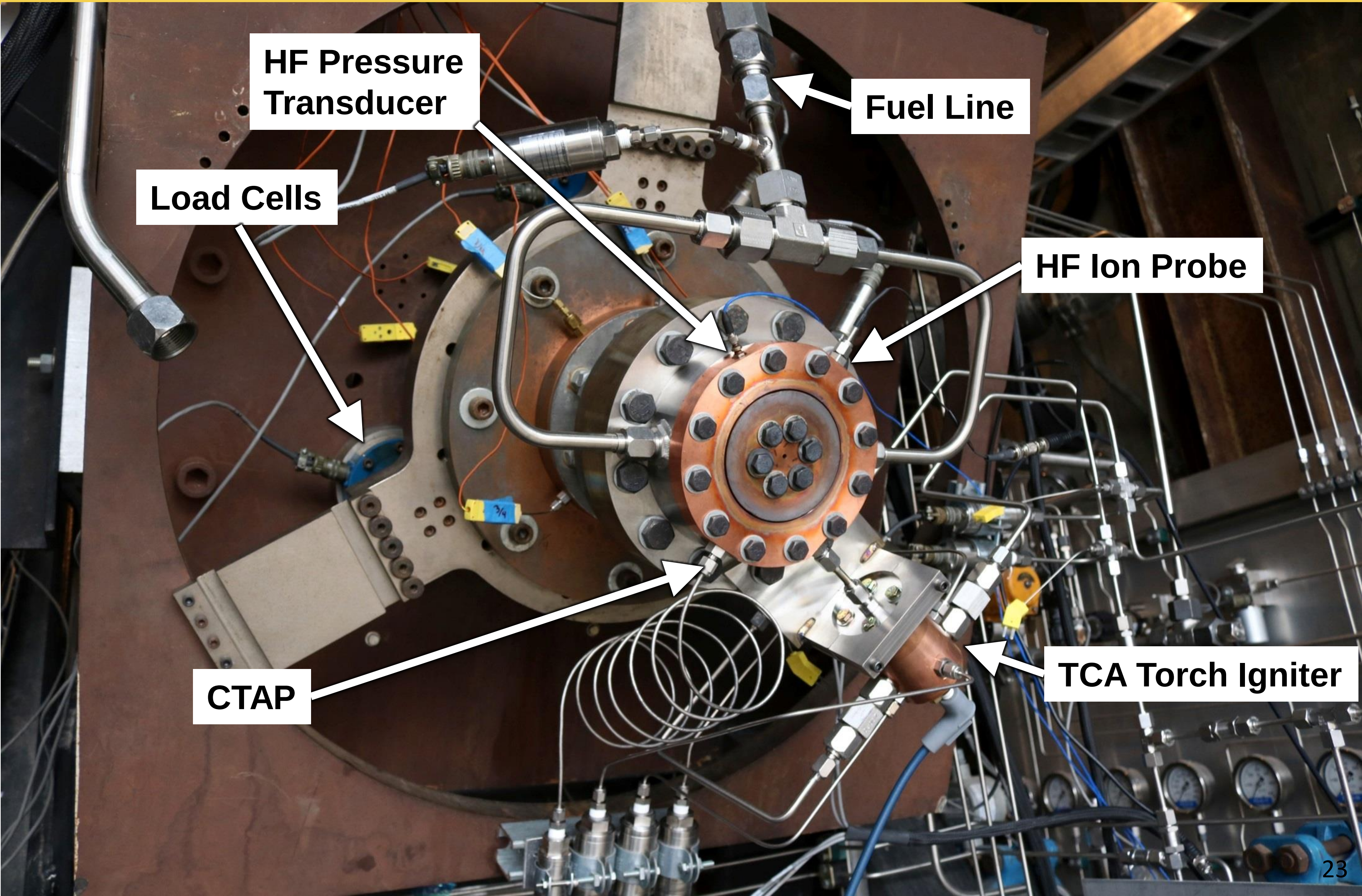
Instrumentation

- Minimum instrumentation suite employed until facility shakeout completed
- Pressure measurements: CTAP and flush mounted PCB in chamber and inlet manifolds
- Ion gage in chamber
- Axial thrust
- Microphone on combustor exit
- High-speed camera on annulus
- Several low-speed cameras and still photos of plume

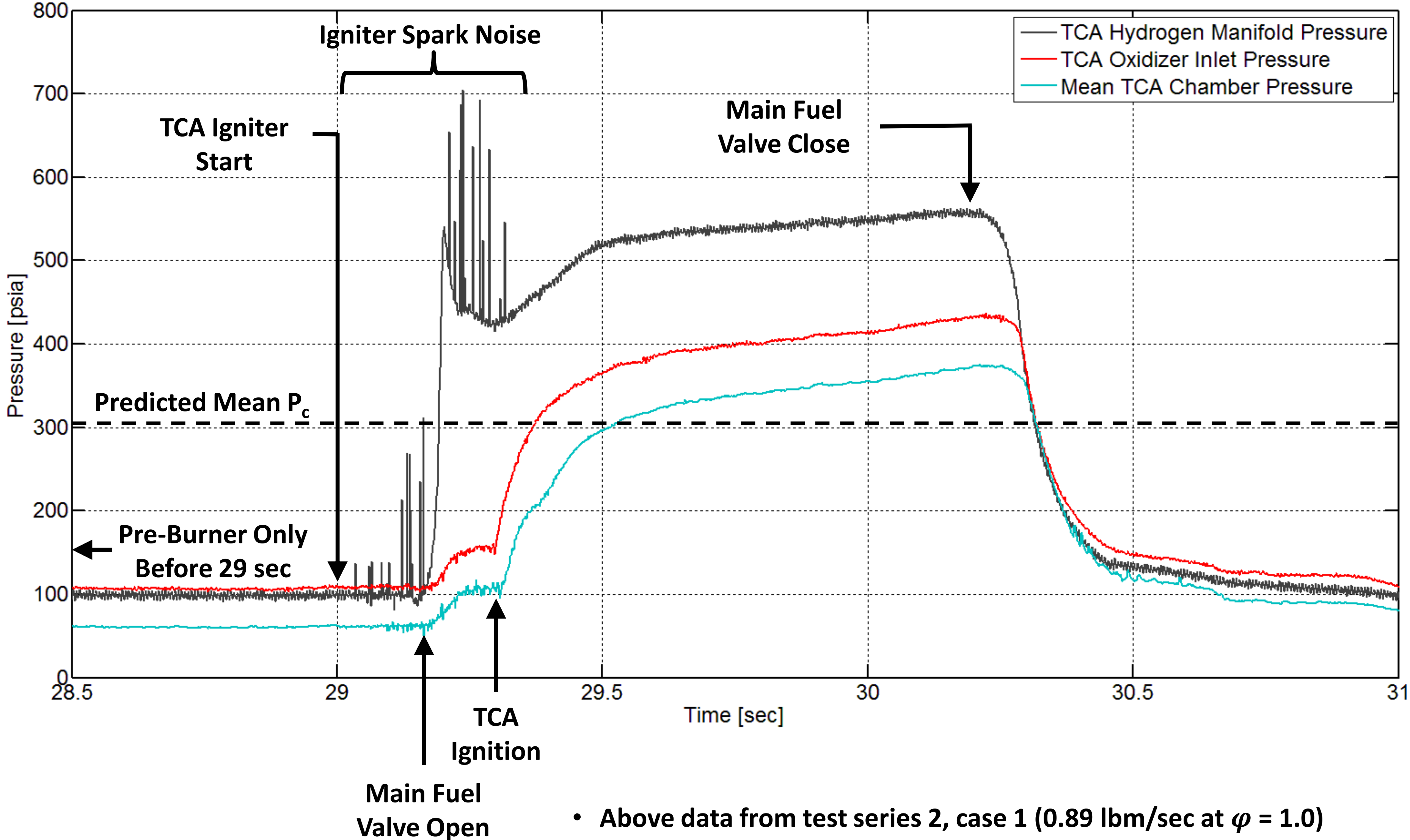
Injector Water Flow



LOX/GH2 RDE on Test Stand

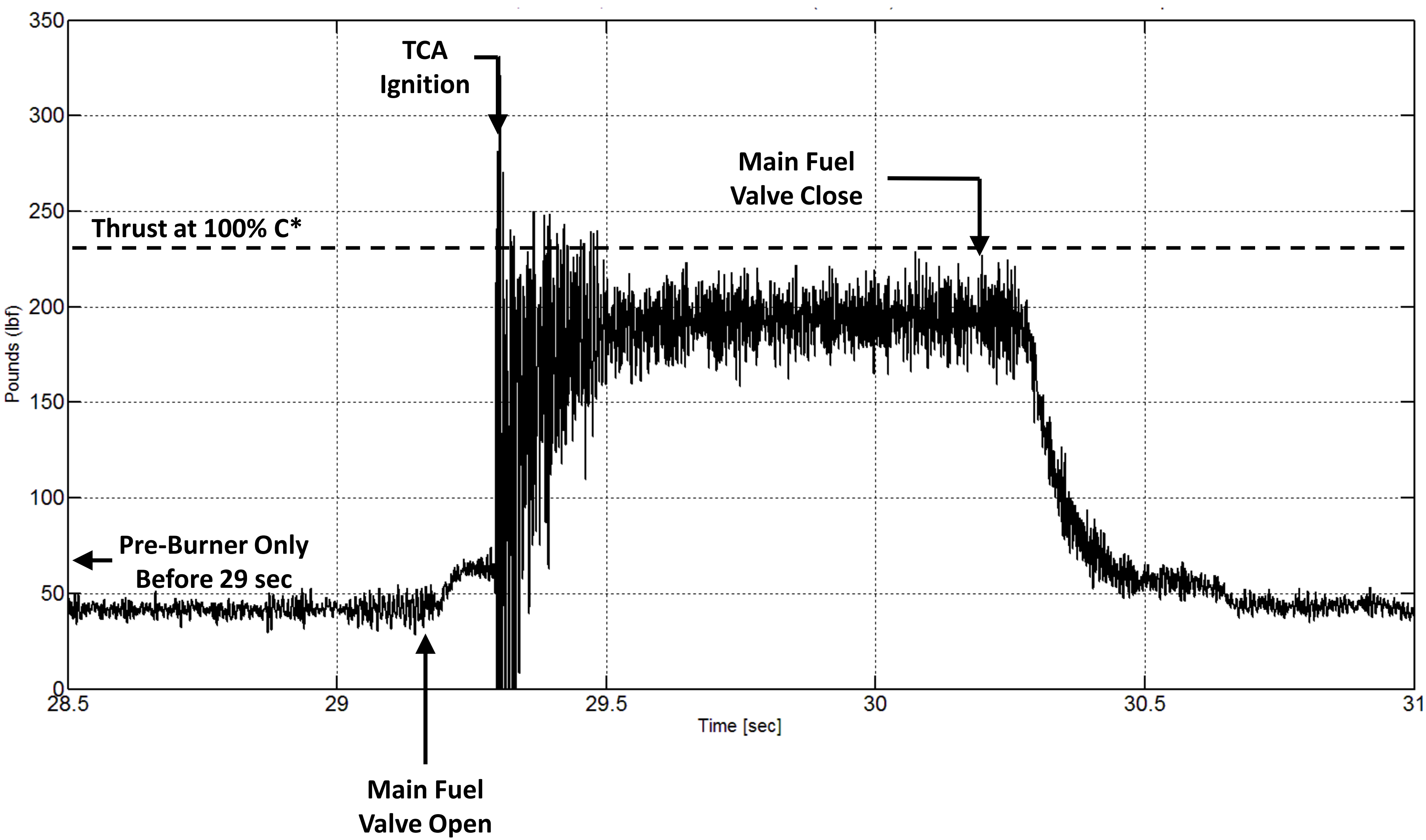


High Pressure RDE Test Results



- Above data from test series 2, case 1 (0.89 lbm/sec at φ = 1.0)
- Chamber pressure increases during the burn due to increasing copper wall temperature and mild throat contraction

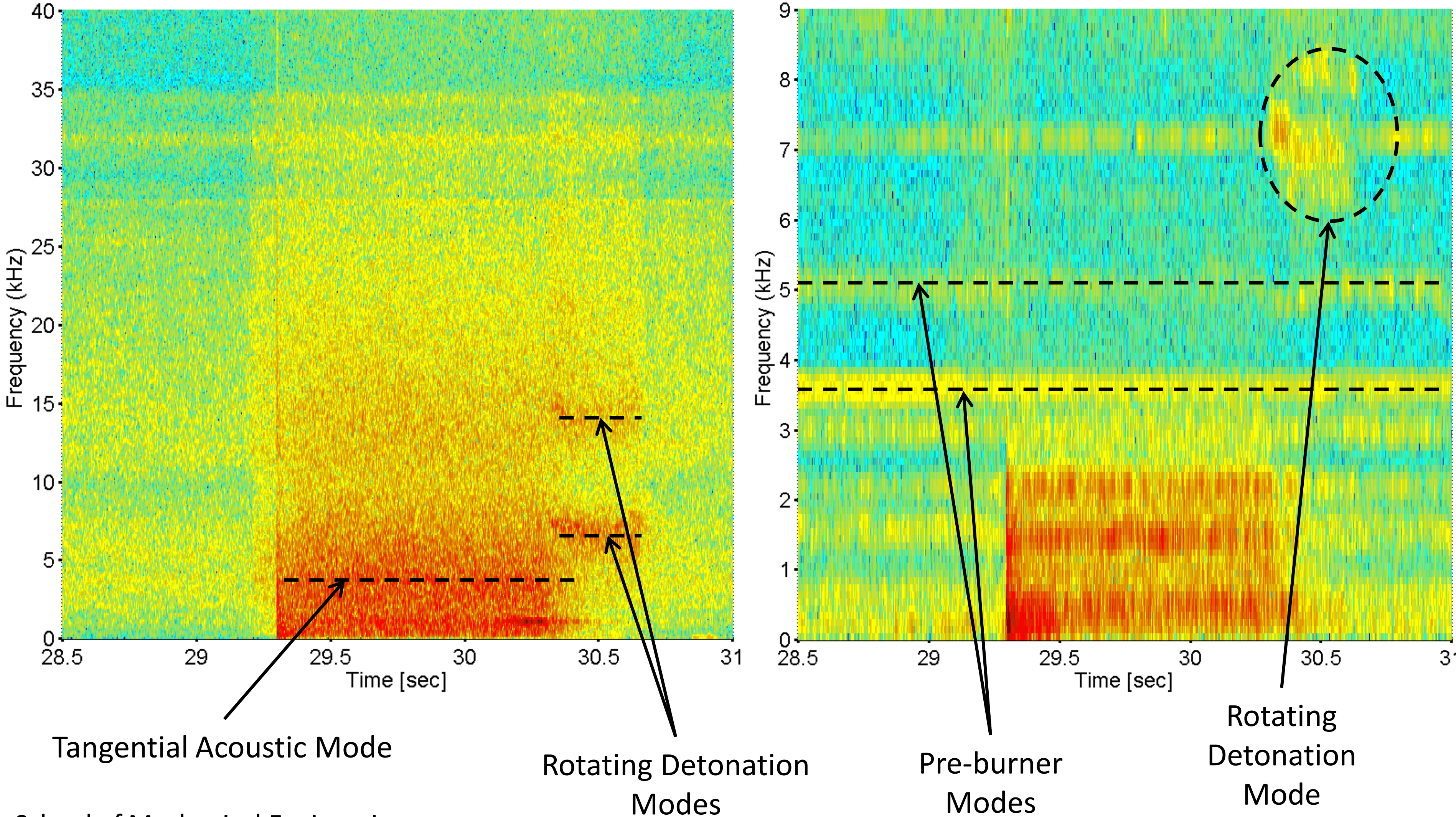
Thrust Data


350
300
250
200
150
100
50
0
28.5
29
29.5
30
30.5
31
Time [sec]
Pounds (lbf)
TCA Ignition
Main Fuel Valve Close
Thrust at 100% C*
Pre-Burner Only Before 29 sec
Main Fuel Valve Open

Test results show 7KHz operation during shutdown

Microphone Spectrogram

Load Cell Spectrogram



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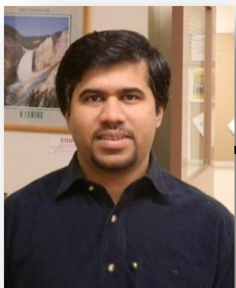
Objectives

- Characterize the performance of injection/mixing systems in a RDE using an optically-accessible, linear platform with actual injector geometry
- Establish an experimental methodology to assess pressure gain utilizing coupled global and local measurements performed at conditions relevant to terrestrial turbine systems (up to a P3 and T3 of 2.0 MPa and 800 K, respectively)
- Evaluate the operability of an RDE combustion chamber over range of operating conditions
- Generate 10 kHz stereoscopic PIV measurements to capture the three component velocity field measurements at the exhaust plane
- Quantify pollutant emission production over a wide range of operability

Research Team

Steve Heister, Raisbeck Distinguished Professor (co-PI)

Carson Slabaugh, Assistant Professor (co-PI)



Dr. Swanand Sardeshmukh, Postdoctoral Researcher

Brandon Kan, Ph.D. student

Kyle Schwinn, M.S. student

Dr. Adam Holley and Mr. Chris Greene, UTRC advisors

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Summary of Proposed Efforts

- Effort Includes Seven Major Tasks
- Task 1.0 – Project Management and Planning
- Task 2.0 – Baseline Canonical Experiments
- Task 3.0 – Subscale Combustor Facility Development
- Task 4.0 – Integral Measurement of Pressure Gain
- Task 5.0 – Detailed Measurements of Exit Conditions
- Task 6.0 – Emissions Measurements
- Task 7.0 – Computational Model Development

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Task 1: Project Management

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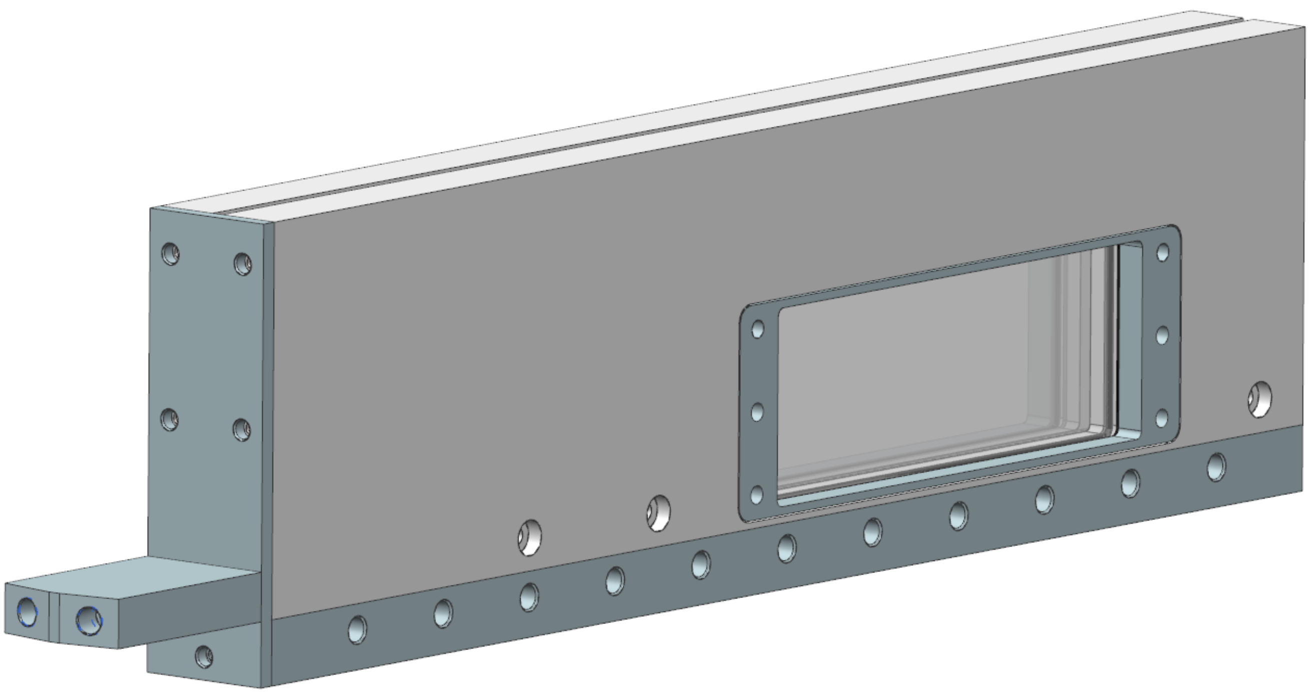
Subtask/Calendar Quarter	1	2	3	4	5	6	7	8	9	10	11	12
TASK 1.0: Project Management And Planning												
SubTask 1.1: Revision of the PMP	X											
SubTask 1.2: Quarterly and Annual Project Reports	X	X	X	X	X	X	X	X	X	X	X	X
SubTask 1.3: Final Progress Report												X
TASK 2.0: Injection Dynamics Characterization												
SubTask 2.1: Experiment Design, Fabrication, and Integration	X	X										
SubTask 2.2: Detailed Measur. with Simultaneous Diag.			X	X	X	X						
Subtask 2.3: Injection Dynamics Characterization.					X	X	X	X	X	X	X	X
TASK 3.0: Subscale Combustor Facility												
Subtask 3.1: Design, Fabrication, and Integration			X	X								
SubTask 3.2: Facility Checkout Testing				X	X							
SubTask 3.3: Operational Mapping						X						
Task 4.0: Evaluation of Pressure Gain												
Subtask 4.1: Integral measurements							X					
Subtask 4.2: CFD results and detailed measurements								X	X	X	X	X
TASK 5.0: Detailed Meas. of Inlet and Exit Conditions												
SubTask 5.1: Exit Velocity Field								X	X	X	X	
SubTask 5.2: Inlet Condition								X	X			
TASK 6.0: Emissions Measurements												
SubTask 6.1: Gas Sampling System Design and Integration			X	X	X	X						
SubTask 6.2: Pollutant Emission Production Survey						X	X	X	X			
TASK 7.0: Computational Model Development												
SubTask 7.1: Injection Dynamics Models	X	X	X	X								
SubTask 7.2: 2-D Combustion Model				X	X	X	X	X				
SubTask 7.3: Comprehensive 3-D Model							X	X	X	X	X	X

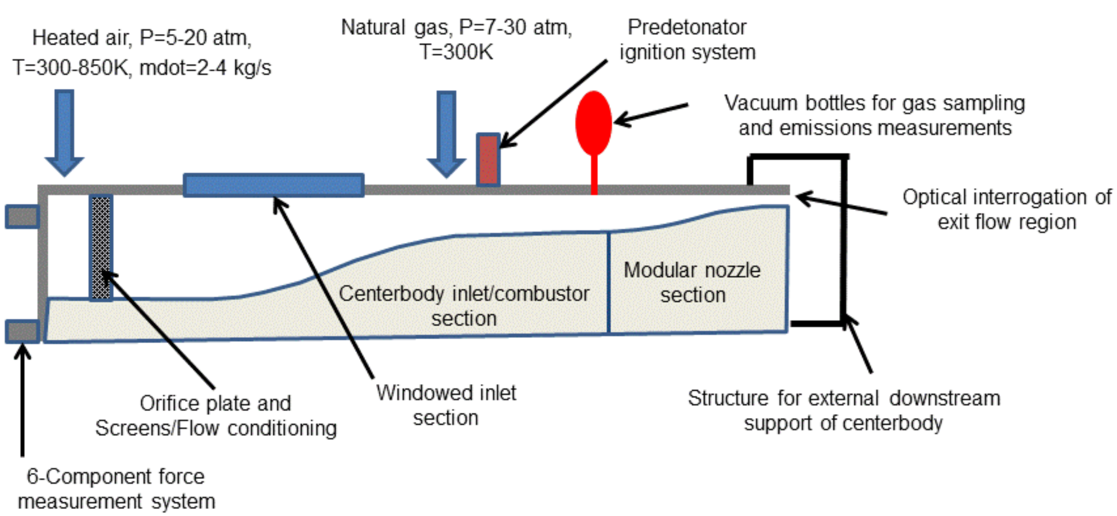
Task 2: Canonical Experiments

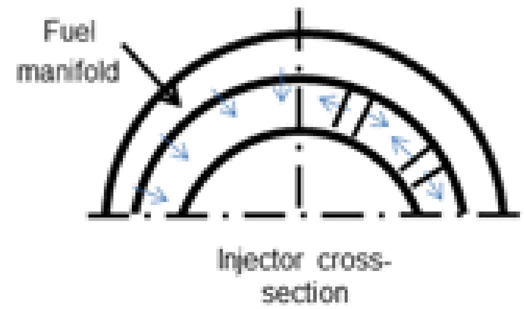
- The **D**etonation **R**ig for **O**ptical, **N**on-intrusive **E**xperimental measurements (‘DRONE’)
  - Injection dynamics
  - Parasitic deflagrative combustion
  - Semi-bounded detonation wave propagation



Task 3: Subscale Combustor Facility Development

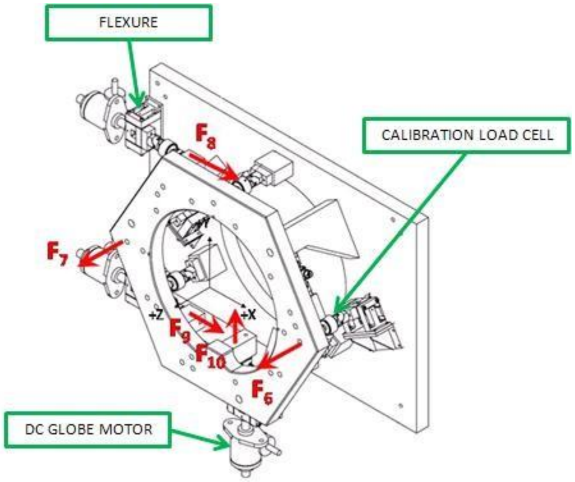
- Air flows up to 10 lbm/s at relevant operating pressures
- Optical accessibility near fuel injection site to monitor dynamic response
- Optical interrogation of exit flow

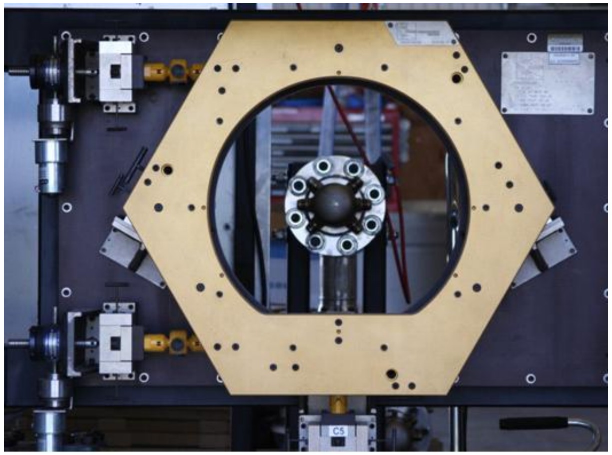




Task 4: Evaluation of Pressure Gain

- Integral measurements (CTAP and thrust)
- Comprehensive assessment
  - High frequency inflow pressure measurement
  - CFD analysis
  - Detailed exit flow measurement/characterization

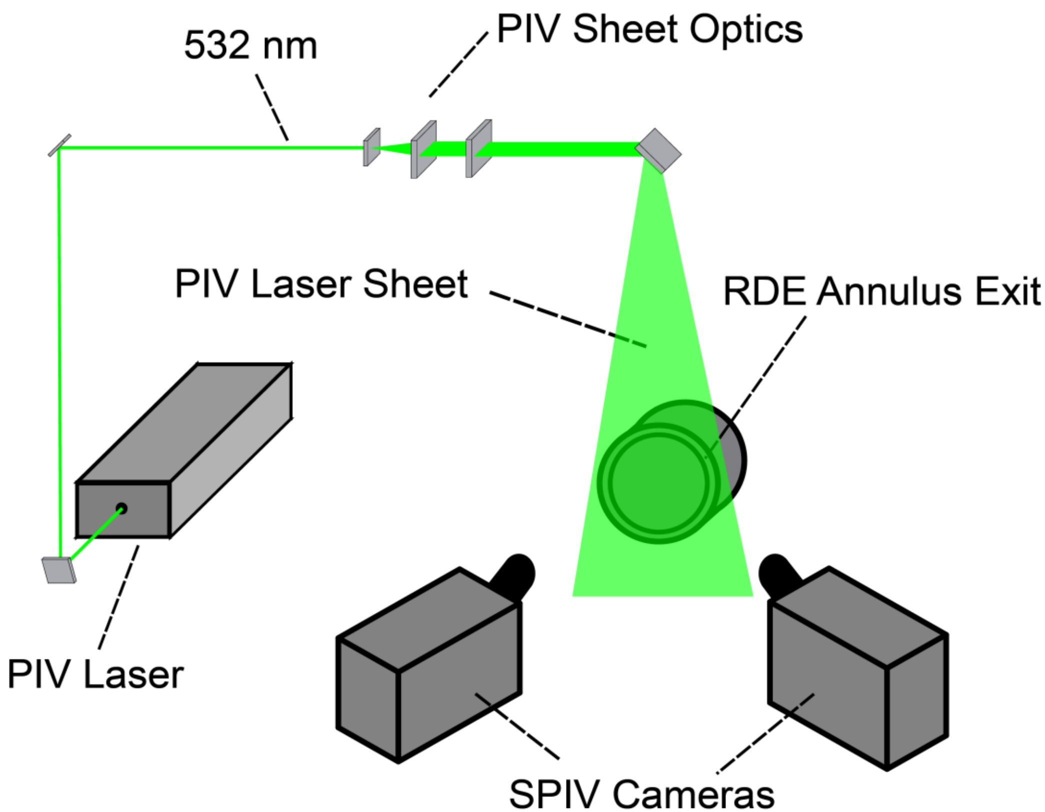




Six-component force measurement system with in-situ calibration system.

Task 5: Detailed Inlet and Exit Flow Measurements

- 10 KHz 3-component Stereoscopic PIV of exit velocity field
- Visible light emission and OH* on inlet manifold

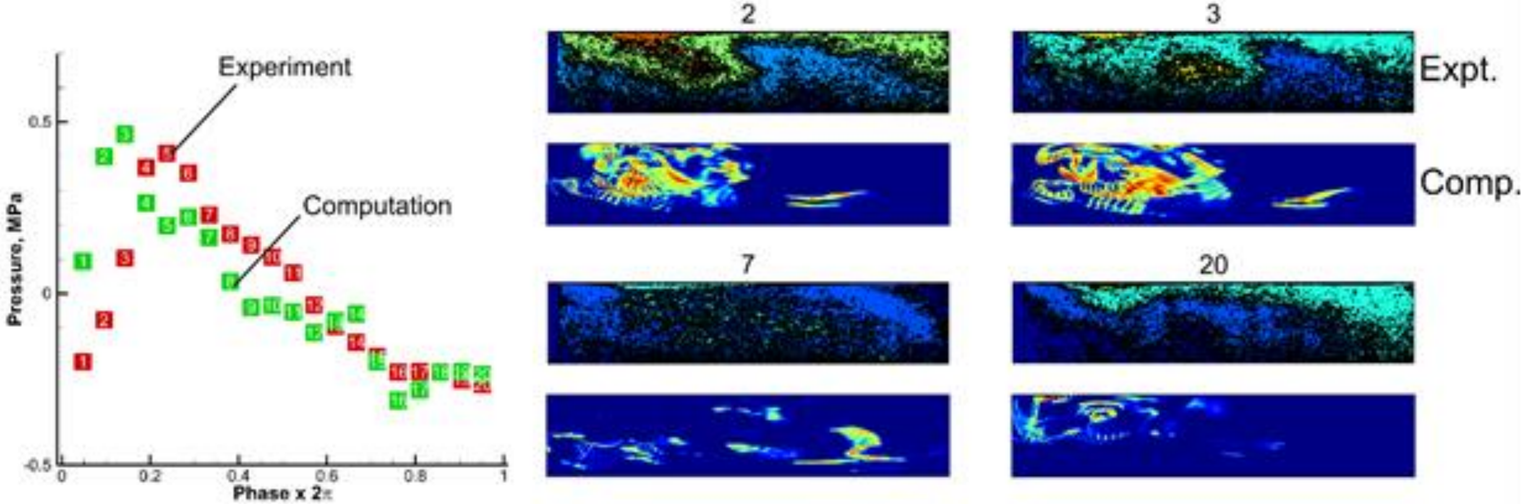


Task 6: Emissions Measurements

- Water-cooled sampling probe
  - Hydraulic average with choked inlet holes
  - Quenched kinetics from sampling and probe cooling
- Sample gas drawn into purged vessel for analysis after completion of transient test operations
- Flame Ionization Detector (FID) measures unburned hydrocarbon concentration
- FTIR spectrometer measures NO, NO_2, CO, CO_2, H_2O concentration
- Separate detector for O_2 concentration

Task 7: Computational Model Development

- Generalize Equation and Mesh Solver (GEMS) code will be principle platform for CFD work
  - Developed over 20+ year period by Dr. Merkle and his students, now in further development at Purdue and AFRL
  - Advanced preconditioning and general fluid treatment for transcritical behavior
  - GRI 3.0 natural gas kinetics mechanism



Comparison of the predicted pressure cycle in Purdue's CVRC and corresponding snapshots comparing experimental chemiluminescence and computed CH* species.