Advancing Pressure Gain Combustion in Terrestrial Turbine Systems

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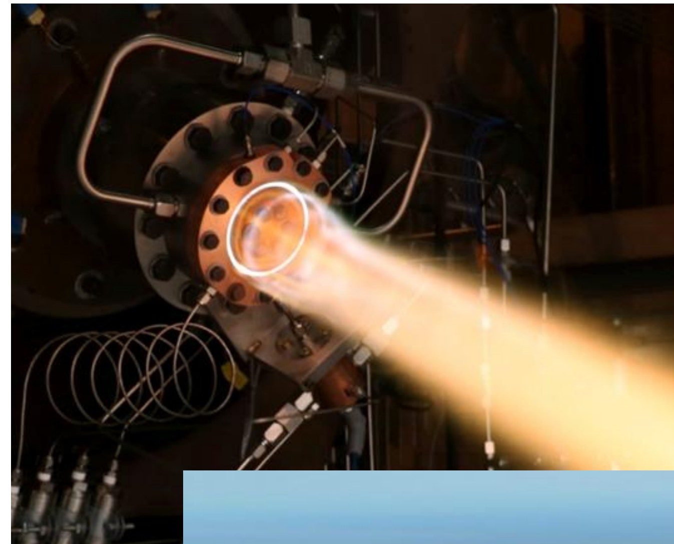
Introduction

PGC Technology for Terrestrial Turbine Systems

- Several Flavors of PGC
  - CV deflagrative devices
  - PDEs
  - RDEs
- Potential for large, single-technology gains in cycle efficiency
  - 4-7% for simple cycles
  - 1-3% in combined cycles
- Challenges to Overcome
  - Combustion ‘Instability’
  - Materials Considerations
  - Component Integration
  - Pollutant Emissions
  - Cost

Purdue High Pressure Rocket RDE Testing



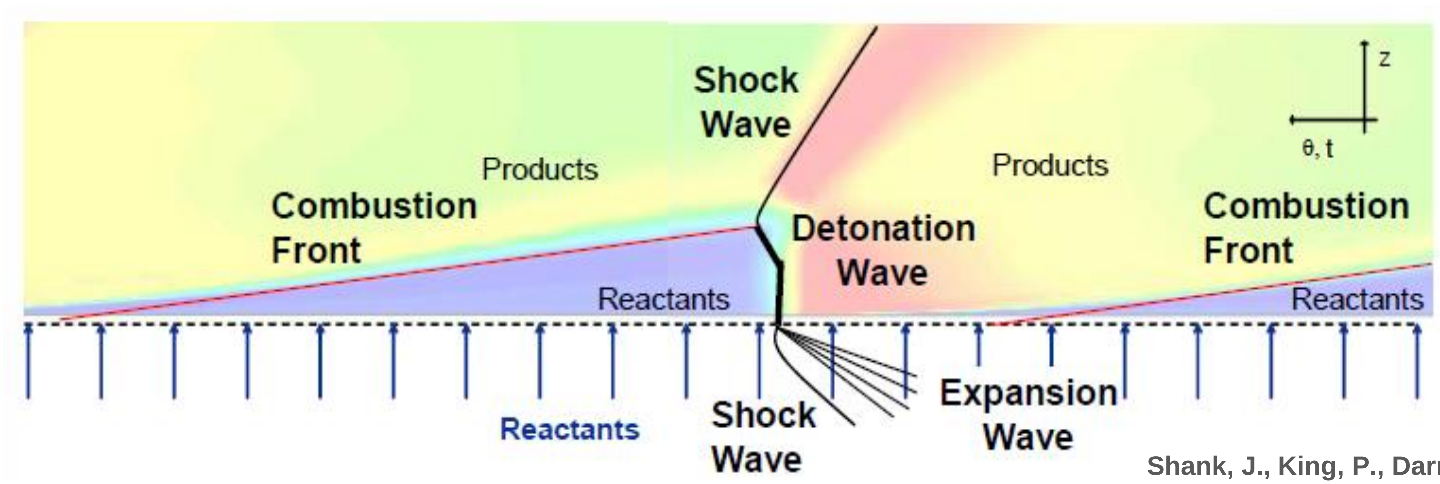
GE FlexEfficiency Combined Cycle Power Plant

Introduction

Rotating Detonation Engines

- ‘Continuous Spin’ Detonation
  - DDT occurs in the starting transient
  - Self-preserving
- Transverse, semi-bounded detonation wave propagation
- High specific power output
- Principal Challenges:
  - Unsteady mixing
  - Mixture stratification
  - Wave Stability/Propagation
  - Parasitic Deflagration
  - Shear Layer Instability
  - Shock Losses

Schwer, D., and Kailasanath, K., AIAA 2010-6880, 2010.

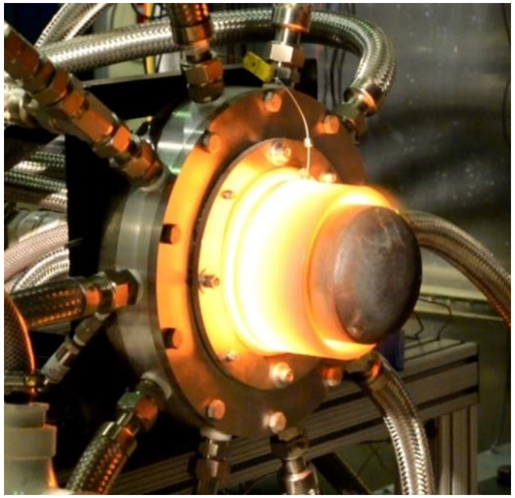


Shank, J., King, P., Darnesky, J., Schauer, F. and Hoke, J., AIAA 2012-0120, 2012.

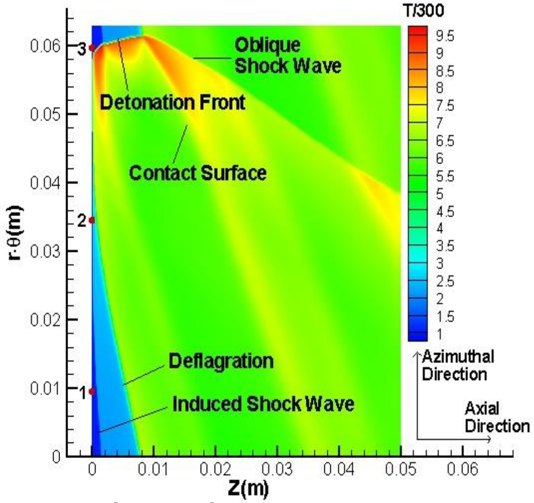
Introduction

Current RDE Research Landscape in the USA

- Government
  - AFRL, Wright-Patterson AFB
  - DOE, NETL
  - NASA, Glenn Research Center
- Industry
  - Aerojet-Rocketdyne
  - General Electric
  - GHKN
  - United Technologies
- Academia
  - Naval Postgraduate School
  - Penn State University
  - Purdue University
  - University of Colorado, Boulder
  - University of Maryland
  - University of Michigan
  - University of Texas, Arlington



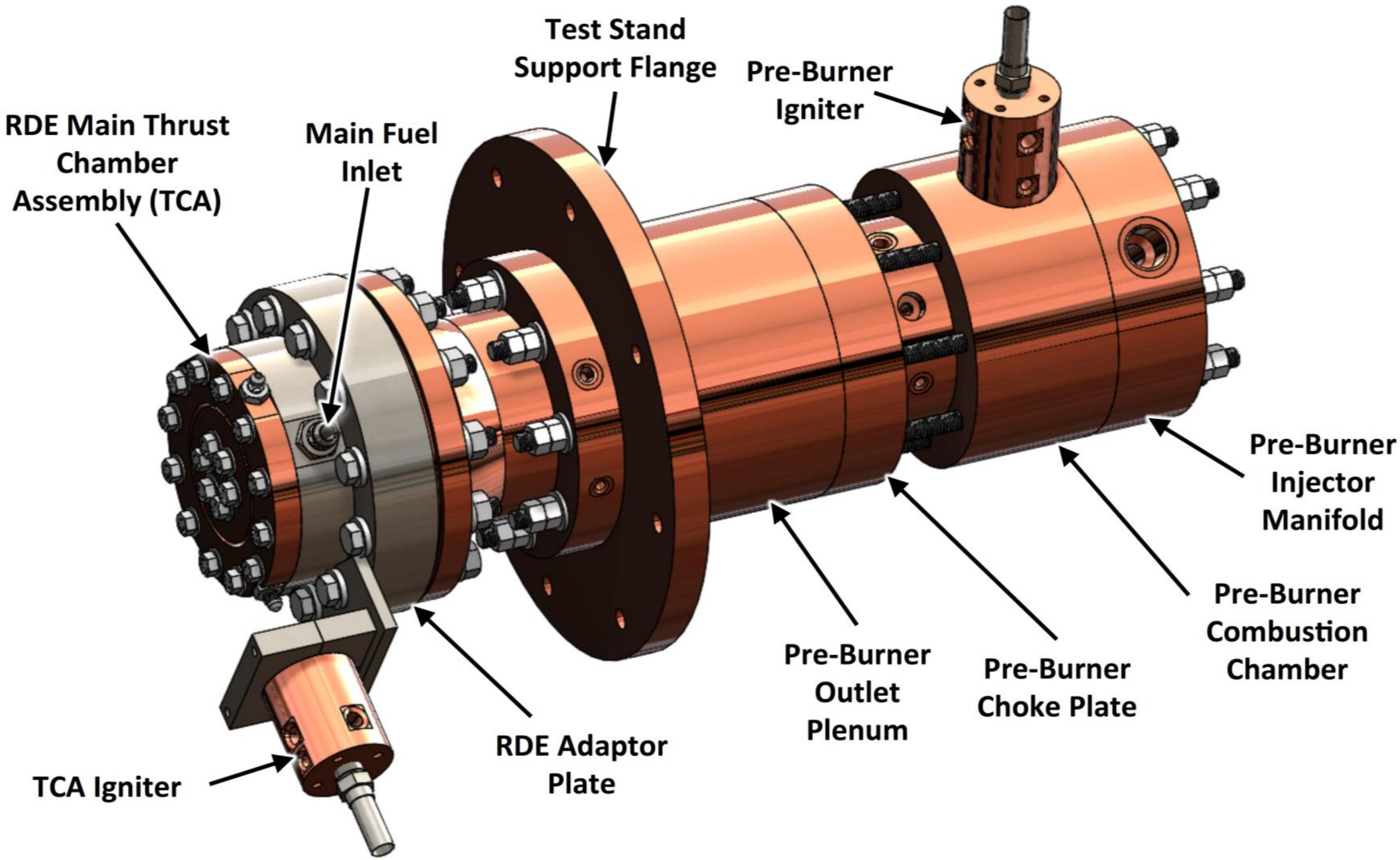
Fotia et al., SciTech, 2015



R. Zhou and J.-P. Wang., Combustion and Flame, 2012

Background

Purdue High Pressure Rocket RDE Test Article



Background

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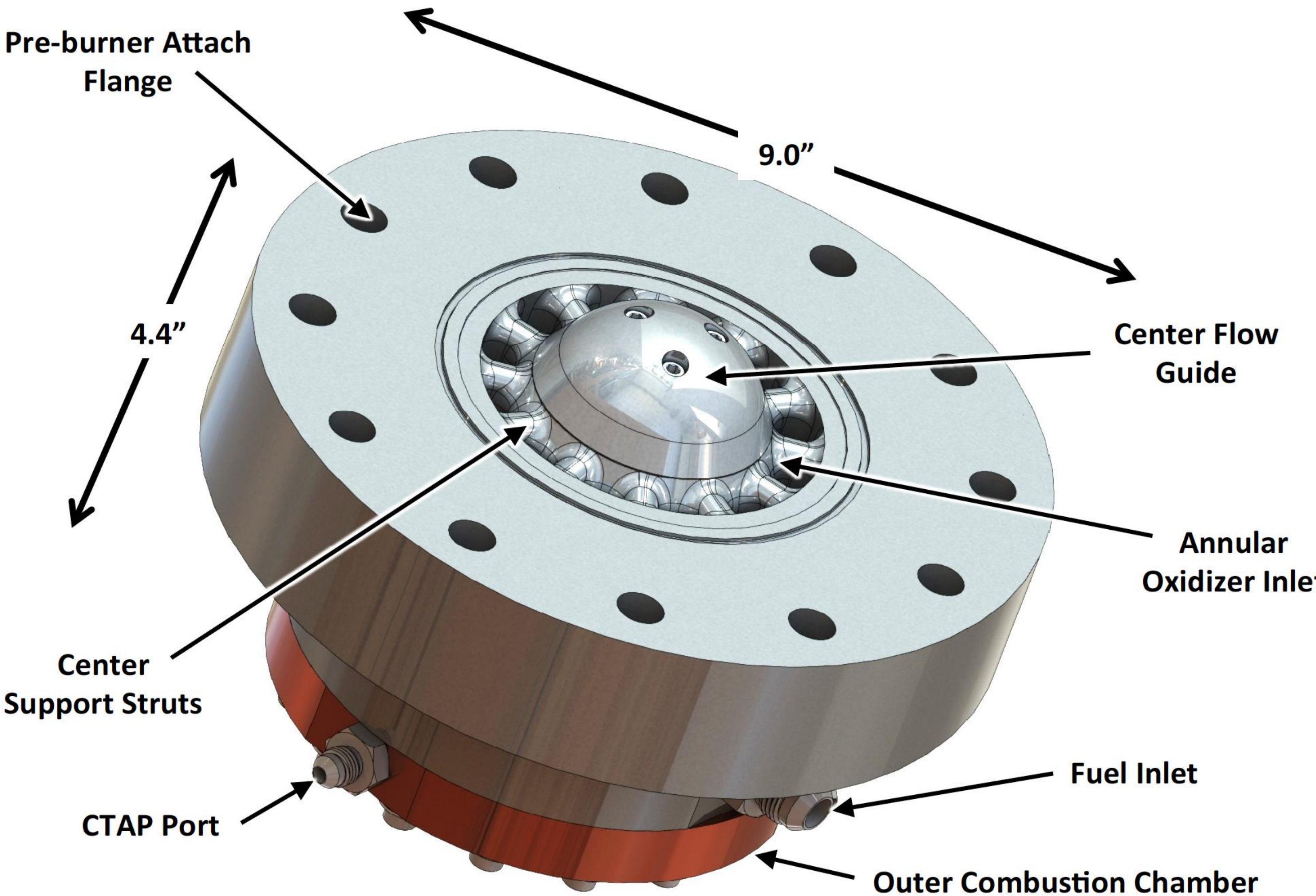
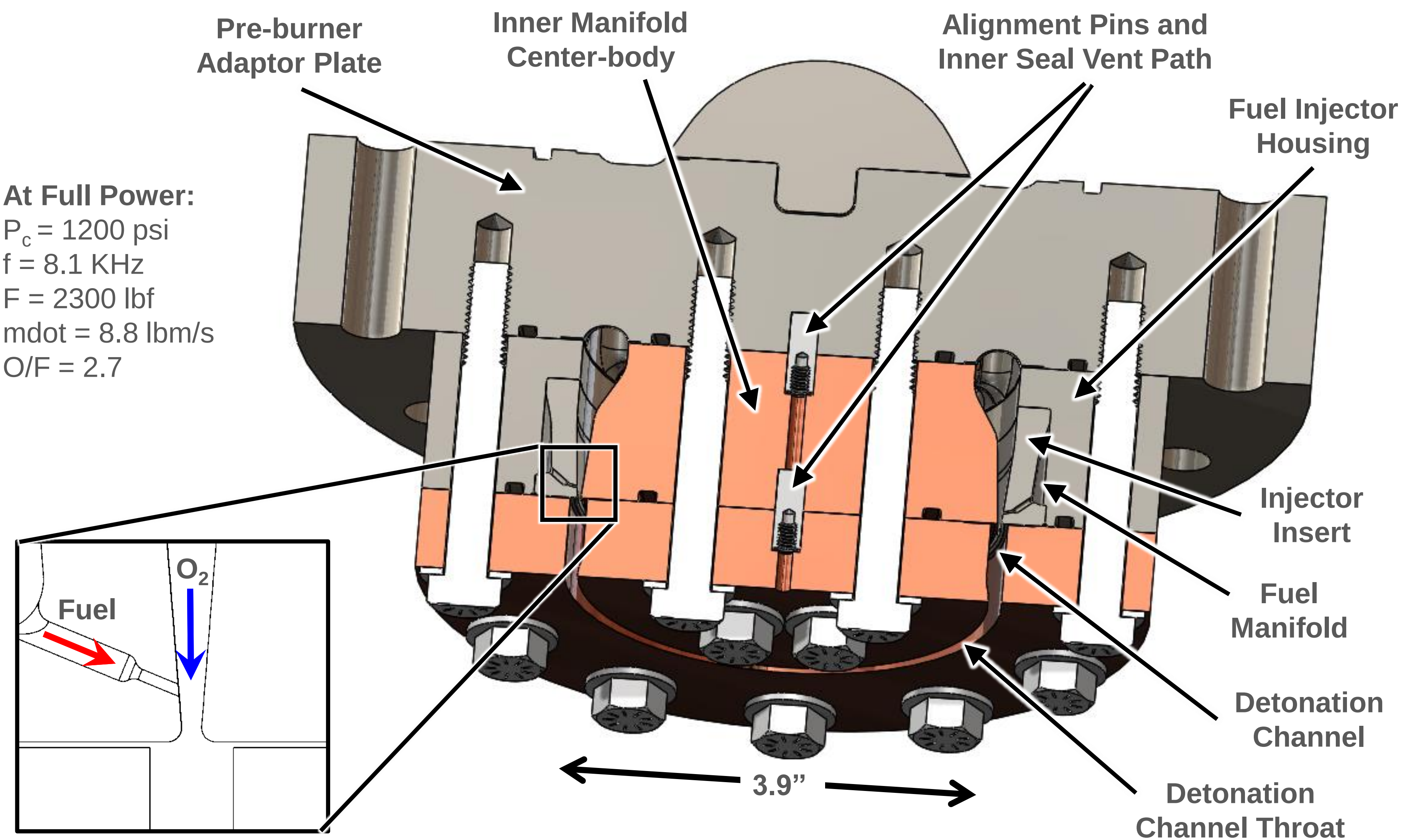


Background

Purdue High Pressure Rocket RDE Test Article

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



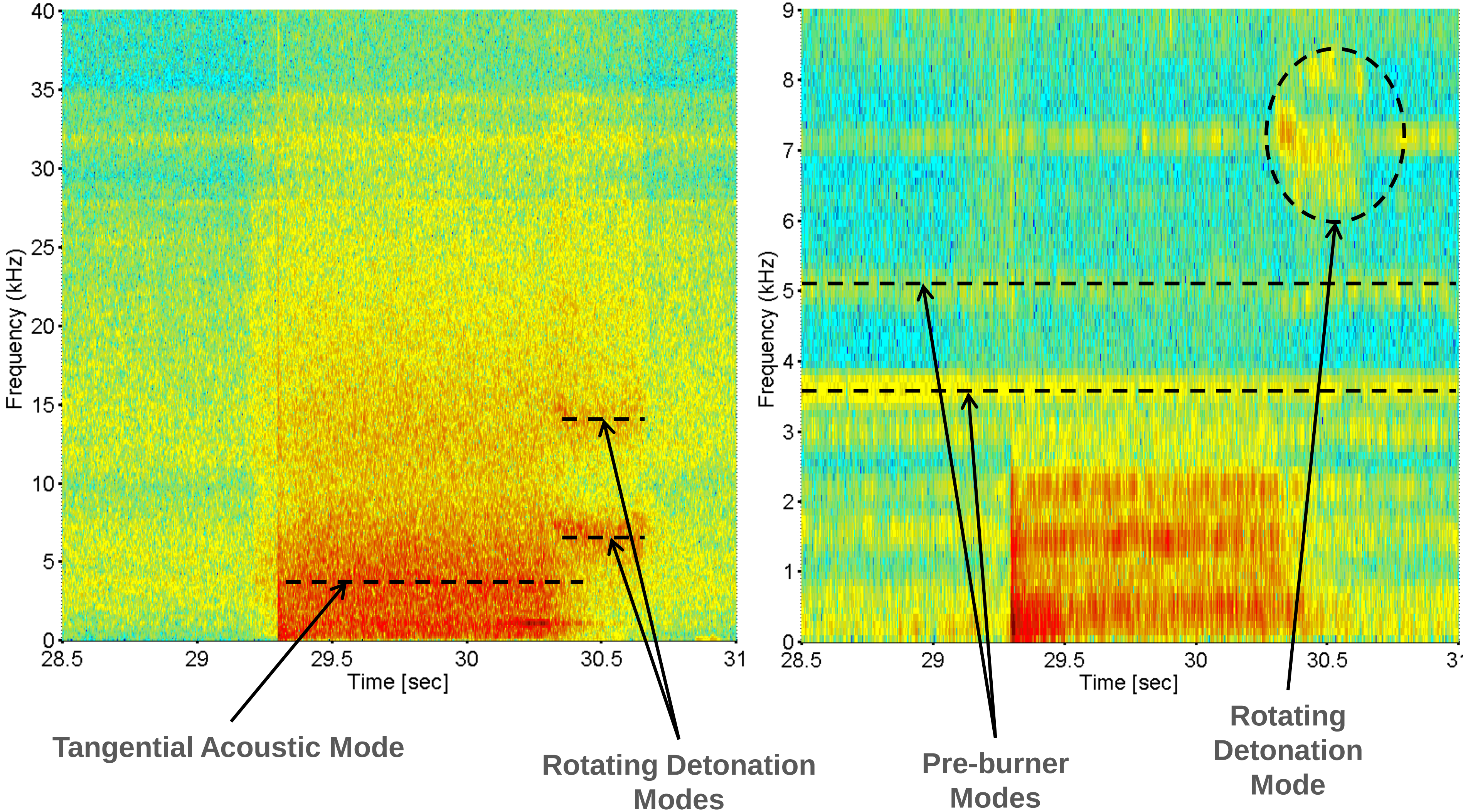
Background

Purdue High Pressure Rocket RDE Testing

Background

Purdue High Pressure Rocket RDE Testing

Microphone Spectrogram | **Load Cell Spectrogram**



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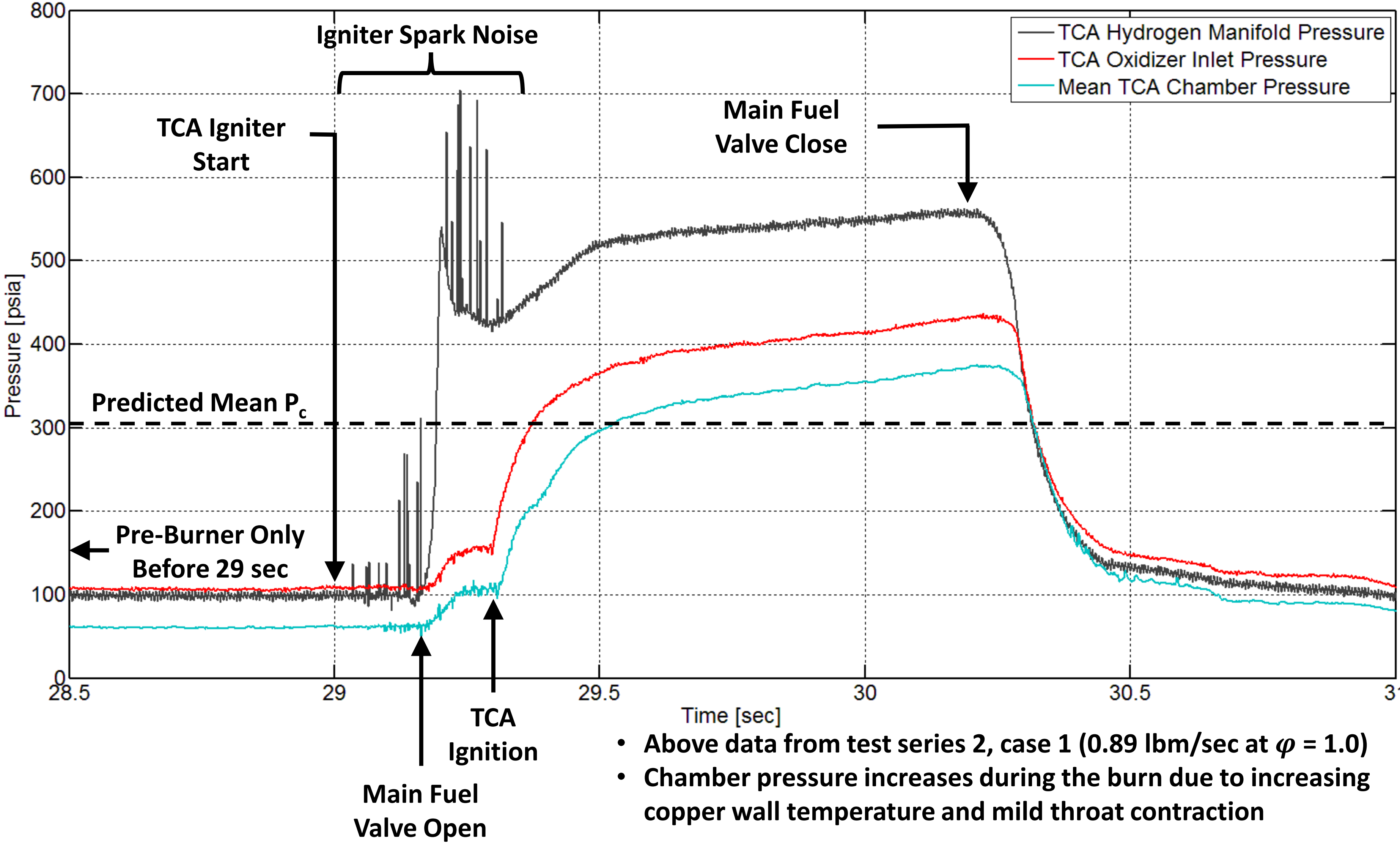
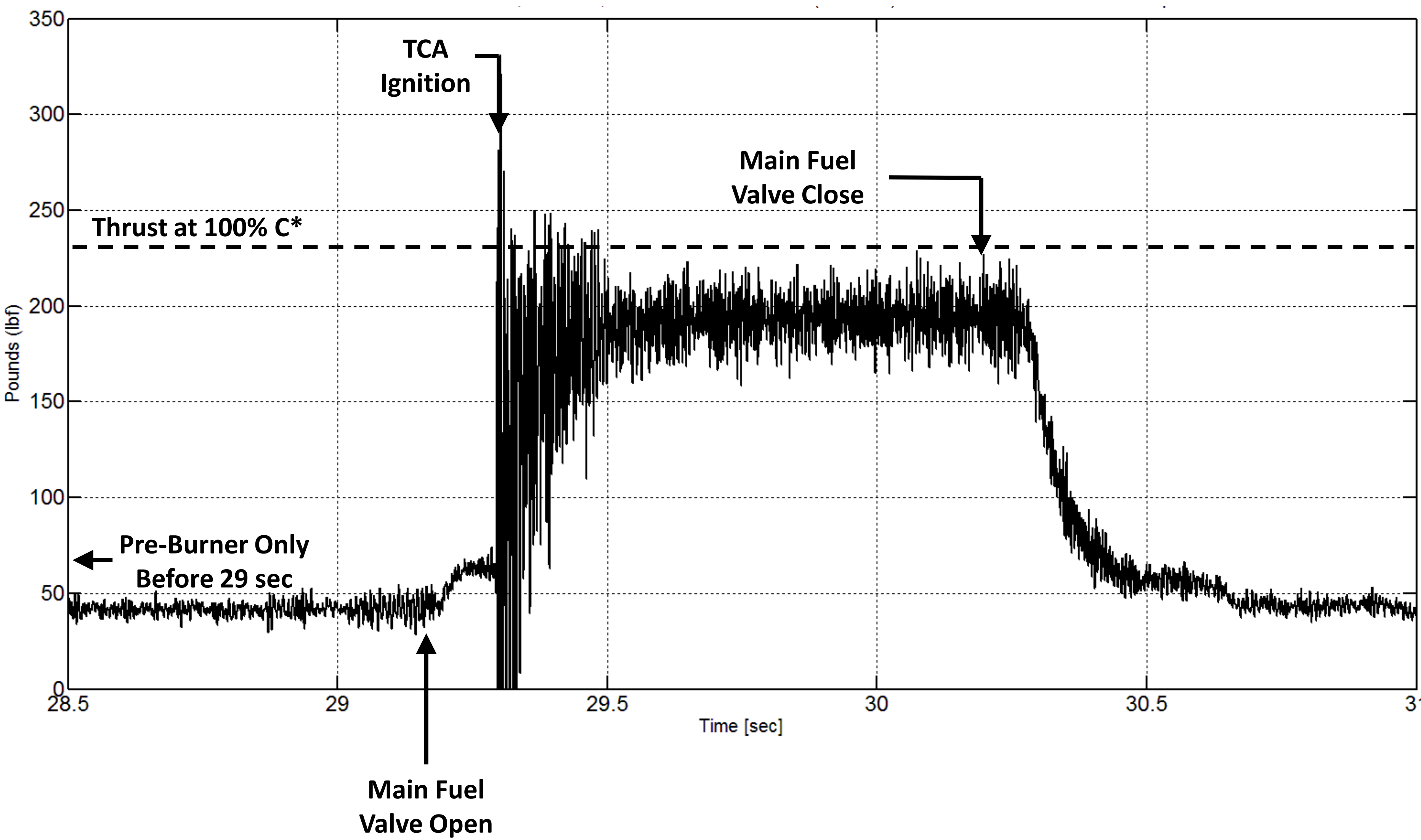
Purdue High Pressure Rocket RDE Testing



- 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

Background

Purdue High Pressure Rocket RDE Testing



Purdue-UTSR Project Overview

Motivation

1) To develop scientific understanding of processes within an RDE, specifically those relating to application-related challenges.
2) To translate that understanding into the design RDE hardware for improved performance at representative cycle conditions

Objectives

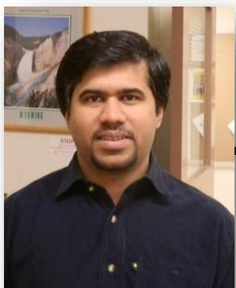
1) Characterize the performance of injection/mixing systems in an RDE using an optically-accessible, linear platform with and advanced diagnostic methods
2) Establish an experimental methodology to assess pressure gain utilizing coupled global and local measurements performed at conditions relevant to terrestrial turbine systems (up to a P3 and T3 of 2.0 MPa and 800 K, respectively)
3) Evaluate the operation of an RDE combustion chamber over range of operating conditions
4) Quantify pollutant emission production over a wide range of operability

Purdue-UTSR Project Overview

Team

Steve Heister, Raisbeck Distinguished Professor (co-PI)

Carson Slabaugh, Assistant Professor (co-PI)



Swanand Sardeshmukh, Postdoctoral Researcher

Brandon Kan, Ph.D. student

Kyle Schwinn, Ph.D. student

United Technologies Research Center

Adam Holley and Chris Greene, UTRC advisors

Purdue-UTSR Project Overview

Experimental Infrastructure

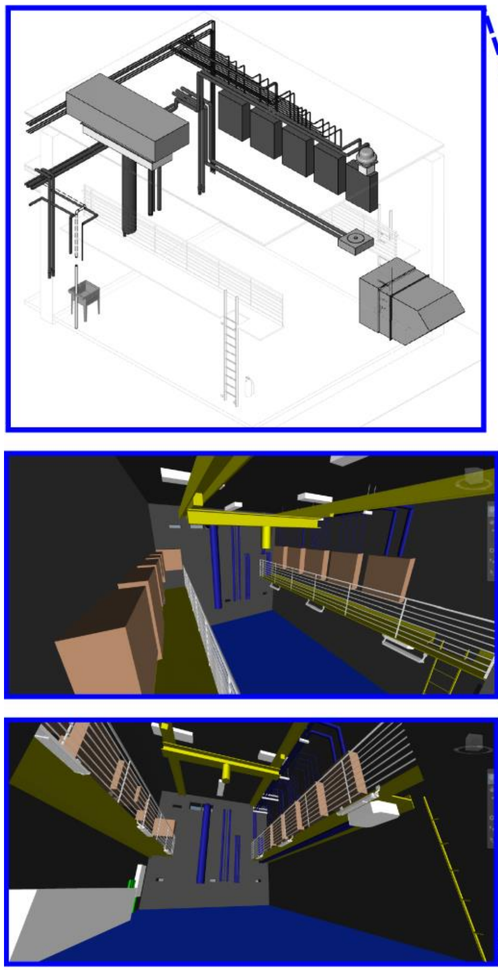
Purdue-UTSR Project Overview

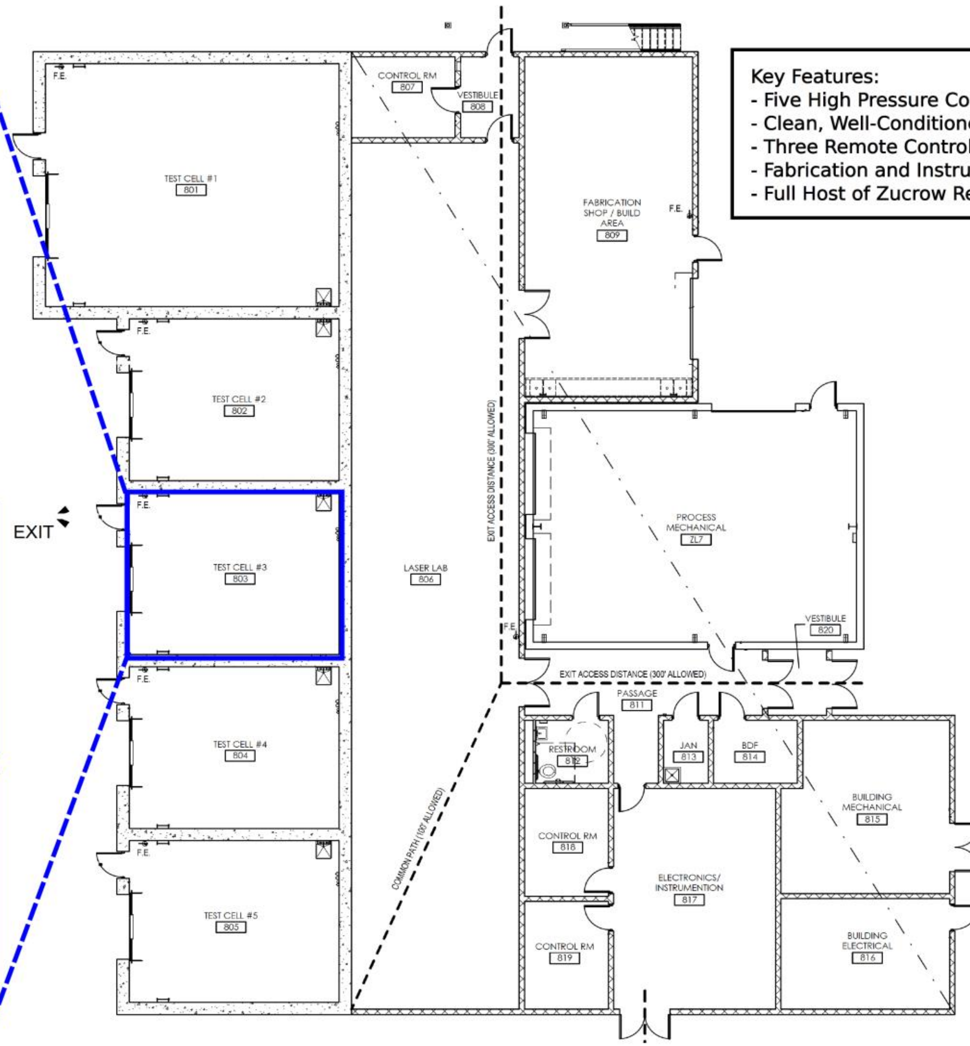
Experimental Infrastructure

Purdue-UTSR Project Overview

Experimental Infrastructure

Renderings of Typical Test Cell



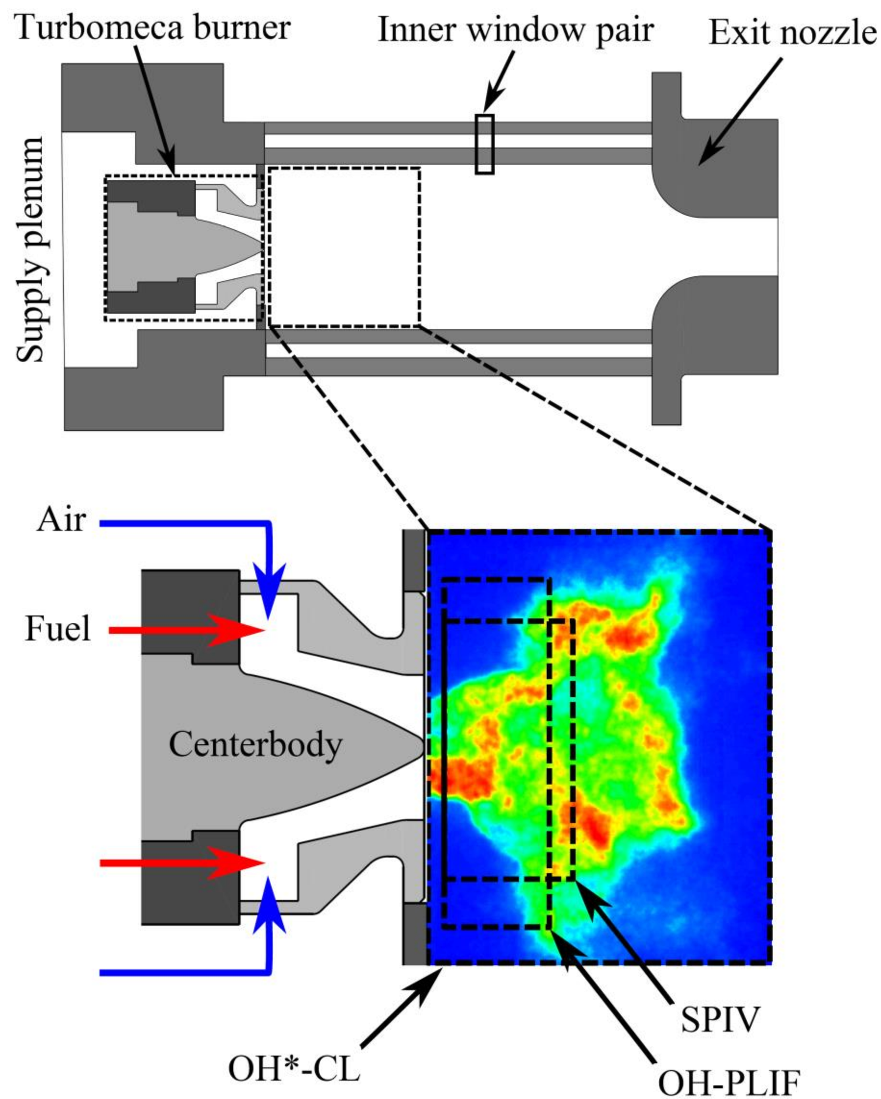


Key Features:
- Five High Pressure Combustion Test Cells
- Clean, Well-Conditioned Laser Laboratory
- Three Remote Control Rooms
- Fabrication and Instrumentation Rooms
- Full Host of Zucrow Research Fluid Services

Purdue-UTSR Project Overview

Measurement Capability

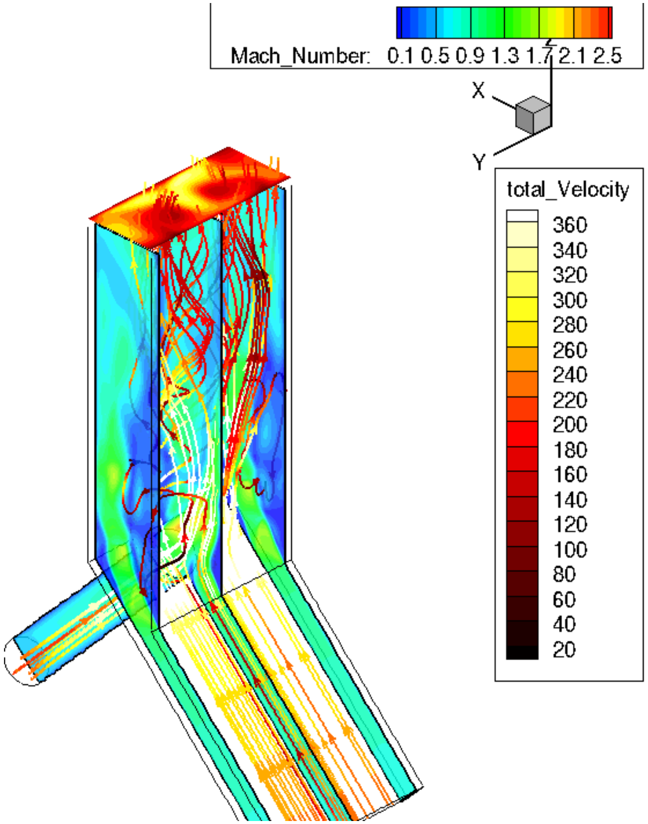
- Imaging (Path Averaged Signals)
  - Chemiluminescence
  - Schlieren (laser Schlieren)
- Planar Laser Induced Fluorescence
  - Hydroxyl (OH)
- Particle Image Velocimetry
  - Stereoscopic (Three Component, Planar Fields)
  - Ultra-High Bandwidth

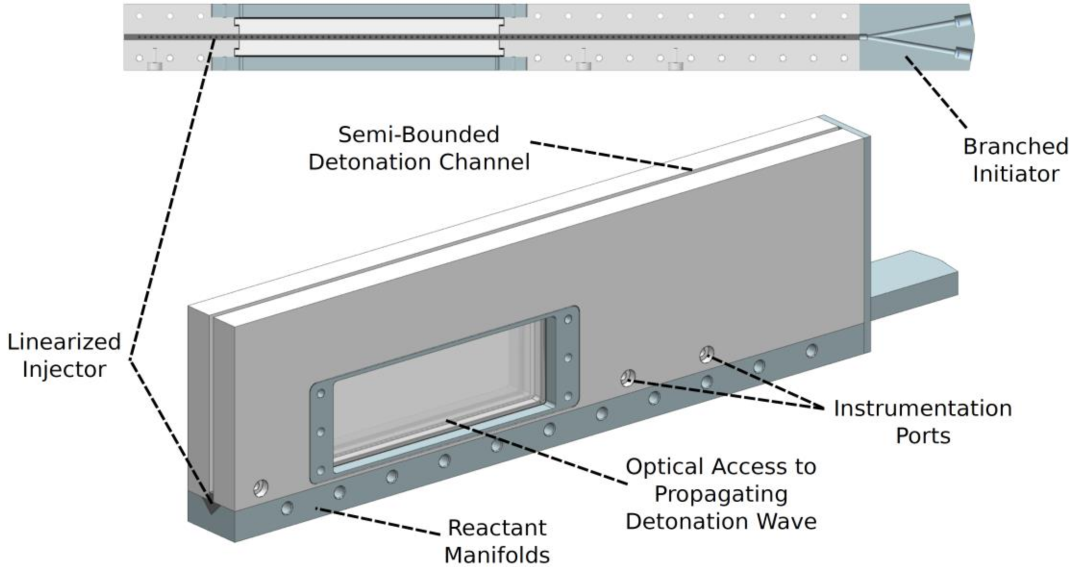


Progress

Task Breakdown

1) Project Management and Planning
2) Baseline Canonical Experiments
3) Subscale Combustor Facility Development
4) Integral Measurement of Pressure Gain
5) Detailed Measurements of Exit Conditions
6) Emissions Measurements
7) Computational Model Development



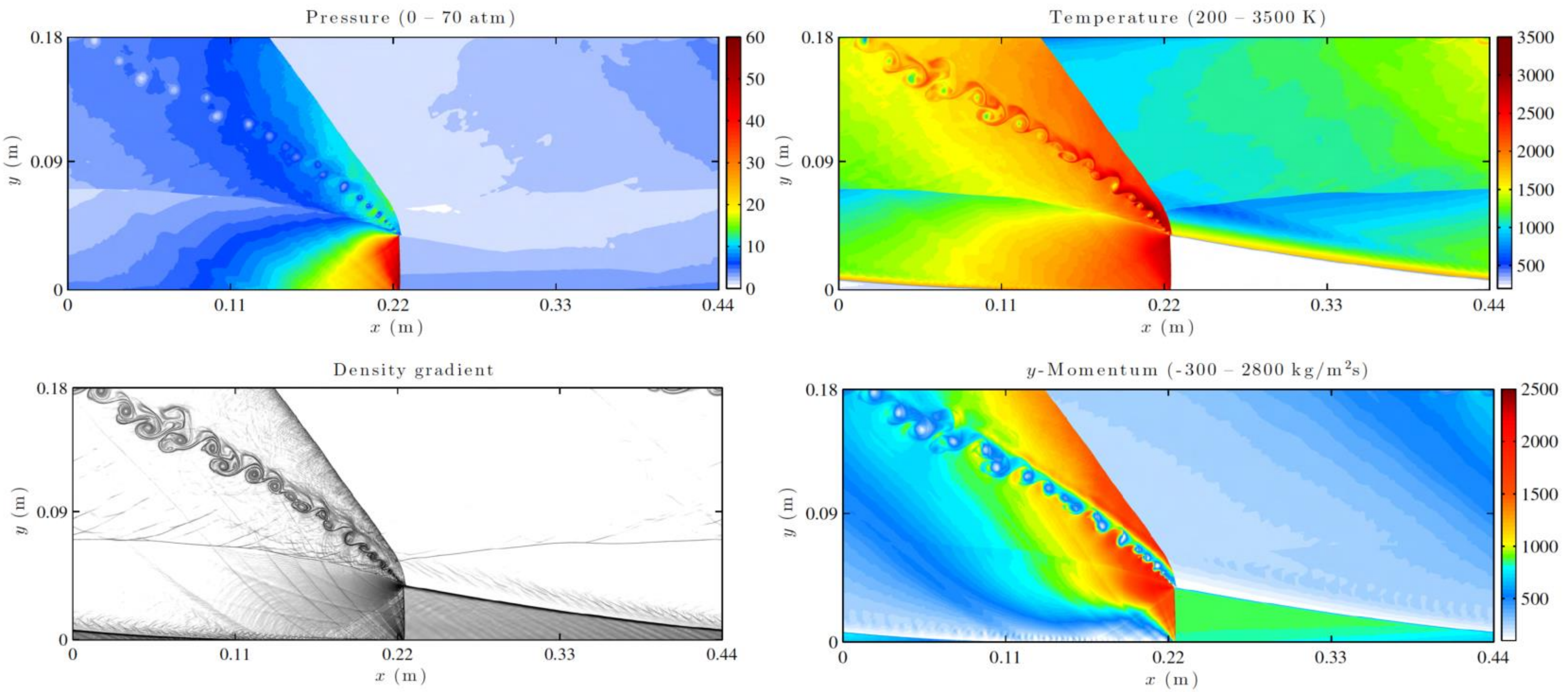


'Unwrapped' RDE test article design is at CDR-level (left) with complementary simulation informing baseline injector design (above)

Task 2.0 Baseline Canonical Experiments

The Detonation Rig for Optical, Non-intrusive Experimental measurements ('DRONE')

- Rapid unsteady mixing
- Parasitic deflagration
- Semi-bounded detonation wave propagation



Computed structure of detonation wave propagation in RDE annulus. Adapted from Towery et al. (AIAA, 2014)

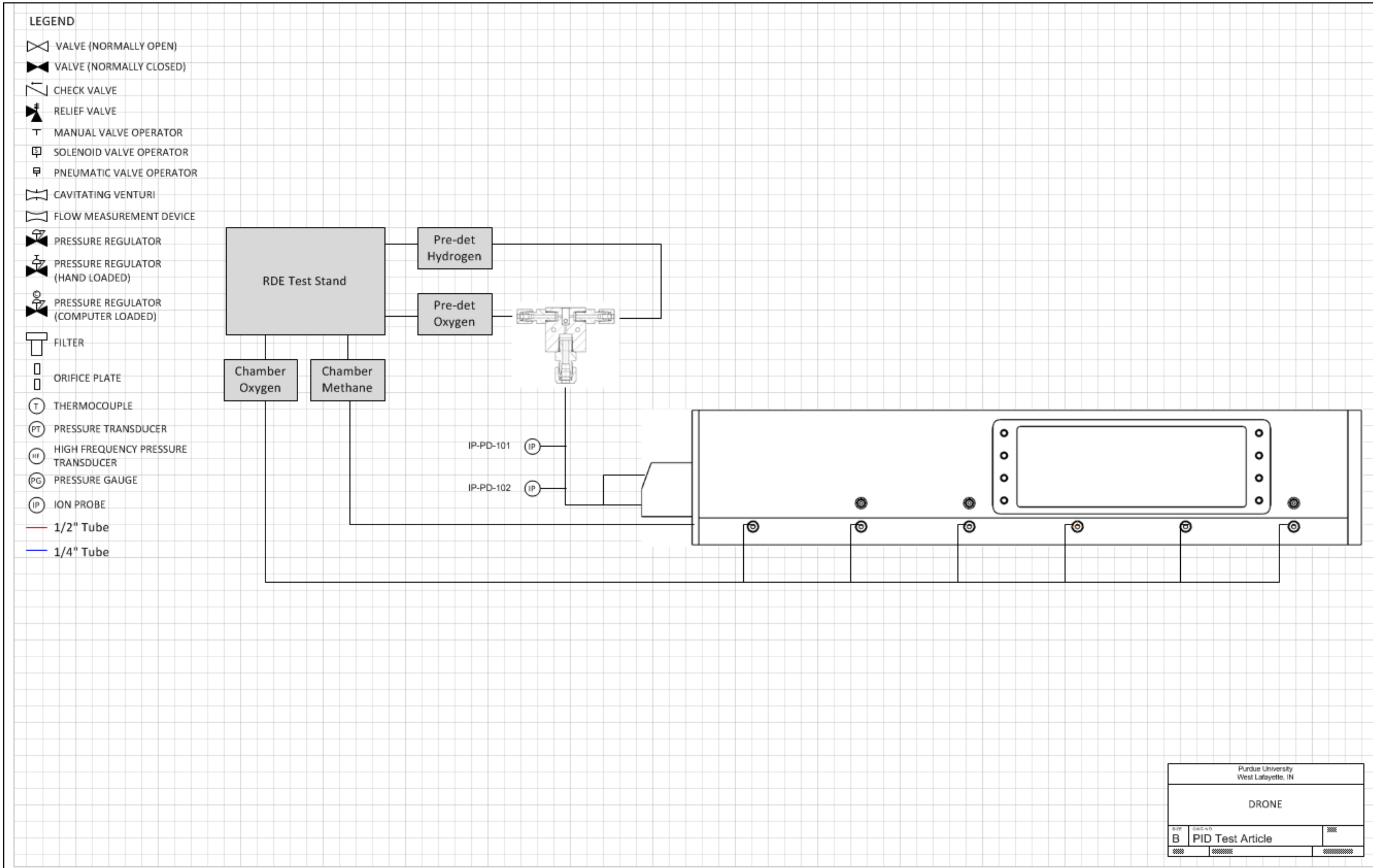
Task 2.0 Baseline Canonical Experiments

DRONE Development

Designation	Description
DRONE_0100	Test Stand and Facility Integration
DRONE_0200	Test Article Hardware
DRONE_0300	Measurement/Ancillary Systems

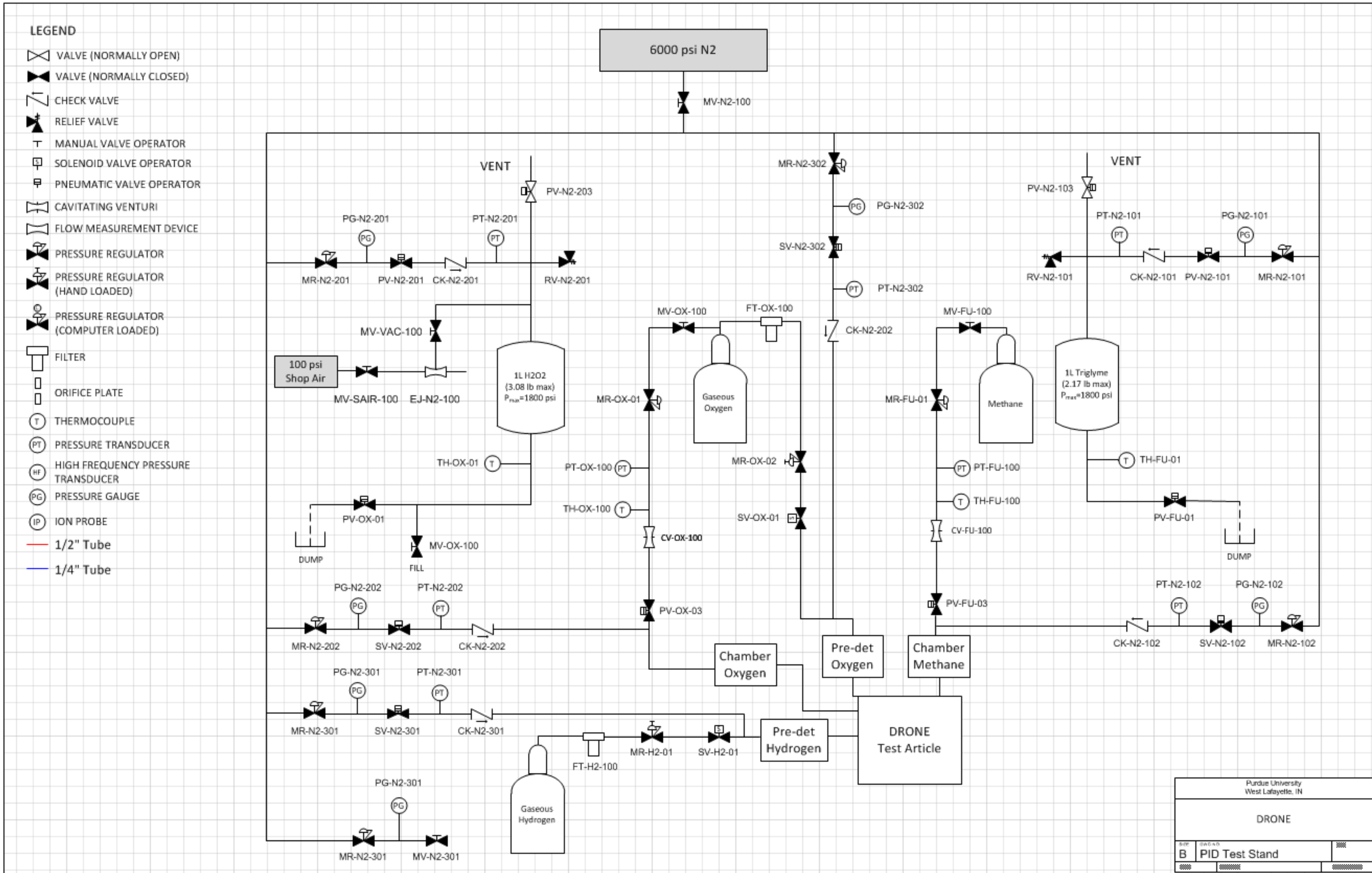
Task 2.0 Baseline Canonical Experiments

DRONE Development



Task 2.0 Baseline Canonical Experiments

DRONE Development



Task 2.0 Baseline Canonical Experiments

DRONE Development

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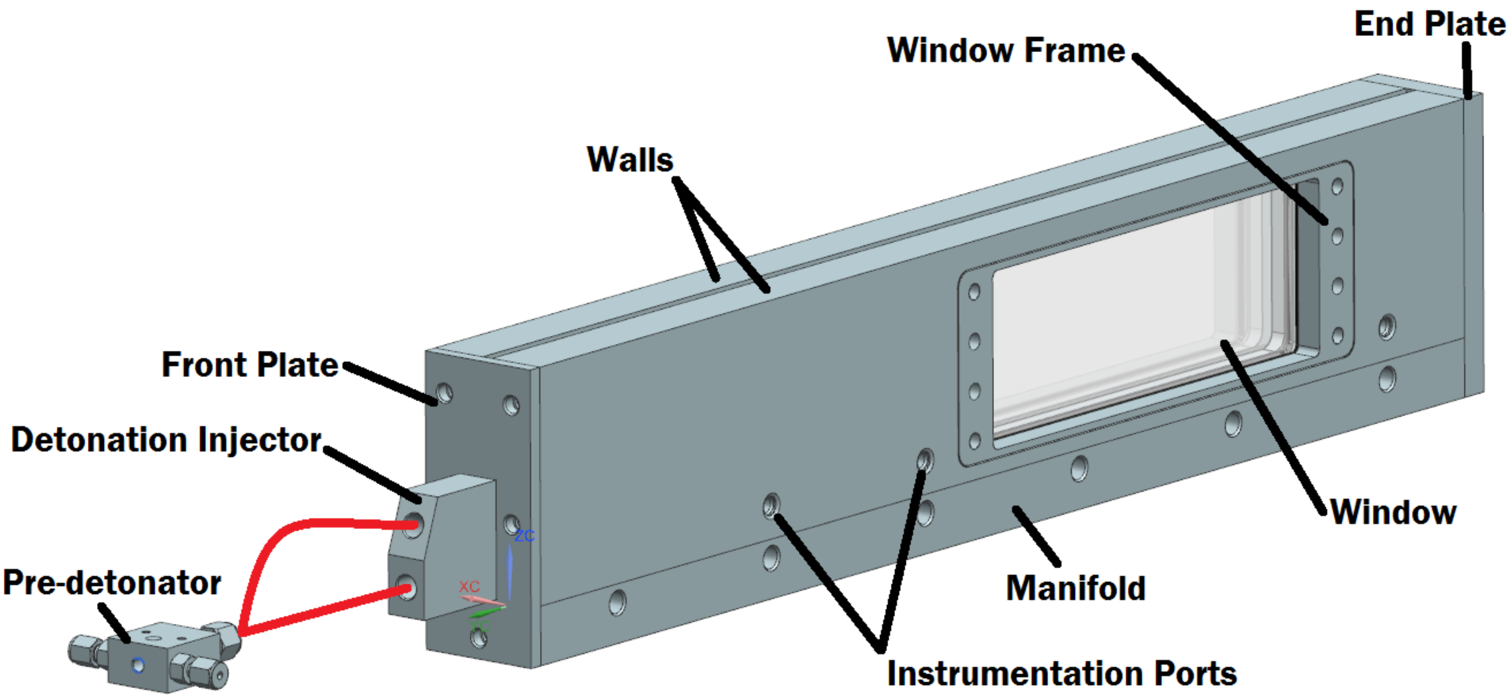
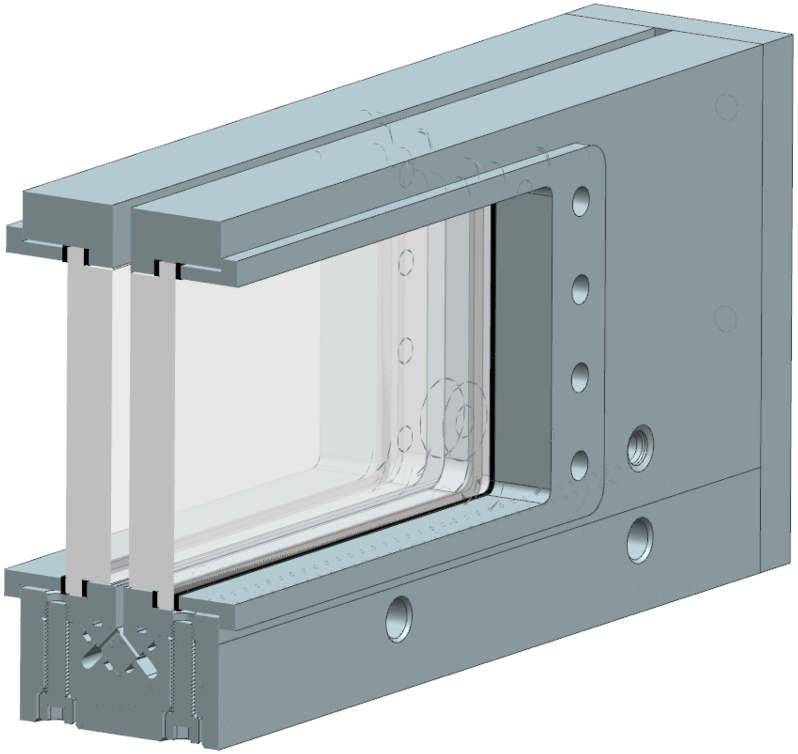
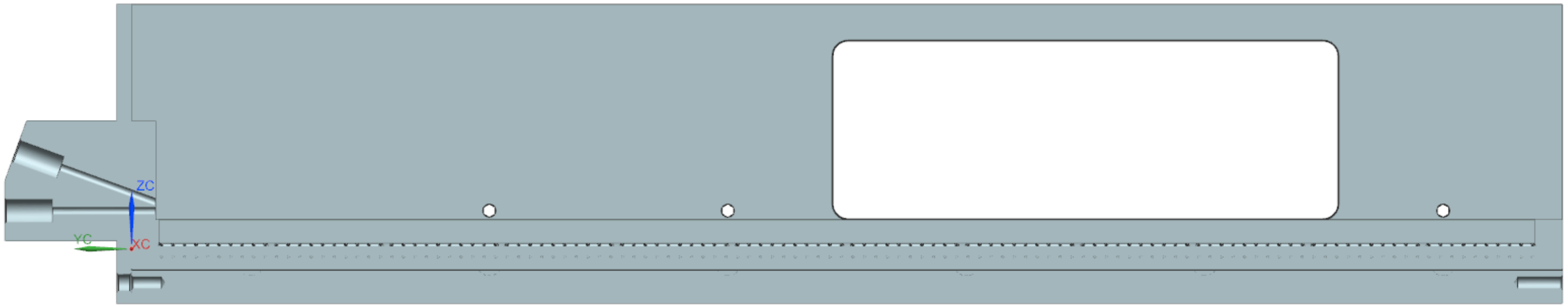


Task 2.0 Baseline Canonical Experiments

Design Conditions

- Propellants
  - Fuel: gaseous methane
  - Oxidizer: gaseous methane (with potential diluent)
- Initial Conditions
  - P = 1 atm
  - T = 298K
- Detonation Properties (CH4-GOx)
  - (Cell Size) = 2.5 mm
  - u_{CJ} = 2390 m/s

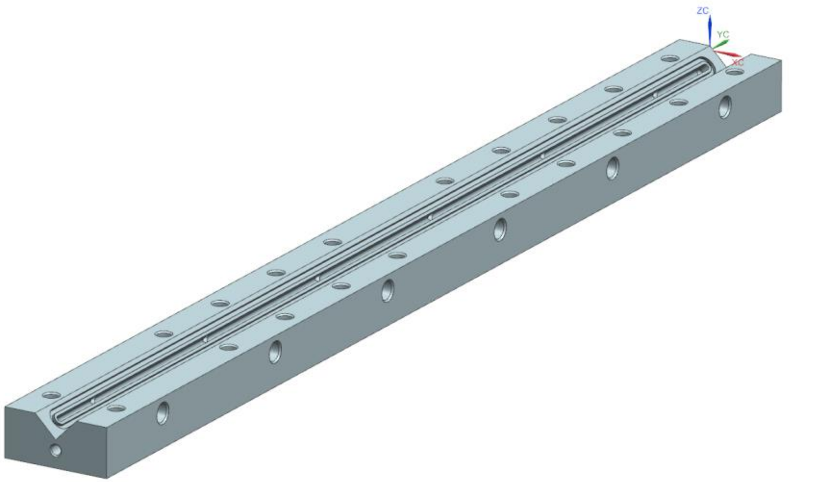


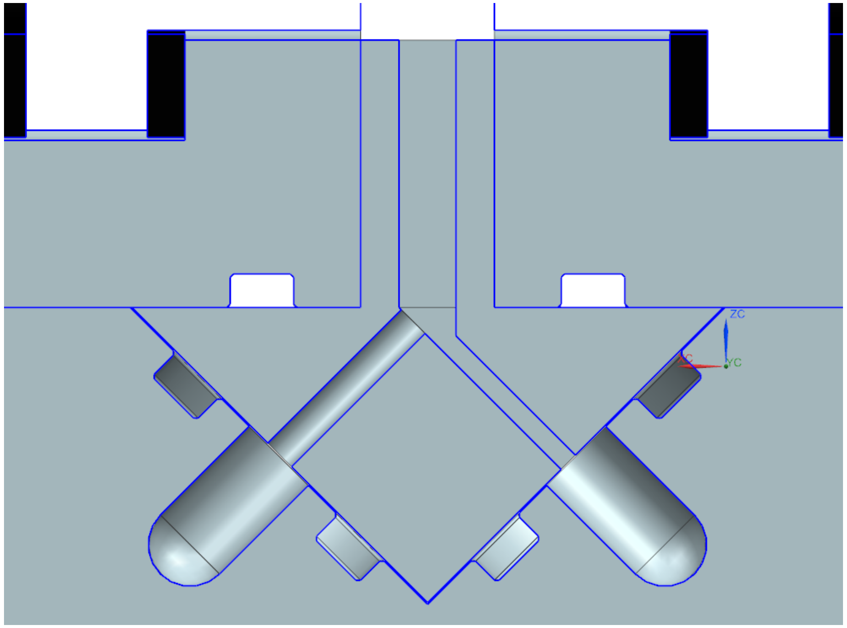


Task 2.0 Baseline Canonical Experiments

Design Conditions

- Modularity optically-accessible test article hardware and ancillary components
- Starting conditions chosen for high confidence level
- Flow Rates
  - Fuel: 0.1288 lbm/s
  - Oxidizer: 0.5152 lbm/s
- Manifold Pressure Ratios
  - Fuel: 2.7
  - Oxidizer: 1.8

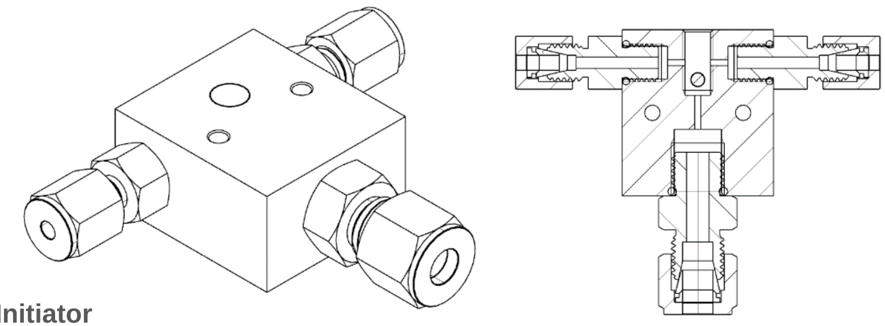




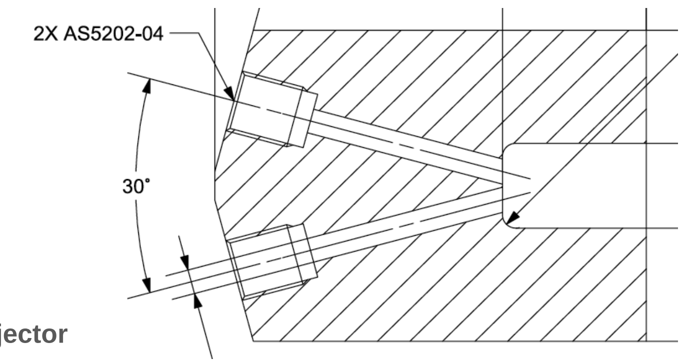
Task 2.0 Baseline Canonical Experiments

Branched Pre-Detonator

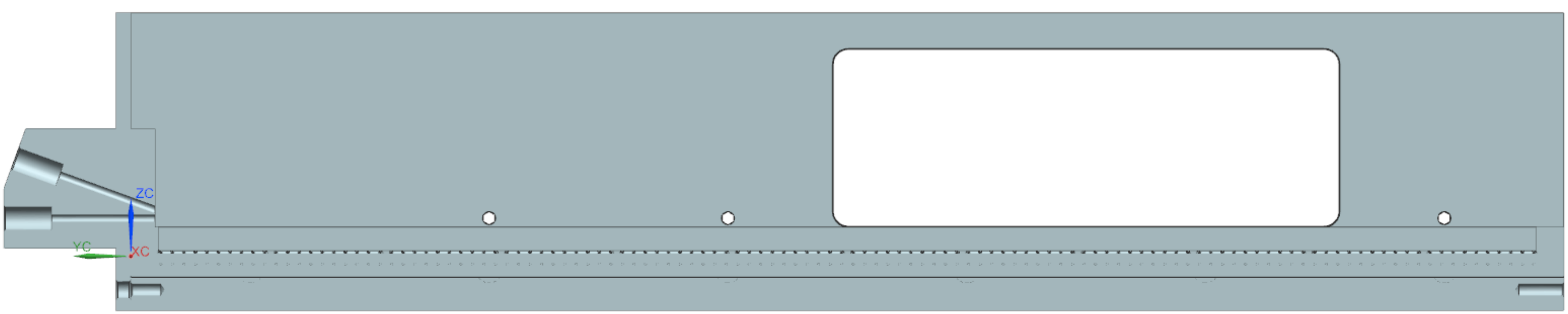
- H_2/O_2 Reactants
- Split Detonation is split through (multiple) legs with different path-lengths
  - ‘circumscription’ frequency is controlled by relative length of delay lines.
- Waves are recombined at detonation injector
- +/- 5 µs timing precision



Initiator

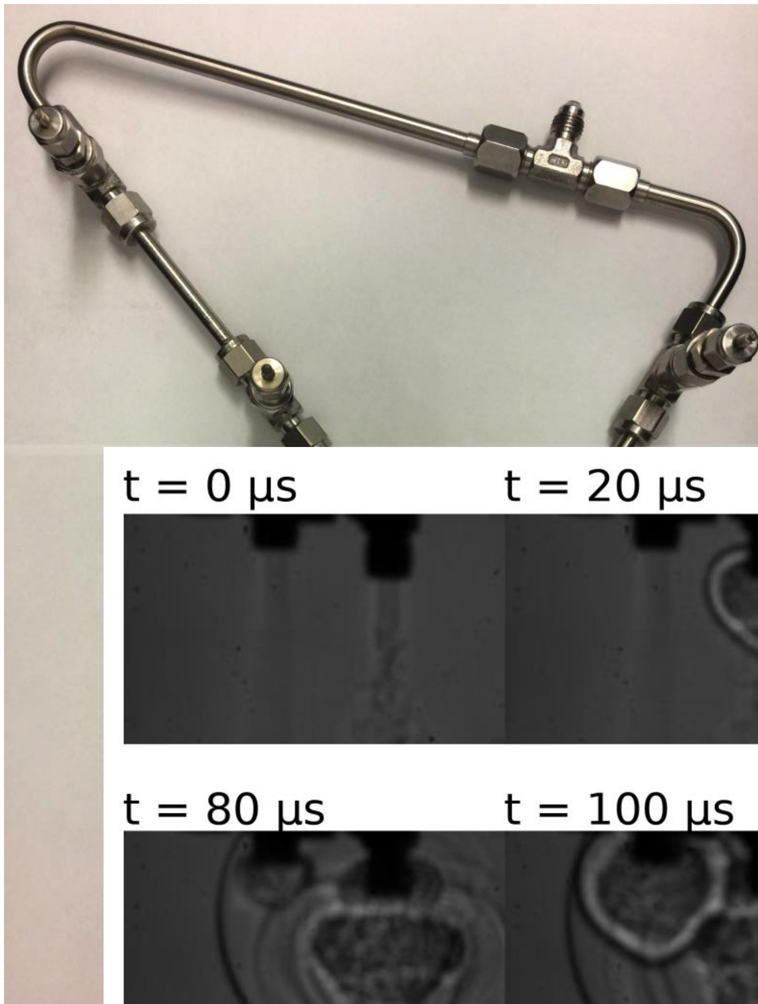


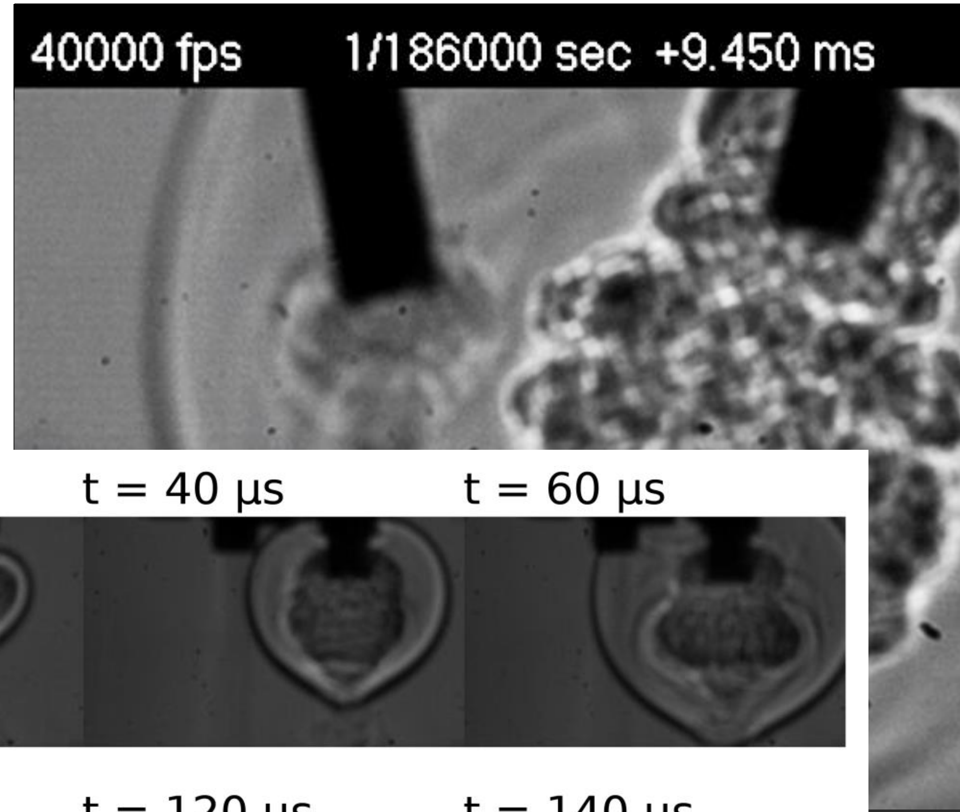
Injector

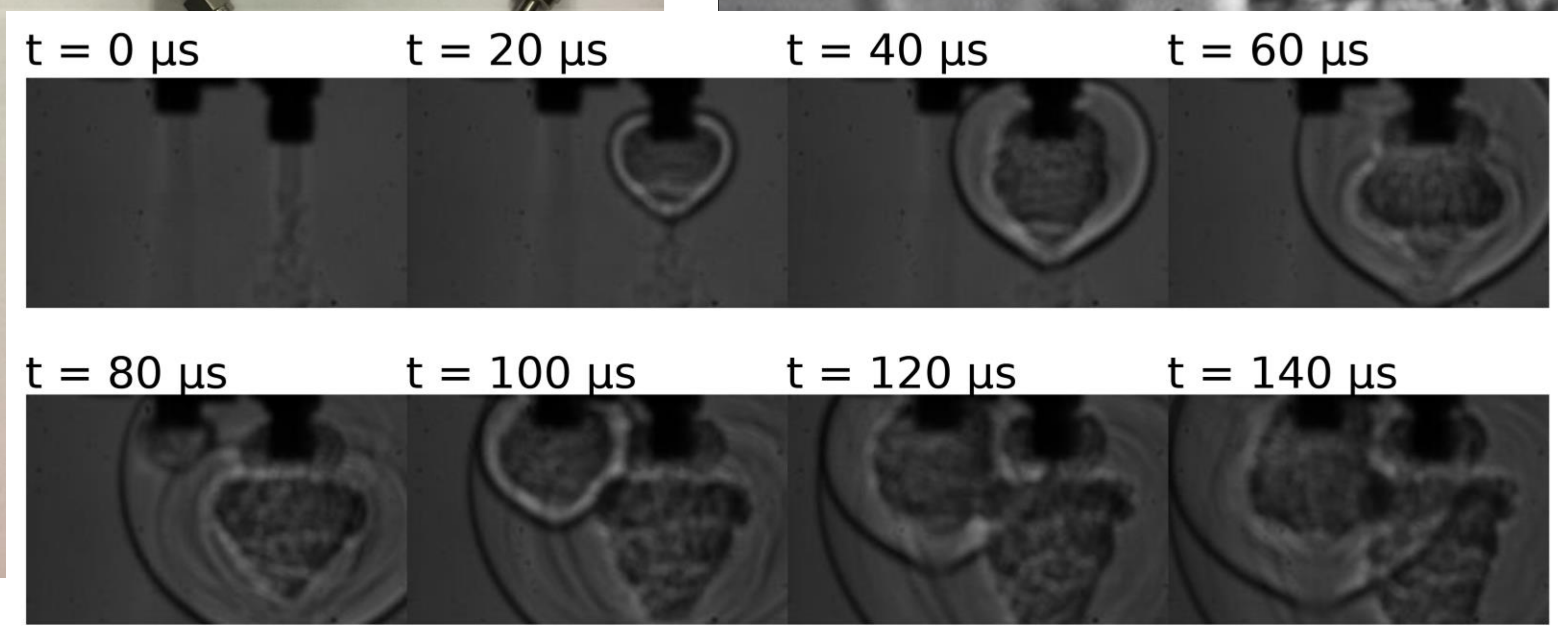


Task 2.0 Baseline Canonical Experiments

Detonation Injector

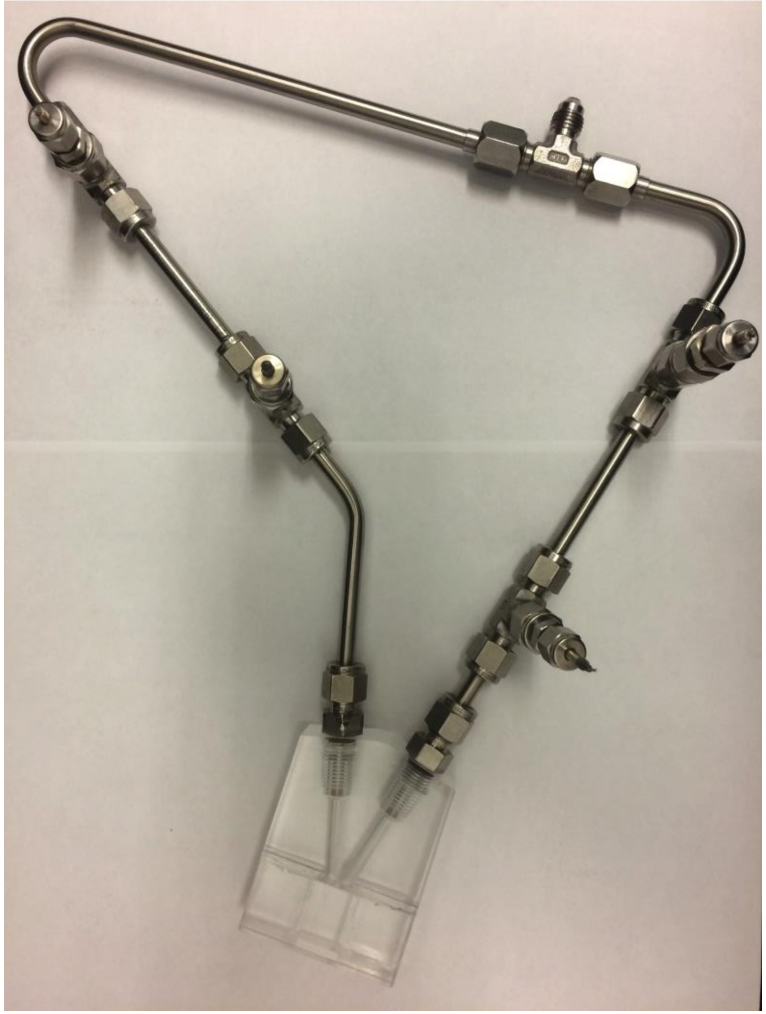


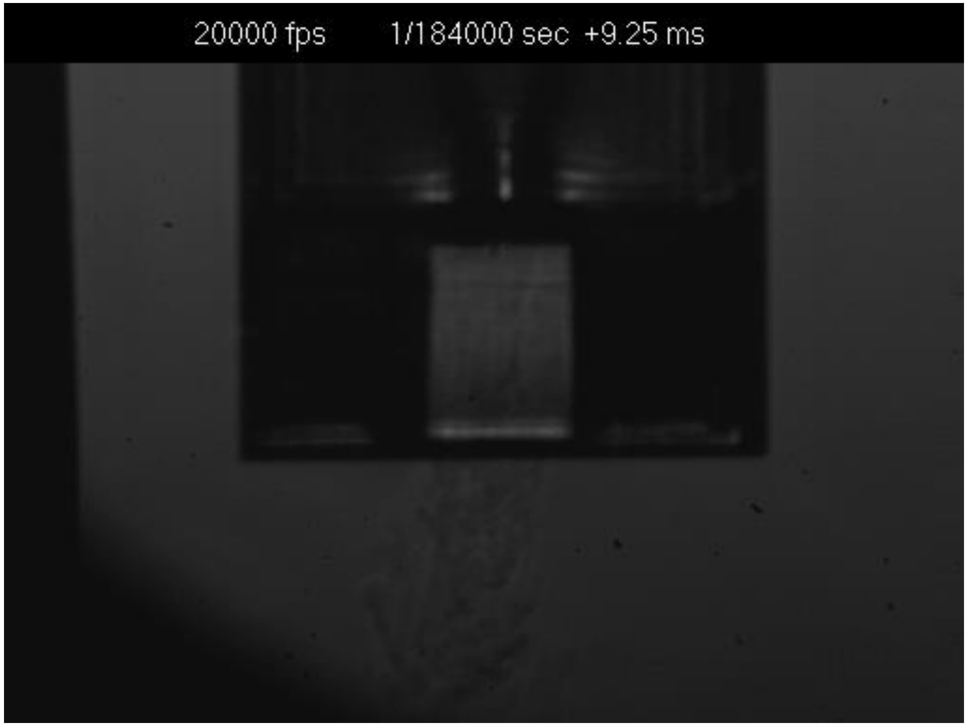




Task 2.0 Baseline Canonical Experiments

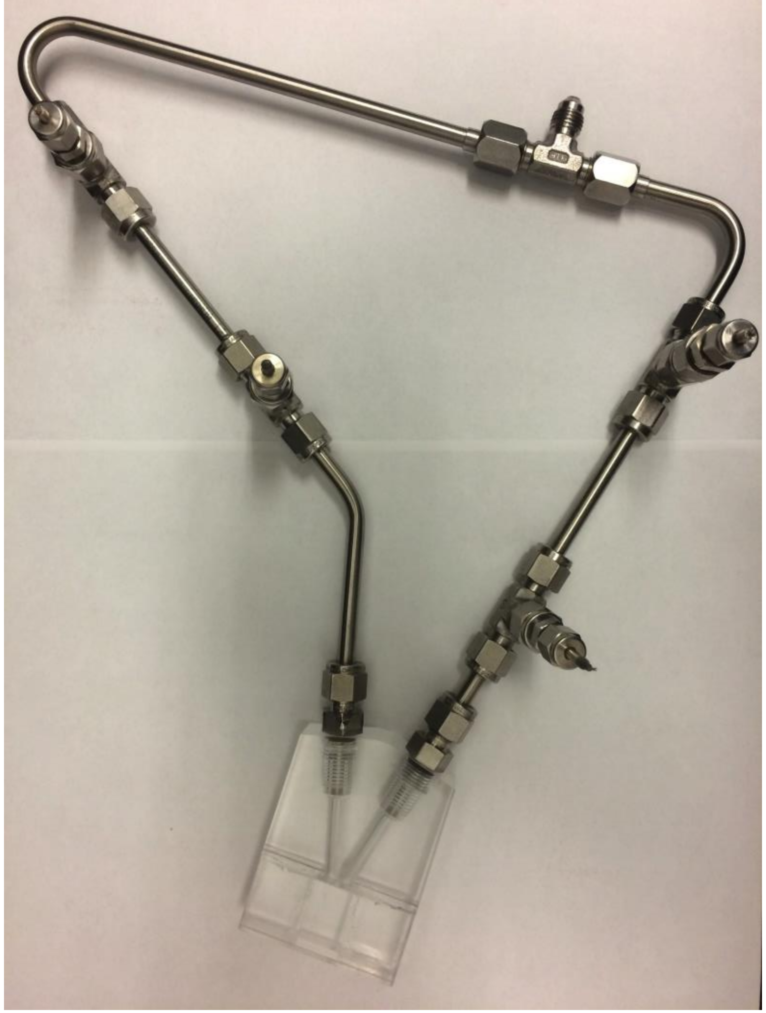
Detonation Injector

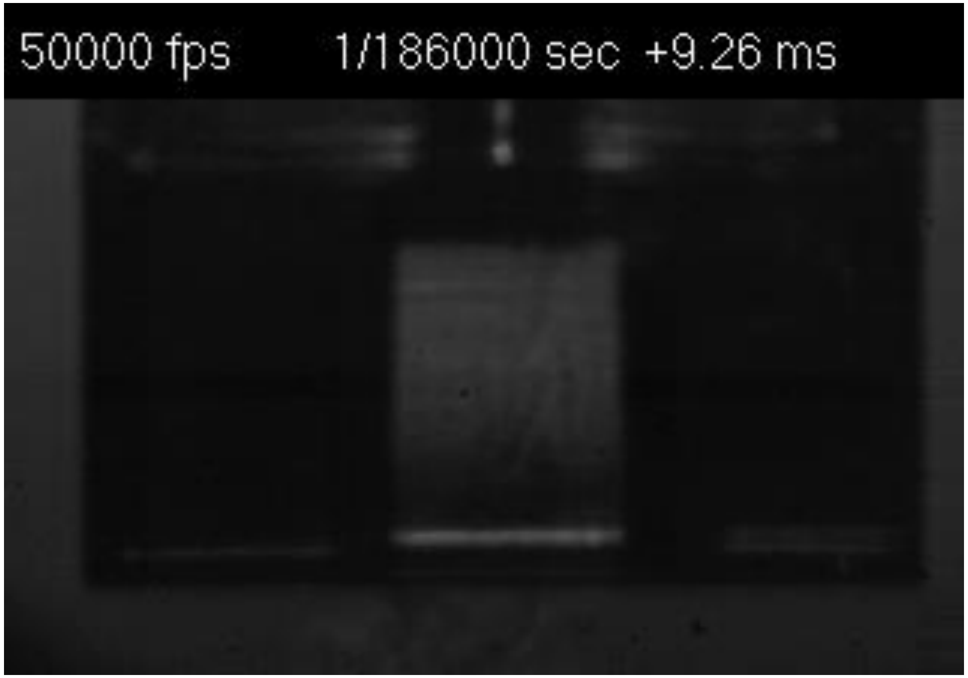




Task 2.0 Baseline Canonical Experiments

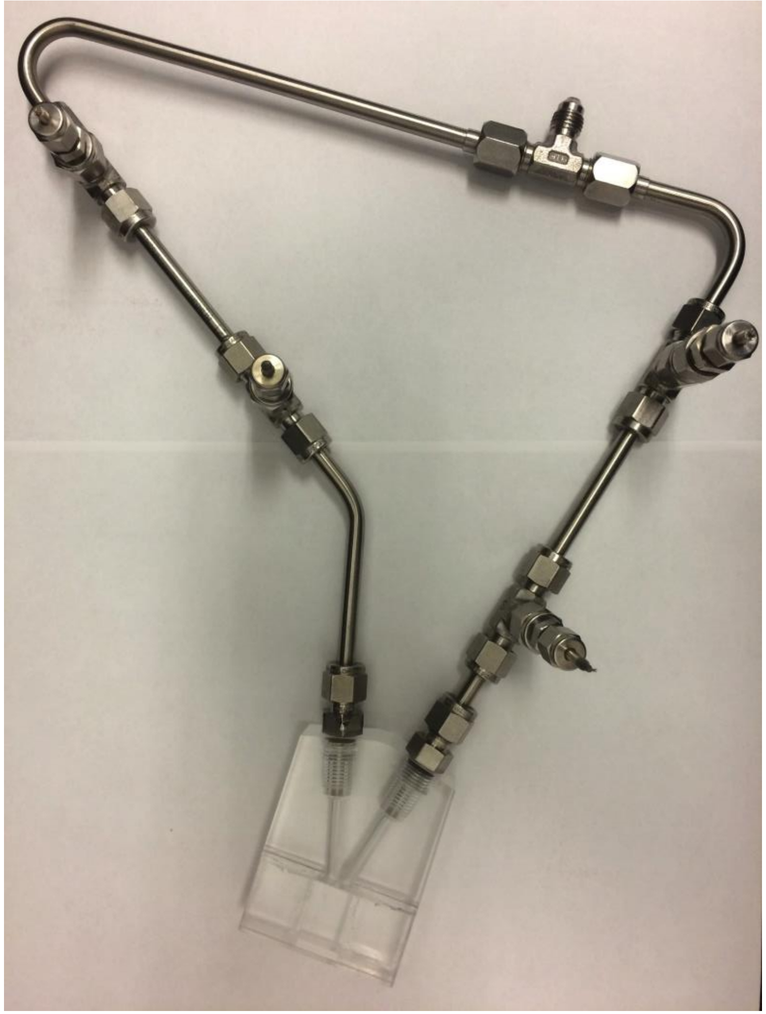
Detonation Injector

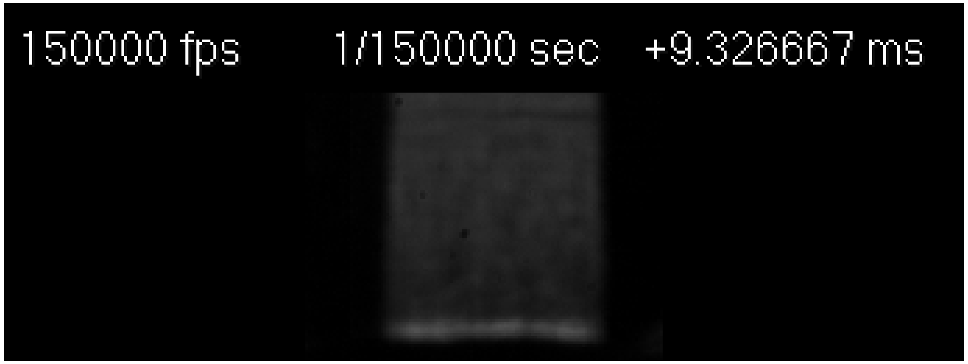




Task 2.0 Baseline Canonical Experiments

Detonation Injector

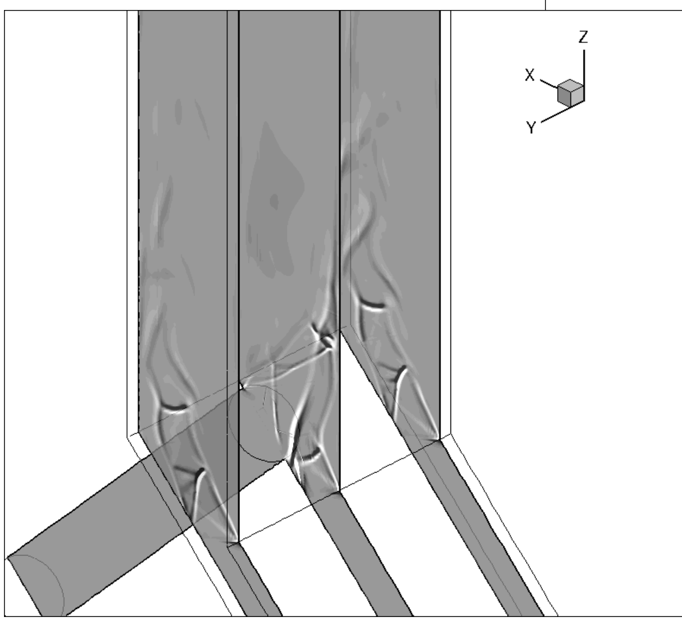




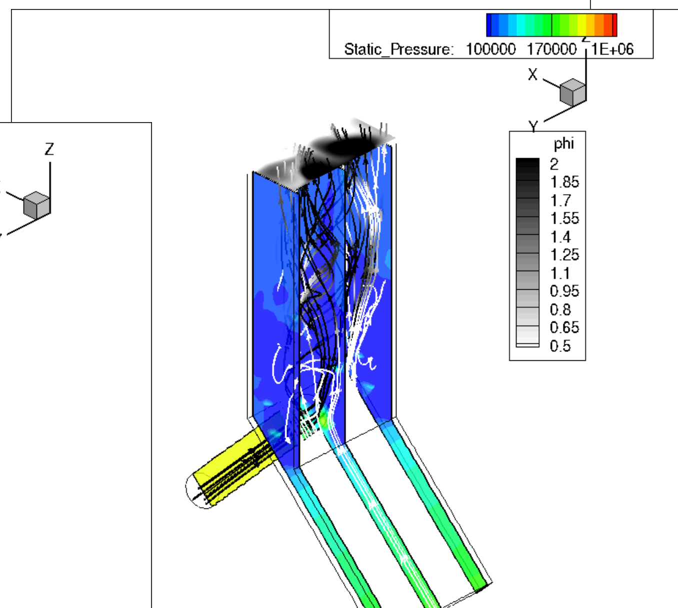
Task 7.0 Concurrent Modeling Effort

Informing Baseline Injector Designs

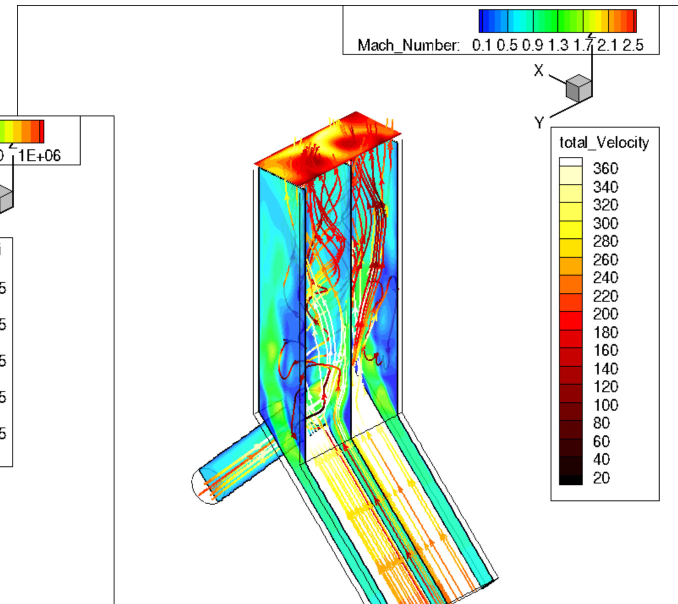
- Generalize Equation and Mesh Solver (GEMS) code
- Unsteady simulations beginning (very soon)
  - Boundary conditions informed by detonation injector tests



Computed density gradient field represented by shadowgraph



Static pressure map of the injector element with equivalence ratio contours and streamline coloring



Velocity and Mach number map of the injector element shows counter-rotating vortices mixing the reactants.

Looking Forward

Fall 2015 – Spring 2016 Project Schedule

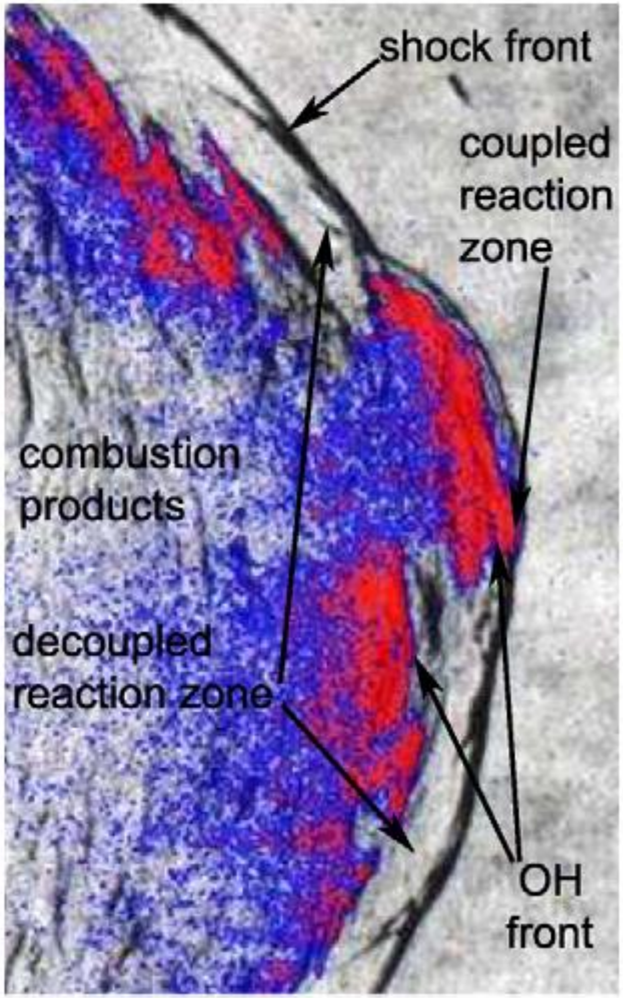
Task	Time Required	Estimated Completion
Detailed Design of DRONE_0200 Test Article	12 weeks	11/20/2015
Demonstration of Branched Initiation	8 weeks	Complete
Test Article Fabrication	10 weeks	January
Detailed Design of DRONE_0300 Ancillary Systems	4 weeks	December
Ancillary System Fabrication	4 weeks	January
Facility Integration	4 weeks	03/01/2016
Validation of System Operations Pressure Checks, Leak Checks, etc.	2 weeks	03/15/2016
Baseline Reacting Tests Verify Safe, Repeatable Operation Data Reduction Code Development	2 weeks	04/01/2016
Initiation of Advanced Optical Measurements	-	-

Looking Forward

Principal Measurements

- Conventional Instrumentation
  - Ion gauges
  - High-frequency pressure transducers

- Optical Measurements
  - High-speed Schlieren
  - Planar Laser-Induced Fluorescence (OH)



Simultaneous Schlieren and OH-PLIF (Extracted from Pintgen et al, Combustion and Flame, 2012)

Looking Farther Forward

Task Breakdown

1) Project Management and Planning
2) Baseline Canonical Experiments
3) Subscale Combustor Facility Development
4) Integral Measurement of Pressure Gain
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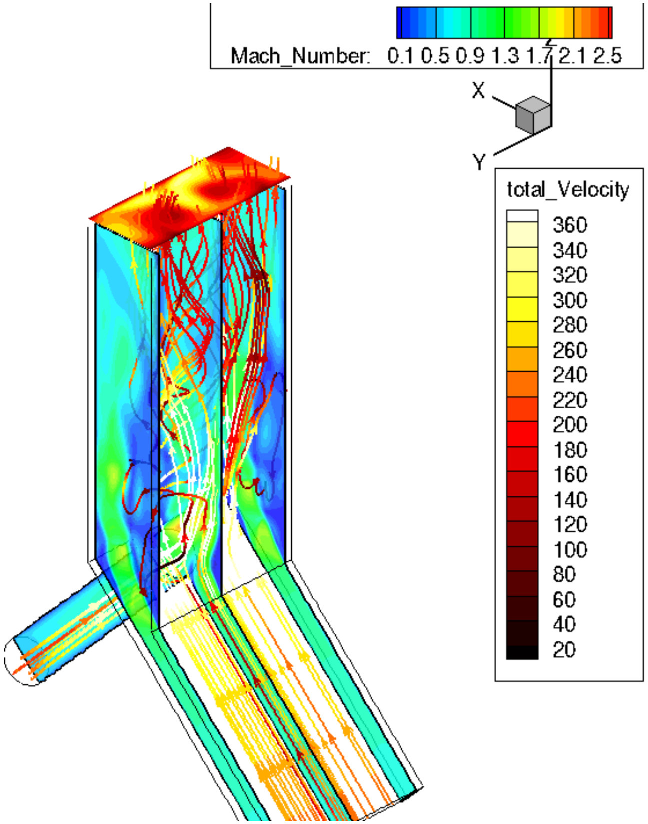
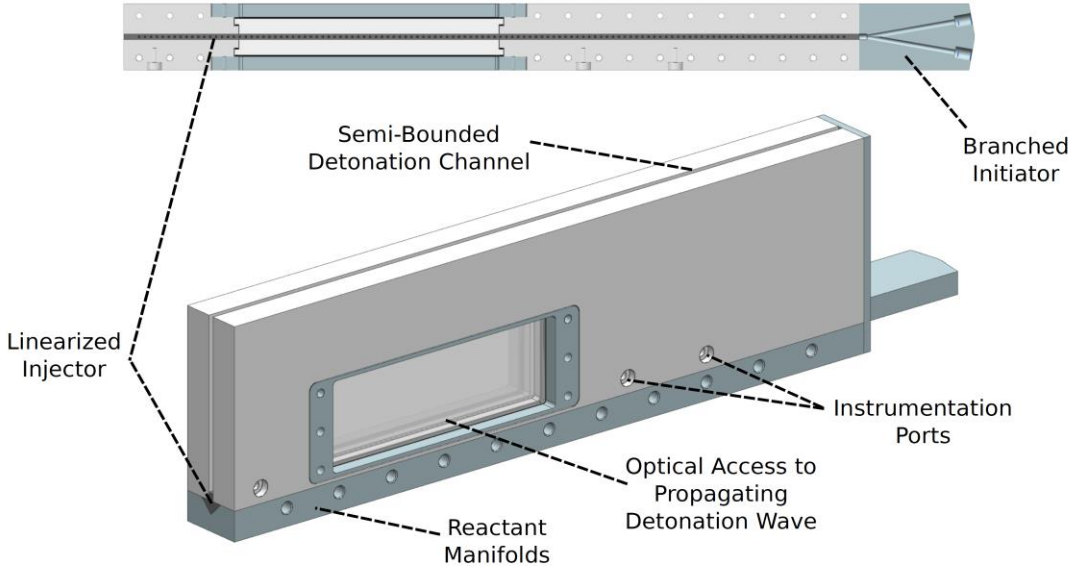


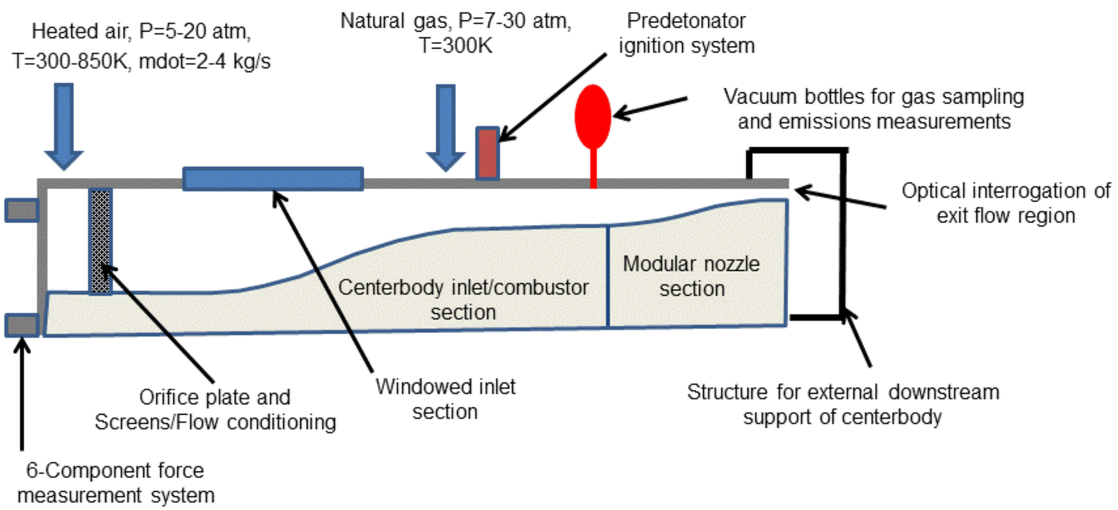


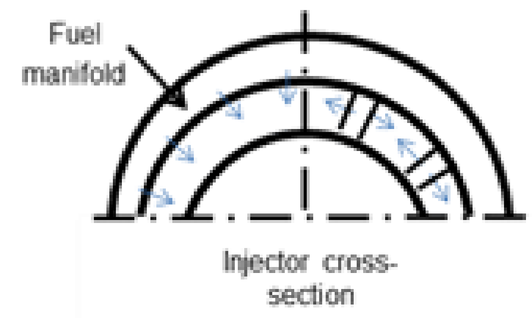
'Unwrapped' RDE test article design is at CDR-level (left) with complementary simulation informing baseline injector design (above)

Task 3.0

Subscale Combustor Development

- Representative cycle conditions easily attained
  - Targeting 2.0 MPa and 900 K
  - Continuous supply at up to 10 lbm/s
- Planned optical access to the region upstream of the chamber

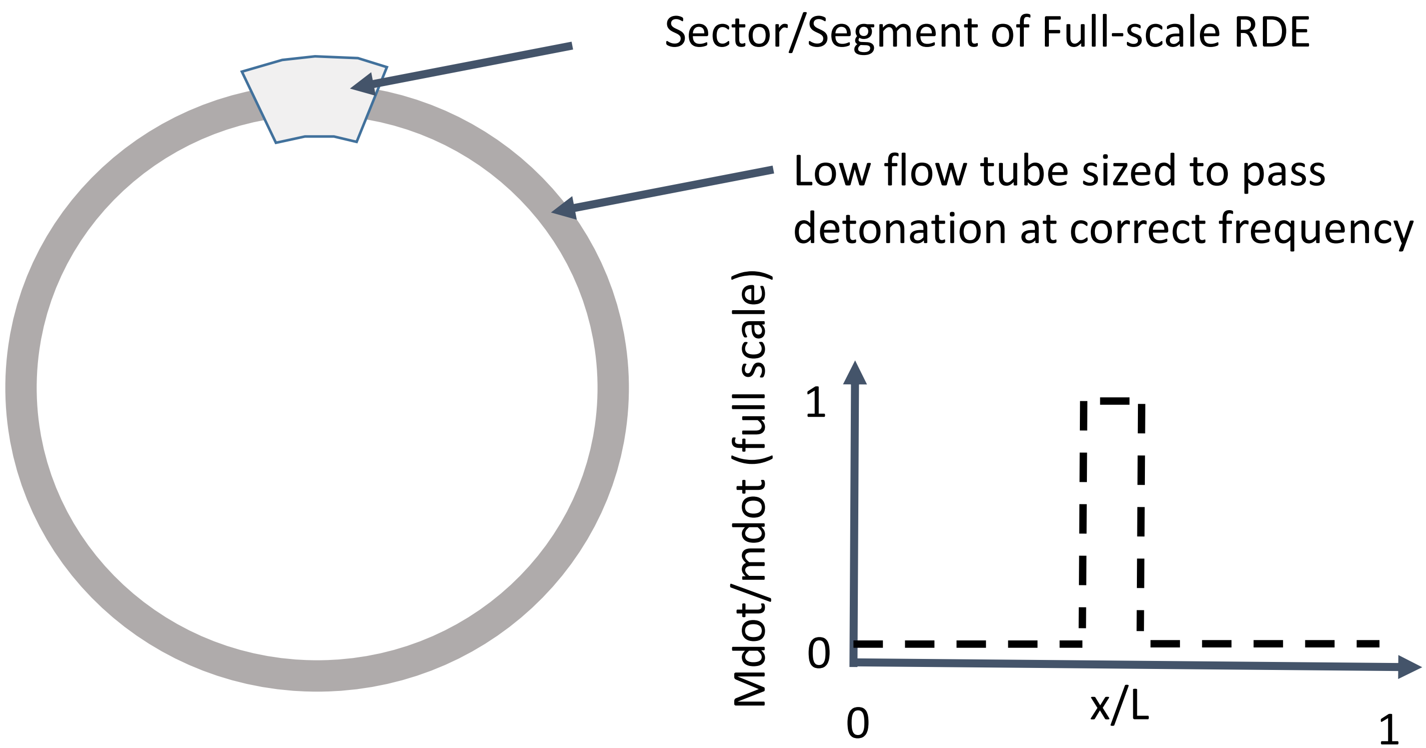




Task 3.0

Scaling Concept

- Large engines require large facilities and lots of propellant to develop
- For RDE it is crucial to match detonation period, but do we need a complete annulus to do so?

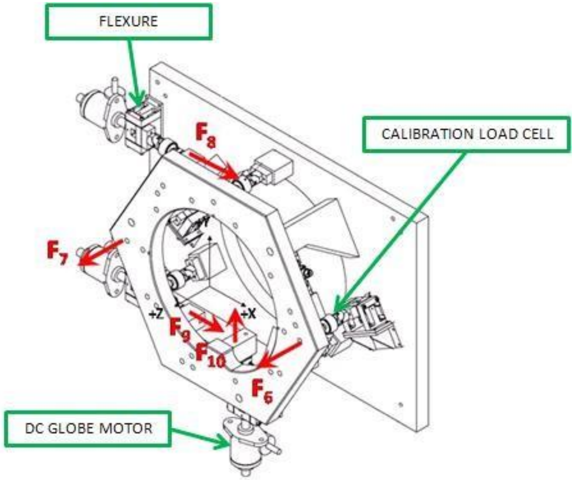


Task 4.0

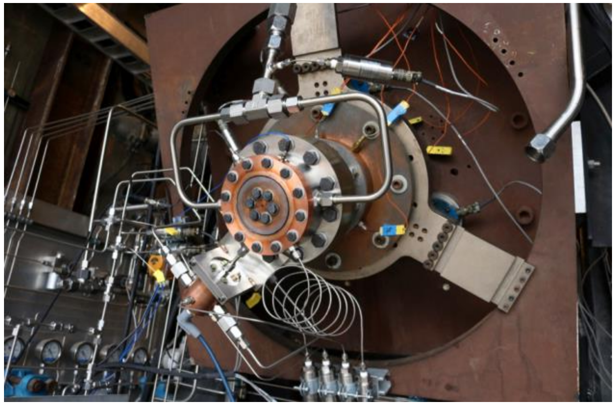
Integral Measurements of Pressure Gain

- Integration of sub-scale combustor to Purdue's 10K Stand
    - CTAP
    - Thrust

- Combined with standard rocket instrumentation suite
    - Ion gage in chamber
    - High frequency transducers in propellant manifolds and chamber
    - Microphone on combustor exit
    - High-speed camera on annulus
    - Several low-speed cameras and still photos of plume



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

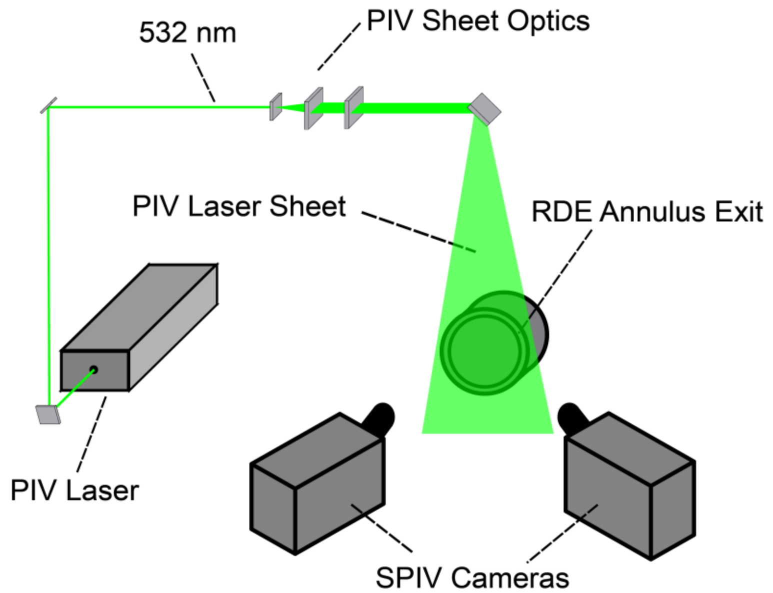


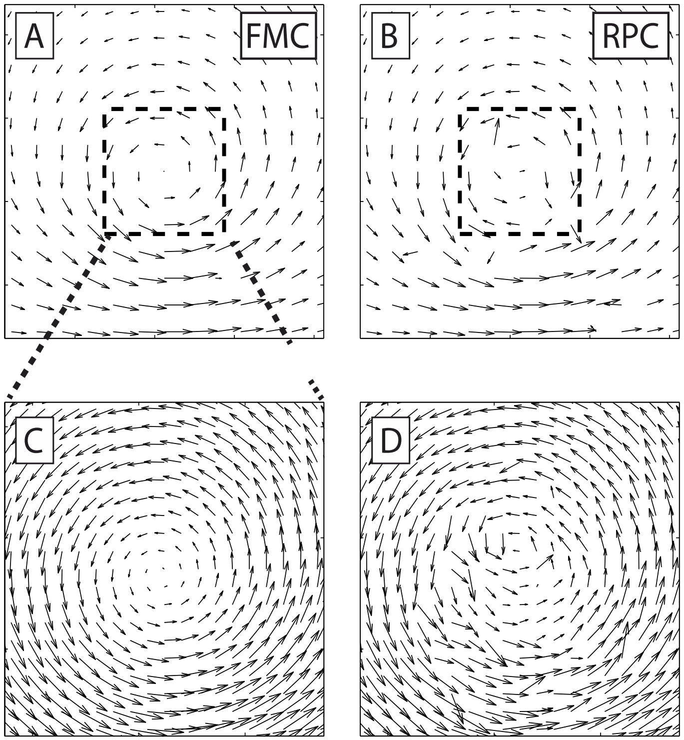
High Pressure Rocket RDE on 10K Stand

Task 5.0

Detailed Exit Flow Measurements

- 10 KHz 3-component Stereoscopic PIV of exit velocity field
- PRANA/REAPER with FMC
  - Enhanced spatial resolution
  - Dynamic range
  - Reduced error





Task 6.0

Emissions Characterization

- 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, NO2, CO, CO2, H2O concentration
- Separate detector for O2 concentration

Summary

Progress and Current Outlook

- Progress is underway on DRONE development
  - Canonical platform to perform advanced measurements of key processes
  - Informing complementary numerical modeling effort
- Branched initiation device has been demonstrated
  - Tunable channel forcing with high precision
  - Pulses remain coupled into channel
- Concurrent efforts with high pressure rocket RDE are developing experience base for Tasks 3.0-6.0 in Years 2 and 3.

PURDUE
UNIVERSITY