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Monopropellant Thruster Development Using a Family of Micro-Reactors

Integrity ★ Service ★ Excellence

17 February 2017

Dr. Marcus Young
Dr. David Scharfe
Gerald Gabrang
In-Space Propulsion Branch
AFRL/RQRS

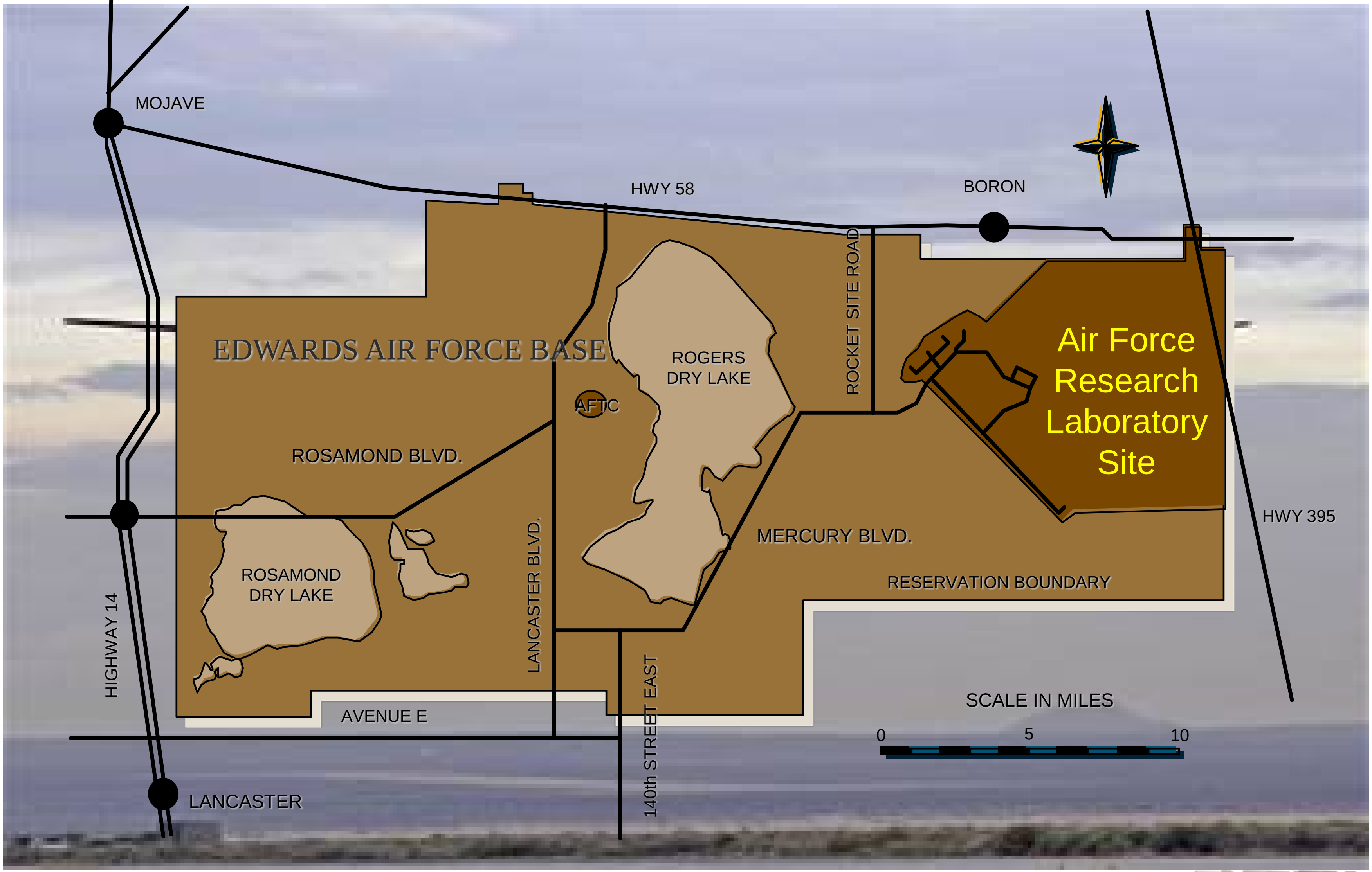
Outline

- The Air Force Research Lab
- Monopropellants for In-Space Propulsion
- Near-Term Monopropellant Thruster Challenges
- Supporting Test Requirements
- AFRL Monopropellant Thruster Test Facilities
- AFRL Monopropellant Thruster Diagnostics
- AFRL Integrated Modeling Effort
- The AFRL Micro-Reactor
- Current Development Status
- Future Test Campaigns
- Summary

Note:
Simplifications and generalizations are made throughout the presentation.

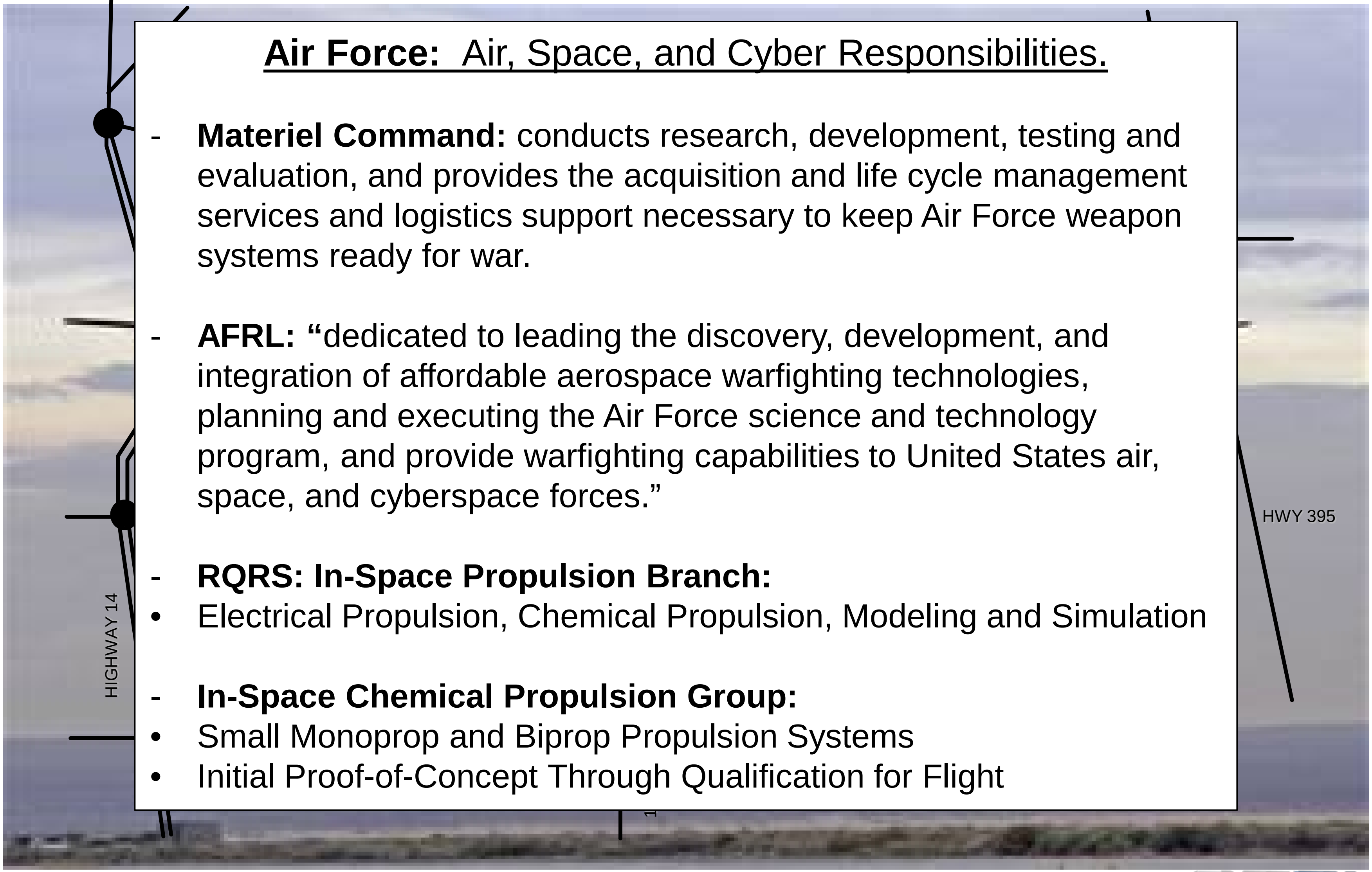
Air Force Research Lab

What it Is and What We Do



Air Force Research Lab

What it Is and What We Do



Air Force: Air, Space, and Cyber Responsibilities.

- **Materiel Command:** conducts research, development, testing and evaluation, and provides the acquisition and life cycle management services and logistics support necessary to keep Air Force weapon systems ready for war.

- **AFRL: "**dedicated to leading the discovery, development, and integration of affordable aerospace warfighting technologies, planning and executing the Air Force science and technology program, and provide warfighting capabilities to United States air, space, and cyberspace forces."

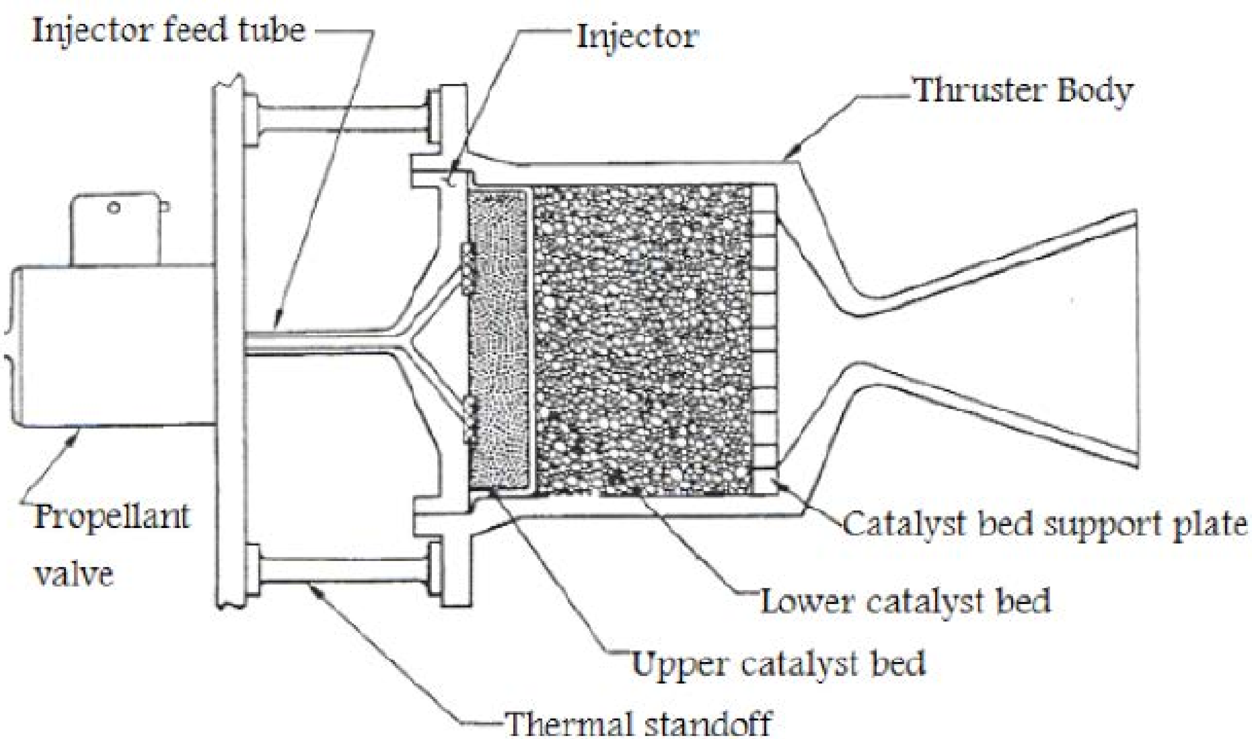
- **RQRS: In-Space Propulsion Branch:**
  - Electrical Propulsion, Chemical Propulsion, Modeling and Simulation

- **In-Space Chemical Propulsion Group:**
  - Small Monoprop and Biprop Propulsion Systems
  - Initial Proof-of-Concept Through Qualification for Flight

In-Space Monopropellant Thrusters

Physical Description

- Small (~1-22N) Thrusters Used for Attitude Control and Maneuvering of Small Spacecraft.



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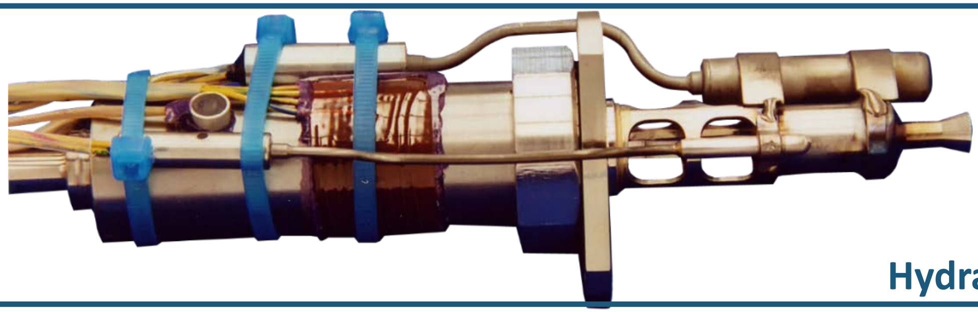
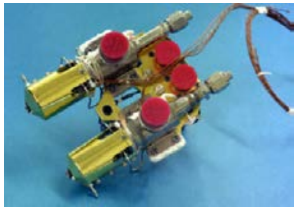


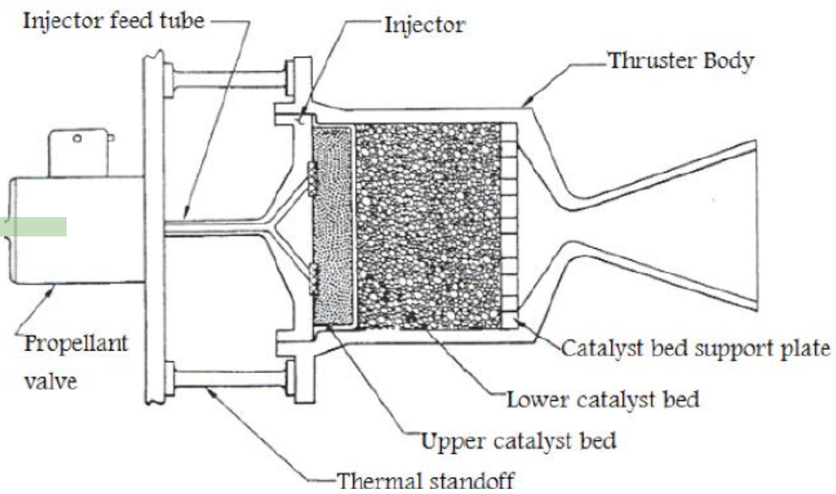


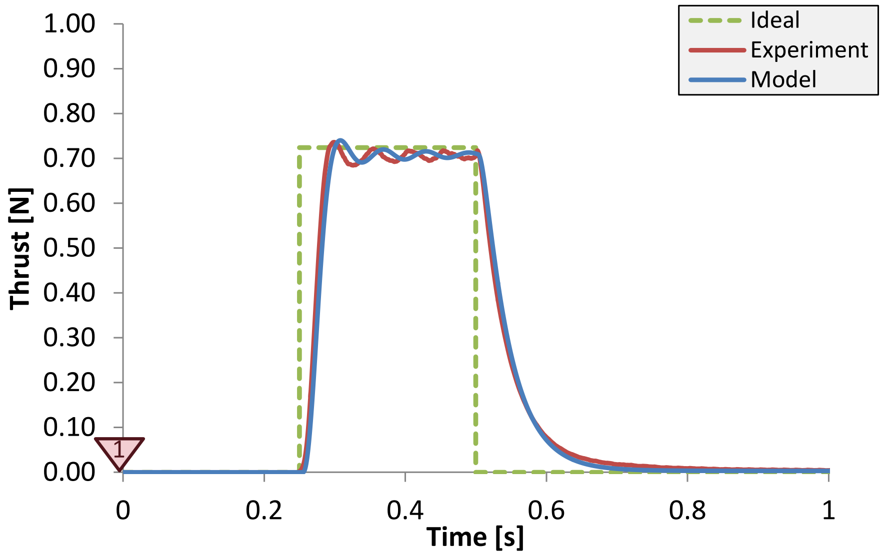
Hydrazine

In-Space Monopropellant Thrusters

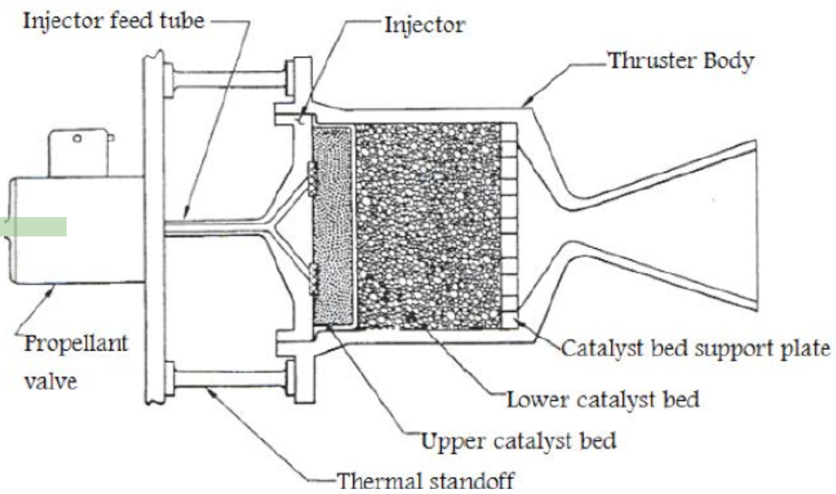
Operation and Applications

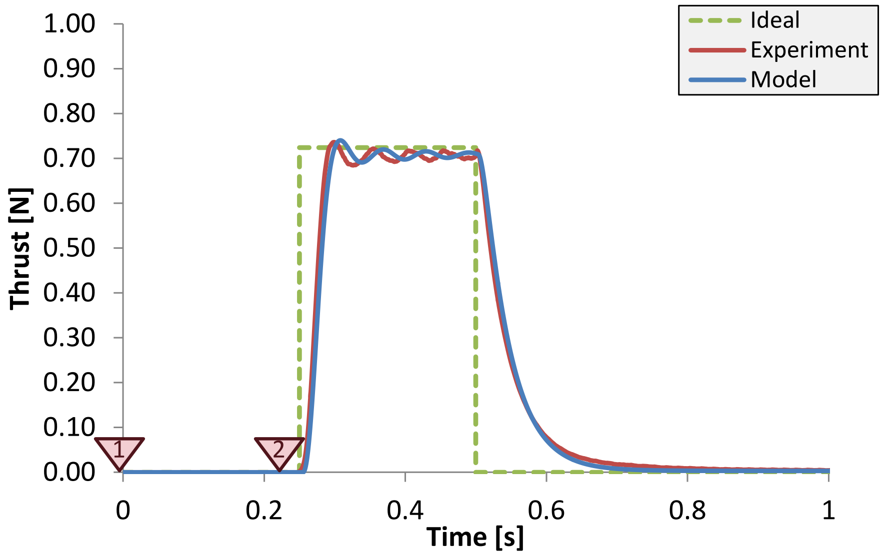
1. Preheat Thruster to Firing Temperature.



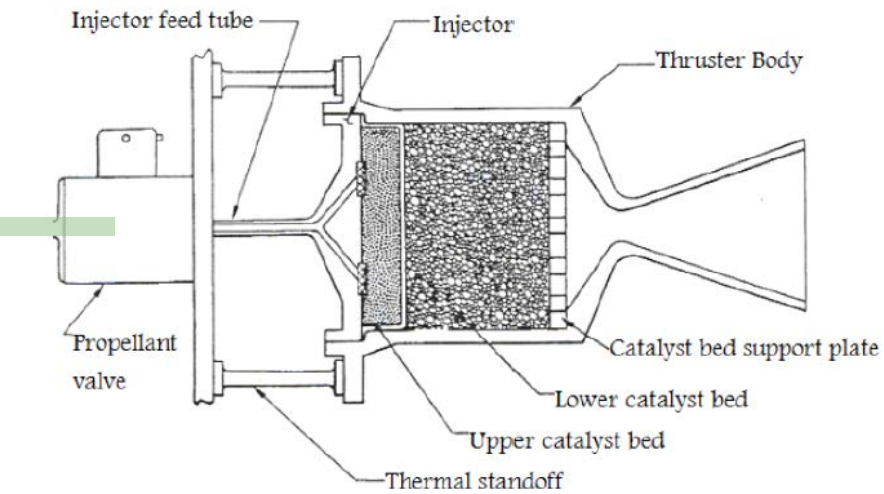


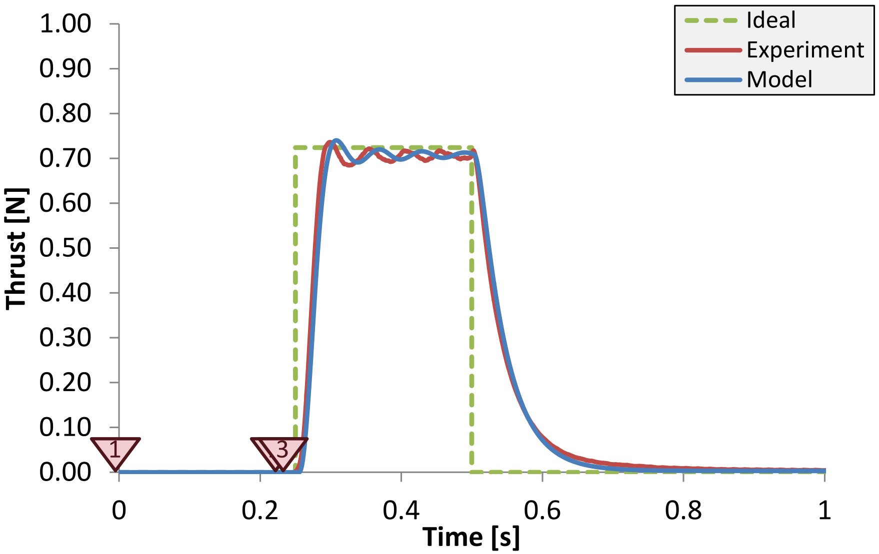
2. Electrically Command Valve to Open.



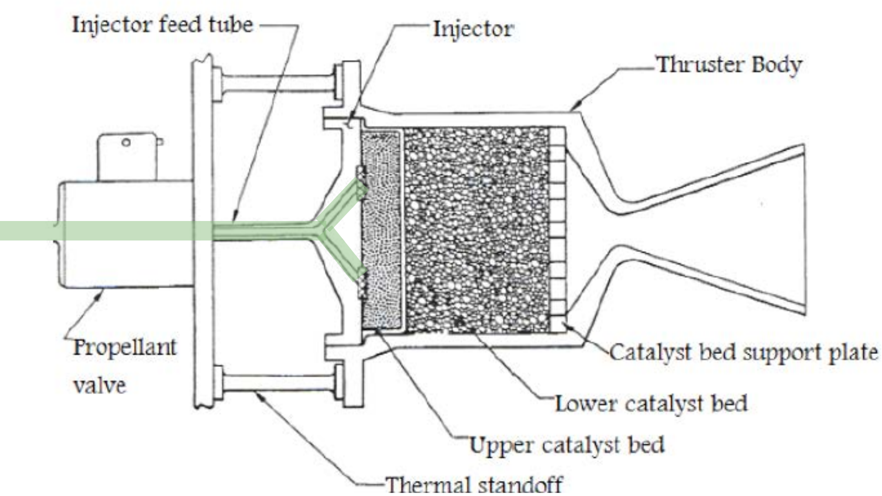


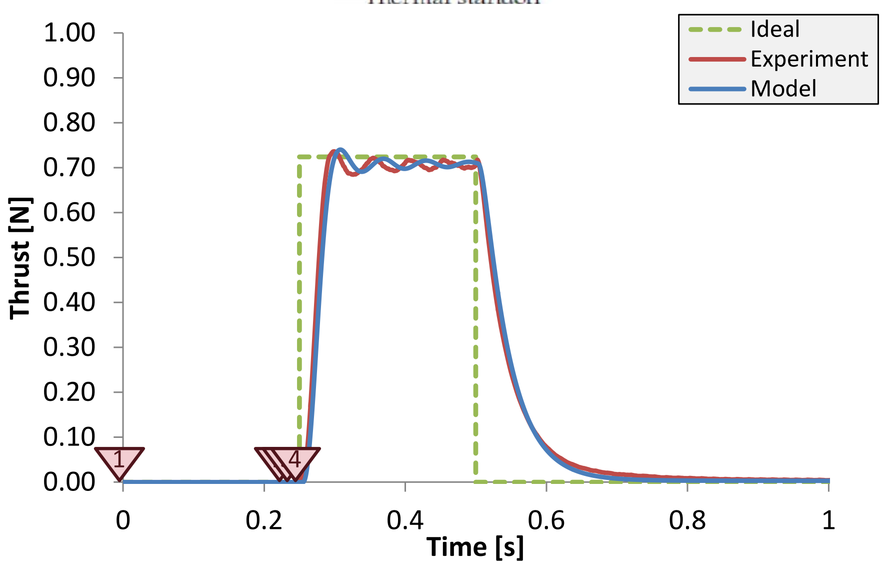
3. Valve Physically Opens.





4. Dribble Volume Full, Injection Begins.

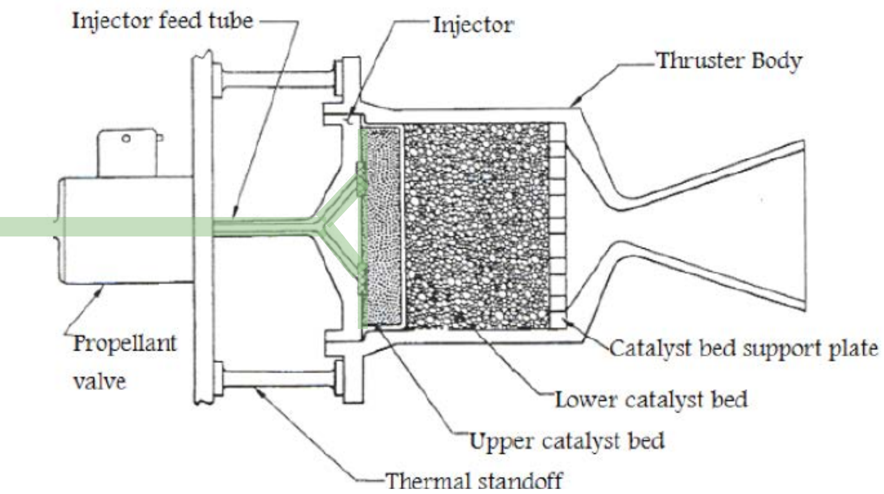


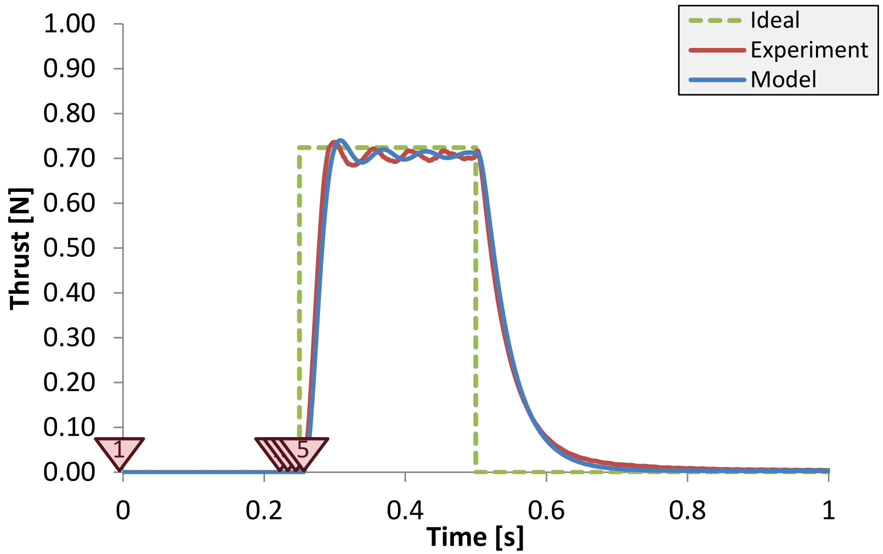


In-Space Monopropellant Thrusters

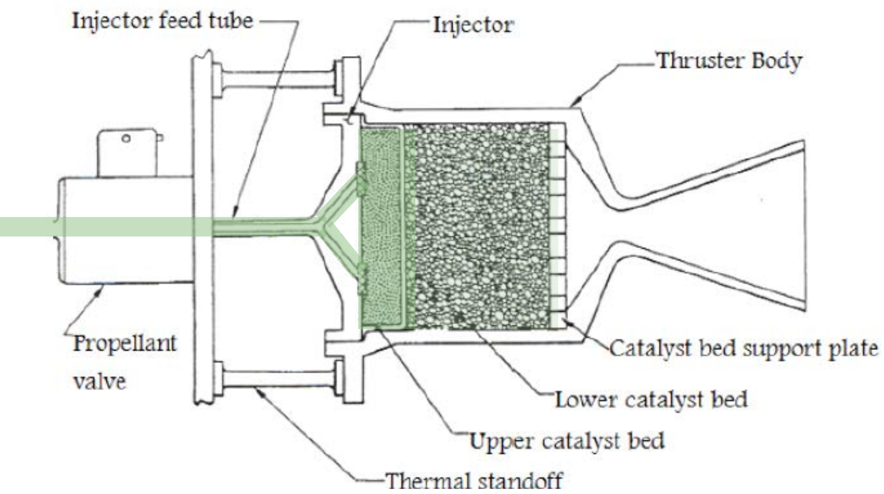
Operation and Applications

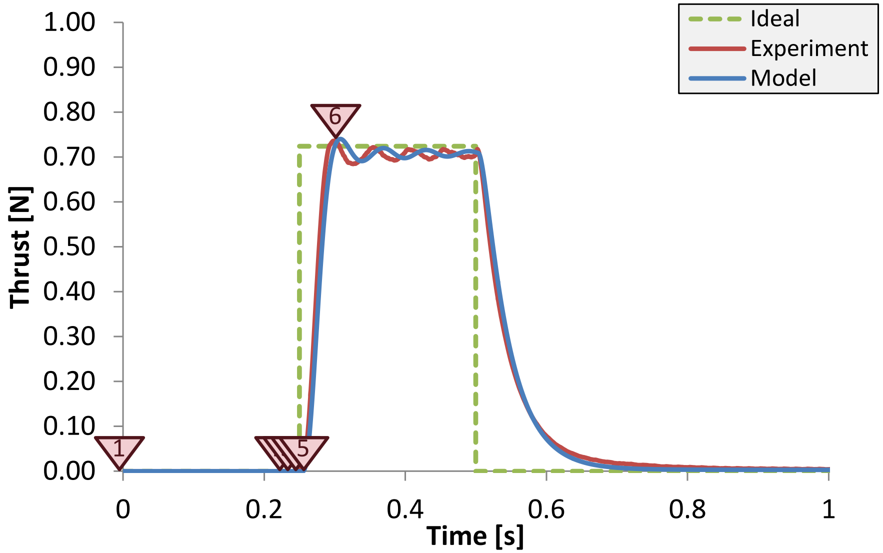
5. Reactions Begin (T, P Increase).



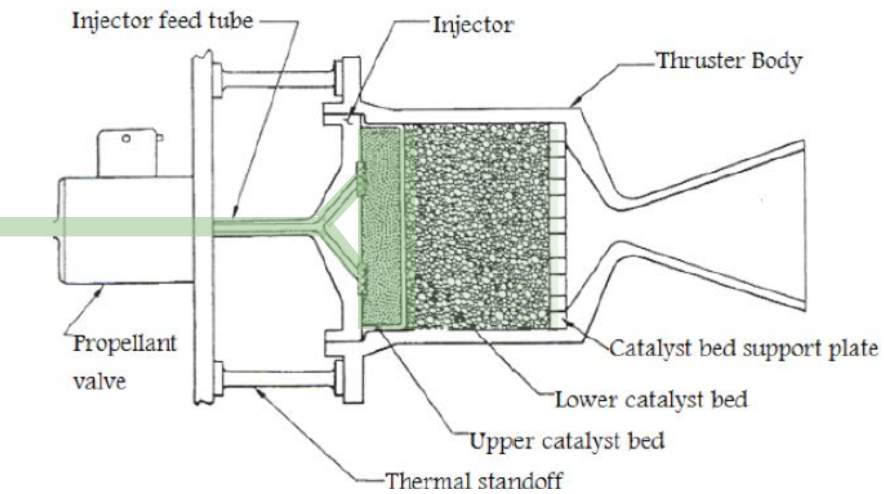


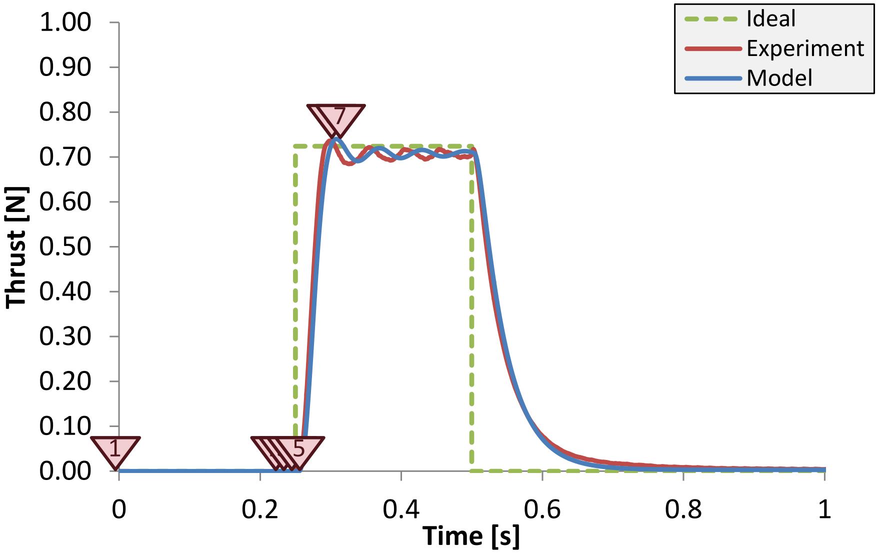
6. Pressure Reaches Nominal Steady-State.



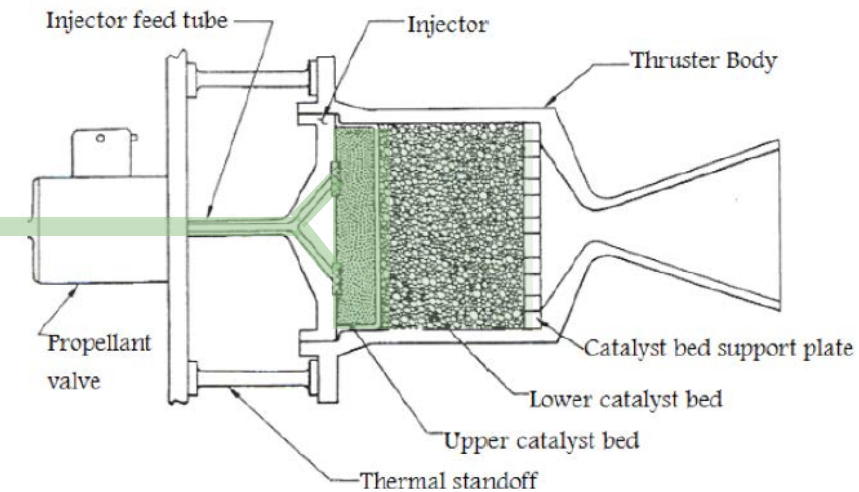


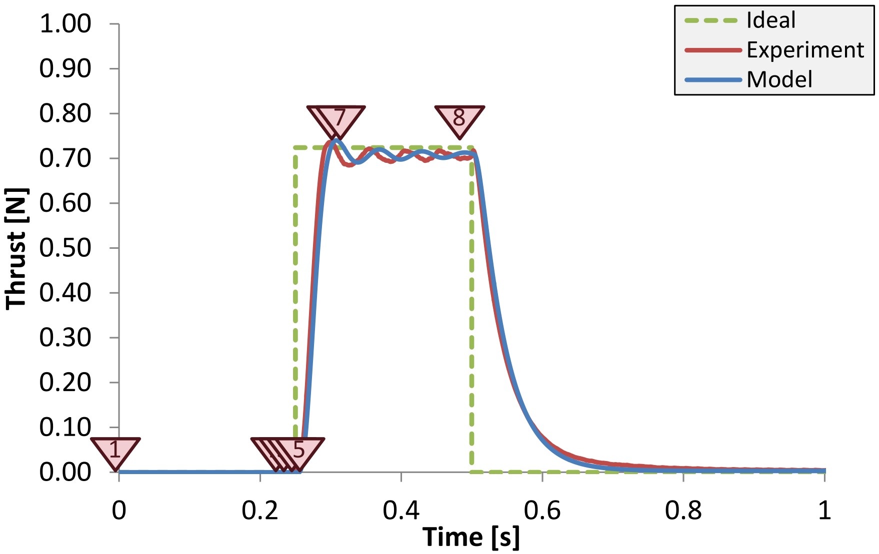
7. Pressure Oscillations (Feed System).



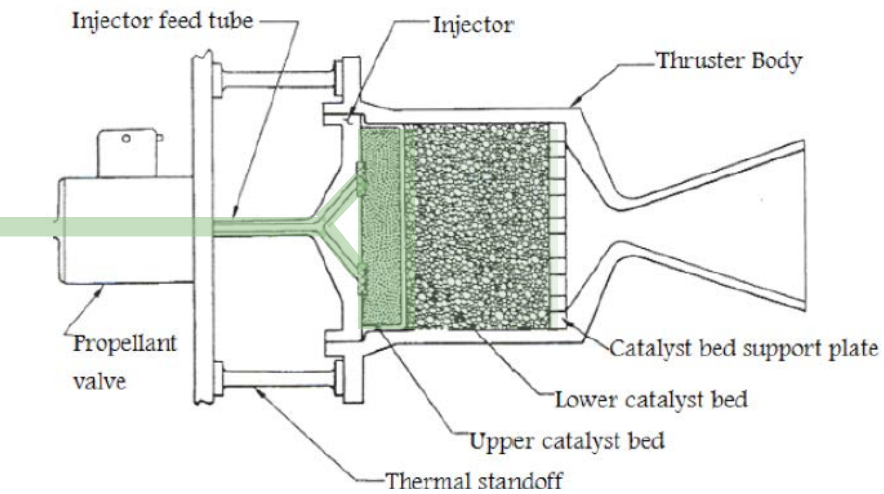


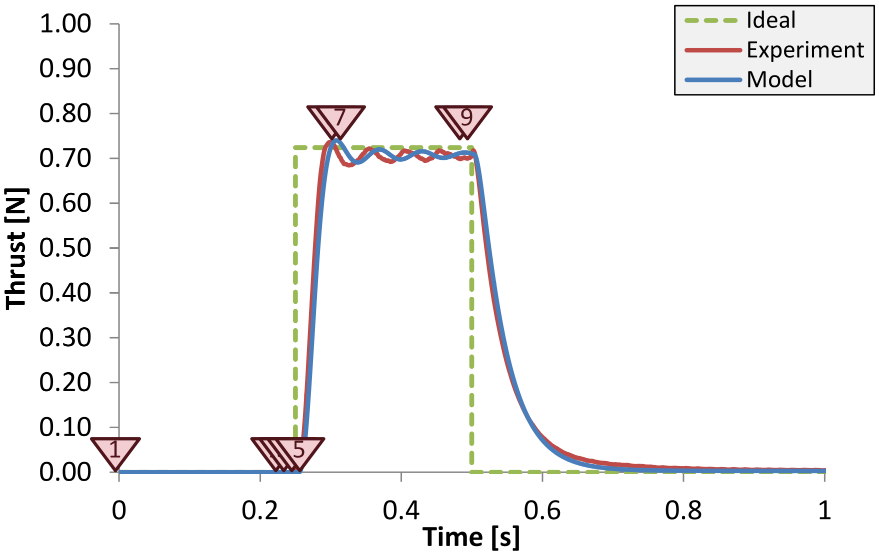
8. Electrically Command Valve to Close.



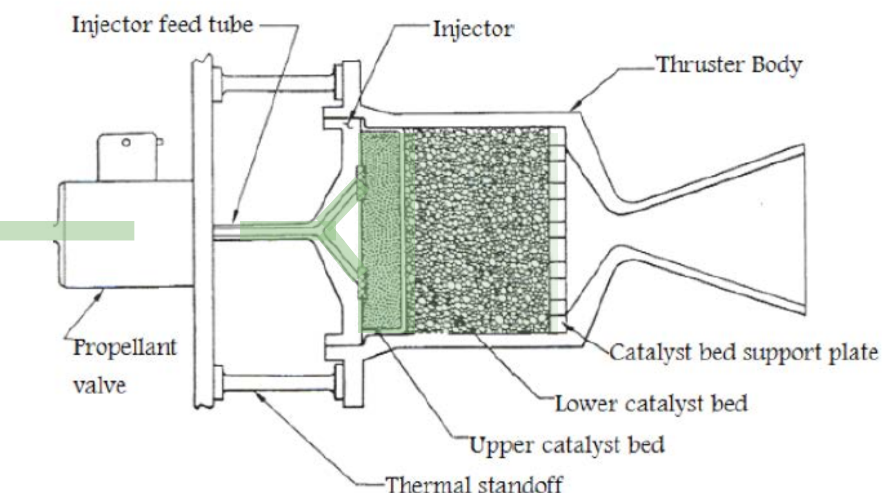


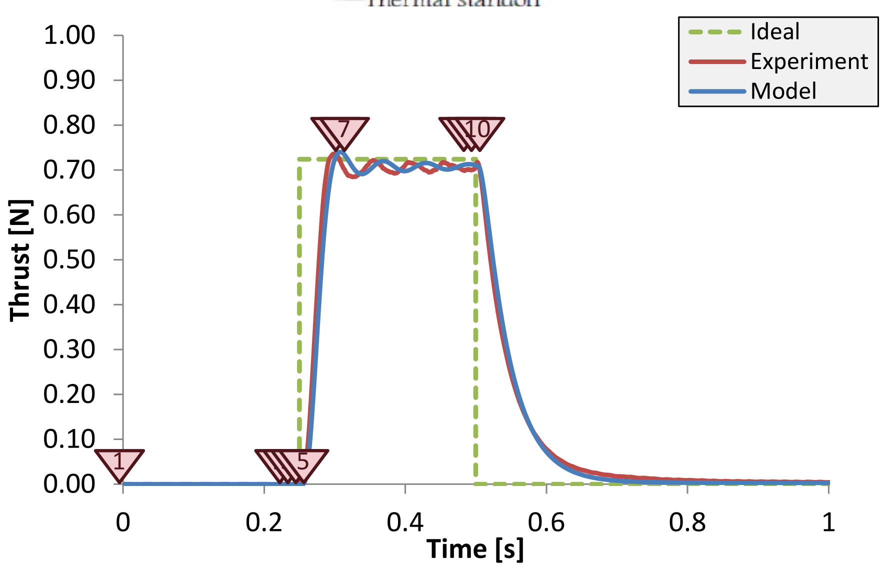
9. Valve Physically Closed.





10. Dribble Volume Begins Emptying.

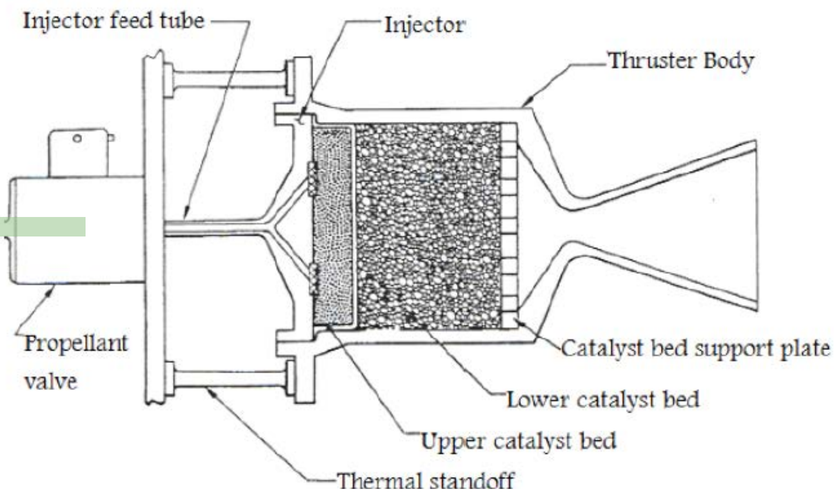


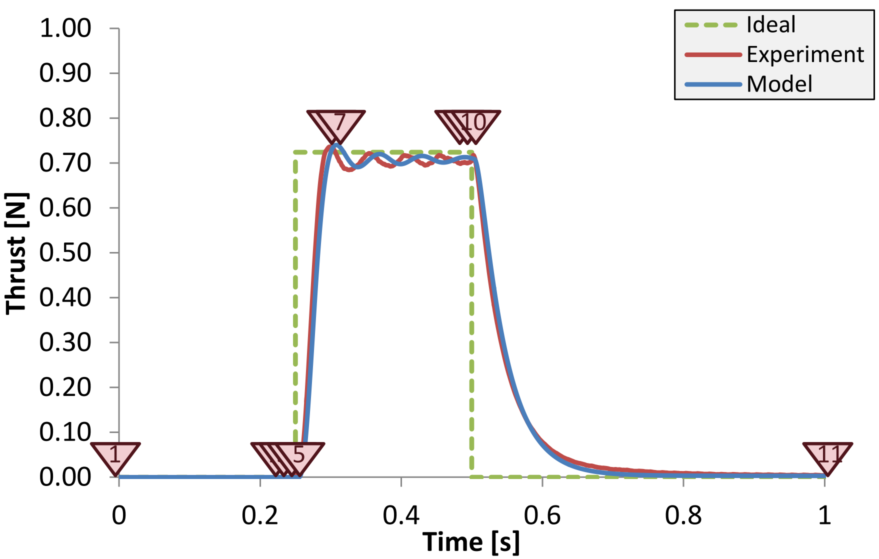


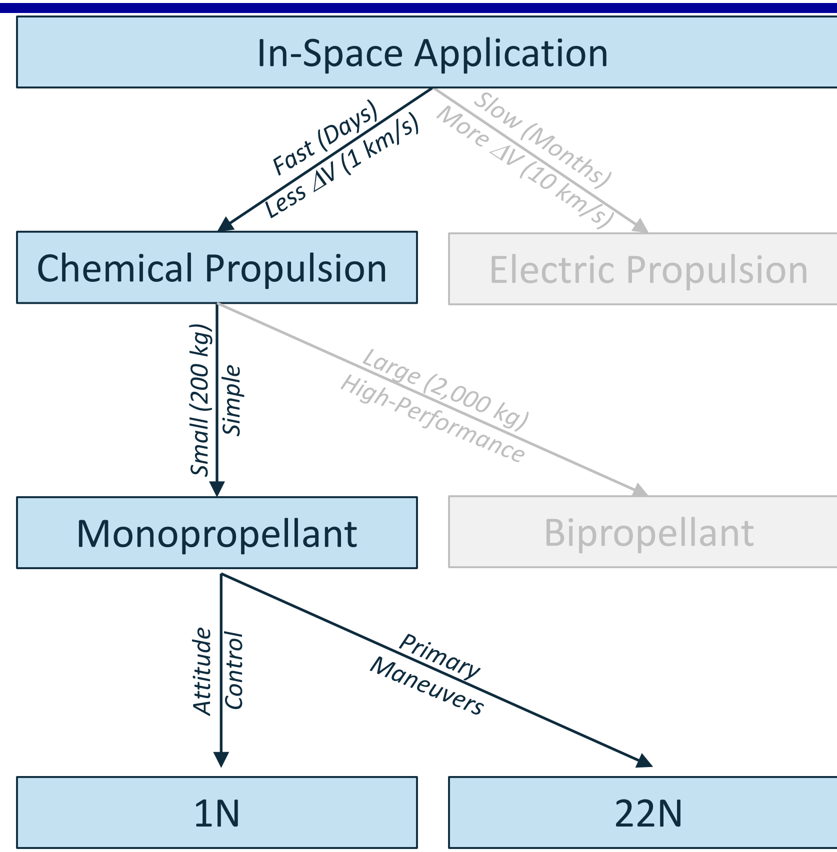
In-Space Monopropellant Thrusters

Operation and Applications

11. All Propellant Reacted and Expelled.





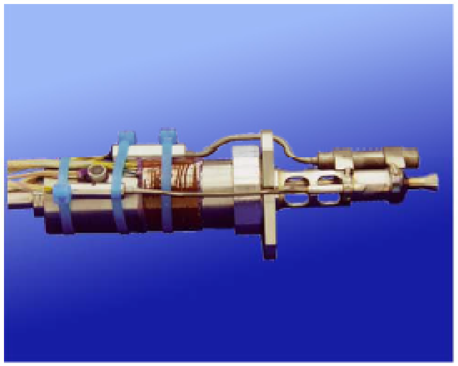


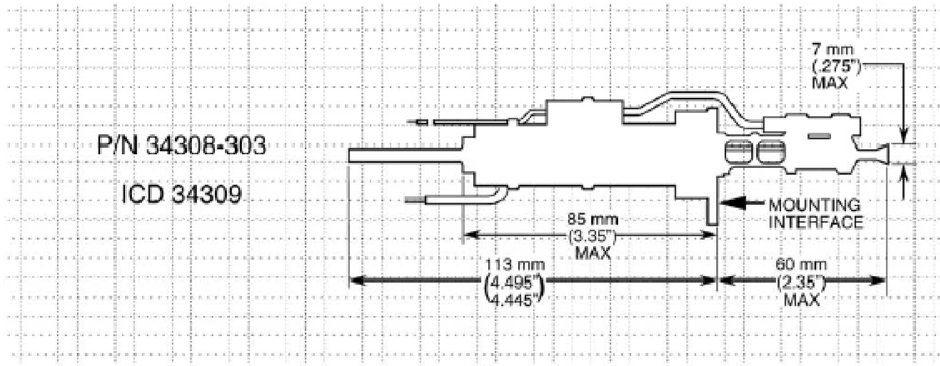
Note:
Simplifications for Air Force Applications.

In-Space Monopropellant Thrusters

Typical Examples and Performance

MR-103G 1N (0.2-lbf) ROCKET ENGINE ASSEMBLY





Design Characteristics

- Propellant..Hydrazine
- Catalyst... S405
- Thrust/Steady State........ 1.13 – 0.19N (0.253 – 0.043 lbf)
- Specific Impulse...................... 224 – 202 sec (lbf-sec/lbm)
- Feed Pressure.................... 28.3 – 4.8 bar (420 – 70 psia)
- Chamber Pressure.............. 23.8 – 4.5 bar (345 – 65 psia)
- Expansion Ratio... 100:1
- Flow Rate.........0.5 – 0.09 g/sec (0.0011 – 0.0002 lbm/sec)
- Valve... Dual Seat
- Valve Power.................. 8.25 Watts Max@28 Vdc & 21°C
- Cat. Bed Heater Pwr...... 6.32 Watts Max@28 Vdc & 21°C
- Mass .... 0.33 kg (0.73 lbm)
  - Engine... 0.127 kg (0.28 lbm)
  - Valve... 0.204 kg (0.45 lbm)

Performance

- Total Impulse... 97,078 N-sec
  .... (21,825 lbf-sec)
- Total Pulses.. 835,017
- Minimum Impulse Bit............ 0.0133 N-sec@0.015sec ON & 6.9 bar
  .... (0.003 lbf-sec@0.015sec) (ON & 100psi)
- Steady State Firing Single firing........ 300 sec 1,000 sec
  ....Cumulative........ 23.8 hrs — 40.6 hrs

Status

- Flight Proven

Reference

- AIAA-2005-3952

Rev. Date: 5/15/06

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Notes

1. Short pulses don't reach steady-state thrust.
2. Listed specific impulse is for long-steady firings.
3. Lifetime defined by roughness threshold.
4. Minimum impulse bit has lower Isp and larger variations.

Near-Term Monopropellant Challenges

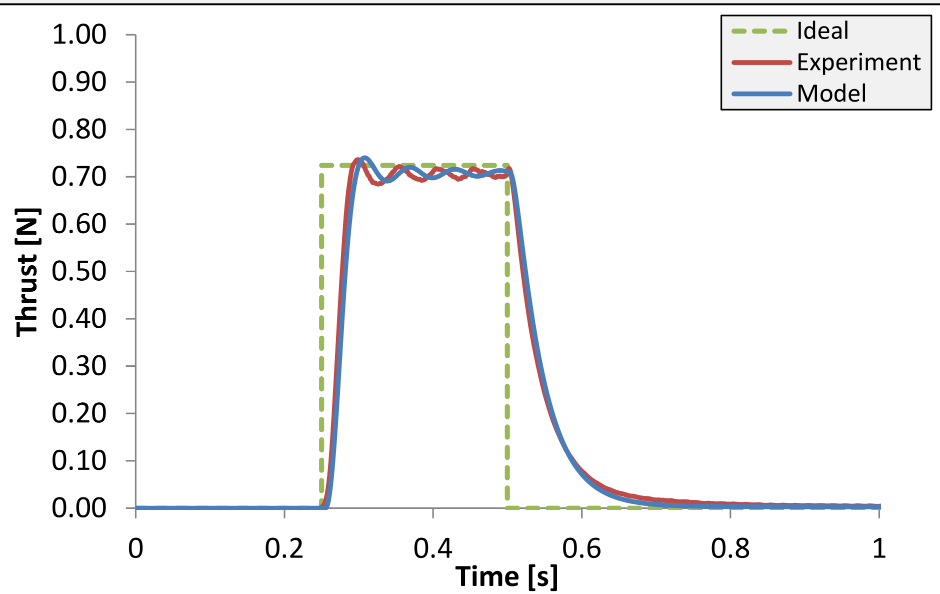
General AF Problems to Address

	Decrease MIB While Increasing Predictability & Repeatability	Increase Lifetime With High-Performance Monopropellants	Increase Performance (ρ*Isp) of Advanced Monopropellants
Test Questions	- What is the MIB capability of existing flight hardware? - What places the ultimate limit on minimizing the MIB? - What causes shot to shot variations and pulse uncertainties?	- What are physical life limiting mechanisms? - How does pulse type affect mechanisms? - How can these mechanisms be minimized?	- Is higher theoretical performance achieved? - Where does performance deviate from theoretical? - What limitations are experienced with new propellants?
Test Articles	Flight Hardware Micro-Reactor	Micro-Reactor	Micro-Reactor
Facility Requirements	Representative Environment Diagnostic Access	Representative Environment Diagnostic Access Significant Propellant Consumption	Representative Environment Diagnostic Access
Diagnostics	High-Speed (1ms) Thrust, Chamber Pressure, Propellant Flow Rate, Valve Response	Iridium loss, iridium flux. High-speed (1ms) Diagnostics Plume Diagnostics	High-speed (1ms) Plume
Supporting Models	Systems Level Model.	Systems Level Model Thruster Aging Model	Detailed Multiphysics Models

Monoprop Thruster Test Requirements

General Considerations and Fidelity

- ❑ Measure Isp improvements < 5%.
- ❑ Resolve shot to shot variations.
- ❑ Resolve oscillations due to feed system stiffness.
- ❑ Resolve chamber pressure roughness.
- ❑ Time sequence physical events.
- ❑ Characterize pulses from MIB (15ms) to steady-state (10 min).
- ❑ Determine when catalyst material is lost.
- ❑ Demonstrate lifetime (>10 hr) of systems.
- ❑ Demonstrate effect of changing single component.



Monoprop Thruster Test Facility

Area 1-42, E-Cell

Unique Capabilities

- *45,200 ft^3 for Passive Firings (Effluent Captured)*
- *Monoprops, Biprops, and Solid Rocket Motors*
- *Cost Effective, Systematic Testing Environment*
- *Full Suite of High-Speed and Plume Diagnostics*

Near-Term Schedule

- ✓ *Function Check/Initial Pump-Down. (Sep ‘16)*
- *Gen II Micro-Reactor Campaign (Apr ‘17)*
- *Gen III Micro-Reactor Campaign (May ‘17)*
- *Advanced Bipropellant Demo (Oct ’17)*

Monoprop Thruster Test Facility

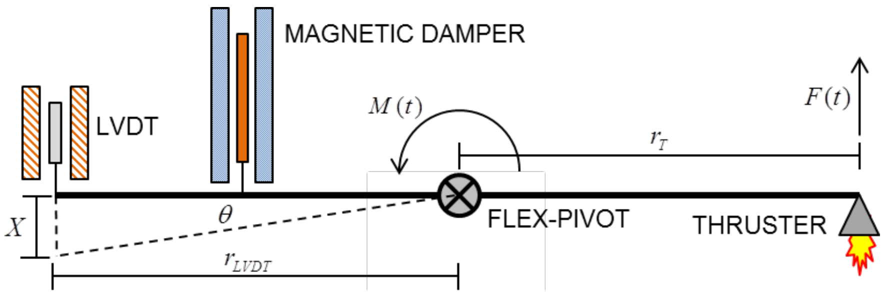
Building 8595, Chamber 4

- 5 ft diameter and 8 ft long.
- Actively pumped (25 mTorr base pressure)
- Short duration (< 1 min total firing time)
- Advanced/green monopropellant test campaigns.
- Diagnostic development.
- Micro-reactor tests to date.

vs

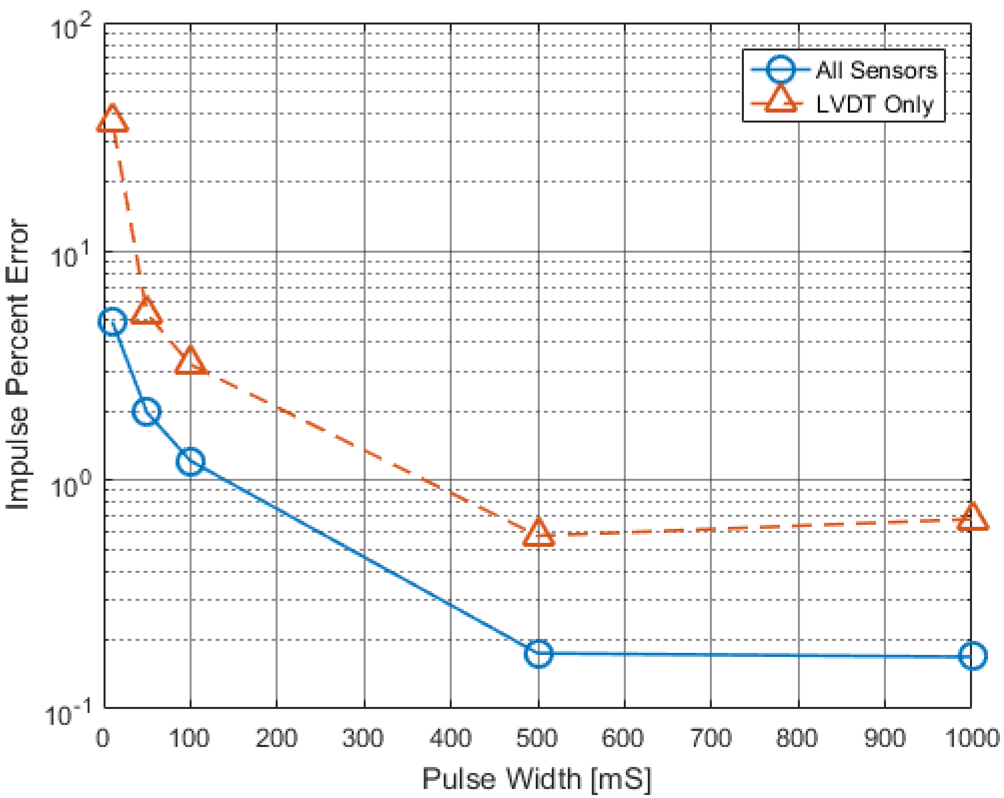
AFRL Monoprop Thruster Diagnostics

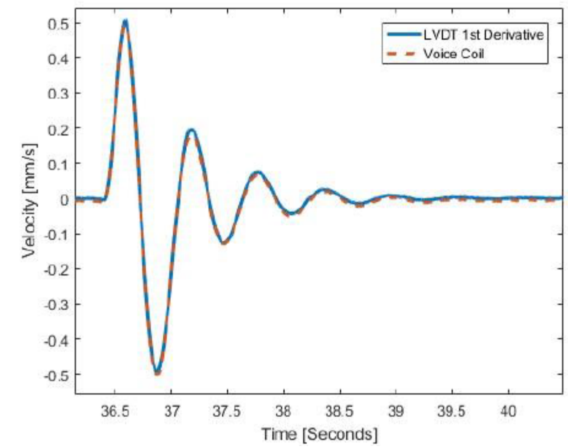
High-Speed Thrust Diagnostic (UCCS)

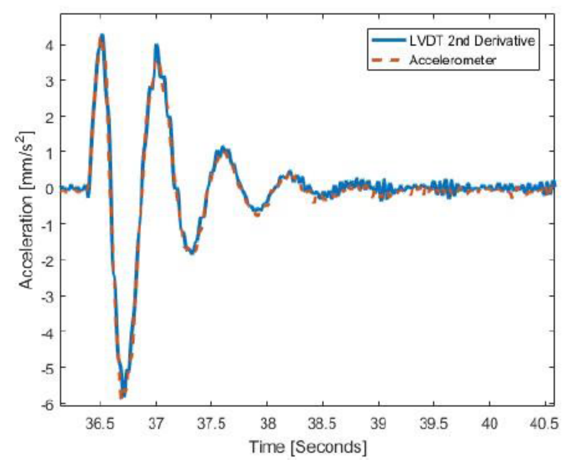


$$I\ddot{\theta}(t)+C\dot{\theta}(t)+K\theta(t)=rF(t)$$

Acceleration **Velocity** **Position**





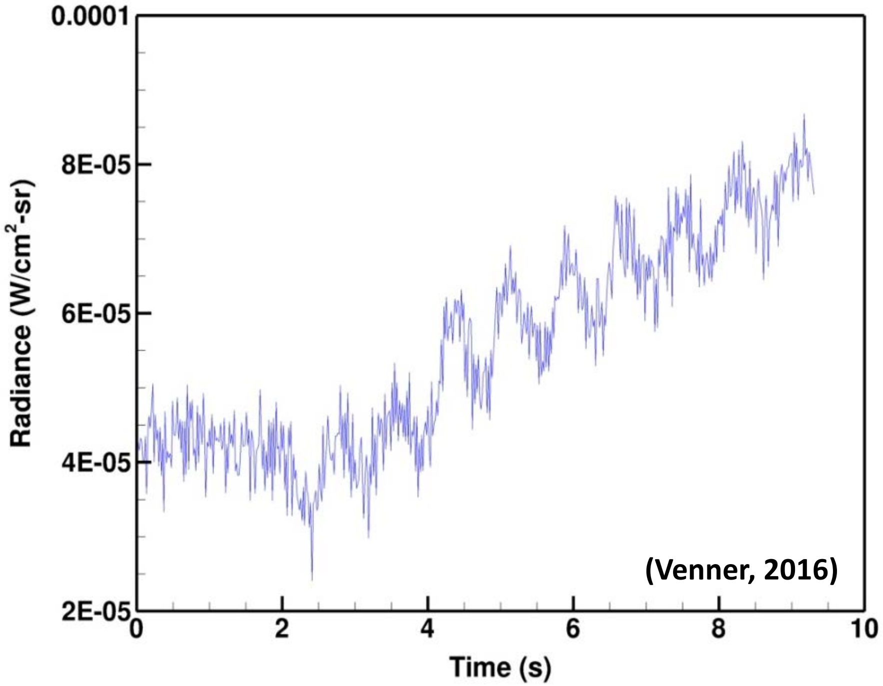


AFRL Monoprop Thruster Diagnostics

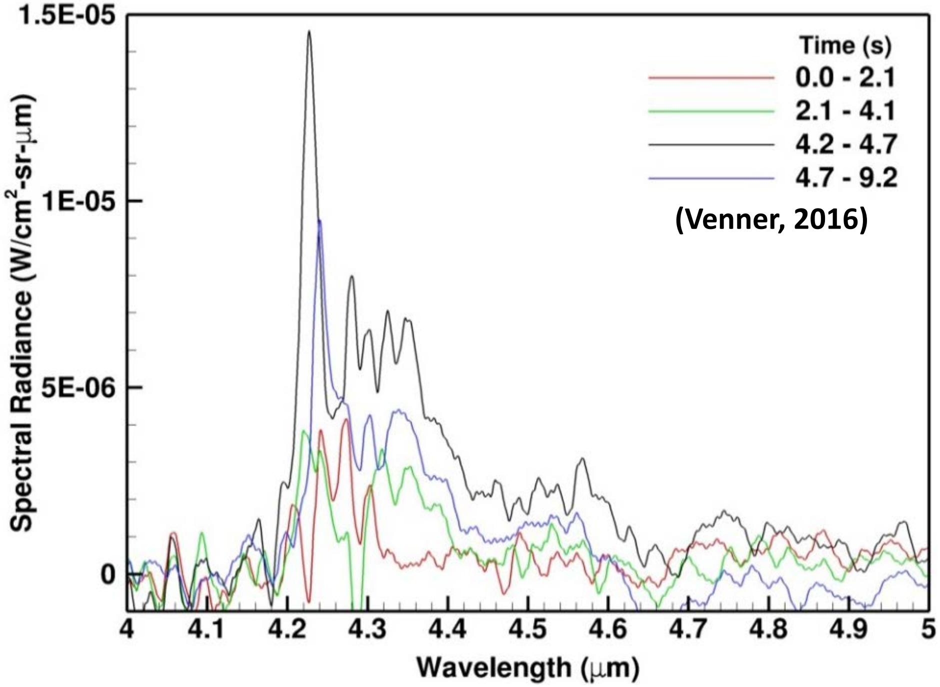
FTIR, DLAS, LIBS

- Fourier Transform Infrared Spectroscopy (FTIR) for General, Slow (100ms), Picture of Exhaust.
- System Tested During Drop-In Replacement Tests (Emission).

Integrated Radiance for a 2 Second Test at 450 PSIA Feed Pressure



Averaged Spectra Over Different Time Periods of a Single Test at 450 PSIA



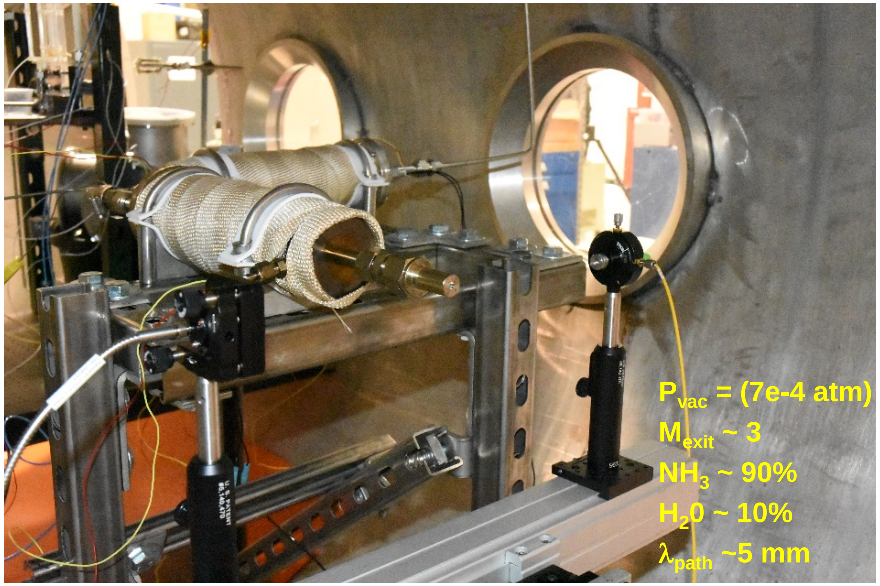
- FTIR (Emission) Demonstrated During Drop-In Replacement Tests.
- Signals Too Weak to Draw Quantitative Conclusions → Absorption.

Thruster Plume Diagnostics

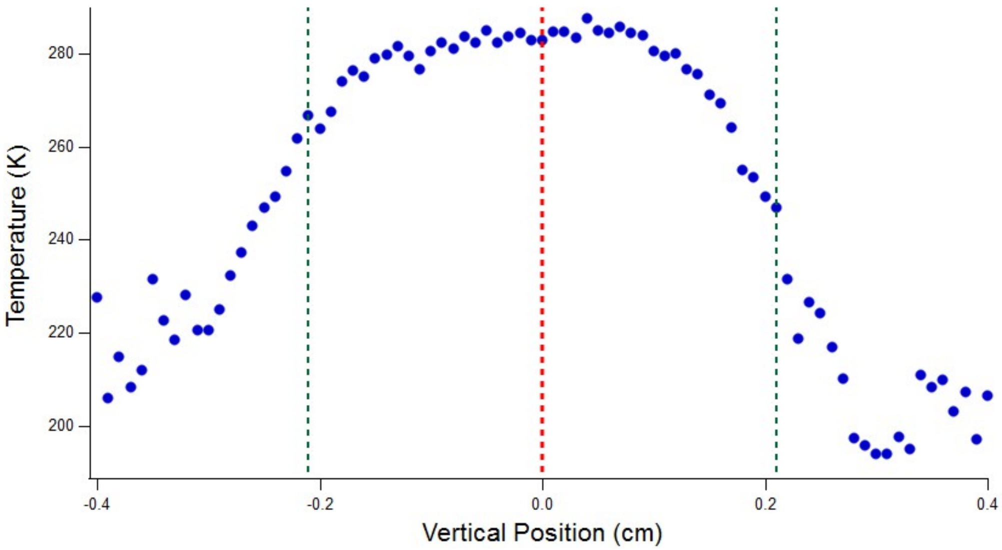
FTIR, DLAS, LIBS

- Diode Laser Absorption Spectroscopy (DLAS) for Targeted, High-Speed Picture of Exhaust.
- System Tested With Hot Ammonia/Water Exhaust Simulator.
- Conditions Relevant to 1N N_2H_4 Thruster.

NH_3 "Thruster" Simulator Under Vacuum



Measured Water Temperature in "Thruster" Plume

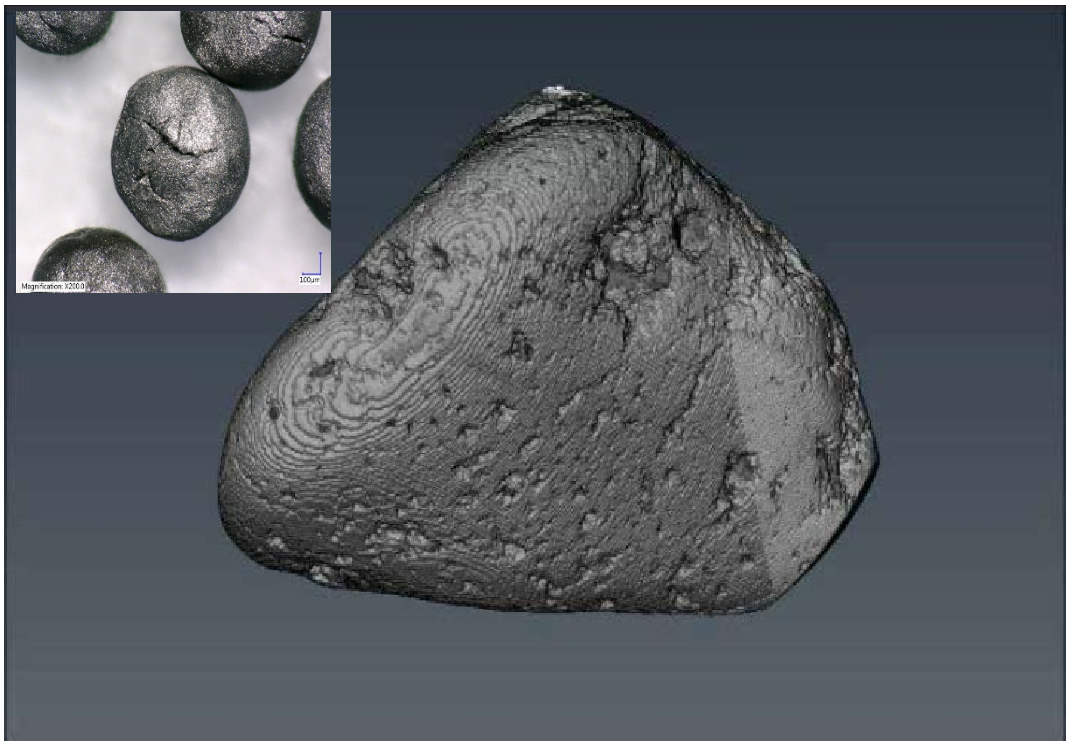


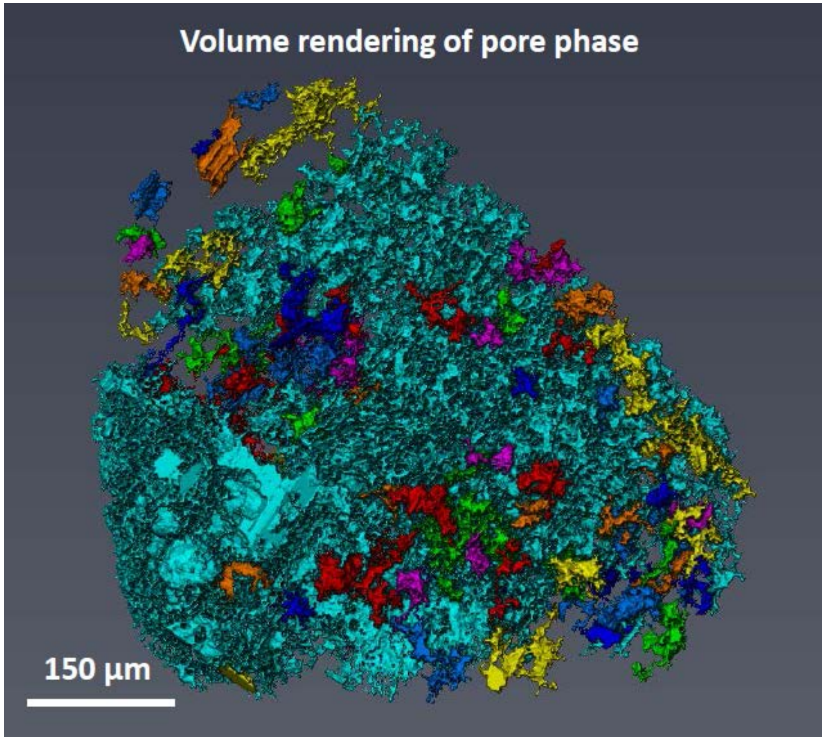
- DLAS Demonstrated Using Relevant Simulated Exhaust.
- Data Analysis Underway and Initial Results Appear Promising.
- CO_2 System (for AF-M315E) Uses Different Laser.

AFRL Monoprop Thruster Diagnostics

Reactor Internal Diagnostics

- Micro-reactor diagnostics Holy Grail: internal (T, p ,species) during firing.
- Current: x-ray micro-tomography of catalyst pre & post firing.
- Can determine shape, porosity, and material distribution.
- Catalyst collected at various times from micro-reactor.
- Data analysis is significant effort and is underway.
- First step towards “real-time” diagnostic.





AFRL Integrated Modeling Effort

General Description

Pomerleau (AFRL/RQRC)

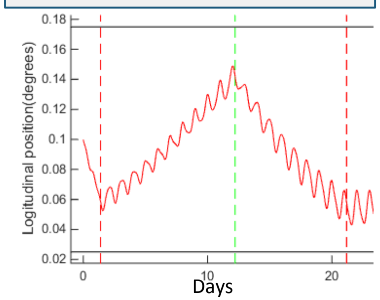
Mission Analysis

- System Change on Mission/Operations
- Performance Variation Effect on Mission.
- Sensitivity to Secondary Effects.

Generic Mission Profile

Generic Maneuvers

Generic Satellite Model



Young (AFRL/RQRS)

Systems Analysis

- Role of Components.
- Component Variation → Performance Variations.

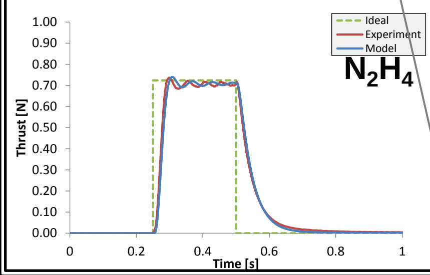
Feed System Models

Valve Models

Injector Models

Reactor Models

Nozzle Models



Bilyeu (AFRL/RQRS)

Multi-Physics Reactor Model

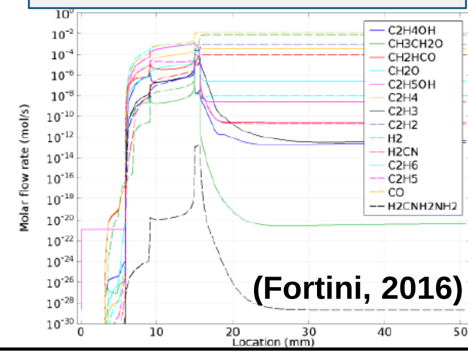
- Detailed Reactor Understanding.
- Performance, Lifetime, and Scaling Recommendations.

Simplified Kinetics

Simplified Surface Chemistry

Internal Flow Model

Thermal Model



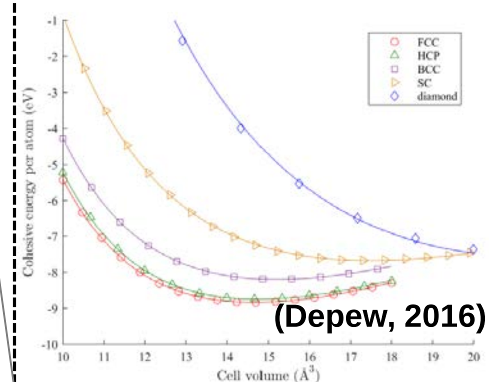
Martin (AFRL/RQRS)

Basic Physics Models

- Thermal vs. Catalytic Surface Chemistry.
- Key Chemical Reaction Pathways.

Chemical Kinetics

Catalytic Reactivity



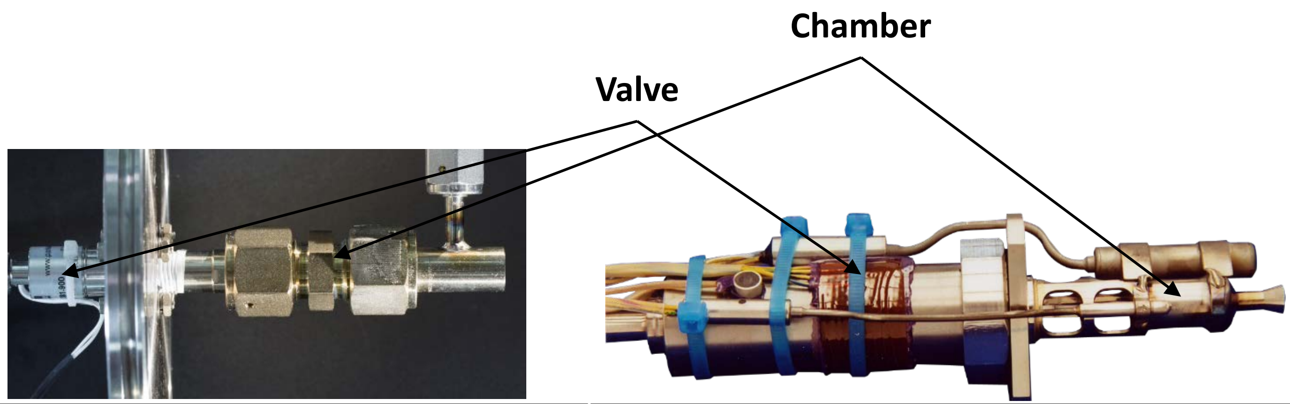
- Thrust Characteristics
- Propellant Flow Rate
- SWAP

- Global Effective Surface Reactivity
- Simplified Reaction Processes

- Surface Reactivity vs. Temperature
- Simplified, Multi-Step Kinetics.

The AFRL Micro-Reactor

Comparison with Flight-weight Thruster Testing



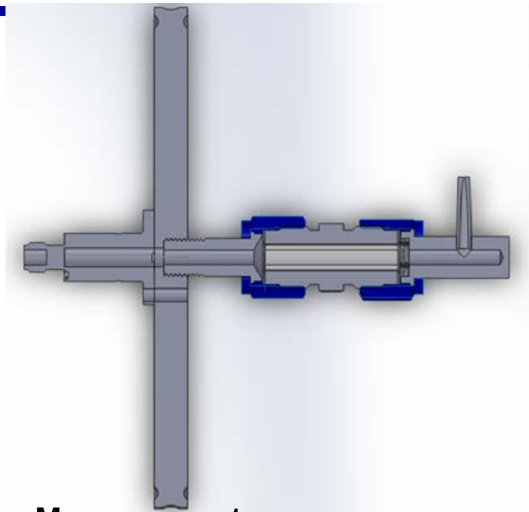
	Micro-Reactor Hardware	Flight Hardware
Cost Magnitude	$100 to $10,000	$100,000
Build Time	Days - Weeks	Months
Variation Support	All Companies	Single Company
Interchangeable Components	Full Replaceable	Welded
Diagnostic Access	Limited Access	Limited Access
Representative Thermal Environment	Possible Fit	Full Environment

The AFRL Micro-Reactor

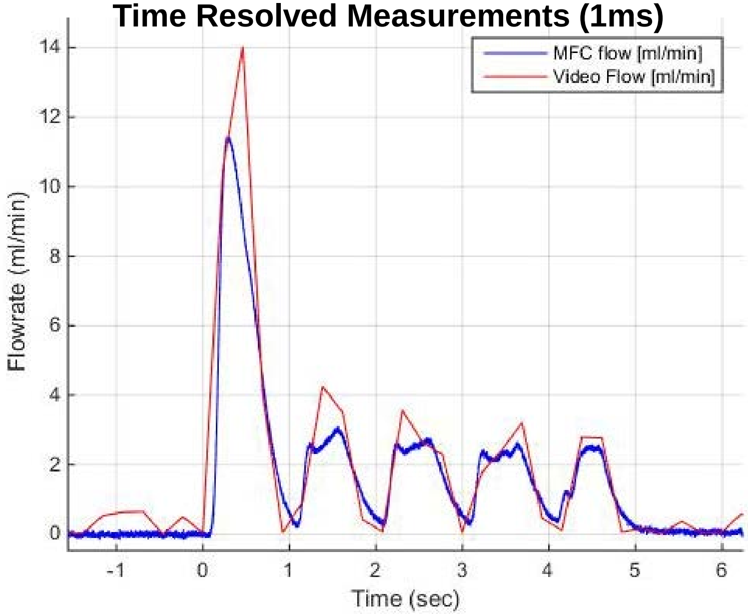
General Concept Description

A 1N Architecture for Testing AF-M315E and Related Ionic liquid Variants.

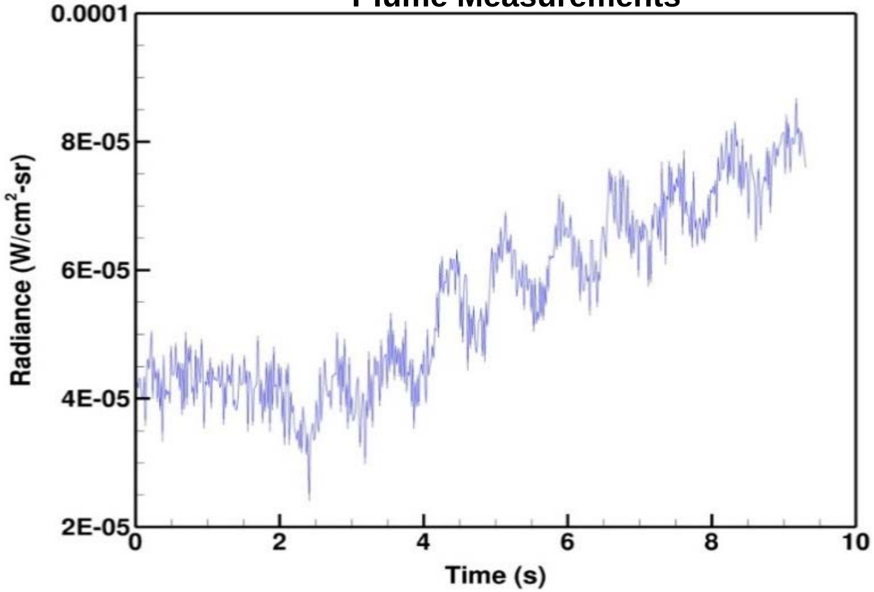
Variant	Practical Lifetime	Cost Estimate	Application	Availability
Short	10 s	$100s	Reactivity, Single Point Performance	✓ FY16 Q4
Medium	10 min	$1,000s	General Performance, Component Sensitivity, Diagnostic Validation, Washout Studies	FY17 Q2
Long	10 hr	$10,000s	Detailed Performance Scans, Degradation/Lifetime	FY17 Q4



Time Resolved Measurements (1ms)

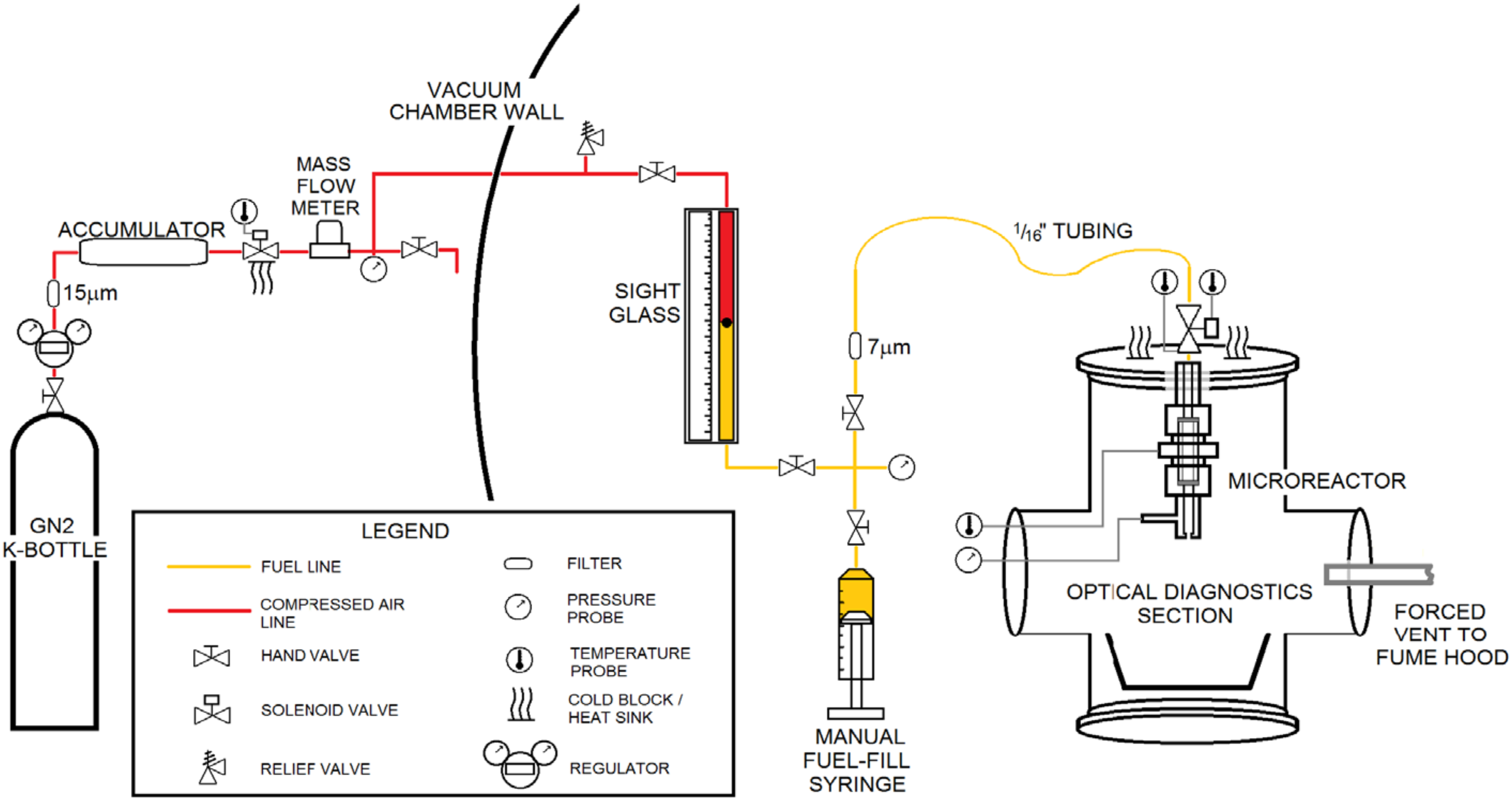


Plume Measurements



AFRL Micro-Reactor Feed System

General Schematic

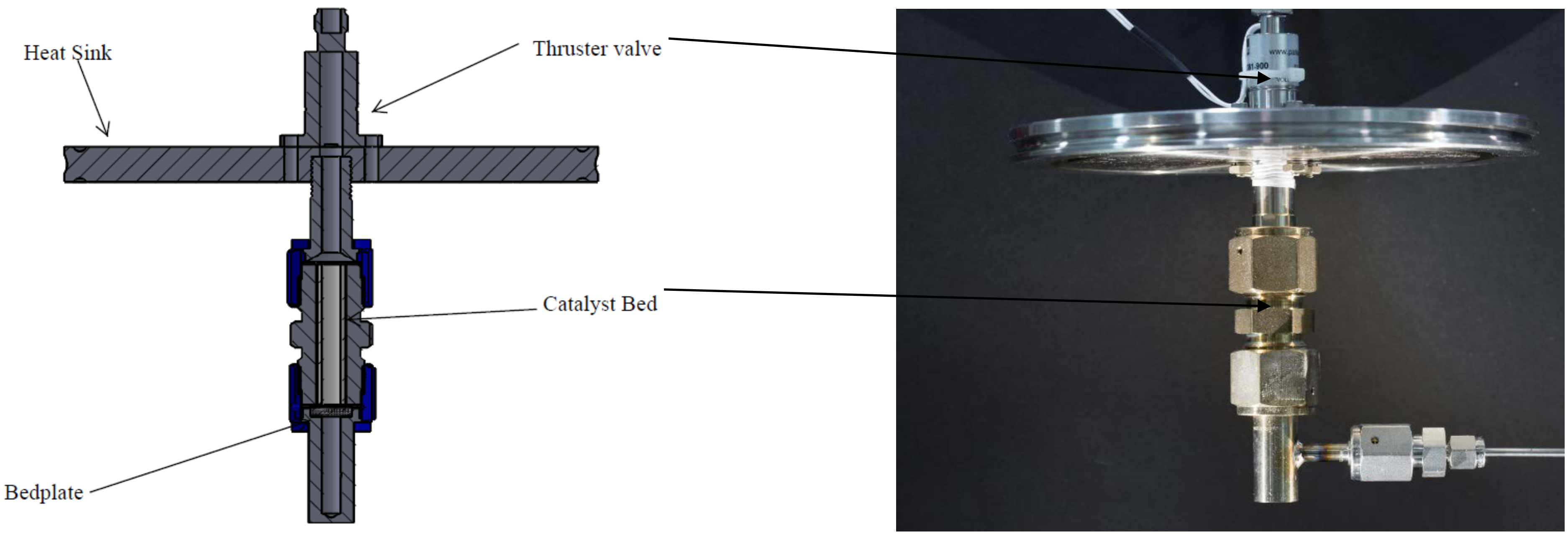


- Sight glass holds 12cc over 18" height.
  - 2560 pixel resolution along sight glass axis

The AFRL Micro-Reactor Family

Short-Life (10s) Version

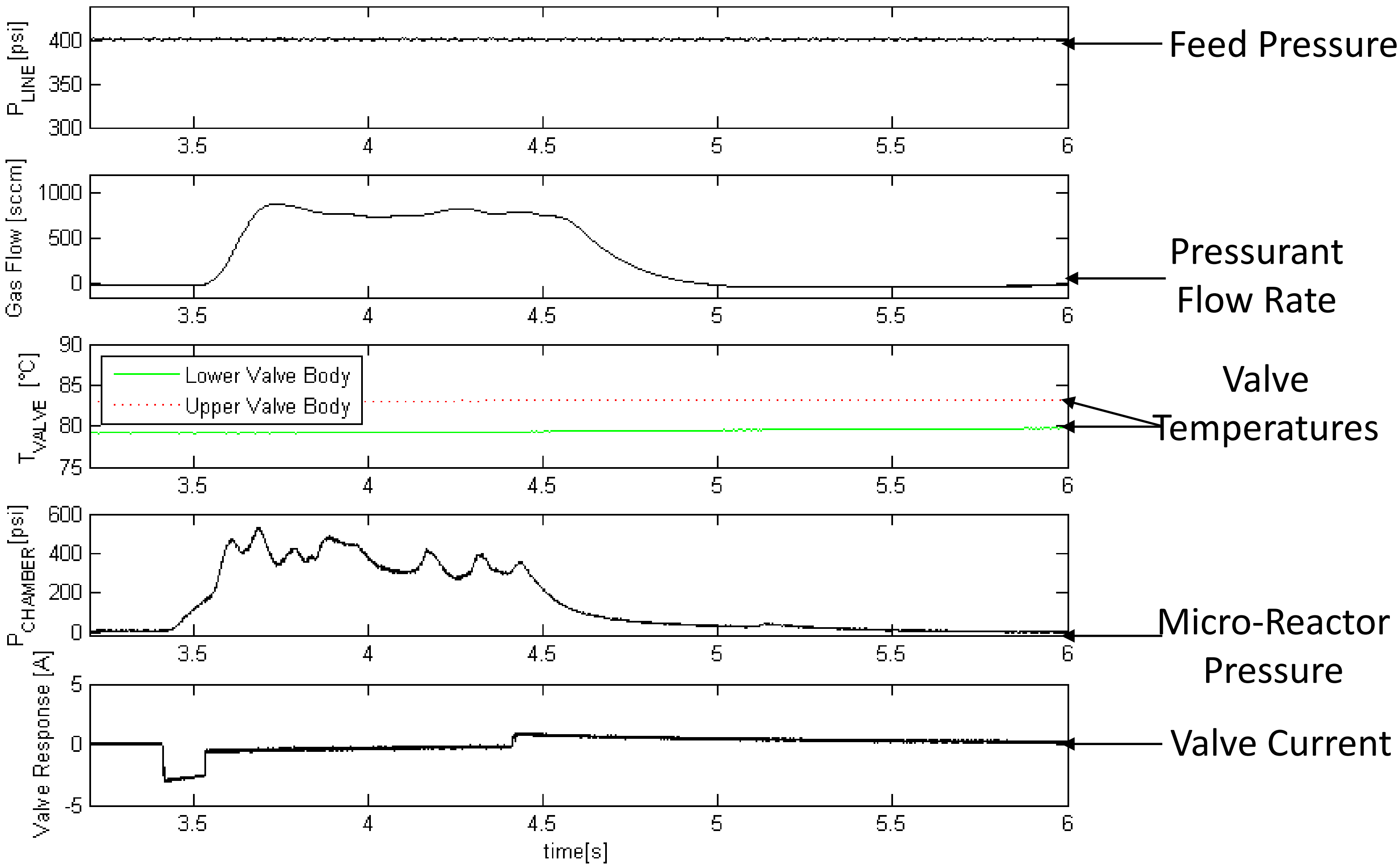
- Primarily composed of commercial stainless steel Swagelok components.
- Heavy-weight (significant thermal mass) vs. flight systems.
- Exit orifice (no real nozzle)
- Preheated using high temperature heat tape.
- Applications: catalyst/propellant reactivity, single point performance, rapid aging studies.



- ✓ Simple, Cost-Effective (< $1,000) Design Enabling Quick Look Tests.
- ✓ 10s of “Scientific Life” Meeting Roughness and Repeatability Requirements (Fall, 2016).

Short Life (10s) Micro-Reactor

General Performance Measurements

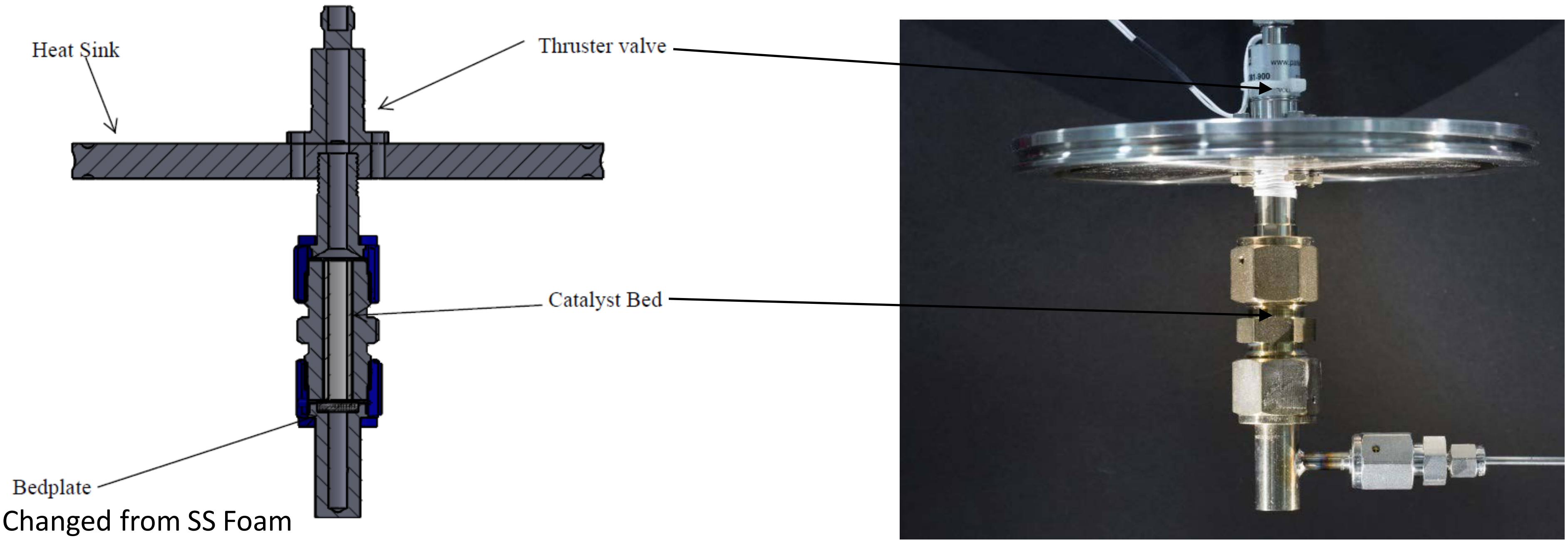


Note: Statistical Variations Very Similar to 10min Version and Are Shown There.

The AFRL Micro-Reactor Family

Medium-Life (10min) Version

- Very similar to short-life micro-reactor (only major change is bedplate).
- Same internal dimensions allowing direct comparison.
- Applications: general performance, component sensitivity, diagnostic validation, washout.



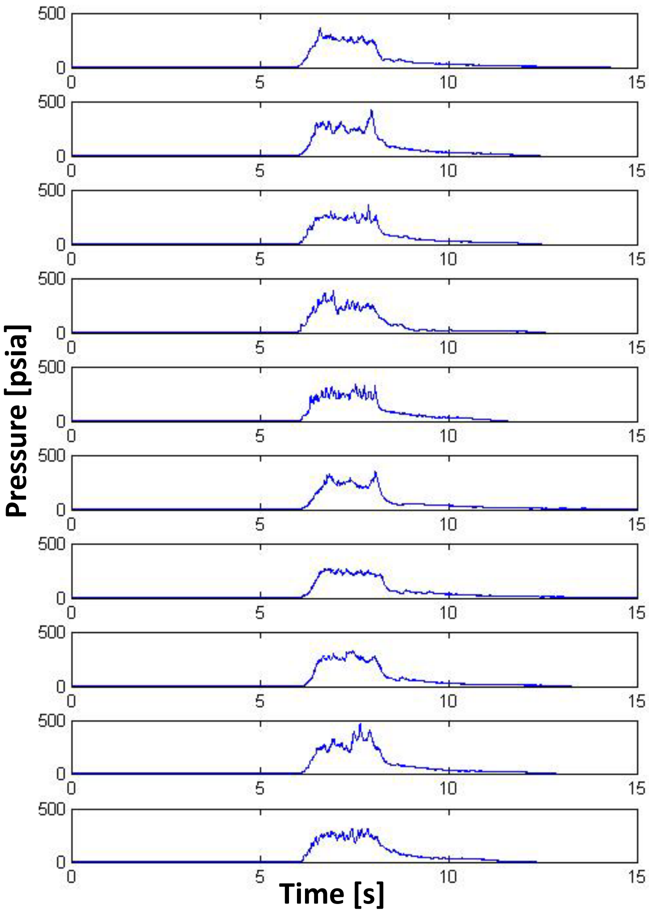
Changed from SS Foam to TZM Slotted Design

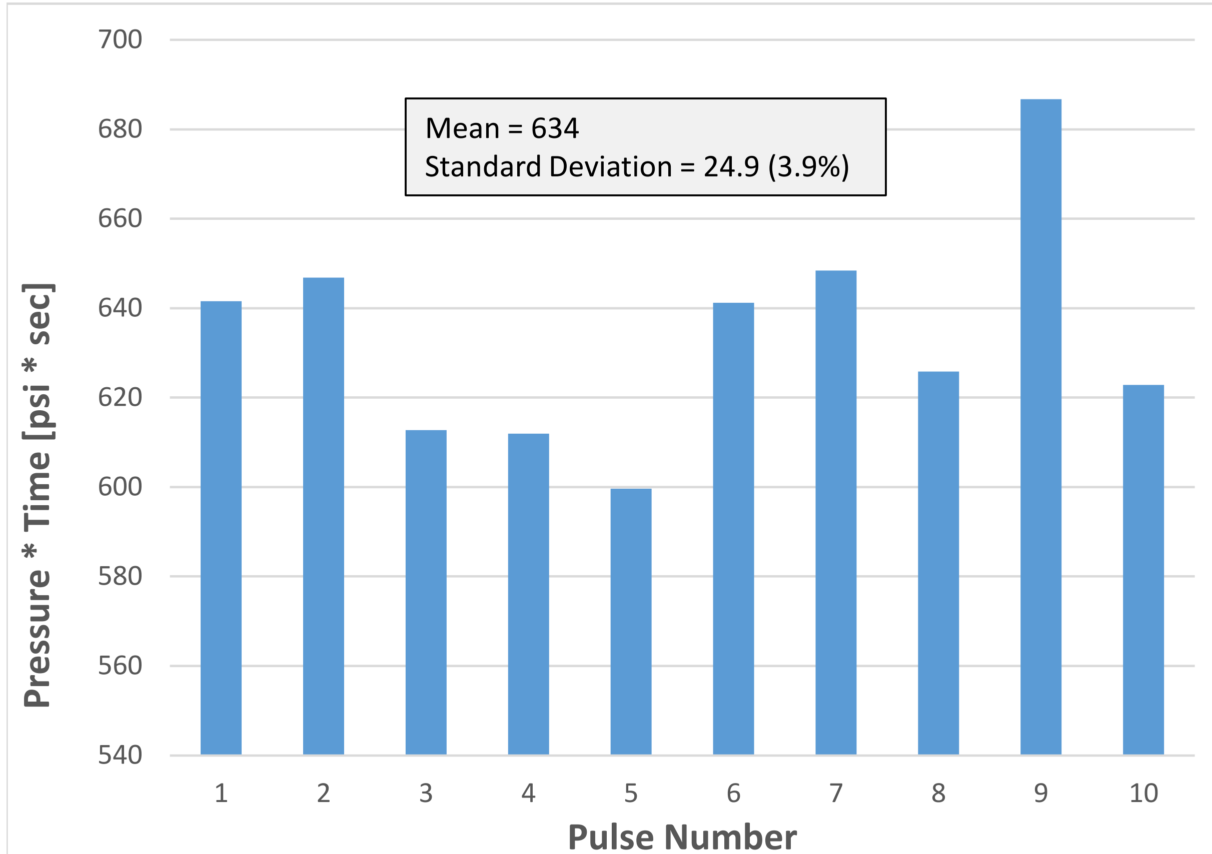
- ✓ Cost-Effective (< $10,000) Design Very Similar to Short-Life Version.
- ❑ 10min of "Scientific Life" Meeting Roughness and Repeatability Requirements (Ongoing).

Medium-Life (10min) Micro-Reactor

BOL Total Impulse Measurements

- Show shot-to-shot Variation of Integrated Pressure*Time for 10x Pulses (2s) at BOL.

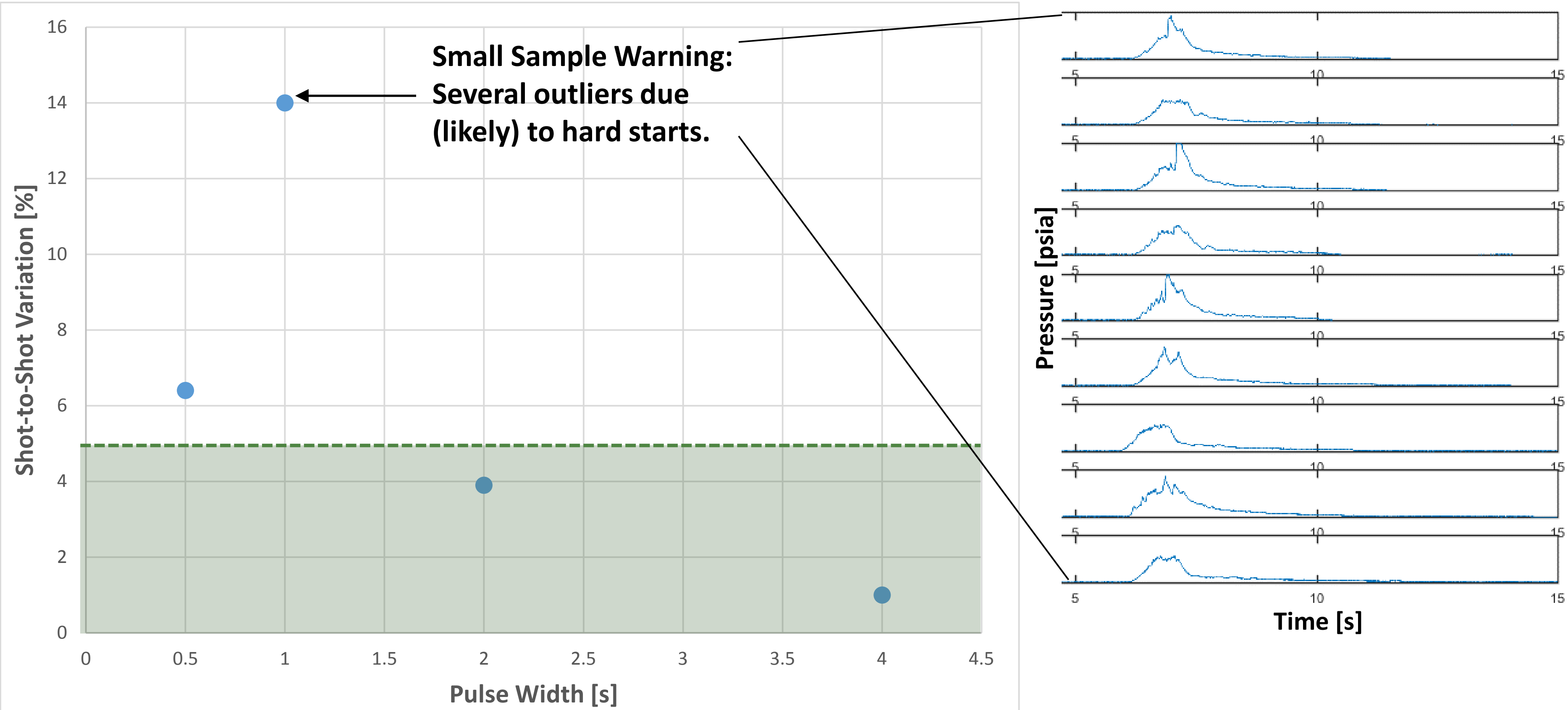




- Pressure Pulses Have Visible Differences.
- Impulse Repeatability Requirement Met at BOL for Medium (2s) Pulses.

Medium-Life (10min) Micro-Reactor

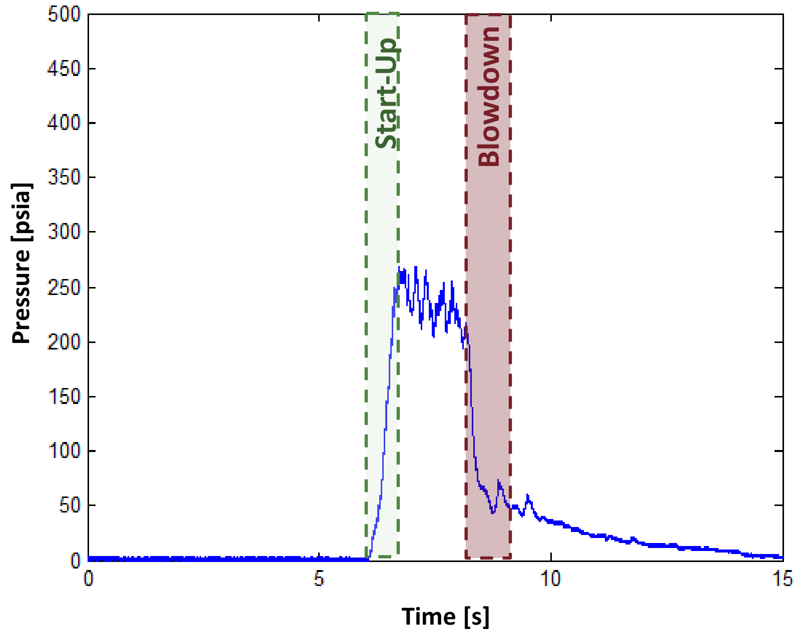
Repeatability vs Pulse Width

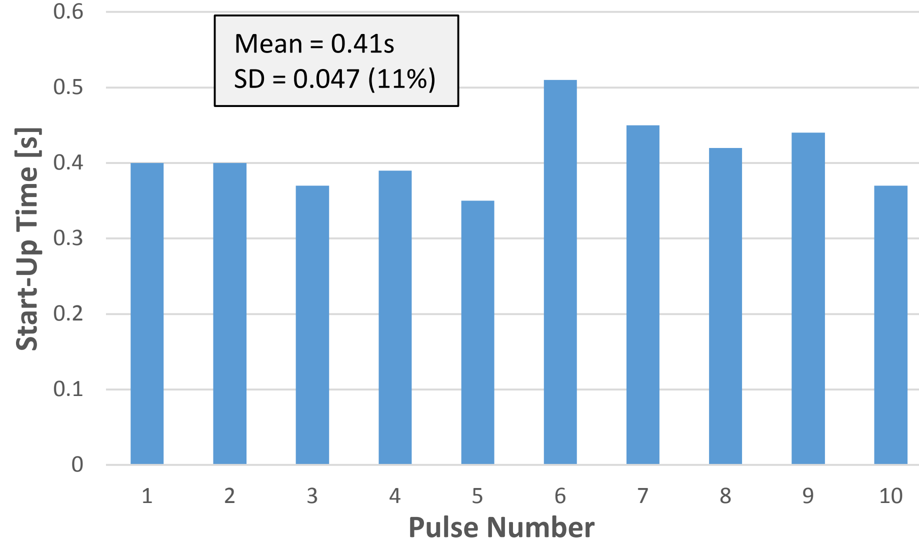


- 2s and 4s pulses meet variation requirements.
- Limited sample size (so far) and rough starts leads to large variations at 1s.
- Improved injectors and reduced inrush will further reduce variations.

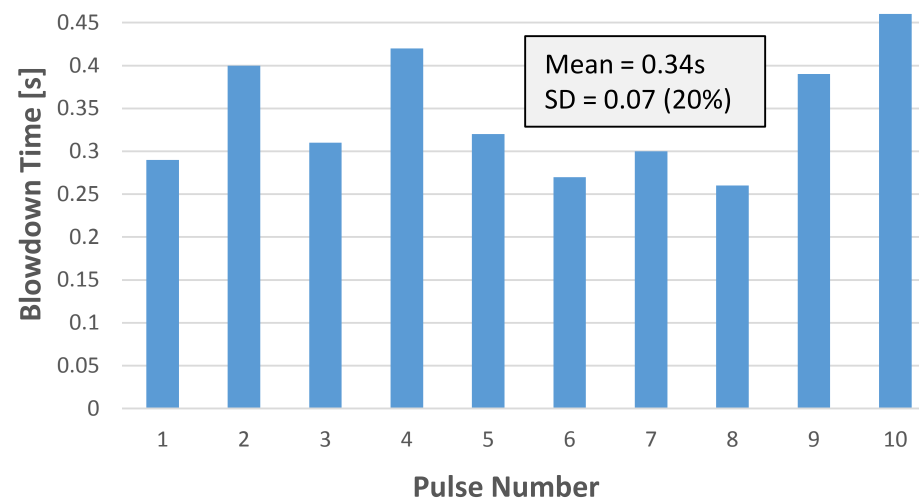
Medium-Life (10min) Micro-Reactor

Reactor Start-Up and Blowdown Times



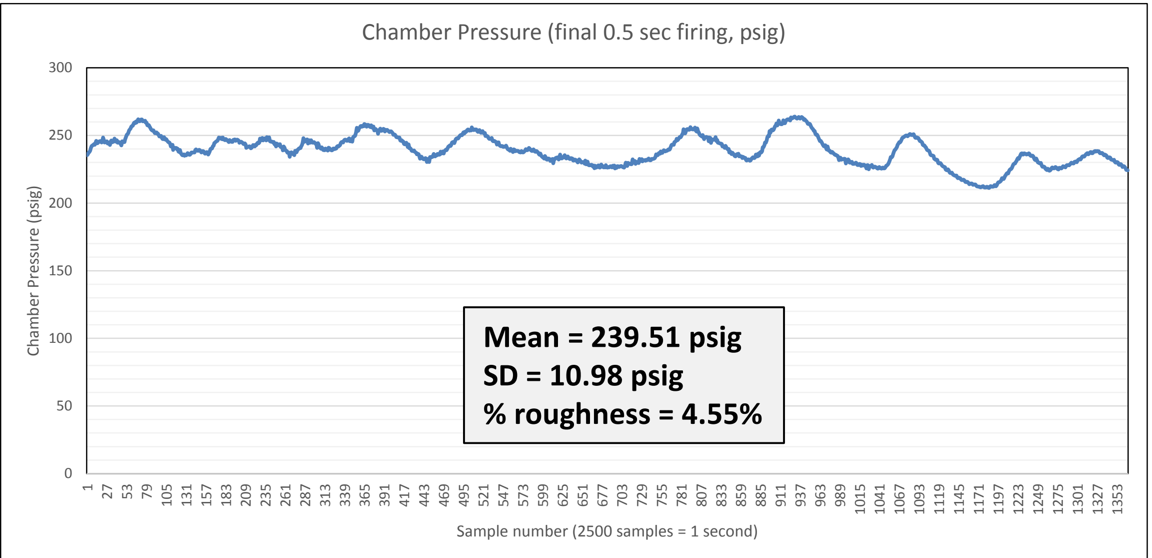


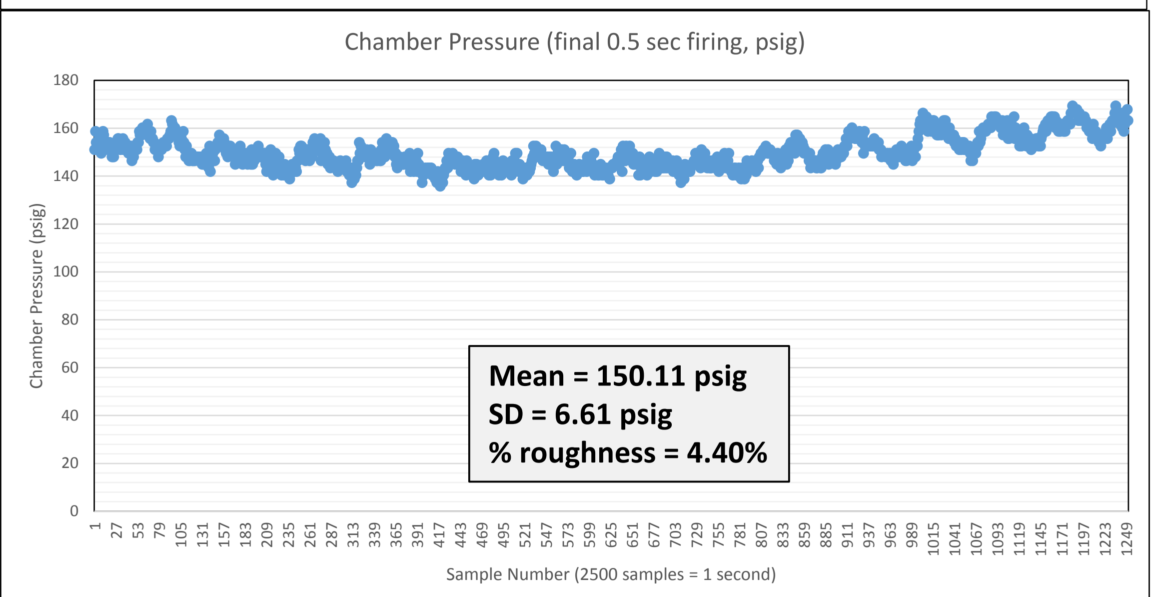
- Start-up and blowdown times both defined at time to achieve 1/e of pressure change.
- Both rise time and blowdown time variations exceed 10% limiting application of current design to longer pulses or more samples.



10min Micro-Reactor

Long-Pulse Chamber Pressure Roughness





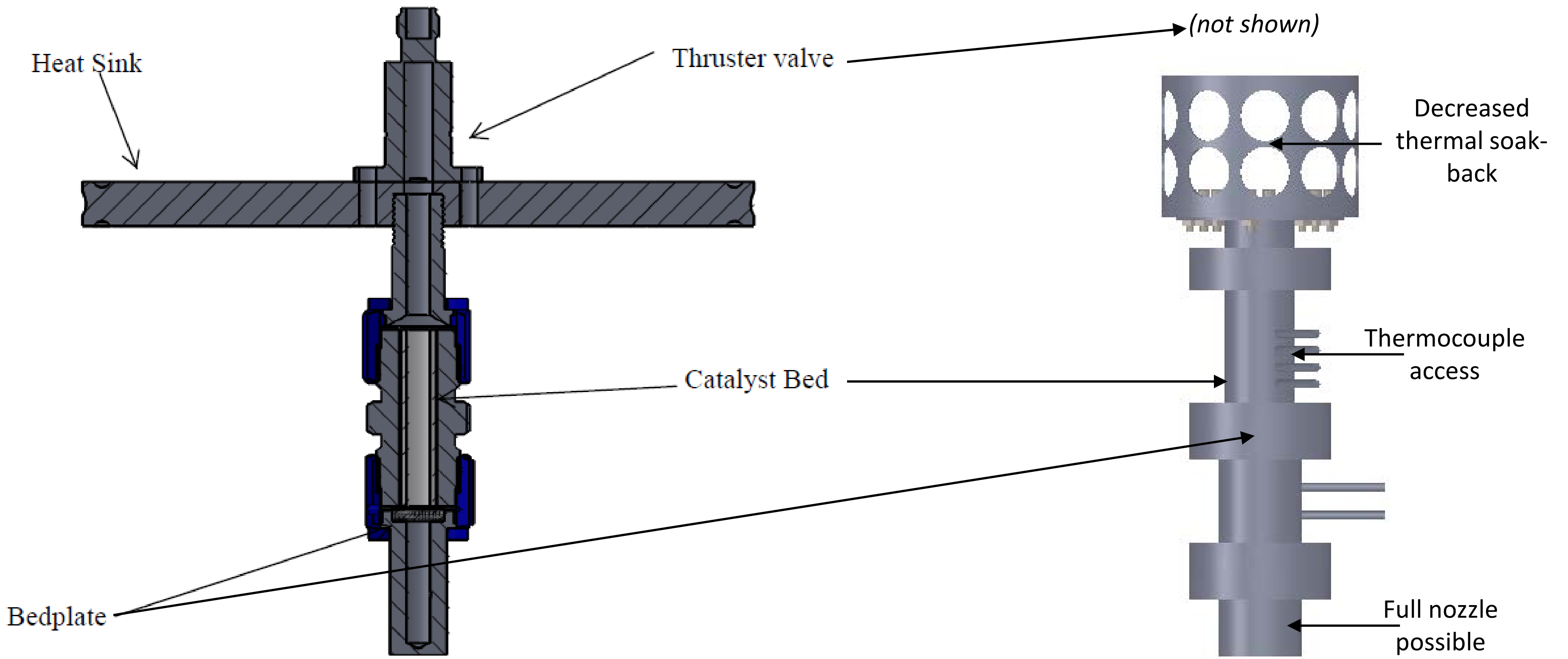
<u>1 Second Pulse</u>

- Mean, SD, and % roughness calculated over final 0.5 seconds of valve open time.
- Average roughness over testing lifetime is 4.5%.
- Adequate for performance testing, but improvements are sought.
- Future tests also explore longer and shorter time-scale variations.
- Reductions in roughness sought through improvements in injector.

The AFRL Micro-Reactor Family

Long-Life (10hr) Version - Notional

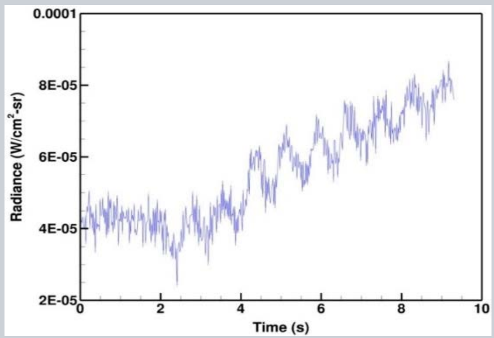
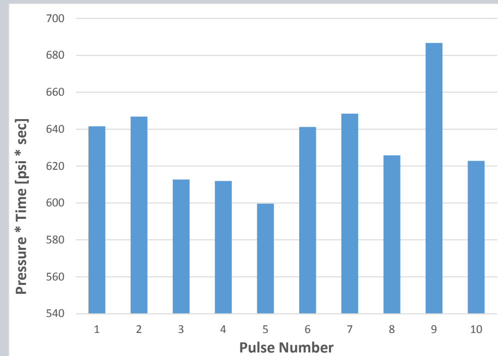
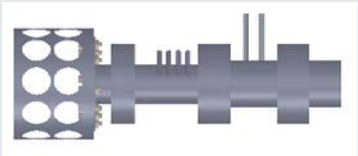
- Still bolt-together, heavy-weight, same internal geometry.
- Fully machined version using flight materials expected.
- Reduced thermal soak-back configuration expected.
- Applications: detailed performance scans, degradation/lifetime.



Design On Hold Until Completion of Medium-Life Micro-Reactor Validation.

Upcoming Micro-Reactor Testing

Short-Term Test Plans

	10s μReactor	10min μReactor	10hr μReactor
Winter 2017	- FTIR (Absorption) Demo. 	- Initial Validation Tests 	
Spring 2017		- Fundamental Injector Tests - Fundamental Thermal Mass Tests	- Complete Initial Design
Summer 2017	- High-Speed (1kHz) Flow Rate Measurement Demonstration	- Fundamental Washout Tests	
Fall 2017	- LIBS Demonstration - DLAS Demonstration	- Fundamental Reactor Tests 	- Complete Initial Assembly 

Summary

- In-Space Propulsion Requirements → Family of Monopropellant μReactors.
  - *Compare Variety of Reactor Types.*
  - *Investigate Thruster Components Individually.*
  - *Support Diagnostics Development.*
  - *Support Systems Level and Multi-Physics Level Model Development.*
- 10s Lifetime μReactor Has Been Validated for Long Pulses (≥ 2s).
- 10min Lifetime μReactor Undergoing Validation (2min/10min).
- 10hr Lifetime μReactor Undergoing Design Studies.
- High-Speed and Plume Diagnostics Ready for Implementation.
- Internal Diagnostics Undergoing Initial Development.
- Upcoming μReactor Component Tests to Focus on Injector and Reactor.
- Upcoming μReactor Operational Tests to Focus on Washout.