HICKAM

Spring Final Review

Advisor: Professor Francisco Lopez Jimenez

Olagappan Chidambaram
Haleigh Flaherty
Kirill Kravchuk
Nate O'Neill

Angel Ortega
Brian Ortiz
Tommy Pestolesi
Gerardo Pulido

Dylan Reed
Jaquelyn Romano
Sage Sherman
Savant Suykerbuyk

Customer: Derek Lerner with Orbital ATK

Agenda

- Project Overview
- System Design
- Test Overview
- Test Results
- Systems Engineering
- Project Management

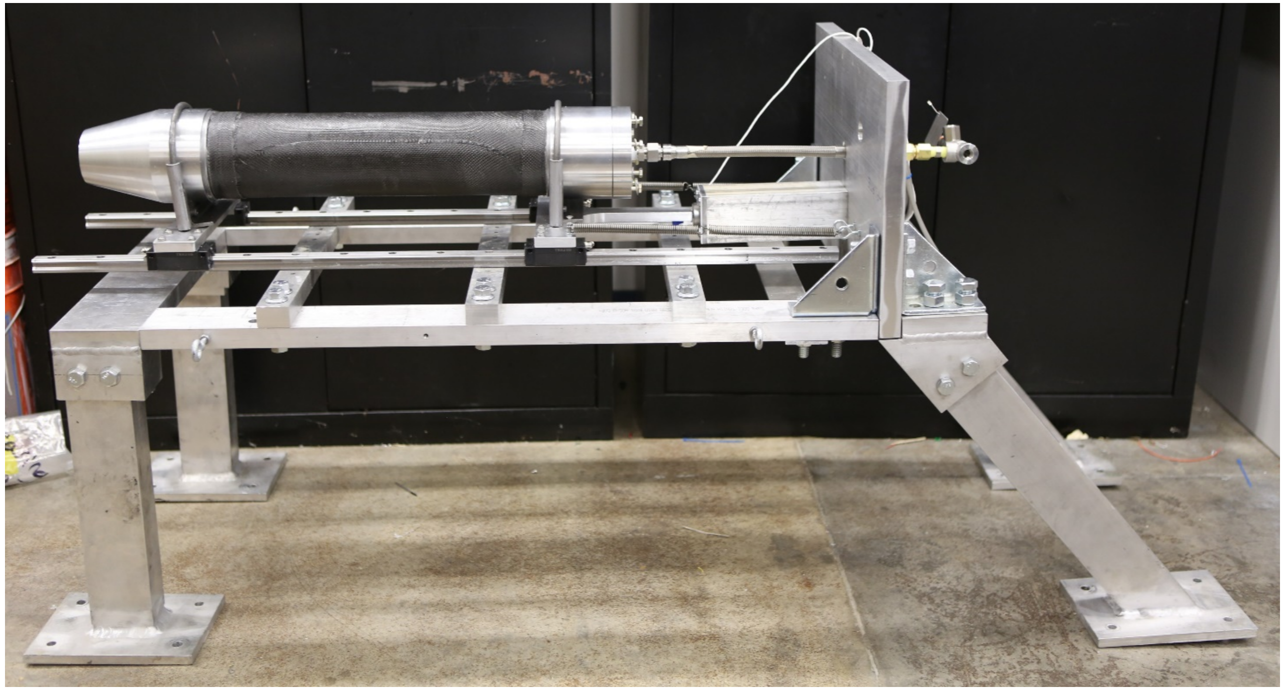
Setting up for the hot fire test

Project Overview

The goal of project HICKAM (**H**ybrid-rocket **I**nformation-**C**ollection, **K**nowledgebase and **A**nalysis **M**odule) is to design and manufacture a modular, compact, and portable testing platform for hybrid rocket engines.

Customer vision:

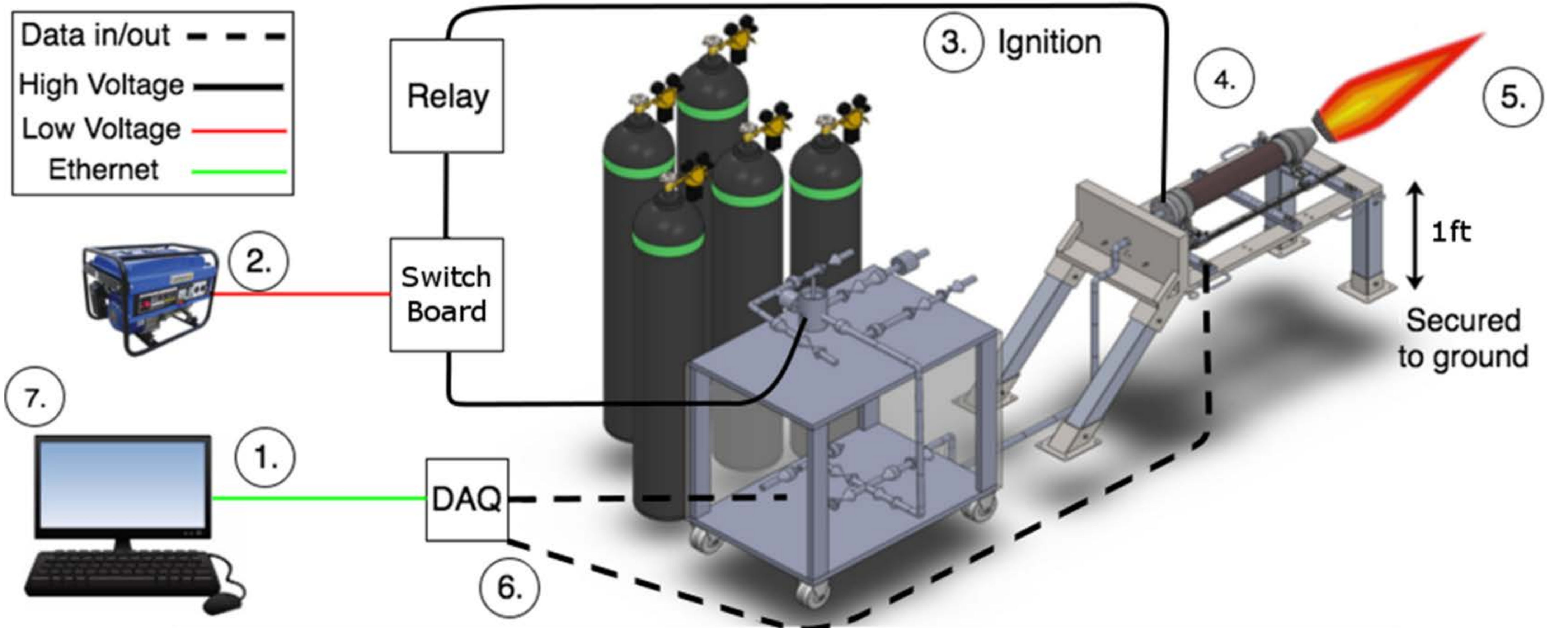
- A plug-and-play test stand for future hybrid rocket projects
- Donated to the department for future rocket project use



Levels of Success

Requirements	Mission Goals	Analysis Items
Level 1 COMPLETED	Successful test of test stand using simulation of loads	Measure thrust (delay, duration, and maximum), total impulse, mass of rocket engine
Level 2 COMPLETED	Successful static cold flow test	Measure nozzle temperature, combustion chamber pressure
Level 3	Successful static hot fire test PARTIAL	Measure of oxidizer flow rate, specific impulse COMPLETED

Hybrid-rocket Information-Collection, Knowledgebase and Analysis Module (HICKAM)



Step 1 - LabVIEW is engaged through USB cable
Step 2 - Low voltage engages relay
Step 3 - High voltage starts ignition
Step 4 - Safety: Check for ignition or start hang-fire/mis-fire procedure
Step 5 - Rocket burns for approximately 20 seconds
Step 6 - DAQ collects data from sensors and saves it to memory
Step 7 - Model is used to validate data and specifications for engine is created

Hybrid-rocket Information-Collection, Knowledgebase and Analysis Module (HICKAM)

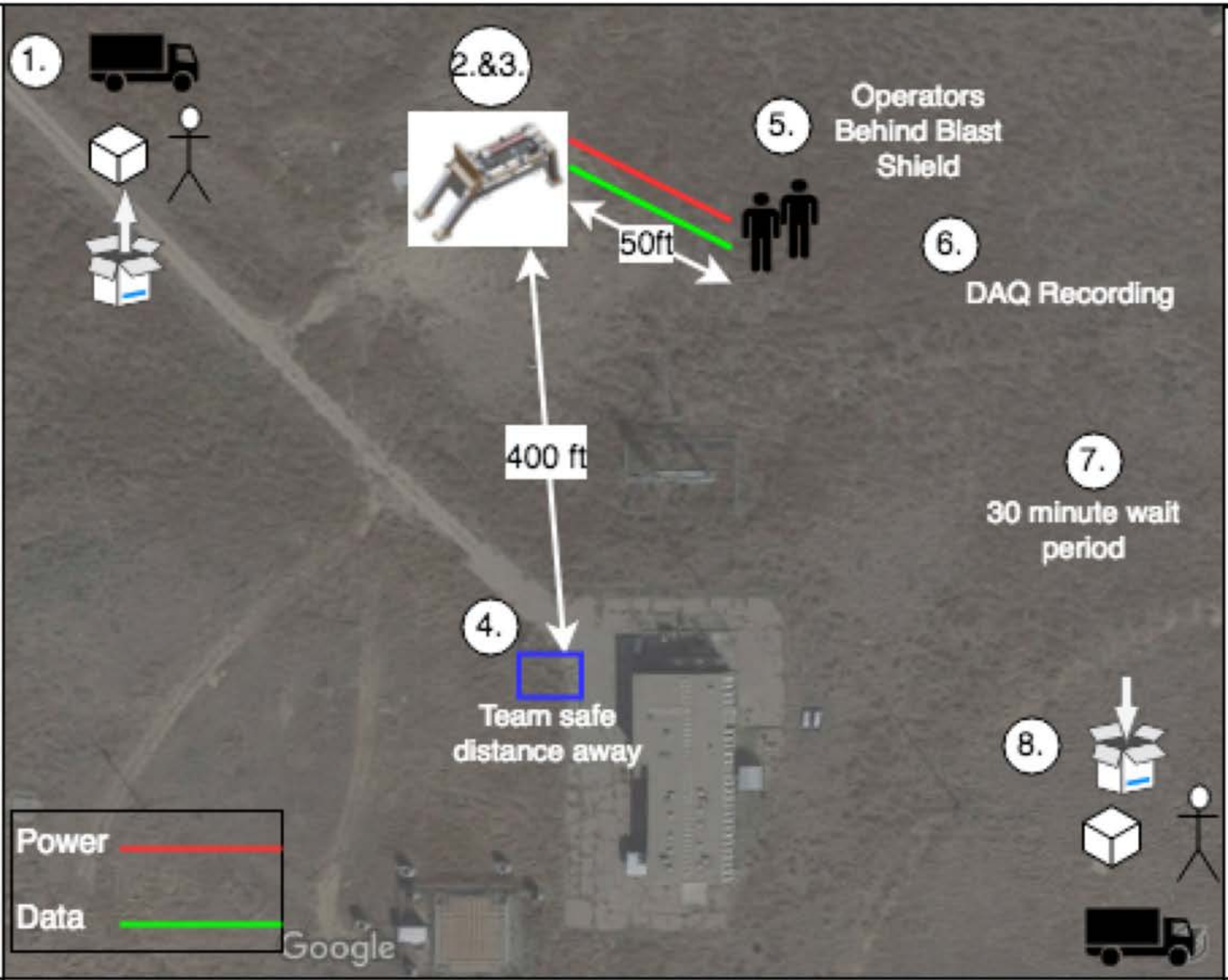
Pre - Test

Step 1 - Transport, unbox, and set up HICKAM at chosen test facility. Secure it to the ground

Step 2 - Integrate test article (rocket engine) to HICKAM

Step 3 - Check system for proper connections, power, and proper valve position

Step 4 - Safety check: check pressures, fail safe procedures, team behind bunker



Post - Test

Step 8 - Disassemble, box, and transport HICKAM

Step 9 - Within 72 hours of PRE-Test start, compile specifications sheet for test article

ASEN 4028: Des Practicum

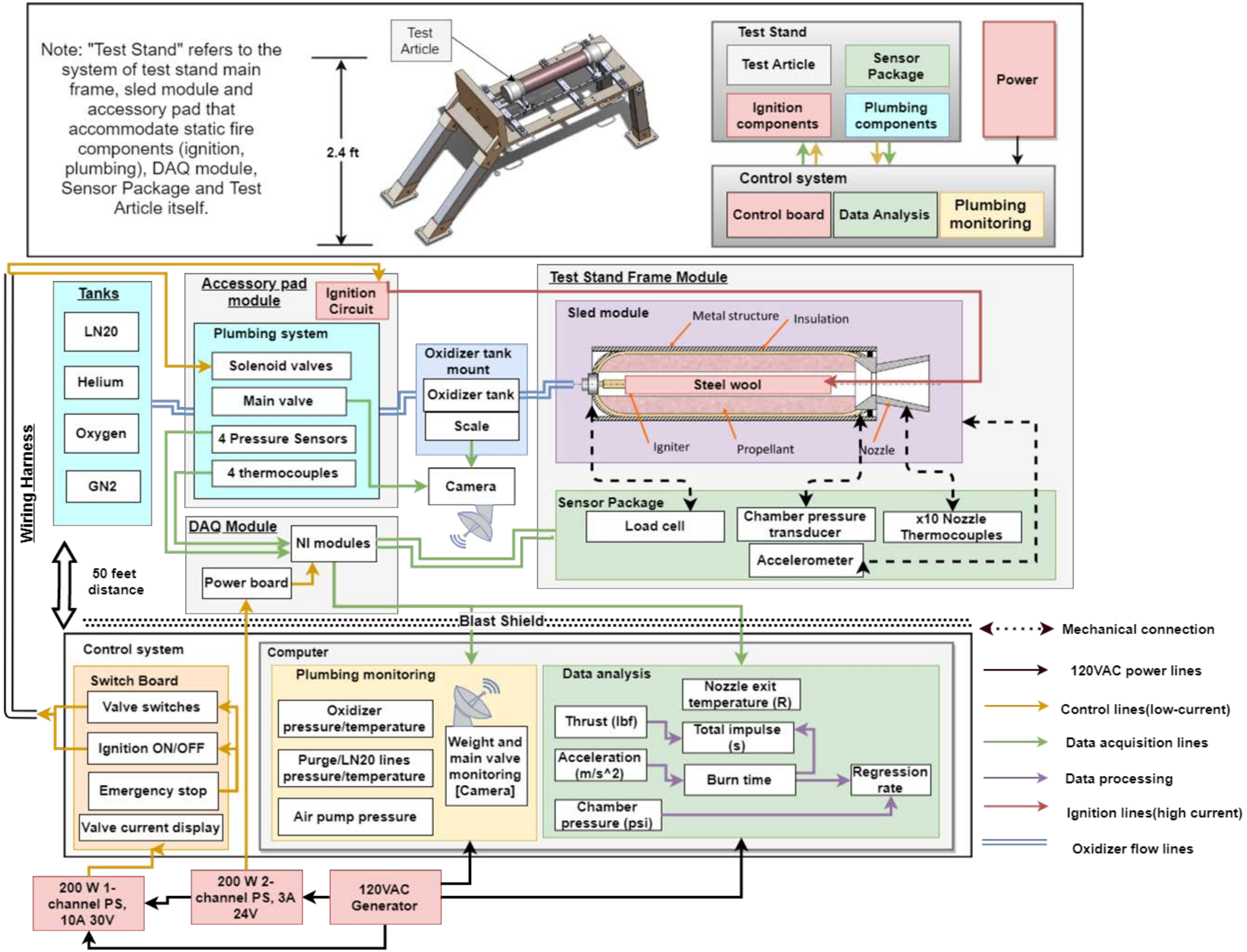
Test

Step 5 - Command to engage DAQ to start recording data, and initiate rocket ignition
Step 6 - DAQ collects data for the 20 second approximate burn and saves it to memory
Step 7 - 30 minute wait time before approaching HICKAM to ensure safety

Spring 2018

System Design

FBD

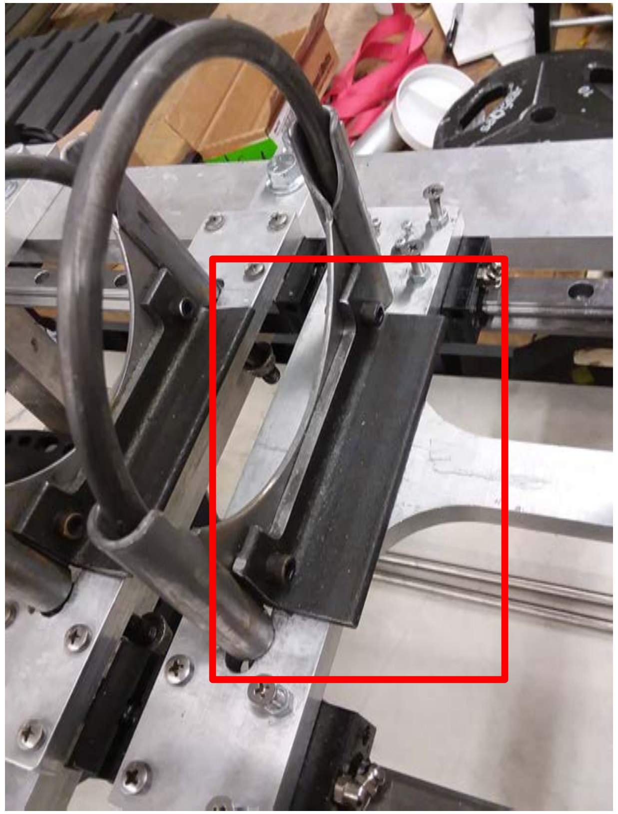


Note: "Test Stand" refers to the system of test stand main frame, sled module and accessory pad that accommodate static fire components (ignition, plumbing), DAQ module, Sensor Package and Test Article itself.
Test Article
2.4 ft
Test Stand
Test Article
Sensor Package
Ignition components
Plumbing components
Power
Control system
Control board
Data Analysis
Plumbing monitoring
Wiring Harness
Tanks
LN20
Helium
Oxygen
GN2
Accessory pad module
Ignition Circuit
Plumbing system
Solenoid valves
Main valve
4 Pressure Sensors
4 thermocouples
Oxidizer tank mount
Oxidizer tank
Scale
Camera
Test Stand Frame Module
Sled module
Metal structure
Insulation
Steel wool
Igniter
Propellant
Nozzle
Sensor Package
Load cell
Chamber pressure transducer
x10 Nozzle Thermocouples
Accelerometer
DAQ Module
NI modules
Power board
50 feet distance
Blast Shield
Control system
Switch Board
Valve switches
Ignition ON/OFF
Emergency stop
Valve current display
Computer
Plumbing monitoring
Oxidizer pressure/temperature
Purge/LN20 lines pressure/temperature
Air pump pressure
Weight and main valve monitoring [Camera]
Data analysis
Nozzle exit temperature (R)
Thrust (lbf)
Total impulse (s)
Acceleration (m/s^2)
Burn time
Regression rate
Chamber pressure (psi)
200 W 1-channel PS, 10A 30V
200 W 2-channel PS, 3A 24V
120VAC Generator
Mechanical connection
120VAC power lines
Control lines(low-current)
Data acquisition lines
Data processing
Ignition lines(high current)
Oxidizer flow lines

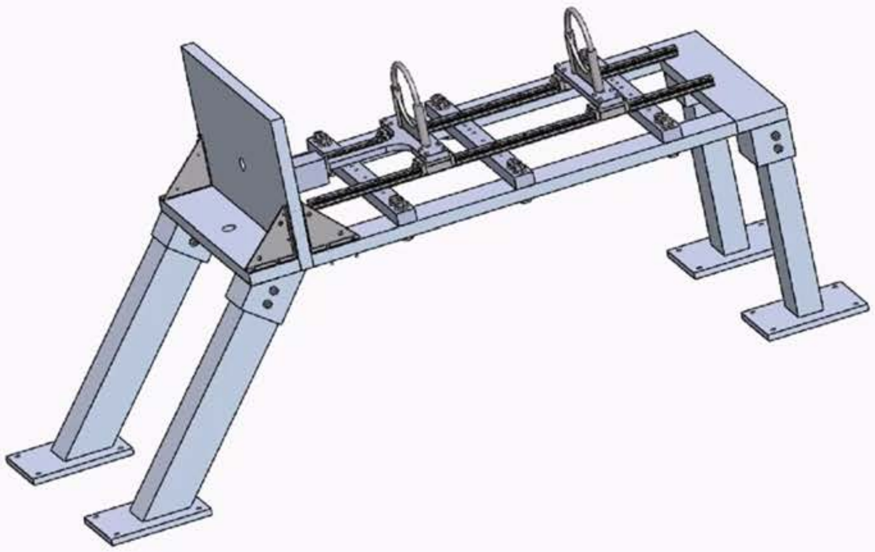
Test Stand Design Update

Major Changes:

- Added spacer block to accommodate plumbing and prevent melting of aft section by exhaust fumes
- Added holes in blast plate and horizontal front plate to allow sturdy mounting of plumbing and PT/TC sensors.
- Added steel L-brackets to U-Bolt brackets to reinforce and prevent bending (which led to slippage in static loads test).

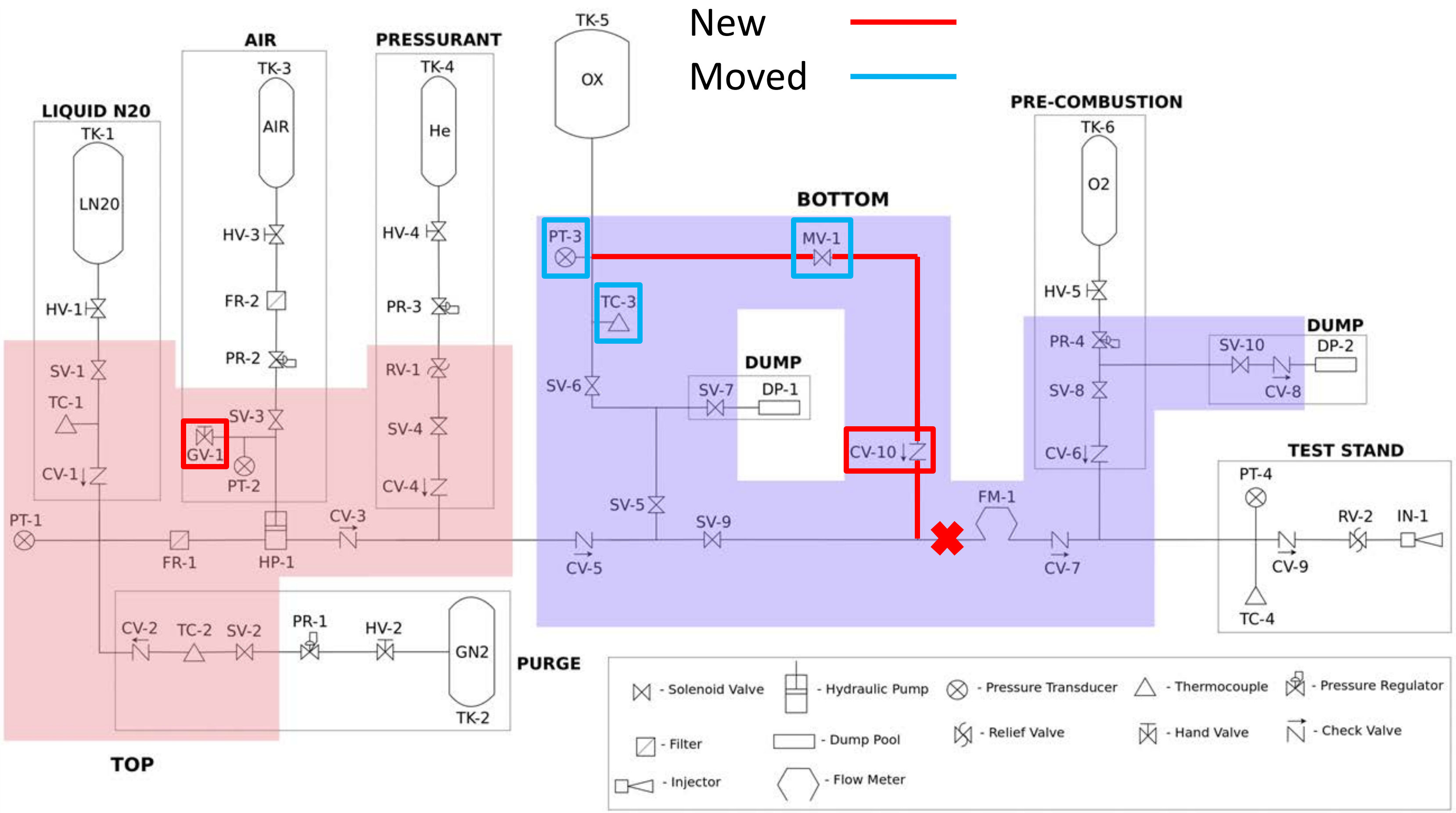


Test Stand Design Update



Feed System Design Update

- Main oxidizer feed:
  - Alternative route for oxidizer feed
  - MV-1 location change
  - Added CV-10
  - Moved TC-3 and PT-3
  - GV-1 added
  - Removed PR-5
- Reasons:
  - Provide required mass flow rate
  - Valve for new route
  - Prevent back flow
  - Closer to oxidizer tank
  - Relieve pressure in air hose
  - Did not require it

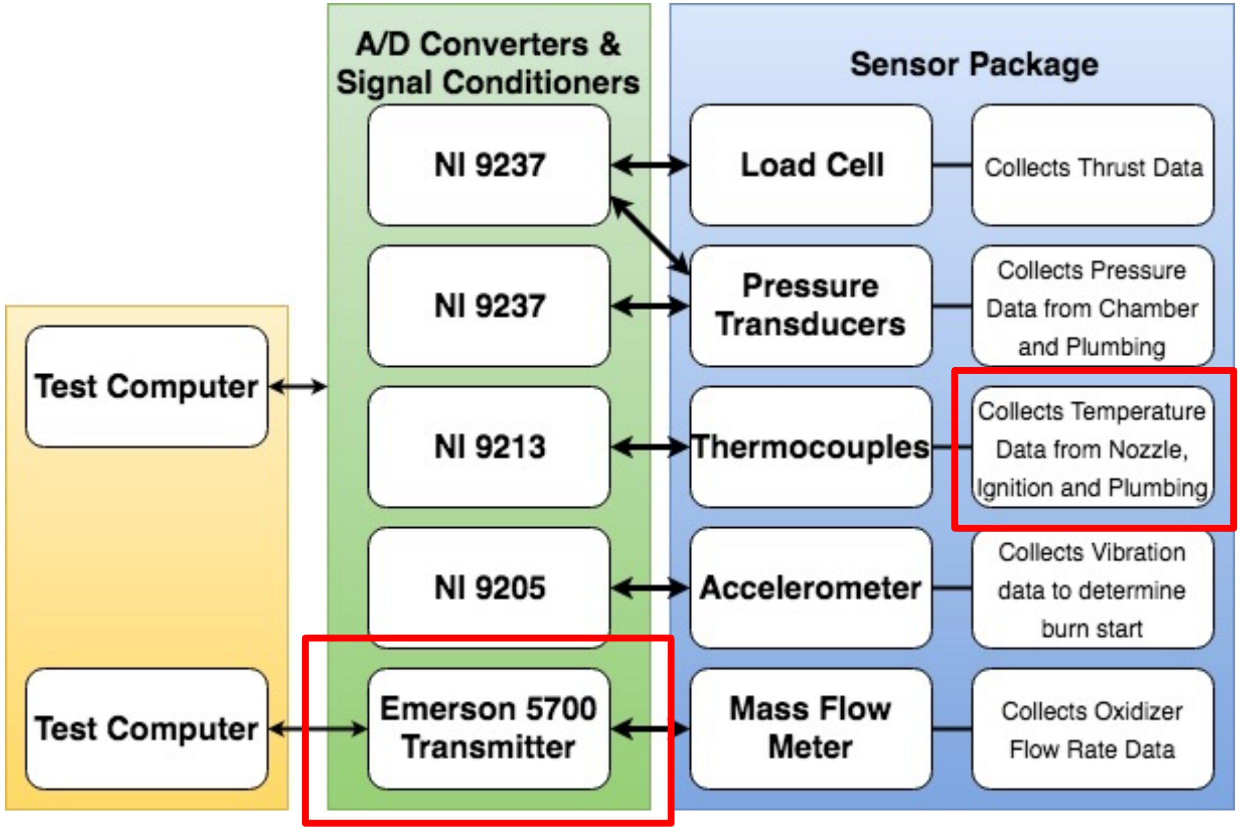


Oxidizer Tank Mount

Requirements:

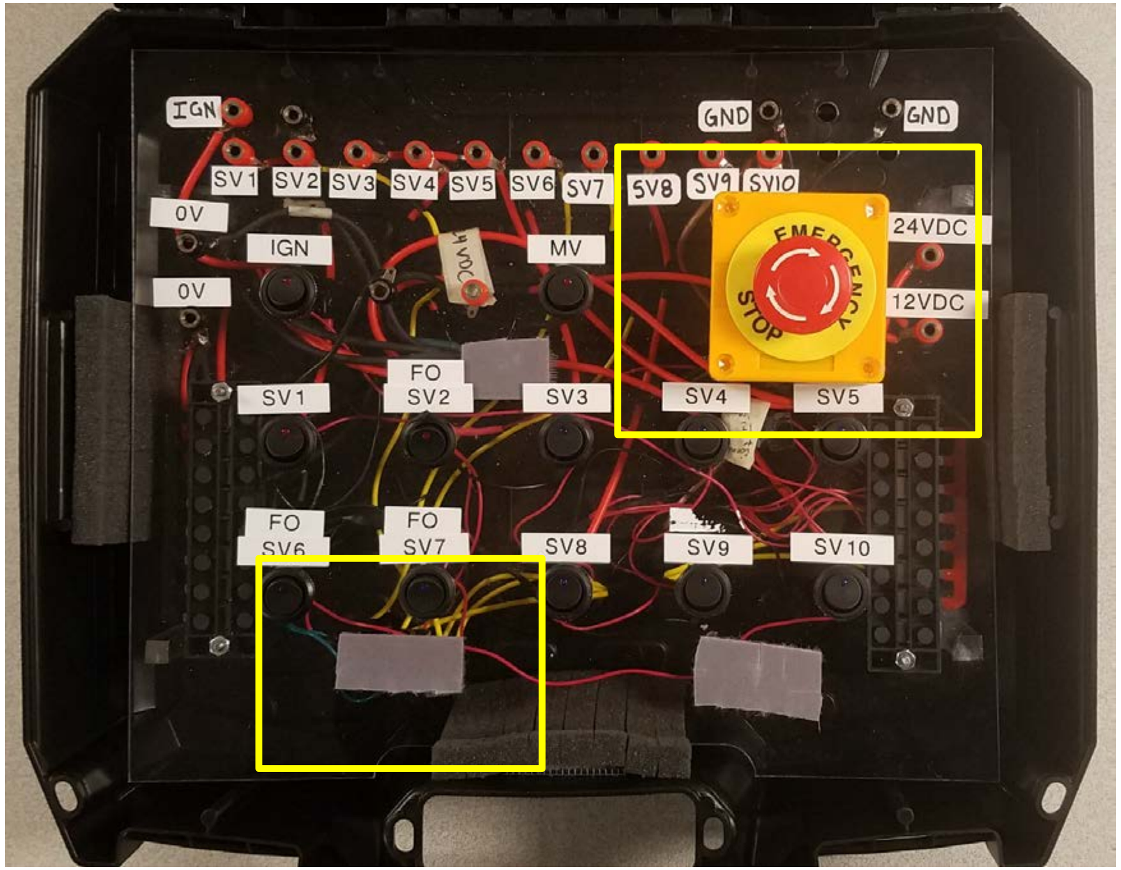
- Contain oxidizer tank from launching in the event of connection failure
- Protect oxidizer tank in the event of tip-over
- Allow limited movement to facilitate live weight measurement
- Allow adjustability to accommodate possible tanks of different sizes

DAQ Design Update



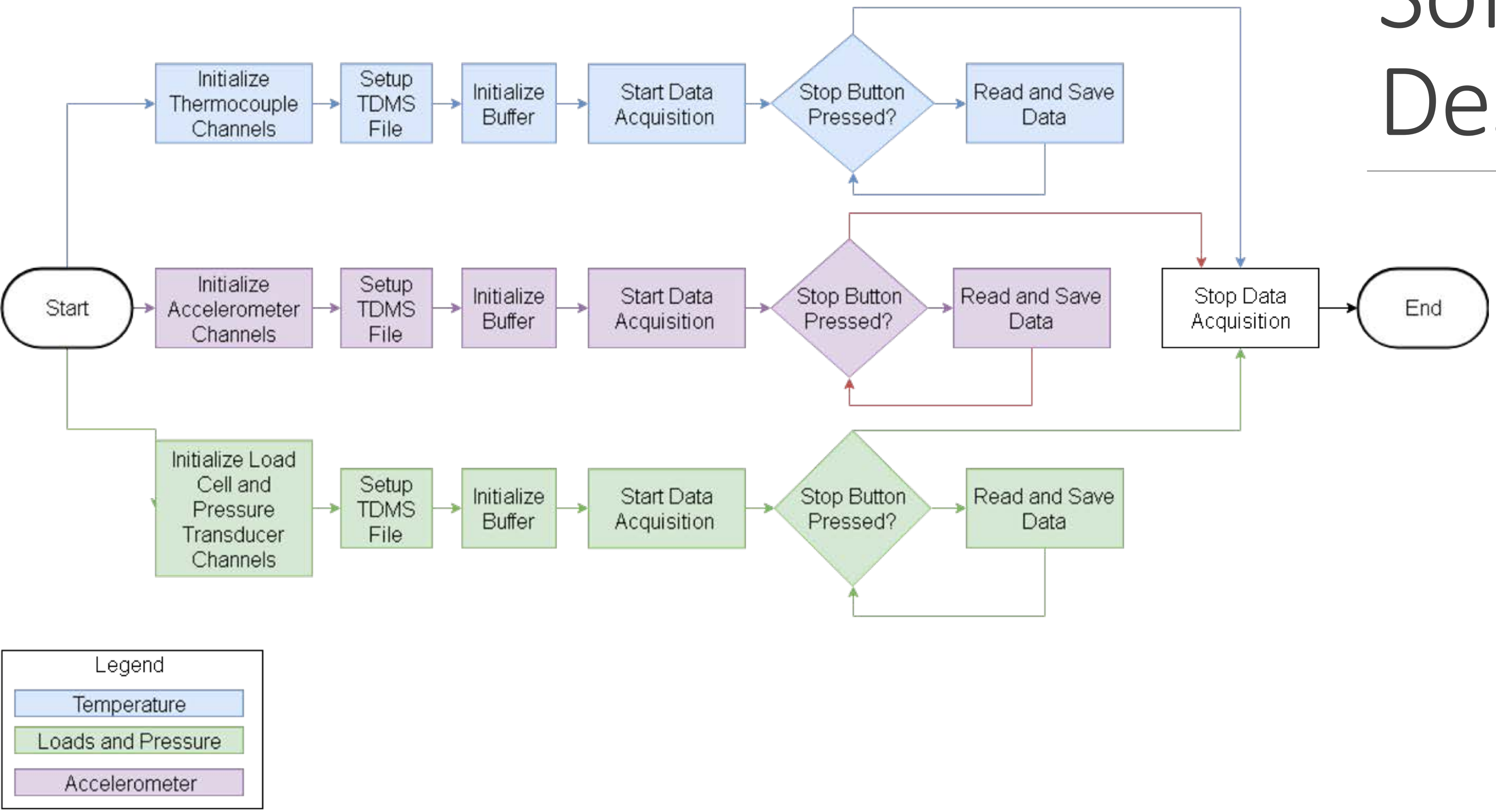
- Data Rate Requirements:
  - Accelerometer: 90 Hz
  - Pressure Transducers: 10Hz – 125Hz
  - Load Cell: 45 Hz
  - Mass Flow Meter: 7 Hz
  - Thermocouples: 10 Hz
- Major Changes:
  - Thermocouples removed from combustion chamber, placed on nozzle and inside rocket
- CPE's: Collection of data from sensors

Power Design Update



Switchboard Update:

- 3 Relays added for fail-open valve control
  - Fail closed valves required to operate as fail-open
- Rewiring of the stop switch for opening 2 fail-closed valves
- Power supply adjustment from 12 to 16 volts to account for length of wiring
  - Allows for valves to be actuated at nominal current draw

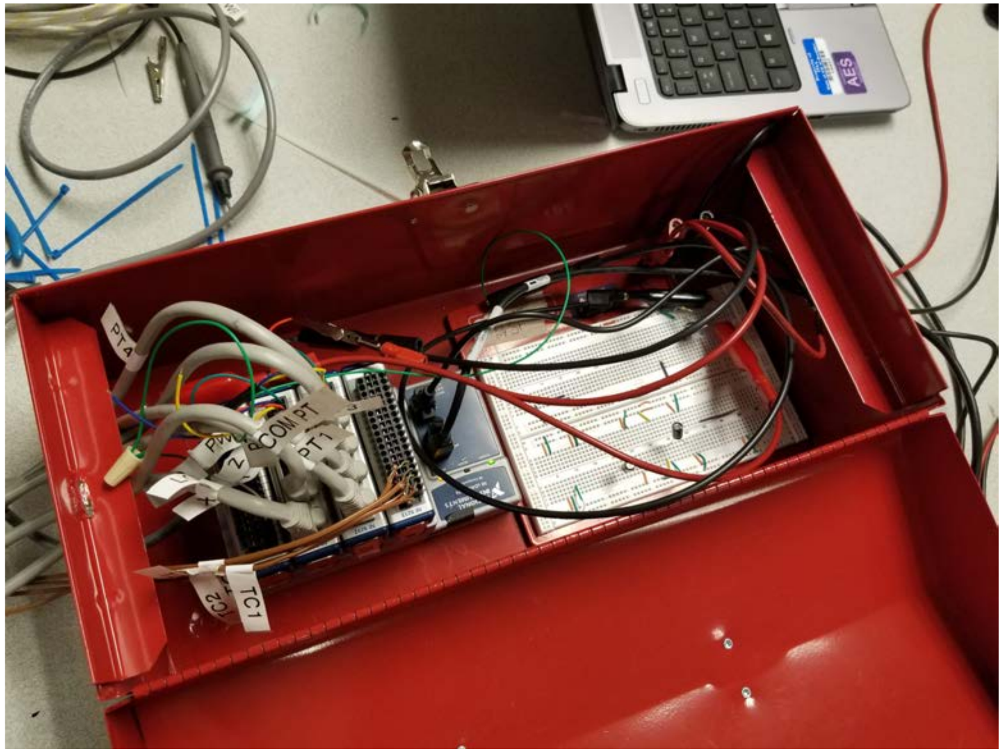


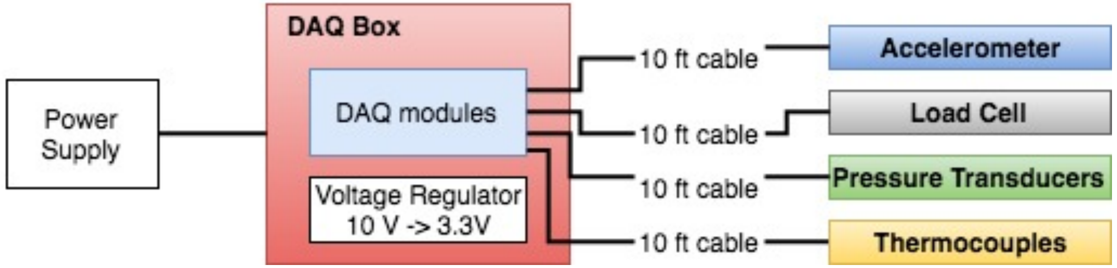
Software Design Update

- Deviated from original design due to problems with code inefficiency
- Reverted to original design after learning how to write directly to file, decreasing software delay
- This design proved to be the most efficient and allowed for optimal sampling rates to be maintained

Test Overview

DAQ System Test





Test Overview: Test software integration with Data Acquisition System by running software with all sensors for 2 hours.

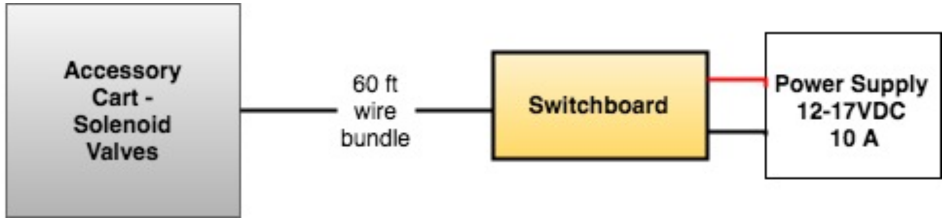
Test Purpose:

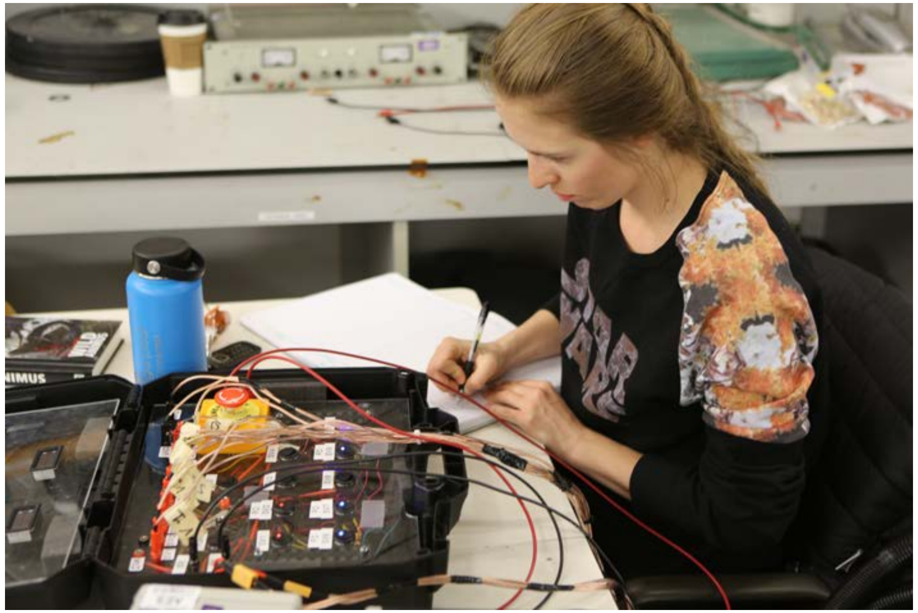
- Verify DAQ model sampling rates
- Verify all sensors functioning properly

Design Requirements Fulfilled:

- DR 4.1 - 4.2, 4.4 - 4.7

Valve Function Test





Test Overview:

- Test functionality of solenoid valve actuation with switchboard; choose power supply voltage for optimal current draw by the valves.

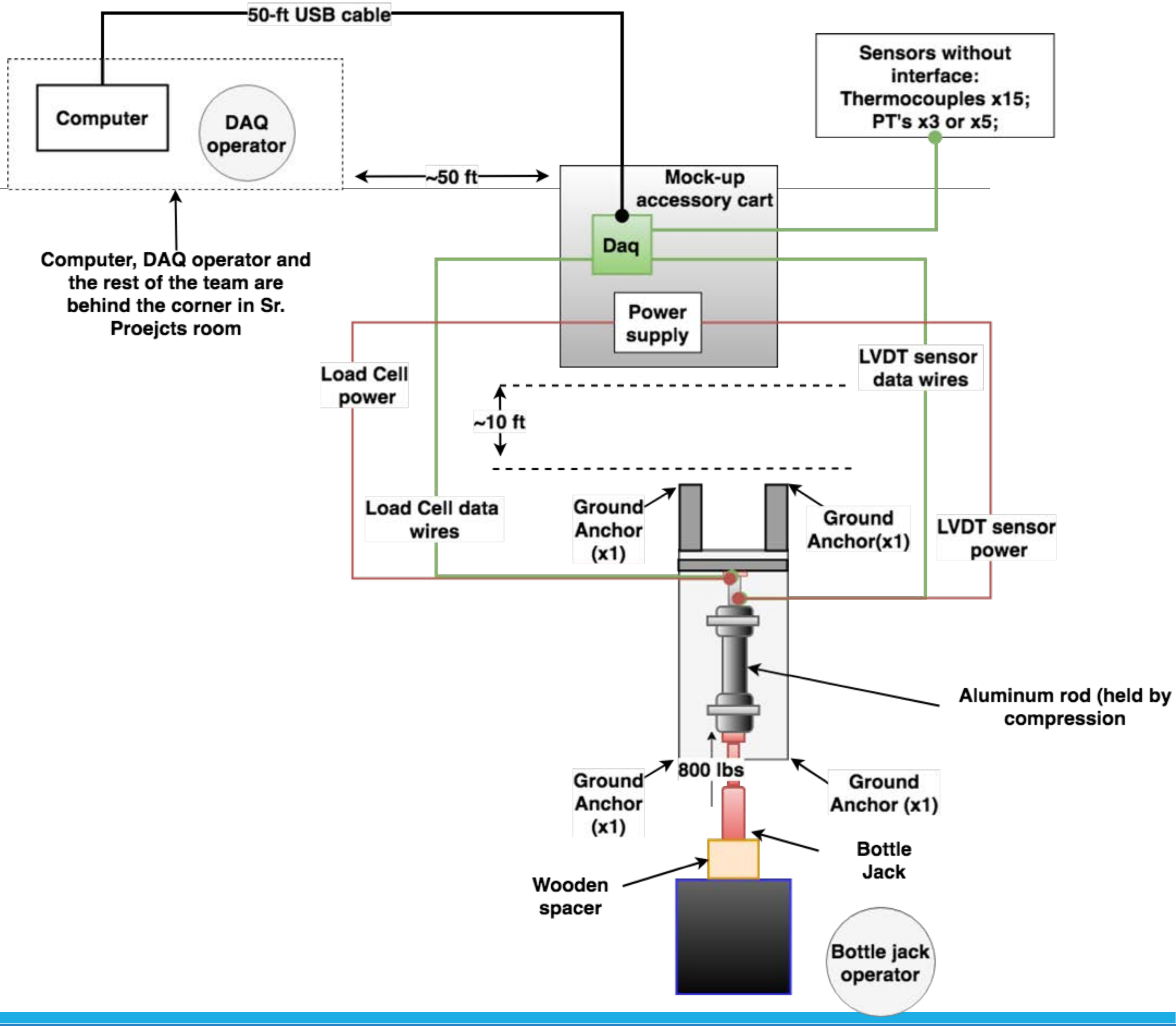
Test Purpose:

- Verify functional operation of feed system which allows for level 2 & 3 success
- Characterize current drawn by valves in different actuation configurations (DR 6.3.1 - 6.3.2)

Test performed in senior projects room

Simulated Loads Test

- Reduced to only loads test
  - Phase 2 – Nozzle Test cancelled due to time restraints.
  - Phase 3 – Chamber Pressure Test cancelled due to high risk to the rocket motor
- Phase 1 – Loads Test Overview: Collect data while using a bottle jack to simulate force on the load cell.
- Test Purpose:
  - Verify the rocket will not slip and push plate will not buckle under 850 lbf (DR 2.1-2.5)
  - Verify that off-axis loading at 17 degrees will not damage the rails (DR 2.1 - 2.5).
  - Verify sampling rates of the DAQ (DR 4.1-4.5).
  - Verify the push plate and rail deformation models.



Cold Flow Test

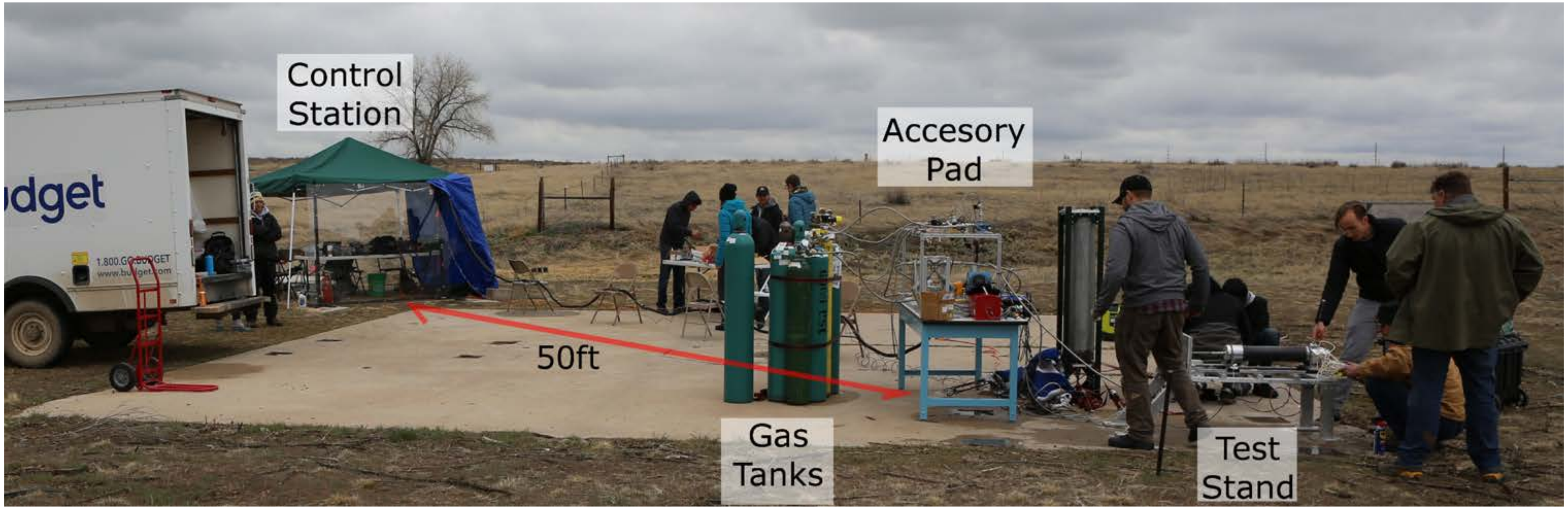
- Test Overview: Supply various testing gases and oxidizer analog (CO_2) into plumbing system up to rocket motor injector plate
- Test Purpose:
  - Verify plumbing system normal function (DR 6.1, 6.2, 6.3, 6.6, 6.8)
  - Identify and eliminate plumbing leaks
  - Verify emergency dump & purge systems to ensure safety at hot fire (DR 6.7)
- Test performed in Platteville, CO

Hot Fire Test

Test Overview: Ignite 300 lbf HTPB rocket to test full functionality of stand

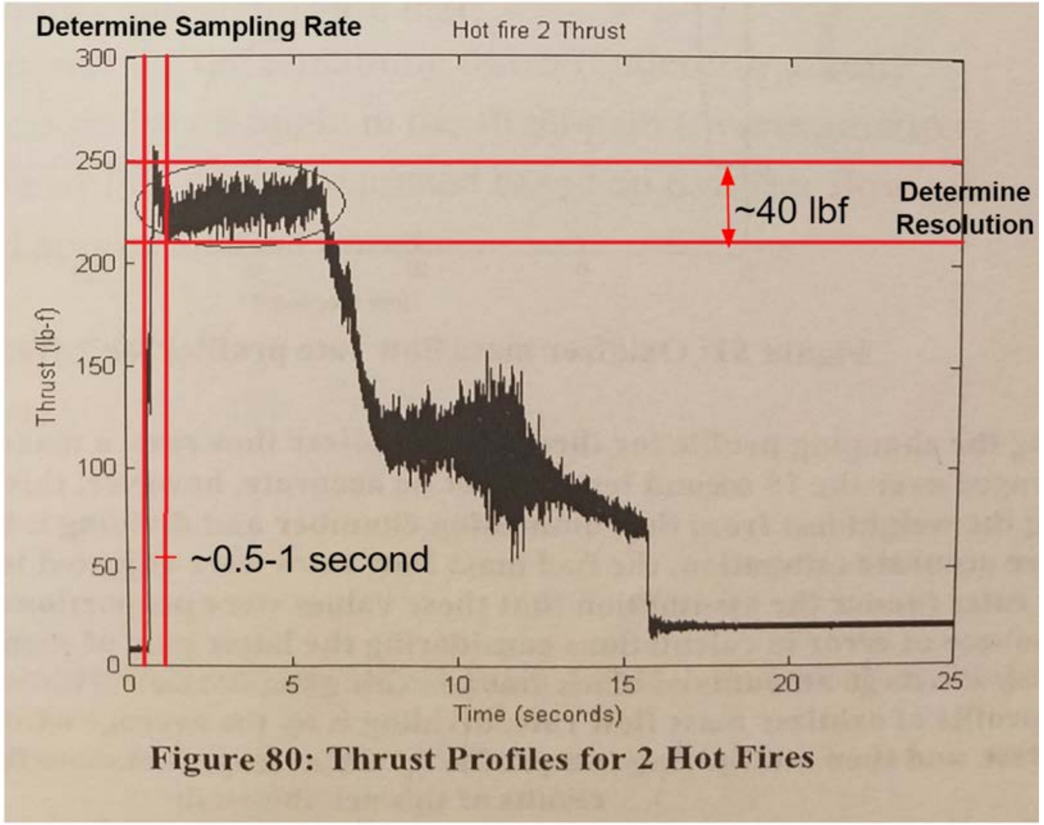
Test Purpose:

- Verify a safe, effective, and useful way to test rocket motors as was the plan for the HICKAM system
- This test is intended to verify all design requirements



Test Results

DAQ Sampling Rate Model



07-08 Mach-SR1 300lbf Engine Successful Hot Fire Test 2 Data

Thrust Variations:

- Fluctuation of ~40 lbf

Max Thrust:

- Occurs within 0.5s, need 30 samples to characterize

Requirements:

- Resolution: minimum 10lbm
- Sampling Rate: minimum 60 Hz

DAQ System Test Results

Sensor	Required Sampling Rate (Hz)	Measured Δt (s)	Derived Sampling Frequency (Hz)
Thermocouples	10	0.06667*	15*
Pressure Transducer	10-125	0.00062±0.01%	1613±0.01 %
Load Cell	60	0.00062±0.01%	1613±0.01%
Accelerometer	60	0.00667*	150*
Mass Flow Meter	7	0.18*	5.5*

*Could not calculate error due to lack of information on data sheet.

DAQ System Requirement Verification

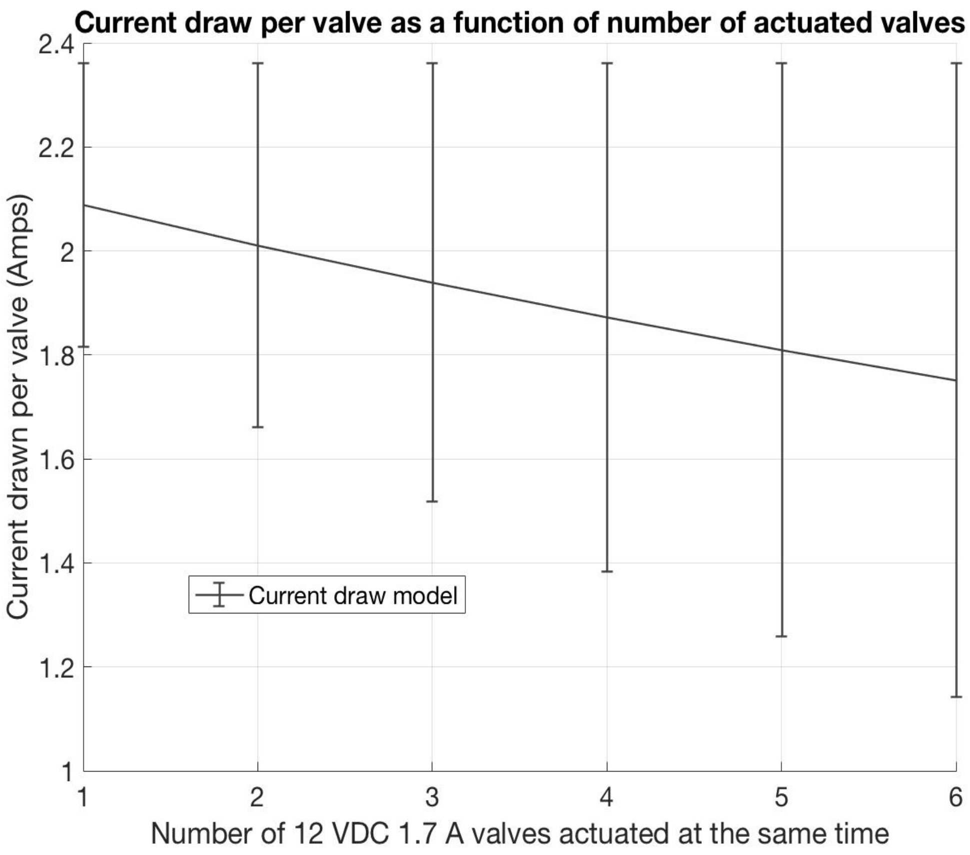
DR	Content	Verification Results	Verification Status
4.1	Pressure sensor shall have a sampling rate of at least 125 Hz and response time of less than 0.01 seconds.	Pressure transducer sampling rate is 1,613 Hz, accuracy of psi and response time of 0.001 seconds.	✓
4.2	The temperature sensors have a sampling rate of at least 10 Hz and response time of less than 0.25 seconds.	Thermocouples have a sampling rate of 15 Hz and a response time of 0.2 seconds.	✓
4.4	The force sensor shall have a sampling rate of at least 45 Hz and response time of less than 0.02 seconds.	The load cell has a sampling rate 1613 of Hz and a response time of 0.01 seconds.	✓

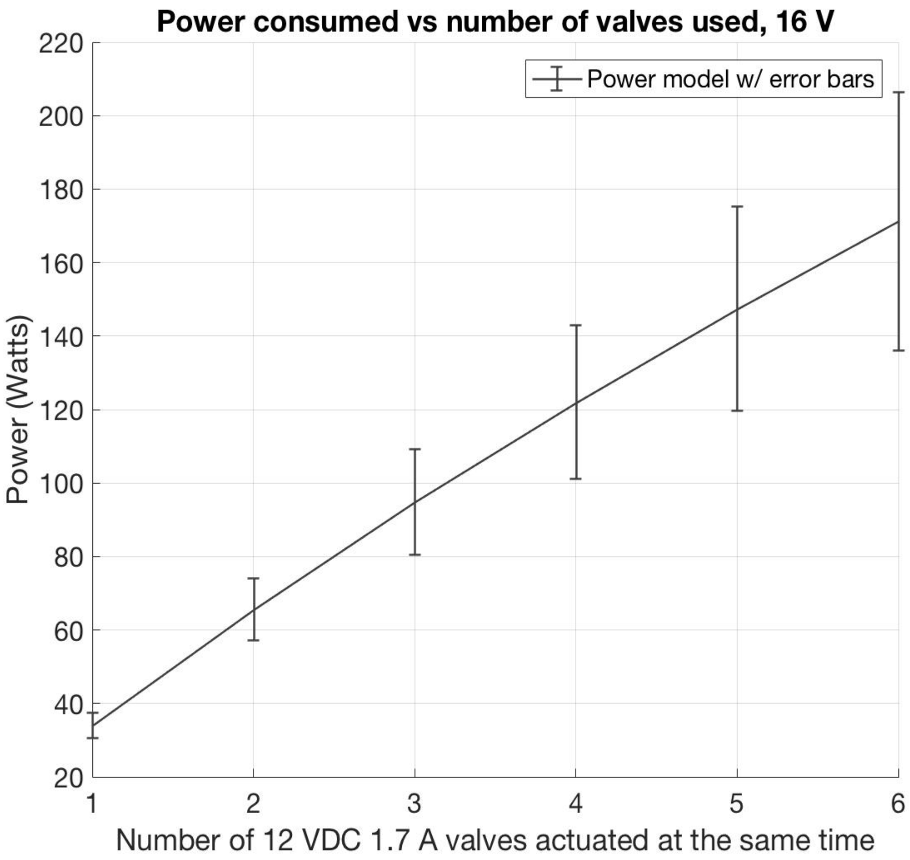
DAQ System Requirement Verification

DR	Content	Verification Results	Verification Status
4.5	The acceleration sensors shall have a sampling rate of at least 90 Hz.	The accelerometer has a sampling rate of 150 Hz.	✓
4.6	The mass flow rate sensor shall have a sampling rate of at least 7 Hz and response time of at most .3 seconds.	The mass flow meter sampling rate is 5.5 Hz, accuracy of psi and response time of .1 seconds.	~
4.7	The oxidizer tank weight measurement sensor shall have a sampling rate of at least 4 Hz and accuracy of at least 0.5 lb.	The oxidizer tank scale was not connected to the DAQ system, but does have an accuracy of 0.1 lb.	~

- DR 4.6: Mass flow meter connection via USB cable with the ProLink software created a maximum limit of 5-6 Hz
- DR 4.7: Budget didn't allow for the purchase of load cells to monitor oxidizer tank weight

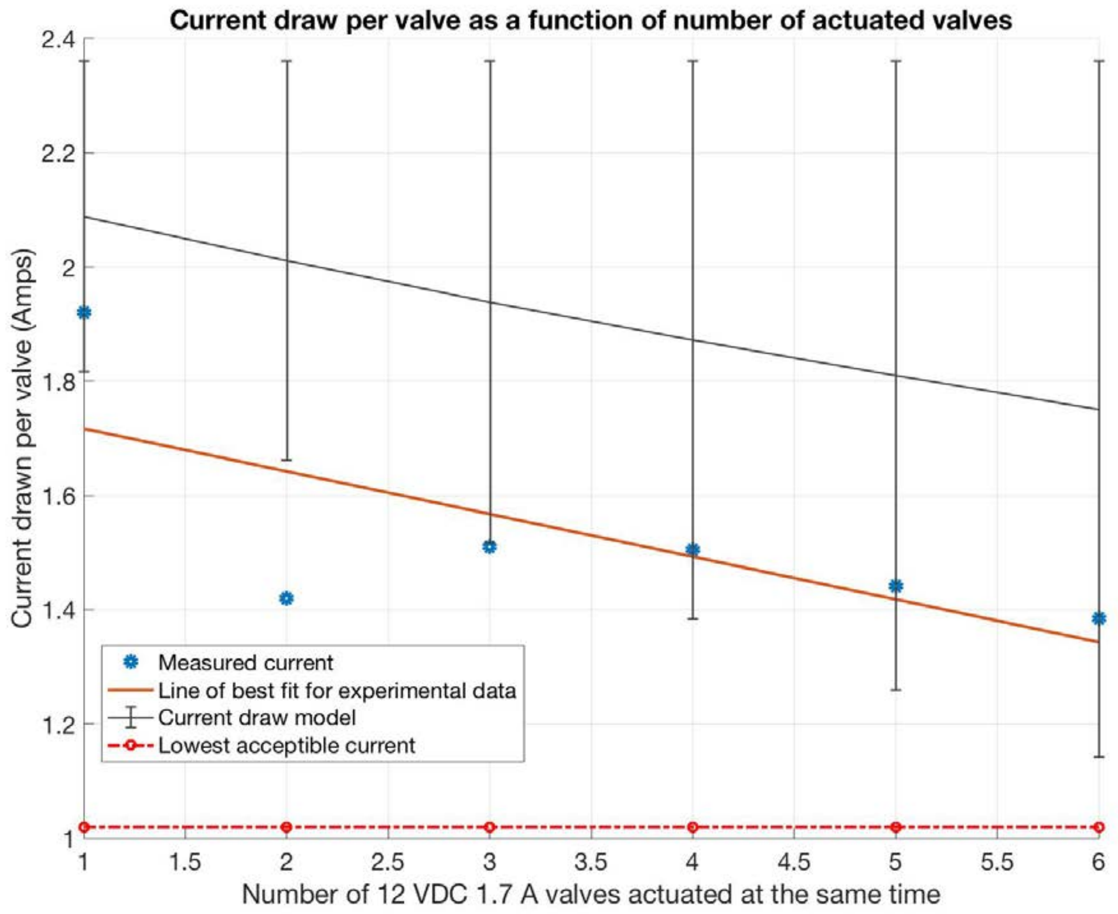
Power Model

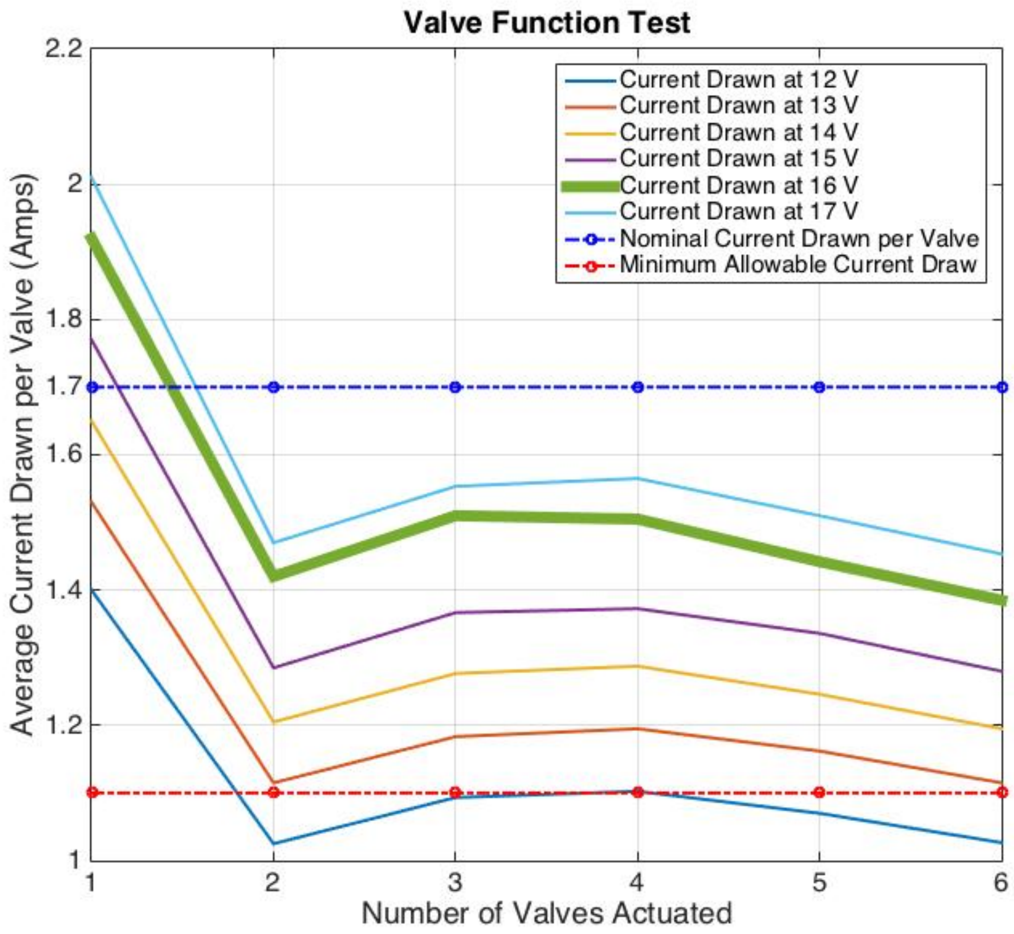




- Model is based on actual resistances of the components
- Error bars come from the uncertainty in resistance measurements (0.2 Ohm error)

Valve Function Test Results





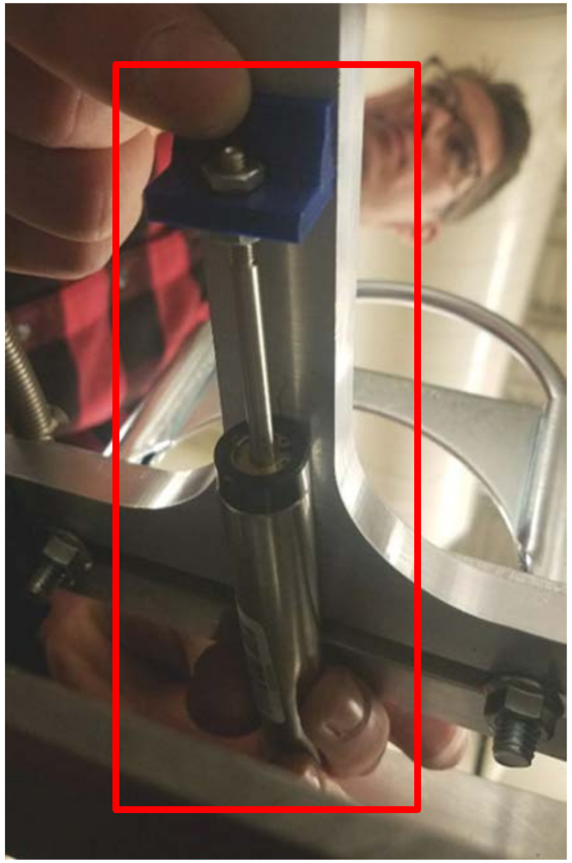
- Test performed at increasing voltages from 12 to 17 VDC to ensure at least minimum current draw of 1.1 A to valves
- 16 V chosen which ensures at least 1.4 A to valves

PO SD TO **Test Results** SE PM

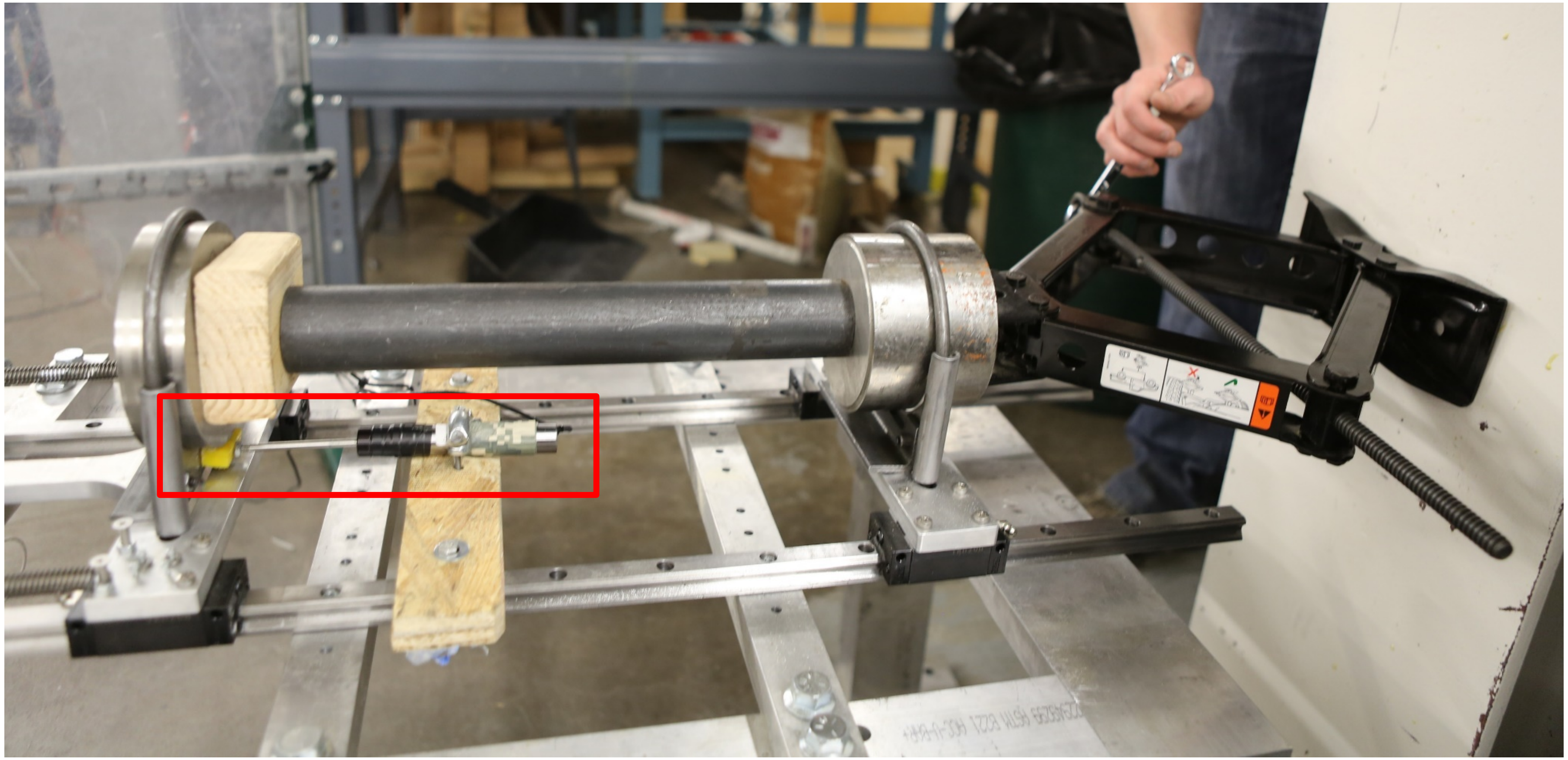
Power Requirement Verification

DR	Content	Verification Results	Verification Status
6.3.1	The power delivery system shall provide total maximum current draw of 7.5 A for at least 60 minutes.	Tested by inspection using ammeters in system for required time and amperage	✓
6.3.2	The system shall be able to stop power delivery to all valves while keeping SV-10 actuated at the push of emergency STOP switch.	Tested by using stop switch and inspecting valves for actuation and power delivery	✓

Simulated Loads



LVDT Attachment (Push Plate)

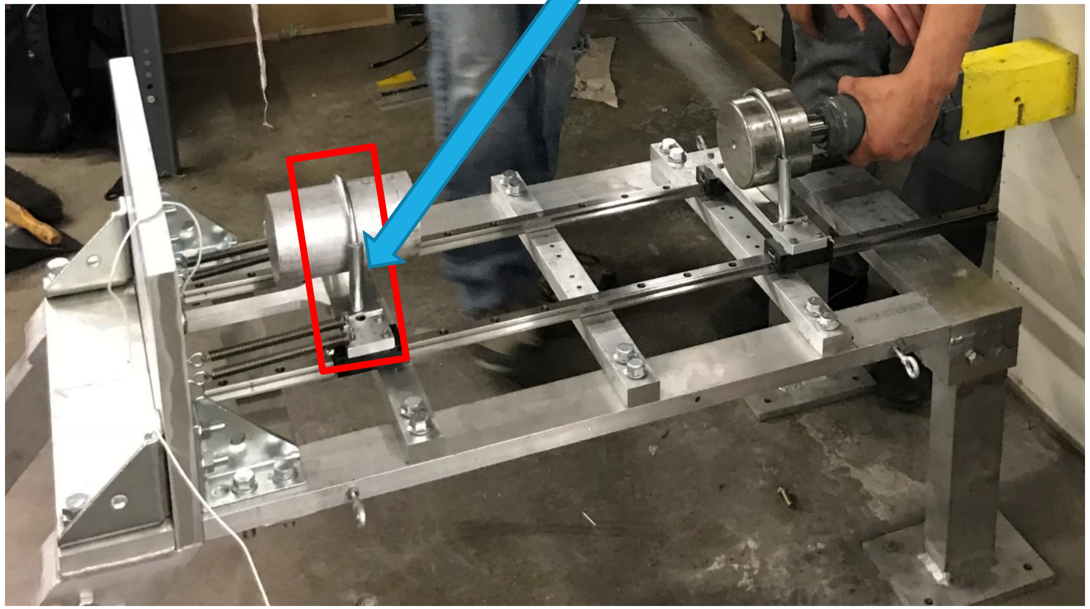


LVDT Attachment (U-Bolt Bracket)

Simulated Loads Test 1 Results

- Successful axial loads test at 330 lbf and 550 lbf
- U-Bolt bracket failure at 675 pounds
- Successful off-axial load simulation of 100 lbf with maximum deformation of ~0.06” deformation of rails
- **Solution:** Reinforced U-Bolts were able to hold up to 850 lbs axial loading as required without slippage

Deformed Bracket



Simulated Loads Trial 1 Setup

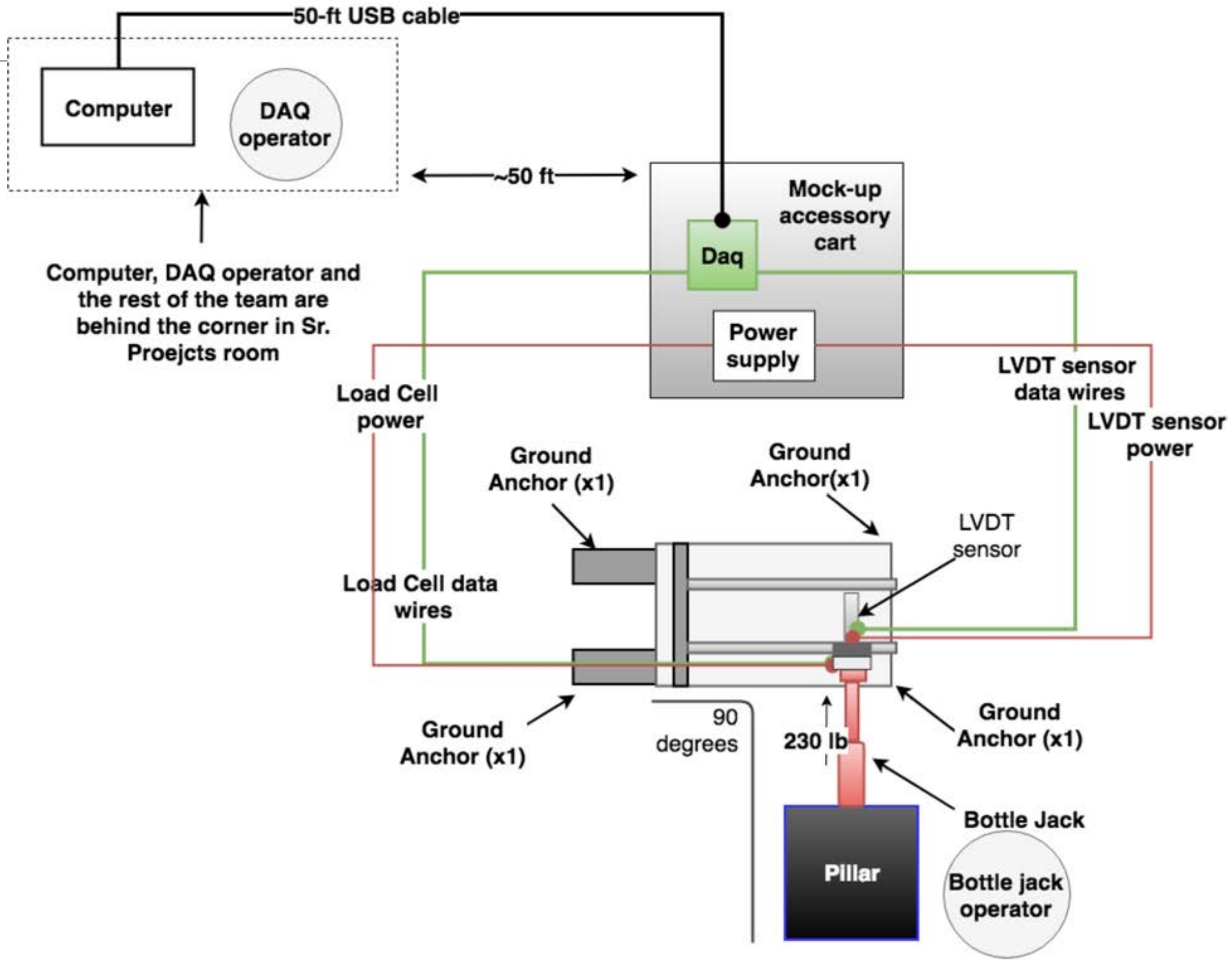
Reinforced U-Bolt solution

Off-Axial Load: Rails Deformation

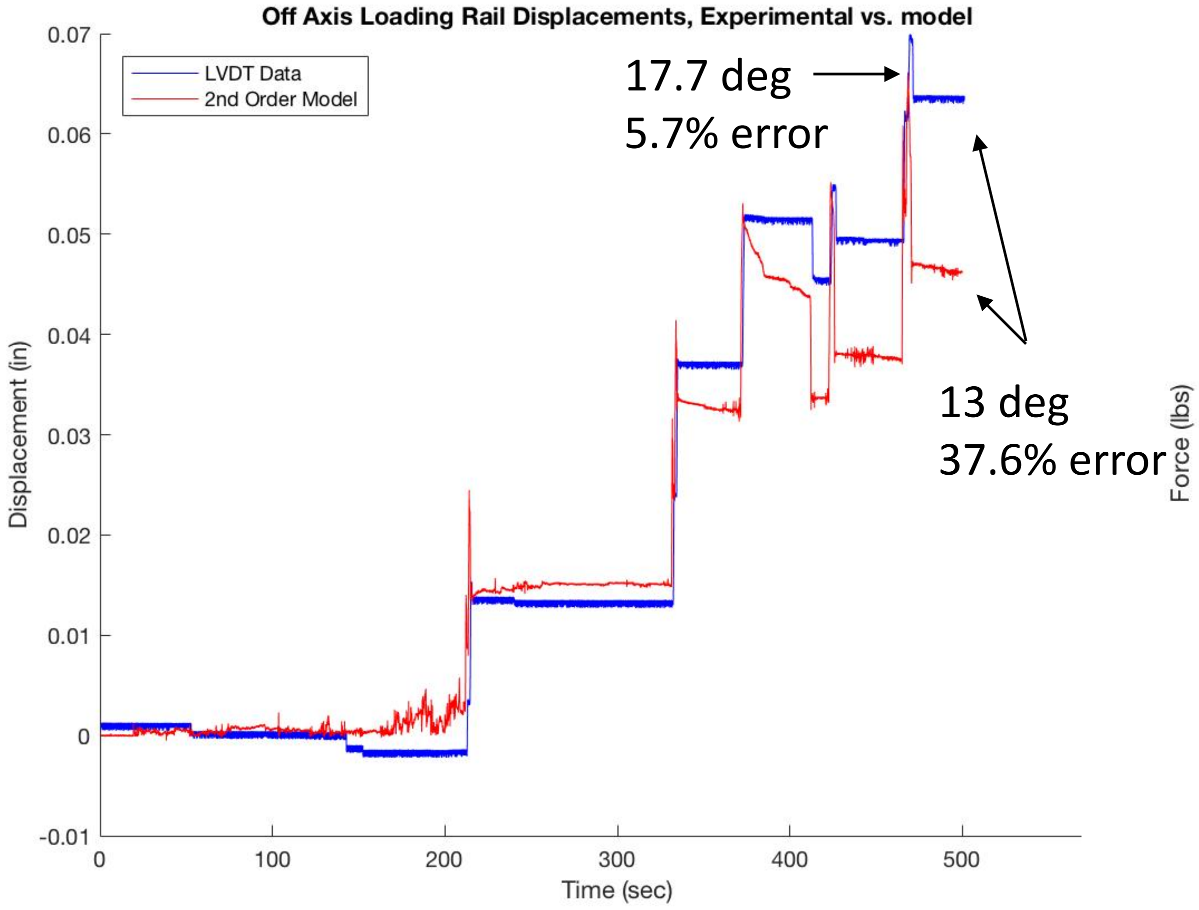
Model: 2nd-Order Bernoulli-Euler Beam

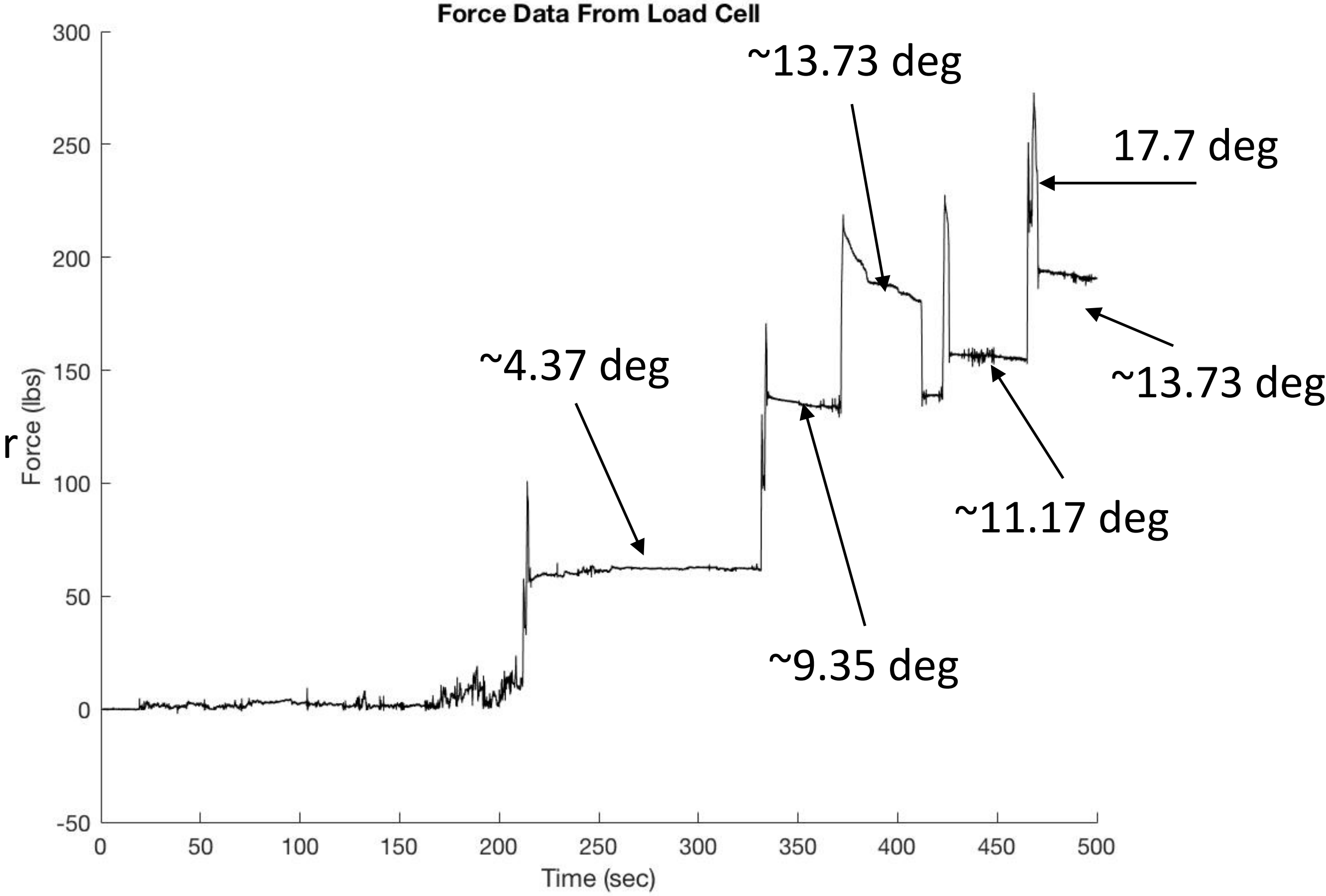
Experiment Assumptions:

- Weakest components for off-axis loading are rails (rear ends).
- Maximum off-axis angle is 17 degrees (taken from expansion angle of the nozzle)
- 850 * sin(17) * 1/2 = 125 lbf per carriage
- 250 lbf was applied due to bottle jack sensitivity.



Off-Axial Load: Rails Deformation





Model deformation behaves linearly with given force

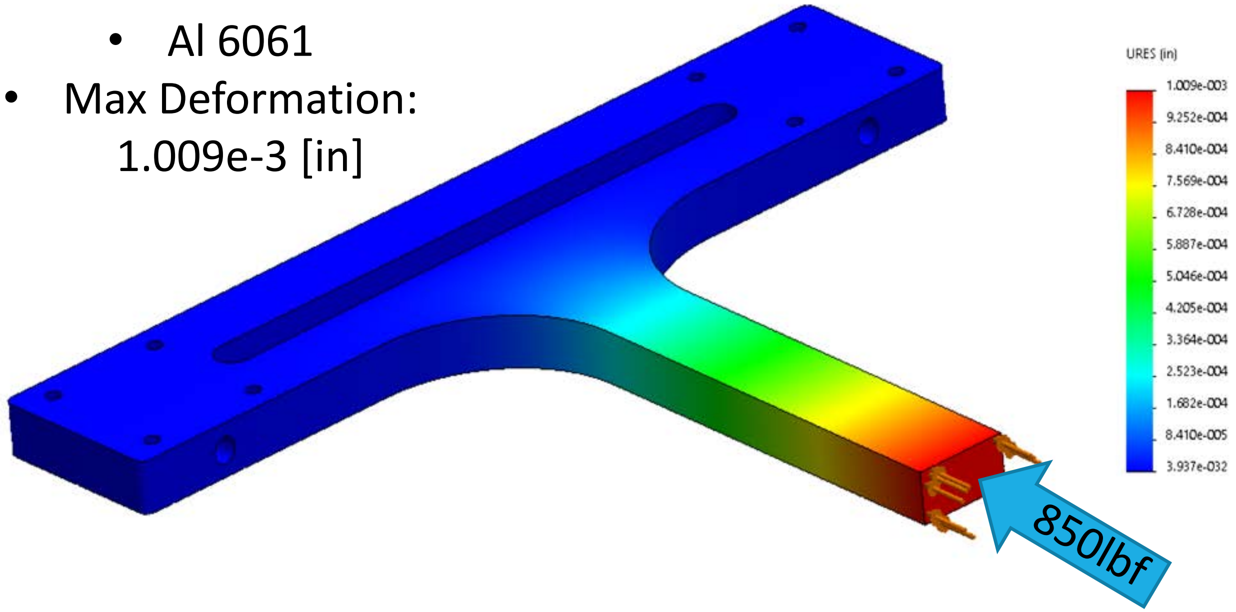
Push Bar Deformation

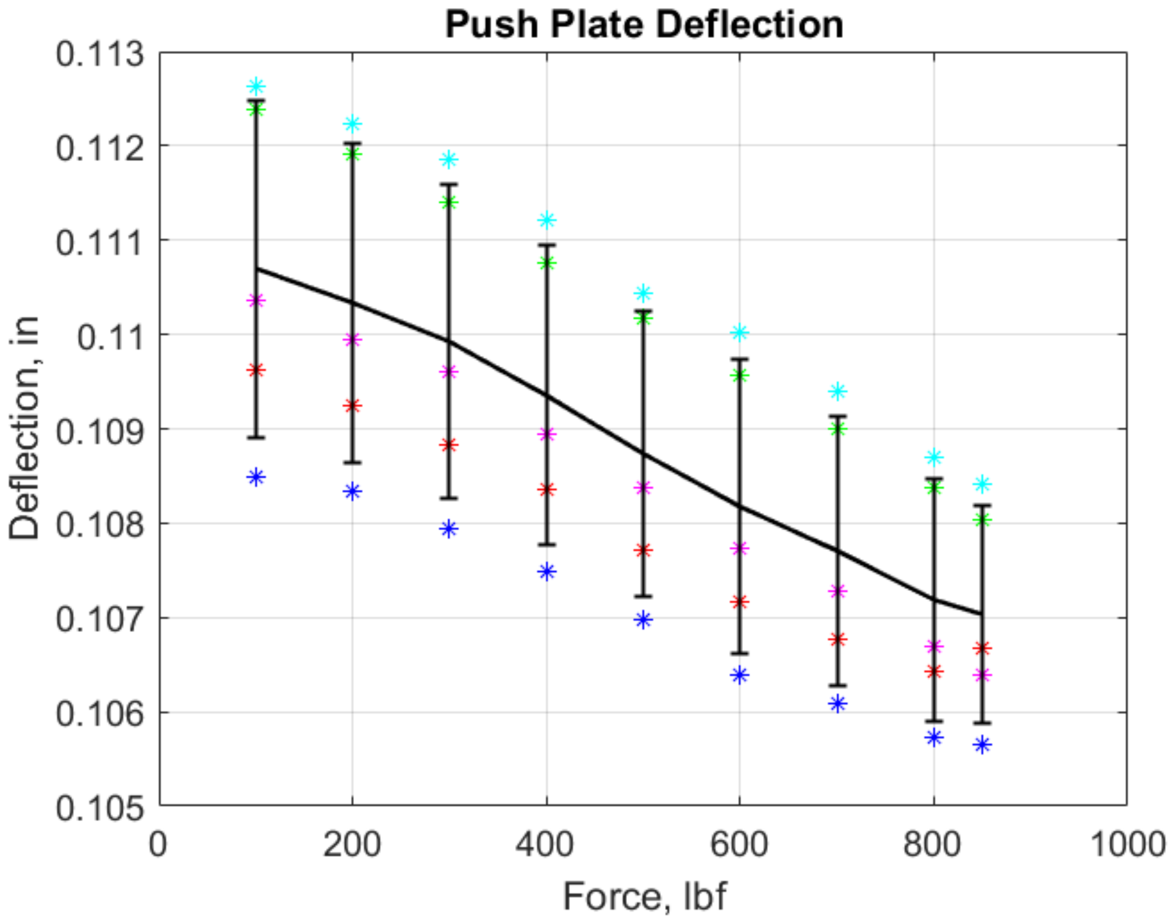
- 1” x 0.5” cross-section
- 6” long push bar

Solid Works Model

- 850 lbf
- Al 6061

- Max Deformation: 1.009e-3 [in]

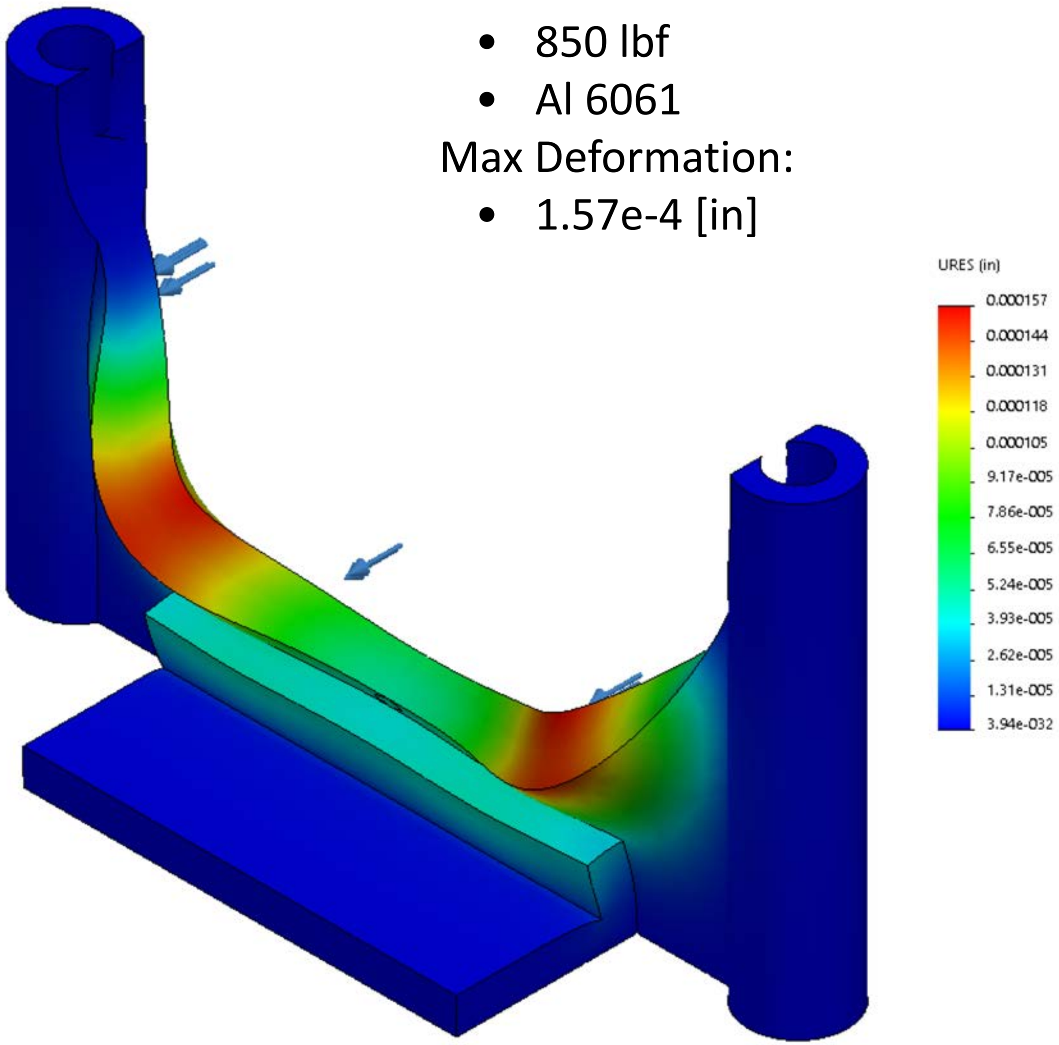


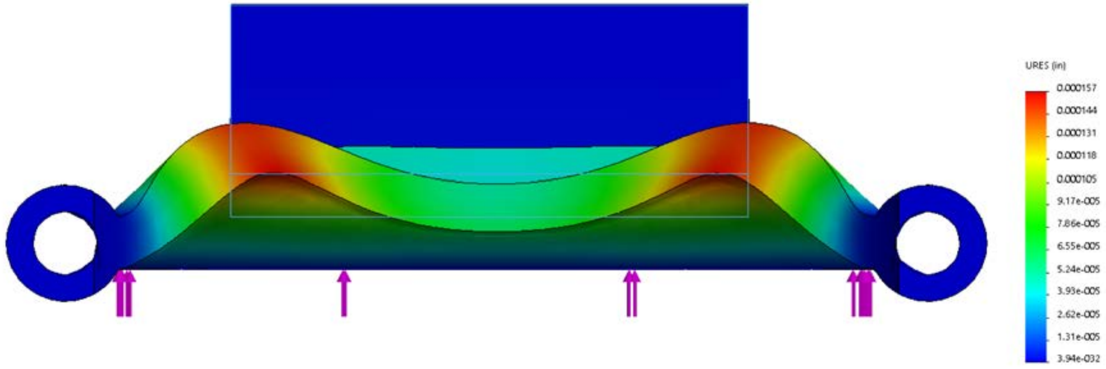


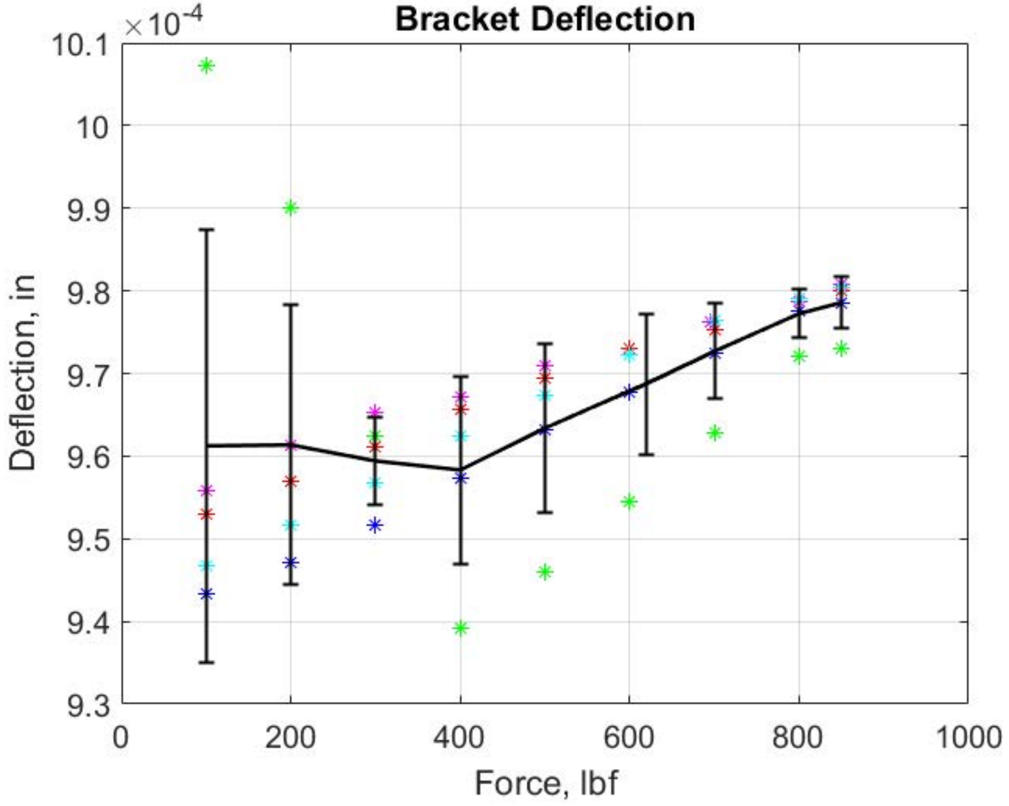
U-Bolt Bracket with Brace

Solid Works Model
- 850 lbf
- Al 6061

Max Deformation:
- 1.57e-4 [in]







Structural Requirement Verification

DR	Content	Verification Method	Verification Status
2.1	The test stand shall endure the maximum 500 lbf testing loads with the additional safety factor of 1.7.	The test stand withstood a load of 850 lbf with minimal deflection.	✓
2.2	The U-bolt interface shall endure the maximum 500 lbf testing loads with the additional safety factor of 1.7.	The U-Bolt interface withstood a load of 850 lbf with minimal deflection.	✓
2.3	The push plate shall endure the maximum 500 lbf testing loads with the additional safety factor of 1.7.	The push plate withstood a load of 850 lbf with minimal deflection.	✓
2.4	The rails shall endure the maximum 500 lbf testing loads at the off-axis loading of at least 17 degrees, with the additional safety factor of 1.7.	The rails withstood a load of 850 lbf at 17.7 degrees with minimal deflection.	✓
2.5	The test stand shall be secured to paved surfaces by the use of ground anchors.	The test stand withstood a load of 850 lbf while secured to the ground via ground anchors	✓

Cold Flow

Cold Flow Trial 1 – 500 psi

Cold Flow Trial 2 – 1500 psi

Mass Flow Rate Model

- Analytical equation used to calculate mass flow through an injector
- Initial model used data from MaCH-SR1 05-06

$$\dot{m} = \rho A V_2 \text{ where } V_2 = C_{dis}\sqrt{2\Delta P/\rho}$$

Inputs	Values
Coefficient of Discharge	0.45
Injection Inlet Area	0.1026 in^2
Liquid Density	45.73 lbm/ft^3
Tank Pressure	900 psi
Chamber Pressure	12.315 psi

Cold Flow Mass Flow : 1.1 lbm/s

Mass Flow Rate Model Results

Inputs	Values from Cold Flow 1	Values from Cold Flow 2	Values from Cold Flow 3
Tank Pressure [psi]	500	1500	2000
Chamber Pressure [psi]	12.3	12.3	35

Trial	Modeled Mass Flow [lbm/s]	Actual Mass Flow [lbm/s]	Error
1	0.81	0.2	75.4 %
2	1.42	1.2	15.5 %
3	1.63	1.2	26.4 %

System Requirement Verification

DR	Content	Verification Results	Verification Status
6.1	The length of the power and DAQ wiring leading from computer system to the test stand shall be at least 50 feet.	The wiring harness is 50 feet in length.	✓
6.2	The system shall acquire its power from the 120VAC generator located at least 10 feet from the control system.	The generator was located 35 feet from the control system during testing.	✓
6.3	The control board shall provide interface for ignition ON/OFF, OPEN/CLOSE valves for the plumbing, STOP button to relieve all pressure from the system, ignition current indicator, and current indicator for each solenoid valve.	The switch board contained for ignition ON/OFF, OPEN/CLOSE valves for the plumbing, STOP button to relieve all pressure from the system, and ignition current indicator. Current indicator was not included.	~

- DR 6.3: Due to late design changes and time constraints, the current indicator for each valve was not included.

System Requirement Verification

DR	Content	Verification Results	Verification Status
6.6	The system shall allow operator to monitor temperature and pressure of the plumbing components at frequency of at least 4 Hz.	The sampling rates of the plumbing pressure transducers and thermocouples are at least 10 Hz.	✓
6.7	The system shall de-pressurize and purge the system in case of plumbing failure modes that are a potential threat to personnel or the environment.	The cold flow test confirmed proper function of the de-pressurize and purge emergency procedures.	✓
6.8	The system shall allow operator to pressurize the LN20 oxidizer to any pressures in range 350 to 2000 psi.	The cold flow tests pressurized the LCO2 at pressures between 300 to 2000 psi.	✓

Hot Fire

Hot Fire Trial 1 – Cold Flow Trial 3

Hot Fire Trial 2 – Partial Success

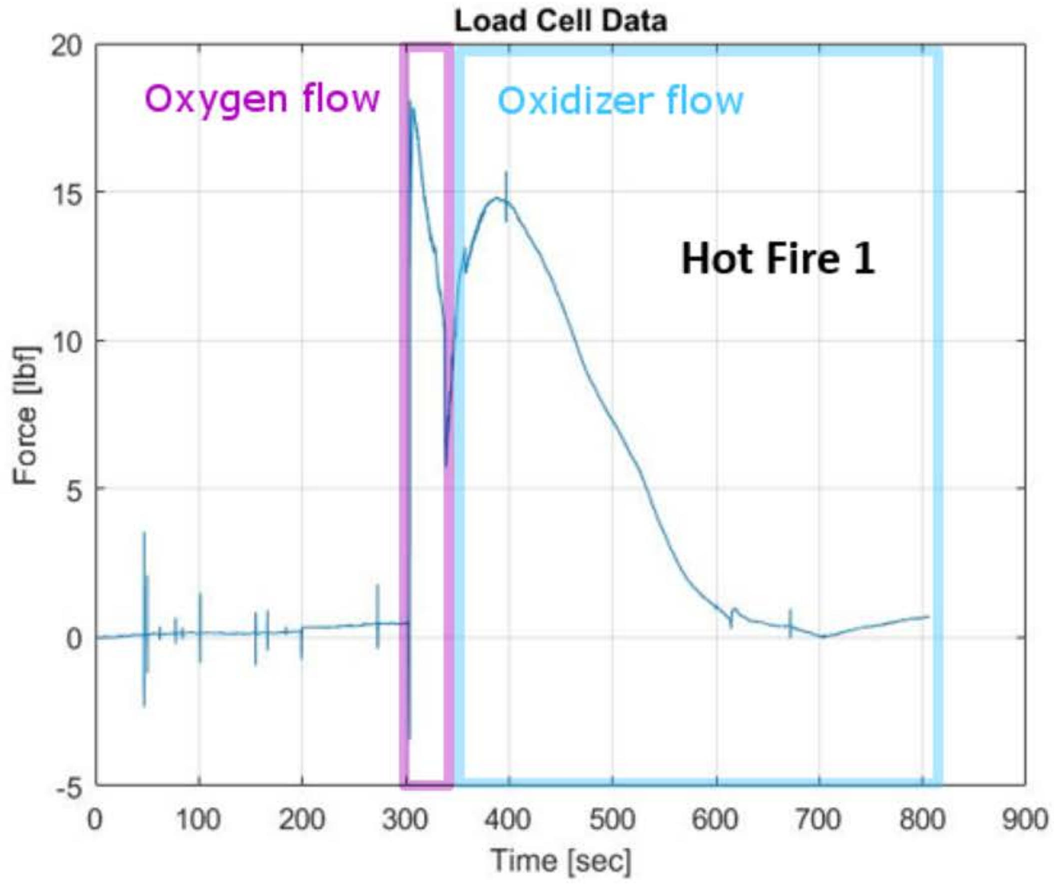
"Hot Fire" Results

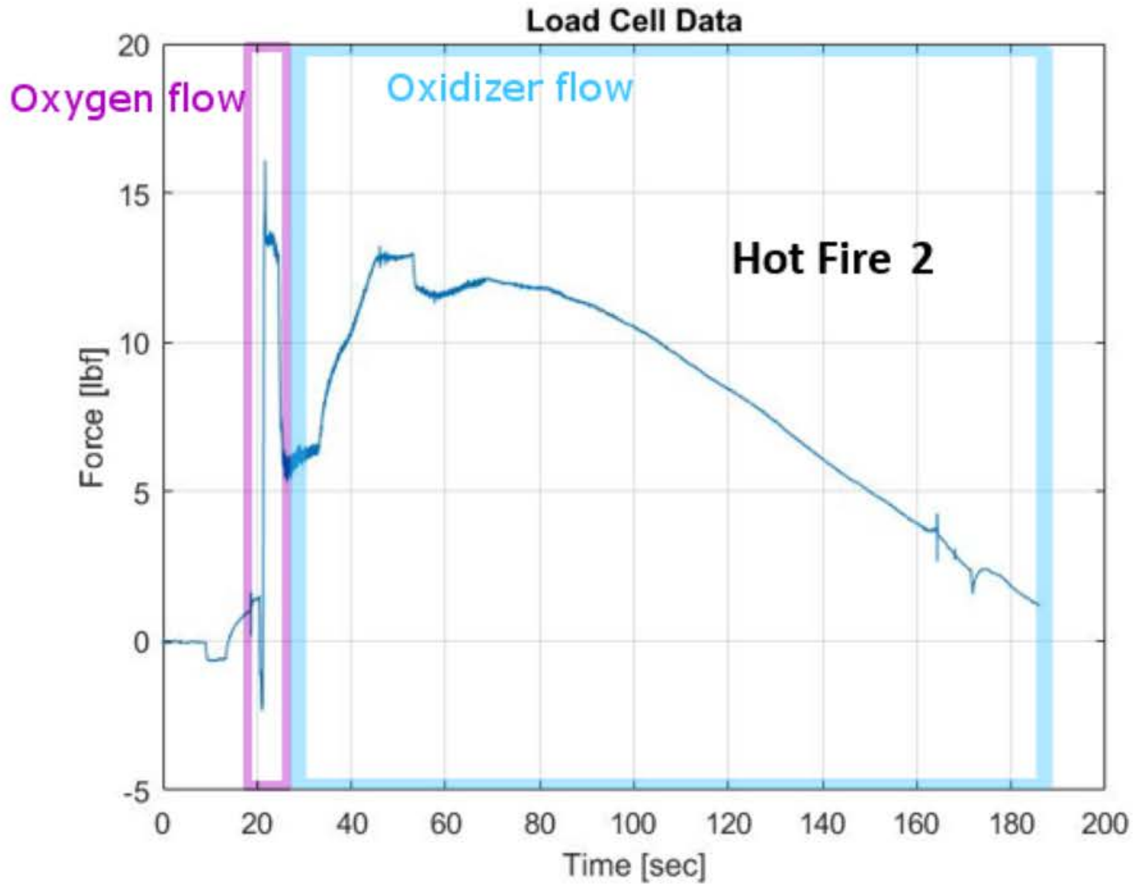
- Trial 1
  - Combustion did not occur due to overpacking of steel wool combined with oxygen supply feed being below cracking pressure of oxygen check valve
  - Successful flow of oxidizer in liquid state through rocket at maximum 1.2 lbm/s for approximately 20 s; model predicted 1.3 lbm/s
- Trial 2
  - Successful pre-combustion
  - Combustion did not occur due to insufficient solid fuel pyrolyzation (fuel wasn't left to burn for long enough); residual
  - Helium blowout extinguished fuel

Pyrolyzed fuel grain post test

Black smoke viewed during pre-combustion due to burning of fuel

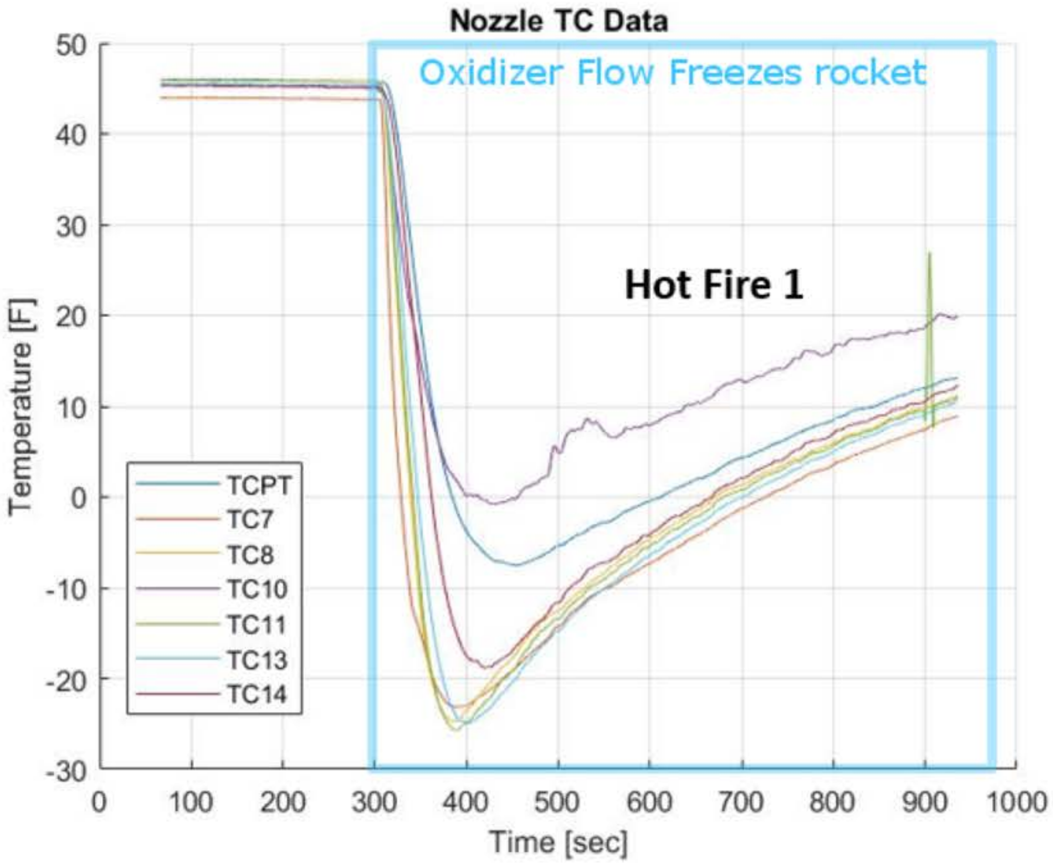
"Hot Fire" Results

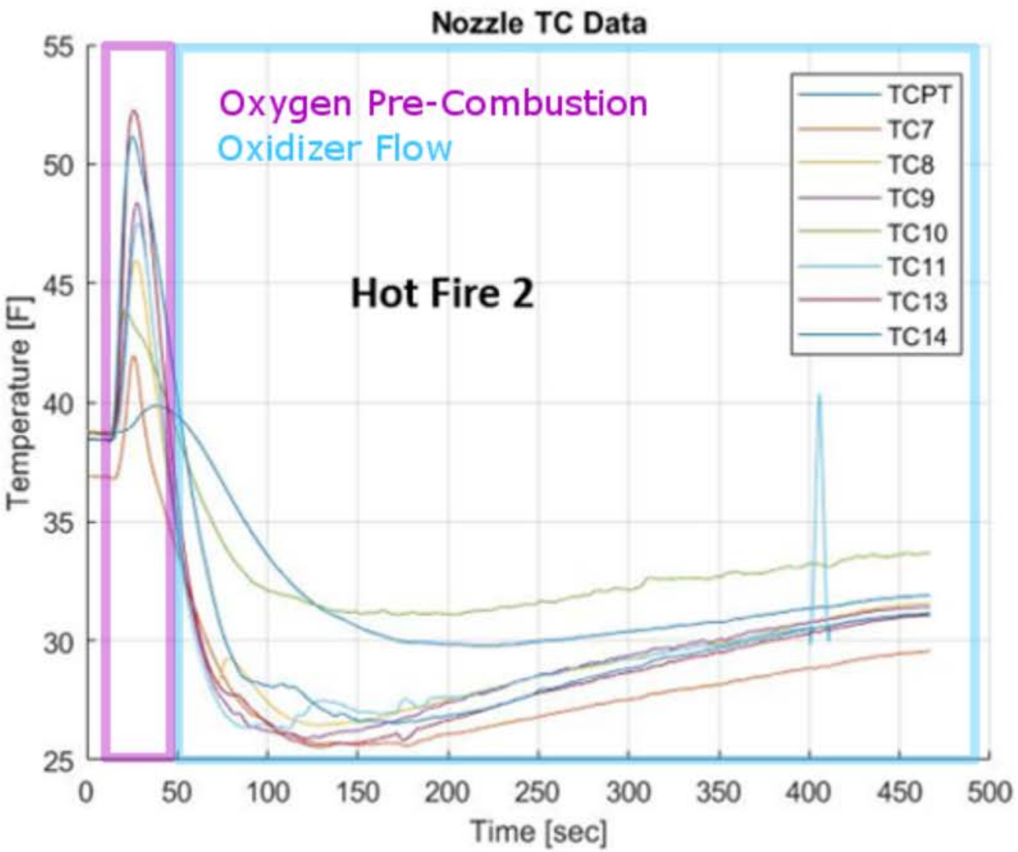




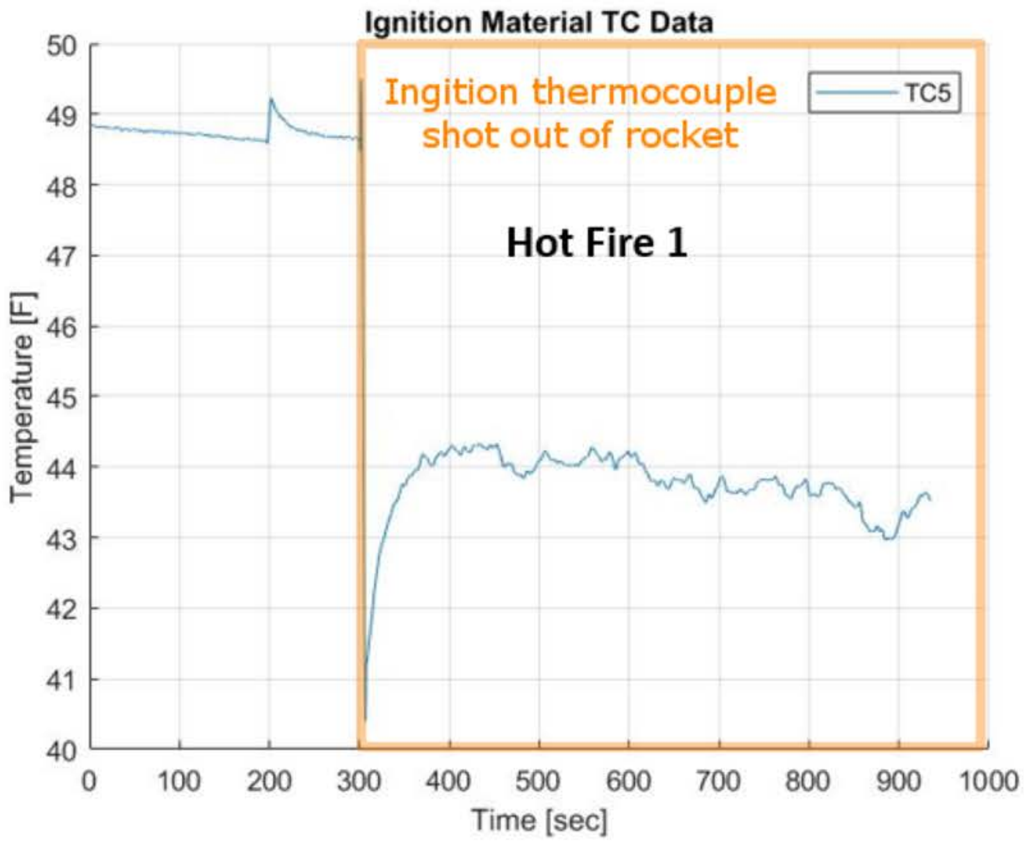
"Hot Fire" Results

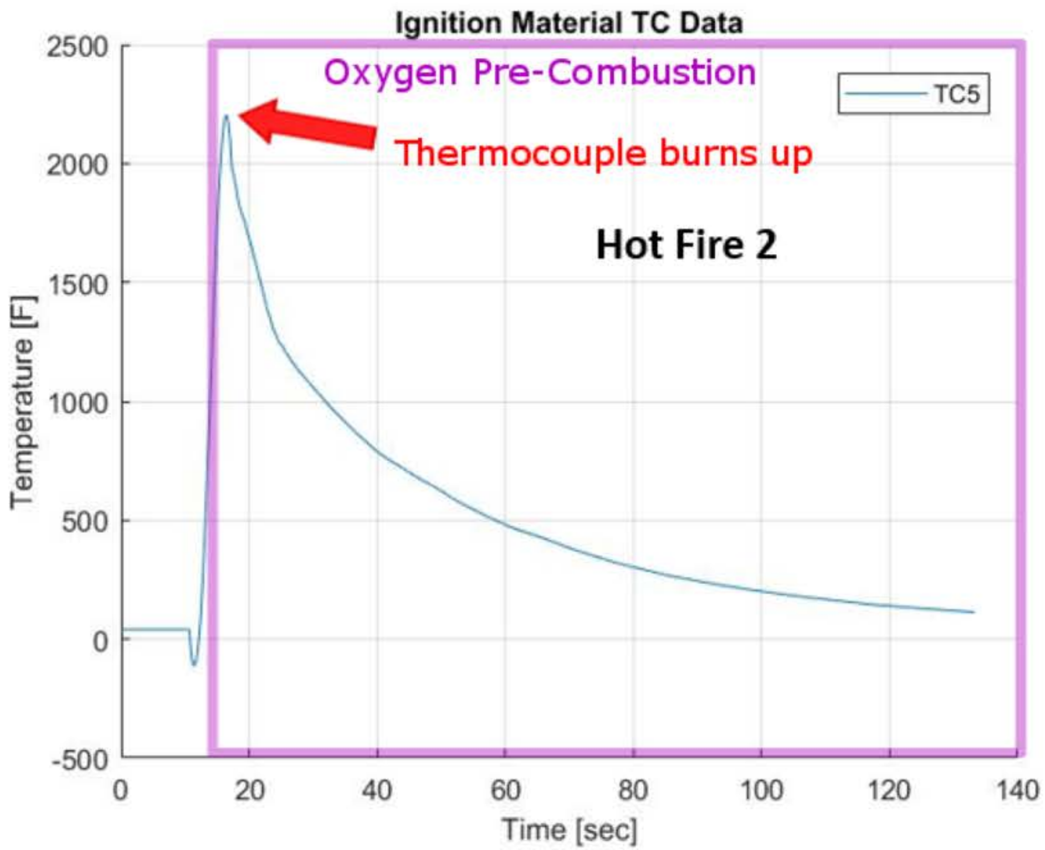
Hot Fire 1 frozen rocket



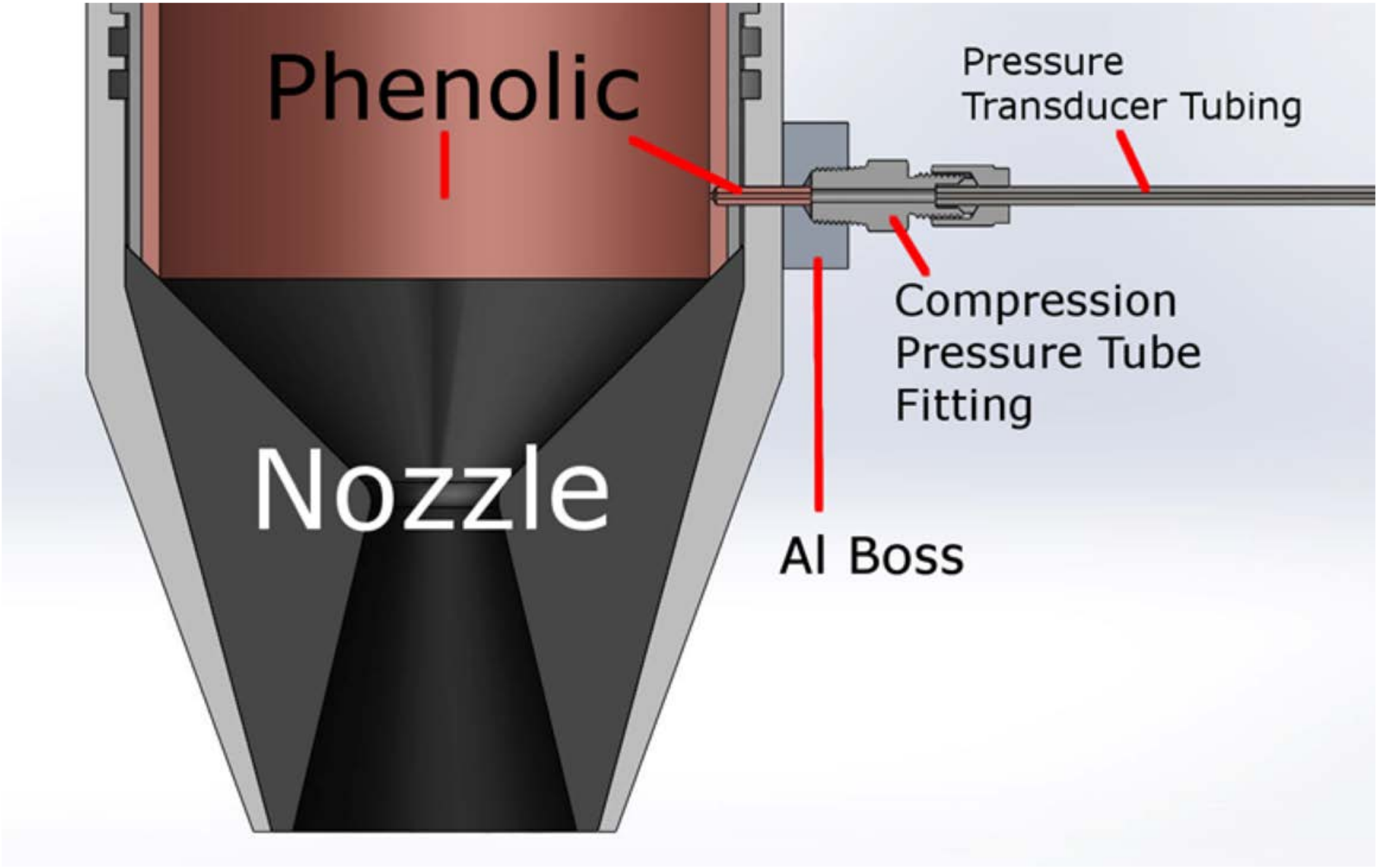


"Hot Fire" Results



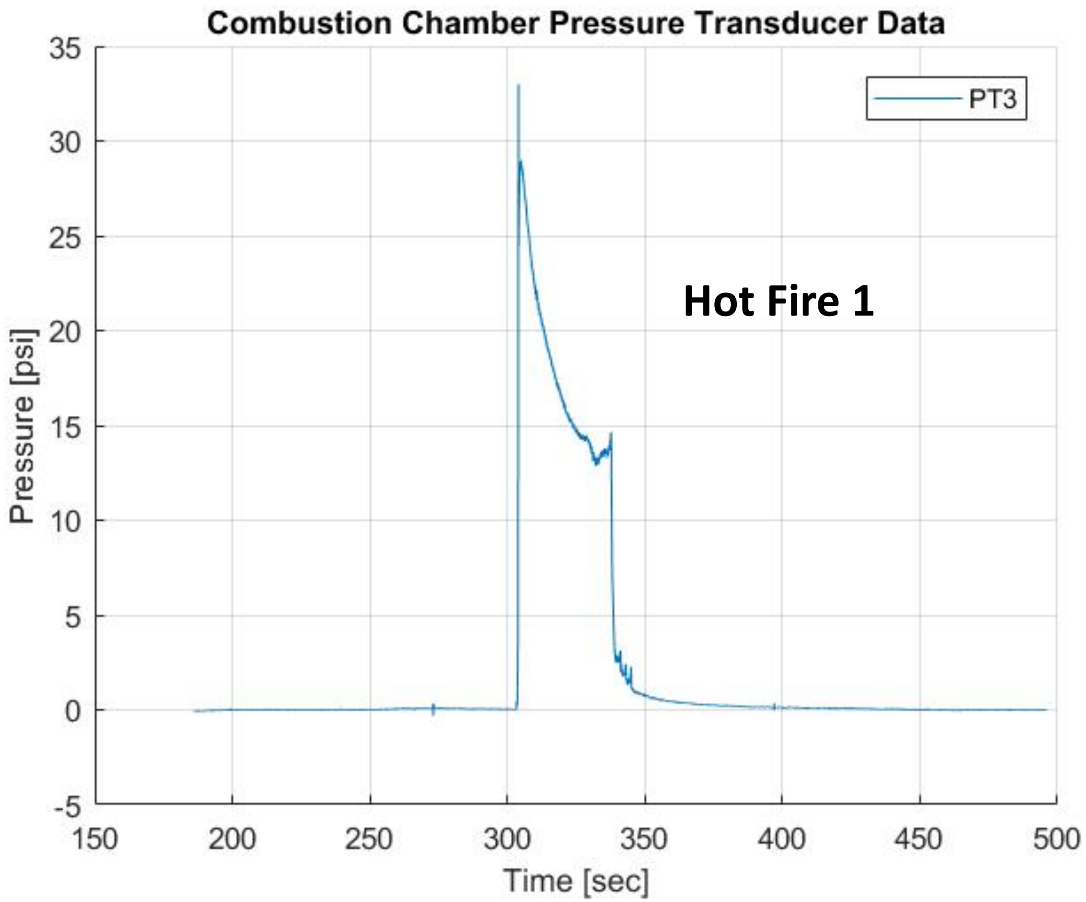


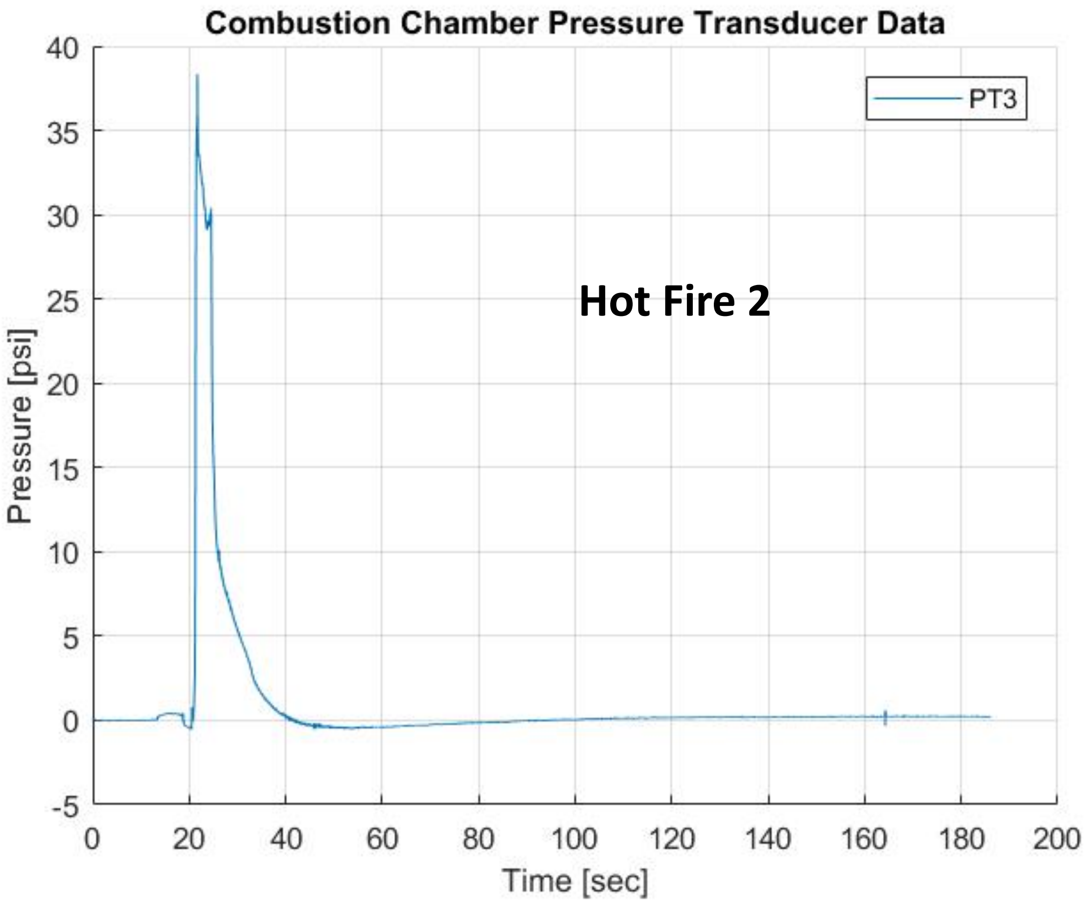
Combustion Chamber Pressure Transducer



Combustion Chamber Pressure Transducer

Combustion Chamber Pressure Transducer





System Requirement Verification

DR	Content	Verification Results	Verification Status
3.1	The test stand shall restrict the motion of a mechanically compatible test article such that the measurements of load in the direction of thrust are available.	Due to the design, the rails restrict the rocket motor to a single degree of freedom in the direction of thrust.	✓
4.1.1	The pressure transducer attachment to the combustion chamber shall not allow the sensor to get hotter than 212 F.	No thermocouple was attached to the combustion chamber pressure transducer attachment.	X
4.1.2	The pressure transducer tubing interface must withstand 500 psi and 5600 F.	Combustion chamber pressure transducer only saw a maximum of 50 psi.	X

- DR 4.1.1 and 4.1.2: Due to the lack of a true hot fire, these requirements cannot be verified.

System Requirement Verification

DR	Content	Verification Results	Verification Status
5.1	Data transfer and power delivery wires shall not get hotter than 60% of their melting point during the hot-fire test.	During testing, the data transfer and power delivery wires did not melt. This was not measured specifically with a thermocouple.	~
6.9	The pre-combustion sequence shall result in pyrolysis of HTPB fuel with gas temperature of at least 570 F.	Pyrolysis of HTPB fuel confirmed observed via fuel burning during successful pre-combustion and post burn fuel grain inspection.	✓
7.1	The data analysis software shall derive total impulse, burn time, and thrust from the calibrated and converted measurements.	Post processing software will perform this data analysis.	~

- DR 5.1: This was not measured specifically with a thermocouple so cannot verify the 60% value.
- DR 7.1: While the post processing software will perform this data, the lack of hot fire data means that this cannot be applied to true test data.

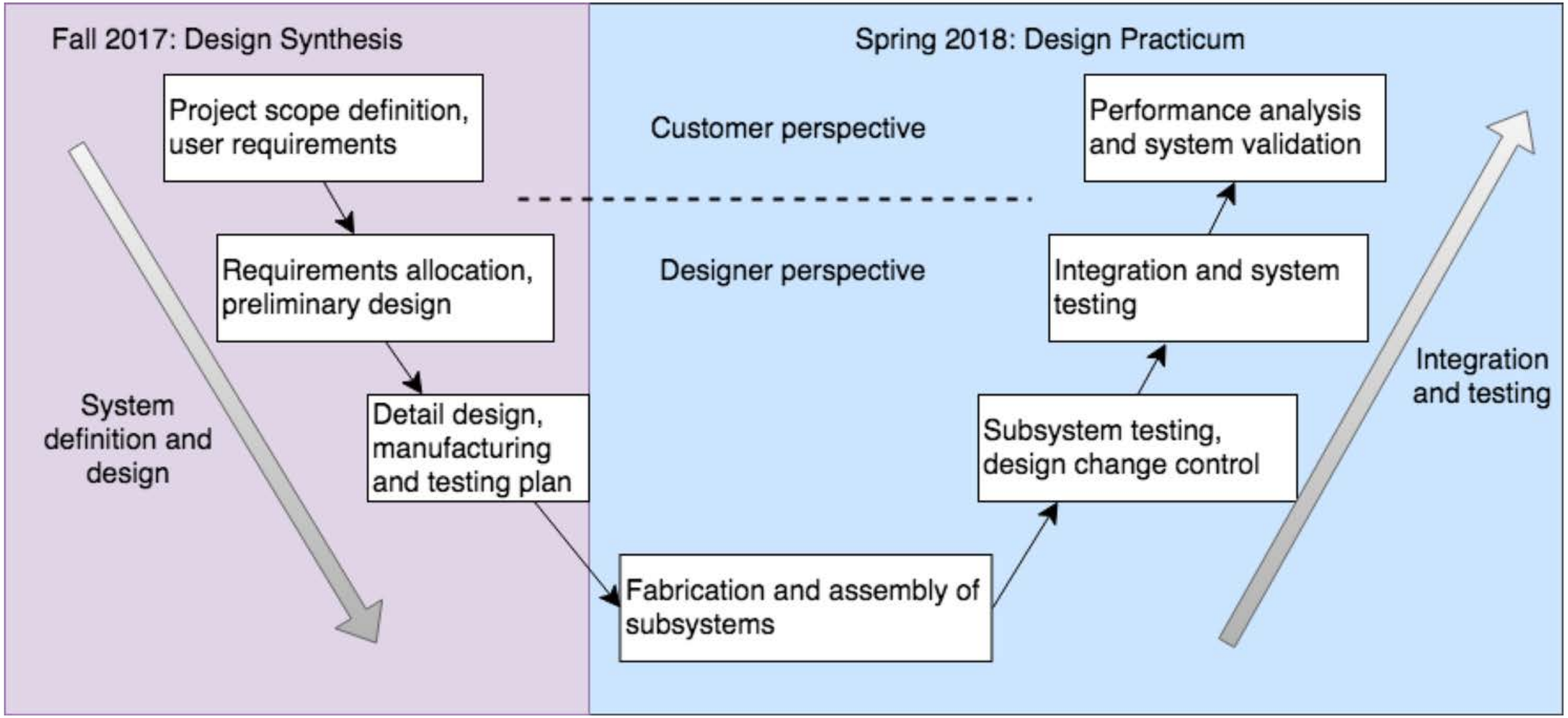
System Requirement Verification

DR	Content	Verification Results	Verification Status
7.3	The data analysis software shall compute the nozzle throat temperature from the thermocouple measurements of the outside temperature within 20 % accuracy.	Thermocouples were placed in several locations around and within the nozzle during test.	X

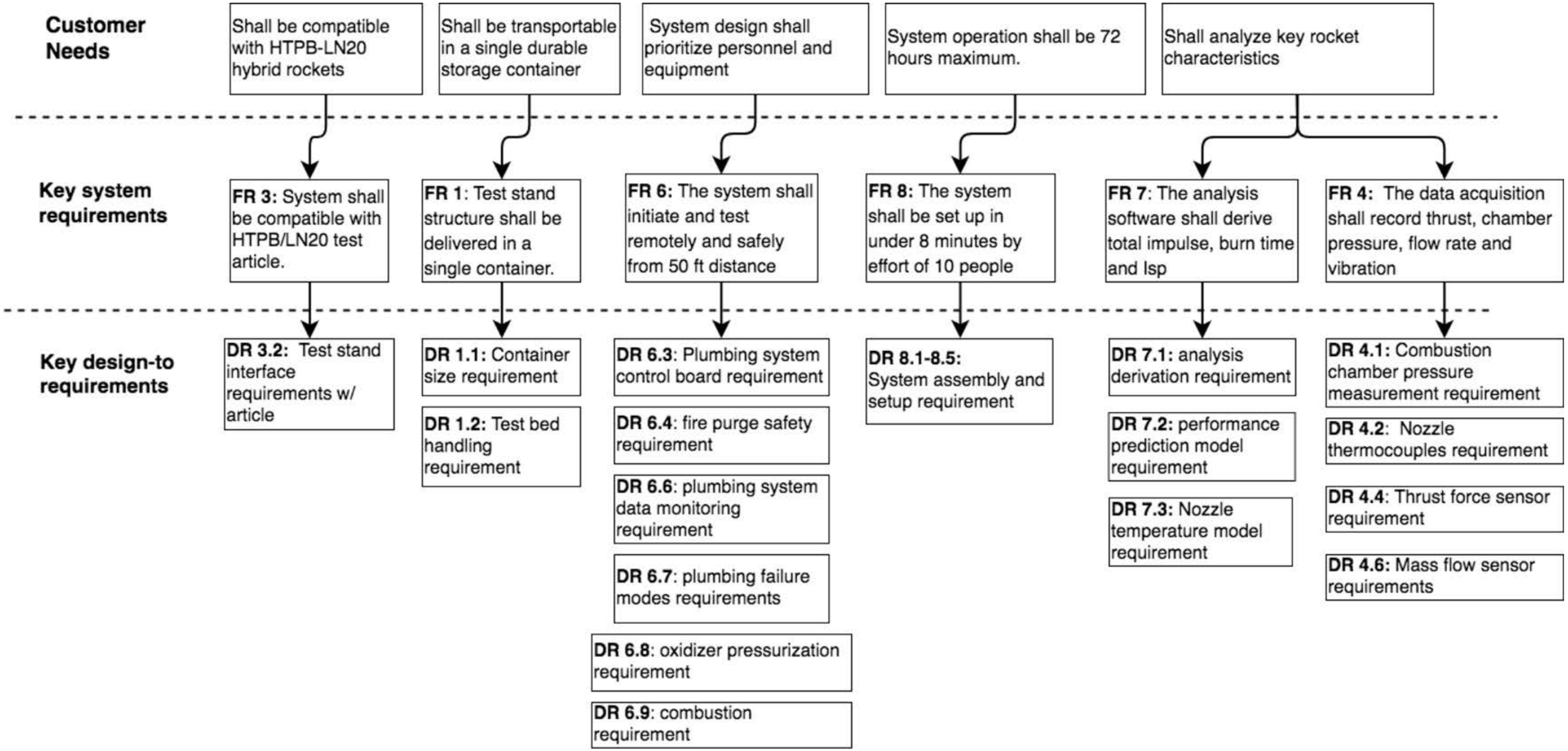
- DR 7.3: Due to the lack of a true hot fire, these requirements cannot be verified.

Systems Engineering

Systems Engineering Approach



Functional Objectives Flowdown



Risk Assessment

Likelihood (rows) vs. Impact (columns)

	Negligible	Minor	Moderate	Significant	Severe
Very Likely			Forgotten Tools/Parts		
Likely					
Possible		Inclement Weather		Fatal Component Break; Human Fatigue Error	
Unlikely			Total Power Failure		Rocket/Oxidizer Tank Explosion
Very Unlikely				Exhausting Gas Supplies	

Likelihood

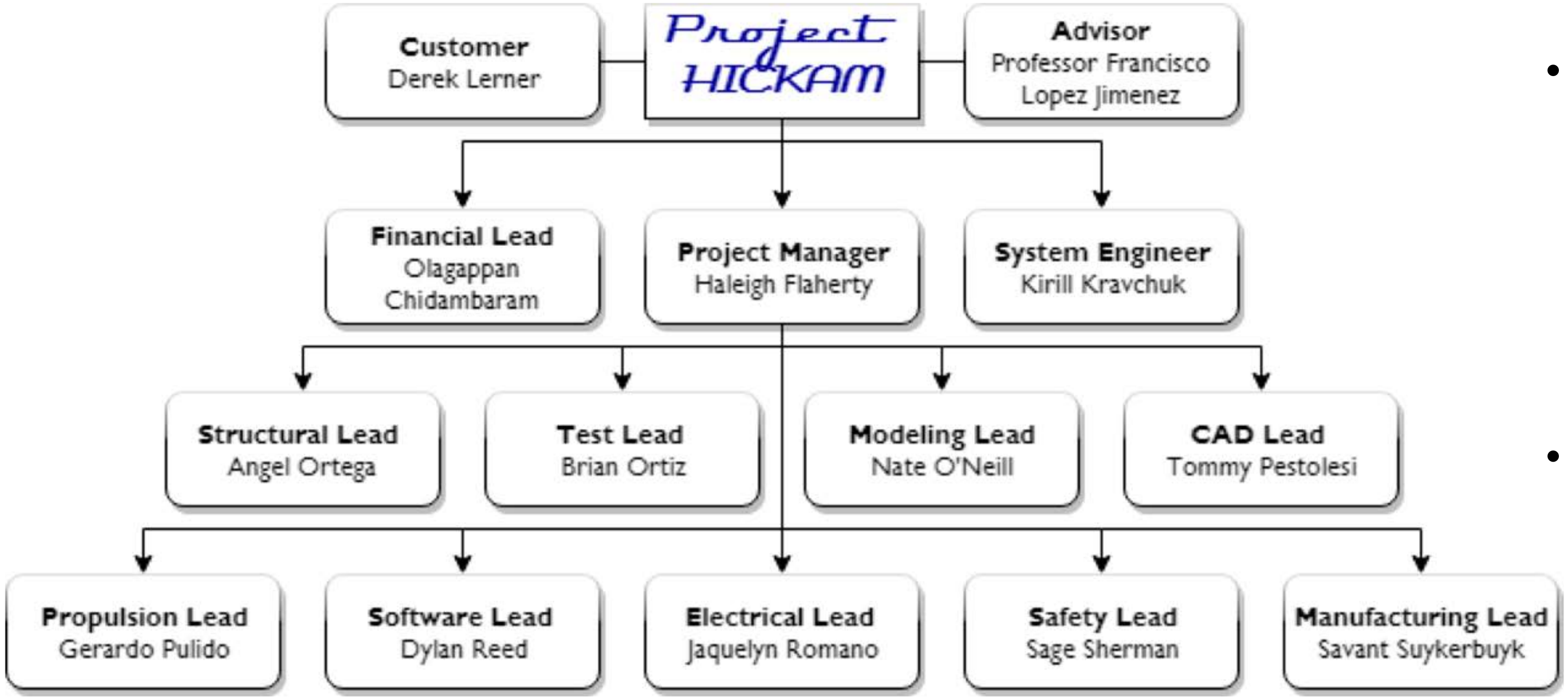
Impact

Issues and challenges

- Derivation of design requirements
  - The client needs gave a lot of freedom for design choices.
  - Extensive research was required to gain understanding of HTPB/LN20 hybrid rocket systems.
- Design change control during integration and testing
  - Budget constraints + high cost of plumbing system.
  - Full system testing brought up necessary modifications.
- Large number of interfaces - interdisciplinary engineering approach was required.
- **Lessons learned:**
  - Do not make requirements that you are unsure you can verify.
  - Keep better track of the tasks assigned to the team members.
  - Perform more detailed interface control and derive interface requirements early on in the project.
  - Be *very* specific about requirement definition and allocation.

Project Management

Project Management Approach



- Divided into sub teams:
  - Test Stand
  - Test Article
  - DAQ and Power
  - Modelling
  - Software
  - Management
- Weekly Status Meetings
  - Sub team status report forum filled out weekly
  - Delegated future tasks

Successes, Challenges, and Lessons Learned

Successes	Challenges
• Weekly team update forums • Gaining funds and donations for project • Dividing the team and working in parallel to complete the rocket manufacturing • Having leads and backups for tasks helped ensure they were completed on time	• Maintaining use of a calendar/Gantt for task progress • Cluttered group messaging chat • Keeping the full team on the same page • Over-scoping of project

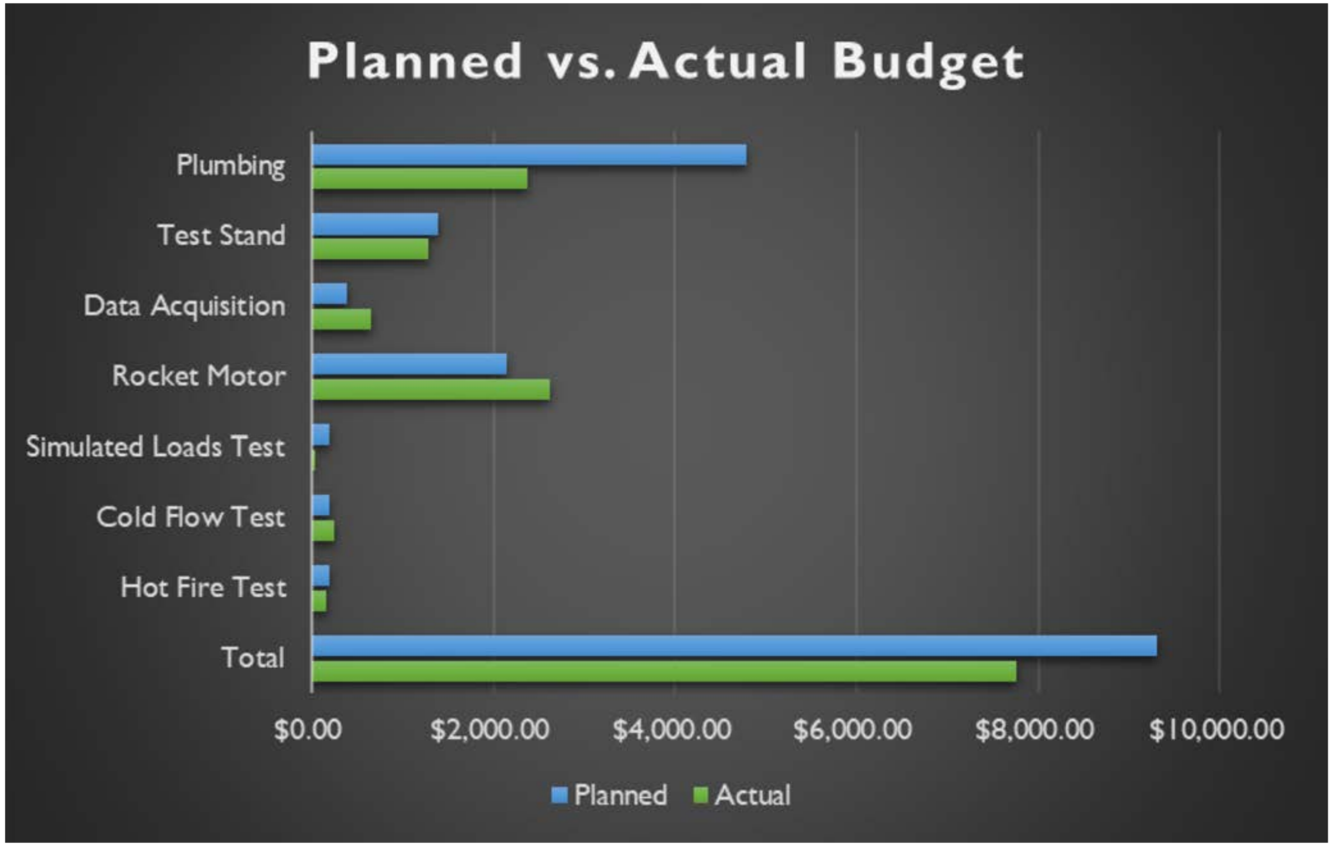
Lessons Learned:

- Require work on deliverables much earlier
- Work on division of labor
- Meet with Matt earlier in the design process
- Ensure the project is scoped to the allotted time and resources

Planned vs. Actual Budget

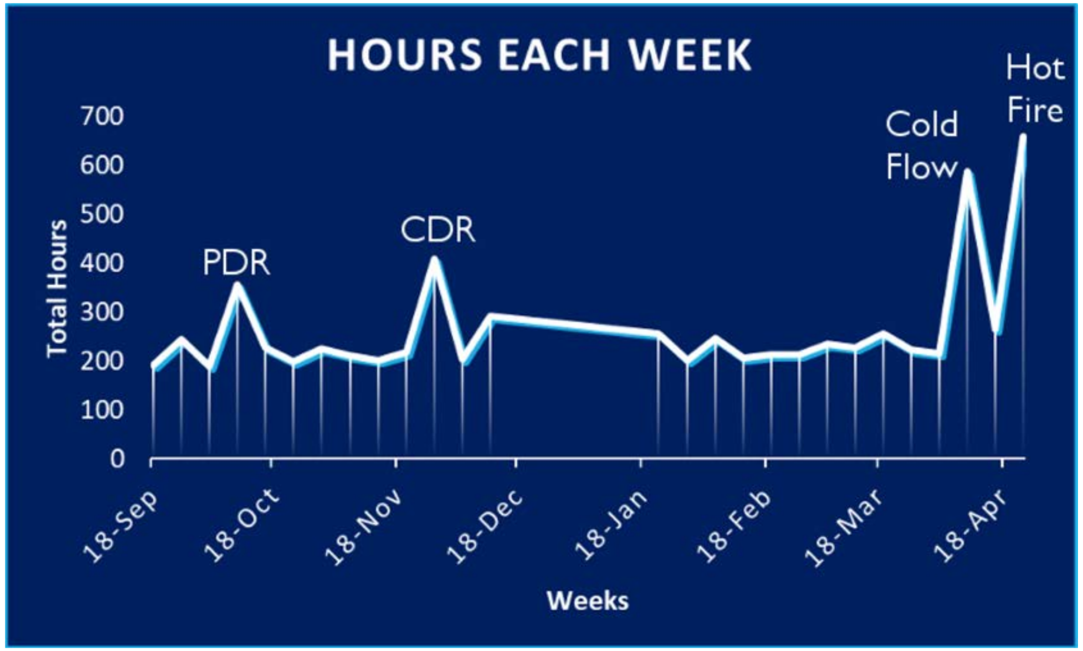
Component	Planned	Actual
Plumbing	$4,785.13	$2,382.50
Test Stand	$1,384.70	$1,291.57
Data Acquisition	$386	$650.84
Rocket Motor	$2,153.94	$2,622
Simulated Loads Test	$200	$40
Cold Flow Test	$200	$246
Hot Fire Test	$200	$160
Total	**$9,309.68**	**$7,763.54**

- Plumbing system cost less than expected as Swagelok donated
- Team members chipped in to get supplies



Industry Cost

Component	Cost
Materials (Actual Spent)	$7,763.5
Materials (Without Donation or Borrow)*	$47,050
Time: Fall Semester**	$98,937.5
Time: Spring Semester**	$124,906.3
200% Overhead	$447,687.5

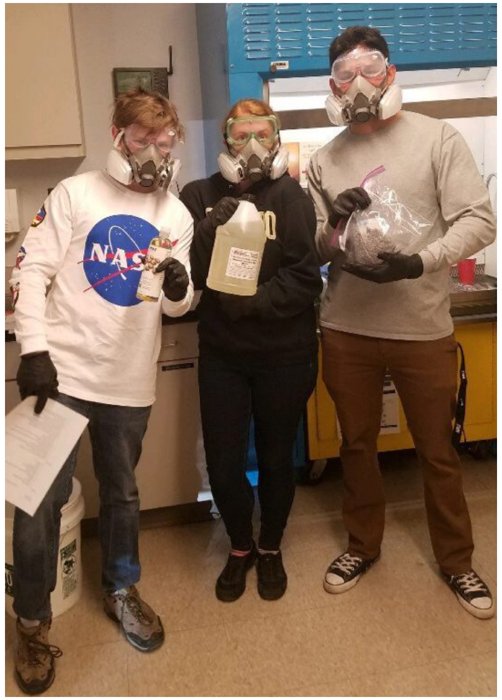


Total (Actual Spent): $679,294.80

True Industry Cost: $726,344.80

*Estimated and does not include pay of experts, such as Anthony Gentile with Emerson

**Based on at $65,000 per 2080hr, or $31.25/hr pay



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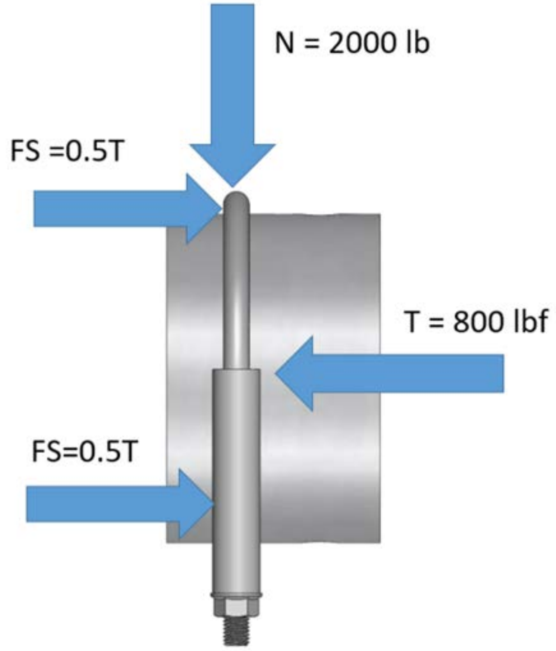
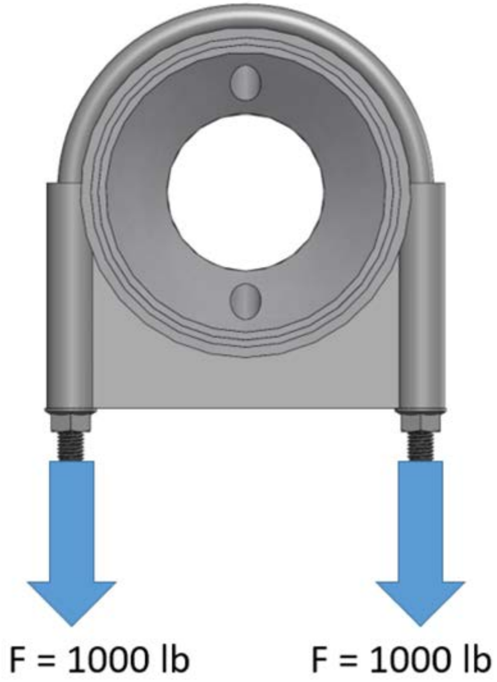
QUESTIONS?

Backup Slide Table of Contents

Axial Load: U-Bolt Friction Model



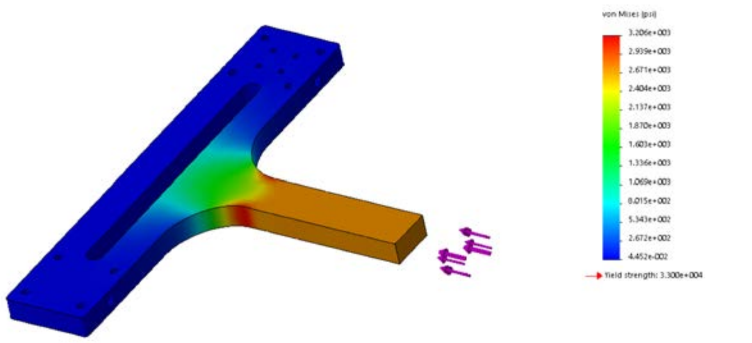
$$F_s = \mu_s N$$



$$\tau = \mu_s D F$$

- Friction must equal thrust to remain static
- Coeff. Of Friction estimated = 0.4 (between Zinc and Aluminum)
- Diameter (D) of bolt 3/8 inch
- Coeff. Of Friction In bolt = 0.2
- Torque each bolt (tau) to **75 in-lbs**

Test Stand Structure - Push Bar



SolidWorks Simulation

Aluminum 6061

Yield Strength = 33,000 psi

Result: 3,206 psi
- 16% difference from hand calculations

Hand Calculations

- Aluminum 6061
  - E = 10(10^3)ksi
  - Yield Strength = 30,000 psi
- Axial loaded rectangle

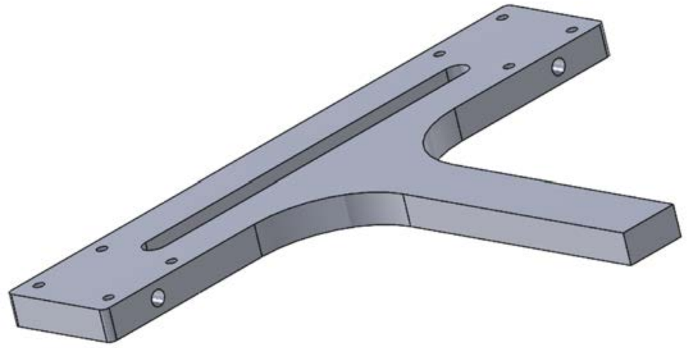
- 1” x 0.5” cross-section
- 6” long push bar

$$\sigma_{avg} = \frac{F}{A}$$

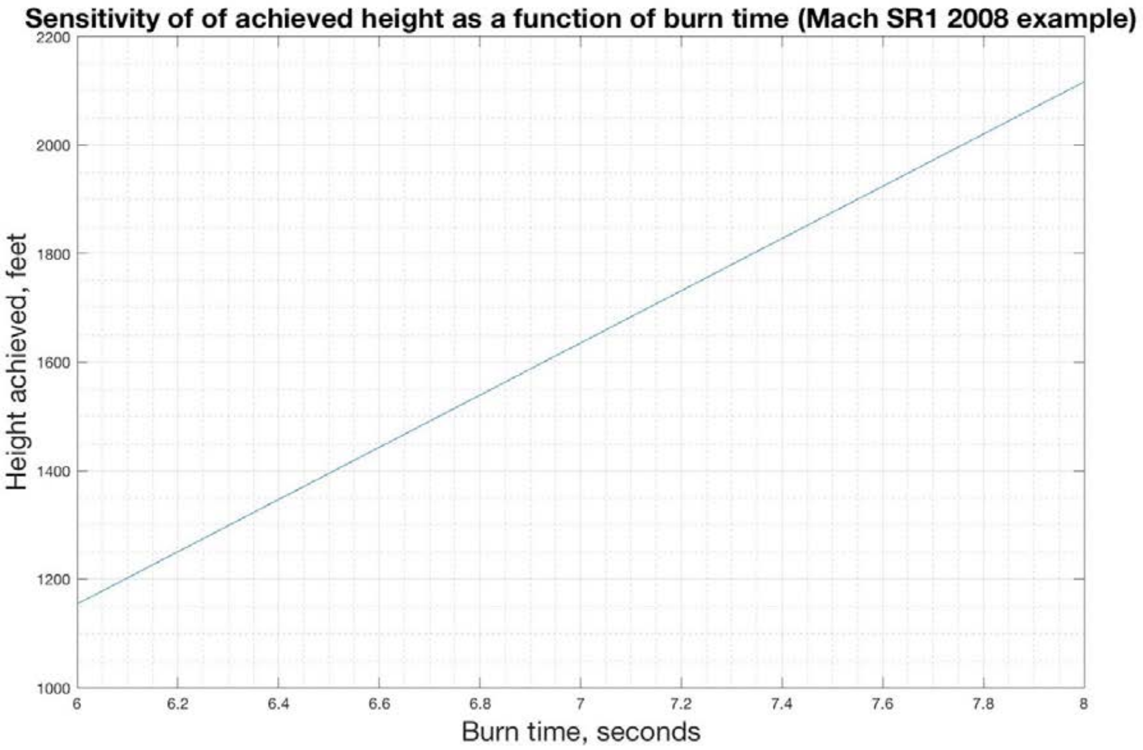
$$P_{cr} = \frac{\pi^2 EI}{(KL)^2}$$

$$I = \frac{bh^3}{12}$$

DR	Requirement	HICKAM Specs
DR 6.8 Structural Stability	**Endure Hot Fire Loads** Max Load: 800 lbf Safety Factor: 1.7	**Custom Slotted Plate Push Bar** σ_{avg}: 2,720 psi Buckling Force: 7,139 lbf ✓



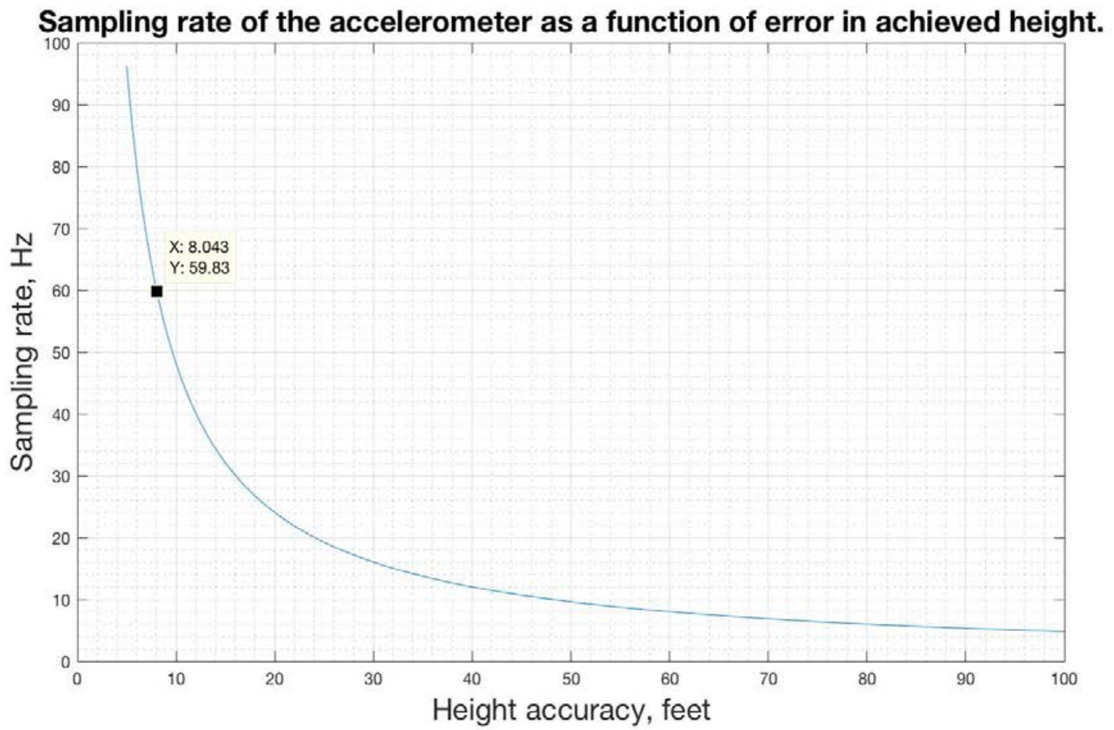
Sensor Requirements: Accelerometer



- Mach SR1 hot fire data was used to find the change of maximum height as a function of burn time.
- 481.2 feet of max height per second of burn.
- Sensitivity of the burn time is used to determine the time source shock occurs.

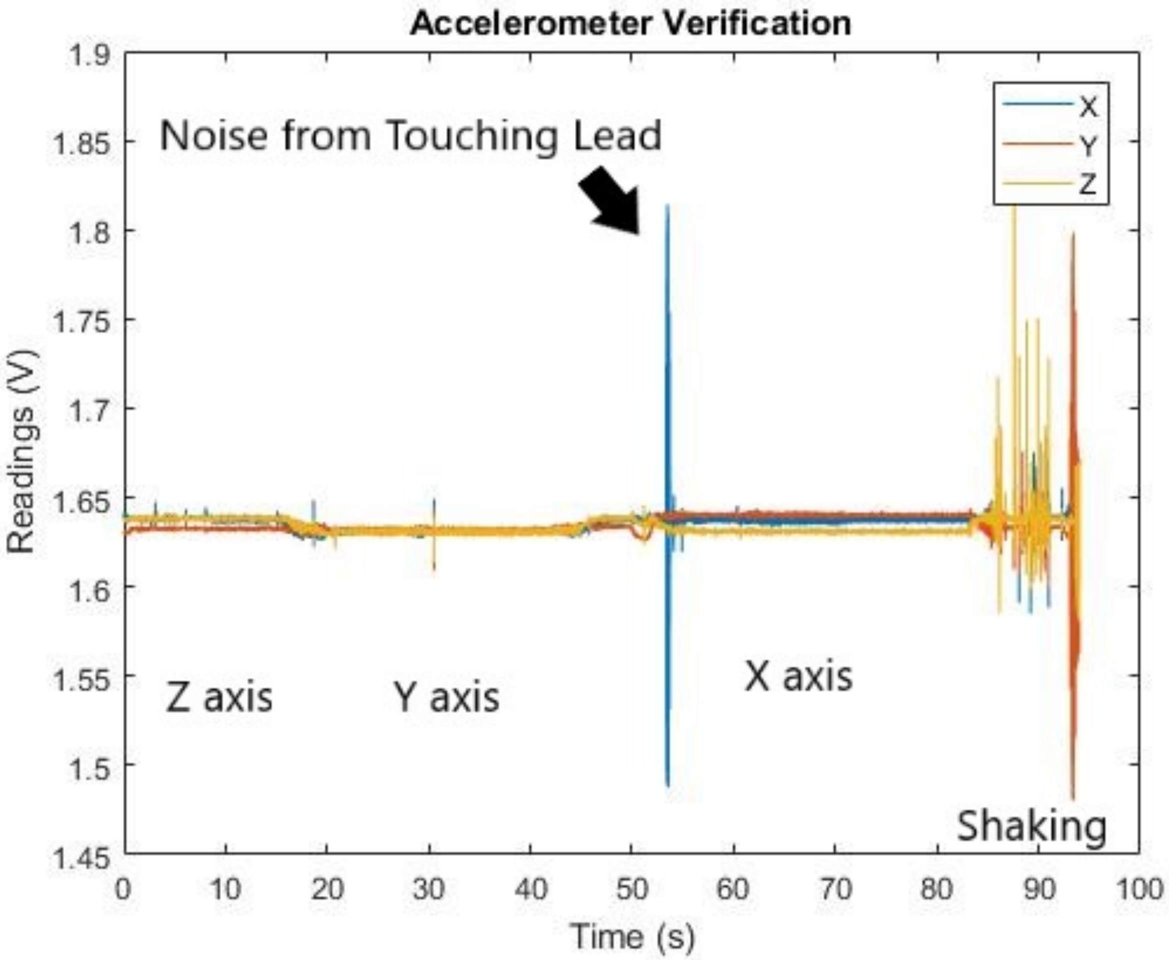
PO | SD | TO | Test Results | SE | PM

Sensor Requirements: Accelerometer



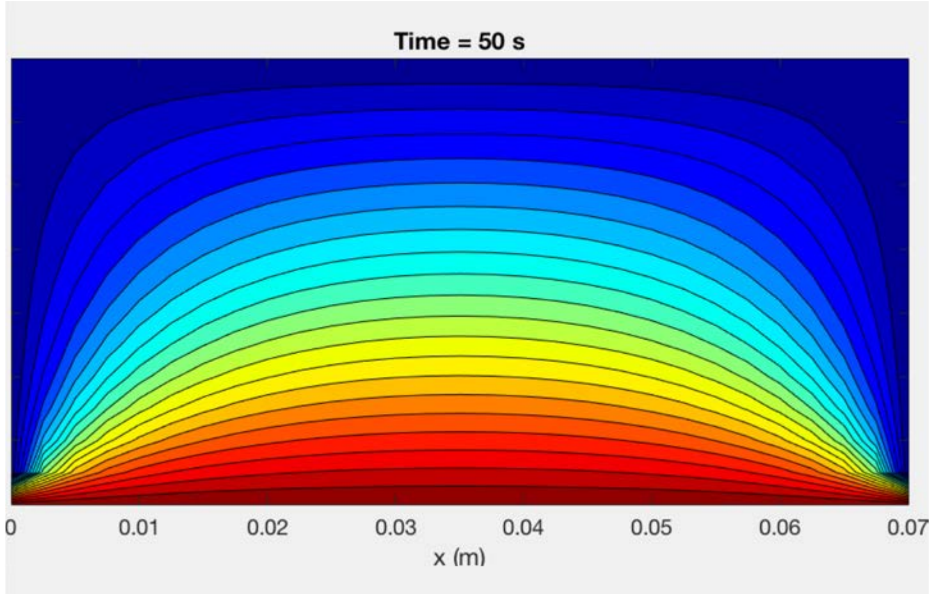
- 481.2 feet of max height per second of burn.
- Sampling at 60 Hz will be adequate to reduce error to 8 feet, thus improving burn time accuracy
- Resolution is not critical for this sensor.
- No high thermal requirements
  - Mounted on push plate.

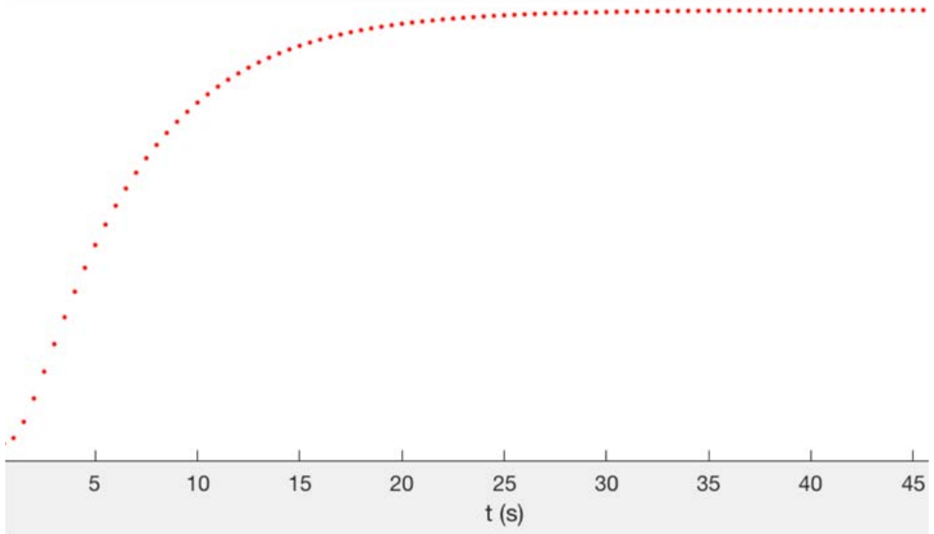
Accelerometer Verification



Sampling Rate: 150 Hz

Satisfied DR 4.5





Sensor Requirements: Nozzle Thermocouples

Assumptions:

- Only graphite, no Aluminum.
- Throat is modelled as a “slice” of the nozzle.
- No convection from the top edge.

Results:

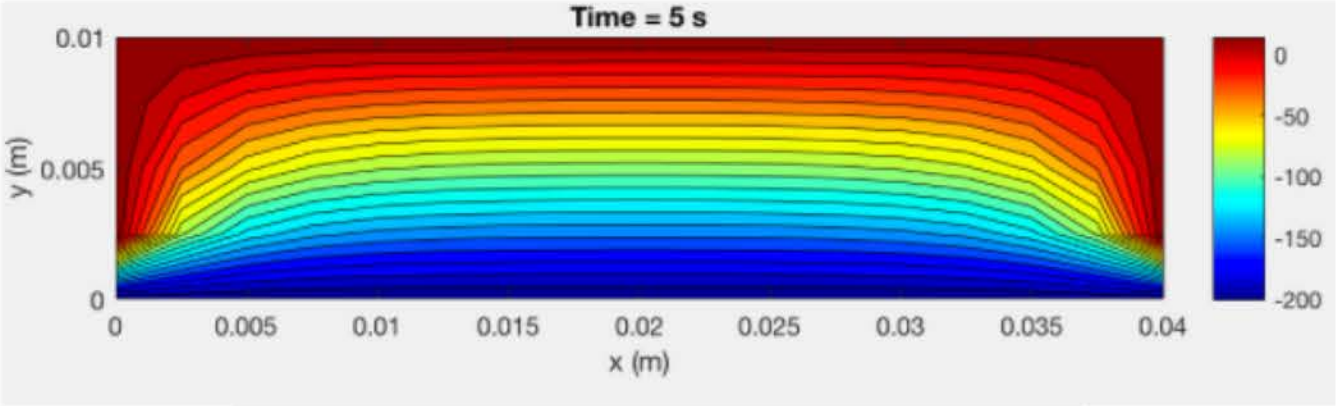
- Fastest change in temperature is around 100°C/s, center of graphite.

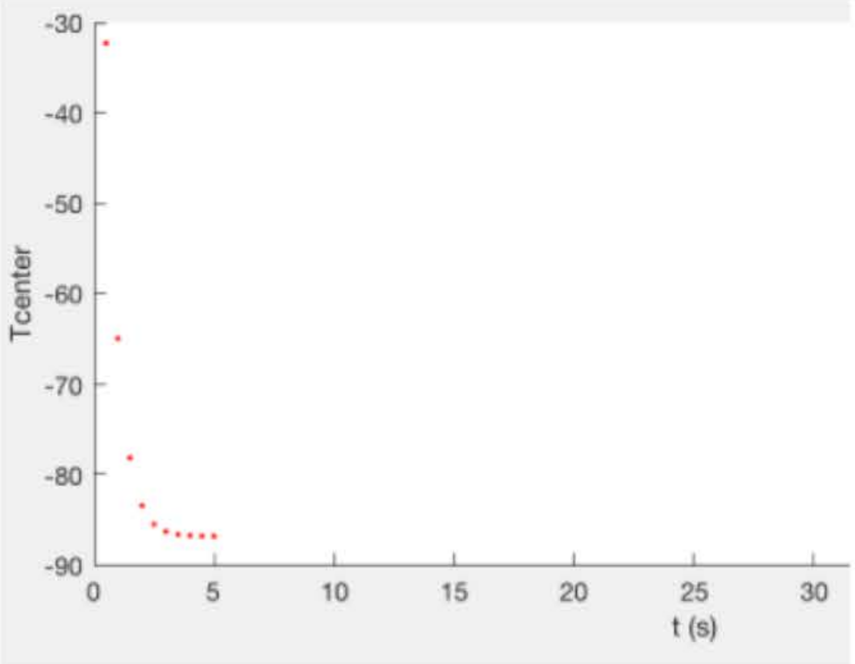
Requirements:

- 10 Hz sampling rate is enough to capture 2°C increments during the fastest changes in temperature.
- Accuracy then must be at least 2° Celsius.
- Must endure 1300°F - aluminum attachment.

Sensor Requirements: Plumbing Thermocouple

- Assumptions:
  - Flow through Aluminum feed lines.
  - No convection from the surface of the feed line.
- Results:
  - Fastest change in temperature is around 90°C/s, center of aluminum wall.
- Requirements:
  - 45 Hz sampling rate is enough to capture 2°C increments during the fastest changes in temperature.
  - Accuracy must be at least 2 °Celsius.
  - Must endure -130 °F temperature - boiling point of N_20.





Thermocouple Verification

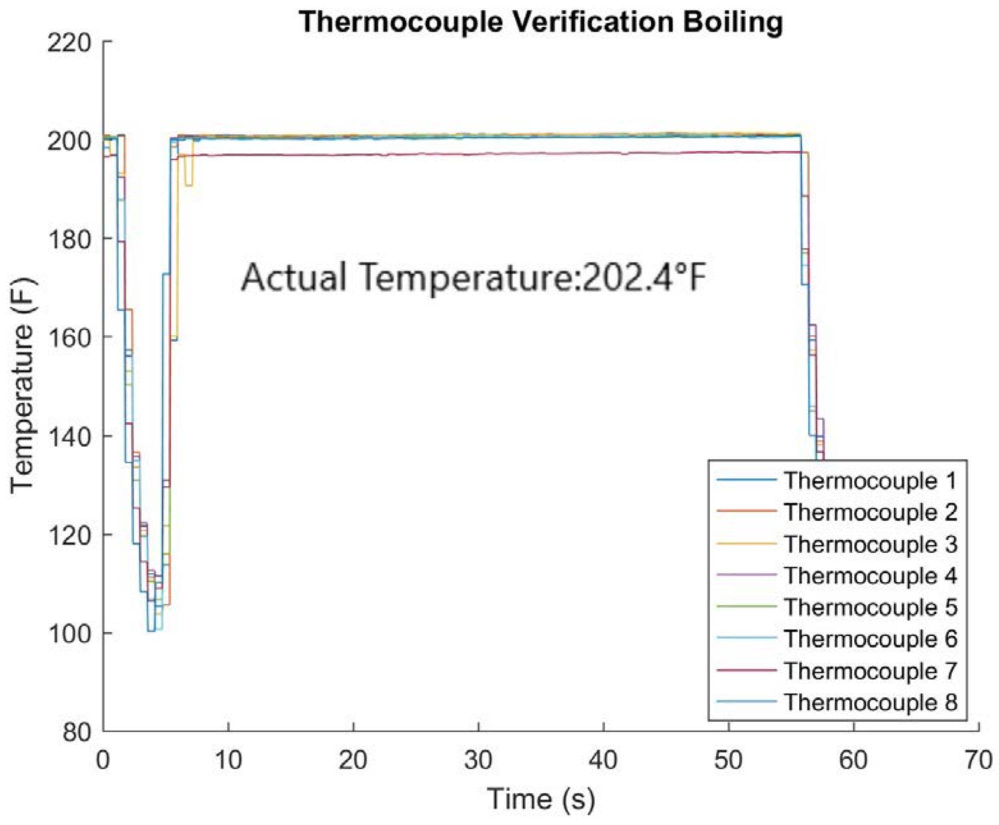
Accuracy of handheld thermocouple: 1°F

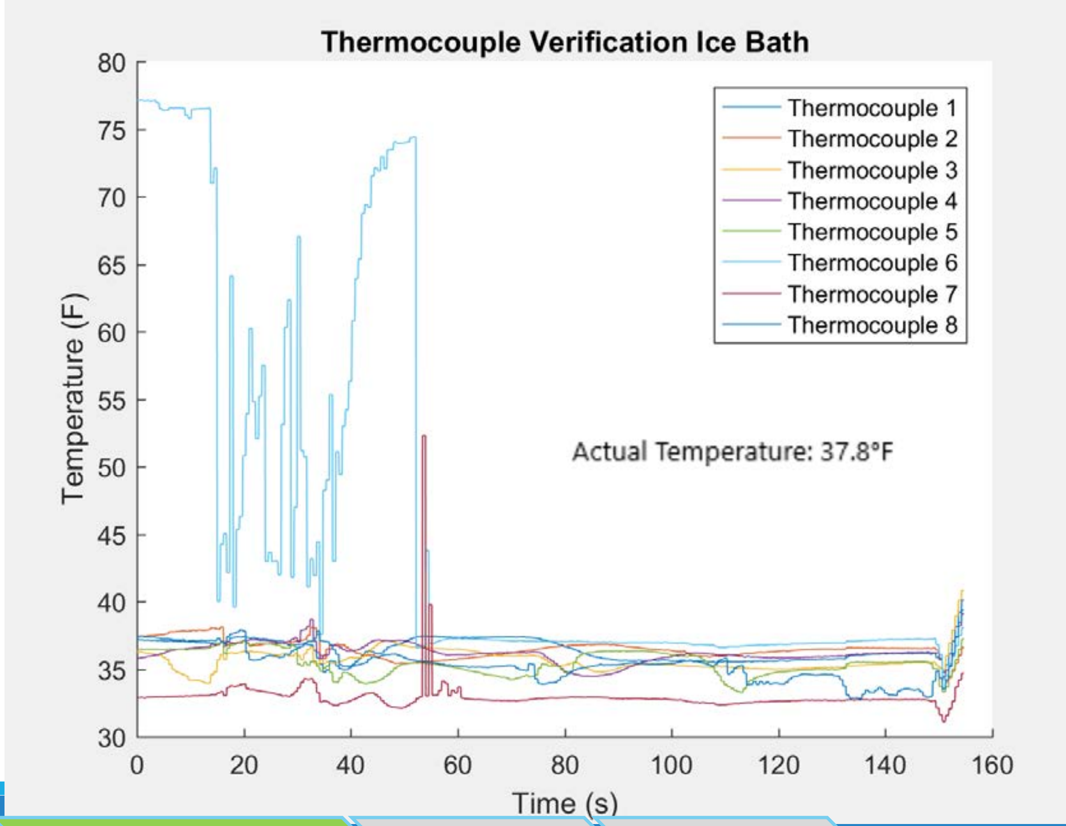
Accuracy of HICKAM thermocouple: 3°F

Final Accuracy: **3.16°F**

Sampling Rate: 15 Hz

Satisfied DR 6.6.5: Accuracies < 4°F Chamber, 5°F Plumbing





Sensor Requirements: Combustion Chamber Pressure Transducer

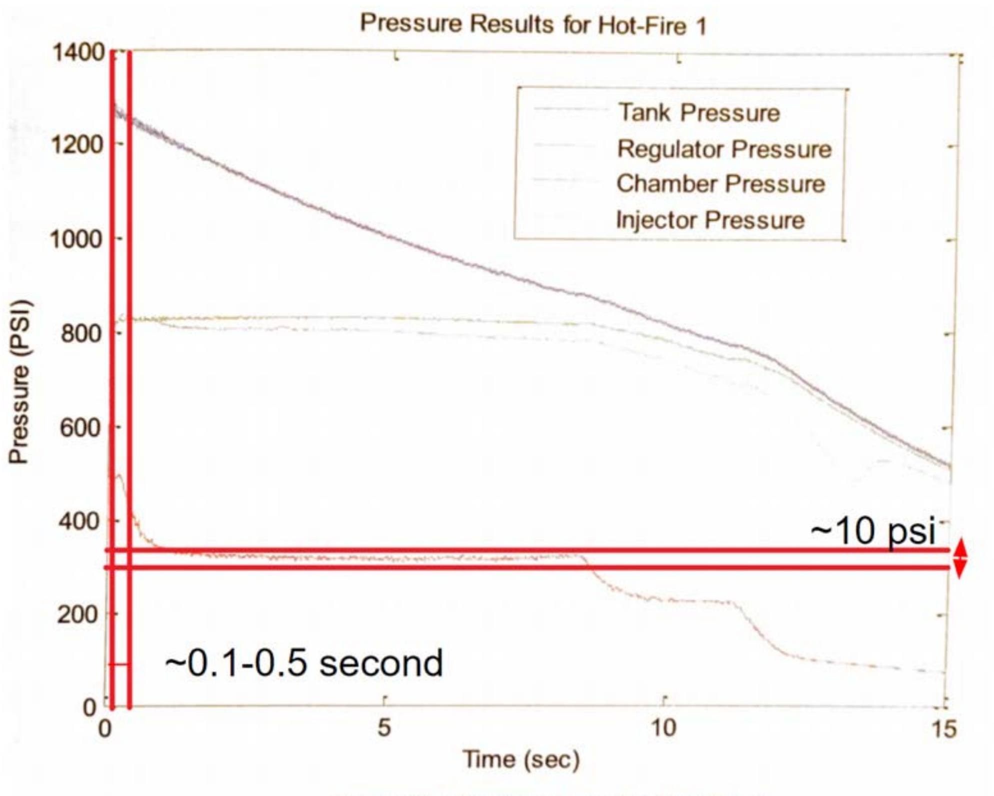


Figure 72: Pressure Data for Hot Fire 1

07-08 Mach-SR1 300lbf Engine Successful Hot Fire Test 2 Data

Observations:

- Pressure peaks between 0.1-0.5 second time frame
- Fluctuation of ~10 psi during steady burn

Results:

- To determine accurate maximum combustion chamber pressure, we would need minimum 50 samples in 0.4 seconds
- Must resolve the combustion chamber pressure to within at least 10% of 10 psia to capture fine changes in combustion chamber pressure

Requirements:

- Sampling Rate: minimum 125 Hz
- Resolution: minimum 1 psi

Sensor Requirements: Load Cell

Determines Accuracy

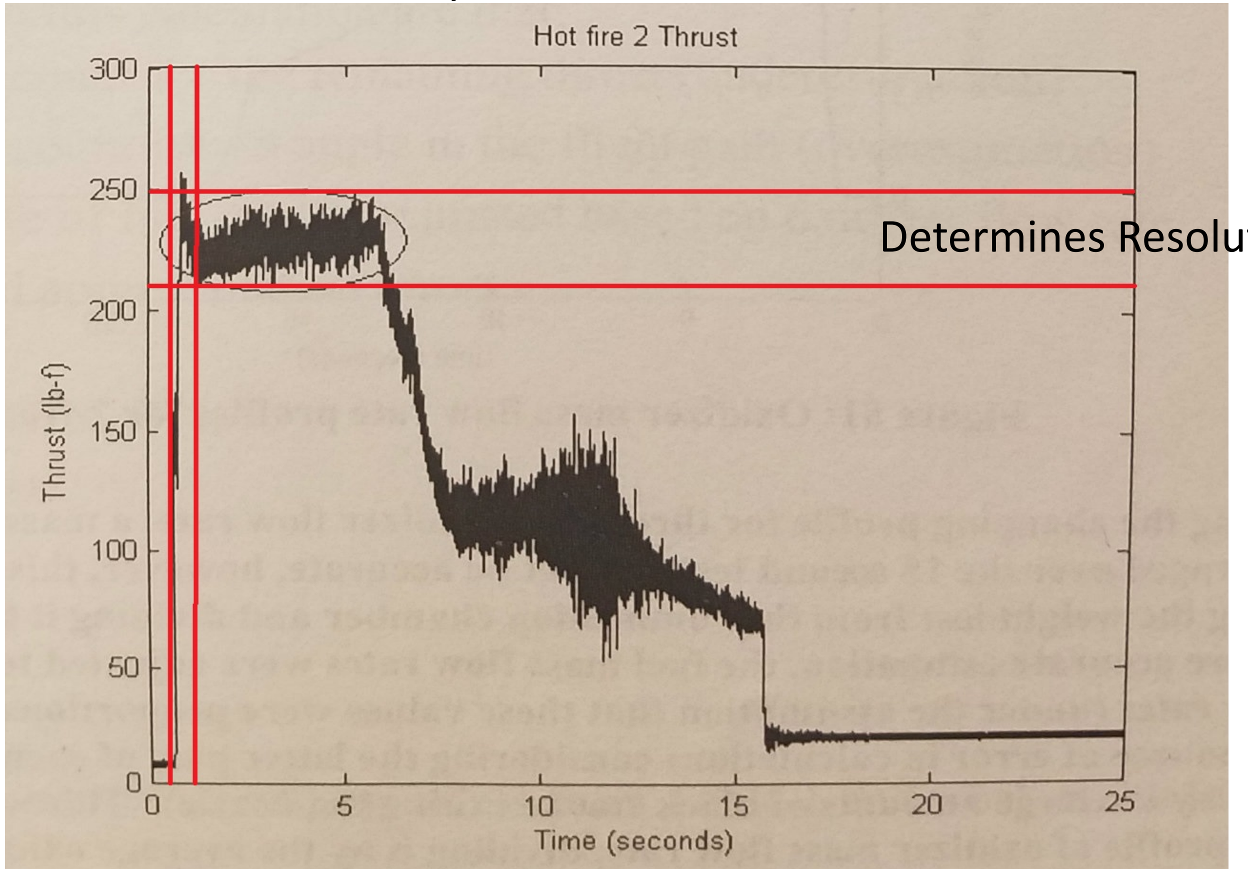
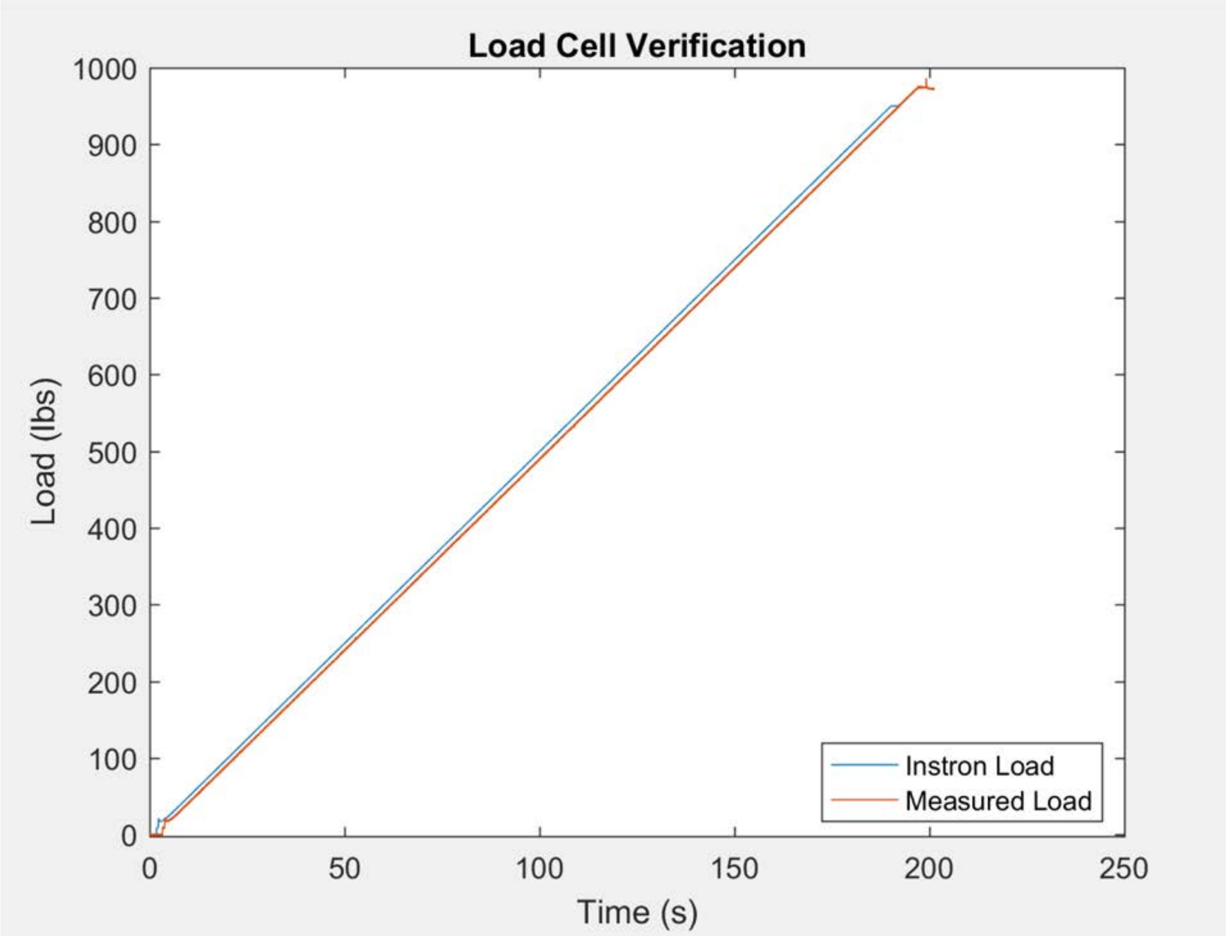


Figure 80: Thrust Profiles for 2 Hot Fires

07-08 Mach-SR1 300lbf Engine Successful Hot Fire Test 2 Data

- Observations:
  - Thrust peaks between 0.5-1 second time frame
  - Fluctuation of ~40 lbf during steady burn
- Results:
  - To determine accurate maximum thrust, we would need minimum ~30 samples in 0.5 seconds
  - Must resolve the thrust to within at least 25% of 40lbf to capture fine changes in thrust
- Requirements:
  - Sampling Rate: minimum 60 Hz
  - Resolution: minimum 10lbf

Load Cell Verification



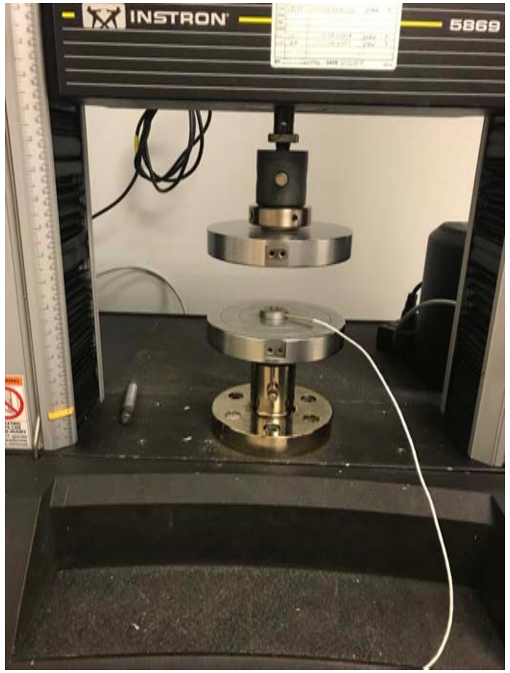
Instron Load Cell Accuracy: 17 lbs

HICKAM Load Cell Accuracy: 21 lbs

Final Accuracy: 2.7%

Sampling Rate: 1.616 kHz

Satisfied DR 4.4: Accuracy < 2.75%



Sampling Rate error calculation

The error in the sampling rate was found using the following equation:

$$f_e = f_s\left(\frac{\pm f_a}{1 \pm f_a}\right) \approx f_s \cdot f_a$$

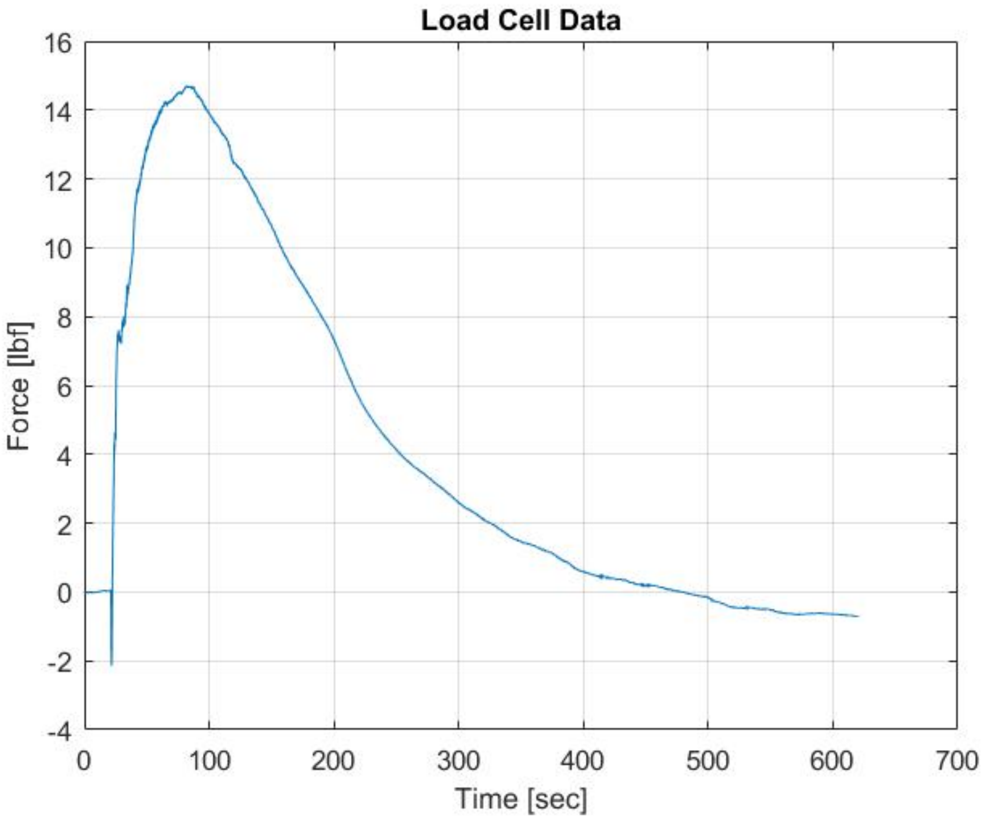
Where f_e is the error in the frequency, f_s is the sampling frequency, and f_a is the frequency accuracy.

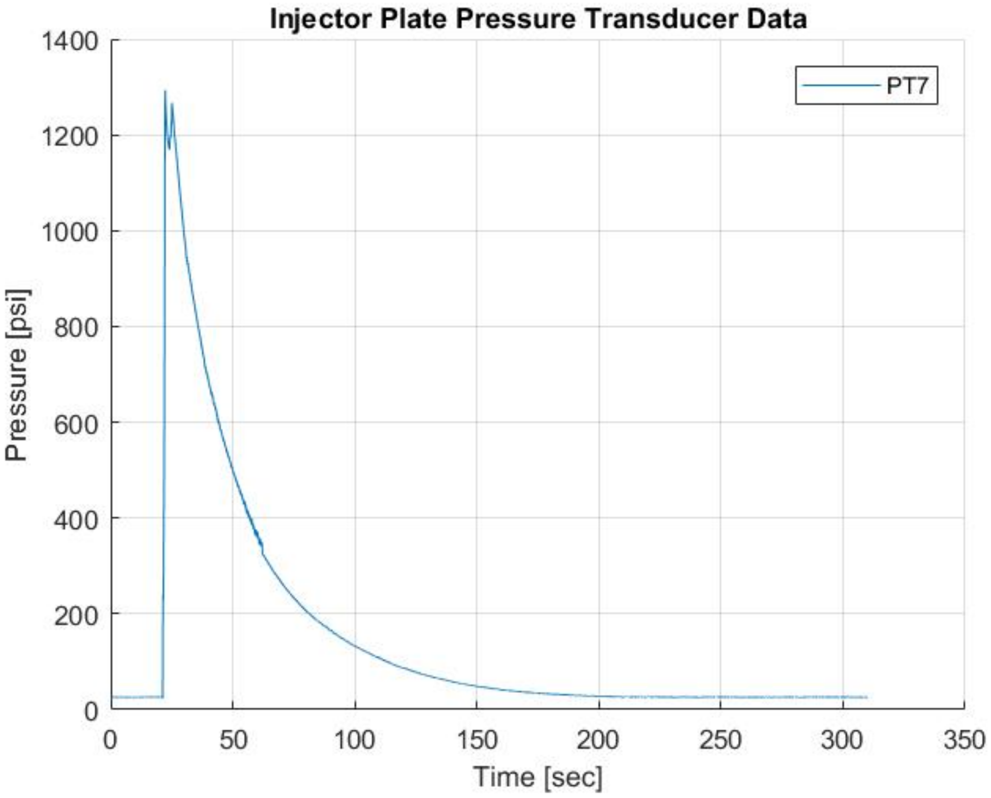
This error was then converted to a percent, for readability.

Cold Flow Observed Results

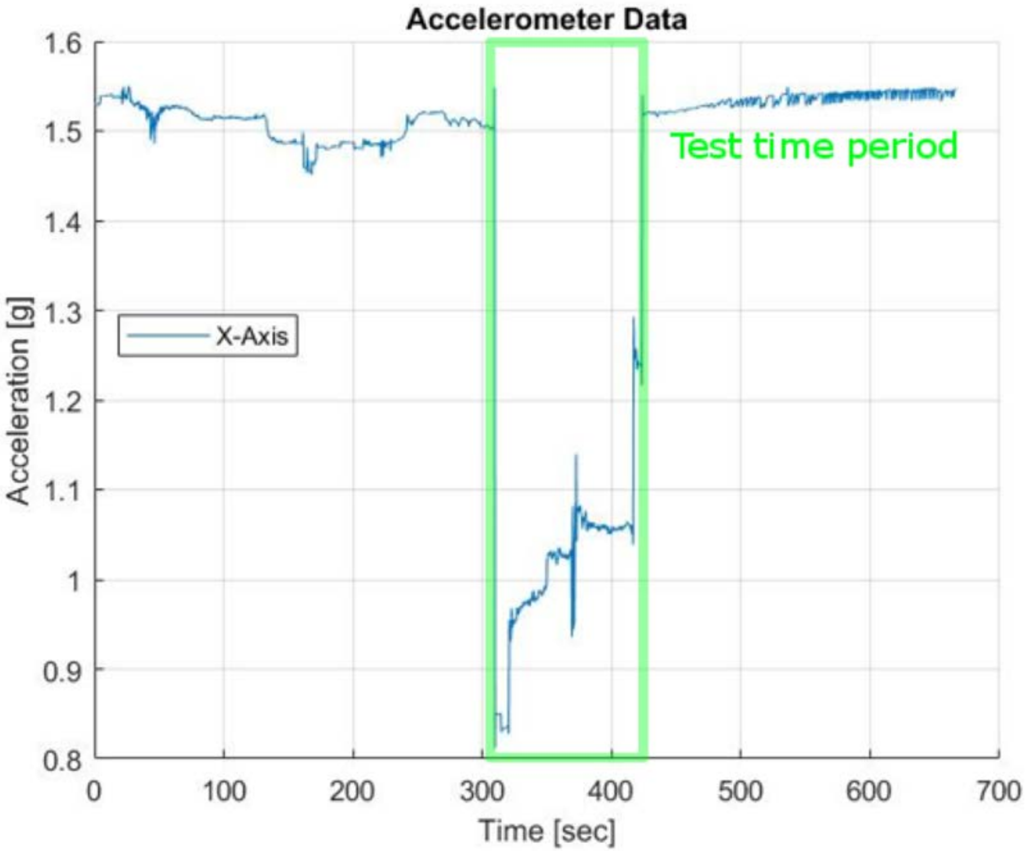
- Oxidizer was not properly pressurized due to incorrect installation of relief valve RV-1
- Pre-injector pressure at PT-4 not measured due to incorrect installation of relief valve RV-2
- "Main Valve" was found to have a leak while actuating
- Rocket motor was found to have a small leak between injector and endcap
- Mass flow rate measured at 0.89 lbm/s, 100% of model prediction
- Successful liquid flow through injector plate for approximately 12s

Cold Flow Trial 2 Data Results



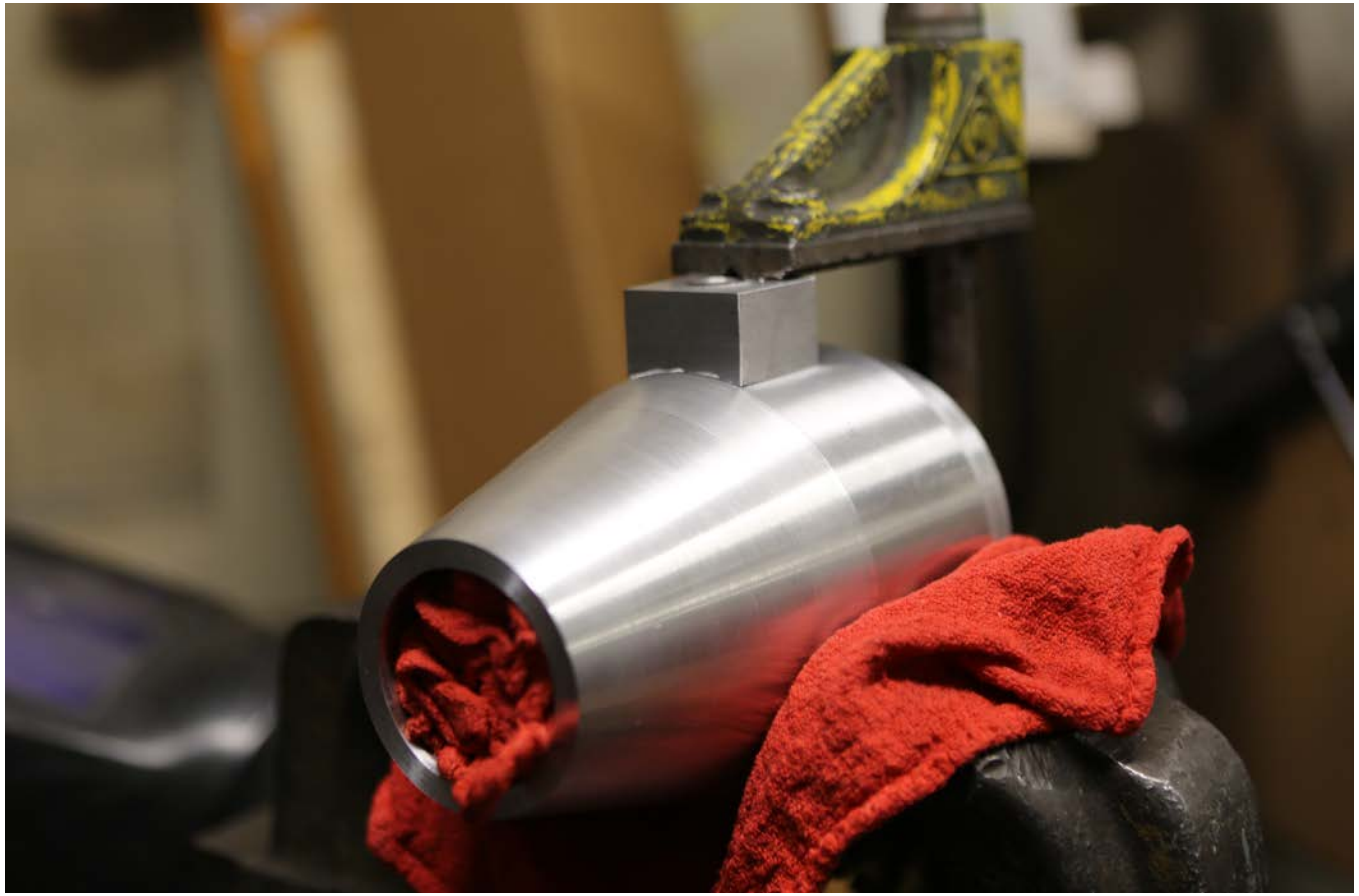


"Hot Fire“ Accelerometer Results



Hot Fire 1

Combustion Chamber Pressure Transducer



Combustion Chamber Pressure Transducer

Cost without Donation Estimation

Donor	Donation	Estimated Cost
Swagelok Denver	Feed system materials	$6,000
Emerson	MFM transmitter and ProLink software	$10,000
Omega	Pressure transducers, high temp thermocouple material	$800
McGuckin	Gift card	$150
Aerospace Department	Additional funds	$3,000
FSI	Cerafiber	$500
ITLL	DAQ System, LabView, MFM	$25,000
Aerospace Department Labs (Trudy and Matt)	Load cell, thermocouple materials, pressure transducers, stock material	$1,600