CU Senior Projects 2017-2018

HICKAM

Hybrid-rocket Information-Collection, Knowledgebase and Analysis Module

Orbital ATK

HICKAM TRR

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Swagelok

Orbital ATK

Agenda

- Overview
- Schedule
- Test Readiness
  - Project Models
  - Test Breakdown
  - Test Details
- Budget

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

<u>H</u>ybrid-rocket <u>I</u>nformation-<u>C</u>ollection, <u>K</u>nowledgebase and <u>A</u>nalysis <u>M</u>odule (**HICKAM**)

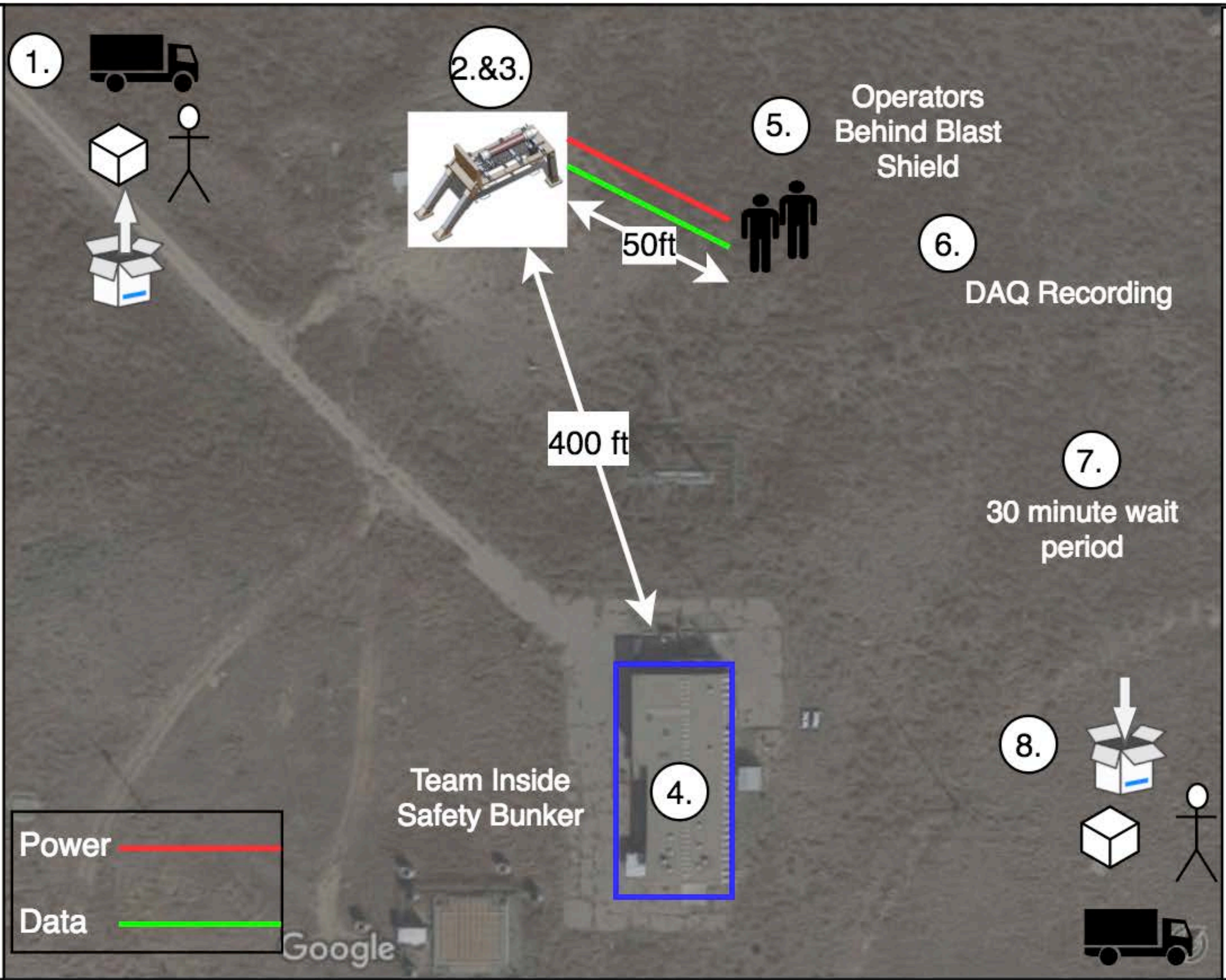
Pre - Test

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

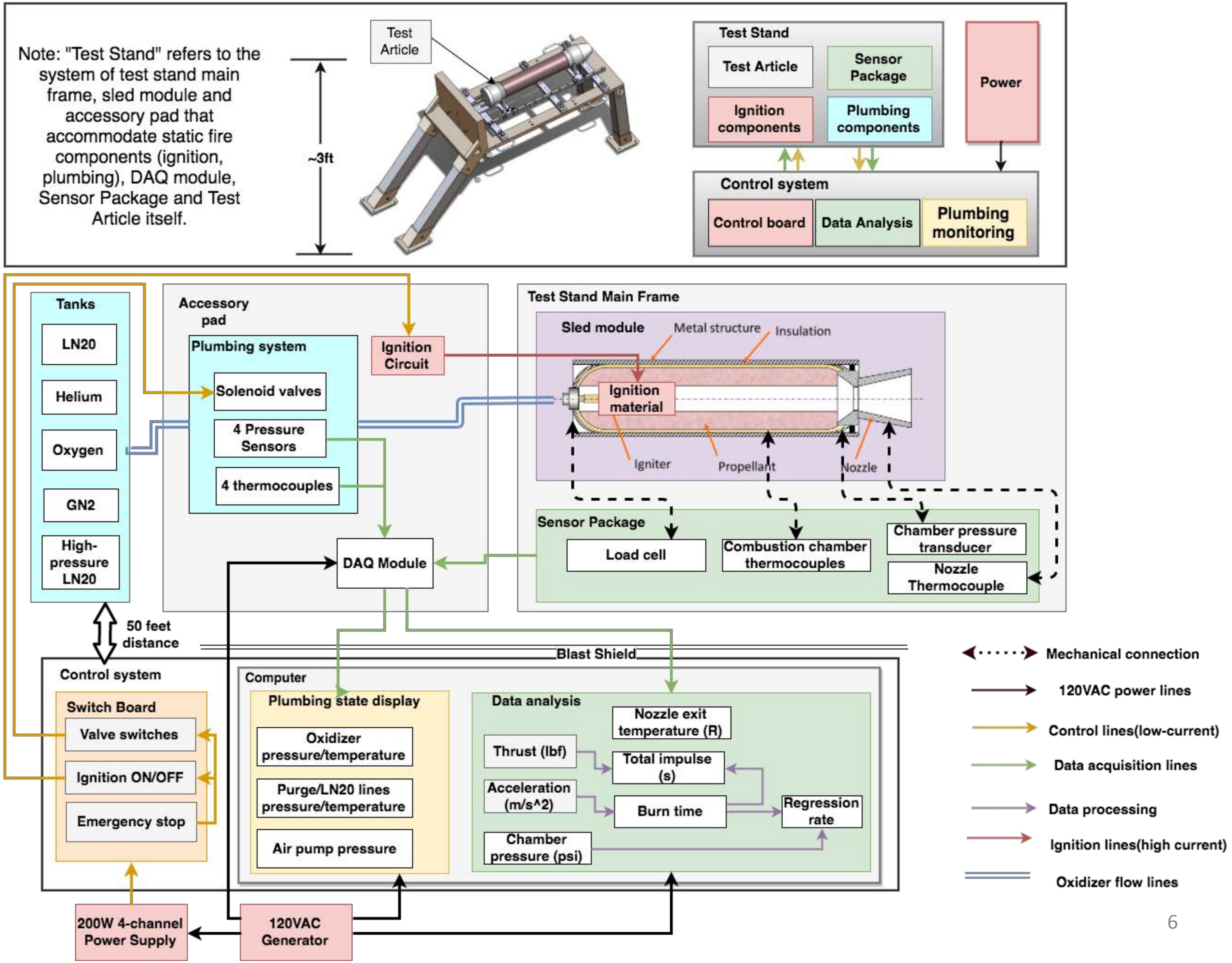
ASEN 4028: Des Practicum

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

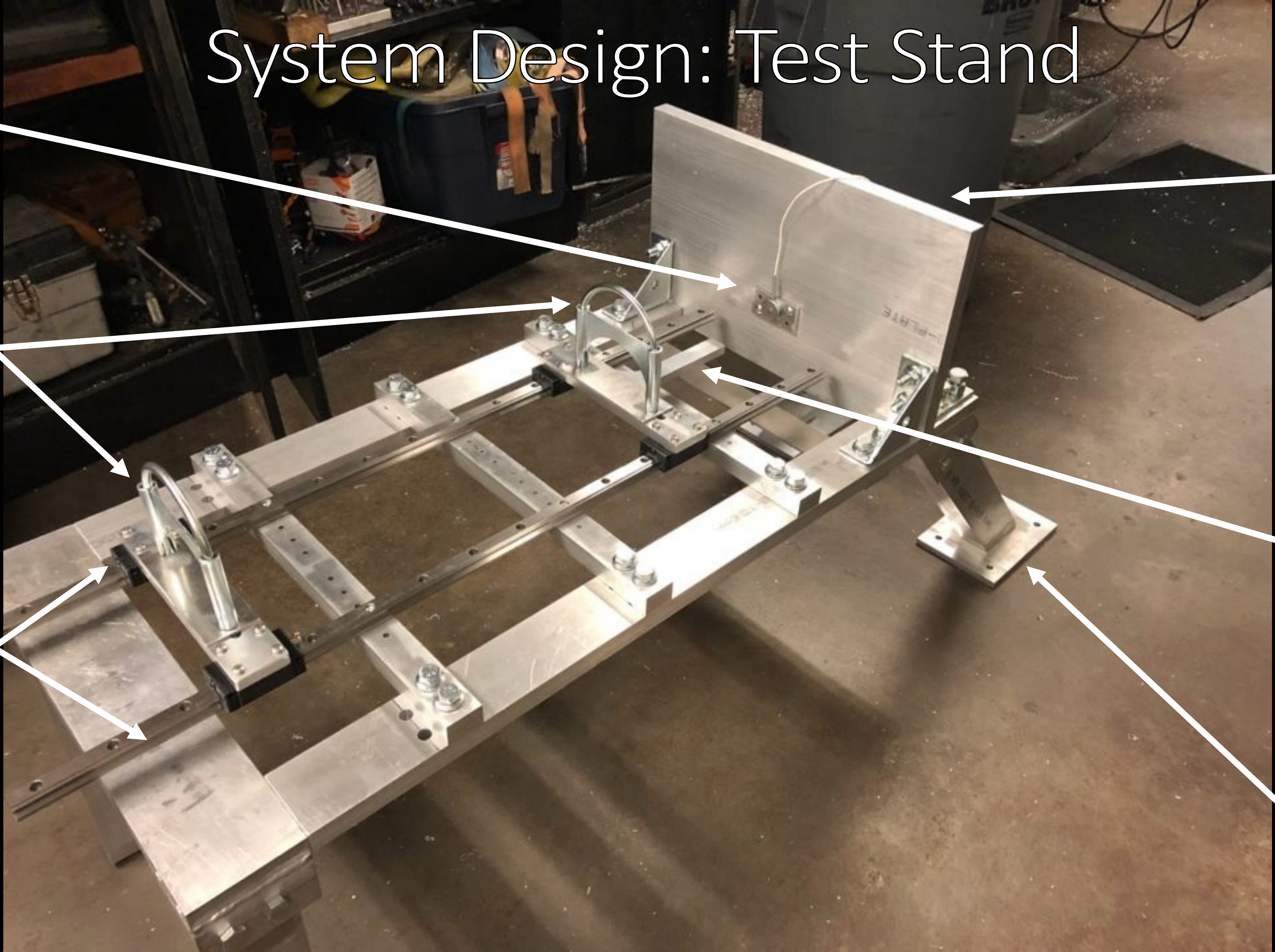
FBD



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.
~3ft
Test Article
Test Stand
Test Article
Sensor Package
Ignition components
Plumbing components
Power
Control system
Control board
Data Analysis
Plumbing monitoring
Tanks
LN20
Helium
Oxygen
GN2
High-pressure LN20
Accessory pad
Plumbing system
Solenoid valves
4 Pressure Sensors
4 thermocouples
Ignition Circuit
DAQ Module
Test Stand Main Frame
Sled module
Metal structure
Insulation
Ignition material
Igniter
Propellant
Nozzle
Sensor Package
Load cell
Combustion chamber thermocouples
Chamber pressure transducer
Nozzle Thermocouple
50 feet distance
Blast Shield
Control system
Switch Board
Valve switches
Ignition ON/OFF
Emergency stop
Computer
Plumbing state display
Oxidizer pressure/temperature
Purge/LN20 lines pressure/temperature
Air pump pressure
Data analysis
Nozzle exit temperature (R)
Thrust (lbf)
Total impulse (s)
Acceleration (m/s^2)
Burn time
Regression rate
Chamber pressure (psi)
200W 4-channel Power Supply
120VAC Generator
Mechanical connection
120VAC power lines
Control lines(low-current)
Data acquisition lines
Data processing
Ignition lines(high current)
Oxidizer flow lines

System Design

System Design: Test Stand



Load Cell

Blast Shield & Plumbing Mount

U-Bolts

Push Plate

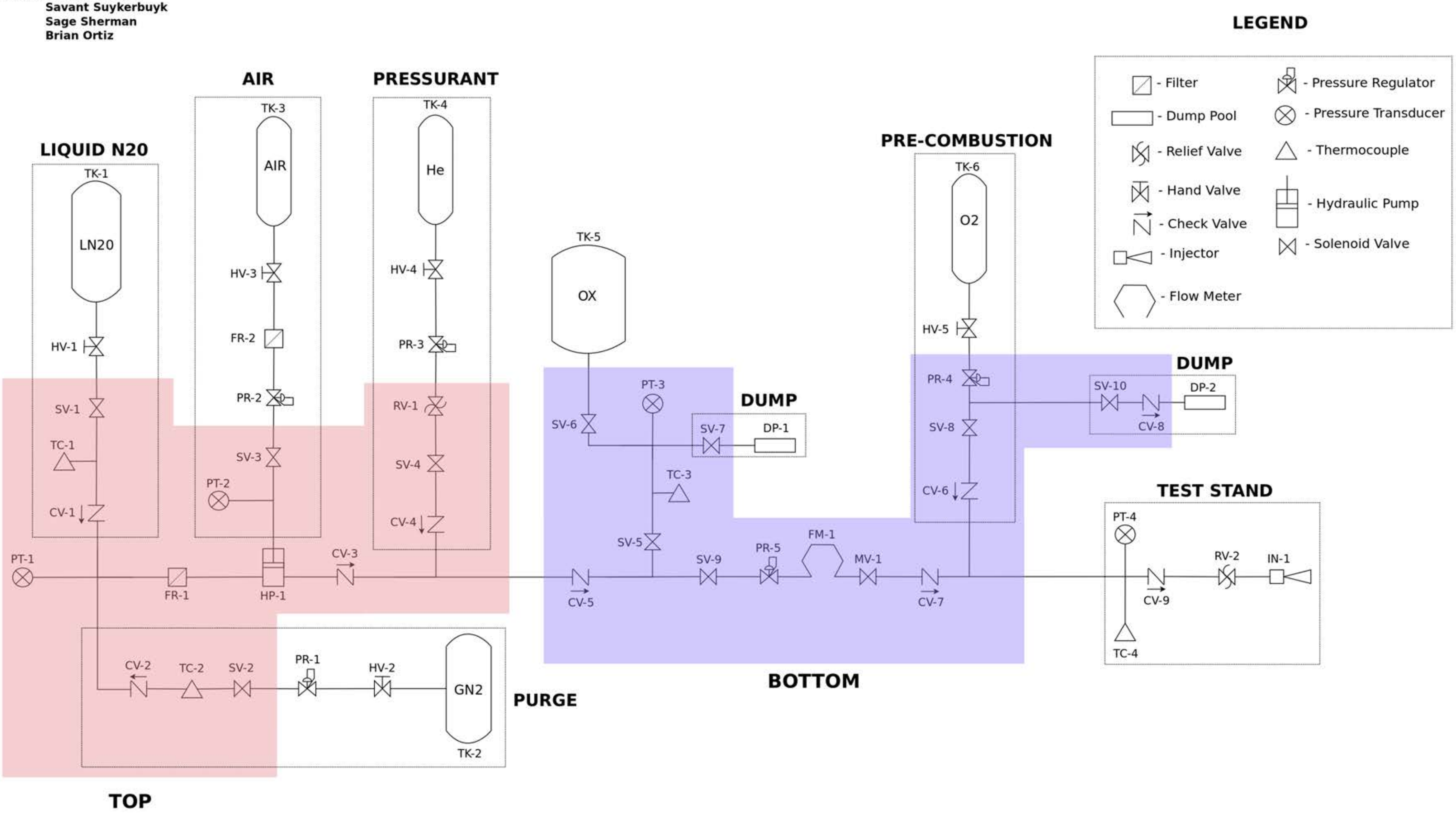
Axial Rails

Foot Pads with Ground Anchor Holes

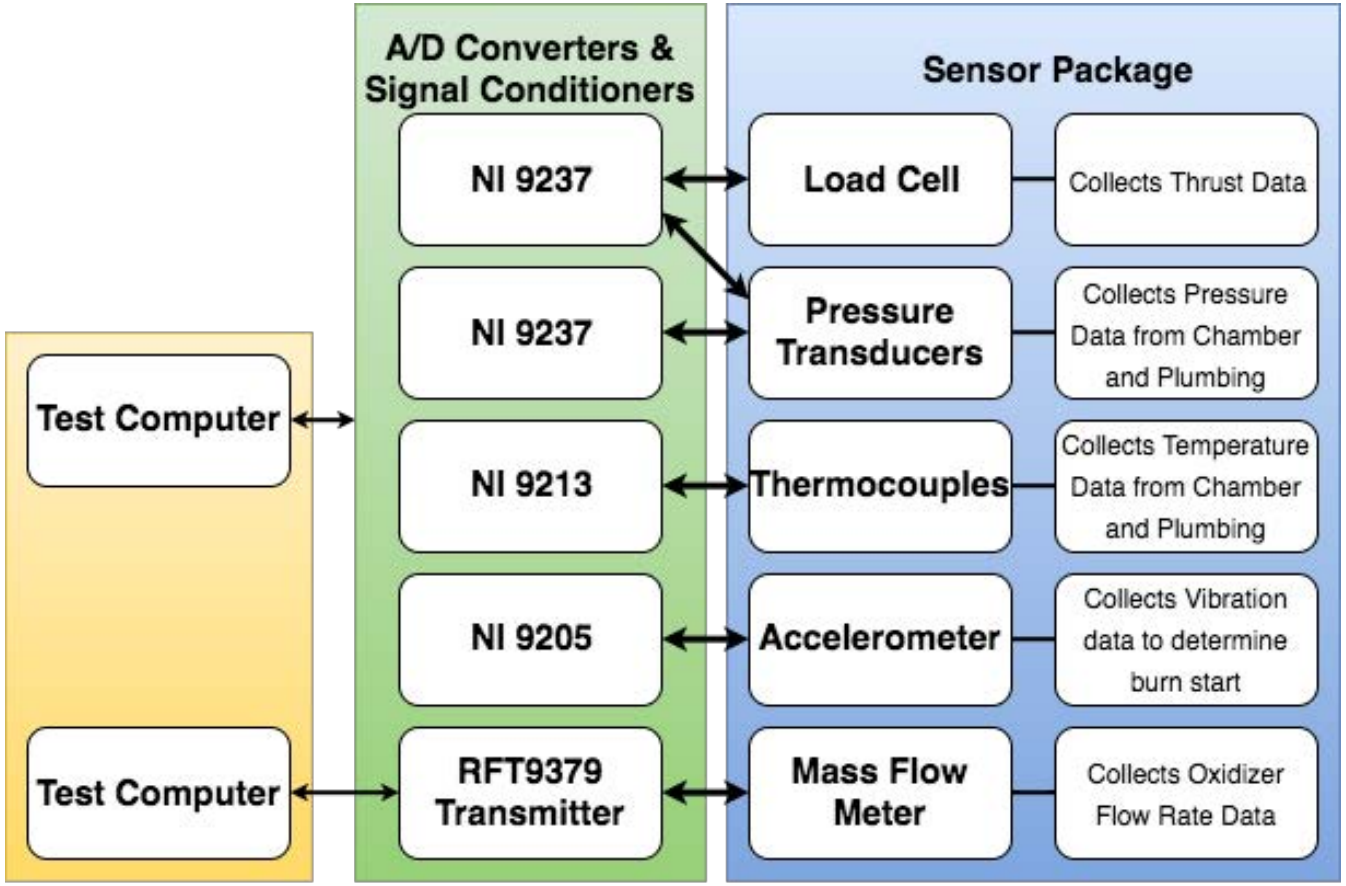
System Design: Test Stand

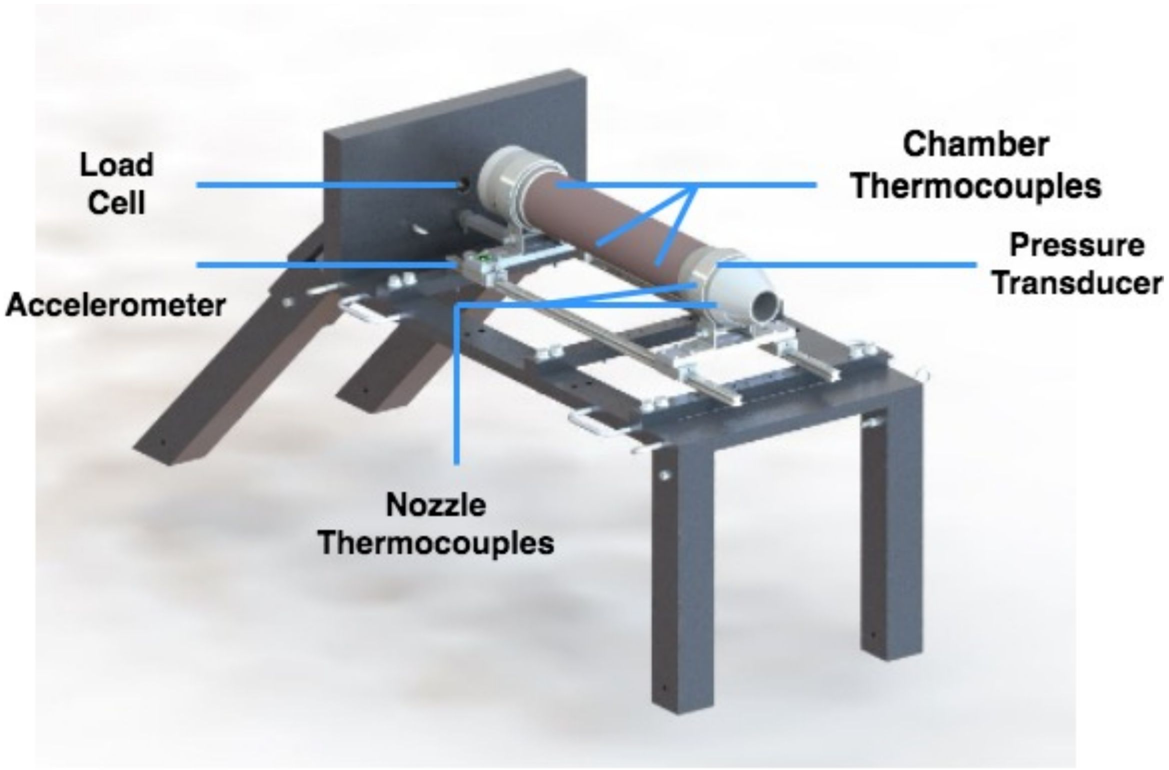
System Design: Feed System

Authors: Gerardo Pulido
Savant Suykerbuyk
Sage Sherman
Brian Ortiz

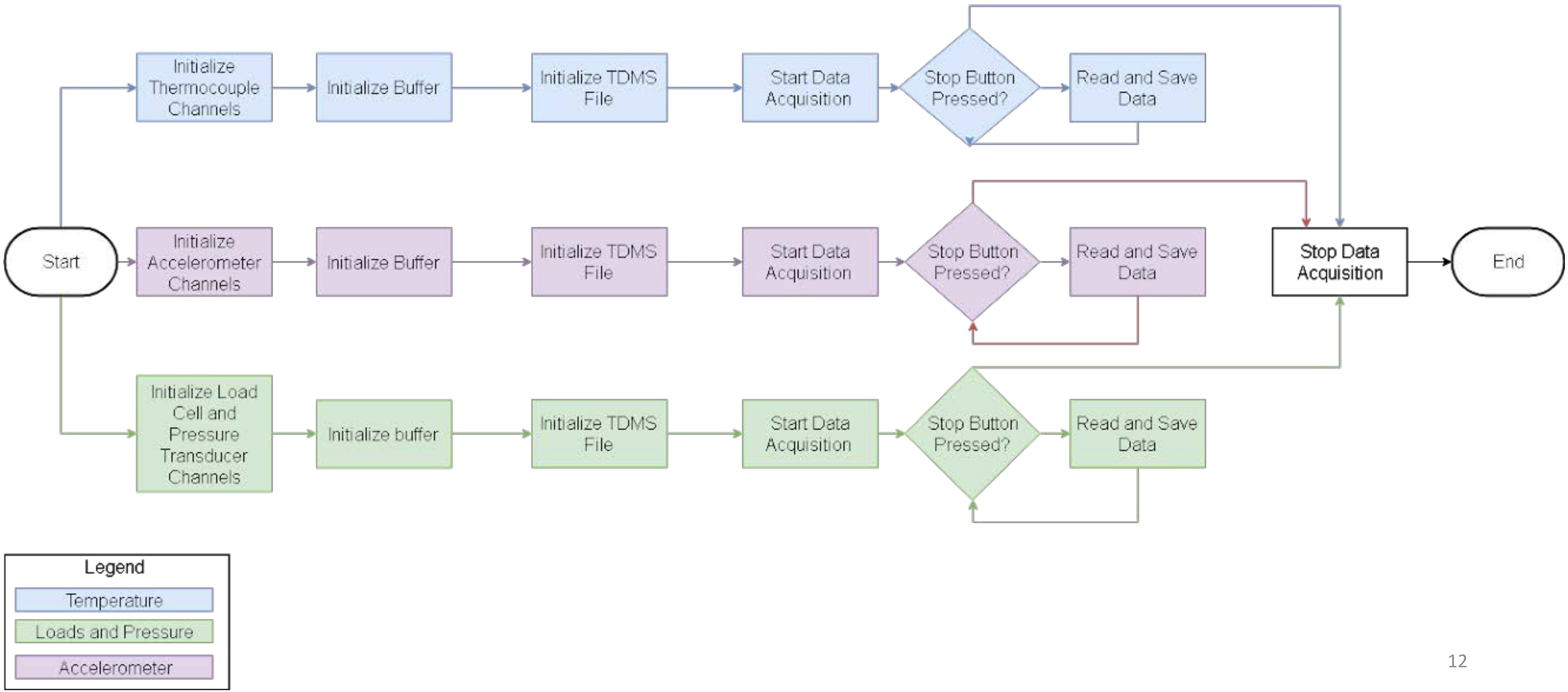


System Design: Data Acquisition



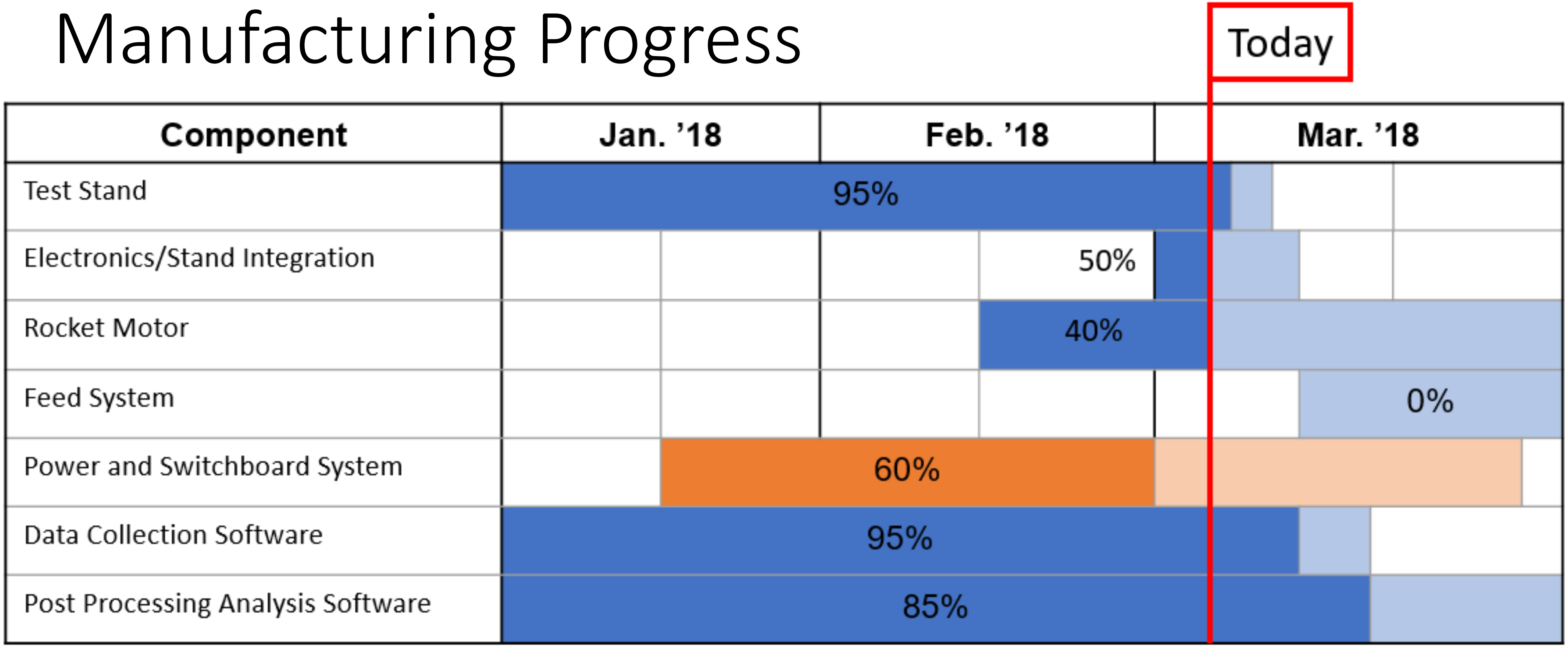


System Design: Software



Schedule

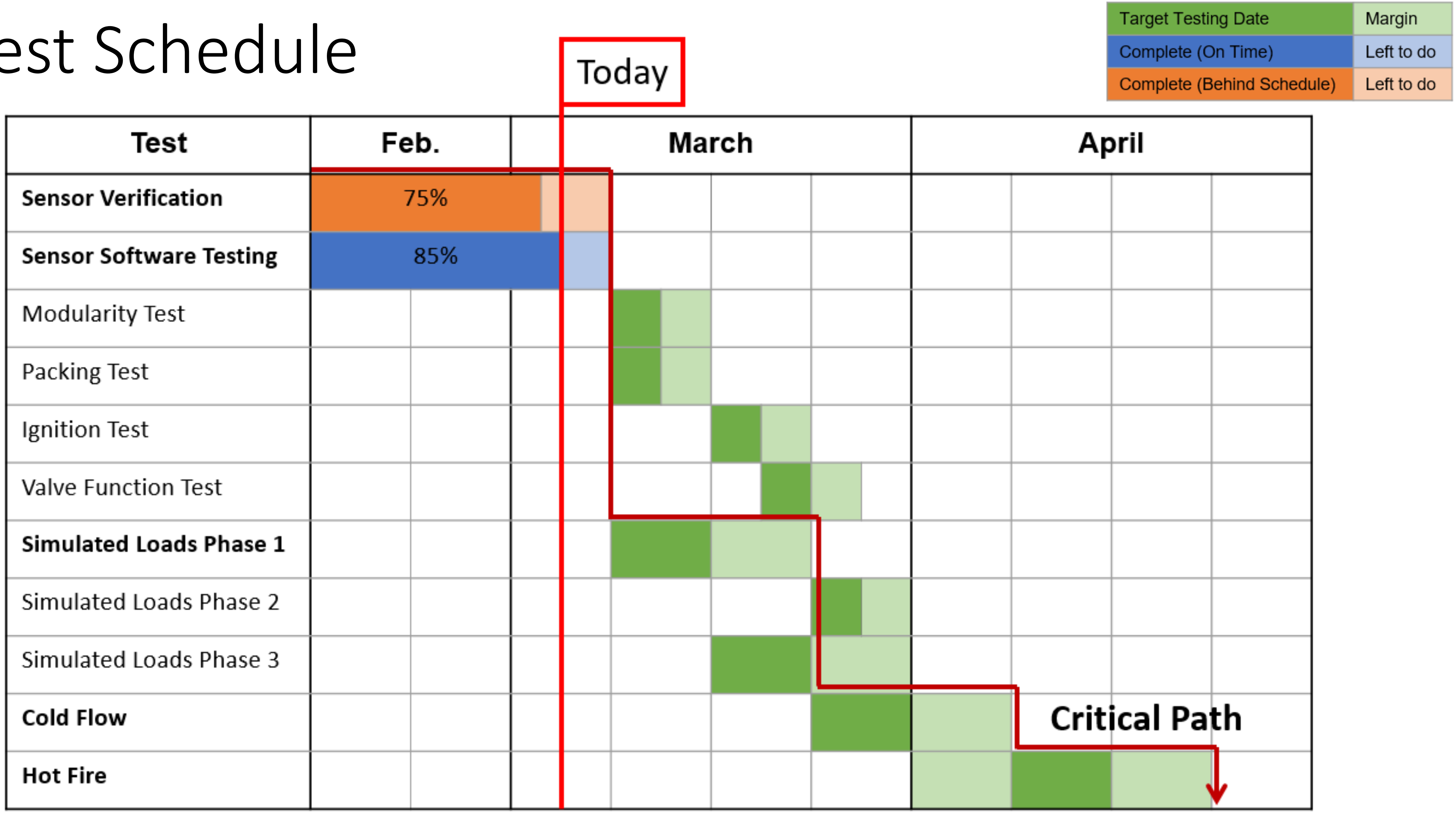
Manufacturing Progress



Complete (On Time)	Left to do
Complete (Behind Schedule)	Left to do

- Switchboard delay due to:
  - Redesign to include relays
  - Redesign of ignition monitoring system

Test Schedule

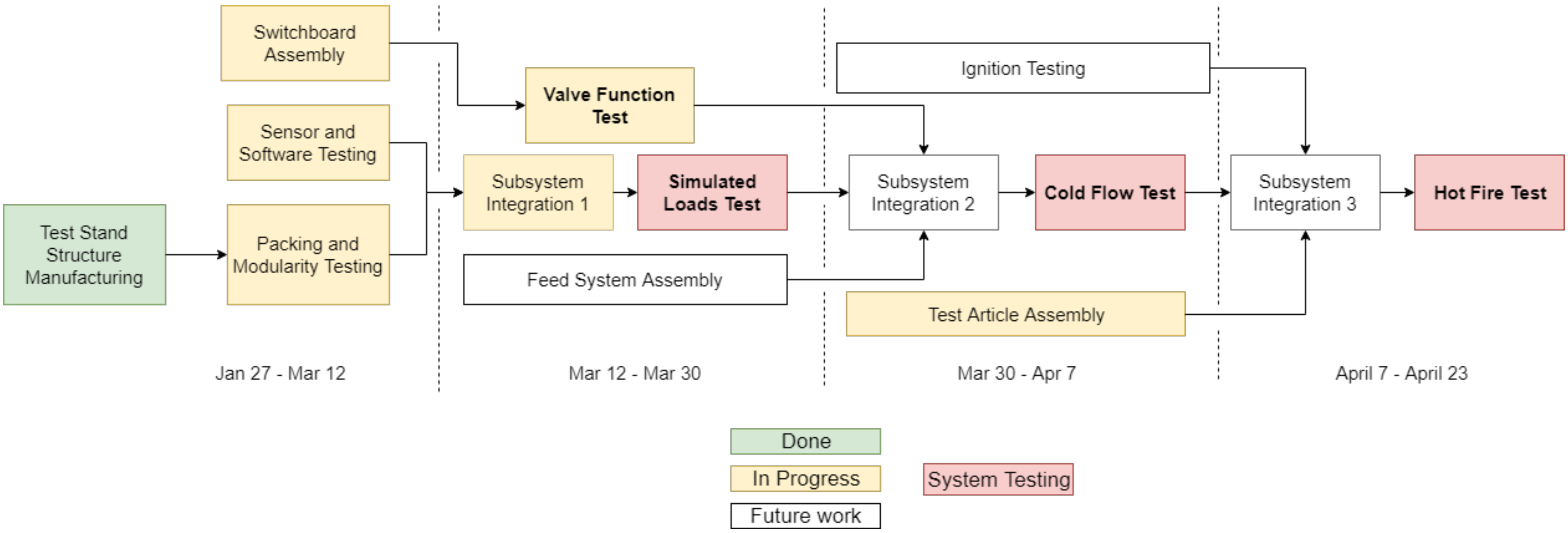


- Sensor verification delay due to procurement delay

Test Readiness

Project Models

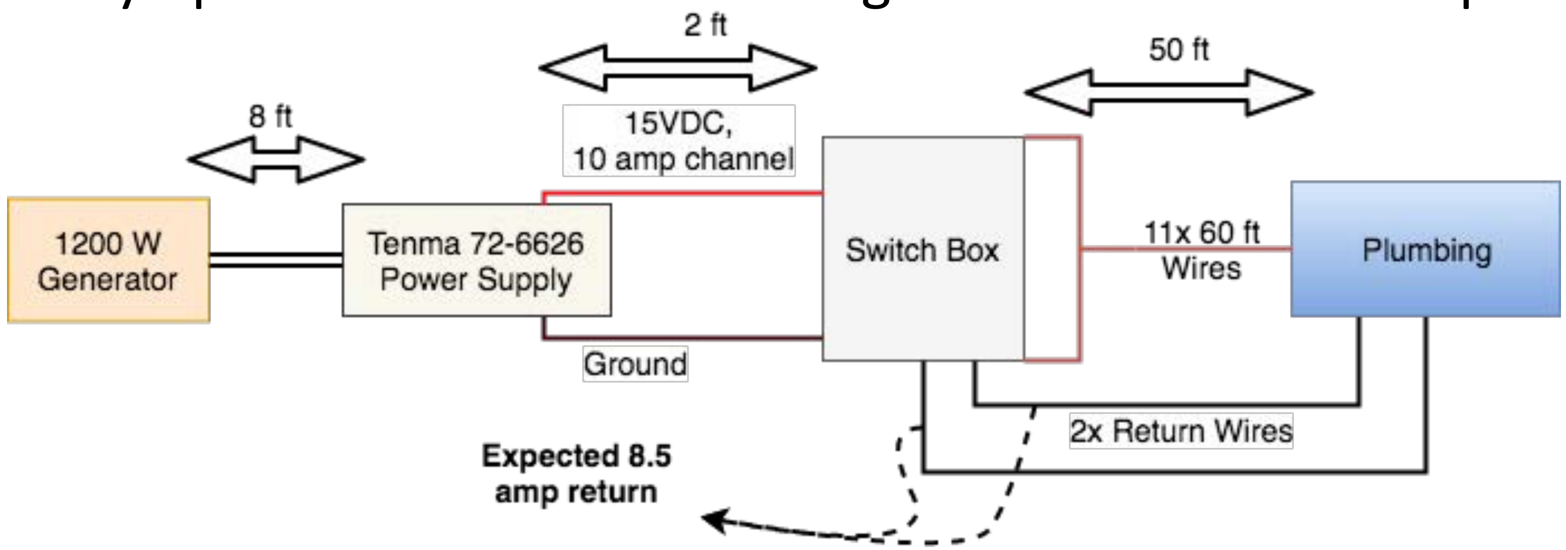
Power Budget Model	Validated through Switchboard Test
Off-Axial Load Model	Validated through Simulated Loads Phase 1
Nozzle Flow Model	Validated through Simulated Loads Phase 2
Mass Flow Model	Validated through Cold Flow Test
Pressure Transducer Model	Validated through Hot Fire Test



Subsystem Integration Plan

Valve Function Test

- Test Overview: Integrate full power chain with the solenoid valves, actuate each valve individually, then actuate 5 valves simultaneously for at least 3 hours.
- Test Purpose:
  - Verify functionality of solenoid valves with switchboard
  - Verify sufficient power delivery with maximum solenoid valve actuation
  - Verify operation endurance through extended actuation period



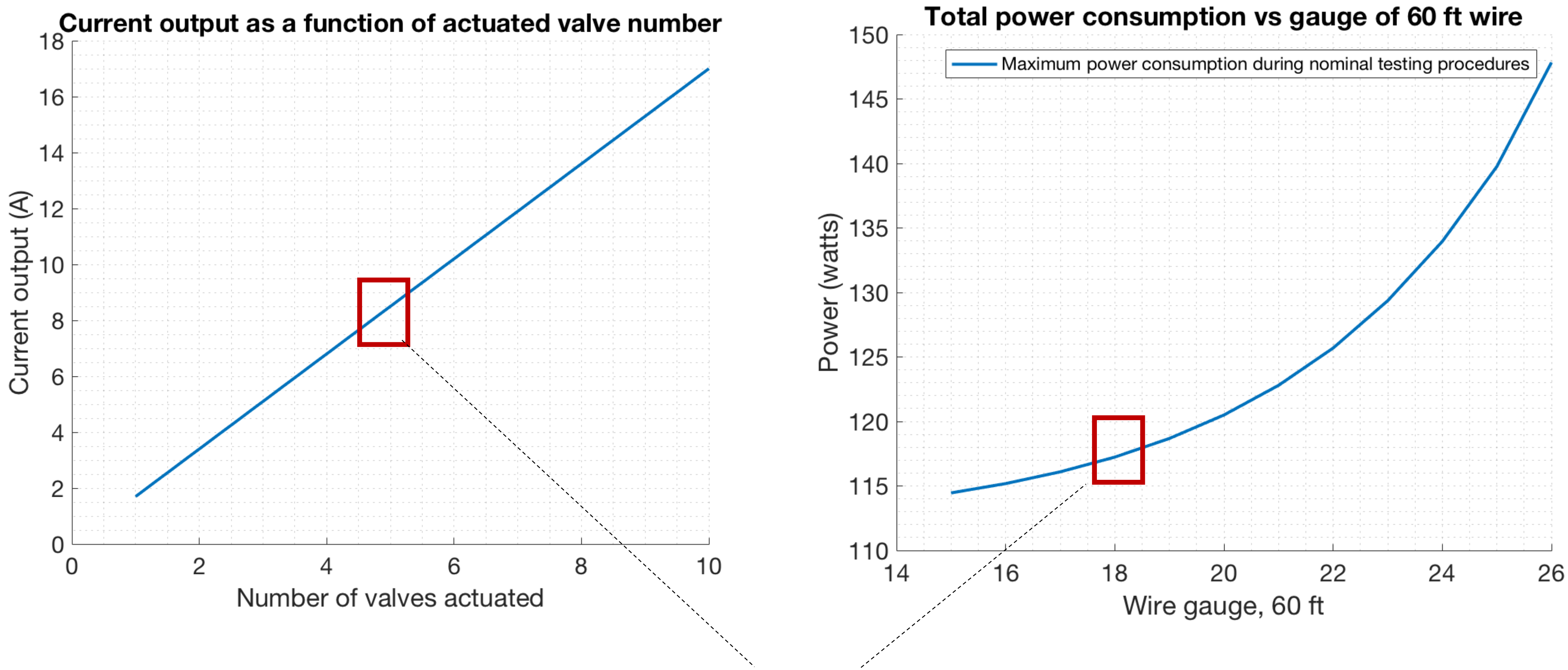
Valve Function Test Logistics

Location	Machine Shop
Date	March 22nd-23rd
Duration	2 days
DRs Verified	6.1, 6.2, 6.3.1, 6.3.2

Equipment
• Generator • Tenma 72-6626 Power Supply • Fully integrated and tested switchbox • Integrated plumbing w/o pre-combustion • 12 wire harnesses

Data Gathered	Post Processing
• Amount of amps drawn from the power supply • Voltage adjustments to account for wire length • Final valve temperature • Valve actuation time	• Total power drawn calculation • Valve temperature rating assessment

Power Budget Model



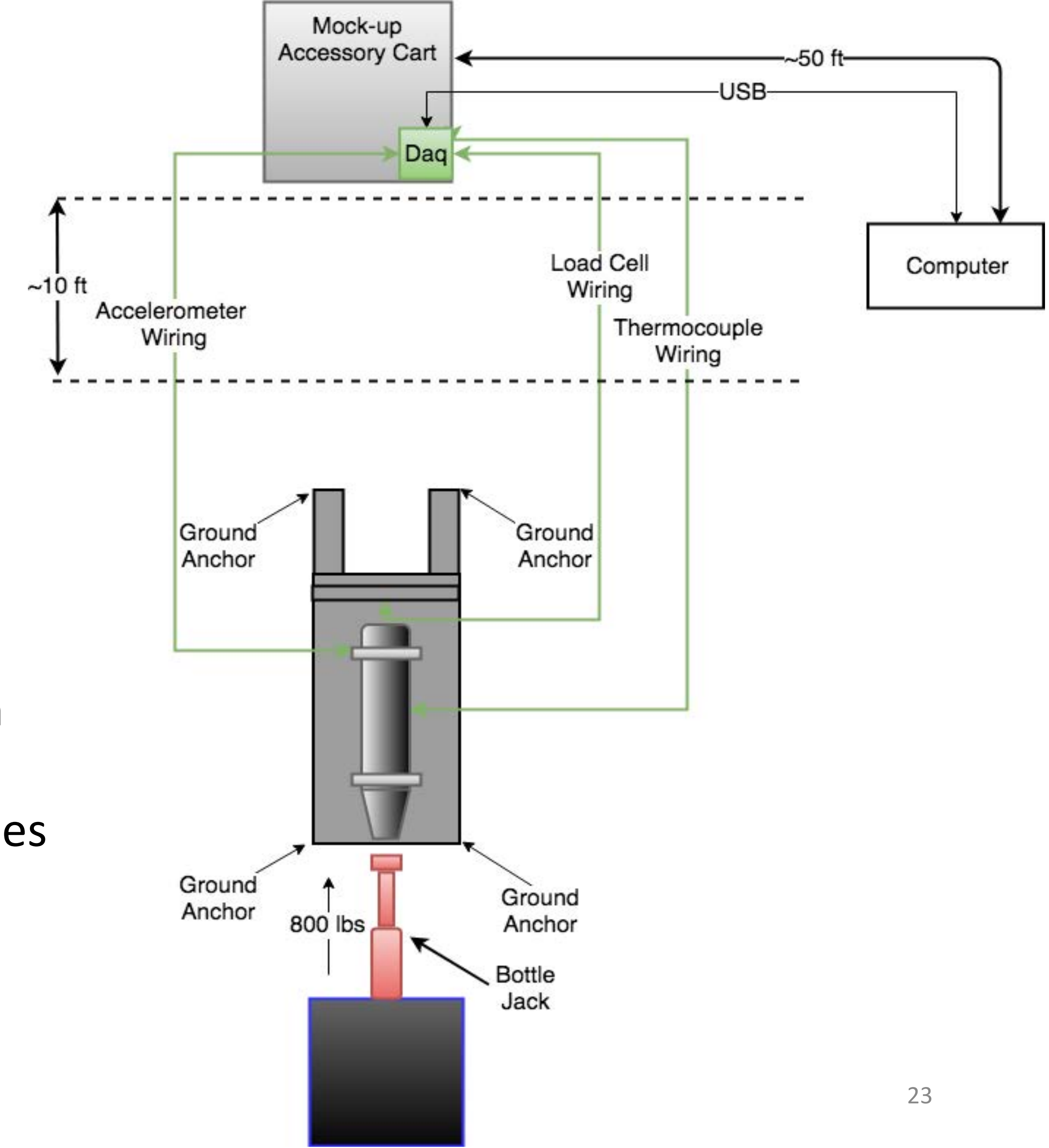
For 18 AWG wire, expected power consumption is 117 W and max current draw of 8.5 A with maximum error of 15%

Simulated Loads Testing

- Test Overview: Three phases to prove the functionality of the test stand
  - Phase 1: Simulated thrust
  - Phase 2: Simulated heating
  - Phase 3: Simulated pressures
- Test Purpose: Use simulated rocket conditions to verify that the test stand can collect data. This will confirm level 1 success of the project
- Test Status: Test Procedure complete. Preparing to start Phase 1, obtaining equipment for Phases 2 & 3

Simulated Loads Testing - Phase 1

- 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 800 lbf.
  - Verify that off-axis loading at 17 degrees will not damage the rails.
  - Verify sampling rates of the DAQ.



Phase 1 Logistics

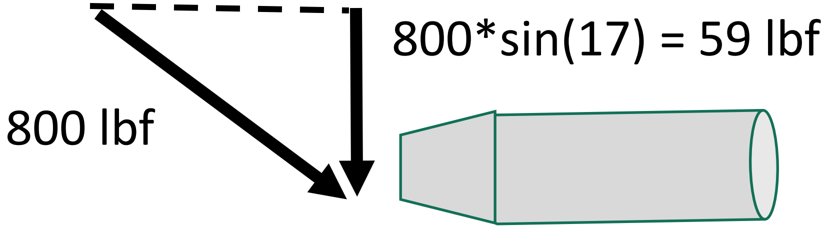
Location	Machine Shop
Date	March 12th-16th
Duration	2-3 days
DRs Verified	1.1, 1.2, 3.1, 4.2, 5.2, 5.3, 6.1, 6.8

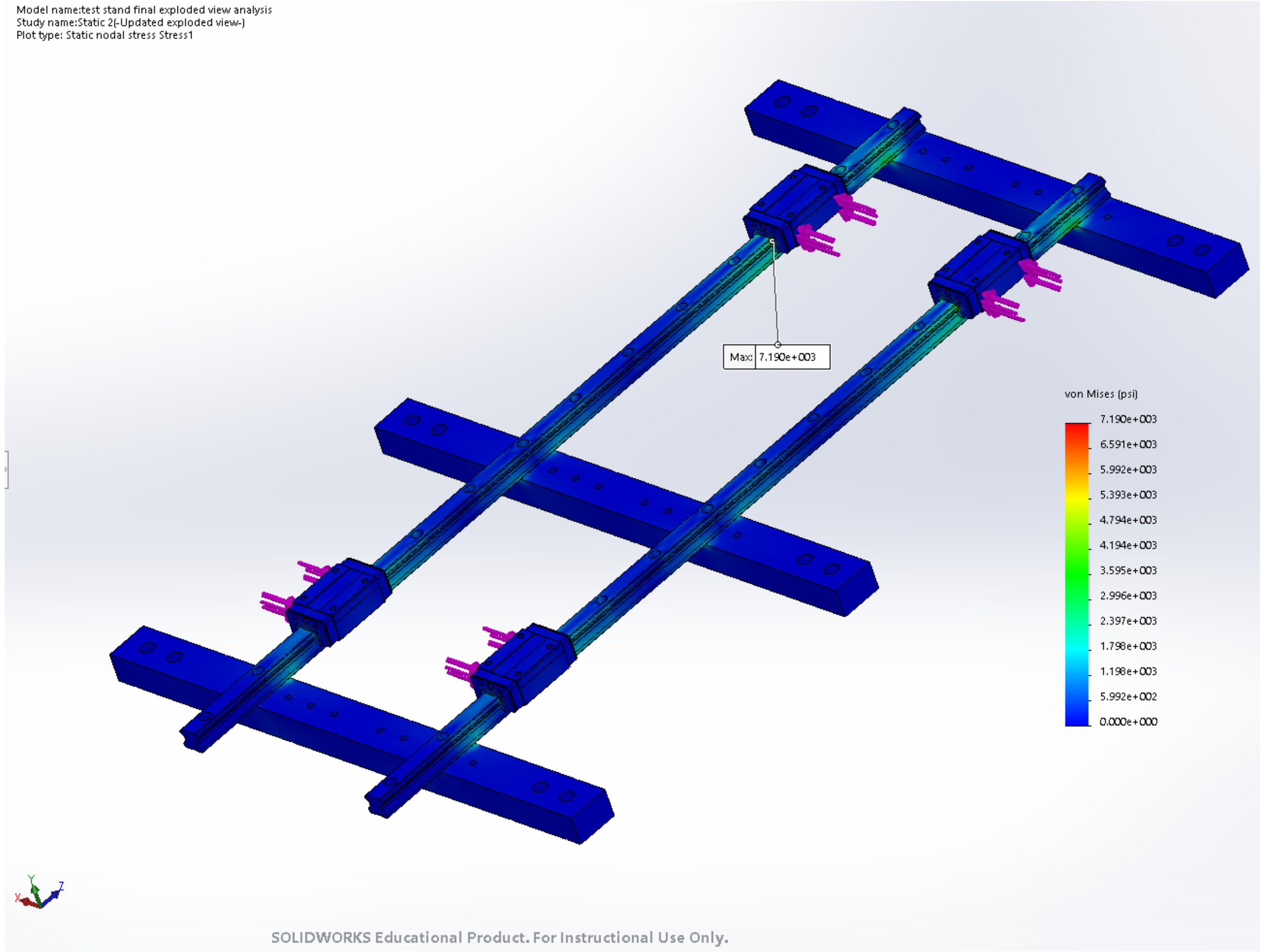
Equipment
• HICKAM Test Stand • HICKAM DAQ System • Bottle Jack • Drill for ground anchors • Mock-up accessory pad

Data Gathered	Frequency	Post Processing
1. Force on load cell 2. Vibration data with accelerometer 3. Temperatures with thermocouples 4. Visual check of stand	1. 45 Hz 2. 90 Hz 3. 5 Hz 4. N/A	• Force data • Check operability of DAQ with all sensors attached and recording

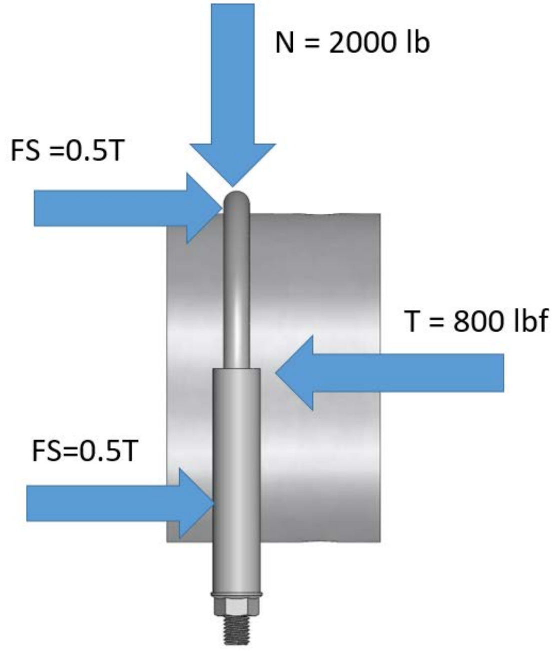
Off-Axial Load: Rails Stress Model

- Assumptions:
    - Weakest components for off-axis loading are rails.
    - Maximum off-axis angle is 17 degrees(expansion angle of the nozzle)
- Demonstrates that rails do not buckle under off-axis load. 100 lbf (SF 1.7) applied to each carriage.



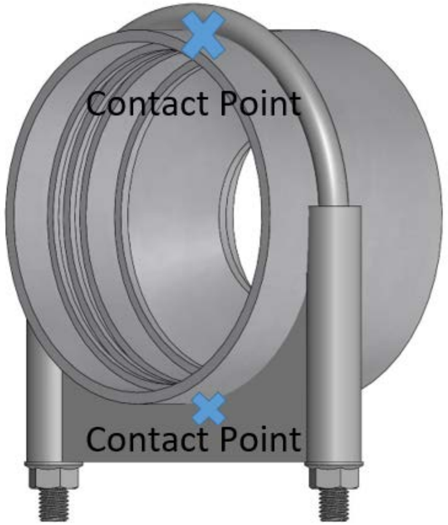


Axial Load: U-Bolt Friction Model



$$F_s = \mu_s N$$

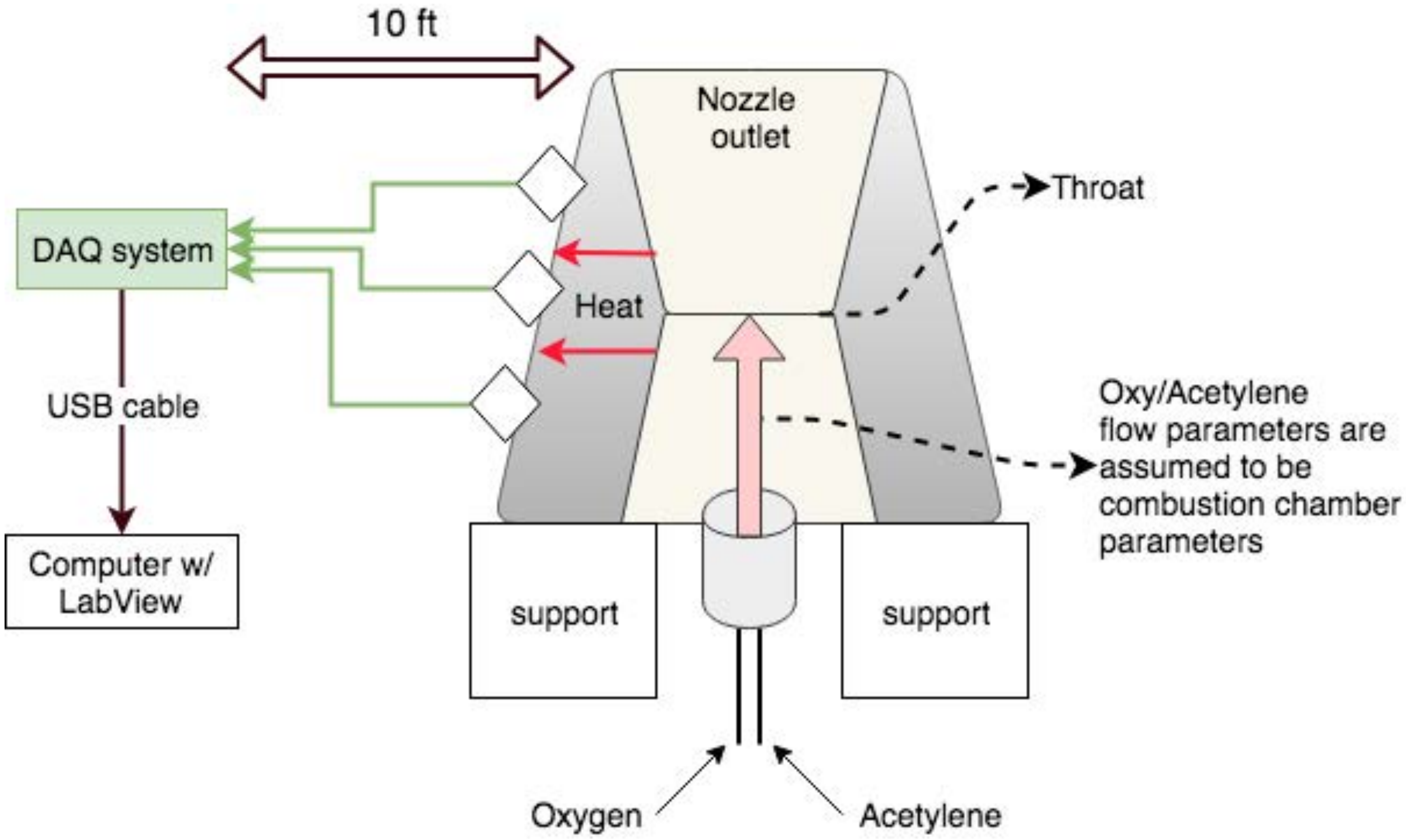
$$\tau = \mu_s D F$$



- 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**

Simulated Loads Testing - Phase 2

- Test Overview: Simulate heating on the rocket nozzle with a 10-second blow torch burn.
- Test Purpose: Verify that developed Bartz' model produces accurate results for temperature distribution in nozzle.



Phase 2 Logistics

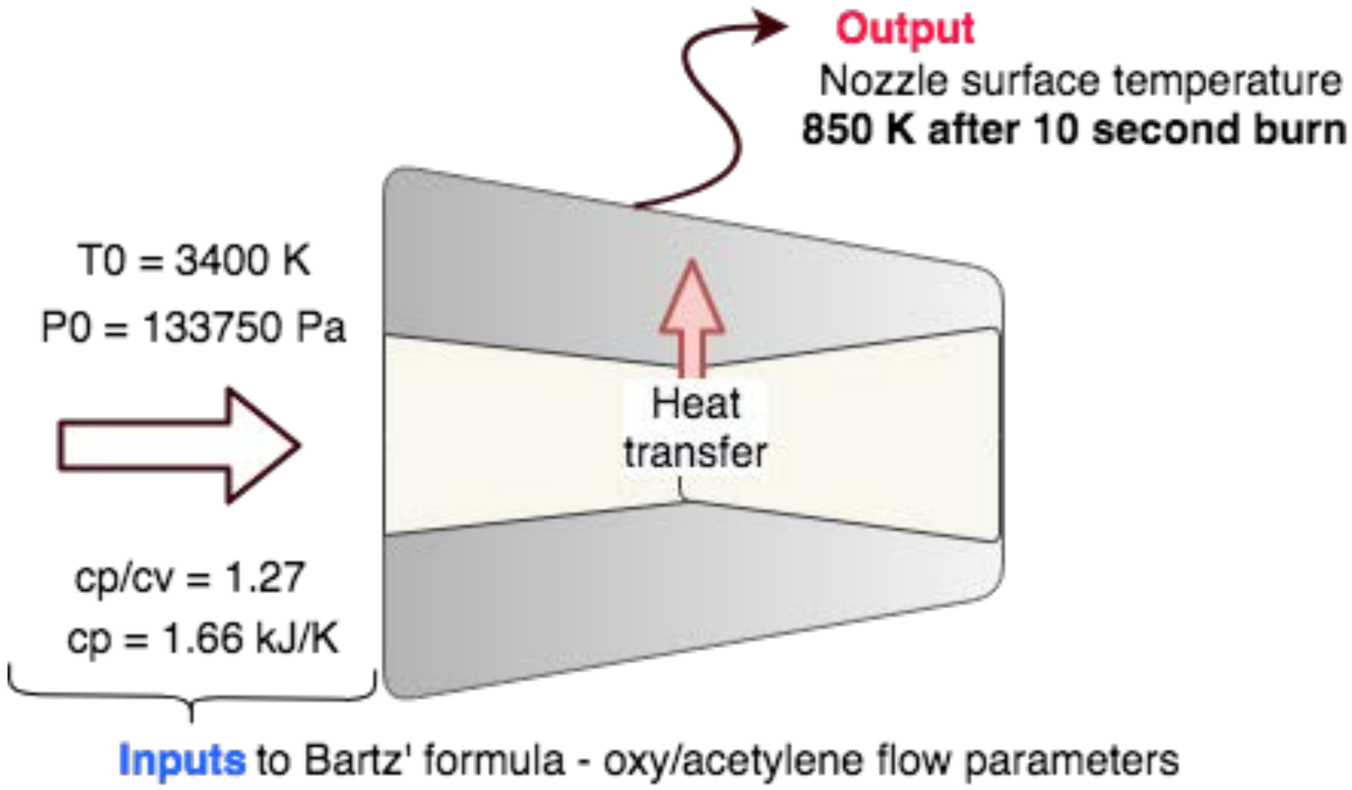
Location	Welding Shop
Date	March 26th – 28th
Duration	2 days
DRs Verified	4.2, 5.2, 5.3, 7.3

Equipment
• HICKAM DAQ System • Rocket Nozzle w/ aluminum sleeve • Acetylene-oxygen torch • 4 concrete blocks • 3 thermocouple • Iron tongs

Data Gathered	Frequency	Post Processing
1. Temperature data from the outside of the nozzle 2. Visual check of the nozzle structure	1. 60 Hz 2. N/A	• Throat temperature (Chamber temperature)

Nozzle Temperature Model

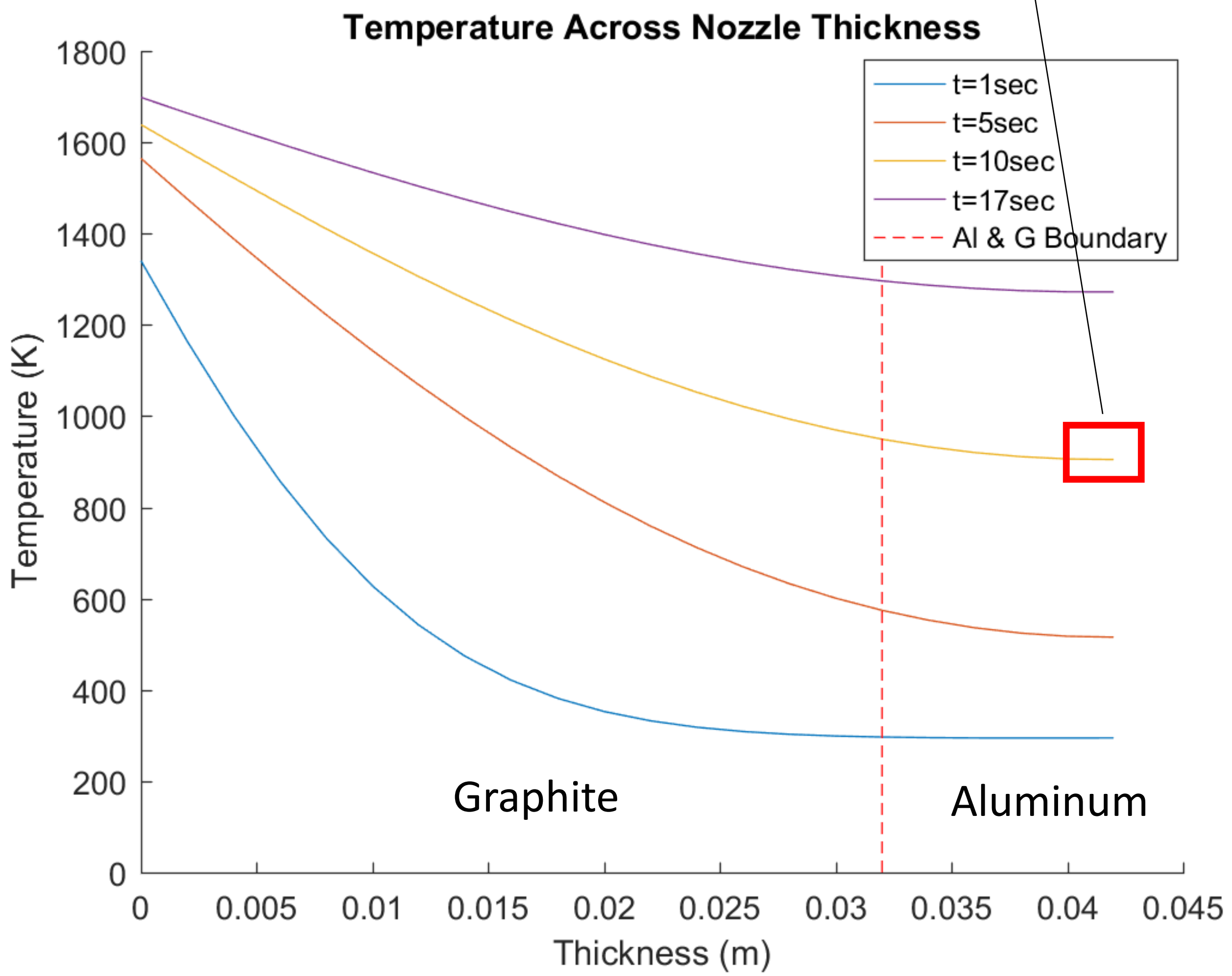
- Bartz' model uses combustion chamber parameters to calculate the heat transfer coefficient from the turbulent boundary layer.
  - Assumptions: axial, symmetric, adiabatic flow w/ boundary layer, stoichiometric combustion
- Oxy/acetylene torch is modeled as combustion chamber.
- Expected results: the outside of the nozzle is within 20% of 850K mark after 10 second burn.



Nozzle Temperature Model

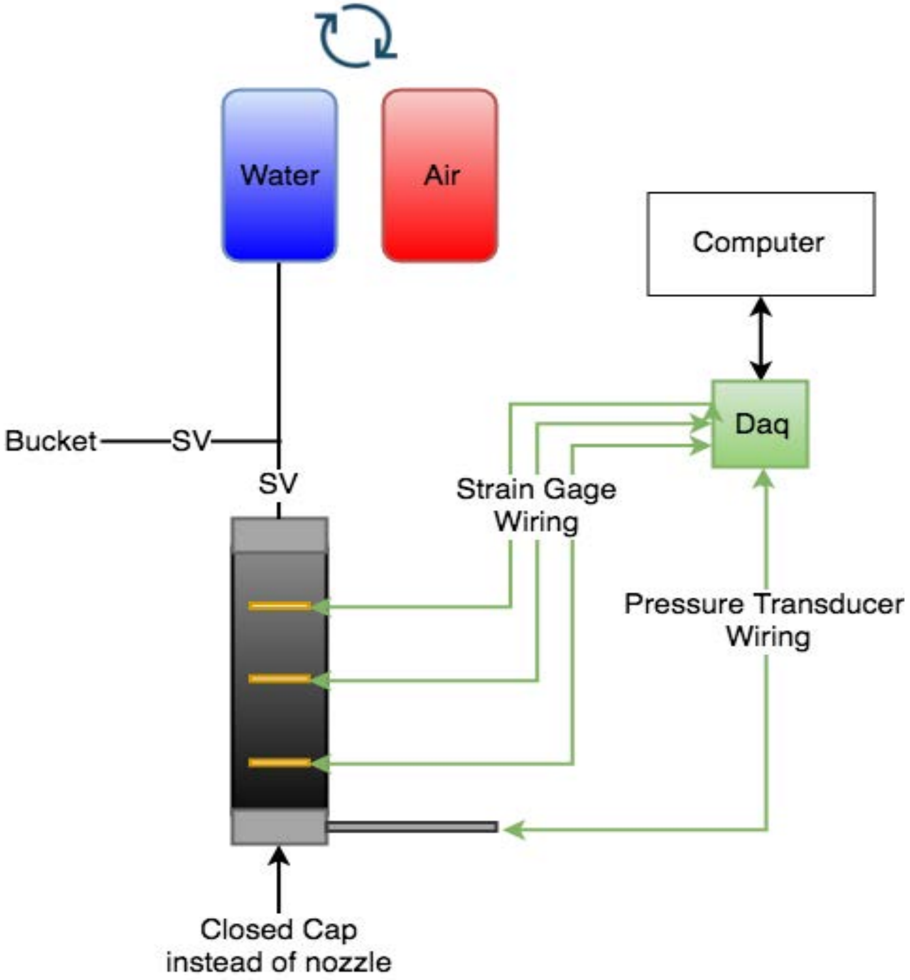
850K expected outside temperature w/ 20% maximum error

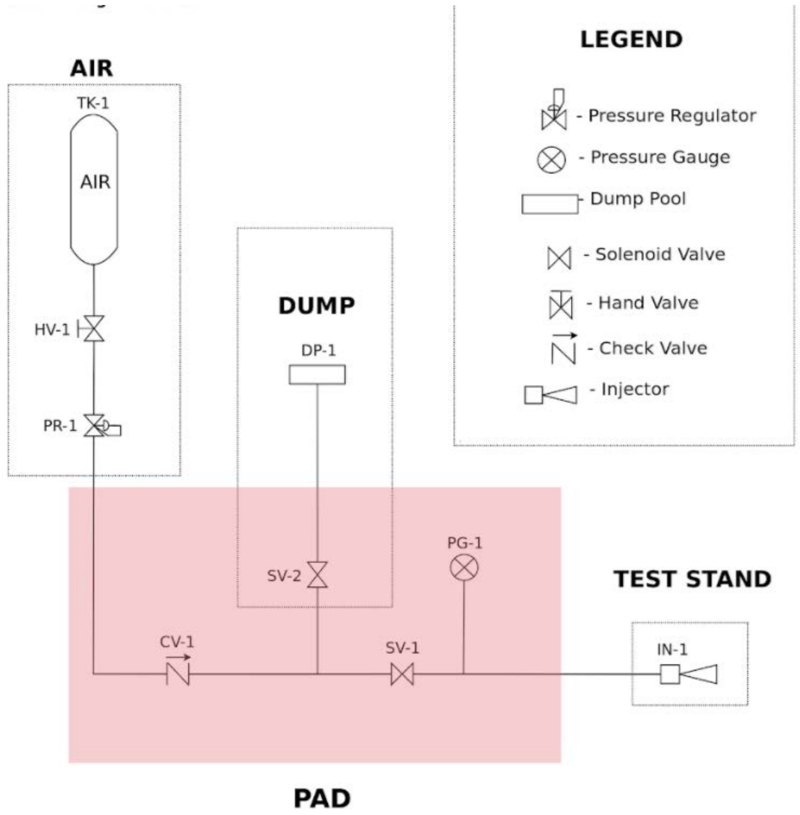
- Model Assumptions
  - One dimensional heat transfer
  - Finite difference discretization
  - Gas side temperature approximation
  - Temperature of the wall estimation
  - Estimated natural convection coefficient



Simulated Loads Testing - Phase 3

- Test Overview: Use compressed air to pressurize water for simulating pressure in the rocket chamber.
- Test Purpose: Verify the pressure transducer attachment.





Phase 3 Logistics

Location	Welding Shop
Date	March 19th - 20th
Duration	2 days
DRs Verified	None

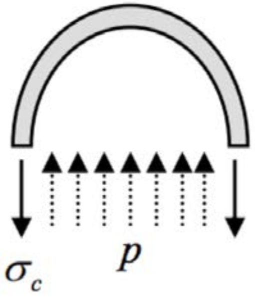
Equipment
• HICKAM Test Stand • HICKAM DAQ System • 3 Strain Gauges • Mock-up accessory pad • Modified plumbing system • Rocket with endcaps instead of nozzle • Compressed air tank • Water

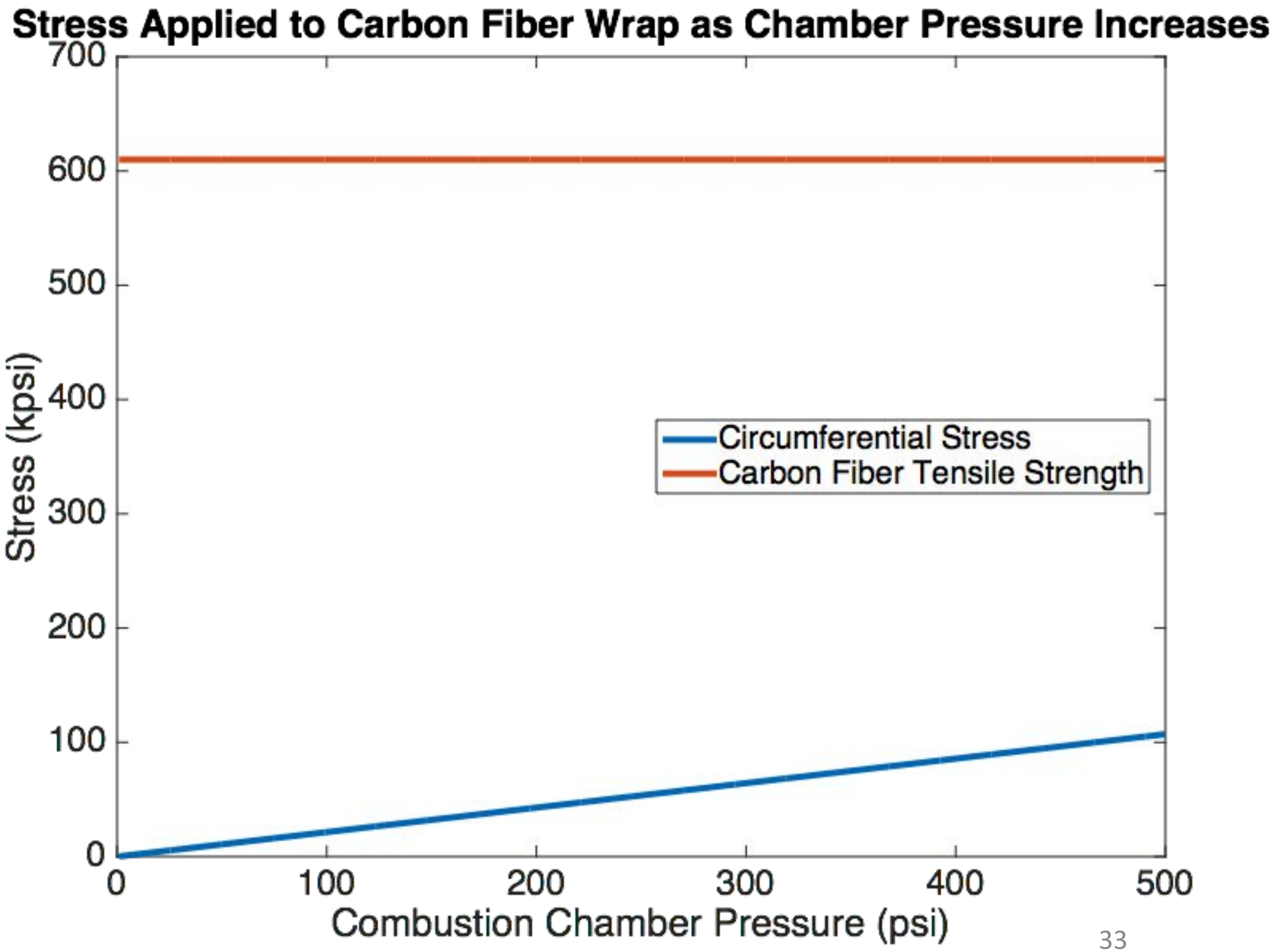
Data Gathered	Frequency	Post Processing
1. Pressure from pressure transducer 2. Visual inspection of rocket chamber	1. 125 Hz 2. N/A	• Pressure data

Chamber Pressure Stress Model

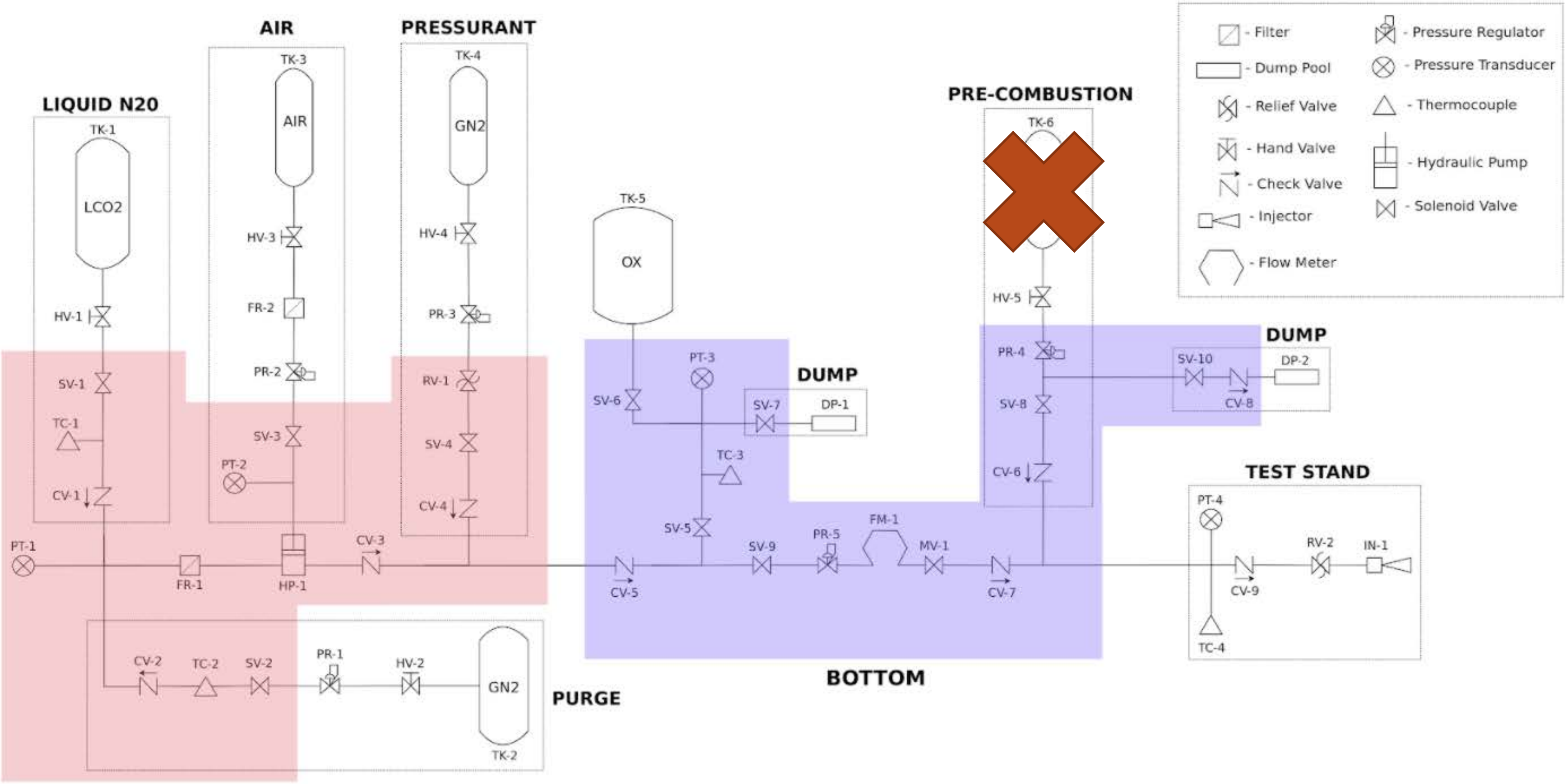
- Determine if worst case scenario will withstand hydrostatic pressure test
- Thin Wall Theory applied to carbon fiber chamber wrap
  - Thickness/Radius < 1/20
  - Strain resulting from pressure is small

$$\sigma_C = \frac{pr}{t}$$





Cold Flow



- Test Purpose:
  - Verify plumbing system normal function
  - Eliminate plumbing leaks
  - Verify emergency dump & purge systems to ensure safety at hot fire
  - Confirm level 2 success of project

Cold Flow Test Logistics

Location	Platteville, CO test site
Date	March 30th-31st || April 6th-7th
Duration	2 days
DRs Verified	4.5, 4.6, 5.2, 5.3, 6.1, 6.2, 6.3.1, 6.3.2, 6.4, 6.6, 6.7, 8.1, 8.2, 8.4, 8.5

Equipment
• HICKAM Test Stand • HICKAM Plumbing System –Helium, N_2O, O_2 • CO_2 Tank • Nitrogen Pressurant • HICKAM Data Collection System • HICKAM Switchboard • MaCH-SR1 Injector Plate

Data Gathered	Frequency	Post Processing
1. Mass Flow Rate	1. 35 Hz	Procedure and plumbing verification
2. Plumbing System Pressures	2. 1.3 kHz	
3. Plumbing System Temperatures	3. 15 Hz	
4. Pre-Injection "Oxidizer" State	4. 5 Hz	

Mass Flow Rate Model

Analytical equation used to calculate mass flow through an injector

Steady-state mass flow will be verified with mass flow meter

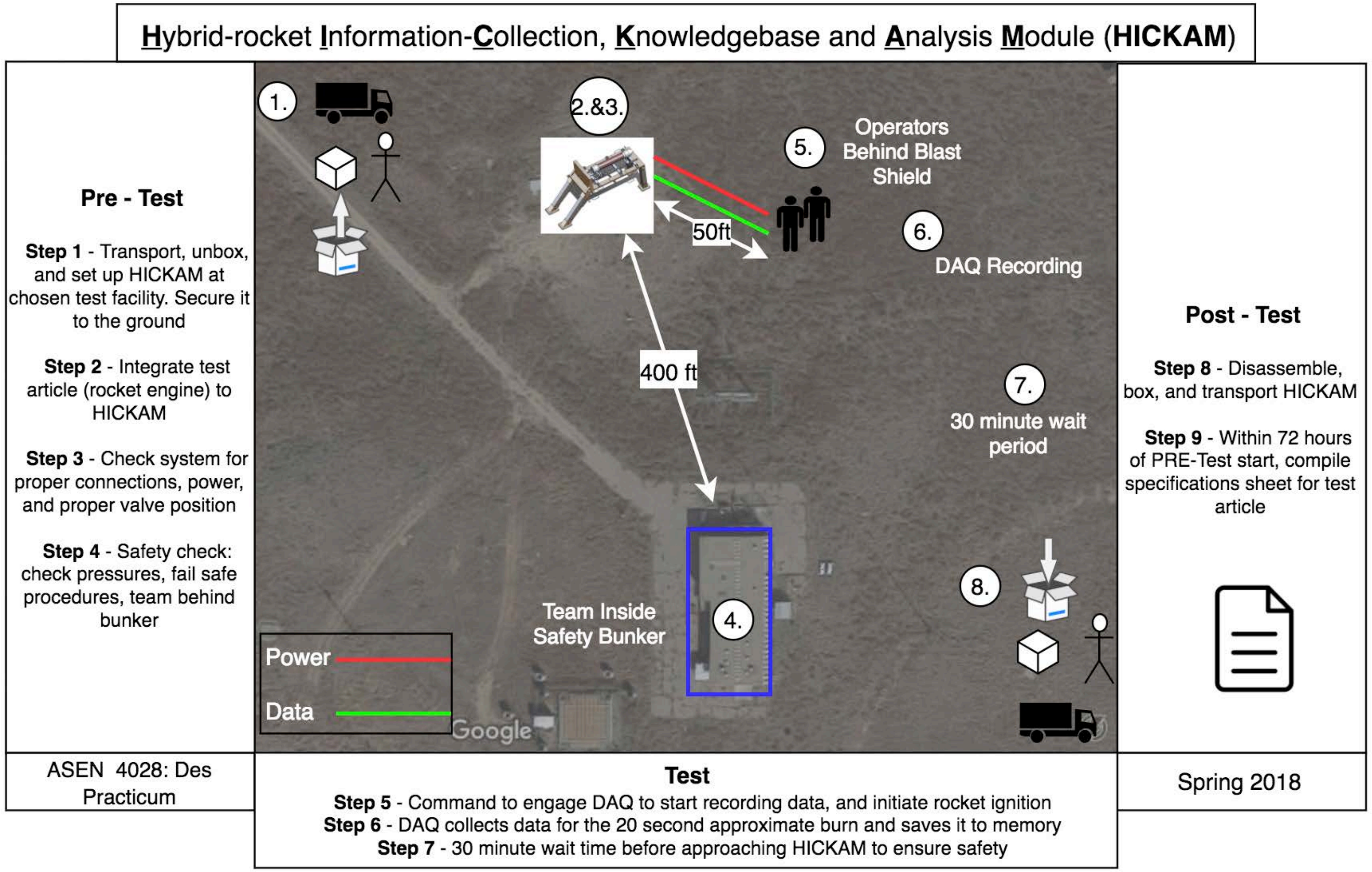
Inputs	Values
Coefficient of Discharge	0.375
Injection Inlet Area	0.017 sq. in
Liquid Density	45.73 lbm/ft^3
Tank Pressure	900 psi
Chamber Pressure	12.315 psi

$$\dot{m} = C_{dis} A_i \sqrt{2\rho_L (P_{tank} - P_c)}$$

Cold Flow Mass Flow : 0.892 lbm/s

Hot Fire Test

- Test Overview: Mission Operation
- Test Purpose:
  - Verify a safe, effective, and useful way to test rocket motors as was the plan for the HICKAM system
  - This test will verify all of the design requirements



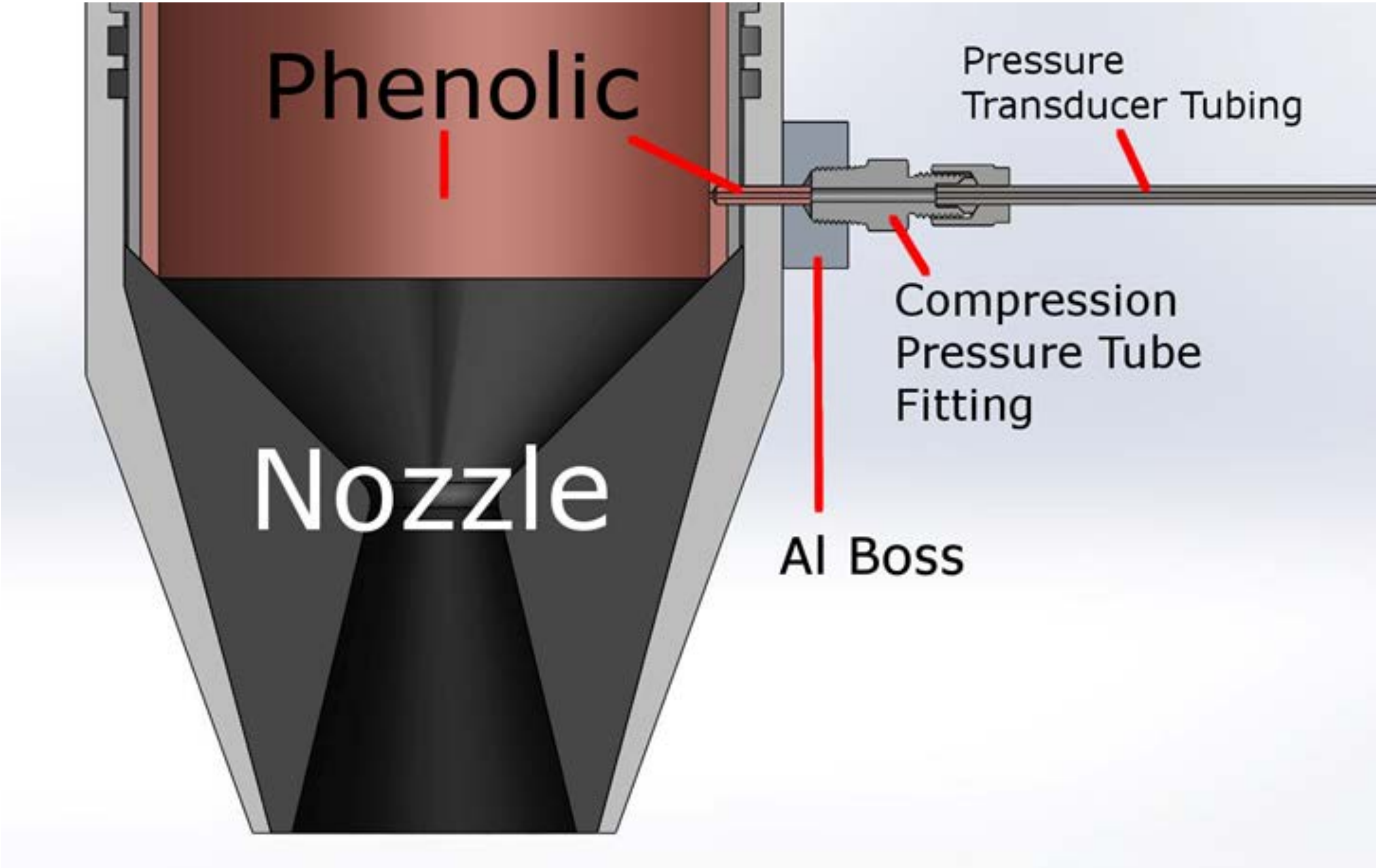
Hot Fire Test Logistics

Location	Platteville, CO test site
Date	April 13th-15th || April 23rd-26th
Duration	3 days
DRs Verified	All

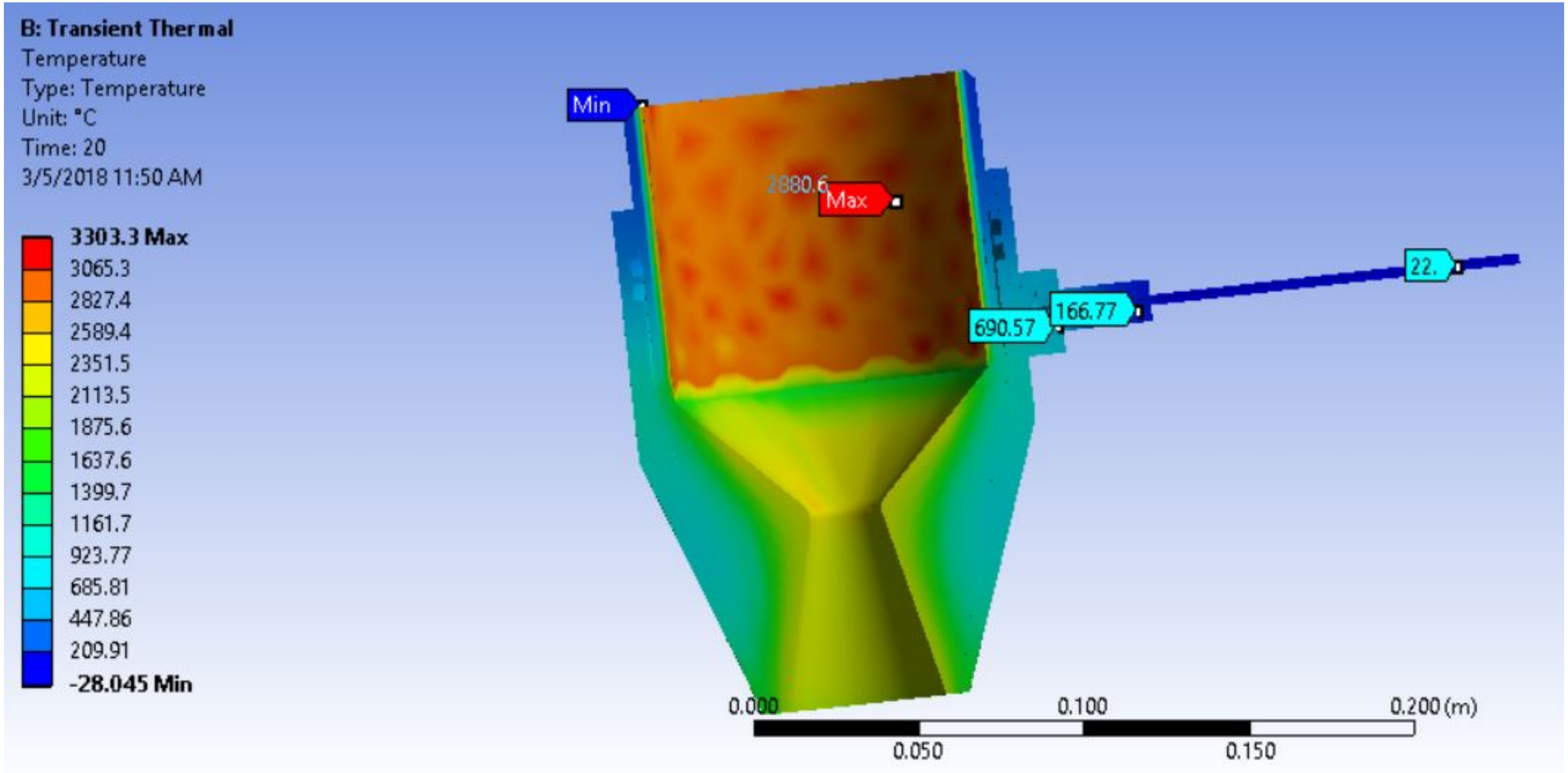
Equipment
• HICKAM Test Stand • HICKAM Feed System • HICKAM Data Collection System • HICKAM Switchboard • MaCH SR-1 Solid Rocket Motor • HySOR Oxidizer Tank • 6K Helium Pressurant • N_2O Oxidizer Supply • Nitrogen Purge • Oxygen Tank • Air tank

Data Gathered	Frequency	Post Processing
1. Force 2. Pressure Transducer 3. External Nozzle Temperature 4. Mass flow rate 5. Plumbing System Pressures and Temperatures 6. Vibration Data	1. 45 Hz 2. 125 Hz 3. 15 Hz 4. 34 Hz 5. 10 Hz 6. 90 Hz	Thrust, Chamber Pressure and Temperature, Oxidizer Flow Rate, Source Shock, Mass Flow Rate, Total Impulse, Specific Impulse, Regression Rate, Burn Duration

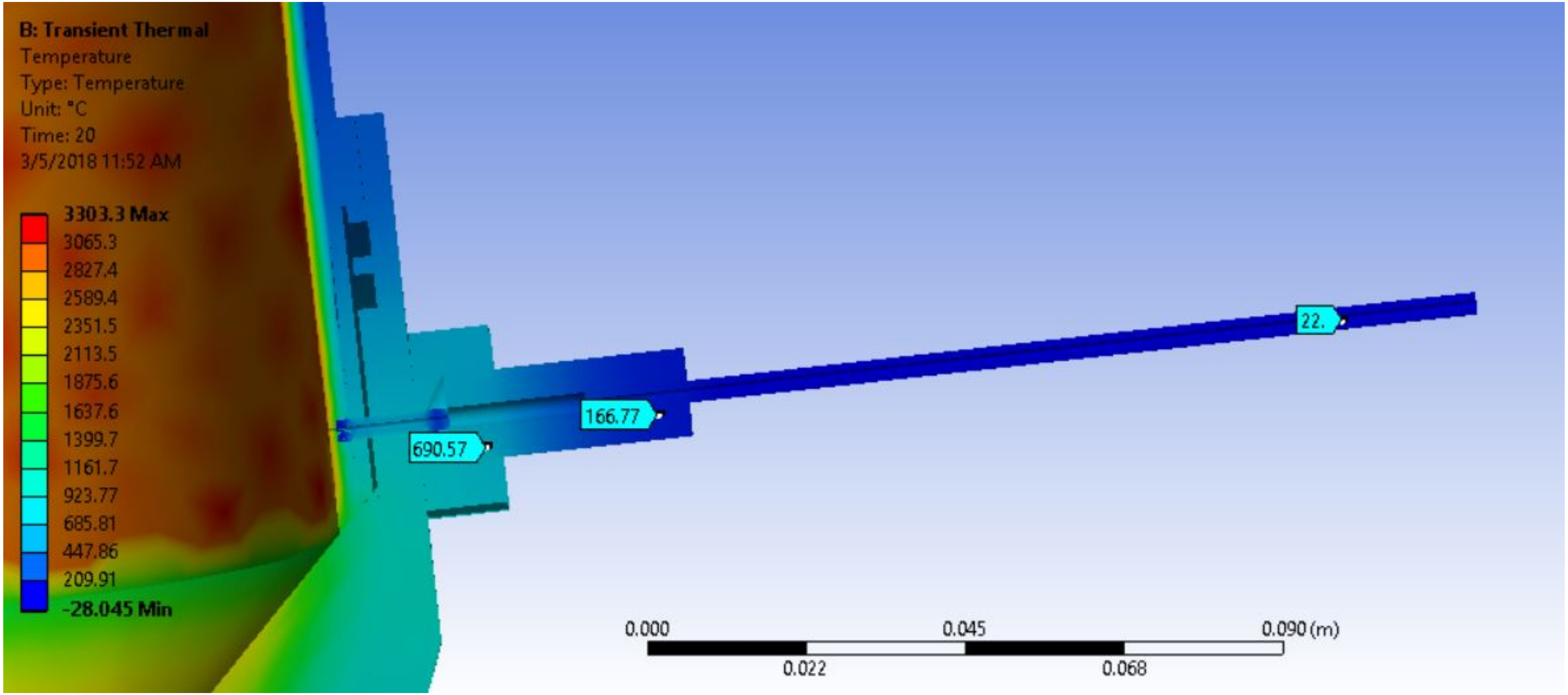
Pressure Transducer Model



Pressure Transducer Model



Pressure Transducer Model



Pressure Transducer Model

- Combustion Chamber Pressure Transducer attachment design validated through hot fire test
  - ANSYS models: need 5 in or more of stainless steel tubing to protect PT (design calls for 18 in)
  - Phase 3 of simulated loads checks for leaks/bad seals
  - Simulated loads cannot simulate combustion environment, therefore cannot validate PT design
- Possible Failure Modes and Implications
  - Threads Shear: models did not properly account for decrease in strength due to increase in temperature
  - Ejection of Pressure Transducer: models did not properly account for thermal expansion
  - Release of Combustion Products: design did not provide adequate seal

Budget

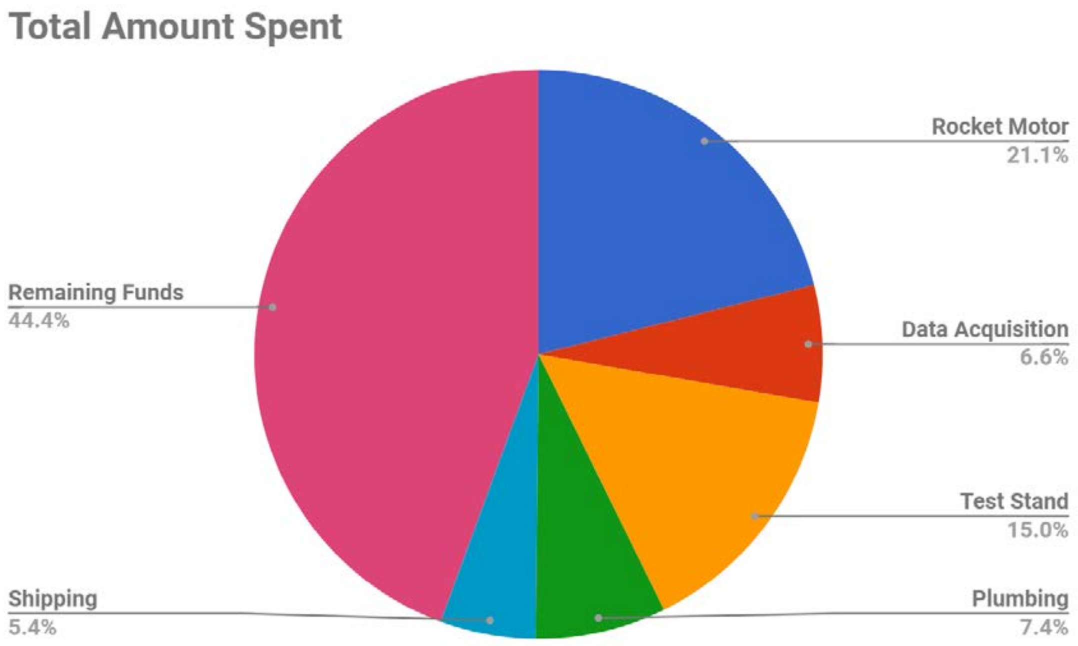
Budget Breakdown

Subsystem	Projected Cost
Plumbing	$1,894.36
Test Stand	$1,369.14
Rocket Motor	$2,143.72
Data Acquisition	$558
Simulated Loads Testing	$200
Shipping	$500
Total	$6,665.22

- Projected Total Cost: $6,502.22
  - Spent: $4,424.01
- Additional $3,000 in funding awarded from department
- Received donations from: McGuckin's, Omega, FSI, Emerson, Swagelok

Budget Breakdown

Subsystem	Total Spent
Plumbing	$594.18
Test Stand	$1,201.47
Rocket Motor	$1,685.60
Data Acquisition	$530.84
Simulated Loads Testing	$0
Shipping	$435.06
Total	$4,424.01



Procurement Status

Arrived

- Test Stand Raw Materials
- Rocket Motor Raw Materials
- Data Acquisition sensors
- Pressure Calibrator

Purchased, Not Arrived

- Pressure Transducers
- Swagelok Plumbing Materials
- Fail Open Valves

Not Yet Purchased

- Tanks for Cold Flow and Hot Fire Test
- Rocket Motor Material: O-rings

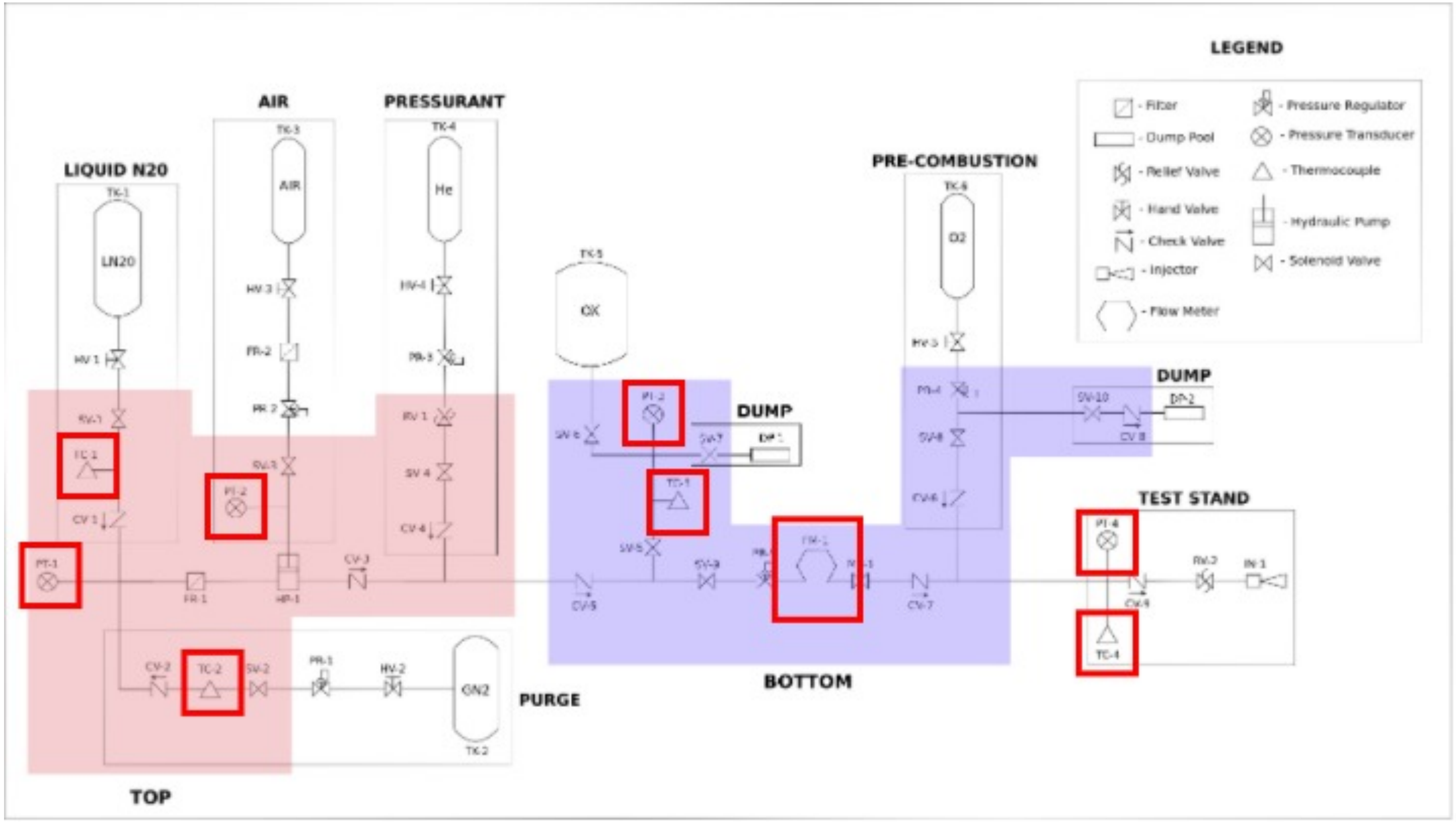
Thank you

And special thanks to all of our sponsors!

Questions?

Backup Slides

Plumbing Sensors Schematic



DAQ software Iterations

Completed

1. Basic software that reads in values and saves to 3 separate files
2. Allowed user to pick an Combination of sensors.
3. Changed code to save values to one file.
4. Changed user interface to be more user friendly (output values to gauges and thermometers that change color depending on the value.

Future Tasks

1. Modularize Code more for easier modifications and debugging.
2. Add button to only save Data when pressed
3. Slow down Load Cell and Pressure transducer Sampling rate.

Sensor Requirements: Pressure Transducer

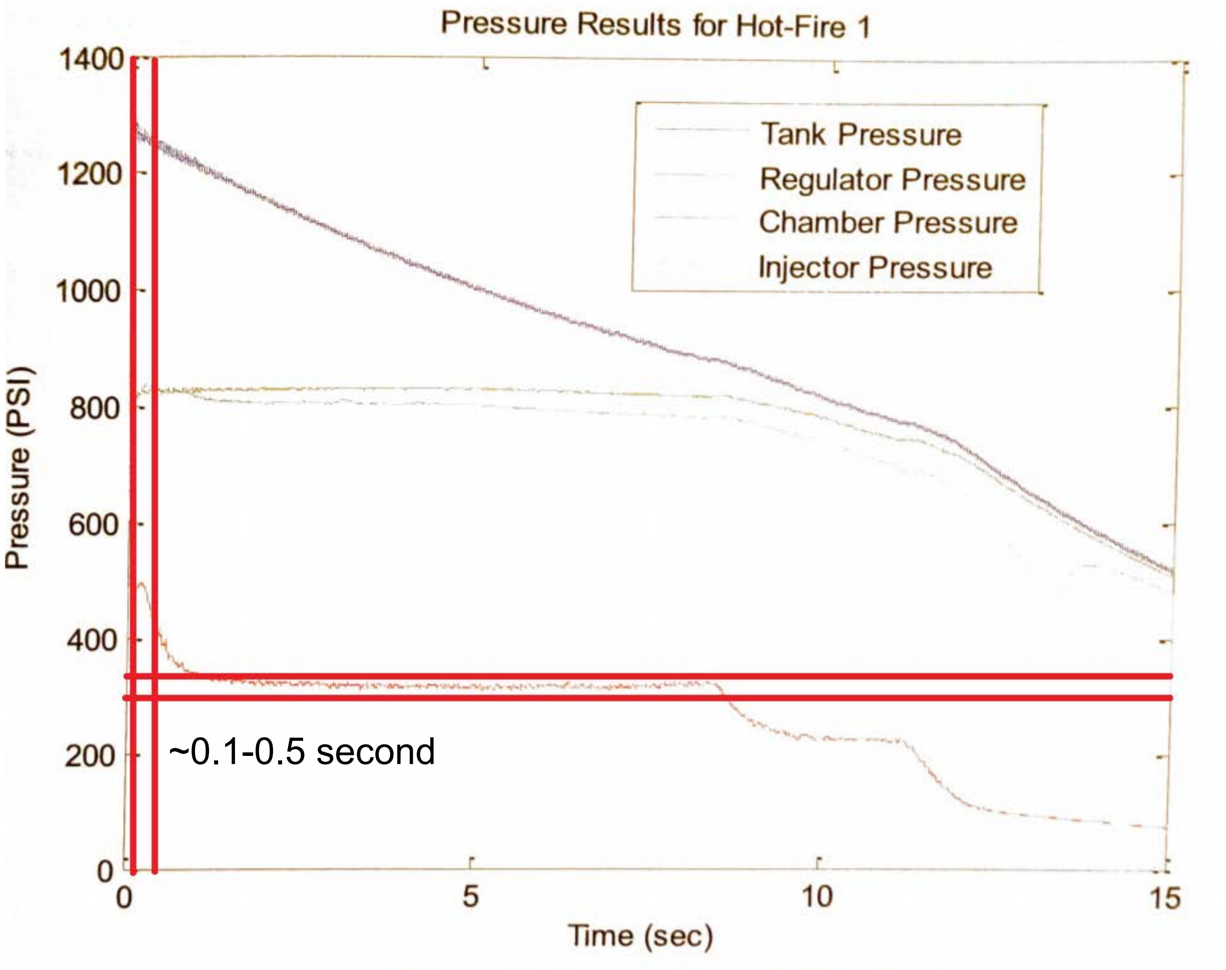


Figure 72: Pressure Data for Hot Fire 1

- 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

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

Determines Accuracy

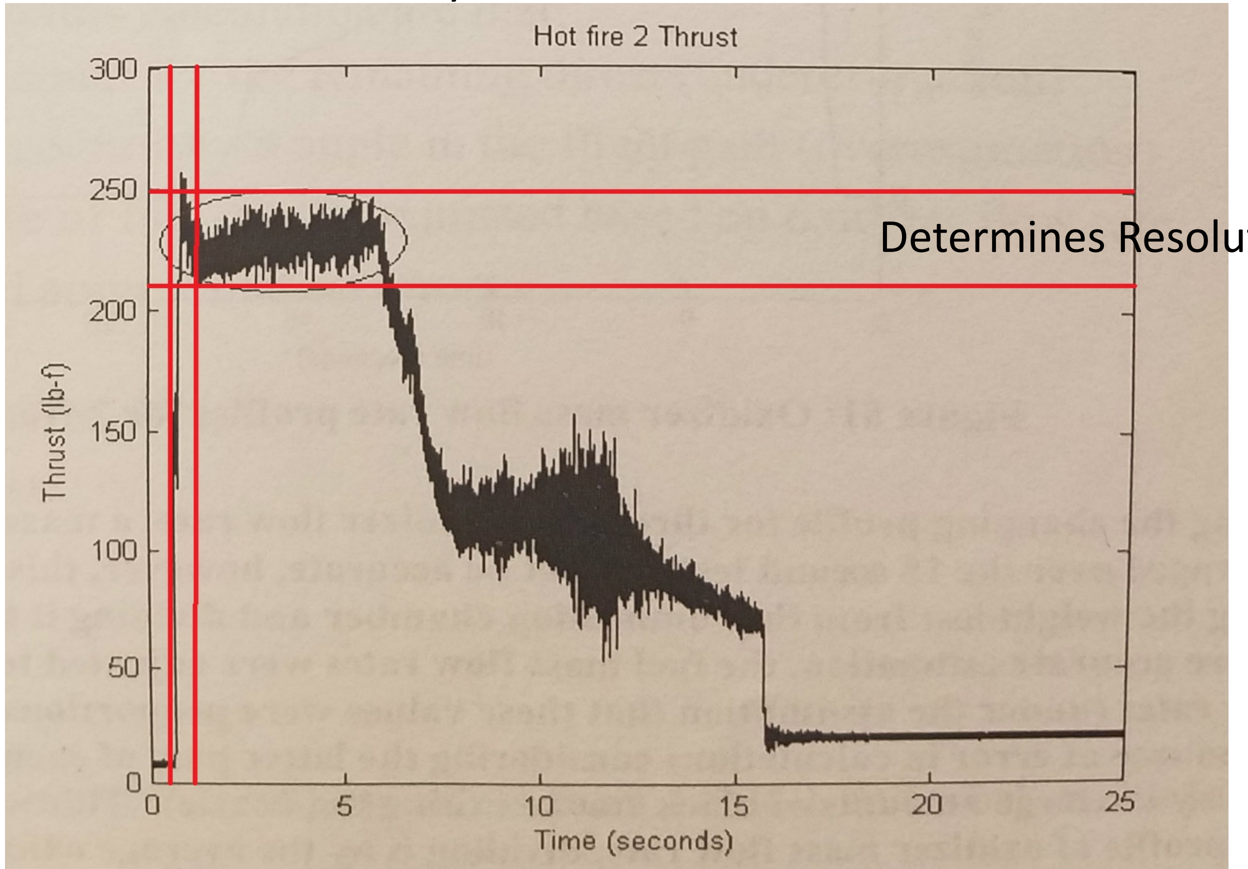
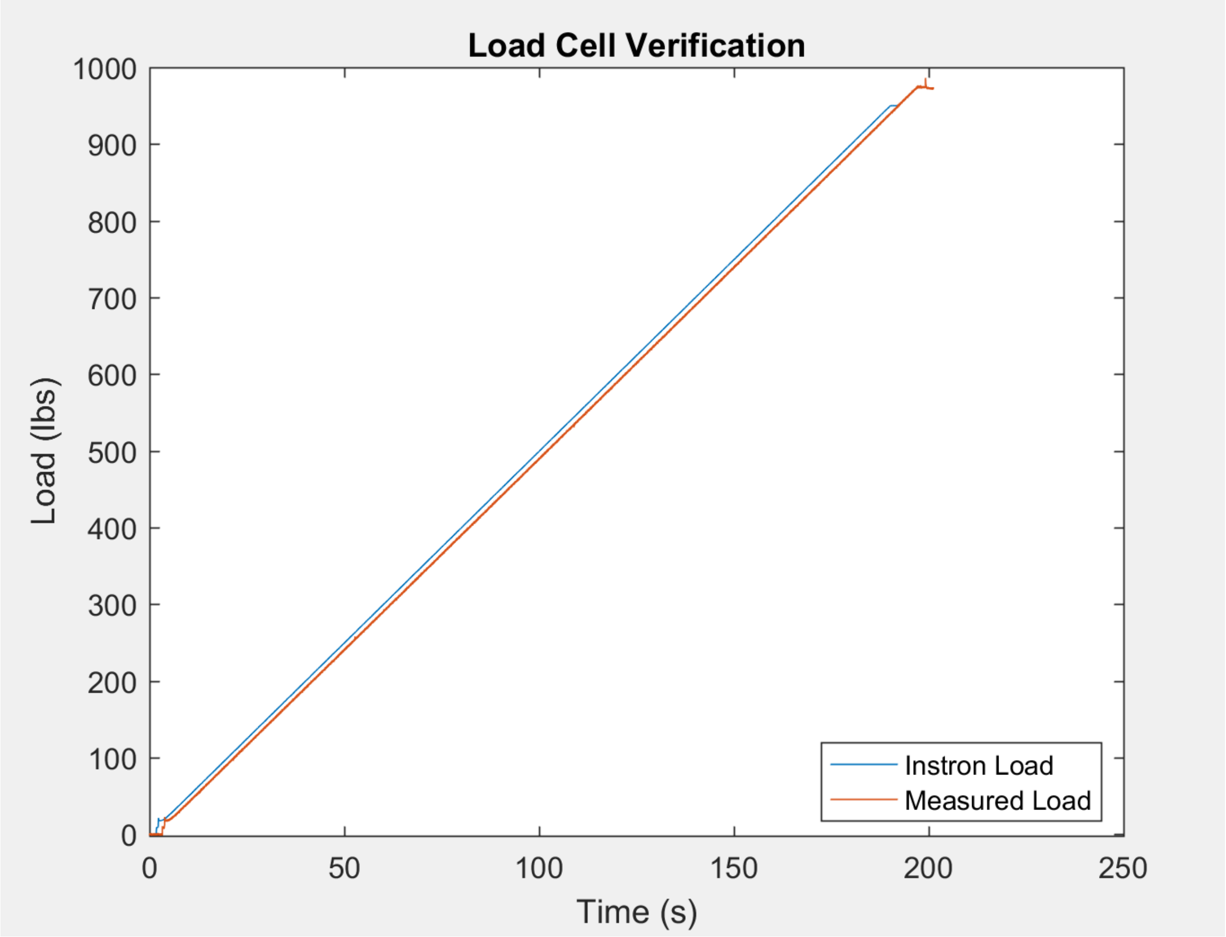


Figure 80: Thrust Profiles for 2 Hot Fires

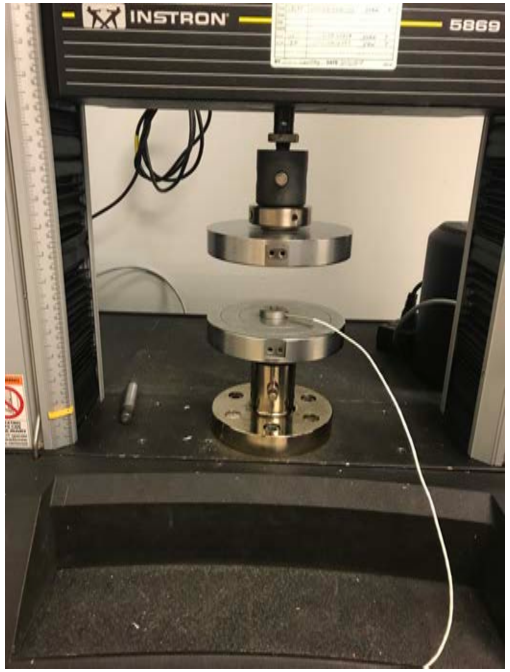
Determines Resolution

- 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

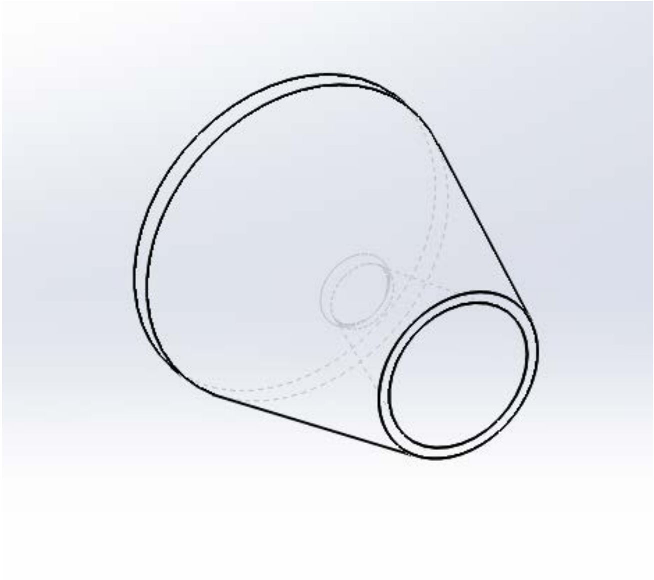
Load Cell Verification



- 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%



Sensor Requirements: Thermocouples

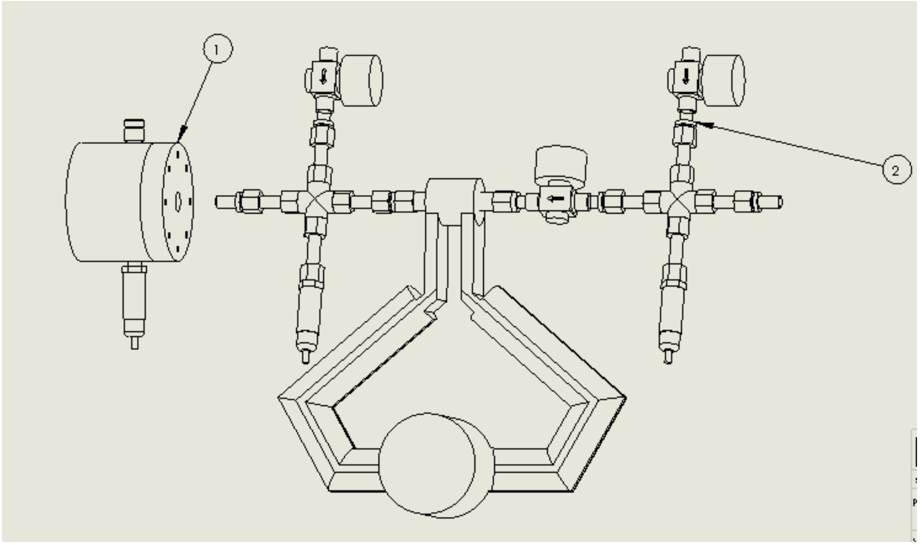


•Transient heat conduction through nozzle wall at the throat:

- Determines sampling rate for Type K.
- Determines temperature requirements for Type K.
- Also drives the requirements for combustion chamber thermocouples.

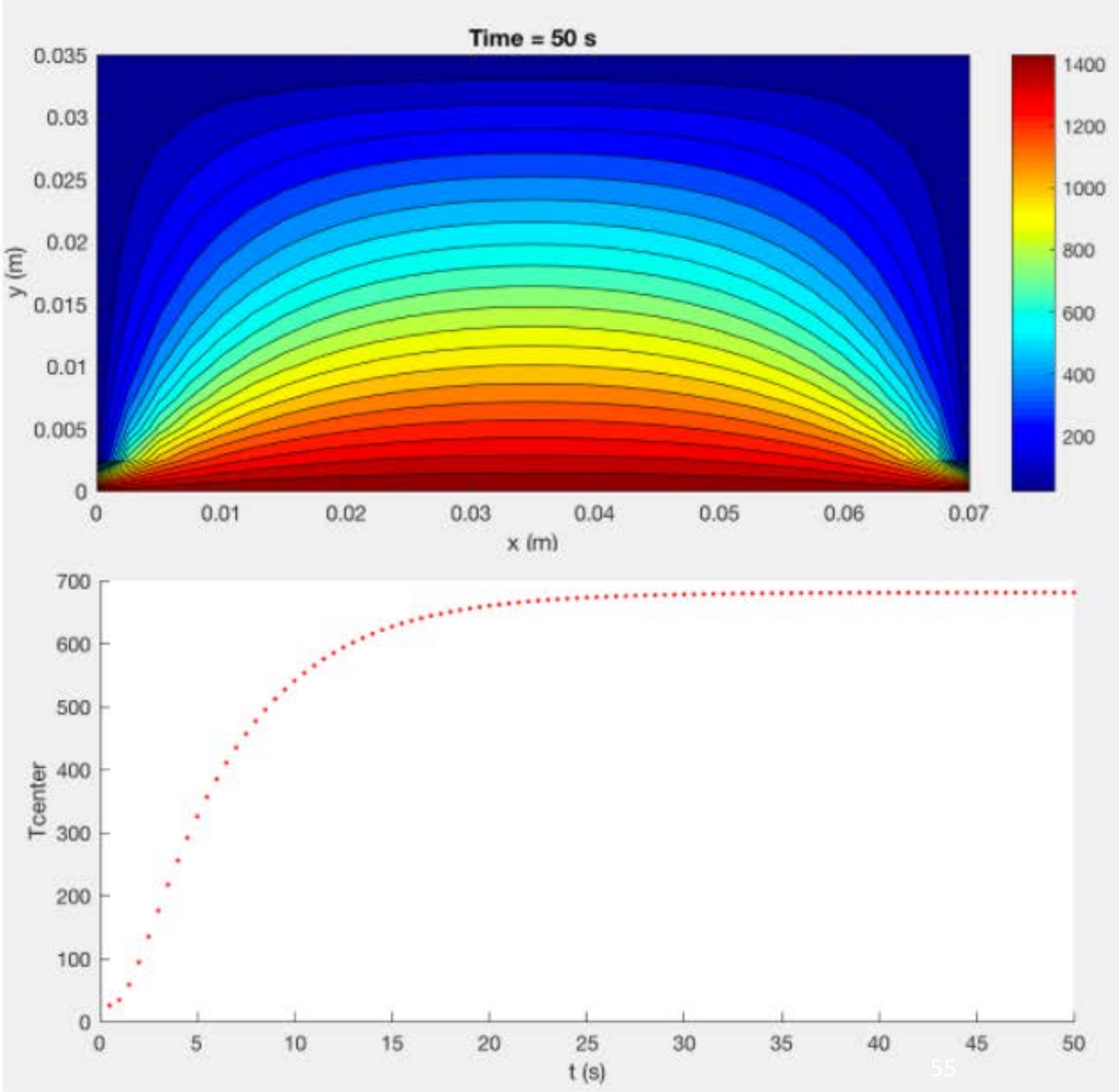
•Transient heat conduction through oxidizer feed lines:

- Determines sampling rate for Type E.
- Determines temperature requirements for Type E.



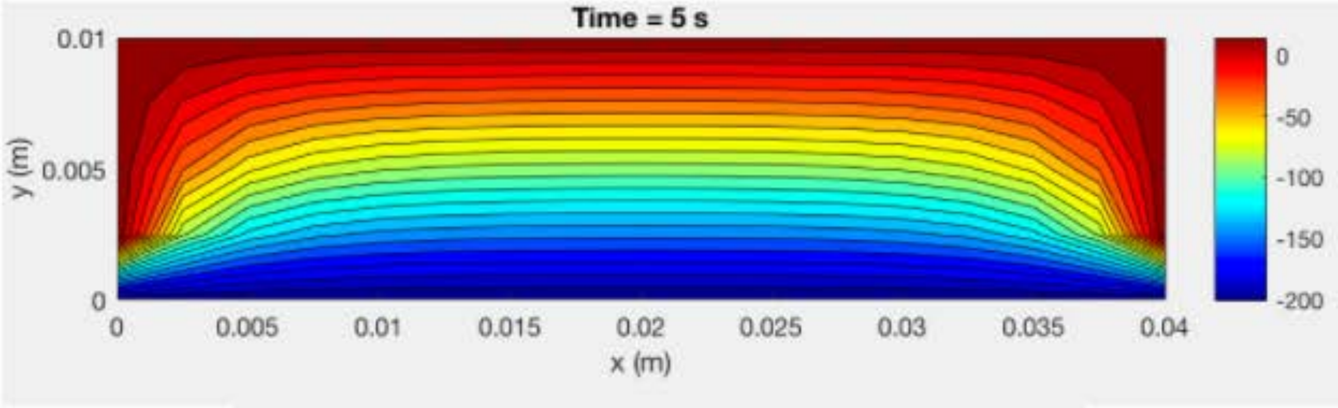
Sensor Requirements: Type K Thermocouple

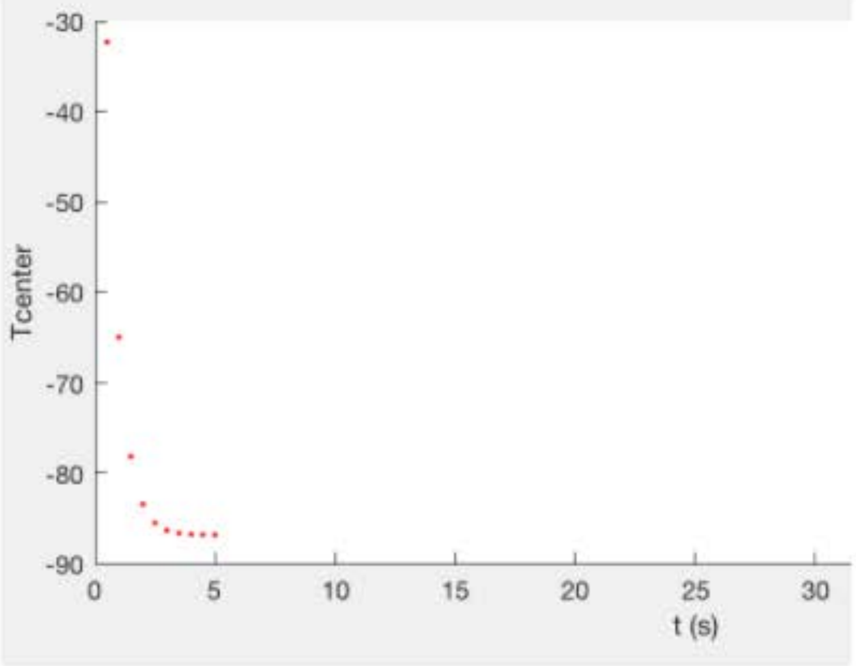
- Assumptions:
  - Only graphite, no Aluminum.
  - Throat is modelled as a “slice” of the nozzle.
  - No convection from the top edge.
- Results:
  - Fastest change in temperature is around 100°C/s, center of graphite.
- Requirements:
  - 50 Hz sampling rate is enough to capture 2°C increments during the fastest changes in temperature.
  - Accuracy then must be at least 2° Celsius.
  - Must endure 1300°F - aluminum attachment.



Sensor Requirements: Plumbing Thermocouple

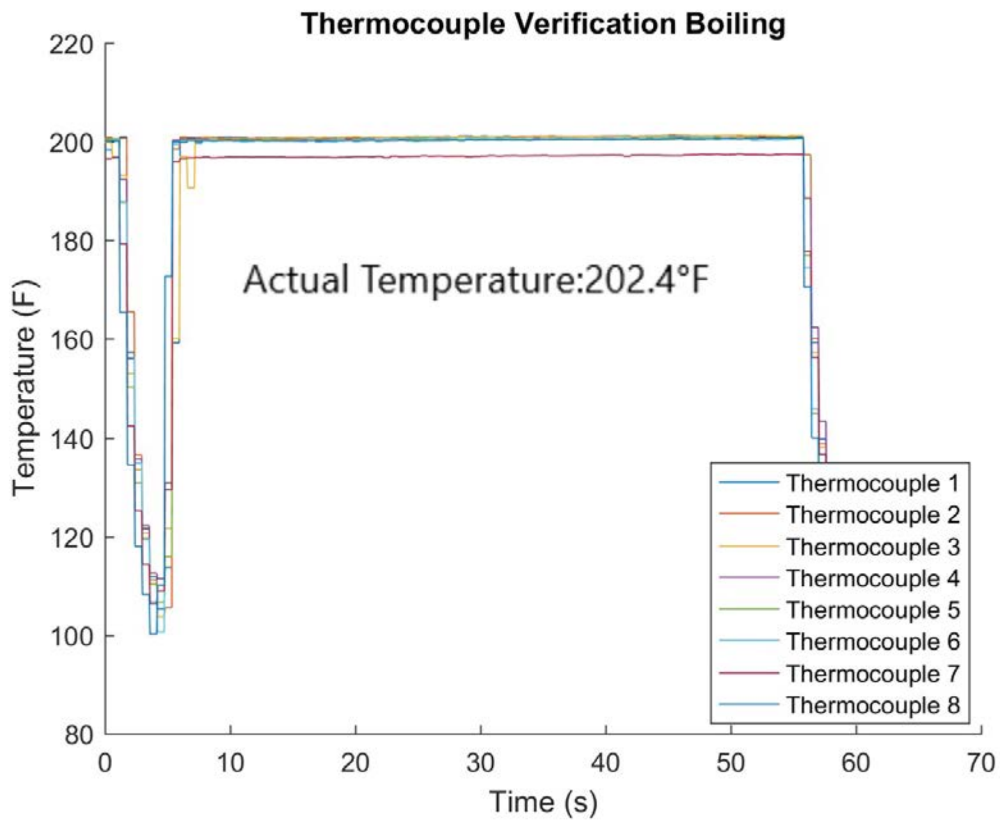
- Assumptions:
  - Flow through Aluminum feed lines.
  - No convection from the surface of the feed line.
- Results:
  - Fastest change in temperature is around 90°C/s, center of aluminum wall.
- Requirements:
  - 45 Hz sampling rate is enough to capture 2°C increments during the fastest changes in temperature.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

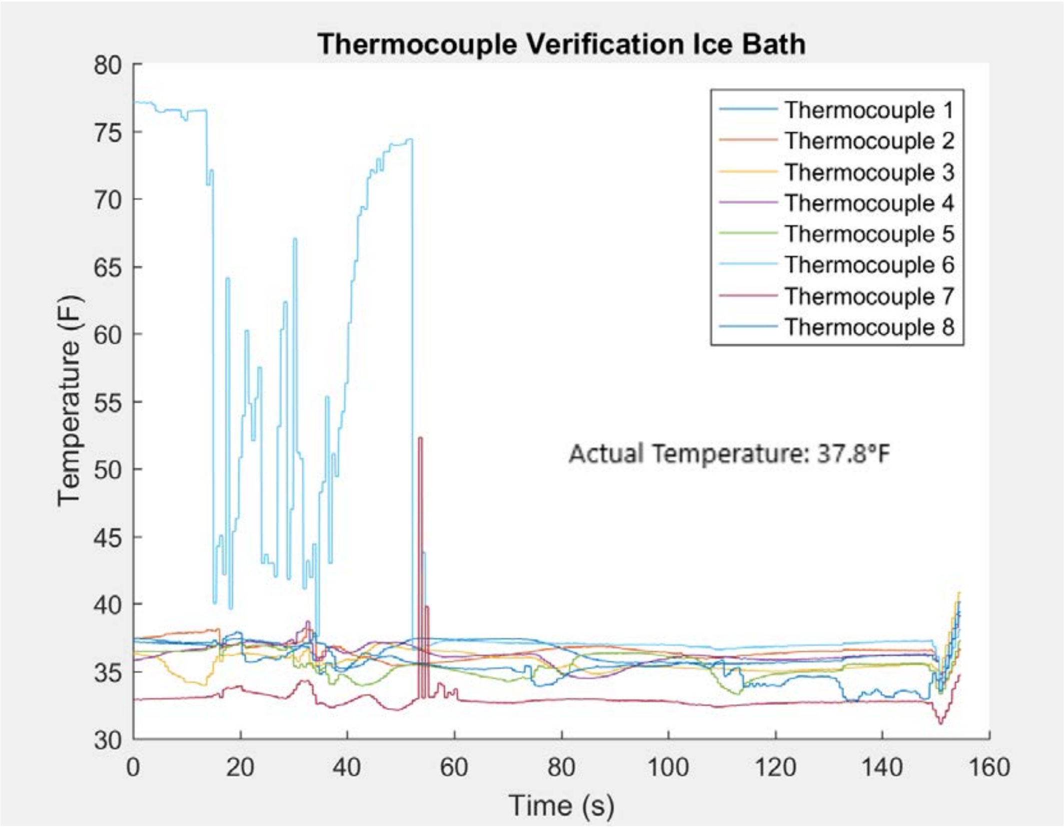




Thermocouple Verification

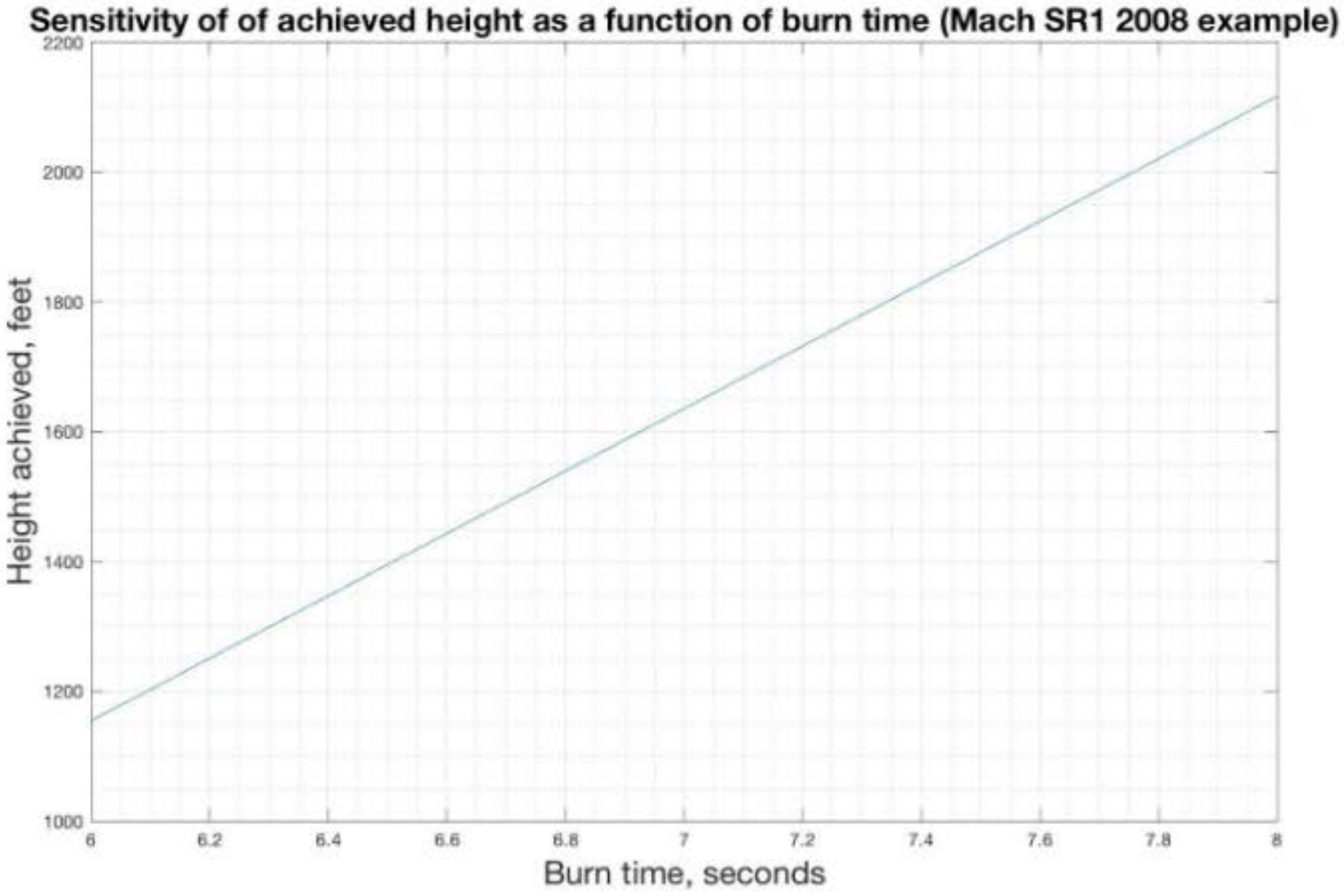
- Accuracy of handheld thermocouple: 1°F
- Accuracy of HICKAM thermocouple: 3°F
- Final Accuracy: **3.16°F**
- Sampling Rate: 15 Hz
- Satisfied DR 6.6.5: Accuracies < 4°F Chamber, 5°F Plumbing





Sensor Requirements: Accelerometer

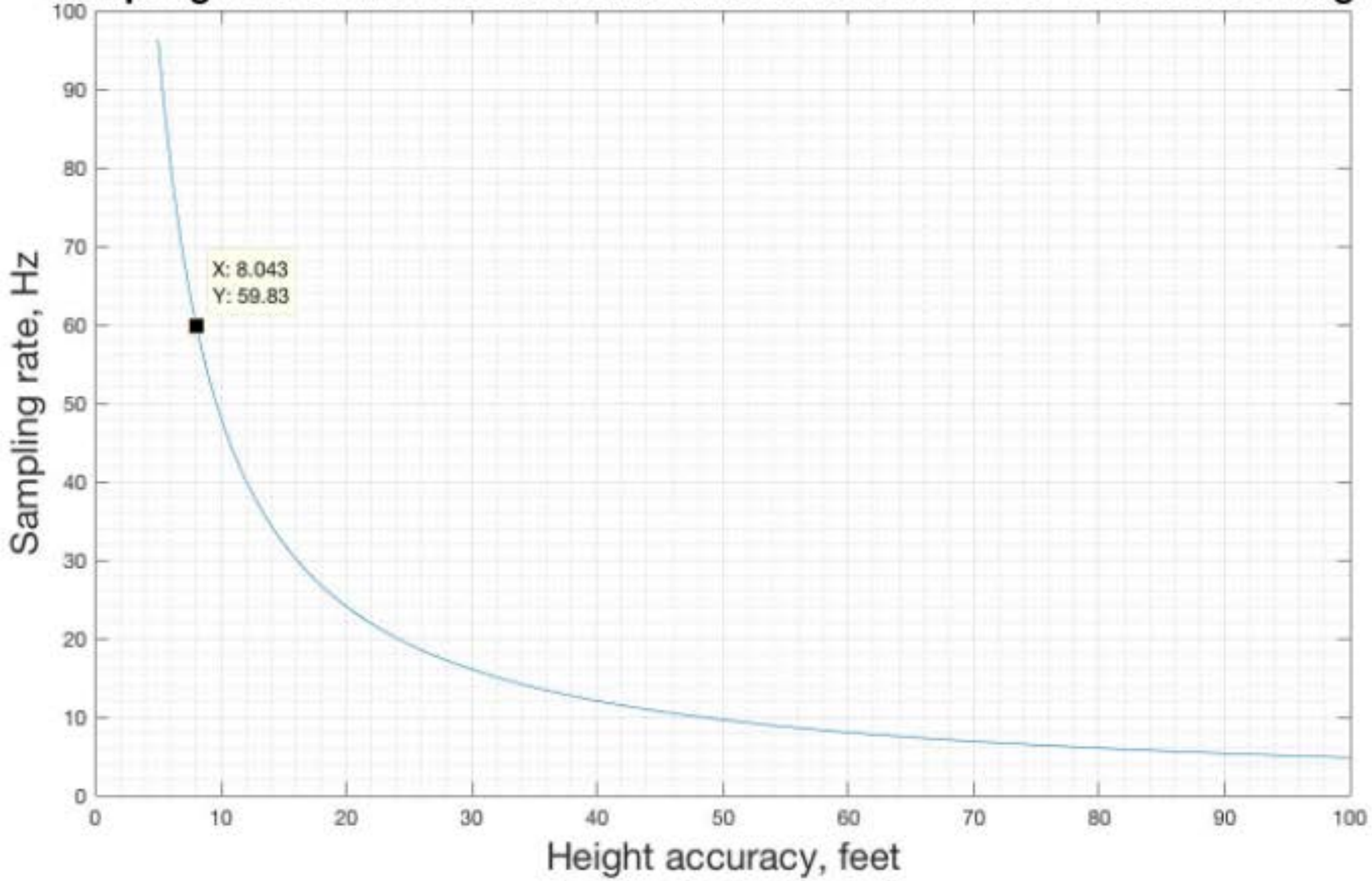
- Mach SR1 hot fire data was used to find the change of maximum height as a function of burn time.
- 481.2 feet of max height per second of burn.
- Sensitivity of the burn time is used to determine the time source shock occurs.



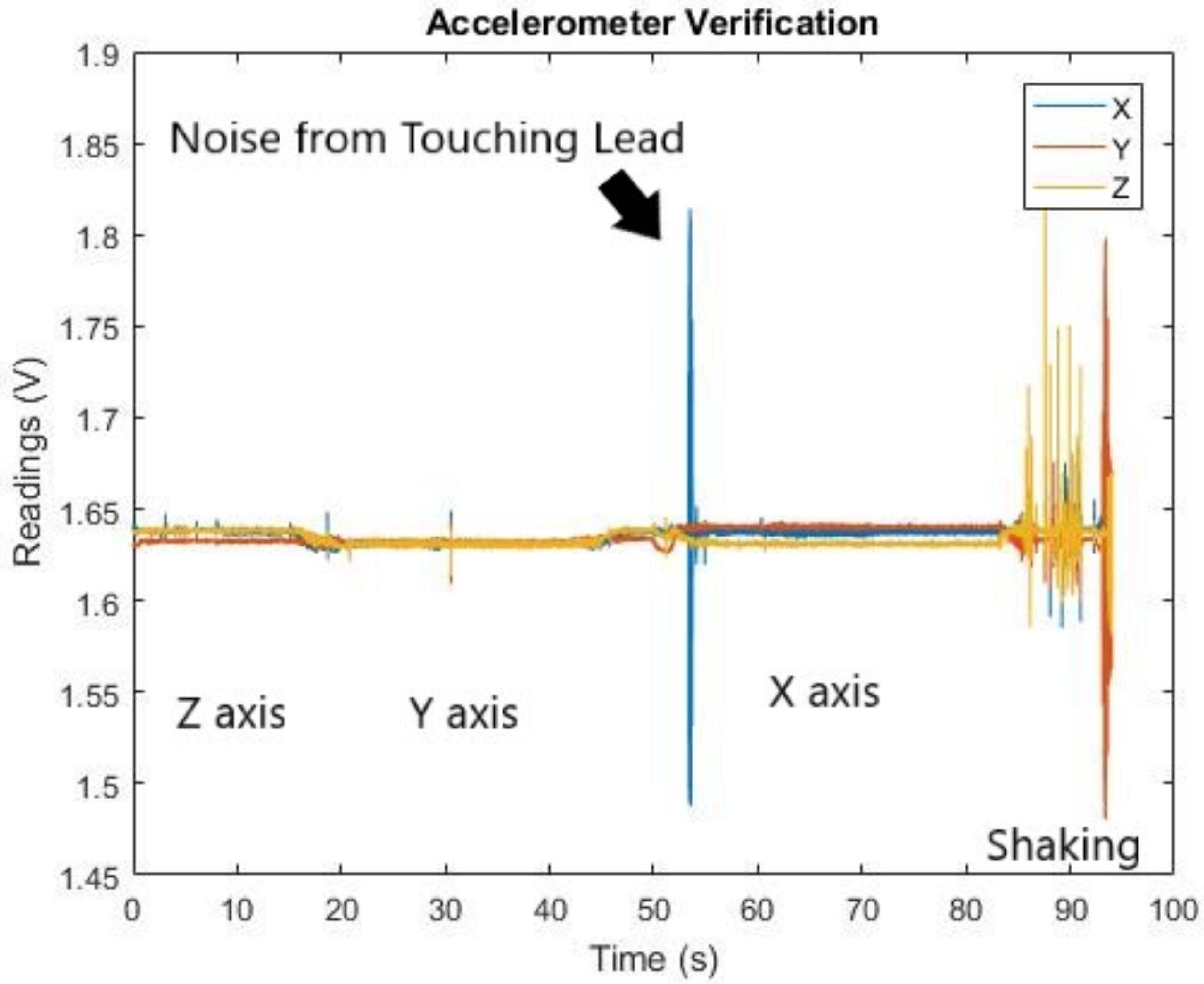
Sensor Requirements: Accelerometer

- 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 rocket sled.

Sampling rate of the accelerometer as a function of error in achieved height.



Accelerometer Verification



- Sampling Rate: 150 Hz
- Satisfied DR 4.5

DAQ Software Rates Test

	Thermocouples(Hz)	Load Cell and Pressure Transducers(Hz)	Accelerometer(Hz)	Test Time(s)
Data Rate Requirements	10	125	100	20
Test One	10.1	1614	151	91
Test Two	15.1*	1618	150.2	278
Test Three	15.6*	1568	150	16

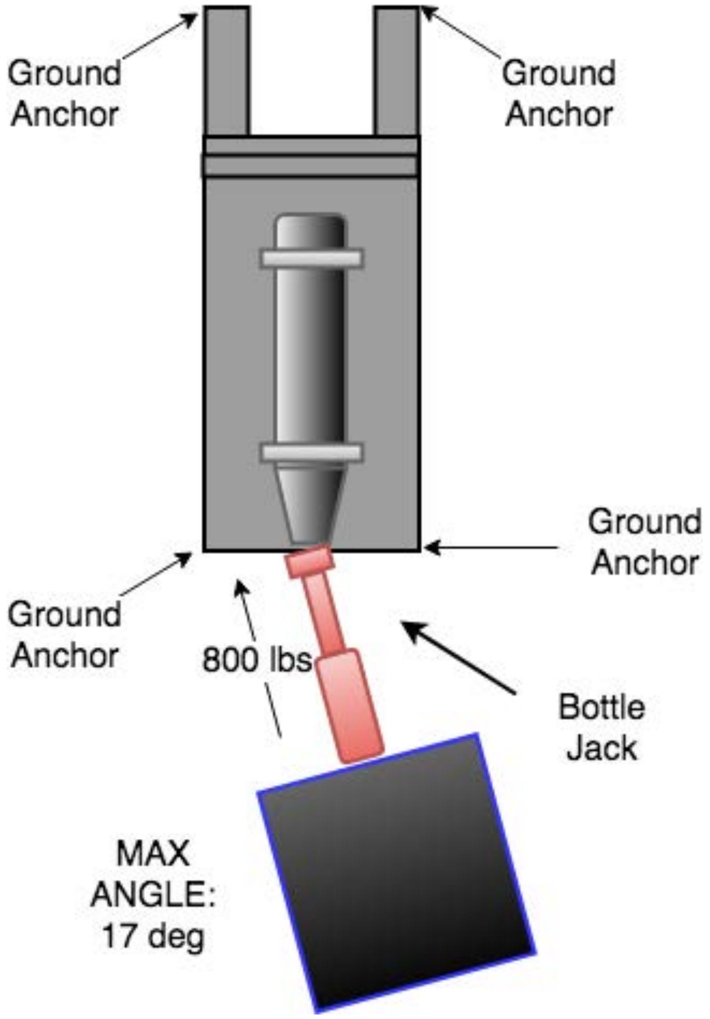
*These test used a sampling rate of 15 Hz for the thermocouples, to allow for some margin of software delay.

Other DAQ Software Tests

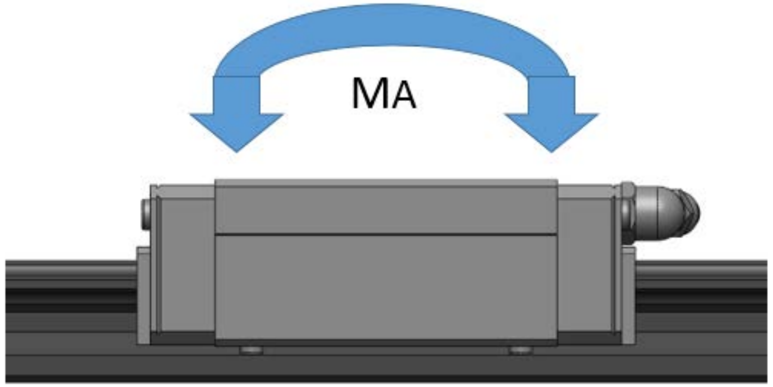
- Did order of magnitude tests with:
  - Load Cell
  - Pressure Transducers
  - Thermocouples
  - Accelerometer

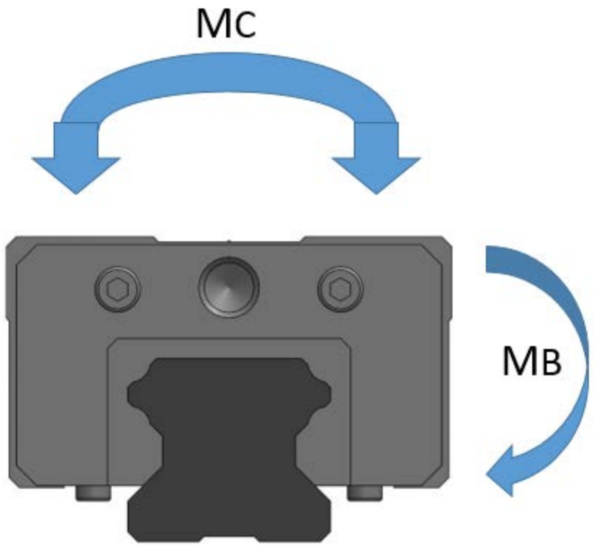
Phase 1 Details

- Replace rocket with aluminum cylinder
- Use bottle jack to simulate thrusting at 300, 550, and 800 lbf
- Place bottle jack at 17° to simulate off-axial thrusting



Carriage Tolerances





Specifications are from the manufactures

Moment A (MA)	Moment B (MB)	Moment C (MC)	Static Load
0.323 kNm	0.323 kNm	0.27 kNm	21 kN

Simulated Loads Safety Precautions

Phase	Safety Concern	Addressing the Concern
1	Physical Safety	Eyewear, gloves, if something goes wrong stop the test
2	Property Damage Physical Safety	Test performed in welding shop on welding blocks Matt Rhode will provide training in torch operation, we will take proper precautions in setup and operation
3	Property Damage Physical Safety	Test will be performed in the welding shop. Operators will be behind an polycarbonate blast shield, fail open and fail closed

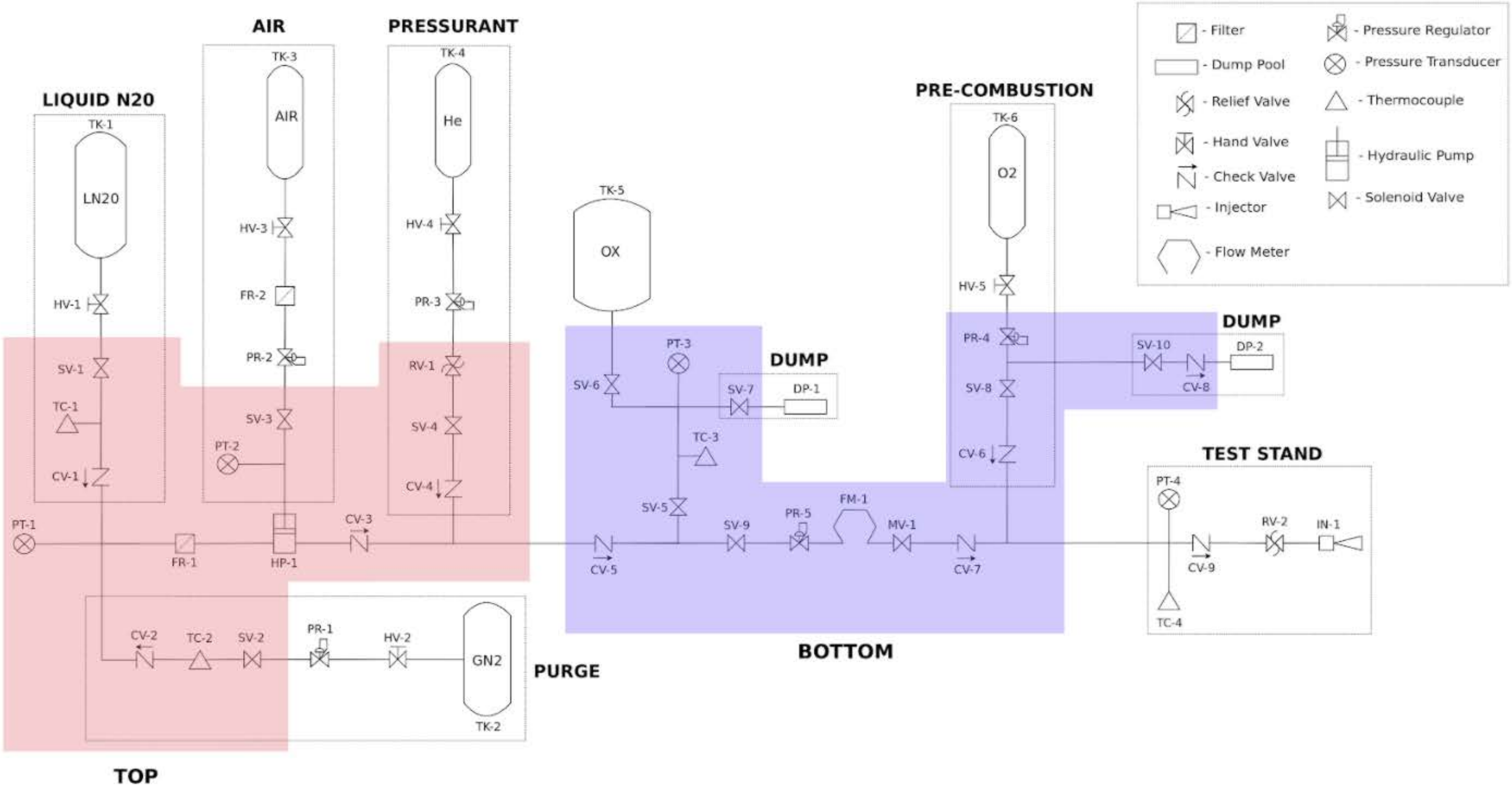
Cold Flow Details

- Install all plumbing as usual, but swap Nitrous tank for CO_2 tank
- Install Injector plate on test stand, but not whole rocket; integrate injector plate with plumbing system to allow flow
- Follow regular filling procedure with CO2 into oxidizer tank to 1000 psi
- Test emergency dump switch
- If test is good, proceed to refill tank to 1950 psi, then pressurize with Nitrogen to 2000 psi
- Proceed with mock “hot fire” test

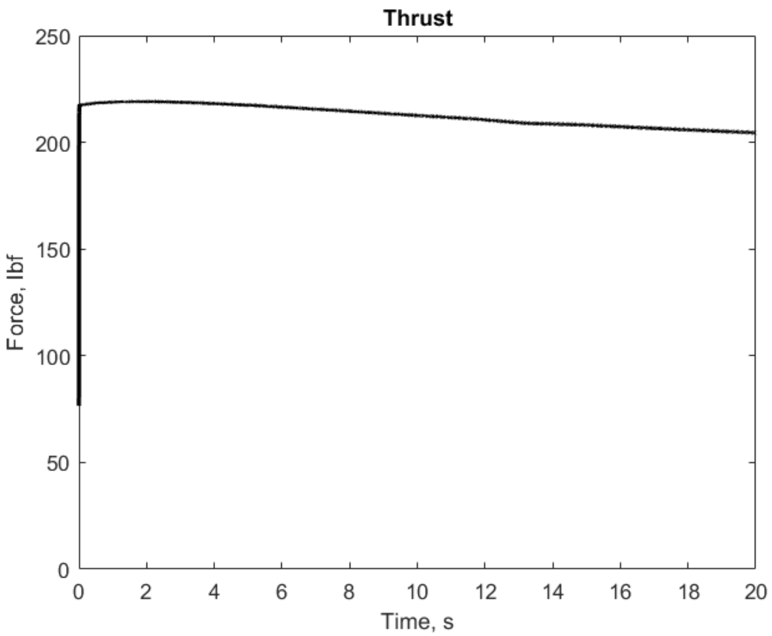
Cold Flow Safety Precautions

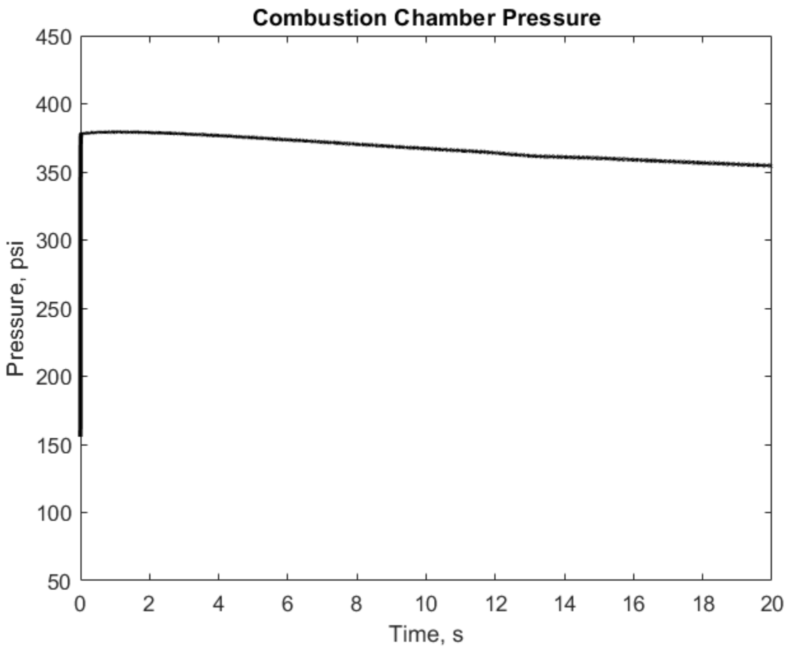
Safety Concern	Addressing Concerns
Plumbing Failure	Operate test as if it were a hot fire test Use failure mode testing procedures in event of emergency Four Operators: 1 Supervisor, 1 RSO/Checklist Operator, 1 Actuator, 1 Analyst
Pressure Tank Failure	Actuate with switchboard from 50 feet away

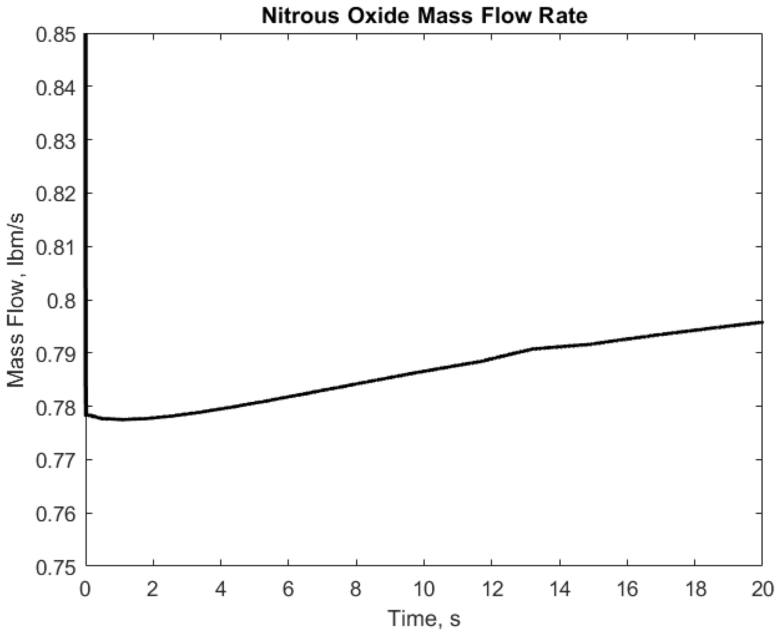
Hot Fire Schematic



Performance Prediction Model







Hot Fire Safety Precautions

Safety Concern	Addressing Concerns
Plumbing Failure	Operate test as if it were a hot fire test Use failure mode testing procedures in event of emergency Four Operators: 1 Supervisor, 1 RSO/Checklist Operator, 1 Actuator, 1 Analyst
Pressure Tank Failure	Actuate with switchboard from 50 feet away
Combustion Chamber Failure	Dump oxidizer and oxygen tanks, purge chamber, Platteville fire department on site in case of fire
In case we thought we were doing good	Matt will be there to yell at us