HICKAM CDR

(**H**ybrid-rocket **I**nformation-**C**ollection, **K**nowledgebase and **A**nalysis **M**odule)

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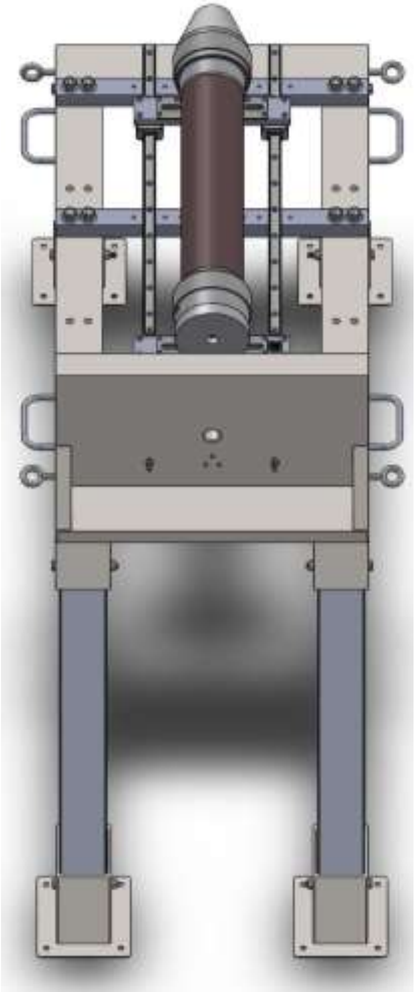
Agenda

- Project Purpose and Objectives
- Design Solution
- Critical Project Elements
- Design Requirements and their Satisfaction
- Project Risks
- Verification and Validation
- Project Planning



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.

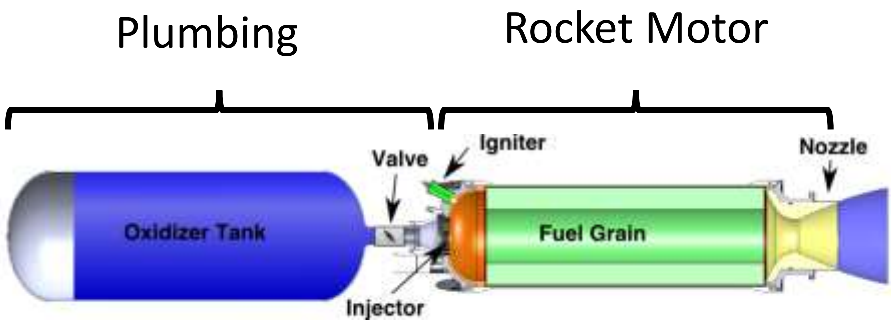
Deliverables:

- Design and manufactured test stand
- Manufactured rocket motor

Customer vision:

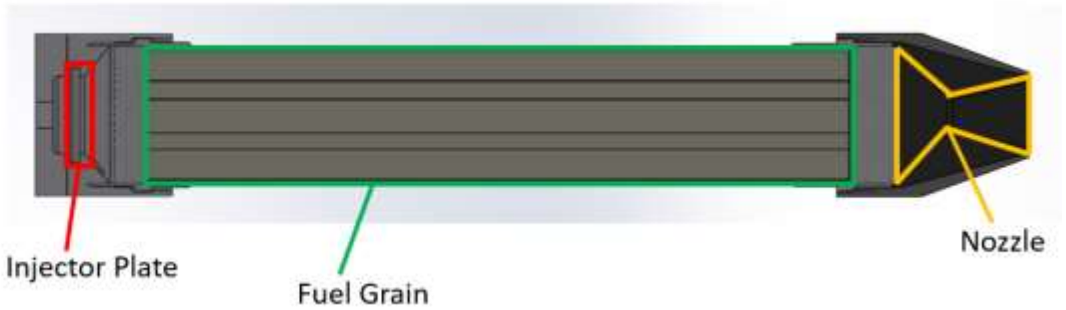
- A plug-and-play test stand for future hybrid rocket projects
- Donated to the department for future rocket project use

Hybrid Rocket 101



- Allows stop/start capability similar to liquid rockets
- Pressure fed, therefore less complicated than liquid rockets
- Uses inert oxidizer and fuel grain, much lower chance of explosion

MaCH-SR1 Rocket Motor



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, nozzle temperature
Level 2	Successful static cold flow test	Measure of combustion chamber pressure
Level 3	Successful static hot fire test	Measure oxidizer flow rate, specific impulse

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

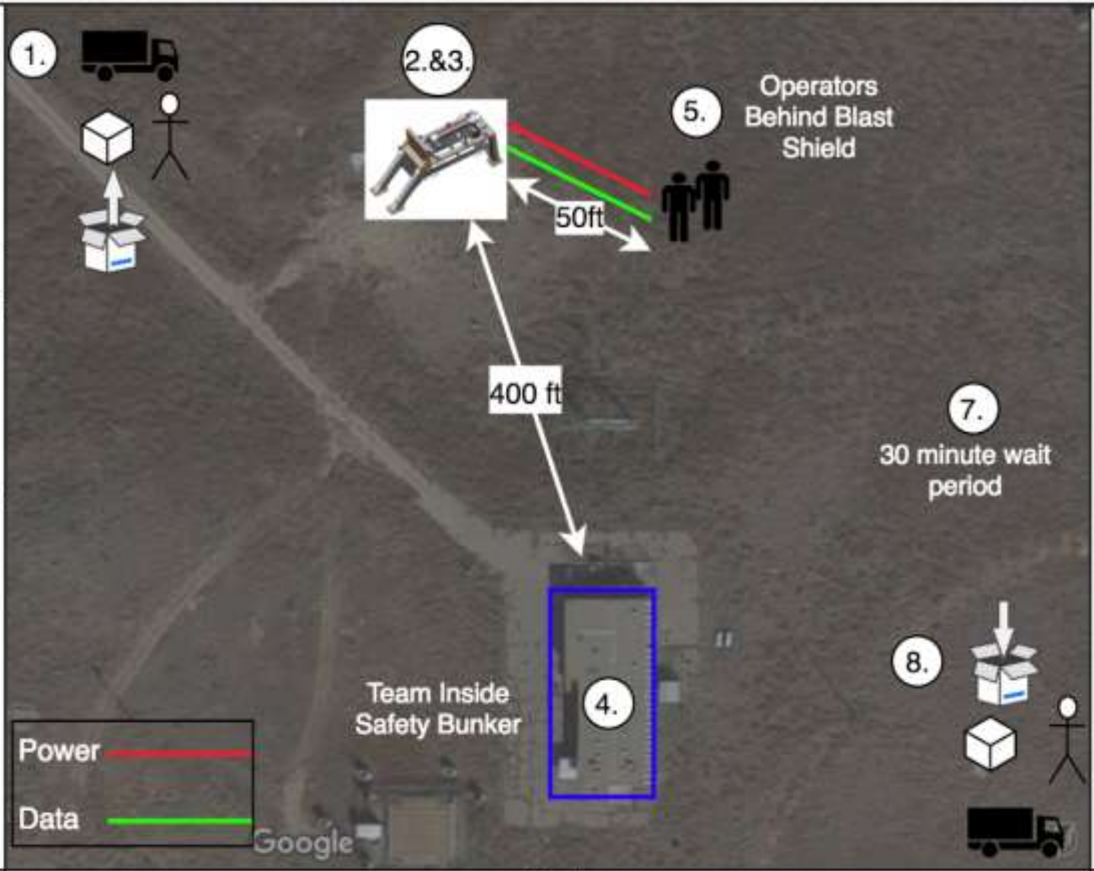
Pre - Test

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

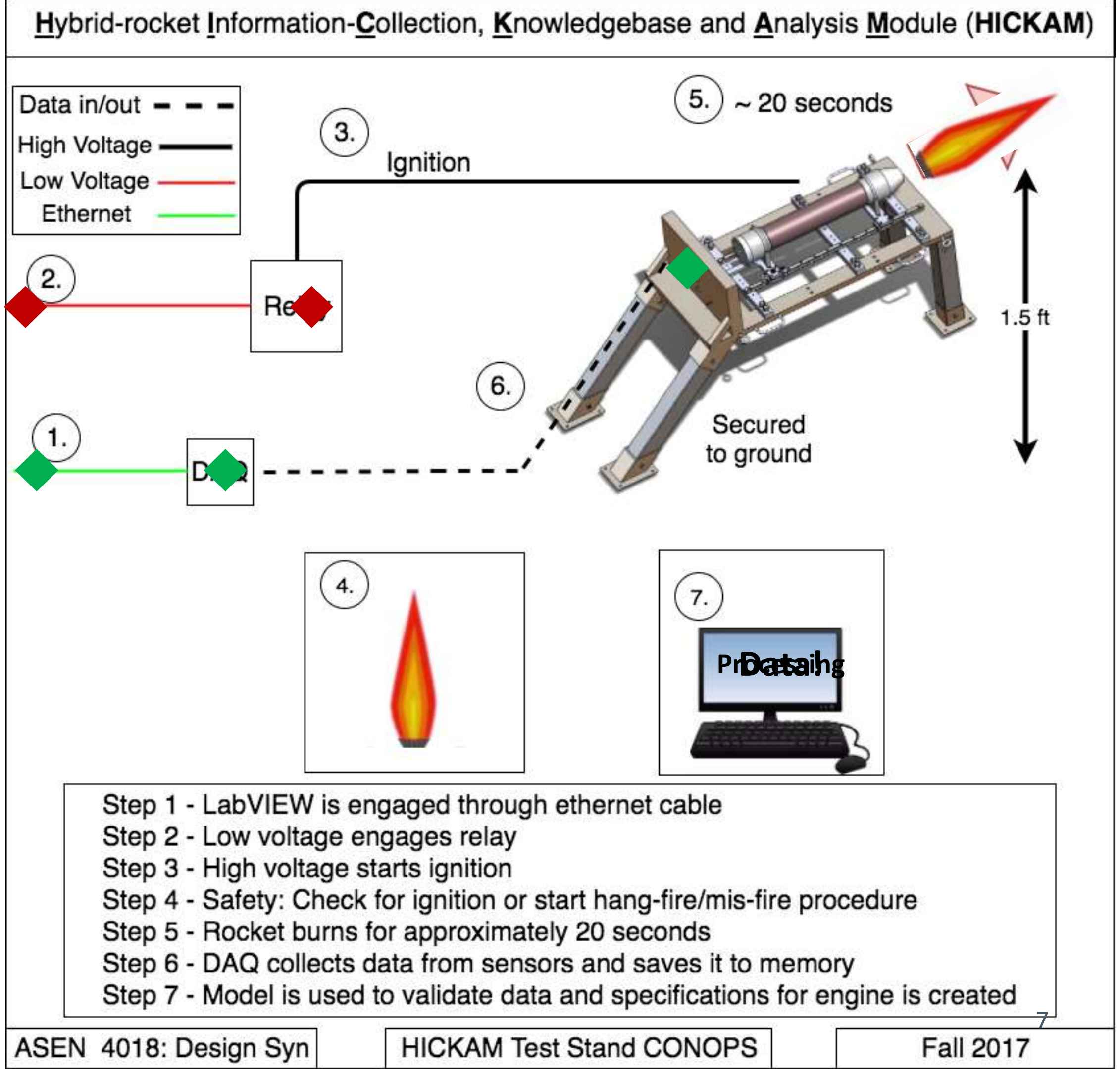
Step 8 - Disassemble, box, and transport HICKAM

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

Test

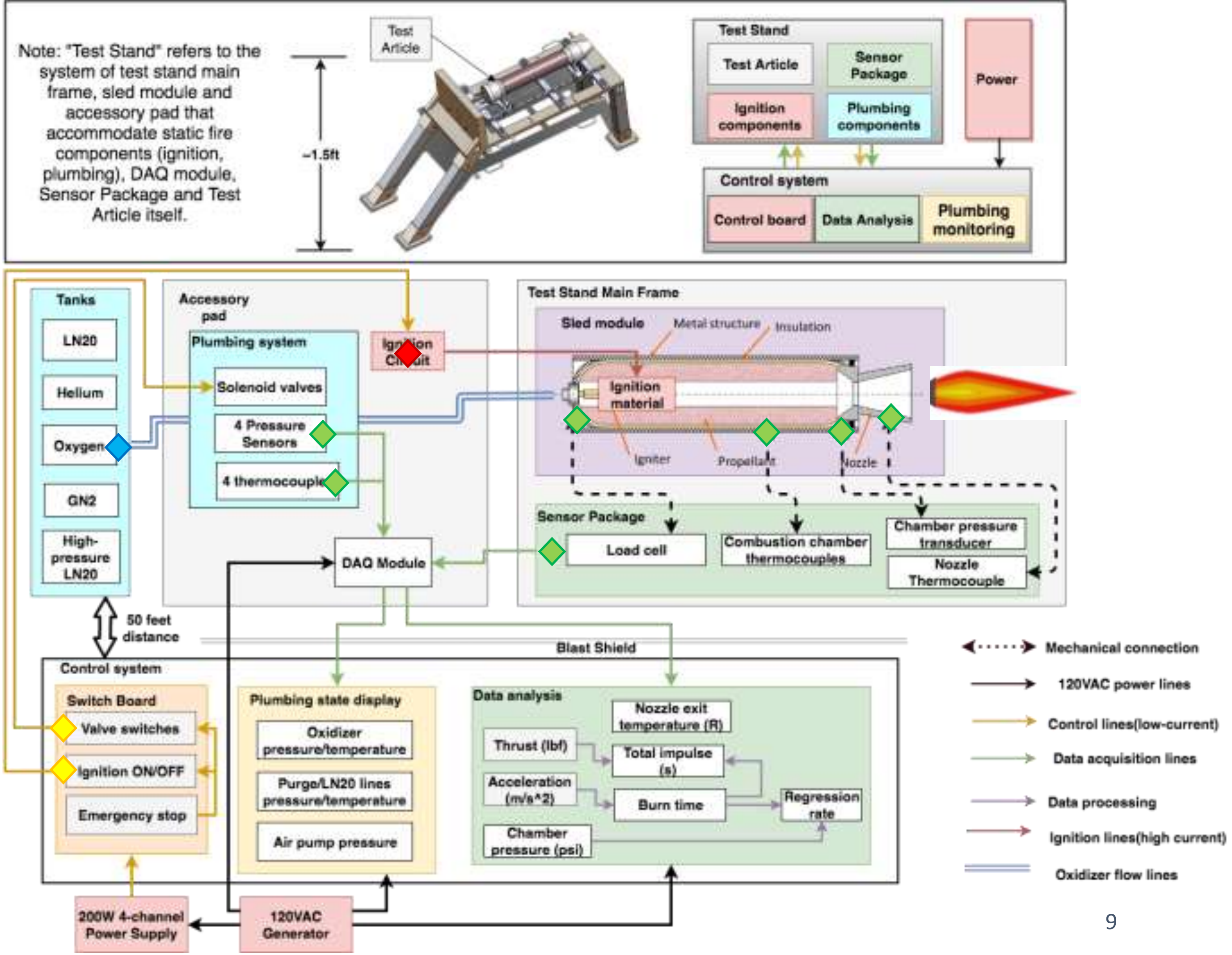
Step 5 - Command to engage DAQ to start recording data, and initiate rocket ignition
Step 6 - DAQ collects data for the 20 second approximate burn and saves it to memory
Step 7 - 30 minute wait time before approaching HICKAM to ensure safety

HICKAM
Test Stand CONOPS

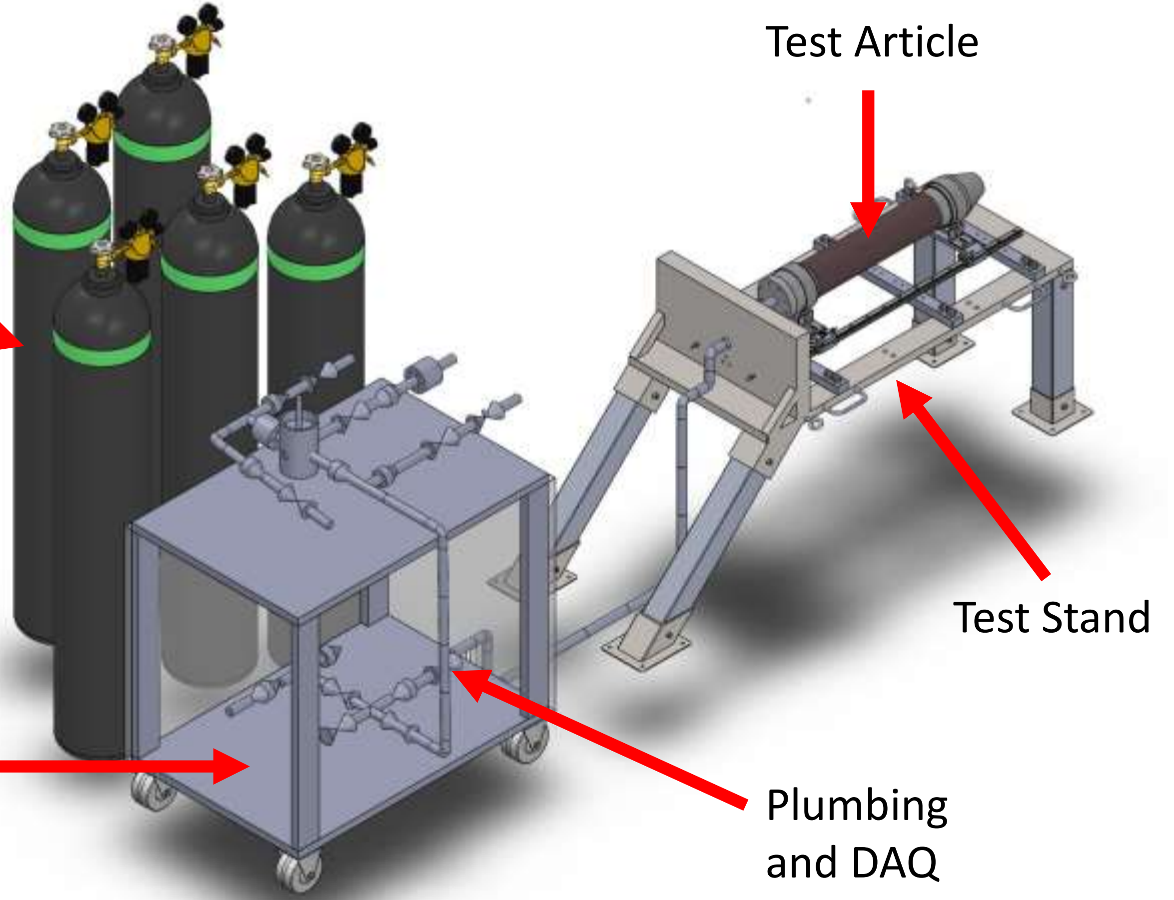


Design Solution

Functional Block Diagram (FBD)



Overview


Plumbing
Tanks
Test Article
Test Stand
Accessory Pad
Plumbing
and DAQ

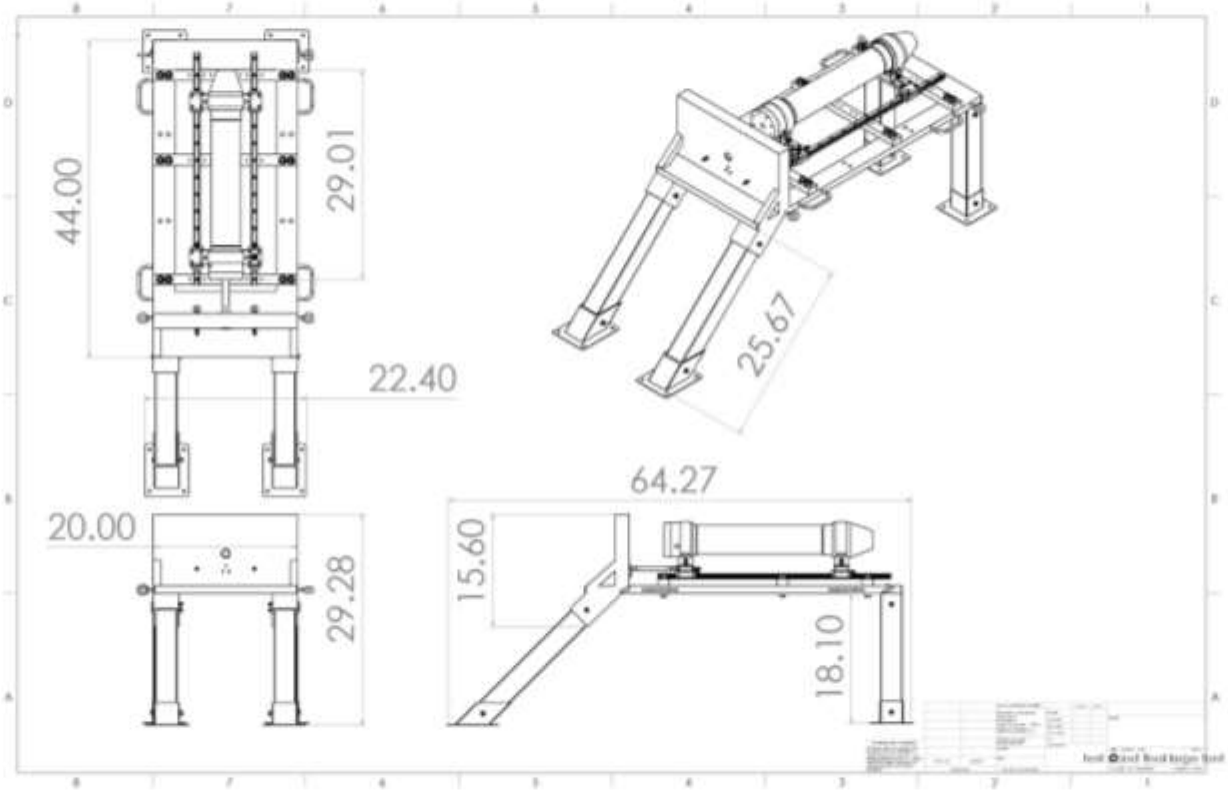
Test Stand Dimensions

Total assembly length:
64.78” ~ 5 feet 4.78 inches

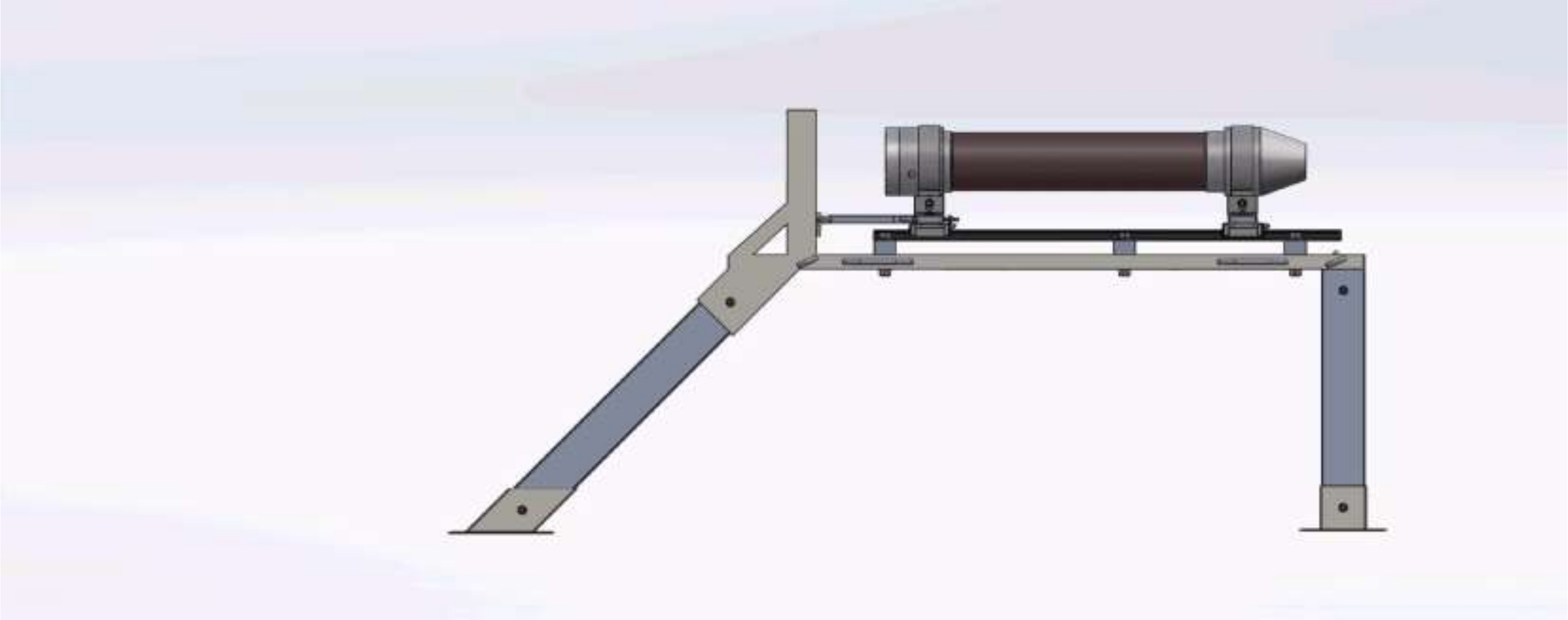
Total assembly height:
29.18” ~ 2 feet 5.18 inches

Total assembly width:
22.50” ~ 1 foot 10.5 inches

Total assembly mass: 305lbs

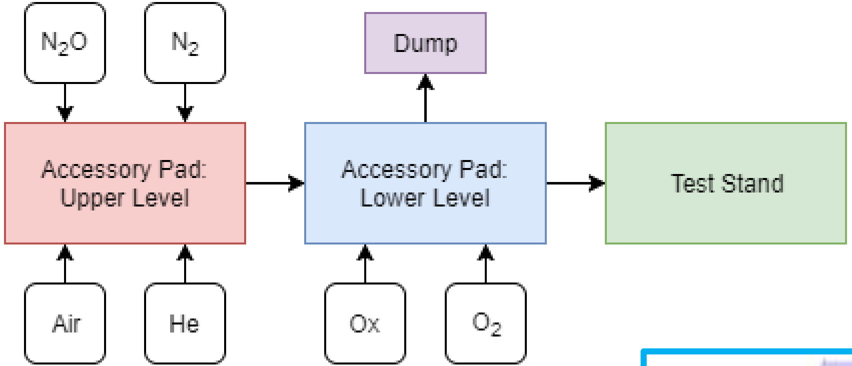


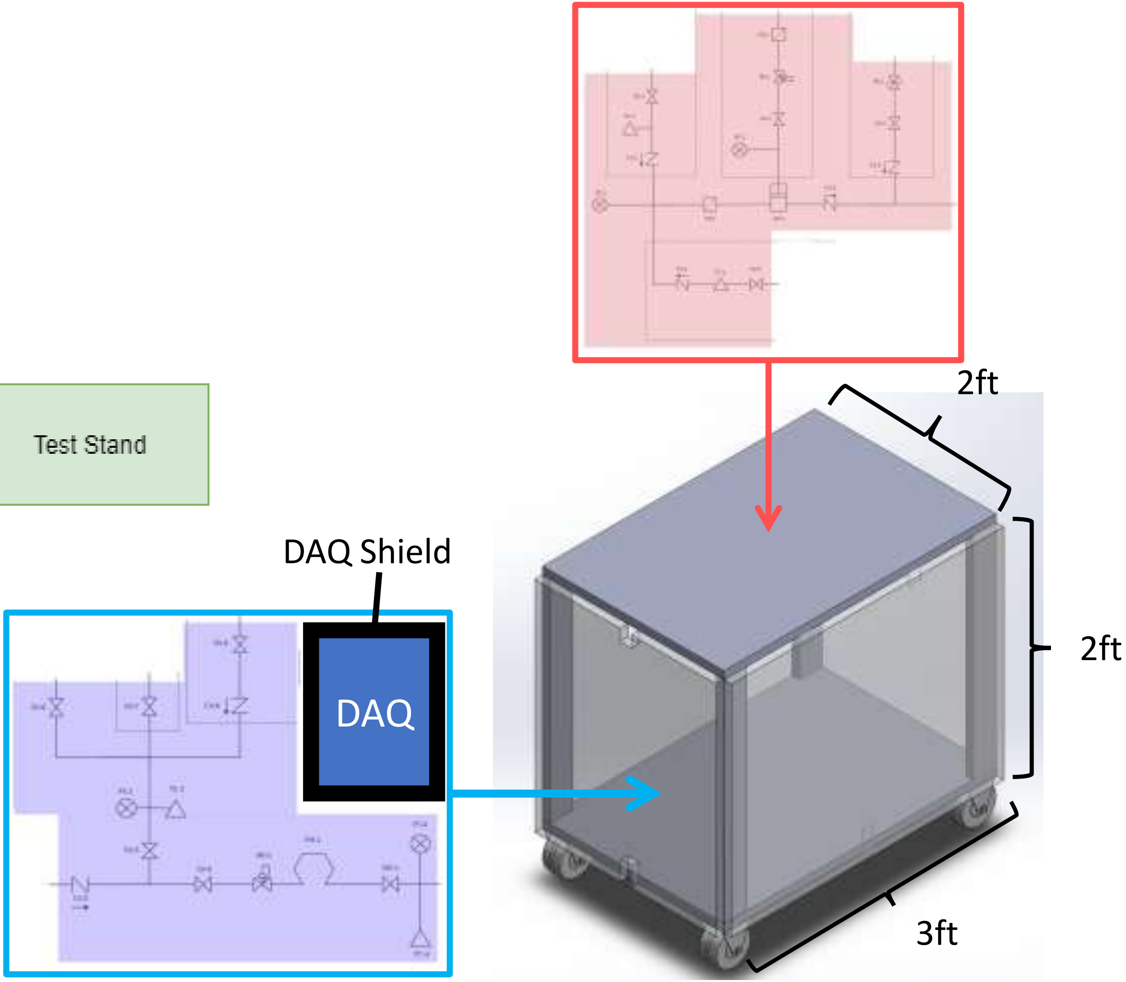
Test Stand Animation



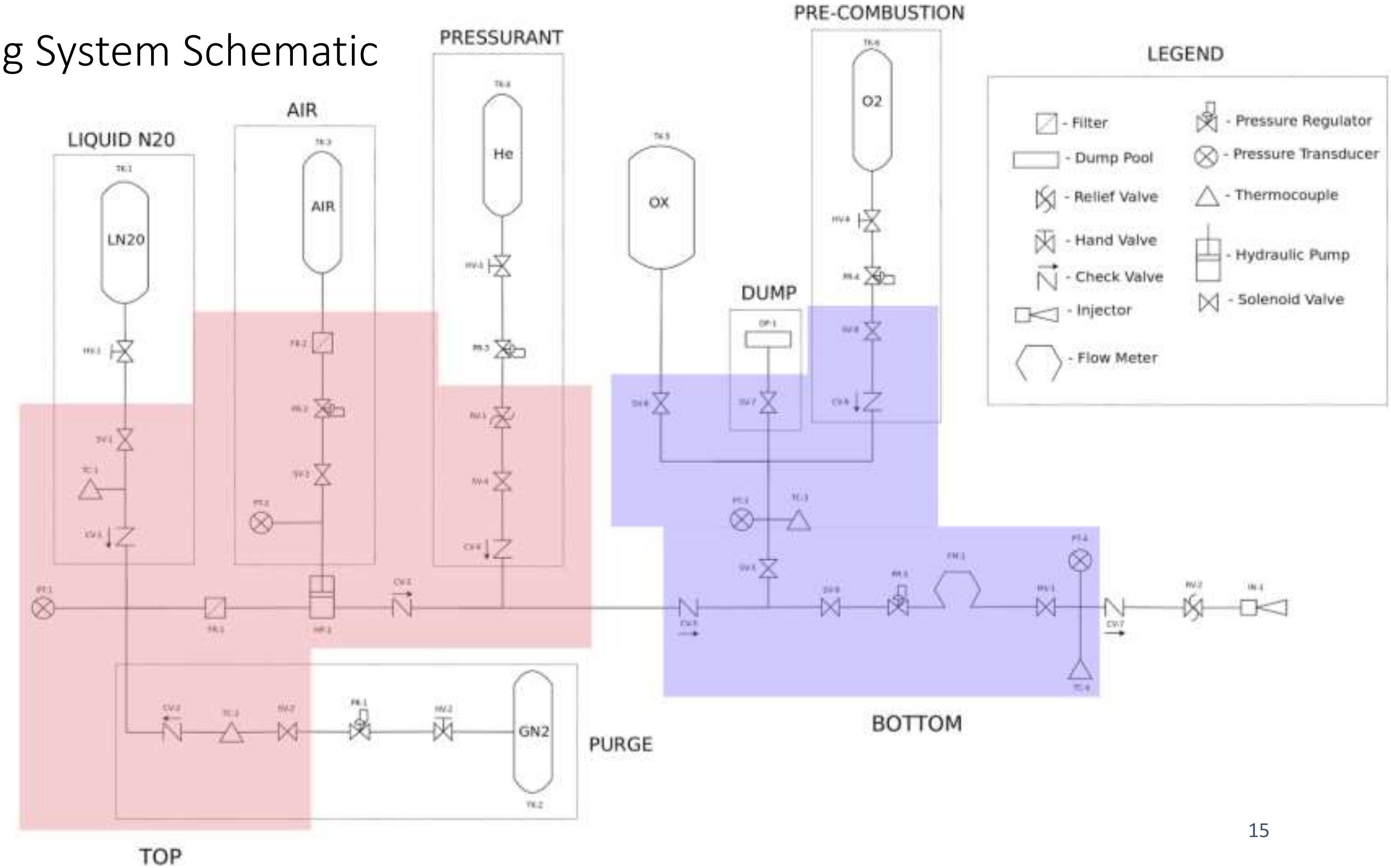
Rocket Mount

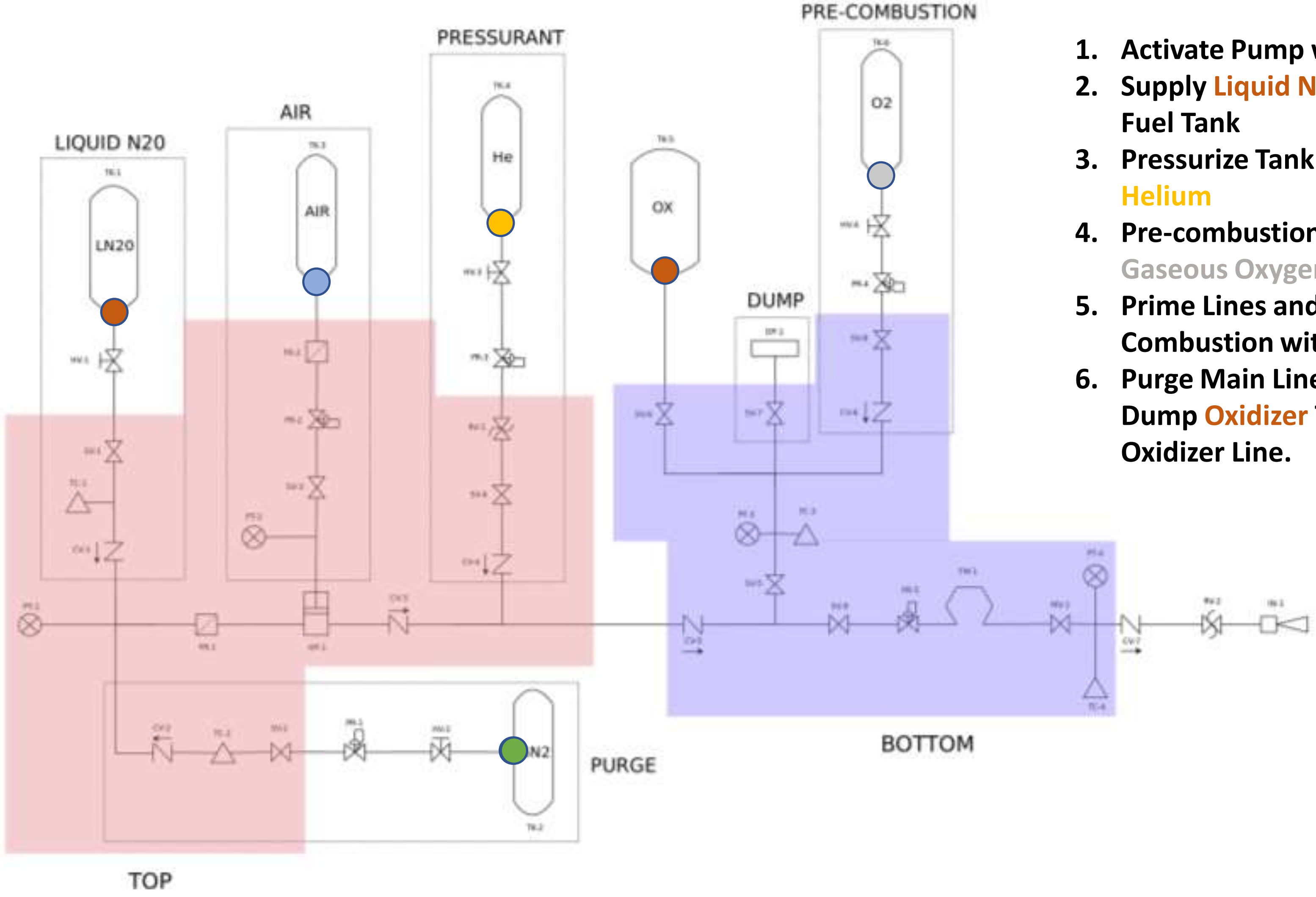
Accessory Pad





Plumbing System Schematic

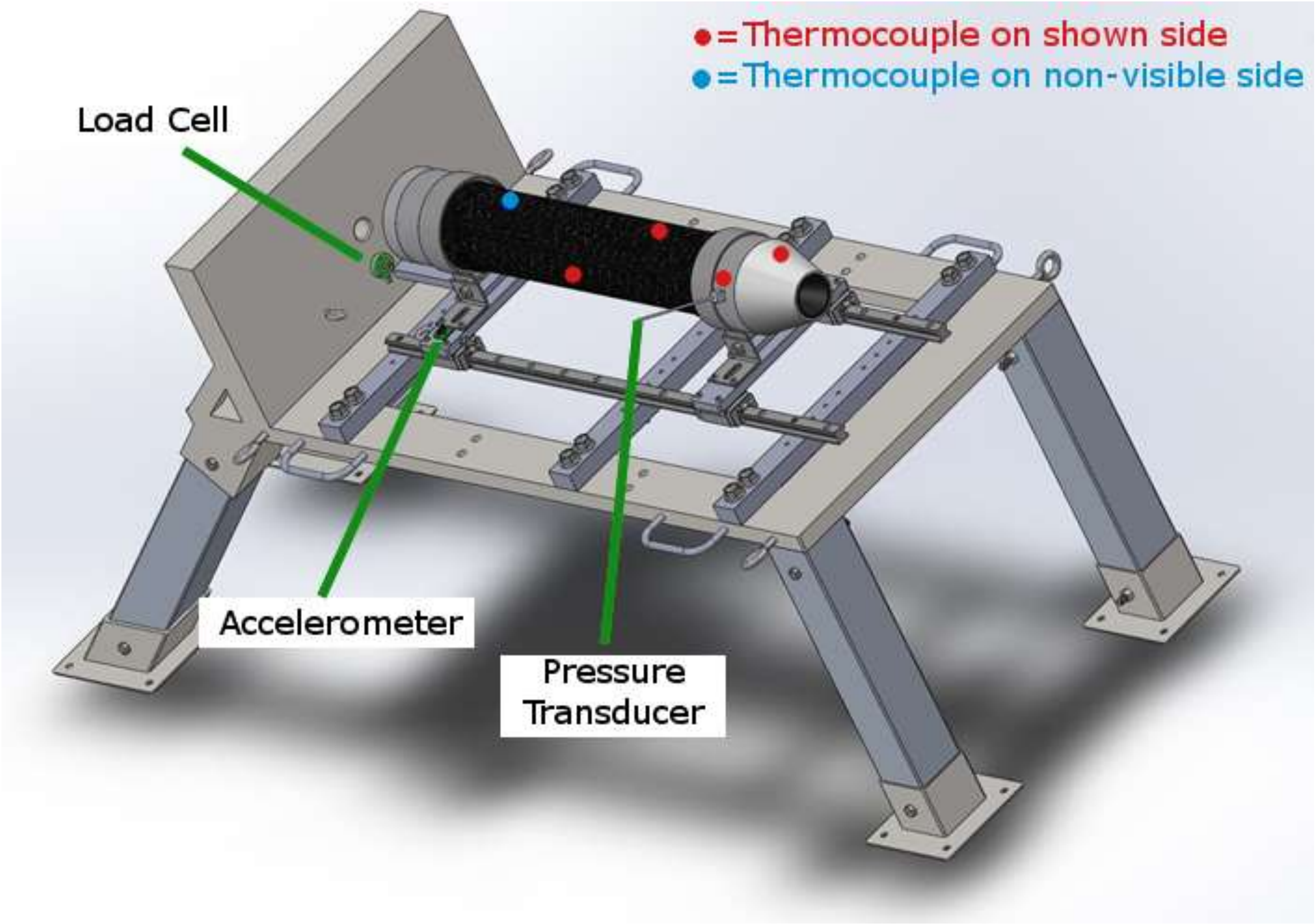




1. Activate Pump with Air
2. Supply Liquid Nitrous Oxide to Fuel Tank
3. Pressurize Tank with Gaseous Helium
4. Pre-combustion Process with Gaseous Oxygen
5. Prime Lines and Begin Combustion with Oxidizer
6. Purge Main Line with Nitrogen, Dump Oxidizer Tank, and Purge Oxidizer Line.

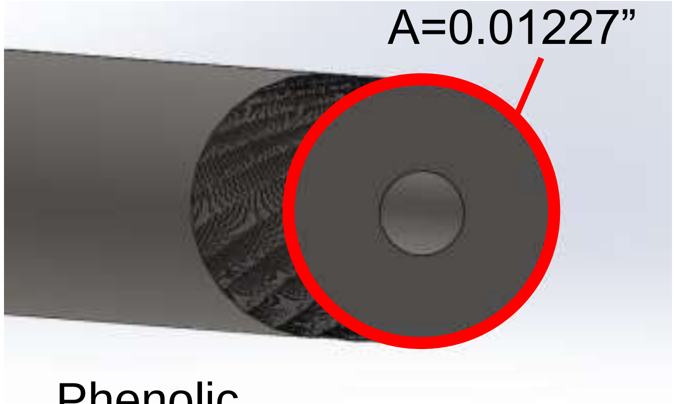
Sensors

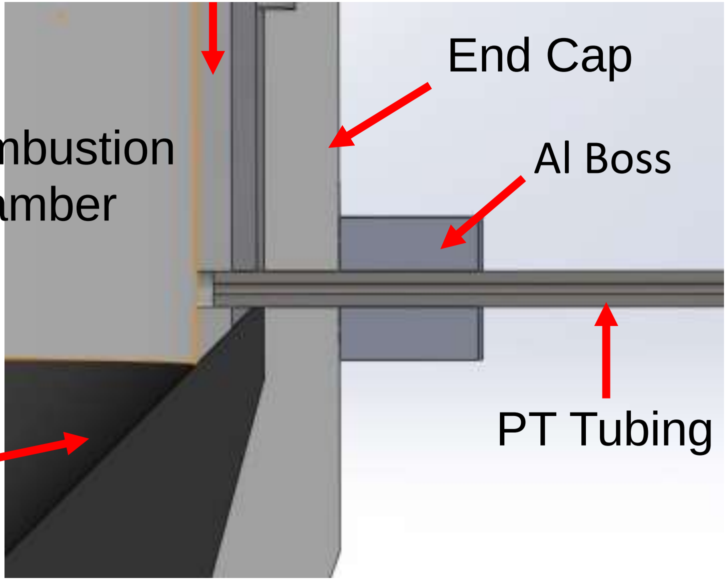
- Test stand sensors shown
- Not shown: Mass flow meter
- Not shown: Plumbing system sensors



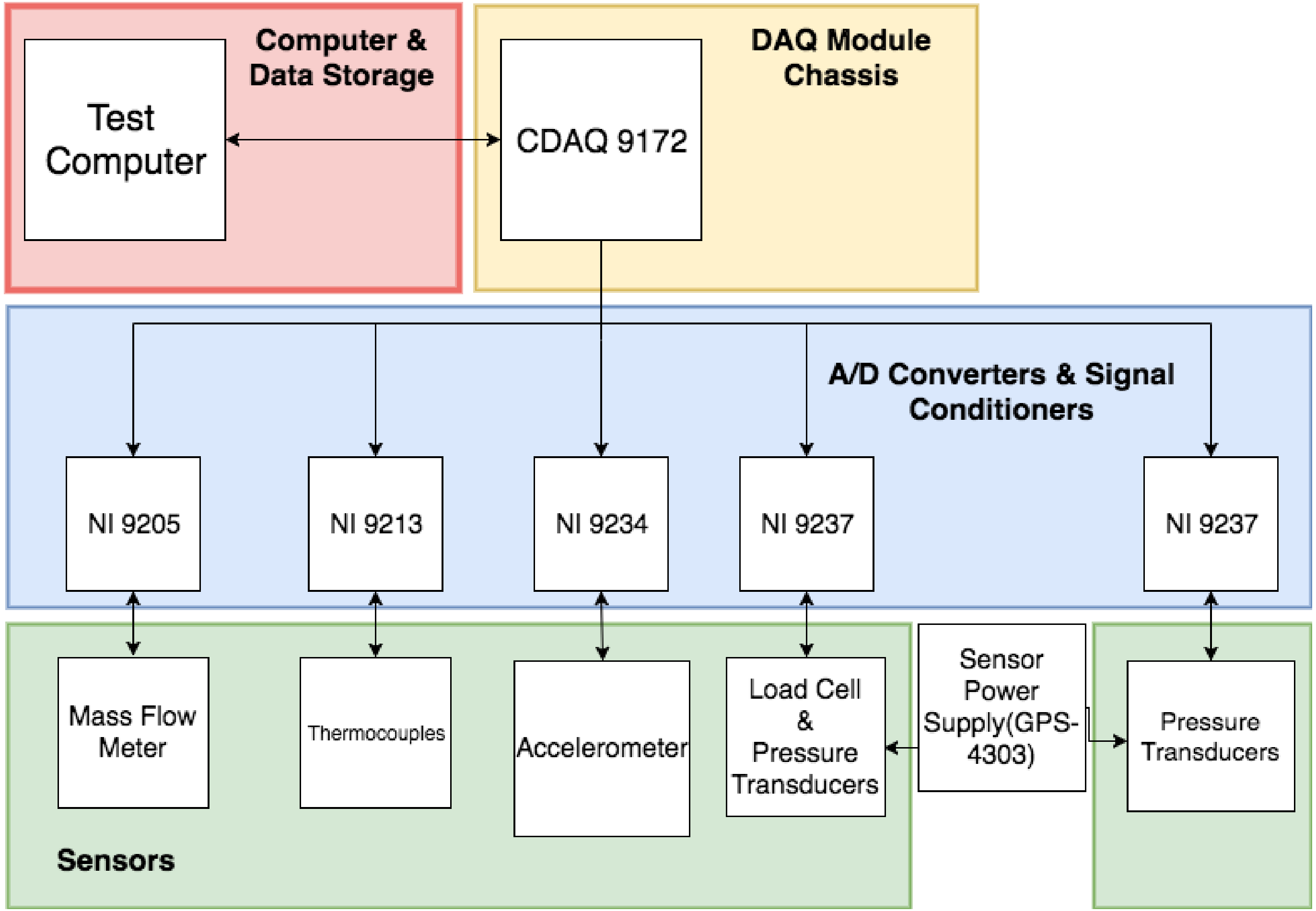
Chamber Pressure Transducer

- Design Plan:
  - Stainless Steel 304 Tubing to Pressure Transducer
    - ID = 0.03”
    - OD = ⅛”
    - Length = 10 in
  - Weld Aluminum Boss onto Aluminum Nozzle End Cap
  - Drill Boss, End Cap, and Phenolic
    - Drill Size: #29 = .136”
  - Tap (8-32) Boss and End Cap
    - Tap Length = .75 inches = 24 threads
  - Die (8-32) Stainless Steel Tube
  - 8-32 Thread Height = 0.034”

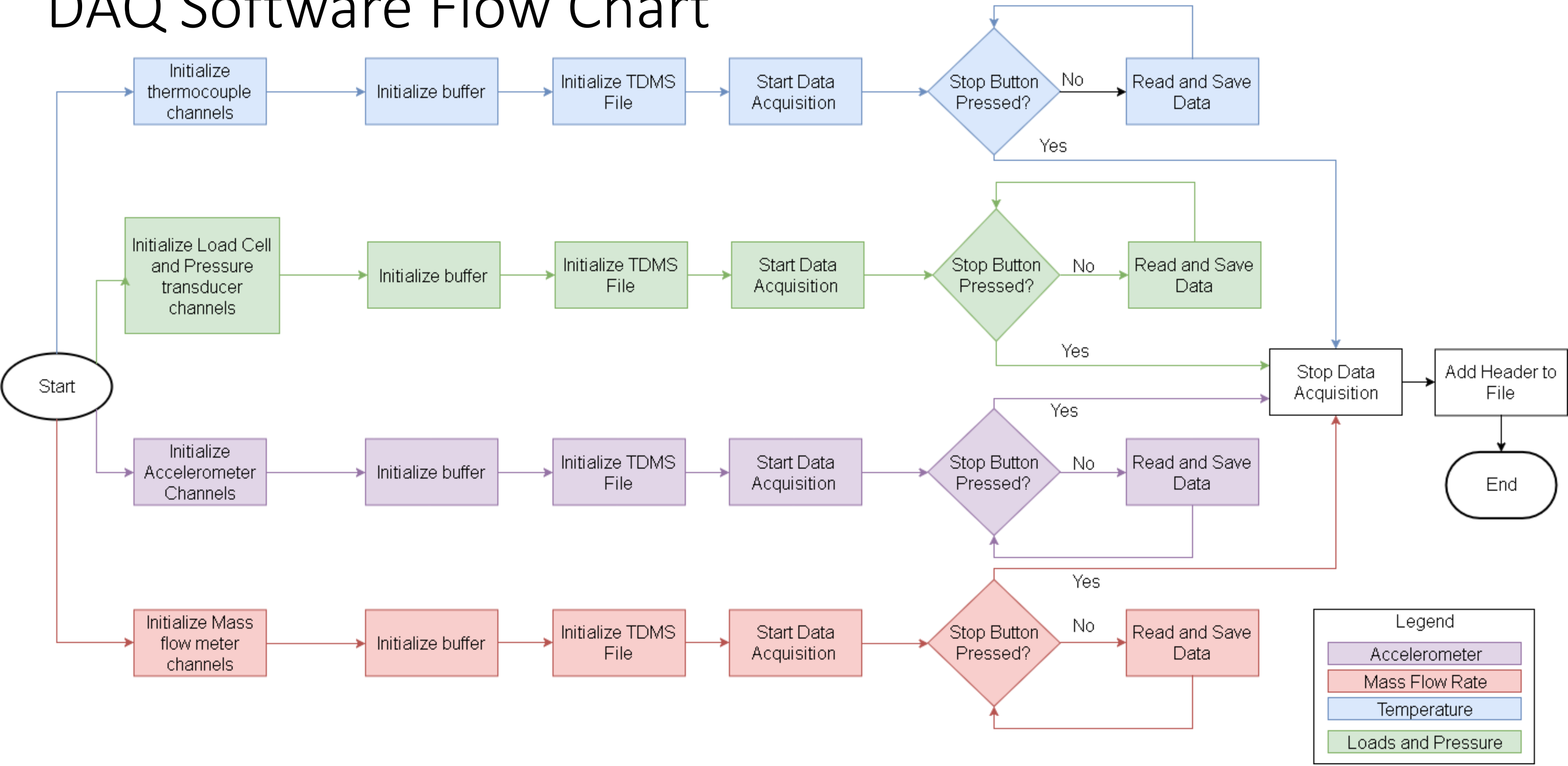




DAQ System


Computer &
Data Storage
Test
Computer
DAQ Module
Chassis
CDAQ 9172
A/D Converters & Signal
Conditioners
NI 9205
NI 9213
NI 9234
NI 9237
NI 9237
Mass Flow
Meter
Thermocouples
Accelerometer
Load Cell
&
Pressure
Transducers
Sensor
Power
Supply(GPS-
4303)
Pressure
Transducers
Sensors

DAQ Software Flow Chart



PO | Design Solution | CPE | DR | PR | VV | PP

Critical Project Elements

PO DS CPE DR PR VV PP

CPE List

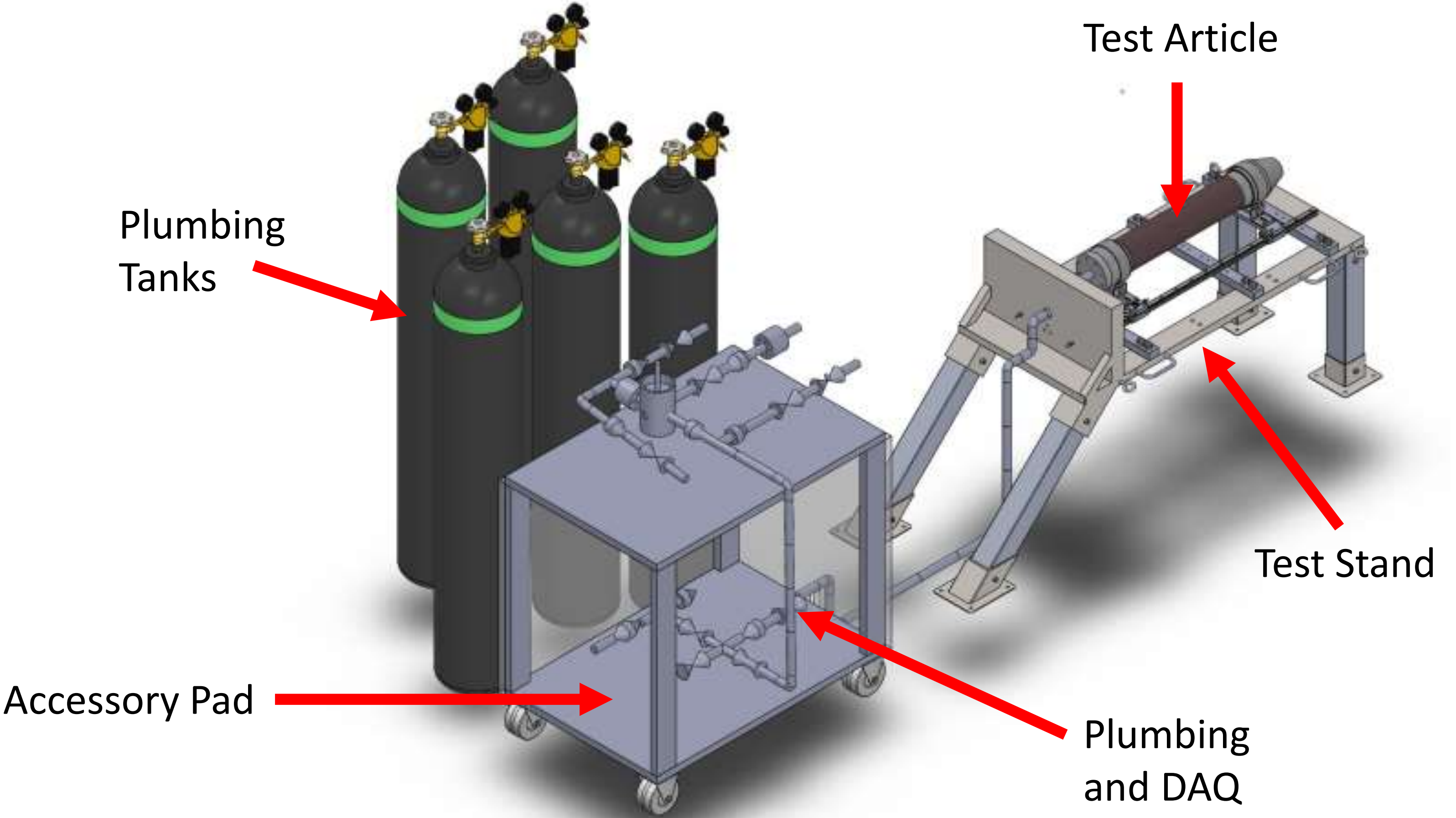
Rank	CPE	Description
1	Safety	• Rocket critical failure risk • Environmental and personnel safety risks • Pressure transducer attachment failure risk
2	Budget	• Costs of four major systems: test stand, plumbing, rocket, and sensor package
3	Data Acquisition and Analysis System	• Data acquisition is a significant portion of the project goal
4	System Validation using Computational Modelling	• Low fidelity performance characterization model • Validation of pressure transducer attachment
5	Manufacturing of the Test Stand and Rocket Engines	• Manufacturing multiple components including the test stand, plumbing, and a rocket

Design Requirements and their Satisfaction

Key Design Requirements

Design CPE's	Related key design requirements	Component design influenced
Safety	DR 6.8: Test stand structural integrity DR 6.1-6.7: Test stand operation/plumbing	Test stand structure, plumbing system, pressure transducer attachment
Data Acquisition	DR 4.1-4.6: Test article sensor requirements DR 5.1-5.2: Signal conditioning. DR 6.6: Plumbing sensors requirements	Sensors package, DAQ software
Computational Modelling	DR 7.1-7.2: Performance prediction model	Test article performance characterization model

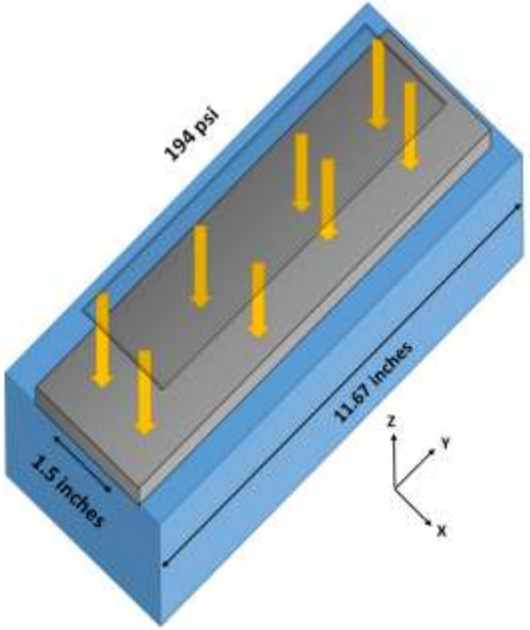
Safety Design Requirements



Test Stand Structure - Clamping Force

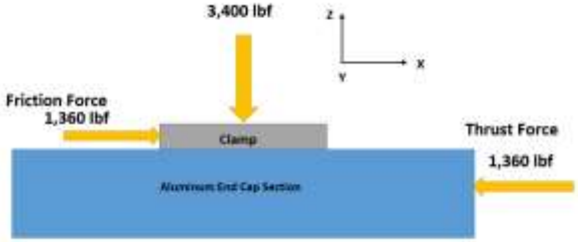
To remain static, friction force must equal thrust force.

- Coeff. Of Friction estimated - 0.4
- Circumference of contact surface = 11.67 inches
- Contact surface width of clamp = 1.5 inches
- Coeff. Of Friction estimated in bolt- 0.2
- Force from pressure assumed to be equal about contact surface and applied as load on the clamping bolt

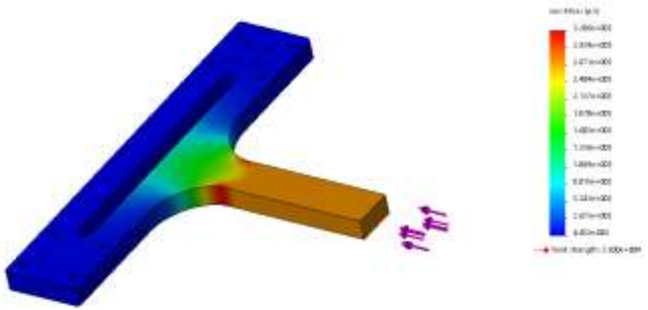


$$F_s = \mu_s N \qquad F_r = \int_L w(x)dx = \int_A dA \qquad T = \mu_s D F_r$$

DR	Requirement	HICKAM Specs
DR 6.8 Structural Stability	**Endure Hot Fire Loads** Max Load: 800 lbf Safety Factor: 1.7	**Clamping Load and Bolt Torque (Minimum)** Clamp Pressure: 194 psi Resulting Force: 3,400 lbs Bolt Torque: 255 in-lb (21.25ft-lb) ✓



Test Stand Structure - Push Bar



SolidWorks Simulation

- Aluminum 6061
- Yield Strength = 33,000 psi
- Result: 3,206 psi
  - 16% difference from hand calculations

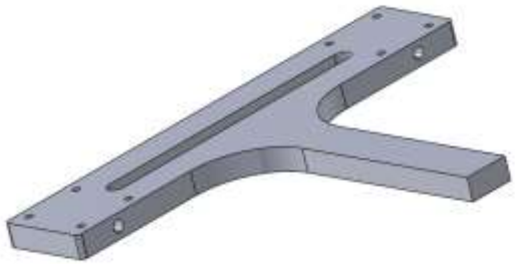
Hand Calculations

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

- 1in x 0.5 in cross section
- 6 inches long push bar

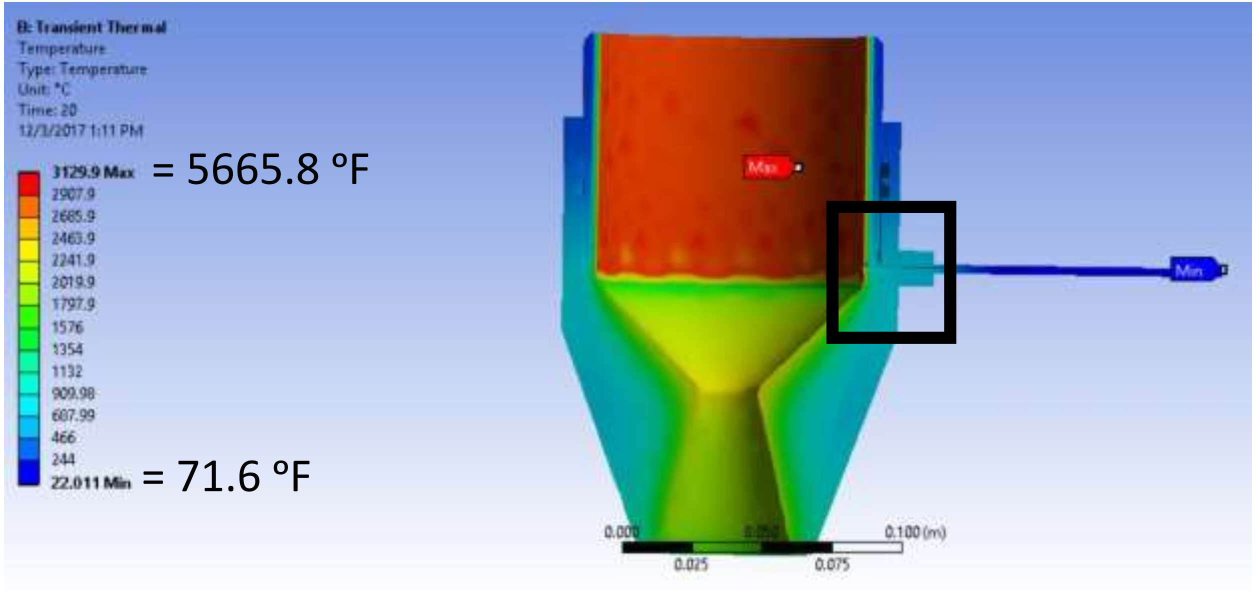
$$\sigma_{avg} = \frac{F}{A} \qquad P_{cr} = \frac{\pi^2 EI}{(KL)^2} \qquad I = \frac{bh^3}{12}$$

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 ✓

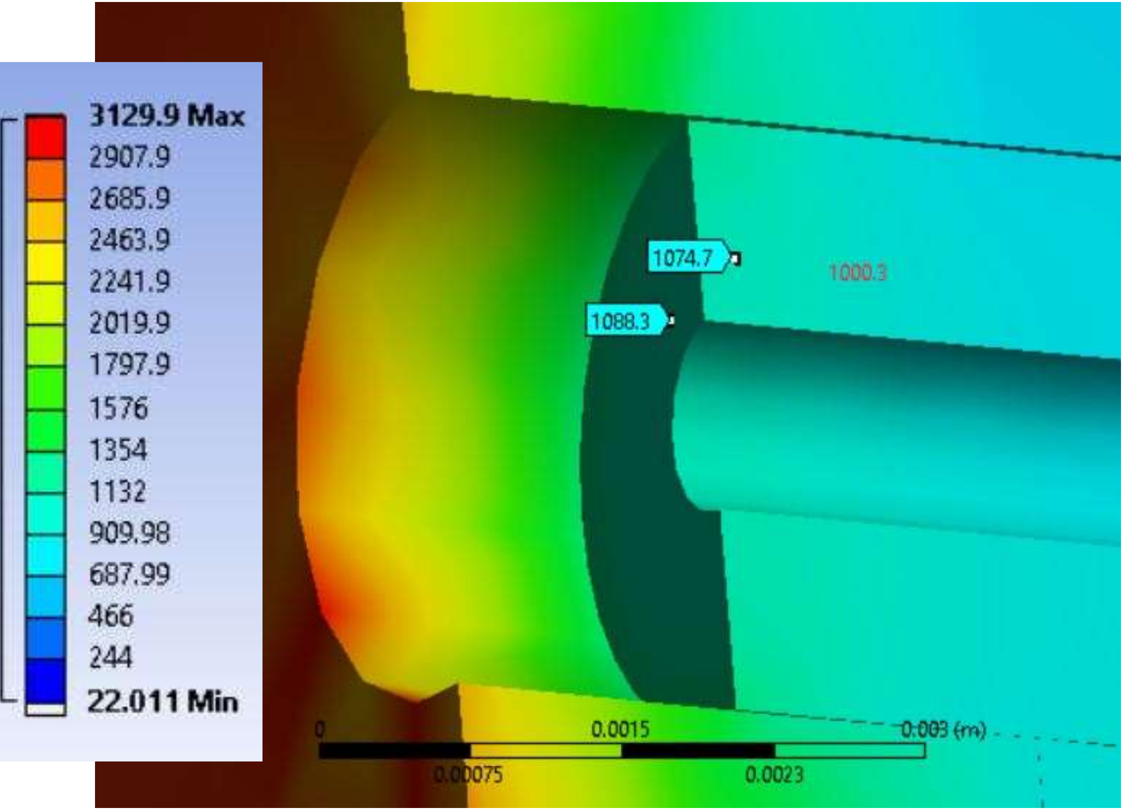


Chamber Pressure Transducer Attachment Requirements

Design requirement	Description
DR 4.1.1	The pressure transducer attachment to the combustion chamber shall not allow the sensor to get hotter than 100F.
DR 4.1.2	The pressure transducer tubing interface with the combustion chamber must withstand 1000 psi and 2600 F.



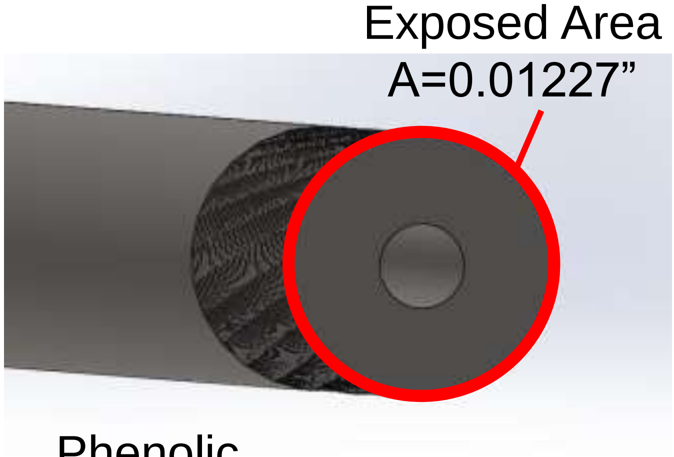
Chamber Pressure Transducer Thermal Model

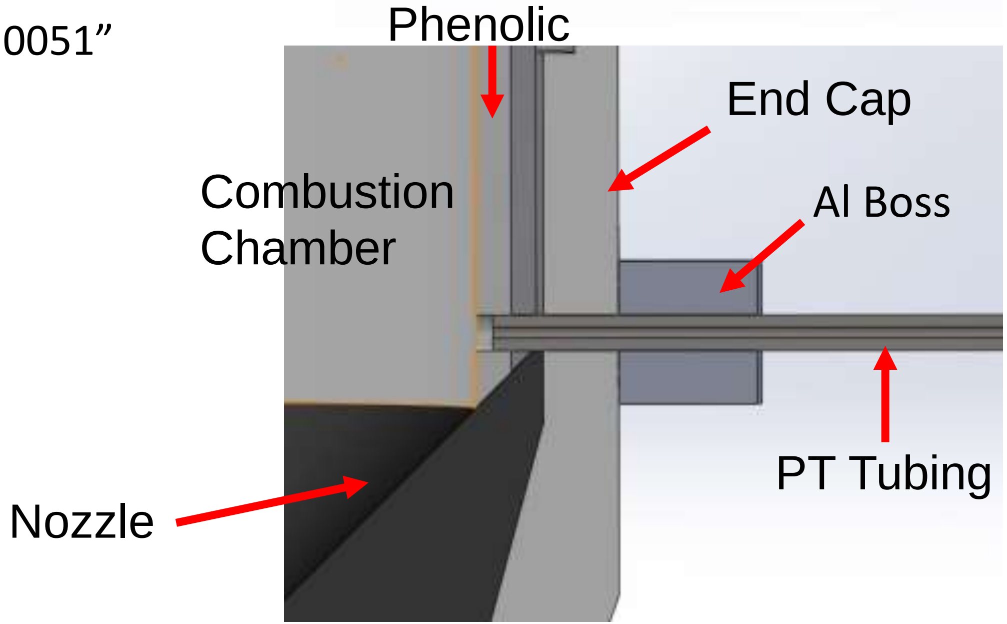


- Thermal simulation takes into account convective and radiative heat transfer.
- Pressure Transducer Tube:
  - Stainless Steel 304
    - Melting Point: ~1450 C (2642 F)
- Simulation run with:
  - Chamber Temperature = 3200 C (5792 F); ~200 C (392 F) higher than expected.
  - Chamber Pressure = 500 psi; ~125 psi higher than expected.

Chamber Pressure Transducer Coupled Thermal-Structural Model

- Maximum Deformation:
  - Aluminum End Cap = 1.05 mm
  - Stainless Steel Tube = .92 mm
  - Deformation Difference = .13 mm = 0.0051”
- 8-32 Thread Height = 0.034”
- Thread Shear Failure
  - Failure Force = 5094 lbf
  - Maximum Expected Force = 484 lbf
- Maximum Allowable Chamber Pressure for Tubing = 2000 psi





Chamber Pressure Transducer Attachment Requirements

Design requirement	Description	HICKAM Design
DR 4.1.1	The pressure transducer attachment to the combustion chamber shall not allow the sensor to get hotter than 100F.	• Temperature at Pressure Transducer = 72^{o}F ✓
DR 4.1.2	The pressure transducer tubing interface with the combustion chamber must withstand 1000 psi and 2600 F.	• Maximum Allowable Pressure = 2000 psi • Maximum Expected Temperature = 2012 F • Maximum expected force = 484 lbf ✓

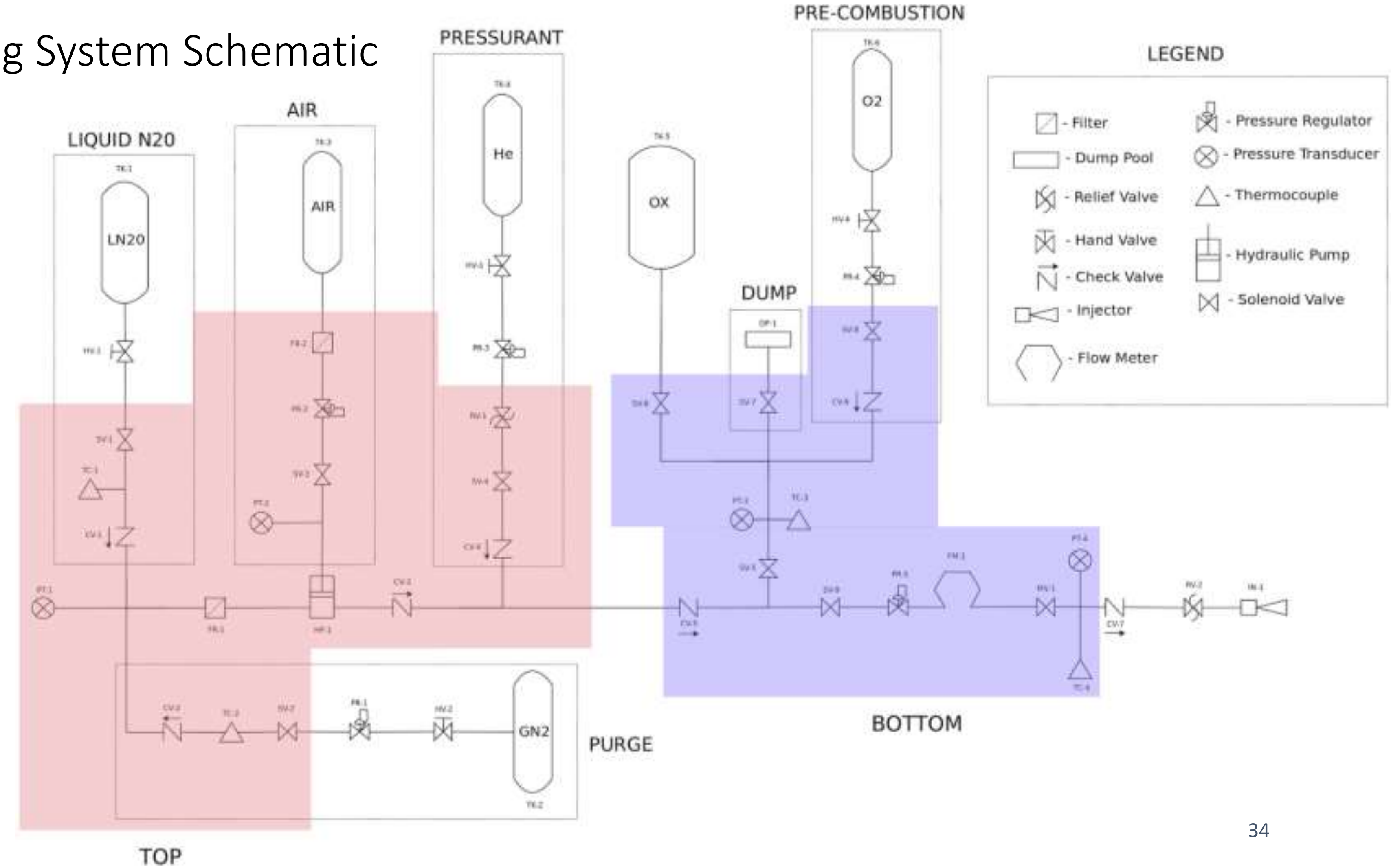
Plumbing System and Testing Requirements

Design CPE's	Related key design requirements	Component design influenced	
DR 6.1	Testing operation will be safely performed 50' away	Polycarbonate Blast Shield (8,000 psi) rated higher than Oxidizer tank burst pressure (7,000 psi)	✓
DR 6.4	System shall be capable of purging at any time	Test procedures and plumbing interface allow for purge, even during dump	✓
DR 6.7	System shall respond to predicted failure modes	Allows for depressurization and purge given detailed procedures	✓

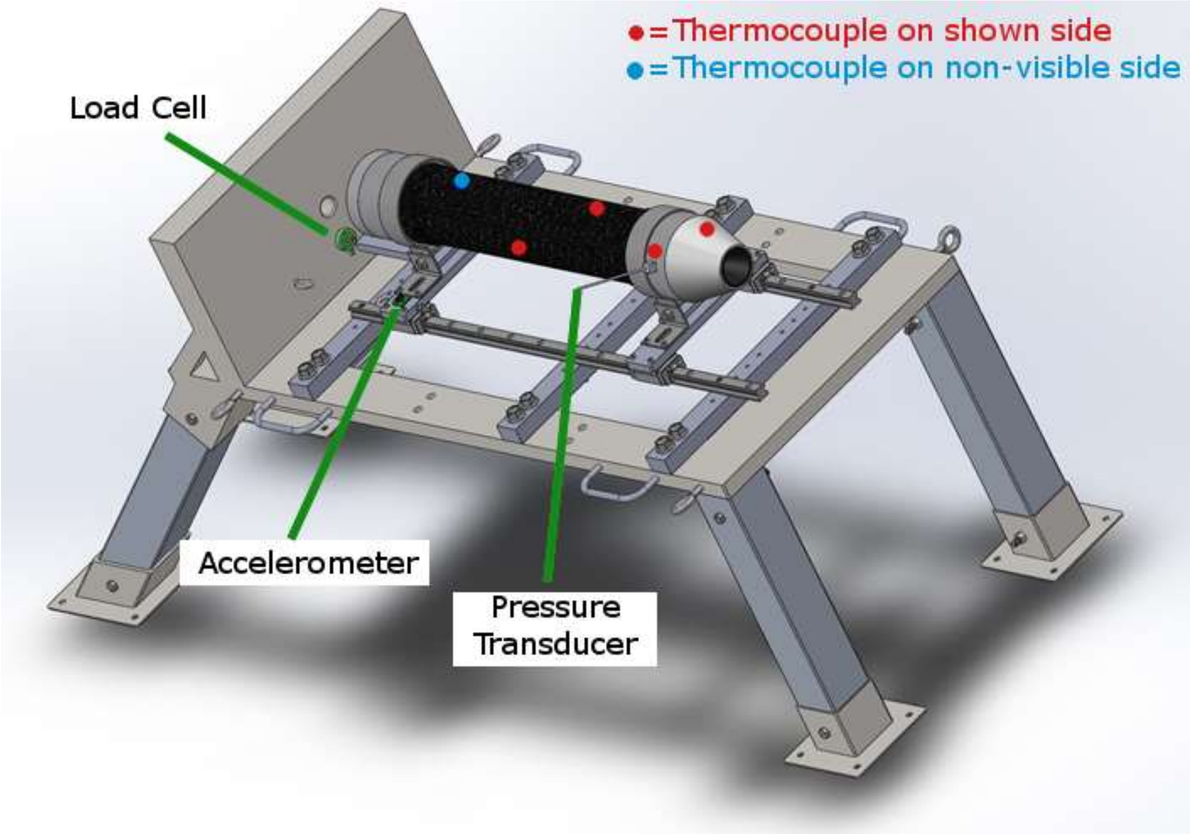
Plumbing Primary Failure Modes: DR Satisfaction

DR	Requirement	HICKAM Components & Method	
DR 6.7.1	Handle Rocket Catastrophic Failure	Relief Valve RV-2, Nitrogen Purge, Oxidizer Dump	✓
DR 6.7.2	Protect System from Helium Pressure Regulator Failure	Relief Valve RV-1 Protects Remaining Components	✓
DR 6.7.3	Avoid Frozen Solenoid Valves	Thermocouples Monitor Line Temperatures to Warn if Temporary Shutdown Necessary	✓
DR 6.7.4	Purge System in Event of Total Power Failure	Fail Open/Close Valves Strategically Placed To Purge System with N2 while Dumping Oxidizer Tank	✓
DR 6.7.5	Shutdown Plumbing or Purge System if Given Abort Command	Protocols Written for Either Stop-Flow or Purge & Dump	✓

Plumbing System Schematic

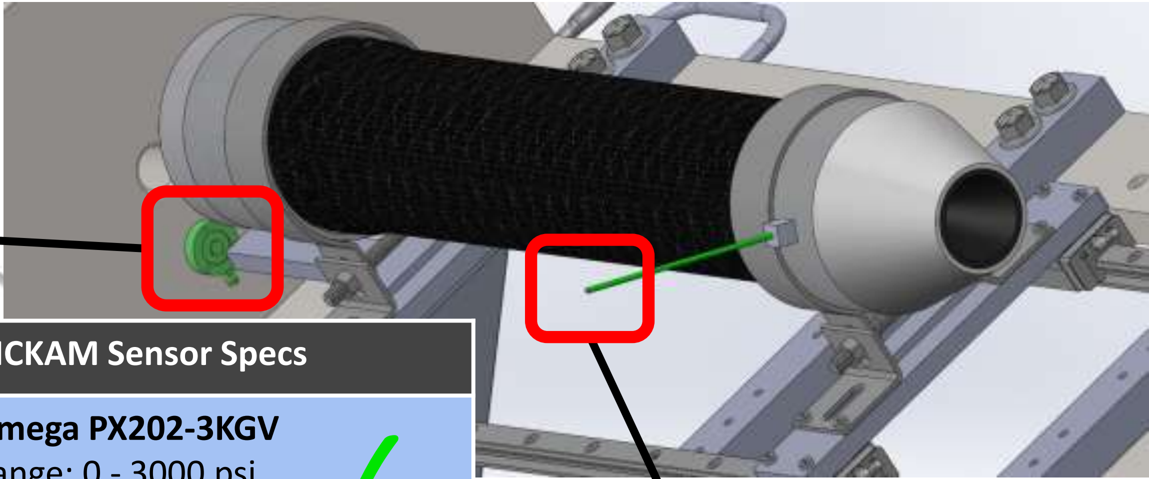


Data Acquisition Design Requirements



Force and Chamber Pressure Sensors

Borrowed

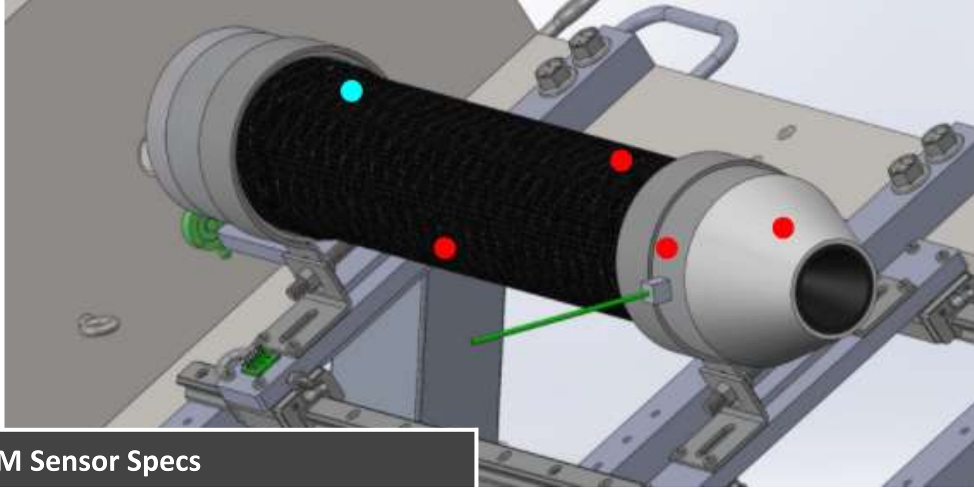


Borrowed

*Calculation in backup slide

DR	Requirement	HICKAM Sensor Specs
DR 4.1 Chamber Pressure Sensor	**Pressure Transducer** Range: Min 0 - 550 psi Accuracy*: +/- 14 psi Resolution*: ≤ 10 psi Response Time: ≤ 8 ms	**Omega PX202-3KGV** Range: 0 - 3000 psi Accuracy: +/- 7.5 psi Resolution: 7.5 psi (25mV) NI 9237 DAQ Res*: 5.96E-5 psi Response Time: 1 ms ✓
DR 4.4 Force Sensor	**Load Cell** Range: Min 0 - 800 lbf Accuracy*: +/- 22 lbf Resolution*: ≤ 8 lbf Response Time: ≤ 20 ms	**Omegadyne LCGD 1K** Range: 0 - 1000 lbf Accuracy: 6 lbf Resolution: 6 lbf (60mv) NI 9237 DAQ Res*: 0.025 lbf Response Time: 10 ms ✓

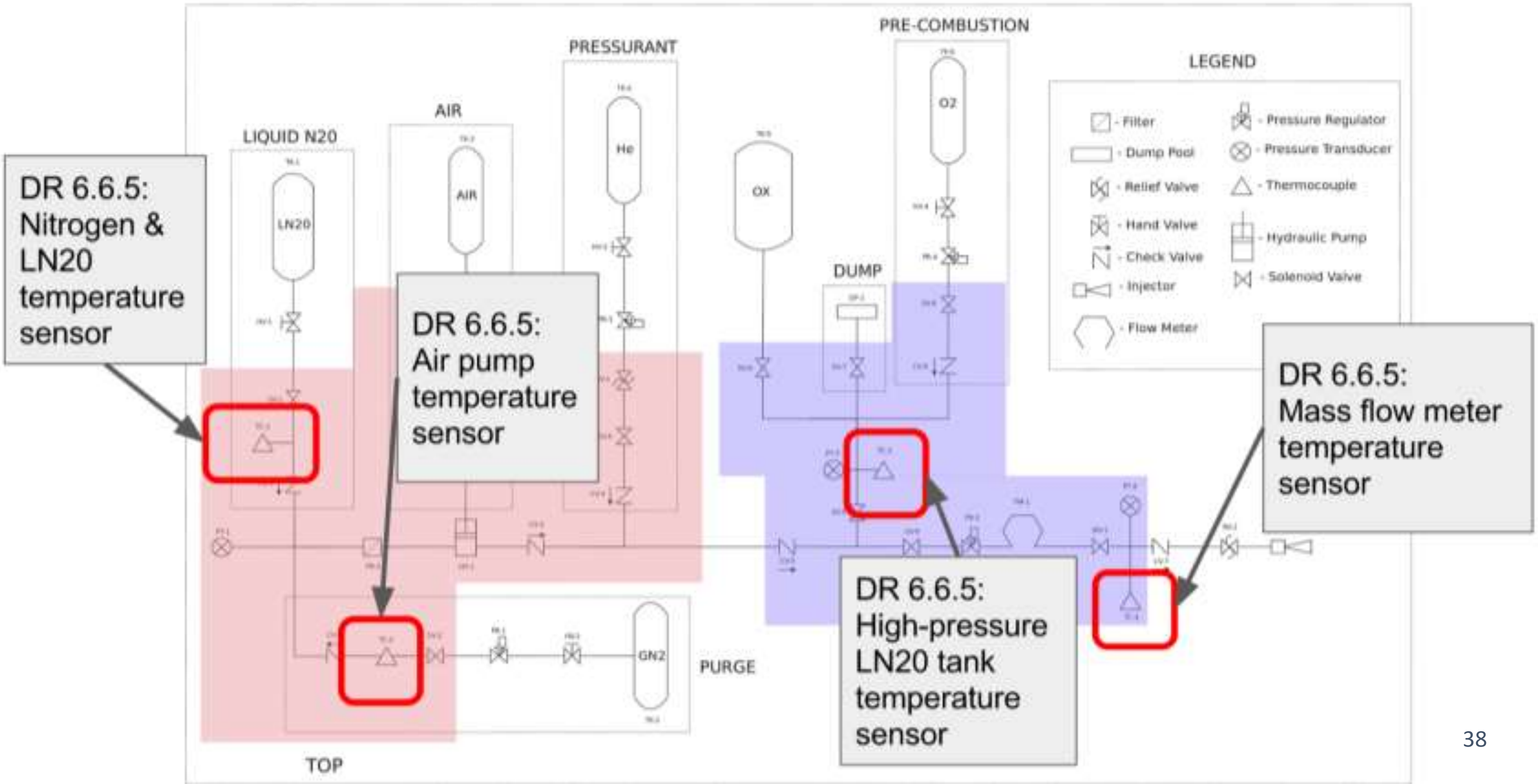
Temperature Sensors



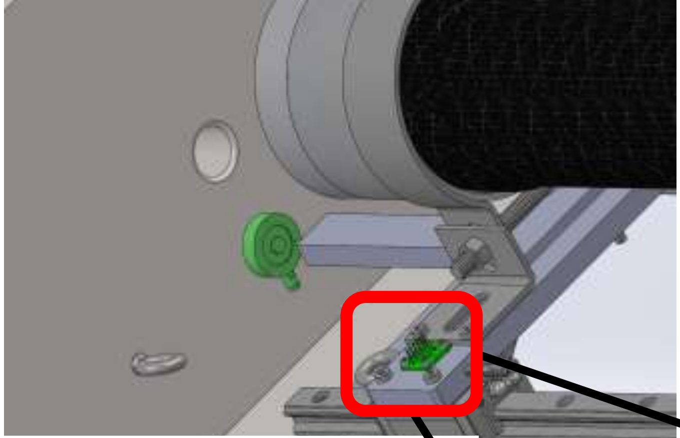
- Chamber thermocouples located radially along outside of chamber & above nozzle & next to pressure transducer rod
- Chamber thermocouples are Nextel ceramic insulated to withstand up to 2200 F
- Plumbing sensor locations shown on next slide

DR	Requirement	HICKAM Sensor Specs
DR 4.2 Chamber/Nozzle Temperature Sensor	**Thermocouple Type K** Range: Min 0 - 1500 F Accuracy: ≤ 4 F Resolution: ≤ 4 F Response Time: ≤ 100 ms	**Omega XC-14-K-12 (9 in total)** Range: - 400 - 2200 F Accuracy: 4 F Resolution: 4 F (85.2nV) NI 9213 DAQ Res*: 0.028 F Response Time: 100ms (30 AWG) ✓
DR 6.6.5 Plumbing Temperature Sensor	**Thermocouple Type K** Range: Min -70 - 270 F Accuracy: 5 F Resolution: 5 F Response Time: ≤ 200 ms	**Omega TC-K-NPT-U-72 Probe** Range: -454 - 2501°F Accuracy: 4 F Resolution: 4 F (85.2nV) NI 9213 DAQ Res*: 0.028 F Response Time: 200ms (20 AWG) ✓

Plumbing Temperature Sensor Locations



Burn Time and Mass Flow Sensors

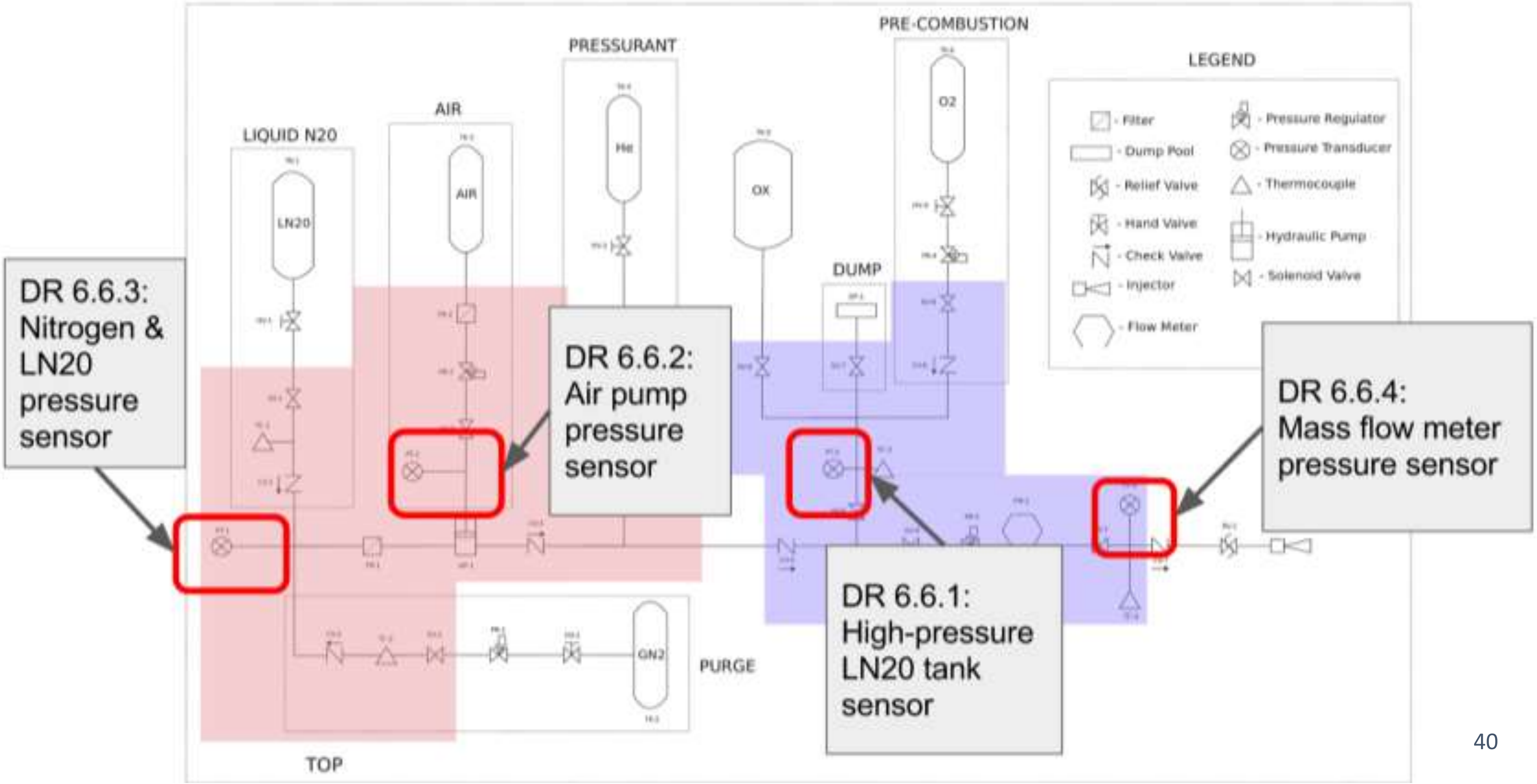


DR	Requirement	HICKAM Sensor Specs
DR 4.5 Burn Time Sensor	**3 Axis Accelerometer** Response Time: < 12 ms	**Adafruit ADXL377 3 Axis** Response Time: 10 ms ✓
DR 4.6 Mass Flow Meter (located in plumbing region)	**Liquid Mass Flow Meter** Range: Min 0 - 2 lbm/s Pressure Limit: > 1350 psi Accuracy*: +/- 0.0754 lbm/s Resolution*: ≤ 0.02 lbm/s Response Time: ≤ 300 ms	**Micromotion CMF050M MFM** Range: 0 - 4.15 lbm/s Pressure Limit: 1500 psi Accuracy: +/- 0.0145 lbm/s Resolution: 0.0145 lbm/s (48.9mV) NI 9205 Res*: 4.52E-5 lbm/s Response Time: 100 ms ✓

Borrowed

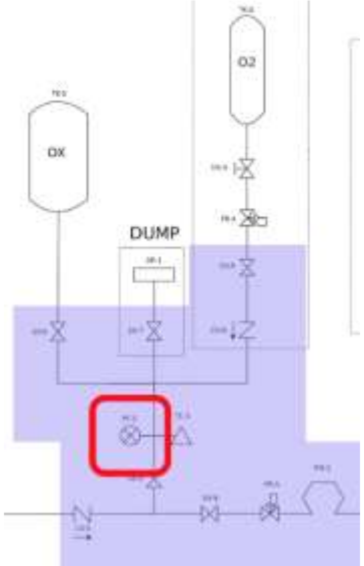
PO | DS | CPE | Design Req | PR | VV | PP

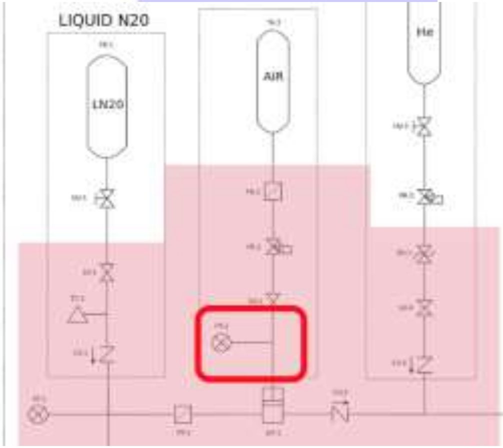
Plumbing Pressure Sensor Locations



Plumbing Pressure Sensors

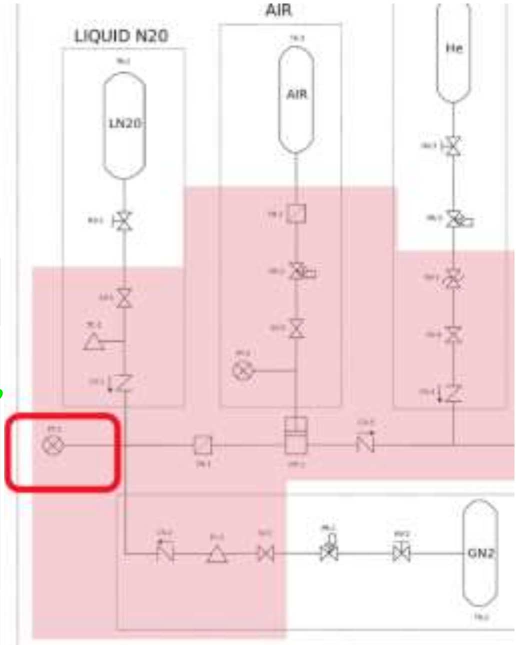
DR	Requirement	HICKAM Sensor Specs
DR 6.6.1 **High-pressure oxidizer tank pressure transducer**	**Pressure Transducer** Range: Min 0 - 4000 psi Accuracy: +/- 50 psi Resolution: ≤ 50 psi Response Time: ≤ 100 ms	**Omega PX4100 - 6KGV** Range: 0 - 6000 psi Accuracy: +/- 15 psi Resolution: 15 psi (37.5mV) Response Time: 10 ms
DR 6.6.2 **Air tank pressure transducer**	**Pressure Transducer** Range: Min 0 - 150 psi Accuracy: +/- 5 psi Resolution: ≤ 5 psi Response Time: ≤ 100 ms	**Omega PX302- 200GV** Range: 0 - 200 psi Accuracy: +/- 0.5 psi Resolution: 0.5 psi (33.3mV) Response Time: 1 ms

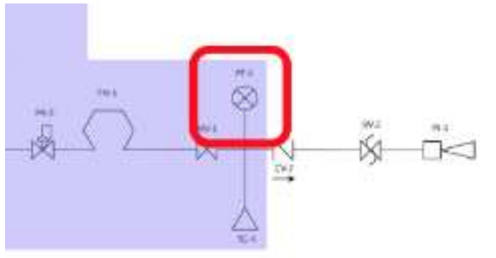




Plumbing Pressure Sensors

DR	Requirement	HICKAM Sensor Specs
DR 6.6.3 Gaseous nitrogen & LN20 pressure transducer	**Pressure Transducer** Range: Min 0 - 3000 psi Accuracy: +/- 50 psi Resolution: ≤ 50 psi Response Time: ≤ 100 ms	**Omega PX4100 - 3KGV** Range: 0 - 3000 psi Accuracy: +/- 7.5 psi Resolution: 7.5 psi (25 mV) Response Time: 10 ms ✓
DR 6.6.4 Injector plate pressure transducer	**Pressure Transducer** Range: Min 0 - 2000 psi Accuracy: +/- 5 psi Resolution: ≤ 5 psi Response Time: ≤ 100 ms	**Omega PX302 - 2KGV** Range: 0 - 2000 psi1 Accuracy: +/- 5 psi Resolution: 5 psi (25 mV) Response Time: 1 ms ✓





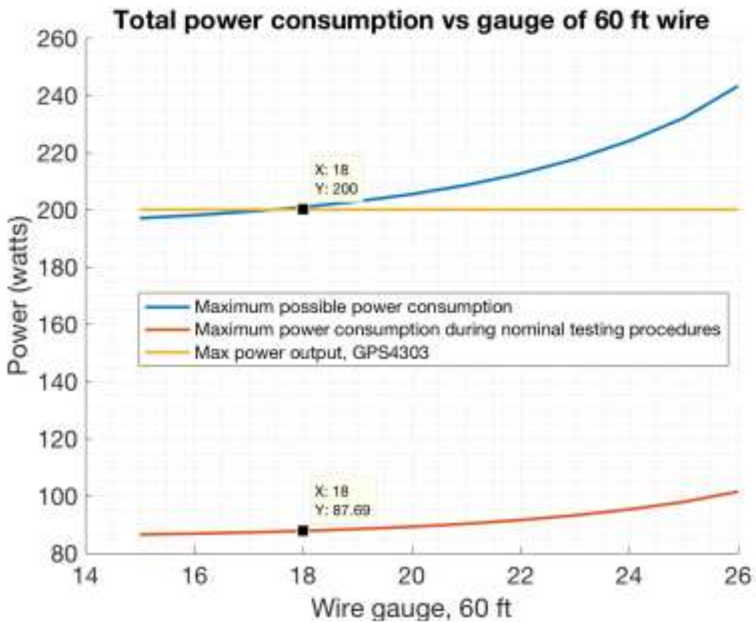
BOTTOM

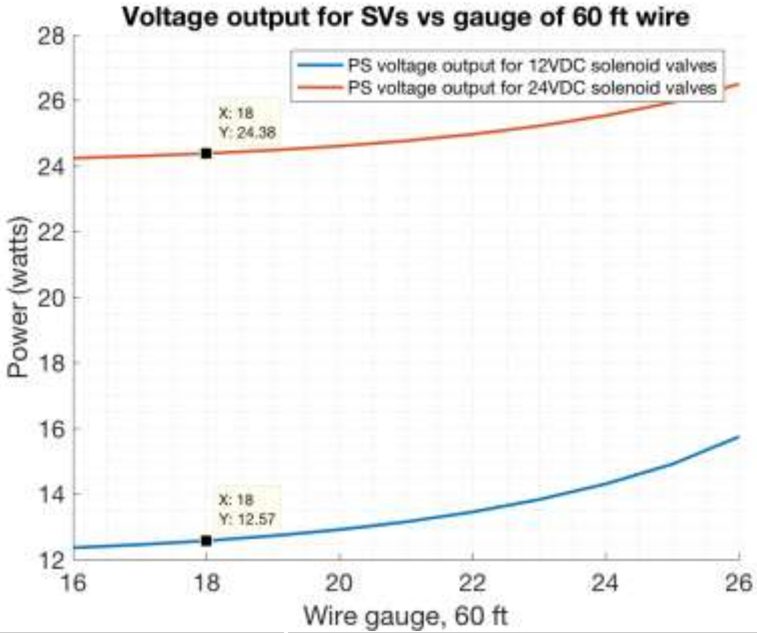
Sensor Sampling Rate

To calculate the sampling rate of non-aggregate modules → $f_s = \frac{f_M \div 256}{n}$

Design Requirement	Required Frequency	# of Sensors	Max Rate with given Sensors	Module
4.1 Pressure Transducers (data)	125 Hz	1	12.5 KHz	NI 9237 ✓
4.2 Thermocouples (data)	10 Hz	5	75 Hz	NI 9213 ✓
4.4 Load Cells	45 Hz	1	12.5 KHz	NI 9237 ✓
4.5 Accelerometer	90 Hz	1	51.2 KHz	NI 9234 ✓
4.6 Mass Flow Meter	34 Hz	1	250 KHz	NI 9205 ✓
6.6 Thermocouples (Plumbing)	5 Hz	4	75 Hz	NI 9213 ✓
6.6 Pressure Transducers (Plumbing)	10 Hz	3	12.5 KHz	NI 9237 ✓

Power



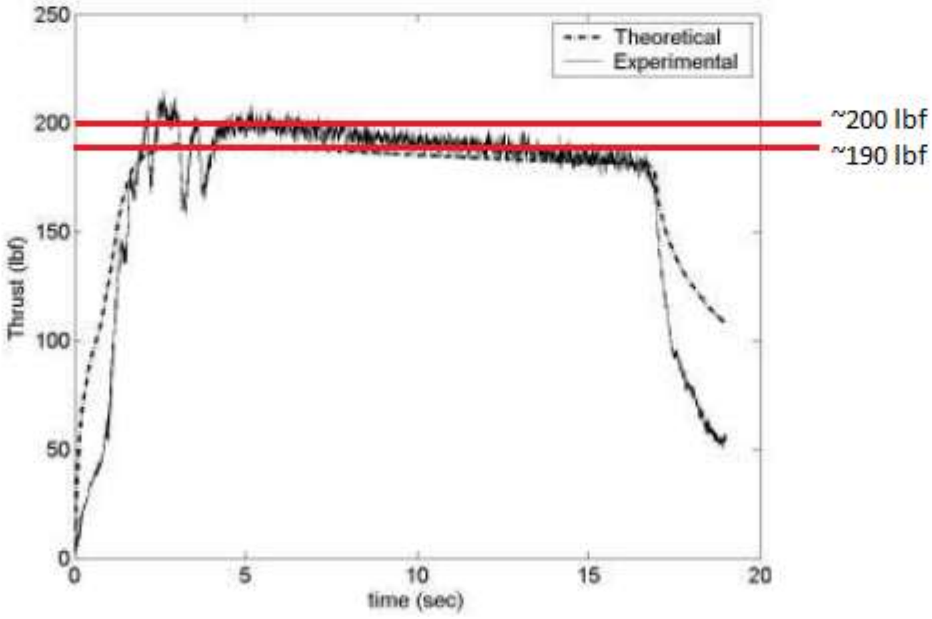


DR	Requirement	HICKAM Specs
DR 6.1	Valve operation from distance of at least 50 feet.	18 AWG 60ft wiring •Max 2.3 A < 1.5 A ✓
DR 6.3	Power delivery to valve actuation and ignition. •12VDC, 1A solenoid valves x7 •24VDC, 1.5A solenoid valves x2	GPS 4303 200W 4-channel power supply •182 W < 200 W ✓

Modelling Design Requirements

Subsystem Testing - Model Comparison Validation

- Previous MaCH SR-1 Models
- Low Fidelity Analytical Model
- Key Assumptions
  - Steady, 1-D axial flow
  - Ideal propellant gases uniform in chamber
  - Adiabatic flow with no friction loss (Rayleigh)



DR	Requirement	HICKAM model
DR 7.1	Data Analysis of hot fire shall compare to analytical model <10% (thrust prediction)	Analytical model is accurate to ~5% of test results at steady burn start ✓

Project Risks

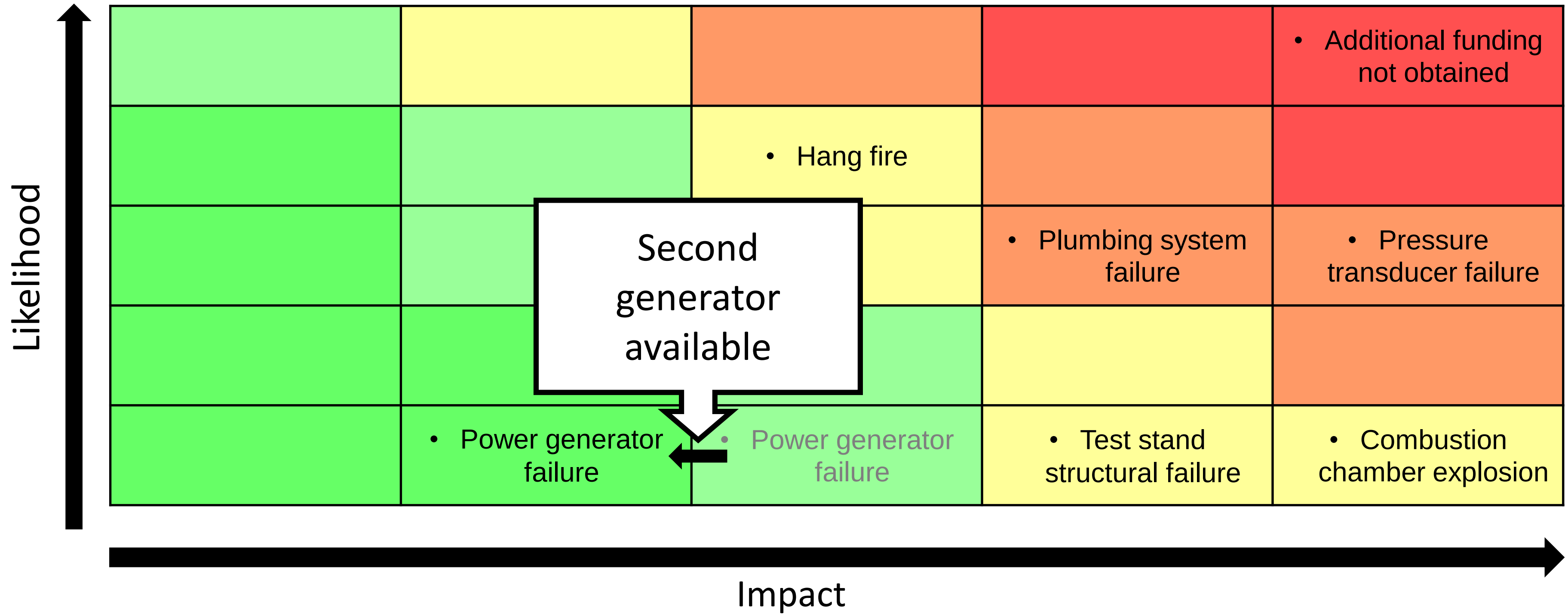
Risk Matrix Pre-Mitigation

Likelihood

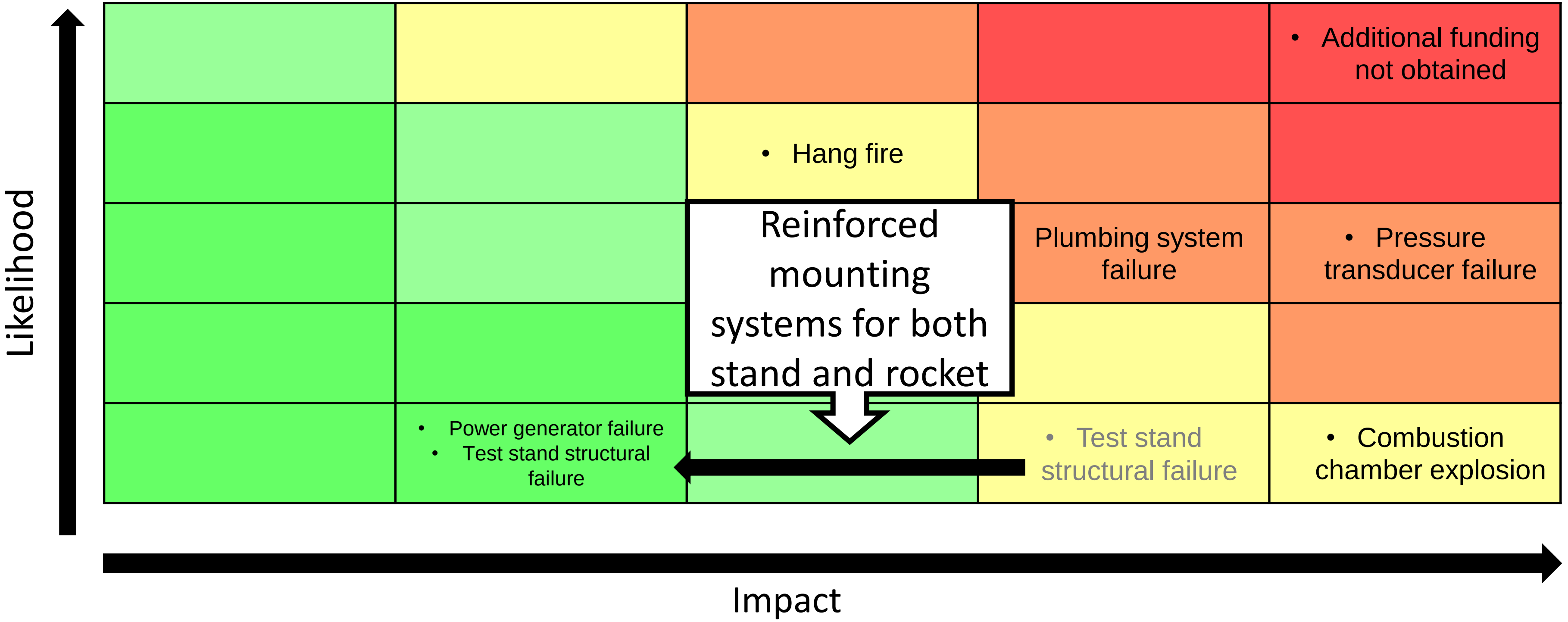
				• Additional funding not obtained
		• Hang fire		
			• Plumbing system failure	• Pressure transducer failure
		• Power generator failure	• Test stand structural failure	• Combustion chamber explosion

Impact

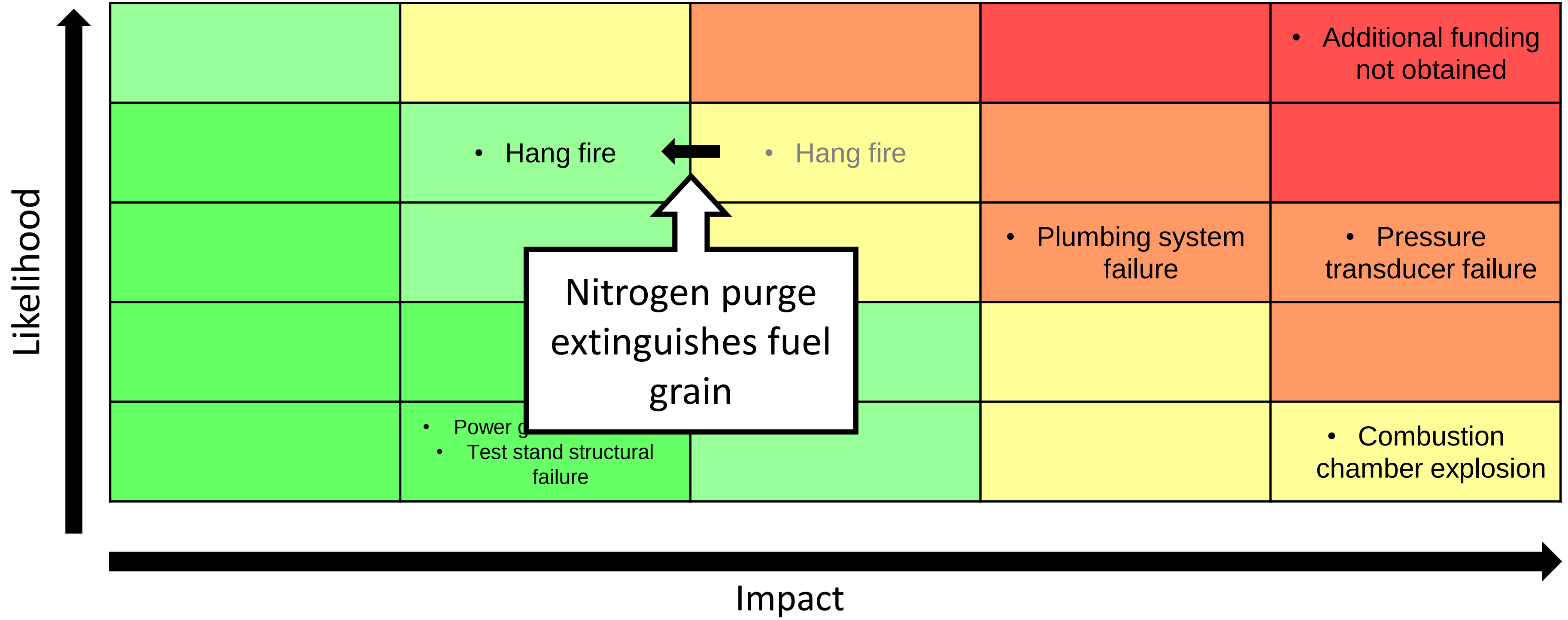
Risk Mitigation



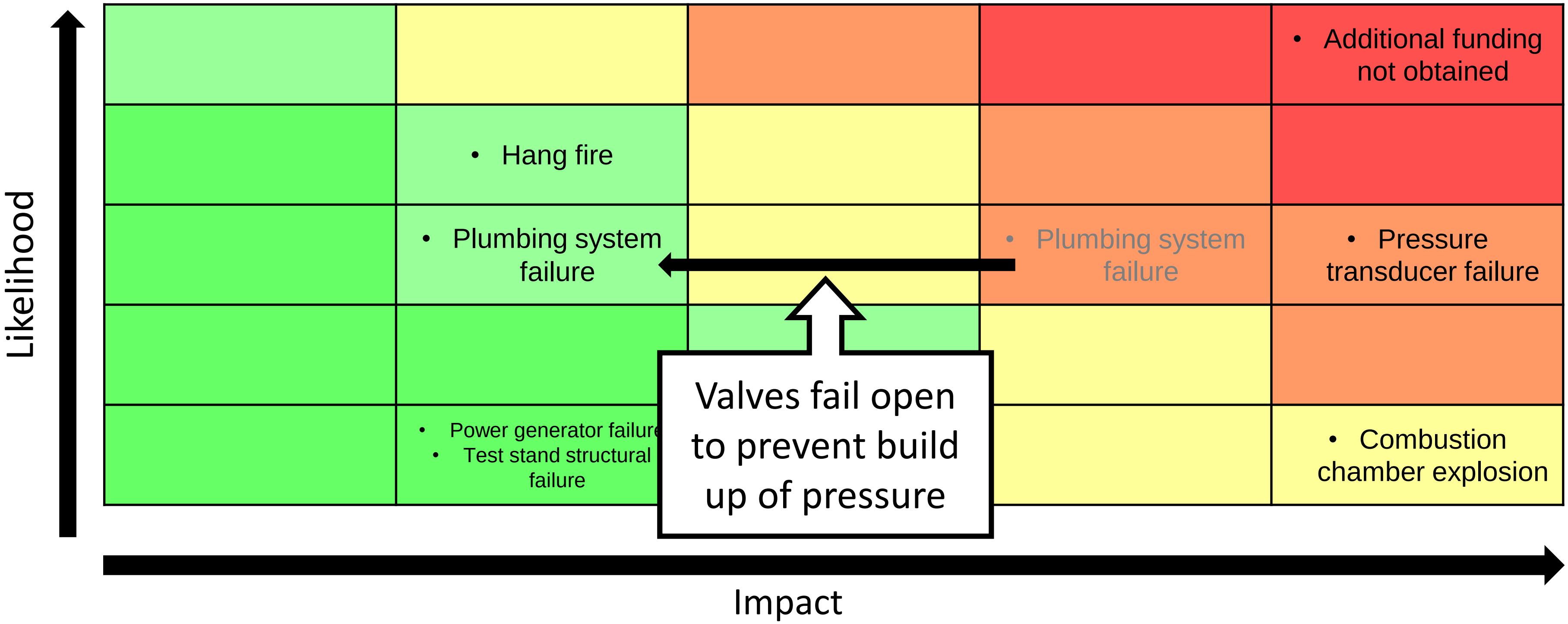
Risk Mitigation



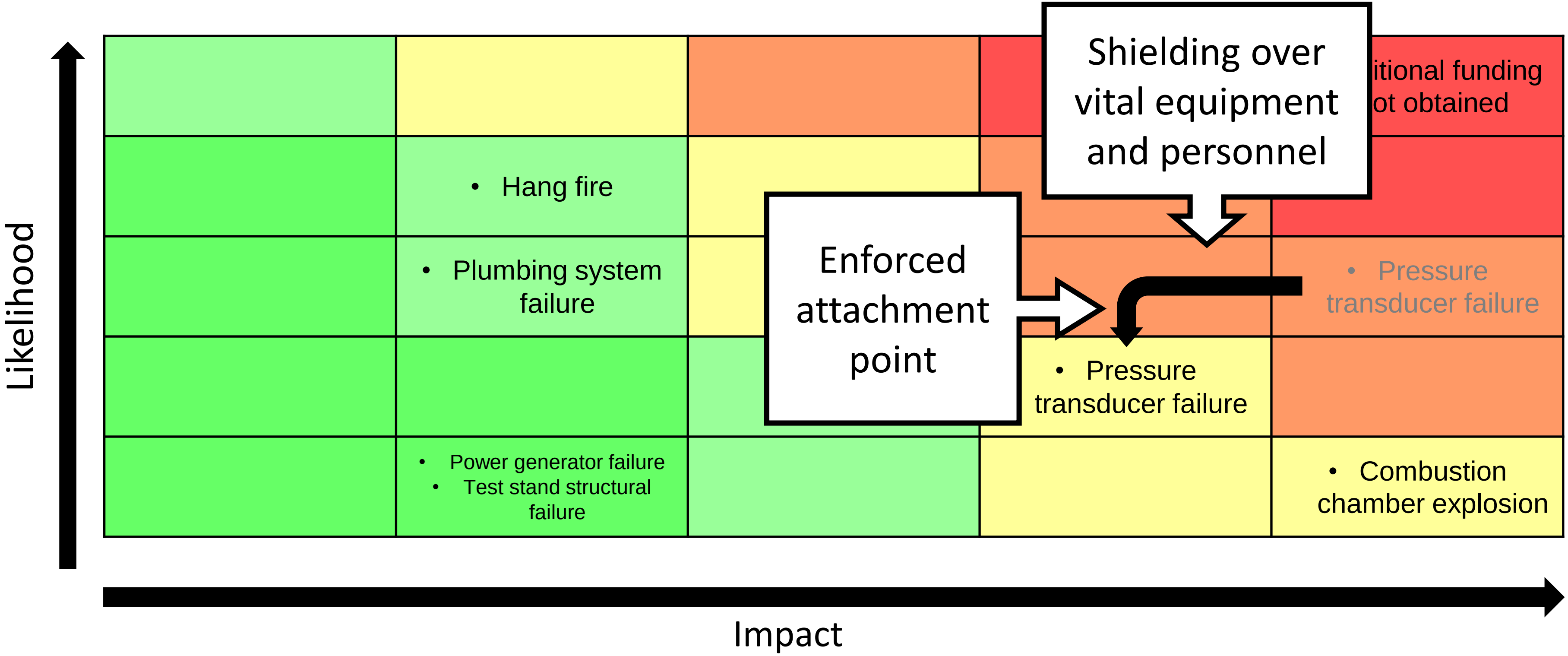
Risk Mitigation



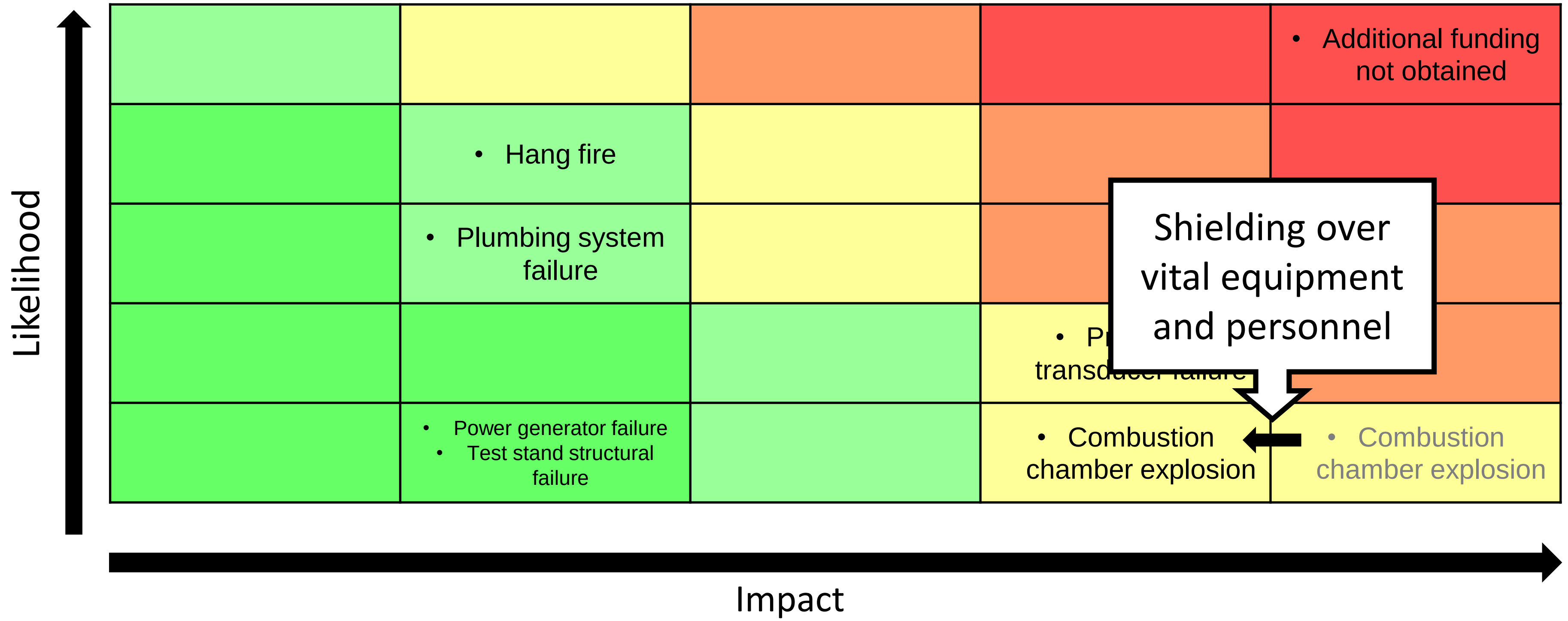
Risk Mitigation



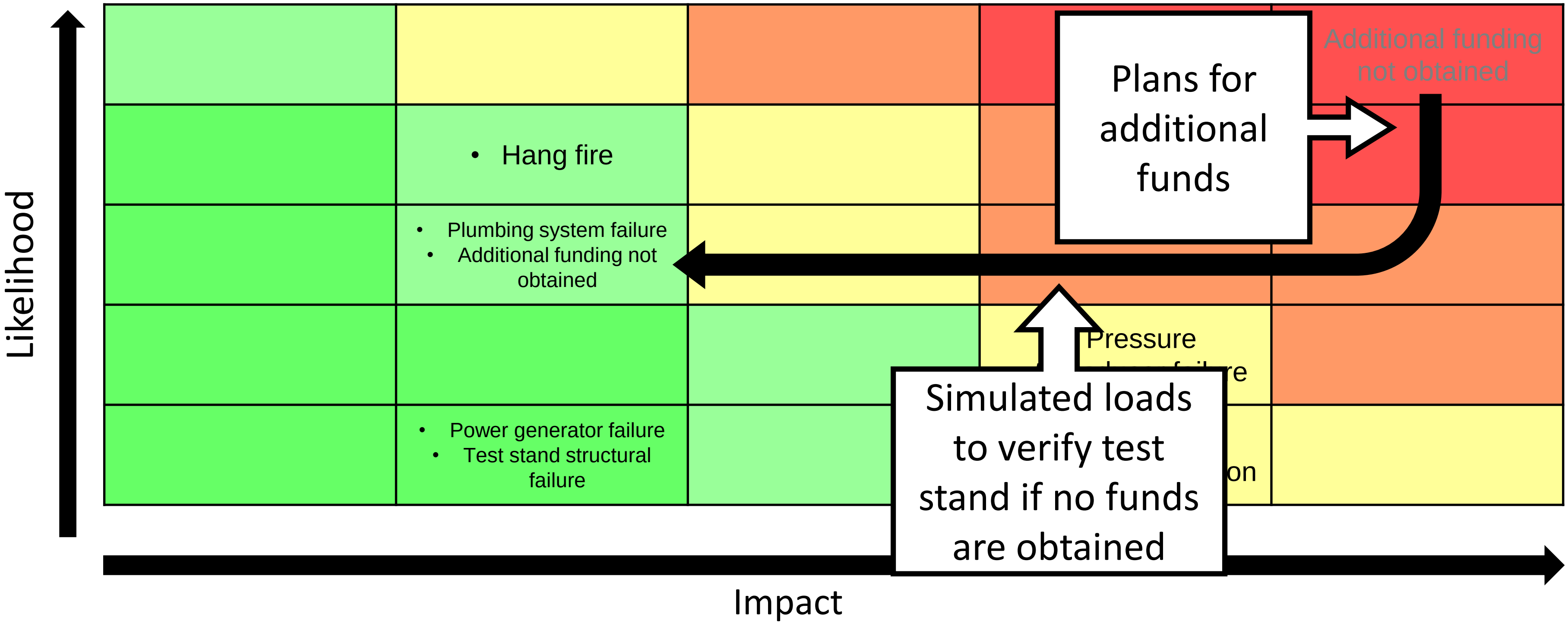
Risk Mitigation



Risk Mitigation



Risk Mitigation



Risk Mitigation – Additional Funds

- Additional Funding Plan (Reduction of Likelihood)
  - BOM submitted to customer, McGuckin, and Swagelok for donations
  - Applying for grant through Student Academic Success Center
  - Arranged manufacturing schedule to create test stand and rocket prior to plumbing system
- Alternative Solution (Reduction of Impact)
  - Verification of test stand via simulated loads

Risk Matrix with Mitigation

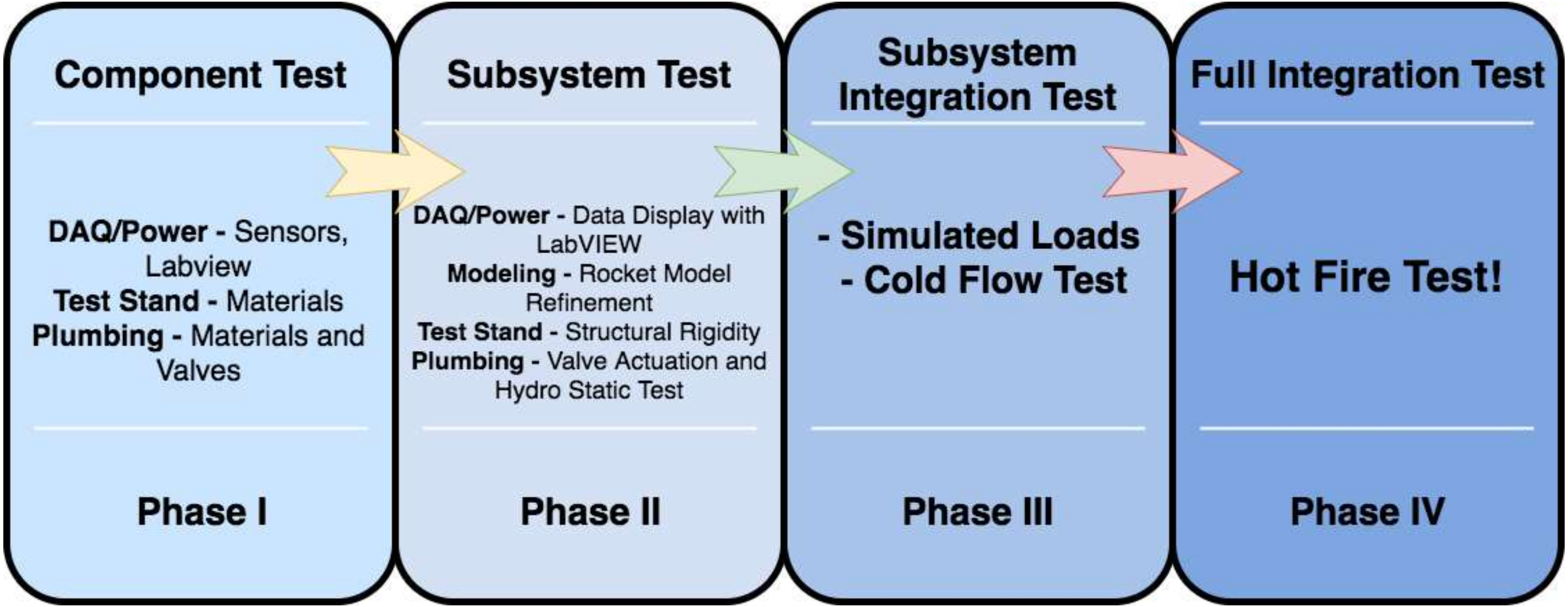
Likelihood

	• Hang fire			
	• Plumbing system failure • Additional funding not obtained			
			• Pressure transducer failure	
	• Power generator failure • Test stand structural failure		• Combustion chamber explosion	

Impact

Verification and Validation

Verification and Validation



PO | DS | CPE | DR | PR | **Verification & Validation** | PP

Phase I: Component Testing

Subsystem	What	How	Accuracy measurement
DAQ/Power	- Sensor Functionality - LabVIEW Runs	- Reading values from thermocouples, pressure transducers, accelerometer, and load cell through LabVIEW	Any value for Phase I
Test Stand	- Materials	- Inspect all materials to ensure there is no critical flaws	No critical flaws
Plumbing	- Materials - Valve Actuation	- Inspect all materials to ensure there is no critical flaws - Send voltage signals to valves to verify actuation before implementation	No critical flaws and full valve actuation

Phase II: Subsystem Testing

Subsystem	What	How	Looking for	Requirements Verified
DAQ/Power	- Sensor reading accuracy and integration with Labview	- **Thermocouples**: Ice bath - **Accelerometer**: 1g measurement - **Pressure Transducers**: Bell Jar - **Load Cell**: Weights - **Mass Flow Meter**: Water Expulsion	+/- 5 deg +/- 0.1 g +/- 5 psi +/- 1 lbf +/- 0.5 lbm/s	FR 4, FR 5
Modelling	- Model Refinement	- Model takes rocket engine, atmospheric, fuel, and pressure parameters to output thrust over time	Within 10% of existing Mach SR1 data	FR 7
Test Stand	- Rigidity of manufactured test stand	- Apply simulated force loads to ensure HICKAM stays stationary and doesn't fall or break. Ensure rails can take of nominal moments.	Does not tip over and minimal to no friction from rails	Safe for Hot Fire
Plumbing	- Valve fail open/close - fluid pump	- Send voltage to valves then cut voltage to ensure correct fail position - Run pump with air compressor and use it to pump water	- Valves fail to the correct position - Water pumped	Safe for Cold Flow

Phase II: Signal to Noise Ratio

$$SNR = 20log(\frac{Avg\ Signal\ (V)}{Noise\ (V)})$$

- Assumptions: System noise is 10 mV
- Minimum SNR 10 dB allowed for sensors if no amplification added

Sensor	Expected Value	Expected SNR (dB)	Amplification Added (dB)	SNR (dB) after Amplification
Load Cell	260 lbf	-5.8	12.04	20.52
Pressure Transducer	192.4 psi	36.2	0	36.2
Accelerometer	50-200 g's	30.2 - 42.2	0	30.2-42.2
Thermocouple	750 C	11.78	0	11.78

Phase II: Signal to Noise Ratio (Plumbing)

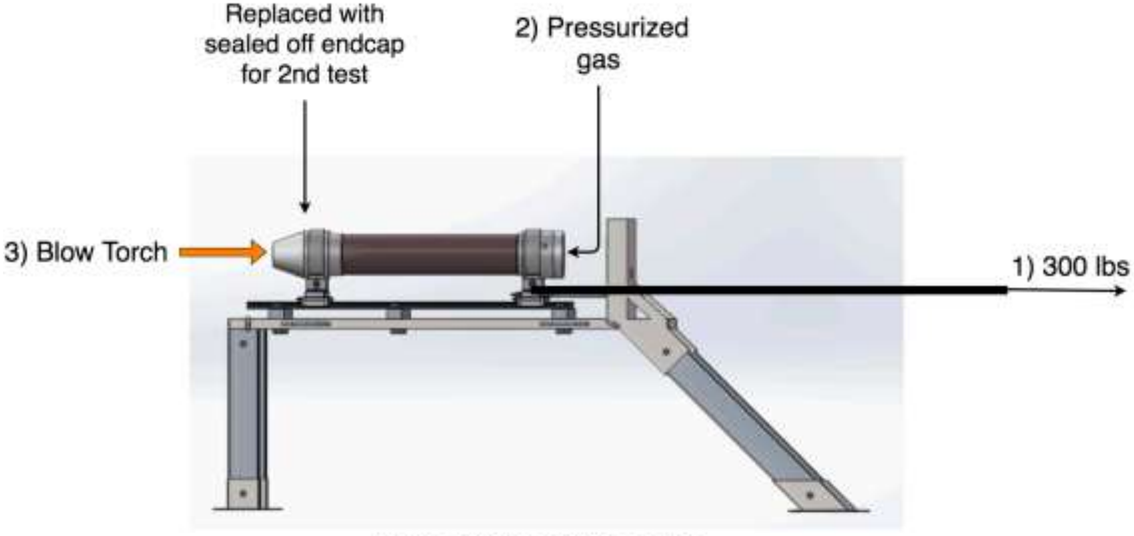
$$SNR = 20log(\frac{Avg\ Signal\ (V)}{Noise\ (V)})$$

- Assumptions: System noise is 10 mV

Sensor	Expected Value	Expected SNR (dB)	Amplification (dB)	SNR(dB) after Amplification
Oxidizer Tank Pressure Transducer	4000 psi	22.50	0	22.50
Air Tank Pressure Transducer	150 psi	17.50	0	17.50
Gaseous nitrogen & LN20 Pressure Transducer	1950 psi	22.28	0	22.28
Mass Flow Meter Pressure Transducer	2000 psi	20	0	20
Oxidizer Line Thermocouples	-34.4 C	-14.995	25.57	10.58

Phase III: Simulated Test Specifics

- **THRUST** - Pull rail system with straps tightened to 300 lbs for 20 seconds
- **PRESSURE** - Hydrostatic pressure test with nozzle replaced by endcap for 20 seconds
- **NOZZLE TEMP** - Simulate temperatures using blowtorch on inside of nozzle for 20 seconds



Burn duration of 20 seconds for each test

Phase III: Simulated Loads, Temperatures, and Pressures

Objective	Full integration simulated test intended to validate and verify HICKAM as a whole as an off ramp to no rocket engine available
Date	First Half of March
Location	ITLL
DRs Verified	All

Equipment
•Weights •Test Stand with Sensors •Blow Torch •Water tank

Data Gathered		Post Processing
•Force on Load Cell •PT and Thermocouples •Rocket Model •Specifications Sheet	•45 Hz •125 and 10 Hz respectively •Simulated output and input it to rocket model •Simulated article parameters	Thrust, total impulse, nozzle temperature

Phase III: Subsystem Integration Testing – Cold Flow Test

Objective	First major subsystem integration test. Intended to test functionality of plumbing system and ensuring liquid fuel is liquid after injector plate
Date	First Half of March
Location	Platteville, CO
DRs Verified	5.2, 5.3, 6.1, 6.2, 6.4, 6.6, 6.7, 9.1, 9.2

Equipment
•Oxidizer Tank •CO2 Tanks •Helium tank •Plumbing up to injector plate •Computer with LabVIEW code •Plumbing Pressure Transducers and Thermocouples

Data Gathered		Post Processing
•PT and Thermocouple (plumbing) •PT and Thermocouple (Data) •Visual data	•10 and 5 Hz respectively •125 and 10 Hz respectively •Ensure CO2 is liquid	Procedure verification and state of CO2 at injector plate

Phase IV: Full System Testing – Hot Fire Test

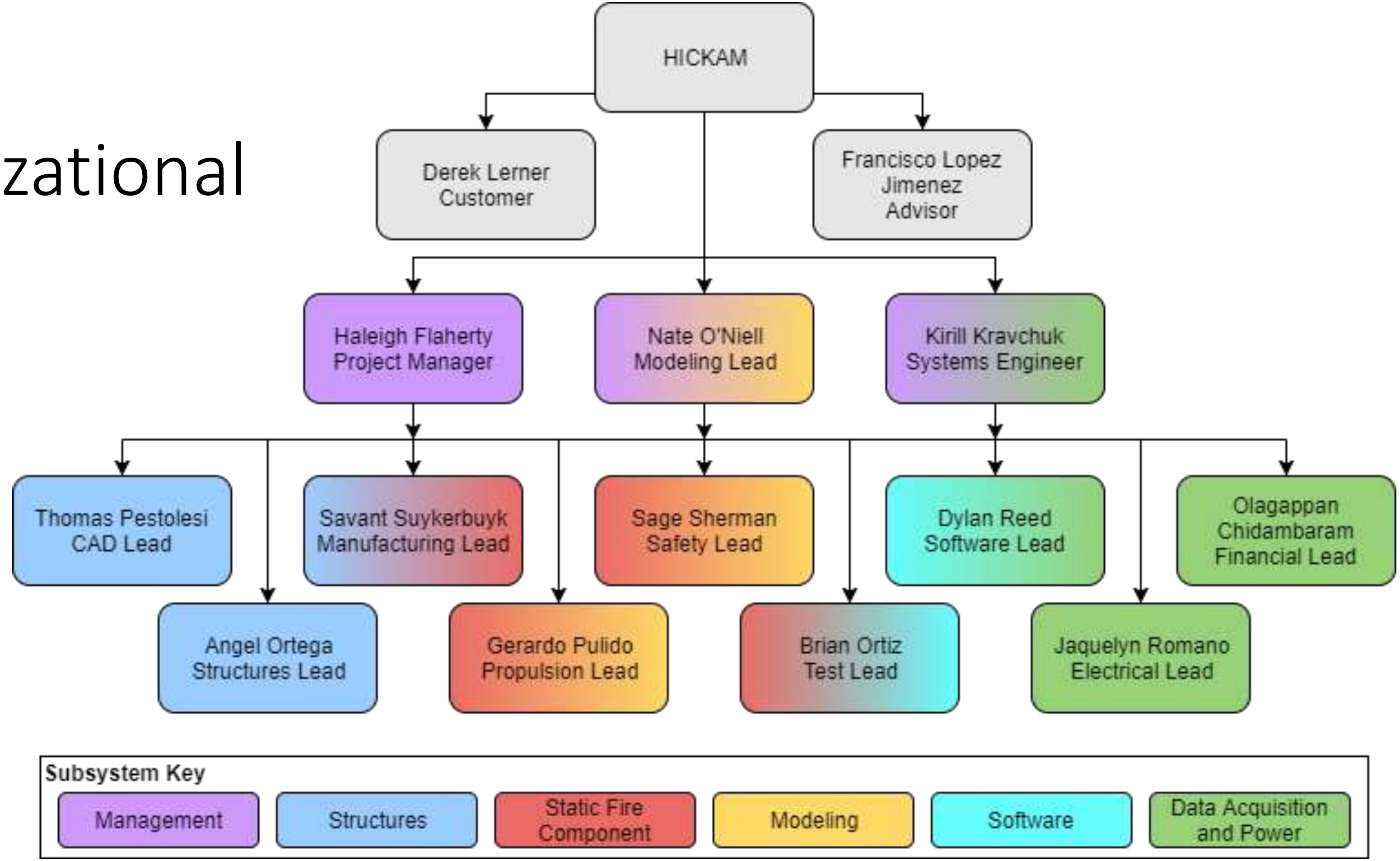
Objective	Full integration test intended to validate and verify HICKAM as a whole
Date	Second Half of March
Location	Platteville, CO
DRs Verified	All

Equipment
•Oxidizer Tank •Nitrogen Tanks •Helium tank •Plumbing •Computer with LabVIEW code •Test Stand with sensors fully integrated •Rocket engine test article

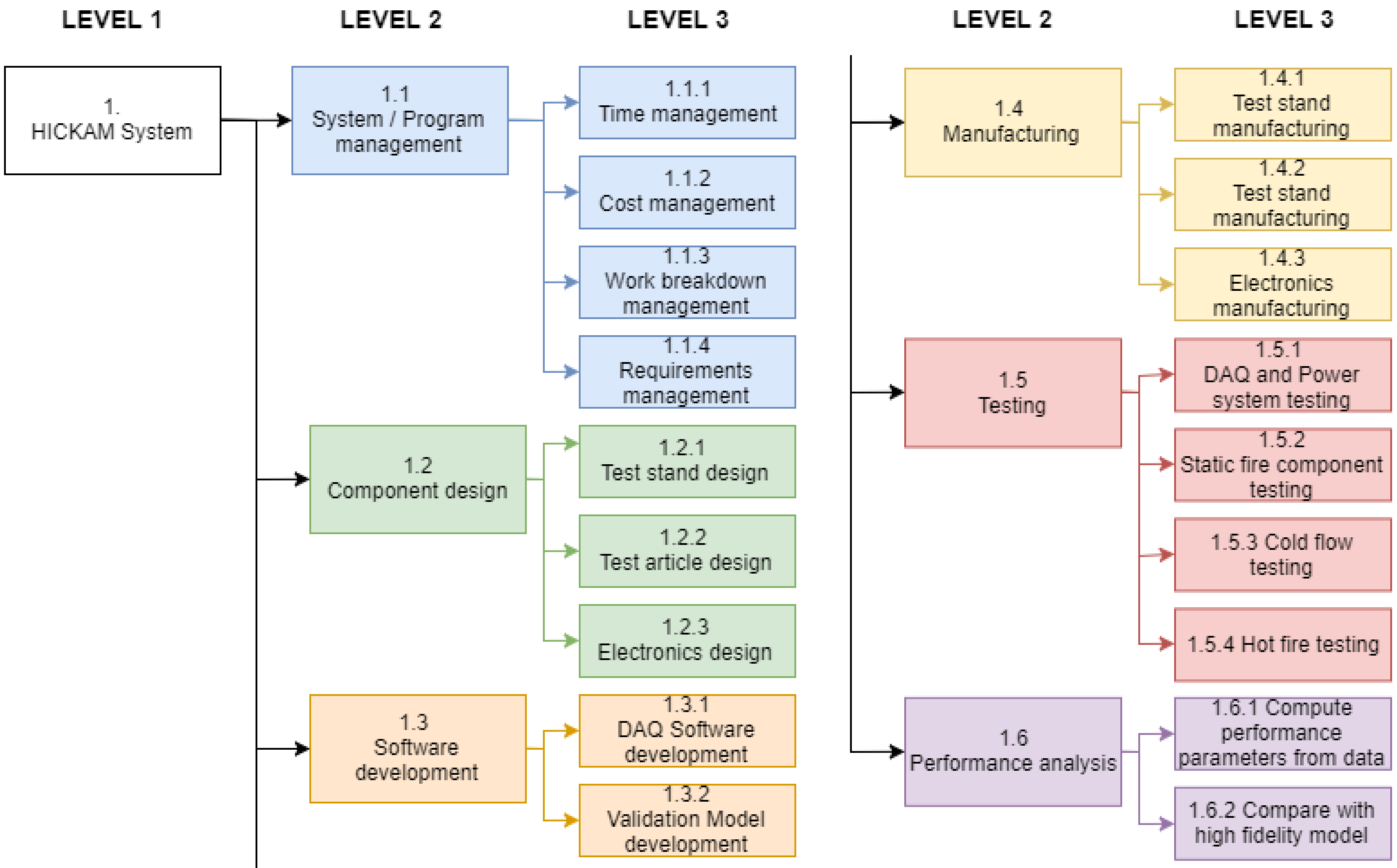
Data Gathered		Post Processing
•Force on Load Cell •PT and Thermocouples •Rocket Model •Specifications Sheet	•45 Hz •125 and 10 Hz respectively •Take output from test and input it to rocket model •Test article parameters to return to customer	Thrust (delay, duration, and maximum), total impulse, mass of rocket engine, nozzle temperature

Project Planning

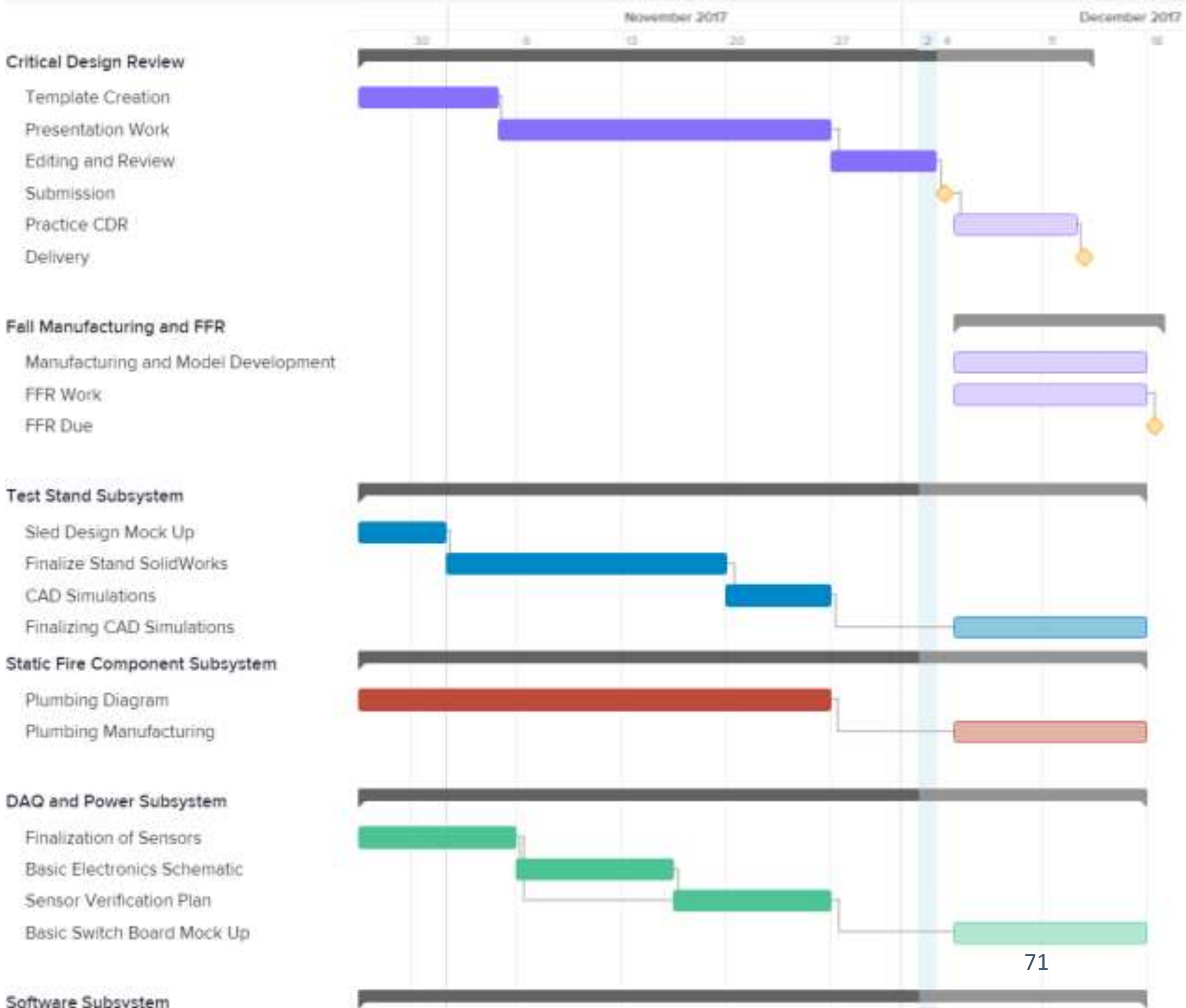
Organizational Chart



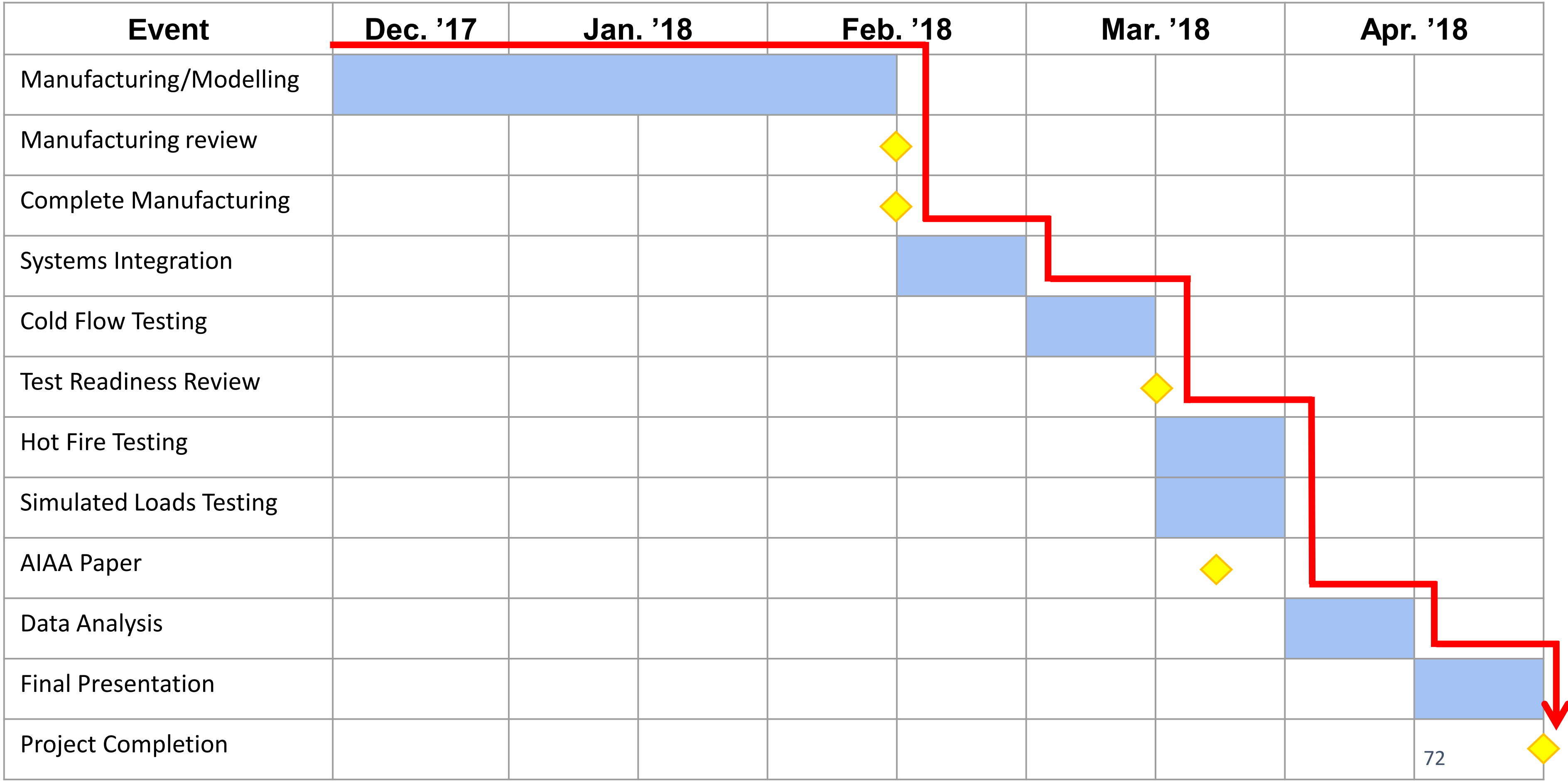
Work Breakdown Structure



Work Plan – This Semester



Work Plan – Next Semester



Test Plan

Date	Conducted Test	Feasibility of Access
01/01/2018 - 01/15/2018	Sensor Validation	ITLL Accessible
02/15/2018 - 02/22/2018	Simulated Loads Test (structure)	ITLL Accessible
03/01/2018 - 03/14/2018	Cold Flow Test	Platteville is a go
03/15/2018 - 03/31/2018	Hot Fire Test	Platteville is a go
03/15/2018 - 03/31/2018	(Off Ramp) Simulated Loads and temperatures test	ITLL Accessible

Cost Plan

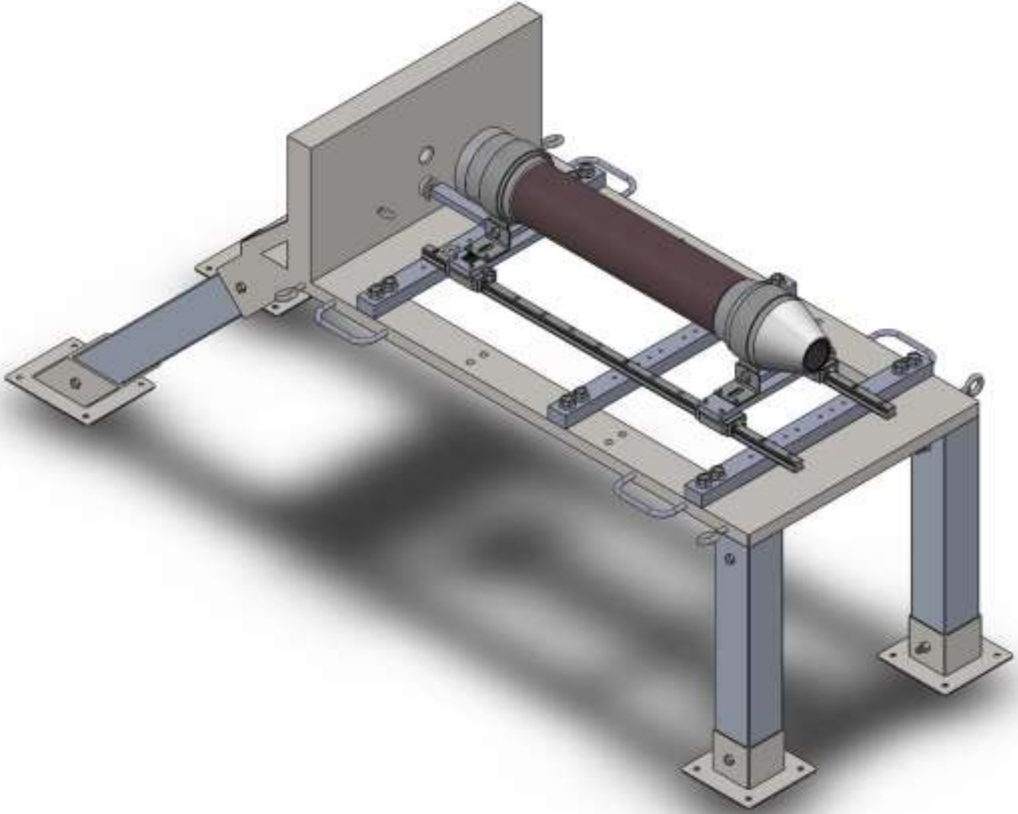
Subsystem	Total Cost	Cost with Borrow
Plumbing	$9,487.07	$4,785.13
Test Stand	$1,384.70	$1,384.70
Data Acquisition	$10,626	$386
Rocket Motor	$2,153.94	$2,153.94
Simulated Loads Test	$200	$200

	Project total cost without borrowing:	$23,852.08
Level 3 Success	**Project total cost with borrowing:**	$8,909.68
Level 1 Success	**Project total cost for simulated loads testing:**	$4,124.55

Thank you, questions?

Special thanks to:

- Our customer Derek Lerner with Orbital ATK
- Our advisor Professor Lopez-Jimenez
- Matt Rhode and Trudy Schwartz
- Dale Lawrence and the PAB
- Tim Kiley
- Grad team AMARCS



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Test Stand	Static Test Component	DAQ and Power	Software	Modelling	Management
•Maximum Clamping Force •Shear Force in Push Bar •Shear Force in M4 Bolts •Adaptability for Rocket •Ground Anchoring System	•Plumbing Safety and Failure Modes •Plumbing Risk Matrix •Fail Open/Close •Pressurization Procedure •Pre-Combustion and Burn Procedure •Post-Burn Procedure •Temperature Drops Across Regulators	•Electronics Diagram •DAQ Module Filters •NI Modules Filters •Common Filters •DAQ Resolution Calculation •Analog Sensor Resolution Calculation •Load Cell Op Amp •DAQ Location and Shielding •Plumbing Sensor •Accelerometer Capacitor Determination •Power •Backup Generator	•Plumbing Safety Software Diagram •LabVIEW VI •LabVIEW Block Diagram •Software Risk Mitigation •Software Risk Matrix	•Modelling Assumptions •Model Inputs •Modelling Fuel Properties •Modelling Thrust and Impulse •Model Results •Model Accuracy Calculation •Sensor Requirements •Assumptions for Sensitivity Models	•Design Requirements •Work Plan – Next Semester •Test Stand Costs •Data Acquisition Costs •Rocket Motor Costs •Plumbing Costs •Simulated Load Test Costs

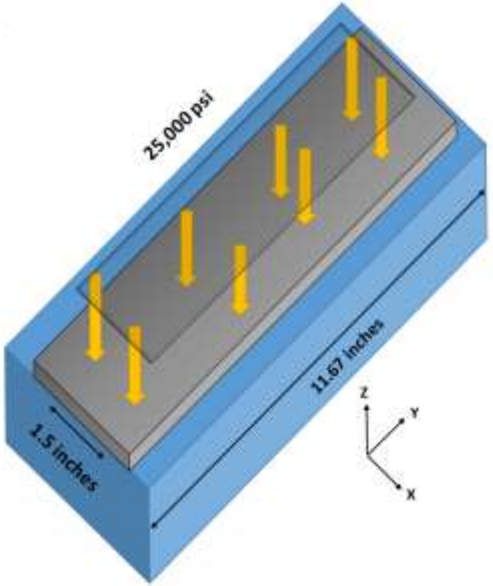
Test Stand

Stand | Rocket | DAQ | SW | Mod | Man

Maximum Clamping Force

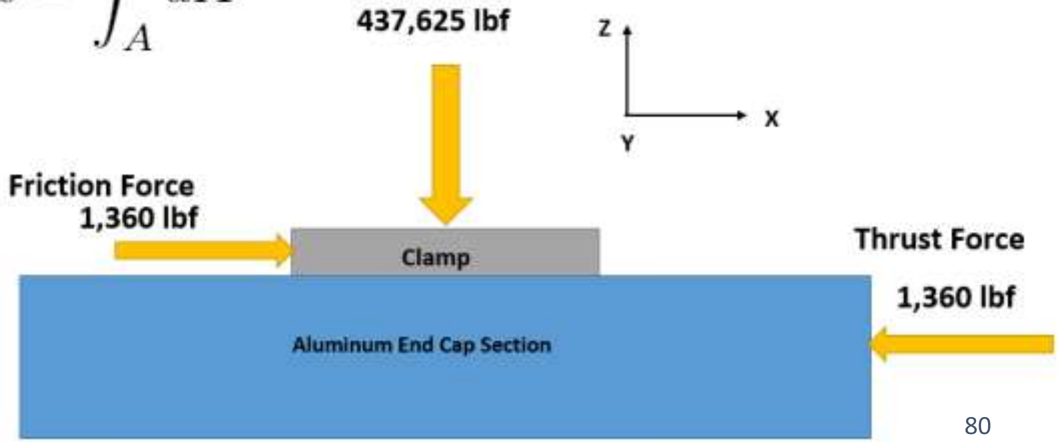
Aluminum yield strength in compression 25,000 psi

- Coeff. Of Friction estimated - 0.4 (between Zinc and Aluminum)
- Circumference of contact surface = 11.67 inches
- Contact surface width of clamp = 1.5 inches

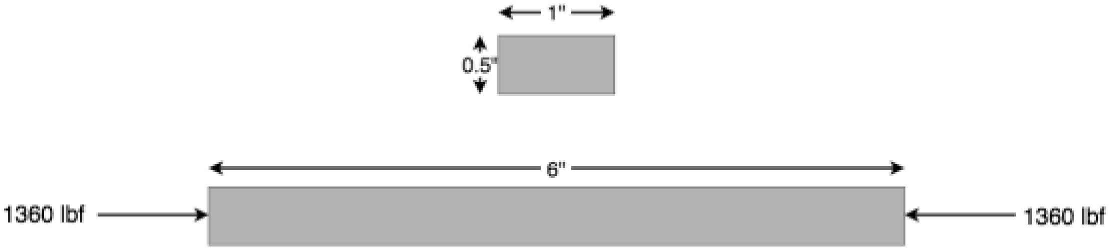


$$F_s = \mu_s N \qquad F_r = \int_L w(x)dx = \int_A dA$$

HICKAM Specs
Clamping Load Clamp Pressure: 25,000 psi Resulting Normal Force: 437,625 lbs Static Friction Force: 175,050 lbs



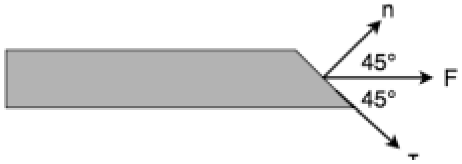
Shear Force in Push Bar



Aluminum shear strength in compression - 30,000 psi

- Axial loaded rectangle
- 800 lbf with SF 1.7
- 1in x 0.5 in cross section
- 6 inches long
  - Yield Strength = 30,000 psi

Bar will not shear



$$A_s = \frac{A}{cos(45)} = A\sqrt{2}$$

$$F = Pcos(45) = \frac{P}{\sqrt{2}}$$

$$\tau_{avg} = \frac{\frac{P}{\sqrt{2}}}{A\sqrt{2}} \longrightarrow \tau_{avg} = \frac{P}{A2}$$

HICKAM Specs
Axial Load on Push Bar Thrust Force: 1360 lb Shear Area: 0.5 in^2 Shear force: 1360 psi

Shear Force in M4 Bolts

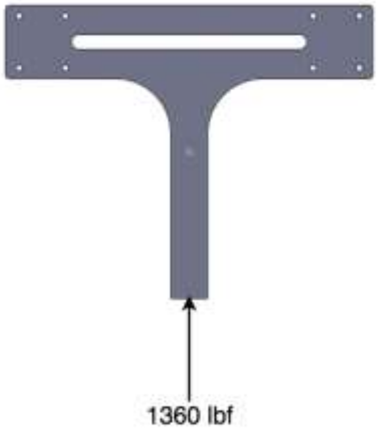
Bolts that secure push plate to rail carriage

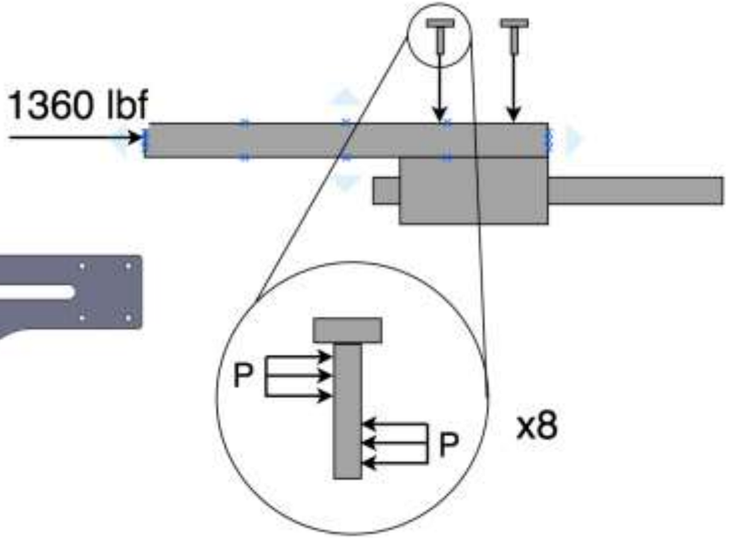
- Modeled on front four bolts
- Dia. Bolt 4mm = 0.15748 inches

Shear Modulus for Steel - 11,000 Ksi

- 800 lbf with SF 1.7

$$\tau = \frac{4PS_F}{\pi d_{bolt}^2}$$





HICKAM Specs

Forces on Bolts

Thrust Force: 1360 lb

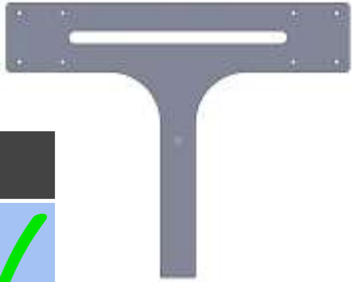
Force on each bolt: 170 lb

Shear Area: 0.019 in^2

Shear force: 17,455 psi

Adaptability for Rocket

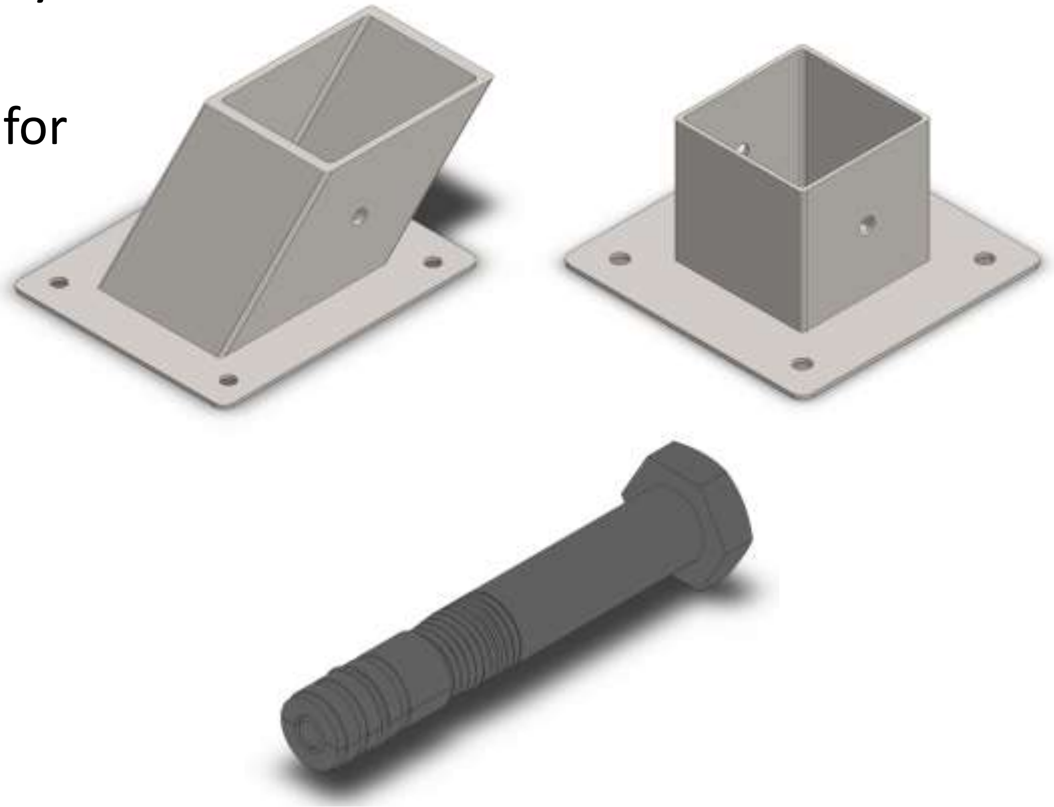
- Clamp integrates with front and rear slotted plates
  - Use ⅜" bolts
  - Rear plate does not have push bar
  - Pre-drilled/tapped holes in table offer adjustability to accommodate other sizes



DR	Requirement	HICKAM Sensor Specs
DR 3.1 **Test Stand Clamp**	**Motion Restriction Compatibility** Measure load in thrust direction	**Adjustable Standoff Clamps** Range: 3-16 inches Tolerance: 0.25 inches (i.e. 4.5-4.75 inches) ✓
DR 3.2 **Adjustability**	**Adjust for various size rockets** Account for rockets sizes capable of 800 lbf of thrust	**Custom Slotted Plate** Diameter Range: 3 - 7 inches Length: 6-30 inches Integrates various clamp sizes ✓

Ground Anchoring System

- Removable Ground Anchors for Concrete
- Zinc plated steel ⅜ in
- 2.25 inches long
- 1000 lb pull out force
- 1700 lb shear force

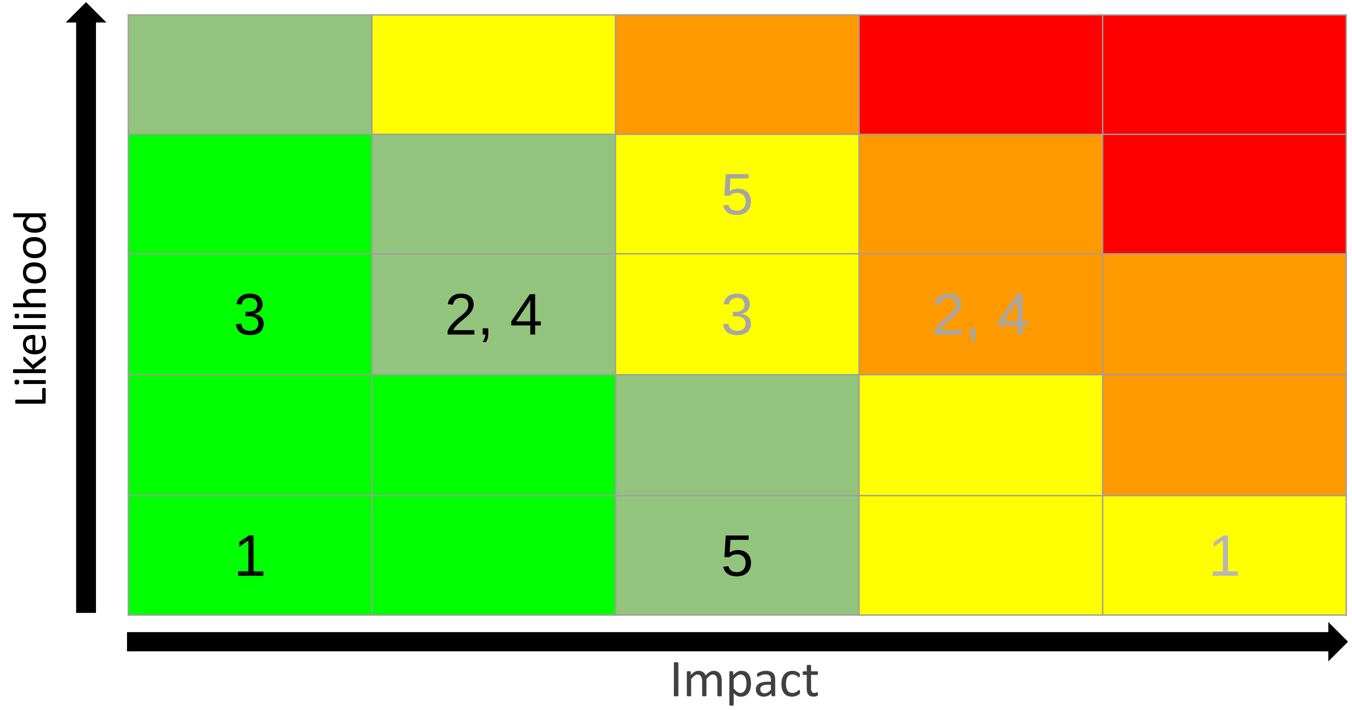


Static Test Component

Plumbing Risk Mitigation - Safety & Failure Modes

- All reasonable failure modes must be considered when designing a plumbing system, and is equally important to actual function. Major Concerns:
- 1 - Rocket Explosion: Mitigated by having relief valve on plumbing directly upstream of rocket, and multiple check valves throughout system to protect subcomponents.
- 2 - Helium Tank Runaway: Relief valve set downstream of He pressure regulator set to pop at 2500 PSI.
- 3 - Valve Freeze: Valve temperatures are monitored to ensure they do not fall below failure temp. If approaching, flow is stopped until temps normalize.
- 4 - Power loss: valves are set to fail such that Oxidizer tank dumps, and nitrogen tank purges system and rocket, but seal all other tanks.
- 5 - Outside test abort: master switch to engage immediate flow stop and dump/purge system.

Plumbing Risk Mitigation - Risk Matrix



1. Rocket Explosion
2. Helium Runaway
3. Valve Freeze
4. Power Loss
5. Outside Abort Command

Plumbing Risk Mitigation – Fail Open/Close

- System is designed to dump oxidizer tank, open Nitrogen tank to purge rocket/main lines, and seal all other tanks in the event of total power loss.

  - **FAIL OPEN:** SV-2, SV-6, SV-7, SV-9, and MV-1.
  - **FAIL CLOSED:** SV-1, SV-3, SV-4, SV-5, SV-8

Plumbing Firing Procedure: Pressurization

- **SYSTEM PRESSURIZATION**

1. Actuate all solenoid valves closed
2. Open HV-1, HV-2, HV-3, HV-4
3. Set PR-1 to 150 PSI
4. Set PR-2 to 150 PSI
5. Set PR-3 to 2000 PSI
6. Set PR-4 to 150 PSI
7. Set PR-5 to 900 PSI
8. Turn on air compressor (or open air tank valve)
9. Open SV-3 to start pump with air
10. Open SV-1 to flow LN20 TK-1
11. Open SV-5, SV-6 to allow LN20 flow into Oxidizer Tank TK-4
12. Close SV-6, SV-1, SV-3. Seals off system and deactivates pump
13. Open SV-7, SV-2, SV-5 to purge remaining LN20 in system to dump DP-1 via GN2 TK-2
14. Close SV-2, SV-7 to stop GN2 flow and close dump
15. Open SV-4, SV-6 to pressurize Oxidizer Tank TK-4 with He TK-3
16. Close SV-6, SV-4 to stop flow of He TK-3
17. Open SV-7 to release remaining He in system to dump DP-1
18. Close SV-7 to seal dump DP-1

NOTES FOR USER:

In case of multiple steps listed in the same line, these actions are to be performed in quick succession but in the order listed.

Items in RED indicate steps that can cause injury, loss of life, or damage to system if not followed properly.

Plumbing Firing Procedure: Pre-Combustion & Burn

- **PRE-COMBUSTION**

1. Open SV-8, SV-9 to start O2 flow from TK-5
2. System is now READY TO FIRE; Await signal to begin ignition
3. Open MV-1
4. Wait until thrust is visible via labview.
5. Close SV-8, MV-1 to stop O2 flow from TK-5; proceed to MAIN BURN with haste

- **MAIN BURN**

1. Open SV-6 to prime N20 from TK-4 into lines through MFM
2. System is now READY TO COMMENCE MAIN BURN; Ensure abort is not necessary, and proceed to next step with haste
3. Open MV-1 to flow N2O to rocket and begin main burn

Plumbing Firing Procedure: Post-Burn

- **POST-BURN**

1. Close SV-6 to stop N2O flow from Oxidizer Tank TK-4 to rocket
2. Open SV-2 to begin purge of main lines and rocket with GN2 from TK-2
3. Open SV-7 to dump remaining N2O from TK-4 to dump DP-1
4. Wait 20 minutes to complete rocket cooling/purge
5. Close SV-6 to seal Oxidizer Tank TK-4
6. Open SV-5 to purge remaining lines
7. Wait 10 seconds
8. Close SV-2, SV-5, SV-9, MV-1, SV-7 to stop GN2 from TK-2 and close entire system
9. Verify all pressure transducers read close to 0 PSI before approaching system
10. Close HV-1, HV-2, HV-3, HV-4

Temperature Drops Across Regulators

Calculated with Joule-Thomson Method

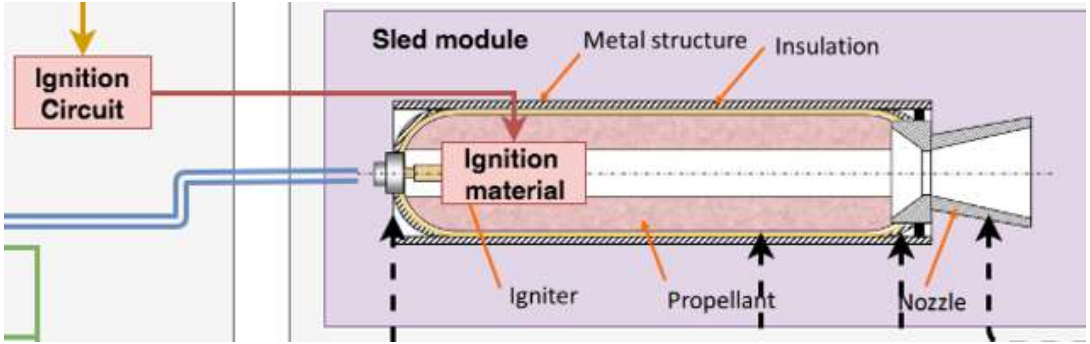
Assume initial starts at ambient temperature 71.33 ºF

$$\mu_J = \frac{\partial T}{\partial P}\Big|_h = \frac{T_2 - T_1}{P_2 - P_1}\Big|_h$$

Gas	Coefficient	Final Temperature
Helium	-0.062	100 ºF
Nitrogen	0.27	3.53 ºF
Oxygen	0.31	-6.502 ºF

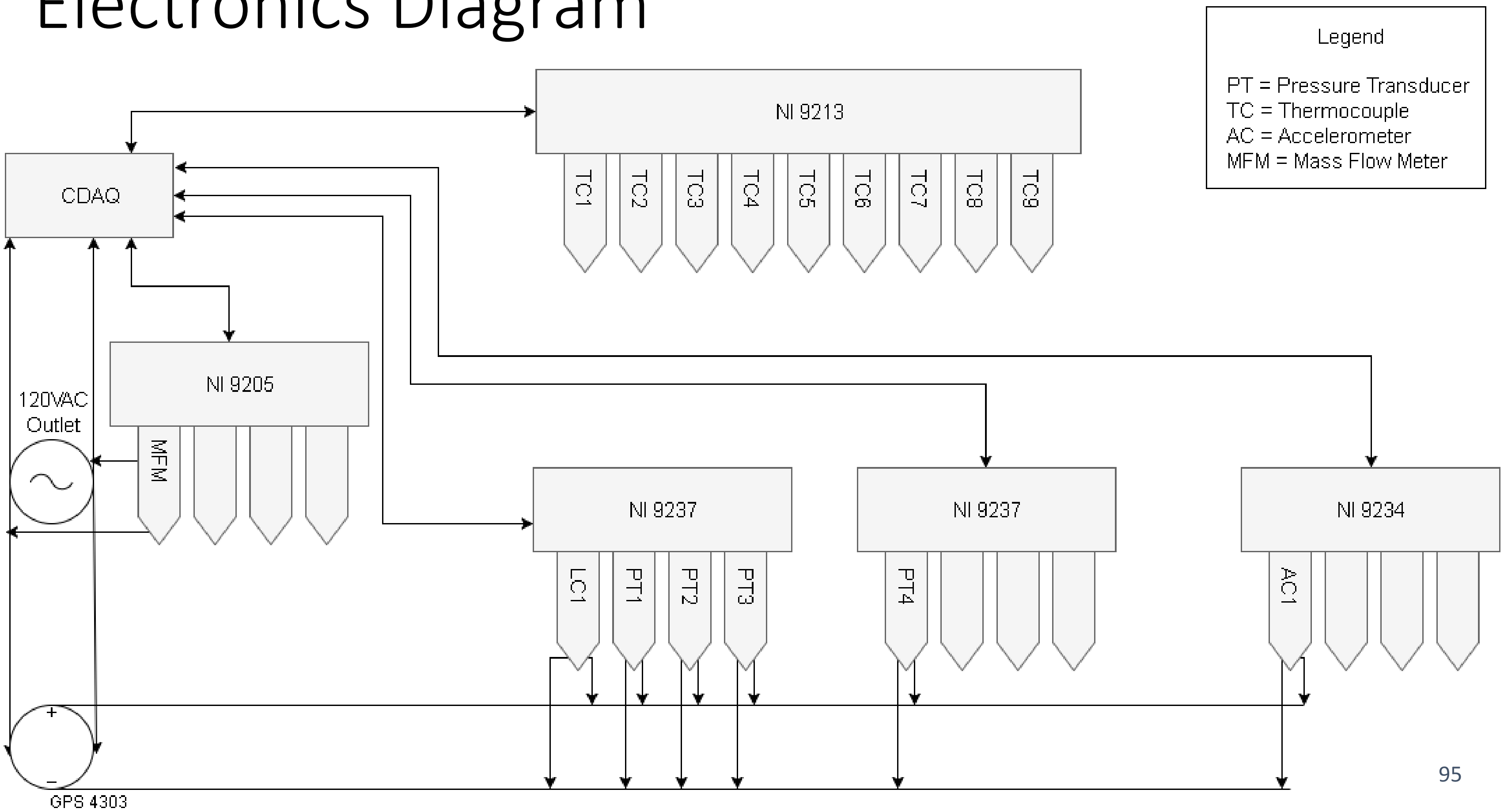
Ignition System

- Low flow ~150 psi
- Gaseous oxygen rich environment
- Electrical leads ignite steel wool
- Solid fuel burns for 10 seconds
- Flow Oxidizer

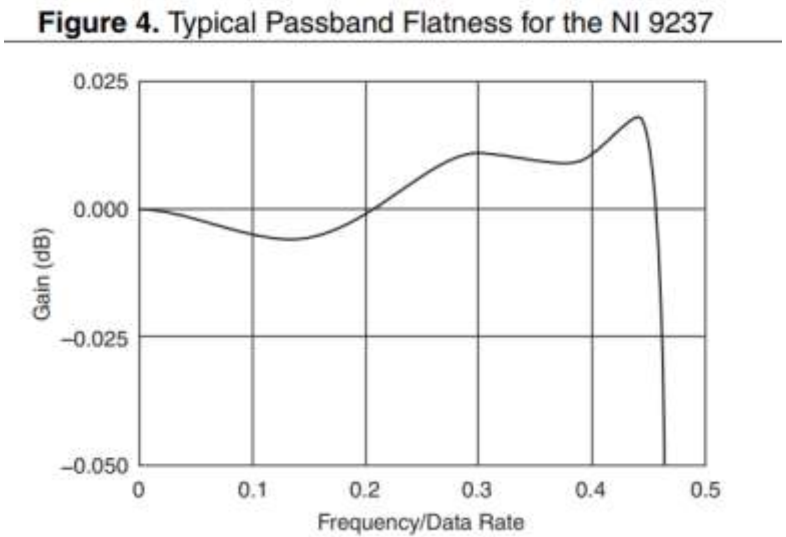


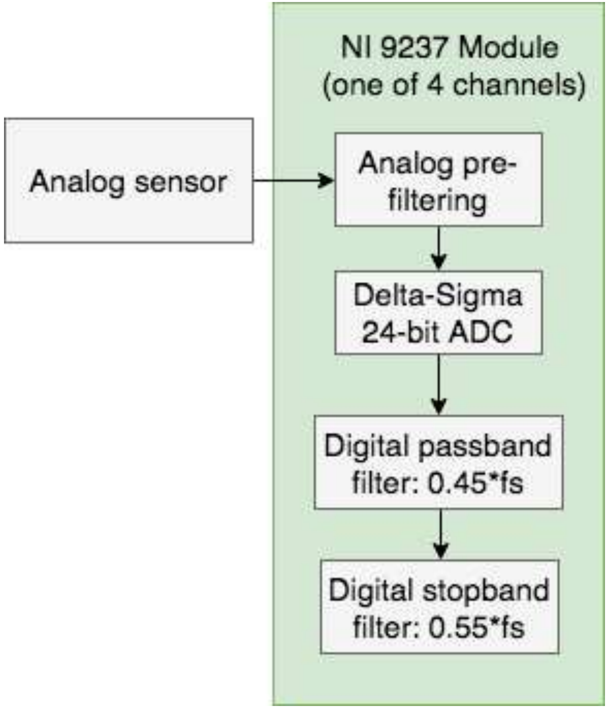
DAQ and Power

Electronics Diagram



DAQ Module Filters





Design requirement	Description	HICKAM
DR 5.2	Signal conditioning to avoid aliasing.	•NI 9237, NI 9234 for load cells, transducers, accelerometers -Alias-free: attenuation above 0.45 * (sampling rate)

Stand | Rocket | DAQ | SW | Mod | Man

NI Module Filters

- NI 9237 for Load cells and Pressure transducers
- (4 sensors per module)
  - Passband-0.45 of sampling frequency
  - Stopband-0.55 of sampling frequency
  - Alias-Free Bandwidth- 0.45 of sampling frequency
  - Oversample-64 times sampling rate

- NI 9234 for Accelerometer (4 sensors per module)
  - Passband-0.45 of sampling frequency
  - Stopband-0.55 of sampling frequency
  - Alias-Free Bandwidth- 0.45 of sampling frequency
  - Oversample-64 times sampling rate

- NI 9213 for Thermocouples (16 sensors per module)
  - 60 dB noise Rejection at 50 Hz and 60 Hz

- NI 9205 for the Mass Flow Meter(16 AI differential or 32 single-ended sensors per module)
  - None

Common Filters

	Amplification	Attenuation	Isolation	Filtering	Excitation	Linearization	CJC	Bridge Completion
Thermocouple	x			x		x	x	
Thermistor	x			x	x	x		
RTD	x			x	x	x		
Strain Gage	x			x	x	x		x
Load, Pressure, Torque (mV/V, 4-20mA)	x			x	x	x		
	x			x	x	x		
Accelerometer	x			x	x	x		
Microphone	x			x	x	x		
Proximity Probe	x			x	x	x		
LVDT/RVDT	x			x	x	x		
High Voltage		x	x					

DAQ Resolution Calculation

- DAQ bit resolution (V) = $\frac{DAQ\ Voltage\ Range}{2^{n\ bits}}$

- DAQ equivalent sensor output resolution (same units as sensor output):

$$\frac{Bit\ resolution}{x\ (lbf, psi, etc)} = \frac{Sensor\ Excitation\ Voltage}{Sensor\ Max\ Output(1000\ lbf, 3000\ psi, etc)}$$

- Solve for x to get DAQ resolution represented in units of force, pressure, temperature etc

Analog Sensor Resolution Calculation

- Sensor Resolution in units of V based on given accuracy of sensor (datasheet)

$$\frac{x \; Resolution \; (V)}{Output \; Resolution \; (lbf, psi, etc)} = \frac{Sensor \; Excitation \; Voltage}{Sensor \; Max \; Output (1000 \; lbf, 3000 \; psi, etc)}$$

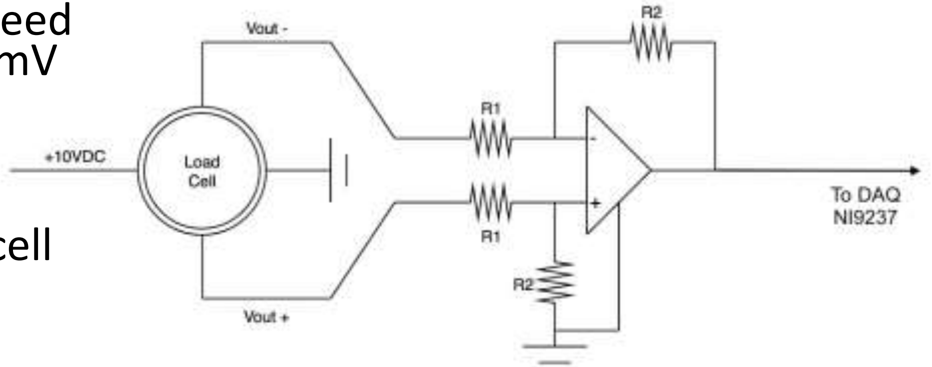
- Solve for x to find resolution in units of sensor output voltage

Load Cell Op Amp

- Used to increase output signal from load cell in order to increase SNR of load cell
- Non-inverting differential Op Amp
- To achieve SNR of 20.52 for load cell need voltage output from op amp to be 28 mV

$$V_{to\ NI} = \left(\frac{R_2}{R_1}\right)(V_{out+} - V_{out-})$$

- 2.6 V across output terminals of load cell for 260 lbf load
- R1/R2 = 0.01
- R1 = 100 ohm
- R2 = 10 k ohm



DAQ Location and Shielding

Location

- On the Accessory Pad
- Must be as close as possible to sensors, to allow for best data.

Shield

- Will be made of steel and cover CDAQ in every direction but the ground.
- Doubles as Faraday Cage.
- Has openings for cables.

Plumbing Sensors

Sensor	Location	Primary Purpose
TC-1	Liquid N20 system. Close to solenoid valve.	Check temperature around solenoid valve.
TC-2	Purge system. Close to solenoid valve.	Check temperature around solenoid valve.
TC-3	Close to the fuel and pre-combustion systems.	Check the state of fuel while filling.
TC-4	After the flow meter.	Check the state of fuel during burn.
PT-1	Manifold between the liquid N20 and purge systems.	Monitor the pressure from purge and liquid N20 systems.
PT-2	Air system, before the hydraulic pump.	Monitor the air pressure entering the hydraulic pump.
PT-3	Close to the fuel and pre-combustion systems.	Moniter pressure of oxidizer tank while filling.
PT-4	After the flow meter.	Check the state of fuel from start to end of burn.

Accelerometer Capacitor Determination

- Minimum 100Hz cutoff frequency
  - Use .05 μF capacitor

Table 4. Filter Capacitor Selection for C_X, C_Y, and C_Z

Bandwidth (Hz)	Capacitor (μF)
50	0.10
100	0.05
200	0.025
500	0.01
1000	0.005

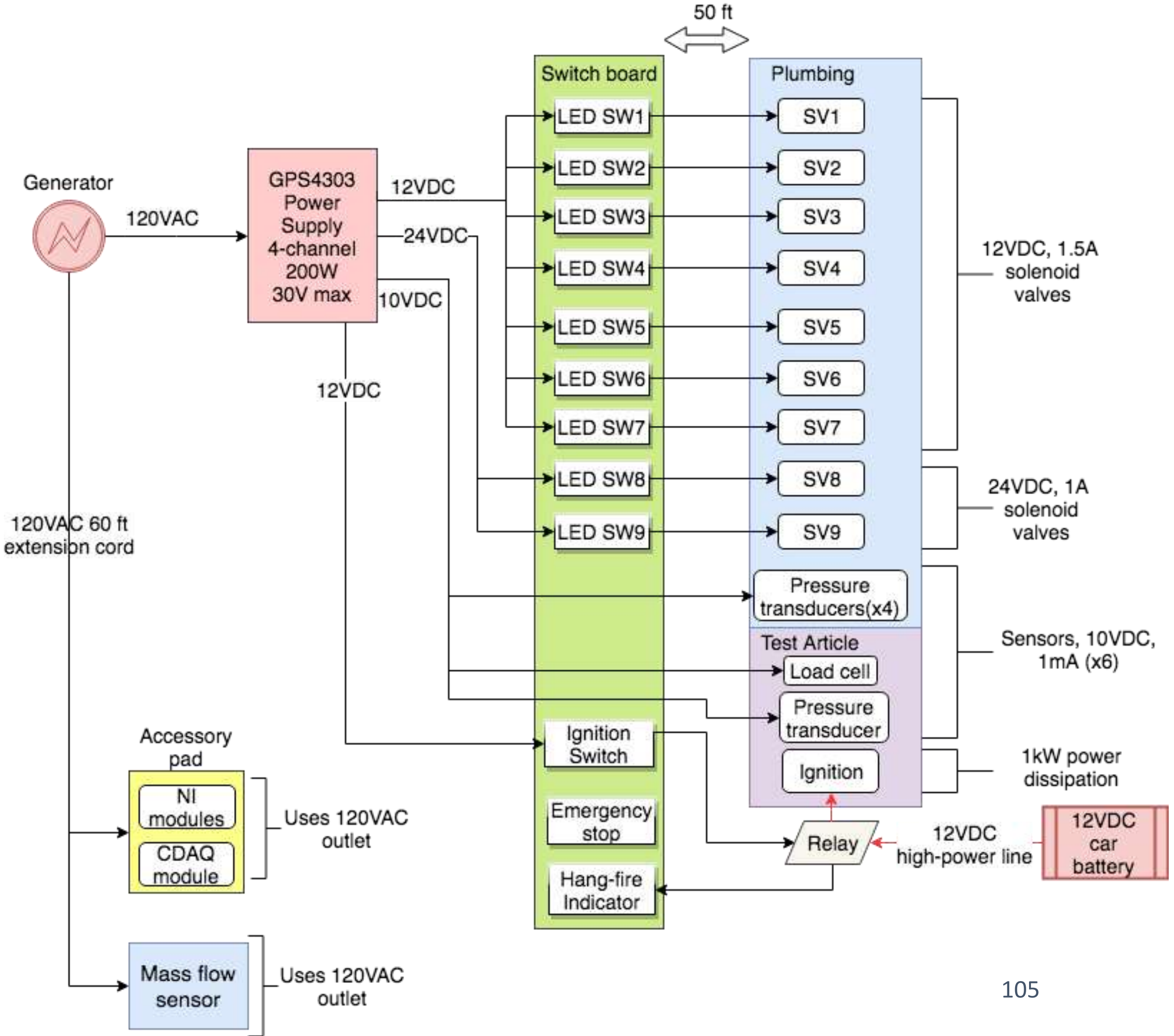
Power

- 200W power supply
  - Max consumption 180 W
- 12VDC car battery for steel wool ignition (high current)
- Ignition activated via relay
- 22 AWG 60ft wires for valve actuation

SV = Solenoid Valve

SW = Switch

MV = Main Valve (by the injector plate)

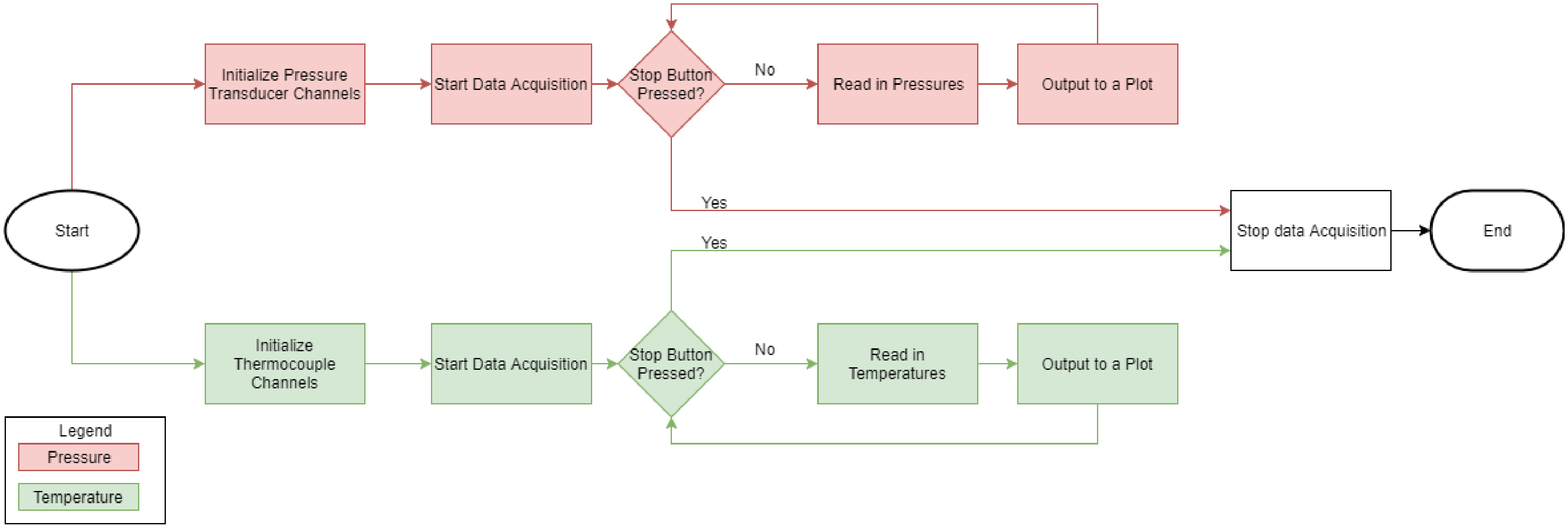


Backup Generator

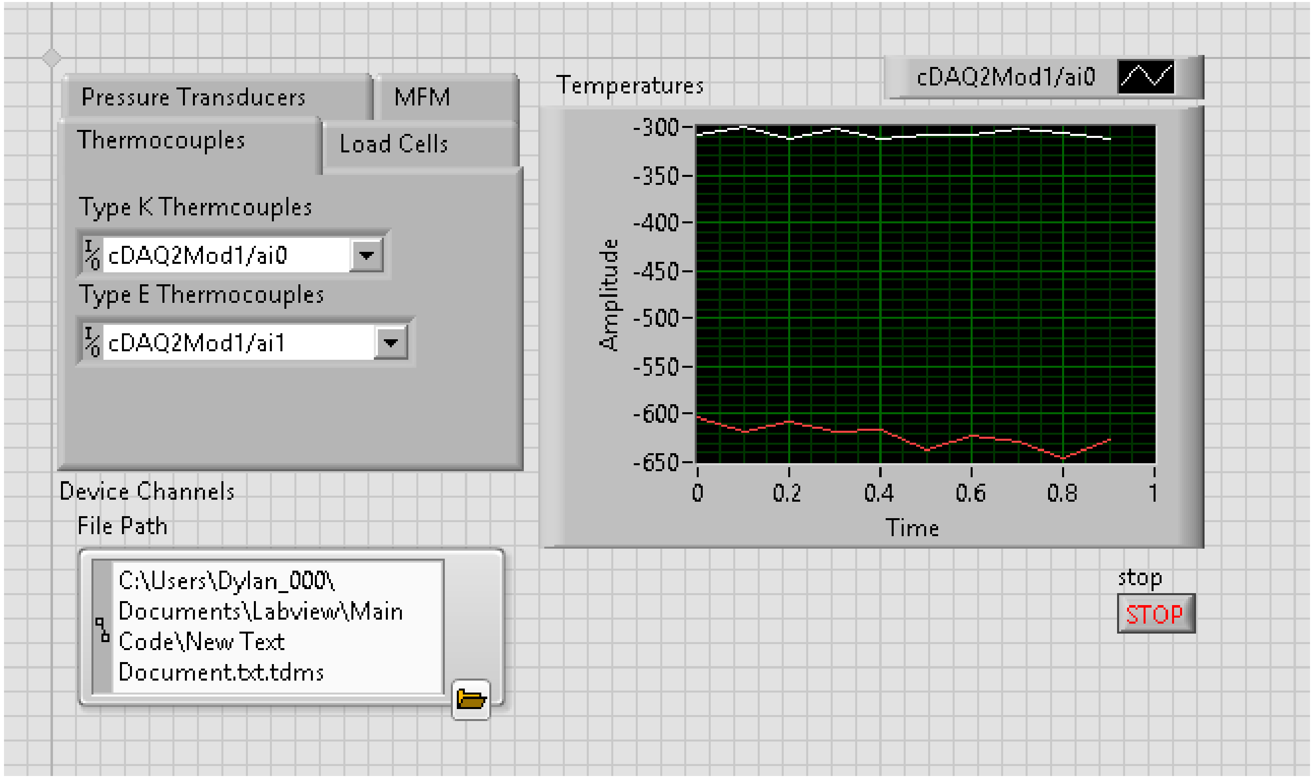
- UST 1200 Watt

Software

Plumbing Safety Software Diagram

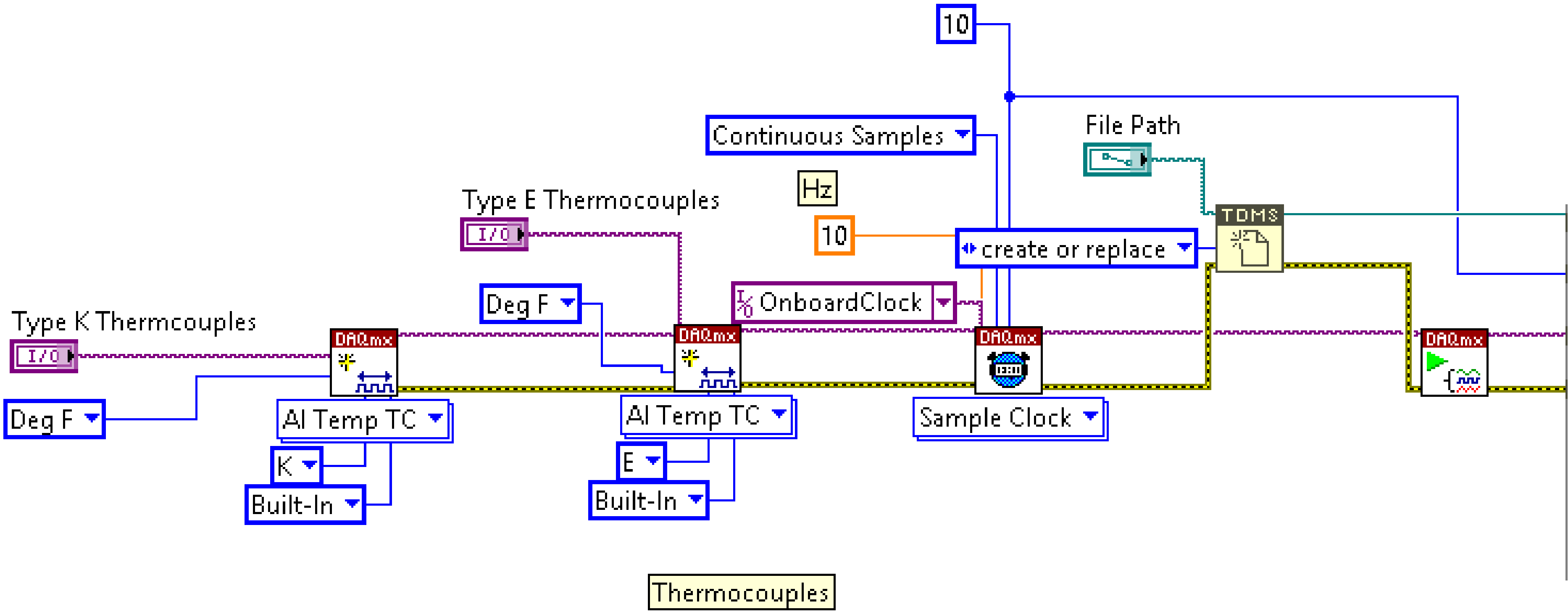


LabVIEW VI

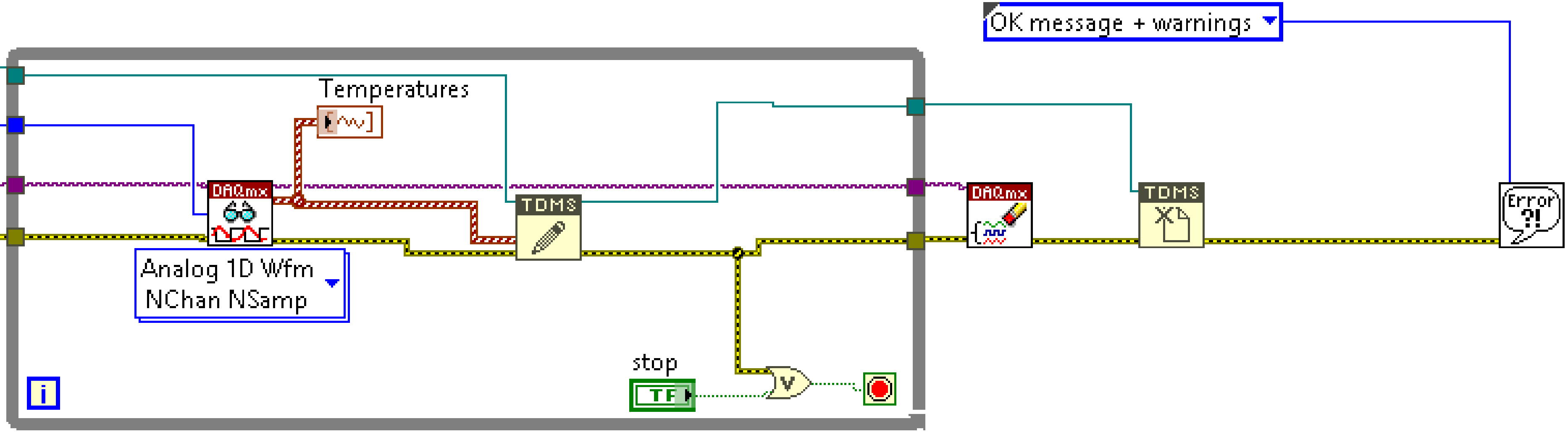


Stand | Rocket | DAQ | SW | Mod | Man

LabVIEW Block Diagram



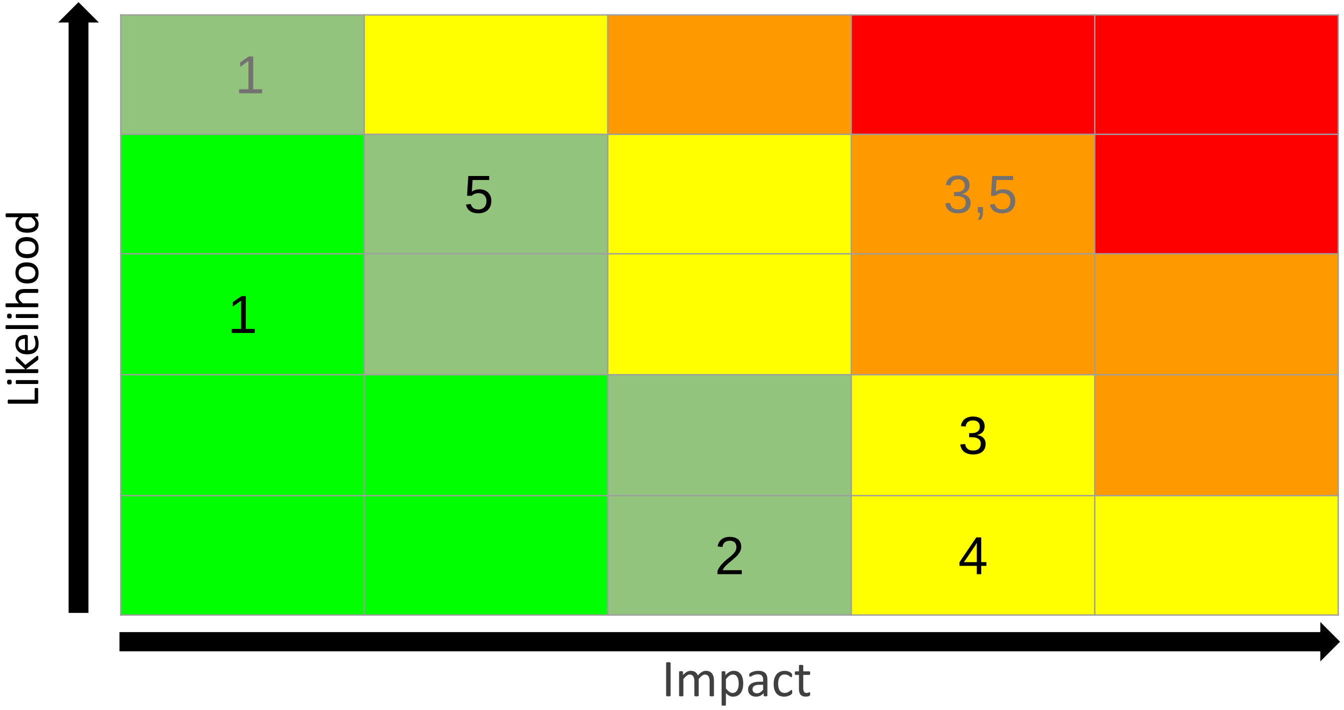
LabVIEW Block Diagram



Software Risk Mitigation

- Software Risk Mitigation
  - 1 - Slow data Acquisition speeds: The speeds obtained from the data acquisition system does not meet the required rates.
  - 2 - Buffer issues: The buffer of the DAQ system has overflow errors, or the Computer buffer has overwrite errors
  - 3 - Not completing on schedule: The code is not finished by the test date.
  - 4 - File writing errors: Errors occur in the way that the file is written, that make data analysis impossible.
  - 5 - Mass Flow Rate Meter Problems: The mass flow rate meter data means nothing, or figuring out how to use the mass flow meter is not completed

Software Risk Mitigation - Risk Matrix



1. Slow Data Acquisition Speed
2. Buffer Issues
3. Behind Schedule
4. File write errors
5. Mass Flow Rate Meter Problems

Modelling

Modelling Assumptions

- Propellant gases are ideal and constant throughout
- Adiabatic with no friction loss
- Steady, 1D axial flow
- Gas velocity is uniform throughout combustion chamber
- Chamber pressure and temperature are total pressure and temperature

Model Inputs

Throat Area	0.4 in^2
Exit Area	2.494 in^2
N_2O Molar Mass	44.103 kg/mol
Atmospheric Pressure	12.314 psi
Atmospheric Temperature	522 ºR
Fuel Mass	3.75 lbm
Fuel Density	57.54 lb/ft^3

Fuel Length	17.8 in
a	0.1741
n	1.03
Discharge Coefficient	0.375
Oxidizer Liquid Density	63.93 lb/ft^3
R	0.0054
“Tank Pressure”	900 psi

Modelling Fuel Properties

- Oxidizer Mass Flow $$\dot{m}_{ox} = C_d A_i \sqrt{2\rho(P_t - P_c)}$$
- Oxidizer Flux $$G_{ox} = \frac{\dot{m}_{ox}}{r^2\pi}$$
- Solid Fuel Regression Rate $$\dot{r} = aG_{ox}^n$$
- Fuel Mass Flow into oxidizer $$\dot{m}_f = \rho_f A_p \dot{r}$$

Modelling Thrust and Impulse

- Dimensionless Gamma

$$\Gamma = \sqrt{\frac{\gamma}{\frac{\gamma+1}{2}^{\frac{\gamma+1}{\gamma-1}}}}$$

- Coefficient of Thrust

$$C_F = \Gamma\sqrt{\frac{2\gamma}{\gamma-1}(1-(\frac{P_e}{P_c})^{\frac{\gamma-1}{\gamma}})} + (\frac{P_e}{P_c} - \frac{P_a}{P_c})\frac{A_e}{A_t}$$

- Thrust

$$F = C_F P_c A_t$$

- Total Impulse

$$I = \int F dt$$

- Characteristic Velocity

$$C^* = \frac{\sqrt{Rg_cT_c}}{\Gamma}$$

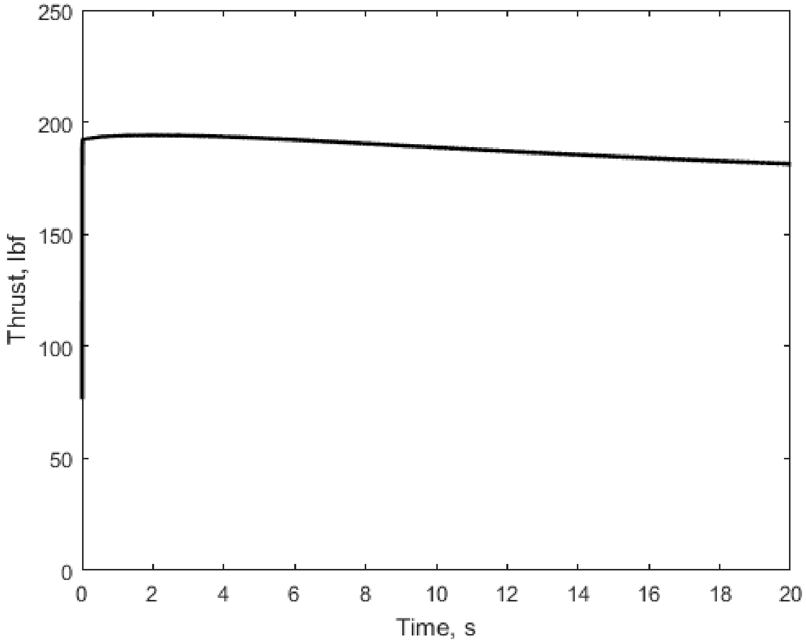
- Effective Exhaust Velocity

$$C = C^* C_F$$

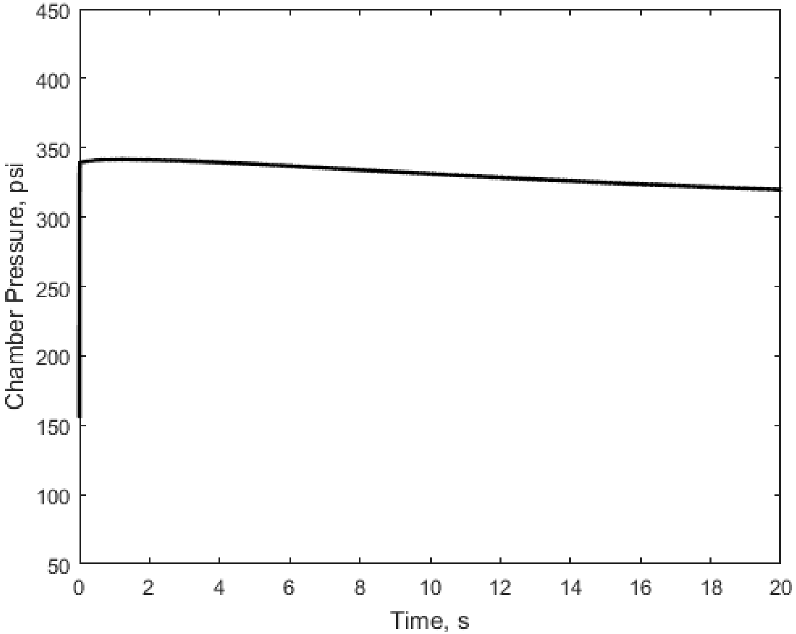
- Specific Impulse

$$I_{sp} = \frac{F}{\dot{m}g_o} = \frac{C}{g_o}$$

What We Should Expect - Model Results

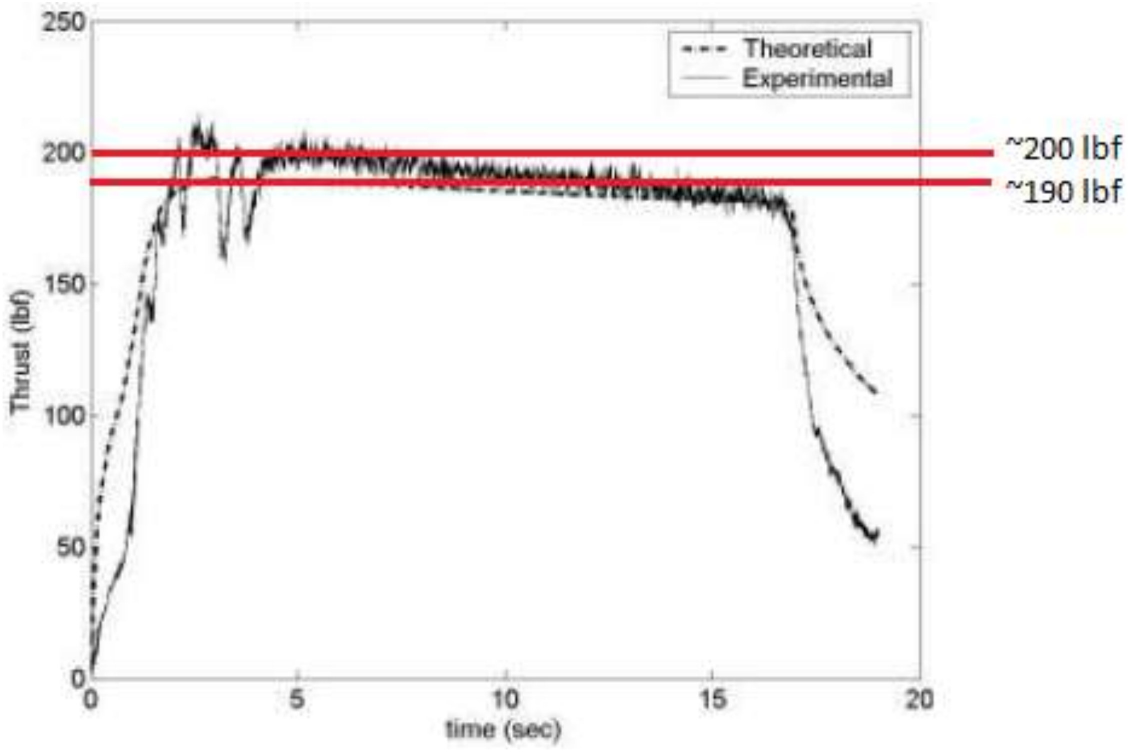


Thrust starts around 195 lbf



Pressure starts around 345 psi

Model Accuracy Calculation

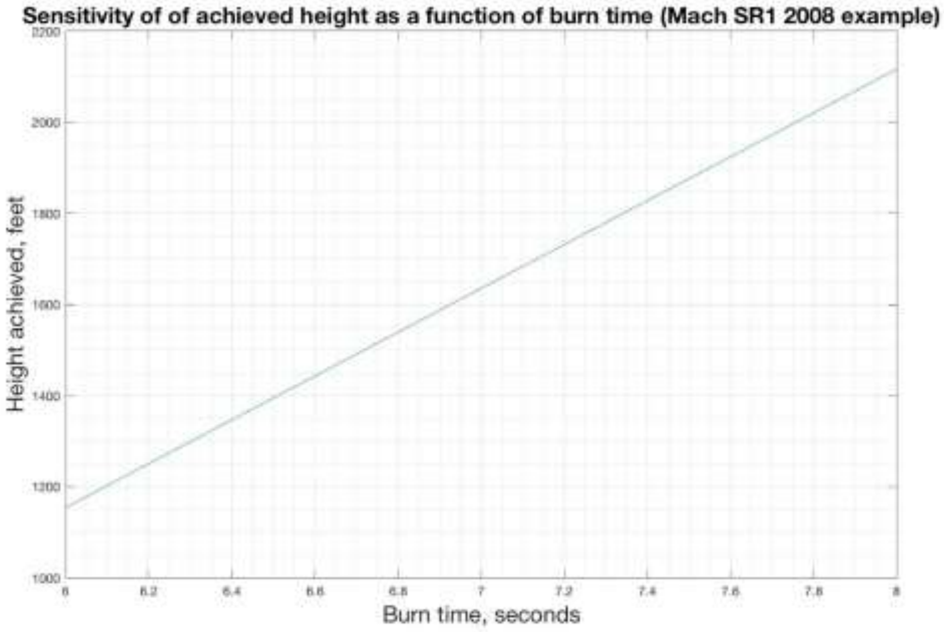


$$Accuracy = \frac{T_{real} - T_{model}}{T_{real}}$$

~5%

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: Load Cell Accuracy

Assumptions:

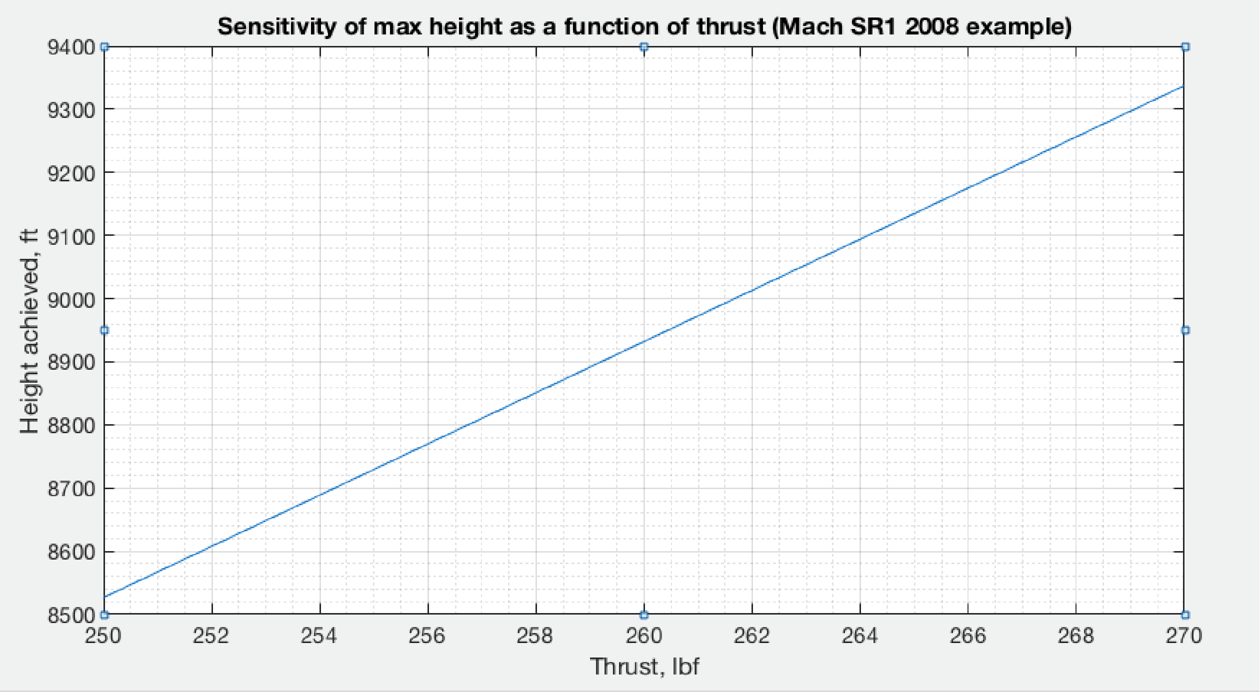
- Burn time and mass flow calculated from average of MACH SR1 test data
- Drag neglected
- Sensitivity is linear for small changes in thrust

Inputs:

- Mass flow = 0.9 lbm/s
- Time of constant burn is 10 seconds
- Pre-burn mass/post burn mass = 1.12

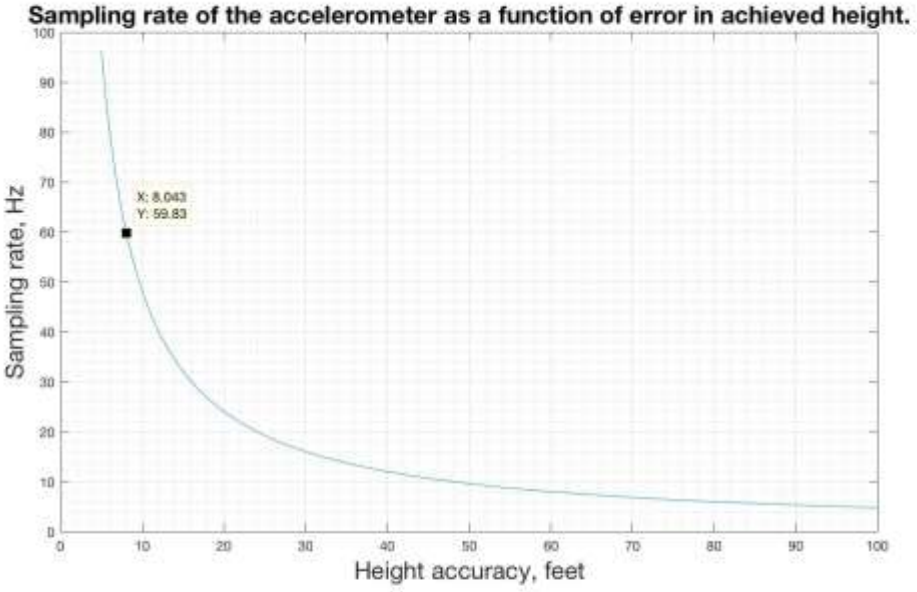
Conclusion:

- 40.5 feet of burn height per lbf of thrust
- Accuracy of 20 lbf gives accuracy of less than 10% in burn height



Sensor Requirements: Accelerometer

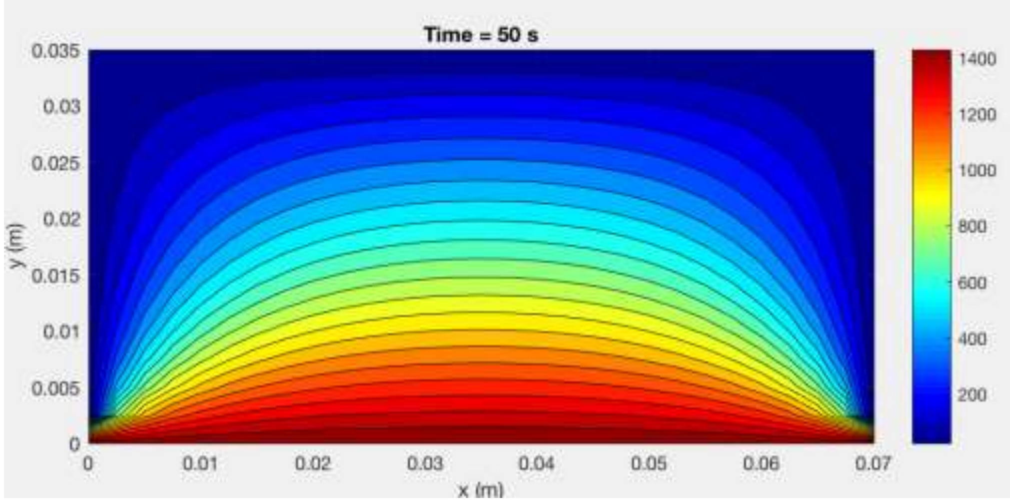
- 481.2 feet of max height per second of burn.
- Sampling at 60 Hz will be adequate to reduce error to 8 feet, thus improving burn time accuracy
- Resolution is not critical for this sensor.
- No high thermal requirements
  - Mounted on rocket sled.

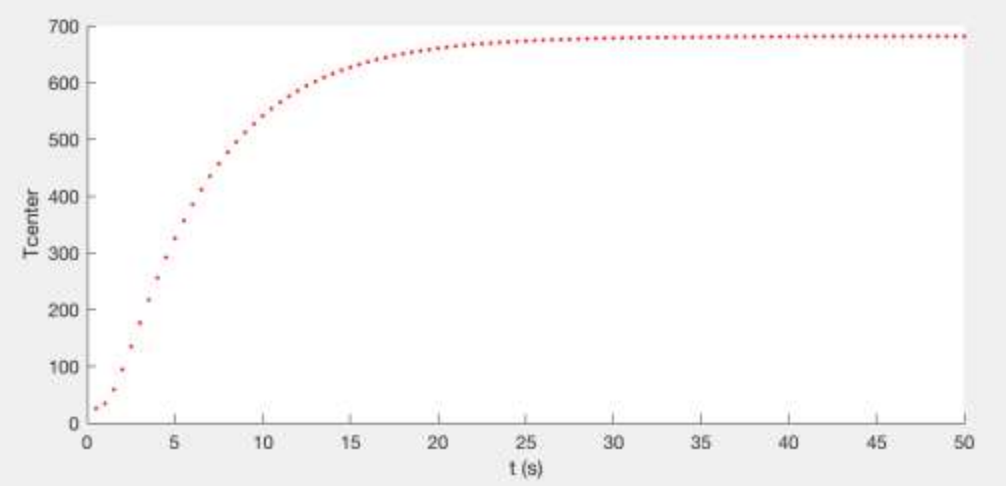


Stand | Rocket | DAQ | SW | Mod | Man

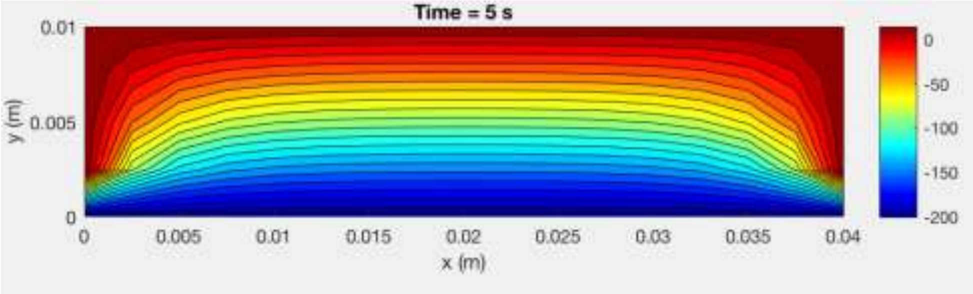
Sensor Requirements: Type K Thermocouple

- 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.

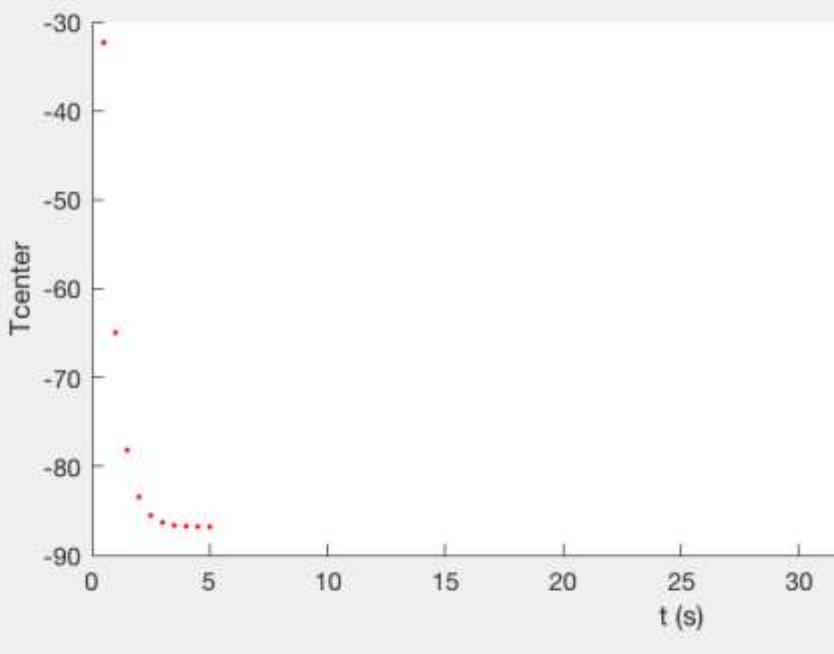




Sensor Requirements: Plumbing Thermocouple



- 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_2O.



Sensor Requirements: Pressure Transducer

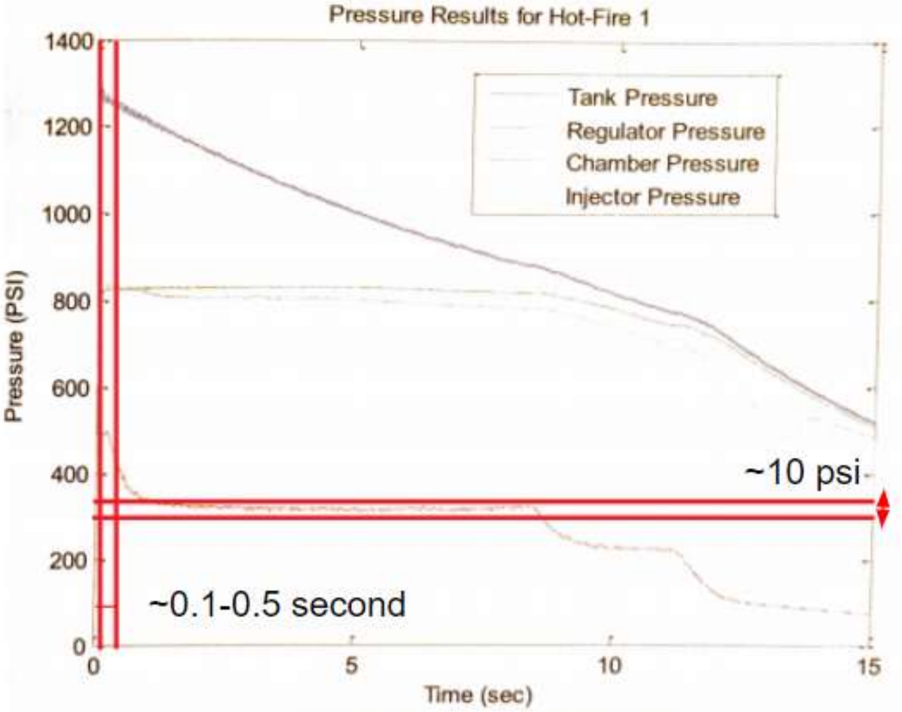


Figure 72: Pressure Data for Hot Fire 1

- 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

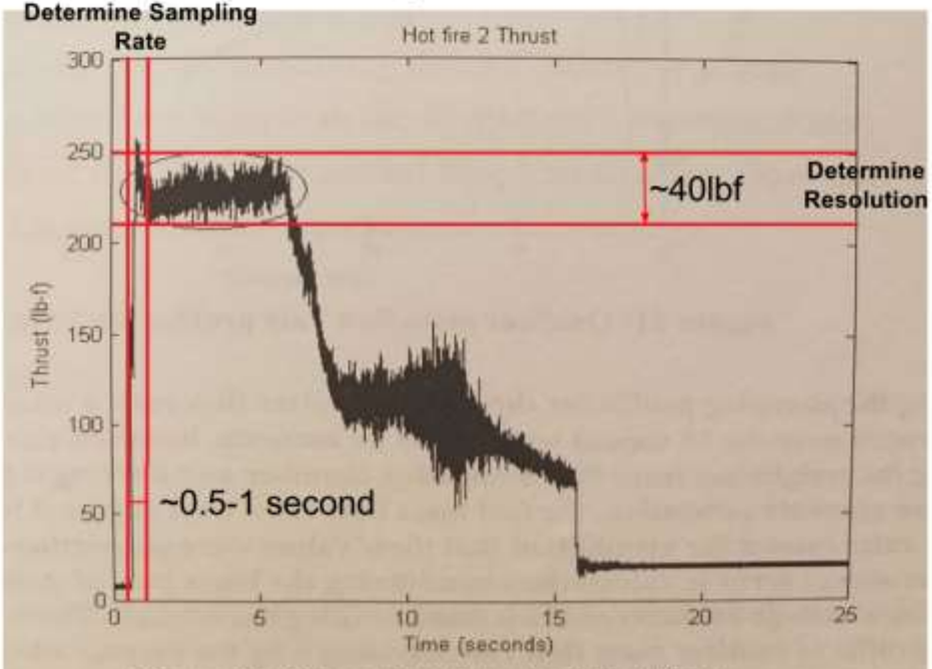


Figure 80: Thrust Profiles for 2 Hot Fires

- 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

Sensor Requirements: Mass Flow Meter

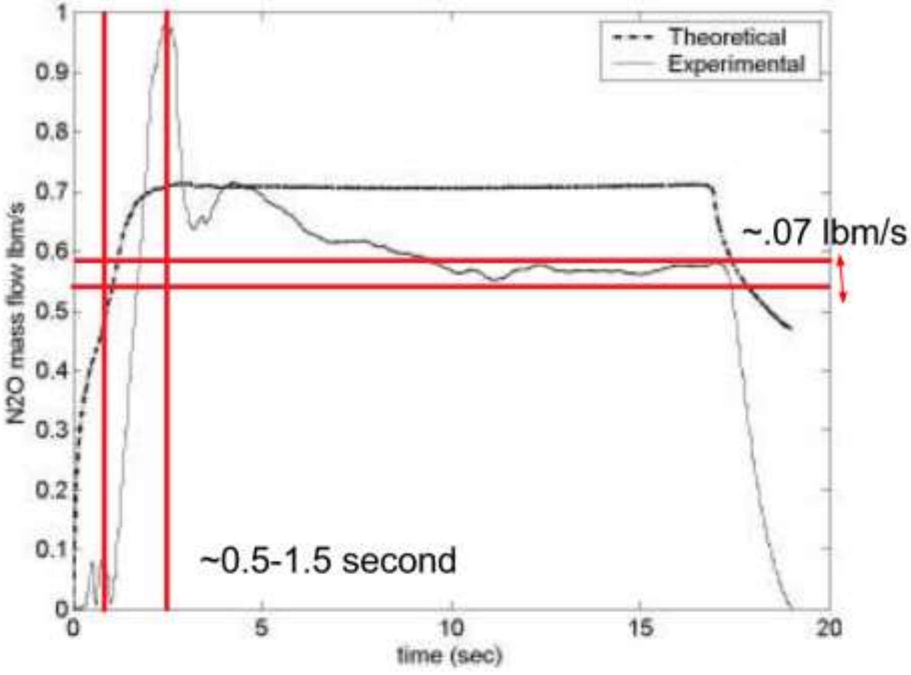


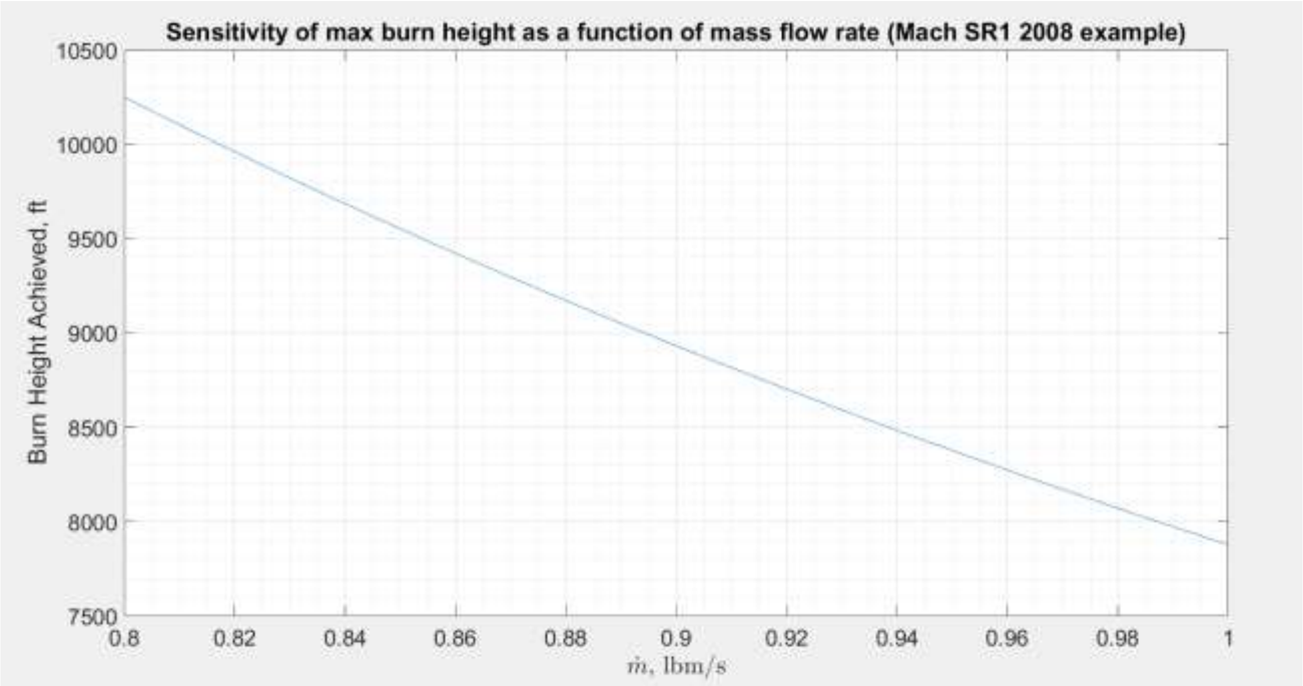
Figure 135: Oxidizer Mass Flow Rate

- Observations:
  - Mass flow peaks between .5 and 1.5 second
  - Fluctuation of ~.07 lbm/s during steady burn
- Results:
  - To determine accurate maximum thrust, we would need minimum ~33 samples in 1 seconds
  - Must resolve the thrust to within at least 33% of .02 lbm/s to capture fine changes in thrust
- Requirements:
  - Sampling Rate: minimum 34 Hz
  - Resolution: .02 minimum lbm/s

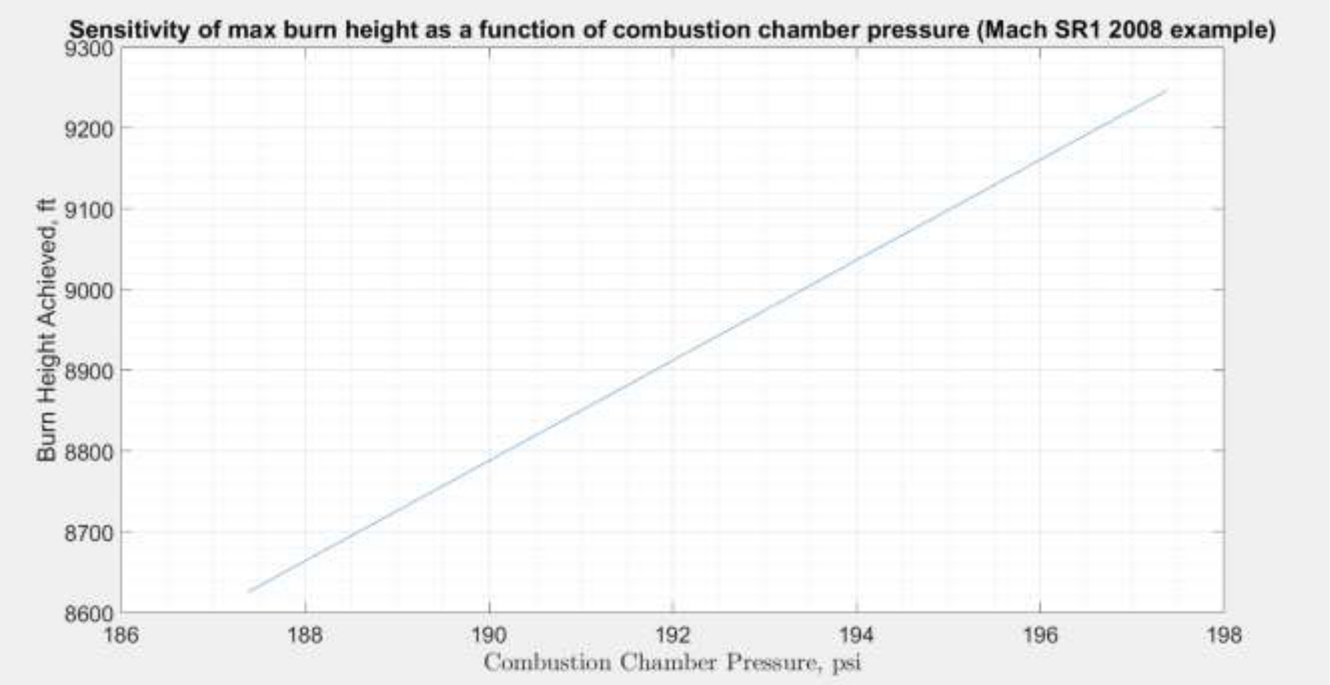
Assumptions for Sensitivity Models

- Air resistance is negligible
- Load
  - Varied ± 3 lbf from expected value of 260 lbf
- Combustion Chamber Pressure
  - Varied ± 5 psi from expected value of 192.4 psi
- Mass Flow Meter
  - Varied ± .1 lbm/s from expected value of .9 lbm/s

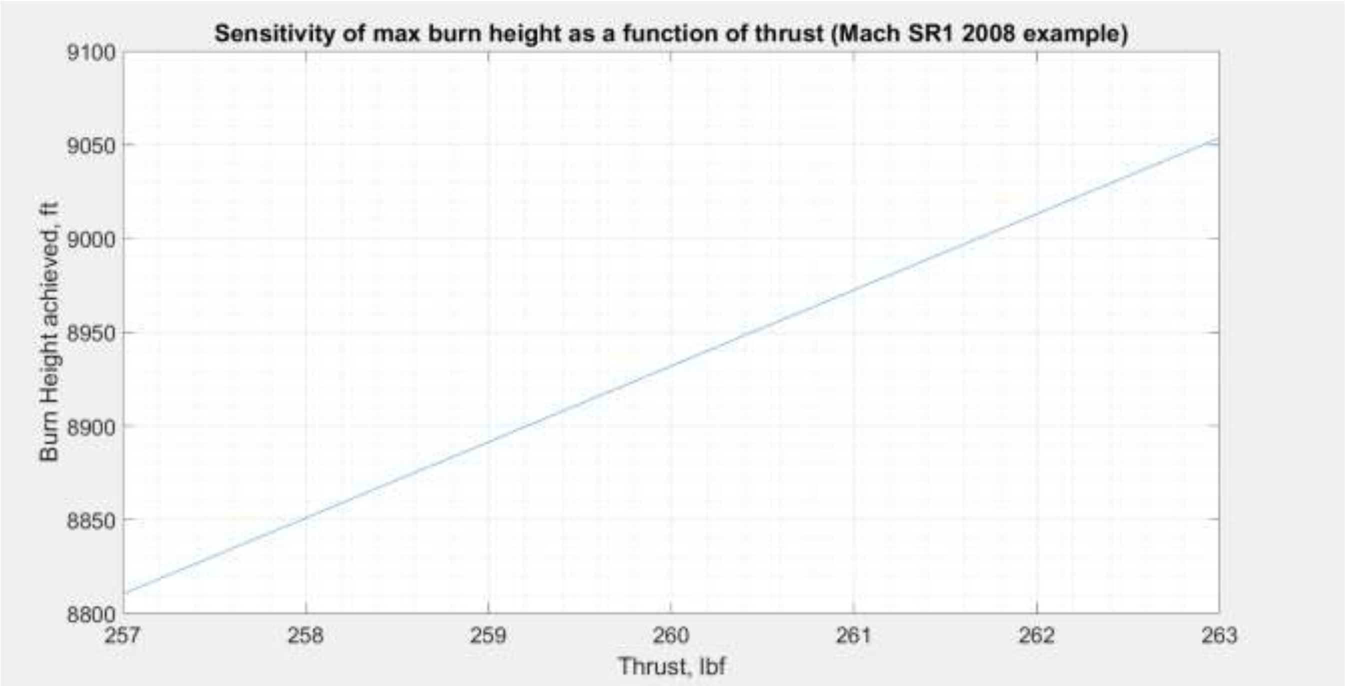
Mass Flow Sensitivity



Combustion Chamber Pressure Sensitivity



Thrust Sensitivity



Stand | Rocket | DAQ | SW | Mod | Man

Management

Design Requirements (FR1-FR3)

FR 1 The complete HICKAM system (excluding test article, computer and pressurized tanks) shall be delivered to and from test sites in a single durable storage container.

- **DR 1.1** The disassembled module shall be able to fit inside a storage container with inner dimensions of 5ft x 3ft x 3ft.
- **DR 1.2** The storage container with the HICKAM module inside shall allow it to be lifted by common effort of 6 people or fewer with 60 lbf of load force per person (OSHA standard).

FR 2 The system structure shall be capable of being secured to the ground with or without the use of padeyes.

- **DR 2.1** The HICKAM Test Stand structure shall secure to the paved surfaces without padeyes by use of ground anchors.
- **DR 2.2** The HICKAM Test Stand structure shall secure to the paved surfaces with padeyes by use of structural support.

FR 3 The test article shall be mechanically compatible with the test stand; i.e., the test article shall be capable of being both installed and uninstalled from the test stand.

- **DR 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.
- **DR 3.2** The test stand shall be adjustable to fit a test article combustion chamber length in range 6-30 inches and end-cap diameter of range 3 - 7 in.

Design Requirements (FR4-FR5)

FR 4 The test stand system shall provide measurements of test article thrust, combustion chamber pressure, mass, nozzle temperature, oxidizer flow rate, and burn time.

DR 4.1 The pressure sensor shall take measurements of test article combustion chamber pressure at sampling rate of at least 125 Hz, accuracy of 14 psi, range 0-550 psi, and response time of less than 0.008 seconds.

DR 4.1.1 The pressure transducer attachment to the combustion chamber shall not allow the sensor to get hotter than 212 F.

DR 4.1.2 The pressure transducer tubing interface must withstand 500 psi and 3200 F.

DR 4.2 The temperature sensors shall be able to endure hot-fire test conditions and have sampling rate of at least 10 Hz, resolution of 3.6 F, and response time of less than 0.02 seconds.

DR 4.3 The HICKAM package shall include device to measure pre-burn mass of the rocket engine.

DR 4.4 The force sensor shall take measurements of the test article thrust during hot-fire test at sampling rate of at least 45 Hz, accuracy of at most 22 lbf, resolution of 3 lbf, range of 0-800 lbf, and response time of less than 0.02 seconds.

DR 4.5 The acceleration sensors shall take measurements of structural vibration and source shock at sampling rate of at least 90 Hz.

FR 5 The system shall transmit measured data to a computer without loss of data integrity.

DR 5.1 Data transfer and power delivery wires shall not get hotter than 60% of their melting point during the hot-fire test.

DR 5.2 The DAQ system shall implement the noise filtering to avoid aliasing.

DR 5.3 The data analysis software shall convert and calibrate the raw measurements (in V) to data with appropriate units, such as lbf for thrust, seconds for duration, °R for temperature, psi for pressure.

Design Requirements (FR6)

FR 6 The system shall allow operator to initiate and end the test remotely and safely from 50 feet distance from the test stand.

DR 6.1 The length of the power and DAQ wiring leading from computer system to the test stand shall be at least 50 feet.

DR 6.2 The HICKAM system shall acquire its power from the 120VAC generator located 10 feet from the control board.

DR 6.3 The control board shall provide interface for ignition ON/OFF, OPEN/CLOSE valves for the plumbing.

DR 6.3.1 The system shall be able to actuate 12VDC, 1.5A solenoid valves.

DR 6.3.2 The system shall be able to actuate 24VDC, 1A solenoid valves.

DR 6.3.3 The system shall be able to deliver 1000W to ignition material.

DR 6.4 The control system shall be able to purge all of the ignition material from the combustion chamber at any point during the test procedure.

DR 6.5 The control system shall determine if misfire occurred and notify the operator.

DR 6.6 The system shall allow operator to monitor temperature and pressure of the plumbing components at frequency of at least 4 Hz.

DR 6.6.1 High-pressure oxidizer feed line pressure transducer shall take data at sampling rate of at least 10 Hz, accuracy of at most 50 psi, resolution of at most 50 psi, response time of at most 100ms, range of 0-4000 psi.

DR 6.6.2 Air tank pressure transducer shall take data at sampling rate of at least 10 Hz, accuracy of at most 5 psi, resolution of at most 5 psi, response time of at most 100ms, range of 0-150 psi.

DR 6.6.3 Gaseous nitrogen and low-pressure liquid nitrogen feed lines pressure transducer shall take data at sampling rate of at least 10 Hz, accuracy of at most 50 psi, resolution of at most 50 psi, response time of at most 100ms, range of 0-3000 psi.

DR 6.6.4 Injector plate pressure transducer shall take data at sampling rate of at least 125 Hz, accuracy of at most 5 psi, resolution of at most 5 psi, response time of at most 100m, range of 0-2000 psi.

DR 6.6.5 Plumbing temperature sensors shall take data at 10 Hz, range of -70 to 270 F, accuracy of at most 5 F, resolution of at most 5 F, and response time of at most 20 ms.

Design Requirements (FR6-cont.)

DR 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.

- **DR 6.7.1** The system shall mitigate the critical rocket failure.
- **DR 6.7.2** The system shall mitigate the helium tank pressure regulator failure.
- **DR 6.7.3** The system shall mitigate solenoid valve failure due to freezing.
- **DR 6.7.4** The system shall mitigate total electrical power loss.
- **DR 6.7.5** The system shall be able to shut down or begin purge at any point of operation if given the command to abort test for external reasons unrelated to the rocket or plumbing.

DR 6.8 The components of the test stand structure shall endure the loads caused by the hot-fire of a test article that produces 800 lbf of thrust with an industry standard factor of safety of 1.7 and at a non-nominal thrust angle of 17 degrees.

Design Requirements (FR7-FR8)

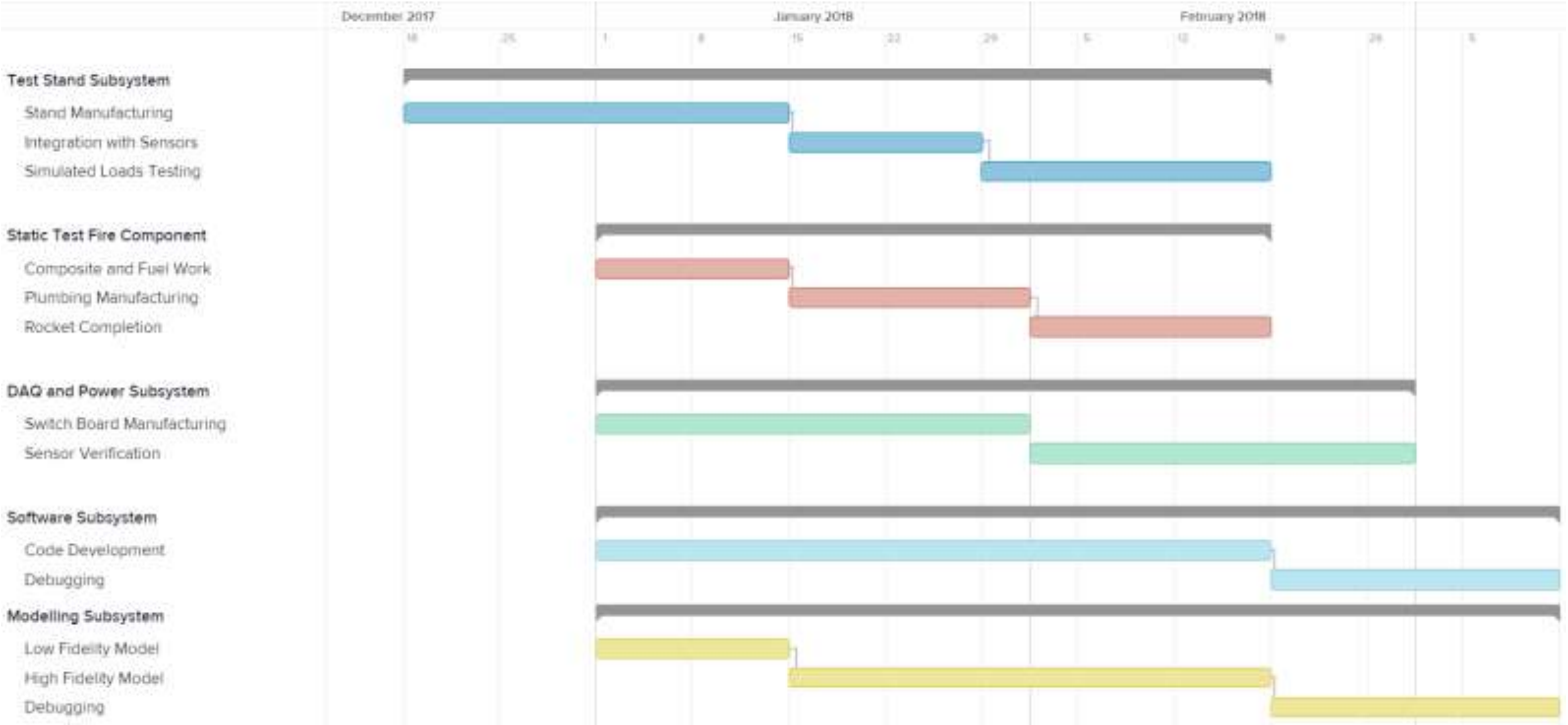
FR 7 The computer shall analyze measured data (FR 4) to provide derived measurements of total impulse, burn time, and thrust.

- **DR 7.1** The data analysis software shall derive total impulse, burn time, and thrust from the calibrated and converted measurements.
- **DR 7.2** The data module of HICKAM shall provide an analytical performance prediction software model in order to compare Isp, total impulse, combustion chamber pressure, and thrust predictions with hot-fire test results with the thrust accuracy of at most 10%.

FR 8 The system shall be capable of being installed and uninstalled in 8 hours or less by the effort of 10 or fewer people working in parallel.

- **DR 8.1** The mechanical components of test stand shall be assembled in under 2 hours by effort of 8 or fewer people.
- **DR 8.2** The test stand shall be secured to/disconnected from the ground in under 2 hours by effort of 8 or fewer people.
- **DR 8.3** The test article shall be mechanically secured to/dismantled from the test stand in under 1 hour by the effort of 12 or fewer people.
- **DR 8.4** The sensor package subsystem shall be attached to/detached from the test article in under 2 hours by the effort of 8 people or fewer.
- **DR 8.5** The system shall be deployed and packed without the intervention of cranes or hydraulic machinery.

Work Plan – Next Semester



Test Stand Costs

Item	Supplier	Quantity	Cost per Item	Total Cost
6061 Al 25mm x 50 mm 3ft long	McMaster	1	$54.29	$54.29
6061 Al 25mm x 50 mm 6ft long	McMaster	1	$92.01	$92.01
Zinc-Alloy Steel Socket Head Scew M6 50mm (pkgs-50)	McMaster	1	$6.45	$6.45
M6 medium strength steel Nylon Insert Lock nuts C8 (pkgs-100)	McMaster	1	$4.68	$4.68
Flanged hex Head screws G5 (pkgs-5)	McMaster	5	$5.76	$28.80
Flanged hex nuts G5 (pkgs-50)	McMaster	1	$10.84	$10.84
6061 Al plate 1/2" thick 8x12"	McMaster	3	$33.04	$99.12
6061 Al Bar 1 " thick 3x36"	McMaster	2	$64.64	$129.28
6062 Al Bar 1 " thick 4x24"	McMaster	2	$57.52	$115.04
6063 Al Bar 1 " thick 12x24"	McMaster	1	$141.62	$141.62
6064 Al Bar 1 " thick 1.5x24"	McMaster	3	$24.05	$72.15
3/8" Zinc plated steel Clamping U Bolts ID 4 5/8"	McMaster	2	$3.21	$6.42
Joomen 20-1000mm 2x Linear Guideway Rails and Carraiges	Amazon	1	$225	$225
Ground Anchoring System (estimate)		4	$20	$80
Galvanized Steel Eyebolt with Nut and with Shoulder 3"	McMaster	2	$4.29	$8.58
Galvanized Steel Eyebolt with Nut and with Shoulder 2"	McMaster	2	$4.00	$8.00
Steel Extension Spring 4.625" (pack of 6)	McMaster	1	$13.53	$13.53
Routing Eyebolt with Nut	McMaster	1	$5.77	$5.77
Zinc Yellow-Chromate Plated Hex Head Screw	McMaster	1	$9.22	$9.22
High-Strength Steel Hex Nut	McMaster	1	$6.34	$6.34
6061 Aluminum Rectangular Tube 3"x3"	McMaster	2	$133.78	$267.56

Total
$1,384.70

Data Acquisition Costs

Components	Cost without Borrowing	Cost with Borrowing
Sensors	$4,780	$160
Switch Board Materials	$198.43	$154.97
Wiring	$70.99	$70.99
DAQ Modules	$5,577	$0
Total	**$10,626**	**$386**

Rocket Motor Costs

Components	**Cost without Borrowing**
Combustion Chamber	$1,372.28
Nozzle	$428.46
Injector Plate	$85.53
Ignitor	$7.69
Fuel	$259.98
Total	**$2,153.94**

Plumbing Costs

Components	**Cost without Borrowing**	**Cost with Borrowing**
Swagelok Plumbing Parts	$2,464.17	$1,859.67
McMaster-Carr Plumbing Parts	$751.48	$437.04
Plumbing System Gasses (Airgas)	$5,458	$2,008
Plumbing Sensors	$813	$480
Total	**$9,487.07**	**$4,785.13**

Simulated Load Test Costs

Components	Total Cost
Hydrostatic Test Facility	$100
Load Test	$50
Torch Test	$50
Total	**$200**

Stand Rocket DAQ SW Mod Man