HICKAM PDR

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

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Agenda

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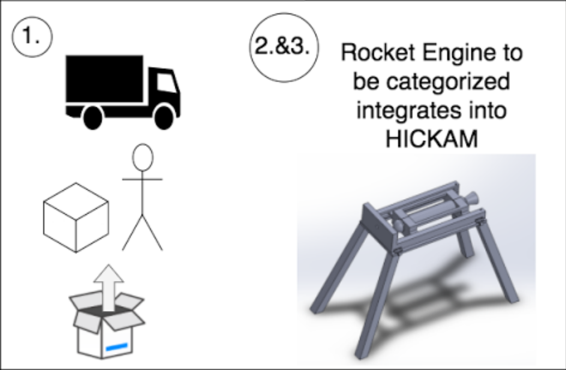
Project Overview

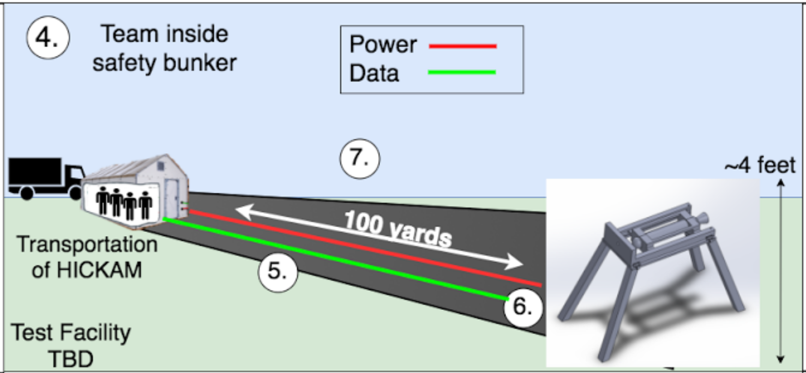
The goal of project HICKAM (**H**ybrid-rocket **I**nformation-**C**ollection, **K**nowledgebase and **A**nalysis **M**odule) is to design and manufacture a modular, compact, and portable testing platform for hybrid rocket engines.

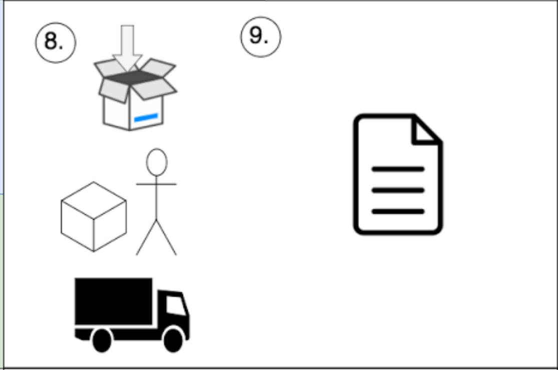
- Designed for "Class O" hybrid rockets (total impulse range of 4,600-9,210 lbf*s)
  - Verified via manufacturing and testing two 300 lbf hybrid rocket motors
- Purpose of the stand is to be able to characterize the components of the rocket motor
  - Testable quantities include:
    - Engine thrust over time (lbf)
    - Thrust duration and delay, maximum thrust (s, s, lbf)
    - Specific impulse (s)
    - Nozzle temperature (ºR)

HICKAM
Mission CONOPS

<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

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

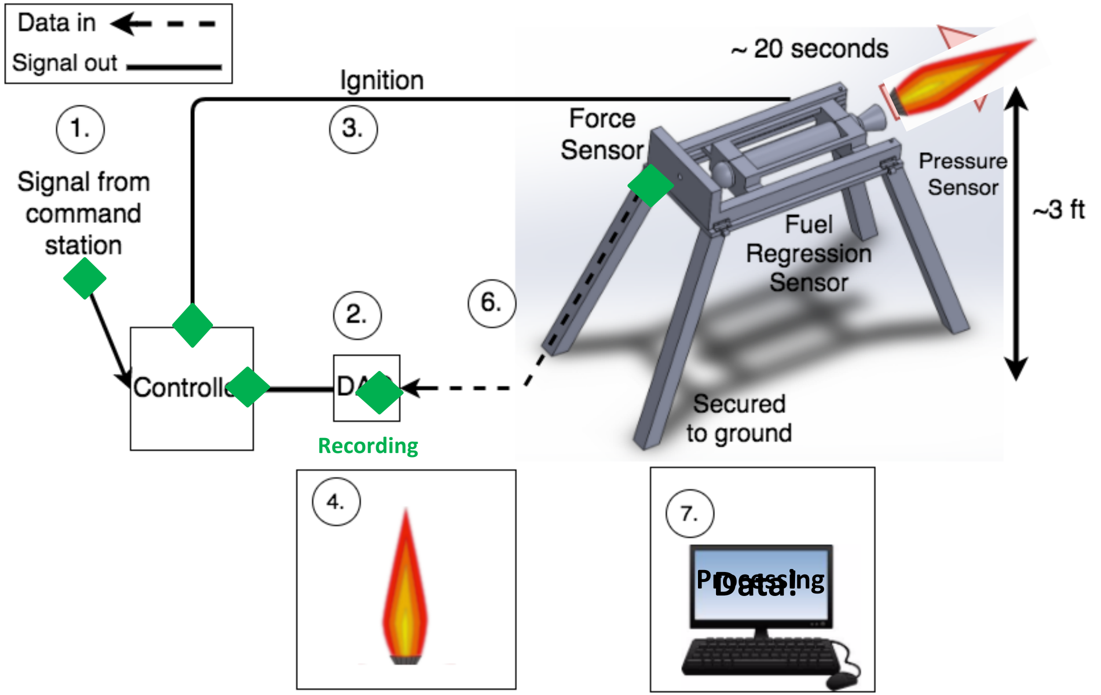
Post - Test

Step 8 - Disassemble, box, and transport HICKAM

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

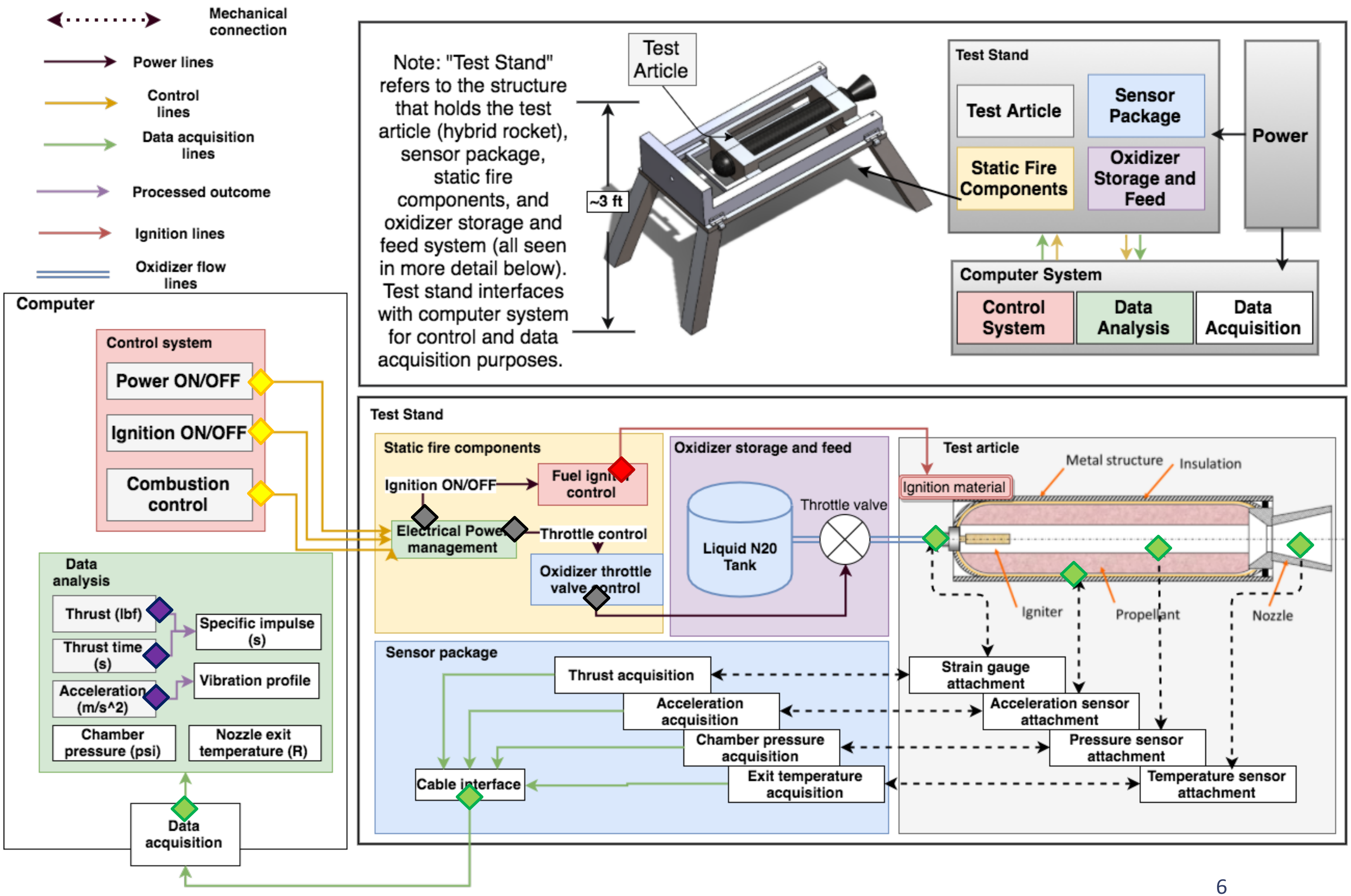
HICKAM
Test Stand
CONOPS

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



Step 1 - Signal is received from command station
Step 2 - Controller initiates DAQ to start recording data from sensors
Step 3 - Controller engages igniter to start hot fire ignition
Step 4 - Safety: Check for ignition or start hang-fire/mis-fire procedure
Step 5 - Rocket burns for approximately 20 seconds
Step 6 - DAQ collects data from sensors and saves it to memory
Step 7 - Model is used to validate data and specifications for engine is created

Functional Block Diagram (FBD)



Requirements

NATE O'NIEL

Functional Requirements

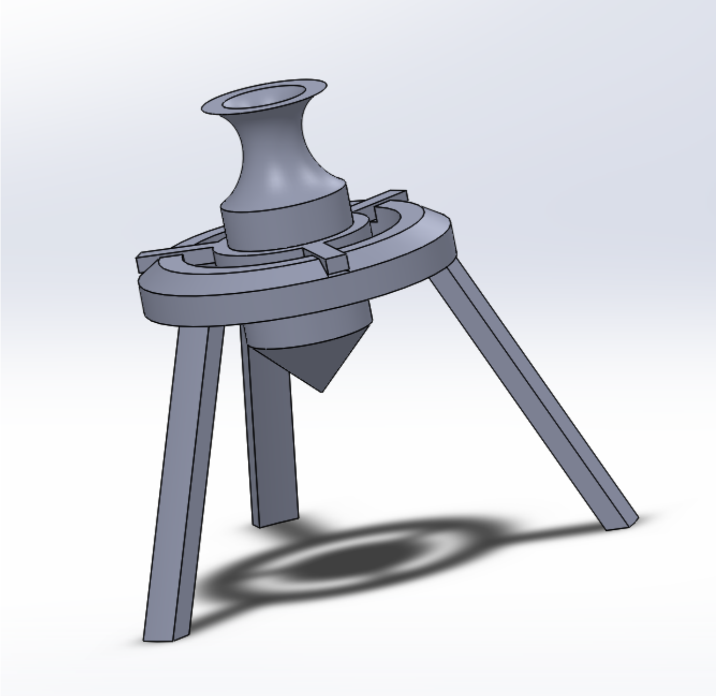
FR 1	The complete HICKAM test stand shall be delivered to and from test sites in a single durable storage container.
FR 2	The system shall be capable of being secured to paved ground surfaces with or without the use of padeyes.
FR 3	The test article shall be capable of being both installed and uninstalled from the test stand.
FR 4	The test stand system shall provide measurements of test article thrust, mass, combustion chamber pressure, oxidizer flow rate, nozzle temperature and test stand vibration.
FR 5	The system shall transmit acquired data to the controlling computer without loss of data integrity.
FR 6	The controlling computer shall initiate and end test remotely from a 100 yards distance from the test stand.
FR 7	The controlling computer shall analyze measured data to derive Isp, total impulse, burn time, and maximum thrust.
FR 8	The system shall be capable of being installed/uninstalled in under 8 hours by the effort of 10 people.
FR 9	The control system shall respond to hang-fire and misfire scenarios for safety.

Baseline Design

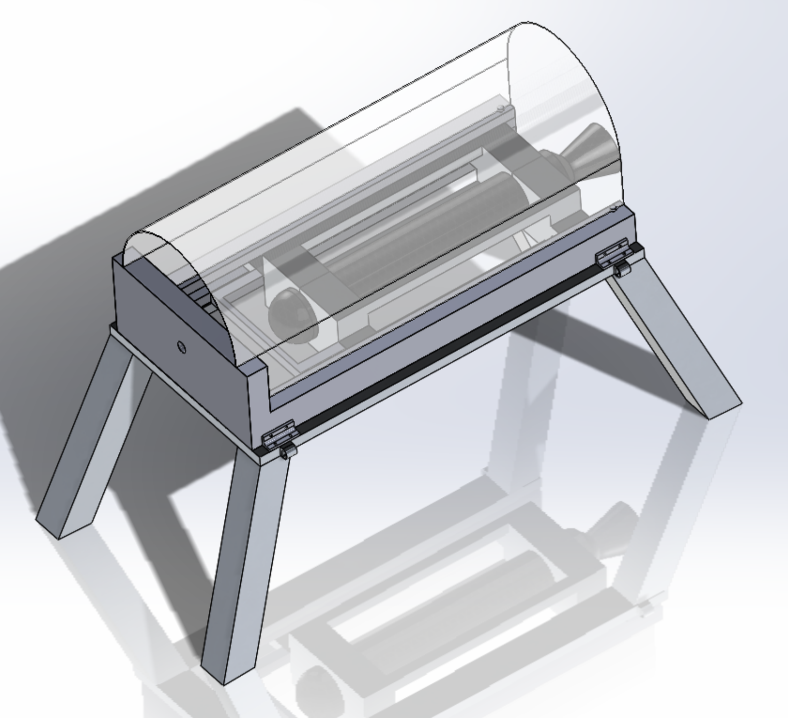
Initial Baseline Design – Vertical Test Stand

Design Reconsidered

- Unknown if inverted oxidizer feed would require additional mechanical feed mechanisms, and cannot determine from test until plumbing system is complete.
- 3 load cells would increase cost (~$500 each)
- Load sensors need to account for the changing mass of the rocket (possible, but complicated)



Revised Baseline Design – Horizontal Test Stand



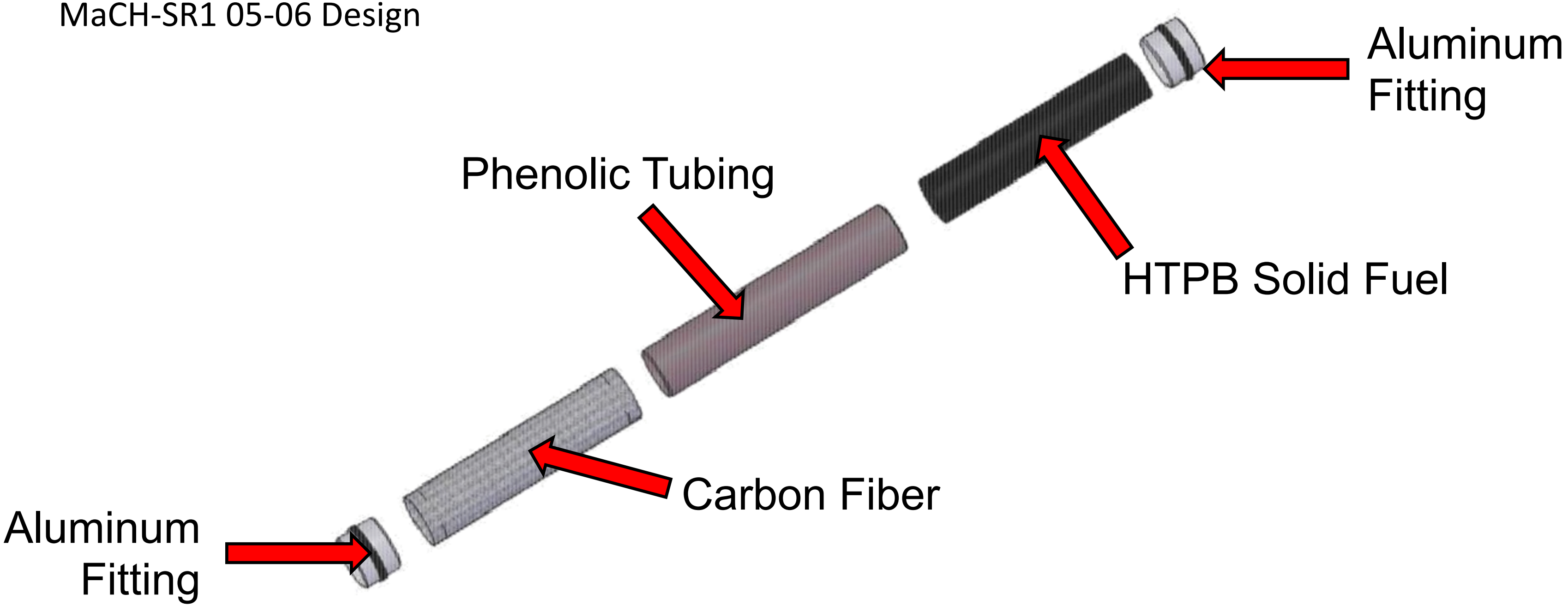
- Conventional design used for many small scale rocket tests.
- Instead of solving a rocket problem, moved to solving a test stand problem
- One load cell, lowering cost
- Redesign of rocket housing to allow for on axis thrust measurements

Safety Features

- Railing would secure rocket in vertical direction
- The front loading plate would secure in horizontal direction
- In case of catastrophic failure explosion is contained under protective housing

Baseline Design - Rocket Motor Main Chamber

MaCH-SR1 05-06 Design

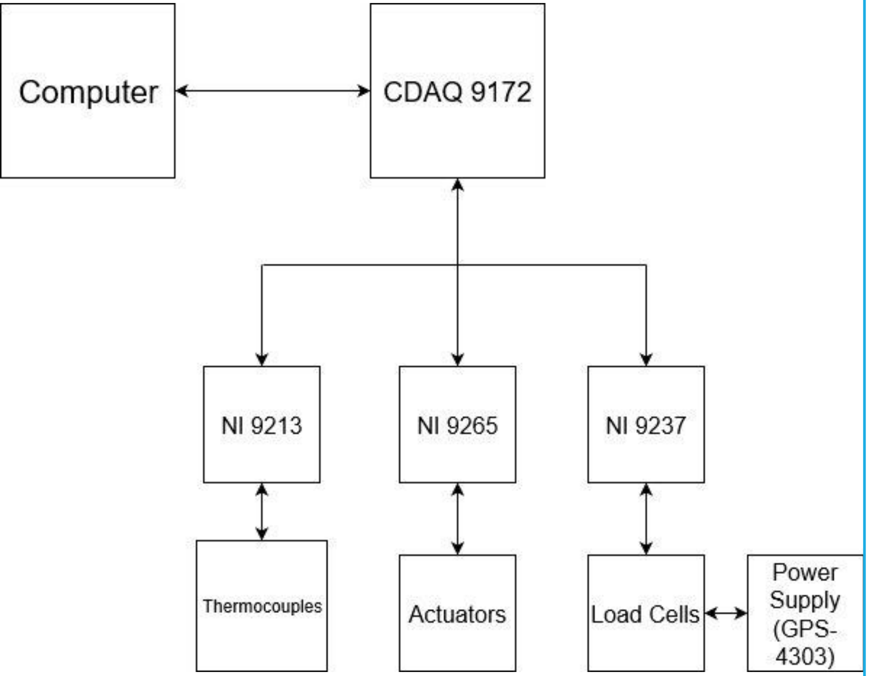


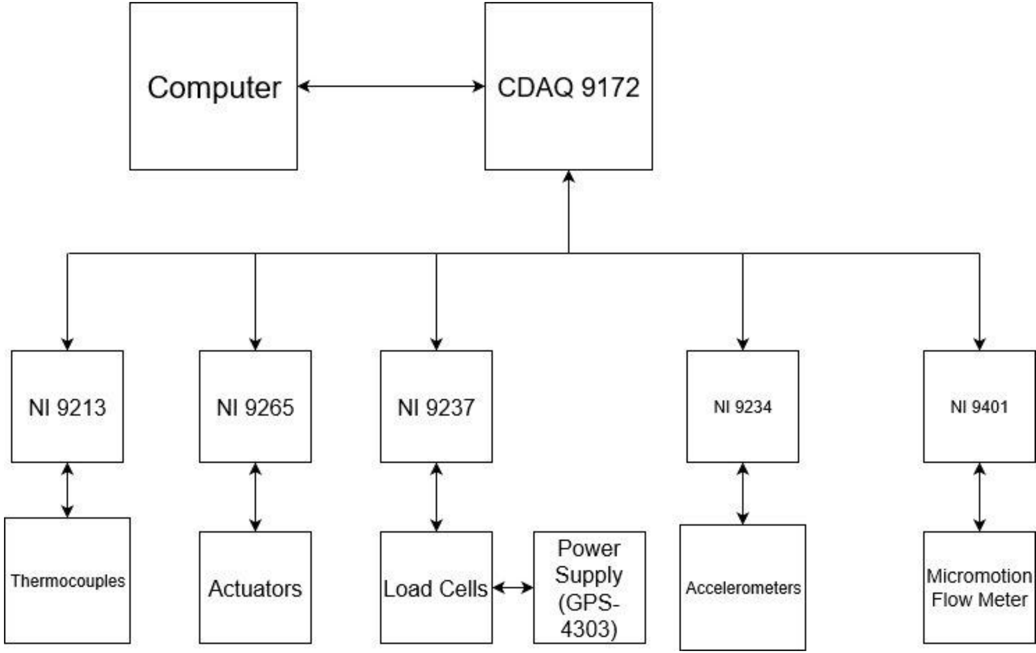
Baseline Design – DAQ

Success level	DAQ system measurements	Baseline design
Level 1	Temperatures, thrust, actuator control	CDAQ 9172 paired with [NI 9213, NI 9265, NI 9237] data acquisition systems
Levels 2-3	Temperatures, thrust, chamber pressure, acceleration	CDAQ 9172 paired with [NI 9213, NI 9265, NI 9237, NI 9234, NI 9401] data acquisition systems

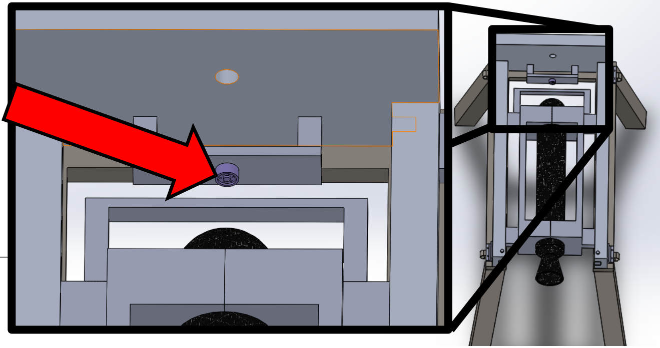
Baseline Design – DAQ Cont.

Level 1 DAQ system diagram	Level 2-3 DAQ system diagram





Load Cell Placement



Baseline Design - Load Cell

Levels of Success	**Level 1 Success**	**Level 2 Success**
Type of Load Cell	1x - Single Axis **Button** Load Cell	1x - Single Axis **Pancake** Load Cell
Requirement to Meet	Satisfies magnitude of thrust requirement of DR 4.4: •Force measurement must endure 300 *lbf* * FOS(1.7) = 510 *lbf* ✓ ~~•Force measurement must endure non-nominal force vectoring in any direction 20° * FOS(1.7) = 34° => ~285 *lbf*~~ ✖	Satisfies full requirement of DR 4.4: • Force measurement must endure 300 *lbf* * FOS(1.7) = 510 *lbf* ✓ •Force measurement must endure non-nominal force vectoring in any direction of 20° * FOS(1.7) = 34° => ~285 *lbf* ✓
Model Considered	Futek FSH03892 1,000 *lbf* button load cell = $450 	Futek FSH04170 1,000 *lbf* pancake load cell = $850 Side load tolerance: > 300 *lb* 

Evidence of Baseline Feasibility

Critical Project Elements

Critical Project Element (CPE)	Description
CPE #1: Budget Management and Scheduling	•Budgeting plan •Accelerated manufacturing schedule
CPE #2: Data Acquisition and Analysis System	•Sensor compatibility
CPE #3: Securing Test Facility	•Feasibility of Platteville •Front Range as a back up
CPE #4: System Validation using Computational Modeling	•Feasibility of deriving engine parameters from chosen Sensor Package •Feasibility of predicting test article performance to compare to test-acquired parameters
CPE #5: Manufacturing of the Test Stand and Rocket Engines	•Feasibility of Manufacturing Rocket and Test Stand Baseline Designs
CPE #6: Safety	•Human and Test Stand Safety

CPE 1: Budget Management and Scheduling

HALEIGH FLAHERTY

Premise

Why is budget and scheduling a CPE?

1) Budget and time are both hard limits.
2) For level 3 success, the budget must appropriately accommodate three major articles; test stand, and two rockets.
3) We predict a large scheduling problem if we wait to start manufacturing until next semester.

Risk Mitigation

Budget Risk mitigation requirement	Action	Requirement verification
Acquire suitable components through donation	•Donation inquiry to Orbital ATK and previous projects	Orbital ATK and previous projects confirmed donation as an option
Acquire suitable components by borrowing	•Borrow components from ITLL and Aerospace machine shop	ITLL and machine shop representatives confirmed borrowing as an option
Increase available funds	•Application to EEF for $3000	Application was submitted

Components Available for Donation

Orbital ATK

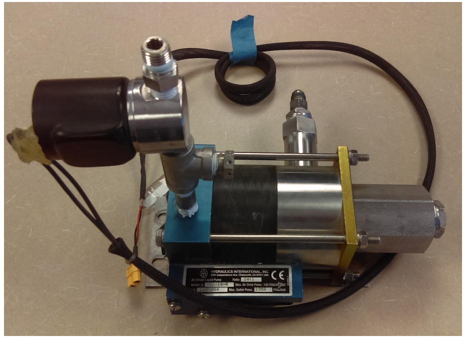
- Submitting a list of components to Customer

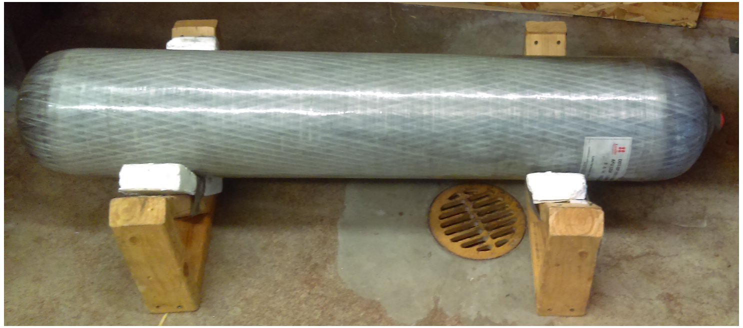
Previous Projects

- Oxidizer tank from HYSOR
- Oxidizer pump from HYSOR

Senior Project Supplies

- CDAQ





Components Available for Borrow

ITLL

- DAQ modules
- Power Supply

Aerospace Machine Shop

- Generator
- Pressure tank

Tank pictured is for Argon, but looks identical to tank we will use

Test Stand Material Budget

Item	Category	Quantity	Cost Per	Cost
Accelerometers	Sensors	4	$30	$120
Braded Cable	Test Stand raw materials	1	$130/10ft	$130
Computer*	Electronics	1	$0	$0
Diesel Generator*	Power	1	$0	$0
Load Cell (Level 1)	Sensors	1	$450	$450
NI 9213(Thermocouples)*	DAQ System	1	$1,268	$1,268
NI 9237(Strain and load sensors)*	DAQ System	1	$1,354	$1,354
NI 9265(Actuators)*	DAQ System	1	$419.00	$419.00
Nitris Oxide	Rocket Motor raw materials	3	$150	$450
Plastic Shield	Test Stand raw materials	2	$15/sheet	$30
Power Supply*	Electronics	1	$299.52	$299.52
Test Stand Container	Test Stand raw materials	1	$400	$400
Wiring (21 gauge)	Electronics	300 yards	$93/100y	$279
Load Cell (Level 2)	Sensors	1	$850	$850
Pressure Transducer	Sensors	2	$500	$1,000
Flow sensor (Used)	Sensors	1	$500	$500
NI 9234(Accelerometers)*	DAQ System	1	$1,992	$1,992
NI 9401(Mass flow rate sensor)*	DAQ System	1	$323	$323

Key
Level 1 Success
Level 2 Success
Level 3 Success
* Available for Donation

Total	
Level 1	$5,200
Level 2	$6,600
Level 3	$9,415

Total w/ Donations	
Level 1	$1,859
Level 2	$3,559
Level 3	$4,059

Rocket Motor Material and Safety Budget

Key
*Would reuse for 2nd rocket motor

Rocket Motor Material

Item	Category	Low Estimate	High Estimate
Aluminum Stock *	Rocket Motor raw materials	$130	$130
Carbon fiber materials	Rocket Motor raw materials	$300	$400
End Fittings	Plumbing materials	$120	$200
Miscellaneous (straps, hardware) *	Rocket Motor raw materials	$100	$100
Oxidizer tank	Test Stand raw materials	$0	$0
Phenolic Tube	Rocket Motor raw materials	$230	$230
Titanium Injector Plate	Rocket Motor raw materials	$85	$85
Tubing *	Plumbing materials	$15	$15

One Rocket

Total (Low)	$980
Total (High)	$1160

Two Rockets

Total (Low)	$1715
Total (High)	$2075

Additional Safety Costs Dependent on Test Facility

Item	Category	Quantity	Cost Per	Cost
Blast Barrier	Test and Safety	1	$350	$350
Test Facility Rental Fees	Test and Safety	2 days	$300/day	$600

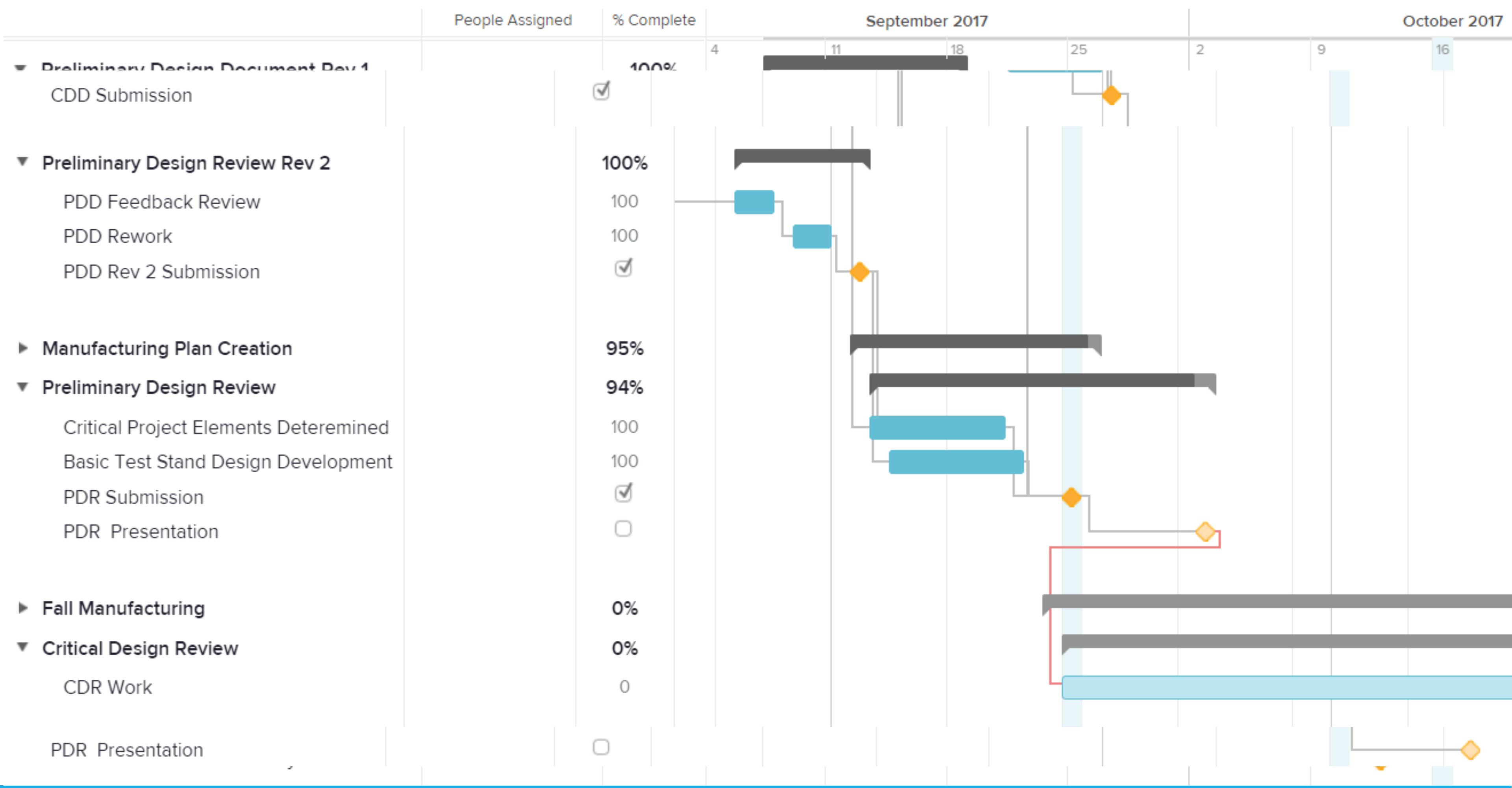
Safety Total

Total	$950

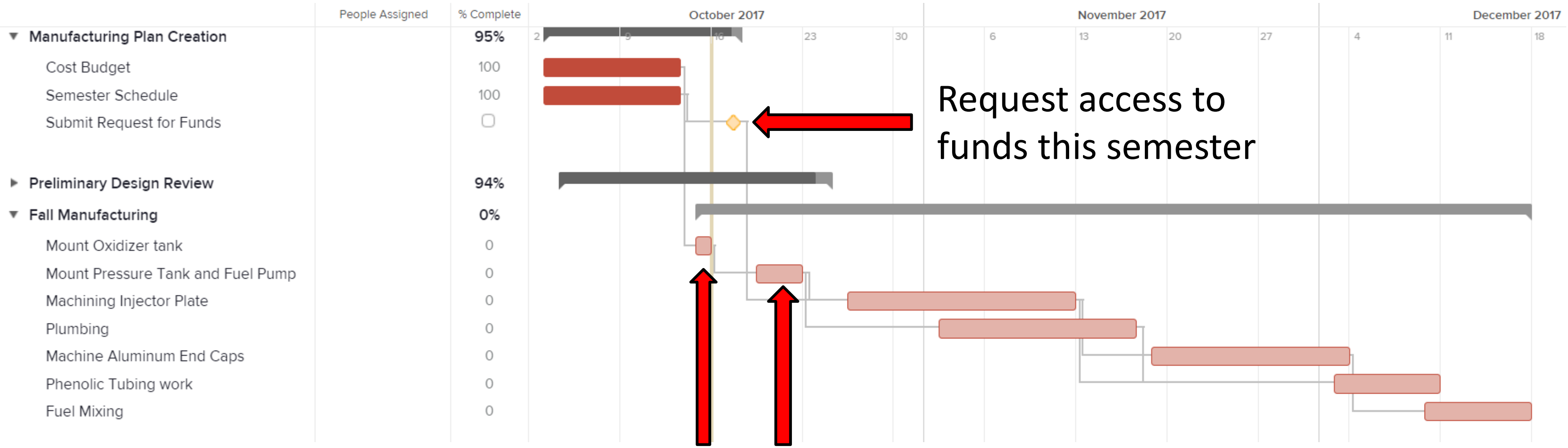
Key
Within Budget
Within Budget w/ EEF
Out of Budget

Total Budget

	One Rocket (low)	Two Rockets (low)	One Rocket (high)	Two Rockets (high)
Level 1 (donations)	$3,789	$4,524	$3,969	$4,884
Level 2 (donations)	$5,489	$6,224	$5,669	$6,584
Level 3 (donations)	$5,989	$6,724	$6,169	$7,084
Level 1	$7,130	$7,865	$7,310	$8,225
Level 2	$8,530	$9,265	$8,710	$9,625
Level 3	$11,345	$12,080	$11,525	$12,440


People Assigned
% Complete
September 2017
October 2017
4
11
18
25
2
9
16
CDD Submission
Preliminary Design Review Rev 2
100%
PDD Feedback Review
100
PDD Rework
100
PDD Rev 2 Submission
Manufacturing Plan Creation
95%
Preliminary Design Review
94%
Critical Project Elements Deteremined
100
Basic Test Stand Design Development
100
PDR Submission
PDR Presentation
Fall Manufacturing
0%
Critical Design Review
0%
CDR Work
0
PDR Presentation

Risk Mitigation - Fall Manufacturing



Request access to funds this semester

Can complete these steps with basic prototypes using currently available materials

CPE 2: Data Acquisition and Analysis System

OLAGAPPAN CHIDAMBARAM

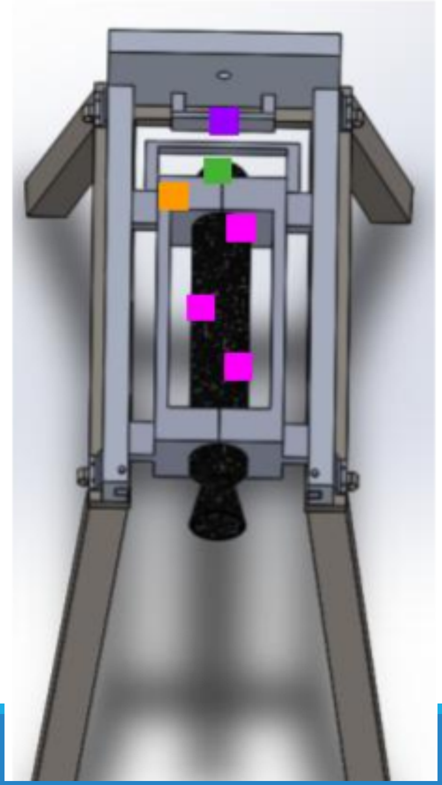
Premise

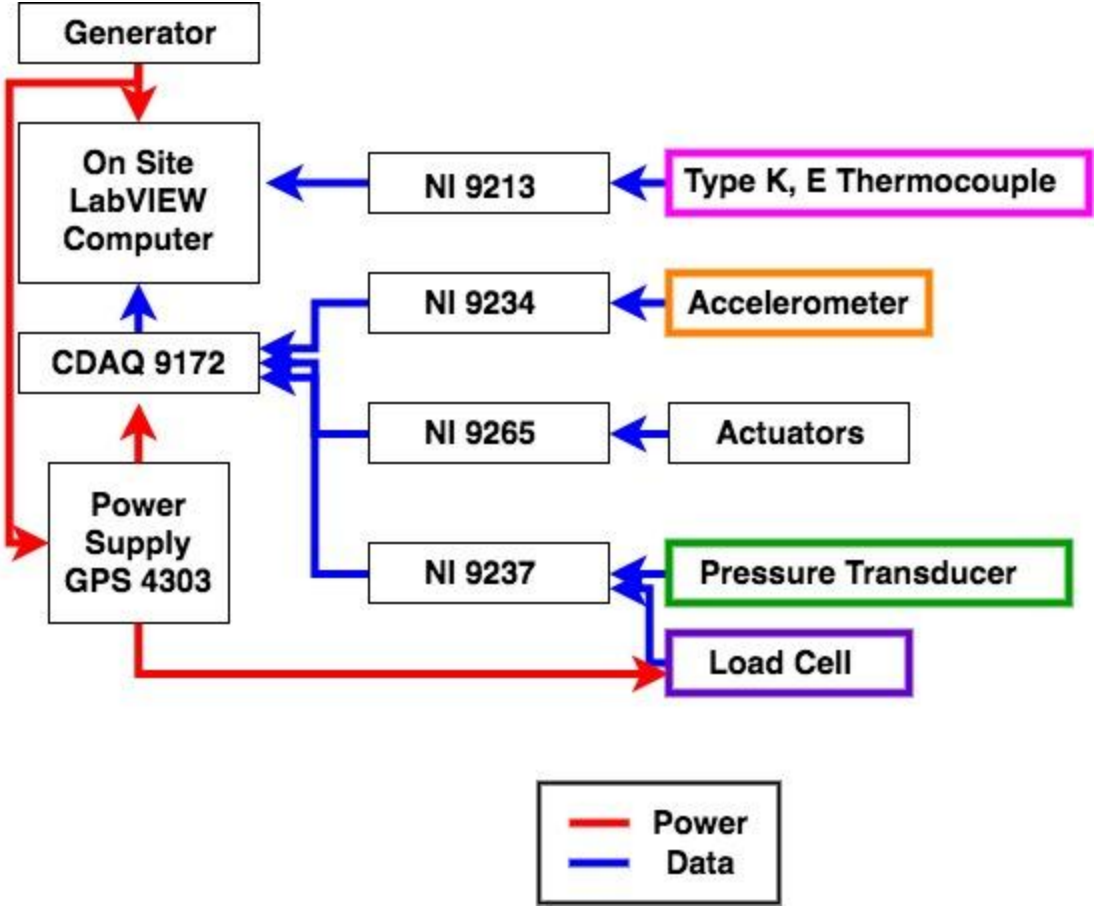
Why is the Data Acquisition and Analysis System a CPE?

1) HICKAM is only effective with the use of the sensor system otherwise there would not be data to characterize the hybrid rocket engine.

2) HICKAM requires the use of several sensors and a DAQ which are not only very expensive but require significant software integration.

Electronics Package

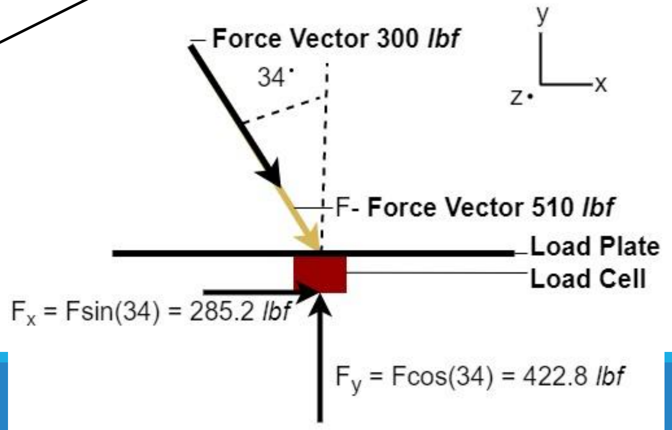




Load Cell Feasibility

	Level 1 Success		Level 2 Success	
Force Sensor Requirement	**1x - Single Axis Button Load Cell**	**Feasibility Verification**	**1x - Single Axis Pancake Load Cell**	**Feasibility Verification**
Load Cells must endure non-nominal thrust vectoring	•No side load tolerance	✖	•Side load tolerance > 300 *lbf*	✔
Load cell must be compatible with NI 9237-4 DAQ	•Verified compatible	✔	•Verified compatible	✔
Must endure at least 510 lbf of normal force (FOS = 1.7)	•1000 lbf rating	✔	•1000 lbf rating	✔

Fulfills Design Requirement 4.4	✔



Combustion Chamber Pressure Sensor Feasibility

Sensor Requirement	Pressure Transducer	F.	Strain gauge	F.
Must measure combustion pressure of maximum 600 psi.	Pressure range 0 - 1000 psi.	✔	Measures strain, so no pressure limitations.	✔
Tested method for combustion chamber pressure acquisition	Has been successfully used by MACH SR-1 team in 2008.	✔	Has not been successfully used on hybrid rocket engines. Chamber pressure is complicated and inaccurate to derive.	✖
Must be compatible with the CDAQ 9172 system	Compatible with CDAQ 9172 system	✔	Compatible with CDAQ 9172 system.	✔

Fulfills Design Requirement 4.1	✔

Fulfills Design Requirement 4.2	✔

Thermocouples Feasibility

Temperature Sensor Requirements	Thermocouple Type K	Feasibility Verification
Rated for temperatures at least 1220 °F	Rated max temperature 2370 °F	✔
	Thermocouple Type E	
Rated for operating temperatures below 30 F to measure feed lines temperature	Used in cryogenic applications, down to -435 F	✔
	Both types	
High sensitivity and resolution	Resolution: 40 μV per degree Celsius Range: 0 - 56 mV	✔
Compatible with NI 9213 DAQ interface	Both types are verified to be compatible with NI 9213 interface	✔

Mass Flow Meter Feasibility

Mass Flow Meter Requirements	Mass Flow Meter	Feasibility
Shall reliably measure oxidizer flow rate	Successfully used to measure oxidizer flow rate in Mach-SR1 2006	✔
Shall cost less than $1000	New costs more than $5000. Used available for $500	X

NOT FEASIBLE

Accelerometer feasibility

Acceleration Sensor Requirements	Accelerometer	Feasibility
Be able to endure high temperatures while being attached to injector housing during ignition.	Temperature range -40 F -> 250 F.	Main purpose for injector acceleration sensor is measuring source shock. During burn start, injector temp is within the range.
Price below $100 each (Acquire x4)	Price range is $6-$35	✔
Compatible with NI 9234 interface	Verified to be compatible with NI 9234 interface	✔

Fulfills Design Requirement 4.5	✔

Design Requirements Fulfilled

DR	Description	Feasibility
4.1	The pressure sensor shall take measurements of combustion chamber pressure.	✔
4.2	The nozzle temperature sensor shall be able to endure hot-fire conditions.	✔
4.3	The HICKAM package shall include device to measure pre-burn mass of the rocket engine.	✔
4.4	The force sensor shall take measurements of the test article thrust during hot-fire test.	✔
4.5	The acceleration sensors shall take measurements of structural vibration and source shock.	✔

CPE 3: Securing Test Facility and Meeting Facility Requirements

HALEIGH FLAHERTY

Premise

Why is securing a test facility a CPE?

1) Without a test location, we cannot run a cold flow or a hot fire test, reducing the mission success to level 1 immediately.
2) Test facility guidelines drive design and protocol requirements.

Platteville Location (Primary Site)

Description:

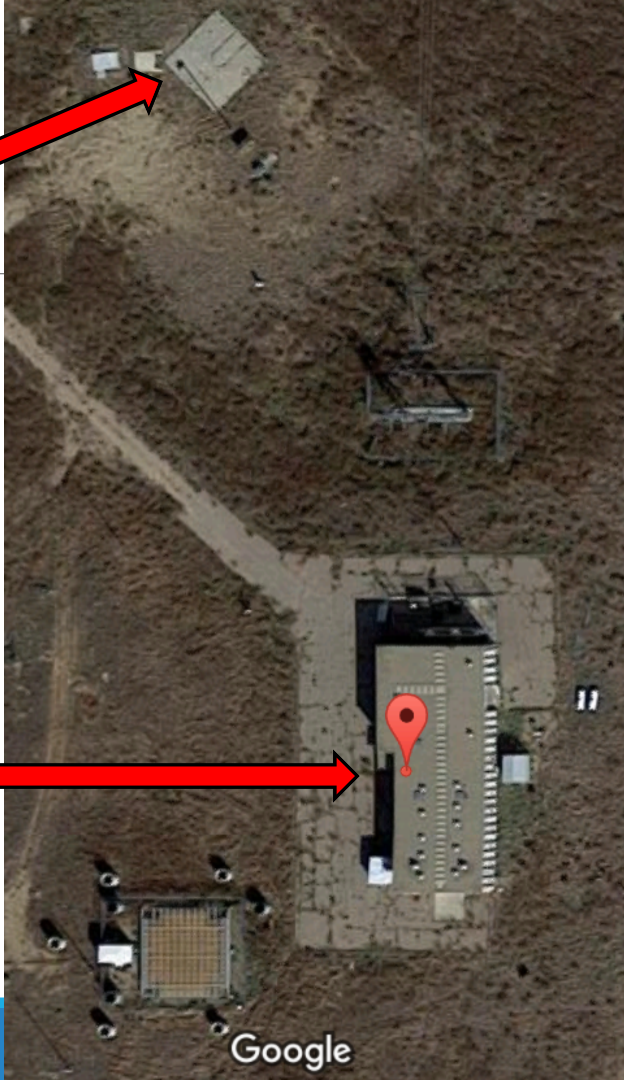
- Already available for a cold fire test
- Open sight, available for several day use

Provided Facilities:

- Power
- Possibly a shelter location
  - Budgeting for a blast shield just in case

Progress:

- Support from Platteville Fire Department
- Waiting on approval from NOAA on hot fire test



Front Range (Backup Site)

Description:

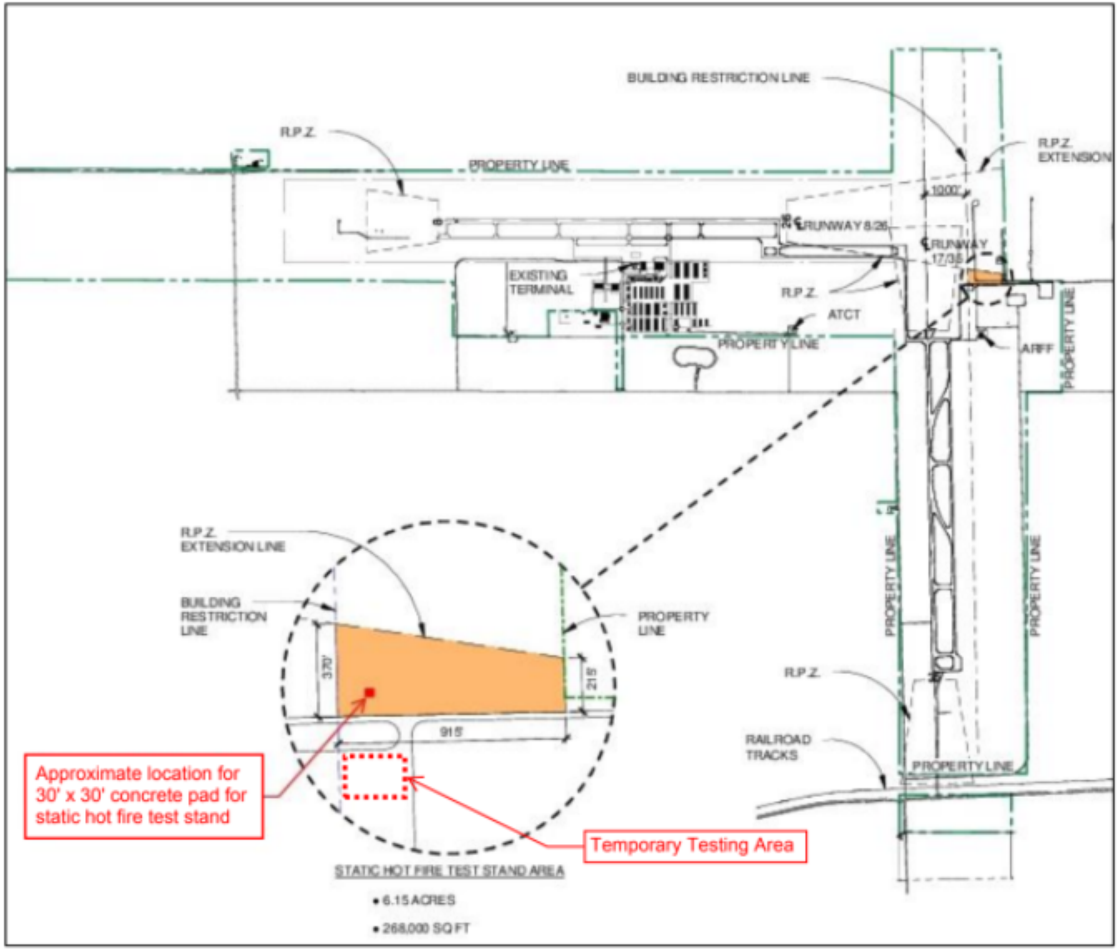
- Mobile Test stand limit 500 lbf
- Free for the first day of use, then $300/day charge

Required to Provide:

- Power
- Bunker/Safety shield
- Free suppressant system

Progress:

- Filled out initial paperwork, waiting on follow up



Front Range Airport
5200 Front Range Parkway
Watkins, CO 80137

CPE 4: System Validation using Computational Modeling

NATE O'NEILL

Premise

Why is system validation using computational modeling a CPE?

1) We need to prove that our sensor package can provide the end user with the information we want to provide.

2) We need to predict the test article performance to categorize the accuracy of our sensor measurements.

3) We need to ensure that our test stand can endure the structural loading placed on it by the rocket.

Directly Measured Data

- Instantaneous thrust data via load cells
- Time of Source Shock via accelerometers
- Chamber Pressure via a pressure transducer
- External Chamber and Nozzle Temperature via external thermocouples
- Oxidizer flow rate via mass flow meter
- Engine mass via a scale

Derived data

- Total impulse via thrust data
- Specific impulse via thrust data
- Internal nozzle temperature via external nozzle temperature
- Maximum thrust, thrust delay, and thrust duration via thrust data
- Oxidizer flow temperature via external thermocouple data
- Rate of fuel regression using combustion chamber pressure and oxidizer flow rate

Sensor Validation

How are we going to get useful information from our sensor selections?

- Thrust - Measure force using load cell
  - Average Thrust, Peak Thrust derived from data
- Burn Time - Use accelerometer to measure when source shock occurs, which corresponds to burn time = 0 s.
- Total Impulse

$$I_t = \int_0^{t_b} F dt = \bar{F} t_b$$

Integrate the thrust data where t_b is the burn time.

- Average Specific Impulse

$$I_{sp_{avg}} = \frac{\bar{F}}{\dot{m} g_0} = \frac{I_t}{m g_0}$$

Using the average thrust and a mass flow rate or the total impulse and the mass of the fuel.

Sensor Validation Continued

- Combustion Chamber Pressure - Use pressure transducer
  - Average, Peak pressure derived from data
- Chamber to Atmospheric Pressure Ratio

$$\frac{P_c}{P_a} = \frac{\bar{P}_c}{P_a}$$

Ratio of average chamber pressure and atmospheric pressure on test day.

- Average Burn Rate

$$\text{Burning Rate} = r = a(\bar{P}_c)^n$$

"a" and "n" are solid fuel constants. $\bar{P}_c$ = average combustion chamber pressure

- Average Mass Flow Rate

$$\bar{\dot{m}} = \frac{w g_c}{t_b g_0}$$

w = fuel weight, g_c = newton's constant, t_b = burn time, g_0 = grav. acc.

Sensor Validation Continued

- Characteristic Velocity

$$C^* = \frac{\bar{P}_c A_t g_c}{\bar{\dot{m}}}$$

A_t = throat area

- Coefficient of Thrust

$$C_F = \frac{\bar{F}}{\bar{P}_c A_t}$$

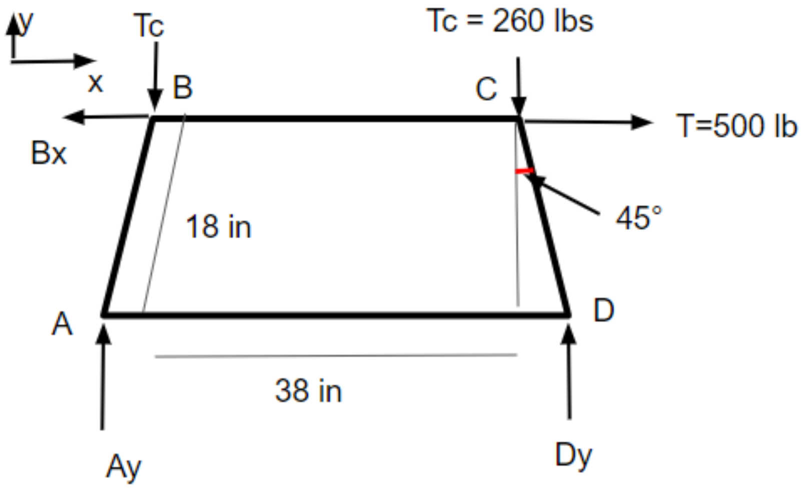
$\bar{F}$ = average thrust

- Effective Exhaust Velocity

$$C = I_{sp_{avg}} g_0$$

- Nozzle Temperature
  - External Surface Temperature measured directly from thermocouple.
  - Internal Surface Temperature derived using steady heat equation and burn time.

Test Stand Strength Estimation



$$d = \sqrt{\frac{F_{DC} S_F}{2\tau_{fail}}} \qquad d_{bolt} = \sqrt{\frac{4 P S_F}{\pi \tau_{fail}}}$$

Summing forces and moments equal to zero

- Ay = 149.1715 lbf, Bx = 500 lbf
- Dy = 370.8284 lbf

Method of Joints Yielded

- F_{AB} = 210.9604 lbf (C)
- F_{AD} = 149.1715 lbf (T)
- F_{CB} = 179.91 lbf (T)
- F_{DC} = 367.696 lbf (C)

Ductile AL Alloy Diameter (rectangle) for 370 lbs

- d ≥ 0.9617 in (SF of 100)

Zinc bolt diameter for single shear plane of 370 lbs

- d ≥ 0.3898 in (SF of 10)

Chamber Pressure Prediction

- Combustion Chamber Pressure

$$P_c = \left(\frac{a \rho_f C^*}{gc} \frac{A_b}{A_t} \right)^{\frac{1}{1-n}}$$

"*a*" and "*n*" are solid fuel constants. ρ_f= solid fuel density. *C**= characteristic velocity. A_b= Burn Area. A_t = throat area.

- Characteristic Velocity

$$C^* = \frac{\sqrt{R g_c T_c}}{\Gamma}$$

R = specific gas constant. T_c= combustion chamber temperature.

- Simplifier Term

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

γ= specific heat ratio

Thrust Prediction

- Thrust

$$T = C_{Fi} P_c A_t$$

- Ideal Coefficient of Thrust

$$C_{Fi} = \Gamma \sqrt{\frac{2\gamma}{\gamma - 1}\left[1 - \left(\frac{p_e}{p_c}\right)^{\frac{\gamma-1}{\gamma}}\right]} + \left(\frac{p_e}{p_c} - \frac{p_a}{p_c}\right)\frac{A_e}{A_t}$$

Subscript e indicates nozzle exit, subscript a indicates atmospheric.

Model Results and Comparison

Using various parameters (given in detail in Appendix), the chamber pressure and thrust were found to be: $P_c = 395 \text{ psia}$ $T = 232.7 \text{ lbf}$

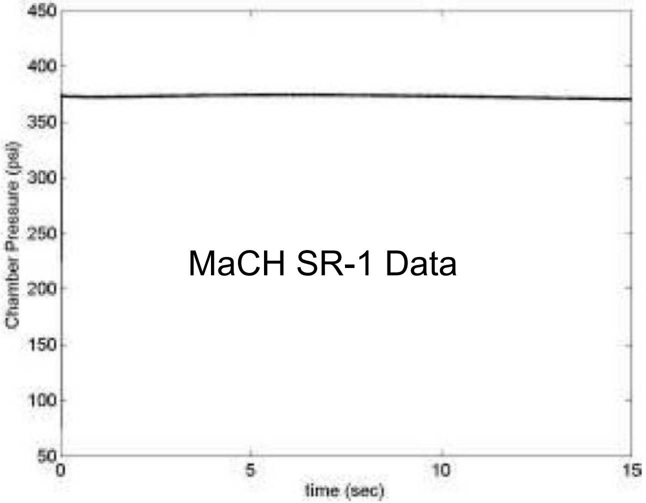


Figure 2: Chamber Pressure vs. Time

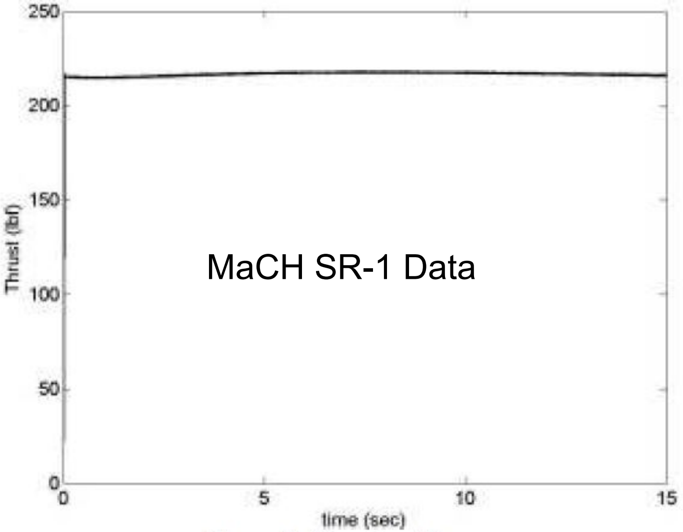
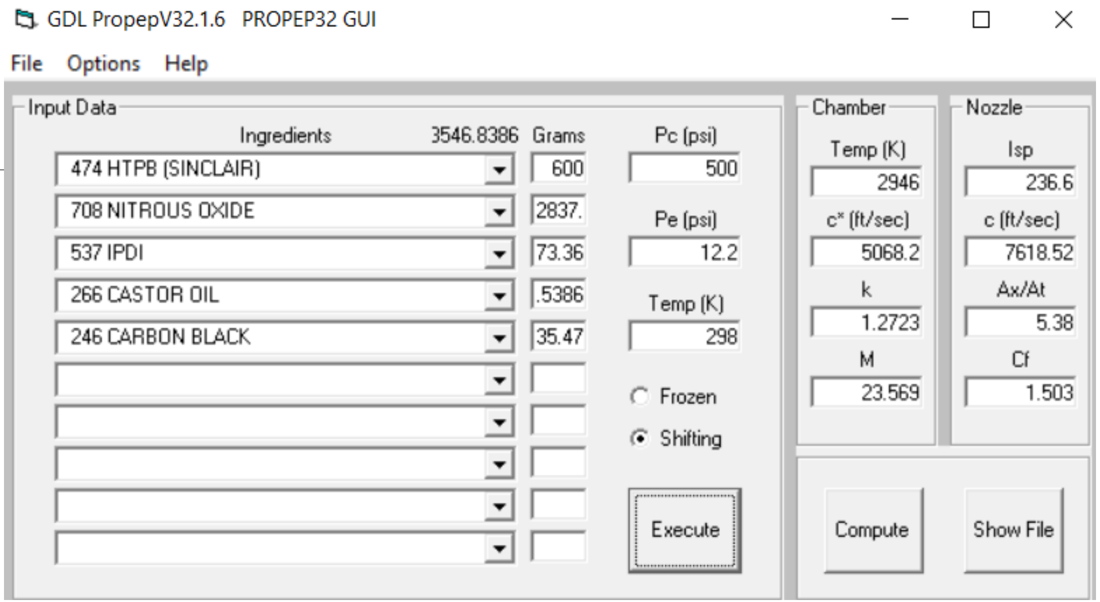


Figure 3: Thrust vs. Time

GDL ProPEP Software Values

- GDL Input Values:
  - Fuel Ingredients
  - Mass of each ingredient
- GDL Output values:
  - Chamber Temperature
  - Characteristic Velocity
  - Ratio of Specific heats
  - Effective Exhaust Velocity
  - Molar Mass
  - Coefficient of Thrust
  - Ratio of exit and throat area
  - Isp
- Use to compare simpler models to.



Fulfills Design Requirement 7.1, 7.2, 7.3	✔

Test Article Performance Prediction

- Predictive Model Assumptions:
  - Baseline Model: MaCH SR1 05-06
    - Blow-down
      - No vaporization
      - No change in temperature
    - Ideal gas for combustion
    - N20 is isothermal
    - Pressurant does not dissolve in N20 liquid
    - Adiabatic System
    - One-phase Flow
    - N20 Properties are constant
    - No throat regression
    - Static ambient conditions
    - Turbulent boundary layer in chamber
    - Chamber Mach < 0.3
    - Isentropic expansion in the nozzle

CPE 5: Proper Manufacturing of the Test Stand and the Rocket Engines

SAVANT SUYKERBUYK

Premise

Why is Proper Manufacturing Procedures a CPE?

1) Improper manufacturing can lead to improper testing conditions or destruction of the rocket and test stand.
2) Improper manufacturing of the plumbing system can lead to dangerous leaks or pressure distribution that can lead to failure.
3) Careful planning of manufacturing schedule is required to avoid not being able to produce the test articles or the test stand itself.

Rocket Baseline Structure: MaCH-SR1 2005-2006

Precision Manufacturing for Safety and Failure Prevention:

- SolidWorks drawings and past procedures have been reviewed and are ready to be used for manufacturing.
- Main Combustion Chamber: Procedures and materials are available and reviewed.
- End caps, Nozzle, and Injector Plate: Drawings are available and have been reviewed.

Rocket Fuel Baseline: MaCH-SR1 2005-2006

Consumables:

- Rocket Fuel: Recipe and procedures have been reviewed.
- Oxidizer: Purchased from Airgas through Matt Rhode
- Purging material: Nitrogen, purchased from Airgas through Matt Rhode

Rocket Plumbing Baseline: MaCH-SR1 2005-2006

- Plumbing schematic from MaCH SR-1 ‘05-’06 will be used as a baseline.
- Plumbing schematic will be modified to accommodate for structural differences between HICKAM and MaCH SR-1 test stands.
- Oxidizer tank and pump recycled from legacy projects.

Test Stand Baseline: Horizontal Configuration

Fulfills DR 2.1, 2.2, & 3.1	✔

- Legacy work available to be modified for greater portability and modularity to meet customer requirements.
- Major components will be made from aluminum and steel.
- Test stand drawings prove machinability.
- Manufacturing schedule for main test stand components to be performed in Spring 2018.

Fulfills DR 1.1 & 1.2	✔

Manufacturing Scheduling

Early Manufacturing Timing and Planning

- Manufacturing begins week of 15/OCT/2017.
- One test article will be completed before the end of the Fall.
- Beginning with cheapest components needed for level 2 objectives (cold flow test) to have least impact on budget and meet mission success; awaiting price quote for certain components.

Design Requirements Fulfilled

DR	Description	Feasibility
1.1	Device is designed to be easily assembled and disassembled, ensuring portability	✔
1.2	Small design and modularity allows for movement without special equipment (carried by hand)	✔
2.1	Test stand allows for multiple securing methods, including ground anchors in concrete	✔
2.2	Test stand can also be secured to padeyes through chains at specific attachment points	✔
3.1	Test stand isolates single dimension of freedom, ensuring accurate single-axis thrust readings	✔

CPE 6: Safety Protocols and Methods

BRIAN ORTIZ

Premise

Why is safety a CPE?

1) Human safety must be prioritized when dealing with combustibles and rocket engines to prevent harm to equipment or personnel, up to and even including death.

2) The use of thorough testing and manufacturing safety protocols ensures careful development and rocket testing, leading to an increased chance of success and reduces risk of injury to personnel.

Ensuring Human Safety

- Personnel
  - RSO and AHJ
  - Group familiar with NFPA guidelines
- Testing Facility
  - Meet NFPA or AHJ standards
  - Blast shield and remote control
- Testing
  - Meet NAR and NFPA testing standards
  - Create testing procedures based off CPIA and NAR procedures
- Failsafes
  - Automated
  - Used in case of hangfire, misfire, or catastrophic failure
- Cold Flow Test
  - Procedure run through
  - Test all integrated parts work properly
- Transportation
  - Rocket motor components transported in separate containers
  - Pressurize gas at testing facility
- Manufacturing
  - Manufacturing procedures for certain materials
  - Consider other group's development needs
- Storage
  - Motor stored in lock box away from heat sources
  - Test stand components also locked away
- Component Testing
  - Operationally test expected stresses on single components
  - Test plumbing and failsafe procedures

Design Requirements Fulfullied

DR	Description	Feasibility
9.1	The control system shall determine if hangfire or misfire occurred.	✔
9.2	The control system shall notify user if hangfire or misfire occurred.	✔
9.3	In case of hangfire, the control system shall be able to purge all fire from the engine.	✔

Status Summary

HALEIGH FLAHERTY

Off Ramps

Failure Mode	Likelihood	Off Ramp
Over Budget	High	•Borrow ITLL equipment •Reduce to 1 rocket motor
Time budget of manufacturing process exceeded	High	•Reduce to Level 1 test stand rocket •Reduce to 1 rocket motor
NOAA does not approve hot fire at Platteville	Medium	•Go to Front Range facility
Rocket Failure	Medium	•Simulate loads using weights and heat
Inaccurate validation model	Low	•Compare with MaCH-SR1 data results

Status Summary and Strategy for Conducting Remaining Studies

- Horizontal test stand design
  - Direct measurements of thrust, mass, nozzle temperature, oxidizer flow rate
  - Derived burn time, Isp, total impulse, peak thrust, fuel rate regression, ignition shock, oxidizer temperature.
  - Modular, light, easy-to-use. Characterizes the most important elements of the engine from systems perspective.
- Start manufacturing the test articles during October 2017
- Develop design for the test stand
  - SolidWorks modelling of structural components.
  - Software development for DAQ, and control system.
  - Preliminary data analysis software development.
- Material acquisition

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Thank you! Any Questions?

Appendix 1: Design Requirements

Design Requirements

Parent FR's	Design requirements
FR 1	**1.1** The disassembled HICKAM shall fit into a 5ft x 3ft x 2ft storage container. **1.2** The storage container with HICKAM shall allow it to be lifted by 6 people or less with 70 lbf per person (OSHA Standard).
FR 2	**2.1** The HICKAM test stand structure shall secure to paved surfaces without padeyes by use of ground anchors. **2.2** The HICKAM test stand structure shall secure to paved surfaces with padeyes by use of structural supports.
FR 3	**3.1** The HICKAM test stand shall restrict movement of the test article such that measurements of load in the direction of thrust are obtained.
FR 4	**4.1** The pressure sensor shall take measurements of combustion chamber pressure. **4.2** The nozzle temperature sensor shall be able to endure hot-fire conditions. **4.3** The HICKAM package shall include device to measure pre-burn mass of the rocket engine. **4.4** The force sensor shall take measurements of the test article thrust during hot-fire test. **4.5** The acceleration sensors shall take measurements of structural vibration and source shock.
FR 5	**5.1** Data and power lines shall not get hotter than 60% of their melting point during the hot fire test. **5.2** DAQ shall acquire the data at least at 2 kHz sampling rate.

Design Requirements

Parent FR's	Design requirements
FR 6	**6.1** The length of power and data lines shall be at least 100 yards. **6.2** HICKAM static fire systems, safety systems, and data acquisition systems shall acquire the power from an isolated source located next to computer system.
FR 7	**7.1** The data analysis software shall convert and calibrate sensor measurements (in V) into data with appropriate units. **7.2** The data analysis software shall derive Isp, total impulse, burn time, maximum thrust, and vibration profile from the converted and calibrated measurements. **7.3** The data HICKAM module 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.
FR 8	**8.1 - 8.5** Time and workload limitations for installation and dismantling of HICKAM subsystems are described in design requirements 8.1 - 8.5.
FR 9	**9.1** The control system shall determine if hangfire or misfire occurred. **9.2** The control system shall notify user if hangfire or misfire occurred. **9.3** In case of hangfire, the control system shall be able to purge all fire from the engine.

Appendix 2: CPE 2

DAQ hardware

Compact DAQ

- CDAQ 9172

DAQ modules

- NI 9237- 4 channel Strain and Load Cells module
- NI 9211-4 channel Thermocouple module
- NI 9213-16 channel Thermocouple module
- NI 9265-4 channel Actuator module
- NI 9234-4 channel Accelerometer module
- NI 9401-8 channel counter module (for mass flow rate sensors)

Power Supply

- GPS-4303 - borrow from Trudy

DAQ Specifications

DAQ modules	Specifications
NI 9237- 4 channel Strain and Load Cells module	•4 channels, 50 kS/s to 1.613 kS/s •±25 mV/V input range •24-bit resolution
NI 9211-4 channel Thermocouple module	•4 TC, ±80 mV •24 Bit, 14 S/s Aggregate
NI 9213-16 channel Thermocouple module	•16 TC,±78 mV •24 Bit, 75 S/s Aggregate
NI 9265-4 channel Actuator module	•4 channels, 100 kS/s per channel simultaneously analog output •0 mA to 20 mA output range, 16-bit resolution
NI 9234-4 channel Accelerometer module	•4 AI, ±5 V, 24 Bit, 51.2 kS/s to 1.652kS/s Simultaneous, AC/DC Coupling, IEPE AC Coupling
NI 9401-8 channel counter module(for mass flow rate sensors)	•8 DIO, 5 V/TTL, Bidirectional, 100 ns, 30 MHz to 5 MHz signal switching frequency

Experiment for Feasibility DAQ

- The NI 9213 module was tested for accuracy in speed, with a CDAQ 9171.
- The test was done for 1-3 thermocouples at the maximum rate of 75 S/s, for 750 test samples, the measured data rate is given below.

Test number	1 thermocouple	2 thermocouples	3 thermocouples
#1	75 S/s	75 S/s	75 S/s
#2	75 S/s	75 S/s	75 S/s
#3	75 S/s	75 S/s	75 S/s

Trade Study: Pressure Transducer vs. Strain Gauge

The combustion chamber effectively has 4 layers: 3 structural layers and the fuel. In order to back out chamber pressure, we have to know how the stress caused by the combustion propagates through each layer of the cylinder, but the fuel changes non-linearly with respect to both time and x-location along the chamber, as seen here:

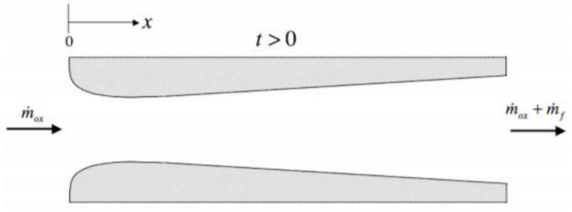

Figure 11.15: *Typical port shape at the end of a burn for* $m > 0$.

Consequently, because we have no information regarding the fuel regression, deriving combustion chamber pressure using strain gauges is not possible.

2008 Mach SR-1 obtained combustion chamber pressure measurements using a pressure transducer placed just downstream of the injector plate.

Thermocouples for Fuel Regression (Not Feasible)

- Concept: Spaced thermocouples embedded in the fuel grain break when flame reaches them, yielding rate of fuel regression
- Past Work: 2004-2005 MaCH-SR1
- Problem: Conduction heat transfer rate overtakes rate of combustion
  - Flame temperature is 5530 ºF
  - K-type thermocouple maximum temperature is 2300 ºF
- Potential Fix: Use eroding thermocouples
- Problem: Expensive and still not reliable

Pressure Transducer

- Pressure Range: 0 - 1000 psi
- 0 - 5 V_dc Output
- Cost: $245
- DAQ Module: NI 9237
- Location: Downstream of the injector plate assembly; no composite drilling required.
- Used by 2008 Mach SR-1
  - Successfully measured combustion chamber pressure

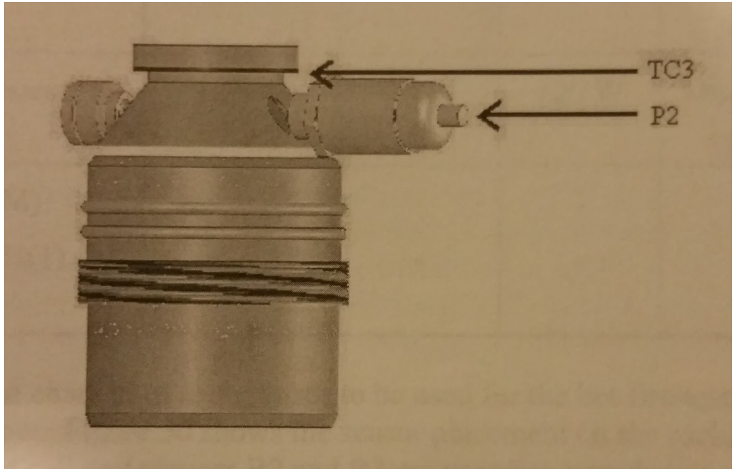

Figure 31: Close-up of Injector Housing

Thermocouples for Fuel Regression

- Concept: Spaced thermocouples embedded in the fuel grain break when flame reaches them, yielding rate of fuel regression
- Past Work: 2004-2005 MaCH-SR1
- Problem: Conduction heat transfer rate overtakes rate of combustion
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  - K-type thermocouple maximum temperature is 2300 ºF
- Potential Fix: Use eroding thermocouples
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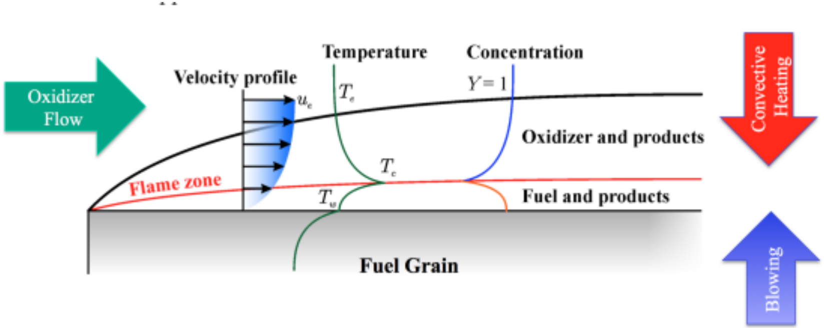


Thermocouples used to Characterize Rocket

- 3 type K thermocouples for the combustion chamber.
- 3 type K thermocouples on the nozzle.
- 2 type E thermocouples to measure state of oxidizer in feed lines.
- Type K thermocouples function at up to 2370 °F, higher than the melting point of aluminum at 1220 °F. Carbon Fiber begins burning at around 930 °F
- Type E thermocouples are typically used for cryogenic purposes, and have been used in previous projects for this purpose.

Mass Flow Meter

- Micromotion Flow Meter
  - Measures flow rate of oxidizer, a level 3 requirement
- Cost ~ $5000
  - ITLL doesn't want it next to rocket
  - Used $500
- NI- 9401-8 DAQ Module
- Not feasible due to cost
  - Looking at buying one used

Accelerometers for Full Vibration Analysis

- Used to measure source shock and vibration
- Need to operate in temperatures ~700 ºF
- Charge Accelerometers
  - $500-$1000
- Lack of accurate vibration measurement with rocket being held down
- Not feasible due to cost

Appendix 3: CPE 3

Safety Bunker

- Sandbags
- Plywood holders and roof
- LEXAN Polycarbonate Sheet
- 4x4 Beams

Appendix 4: CPE 4

Exhaust Temperature

- NASA CEARUN software model
  - Exhaust temperature of ~3000K
- Level 3 objective
- Temperature Sensors
  - Range Max: 2732 F
  - Cost: >$1000
- Not Feasible

Test Article Performance Prediction

- Predictive Model Assumptions:
  - Baseline Model: MaCH-SR1 05-06
    - Blow-down
      - No vaporization
      - No change in temperature
    - Ideal gas for combustion
    - N_2O is isothermal
    - Pressurant does not dissolve in N_2O liquid
    - Adiabatic System
    - One-phase Flow
    - N_2O Properties are constant
    - No throat regression
    - Static ambient conditions
    - Turbulent boundary layer in chamber
    - Chamber Mach < 0.3
    - Isentropic expansion in the nozzle
    - N_2O is liquid when going into combustion chamber

Sensor Validation cont.

- Nozzle Temperature
  - External Surface Temperature provided directly from thermocouple.
  - Internal Surface Temperature derived using steady heat equation and burn time:

Due to nozzle symmetry, we need only consider the *one-dimensional* steady heat equation. The heat equation can then be stated as follows:

Find the temperature field in the nozzle such that the partial differential equation:

$$-\nabla \cdot (\kappa(r)\nabla T(r)) = f(r) \tag{9}$$

holds for every point inside the nozzle domain and the temperature boundary condition:

$$T(r) = g(r) \tag{10}$$

holds for the point on the boundary of the nozzle domain.

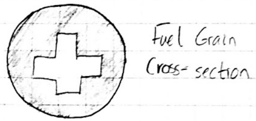
Above, T denotes the temperature field, κ denotes the thermal conductivity, f denotes the applied heating, and g denotes the fixed temperature field at the boundary of the domain (obtained from thermocouple measurements).

Thrust and Pressure Mode

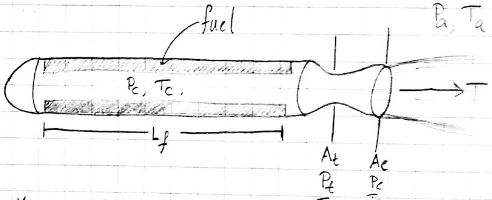
Given:

- Fuel Type
  - HTPB (600 g)
  - NO2 (2,837 g)
  - IPDI (73.36 g)
  - Castor Oil (0.5386 g)
  - Carbon Black (35.47 g)
- Atmospheric Pressure, Temperature
  - P_a = 12.2 psi
  - T_a = 278 K
- Fuel characteristics
  - a = 0.05 in/s
  - n = 0.2
  - ρ_f = 57.54 lbm/ft^3
  - L_f = 17.8 in
- Nozzle Info
  - A_t = 0.40 in^2
  - A_e = 2.494 in^2

Sketch:



Find: P_c, T



Assumptions:

- γ = 1.25, R = 8.314 kJ/kg·K
- Calorically Perfect Gas
- Isentropic Nozzle
- Density of oxidizer/fuel mixture after combustion is much less than density of solid fuel
- T_c = 3000°C (From Mach SR-1, Mattingly text)
- Linear Fuel Regression
- Perfectly expanded nozzle

Fundamental Equations:

$$P_c = \left(\frac{a \rho_f C^*}{g_c}\frac{A_b}{A_t}\right)^{\frac{1}{1-n}}$$

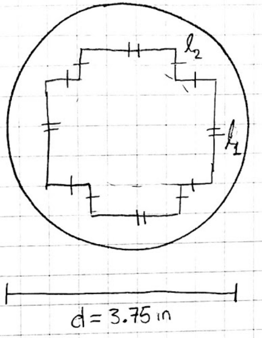
$$T = C_{Fi} P_c A_t$$

$$C^* = \frac{\sqrt{R g_c T_c}}{\Gamma}, \quad \Gamma = \sqrt{\frac{\gamma}{\left(\frac{\gamma+1}{2}\right)^{(\gamma+1/\gamma-1)}}}$$

$$C_{Fi} = \Gamma \sqrt{\frac{2\gamma}{\gamma-1}\left[1-\left(\frac{P_e}{P_c}\right)^{\gamma-1/\gamma}\right]} + \left(\frac{P_e}{P_c} - \frac{P_a}{P_c}\right)$$

Solution:

→ Consider the following (more-detailed) sketch of the cross-section of the fuel grain:



l_1 = 1 in
l_2 = 0.5 in

Note: Data from testing suggests that after steady burn is reached, the combustion chamber pressure stays fairly constant. For this model, we assume some fuel burning has occurred, so we can further assume this point will provide a reasonable combustion chamber pressure.

Note: Values for a, n, R, and T_c were taken from Mattingly text as typical values. T_c came from HTPB flame temperature tables.

→ Calculate the Burn Area:

$$A_b = (8 l_1 + 4 l_2) \cdot L_f$$

$$= (8 \cdot 1\text{in} + 4(0.5\text{in})) \cdot 17.8 \text{ in}$$

$$= 178 \text{ in}^2 = 0.114838 \text{ m}^2$$

→ Calculate Characteristic Velocity:

$$C^* = \frac{\sqrt{R g_c T_c}}{\Gamma}, \quad \Gamma = \sqrt{\frac{1.25}{\left(\frac{2.25}{2}\right)^{(2.25/0.25)}}} = 0.6581$$

$$\hookrightarrow C^* = \frac{\sqrt{(112)(32.174)(5891.4R)}}{0.6581} = 7{,}001.3 \text{ ft/s} \approx 7000 \text{ ft/s}$$

→ Calculate P_c:

$$P_c = \left(\frac{(0.05)(0.0333)(7000)}{1}\left(\frac{178\text{in}^2}{0.4\text{in}^2}\right)\right)^{\frac{1}{1-0.2}} = \boxed{395.3 \text{ psia} = P_c}$$

From Page No. ___
To Page No. ___

Things we’re measuring/deriving

- Thrust (Average, Peak, Duration)
- Average Specific Impulse
- Total Impulse - derived from thrust and burn time
- Combustion Chamber Pressure (During Fire, Average, Peak)
- Burn Rate of Fuel? - derived from source shock and thrust readings
- Average mass flow rate - derived from burn time and propellant mass
- C^* (Characteristic Velocity) - derived from chamber pressure
- C_F (Coefficient of Thrust)- derived from chamber pressure
- C (Effective Exhaust Velocity)- derived from chamber pressure
- Pc/Pa- derived from chamber pressure
- Nozzle Temperature

Thrust and Pressure Model cont.

→ Calculate T:

$$T = C_{Fi} P_c A_t \quad , \quad C_{Fi} = \Gamma \sqrt{\frac{2\gamma}{\gamma - 1}\left[1 - \left(\frac{P_e}{P_c}\right)^{\gamma-1/\gamma}\right]} + 0$$

(Assuming perfectly expanded nozzle)

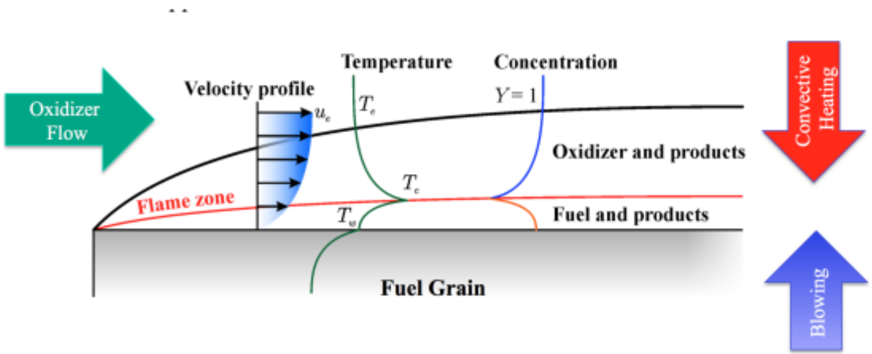
$$T = 0.6581 \sqrt{\frac{2(1.25)}{0.25}\left[1 - \left(\frac{12.2}{395}\right)^{0.25/1.25}\right]} \cdot 395 \cdot 0.4 = 232.7 \text{ lbf}$$

$$\boxed{T = 232.7 \text{ lbf}}$$

Regression Rate of Fuel and Mass Flow Rate

Method developed by Rajiv Kumar and P.A. Ramakrishna assuming choked flow

Requires combustion chamber pressure from the transducer, mass flow of the oxidizer given by the mass flow meter, and rocket and fuel geometries



$$C^*_{expt} = \frac{\bar{P}_c A_t \Delta t_0}{m_f + m_{ox}} \qquad \dot{m}_f = \frac{P_c A_t}{C^*_{expt}} - \dot{m}_{ox}$$

$$G_{ox} = \frac{4\dot{m}_{ox}}{\pi d_p^2} \qquad \dot{r} = \frac{\dot{m}_f}{\pi \rho_f d_p L_g}$$

Validate data using the same method with ideal values produced by GDL Propep

Derived Values from Mass Flow

Specific impulse

- Requires mass flow rate of the fuel
- Thrust

$$I_{sp} = \frac{T}{\dot{m}_{ox} + \dot{m}_f}$$

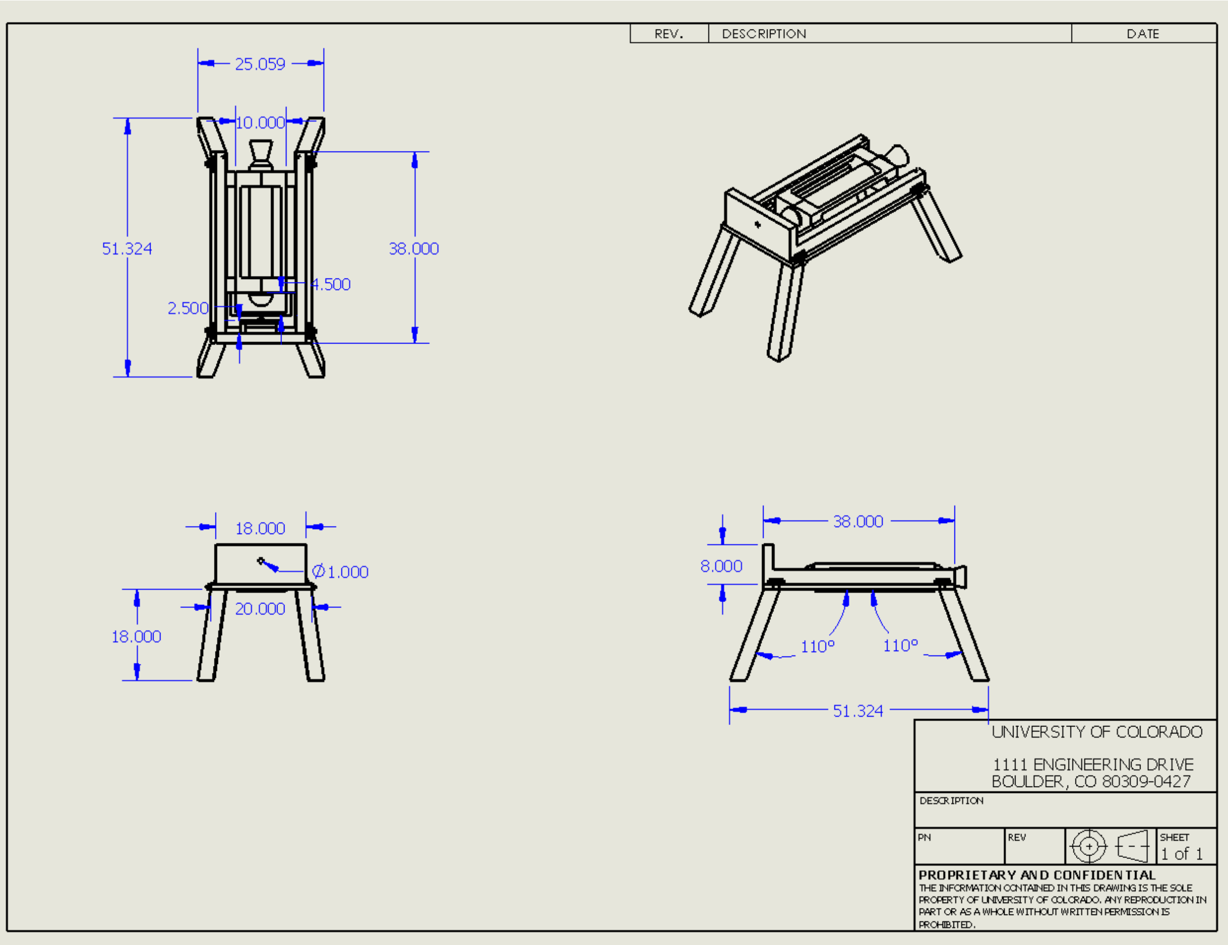
Port geometry estimates as fuel burns (Euler's Method)

- Derived regression rate of fuel
- Previous diameter

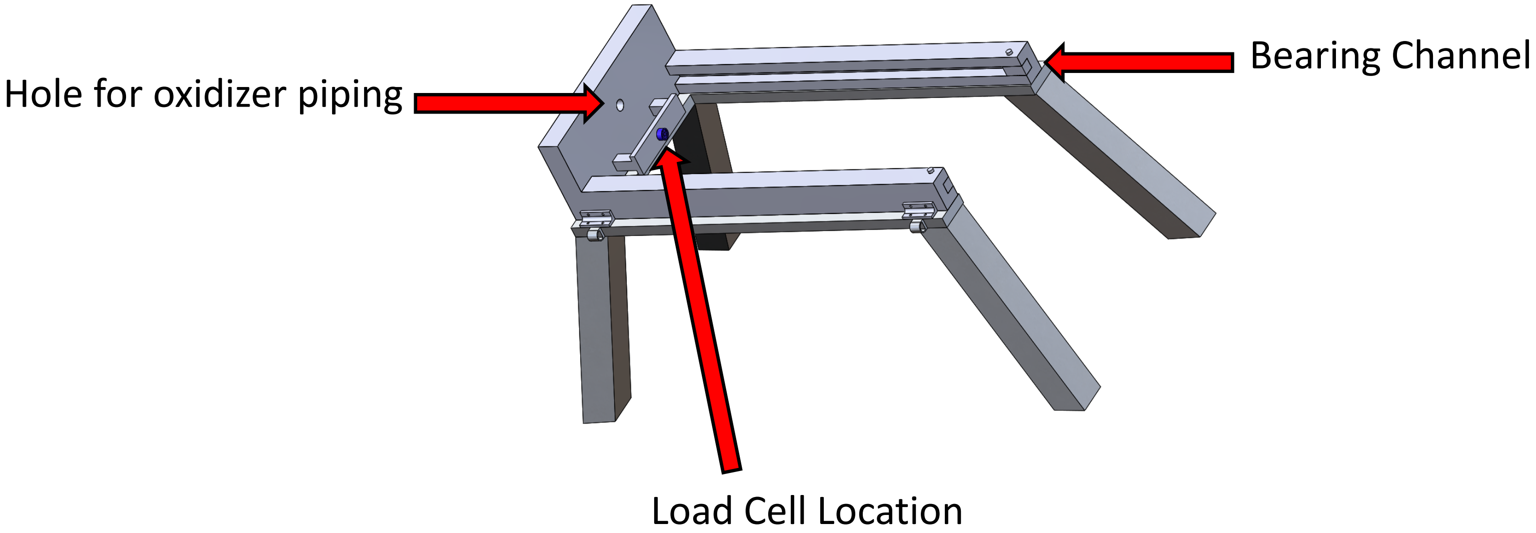
$$d_{p(i+1)} = d_{p(i)} + 2\dot{r}\Delta t$$

Appendix 5: CPE 5

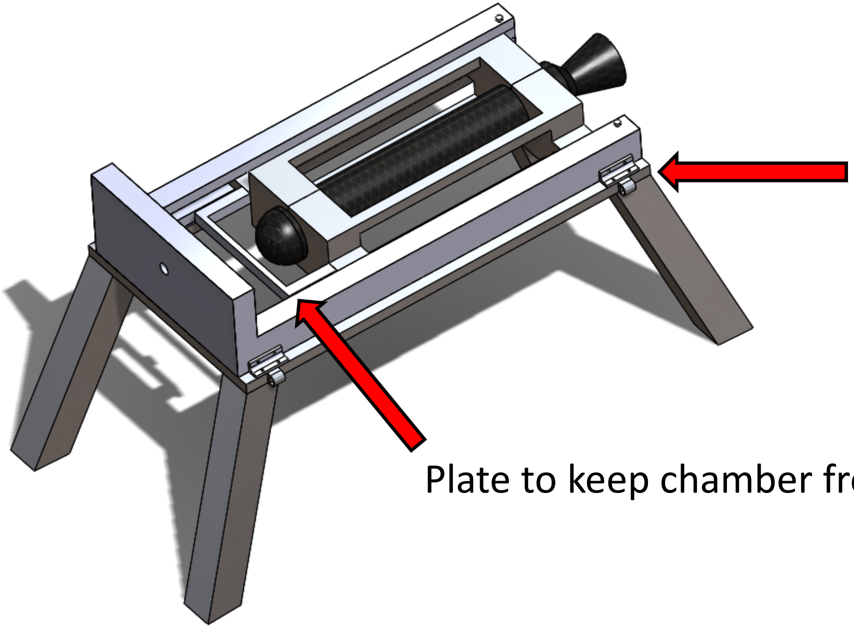
Dimensions for Horizontal Test Stand



Horizontal Test Stand Components



Horizontal Test Stand Components

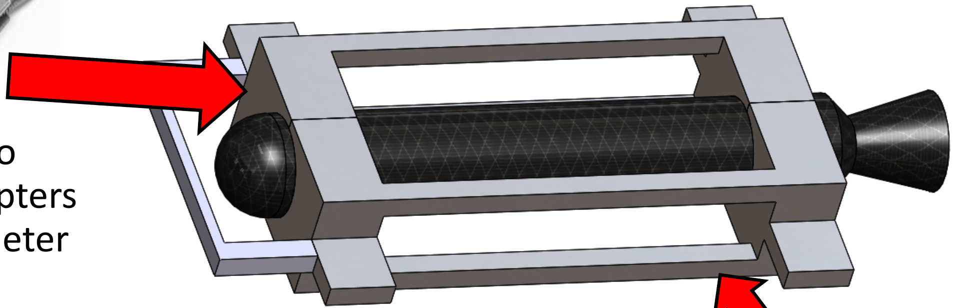


Rail mounting-rides on bearings for horizontal movement

Plate to keep chamber from hitting wall

Horizontal Test Stand Components

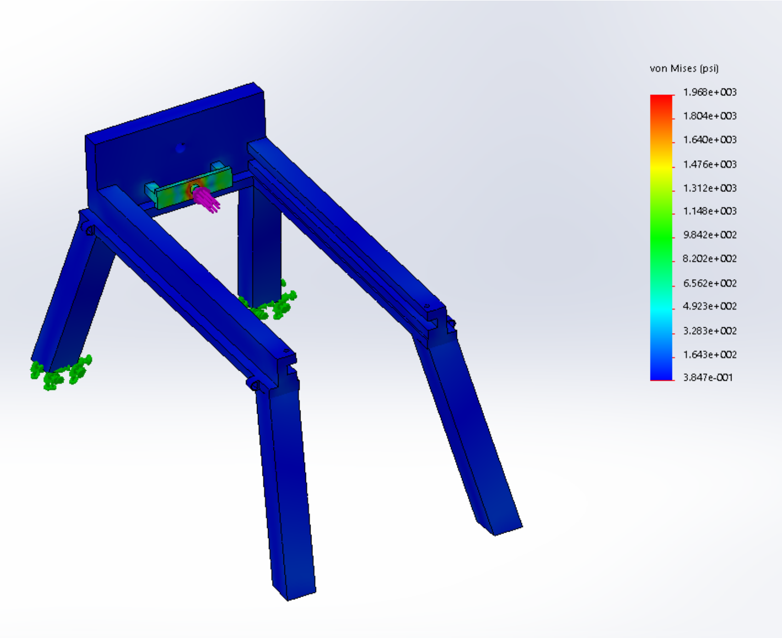
U-bolt Clamps- hold combustion chamber to maintain position. Adapters used for different diameter rockets

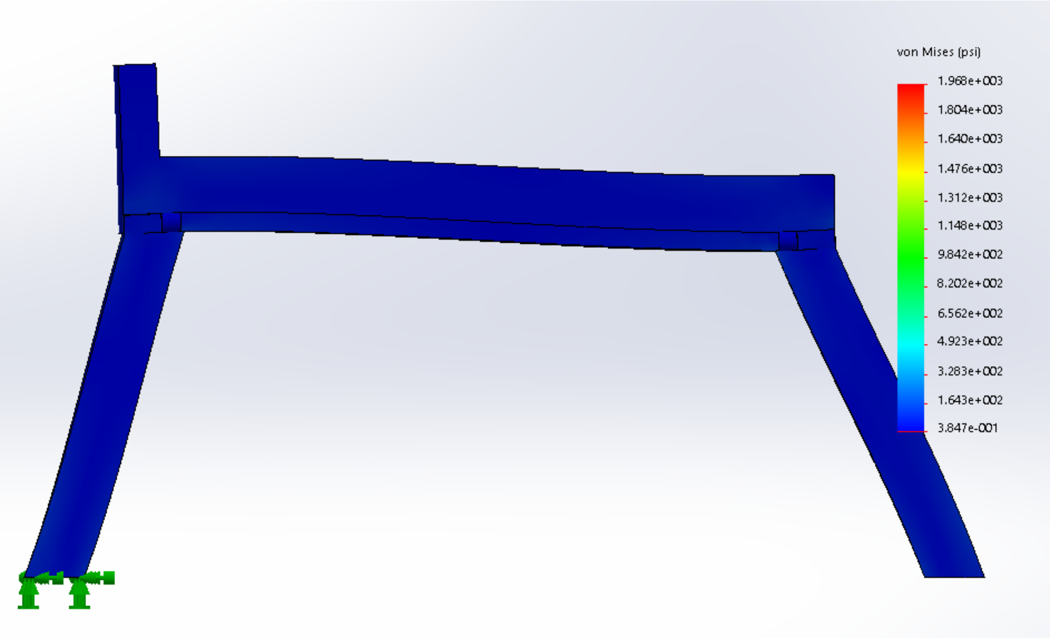


Rail mounting-rides on needle bearings for horizontal movement

Stress Test Simulation

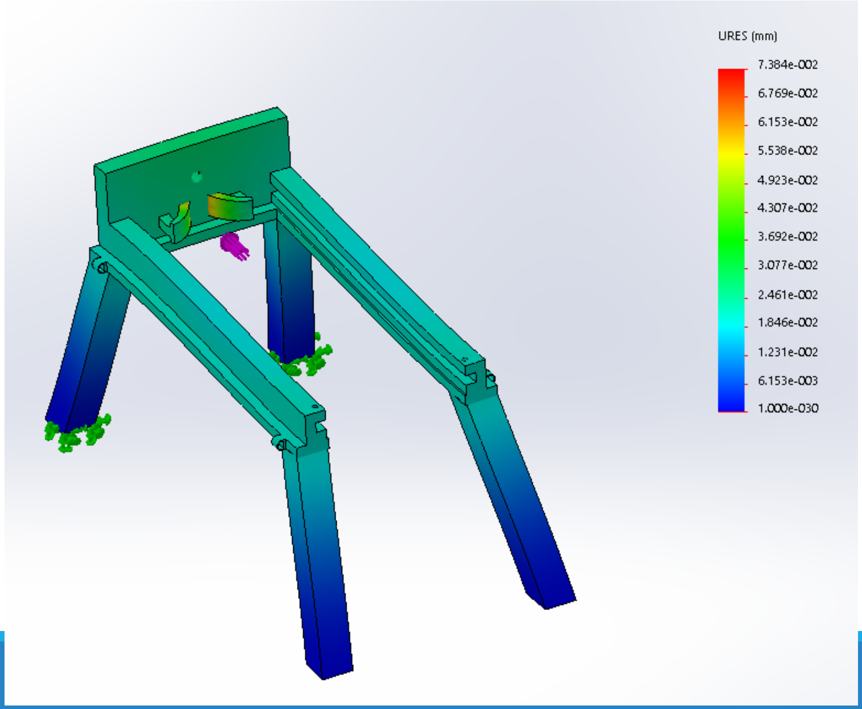
Stress tests on load sensor SolidWorks model (psi)

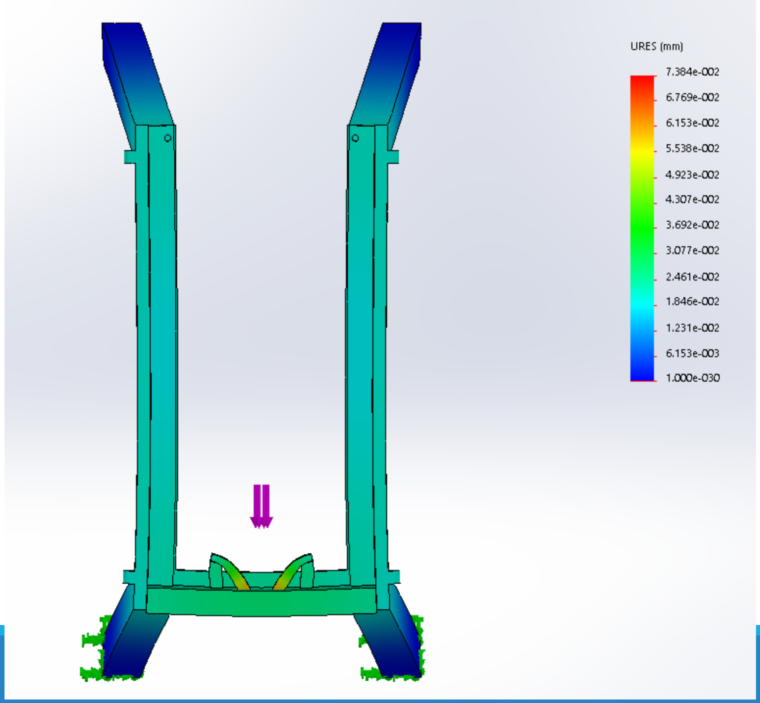




Deformation Simulation

Displacements are exaggerated to show where maximum deformity occurs (mm)





Test Stand Feasibility of Key Elements

- Stability: Structure of stand provides a good foundation with minimal flexing or bending, keeping rocket along same axis
- Safety: Secured with chains/straps, ground anchors, and front plate able to withstand full rocket force with FOS of 1.7
- Portability: Disassemble into a rolling container
- Ease of Setup: Same bolt size or slots for connection, minimal (included) tools used, no special equipment (cranes, forklifts, welding torches)
- "Flight Ready": Test stand requires little to no permanent modification of motor, giving near ideal representation of flight performance

Rocket Engine Feasibility of Key Elements

- Oxidizer: N2O, as specified by customer and as used in Mach-SR1 projects; tank recycled from legacy project
- Purge gas: Nitrogen tank, very cheap and effective; provided (minus gas cost) by Matt Rhode
- Plumbing system: Swagelock stainless steel tubing, valves for multi-function, mounted on separate plate with oxidizer tank, flow meter, and purge tank
- Injection system: Titanium plate, with countersunk style nozzles to achieve desired pressure
- Main body: Carbon fiber wrap and phenolic tube; best performance from legacy projects
- Fuel: HTPB, as specified by customer and as used in Mach-SR1 projects

Appendix 6: CPE 6

Feasibility of Manufacturing Safety

- Manufacturing of carbon fiber wrap, graphite nozzle, and phenolic tube require respirator masks which will be acquired.
- Vacuum will be used during manufacturing to minimize particle propagation
- HTPB is hazardous to skin contact, so long rubber gloves will be used when handling it

Feasibility of Personnel Safety

- Range Safety Officer and Authority Having Jurisdiction will be present
- Personnel will be familiar with National Fire Protection Agency guidelines
- Hazards of hybrid rockets do not include fuel borne explosions, but instead include explosions from pressure vessel failure, blowback, hard start, or projectile danger.
- Both test locations provide more than enough space to be a safe distance of 100 yards from the test article and behind a blast shield or building in case of a pressure vessel failure
- Oxidizer tank is pressurized to prevent blow back and one-way valves will also be implemented
- Test stand key element of safety shows engine won't dismount from test stand, preventing it from becoming a projectile

Feasibility of Misfire/Hangfire Procedure

- In case of propellant not igniting after triggering, the system will undergo a Misfire Procedure.
  - A waiting period of 30 minutes after closing valves is implemented before approaching the test stand
  - In this case the test article will still be able to undergo a second attempt
- In case of propellant only partially igniting or other incomplete burn after triggering, the system will undergo a Hangfire Procedure.
  - Automated system closes oxidizer tank valve and opens nitrogen valve to purge system for 5 minutes
  - A waiting period of 30 minutes after purge is implemented before approaching the test stand
  - In this case the test is considered a fail and the test article can no longer be used

Feasibility of Transportation Safety

- The biggest hazard imposed while in transportation is from the Nitrous Oxide and Nitrogen bottles. They will be outsourced making them inherently safe to spontaneous explosion and will be secured from movement while transported
- HICKAM will be delivered in durable container and poses no danger while in transportation making it a feasible key element
- Hybrid rocket engines will be delivered in secured container and pose no hazards during transportation