Final Presentation

COOPER A. DRAIN

ANDREW A. ALLISON
BENJAMIN B. SHELDON

BISWAS POUDEL
KIMIYA GHOBADI

MCCONNELL E. GOU
SHANE P. CULLEN

SKULD
PROPULSION

Design Team Organization

Team

Cooper A. Drain

Systems Engineer

Benjamin B. Sheldon

Programmer

Biswas Poudel

Test Engineer

Shane P. Cullen

Structural Engineer

Kimiya Ghobadi

Systems Engineer

Andrew M. Allison

Instrumentation Engineer

McConnell E. Gou

Agenda

- Problem Description
- System Requirements
- Design Solution
- Supporting Analyses
- Verification Tests
- Compliance Summary
- Conclusions and Recommendations

Purpose & Problem Statement

The current process for characterizing propellant at Embry-Riddle Aeronautical University is time-consuming, inefficient, and unreliable. To effectively characterize solid rocket propellant and cut costs, a strand burner with a new data acquisition system was designed.

System Requirements

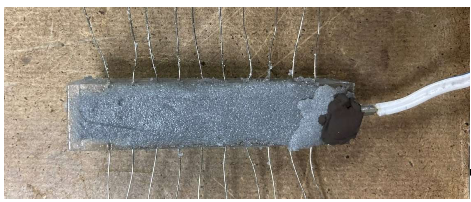
System Requirements

1. Cut cost of characterization by 80%
2. Cut characterization time to 6 months
3. Characterize propellant at pressure range of 200 -1000 psi.
4. Function for 10 years
5. Withstand three times max operation pressure
6. Calculate Burn rate to 5% accuracy
7. Calculate ‘a’ and ‘n’ values to 8% accuracy

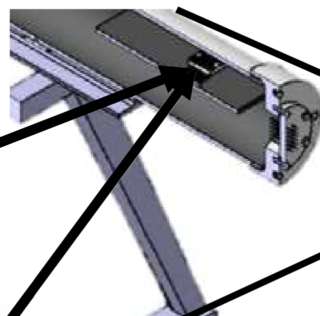
Design Solution

System Overview

Pressure System



Propellant Strand vs French Fry



[1]

Structures

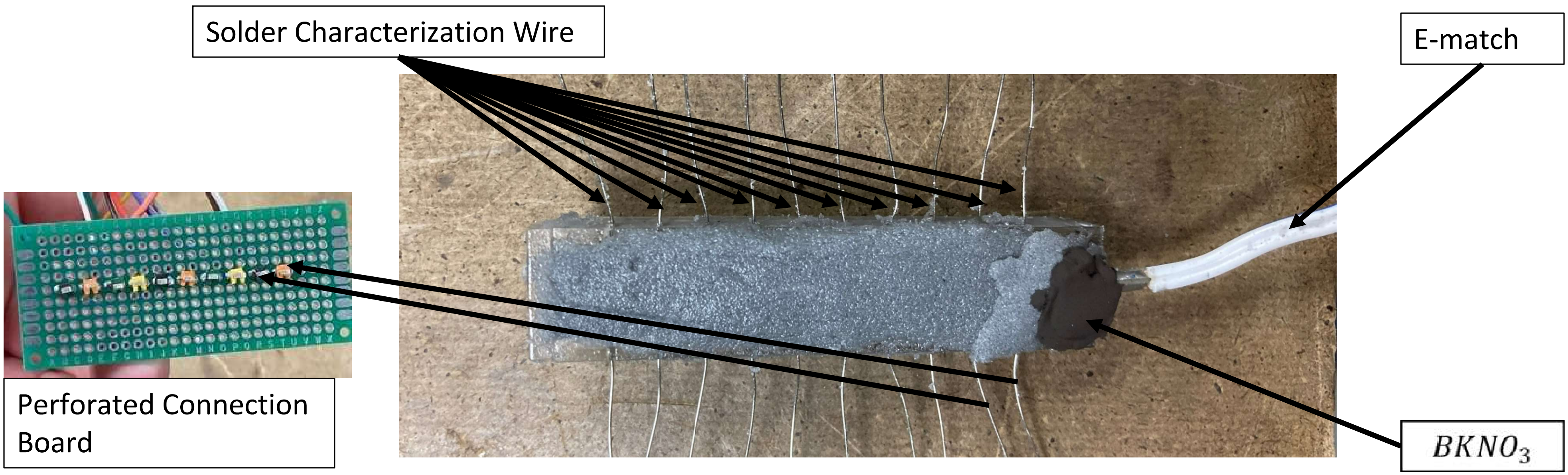
Ignition

Data Acquisition and Software Interfacing

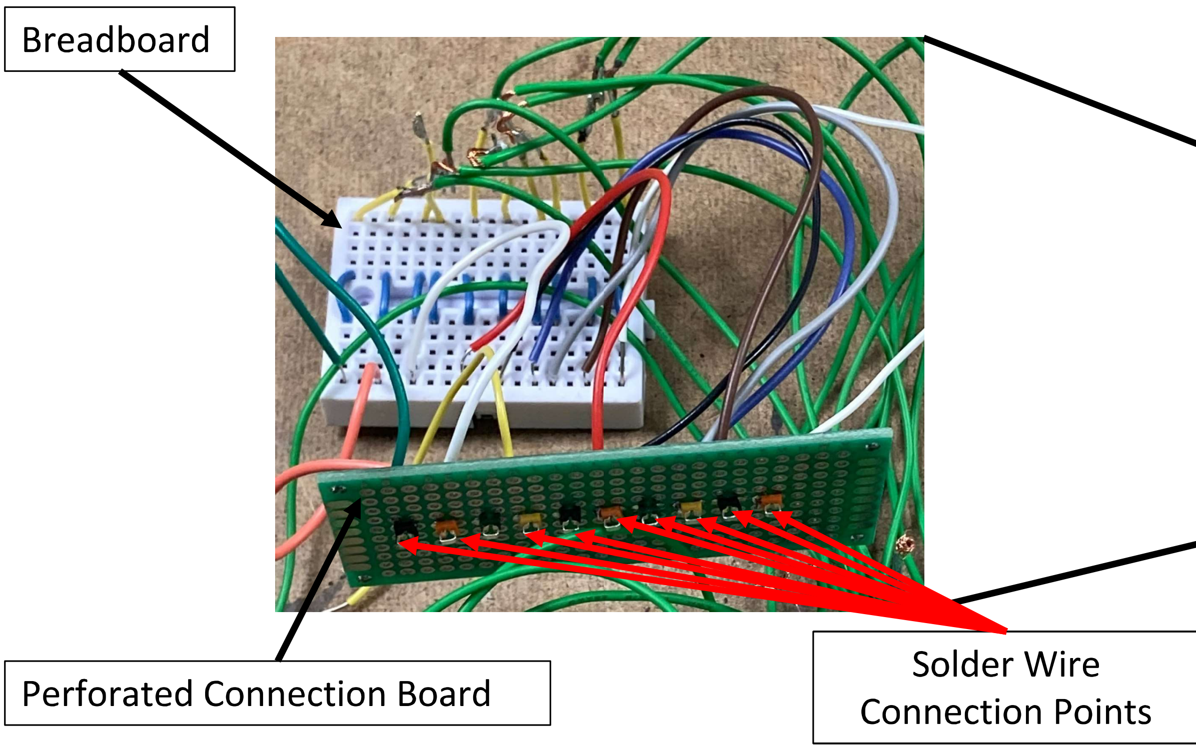
Strand Burner: a pressurized chamber used to characterize solid propellants

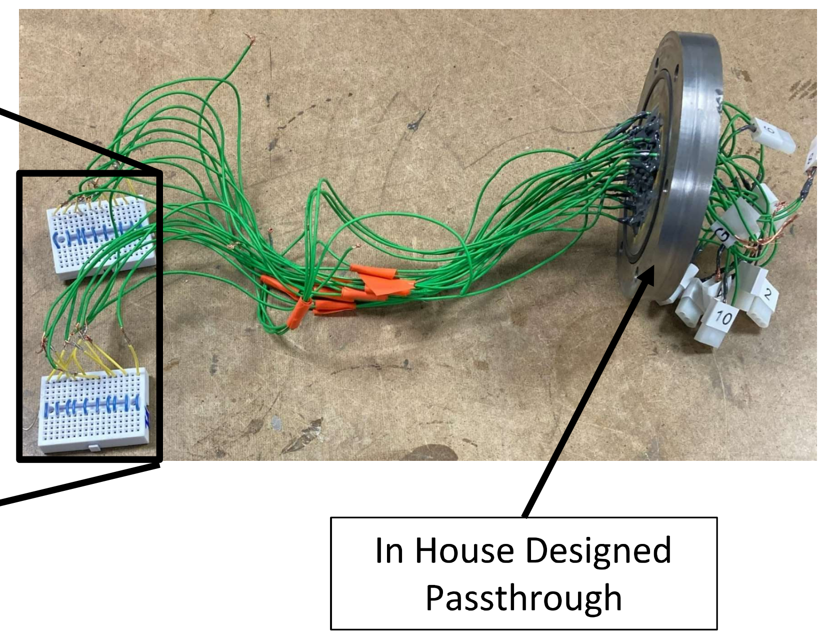
Saint Roberts Law $\dot{r} = aP_c{}^n$

System Overview



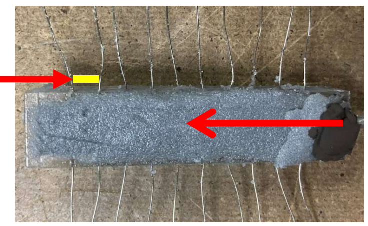
System Overview





Linear Burn Rate Equation and Saint Roberts Law

W_d: distance between two wires
Measured using calipers ± .05 mm



$\dot{r}$: burn rate of the propellant and input to Equation Two

$$\dot{r} = \frac{W_d}{t}$$ [3]

t: time to burn the wires measured using PXIe ± 0.001 s

a: burn rate coefficient derived from curve fit

n: pressure exponent derived from curve fit

$$\dot{r} = aP_c^{\,n}$$ [2]

$\dot{r}$: burn rate and input from Equation One

P_c: chamber pressure measured from pressure transducer to ± 7 psi.

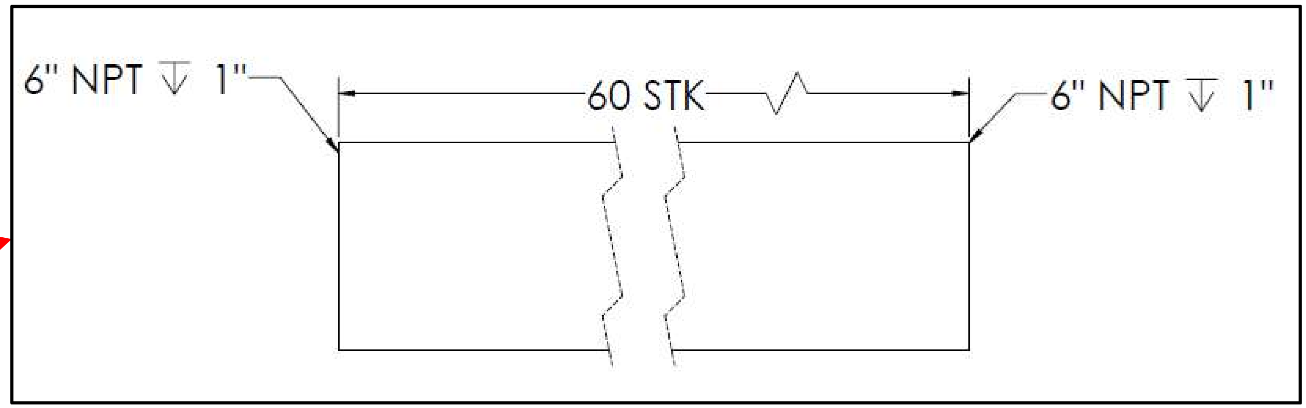
Materials and Construction – Strand Burner

1018 Hot roll steel threaded cap
Machined in house

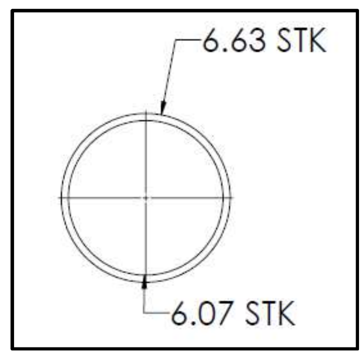
ASTM A500 Grade B threaded steel pipe
Pipe threading outsourced

12L14 Cold rolled steel face plate
Machined in house

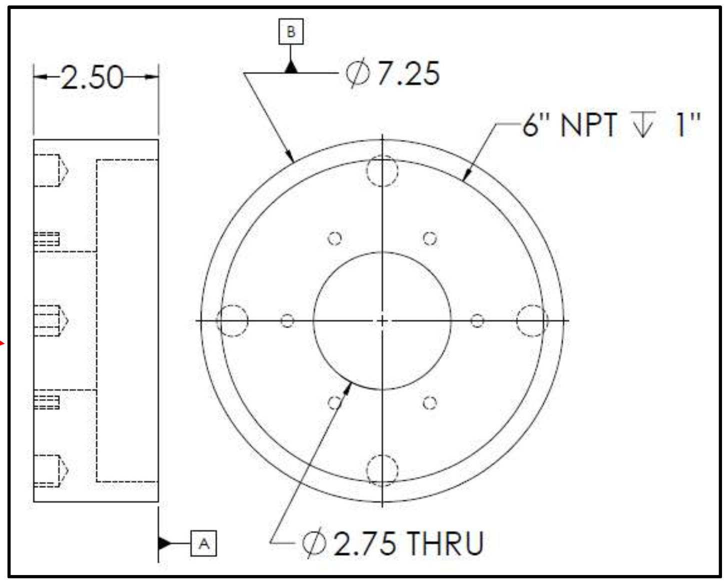
Dimensions – Strand Burner



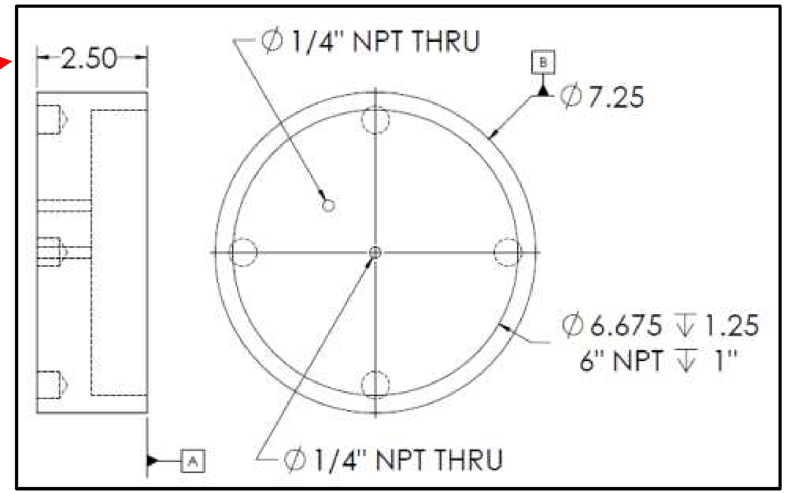
Pipe drawing



Dimensions – Strand Burner Cont.

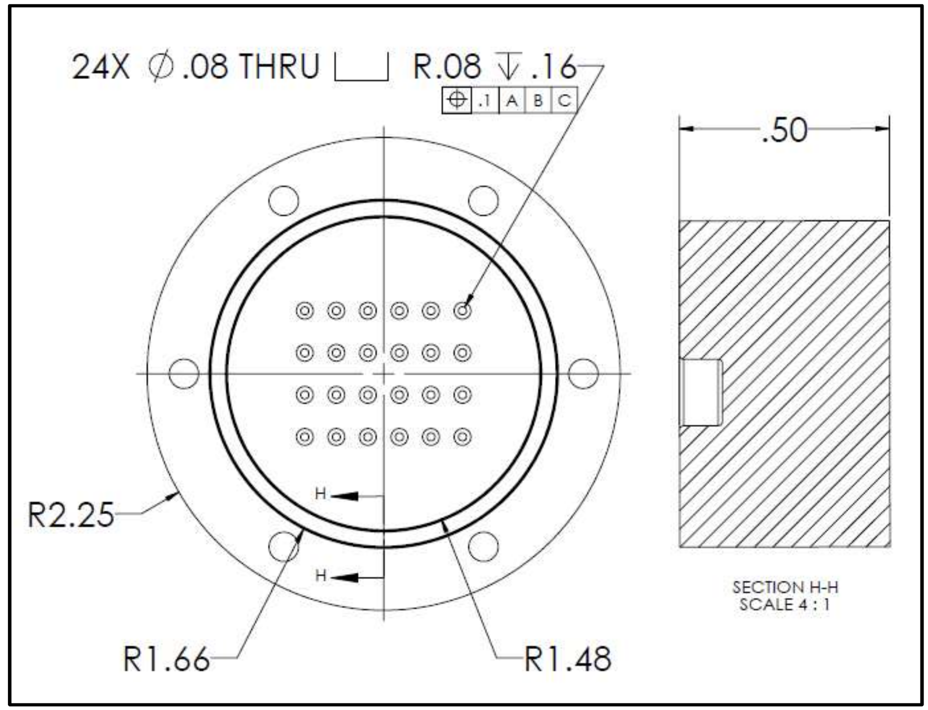


Front end cap



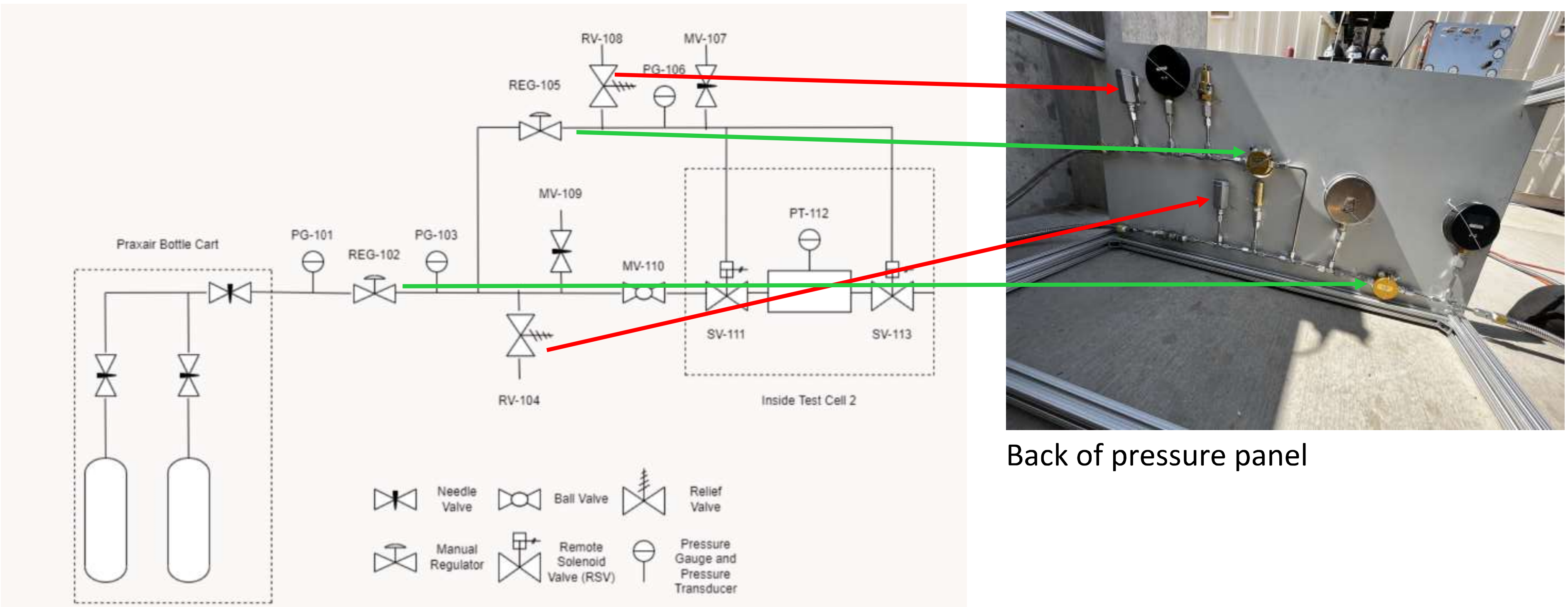
Back end cap

Dimensions – Strand Burner Cont.



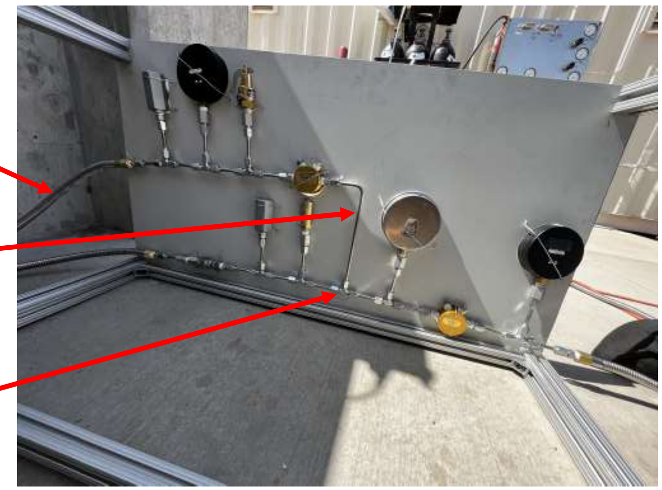
Face plate with wire pass through

Materials and Construction – Pressure System



Back of pressure panel

Materials and Construction – Pressure System



Flex hoses used to take gas to and from panel

304 stainless steel tubing; ¼ in. OD; 0.28 in. wall thickness

Steel AN and NPT pressure fittings

8020 rails used for panel frame and cut to desired length

Panel is cut from aluminum composite sandwich

Pre-assembly of the pressure components
Cut holes according to the components' positions and assembled the panel

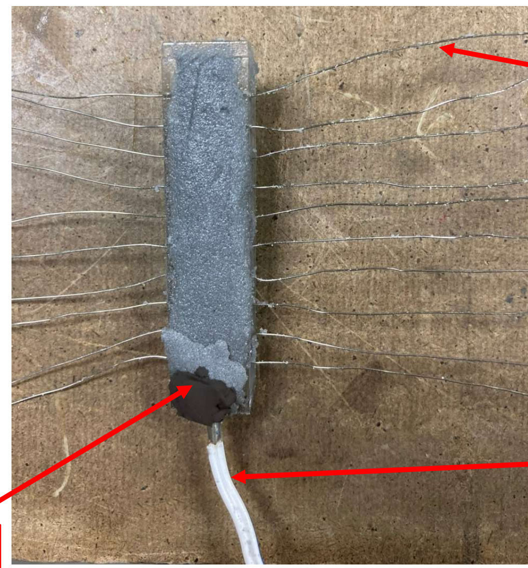
Materials and Construction – Propellant Strand

Propellant jig made from plexiglass
Sides are laser cut and glued together

Propellant mixing was done by hand

Dimensions and Construction – Propellant Strand

Propellant packed into the jigs, the wires and an E-match were inserted
After curing, the BKNO3 was added



2 in. x 0.5 in x 0.5 in.

BKNO3

E-match

0.3 mm diameter lead free solder wire
10 wires inserted at equal intervals with 0.143 in. ± 0.01 spacing

Materials and Construction – Data Acquisition and Software Interfacing

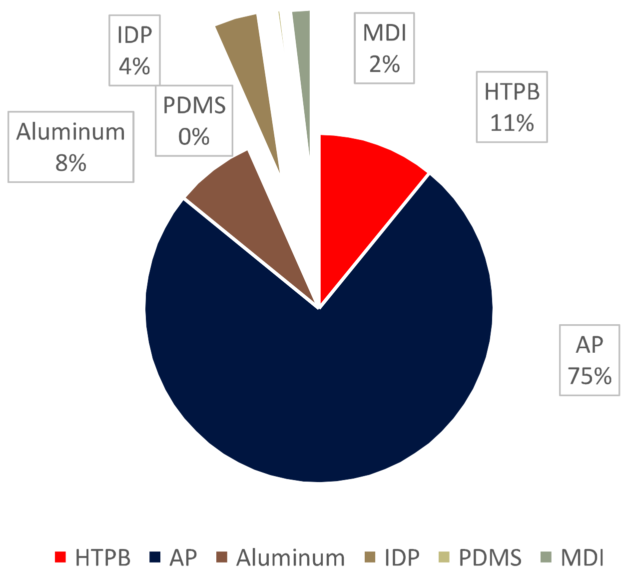
TC3

PXIe [13]

NEMA-4 rated box holds the connection for wires going to the PXIe

Supporting Analyses

Performance Analysis



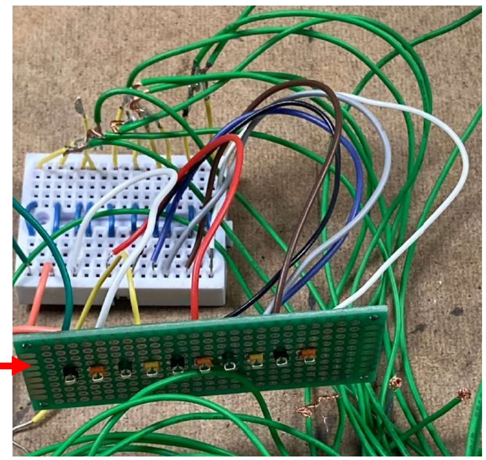
Below melting point of structural components

Simulation Results from NASA

Properties	Values
Gas Temperature, T_g	306 K, 91°F
Energy Released, ΔU	797.45 kJ/kg
Specific Heat Ratio, γ	1.227
Molecular weight, M	27.356 g/mol

Performance Analysis

- Ideal Gas Law → Pressure Rise
- Gas temperature below melting point of all components



Copper-coated Fiberglass perf boards shield heat locally

Additional Heat Shield from Rubber Lining

Structural Analysis – Pipe Thickness

From ASME Pressure Vessel Codes[7]

Minimum thickness of pipe

Inner radius from Pressure Analysis

Chamber Pressure of 3000 psi

$$th = \frac{r_i P}{A_S E - 0.6P}$$

Max. allowable stress of material

Joint Efficiency

Additional thickness due to threads

$$t = \frac{0.8}{n}$$

Threads per inch

Structural Analysis – Pipe Thickness

From ASME Pressure Vessel Codes[7]

Minimum thickness of pipe

Inner radius from Pressure Analysis

Chamber Pressure of 3000 psi

$$th = \frac{3.0125 * 3000}{* 1 - 0.6 * 3000}$$

Max. allowable stress of material

Joint Efficiency

Additional thickness due to threads

$$t = \frac{0.8}{n}$$

Threads per inch

Structural Analysis – Threaded Cap Thickness

Moment at point b [8]

$$M_{rb} = qa^2\left(\frac{L14}{C5}\right)$$

M_{rb} = Moment at point b

q = Pressure

a = Radius of plate

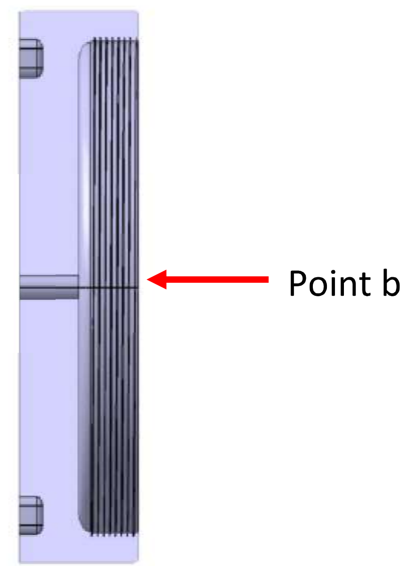
L14 & C5 = Constants

Stress at point b [8]

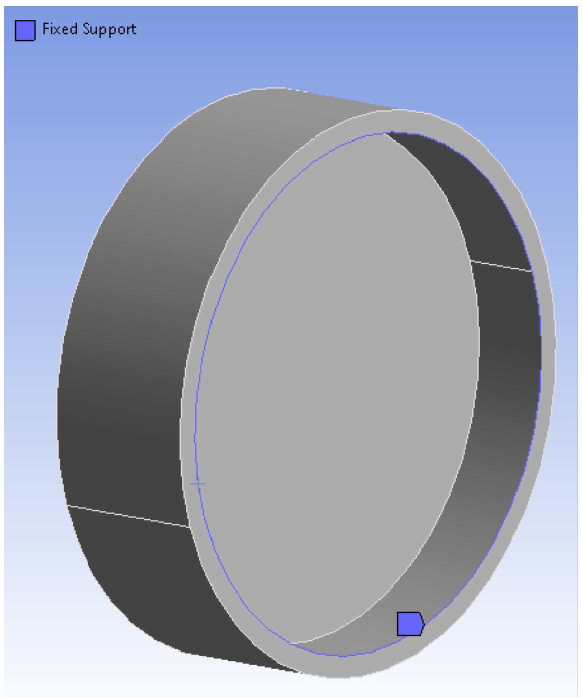
$$\sigma_{rb} = \frac{6M_{rb}}{th^2}$$

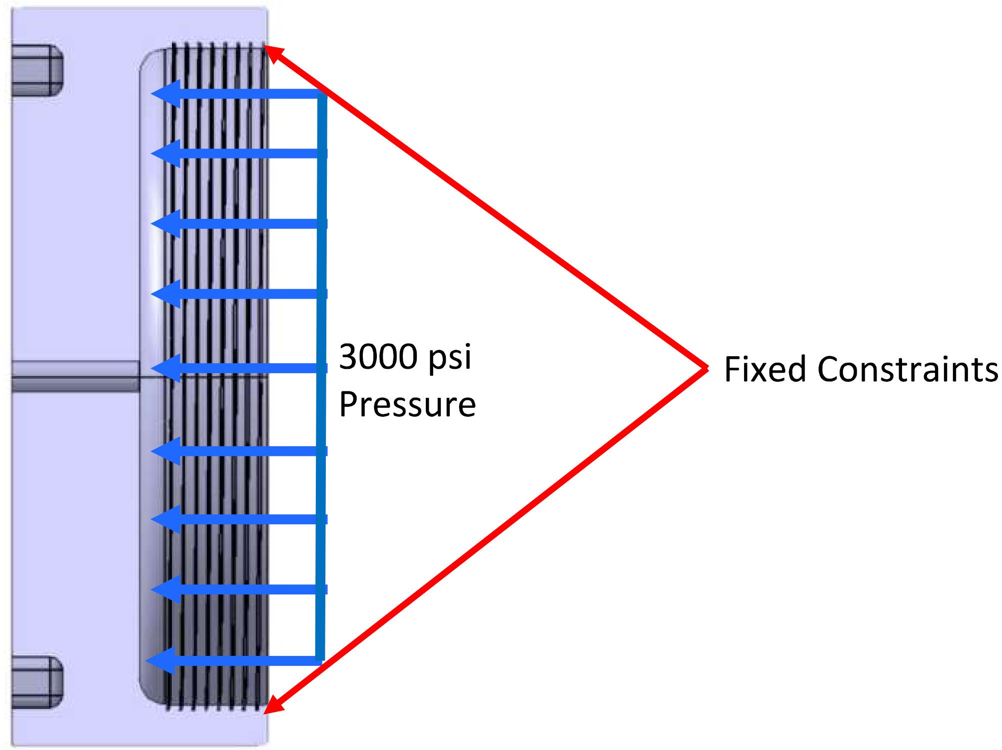
σ_{rb} = Stress at point b

th = Minimum thickness of caps

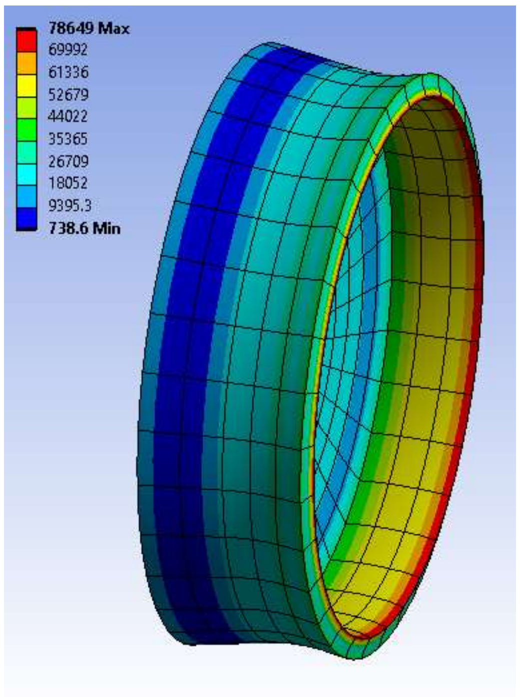


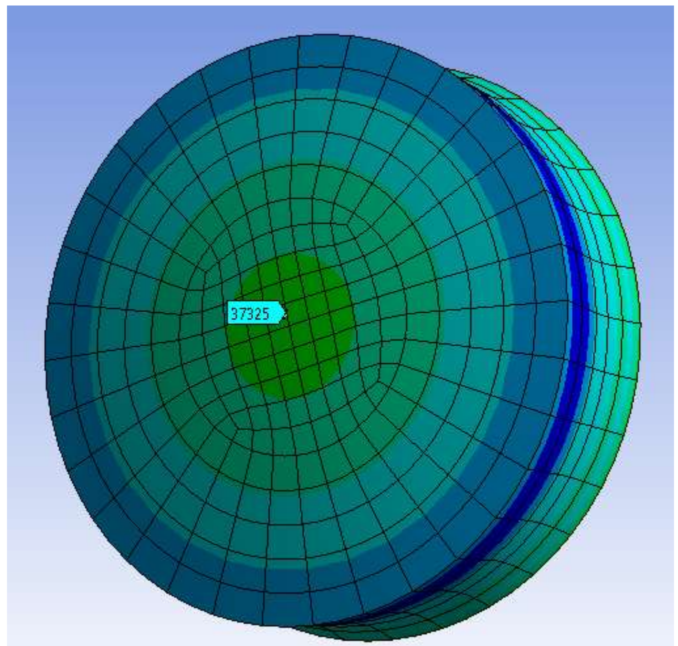
Structural Analysis – Numerical Analysis of Threaded Caps





Structural Analysis – Numerical Analysis of Cap Thickness





- Maximum stress: 37325 psi
- Hand calcs: 38352 psi
- Tensile strength: 58000 psi

Structural Analysis – Caps and Bolts

Number of threads in caps [9]

$$n = \frac{F_p}{0.5\tau_s p \pi d}$$

n = Number of threads

τ_s = Shear strength

p = Pitch

d = Pitch diameter

F_p = Force on the plate

$$\sigma = \frac{\pi d^2}{\;} \frac{p}{\;}$$

2863 psi

d = Diameter of face plate

P = Chamber pressure

σ = Stress in bolts

Tensile strength of ¼ 28 bolts:
3000psi

Structural Analysis – Fatigue Analysis

Number of cycles before failure [10]

$$a = \frac{(fS_{ut})^2}{S_e}$$

f = Fatigue strength fraction

S_{ut} = Ultimate tensile strength

S_e = Endurance limit

a = Constant

$$b = -\frac{1}{3}\log\left(\frac{fS_{ut}}{S_e}\right)$$

b = Constant

N = Number of cycles before failure

σ_{rev} = Completely reversed stress

$$N = \left(\frac{\sigma_{rev}}{a}\right)^{\frac{1}{b}}$$

N = 37430 cycles

Uncertainty Analysis

Burn Rate Calculation:

$U_{W_d} = \pm 0.001\ in$

$U_t = \pm 0.001\ seconds$

$UU_{\dot{r}} = \dot{r}\sqrt{(\frac{U_{W_d}}{W_d})^2 + (-\frac{U_t}{t})^2}$

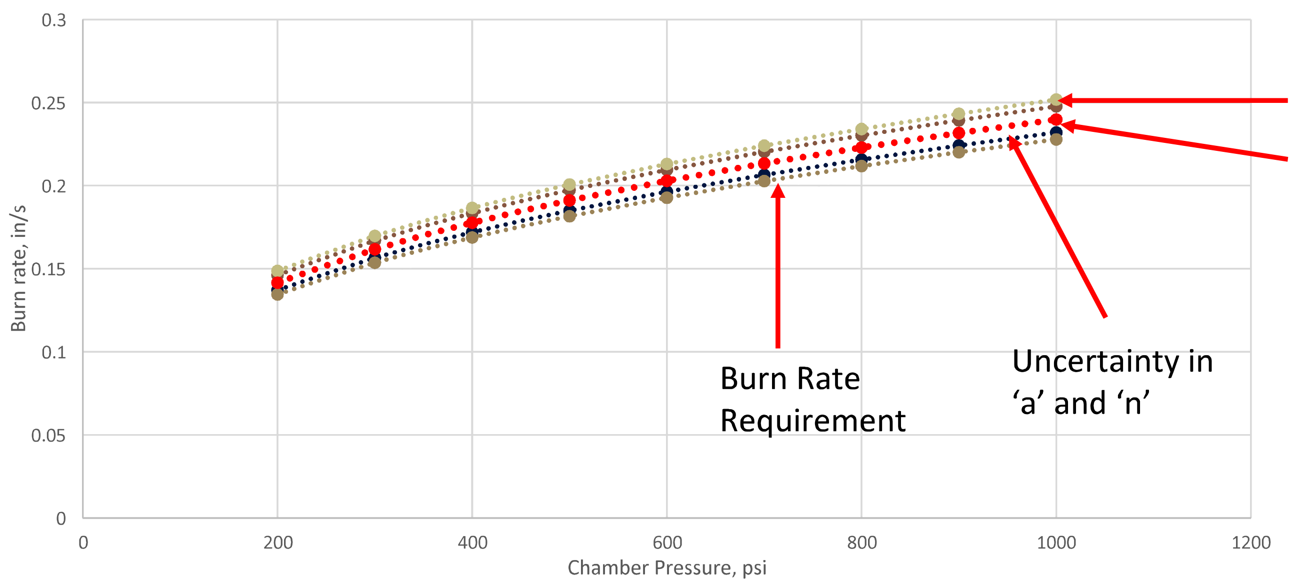
- $= \pm \mathbf{0.001}\ \boldsymbol{in/s}$

'a' and 'n' value Calculation

- Assuming $\frac{U_a}{a} = \frac{U_n}{n}$
- $U_P = 7.5\ psi$
- $U_{r\_t\dot{o}tal} = 0.001 \frac{in}{s}$
- $U_a = \sqrt{(\frac{\partial a}{\partial \dot{r}} U_{\dot{r}})^2 + (\frac{\partial a}{\partial P} U_P)^2 + (\frac{\partial a}{\partial n} U_n)^2}$

$$= \pm \mathbf{0.0007}\ \boldsymbol{in/s}$$

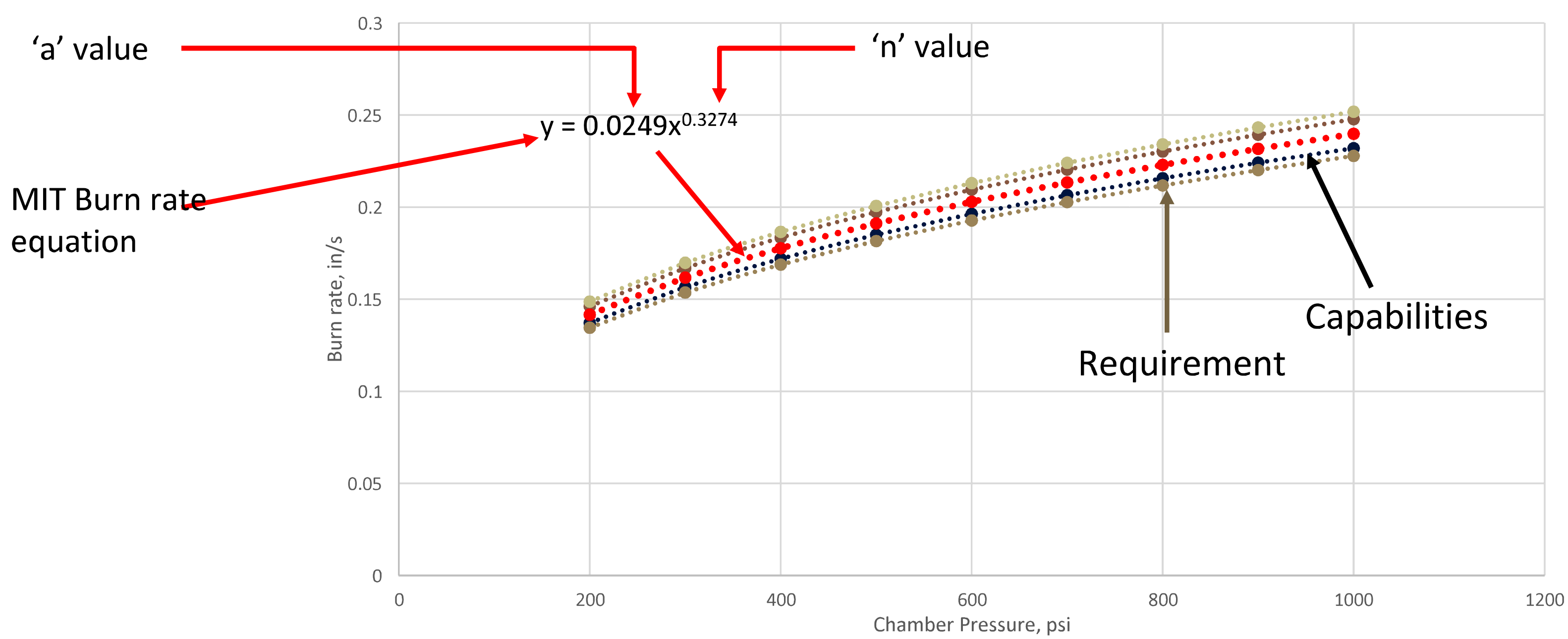
Uncertainty Analysis



'a' within 2.8%
'n' within 0.2%

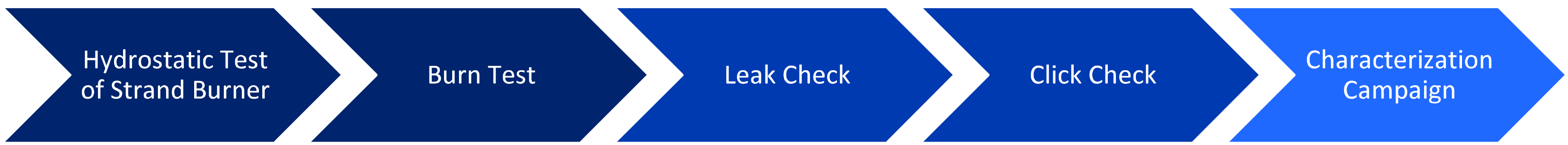
Verification Tests

Projected Outcomes Derived From MIT Data



[4]

Verification Plan



Hydrostatic Test

Hydrostatic Test Setup at Test Cell 2

Hydrostatic Test

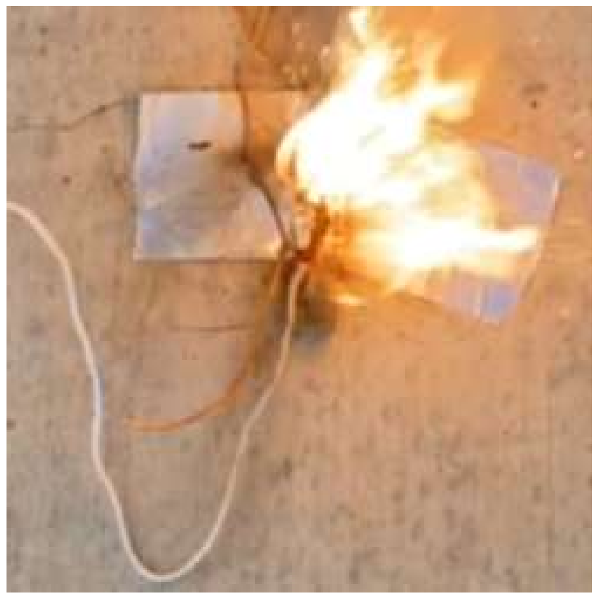
- Result:
  - 3 Attempts
  - Failed
  - Max pressure – 1600 psi.

Test 2

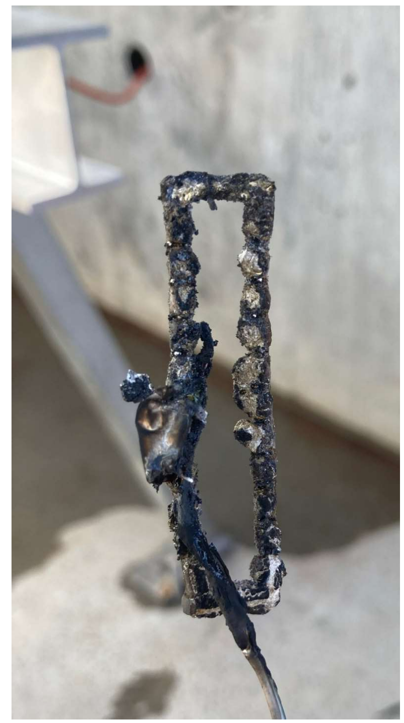
Test 3

Propellant Burn Test

- BKNO3 Igniter Worked
- Wires Burned
- Kept Jig On
- Passed



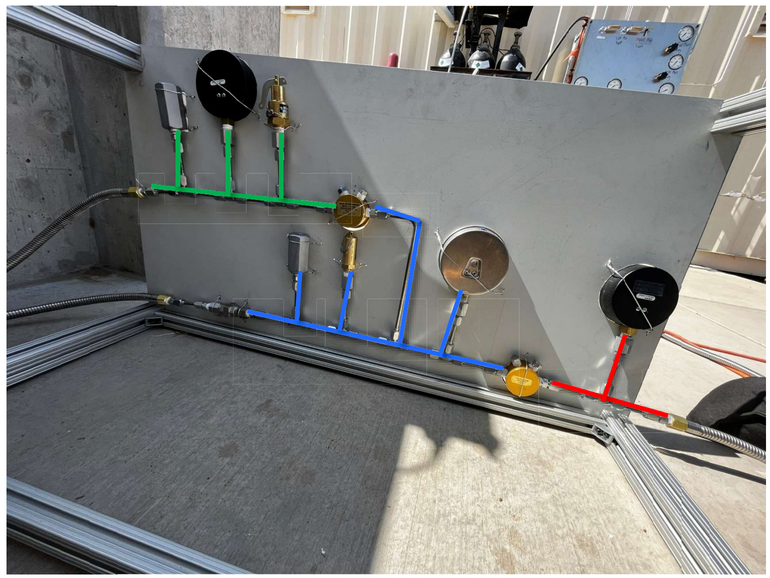
During Ignition Test



After Ignition Test

Leak Check of Panel

- 1600 psi. in Bottle
- 100 psi. Check
- Check Red, Blue, Green
- Passed



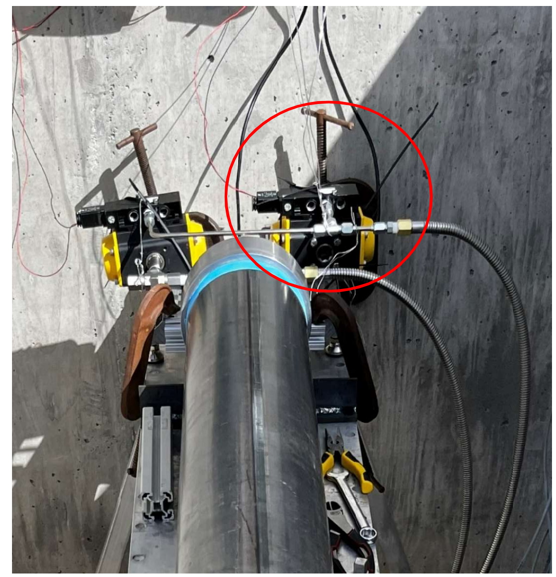
Sections of Pressure Panel and Strand Burner

Click Check

- 100 psi. Supply
- Strand Burner Press Valve

  Failed

Actuator on Valve



Setup of Actuators

Leak Check of Strand Burner

- 1600 psi. in Bottle
- 100 psi. Check
- Failed
- Could not Continue to Characterization Campaign

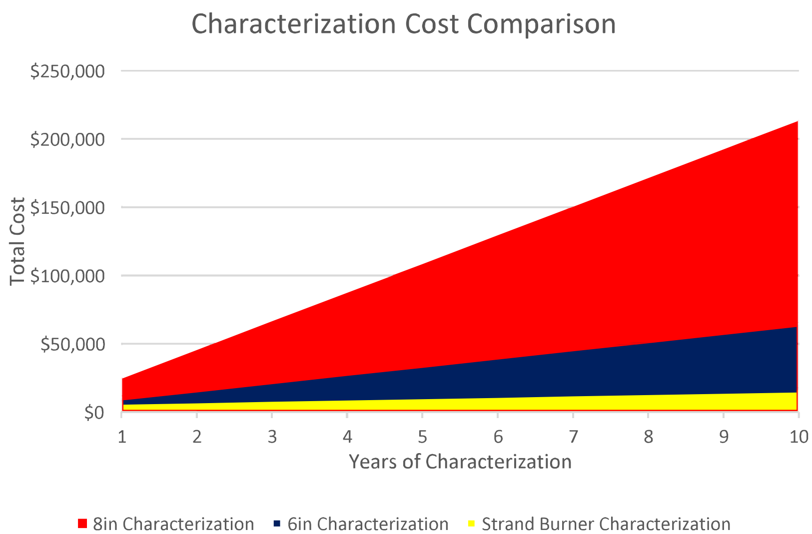
Strand Burner Setup for Leak Check

Compliance Summary

Requirement 2.1 - Compliance

Project must cut cost of characterization by 80%

Status: COMPLETE



Method	Initial Cost	Reoccurring Cost	Total Cost at 10yrs
8in Characterization	$4,000	$21,000	$214,000
6in Characterization	$4,000	$6,000	$64,000
Strand Characterization	$6,000	$1,000	$16,000

Initial Costs: Chambers, test stands, reusable equipment

Reoccurring Costs: Chemicals

Requirement 2.4 - Compliance

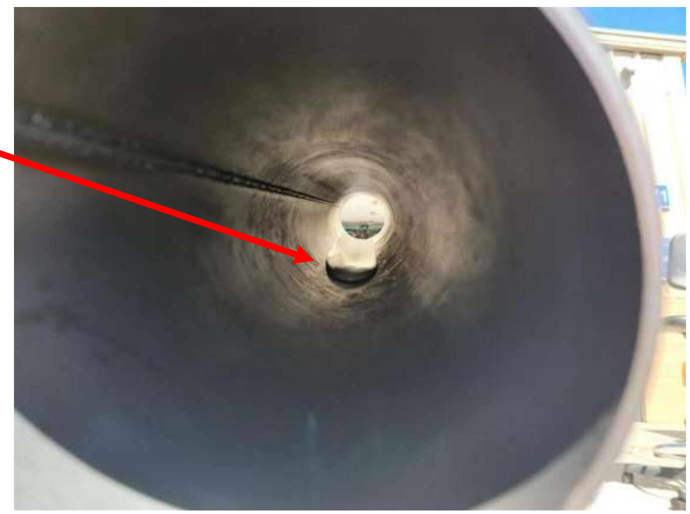
System must function properly for 10 years.

Status: COMPLETE

$$N = \left(\frac{\sigma_{rev}}{a}\right)^{\frac{1}{b}}$$

$$\boxed{N = 37430 \text{ cycles}}$$

Rubber Coating

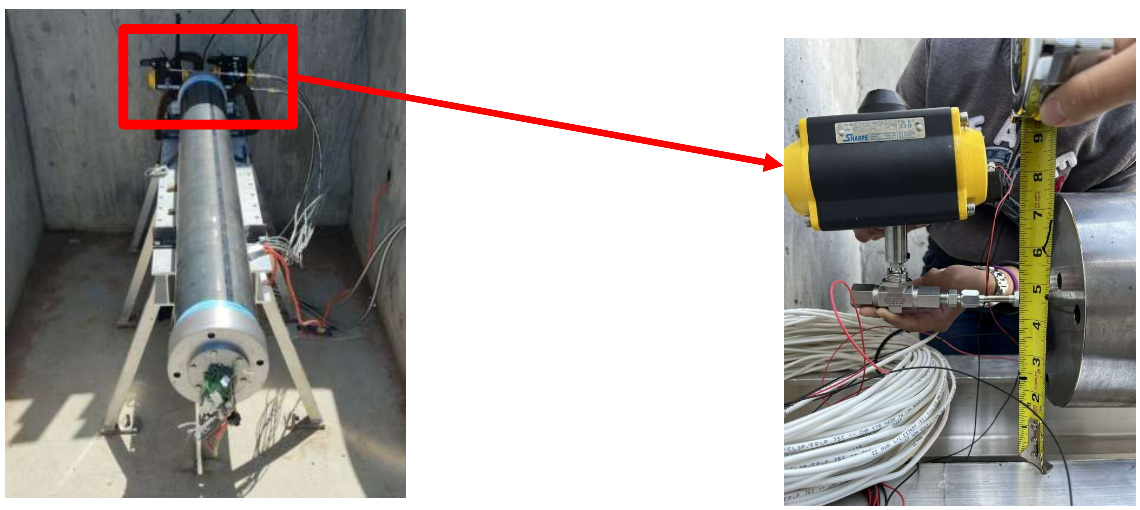


Rubberized coating application to chamber interior

Requirement 2.2 - Compliance

Lower time of characterization to 6 months for all rocket motor sizes used by ERAU

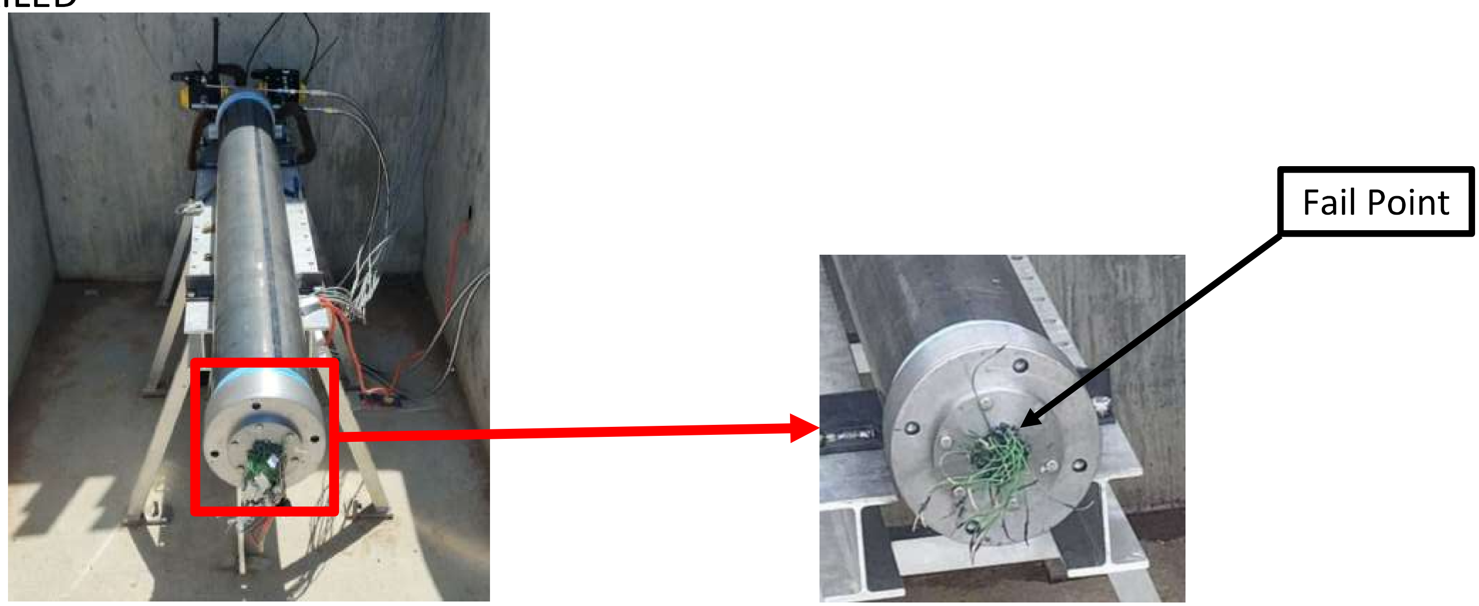
Status: FAILED



Requirement 2.3 - Compliance

System must be able to characterize propellant at chamber pressure of 200 - 1,000psi.

Status: FAILED



Requirement - Compliance

2.5

System must withstand up to 3 times the max operating pressure without failure

Status: FAILED

2.6

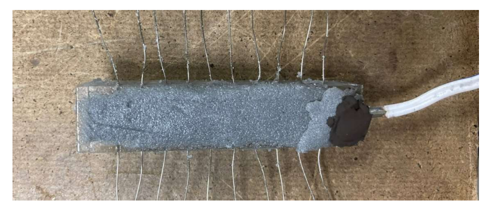
Calculate Burn rate to 5% accuracy

Status: INCOMPLETE

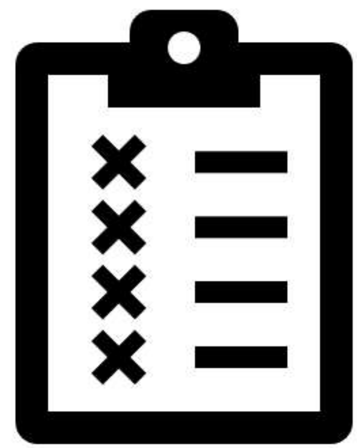
2.7

Calculate ‘a’ and ‘n’ values to 8% accuracy

Status: INCOMPLETE



Failure Analysis



Hydrostatic Test

- Failure Modes:
  - Liquid Thread Seal – Replaced with Teflon
  - Wire Pass Through
  - Max pressure – 1600 psi.

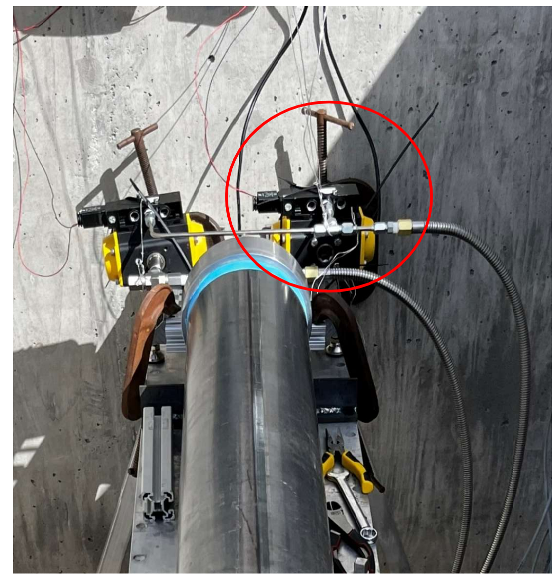
Test 2

Test 3

Remote Valve Actuators

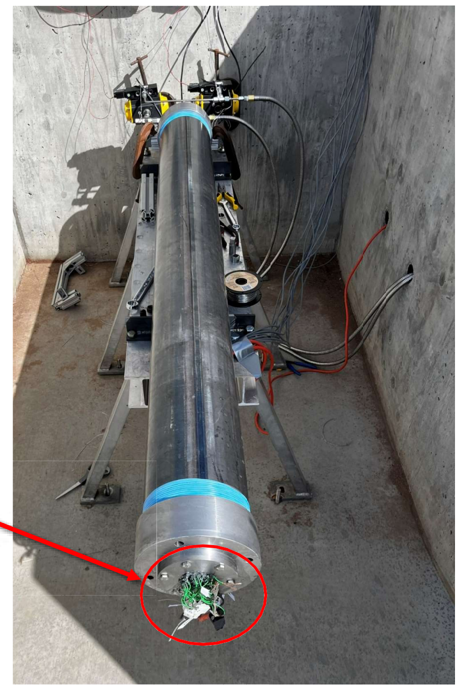
Failure Mode:
- Thought it was Alignment
- Strand Burner Press Valve Actuator Broken

Actuator on Valve


Setup of Actuators

Leak Check of Strand Burner

Failure Mode:
- ~100 psi.
- Snooped Caps, Faceplate, Plumbing – No Leaks
- Pass Through Whistling – Determined to be Leak Point



Strand Burner Setup for Leak Check

Conclusion and Recommendations

Conclusion

Project accomplishments:

- Theoretically reduces the cost of characterization up to 80%
- Test article life span up to 10 years

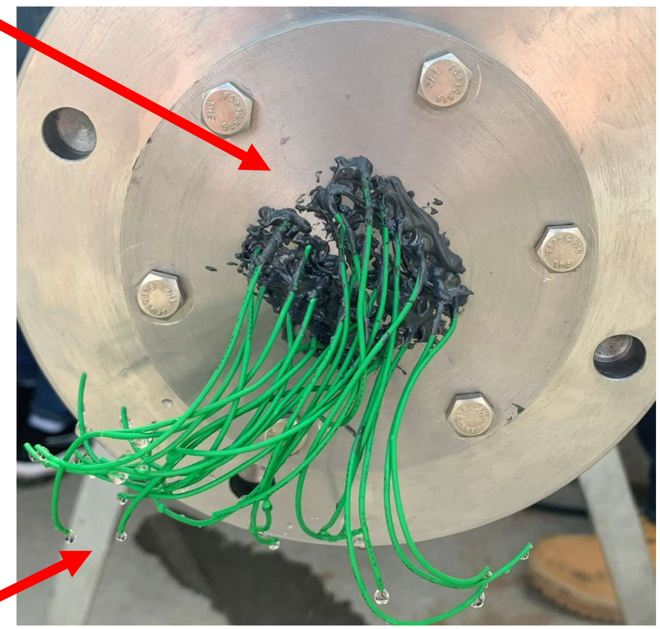
Project setbacks:

- Supply chain delays
  - Wire pass through
  - Argon
  - Hydrostatic pump

Project Failures

- Face Plate wire pass through
- Hydrostatic Test (Sealing)
- Actuator

Wire Pass Through

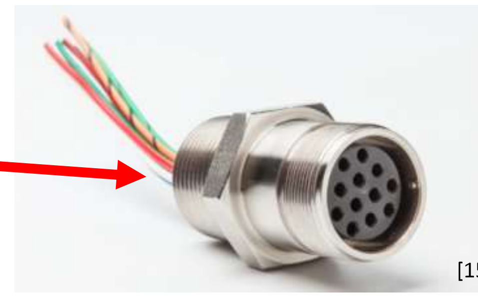


Water Droplets

Recommendations

Buy Commercial Passthrough

- Screws into plate via NPT fitting
- Connections are more reliable



[15]

Make Passthrough

- Solid core Wires
- Better labeling
- New way to seal wire holes
- Strip and seal wires
- Shorter wires

Recommendations Cont.

- **Perform full hydrostatic test**
  - Make a test plate
  - Use new pump
  - New method of filling strand burner

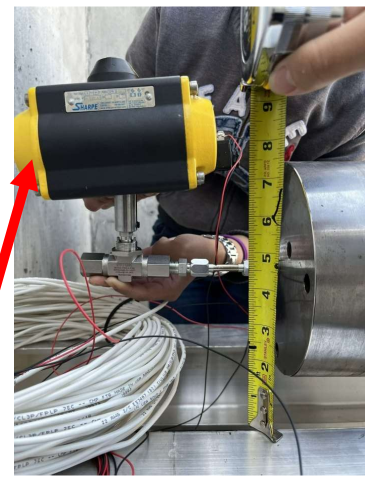
[14]

- **Seal the inside of the caps with rubber**
  - Prevent rust
  - Use blue Teflon for threads

Recommendations Cont.

Pressure/Data Acquisition system:

- New actuator
- Attachable valve harness to support the valves
- LabVIEW code
  - Run all LabVIEW through PXIe to control actuation and data acquisition



Actuator

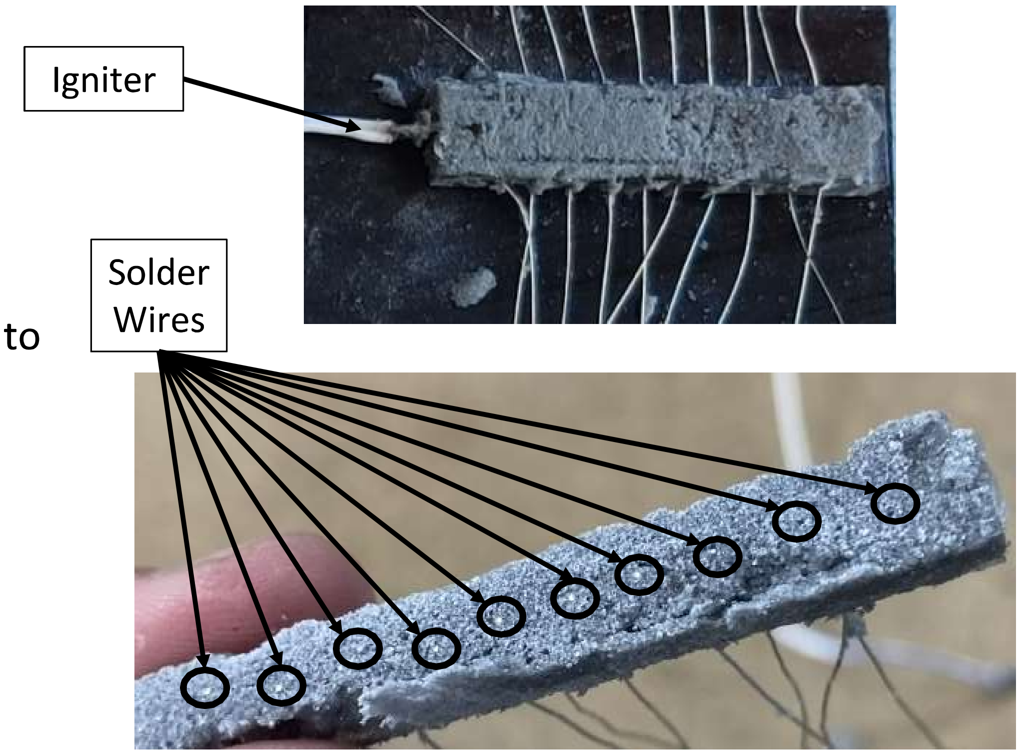
Actuator Support

Future Improvements

Future Improvements

Propellant sample:

- Redesign propellant jig
- Ignition method E-match
  - BKNO3 (boron/potassium nitrate)
- Mix enough propellant for a full-size motor to verify test results



Future Improvements Cont.

Future Addons:

- Patch Box Capabilities
  - Analog
  - Digital
  - Bridge Completion
  - Color Coding
  - Thermocouple
- Integrate the liquids rocket control box to control the ignition system and actuation
- Propellant combustion byproduct collection system

Acknowledgments

- Dr. Steven F. Son, Purdue University
- Tim Manship, Purdue University
- Dr. Darrel Smith, Professor of Physics
- Dr. Michele Zanolin, Professor of Physics
- Dr. Istemi Ozsoy, Assistant Professor of Mechanical Engineering
- Dr. Elliott Bryner, Assistant Professor of Mechanical Engineering
- Dr. Daniel White, Assistant Professor of Mechanical Engineering
- Dr. Brent Solie, Associate Professor of Mathematics
- Dr. Karl Heine, Assistant Professor of Mechanical Engineering
- Dr. Katherine Wood, Associate Professor of Engineering
- Dr. Jonathon Adams, ssistant Professor of Humanities and Communication
- Professor Robert errick, epartment Chair of Engineering
- Jefferey Hiatt, ngineering Lab Specialist
- Jared anatta, ollege of Engineering Lab Manager
- Patrick David, achinist
- Andrew Hamilton, echanical Engineering Student
- McNeil W. Allison, Industrial Engineer, Consultant – Global Healthcare Solutions
- Michael Brady, EHS Program Manager

References

[1] Timquo. (n.d.). *Single potato French fry chip isolated stock photo (edit now) 567056539*. Shutterstock. Retrieved April 17, 2022, from https://www.shutterstock.com/image-photo/single-potato-french-fry-chip-isolated-567056539

[2] White. (n.d.). Burn Rate Equation Interview. other.

[3] Richard Nakka's Experimental Rocketry Site. (n.d.). Retrieved January 28, 2022, from https://www.nakka-rocketry.net/burnrate.html

[4] *Cherry limeade*. Cherry Limeade - MIT Rocket Team - MIT Wiki Service. (n.d.). Retrieved April 17, 2022, from https://wikis.mit.edu/confluence/display/RocketTeam/Cherry+Limeade

[5] Bryner. (2021). *PXIe Assembly*. photograph.

[6] DENPETEC. (n.d.). *Amazon.com: Ariceleo led Fairy Lights Battery operated, 1 pack mini battery ...* Amazon. Retrieved April 18, 2022, from https://www.amazon.com/Ariceleo-Operated-Christmas-Centerpiece-Decoration/dp/B07S3R6MKJ

[7] *Female thread stainless steel pneumatic sanitary butterfly valve*. COVNA. (2021, December 1). Retrieved April 18, 2022, from https://www.covnagroup.com/product/female-thread-stainless-steel-pneumatic-sanitary-butterfly-valve

[8] Erik. (2022, March 31). *5A micro limit switch with roller - 5 pcs*. Opencircuit. Retrieved April 18, 2022, from https://opencircuit.shop/product/5A-Micro-limit-switch-with-roller-5-pcs

[9] Omega. *General Purpose, Stainless Steel Pressure Transducers.* Accessed on April 18, 2022 from https://www.omega.com/en-us/pressure-measurement/pressure-transducers/px309/p/PX309-3KGV

References

[1] Richard Nakka's Experimental Rocketry Site. (n.d.). Retrieved January 28, 2022, from https://www.nakka-rocketry.net/burnrate.html

[2] Threaded Pipe Cap. Red Earth Steels PVT LTD. (n.d.). Retrieved January 28, 2022, from https://www.redearthsteels.com/threaded-pipe-cap.html [2] X. Picard, *Embry Riddle Prescot Rocket Test Facilities*.

[3] 5.7US $: Megairon BSPT 1/2" 2" stainless steel SS304 male to male threaded pipe fittings length 150mm: Threaded pipe fittings: Pipe fittingsmale thread - aliexpress. aliexpress.com. (n.d.). Retrieved January 28, 2022, from https://www.aliexpress.com/item/32408858161.html

[4] Stainless Steel Round Plate. indiamart.com. (n.d.). Retrieved February 11, 2022, from https://www.indiamart.com/proddetail/stainless-steel-round-plate-16523766248.html

[5] G. Sutton and O. Biblarz, *Rocket Propulsion Elements*. New York, NY: J. Wiley and Sons, 2001.

[6] Y. A. Cengel and M. A. Boles, *Thermodynamics: An Engineering Approach*, Eighth. McGraw Hill Education, 2015.

[7] BPVC Section III-subsection NCA-general requirements for div1 & div 2. ASME. (n.d.). Retrieved January 28, 2022, from https://www.asme.org/codes-standards/find-codes-standards/bpvc-iii-nca-bpvc-section-iii-rules-constructions-nuclear-facility-components-subsection-nca-general-requirements-division-1-division-2/2021/print-book

[8] Roark, R. J., & Young, W. C. (1984). Formulas for stress and strain. McGraw Hill.

[9] Dr. Ozsoy

[10] Budynas, R., *Shigley's Mechanical Engineering Design,* McGraw Hill Education, 2015

[11] H-3 compound e-match dip - apogeerockets.com. (n.d.). Retrieved February 11, 2022, from https://www.apogeerockets.com/Rocket-Motors/Motor-Starters/H3-Igniter-Dip

[12] Dr. White, "Strand Burner Discrete Voltage Measurement."

[13] Dr. Bryner

[14] HP10-V pneumatic hydrostatic test pump. Rice Hydro. (n.d.). Retrieved January 28, 2022, from http://ricehydro.com/product/hp10-v-pneumatic-hydrostatic-test-pump/

[15] Douglas Electrical Components. Retrieved April 26, 2022, from https://douglaselectrical.com/douglas-products/sealed-cable-feedthrough/

Back-up Slides

Dimensions – Strand Burner Cont.

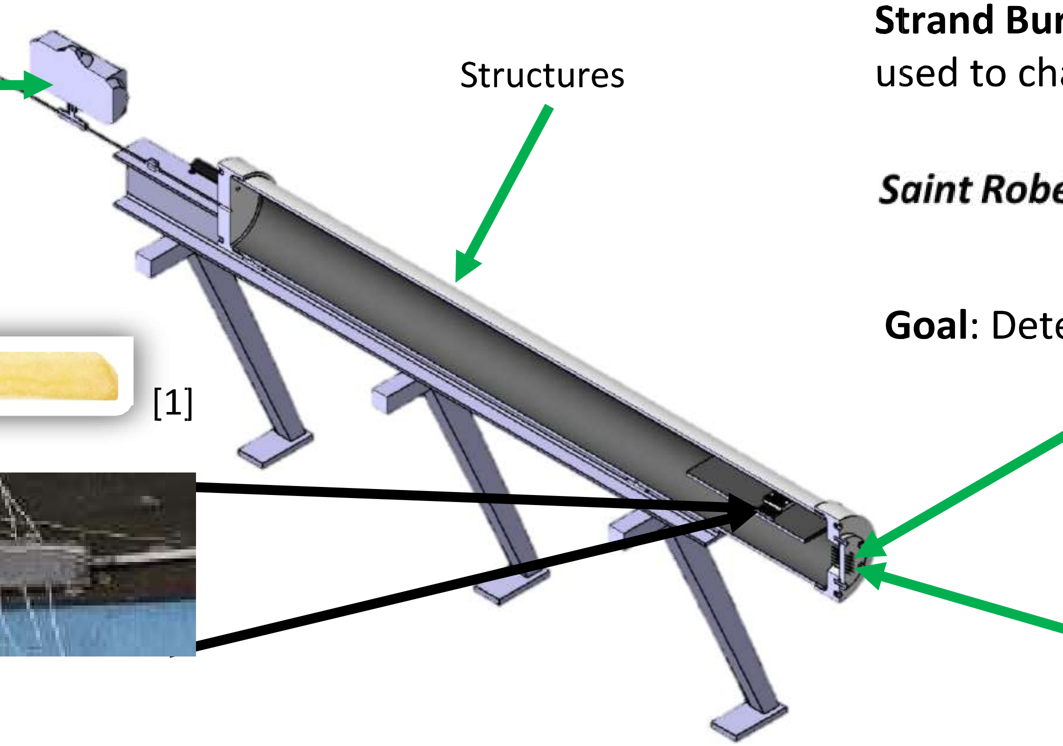
Feet
2 12 in. x 2in. X 2 in.

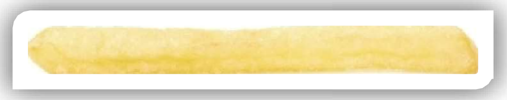
System Overview

Strand Burner: a pressurized chamber used to characterize solid propellants.

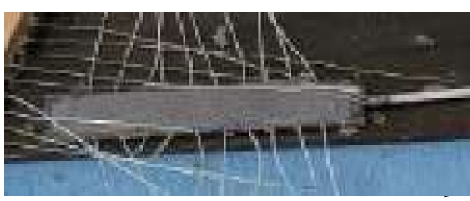
Saint Roberts Law $\dot{r} = aP_c{}^n$

Goal: Determine the ‘a’ and ‘n’ values





[1]



Linear Burn Rate Equation

$\dot{r}$: burn rate of the propellant and input to Equation Two

$$\dot{r} = \frac{W_d}{t}$$ [3]

W_d: distance between two wires
Measured using calipers ± .05 mm

t: time to burn the wires
measured using PXIe ± 0.001 s

Saint Roberts Law

P_c: chamber pressure measured from pressure Transducer to ± 7 psi.

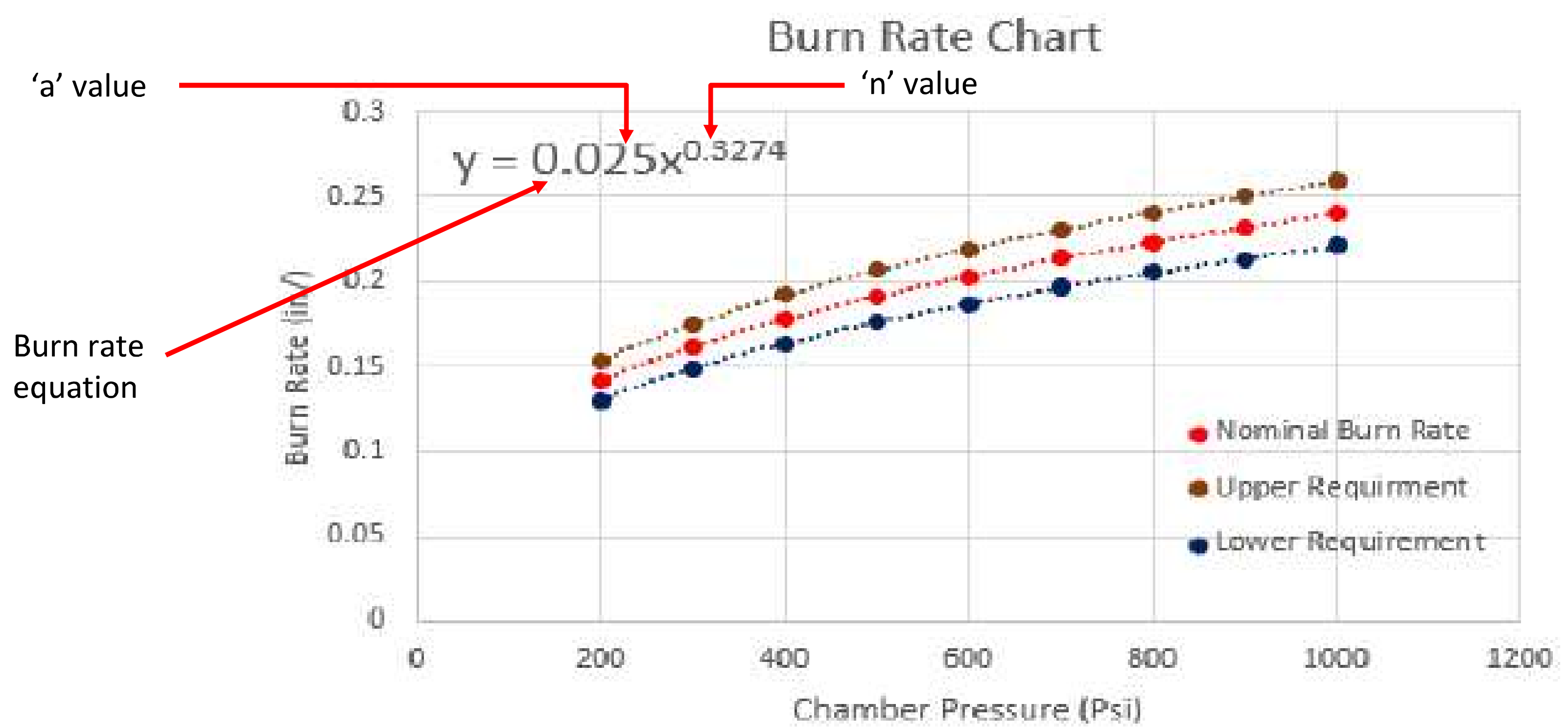
a: burn rate coefficient derived from curve fit

$\dot{r}$: burn rate and input from Equation One

$$\dot{r} = aP_c^{\,n}$$ [2]

n: pressure exponent derived from curve fit

Projected Outcomes Derived From MIT Data



[4]

System Requirements

System Requirements

Test Objectives and Requirements

Objectives

1. Test accuracy of data collection methodology by comparing gathered data to MIT's posted values
2. Demonstrate the practicality of the strand burner
3. Accurately collect pressure data over the range of 200 - 1000 psi.
4. Accurately collect burn rate data over the range of 200 - 1000 psi.

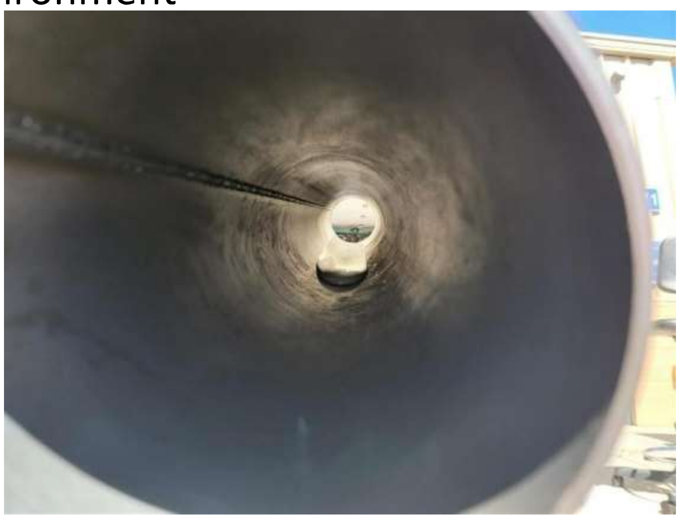
Requirements

1 Measure "a" to an accuracy of 8%
2 Measure "n" to an accuracy of 8%
3 Measure the burn rate accuracy to 5%
4 Pressure range must be 200 psi to 1000 psi
5 Testing shall take no longer than 6 months

Test Article

Strand Burner Chamber

- Holds test sample
- Creates/maintains testing environment
- Allows for instrumentation access to the test environment

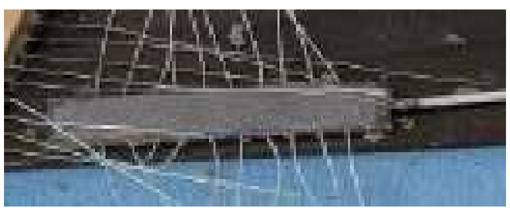


Coating application to chamber

Strand burner chamber ready to go

Propellant Sample

Propellant Jig



Propellant Sample

Propellant Samples being made

Support System - Pressure System

Pressure System control panel

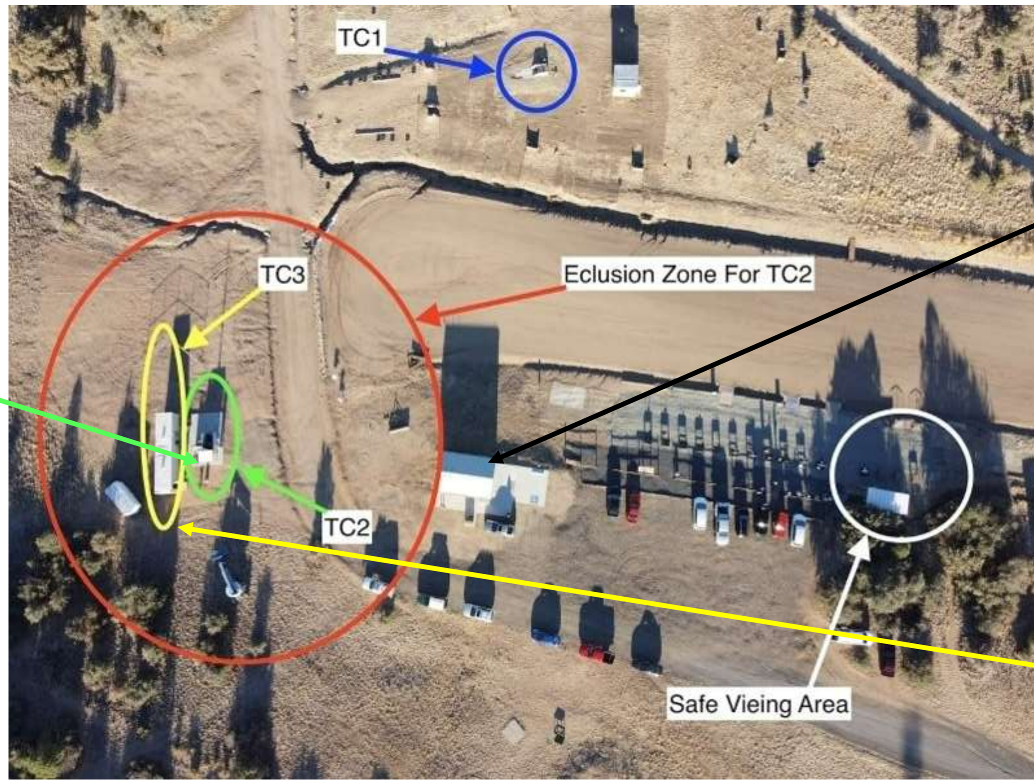
Argon bottles, cable management solution, weatherproof interface box

Pressure Panel Current Construction Progress

Test Facilities

Test Facilities

Test Cell
2



Building 91

Test Cell 3

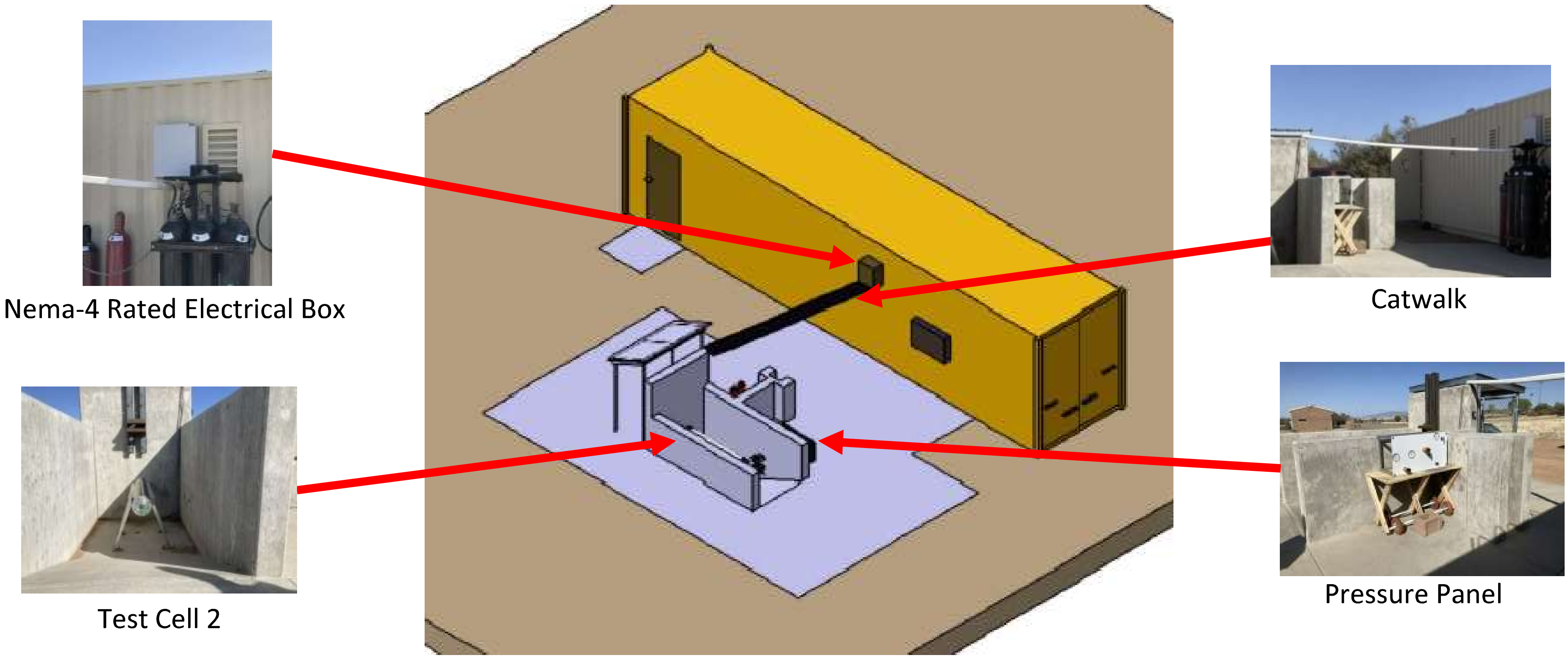
Test Facilities– PXI Express (PXIe)

- Pressure Transducer Ports
- Voltage Source
- Voltage Block
- 20 Talk Back Channels
- Power Back Up
- Uncertainty: ± 0.001 sec

TC3

PXIe [13]

Test Facilities– Integration



Instrumentation

Instrumentation List

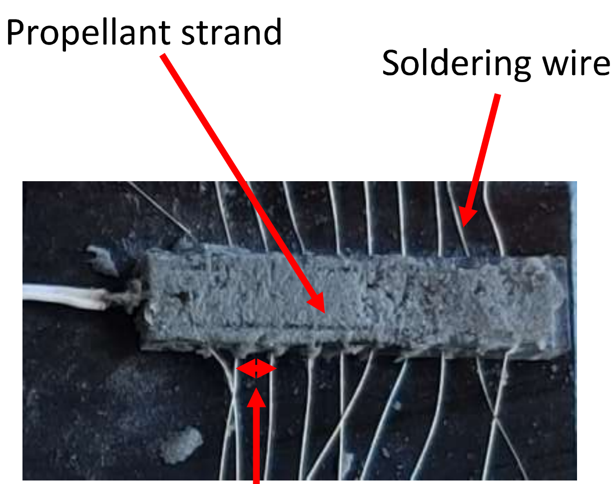
3000 psi Pressure Transducer [9]

- Measures chamber pressure to ± 7 psi
- Response time < 1 millisecond
- Can measure up to 3000 psi

Project Box and Resistors

- 9 Resistors in parallel inside Project Box
- Time of voltage drop across resistors recorded using PXIe to ± 0.001 seconds
- Under construction

Instrumentation List Cont.



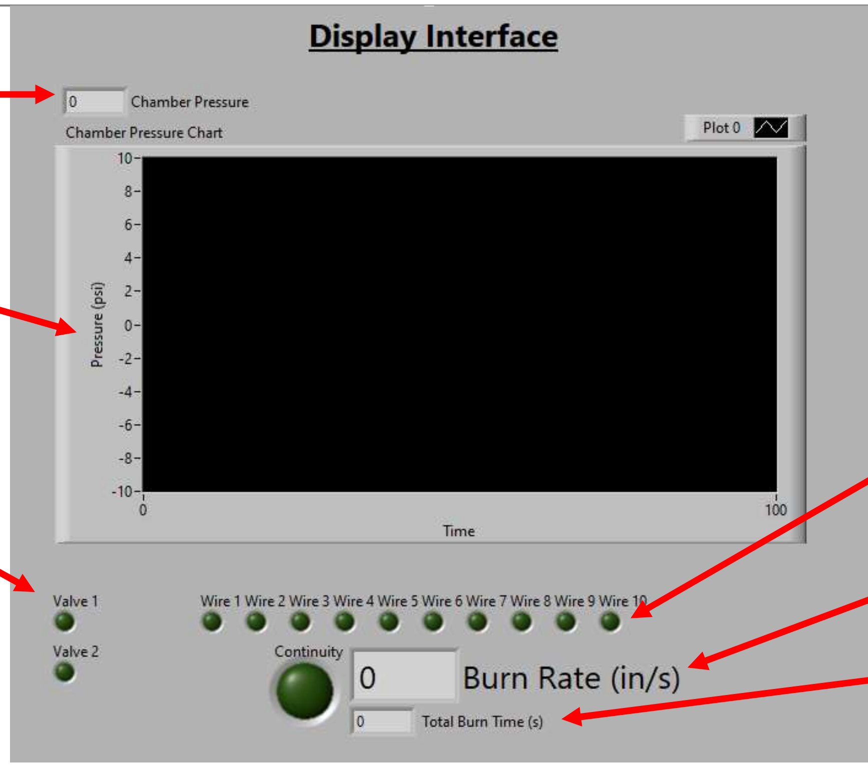
- Standardizes distance between wires across several strands
- The wire slots measured to ± 0.001 in

Instrumentation List Cont.

Final Chamber Pressure

Pressure Chart

Remote Valve States



Burnt Wire Indicator

Average Burn Rate (in/s)

Total Burn Time (s)

Uncertainty Analysis

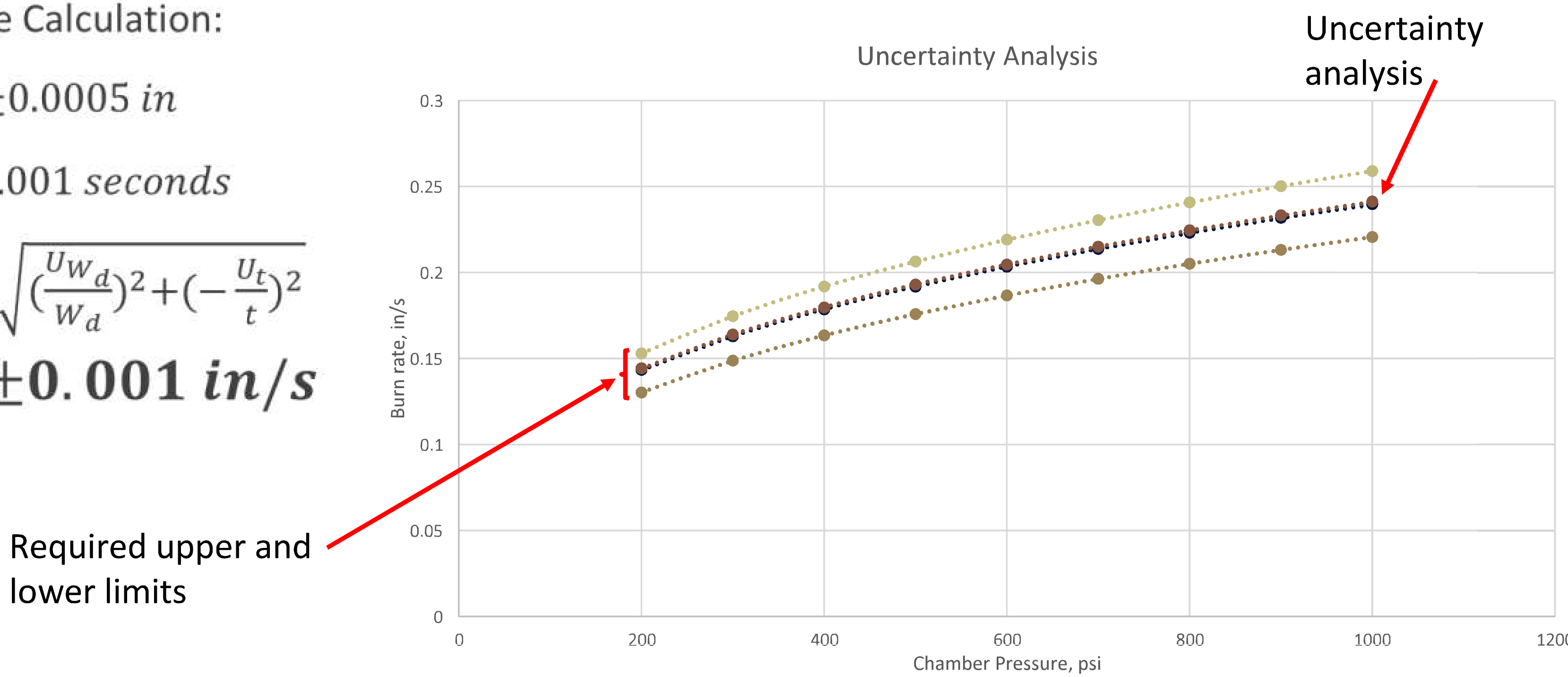
Burn Rate Calculation:

$U_{W_d} = \pm 0.0005\ in$

$U_t = \pm 0.001\ seconds$

$UU_{\dot{r}} = \dot{r}\sqrt{(\frac{U_{W_d}}{W_d})^2 + (-\frac{U_t}{t})^2}$

- $= \pm \mathbf{0.001}\ \boldsymbol{in/s}$



Uncertainty Analysis Cont.

‘a’ and ‘n’ value Calculation

- Assuming $U_a = U_n$
- $U_P = 7.5\ psi$
- $U_{\dot{r}} = 0.001 \frac{in}{s}$
- $U_a = \sqrt{(\frac{\partial a}{\partial \dot{r}} U_{\dot{r}})^2 + (\frac{\partial a}{\partial P} U_P)^2 + (\frac{\partial a}{\partial n} U_n)^2}$

$$\boldsymbol{U_a = 0.0003\ in/s}$$

Risk Analysis

Risk to Personnel – Risk Cube

Risk Cube: Personnel					
Risk Probability/ Severity	Catastrophic (A)	Critical (B)	Moderate (C)	Minor (D)	Negligible (E)
5					
4			35		
3		2	1, 5, 6, 14, 27	13, 22	
2		3	21	12, 32	
1	33, 34	4, 19	20		

Tripping/Slipping/Falling/Health Hazards
- 1-6, 32, 35

Handling of Test Article/Equipment
- 13-14, 20-22, 27

Rapid Unscheduled Disassembly
- 19, 34

Argon Exposure
- 33

A) multiple deaths
B) one death; serious/multiple long-term injuries or resulting in hospitalizations
C) minor injury
D) no injury or minor injury
E) no injury

Risk to Personnel – Mitigations Cube

Mitigation Cube: Personnel					
Risk Probability/ Severity	Catastrophic (A)	Critical (B)	Moderate (C)	Minor (D)	Negligible (E)
5					
4					
3					
2					
1			1, 2, 3, 4, 6	12, 13, 14, 20, 27, 22	5, 19, 21, 32, 33, 34, 35

Markings/Signage In and Around Test Cell 2
- 2-3, 6

Proper Training
- 12, 13, 22, 27

Handling of Test Article/Equipment
- Use of X-frame
- 14, 21, 33-34

Personnel Limitation/Exclusion Zone
- 1, 19-20

Other
- 4-5, 32, 35

Risk to Facilities and Equipment – Risk Cube

Risk Cube: Facilities and Equipment					
Risk Probability/ Severity	Catastrophic (A)	Critical (B)	Moderate (C)	Minor (D)	Negligible (E)
5					
4		30			10
3		17, 18, 23, 37, 38, 43	15, 24, 25, 28, 29, 36		
2		16, 26		44	
1	34		11		

Installation/Handling of Test Article/Equipment
- 15-16, 44

Operations
- 10, 36-38, 43

Manufacturing
- 11

Rapid Unscheduled Disassembly
- 17-18, 23-26, 34

Weather
- 28-30

A) cost of $250 or more or complete destruction of TC2 and/or equipment
B) $50k or more; severe damage to equipment
C) $5000 or less; some damage to equipment
D) $1000 or less; slight to no damage to equipment
E) $100 or less; no damage to equipment

Risk to Facilities and Equipment – Mitigations Cube

Mitigation Cube: Facilities and Equipment					
Risk Probability/ Severity	Catastrophic (A)	Critical (B)	Moderate (C)	Minor (D)	Negligible (E)
5					
4					
3					
2					43
1				11, 15, 16, 18, 37, 38	10, 17, 23, 24, 25, 26, 28, 29, 30, 34, 36, 44

Inspection of Setup
- 11, 16

Operations
- 16, 26, 34

Handling of Test Article/Equipment
- 15, 44

Design Parameters
- 10, 17-18, 23-25, 36-38, 43

Storage of Test Article/Equipment
- 28-30

Risk to Success of the Test – Risk Cube

Risk Cube: Success of the Test					
Risk Probability/ Severity	Catastrophic (A)	Critical (B)	Moderate (C)	Minor (D)	Negligible (E)
5				31	
4		30	7		
3		17, 18, 23, 24, 25, 43	15, 28, 29, 36, 37, 38, 42	39, 40, 41	
2		16, 26	8, 9	12, 44	
1	34		11		

Operations
- 7-9, 31, 36, 37-43

Manufacturing
- 11

Installation/Handling of Test Article/Equipment
- 12, 15-16

Rapid Unscheduled Disassembly
- 17-18, 23-26, 34

Weather
- 28-30, 44

A) greater than a month schedule delay; complete failure of testing
B) schedule delay greater than two weeks
C) schedule delay greater than three days
D) schedule delay greater than 1 day
E) schedule delay due to equipment malfunction (couple of hours)

Risk to Success of the Test – Mitigations Cube

Mitigation Cube: Success of the Test					
Risk Probability/ Severity	Catastrophic (A)	Critical (B)	Moderate (C)	Minor (D)	Negligible (E)
5					
4					
3					
2					
1				11, 12, 15, 16, 18, 37, 38, 39, 40, 42	7, 8, 9, 17, 23, 24, 25, 26, 28, 29, 30, 31, 34, 36, 41, 44

Design Parameters
- 7-9, 17-18, 23-25, 36-38, 42-43

Inspection of Test Article/Equipment
- 11, 16

Operation
- 16, 26, 31, 34

Training
- 12, 39-42

Handling of Test Article/Equipment
- 15

Storage of Test Article/Equipment
- 28-30, 44

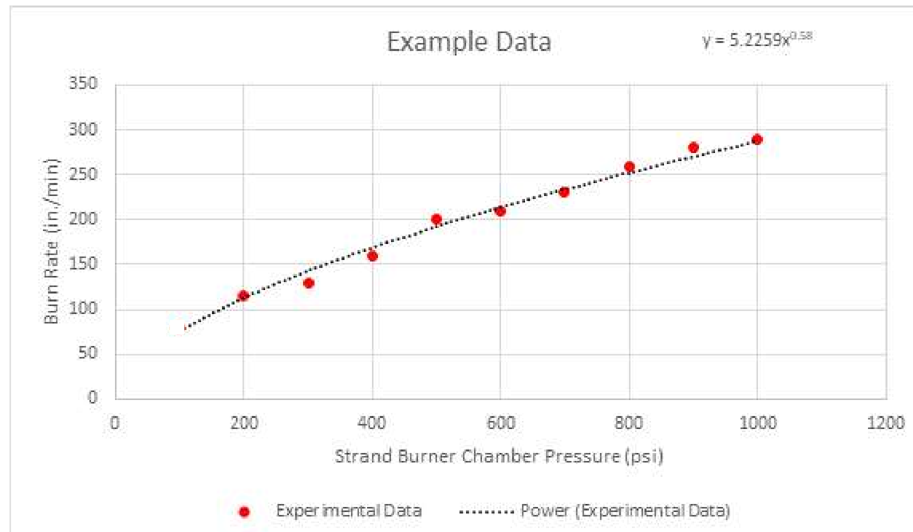
Post-Test Analysis

Post Test Analysis

- Calculate burn rate for each wire section
- Plot the burn rate versus Pressure from all tests
- Obtain ‘a’ and ‘n’ values from power line best fit
- Compare results from MIT data and new collected data
- Perform uncertainty calculations for ‘a’ and ‘n’ values

Post Test Analysis

- 9 burn rates per test plotted against respective pressures
- Power line of best fit for a and n values
- a and n used to find mass flow rate, thrust, and nozzle design
- Makes testing safer and more efficient



Testing Schedule

Testing Schedule

Tests 1-3
Thursday

Tests 4-6
Friday

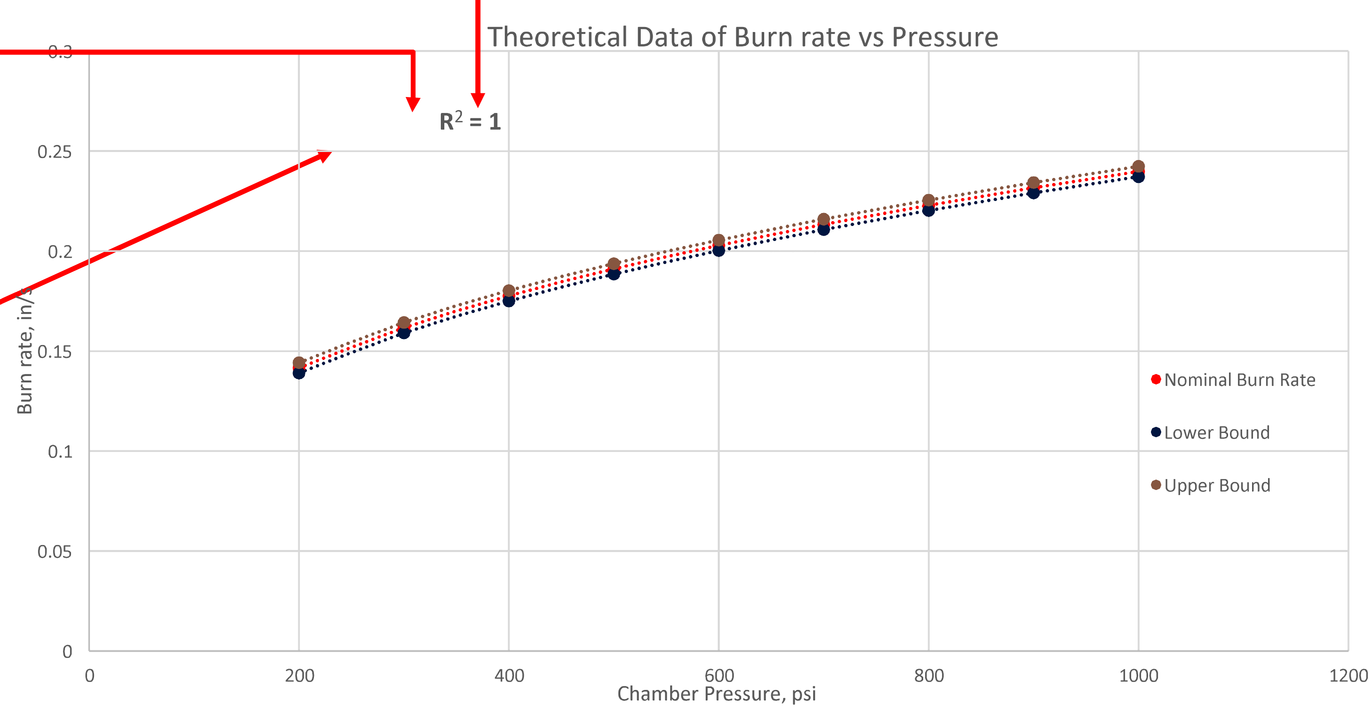
Tests 7-9
Saturday

Instrumentation Analysis

‘a’ value
± 1.3%

Burn rate
equation

‘n’ value ± 0.1%



Structures

Subsystem Requirements – Structures

- The strand burner must have a factor safety of 3 [1.1.13]
- Compatible with all current motor sizes build on campus [1.1.2]
- Structurally sound for up to 10 years [1.1.7]

Subsystem Materials – Structures

Materials

1018 Hot Roll Steel Threaded cap [2]

ASTM A500 Grade B Threaded Steel pipe [3]

12L14 Cold Rolled Steel face plate [4]

Subsystem Governing Equation - Structures

Temperature of combustion gases in Kelvin [5]

$$T_f = \frac{\Delta u m_p}{C_v} + T_i$$

T_g = Temperature of gases including Argon

Δu = Amount of energy released (NASA CEA)

m_p = Mass of propellant

C_v = Specific heat capacity of gases

T_i = Initial temperature = 293 K

Final chamber pressure after propellant is burnt [5]

$$P = \frac{m_g R_g T_g}{V_{ch}}$$

m_g = Mass of all gasses including argon

R_g = Gas constant (including argon)

T_g = Final temperature in chamber

V_{ch} = Volume of the chamber

Subsystem Governing Equation - Structures

Percent increase in chamber pressure

$$P_{inc} = \frac{p_i - p_f}{p_i} \times 100$$

Maximum Pressure increase is 5%

p_{inc} = Percent increase in pressure

p_i = Initial chamber pressure
p_f = Final chamber pressure

Temperature of outer surface of the pipe [6]

$$T_2 = \frac{\Delta U}{mC_p} + T_1$$

m = Total mass of structural components

C_p = Specific heat capacity of steel

T_1 = Initial temperature of chamber

T_2 = Final temperature in chamber
ΔU = Total energy released

Pipe Wall Numerical Heat Transfer Analysis

Assumptions:

- Plane wall transient heat transfer
- Adiabatic (heat does not enter or leave the system) back face with infinite convection coefficient
- Gas temperature obtained from NASA CEA
- All energy released transferred to the pipe

Temperatures in the table are in Kelvin

303.3	303.6	303.9	304.2	304.6	304.9	305.2
303.4	303.7	304.0	304.3	304.6	304.9	305.2
303.4	303.7	304.0	304.3	304.6	304.9	305.2
303.4	303.7	304.0	304.3	304.6	304.9	305.3
303.5	303.7	304.0	304.3	304.6	304.9	305.3
303.5	303.8	304.1	304.3	304.7	305.0	305.3
303.5	303.8	304.1	304.4	304.7	305.0	305.3
303.6	303.8	304.1	304.4	304.7	305.0	305.3
303.6	303.8	304.1	304.4	304.7	305.0	305.3
303.6	303.9	304.1	304.4	304.7	305.0	$\boxed{305.3}$

90°F

Subsystem Governing Equation - Structures

Minimum thickness of pipe [7]

$$th = \frac{r_i P}{A_S E - 0.6P}$$

th = Minimum thickness of pipe

r_i = Inner radius of pipe

P = Chamber pressure

A_S = Maximum allowable stress of pipe material
E = Joint efficiency

Additional thickness due to threads [7]

$$t = \frac{0.8}{n}$$

t = Additional thickness due to threads on the pipe

n = Number of threads per inch

Subsystem Governing Equation - Structures

Moment at point b [8]

$$M_{rb} = qa^2 \left(\frac{L14}{C5}\right)$$

M_{rb} = Moment at point b

q = Pressure
a = Radius of plate
L14 & C5 = Constants

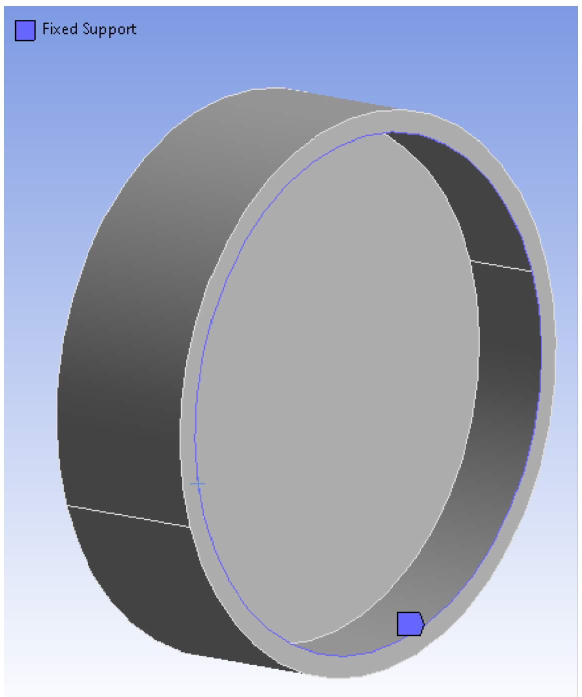
Stress at point b [8]

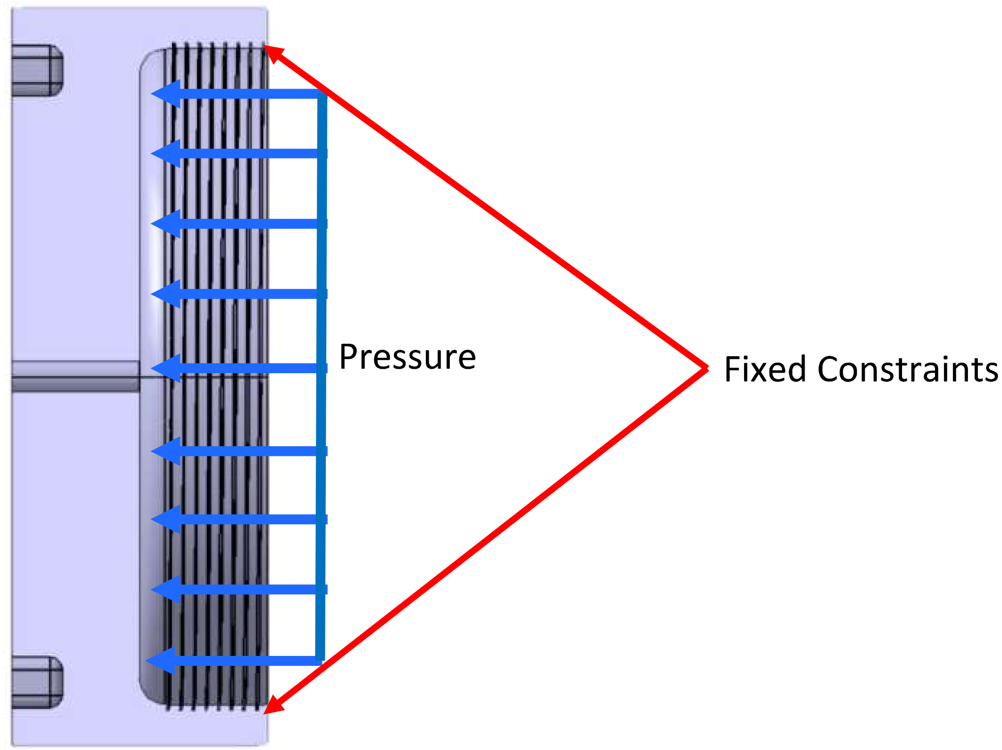
$$\sigma_{rb} = \frac{6M_{rb}}{th^2}$$

σ_{rb} = Stress at point b

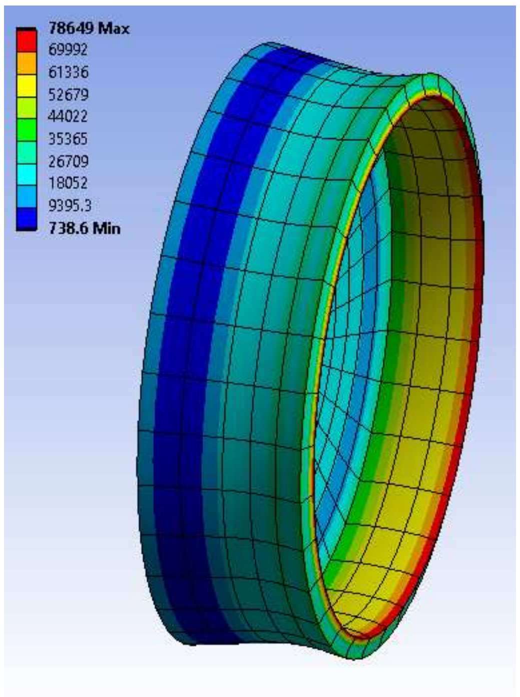
th = Minimum thickness of caps

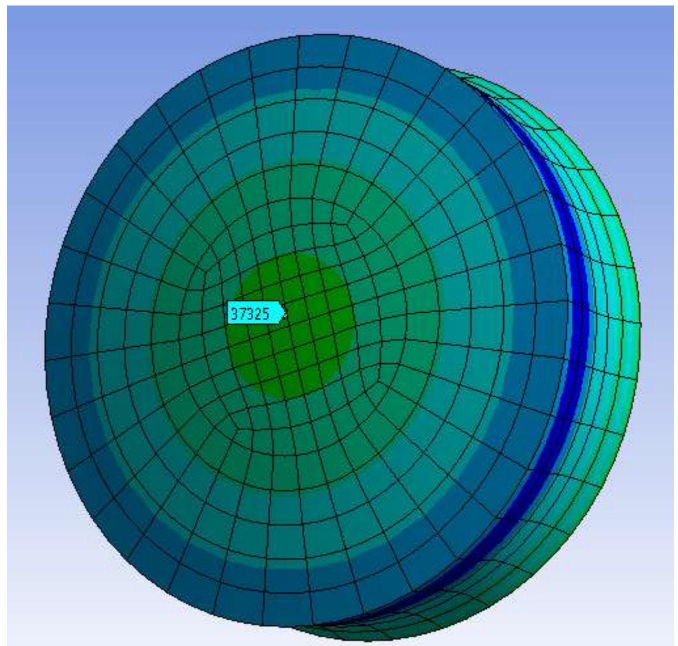
Numerical Analysis of Threaded Caps





Numerical Analysis of Cap Thickness





- Maximum stress: 37325 psi
- Hand calcs: 38352 psi
- Tensile strength: 58000 psi

Subsystem Governing Equation - Structures

Number of threads in caps [9]

$$n = \frac{F_p}{0.5\tau_s p \pi d}$$

n = Number of threads

τ_s = Shear strength
p = Pitch
d = Pitch diameter
F_p = Force on the plate

Subsystem Governing Equation - Structures

Number of cycles before failure [10]

$$a = \frac{(f S_{ut})^2}{S_e}$$

$$b = -\frac{1}{3}\log\left(\frac{f S_{ut}}{S_e}\right)$$

$$N = \left(\frac{\sigma_{rev}}{a}\right)^{\frac{1}{b}}$$

f = Fatigue strength fraction

S_{ut} = Ultimate tensile strength

S_e = Endurance limit

a = Constant

b = Constant

N = Number of cycles before failure

σ_{rev} = Completely reversed stress

N = 37430 cycles

Subsystem Governing Equation-Structures

Stress in bolts of face plate

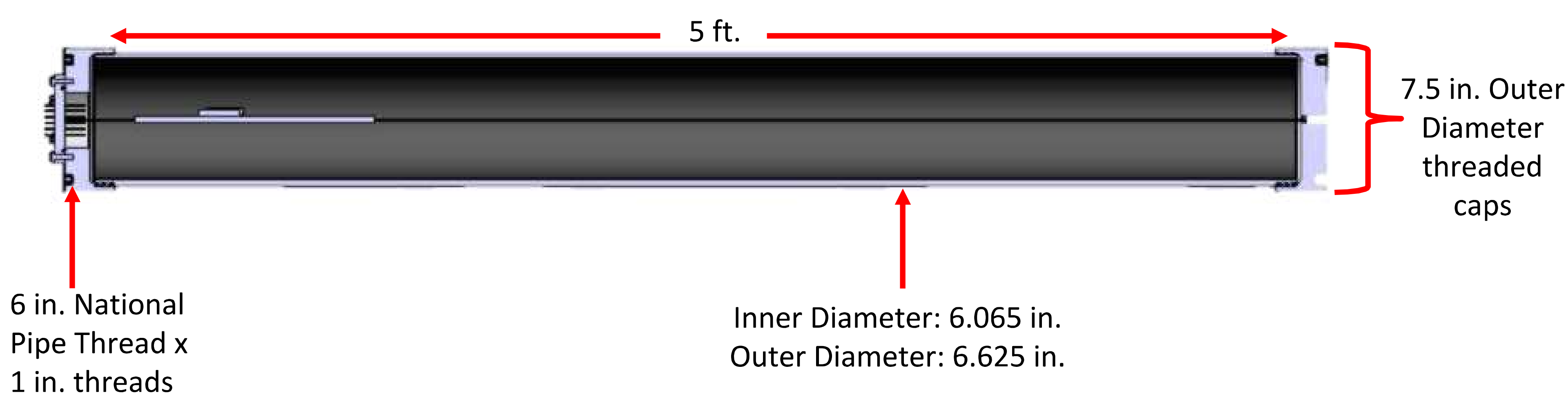
$$\sigma = \frac{\pi d^2}{4} \frac{p}{6}$$

$\boxed{2863 \text{ psi}}$

Tensile strength of ¼ 28 bolts: **3000psi**

d = Diameter of face plate
P = Chamber pressure
σ = Stress in bolts

Subsystem Dimensions- Structures



Subsystem Summary- Structures

- Strand burner is made of ASTM A500 Grade B pipe with inner diameter of 6 in. and length of 5 ft.
- 1 in. NPT 6 in. threading on both ends of the pipe
- Two 2 in. threaded caps are made of 1018 Hot Roll Steel

Requirements					
Number	Title	Value	Analysis Value	Verification Method	Meets Requirements
1.1.13	Factor of Safety for pipe and caps	≥ 3	≥ 3	Hydrostatic Test	TBD

Pressure System

Subsystem Requirements – Pressure System

The Pressurization Panel must meet these requirements:

- Pressurization Panel will be proofed to 1.5x MEOP; 4.5 ksi. [1.1.14]
- Must deliver Argon to valve actuators at a pressure of 80 psi., but no more than 120 psi.
- Must deliver Argon to Strand Burner at a pressure of 1000 psi.
- Methods to relieve pressure from system in event of over-pressurization

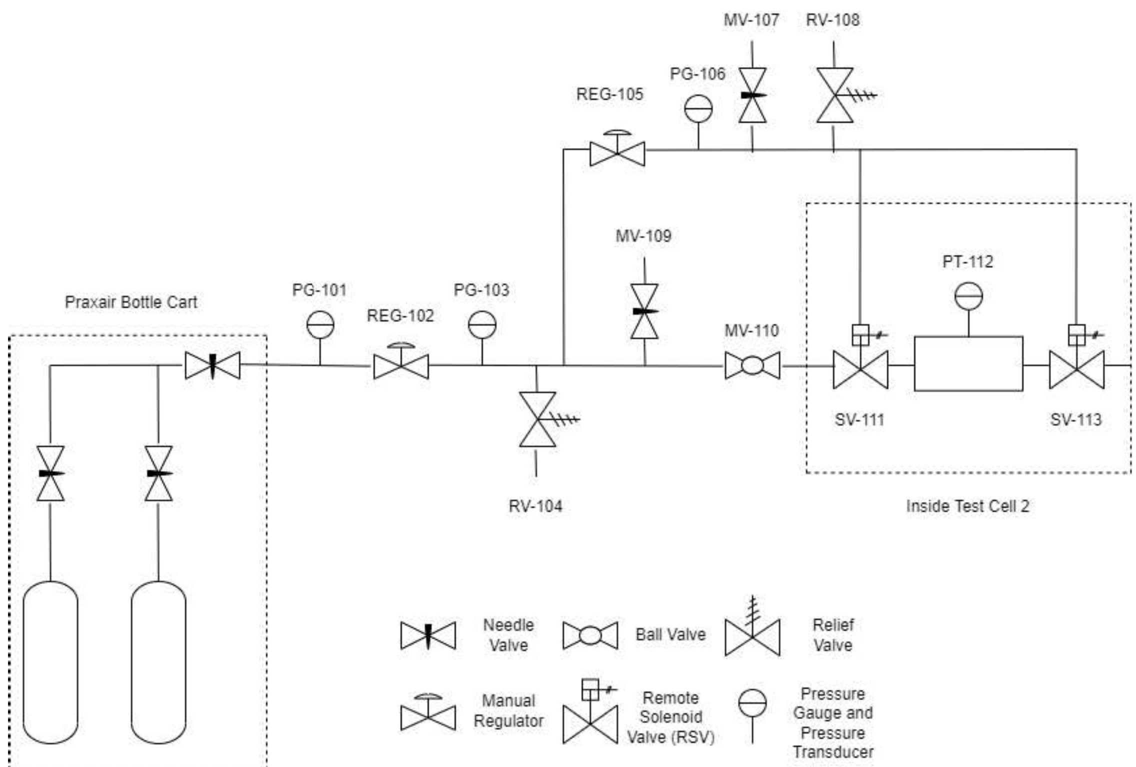
The Strand Burner must meet these requirements:

- Strand Burner will be proof tested to 3x MEOP; 3 ksi. [1.1.13]
- Must be able to vent pressure from Strand Burner remotely

Subsystem Materials – Pressure System

- ¼” x 0.049” S.S. Tubing
- High Pressure Regulator with 6 ksi. input/2 ksi. output
- Muscle Pressure Regulator with 6 ksi. input/200 psi. output
- ¼” Needle Valves rated to 6 ksi.
- ¼” Ball Valve rated to 6 ksi.
- High Pressure Relief Valve set at 3 ksi.
- Muscle Pressure Relief Valve set at 125 psi.
- Pressure Transducer rated to 3 ksi.

Subsystem Integration – Pressure System



Unless otherwise specified, components will be located on the pressurization panel

The electronically actuated valves will be inside Test Cell 2 and connect to the PXIe located in TC3

Regulators control the pressure level to the valves and strand burner

Hazardous Operation Assessment Definition

Severity Ratings:

1 – Not a risk to system/personal/data and/or minor time loss
2 – Loss of consumables and/or minor to no injury to personnel and/or major time loss
3 – Damage to component and/or minor injury to personnel and/or loss of data
4 – Damage to system and/or loss of component and/or severe injury to personnel
5 - Complete loss of article and/or loss of life

Likelihood Ratings:

1 - Will most likely never occur in the life of the system
2 – Likely to occur once every 100+ uses of system
3 - Likely to occur once every 50+ uses of system
4 - Likely to occur once every 10+ uses of system
5 - Guaranteed to occur with every use of system

S L	1	2	3	4	5
1	1	2	3	4	5
2	2	4	6	8	10
3	3	6	9	12	15
4	4	8	12	16	20
5	5	10	15	20	25

Risks – Pressure System

- Manual Iso (MV-110): Misconfigured Closed
- Remote Press (SV-111): Loss of control
- **Remote Vent** (SV-113): Loss of control
- **Manual Vents** (MV-107,109): Misconfigured Open
- **REG's** (REG-102,105): Fail full open

Severity \ Likelihood	1	2	3	4	5
1				**Manual Iso**	
2		**Remote Press**		**Manual Vents**	
3					
4		**REG's, Remote Vent**			
5					

Mitigation – Pressure System

- Manual Iso (MV-110): Procedures, Training
- Remote Press (SV-111): Fail state closed, procedures, isolation
- **Remote Vent** (SV-113): Proofing, fail open
- **Manual Vents** (MV-107,109): Procedures, training
- **REG's** (REG-102,105): Proofing, isolation, pressure visibility, relief valves.

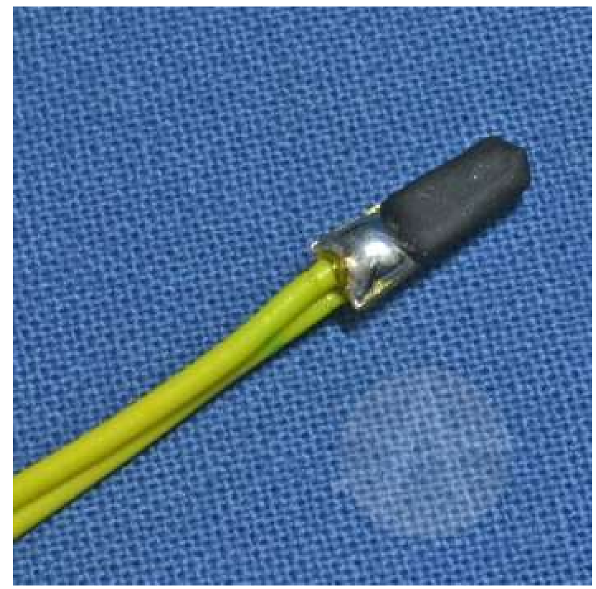
Severity \ Likelihood	**1**	**2**	**3**	**4**	**5**
1		**Remote Press**			
2		**Manual Iso, Remote Vent, Manual Vents, REG's**			
3					
4					
5					

Ignition

Subsystem Requirements – Ignition

The ignition system must satisfy requirement [1.1.5]:

- Must ignite propellant 90% of the time



E-Match [11]

Subsystem Materials – Ignition

- Electric Matches
- Ignition Switch Box
- Continuity Lights
- Ignition and Continuity Wiring

Subsystem Analysis – Ignition

Benefits:

- Highly versatile
- Easy to implement and use
- Good compromise between cost and reliability
- Existing protocols that address safety concerns

Concerns:

- Premature Ignition
  - Mitigation: Circuit continuity lights & control lockout key

Manufacturing Plan – Ignition

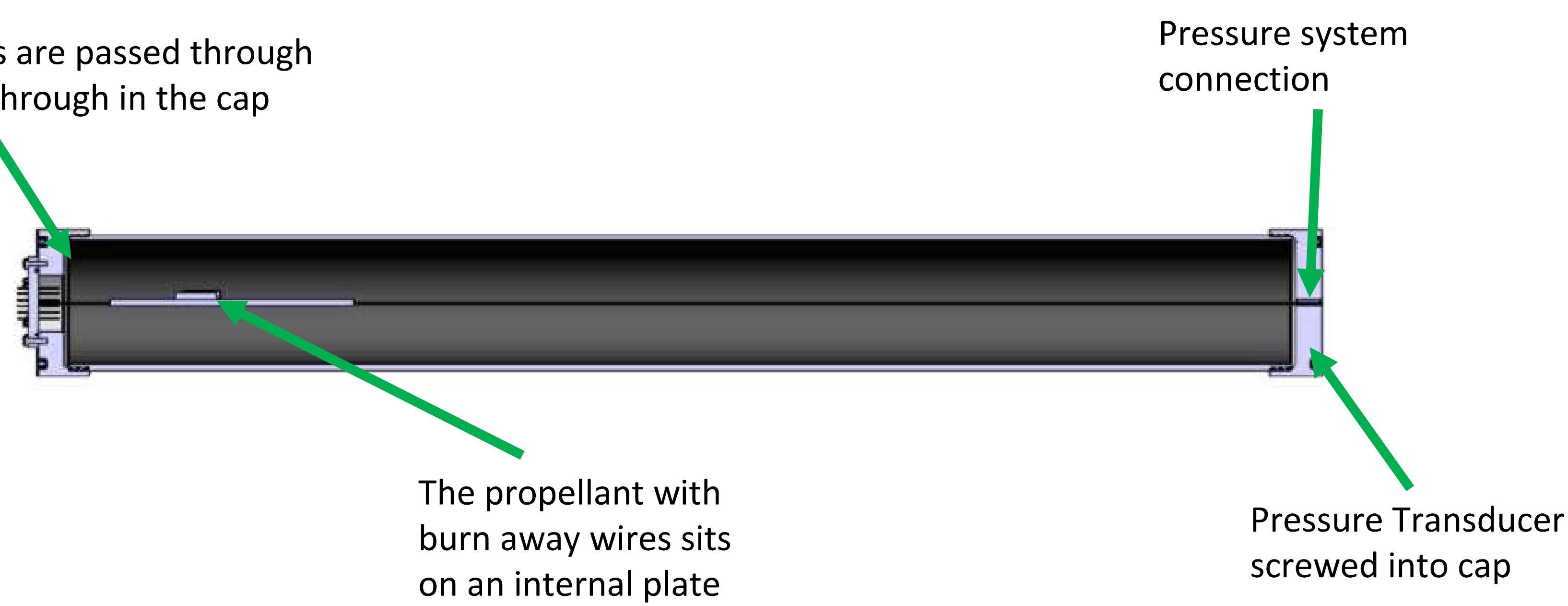
The manufacturing plan for the ignition system consists of two parts:

- Propellant Integration
  - Match is placed in propellant jig during the propellant casting processes

- Electrical System
  - Electric connector/wires for match are routed out of strand burner via pass-throughs
  - Wiring will connect to ignition switch box
  - Continuity lights will be installed in the switch box and/or wiring that show when the circuit is hot

Burn-Away Solder Wires

Subsystem Overview – Burn-Away Solder Wires



Subsystem Requirements – Burn-Away Solder Wires

The subsystem must meet requirement [1.1.1] :

- Must be able to support a 100 Hz. measurement speed
- Must have a 90% confidence interval for data collected

Materials – Burn-Away Solder Wires

Material	How to acquire?	Dimensions
Fire Lizard Propellant	Produced on Campus	0.25 in. X 0.25 in. X 2 in.
Propellant Jig	Machined	0.25 in. X 0.25 in. X 2 in.
Plexiglass	Purchase	N/A
Thin Solder Wire	Purchase	0.3 mm.
Sealant	Purchase	N/A
Mold Release	Purchase	N/A

Subsystem Governing Equation – Burn-Away Solder Wires

Discrete linear burn rate [12]

$$\dot{r}_i = \frac{l}{t}$$

Average burn rate [12]

$$\dot{r}_{avg} = \frac{\sum \dot{r}_i}{\# \, \dot{r}_i{}'s}$$

$\dot{r}$ = Burn Rate

l = Distance between wires

t = Time between wire breaks

Subsystem Analysis - Burn-Away Solder Wires

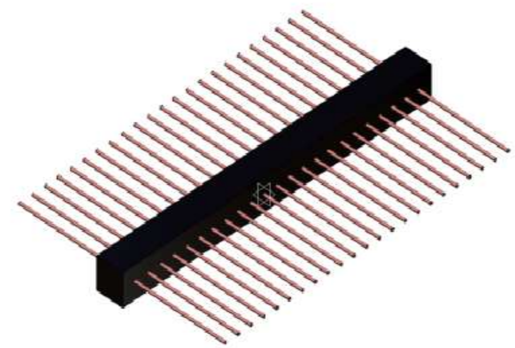
- The burn rate is calculated for each of the individual lengths and averaged
- The burn rate is plotted against the corresponding pressure
- A series of 9 tests is conducted before one can calculate the a and n values

Manufacturing Plan- Burn-Away Solder Wires

The manufacturing plan for this system includes two parts:

- The propellant itself:
  - Made in small batched using the RDL mixing procedures
  - Fire Lizard Recipe (Eagle Space Flight team working propellant)
  - Poured into jigs for consistency

- The propellant jigs consists of:
  - Plexiglass
  - Sealed with epoxy
  - Coated with mold release
  - Wire Slots



Data Acquisition Software and Interfacing

Subsystem Requirements – Data Acquisition Software and Interfacing

Subsystem must satisfy the following requirements:

- The data acquisition system must interface with the *PXIe* and Test Cell 3

  [1.1.4]

- Continuity light must turn on while connected to the ignition circuit [1.1.8]

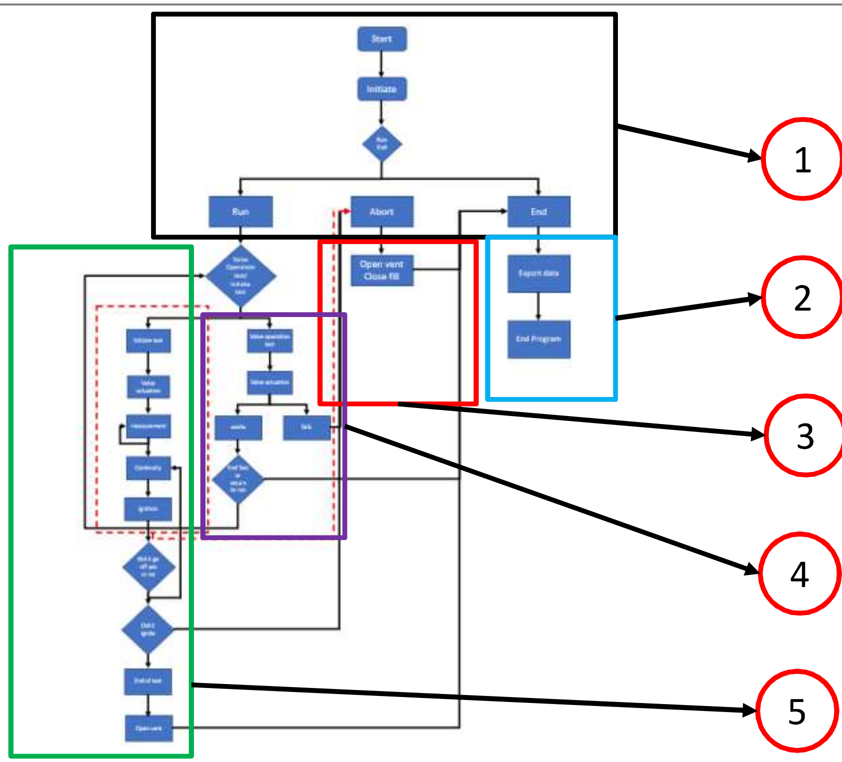
- Lockout key must be used in the ignition box to prevent premature ignition

  [1.1.9]

Materials– Data Acquisition Software and Interfacing

Material	How to acquire?	Dimensions
Connection Wires	Produced on Campus	N/A
PXIe	Customer Supplied Equipment	N/A
LabVIEW	Customer Provided Code	N/A
NEMA 4 Rated Box	Purchase	20x16x6
Catwalk	Purchase	N/A
Cable Connections	Purchase	N/A

Subsystem Integration – Control Code Flow Diagram



1: Initialization and High -Level Breakdown

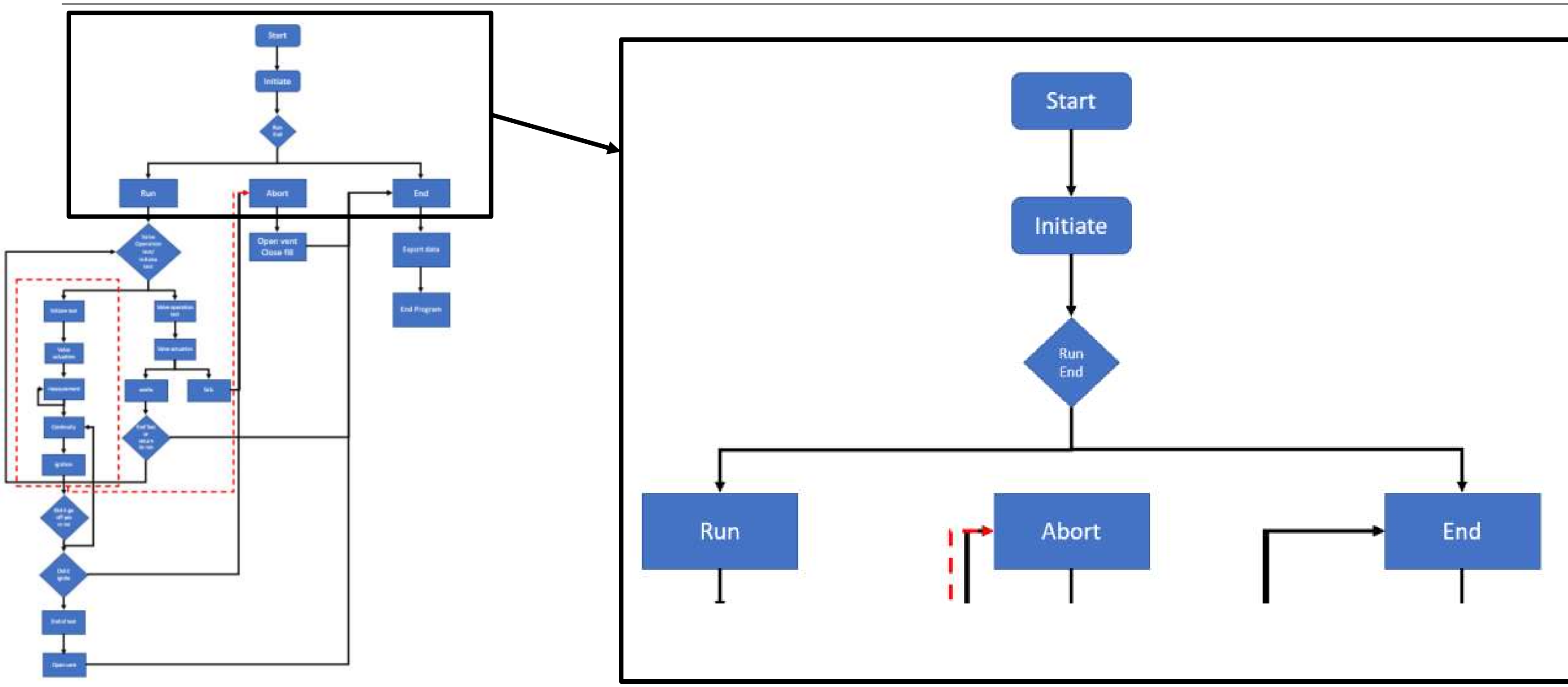
2: End of Program

3: Abort Case

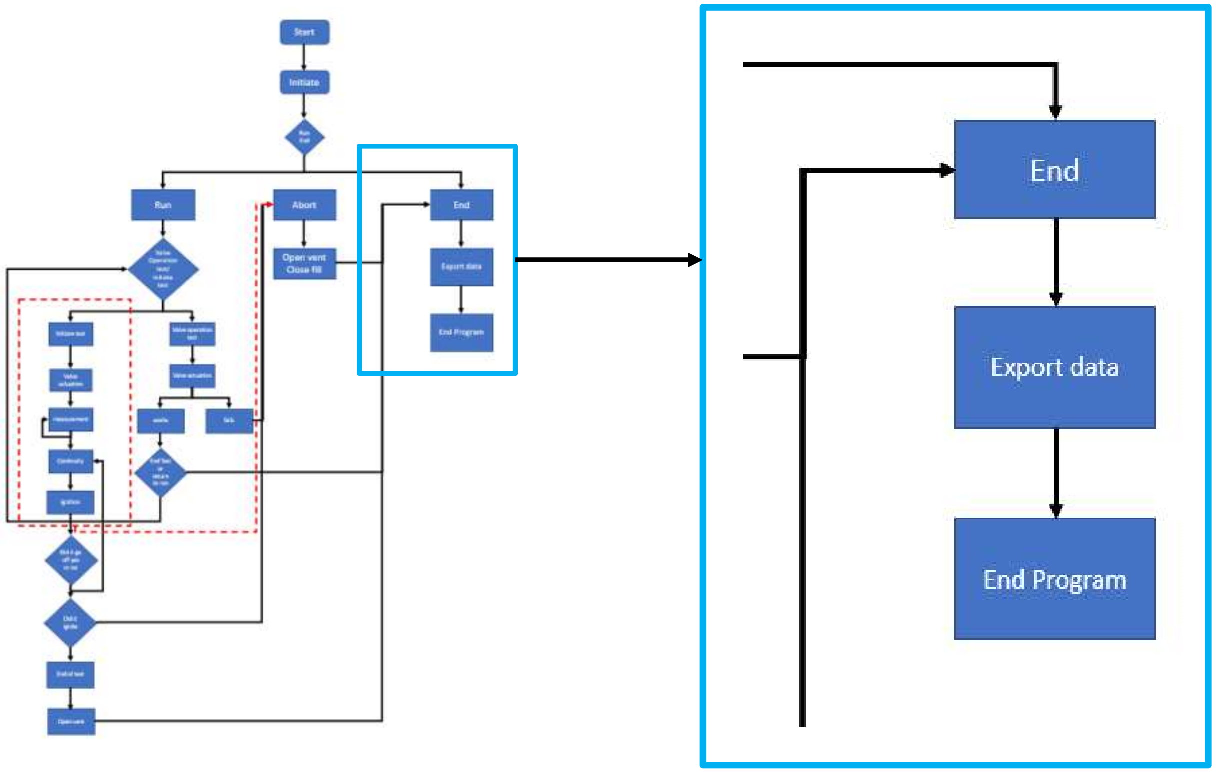
4: Valve Test Case

5: Test Run Case

Control Code Flow Diagram- 1: Initialization and High-level Breakdown



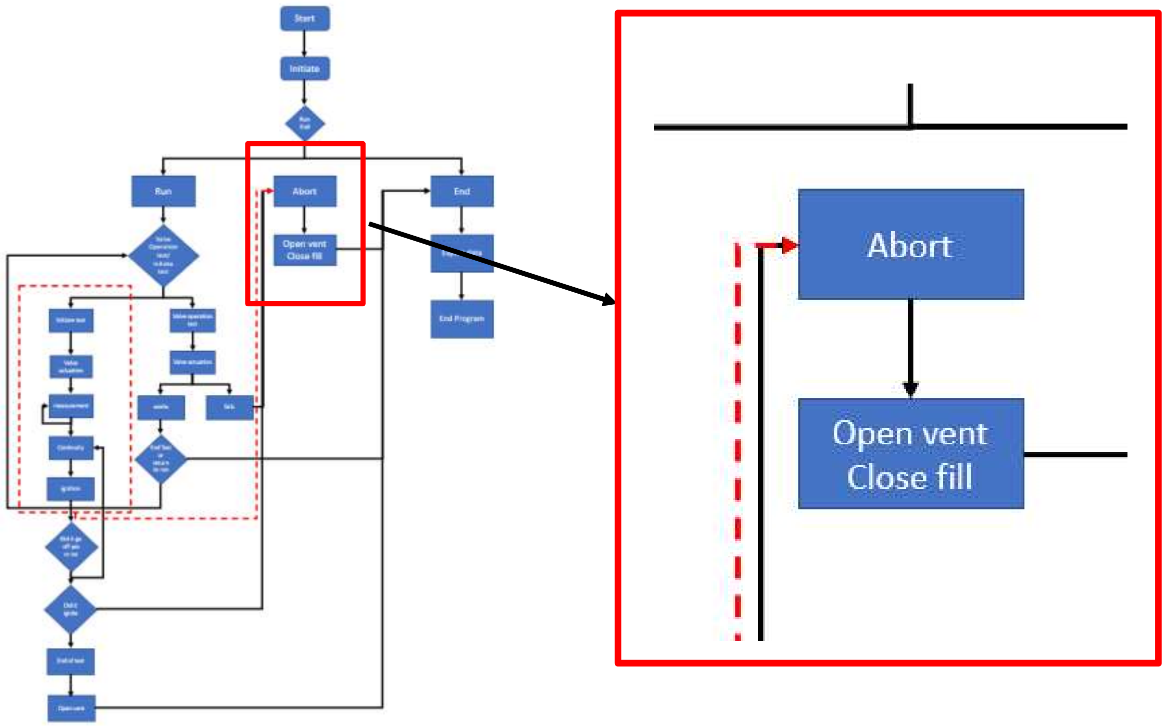
Control Code Flow Diagram- 2: End Case



Inputs from command on:

- Initialization
- Valve Test
- Measurement and Testing
- Abort

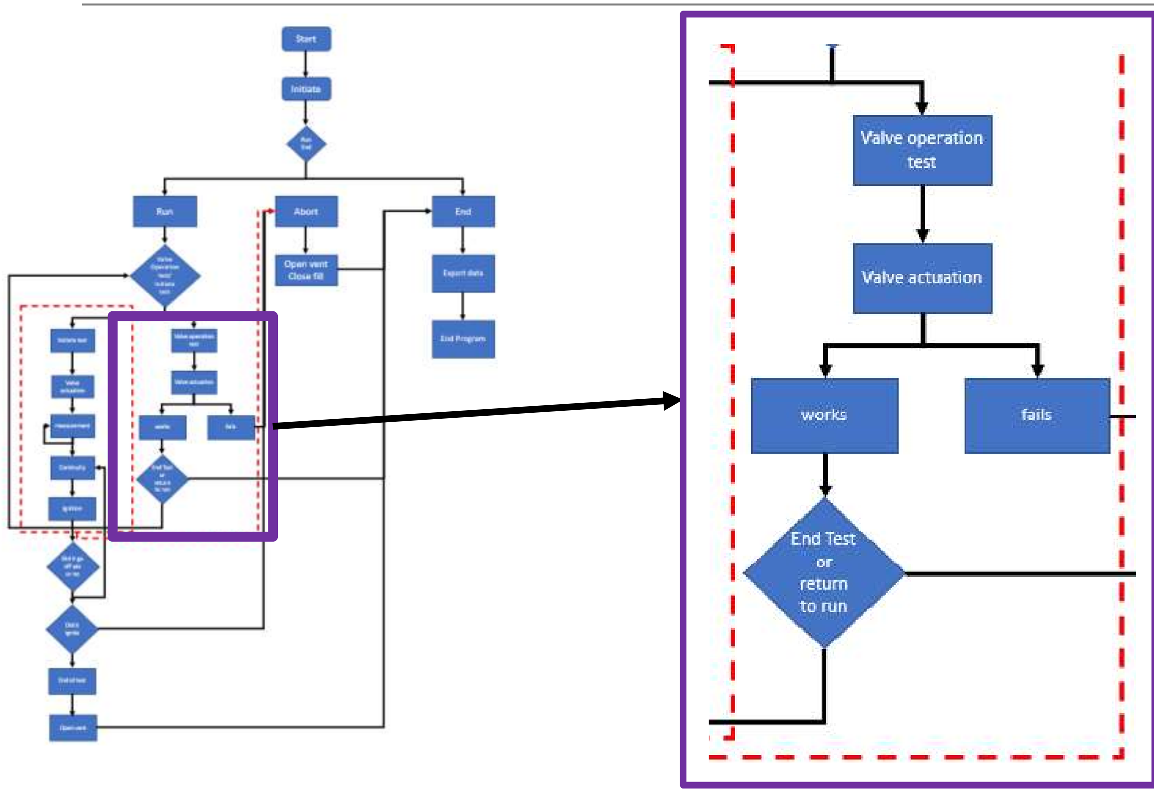
Control Code Flow Diagram- 3: Abort Case



Inputs from command on:
- Manual Button
- Valve Test

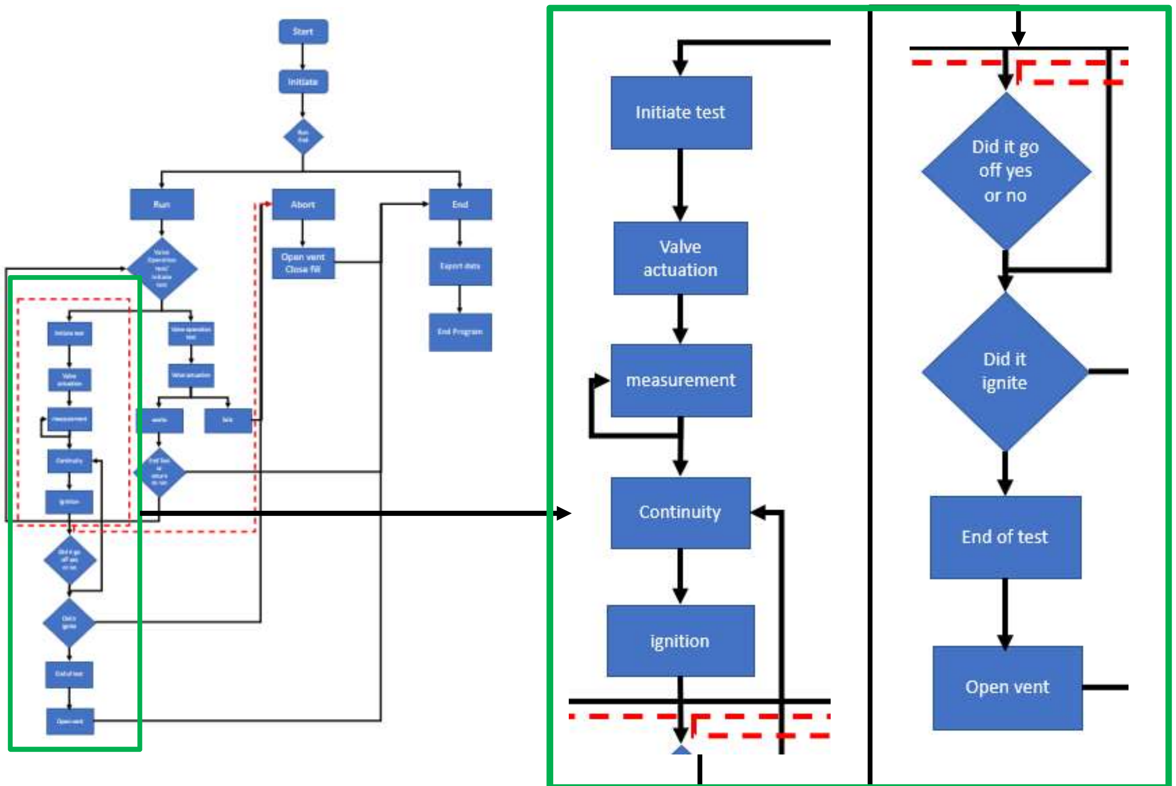
Output:
- End
- Reset

Control Code Flow Diagram- 4: Valve Test Case



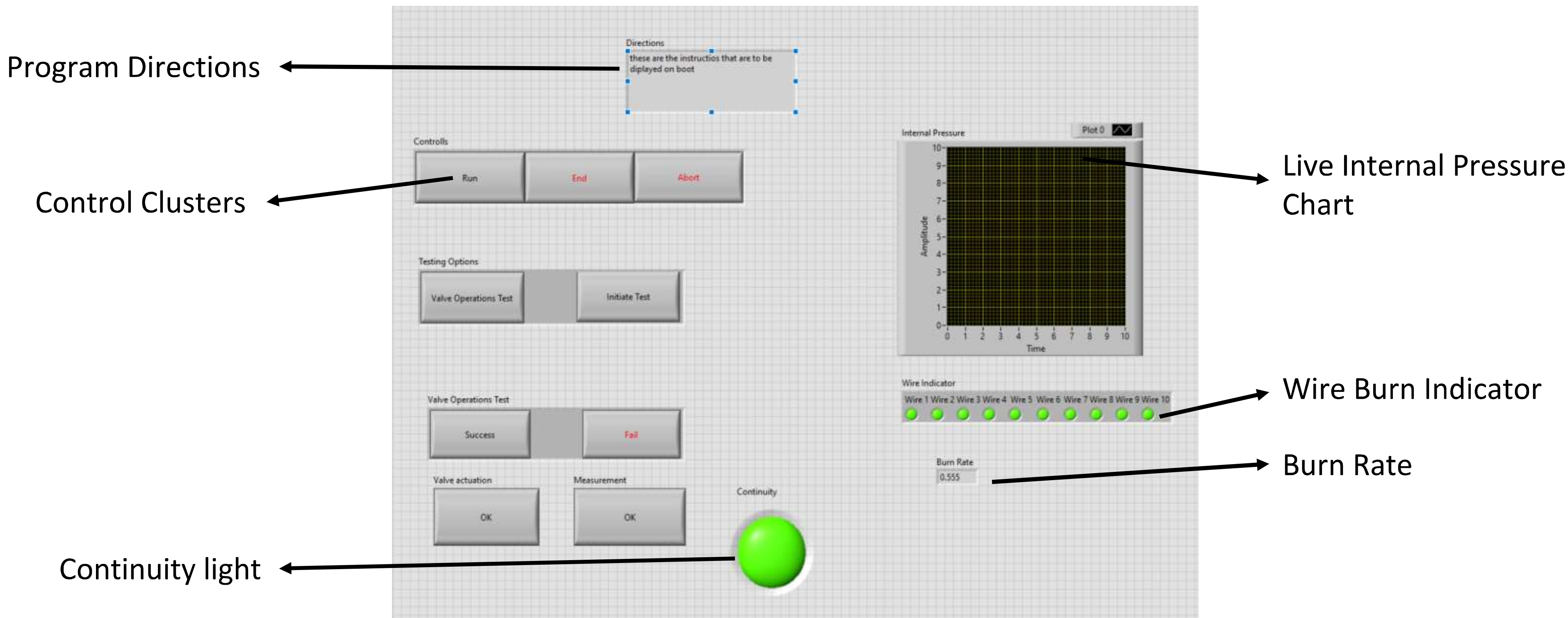
- One branch of the Run Case
- Allows for pre-test verification of valve operation
- Allows for user to end program or to continue to testing

Control Code Flow Diagram- 5: Test Run Case



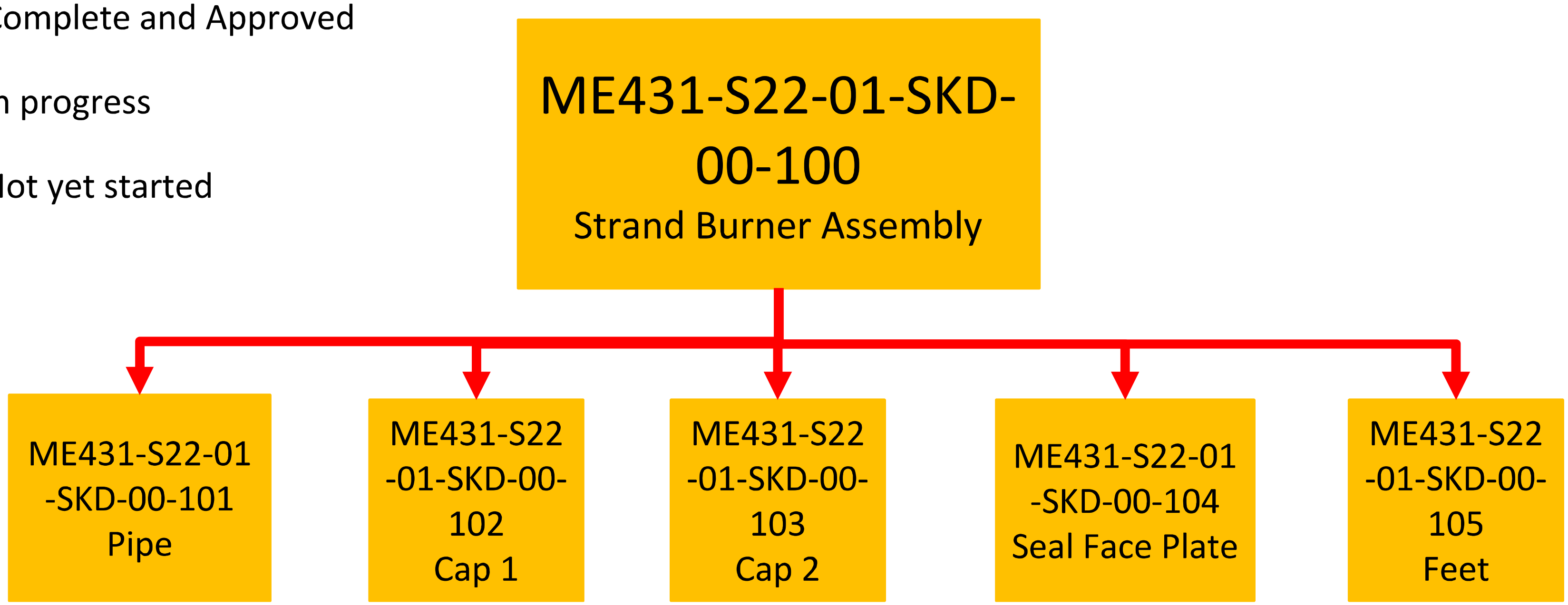
- Holds code to run the test
- Actuate valves for testing
- Records measurements and live data in recursive loop
- Can abort during test if needed

Subsystem Integration – Control Code Interface Panel

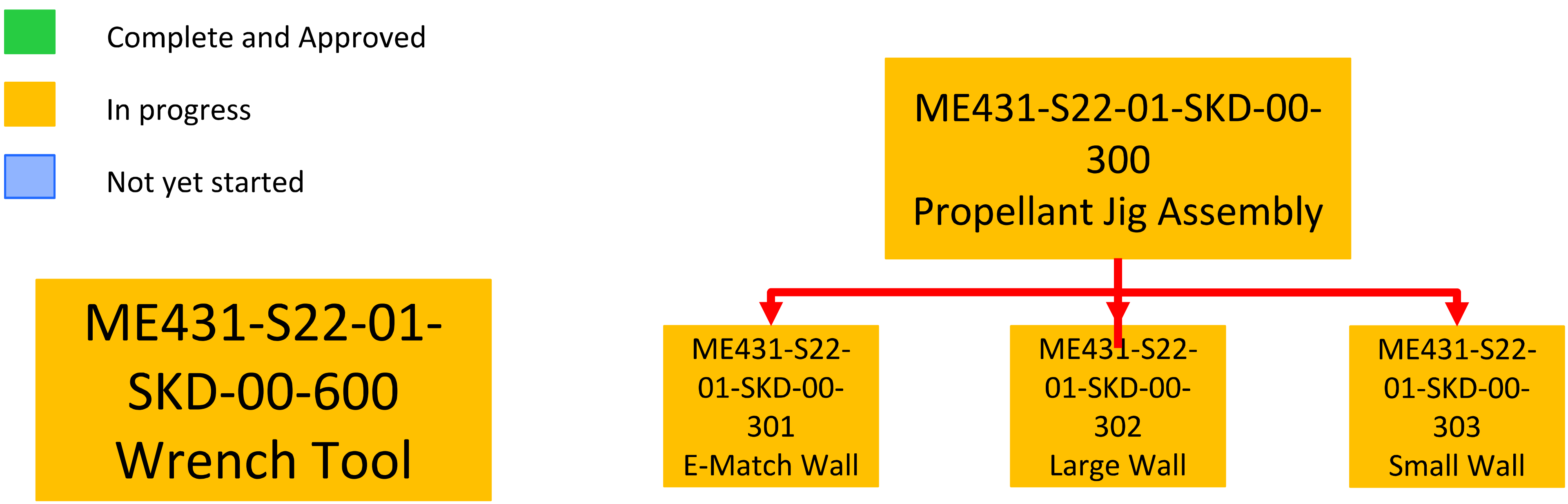


Drawing Trees

- Complete and Approved
- In progress
- Not yet started



Drawing Trees

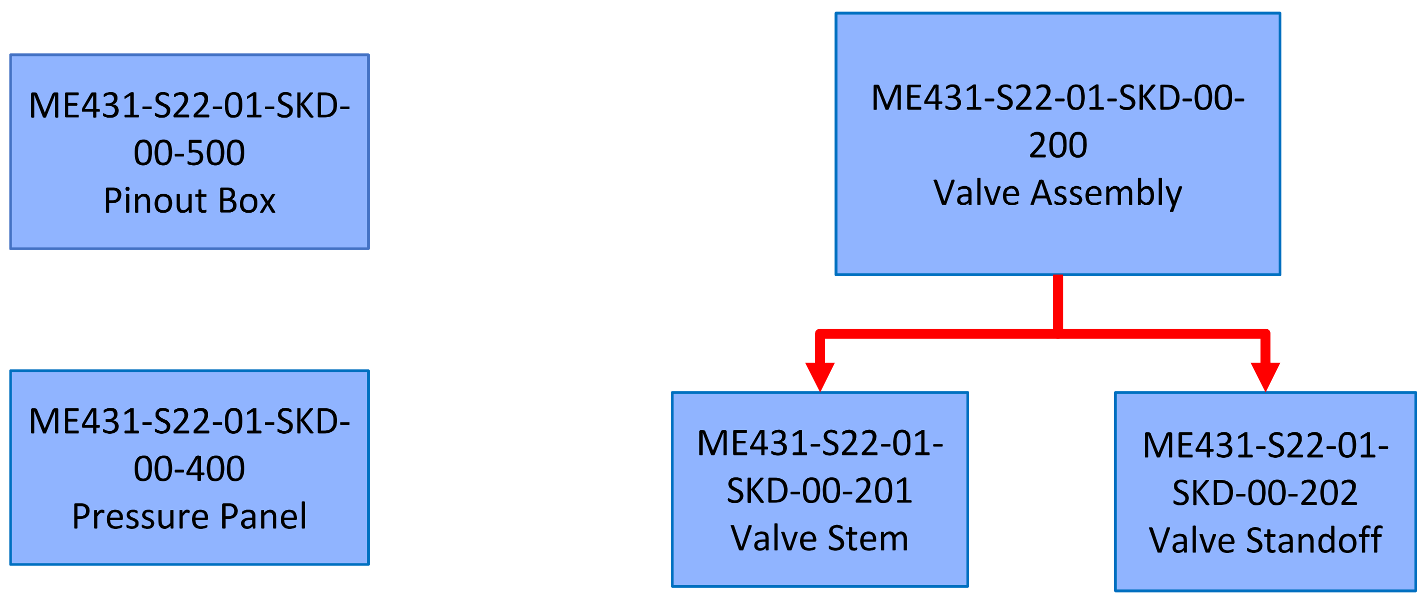


Drawing Trees

Complete and Approved

In progress

Not yet started



Manufacturing Plan

Step 1
- Place an order of materials

Step 2
- Receipt of ordered materials

Step 3
- Outsource pipe for threads
- CNC caps out of round bar
- Cut out propellant jig
- Water jet pressure panel

Manufacturing Plan

- **Step 4** — Cut out Valve stems
- **Step 4** — CNC Face plates & thread caps
- **Step 4** — Mill wrench tool & Pinout Box

Manufacturing Plan

- **Step 5** — Standoffs for valves & tap caps
- **Step 5** — Machine Feet & Shrink fit wrench tool
- **Step 5** — Install wires and seal them in Epoxy

Manufacturing Plan

- **Step 6** — Coat the Pipe interior
- **Step 6** — Coat the Caps interior
- **Step 6** — Install the NEMA box in TC3

Bill of Materials

Item	Cost per It	Quanti	Extended P	Website	Shipping	Tax	Total
Strand Burner							$ 1,176.16
6" diameter, sch 40 steel pipe	$ 254.75	1	$ 254.75	https://www.metalsdepot.co	$ 17.28	$ 24.20	$ 296.23
steel round bar (1018 hot rolled	$ 140.67	1	$ 140.67	https://www.midweststeelsu	$ 28.97	$ 13.36	$ 183.00
Steel round bar (4 3/4" diamet	$ 15.76	2	$ 31.52	https://www.midweststeelsu	$ 28.97	$ 2.99	$ 63.48
mounting brackets (A36 2x2x	$ 127.46	1	$ 127.46	https://www.mkmetal.net/hr	$ 50.00	$ 12.11	$ 189.57
Pipe threading at Blake Mach	$ 250.00	1	$ 250.00	Blake Machine	$ -	$ 23.75	$ 273.75
tube sealant tape	$ 112.99	1	$ 112.99	https://www.grainger.com/p	$ 4.08	$ 10.73	$ 127.81
O-ring	$ 8.51	1	$ 8.51	https://www.mcmaster.com	$ 7.69	$ 0.81	$ 17.01
j-b weld 8281 (10oz) (Epoxy)	$ 14.88	1	$ 14.88	Amazon.com: J-B Weld 82	$ -	$ 1.41	$ 16.29
Hex Bolts	$ 0.55	6	$ 3.30	https://www.boltdepot.com	$ 2.48	$ 0.31	$ 6.09
washers	$ 0.07	6	$ 0.42	https://www.boltdepot.com	$ 2.48	$ 0.04	$ 2.93
Plumbing							$ 4,153.33
1/4" pipes	$ 34.33	3	$ 102.99	https://www.mcmaster.com	$ 7.69	$ 9.78	$ 120.47
Sleeves	$ 1.66	55	$ 91.30	https://www.mcmaster.com	$ 7.69	$ 8.67	$ 107.67
Adaptor	$ 13.78	15	$ 206.70	https://www.mcmaster.com	$ 7.69	$ 19.64	$ 234.03
Tees	$ 31.42	15	$ 471.30	https://www.mcmaster.com	$ 7.69	$ 44.77	$ 523.77
Nuts	$ 3.82	55	$ 210.10	https://www.mcmaster.com	$ 7.69	$ 19.96	$ 237.75
Pressure Gauge (0 - 200 psi)	$ 18.02	1	$ 18.02	https://www.mcmaster.com	$ 7.69	$ 1.71	$ 27.42
Pressure Gauge (0 - 1500 psi)	$ 37.51	1	$ 37.51	https://www.mcmaster.com	$ 7.69	$ 3.56	$ 48.77
Pressure Gauge (0 - 4000 psi)	$ 18.02	1	$ 18.02	https://www.mcmaster.com	$ 7.69	$ 1.71	$ 27.42
Needle Valve	$ 53.45	2	$ 106.90	https://www.mcmaster.com	$ 7.69	$ 10.16	$ 124.75
Ball Valve	$ 109.78	3	$ 329.34	https://www.fitokgroup.com	$ 20.00	$ 31.29	$ 380.63
regulator 1 (7k in 0-1.5k out)	$ 275.00	1	$ 275.00	https://valvesandregulators	$ 7.80	$ 26.13	$ 308.93
regulator 2 (6k in 0-400 out)	$ 275.00	1	$ 275.00	https://valvesandregulators	$ 7.80	$ 26.13	$ 308.93
argon bottles (6 pack)	$ 19.44	6	$ 116.64	https://www.lindeus.com/ga	$ 39.95	$ 11.08	$ 167.67
valve switches	$ 2.69	2	$ 5.38	https://www.newark.com/va	$ 9.99	$ 0.51	$ 15.88
125 psi set pressure relief valv	$ 75.20	1	$ 75.20	https://www.grainger.com/p	$ 4.00	$ 7.14	$ 86.43
3000 psi set pressure relief va	$ 141.87	1	$ 141.87	https://www.mcmaster.com	$ 7.69	$ 13.48	$ 163.04
Pressure Pannel	$ 39.44	1	$ 39.44	OPTIX 24 in. x 48 in. x .093 i	$ -	$ 3.75	$ 43.19
3000 psi pressure transducer	$ 233.95	1	$ 233.95	https://www.omega.com/en	$ 15.00	$ 22.23	$ 271.18
Pipe sealant tape	$ 87.79	1	$ 87.79	https://www.grainger.com/p	$ 4.00	$ 8.34	$ 100.21
flex hose	$ 258.00	3	$ 774.00	https://www.mcmaster.com	$ 7.69	$ 73.53	$ 855.22
Wiring							$ 943.13
railing (width: 4", length: 6' 7" (2	$ 28.08	2	$ 56.16	https://www.cableorganizer.	$ 20.00	$ 5.34	$ 81.50
nema-4 rated box (20x16x8)	$ 209.99	1	$ 209.99	https://www.amazon.com/V	$ -	$ 19.95	$ 229.94
Thin insulated copper wire 22	$ 5.99	2	$ 11.98	https://www.amazon.com/R	$ -	$ 1.14	$ 13.12
thermocouple pannel	$ 117.18	1	$ 117.18	https://www.omega.com/en	$ 15.00	$ 11.13	$ 143.31
A1360-ND	$ 4.25	1	$ 4.25	https://www.digikey.com/en	$ 1.64	$ 0.40	$ 6.30
A1357-ND	$ 4.99	16	$ 79.84	https://www.digikey.com/en	$ 1.64	$ 7.58	$ 89.07
A32515-ND	$ 5.64	16	$ 90.24	https://www.digikey.com/en	$ 1.64	$ 8.57	$ 100.46
A31990-ND	$ 0.50	10	$ 5.00	https://www.digikey.com/en	$ 1.64	$ 0.48	$ 7.12
A31986-ND	$ 0.45	75	$ 33.75	https://www.digikey.com/en	$ 1.64	$ 3.21	$ 38.60
A1381-ND	$ 15.58	3	$ 46.74	https://www.digikey.com/en	$ 1.64	$ 4.44	$ 52.82
A1383-ND	$ 16.10	3	$ 48.30	https://www.digikey.com/en	$ 1.64	$ 4.59	$ 54.53
A1008-ND	$ 0.19	200	$ 38.00	https://www.digikey.com/en	$ 1.64	$ 3.61	$ 43.25
66504-4	$ 0.12	250	$ 30.00	https://www.digikey.com/en	$ 1.64	$ 2.85	$ 34.49
A135644-ND	$ 11.17	3	$ 33.51	https://www.digikey.com/en	$ 1.64	$ 3.18	$ 38.34
mini breadboard	$3.95	2	$ 7.90	https://www.digikey.com/en	$ 1.64	$ 0.75	$ 10.29
Propellant Samples							$ 268.55
propellant jig	$ 87.38	1	$ 87.38	https://www.homedepot.co	$ -	$ 8.30	$ 95.68
Ultra Thin Solder Wire .3 mm	$ 14.99	3	$ 44.97	https://www.amazon.com/S	$ -	$ 4.27	$ 49.24
ignitors (80 3ft ignitors)	$ 55.00	1	$ 55.00	https://www.pyrocreations.	$ 10.95	$ 5.23	$ 71.18
2 wire patch cabel	$ 47.90	1	$ 47.90	Amazon	$ -	$ 4.55	$ 52.45
Strand Burner Tooling							$ 49.97
Square Tubing (1"x1"x24"x11Ga	$11.36	1	$ 11.36	https://www.metalsdepot.co	$ 17.28	$ 1.08	$ 29.72
Hardened Pin (.5"x1.5") (10pc	$11.47	1	$ 11.47	https://www.mcmaster.com	$ 7.69	$ 1.09	$ 20.25
Total							$ 6,591.15

Bill of Materials

Item	Cost per It	Quantit	Extended P	Website	Shipping	Tax	Total
Strand Burner							$ 1,176.16
6" diameter, sch 40 steel pipe	$ 254.75	1	$ 254.75	https://www.metalsdepot.c	$ 17.28	$ 24.20	$ 296.23
steel round bar (1018 hot rolled	$ 140.67	1	$ 140.67	https://www.midweststeelsu	$ 28.97	$ 13.36	$ 183.00
Steel round bar (4 3/4" diamet	$ 15.76	2	$ 31.52	https://www.midweststeelsu	$ 28.97	$ 2.99	$ 63.48
mounting brackets (A36 2x2x	$ 127.46	1	$ 127.46	https://www.mkmetal.net/ir	$ 50.00	$ 12.11	$ 189.57
Pipe threading at Blake Mach	$ 250.00	1	$ 250.00	Blake Machine	$ -	$ 23.75	$ 273.75
tube sealant tape	$ 112.99	1	$ 112.99	https://www.grainger.com/p	$ 4.08	$ 10.73	$ 127.81
O-ring	$ 8.51	1	$ 8.51	https://www.mcmaster.com	$ 7.69	$ 0.81	$ 17.01
j-b weld 8281 (10oz) (Epoxy)	$ 14.88	1	$ 14.88	Amazon.com: J-B Weld 82	$ -	$ 1.41	$ 16.29
Hex Bolts	$ 0.55	6	$ 3.30	https://www.boltdepot.com	$ 2.48	$ 0.31	$ 6.09
washers	$ 0.07	6	$ 0.42	https://www.boltdepot.com	$ 2.48	$ 0.04	$ 2.93
Plumbing							$ 4,153.33
1/4" pipes	$ 34.33	3	$ 102.99	https://www.mcmaster.com	$ 7.69	$ 9.78	$ 120.47
Sleeves	$ 1.66	55	$ 91.30	https://www.mcmaster.com	$ 7.69	$ 8.67	$ 107.67
Adaptor	$ 13.78	15	$ 206.70	https://www.mcmaster.com	$ 7.69	$ 19.64	$ 234.03
Tees	$ 31.42	15	$ 471.30	https://www.mcmaster.com	$ 7.69	$ 44.77	$ 523.77
Nuts	$ 3.82	55	$ 210.10	https://www.mcmaster.com	$ 7.69	$ 19.96	$ 237.75
Pressure Gauge (0 - 200 psi)	$ 18.02	1	$ 18.02	https://www.mcmaster.com	$ 7.69	$ 1.71	$ 27.42
Pressure Gauge (0 - 1500 psi)	$ 37.51	1	$ 37.51	https://www.mcmaster.com	$ 7.69	$ 3.56	$ 48.77
Pressure Gauge (0 - 4000 psi)	$ 18.02	1	$ 18.02	https://www.mcmaster.com	$ 7.69	$ 1.71	$ 27.42
Needle Valve	$ 53.45	2	$ 106.90	https://www.mcmaster.com	$ 7.69	$ 10.16	$ 124.75
Ball Valve	$ 109.78	3	$ 329.34	https://www.fitokgroup.com	$ 20.00	$ 31.29	[illegible]
regulator 1 (7k in 0-1.5k out)	$ 275.00	1	$ 275.00	https://valvesandregulators	$ 7.80	$ 26.13	[illegible]
regulator 2 (6k in 0-400 out)	$ 275.00	1	$ 275.00	https://valvesandregulators	$ 7.80	$ 26.13	$ 308.93
argon bottles (6 pack)	$ 19.44	6	$ 116.64	https://www.lindeus.com/g	$ 39.95	$ 11.08	$ 167.67
valve switches	$ 2.69	2	$ 5.38	https://www.newark.com/v	$ 9.99	[illegible]	$ 15.88
125 psi set pressure relief valv	$ 75.20	1	$ 75.20	https://www.grainger.com/p	$ 4.00	$ 7.14	$ 86.43
3000 psi set pressure relief va	$ 141.87	1	$ 141.87	https://www.mcmaster.com	$ 7.69	$ 13.48	$ 163.04
Pressure Pannel	$ 39.44	1	$ 39.44	OPTIX 24 in. x 48 in. x .093	$	$ 3.75	$ 43.19
3000 psi pressure transducer	$ 233.95	1	$ 233.95	https://www.omega.com/en	$ 15.00	$ 22.23	$ 271.18
Pipe sealant tape	$ 87.79	1	$ 87.79	https://www.grainger.com/	$ 4.00	$ 8.34	$ 100.21
flex hose	$ 258.00	3	$ 774.00	https://www.mcmaster.com	$ 7.69	$ 73.53	$ 855.22
Wiring							$ 943.13
railing (width: 4", length: 6' 7" (2	$ 28.08	2	$ 56.16	https://www.cableorganizer.	$ 20.00	$ 5.34	$ 81.50
nema-4 rated box (20x16x6)	$ 209.99	1	$ 209.99	https://www.amazon.com/	$ -	$ 19.95	$ 229.94
Thin insulated copper wire 22	$ 5.99	2	$ 11.98	https://www.amazon.com/	$ -	$ 1.14	$ 13.12
thermocouple pannel	$ 117.18	1	$ 117.18	https://www.omega.com/en	$ 15.00	$ 11.13	$ 143.31
A1360-ND	$ 4.25	1	$ 4.25	https://www.digikey.com/en	$ 1.64	$ 0.40	$ 6.30
A1357-ND	$ 4.99	16	$ 79.84	https://www.digikey.com/en	$ 1.64	$ 7.58	$ 89.07
A32515-ND	$ 5.64	16	$ 90.24	https://www.digikey.com/en	$ 1.64	$ 8.57	$ 100.46
A31990-ND	$ 0.50	10	$ 5.00	https://www.digikey.com/en	$ 1.64	$ 0.48	$ 7.12
A31996-ND	$ 0.45	75	$ 33.75	https://www.digikey.com/en	$ 1.64	$ 3.21	$ 38.60
A1381-ND	$ 15.58	3	$ 46.74	https://www.digikey.com/en	$ 1.64	$ 4.44	$ 52.82
A1383-ND	$ 16.10	3	$ 48.30	https://www.digikey.com/en	$ 1.64	$ 4.59	$ 54.53
A1008-ND	$ 0.19	200	$ 38.00	https://www.digikey.com/en	$ 1.64	$ 3.61	$ 43.25
66504-4	$ 0.12	250	$ 30.00	https://www.digikey.com/en	$ 1.64	$ 2.85	$ 34.49
A135644-ND	$ 11.17	3	$ 33.51	https://www.digikey.com/en	[illegible]	[illegible]	[illegible]
mini breadboard	$3.95	2	$ 7.90	https://www.digikey.com/en	$ 1.64	$ 0.75	$ 10.29
Propellant Samples							$ 268.55
propellant jig	$ 87.38	1	$ 87.38	https://www.homedepot.co	$ -	$ 8.30	$ 95.68
Ultra Thin Solder Wire .3 mm	$ 14.99	3	$ 44.97	https://www.amazon.com/S	$ -	$ 4.27	$ 49.24
ignitors (80 3ft ignitors)	$ 55.00	1	$ 55.00	https://www.pyrocreations.	$ 10.95	$ 5.23	$ 71.18
2 wire patch cabel	$ 47.90	1	$ 47.90	Amazon	$ -	$ 4.55	$ 52.45
Strand Burner Tooling							$ 49.97
Square Tubing (1"x1"x24"x11Ga	$11.36	1	$ 11.36	https://www.metalsdepot.c	$ 17.28	$ 1.08	$ 29.72
Hardened Pin (.5"x1.5") (10pc	$11.47	1	$ 11.47	https://www.mcmaster.com	$ 7.69	$ 1.09	$ 20.25
Total							$ 6,591.15

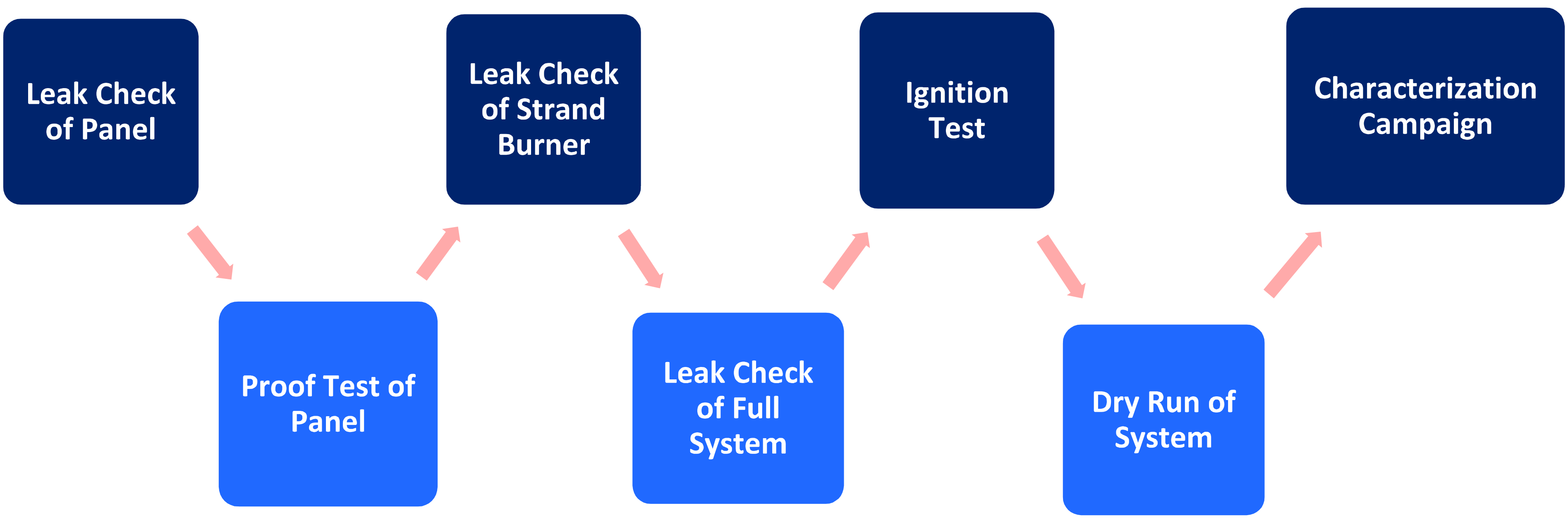
Pin-Out Board Part Numbers

A1360-ND	$ 4.25	1	$ 4.25
A1357-ND	$ 4.99	16	$ 79.84
A32515-ND	$ 5.64	16	$ 90.24
A31990-ND	$ 0.50	10	$ 5.00
A31996-ND	$ 0.45	75	$ 33.75
A1381-ND	$ 15.58	3	$ 46.74
A1383-ND	$ 16.10	3	$ 48.30
A1008-ND	$ 0.19	200	$ 38.00
66504-4	$ 0.12	250	$ 30.00
A135644-ND	$ 11.17	3	$ 33.51

Testing Overview

- Testing Plan
- Con-Ops
- Facilities and Equipment
- Instrumentation Plan

Testing Plan



Overview/Con-Ops of Verification Tests

Leak Check:

Verification of seals and torquing with 100psi. Argon

1. Close-up system
2. Attach argon bottles
3. Open argon bottle halfway
4. Set reg to ~100 psi.
5. Allow system to pressurize and look for leaks
6. Once all leaks are sealed, close argon bottles
7. Vent system
8. Close-out system

Overview/Con-Ops of Verification Tests

Proof Testing:

Verification of pressure 1.5x or 3x above rating with water

1. Close-up system
2. Attach hydrostatic pump
3. Fill system with water with highest vent open to release all air
4. Turn on pump to 500 psi.
5. Increment pressure to 4500 psi. or 3000 psi. Hold for 10 min.
6. Turn off pump
7. Drain system
8. Close-out system

Overview/Con-Ops of Verification Tests

<u>Ignition Test:</u>

Verify E-match ignites propellant, ig sense and ignition circuit work correctly

1. Connect igniter to ignition circuit
2. Insert igniter into propellant
3. Spark igniter
4. Perform 3 times, if all successful then testing is complete

Overview/Con-Ops of Verification Tests

Dry Run:

Go through procedures as if doing actual test

1. Perform leak check
2. Perform click checks
3. Insert test specimen into the test article, leave igniter outside
4. Close-up test article
5. Pressurize system
6. Spark igniter
7. Vent System
8. Close-out system

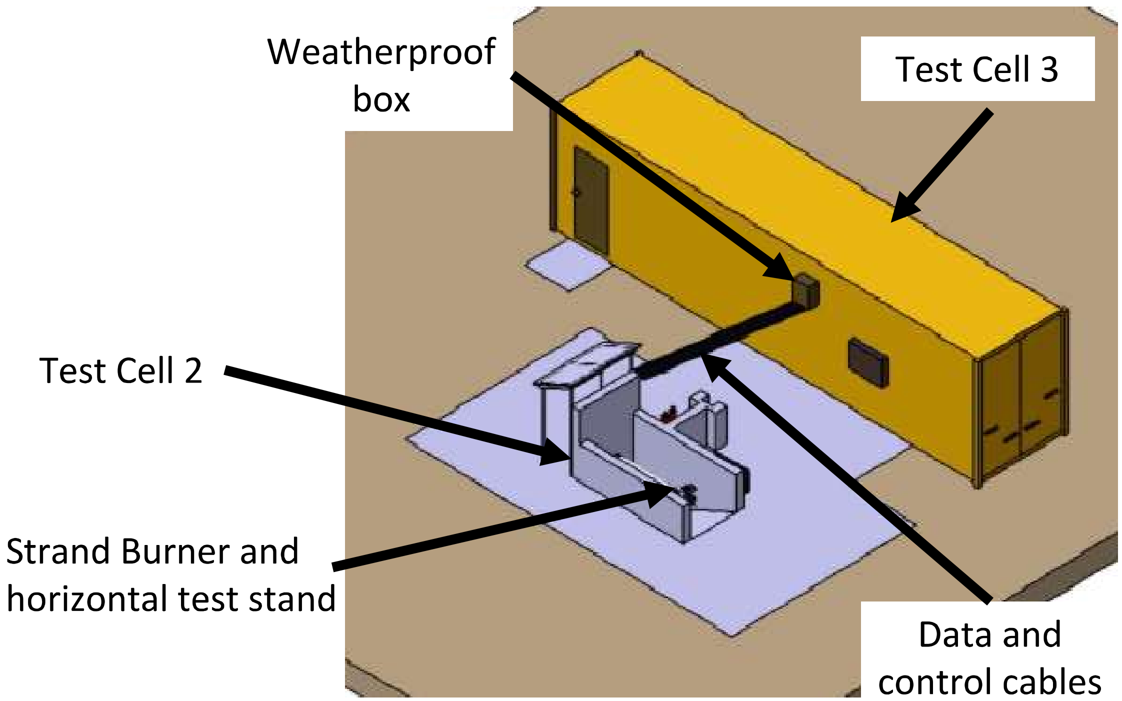
Test Facilities

Test Cell 2:
- Houses Strand Burner

Test Cell 3:
- Houses PXIe
- Stores DAQ Cables

Building 91:
- Main Control Room
- Operate and Control Strand Burner

Facilities and Equipment



Hydrostatic Test Pump

[14]

Instrumentation Plan

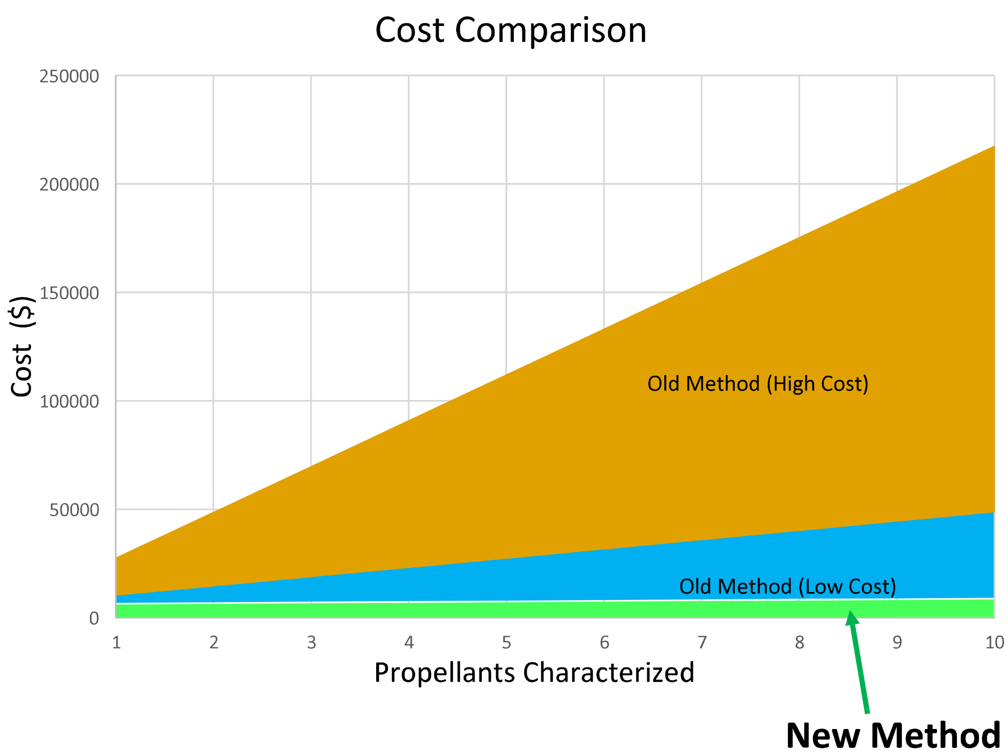
What we want?	How to acquire?	Signal Type	Location	Storage: Physical	Storage: Digital
Burn Rate	Talk Back	Digital	Prop Strand	Trailer /TC3	Data Write to Excel, RDL One Drive, Physical Hard Drive
Pressure	**PX309-3KGV** Pressure Transducer	Analog	On strand burner		
	Pressure Gauge 4089K81 (0-200 psi) 4003K61 (0-1500 psi) 4089K81 (0-4000 psi)	Analog	In line around regs		
Valve State	DB2C-A1RC Limit Switch	Digital	Attached to valve		
Continuity	Ig-Sense	Digital	Igniter, *PXIe*		

Conclusion and Compliance Summary

This project delivers:

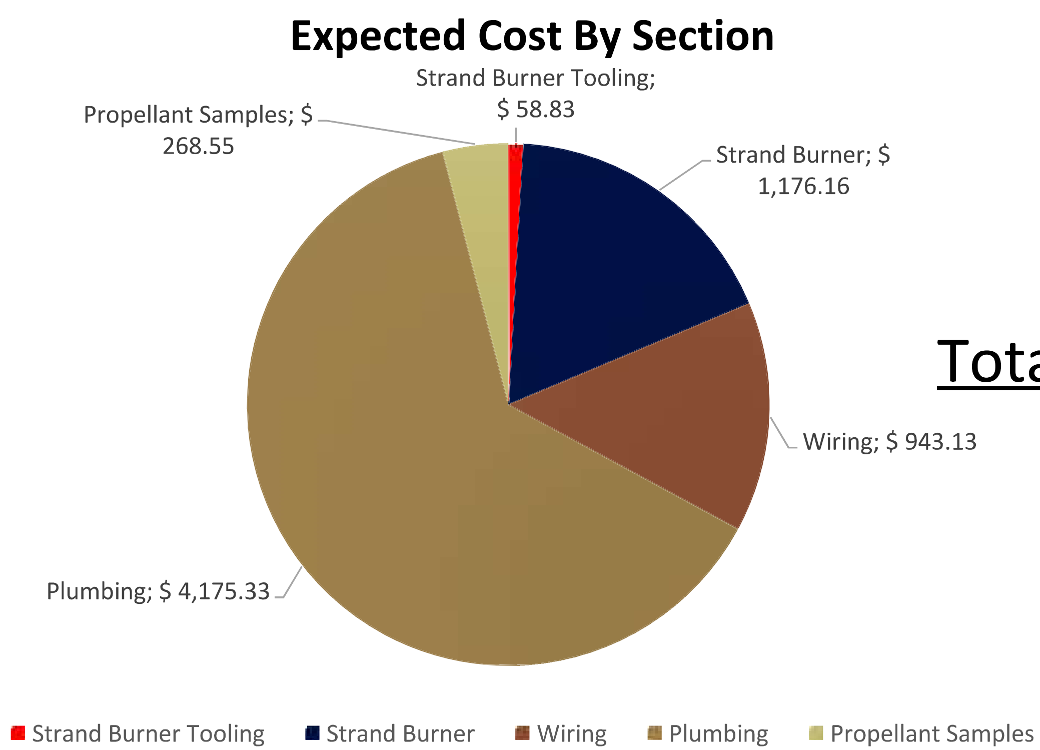
- Permanent test article to efficiently characterize solid rocket propellants at ERAU
- Reduces the costs by more than half
- More accurate data collection
- Meets the safety requirements of ERAU for similar projects

Cost Comparison



Method	Cost per characterization	Cost at year 1	Cost after 9 propellants characterized
Old Method (High Cost)	$16,834.88	$16,834.88	$168,348.80
Old Method (Low Cost)	$4,016.94	$4016.94	$40,169.40
New Method	$259.30	$6459.37	$8793.03

Expected Cost Section Breakdown



Total Cost: $6,622

Source of Funding

Requested Budget	Funding Source
$2500	College of Engineering Excellence Fund
$1175	Capstone General Budget
$2500	Mechanical Engineering Fund for Excellence
$600	Rocket Development Fund (RDF)
Total: $6,775	

Major Risks to the Project

- Operations Risks
  - Fabrication/Parts availability
  - Disapproval of grant applications for required funding
- Scheduling Risks
  - Long lead times for acquiring parts/supplies
  - Safety approval of test operations

Major Risks

Risk Number	List of Potential Hazards Present Within the Defined Facility Limits
4	Trip/fall over data, power, or other cords or wires
10	Accidental pressing of the ignition button (with the igniter inserted)
13	Accidental pressing of the ignition button (igniter not inserted)
14	Improper instillation of the snap ring causes it to be liberated
15	Excessive wear and tear on the case causing shrapnel or the snap ring to be liberated
20	Dropping of the case
23	Over pressurization causes loss of test article due to rapid unscheduled disassembly of test article

Major Risks

Risk Number	List of Potential Hazards Present Within the Defined Facility Limits
25	Impact hazard to operational spectators
29	Ignition to surroundings due to flying shrapnel caused by rapid unscheduled disassembly of the motor
38	Over pressurization due to failure of regulator valve
43	Damage to electrical connections due to weather
45	Damage to strand burner due to rust
46	Failure of igniting propellant
54	High lead time on receiving materials and/or machining processes

Major Risks

L \ S	1	2	3	4	5
1			15,16	25,7,17, 24,26	21,42,50,5 1
2			54,6,18, 33,34,35, 36,48,49		6,38,11,12, 30,31,32,3 8,39,40
3		13,5,9,13,4 4,53	43,47	20,19,27	10,29,23, 22,28,37, 41
4		4,3	14,1		
5	46	45,2,8,52			

Mitigations

Risk Number	Corrective / Preventive Action Recommended
4	Coiling the cords and securing them away from the walkways
10	Having a safety key for the ignition system, design a new ignition box with built in safety interlocks
13	Having a safety key for the ignition system, design a new ignition box with built-in safety interlocks
14	Safety glasses and verbal communication about installation of snap ring
15	Visual inspection of ring and case for defects
20	Properly secure to a rolling cart with rachet straps during transportation
23	Ensure the case can handle higher than design point pressures and throat diameter is larger than minimum calculated diameter

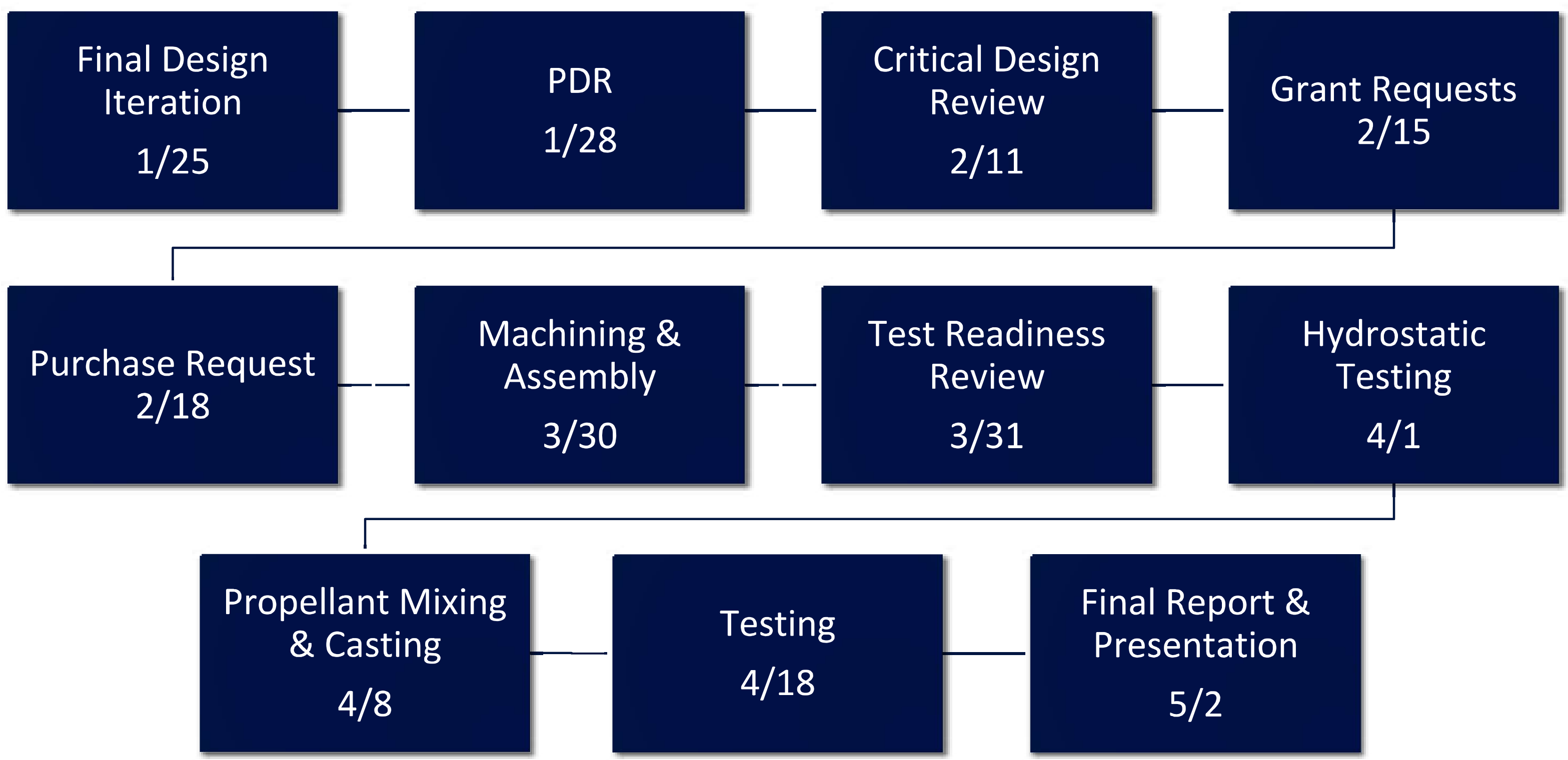
Mitigations

Risk Number	Corrective / Preventive Action Recommended
25	Trail spotter makes sure all operational personnel are in the designated observation point
29	Have a margin of safety higher than 0.5, and have the test article inside of the test cell, and have the case be made from aluminum
38	The strand burner shall have an electronically actuated ball valve to release the pressure at 2500 psi
43	The data interface box on test cell 3 will be NEMA 4 rated to protect the connections from the weather
45	The strand burner will be removable and able to be stored in TC3
46	Strand burner must be vented and reset. The ignition system must be tested in the empty, pressurized strand burner
54	Utilize multiple sources

Mitigations

L \ S	1	2	3	4	5
1		13,2,3,5,4 4,53	6,15,43,15,16, 18,33,34,35,3 6,43,48,49	25,7,17, 24,26, 27	10,23,29,38,11, 12,21,22,23, 28,29,30,31,32, 37,39,40,41, 42,50,51
2		4,45,9,52	20,54,47		
3	46,19	14,1,8			
4					
5					

Project Timeline



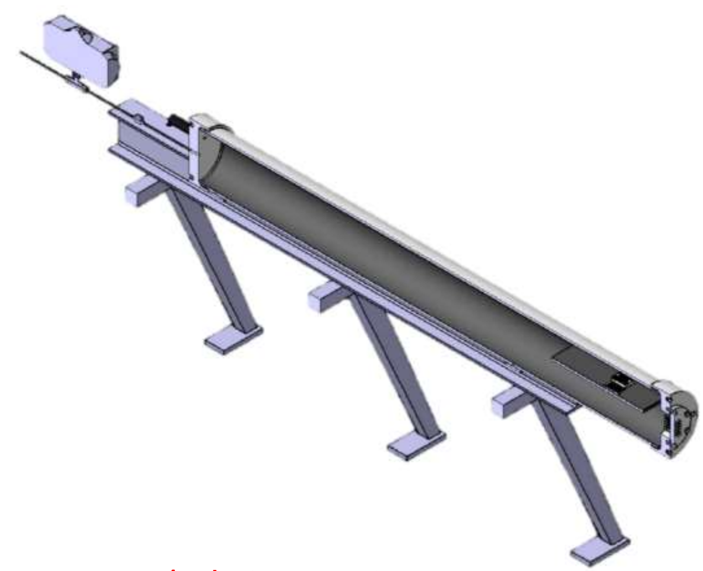
Back-up Slides

System Overview

use this so that the bullets point at there corresponding parts

Strand Burner: a pressurized chamber that simulates chamber pressure of a rocket motor

Consists of 5 subsystems:
- Structures
- Pressure System
- Ignition
- Burn-Away Copper Wires
- Data Acquisition Software and Interfacing



Include isometric **cross section image here, label subsystems** on image

Constants for moment calculations

$$L_{11} = \frac{1}{64}\left\{1 + 4\left(\frac{r_o}{a}\right)^2 - 5\left(\frac{r_o}{a}\right)^4 - 4\left(\frac{r_o}{a}\right)^2\left[2 + \left(\frac{r_o}{a}\right)^2\right]\ln\frac{a}{r_o}\right\}$$

$$L_{12} = \frac{a}{14{,}400(a - r_o)}\left\{64 - 225\frac{r_o}{a} - 100\left(\frac{r_o}{a}\right)^3 + 261\left(\frac{r_o}{a}\right)^5 + 60\left(\frac{r_o}{a}\right)^3\left[3\left(\frac{r_o}{a}\right)^2 + 10\right]\ln\frac{a}{r_o}\right\}$$

$$L_{13} = \frac{a^2}{14{,}400(a - r_o)^2}\left\{25 - 128\frac{r_o}{a} + 225\left(\frac{r_o}{a}\right)^2 - 25\left(\frac{r_o}{a}\right)^4 - 97\left(\frac{r_o}{a}\right)^6 - 60\left(\frac{r_o}{a}\right)^4\left[5 + \left(\frac{r_o}{a}\right)^2\right]\ln\frac{a}{r_o}\right\}$$

$$L_{14} = \frac{1}{16}\left[1 - \left(\frac{r_o}{a}\right)^4 - 4\left(\frac{r_o}{a}\right)^2\ln\frac{a}{r_o}\right]$$

$$L_{15} = \frac{a}{720(a - r_o)}\left[16 - 45\frac{r_o}{a} + 9\left(\frac{r_o}{a}\right)^5 + 20\left(\frac{r_o}{a}\right)^3\left(1 + 3\ln\frac{a}{r_o}\right)\right]$$

$$L_{16} = \frac{a^2}{1440(a - r_o)^2}\left[15 - 64\frac{r_o}{a} + 90\left(\frac{r_o}{a}\right)^2 - 6\left(\frac{r_o}{a}\right)^6 - 5\left(\frac{r_o}{a}\right)^4\left(7 + 12\ln\frac{a}{r_o}\right)\right]$$

$$L_{17} = \frac{1}{4}\left\{1 - \frac{1 - \nu}{4}\left[1 - \left(\frac{r_o}{a}\right)^4\right] - \left(\frac{r_o}{a}\right)^2\left[1 + (1 + \nu)\ln\frac{a}{r_o}\right]\right\}$$

$$C_1 = \frac{1 + \nu}{2}\frac{b}{a}\ln\frac{a}{b} + \frac{1 - \nu}{4}\left(\frac{a}{b} - \frac{b}{a}\right)$$

$$C_2 = \frac{1}{4}\left[1 - \left(\frac{b}{a}\right)^2\left(1 + 2\ln\frac{a}{b}\right)\right]$$

$$C_3 = \frac{b}{4a}\left\{\left[\left(\frac{b}{a}\right)^2 + 1\right]\ln\frac{a}{b} + \left(\frac{b}{a}\right)^2 - 1\right\}$$

$$C_4 = \frac{1}{2}\left[(1 + \nu)\frac{b}{a} + (1 - \nu)\frac{a}{b}\right]$$

$$C_5 = \frac{1}{2}\left[1 - \left(\frac{b}{a}\right)^2\right]$$

$$C_6 = \frac{b}{4a}\left[\left(\frac{b}{a}\right)^2 - 1 + 2\ln\frac{a}{b}\right]$$

$$C_7 = \frac{1}{2}(1 - \nu^2)\left(\frac{a}{b} - \frac{b}{a}\right)$$

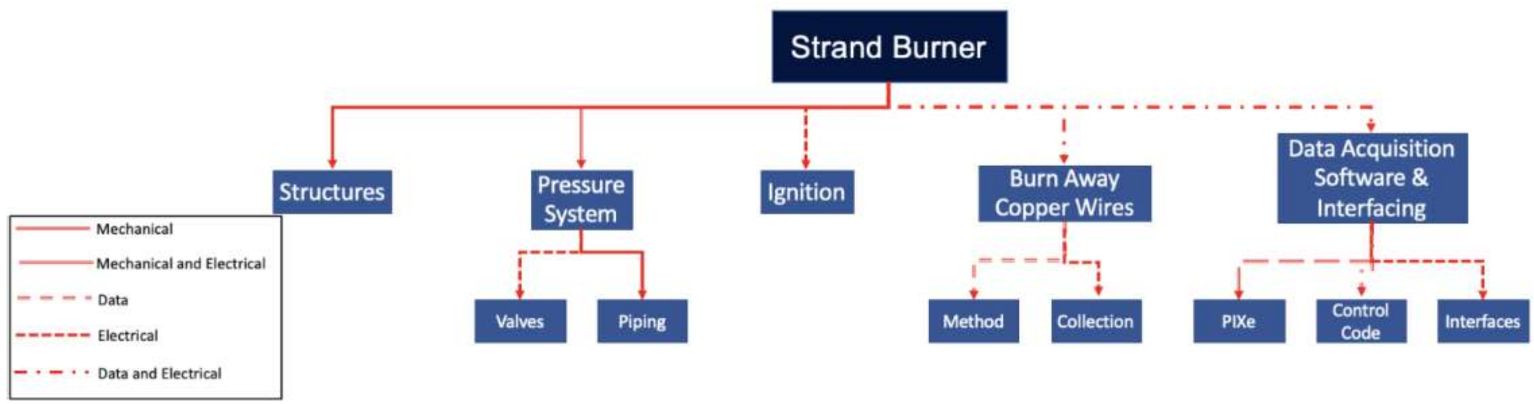
$$C_8 = \frac{1}{2}\left[1 + \nu + (1 - \nu)\left(\frac{b}{a}\right)^2\right]$$

$$C_9 = \frac{b}{a}\left\{\frac{1 + \nu}{2}\ln\frac{a}{b} + \frac{1 - \nu}{4}\left[1 - \left(\frac{b}{a}\right)^2\right]\right\}$$

Subsystem Analysis- Pressure System

		No Mitigation					With Mitigation				
PID	Component	Failure Mode	Consequence of Failure	Likelihood	Severity	Rating	Mitigation	Consequence	Likelihood	Severity	Rating
REG-102	Panel Iso Regulator	Fail Full Open	Over-pressurization of circuit	2	4	8	Relief valve, pressure visibility, downstream isolation valves, proof to 1.5x MEOP	Loss of consumables	2	2	4
REG-105	Muscle Pressure Regulator	Fail Full Open	Over-pressurization of circuit	2	4	8	Pressure visibility, relief valve, proof to MEOP	loss of consumable	2	2	4
MV-107	Muscle Pressure Vent	Misconfigured open	loss of consumable	4	2	8	Procedural control, training of personnel	loss of consumable	2	2	4
MV-109	High Pressure Manual Vent	Misconfigured open	loss of consumable	4	2	8	Procedural control, training of personnel	loss of consumable	2	2	4
MV-110	Manual Panel Iso	Misconfigured closed	unable to pressurize circuit, loss of time to reconfigure	4	1	4	Procedural control, training of personnel	minor loss of time	2	2	4
SV-111	Test Article Press	Loss of control	unwanted pressure in test article, possible loss of consumable	2	2	4	fail state is closed, procedural controls, upstream isolation valve	minor time loss	2	1	2
SV-113	Test Article Vent	Loss of control	Over-pressurization of test article	2	4	8	Proof to 1.5x MEOP, fail state is open	loss of consumable	2	2	4

System Overview



Hazardous Operation Assessment Definition

Severity Ratings:
1 – Not a risk to system/personal/data and/or minor time loss
2 – Loss of consumables and/or minor to no injury to personnel and/or major time loss
3 – Damage to component and/or minor injury to personnel and/or loss of data
4 – Damage to system and/or loss of component and/or severe injury to personnel
5 - Complete loss of article and/or loss of life

Likelihood Ratings:
1 - Will most likely never occur in the life of the system
2 – Likely to occur once every 100+ uses of system
3 - Likely to occur once every 50+ uses of system
4 - Likely to occur once every 10+ uses of system
5 - Guaranteed to occur with every use of system

S L	1	2	3	4	5
1	1	2	3	4	5
2	2	4	6	8	10
3	3	6	9	12	15
4	4	8	12	16	20
5	5	10	15	20	25

Requirements

Requirement			Design Metric Benchmarks	Tools	Verification Method
Number	Title	Description			
1.1.1	Measurement Standards	Ability to measure chamber pressure, thrust and temperature	90% Confidence	Equipment error specifications	Error Analysis
1.1.2	Measurement System Compatibility	Obtain data for 38 mm, 54 mm, 75 mm, 98 mm, 6 in, diameter motors, and strand burner	Be able to get data for all measurements	Strand Burner system and test materials	Conduct tests to simulate each motor type
1.1.3	Detachability	The data acquisition cables must be detachable for storage.	Must be detachable	Personnel and appropriate wiring	Wires and connections will be plugged and unplugged from the system interfaces
1.1.4	Interface	Data acquisition system must interface with PIXe Test Cell 3.	Must successfully interface	Appropriate wiring	Appropriate wiring will be connected between interfaces and PIXe and test for proper data transfer
1.1.5	Ignition	Ignition system must set off propellant.	90% of the time	Strand Burner, ignition system, test propellant	Multiple ignitions and burn tests will be conducted
1.1.6	Cost Cutting	Cut cost of Characterization	Cut by 15%	Previous testing cost data	Verify by Spreadsheet

Requirements – Cont.

Requirement			Design Metric Benchmarks	Tools	Verification Method
Number	Title	Description			
1.1.7	Strand Burner Integrity	The Ability for strand burner to safely function	10 years	Excel sheet, appropriate information required for calculations	Fatigue calculations
1.1.8	Ignition Safety	Continuity light on while connected to ignition circuit	Lights up while there is continuity	Continuity light, supporting equipment	Electrical Continuity Test
1.1.9	False Ignition Prevention	Prevent premature ignition	Lockout Keys prevent ignition	Lockout keys and switches, supporting equipment	Electrical Continuity Test
1.1.10	Safety/Testing Procedures	Re-evaluation, adjustment, and re-approval of testing procedures	Safety standards	N/A	Safety, Dr. Bryner, RDL Safety Committee, Professor Gerrick
1.1.11	Test Procedure Changes	Changes to test procedure must adhere to risk assessment	Risk assessment	N/A	Review, Safety, Dr. Bryner, RDL Safety
1.1.12	Strand Burner Operations	No personnel allowed to be within the defined exclusion zone during pressurization	Exclusion zone map	Personnel	Follow proper SOPs and safety precautions
1.1.13	Factor of Safety	Material withstands internal pressure	Factor of safety of 3 for the pipe and flanges and 1.2 for bolts	Strand burner and pressure subsystem	Theoretical calculations and pressurize to the highest pressure
1.1.14	Pressurization Circuit Proof	Circuit will be proofed to the ASTM B31.3 Standard	Hydrostatic proof test to 1.5x MEOP	Hydrostatic Pump	Hydrostatic proof test

Trade Studies

Following alternative were considered while design the current system:

(also include picture that’s in poster)

- Closed chamber for maintaining constant pressure
- Discrete voltage/capacitance measurement for data
- Laser interferometer (include what we learnt)

Structures

Subsystem Governing Equation - Structures

$$n = \frac{S_y}{\sigma}$$

Equation 2:Factor of Safety for Pipe [4]

$$n_p = \frac{S_p A_t}{C_k P + F_i}$$

Equation 3:Yielding Factor of Safety for Bolts [4]

$$n_o = \frac{F_i}{P(1 - C_k)}$$

Equation 4:Joint Separation of Bolts [4]

$$T_2 = \frac{\Delta U}{m C_p} + T_1$$

Equation 5: Energy Release from the combustion of the Propellant [5]

n = factor of safety

S_y = yield strength of pipe material
σ = stress
n_p = yield factor of safety for bolts
S_p = proof strength

A_t = tensile area

C_k = stiffness of frustum
P = external tensile load
F_i = preload
ΔU = internal energy
m = mass of argon gas and propellant gasses

C_v = specific heat capacity at constant volume

T_2 = final temperature in chamber
T_1 = initial temperature of chamber before burning of propellant

Subsystem Trade Studies – Structures

Criteria	Weight	Scale	Steel 4140	Steel 6150	Aluminum 6061
Cost	20	9 (Best) 5 1 (Worst)	5	1	9
Material Strength	30		9	9	9
Availability	30		9	1	1
Machinability	15		5	1	9
Total			**715**	**335**	**615**

Pressure System

Subsystem Trade Studies – Pressure System

Trade Study Results: Ball Valve

- Excellent durability and functionality
- Good compromise between speed of actuation and high-pressure capability
- Cheaper than other trade options

Subsystem Summary- Pressure System

It integrates into the system by connecting the:

- Pressurant gas to the valves and strand burner
- Valves to the data and control cables

Requirements			Analysis Value	MOC	Meets Requirements
Number	Title	Value			
1.1.13	Factor of Safety	≥ 3	3	Hydrostatic Testing	TBD

Ignition

Burn Away Copper Wires

Subsystem Trade Studies – Burn-Away Copper Wires

Trade Study Results: Discrete Voltage Measurement

- Easiest to standardize
- Easiest to implement
- Reduces recurring cost the most

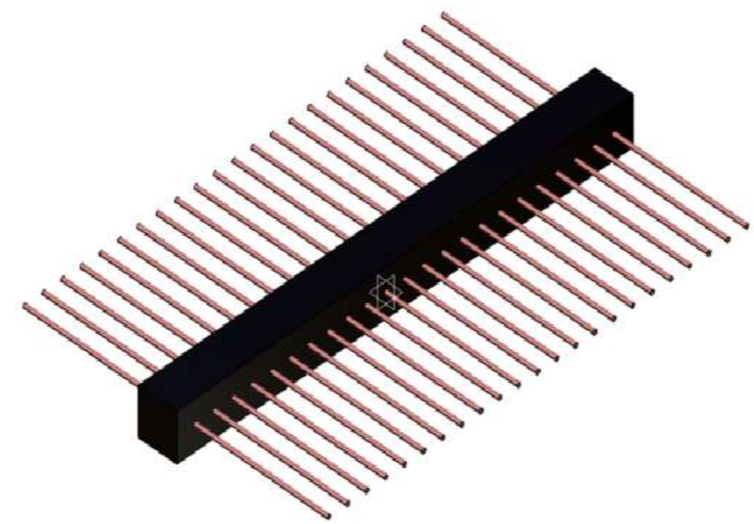
Requirements			Analysis Value	MOC	Meets Requirements
Number	Title	Value			
1.1.1	Measurement standards	≥ 90% confidence	TBD	Error Analysis	TBD
1.1.1	Measurement Standards	100 Hz	TBD	Run Data Acquisition Test	TBD

Subsystem Definition – Burn-Away Copper Wires

Discrete Voltage Measurement Method is used to collect the burn rate data

Copper wires are imbedded inside the propellant

As the propellant burns the wires melt breaking the circuit



Data Acquisition Software and Interfacing

Subsystem Summary- Data Acquisition Software and Interfacing

Requirements		Method of Characterization
Number	Title	
1.1.3 & 1.1.4	DAC	Check cables interface with system and are detachable and storable
1.1.8 & 1.1.9	Ignition	Lock out key prevents ignition and light turns on with continuity

Subsystem Analysis- Data Acquisition Software and Interfacing

The team will perform a dry run test setup:

- Connection of the data acquisition cables interfacing the strand burner to the PXIe will be checked

- PXIe will be connected to the ignition system to check for continuity

Full Bill of Materials

ITEM	QUANTITY	PRICE	LINK	SHIPPING	TAX	TOTAL PRICE
Hydrostatic test						$ 7,475.64
Water pump	1	$ 6,513.00	https://ww	$ 100.00	$ 521.04	$ 7,134.04
Water pump hose	1	$ 270.00	https://ww	$ 50.00	$ 21.60	$ 341.60
Strand Burner						$ 1,002.52
6" diameter, sch 40 steel pipe	1	$ 328.25	https://ww	$ 23.60	$ 26.26	$ 378.11
steel round bar (4140 hot rolled)	1(8 in length)	$ 221.97	https://ww	$ 55.00	$ 17.76	$ 294.73
mounting brackets (A36 2x2x20)	1	$ 127.46	https://ww	$ 50.00	$ 10.20	$ 187.66
Pipe threading at a shop					$ -	$ -
tube sealnt tape	1	$ 112.99	https://ww	$ 20.00	$ 9.04	$ 142.03
plumbing sealnt tape	1	$ 87.79	https://ww	$ 20.00	$ 7.02	$ 114.81
Wiring						$ 1,169.82
wire pass through	1	$ 800.00		$ 20.00	$ 64.00	$ 884.00
railing	2	$ 36.62	https://ww	$ 20.00	$ 2.93	$ 59.55
nema-4 rated box	1	$ 190.99	https://ww	$ 20.00	$ 15.28	$ 226.27
Plumbing						$ 2,334.57
1/4" pipes	3	$ 145.38	https://ww	$ 20.00	$ 11.63	$ 177.01
Pipe joints?	1	$ 200.00		$ 20.00	$ 16.00	$ 236.00
regulator 1 (7k in 0-1.5k out)	1	$ 275.00	https://val	$ 20.00	$ 22.00	$ 317.00
regulator 2 (6k in 0-400 out)	1	$ 275.00	https://val	$ 20.00	$ 22.00	$ 317.00
argon bottles	1	$ 200.00		$ 50.00	$ 16.00	$ 266.00
valve switches	2	$ 20.00		$ 10.00	$ 1.60	$ 31.60
relief valves	1	$ 44.10	https://ww	$ 20.00	$ 3.53	$ 67.63
burst disk	1	$ 8.79	https://ww	$ 10.00	$ 0.70	$ 19.49
flex hose	2	$ 165.18	https://ww	$ 20.00	$ 13.21	$ 376.79
Panel (3x3 6061 alum)	1	$ 94.51	https://ww	$ 20.00	$ 7.56	$ 122.07
3000 psi Pressure Transducer	1	$ 301.30	https://ww	$ 20.00	$ 24.10	$ 345.40
wheels for the panel (300 lb hand cart)	1	$ 44.98	https://ww	$ 10.00	$ 3.60	$ 58.58
Propellant Samples						$ 206.80
propellant jig	1	$ 39.44	https://ww	$ 10.00	$ 3.16	$ 52.60
thin copper wire .02 mm	1	$ 10.00	https://ww	$ 10.00	$ 0.80	$ 20.80
ignitors	1	$ 55.00	https://ww	$ 10.00	$ 4.40	$ 69.40
ig-sense wire	1	$ 50.00		$ 10.00	$ 4.00	$ 64.00

Presentations	**92 days**	**Fri 1/28/22**	**Fri 4/29/22**			**3 days**
Delta PDR	1 day	Fri 1/28/22	Fri 1/28/22	18		94 days
CDR	1 day	Fri 2/4/22	Fri 2/4/22	20	48FS-1 d	0 days
TRR	1 day	Tue 3/22/22	Tue 3/22/22	133,122	135,128,:	0 days
Final Technical	1 day	Wed 4/27/22	Wed 4/27/22	152	147,6	0 days
Symposium	1 day	Fri 4/29/22	Fri 4/29/22	5		0 days
Design	**22 days**	**Wed 1/12/22**	**Thu 2/3/22**			**88 days**
Controll Code (Labview)	**52 days**	**Fri 1/14/22**	**Mon 3/7/22**			**56 days**
Procurement	**21 days**	**Fri 2/4/22**	**Thu 2/24/22**	**3FS-1 day,35,30,25**	**123**	**0 days**
Fabrication	**12 days**	**Fri 2/25/22**	**Tue 3/8/22**			**11 days**
Hydrostatic Test	2 days	Wed 3/9/22	Thu 3/10/22	116,49,54,59	135,4,13'	11 days
Test Plan	**30 days**	**Fri 2/25/22**	**Sat 3/26/22**	**48**	**135**	**0 days**
Test Readiness Review	**9 days**	**Sun 3/13/22**	**Mon 3/21/22**			**0 days**
Testing	**13 days**	**Sun 3/27/22**	**Fri 4/8/22**	**122,46,123,4**		**0 days**
propellant production	5 days	Sun 3/27/22	Thu 3/31/22	4	137,143	0 days
test 1-3	2 days	Fri 4/1/22	Sat 4/2/22	136,4,128,122	138	7 days
test 4-6	2 days	Sun 4/3/22	Mon 4/4/22	137,4,128,122	139	7 days
test 7-9	2 days	Tue 4/5/22	Wed 4/6/22	138,4,128,122	140	7 days
System Verification	2 days	Thu 4/7/22	Fri 4/8/22	139,4	146FF+3	7 days
Final Report	**32 days**	**Fri 4/1/22**	**Mon 5/2/22**			**0 days**
Final Technical Review	**8 days**	**Tue 4/19/22**	**Tue 4/26/22**			**0 days**
Testing Manual	39 days	Fri 3/25/22	Mon 5/2/22			0 days

Nema 4 Rated Electrical Box

Overview of Verification Tests

Leak Check:
- Verification of seals and torquing
- Pressure set to ~100 psi but no greater than 150 psi.
- Performed with Argon
- Panel, Burner, Full system

Proof Test:
- Verification of pressure 1.5x or 3x above rating
- Performed with water and hydrostatic pump
- Pressures of 4500 psi for pressure system and 3000 psi for burner

Ignition Test:
- Perform 3* tests
- Place E-match into propellant "blob"
- Verify E-match ignites propellant, ig sense and ignition circuit work correctly

Dry Run:
- Go through procedures as if doing actual test

* Subject to change

Subsystem Trade Studies – Structures

Trade Study Results:

Pipe: ASTM A500 Grade B Steel

- High material strength and availability compared to other options
- Easier to machine
- Lowest cost compared to other options

Caps: 12L14 Cold Rolled

- High material strength
- Easier to machine

Cost Breakdown by High-Cost Item

Item	Cost	Use/Purpose
Wire Passthrough	$884	Allows data transfer
Regulators	$634	Regulates the pressure between the argon bottle and the pressure system
Strand Burner Body	$380	Stand burner material
Flex Hose	$376.79	Helps gas travel through sharp turns
Pressure Transducer	$301.30	Measures the internal pressure
Pipe Threading	$280	No capabilities on campus