Skuld Propulsion Test Plan

SKULD PROPULSION

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Abstract

The following document outlines the tests that will be done to satisfy the project requirements and prove the validity of Skuld Propulsion's design. A detailed plan for how the team will verify the design and the instruments used to do so is necessary. This document includes a detailed plan of analysis of how the data will be collected and analyzed as well as the uncertainty analysis of the data. It also includes a thorough safety analysis to ensure team's safety during testing.

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1.0 Test Objectives and Requirements

To ensure successful testing, the following objectives must be met. The objectives are test the accuracy of the data collection methodology by comparing gathered data to MIT's posted values, demonstrate the practicality of the strand burner, and accurately measure the camber pressure over the range of 200 – 1000 psi. and accurately collect the burn rate data over the range of 200 – 1000 psi.

1.1 Test Objectives

1.1.1 Test the Accuracy of the Data Collection Methodology by Using Comparative Results

By meeting objective 1.1, the team will be able to demonstrate that their strand burner can collect useful and meaningful data. This is needed to meet project requirement 1.1: The solution shall cut the cost of characterization by at least 80%. An analysis of the cost of characterization was performed and it shows when successful, the cost of characterization will be cut by 90%. To meet this requirement, the strand burner must be proven to be accurate. Embry-Riddle Aeronautical University's Rocket Development Laboratory (RDL) has burn rate data for its Fire Lizard propellant recipe; however, upon comparison to other posted values, the recorded burn rate was more than 10 times larger. This shows that the way the burn rate is calculated was flawed. This means that these values could not be used as comparators to prove the accuracy of the strand burner. The team combated this by looking for accurate posted burn rate values and their corresponding propellant formulas. The team found a propellant recipe and appropriate burn rate values for MIT's "Cherry Limeade" [1]. It was decided that these values would be used as comparators for the strand burner. If the team can match MIT's result within a reasonable uncertainty the test will be considered a success.

1.1.2 Accurately Collect Burn Rate Data of Varying Propellants Over the Range 200 – 1000 psi.

The burn rate is calculated using Equation 1 below where $\dot{r}$ is the burn rate, W_d is the horizontal distance between wires, and t is the time it takes to burn through the wires.

$$\dot{r} = \frac{W_d}{t}$$

Equation 1: Linear Burn Rate Equation [1]

The $\dot{r}$ calculated in Equation 1 is then fed into Equation 2 below where $\dot{r}$ is the burn rate, a is the burn rate coefficient, P_c is the chamber pressure, and n is the pressure exponent.

$$\dot{r} = aP_c{}^n$$

Equation 2: Saint Roberts Law [2]

The a and n values in Saint Roberts Law are what are being compared to MIT's data. In the team's test, P_c is measured using a pressure transducer and $\dot{r}$ is calculated using Equation 1. 'a' and 'n' are found using a power line of best fit through the data collected from the tests. To achieve objective 1.1, the team needs to measure the burn rate accurately to compare to MIT's posted ‘a’ and ‘n’ values. If $\dot{r}$ is not calculated accurately enough, the team will not meet objective 1.1.

1.1.3 Accurately Collect Pressure Data Over a Range of 200 – 1000 psi

From Equation 2 above, it is seen that the chamber pressure also needs to be calculated as accurately as possible. The team will be performing tests at pressures between 200 – 1000 psi. Measuring the chamber pressure as accurately as possible minimizes the error in the ‘a’ and ‘n’ values and allows the team to meet objective 1.1.

1.1.4 Demonstrate Practicality of project

Another objective for the team is to demonstrate the practicality of the strand burner. The practicality of this experiment is measured by how long it takes to complete the characterization of the propellant. In the past, the fastest university could complete a characterization was two and a half years. To demonstrate the practicality of the project, the team needs to characterize the propellant more rapidly. Another way to characterize the practicality of the project is by comparing ease of use. By asking people who have participated in the characterization process before, what their opinions on the ease of use of the new method is, the team can form a consensus on what the practicality of the project is.

1.2 Test Requirements

1.2.1 Measure ‘a’ to an Uncertainty of 8%

If objectives 1.1.2 and 1.1.3 are completed, they will demonstrate that they have satisfied this requirement. By measuring the $\dot{r}$ and P_c as accurately as possible, the team will be able to measure ‘a’ to an uncertainty of less than 8%. This requirement is important because if met along with requirement 1.2.2 then Objective 1.1.1 will also be met.

1.2.2 Measure ‘n’ to and Uncertainty of 8%

If objectives 1.1.2 and 1.1.3 are completed, they will demonstrate that they have satisfied this requirement. By measuring the $\dot{r}$ and Pc as accurately as possible the team will be able to measure ‘n’ to an uncertainty of less than 8%. This requirement is important because if met along with 1.2.1 then Objective 1.1.1 will also be met.

1.2.3 Measure Burn Rate to and Uncertainty of 5%

By measuring the burn rate to an uncertainty of 5%, requirements 1.2.1 and 1.2.2 can be met. This allows for objectives 1.1.1, 1.1.2, and 1.1.3 to be satisfied.

1.2.4 Pressure Range Must Go From 200 – 1000 psi

This requirement comes from the pressure range that is covered by the solid propellant motors tested on campus. This project is meant to solve the problem of characterizing the solid propellants on campus. If the strand burner could not meet this range, then it would fail to meet objective 1.1.4.

1.2.5 Testing Shall Take no Longer Than 6 Months

Currently, it takes the university at least two and a half years to characterize a propellant recipe. To meet Objective 1.1.4 the strand burner must be practical. By cutting the time it takes to characterize a propellant recipe by 75% or more the practicality is shown.

2.0 Test Article

The Skuld Propulsion's strand burner project will characterize solid rocket propellant, reduce testing costs, and interface with existing data acquisition systems. The test articles presented below will directly accomplish this by meeting specific project objectives and requirements.

2.1 Strand Burner Chamber

The strand burner will characterize rocket fuel across nine tests as proof of concept for economical characterization for future testing by the university. The chamber is made from ASTM A500 Grade B threaded steel pipe with 2 1018 Hot Roll Steel threaded caps. The pipe measures 6 in. in diameter by 60 in. in length with a wall thickness of 0.56 in.

The chamber housing the test sample during the tests creates a sealed environment capable of replicating the pressure environments of the rocket motors tested by ERAU. Once sealed, the pipe can maintain an internal pressure of 1000 psi for testing. The front-end cap of the chamber houses a seal plate with a wire pass through that allows for data collection. This directly meets all test objectives. The face seal plate is made from 12L14 Cold Rolled Steel.

Figure 1: Strand Burner Chamber and Face Seal Plate With Pass Through Wiring

The chamber must have an operational lifespan of at least 10 years. Appropriate material was selected that would handle the fatigue induced by high pressures with this in mind.

Additionally, the interior of the pipe has been coated with a rubber lining. This lining will protect the steel from oxidation during the test and increase its lifespan.

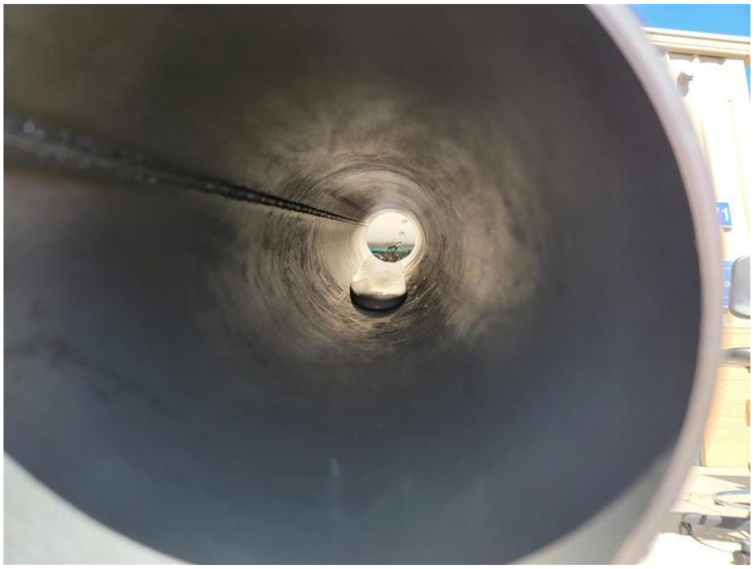

Figure 2: Coating Application to the Chamber

2.2 Propellant Sample and Jig

The propellant sample will provide sample data like full motor tests and allow for proof of concept for the strand burner project. The sample is a rectangular stick measuring 0.26 in. x 0.25 in. x 2.06 in. Solder wires are placed equally spaced throughout the sample. These wires will break as the sample burns resulting in an overall drop in voltage that allows us the measure the sample's burn rate. The sample itself is made from the "Cherry Limeade" solid propellant recipe from MIT. To ensure standardization and repeatability between tests, all samples were constructed using an acrylic jig with slits for installing the ignition E-Match and solder wires.

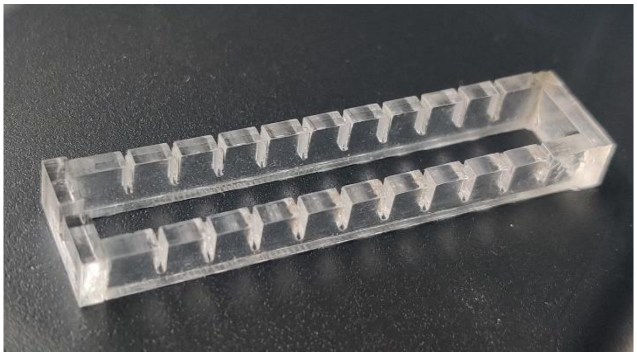

Figure 3: Propellant Jig

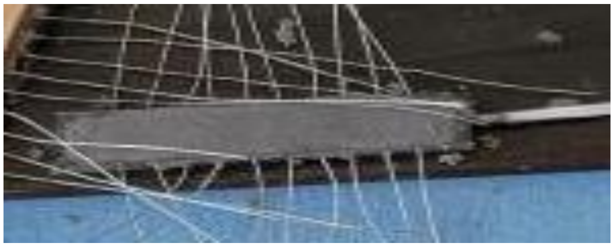

Figure 4: Cherry Limeade Propellant Sample

2.3 Pressure System

The pressure system will safely manage the pressures required for the strand burner testing. It will consist of a piping network that connects the strand burner chamber to argon bottles with switches for controlling pressure levels and safety releases. It will deliver argon to the pressure actuators between 80 – 120 psi to the strand burner chamber up to 1000 psi. Appropriate fittings and valves were selected to provide a minimum safety rating of 1.5 of the maximum expected testing pressures.

Figure 5: Mobile Pressure Control Panel

Figure 6: Pressure System Gauges, Actuators, Switches, and Piping Construction Process

3.0 Instrumentation

3.1 Instrumentation Requirements

The testing campaign involves the use of several instruments. These instruments are essential for gathering data, operating the strand burner, and ensuring the safety of the test personnel. This section covers a range of requirements that must be met by the instruments used, for a successful test.

3.1.1 The Data Acquisition System Must Interface With Test Cell 2 (TC2) and Test Cell 3 (TC3)

The main component of the system which is strand burner is placed in TC2. To collect data from tests conducted at TC2, the data acquisition system developed must connect the strand burner and the PXI Express (PXIe) which is already in TC3. PXIe is an instrumentation system that already exists in TC3 and will be the data acquisition during the test. The PXIe is connected to TC2 through an electrical box attached on outer wall of TC3. The electrical box contains the necessary ports to connect wires from strand burner to the PXIe.

3.1.2 Possible Premature Ignition Must be Handled Safely

A premature ignition is an event that has directed the design to place some safety measures. To handle this, continuity light will turn on when connected to the ignition circuit. This will alert the test personnel to be careful working around the ignition. A lock-out key will also be used to prevent accidental pressing of ignitor button. When the key is locked, no one will have access to press the ignition button. The key will be unlocked only when the Standard Operating Procedures call for it. The PXIe will be in TC3 which will be wired with the rest of the system in TC2.

3.1.3 Must be Able to Capture Burn Rate Across Each Individual Wire Sections

To meet the test objectives, the burn rate across each wire section must be calculated individually. This is ensured using a pressure sensor that has a rise time of less than one millisecond. This is less than 1/10th of the event time which is an industry-standard for selecting the right sensors. The event time which is the time to burn through a wire section is 0.7 seconds.

3.2 Instrumentation list

The instruments used in this test are carefully chosen according to the test requirements while staying within the allocated budget. All these instruments are included in the instrumentation plan of the project. Below is a list of all the instruments used during a test, their function, and why they were selected.

3.2.1 Pressure Transducer

A pressure transducer will be used for the test to record pressure inside the strand burner vessel. Measuring pressure in the chamber is fundamental to achieving test objectives. The transducer records the increasing pressure as the propellant burns continuously. The last measurement is vital in confirming that the pressure rise after the burn is less than 5% which was one of the assumptions during system design. A LabVIEW VI is used to record the data which is processed through PXIe. The data is obtained in *tdms* format for post-test processing.

Figure 7: Pressure Transducer Used During the Test [3]

3.2.2 Propellant Strand and Soldering Wires

A propellant strand burning during the test is another instrumentation that provides the distance between two soldering wires. The strand itself is manufactured using the Standard Manufacturing Procedures to maintain consistency across several strands used for the test. However, since the wires may have moved from the original position, the actual distance between them is measured using calipers. The calipers have an uncertainty of $\pm$ 0.001 in. The distance measured and the uncertainty is used in calculating burn rate and uncertainty in the results.

Figure 8: A Propellant Strand With Soldering Wires Embedded In It

3.2.3 LabVIEW Codes and PXIe

LabVIEW is used to write codes that collect data from the pressure transducer and measure the time taken to burn individual wire sections. There are 10 physical channels on PXIe that record voltage drop in the circuit when each wire breaks. This drop in voltage is recorded with the associated timestamp through the codes. Using the timestamp of two successive voltage drops the burn time for an individual wire section is calculated. This burn time and the distance between the wires are later used in calculating the burn rate for the respective sections. All the data is stored as a *tdms* file in the specified folder.

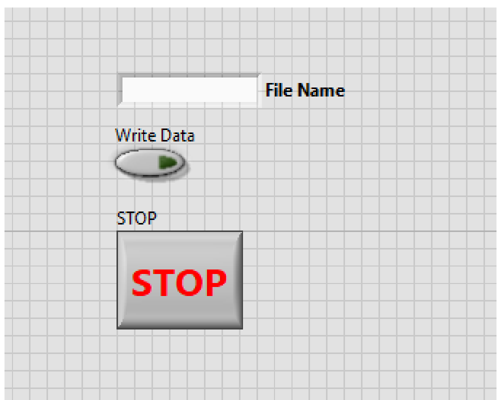

Figure 9: Front Panel of the LabVIEW Codes Used For The Test

3.3 Instrumentation Analysis

A series of analyses were performed to study the impact of instrument readings on the burn rate calculation. These analyses form a baseline in determining the accuracy of the data collected and the associated uncertainties in the calculated quantities.

3.3.1 The ‘a’ and ‘n’ Values Must be Measured to a 5% Accuracy

One of the propellant recipes from MIT called, “Cherry Limeade” is used as a baseline to compare the ‘a’ and ‘n’ calculated after the test. These ‘a’ and ‘n’ values are obtained from the burn rate calculated for each wire section. The errors in these burn rates are estimated to be less than 1% at a 95% confidence interval. A power line curve fit on the burn rate of 81 test data points provides ‘a’ and ‘n’ values. These values were assumed to have the same uncertainty. Using partial differentials, the error in them was calculated to be 1% which is less than the required 8% error. A log-log plot of burn rate against chamber pressure also produced an error of less than 1% at a 95% confidence interval. When plotting, the individual burn rates are used as it reduces an error introduced due to the assumption of constant pressure during the burn at each pressure level.

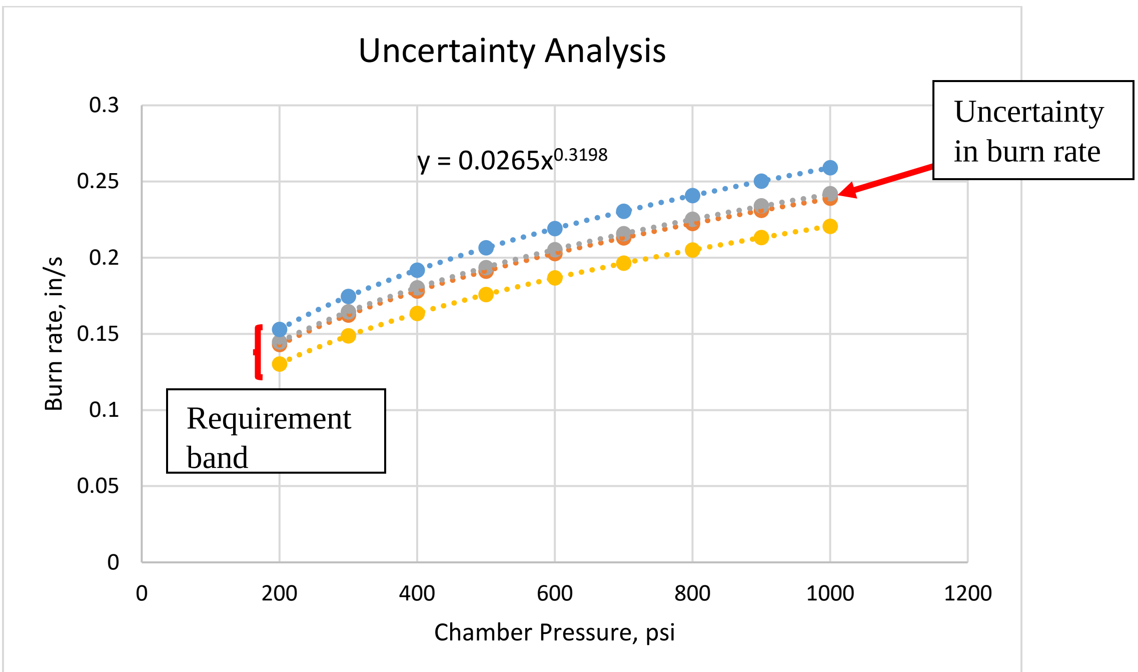

Figure 10: Uncertainty Analysis on Burn Rate and The Curve Fit

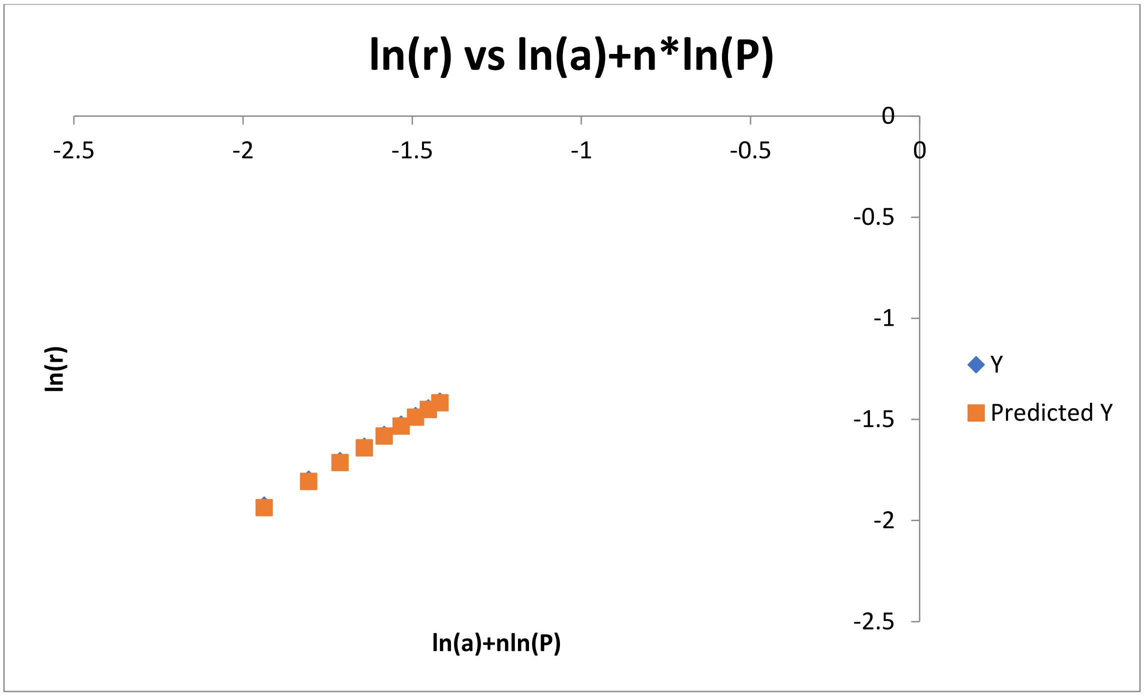

Figure 11: Log-log Plot of Burn Rate Against Pressure

3.3.2 Chamber Pressure Must be Maintained at a Constant Level During the Burn

As mentioned in Equation 2, the burning of the propellant strand is governed by Saint Robert's Law. To comply with the law, the chamber pressure must be maintained at a constant level during the burn. This, however, is not possible due to the closed vessel. To maintain the constant pressure, the chamber was designed to be large enough to not exceed the pressure rise by more than 5%. This is a general practice in other institutions that have years of experience in operating strand burner. To accurately measure the pressure the pressure transducer has a response time of fewer than one millisecond. This is enough to capture enough samples during the burn of one section which is 0.7 seconds.

3.3.3 Must Sample the Data at a Minimum of 3 Hz

PXIe is used for sampling the pressure and time data obtained from the pressure transducer and voltage drops. These data are sampled at 1000 Hz which is much larger than the minimum requirement of 3 Hz.

4.0 Test Facility

The testing facilities which Skuld Propulsion will use on campus consist of Test Cell 2, Test Cell 3, and Building 91. Figure 14 displays the testing facilities on campus as well as the safety zones. The exclusion zone, shown in red, indicates the area in which all personnel must leave while testing is in progress. The exclusion zone will ensure no personnel will be near the test article in the event of an unscheduled disassembly of the test article. The safe viewing area, shown in white, indicates the area where all non-essential personnel may reside during testing.

The testing facilities at Embry Riddle Aeronautical University satisfy the requirements 1.1.3 and 1.1.4 to enable Skuld Propulsion to begin the testing phase.

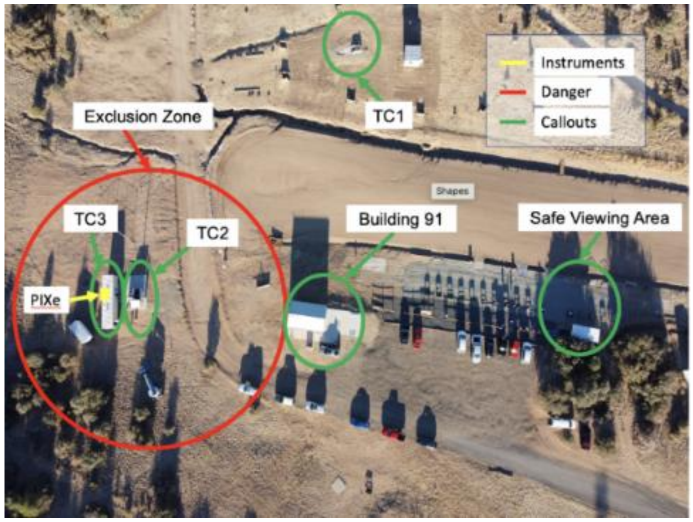

Figure 12: Testing Facilities

4.1 Building 91

Building 91 shown in Figure 15 will be used as the main control room during testing. The computer inside Building 91 will interface with the PXIe in Test Cell 3 so that the data acquisition and ignition system can be operated from Building 91. A circuit was then built to actuate the solenoid valves in the pressure system and connected to a switch box inside Building 91.

Figure 13: Building 91

4.2 Test Cell 2

The strand burner shown in Figure 16 will be mounted to the test stand in Test Cell 2. To prepare Test Cell 2 for testing, the horizontal test stand needs to be installed so that the strand burner can be secured in place. Testing personnel will then perform a sweep to clear the surrounding area of any debris.

Figure 14: Test Cell 2

4.3 Test Cell 3

Test Cell 3 houses the PXIe, which will be used as the main data acquisition system during testing. The PXIe shown in Figure 17 will be used to collect data from the strand burner with a degree of accuracy. To satisfy the requirement 1.1.4, data acquisition cables will be run from the PXIe to the strand burner inside TC2.

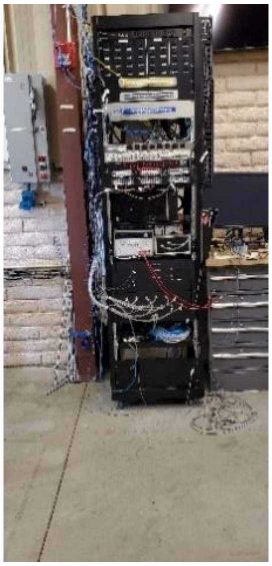

Figure 15: PXI Express

The PXIe has a voltage power source that can provide up to 24 volts. The power source will be used to provide power to the ignition system as well as provide a current to the solder wires. The PXIe also includes a power backup in case of a power failure. The power backup will allow for the actuation of valves and abort codes to be executed in the event of a power outage or power failure. The PXIe can support up to 23 pressure transducers ports and 20 talk back channels while maintaining an uncertainty of $\pm$ 0.001 sec.

Figure 16: NEMA-4 Rated Electrical Box

To prepare TC3 for testing, the PXIe must be able to interface with the strand burner in TC2. To do this a NEMA-4 rated weatherproof electrical box shown in Figure 18 was installed on the outside sidewall of TC3. The NEMA-4 rated electrical box allows for the data acquisition cables to pass from the PXIe through TC3 to the strand burner. To mitigate possible tripping hazards, roof gutters shown in Figure 19 were installed in between TC2 and TC3.

Figure 17: Cable Passover

5.0 Test Procedures

The Skuld Propulsion team has created thorough procedures to allow for safe and efficient testing of the strand burner.

5.1 Propellant Production Procedures

The propellant production procedures outline the process for mixing the propellant and forming it into the required test specimen shape. For this test, we are using the “Cherry Limead” formula created by the MIT rocket team and published online. The propellant production procedures are modeled after the already approved and tested RDL propellant production procedures and modified to better suit the “Cherry Limeade formula”. These can be found in Appendix A.

5.2 Testing Procedures

The procedures for testing keep the safety of personnel in mind throughout and ensure efficient testing can occur. The test procedures include the main test procedures, misfire procedures, a continuation of test procedures, and end of test procedures. Our testing procedures are modeled after the already approved and tested RDL solid and liquid propulsion testing procedures. They can be found in Appendix A.

6.0 Risk Analysis

Skuld Propulsion conducted risk analysis in three categories of personnel, facilities, and equipment and tested to eliminate all potential risks. The risks and their mitigations were ranked by their probability and severity.

Probability was ranked from 1 through 5. The probabilities are defined as 1 being improbable, 2 being seldom, 3 being occasional, 4 is likely, and 5 being frequent. Severity was ranked from A through E. A is defined as multiple deaths or cost of $250,000 or more or complete destruction of TC2 and/or equipment or greater than a month schedule delay complete failure of testing. B is defined as one death or serious/multiple long-term injuries or resulting in hospitalizations or $50k or more or severe damage to equipment or schedule delay greater than two weeks. C is defined as a minor injury or $5,000 or less or some damage to equipment or schedule delay greater than three days. D is defined as no injury or minor injury or $1,000 or less or slight to no damage to equipment or schedule delay greater than 1 day. E is defined as no injury or $100 or less or no damage to equipment or schedule delay due to equipment malfunction (a couple of hours). The number in parenthesis refers to the risk number the risk is associated in the risk and mitigation matrices.

6.1 Risk Analysis for Personnel

Skuld Propulsion’s risk analysis guarantees personnel safety is ensured during testing. Below are risks and their mitigations regarding the personnel safety.

The risk of tripping on the test stand inside the test cell is mitigated by limiting the number of people inside the test cell at a time (1). The risk of tripping/falling on the lip of the test cell pad is mitigated by putting yellow tape on the lip of the test pad (2). The risk of tripping/falling on the bolts that protrude from the test cell pad is mitigated by marking the bolts (3). The mitigations of the first three risks reduce the likelihood of occurrence of minor injuries. The risk of slipping on the incline down into the test cell is mitigated by careful inspection of the test cell before testing after severe weather and holding safety briefings. Also, providing signage and grip tape if needed (4). These mitigations will reduce the likelihood of occurrence of a death or serious or multiple long-term injuries. The minor injuries caused by the risk of slipping, tripping, or falling on the unimproved landscaping are mitigated by maintenance of the landscaping of the area before testing (5). A minor injury can occur due to the risk of pinching of fingers while tightening the faceplate. The mitigation would be to ensure proper tooling is used and the personnel involved are trained in installing the faceplate (11). The weight of the strand burner can cause minor injury to the personnel due to lifting or dropping of the strand burner. The mitigation is to have a minimum of 4 people lifting the strand burner at once or to secure the strand burner on a rolling cart (12). The risk of impact hazard to personnel due to over-pressurization of the strand burner can cause death or serious/long-term injuries. The mitigation is to ensure personnel keeps out of the exclusion zone (17). The risk of pinching the fingers during installation of strand burner causing minor to no injury can be mitigated by ensuring personnel with proper training and experience install the strand burner into TC2 (18). The risk of tripping on exposed cables can cause minor injury which is mitigated by routing the exposed cabling through an overhead cable tray (26).

Risk Matrix: Personnel					
Risk Probability/ Severity	Catastrophic (A)	Critical (B)	Moderate (C)	Minor (D)	Negligible (E)
5					
4			26		
3			1, 6, 12	18	
2		4	2, 3	5, 11	
1		17			

Table 1: Personnel Risk Matrix

Mitigation Matrix: Personnel					
Risk Probability/ Severity	Catastrophic (A)	Critical (B)	Moderate (C)	Minor (D)	Negligible (E)
5					
4					
3					
2					
1		4	1, 2, 3, 6	12, 18	5, 11, 17, 26

Table 2: Personnel Mitigation Matrix

6.2 Risk Analysis for Facilities and Equipment

Skuld Propulsion's risk analysis guarantees the testing facilities safety is ensured during testing. Below are risks and their mitigations regarding the testing facilities safety.

The risk of a manufacturing defect on the faceplate causing it to be liberated, which can cause some damage to equipment or cost $5,000 or more, can be mitigation by performing hydrostatic testing (9). If the strand burner is dropped, there can be some damage to the strand burner; however, this risk can be mitigated by properly securing the strand burner to a rolling cart with ratchet straps during transportation (13). The risk of improper tightening of end caps leading to them being liberated from the test article can cost $50,000 or more in damages or cause serious damage to the test facility and equipment. The mitigation would be to only have experienced personnel perform the task and visually inspect the setup before testing (14).

The risk of damaging the facility due to rapid unscheduled disassembly of strand burner costing $50,000 or more or causing serious damage can be mitigated by having a margin of safety higher than 3. Also, by having the test article inside of the test cell, keeping observers away from the test, and performing hydrostatic testing (15). The risk of over-pressurization causing loss of test article due to rapid unscheduled disassembly of the strand burner can cost $50,000 or more. This can be mitigated by having a margin of safety higher than 3 and having a relief valve upstream of the strand burner (16). The risk of over-pressurization of the strand burner causing $50,000 or more in damages can be mitigated by the strand burner being designed with a factor of safety of 3 as the minimum and operational pressures will be determined from this. Also, this will be confirmed via hydrostatic testing before any hot testing is done [19].

The risk of over-pressurization due to failure of the regulator valve causing serious damage to equipment and facility can be mitigated by the strand burner having an electronically actuated ball valve to release the pressure at 2500 psi coded into the program. Also, the implementation of a relief valve set to blow at 3000 psi will lower the severity of risk (20). The risk of being unable to remotely release pressure causing serious damage to the equipment can be mitigated by the strand burner having a pressure relief valve set to release the pressure at 3000 psi (21).

The risk of damaging electrical connections due to weather causing some equipment damage can be mitigated by implementing a NEMA-4 rated box on test cell 3 to protect the connections from the weather (22). The risk of damage to electrical cables due to weather causing some equipment damage can be mitigated by the data and control cables being detachable and stored in TC3 (23).

The risk of damage to the strand burner due to rust causing serious equipment damage can be mitigated by the strand burner being removable and stored in TC3. Also, the inside will have a protective coating (24). The risk of loss of control of the test article vent causing over-pressurization of the test article and serious equipment damage can be mitigated by proofing the pressurization panel to 1.5x MEOP and setting the failure state of the vent to open (32). The risk of improper wiring of the data cables causing minor equipment damage can be mitigated by proper labeling, developing a wiring diagram, and proper training of personnel (33).

Risk Matrix: Facilities and Equipment					
Risk Probability/ Severity	Catastrophic (A)	Critical (B)	Moderate (C)	Minor (D)	Negligible (E)
5					
4		24			
3		15, 16, 19, 32	13, 20, 21, 22, 23		
2		14		33	
1			9		

Table 3:Facilities and Equipment Risk Matrix

Mitigation Matrix: Facilities and Equipment					
Risk Probability/ Severity	Catastrophic (A)	Critical (B)	Moderate (C)	Minor (D)	Negligible (E)
5					
4					
3					
2					32
1				13, 14, 16	9, 15, 19, 20, 21, 22, 23, 24, 33

Table 4: Facility and Equipment Mitigations Matrix

6.3 Risk Analysis to Success of the Test

Skuld Propulsion's risk analysis guarantees the success of the test is ensured during testing. Below are risks and mitigations regarding the success of the test.

Accidental pressing of the ignition button (with the igniter inserted) in the propellant strand of the strand burner will cause a minimum of three days of delay. The mitigation to the risk is to have a safety key for the ignition system and design a new ignition box with built-in safety interlocks (6). The risk of igniter leads discharging static while inserted in the propellant strand can cause at least three days of delay but can be mitigated by designing a new ignition box and circuit with a static grounding strap or another preventative measure at the leads (7). The risk of having an energized circuit when the igniter leads are connected causing at least three days of delay can be mitigated by having a new ignition box with an arming key, and a lockout tagout at the test cell (8).

The risk of a manufacturing defect on the faceplate causing it to be liberated, which can cause some damage to equipment or cost $5,000 or more, can be mitigation by performing hydrostatic testing (9). The risk of argon gas escaping due to improper installation of the face plate and delaying the test by at least a day can be mitigated by ensuring the personnel is properly trained in the installation of the faceplate, and ensuring no personnel is in the testing area (10).

If the strand burner is dropped, there can be some damage to the strand burner; however, this risk can be mitigated by properly securing the strand burner to a rolling cart with ratchet straps during transportation (13). The risk of improper tightening of end caps leading to them being liberated from the test article can cost $50,000 or more in damages or cause serious damage to the test facility and equipment.

The mitigation would be to only have experienced personnel perform the task and visually inspect the setup before testing (14). The risk of damaging the facility due to rapid unscheduled disassembly of strand burner costing $50,000 or more or causing serious damage can be mitigated by having a margin of safety higher than 3. Also, by having the test article inside of the test cell, keeping observers away from the test, and performing hydrostatic testing (15). The risk of over-pressurization causing loss of test article due to rapid unscheduled disassembly of the strand burner can cost $50,000 or more. This can be mitigated by having a margin of safety higher than 3 and having a relief valve upstream of the strand burner (16). The risk of over-pressurization of the strand burner causing $50,000 or more in damages can be mitigated by the strand burner being designed with a factor of safety of 3 as the minimum and operational pressures will be determined from this. Also, this will be confirmed via hydrostatic testing before any hot testing is done (19).

The risk of over-pressurization due to failure of the regulator valve causing serious damage to equipment and facility can be mitigated by the strand burner having an electronically actuated ball valve to release the pressure at 2500 psi coded into the program. Also, the implementation of a relief valve set to blow at 3000 psi will lower the severity of risk (20). The risk of being unable to remotely release pressure causing serious damage to the equipment can be mitigated by the strand burner having a pressure relief valve set to release the pressure at 3000 psi (21).

The risk of damaging electrical connections due to weather causing some equipment damage can be mitigated by implementing a NEMA-4 rated box on test cell 3 to protect the connections from the weather (22). The risk of damaging electrical connections due to weather causing some equipment damage can be mitigated by implementing a NEMA-4 rated box on test cell 3 to protect the connections from the weather (22). The risk of damage to electrical cables due to weather causing some equipment damage can be mitigated by the data and control cables being detachable and stored in TC3 (23).

The risk of failure of igniting the propellant can delay the test by at least a day; however, it can be mitigated by the strand burner must be vented and reset, and the ignition system must be tested in the empty, pressurized strand burner (25). The risk of muscle pressure regulator failing and remaining open causing over-pressurization of the pressurization circuit can lead to at least three days of delay in the testing schedule. Mitigations would be to monitor pressure using pressure gauges, having a relief valve downstream of the regulator, and proofing the pressurization panel to 1.5x MEOP (27).

The risk of muscle pressure vent being misconfigured open resulting in loss of consumables can cause at least a day of delay in testing but can be mitigated by proper training of the personnel and following the approved written procedures during testing (28). The risk of a high-pressure manual vent being misconfigured open resulting in loss of consumables can cause at least a delay in the testing schedule and can be mitigated by proper training of the personnel and following the approved written procedures during testing (29). The risk of the manual panel isolation valve being misconfigured closed, preventing the pressurization of the panel, and causing a loss of at least a day of delay to reconfigure can be mitigated by proper personnel training and must follow the approved written procedures during testing (30).

The risk of loss of control of the test article pressurization solenoid valve causing unwanted pressure in the test article and possible loss of consumables and leading to at least a three delay can be mitigated by personnel following the approved written procedures during testing, the failure state to be set to close, and having an upstream isolation valve (31). The risk of loss of control of the test article vent causing over-pressurization of the test article and serious equipment damage can be mitigated by proofing the pressurization panel to 1.5x MEOP and setting the failure state of the vent to open (32). The risk of improper wiring of the data cables causing minor equipment damage can be mitigated by proper labeling, developing a wiring diagram, and proper training of personnel (33).

Risk Matrix: Success of the Test					
Risk Probability/ Severity	Catastrophic (A)	Critical (B)	Moderate (C)	Minor (D)	Negligible (E)
5				25	
4		24	6		
3		15, 16, 19, 20, 21, 32	13, 22, 23, 27, 31	28, 29, 30	
2		14	7, 8	10, 33	
1			9		

Table 5: Success of the Test Risk Matrix

Mitigation Matrix: Success of the Test					
Risk Probability/ Severity	Catastrophic (A)	Critical (B)	Moderate (C)	Minor (D)	Negligible (E)
5					
4					
3					
2					
1				10, 13, 14, 16, 27, 28, 29, 31	6, 7, 8, 9, 15, 19, 20, 21, 22, 23, 24, 25, 38, 33

Table 6: Success of the Test Mitigations Matrix

7.0 Post Test Analysis

The Skuld Propulsion team will find the ‘a’ and ‘n’ valuers after the test is conducted. This will be done by calculating the burn rate in between each wire section of a single solid rocket propellant sample, at various pressures. A total of nine different burn rate groups will be plotted against their respective pressure. Each group will have nine data points giving a total of 81 data points. This will be done for pressures ranging from 200 – 1000 psi. From there, a power line of best fit will be plotted on the graph to show what the ‘a’ and ‘n’ values are. A rough example of what the final graph will look like is pictured in Figure 18.

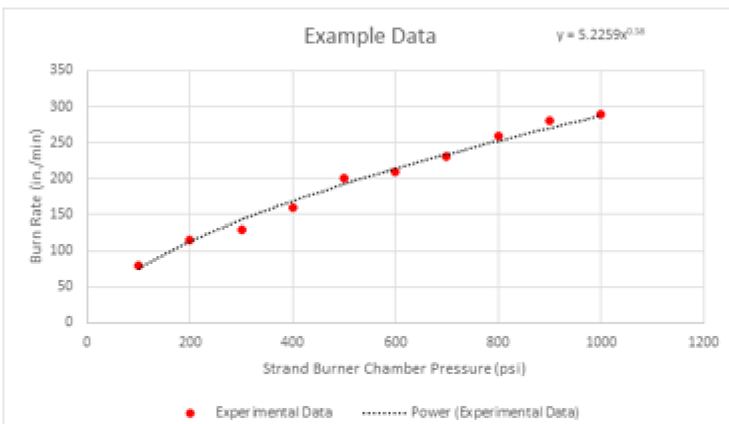

Figure 18: Example of Power Line Best Fit

Once the ‘a’ and ‘n’ values are found, the team will be conducting an uncertainty test for the values to account for any errors or outside factors. With the uncertainty tests finished, the team will compare the data found from testing with the results that the MIT has posted about the “Chery Limeade” solid propellant. This discussion will elaborate on the accuracy of the new testing method along with whether Skuld Propulsion was successful in creating a better testing method for solid rocket propellant on campus.

8.0 Testing Schedule

The team plans to finish its manufacturing on Thursday, April 21, and begin testing on Friday, April 22. Testing should only take 2 days due to the limited supply of pressurant gas and will finish on Saturday, April 23. If any unexpected delays come up Sunday, April 24 is available for the team to test as well. Testing cannot continue the next week due to the final technical presentation and the symposium taking place.

9.0 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, Associate 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, Assistant Professor of Humanities and Communication; Professor Robert Gerrick, Chair of Mechanical Engineering; Jefferey Hiatt, Engineering Lab Specialist; Jared Vanatta, College of Engineering Lab Manager; Patrick David, Machinist; Andrew Hamilton, Mechanical Engineering Student; McNeil W. Allison, Industrial Engineer, Consultant – Global Healthcare Solutions; Michael Brady, EHS Program Manager

10.0 References

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Appendix A

Mixing Procedures:

Rocket Development Lab

Eagle Space Flight Team

Ammonium Perchlorate Composite Propellant

Hand-Mixing Procedure for Propellant Strands

Version 5 – 2/14/2022

Created by:

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Safety

Safety of those working with propellant is the highest priority of any propellant manufacturing operation. During the entire propellant mixing process, all personnel will wear eye protection. Those working directly with propellant chemicals will wear nitrile gloves with extended cuffs and Tyvek lab coats, and all personnel will wear dust masks during the measuring and incorporation of the dry components of the propellant. Those working directly with propellant will wear clothing which does not fit excessively loosely and is made of 100% cotton or wool or all natural fibers (**No synthetics!**), and long hair will be tied back.

To keep dust to a minimum, dry propellant chemicals will be added with the mixer powered off and gently incorporated by hand until they are sufficiently wetted out to prevent any dust from being kicked up when the mixer is restarted.

During all mixing operations, one person will constantly man an ABC fire extinguisher (**No water-filled "pump cans" or Class A extinguishers**). In the extremely unlikely event of the propellant igniting during mixing, all team members will move away from the mixer and will then be allowed to burn until all propellant in the mixing bowl has been consumed. It is only at that time that the person with the fire extinguisher will attempt to put out any remaining fires fueled by what remains of the mixer.

Do not attempt to extinguish burning propellant! The propellant is self-oxidizing and burns at approximately 4000°F. Once it ignites, there is nothing that can be done to extinguish it. **Do not attempt to extinguish burning propellant with water!** Like other high temperature metal fires, throwing water on burning propellant simply makes the fire more intense.

To effectively segregate and minimize the hazardous waste created during the mixing sessions there are safety/hazardous waste stops built into the process where participants will discard gloves, wipes, and residues into specifically labeled containers. Then they will put on fresh gloves and proceed to the next safety/hazardous waste stop.

After mixing, vacuum processing, and the pouring of propellant is complete, it will be allowed to cure in a fire cabinet designated for solid rocket propellant and other self-oxidizing materials. After the propellant has cured completely and removed from the jig, the propellant will continue to be stored in the same cabinet until it is needed for testing. Mix sessions will be scheduled such that this storage interval is as short as is feasible. When not in use, containers of raw ammonium perchlorate must be stored in the designated oxidizer cabinet in the Structures Lab within AXFAB.

Introduction

This document is a procedure for the mixing and processing of small (2 in. long by ¼ in. square cross section) strands of **ammonium perchlorate composite propellant (APCP)** for use in the strand burner. Its purpose is to provide a means for the student groups to safely produce consistent, reliable solid rocket propellant strands for the purpose of characterization. This version of the document, specifically, is tailored to the mixing and processing of propellant using hand-mixing and vacuum bowl setup shared by Eagle Space Flight Team (ESFT) and Rocket Development Lab (RDL).

All propellant mixing is performed outside, behind the Propulsion Lab (Building 71), in front of the roll-up garage door. This document assumes that the propellant formula being mixed is conventional, using ammonium perchlorate as its oxidizer; powdered metals as its fuel; all held together with HTPB binder (R-45M or R-45HTLO). The binder is assumed to utilize modified MDI isocyanate curative, isodecyl pelargonate (IDP) plasticizer, an anti-foam agent, and a bond strengthener (if used). Refer to the mix sheet enclosed at the end of this document for more specifics on fuels and additives. The mix sheet must be completed in preparation for the mix. The exact amount for each component is calculated within a 1-gram tolerance.

Method

For mixing the propellant, a propellant bowl and ice cream spade will be used. The propellant will be mixed by hand. After mixing, the bowl of propellant will be fitted with an acrylic lid attached to a vacuum pump and the bowl with lid will be strapped to a shaker table. The vacuum pump will then be used to pull a vacuum on the contents of the mixing bowl. This will remove any air bubbles introduced into the propellant during mixing as well as any trapped gas from the curing process of the propellant's binder. The shaker table will aid in the release of trapped gas in the propellant.

After vacuum processing, curative will be added and mixed by hand. Then the propellant will be put under vacuum again. The propellent will then be poured into the jig and allowed to cure.

Personnel

The personnel present for any mixing session will be assigned to one of these duties:

Chemical Measuring:	Weighs out precise amounts of propellant chemicals into temporary containers before or during mixing. This makes the mixing operation itself run more smoothly.
Ingredient Incorporation:	Adds propellant chemicals to mixing bowl one at a time in the order presented later in this document. Occasionally checks propellant during mixing to ensure that it is being mixed thoroughly enough to produce a consistent product.
Mix Observer:	Keeps mix sheet and tracks actual amounts of each chemical added to the mix. Takes notes during mix session.
Fire Extinguisher Operator:	Stands ready with fire extinguisher. In unlikely event of propellant ignition, they will wait until propellant has been fully consumed before extinguishing remains of mixer.
Safety Observer:	Watches area surrounding mixing operation for safety hazards. Keeps unrelated personnel a safe distance away from mixing operation.

Preparation

Before beginning to follow the procedures outlined in this document, a mix sheet for the desired propellant formula and batch must be created using the Excel worksheet accompanying this document. Read the mix sheet's instructions before filling out and printing the sheet. The Chemical Measurer is also responsible for checking the sheet's calculations before proceeding to mix, and make sure that the mix observer understands their role and the role of the mix sheet during the mix session.

Equipment List

The following equipment is required for each mix session; however, if a list has been created for the specific mixture to be used, defer to that.

___ ABC dry chemical fire extinguisher (water extinguishers are prohibited)

___ Small mixing bowl

___ Ice cream spade

___ Extension cord, minimum length of 30'

___ Vacuum pump with hose (check oil level)

___ Plexiglass lid fitted to mixing bowl, with fitting for vacuum hose

___ Popsicle stick

___ Paper towels

___ Mineral spirits

___ Hazardous waste container

___ Plastic spoons

___ 10 Jigs

___ 100 thin solder wires cut to length

___ Mold release

___ Curing Plates

___ 10 e-matched

___ Labeled waste bag/box for metal powder fuel, binding, and curing agents

___ Labeled waste bag/box for gloves and containers contaminated with ammonium perchlorate

___ Labeled waste bag/box for gloves, cleaning wipes, and incidental propellant

___ Labeled waste bag/box for hardened propellant trimmed from completed jig

PPE List

Listed below are the necessary personal protective equipment require to begin performing the mix session.

___ Impact safety glasses

___ Dust masks

___ Nitrile gloves with extended cuffs

___ Tyvek lab coats

Read through this procedure in its entirety before beginning to mix!

The process of mixing propellant is both time sensitive and unforgiving of mistakes. It is imperative that all personnel know exactly what tasks to perform and exactly when to perform them.

Throughout this procedure, important safety notes will appear in boxes such as this one. Important procedural notes will appear bolded within the text.

Throughout this procedure, initial the box next to each step as it is completed. This is to help minimize mistakes and confusion during the mix.

Procedure

☐ 1. Set up the shaker table, vacuum pump, extension cord, fire extinguisher, and propellant mixing area.

☐ 2. Spray inside each jig and the curing plates with mold release. Make sure there is a good coat on all surfaces but that it is not dripping.

If not wearing them already, all personnel don safety glasses at this time. Additionally, personnel measuring or mixing propellant don nitrile gloves with extended cuffs, Tyvek lab coats and dust masks. Any personnel in the chemical mixing area need to don dusk masks as well.

☐ 3. Locate the mix sheet prepared earlier for the specific propellant formula and batch size being mixed. Perform one final check of the calculations before moving forward.

☐ 4. Measure the dry chemicals into **separate** disposable containers. The plasticizer and curative should be measured directly into the bowl to limit the errors in chemical weights.

Ammonium perchlorate and powdered fuel or other dry chemicals are never to be allowed to come into contact without the binder!!!

The binder acts as a burn rate suppressant for the ammonium perchlorate/fuel mixture and increases the activation energy of the propellant. With the binder, this mixture will burn at the same rate as office paper and requires a substantial energy input to ignite. Without the binder, the mixture is virtually identical to pyrotechnic flash powder, possessing a fast burn rate and sensitivity to friction and physical shock.

☐ 5. Measure out the HTPB resin directly into the mixing bowl. Now use a popsicle stick to measure out the bond strengthener into the bowl and combine by hand with the ice cream spade.

When each chemical is added, note the true amount added in the appropriate box on the mix sheet. Do this for every chemical added during the mix session

☐ 6. Next, add the plasticizer to the bowl. Mix the ingredients for three (3) minutes.

Dust Prevention Measures:

When measuring out the dry powders make sure to gently measure out the powders low over the surface of the container to help keep dust to a minimum.

☐ 7. Measure out the powdered fuel into a separate disposable container before adding the powdered fuel to the bowl. When pouring in fuel or other fine powders, keep the container low over the surface of the liquid to keep dust to a minimum. Gently combine the fuel chemicals into the mixture by hand using the ice cream spade and proceed to mix by hand until a uniform mixture is achieved.

☐ 8. Next, add the anti-foaming agent into the bowl. Mix with hand for eight (8) minutes.

☐ 9. Once the eight (8) minutes is over, the vacuum lid is placed on the bowl and the vacuum pump is switched on and allowed to pull vacuum on the propellant for five (5) minutes. The bowl, with the vacuum lid, is strapped to the shaker table, which is then turned on. The propellant is then allowed to be shaken under vacuum for five (5) minutes. Note the true time under vacuum on the mix sheet. If the propellant begins to get close to the top of the bowl, open the vacuum release valve while continuing to shake the propellant and allow the propellant to settle before closing it again.

From this point on, all waste will be disposed of in the appropriately labeled hazardous waste container.

Waste which has not come into contact with any of the ingredients are safe to dispose of in normal garbage, but any chemical-contaminated waste must be disposed of in the appropriately labeled hazardous waste container.

☐ 10. **SAFETY/HAZARDOUS WASTE STOP** Remove your gloves and discard them and any contaminated wipes into the hazardous waste container labeled for binder and metal powder fuel. Put on fresh gloves.

☐ 11. Add the ammonium perchlorate to the bowl at this time, employing the same dust prevention practices used with the other dry components. The ammonium perchlorate is then wetted out by hand using the ice cream spade and incorporated into the mixture as before. The mixture is then mixed by hand for eight (8) minutes. If the propellant requires more than one size of AP, then repeat these steps for the other sizes before moving on to the next steps.

☐ 12. **SAFETY/HAZARDOUS WASTE STOP** Remove your gloves and discard them and any contaminated containers and wipes into the hazardous waste container labeled for ammonium perchlorate. Put on fresh gloves.

☐ 13. Add any additional powdered additives, if the formula incorporates any, to the bowl using the dust prevention techniques explained earlier. Wet out by hand using the ice-cream spade.

☐ 14. Once all additives have been added, the propellant is mixed by hand for eight (8) minutes.

☐ 15. The vacuum lid is placed on the bowl and the vacuum pump is switched on and allowed to pull vacuum on the propellant for five (5) minutes. The bowl, with the vacuum lid, is strapped to the shaker table, which is then turned on. The propellant is then allowed to be shaken under vacuum for five (5) minutes. Note the true time under vacuum on the mix sheet. If the propellant begins to get close to the top of the bowl, open the vacuum release valve while continuing to shake the propellant and allow the propellant to settle before closing it again.

☐ 16. Add the curative to the bowl. **On the mix sheet, note the time at which the curative was added.** Hand-mix the propellant for eight (8) minutes.

☐ 17. The vacuum lid is placed on the bowl and the vacuum pump is switched on and allowed to pull vacuum on the propellant for five (5) minutes. The bowl, with the vacuum lid, is strapped to the shaker table, which is then turned on. The propellant is then allowed to be shaken under vacuum for five (5) minutes. Note the true time under vacuum on the mix sheet. If the propellant begins to get close to the top of the bowl, open the vacuum release valve while continuing to shake the propellant and allow the propellant to settle before closing it again.

☐ 18. The propellant is then poured carefully into the jigs on the curing plate until the jigs are half full.

19. Place the wires into their intended slots and an e-match with twisted leads in its intended slot. Fill the jigs the rest of the way up.

☐ 20. The jigs are then carefully transported to the RDL and are placed in the fire cabinet and allowed to cure. This process will usually take three (3) to five (5) days.

☐ 21. The mixing bowl, mixer paddle, and ice cream spade are all thoroughly cleaned with paper towels and mineral spirits. **SAFETY/ HAZARDOUS WASTE STOP** These paper towels, gloves, and any incidental propellant are disposed of in the hazardous waste container labeled for gloves, cleaning wipes, and incidental propellant.

After cleanup is complete, no propellant residue whatsoever may remain on any tools or equipment.

☐ 22. After three (3) to five (5) days, the propellant should be fully cured.

☐ 23. **SAFETY/HAZARDOUS WASTE STOP** Place any unusable propellant created from the jig into the hazardous waste container labeled for labeled for waste propellant.

☐ 24. **SAFETY/HAZARDOUS WASTE STOP** Remove your gloves and discard them any contaminated wipes into the hazardous waste container labeled for labeled for gloves, cleaning wipes, and incidental propellant. Dispose of the lab coats if there is any propellants on them as well.

Mix Sheet Example

Manually-Entered Value	
Calculated Value	
Use During Mix Session	

Procyon Propulsion Propellant Mix Sheet - Small Scale

Propellant Formula: Fire Lizard v2.5

Contact: Anthony Bernard (949) 521-0432

Mixing Calculations

Number of Grains	1
Casting Tube Length Total (in)	12
Casting Tube ID (in)	4.75
Coring Rod OD (in)	1.48
Total Casting Volume (in^3)	192.002
Propellant Density (lb/in^3)	0.061
Slop Factor	3%
Propellant Mass (lbm)	12.064
Propellant Mass (g)	5470.979
Propellant Volume (in^3)	**197.762**
(quarts)	**3.424**

Propellant Formula

Chemical	Proportion
HTPB	11.63%
Tepanol	0.30%
Plasticizer (IDP)	4.55%
Aluminum	7.00%
PDMS	0.02%
400 micron AP	15.61%
200 micron AP	46.83%
90 micron AP	9.36%
Oxamide	2.50%
Carbon Black	0.20%
Curative (MDI)	2.00%
Cross Check %	**100.00%**

Mixing Masses (All Valules Calculated)

Chemical	Installment Mass (g)	Running Total (g)	Checkbox	True Value (g)
HTPB	**636.27**	**636.27**		
Tepanol	**16.41**	**652.69**		
Plasticizer (IDP)	**248.93**	**901.62**		
Aluminum	**382.97**	**1284.59**		
PDMS	**1.09**	**1285.68**		
400 micron AP	**854.02**	**2139.70**		
200 micron AP	**2562.06**	**4701.76**		
90 micron AP	**512.08**	**5213.84**		
Oxamide	**136.77**	**5350.62**		
Carbon Black	**10.94**	**5361.56**		
Curative (MDI)	**109.42**	**5470.98**		
Drops of PDMS	**16.41**		**True Total (g):**	

Record Mix Times and Mix Session Notes Below

Mix Session Date: **Start Time:** **End Time:** **Personnel:**

Appendix B

Testing Procedures:

Skuld-ERAU
Strand Burner Standard Operating Procedures

Discrete Voltage Measurement Version

Version 2 – 4/21/2022

Created by:
Cooper Drain and Shane Cullen

Edited by:

Cooper Drain and Shane Cullen

Opening Statement

Safety of those involved in testing solid rocket motors is the highest priority of any testing campaign. For the purpose of this document, and all other testing procedure documents pertaining to the strand burner, the program will be broken down into six sections: Pre-test, Test, Misfire, Recycle, Post-Test, and Data Analysis. Each section will have its own safety statement and standard operating procedures. Read this document in whole before beginning any tests to ensure all involved personnel know what is going on, and any potential risks that exists during testing. Please note that this document will only address the safety hazards that have been deemed the most pertinent by the Skuld Propulsion Team, Dr. Bryner, and campus EHS. For a full and in-depth analysis of the risks and hazards presented by these operations please read the Risk-Hazzard Assessment and Job Safety Assessment. Later iterations of this document will also be included in a user's manual.

Introduction

This document is a procedure for the testing and analysis of propellant in the Skuld Propulsion strand burner. Its purpose is to provide a means for student groups to safely set up and operate the system. This version of the document is specifically tailored for using the Discrete Voltage Measurement (DVM) method on small propellant strands. A small propellant strand is defined as being 6 in. in length or less and having a square cross-section of 0.5 in. by 0.5 in. (see Appendix C). This version is only for use in Test Cell Two (TC2). For more information on the exclusion zones and locations of buildings, see Appendix A.

Safety

The safety of those involved in testing solid rocket motors is the highest priority of any testing campaign. During pretest operations, all personnel in the testing area must wear eye protection. Those working directly with strand burner and any affiliated equipment will wear closed-toed shoes and clothing that does not fit excessively loose. Clothing must be made of 100% cotton or other natural fibers (**No synthetics!**). This is the same requirement used when handling any solid propellant regardless of application. Because the strand burner has components that will be torqued down tightly to prevent any leaks, all personnel will tie back all long hair and no jewelry will be worn. To keep personnel from hurting themselves during set up, any equipment that ways over thirty pounds will need two people or more to move into position.

The strand burner will be **operated at high pressures (100 psi – 1000 psi)** during operations. The strand burner is designed with a factor of safety of three in mind and as such the maximum pressure it can take is 3000 psi. During operations, the strand burner will be pressurized to the working pressure before being vented after testing is complete. The bolts holding the strand burner to the test stand need to be securely fastened to avoid test article movement while venting.

During all testing operations, one person will constantly man a chemical ABC fire extinguisher **(No water-filled "pump cans").** In the extremely unlikely situation where the propellant lights prematurely outside the strand burner, all team members will move away from the test cell. The propellant will then be allowed to burn out before any team member will continue to put out any other fires that started because of the propellant ignition.

Do not attempt to extinguish burning propellant! The propellant is self-oxidizing and burns at approximately 4000°F. Once it lights, there is nothing that can be done to extinguish it. **Do not attempt to extinguish burning propellant with water!** Like other high-temperature metal fires, throwing water on burning propellant simply makes the fire more intense.

The built-in safety checks for this system include: two checks of valve operations, ignition operation checks, coded abort sequences, and a manual abort button. If these checks fail, troubleshooting will take place to find the issue. If the issue is found and is fixable, then after repairing the system, testing can begin.

Personnel & Responsibilities

Role	Responsibility	Personnel
Test Conductor	Responsible for conducting the test. Reads all pertinent safety and procedural steps. Has authority to end test for any reason. Coordinates with Dr. Bryner, Safety, and the RDL Technical Committee.	
Data Acquisition Specialist	Responsible for knowing how to operate the strand burner and operating software. Responsible for working with Dr. Bryner on the LabVIEW code. Responsible for reporting test data.	
Red Team	Two people have this role. Responsible for operating the manual valves during operation.	
Trail Spotter	Responsible for keeping unauthorized personnel out of the testing area.	
Parking Lot Spotter	Responsible for keeping unauthorized personnel out of the testing area.	

Equipment List

Item	Checkoff	Item	Checkoff
Strand Burner (See Appendix B)		Impact Wrench	
Air Compressor		Pressure Line	
Argon Bottles		Voltmeter	
Igniter		Propellant Test Pieces	
Inferred Thermometer		Pressure Transducer	
Detachable Connector Cable		Overhead Cable Rail	
Strand Burner Bolts and Nuts		Valves	
Actuators		Regulators	
O-Ring			

PPE List

Equipment	Checkoff
2 Pairs of Welding Gloves	
Face Shield	
Nitrile Gloves	

Strand Burner Testing P&ID

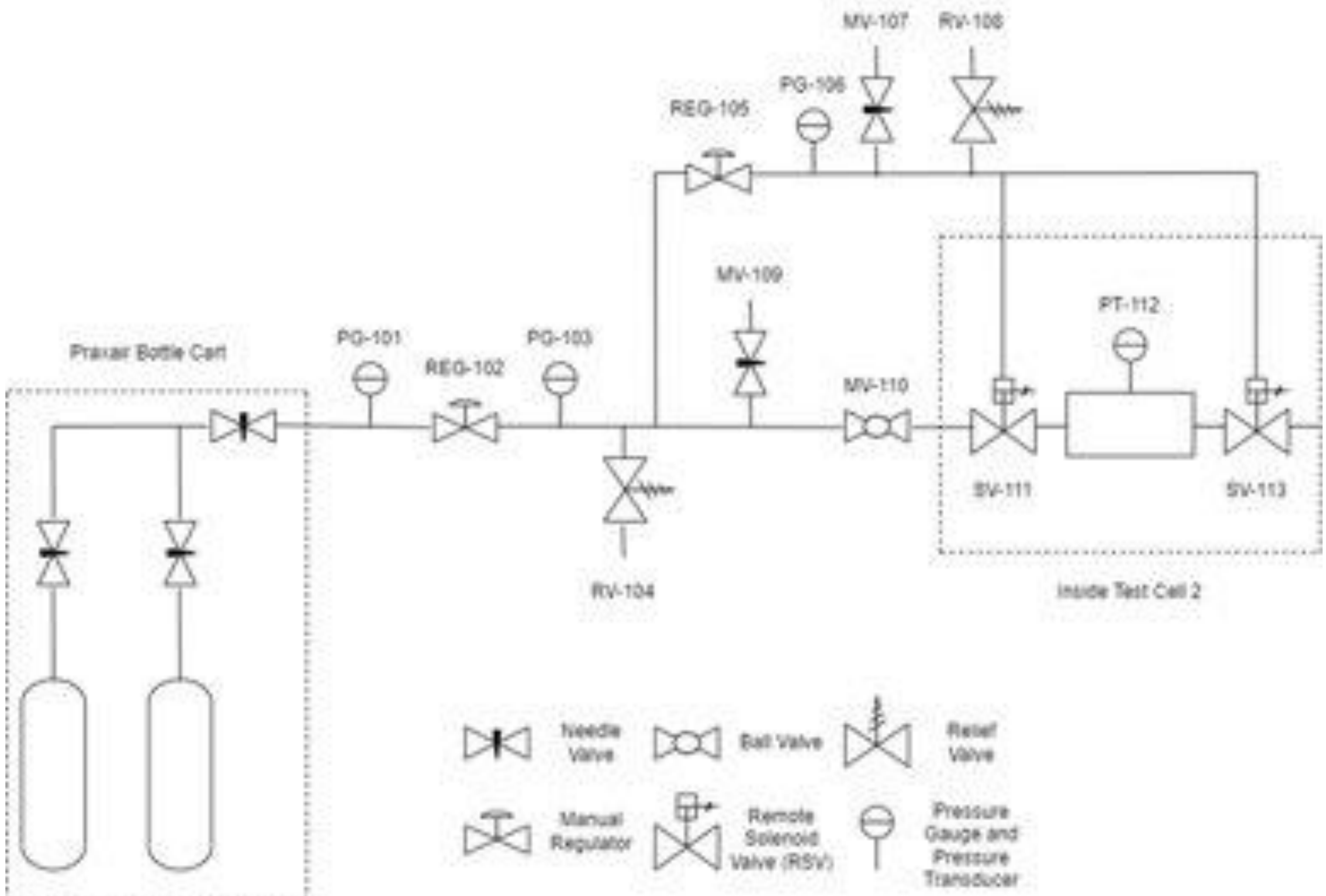

Figure 19: P&ID

1. Pre-Test Operations

Step	Operator	Procedure	Signoff
		Note: Before beginning to follow the procedures outlined in this section, the correct test specimens must be located, and the procedures read. Read both the SOP's and the accompanying risk assessment at least one day before the test. All the pressure lines must be inspected for damage or rusting. If any damage is located, then the concerned parts need to be replaced before testing can take place.	
		WARNING: All operations listed below must be completed before any test team is allowed to move on to the Test Operations. Any faults in the system at this point must be fixed before moving into testing operations. If there is a failure in any of the systems more than **THREE TIMES**, then testing will end for that day.	
		CAUTION: Read through this procedure in its entirety before beginning to test! The process of testing propellant is unforgiving of mistakes. It is imperative that all personnel know exactly what tasks to perform and exactly when to perform them. Throughout this procedure, important safety notes will appear in boxes such as this one. Important procedural notes will appear bolded within the text. Throughout this procedure, initial the box next to each step as it is completed. This is to help minimize mistakes and confusion during the mix.	
1.1	TCON	Test Conductor will assign qualified personnel as the Data Acquisition Specialist, Red Team, Trail Spotter, and Parking Lot Spotter.	
1.2	Red Team	Verify Strand Burner and pressurization circuit is properly assembled.	
1.3	Red Team	Locate piping system and check the system for damage or rust	
1.4	Red Team	Red Team set test facility to GREEN	
1.5	Red Team	**Verify/CLOSE** Argon Bottle Valves	
		Connect Bottle to piping system	
		Perform whip check of flex hose	
		WARNING: While Argon is non-toxic, it is an asphyxiant. As such, personnel operating the argon need to be careful. If team member is feeling lightheaded, leave testing facility immediately to get fresh air. Report incident to Test Conductor and halt testing until leak is fixed.	
1.6	TCON	**VERIFY** lockout key is in the **"SAFE"** position and key is not in the ignition box.	

1.7	Red Team	Set test facility to **AMBER**. All non-necessary personnel must leave to the exclusion zone (refer to Appendix A for more information on the exclusion zone).	
1.8	Red Team	**VERIFY SV-111** (strand burner press valve) is **CLOSED.**	
1.9	Red Team	**CLOSE MV-110 (**manual shut-off valve)	
		NOTE: The **manual shut-off valve** is to make sure that we **don't allow the strand burner to be pressurized** during pressurized valve checks. This is a **safety feature** to ensure Red Team is not hurt by a high burst of pressure. All pressures will be read number by number. For example, 100 is one, zero, zero.	
1.10	Red Team	**DON** face shields.	
1.11	Red Team	**SLOWLY OPEN** argon bottle valve a ½ turn at a time.	
1.12	Red Team	**SLOWLY OPEN** argon family iso-valve halfway open.	
1.13	Red Team	**LOAD REG-102** (strand burner pressure regulator) to ~80 psi.	
		LOAD REG-105 (muscle pressure regulator) to 80 psi.	
1.14	Red Team	Check for leaks.	
		If leaks are found:	
		CLOSE argon bottle valves	
		OPEN MV-107 and MV-109 (manual vents)	
		BACK-OFF REG-102 and REG-105 (manual regulators)	
		CLOSE argon family iso-valve	
		CLOSE MV-107 and MV-109 (manual vents)	
		Once leak is repaired, return to step 1.11.	
		If no leaks are found: continue to next step	
1.15	TCON	**INSERT** lockout key into ignition box and **turn to "HOT**."	
1.16	TCON	**VERIFY** prop flow enable is **OFF**	
		NOTE: Valves should not be able to actuate with prop flow enable off.	
1.17	TCON/Red Team	**OPEN** then **CLOSE** SV-111 (strand burner press valve). Red Team, check for actuation. **NO actuation should occur.**	
		If no actuation occurs, continue to next step.	
		If actuation occurs, DO NOT continue with procedures. Begin troubleshooting.	
1.18	TCON	**VERIFY/CLOSE** SV-111 (strand burner press valve)	
1.19	TCON/Red Team	**OPEN** then **CLOSE** SV-113 (vent RSV). Red Team, check for actuation. **NO actuation should occur.**	
		If no actuation occurs continue to the next step	
		If actuation occurs, **DO NOT** continue with procedures. Begin troubleshooting.	
1.20	TCON	**VERIFY/CLOSE SV-113** (vent RSV)	
1.21	TCON	Turn prop flow enable **ON**	
1.22	TCON/Red Team/DAQ	**OPEN** then **CLOSE** SV-111 (strand burner press valve). Red Team and DAQ verify actuation.	

		If actuation occurs, continue to next step	
		If actuation does not occur, **DO NOT** continue with procedures. Begin troubleshooting.	
1.23	TCON/Red Team/DAQ	**OPEN** then **CLOSE SV-113** (vent RSV). Red Team and DAQ verify actuation.	
		If actuation occurs, continue to next step	
		If actuation does not occur, **DO NOT** continue with procedures. Begin troubleshooting.	
1.24	TCON	Turn prop flow enable **OFF**	
1.25	TCON	Set lockout key to **SAFE** and remove the key from the ignition box	
		Perform the following to vent down the system	
1.26	Red Team	**CLOSE** the argon bottle valves	
1.27	Red Team	**OPEN MV-110** (manual shut-off valve)	
1.28	Red Team	**OPEN MV-107 and MV-109** (manual vents)	
		VERIFY venting is complete by listening for venting to stop and have TCON verify there is no pressure being read by the PT's.	
1.29	Red Team	**CLOSE** MV-107 and MV-109 (manual vents)	
1.30	Red Team	**CLOSE** the argon family iso-valve.	
1.31	Red Team	**BACK-OFF** REG-102 and REG-105 (manual regulators)	
1.32	Red Team	Set the test cell to **GREEN**.	

2. Test Operations

Step	Operator	Procedure	Signoff
		WARNING: Before beginning to follow the procedures outlined in this section, all pretest operations must be successfully completed. Read both the SOP's and the accompanying risk assessment at least one day prior to the test. Prior to start of the test, all pressure lines must be inspected for damage or rusting. If any damage is located, then the concerned parts need to be replaced before testing can take place.	
		NOTE: Read through this procedure in its entirety before beginning to test! The process of testing propellant is unforgiving of mistakes. It is imperative that all personnel know exactly what tasks to perform and exactly when to perform them. Throughout this procedure, important safety notes will appear in boxes such as this one. Important procedural notes will appear bolded within the text. **Throughout this procedure, initial the box next to each step as it is completed. This is to help minimize mistakes and confusion during the test.**	
2.1	TCON	Announce Pre-Test Procedures are complete, and that you are moving on to test procedures	
2.2	TCON	**VERIFY** all valves are commanded **OFF,** prop flow enable is **OFF**, and the ignition key is set to **SAFE** and **REMOVED** from the box.	
2.3	Red Team	**VERIFY** the ignition system on the PXIe is **OFF** and that the key is **REMOVED.**	
2.3	Red Team	Set the test facility to **AMBER**	
2.4	Red Team	**OPEN** the strand burner at the forward closure by removing all the bolts from the strand burner. **NOTE:** This is best done using an impact drill.	
2.5	Red Team	**CONNECT** the pressure transducer to the strand burner and to the appropriate cable leading to the PXIe.	
2.6	Red Team	**CONNECT** the igniter and continuity wires to the ignition circuit.	
2.7	Red Team	**CONNECT** a voltmeter to the continuity line in the ignition circuit and the ignition leads to themselves.	
		Using the shut-off key, turn the ignition system at the PXIe **ON.**	
2.8	TCON	**TURN** the lockout key to **HOT** on the ignition box.	
		PRESS the ignition button. Have Red Team confirm that they have continuity.	
2.9	TCON	**UNPRESS** the ignition button.	
		TURN the ignition key to **SAFE** and **REMOVE** the key.	

2.10	Red Team	**TURN OFF** the ignition system using the lockout key at the PXIe and **REMOVE** the key.	
2.11	Red Team	**PLACE** the propellant specimen onto the flat plate. **INSERT** the plate into the test article.	
2.12	Red Team	**CONNECT** the wires in the propellant to the corresponding cables leading to the PXIe.	
		VERIFY with DAQ that they are reading continuity.	
2.13	Red Team	Red Team place the flange with the bottom bolts 1, 5, 7, and 4 in the strand burner. Insert the O-ring into the space and add the rest of the bolts and washers into their places. Hand-tighten the nuts on the bolts before using the impact wrench. **Make several passes, with the impact wrench, in a star pattern to tighten the nuts**. (see Appendix D) After each pass, check the bolts are equally tightened, and there are no loose nuts. Each pass should be longer than the last one until the blind flange is completely tightened.	
		WARNING: When using an impact wrench to tighten the **bolts, no one will hold on to the nut with a wrench**. The impact wrench will tighten the bolt on its own and does not need external help. If you use a wrench to hold the nut in place, there is a high possibility for injury as the **wrench is ripped out of your hand or your hand is smashed into the strand burner**.	
		NOTE: Red Team press the wires flat against the face of the strand burner flange to improve sealing with O-ring	
2.14	Red Team	Set test facility to **RED**	
2.15	TCON	Direct trail spotter and parking lot spotter to their designated locations.	
		Make sure all non-affiliated people are in the safe viewing area and **no one besides, Red Team is inside the exclusion zone** (see Appendix A).	
		VERIFY that Red Team is wearing face shields.	
2.16	Red Team	**OPEN MV-110** (manual shut-off valve)	
2.17	Red Team	**BACK-OFF** REG-102 and REG-105 (manual regulators) and verify they are reading 0 psi.	
2.18	Red Team	**OPEN** the argon bottle valves a ½ turn at a time until they are fully open.	
2.19	Red Team	**SLOWLY OPEN** the argon family-iso valve until fully open.	
		CAUTION: The strand burner has a factor of safety of three. This means that the strand burner should be safe up to 3000 psi. As such, the maximum allowable pressure in the strand burner is 1000 psi. If the pressure exceeds 2500 psi, an abort will be issued by the code and the venting will begin,	

		regardless of what phase the test program is in. If for any reason the **Test Conductor needs to abort** the process, a **manual abort button is available to press which will immediately vent the system**. If this happens, cycle to Misfire Procedures. All pressures will be read number by number. For example, 100 is one, zero, zero.	
2.20	Red Team	Set REG-102 (strand burner pressure regulator) as specified in the test plan.	
		WARNING: This pressure shall never exceed 1000psi	
2.21	Red Team	Set REG-105 (muscle pressure regulator) at 80psi.	
2.22	Red Team	**VERIFY/CLOSE** the following valves:	
		MV-107 (Muscle Pressure Manual Vent)	
		MV-109 (Manual Vent)	
2.23	Red Team	**VERIFY/OPEN** the following valves:	
		Argon Bottle Valves	
		Argon Family Iso	
		MV-110 (Manual Shut-off)	
2.24	Red Team	**TURN ON** the ignition system at the PXIe	
2.25	Red Team	**RETREAT** to the block house (Building 91)	
2.26	TCON	**CONFIRM** with Trail Spotter and Parking Lot Spotter that they are clear to continue, and no one is in the exclusion zone.	
2.27	TCON	**TURN** the Lockout key on the **ignition box** to **HOT.**	
2.28	TCON	**TURN ON** prop flow enable.	
2.29	TCON	**OPEN** the strand burner press valve.	
2.30	DAQ	Inform TCON once pressure in the test article is at desired level and stable.	
2.31	TCON	**CLOSE** SV-111 (strand burner press valve)	
2.32	TCON	**RECEIVE PERMISSION** from responsible party to run test.	
2.33	TCON	**PRESS** ignition switch to initiate test.	
		NOTE: When the igniter goes off, the continuity will fail. **This means that the blue continuity light on the test cell will turn off**. This is to help with troubleshooting. If the continuity light turns off, but the propellant does not ignite, then recycle the test. This means the Test Conductor will announce misfire and will cycle to Misfire Procedures.	
2.34	DAQ	**VERIFY** that test is complete.	
		Move to Post-Test or Recycle Operations. This is determined by that day’s testing program.	

3. Misfire Operations

Step	Operator	Procedure	Signoff
		The test team only needs to enter Misfire Procedures when the ignitor goes off but does not ignite the propellant or when an abort condition is met.	
		WARNING: If Test Team has cycled to Misfire Procedures three times and a successful test is not completed, then all testing for the day must end.	
3.1	TCON	Announce cycling to misfire procedures	
3.2	TCON	**OPEN** SV-113 (strand burner vent valve)	
3.3	DAQ	**VERIFY** that pressure in the strand burner is at atmospheric pressure	
3.4	TCON	**CLOSE** SV-113 (strand burner vent valve)	
3.5	TCON	**TURN** prop flow enable **OFF**	
3.6	TCON	**TURN** lockout key on ignition box to **SAFE**.	
3.7	ALL	**CHECK FOR FIRES.**	
		WARNING: If any propellant is still burning **do not attempt to put it out** as it is self-oxidizing. **Never use the water-filled "pump" cans to put out propellant.** Only put out fires that start in the brush due to burning propellant after propellant has finished burning.	
		CAUTION: The strand burner may not have pressure in it, but the pipeline still does. As such, Red Team needs to be wearing appropriate PPE when entering the exclusion zone.	
3.8	TCON	**VERIFY** that the test cell is safe to approach. Give Red Team the all clear if it is safe.	
3.9	Red Team	**TURN** the lockout key on the DAQ box to **SAFE**	
3.10	Red Team	**CLOSE** the argon bottle valves	
3.11	Red Team	**OPEN MV-107 and MV-109** (both manual vents)	
		CAUTION: Potential loud noise	
3.12	Red Team	Once audible venting has ceased, **CLOSE** argon family iso-valve	
3.13	Red Team	**CLOSE** MV-107 and MV-109 (both manual vents)	
3.14	Red Team	Set test facility to **GREEN**	
3.15	Red Team	**Use** the impact wrench to remove the forward closure. As stated before, **do not use a wrench** when loosening the bolts on the forward closure to prevent injury	
3.16	Red Team	**REMOVE** the flange and open the strand burner. If hot, the flange will be placed next to the strand burner on a non-flammable surface.	
3.17	ALL	Begin troubleshooting	

		Once complete, return to 2.5 to go back into test.	

4. Continuation of Testing Procedures

Step	Operator	Procedure	Signoff
		The test team only needs to enter Continuation of Test Procedures if a successful test has been performed and there is another test planned.	
		WARNING: If Test Team has cycled to Misfire Procedures three times and a successful test is not completed, then all testing for the day must end.	
4.1	TCON	Announce cycling to continuation of test procedures	
4.2	TCON	**OPEN** SV-113 (strand burner vent valve)	
4.3	DAQ	**VERIFY** that pressure in the strand burner is at atmospheric pressure	
4.4	TCON	**CLOSE** SV-113 (strand burner vent valve)	
4.5	TCON	**TURN** prop flow enable **OFF**	
4.6	TCON	**TURN** lockout key on ignition box to **SAFE**.	
4.7	ALL	**CHECK FOR FIRES.**	
		WARNING: If any propellant is still burning **do not attempt to put it out** as it is self-oxidizing. **Never use the water-filled "pump" cans to put out propellant.** Only put out fires that start in the brush due to burning propellant after propellant has finished burning.	
		CAUTION: The strand burner may not have pressure in it, but the pipeline still does. As such, Red Team needs to be wearing appropriate PPE when entering the exclusion zone.	
4.8	TCON	**VERIFY** that the test cell is safe to approach. Give Red Team the all clear if it is safe.	
4.9	Red Team	**TURN** the lockout key on the DAQ box to **SAFE**	
4.10	Red Team	**CLOSE** the argon bottle valves	
4.11	Red Team	**OPEN MV-107 and MV-109** (both manual vents)	
		CAUTION: Potential loud noise	
4.12	Red Team	Once audible venting has ceased, **CLOSE** argon family iso-valve	
4.13	Red Team	**CLOSE** MV-107 and MV-109 (both manual vents)	
4.14	Red Team	Set test facility to **GREEN**	
4.15	Red Team	**Use** the impact wrench to remove the forward closure. As stated before, **do not use a wrench** when loosening the bolts on the forward closure to prevent injury	
4.16	Red Team	**REMOVE** the flange and open the strand burner. If hot, the flange will be placed next to the strand burner on a non-flammable surface.	
		Once complete, return to 2.5 to go back into test.	

5. End of Day Procedures

Step	Operator	Procedure	Signoff
5.1	TCON	**VERIFY** test facility is in **AMBER** and that the stand is clear of personnel before proceeding.	
		VERIFY PXIe is **ON**, ignition box is turned to **HOT**, and prop flow enable is **ON**.	
		NOTE: In the event the PXIe is off, ensure the test cell is safe to approach, then have a red team member don a face shield and turn it on before proceeding.	
5.2	TCON	Announce that you are moving into end of day closeout procedures	
5.3	DAQ	**VERIFY** that the DAQ system can move into shutdown	
5.4	TCON	**OPEN** SV-113 (vent valve)	
5.5	DAQ	**VERIFY** that PT-112 is reading atm pressure before proceeding	
5.6	TCON	**TURN** prop flow enable **OFF**.	
5.7	TCON	**TURN** lockout key on ignition box to **SAFE**	
5.8	TCON	**VERIFY** test cell is safe to approach, then allow red team to approach with face shields	
5.9	Red Team	**TURN** the key on the PXIe to **OFF**	
5.10	Red Team	**CLOSE** argon bottle valves	
5.11	Red Team	**OPEN** MV-107 and MV-109 (manual vents)	
5.12	Red Team	**CLOSE** argon family iso	
5.13	Red Team	Set test facility to **GREEN**	
5.14	Red Team	**BACK-OFF** REG-102 and REG-105 (manual regulators)	
5.15	DAQ	**VERIFY** all PT's are reading atm pressure, then proceed to shutting down DAQ system.	
5.16	Red Team	**VERIFY/OPEN** the following valves:	
		MV-107 (Manual Vent)	
		MV-109 (Manual Vent)	
		MV-110 (Manual shutoff valve)	