Cooled Liquid Rocket Thrust Chamber

F24

Senior Project Final Design Review Outline
Prepared for: Cal Poly Space Systems

By

Ben Gibson, bgibso03@calpoly.edu
Ryan Schackel, rschacke@calpoly.edu
Bjorn Thorsen, bthorsen@calpoly.edu
Kealan Harris, kharri28@calpoly.edu

Mechanical Engineering Department
California Polytechnic State University
San Luis Obispo
June 9, 2023
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Abstract

Cooling may affect the thrust output of a small-scale rocket. Little research is published about small-scale rocket performance. We hypothesize the thrust produced varies as the amount of cooling varies. To facilitate assessing this hypothesis, we have designed and built a liquid rocket engine rated for at approximately 25 lb of thrust. Our objective was to build in parallel with Cal Poly Space Systems, who built a rocket engine with similar specifications except without cooling. Our challenge is to integrate film cooling, so that the effects of cooling may be compared to Cal Poly Space System’s engine which has no cooling. The results will allow for analysis of the effects of cooling on the thrust output of small-scale rocket engines. Utilizing a stacked injector plate design to solve our pressure-drop issues and consequently also solve our mass flowrate issues, we performed more preliminary calculations to justify our decision. We determined suitable material choices with desirable material properties such as the coefficient of thermal expansion and thermal conductivity for our design to be 303 stainless-steel and copper alloy 110. We decided on utilizing copper alloy 110 for our nozzle and combustion chamber, 6061 aluminum for our top injector plate, mild steel for our retaining ring, and 303 stainless-steel for our bottom injector plate. Our finished prototype will be utilized by Cal Poly Space Systems to aid their investigation of the effects of film cooling on the thrust output of small-scale rocket engines. Hot fire attempts were unsuccessful and resulted in only 15ms of combustion. Recommend more heat to the ignition system to produce self-sustaining combustion to get more effective results in the future.
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1 Introduction

We are a group of Mechanical Engineering students from California Polytechnic State University, San Luis Obispo in California. This report contains the concept and initial design for our senior project. The objective of our design is to design, manufacture, and ignite a rocket engine for 3 seconds, producing 25 lbs of thrust and providing film cooling to the combustion chamber. Our plan is to be able to throttle the amount of cooling that we can provide using regulation of the pressures and subsequent mass flowrates of the fuel and oxidizer. In addition, we encountered issues when discussing the possibility of 3-D printing our cavity-based injector out of stainless steel with the additive manufacturing professor. As such, we have changed our injector design to 2 plates which stack together and guide the propellants to the combustion chamber to achieve the correct mixture ratio of fuel and oxidizer. As the injector only consists of two plates now, we have updated the design with redundant O-rings and gaskets for sealing and safety. More detailed updates will be included later in the document. The contents of this document include our final design direction. Our design will include a description, explanation, bill of materials, and manufacturing plan. This is still our improved design, and as such, we are expecting changes as we advance through the prototyping process. The biggest changes that have been made from the Preliminary Design Review are in the design of the injector and test plan.

Since their original release in the scope of work four of the engineering specifications have been modified. With the first modification being specification #2, the original specification stated that at the max temperature the structure would hold with a factor of safety on the ultimate strength. This has been changed to keeping the peak temperature below the melting point of the copper. The second specification that has been modified was specification #4. The original specification was that all components would be manufactured at Cal Poly. This has been modified to mean that all components have the capability of being manufactured at Cal Poly. The third specification modified was specification #8. Originally stating that the engine would have a burn time of 5 seconds. This has now been reduced to only 3 seconds. The final specification that has been modified was specification #9. This originally stated that there would be film cooling provided at roughly 15% of the fuel for combustion. This has been modified to mean that the engine will provide film cooling, not specifically at 15% of the fuel’s mass flow rate.

2 Design Overview

2.1 Design Description

The overall design is composed of an injector assembly, a combustion assembly, and miscellaneous parts as summarized in Figure 2-1. The injector assembly is made up of two plates, a gasket, O-rings, and alignment pins. The combustion chamber assembly is comprised of the combustion chamber body, matching retaining ring, and gaskets.
2.2 Design Changes Since CDR

2.2.1 Combustion Chamber

The combustion chamber was adapted to improve manufacturability as we shifted from CNC machining to manual machining. The inlet was adjusted to match the 118° drill point angle of a standard drill and the exit was adapted to be conical rather than a bell.

The piston style O-ring between the combustion chamber and retaining ring was removed as compression of the copper taper is going to provide enough sealing and the O-ring would have most likely melted as well.

2.2.2 Injector

The L1 injector plate was adjusted to countersink the film cooling holes for improved manufacturability and flow.

3 Implementation

To implement our design there were three main stages to get through. Procurement where we sourced all of our material and tooling, manufacturing where we created all of our components, and assembly where we put all of our components together to prepare for testing.

3.1 Procurement

The material for the injector was procured from existing stock available to the club. The L2 plate was from 6061 aluminum stock and the L1 plate was from 303 stainless steel stock. The material
that we ordered was the stock for the combustion chamber and retaining ring. For the combustion chamber 1ft of copper round stock was purchased. For the retaining ring, a 1in disk was purchased. The tooling was procured from multiple sources. West Coast Tooling, Helical Tools, Harvey Tools, Haas Tools, and McMaster Carr were all used to procure the tooling. A detailed list of tools and suppliers is provided in the budgeting sheet in Appendix C. Solid rocket engines for ignition were purchased from Estes Rockets.

3.2 Manufacturing

3.2.1 Injector

The initial injector prototype was outsourced, and this gave us the final L1 plate. The L2 plate was done with a combination of manual and CNC (Computer Numerical Control) machining. The manual machining was done on the angled holes with the rest being done on the CNC. All machining was done by the group, including the CAM (Computer Aided Manufacturing) for the injector. Figure 3-1 shows the team operating the Haas VF-4 for the L1 injector plate.

The manual machining for this operation was the most challenging component of the whole manufacturing process. The manufacturing process for this step is something that was iterated throughout the whole prototyping process. The first part of this process was done by testing how to drill with the microdrill bits. This was done to get the speed and pressure that is needed to drill without breaking the drill bit. This was done on aluminum at first and then on stainless steel.

The other process of the drilling was done with the setup. The first time drilling angled holes was done by angling the mill head. This setup is shown in Figure 3-2. This process was very time-consuming and was only used in initial testing of the manufacturing. The final setup was done using a tilting rotary vice. Figure 3-2 shows the setup of the vice.
The process for drilling the holes was done from the bottom of the part with the holes from the microdrill bit meeting with the holes from the CNC operation. The locating for these holes was done using a modified drawing to account for the angle of the holes. Once the part was placed in the vice the orientation was zeroed from the flats. The flats were placed parallel to the y-axis of the mill, and this is where the rotation of the part was zeroed. The next step was to angle the vice and go to the coordinate of the hole given to us from the modified drawing. To drill all the holes the vice was rotated. Before the part could be drilled an end mill had to be plunged at the location of each hole to make a flat surface. The flat surface created by the end mill was found to be necessary when testing with the drill bits to get them to not break.

This process allowed us to drill multiple holes with minimal movement of the mill. This process lead to varying success in our prototyping process. This is due to how precise the location of the holes must be, which can be hard to achieve by hand. We were able to make a part out of aluminum with all the hole locations correct, but it took multiple attempts. For our verification prototype we created two injector plates to have a backup part in case the drilling went wrong. Our first attempt with the stainless steel had the film cooling holes off center of the holes done by the CNC operation. For the next part we were able to get the location correct for all the holes.
3.2.2 Retaining Ring

The retaining ring was the simplest part to manufacture. This was done manually on the lathe. The process was done by drilling a hole in the part and then using a boring bar to get the smallest diameter of the retaining ring. The large diameter of the taper was created using the same process but was not done for the whole length of the part to allow for the creation of the taper. The last step on the lathe was to make the taper with a boring bar and face the part to the correct length. To finalize the part, we utilized a rotary index on the manual mill to locate the correct placement of the drilled holes for our fasteners. Various stages in the manufacturing process are shown below in Figure 3-3.

3.2.3 Combustion Chamber

The combustion chamber was machined from 2-¼" round copper stock on a Haas TL-1 CNC lathe. The CAM producing the G-code was built in Fusion 360. The first operation completed the outside contour of the engine and the exit of the nozzle. The second operation completed the combustion chamber portion and the entrance of the nozzle.
3.3 Assembly
1. Clean components with compatible solution of isopropyl alcohol or acetone for metallic components and distilled water for Viton components.
2. Press fit locating pins into the L2 injector plate.
3. Install all seals. 3 Viton O-rings, 1 Viton gasket, and 2 graphite gaskets.
4. Install the L1 injector plate into the L2 injector plate ensuring the Viton gasket does not rotate and the etch marks on the plate flats are lined up.
5. Insert the combustion chamber into the taper of the retaining ring.
6. Place all ten bolts in with a washer between the L2 injector plate and the head of the bolt.
7. Place a washer and then a nut on the end of the bolt and hand tighten.
8. Secure the assembly in a vice on the flats of the L2 plate.
9. Torque each bolt to 6Nm skipping 2 bolts in-between as to follow a crossing pattern.
10. Inspect assembly for gaps or misalignment.
11. Apply LOX-8 thread sealant to 1/8” NPT threads and install into L2 plate with 1Nm of torque.
12. Install interface plate and fasten into place with 4 ¼-20 bolts.
13. Final assembly shown in Figure 3-5.
4 Design Verification

4.1 Specifications

The specifications for the verification of our design are included in Table 1.

<table>
<thead>
<tr>
<th>Spec. #</th>
<th>Specification Description</th>
<th>Requirement or Target</th>
<th>Tolerance</th>
<th>Compliance**</th>
<th>Pass/Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Thrust</td>
<td>25 lb,</td>
<td>±10</td>
<td>A</td>
<td>Fail</td>
</tr>
<tr>
<td>2</td>
<td>Max temperature</td>
<td>1600°F,</td>
<td>Max</td>
<td>A, T</td>
<td>Pass</td>
</tr>
<tr>
<td>3</td>
<td>Fit to Test Stand</td>
<td>5’x3’x2’</td>
<td>Max</td>
<td>I, T</td>
<td>Pass</td>
</tr>
<tr>
<td>4</td>
<td>Components manufactured at Cal Poly</td>
<td>All</td>
<td>Min</td>
<td>I</td>
<td>Pass</td>
</tr>
<tr>
<td>5</td>
<td>Pressure Capacity</td>
<td>2.0 FOS</td>
<td>Min</td>
<td>A, T</td>
<td>Pass</td>
</tr>
<tr>
<td>6</td>
<td>No Welded/Permanent joints</td>
<td>0</td>
<td>Min</td>
<td>I</td>
<td>Pass</td>
</tr>
<tr>
<td>7</td>
<td>Cost</td>
<td>$1200</td>
<td>Max</td>
<td>I</td>
<td>Pass</td>
</tr>
<tr>
<td>8</td>
<td>Burn time</td>
<td>3 seconds</td>
<td>±2</td>
<td>A, S</td>
<td>Fail</td>
</tr>
<tr>
<td>9</td>
<td>Provide Fuel for film cooling</td>
<td>15%</td>
<td>Min</td>
<td>A, T</td>
<td>Pass</td>
</tr>
</tbody>
</table>

* Risk of meeting specification: (H) High, (M) Medium, (L) Low
** Compliance Methods: (A) Analysis, (I) Inspection, (S) Similar to Existing, (T) Test
4.2 Testing and Results

We completed three tests to verify our design. A hydrostatic, cold flow test, and hot fire test. These tests were done to verify various aspects of our design. The hydrostatic test successfully verified that our gaskets, O-rings, and fasteners provided adequate sealing of 800 psi for our design. The cold flow test was performed to verify the impingement of our fuel and oxidizer orifices, as impingement is necessary for combustion to occur. The hot fire test was performed to determine the effects of film cooling on the pressure and temperature in the combustion chamber.

4.2.1 Hydrostatic

The hydrostatic test was done during the manufacturing process of the injector. The purpose of this test was to determine if the seal design would hold pressure. Before the holes were drilled, the injector was connected to a hand pump and water was pumped to a pressure of 800 psi. The setup for this test is shown in Figure 4-1.

![Figure 4-1 Hydrostatic Pressure Testing the Injector Assembly](image)

The initial results from this test were inconclusive. The pressure gauge was watched while the injector was fully submerged in water. The gauge showed a decrease in pressure and due to the setup, it was not apparent where the leak was occurring. The next trial of the hydrostatic test
was done without the injector submerged in water. This showed a leak in the connection between the pump and the injector. The water pumped into the injector was contained by the seal design.

The conclusion from the hydrostatic test is that the seals worked in keeping the fuel and oxidizer from mixing and keeping everything contained in the injector. The other conclusion is that the connection between the feed system from the test stand and the injector needs to be sufficiently tightened with Teflon tape.

4.2.2 Injector Component Level Cold Flow

The cold flow test was performed to verify the flow of the injector. The impingement of the fuel hole, fuel for film cooling, and oxidizer hole were all tested. The cold flow test was performed outside of the aerospace hangar on campus. The set up for this test was done by connecting the injector to a pressure washer and testing each injector hole. Figure 4-2 below show the test being conducted on each connection point to the injector.

![Figure 4-2: From left to right, film cooling, fuel, and oxidizer flow paths being tested for impingement.](image)

The conclusions from the cold flow test are that all the exit holes in the injector function properly. The fuel holes have proper impingement and atomization. The fuel cooling holes have the proper angle to swirl around the combustion chamber. The oxidizer hole functions as intended with the flow going directly down the center of the injector. When testing the film cooling and fuel holes there was leaking between the gasket that separates them. This leak is noncritical because the film cooling and fuel holes have the same fluid. The effect on performance from the leak cannot be properly tested until the hot fire is complete. Due to the timing of when this test could be completed, no design changes were made from the leak as it is not a safety concern and will only affect performance. The results from the cold flow test verify that we meet specification 9 because we provided the target percentage of film cooling.

4.2.3 Hot Fire

The hot fire test was done at the aerospace propulsion laboratory on campus with the test stand made by Cal Poly Space Systems. The goal of this test was to measure the thrust produced by the engine. The hot fire test was not successful as steady combustion could not be achieved. Moment
of successful combustion shown in Figure 4-3. Thrust data was still collected and showed that some thrust was produced, but there was no steady combustion. The propellants lit for a fraction of a second and supersonic flow was achieved but it did not last enough time for our specifications and to give enough thrust data.

![Figure 4-3. Hot fire test](image)

The reason for the lack of success in the hot fire is still unclear but it is most likely due to the feed system of the test stand, which is out of the scope of this project, or improper ignitor design. The ignition was done by wrapping a nichrome wire around a sparkler and sending current through it to heat it up and light the sparkler. This method was successful in creating a consistent spark, but it might not be enough to ignite the propellants.

The hot fire did show that our design could produce supersonic flow and that our injector design could properly distribute the propellants. The data from the test are included in Figure 4-4.
4.2.3.1 Chamber Pressure Uncertainty Analysis

During the hot fire test of the engine the thrust produced was collected by a load cell. Using Equation 1 and Equation 2 from ref [1] and uncertainty propagation from ref [2]. Where $k$ is the isentropic exponent, $p_1$ is the chamber pressure, $p_2$ is the exit pressure, $p_3$ is the ambient pressure, $A_2$ is the exit area, $A_t$ is the throat area, $C_F$ is the coefficient of thrust, and $F$ is the thrust.

$$C_F = \sqrt{\frac{2k^2}{k-1}} \left( \frac{2}{k+1} \right)^{(k+1)/(k-1)} \left[ 1 - \left( \frac{p_2}{p_1} \right)^{(k-1)/k} \right] + \frac{p_2 - p_3 A_2}{p_1 A_t}$$

Equation 1

$$F = p_1 A_t C_F$$

Equation 2

Load cell data is collected as voltage as shown in Figure 4-5. When the nitrous run pressure and fuel run pressures spike up that is when combustion occurs and our split second of thrust is produced. The drop in load cell voltage is the thrust being produced for that short period of time, as the load cell is being compressed more than usual. Using the load cell constant, a load difference can be calculated which is assigned to as thrust with uncertainty from the load cell documentation.

The uncertainty of the load cell voltage is represented by a percentage of 5%, the isentropic exponent, $k$, has an absolute uncertainty of .05, and the exit pressure has an absolute uncertainty of 0.5psi. Propagating the uncertainty and solving for the for the chamber pressure gives us $40.67\pm1.68$ psia, full code available in Appendix D. This is significantly different from our design pressure, which could account for why it did not function as expected.
4.2.4 Inspection/Analysis

Inspection and analysis were done to verify specifications 3, 4, 5, 6, and 7. Specification 3 was met by connecting the full assembly to the test stand. All parts were manufactured on the Cal Poly campus so specification 4 was met. The pressure capacity analysis shows a factor of safety of over 5. The design had no permanent joints, meeting specification 6. The total budget is shown in Appendix C and the target of $1200 was met.

We will be testing and verifying our design using both inspection and analysis compliance methods. The thrust produced from the hot fire test will be measured utilizing a load cell.

Thrust: The thrust generated by the rocket engine during the three-second firing will be measured and analyzed to ensure it meets the desired level of performance. This will involve monitoring and recording the thrust output of the engine throughout the firing period and comparing it with the expected thrust levels based on design calculations.

Maximum Temperature: The temperature reached by the rocket engine during operation will be monitored to ensure it does not exceed the maximum temperature limits set for the engine components. This will involve measuring and recording the temperatures at various points in the engine and verifying that they remain within safe operating limits.

Fit to Test Stand: The rocket engine will be evaluated for its compatibility and proper fit to the test stand used for the testing. This will involve verifying that the engine is securely mounted and properly aligned on the test stand, and that all necessary connections and fixtures are in place for safe and reliable testing.

Components Manufactured at Cal Poly: Any components of the rocket engine that are manufactured at California Polytechnic State University (Cal Poly) will be inspected to ensure they meet the required quality standards. This will involve checking for proper manufacturing techniques, dimensions, and materials, and verifying that they comply with the design specifications.

Pressure Capacity: The pressure capacity of the rocket engine, including the combustion chamber and fuel/oxidizer lines, will be evaluated to ensure it can withstand the expected pressures during operation. This will involve measuring and recording the pressure levels during testing and verifying that they do not exceed the pressure capacity of the engine components.

No Welded/Permanent Joints: The rocket engine will be inspected to ensure that there are no welded or permanent joints that may cause potential weak points or failure points during operation. This will involve checking for proper fabrication techniques and connections and verifying that all joints are secure and reliable.
Cost: The overall cost of the rocket engine, including materials, manufacturing, and testing, will be assessed to ensure it is within the allocated budget. This will involve tracking and recording the costs associated with the engine's design, fabrication, and testing, and comparing them with the budgeted costs.

Burn Time: The duration of the rocket engine's firing or burn time during the three-second test will be measured and recorded to ensure it meets the desired time frame. This will involve timing the duration of the engine's operation from ignition to shut down and verifying that it aligns with the intended burn time.

Percentage of Fuel for Film Cooling: The percentage of fuel used for film cooling, which is the process of spraying fuel on the engine's combustion chamber walls to cool them, will be evaluated to ensure it meets the design requirements. This will involve measuring and calculating the amount of fuel used for film cooling during the test and verifying that it aligns with the intended percentage.

Thorough testing of the rocket engine based on these specifications will be critical to ensure its performance, safety, and compliance with the design requirements. Data collected during the testing process will be analyzed to validate the engine's design, identify any issues or areas for improvement, and ensure that the engine meets the intended specifications.

5 Discussion & Recommendations

5.1 Discussion

The biggest thing that we learned about this design during the project was design for manufacturability. Most of the changes that were made during the design process were made to make sure that we were able to manufacture our parts. This was a big challenge with the combustion chamber as we had to significantly change the design of the combustion chamber to be able to manufacture it with machines on campus. The injector plates also had similar challenges with manufacturability. The size of the orifice holes made drilling them very challenging and the design of the injector plates had to be adjusted to minimize the possibility of the drill bits breaking.

The design changes that would be made if we continued to design would be improved gasket design between film cooling and fuel. The improved gasket design could be done to minimize leaking and make sure the functionality of the film cooling easier to verify. Initially leaking was a big concern with the multiple plate design but this was never a problem in testing so it would be possible to add another plate for film cooling so there would be no leaking between fuel and film cooling. An additional design change would be to separate the chamber and nozzle into two different pieces. This would make the manufacturing of the nozzle easier, and a more efficient nozzle could be made.
5.2 Recommendations and Next Steps

The recommendations made for the next step are to investigate how the feed pressure and timing effects combustion. This is done for the firing of the engine. More research and testing still needs to be completed to get a successful hot fire and to verify the performance of the design. The user manual in Appendix A describes the procedure used for the hot fire test and how to assemble the engine for the test, but the timing and pressures of the fuel and oxidizer need to be tweaked to get better results. An alternative proposal to produce more effective hot fires is to increase the heat energy in the combustion chamber prior to full propellant flow. Nitrous flowing over the orifice plate and changing state is theorized to remove enough heat from the chamber to bring the temperature below the flash point of ethanol and extinguish the flame. Recommend using a bigger ignition motor with more heat and preheating the combustion chamber.

6 Conclusion

The goal of this project was to manufacture a liquid bipropellant rocket engine with film cooling that produces 25 lbf of thrust and has a burn time of 3 seconds. We successfully manufactured and tested the functionality of each component of the engine. We were not able to get a successful hot fire of the engine because of variables relating to the ignition of the propellants. Additional testing will need to be done to verify if the design meets all the specifications. The project provided a starting point for Cal Poly Space Systems to further develop liquid bipropellant engines. We were able to demonstrate how to manufacture an engine with the resources available on campus. The problems that came from the unsuccessful hot fire were expected as this is a new project and the results from the hot fire can be used to help future projects have a successful hot fire.
7 References


1. Safety Message
Test firing the engine is a complex and potentially dangerous process. To maintain safety follow the procedures exactly, exercise caution, and keep these general safety notices in mind.

- Hazardous materials
  - Ethanol (CAS 64-17-5):
    - Flammable: keep away from open flames, high heat sources, sparks, or other sources of ignition
  - Nitrous (10024-97-2):
    - Strong Oxidizer: may cause or intensify fire. Keep away from flame sources
    - Gas under pressure: tank may explode if heated. Store tank in cool area and monitor temperature.
    - Gas: may displace oxygen and cause suffocation. Use in well-ventilated room
- PPE: Safety glasses ("ANSI Z87+") or better must be worn at all times in the test cell along with closed toe shoes, long pants, and sleeved shirt.
- The bi-prop rocket engine is extremely loud, so ear protection is always required in the control room while the engine is running.
- No personnel are allowed in the test cell, in direct line of sight of the engine when there is only one switch flip (or other actuation mechanism) keeping the three components of the fire triangle separate (in this case gaseous nitrous oxide, ethanol, and electric spark).
- Safety is number one! When in doubt (with respect to safety):
  - Secure the area, do not allow anyone to enter the "danger zone"
  - In case of large "danger zone" or earthquake, evacuate to parking lot immediately south of lab
  - Call lab and/or project advisor
  - Call Cody Thompson (Aerospace Dept. Safety Coordinator: 805-756-1309)
  - Call Environmental Health and Safety (for immediate assistance: 805-756-6661)
  - Call 911

2. **Assembly Instructions**

For the assembly of the Rocket Engine all manufactured parts will be needed. The assembly of the engine is straightforward as the parts are marked for the correct orientation. Figure O-1 Shows the assembly order and additional parts. The color version is provided in Figure O-2. The assembly instructions will include a consumable part list, preparation, and final assembly.
Figure 0-0-2: Exploded view with BOM showing correct assembly of parts

Retaining Ring

Figure 0-0-3: Exploded view provided for better visualization.
2.1 Consumable Part List

The part list will contain the consumable parts as these can be bought off the shelf and will be replaced at regular intervals.

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Description</th>
<th>Qty</th>
<th>Replacement Frequency</th>
<th>Replacement Link</th>
</tr>
</thead>
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<tr>
<td>113000</td>
<td>010 O-Ring</td>
<td>1</td>
<td>Every test</td>
<td><a href="https://www.mcmaster.com/9464K104/">https://www.mcmaster.com/9464K104/</a></td>
</tr>
<tr>
<td>114000</td>
<td>109 O-Ring</td>
<td>1</td>
<td>Every test</td>
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<td>149 O-Ring</td>
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<td>Every test</td>
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</tr>
<tr>
<td>117000</td>
<td>Viton Gasket*</td>
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<td>Every test</td>
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<tr>
<td>118000</td>
<td>1/4 Swagelok Compatible Compression Ferrule Set Stainless Steel**</td>
<td>3</td>
<td>Every test</td>
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<tr>
<td>124000</td>
<td>Inner Graphite Gasket*</td>
<td>1</td>
<td>Every 3 tests</td>
<td>Same as above</td>
</tr>
<tr>
<td>130000</td>
<td>Bolt, A286 Steel, #10-32</td>
<td>10</td>
<td>If visual inspection suggests threads have yielded</td>
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</tr>
<tr>
<td>140000</td>
<td>Nut, MS35650-304, #10-32</td>
<td>10</td>
<td>Every test</td>
<td><a href="https://www.mcmaster.com/91240A411/">https://www.mcmaster.com/91240A411/</a></td>
</tr>
<tr>
<td>150000</td>
<td>Washer, 18-8 SS</td>
<td>10</td>
<td>If bent or cut</td>
<td><a href="https://www.mcmaster.com/92141A011/">https://www.mcmaster.com/92141A011/</a></td>
</tr>
</tbody>
</table>

*indicates are part that has to be made/modified from an ordered part

**Replacement part for component ordered as system originally

2.2 Assembly Preparation
Before everything can be assembled, gaskets and O-Rings need to be placed in the correct place. The L1 plate has three O-rings and one gasket. The retaining ring has one gasket. The L2 plate has the Swagelok connection.

### 2.2.1 L2 Plate

The required parts for L2 plate are:
- 3 Swagelok 1/4” compression to 1/8” NPT (part 118000)
- LOX-8 Paste
- It should look like Figure 0-4

![Figure 0-4 L2 Plate and Swageloks ready for assembly](image)

### 2.2.2 L1 Plate

The required parts for the L1 plate are:
- O-ring
- O-ring
- Viton Gasket

The gasket alignment should be checked to make sure that all holes are aligned correctly. Be sure that there are no holes in the gasket that are not above features in the L1 plate. Figure 0-5 shows the proper orientation.
2.2.3 Retaining Ring/Combustion Chamber

The required parts the retaining ring and combustion chamber are:
- 2X Graphite Gaskets
One gasket seats in the combustion chamber and one gasket seats in the retaining ring. They both are compressed against the L1 plate as shown in Figure 0-6.
2.3 Alignment

The alignment of the inlet holes is crucial for a safe test. The alignment of the L1 and L2 is the most important step of the assembly. The flats on the plates are the first step of alignment. The next step is to align the score on the L1 and L2 plate. This ensures that the film and oxidizer holes are in the correct orientation to allow for flow. Be sure to pay attention to the F, O, C corresponding to Fuel, Oxidizer, and Coolant. If the assembly is not aligned correctly, it will inadvertently become a pressure vessel due to the incorrect position of the inlet holes and grooves not allowing flow to occur.

2.4 Final Assembly

With everything aligned, the next step is placing the bolts, washers and nuts. Each bolt and nut should have a washer. The final step is to tighten the bolts to 6 Nm. Once tightened the assembly is complete and is ready to be connected to the test stand.

To attach to the test stand unscrew the 4 nuts on the bottom of the rods, insert the engine and retighten the nuts. Then attach the 3 tubes via the Swagelok connectors. The engine is now assembled as seen in Figure 0-7.
3. Maintenance and Repair

The maintenance of the design is very minimal. After each test fire each gasket and O-ring should be replaced. The nuts should also be replaced to ensure proper safety for the following tests, however the bolts will not need to be replaced. Both gaskets are non-standard parts but can be cut from ordered parts. The dimensions of these gaskets are included in the drawing package. The Swagelok fittings need to have the ferrule replaced after each test. All other components should be inspected for any damage. If any damage is found the part should be inspected and determined whether remanufacturing is required.

4. Operation

Please refer to Appendix F for procedures. Specifically, Appendix F, section 6.1 and section 6.2 are the hot-fire and cold flow procedure respectively.
## Appendix B – Risk Assessment

<table>
<thead>
<tr>
<th>Item Id</th>
<th>User / Task</th>
<th>Hazard / Failure Mode</th>
<th>Initial Assessment Severity</th>
<th>Initial Assessment Probability</th>
<th>Risk Level</th>
<th>Risk Reduction Method / Control System</th>
<th>Final Assessment Severity</th>
<th>Final Assessment Probability</th>
<th>Risk Level</th>
<th>Status / Responsible / Reference</th>
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<td>1-1-8</td>
<td>operator normal operation</td>
<td>noise / vibration / noise / sound levels &gt; 120 dBA inauditory</td>
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<td>Medium</td>
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<td>Very Likely</td>
<td>Medium</td>
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<td>Very Likely</td>
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<td>1-1-9</td>
<td>operator normal operation</td>
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<td>Minor</td>
<td>Medium</td>
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<td>1-1-11</td>
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<td>environmental / industrial hygiene / emissions</td>
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<td>Likely</td>
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<td>Very Likely</td>
<td>Medium</td>
<td>Minor</td>
<td>Very Likely</td>
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</table>
| 1-1-12  | operator normal operation | chemicals and gases / nitrous oxide / Nitrous feed system does not guide nitrous property | Serious | Serious | Very Likely | High | Contained in a vessel and feed system can be flushed with nitrogen in case of emergency | Serious | Very Likely | High | Project
| 1-1-13  | operator normal operation | fluid / pressure / explosion / implosion | Catastrophic | Catastrophic | Unlikely | Medium | Catastrophic | Medium | Catastrophic | Unlikely | Cooled Liquid Rocket Thrust Chamber
<p>| 1-1-14  | operator normal operation | fluid / pressure / high pressures / propellants / high pressure / fuel / high temperature / fuel | Moderate | Moderate | Very Likely | High | Large factors of safety on all pressurized components | Moderate | Very Likely | High | Cooled Liquid Rocket Thrust Chamber |
| 1-3-1   | operator minor adjustments to machine | mechanical / pinch point | Negligible | Negligible | Remote | Minor | Remote | Negligible | Negligible | Cooled Liquid Rocket Thrust Chamber |
| 1-3-2   | operator basic troubleshooting | electrical / electronic / energized equipment / live parts | Negligible | Negligible | Remote | Minor | Remote | Negligible | Negligible | Cooled Liquid Rocket Thrust Chamber |</p>
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<th>Risk Level</th>
<th>Final Assessment</th>
<th>Risk Level</th>
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<th>Comments / Reference</th>
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<td>Very Likely</td>
<td>Minor</td>
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<td>Red</td>
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Designsafe Report
Application: Rocket Engine Risk Analysis
Description: [Blank]
Product identifier: [Blank]
Assessment Type: Detailed
Limits: [Blank]
Sources: [Blank]
Risk Scoring System: ANSI B31.3 Two-Factor
Guide sentence: When doing task, the [ Fail ] could be injured by the [ hazard ] due to the [ failure mode ].
# Cooled Liquid Rocket Thrust Chamber

## Appendix C – Final Project Budget

### F24 Budget Summary

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### Used in Part #

#### Components

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<tr>
<td><strong>Surplus</strong></td>
<td><strong>$303</strong></td>
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</tbody>
</table>
Appendix D – Uncertainty Analysis

Coefficient of Thrust

\[ C_F = \sqrt{\frac{2}{k - 1} \cdot \left( \frac{2}{k + 1} \right)^{\frac{k + 1}{k - 1}} \cdot \left[ 1 - \frac{p_2}{p_1} \right]^{\frac{k - 1}{k}}} + \frac{p_2 - p_3}{p_1} \cdot \frac{A_2}{A_t} \]

Measured Values

\[ F = 4 \text{ [lbf]} \]
\[ F = C_F \cdot p_1 \cdot A_t \]
\[ p_2 = 14.7 \text{ [psi]} \]

Given Values

\[ p_3 = 14.7 \text{ [psi]} \]
\[ k = 1.27 \]
\[ D_1 = 0.374 \text{ [in]} \]
\[ D_2 = 0.69 \text{ [in]} \]
\[ A_t = \frac{\pi}{4} \cdot D_1^2 \]
\[ A_2 = \frac{\pi}{4} \cdot D_2^2 \]

Unit Settings: SI C kPa kJ mass deg

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<tr>
<th>Variables</th>
<th>Uncertainty</th>
<th>Partial derivative</th>
<th>% of uncertainty</th>
</tr>
</thead>
<tbody>
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<td>( p_1 )</td>
<td>( 40.67 \pm 1.683 \text{ [psi]} )</td>
<td>( \partial p/y \partial F = 7.06 )</td>
<td>70.43 %</td>
</tr>
<tr>
<td>( F )</td>
<td>( 4 \pm 0.2 \text{ [lbf]} )</td>
<td>( \partial p/y \partial k = -3.582 )</td>
<td>1.13 %</td>
</tr>
<tr>
<td>( p_2 )</td>
<td>( 14.7 \pm 0.5 \text{ [psi]} )</td>
<td>( \partial p/y \partial p_2 = -1.794 )</td>
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No unit problems were detected.

Compilation time = 110 ms  Calculation time = 459.52 s
## Cooled Liquid Rocket Thrust Chamber

### Appendix E – Design Verification Plan & Report (DVPR)

#### Test Plan

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<thead>
<tr>
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<td>Full assembly</td>
<td>Ryan</td>
<td>5/4/2023</td>
<td>5/7/2023</td>
<td>Fail, 4 lbf measured</td>
<td>Hotfire test was unsatisfactory and only lasted 15s. This was not enough time to build up continuous combustion which could have lead to full thrust.</td>
<td></td>
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<tr>
<td>2</td>
<td>Hot Fire Test</td>
<td>Temperature</td>
<td>Cylinder chamber and nozzle Not Melted</td>
<td>CPS3 Test stand and feed system</td>
<td>Full assembly</td>
<td>Ben</td>
<td>5/4/2023</td>
<td>5/7/2023</td>
<td>Chamber not melted after 10s of hotfire</td>
<td>Hotfire test was unsatisfactory and only lasted 15s. While we did pass, if the engine worked properly it is unknown if we would have passed this specification.</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Test Stand Dry Fit Inspection</td>
<td>Freeze Fit in test stand securely</td>
<td>CPS3 Test stand</td>
<td>Full assembly</td>
<td>Byn</td>
<td>5/2/2023</td>
<td>5/5/2023</td>
<td>Pass</td>
<td>The engine fits into the test stand as designed.</td>
<td></td>
<td></td>
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<tr>
<td>4</td>
<td>Hydrostatic Pressure Test</td>
<td>Pressure</td>
<td>Structure holds at pressure &gt;45psi</td>
<td>ISD Propulsion systems</td>
<td>Hydrostatic test system</td>
<td>Injector assembly</td>
<td>Ryan</td>
<td>2/24/2023</td>
<td>3/2/2023</td>
<td>Hold up to 800psi</td>
<td>Plan to test with never set up before week 2 spring quarter to reach higher pressures</td>
</tr>
<tr>
<td>5</td>
<td>Hot Fire Test</td>
<td>Burn time</td>
<td>3 second of fire</td>
<td>CPS3 Test stand and feed system</td>
<td>Full assembly</td>
<td>Keanan</td>
<td>5/4/2023</td>
<td>5/7/2023</td>
<td>Fail, 15ms of burn time</td>
<td>We were unable to achieve continuous combustion.</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>High Pressure Flow Test</td>
<td>Flow rate</td>
<td>Flow rate matches theoretical values</td>
<td>CPS3 high pressure flow test system</td>
<td>Injector assembly</td>
<td>Ben</td>
<td>3/12/2023</td>
<td>3/15/2023</td>
<td>Unsure of exact flow rate, but direction of flow OXY was correct.</td>
<td>Injector assembly assembled high pressure up to 800 PSI, and an insufficient amount of propellant. There was a leak in the fuel and oxidizer line which will be achieved by changing the packing.</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Propellant ignition from PMEA</td>
<td>Burn time, height, and flame temperature</td>
<td>Burns 9 seconds and flame height &gt; 9in</td>
<td>Aero-propulsion lab</td>
<td>Voltage source</td>
<td>Ignition system</td>
<td>Byn</td>
<td>4/20/2023</td>
<td>4/25/2023</td>
<td>Burned for &lt;3 seconds and flame height was &gt;9 in.</td>
<td>We believe that there are issues with the insulation and cryo system which are insufficient to ignite our engine.</td>
</tr>
<tr>
<td>8</td>
<td>Propellant leakage in injector manifold from PMEA</td>
<td>Pressure</td>
<td>No leakage at 700 psi</td>
<td>ISD Propulsion systems</td>
<td>Hydrostatic test system</td>
<td>Injector assembly</td>
<td>Ryan</td>
<td>2/24/2023</td>
<td>2/27/2023</td>
<td>Minor leakage, at 800psi</td>
<td>Plan to test with never set up before week 2 spring quarter to reach higher pressures with less system leakage</td>
</tr>
</tbody>
</table>
Appendix F – Test Procedures

7.1 Hot Fire Test

LIQUID ROCKET FIRING PROCEDURES

F24 Bipropellant Rocket Engine Firing Procedure
Last Modified: March 2023
Note: Adapted from Aero 402 lab manual

PURPOSE:
The purpose of this hot-fire test is to validate the performance and reliability of our bipropellant rocket engine design. During the hot fire test, our rocket engine will be fired at full power for a short period of time while it is securely mounted to a test stand. This allows engineers and technicians to collect data on the engine’s thrust, efficiency, stability, and other critical parameters. By analyzing the data from our hot fire test, Cal Poly Space Systems club engineers can make the necessary adjustments to the engine’s design, materials, and manufacturing processes to ensure it meets the required specifications for a successful mission.

SCOPE:
The scope of our hot-fire rocket engine test is to assess the performance, reliability, and safety of the rocket engine under various operating conditions. We are hoping to gain further knowledge of the effects of film cooling on the wall temperature of the throat and nozzle of the rocket. The specific objectives of our hot-fire rocket engine test include:
1. Evaluating the engine’s thrust, burn time, chamber pressure, and outside wall temperature at a set power level and operating condition.
2. Testing the engine’s ability to start, shut down, and be disassembled.
3. Assessing the engine’s stability and thermal parameters during operation, including monitoring for any heat fluctuations, pressure fluctuations, or other anomalies.

EQUIPMENT:
• Engine
• Test stand and connections
• Propellants
• Ignition system
• Pressure transducer
• Load cell
• Video camera
• Thermal camera
• thermocouple

Facility:
• Cal Poly Aerospace Propulsion Lab
• 1 Grand Ave, San Luis Obispo, CA 93407
• Bld. 41C Rm. 144
PROCEDURE HAZARDS, REQUIRED PERSONAL PROTECTIVE EQUIPMENT (PPE), AND SAFETY GUIDELINES:

- Test firing the engine involves the use of liquid ethanol and liquid nitrous:
  - Ethanol (CAS 64-17-5):
    - Flammable: keep away from open flames, high heat sources, sparks, or other sources of ignition
  - Nitrous (10024-97-2):
    - Strong Oxidizer: may cause or intensify fire. Keep away from flame sources
    - Gas under pressure: tank may explode if heated. Store tank in cool area and monitor temperature.
    - Gas: may displace oxygen and cause suffocation. Use in well-ventilated room

- **PPE**: Safety glasses ("ANSI Z87+" or better) must be worn at all times in the test cell along with closed toe shoes, long pants, and sleeved shirt.
- The bi-prop rocket engine is extremely loud, so ear protection is always required in the control room while the engine is running.
- No personnel are allowed in the test cell, in direct line of sight of the engine when there is only one switch flip (or other actuation mechanism) keeping the three components of the fire triangle separate (in this case gaseous nitrous oxide, ethanol, and electric spark).
- Safety is number one! When in doubt (with respect to safety):
  - Secure the area, do not allow anyone to enter the "danger zone"
  - In case of large "danger zone" or earthquake, evacuate to parking lot immediately south of lab
  - Call lab and/or project advisor
  - Call Cody Thompson (Aerospace Dept. Safety Coordinator: 805-756-1309)
  - Call Environmental Health and Safety (for immediate assistance: 805-756-6661)
  - Call 911

PROCEDURE DETAILS:
This procedure is formatted as a checklist; please print out a hardcopy and use it as such. During the lab activity, please make hand-written notes of any deviations from nominal behavior, if any errors are found, or if any additions or changes must be made to the procedure to allow for better subsequent operations. All corrections, additions, or changes must be recorded as soon as possible, and all old versions collected and disposed of properly to prevent use of out-of-date documentation.

PROCEDURE CONVENTIONS:
- General heading titles are UNDERLINED AND ALL UPPERCASE LETTERS, e.g., PROCEDURE CONVENTIONS.
A. TEST CELL PREPARATION

A.1. Post signs outside around the perimeter of the Propulsion Laboratory to warn passersby of the loud noises from the tests to be performed

A.2. Warn people in the surrounding laboratories of the loud noise from the tests to be performed

A.3. Fully open both test cell "roll-up" doors and lock the doors' chain in place

A.4. Clear test cell area of any loose objects near the rocket test stand (anything that may be kicked up by the rocket)

A.5. Clear test cell area of any flammable materials (put away in flammables cabinet or put outside the building)
A.6. Check the test cell area for fuel spills or leaks; clean up any spills or leaks

B. PERSONNEL PREPARATION

Note: while you can hear people yelling during a firing, you will only know that you are being yelled at if you are looking at the person who is yelling. So, coordinate how you plan to communicate while the engine is running beforehand. (Use hand signals...)

B.1. Familiarize all personnel with features of the rocket apparatus, including fuel and oxidizer flows, load cell(s), and ignition system

B.2. Review all safety information for the facility and lab. Refer to the front cover page for emergency contact numbers and evacuation exits/location

B.3. Point out where the fire extinguishers are located

B.4. Familiarize all personnel with the lab procedure (go over the section headings) and control room set up (data collection computer and control box)

B.5. Clearly determine which personnel will execute the various duties of the lab activity

B.6. Dry-run Sections C through H (as appropriate) of this procedure with the personnel who will execute those activities prior to running the procedure "for real"

C. ROCKET PREPARATION

C.1. All personnel in test area don ear and eye protection

C.2. Unscrew nitrogen regulator adjustment screw setting the regulated pressure to zero (do not unscrew all the way, just until no resistance is felt)

C.3. Place glass fuel beaker below fuel drain valve

C.4. Confirm no residual fuel in system by opening the fuel drain and then the fuel fill valves

C.5. Close fuel drain and fuel fill valves

C.6. Turn on the sensor power on the test stand

C.7. Power on the DAQ computer and open LabView VI

C.8. Test operation of VI and sensors:
   □ a. Click the Run button (white arrow, top of the VI window under the menu bar)
   □ b. Enter a test data file name and file location in the prompt (a default file name will appear which can be used or changed)
   □ c. Verify that the VI is operating (the readouts for thrust and pressure should start updating)
   □ d. Tare/zero all readouts in the VI when all the load cells and pressure transducers are at zero. Before zeroing all the sensor readouts should be within +/- 51bf on the load cell and +/- 10 psi on the pressure transducer readouts. If they're not, it means something is wrong
C.9. Once the load cell readings have been zeroed, the load cells may be loaded with the engine support rail and the duct attachment harness. The engine support rails bolts must be tightened starting with bolt labeled 1 and then bolt 2 using a ½” combo wrench.

D. FUEL FILLING PROCEDURE

**SAFETY NOTE:** Fuel filling is a potentially dangerous procedure, ethanol is flammable. Review the MSDS, and use proper procedures and safety equipment when handling. Be sure to ground any containers or people handling ethanol to reduce the chance of static electricity. The fuel handler must wear gloves and grounding wrist strap.

Again, no personnel are allowed to be in the test cell, in direct line of sight of the engine when there is only one switch flip (or other actuation mechanism) keeping the three components of the fire triangle separate (in this case gaseous oxygen, ethanol, and electric spark).

Recheck all personnel are wearing the proper personal protective equipment.

**Only the minimum number of personnel is to take part in any steps that require entering the test cell.**

If Rocket Firing (section E) procedure has already been followed, skip to check point D5.

| D.1. Make sure the power cord to the control box is unplugged and once inside the test cell unplug the air supply to the pneumatic valves |
| D.2. Slowly open nitrogen cylinder |
| D.3. Set nitrogen regulator to 100psi (unless previously set) |
| D.4. Close oxygen cylinder |
| D.5. Close nitrogen cylinder |
| D.6. WARNING LOUD Depressurize fuel line by slowly opening the fuel drain (needle) valve, close the valve when no more noise is heard |
| D.7. Pull out the cap on the Fuel Drum to deploy the spout and remove cap |
| D.8. Use syringe to pull out the desired amount of fuel (300mL max) |
| D.9. Open fuel fill valve |
| D.10. Make sure the nitrogen line that feeds into the fuel tank is above the fuel tank to prevent ethanol from flowing backwards to the nitrogen regulator and cylinder |
| D.11. The fuel handler must ground himself/herself |
| D.12. Inject the ethanol into the fuel tank, make sure fuel does not back up and overflow |
| D.13. | If one syringe full of fuel is not enough return to E.8 and repeat up to 300mL total fuel in the fuel tank |
| D.14. | Close fuel fill valve |
| D.15. | Remove grounding method |
| D.16. | Unless previous tests set the regulators to the required pressure output and it would be difficult to set them to the same value, make sure the nitrogen and oxygen pressure regulators are unscrewed (set to zero) |
| D.17. | Slowly crack open the nitrogen cylinder, once the regulator high pressure gauge stops moving fully open the cylinder valve |
| D.18. | Unless previously set, now set the nitrogen pressure regulator to desired testing pressure (maximum 750 psi) |
| D.19. | Slowly crack open the oxygen cylinder, once the regulator high pressure gauge stops moving fully open the cylinder valve |
| D.20. | Unless previously set, now set the oxygen pressure regulator to desired testing pressure (maximum 750 psi) |
| D.21. | Plug in the air supply to the pneumatic valves and all personnel return to the control room and close the doors to the test cell. |

**E. ROCKET FIRING**

Before firing the rocket with fuel check all personnel have returned to the control room, the control room doors are secured/closed, and that these procedures are strictly followed.

Only the minimum number of personnel are to take part in any steps that require entering the test cell.

| E.1. | All personnel return to the control room from the test cell |
| E.2. | Post range safety officers outside around the perimeter of the Propulsion Laboratory to warn passersby of the loud noises from the tests to be performed. Warn anybody working in nearby labs (eg. Wind Tunnel) of the imminent loud noise. |
| E.3. | Confirm all switches on the control box are in the OFF position |
| E.4. | Plug in the control box |
| E.5. | Confirm the sensor power switch is turned ON and the sensors are active |
| E.6. | On the LabVIEW GUI:  
  - a. Click the Run button to begin LabVIEW GUI  
  - b. Enter in file name when prompted  
  - c. Click the Record button on the front panel of the VI |
| E.7. | Power ON the control box (plug in, turn on power breaker, plug in and turn on the key switch) |
E.8. CRITICAL Turn ON Coolant Timed Relay Override Switch and confirm coolant flow, observing a strong steady stream of water coming out of coolant exit and the water pressure gauge reading about 50 psi

E.9. Press and hold the Spark switch ON

E.10. Switch the Fuel Enable and Nitrous (Oxygen) Enable Switches to ON
   □ a. Trigger the actuators
   □ b. If the rocket ignites with combustion in the chamber release the Spark switch
   □ c. If the rocket does not ignite or ignites outside the combustion chamber, turn all control box switches to OFF and skip to misfire procedures section G

E.11. At the end of the run, switch Fuel Enable and Nitrous (Oxygen) Enable Switches to OFF

E.12. On the LabVIEW GUI:
   □ a. Click the Record button to stop LabVIEW data recording
   □ b. You may click the Stop button to stop running the LabVIEW GUI, but it is not necessary if further monitoring of the sensors is required

E.13 Allow coolant to circulate through the engine for at least 10 extra seconds after the firing

E.14. Turn all control box switches to OFF

E.15. If multiple runs are required continue to section F, if not skip to section G: Rocket Safing and Closeout

F. ROCKET MISFIRE AND/OR MULTIPLE RUNS

Only the minimum number of personnel are to take part in any steps that require entering the test cell.

F.1. Confirm all switches on Main Control Box are in the OFF position and the box is unplugged

F.2. Confirm no residual ignition source is in test area by checking for flames, heat waves, or other signs of fire

F.3. Enter the test cell and check or troubleshoot the system while taking no action
   □ a. If the system is in correct working order go back to section FE or DE (as appropriate) and repeat if multiple runs are desired. If multiple runs are not desired proceed to section GH.
   □ b. If the system is not in correct working order, close cylinder valves, reenter control room, and vent all remaining pressure in the oxygen and then the fuel lines as done in GH6 and GH7 sections. After depressurizing the system enter test cell and disconnect oxygen and nitrogen cylinders. Proceed with system investigation and troubleshooting. If at any point in doubt, secure the area and contact advisor, department safety coordinator, EHS, and/or campus police as described under the first section, "PROCEDURE HAZARDS..."
### G. ROCKET SAFING AND CLOSEOUT

| **G.1.** Before entering test area, confirm there is no ongoing combustion or fire by checking for flames, heat waves, or other signs of fire. Unplug the power cord to the control box and the test conductor has possession of the control key |
| **G.2.** Close Nitrous cylinder |
| **G.3.** Close nitrogen cylinder |
| **G.4.** Return to control room, plug in the power cord to the control box |
| **G.5.** Depressurize oxygen line by turning ON the Power Breaker Switch, the Key Switch, the Oxygen Enable Switch, and the Fire Trigger until no sound is heard, the regulated pressure gauge reads zero, and the LabView output on the Oxygen Venturi Pressures is zero. Turn OFF the Oxygen Enable Switch |
| **G.6.** Depressurize nitrogen line by turning ON the Power Breaker Switch, the Key Switch, the Fuel Enable Switch, and the Fire Trigger until no sound is heard, the regulated pressure gauge reads zero, and the LabView output on the Ethanol Venturi Pressures is zero. Turn OFF the Fuel Enable Switch |
| **G.7.** Turn OFF the Power Breaker Switch and unplug the power cord to the control box |
| **G.8.** The test conductor takes possession of the Key to the Key Switch and it is now safe to enter test cell |
| **G.9.** In case there is any fuel left in the fuel tank, place glass fuel beaker below fuel drain (needle) valve and drain the residual fuel by opening the fuel drain needle valve and fuel fill valve |
| **G.10.** Close fuel drain (needle) valve and fuel fill valve |
| **G.11.** Residual fuel in beaker can be disposed of in the hazardous waste container supplied by EHS. Continue to follow the same static electricity precautions and "PROCEDURE HAZARDS... wearing gloves as when disposing. If the container cannot be found or it is full contact EHS for a replacement |
| **G.12.** Unscrew nitrogen regulator (turn it OFF) |
| **G.13.** Slowly open nitrogen cylinder |
| **G.14.** Set nitrogen regulator to 100psi |
| **G.15.** Reenter control room and plug in the power cord to the control box |
| **G.16.** Double check that the fuel line is clear by turning the Power Breaker Switch, the Key Switch, and the Fuel Enable Switch to ON |
| **G.17.** Pulse the Fire Trigger until no liquid is seen exiting the rocket nozzle |
| **G.18.** Turn OFF the Fuel Enable, the Key Switch, and the Power Breaker Switch, test conductor has possession of the key, enter the test cell, and close the nitrogen cylinder |
| **G.19.** WARNING LOUD Depressurize fuel line by slowly opening the fuel drain (needle) valve |
G.20. Unplug air supply hose
G.21 Close coolant water supply valve
G.22. Turn ON the control box and flip the Coolant Override Switch so the coolant solenoid valve is kept open. The readout on the water pressure gauge should go to zero
G.23. Turn OFF control box and remove the key. The test conductor has possession of the key
G.24. Put away the air supply hose and control box key
G.25. Close LabView
G.25. Unload load cell by loosening bolts to lower rocket carriage

H. LAB CLOSE-OUT

H.1. Close roll up doors
H.2. Clean up any remaining tools, equipment, etc. and lock up equipment cabinet
H.3. Replace ear and eye protection in the cabinet
H.4. Test conductor collects all hard copies of the procedures and makes sure none are left lying around. This is to make sure only the most up-to-date version is used
H.5. Close lab

RESULTS

A test is considered a pass when the engine fires and reaches choked flow. The test is a pass regardless of the amount of thrust produced, but rather just the production of thrust.
A test is considered a failure when the engine runs into any of the following:

- Does not ignite.
- Does not reach choked flow.
- Nozzle ablates to point of no thrust
- Combustion occurs outside of the combustion chamber.

After 3 passing tests are conducted analysis can be conducted on the results. Three values of thrust will be compared. One value of thrust gathered from the load cell, one value calculated from the measured chamber pressure, and a final values of thrust from our theoretical predictions. Uncertainty will be applied to both the measured values.

The uncertainty of the thrust from the load cell is strictly from the uncertainty provided from the load cell as no other calculations need to be done. The uncertainty of the thrust from the chamber pressure will have uncertainty drawn from a few different places. The largest being the uncertainty of the measured chamber pressure, followed by the gas isentropic exponent, and finally the exit pressure.
7.2 High Pressure Component Test

High Pressure Flow Test

Purpose
The purpose of this test is to qualify the flow characteristics of the injector and manifold of a bipropellant rocket engine.

Scope
The test will only be conducted using the injector assembly of the bipropellant engine. Running high pressure water through the manifold and injector orifices will confirm the expected flow characteristics of the engine.

Equipment
- High pressure flow test set up
- Proper fittings to integrate with manifold
- Method of securing engine

Hazards
- Pressurized components
- High pressure concentrated water

PPE Requirements
- Safety glasses
- Face shield for anyone within 10 feet of pressurized components

Facility
- Outdoors of Cal Poly machine shops or Cal Poly Aerospace propulsion laboratory

Procedure
1. Assemble manifold and injector and tighten fasteners to specified torque.
2. Attach manifold securely to test stand apparatus.
3. Set up camera down stream
4. Apply Teflon tape to desired testing orifice threads.
5. Securely tighten threads to rated torque (7in-lbf for 1/8” NPT)
6. Turn on pressure washer
7. Increase flowrate until its at the desired flowrate of the specified orifice
8. Repeat as necessary for all orifices

Results
Review video and confirm all flows are as anticipated.

7.3 Motor Flame Test

SOLID MOTOR FLAME HEIGHT TEST PROCEDURES

F24 Thrust or Bust
TEST GOAL:
To determine the maximum consistent flame height produced by a solid ‘B’ Class motor. This information will be used to determine if this is a valid method for lighting our engine

TEST DATE: 4/10/23

EQUIPMENT:
• Solid Motor Test Stand
• ‘B’ Solid motor
• Hearing protection
• Safety glasses
• Ruler/ meter stick
• 2x4 wood block
• Duct tape
• Wood Clamps
• Igniter
• Nitrile gloves

Facility:
• Cal Poly Aerospace Propulsion Lab
• 1 Grand Ave, San Luis Obispo, CA 93407
• Bld. 41C Rm. 144
• Lab Contact: Cody Thompson: 805-756-1309

PROCEDURE HAZARDS, REQUIRED PERSONAL PROTECTIVE EQUIPMENT (PPE), AND SAFETY GUIDELINES:
• PPE: Safety glasses ("ANSI Z87+" or better) must be worn at all times in the test cell along with closed toe shoes, long pants, and sleeved shirt.
• The bi-prop rocket engine is extremely loud, so ear protection is always required in the control room while the engine is running.
• No personnel are allowed in the test cell, in direct line of sight of the engine when there is only one switch flip (or other actuation mechanism) keeping the three components of the fire triangle separate (in this case gaseous nitrous oxide, ethanol, and electric spark).
• Safety is number one! When in doubt (with respect to safety):
  o Secure the area, do not allow anyone to enter the "danger zone"
  o In case of large "danger zone" or earthquake, evacuate to parking lot immediately south of lab
  o Call lab and/or project advisor
  o Call Cody Thompson (Aerospace Dept. Safety Coordinator: 805-756-1309)
  o Call Environmental Health and Safety (for immediate assistance: 805-756-6661)
PROCEDURE OVERVIEW

The rocket motor is clamped into place next to a ruler. There is a thermal camera pointed at the ruler. The test conductor activates the motor from the safety behind the test cell wall. See figure 1 for component names.

PROCEDURE LIST

1. Setup
   1.1. Insert Igniter into motor
   1.2. Attach rocket motor to test stand
   1.3. Attach 2x4 to test stand via wood clamps
   1.4. Attach meter stick to 2x4 such that it is in plane with the motor, has at least 0.25m of space above the motor, and is no more that 150mm away from the motor using duct tape
   1.5. Angle camera such that it is perpendicular to the plane formed by the motor and the meter stick and is approximately the same height as the motor
1.6. Ensure that the firing system is not armed
1.7. Attach leads to the igniter.
1.8. Turn on the camera and leave the test cell

2. Test
2.1. Ensure everyone has left the test cell
2.2. Arm firing system
2.3. Flick switch and fire the motor
2.4. After firing disconnect the contacts of the switch and replace the safety.
2.5. Wait 2 minutes

3. Safing
3.1. Don nitrile gloves
3.2. Enter test cell
3.3. Remove leads from motor
3.4. Turn off camera
3.5. Remove motor
3.6. Clean up residue
3.7. Reset test stand

TEST CRITERION
Max height of flame is ____
Max height of flame is greater than 4.5 in (Pass/Fail)