SMORE Phase 2: An Upgrade in Valve Systems & Startup Procedure for A Small Methanol Oxygen Liquid Rocket Engine

A Senior Project

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Bachelor of Science

by

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Abstract

A Methanol-Oxygen liquid rocket engine was designed and manufactured under the California Polytechnic State University Aerospace Department by students in a graduate level rocket propulsion class. The SMORE, previously known as the KORE, is now in an ongoing testing and developing stage with plans to incorporate it into the aerospace undergraduate propulsions lab. Phase 2 of the liquid rocket engine development is to produce a startup procedure that will improve the safety due to manual operation and poor ignition conditions. A propane ignition system along with the implementation of electrically operated solenoid valves to control the fuels and oxidizer were the preliminary approach to meeting the objective. However, after testing the propane ignition system it was found to have several shortcomings and instead a simpler re-designed spark igniter became the proven method for ignition without the need of an extra priming fuel, such as propane. Overall the objectives of the second phase of the SMORE were met and proven through live tests.

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Introduction

In 2008, phase 1 of the Static Methanol Oxygen Rocket Engine (SMORE[1]) project was inspired by Noelle Cahill's 1998 senior project[2] based on "How to Design, Build, Test Small Liquid Rocket Engines"[3] by Leroy Krzycki of M.I.T. The first phase of the SMORE project employed the lessons learned from Noelle Cahill's senior project along with implementing new research to develop a modified rocket engine capable of meeting a primary design goal of 20 pounds of thrust. In order to achieve this goal the design improvements included: an increase in combustion chamber characteristic length to maintain combustion within the engine rather than outside the throat; redesigned oxidizer and fuel manifolds and injectors to produce better mixtures; building the engine as an assembly to increase interchangeability and to allow for future advancements; and finally the design of a new test stand to measure dynamic thrust loads. These design measures proved themselves during the testing of the phase 1 SMORE in the spring of 2008, but progress, especially in safety and reliability was still necessary prior to the use of the engine as a long term lab demonstration. The startup procedure required further revision of the ignition system and a reduction in the trial and error associated with the operation of the fuel and oxidizer ball valves.

The second phase of the SMORE liquid rocket engine corresponding to this report attempts to address the ignition issue primarily by testing a propane priming system. In theory the propane priming system will prime the combustor and be ignited electronically, creating a pre-combustion flame that will serve as a pilot to ignite the incoming methanol and oxygen. The propane priming system is based on a similar proven system found in the Cal Poly Aerospace

[1] (Morantz, Sanchez and Soria)
[2] (Cahill)
[3] (Krzycki)

Propulsion Lab's hybrid rocket engine experiment. The hybrid rocket apparatus employs a propane priming procedure which ignites propane in the combustion chamber of the solid fuel rod prior to adding the oxidizer, afterwards the propane is shut off and the rocket runs only on the solid fuel and oxidizer. This procedure is innately complex and susceptible to an increase in errors. In response to a faulty and intricate propane ignition system, the goal is to test a secondary ignition method which eliminates the propane, consists of a dual copper wire igniter, and requires a simpler procedure.

Phase 2 of the SMORE also aims at upgrading the control valves and increasing consistency by replacing the manually operated ball valves with electrically operated solenoid valves. The renovation of the valve system encompasses an entire rework of both the oxidizer and fuel systems, along with the installation of a new electrical control board. The electric solenoid valves are instantaneous on/off valves to aid in achieving the goal of rocket operation with the flip of a few switches. For safety reasons, these electric solenoid valves will be backed by a redundant safety manual override system. The scope of this report will focus on the renovation of the startup ignition system and procedures with the employment of the electric solenoid valves and the testing of multiple ignition methods. Any research, design, manufacturing, or original performance data of the engine itself is discussed in a separate phase 1 senior project paper written by Josef Sanchez and Chaz Morantz.

Apparatus

The apparatus for the SMORE phase 2 development is a continuation of the original SMORE apparatus, utilizing many of the same components while upgrading various others. Figure 1 is an engine cycle schematic of the phase 2 SMORE test apparatus. Its conceptual simplicity is helpful to portray the generalized flow-path for the primer, fuel, oxidizers, nitrogen and cooling systems;

each denoted by different colors. Since the phase 2 SMORE utilizes high pressure flow media to operate properly, the liquid methanol fuel also needs to be pressurized. Therefore, as seen in Figure 1, a non volatile inert gas such as nitrogen is used to pressurize the fuel. The fuel is pressurized at ranges between 350 and 400 pounds per square inch (psi), along with an equivalent oxidizer pressure and a lower propane primer pressure of 30-60 psi. This schematic shows systems which have been upgraded and added from the previous SMORE phase 1. The propane system, electric solenoid valves (ESV), and the safety redundant valves (SRV) are all phase 2 additions.

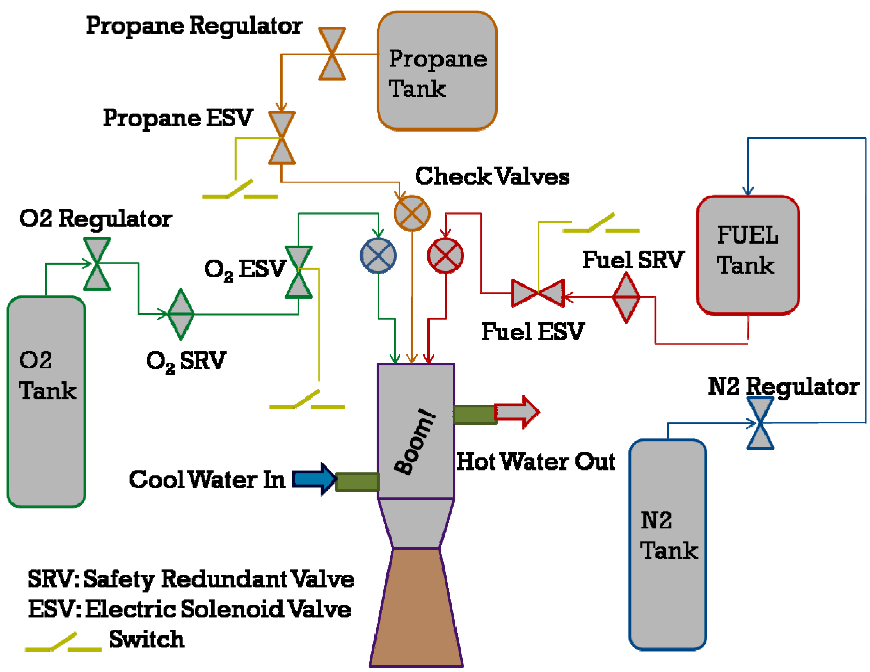


Figure 1: Phase 2 SMORE Apparatus Schematic

Figure 2 is a photo of the actual test apparatus which consists of the test stand, three electric solenoid valves (ESV), two safety redundant valves (SRV), three check valves, the oxygen and fuel manifolds, the ignition wire, the cooling system, and the actual rocket engine. The third ESV, belonging to the propane tank, is not seen in Figure 2 because it is mounted on the propane tank located outside the test cell. However, Figure 2 does include the 3/8in. copper oxygen and

propane lines, 1/2in. stainless steel braided fuel hose, and standard water hose cooling lines. It is important to note at this stage that any component used in one of the flow systems of the apparatus is pressure rated to maximum working pressure of at least 650 psi and 1000 psi for the lines; further specifications of each part are found in Appendix A. Also, the ignition wire system shown in Figure 2 is part of the phase 2 development; a thorough review of the detailed design of the phase 2 wire igniter is found in Figures 18, 19, 20. Due to the perspective of Figure 2, the design improvements between phase 1 and phase 2 are not distinguishable.

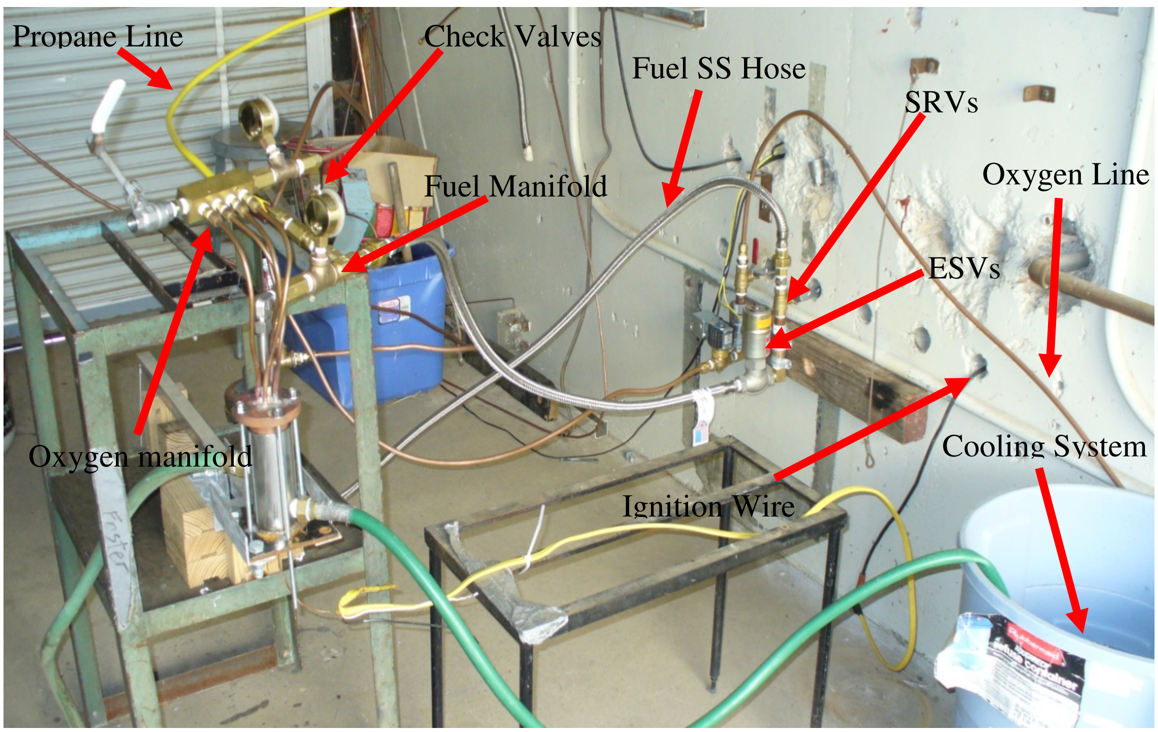


Figure 2: Phase 2 SMORE Test Apparatus

Valves

The electric solenoid valves (ESVs) are an upgrade to the initial phase 1 manual ball valves. The manual ball valves previously used in phase 1 changed the flow properties every time their position was altered, causing instabilities in the injection and ignition processes. However, the ESVs of Figure 3 are implemented in the second phase of the SMORE for their quick open-close

capabilities that help reduce the transient instabilities of the flow during the open-close cycle. They also work to improve the safety of the system by decreasing the human error and slow time response that is coupled with quickly needing to manually open and close the valves. Now with the ESVs it is only necessary to flip a switch for instant turn on or shutoff. A 1/4in., 3/8in., and 1/2in. ESV is used for the propane, methanol and oxygen respectively.

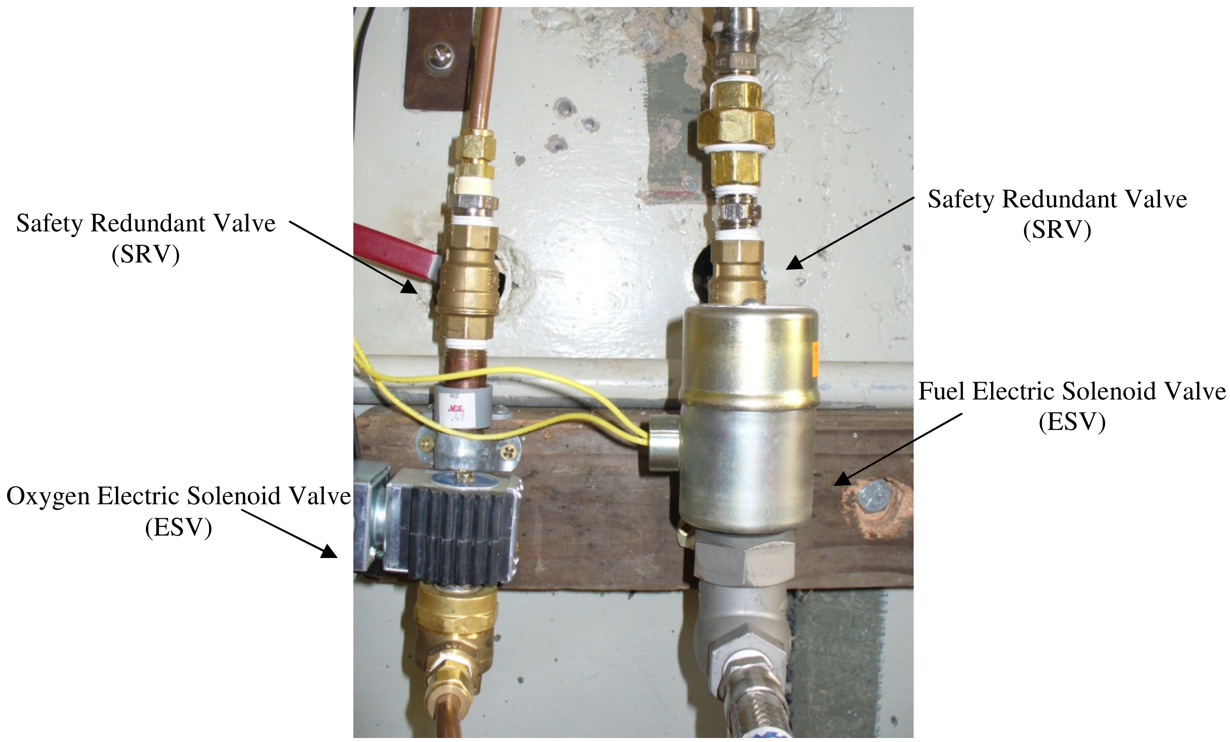


Figure 3: Oxygen & Methanol ESVs and SRVs

In addition, as seen in Figure 3 the oxidizer and fuel ESV's are each assembled in-line with a safety redundant valve (SRV), which is a manual ball valve used if the ESVs ever fail to respond. Both the fuel and oxidizer valve assemblies are securely mounted on the test cell wall and are linked to a manually operated handle inside the control room (Figure 4). Once again these valve systems are employed with safety in mind, adding multiple shut off options and not necessarily as performance enhancements. The third valve system, unlike the oxidizer and the fuel systems, is a whole new phase 2 addition, which as explained later in the report is ultimately

proven unnecessary. Also unlike the two wall-mounted valve assemblies, the propane electric solenoid valve is attached directly to a variable pressure regulator on the propane tank. The propane tank and its respective ESV are kept outside of the test cell during all live tests; therefore a manual SRV inside the control room is not available. However, the propane tank has its own built-in shut off and regulator valves in addition to its ESV. Under this phase 2 design methodology each system has two redundant shutoff options besides the main ESV.

Figure 4: Redundant Emergency Shutoff Valves

To operate the electric solenoid valves, all three are wired to an electrical panel inside the control room. The electrical control panel is made up of four switches: from right to left in Figure 5; one master switch and a switch for each respective valve. The switches are all 120 volt flip switches wired in parallel, so if one fails or short circuits, the others will maintain functionality. The master (red capped) switch serves as redundant safety switch, minimizing the accidental activation of one of the switches and at the same time allowing for an immediate shut off of all the ESVs during an emergency.

Figure 5: Electric Solenoid Switch Board

Check valves are implemented on all 3 main system lines in close proximity to the rocket engine in order to reduce the risk of combustion or backflow upstream of the direction of the flow. The check valve on the propane line is placed on a T-fitting in conjunction with the methanol fuel line, so that both fuels can enter the combustion chamber through the same injector with an almost seamless transition and without the danger of having one back flow into the other. Figure 6 depicts the relative location of check valves when all three systems are connected to the rocket engine; as already stated the final assembly of the Phase 2 SMORE does not incorporate the propane system, therefore the check valve seen in Figure 6 is no longer in the apparatus.

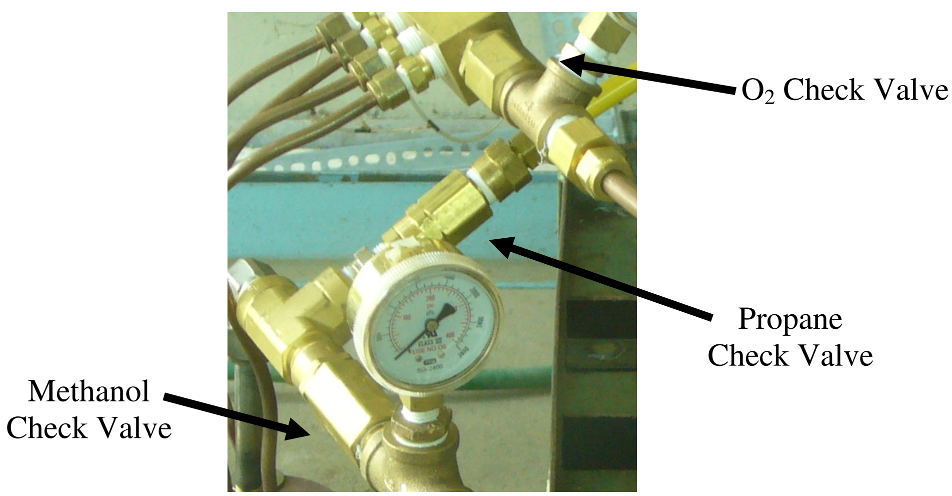


Figure 6: Check Valves

Tanks

Four different tanks are initially used in the phase 2 SMORE project as opposed to the three used in the first phase. Two 80 lb nitrogen and oxygen tanks are used with a Ranteck adjustable regulator max pressure rated for 3000 psi. Both tanks are retrofitted with 3/8in. compression fitting outlets to connect to the copper lines. The fuel tank is built out of a 3in. diameter steal nipple with welded end caps, both sides drilled and tapped for 1/2in. tube fittings. Propane gas, the short lived fourth gas, is stored in a 20 lb tank adapted with an adjustable regulator max pressure rated for 60 psi. Dictated by the new phase 2 procedure, the tanks are all placed outside of the test cell during live tests, minimizing the hazard of exploding tanks due to an accidental uncontrolled rocket fire inside the test cell.

These four substances are found locally and need to be ordered ahead of time to ensure their arrival for the required test day. The nitrogen and oxygen, Figure 7, are ordered through the department's head lab tech and the other two can be purchased by any member assigned to the task. The methanol and propane can be purchased at J.B. Dewar, Inc. in San Luis Obispo. It is important to check the gaseous tanks throughout their lab use to ensure that they contain the necessary pressure required, at least 800 psi for the operation of the phase 2 SMORE.

Figure 7: Nitrogen & Oxygen Tanks

Manifolds

The SMORE apparatus has always employed two different manifolds; an oxygen manifold and a fuel manifold, however during initial phase 2 testing the fuel manifold was converted to form a shared primer/fuel manifold. The oxygen manifold serves as a central distributor to evenly distribute the oxygen into the injector plate via 4 1/4in. outlet ports. Another helpful design feature of the oxygen manifold is the availability of two 3/8in inlet ports, which allow for system configuration flexibility. As seen on the left side of Figure 8, the second of these inlet ports can serve as an attachment point for a system pressure release valve during pressure testing.

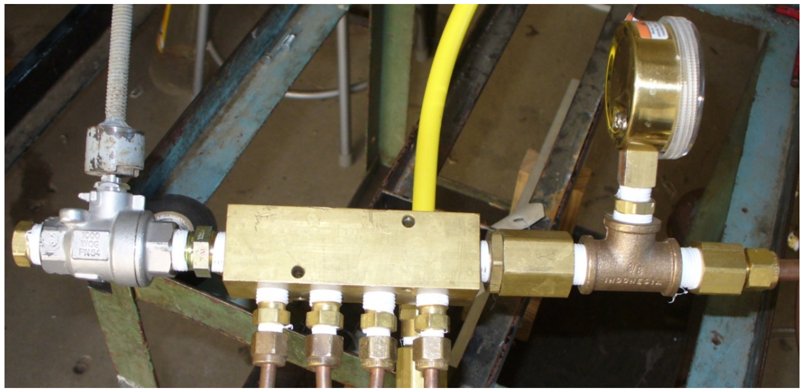


Figure 8: Oxygen Manifold W/ Gauge, Check Valve, & Pressure Release Valve

The combined primer and fuel manifold of Figure 9 is simpler than the oxygen manifold because it only has one outlet into the injector plate, but it is equally important. The primer/fuel manifold is composed of a 1/2in. T fitting and two 1/2in. check valves which form the section in which the propane primer initially enters the combustor followed by the methanol fuel. Combining both the primer and the fuel into one manifold allows for seamless transition between propane and methanol during the ignition process.

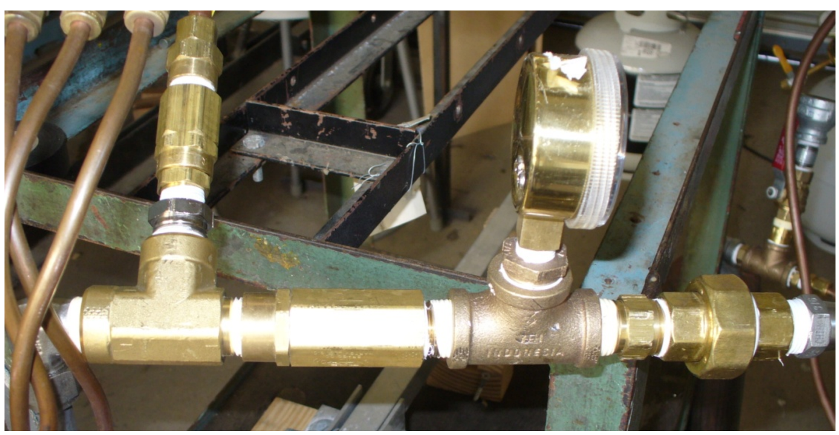


Figure 9: Fuel Manifold W/ Quick Union, Gauge, Check Valve, & Propane Port

Rocket Engine

The rocket engine itself is made up of three components and has seen no change in design since the original phase 1 development. It includes: an injector plate, a one piece thrust chamber with an integrated nozzle, and the coolant sleeve. The injector plate seen in Figure 10 is a

manifold that feeds the oxygen and fuel through the oxygen ports and fuel injector into the combustion chamber. It consists of the four 1/4in. copper pipes from the oxygen manifold and one 3/8in. stainless steel fuel pipe with a compression fitting brazed onto the copper injector plate. A silver brazing joins and seals the pipes and the plate together as one unit. Brazing proved to be a difficult task because of the heat conducting nature of the copper; it quickly dissipates the heat required to bind the silver brazing to the plate and pipes. This issue was overcome late in phase 1 of the SMORE project by heating the plate while brazing. The injector plate-combustor assembly then slides into the coolant sleeve which is made out of a stainless steel pipe welded onto a steel plate. The pipe sleeve has two ports seen in Figure 10 which serve as an inlet and outlet for the coolant flow. The steel plate serves as a means of mounting the engine onto the test stand lever arm.

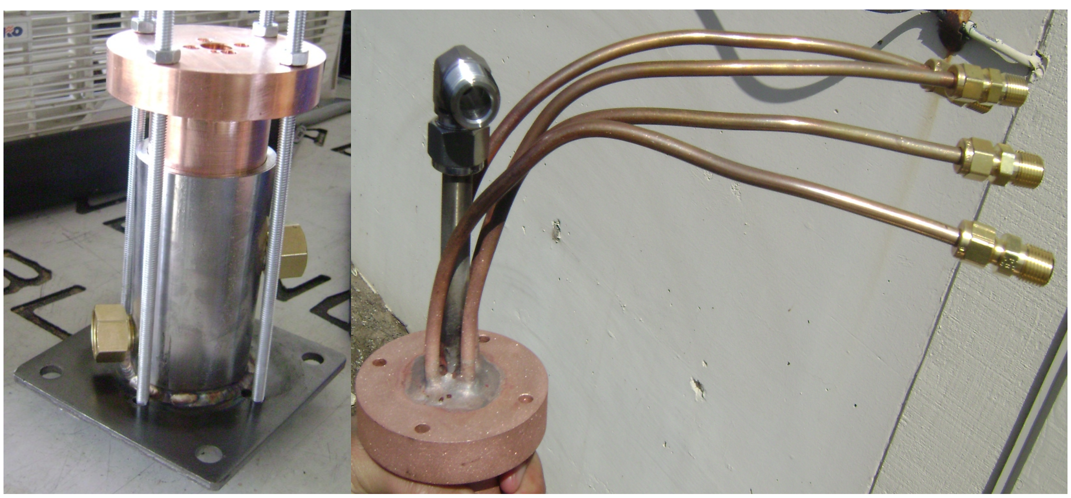


Figure 10: Rocket Engine and Injector Plate

Test Stand

The test stand was built off of a previous stand during phase 1 and is designed to measure the thrust force exerted by the rocket engine by supporting a dynamic thrust arm to which the engine is mounted on. The thrust arm is built out of aluminum square tubing and the engine cradle is

built out of aluminum angle stock, all welded together as one piece. Then the arm is attached to the engine stand on a pivot joint composed of a 1/2in. bolt sustained by a bracket on each side of the arm; note the 1/2in. bolt is not shown in Figure 11. A load cell block, constructed out of wood, holds the load cell capable of measuring the compression applied by the arm when the rocket's thrust causes a rotation around the pivot point.

Figure 11: Test Stand

Coolant System

The coolant system is yet another unchanged phase 1 design composed of a water source, a copper coil and approximately 8 feet of water hose. The water source is connected to the copper coil which is submerged in a container filled with ice water. Acting as heat exchanger, the copper coil in Figure 12 increases the dissipation of the heat in the water by creating a large surface area. The water flowing through the coil is chilled and continues to the rocket engine by means of a water hose connected to the lower port of the coolant sleeve. Water then flows

through the coolant sleeve absorbing the heat transferred through the copper combustor and exits out into the ground or a holding tank.

Figure 12: Coolant Tank W/ Submergible Copper Thermal Exchange Coil

Procedure

The procedure section is split into three sections, comprised of: the assembly, systems testing, and live testing. The sections are laid in a chronological manner to describe the process behind setting up the apparatus all the way through the testing of the rocket engine.

Assembly

The phase 2 SMORE is assembled in multiple segments, beginning with the test stand assembly, followed by the engine assembly, valve assembly, fuel tank assembly, then the regulators, and finally the lines connecting one to the other. The assembly procedure is for the most part similar to the phase 1 procedure with the exception of the upgraded features. The test stand is mostly pre-assembled, requiring only the placement of the load cell and the fuel tank. The load cell is removed after every day of testing, so each time it needs to be reassembled onto its holding block. A threaded end of the load cell is screwed into the block shown in Figure 13

and then the entire assembly is placed below the lever arm opposite of the engine cradle. A wooden bumper separate from the wooden block that holds the load cell is placed at the end of the arm helping to stop the arm from traveling too far and damaging the load cell. The fuel tank is attached to the test stand at the opposite end of the rocket and on the side nearest the fuel ESV on the wall. Two large hose clamps are tightened around the top and bottom of the fuel tank and around the test stand leg. It is important to ensure that the inlet and outlet fittings face their respective destinations; the inlet towards the nitrogen line and the outlet towards the fuel solenoid valve. Also as shown in Figure 13 one of the clamps is always placed above the first shelf of the stand to support the fuel tank from sliding down.

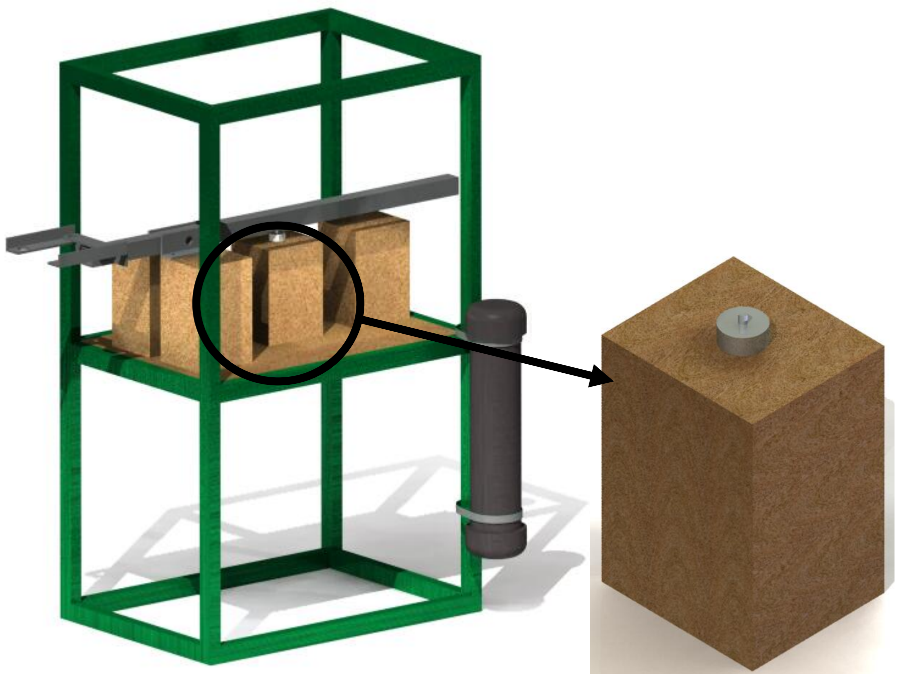


Figure 13: Placement of Load Cell on Test Stand

The engine is assembled beginning by inserting the injector plate's smaller diameter into the combustor chamber of the combustor. Figure 14 shows the aluminum crush gasket that is used between the two parts to maintain a tight seal. As stated before, the crush gasket is a purchased part (NAPA Auto Parts), but it does not fit the injector plate without being modified.

The inner diameter of the gasket needs to be enlarged using a rotary grinding tool, a method developed during phase 2. Also a rubber o-ring is required to seal the injector plate and the coolant sleeve together, but this piece is also not a standard part, so it is best to purchase o-ring stock and cut to size. The injector plate-combustor assembly is then held together and tightened by four threaded aluminum rods, shown in Figure 10, inserted through the injector plate and the coolant sleeve plate.

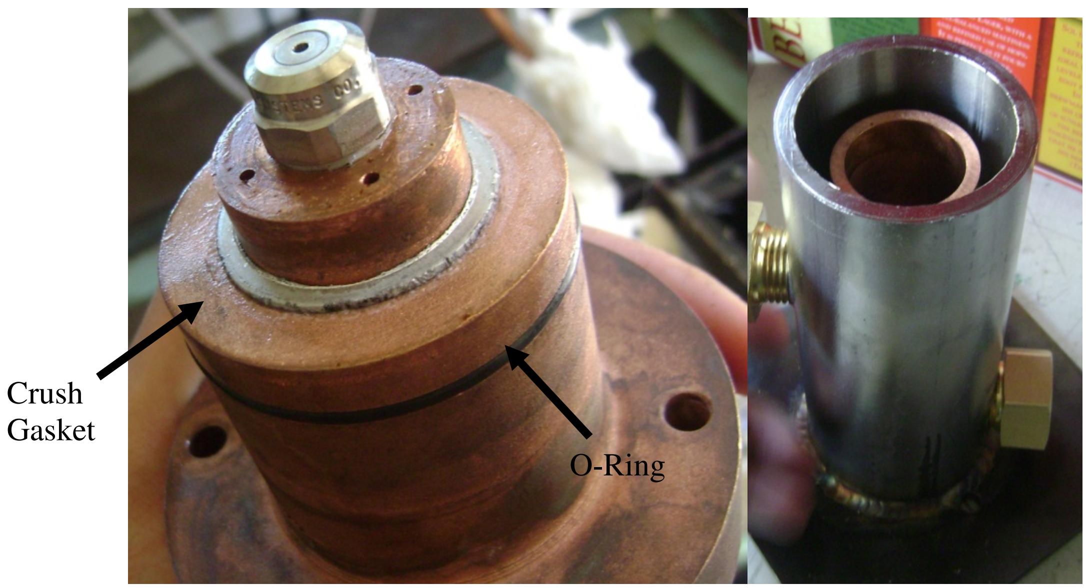


Figure 14: Multi-Tiered Injector (right) to be Assembled into Combustor (left)

The new phase 2 ESV/SRV assemblies, consisting of multiple pieces with no similarities to the phase 1 valve assemblies. Without the ESV, the main valve assembly is built first and consists of an elbow attached to a 3in. copper nipple and an SRV (see Figure15). An extension arm is added to the SRV handle in order to control it manually from the control room. All the threaded fittings are spun with Teflon tape to protect the threads and to seal the joints. The ESV is then attached to the main valve assembly via the 90^0 elbow. It is important that the ESV outlet be facing the opposite direction of the SRV handle and always secured in a vertical position. Finally, the entire valve assembly is attached on the wall using U-brackets screwed into a pre-

existing wooden block (see Figure 15). This assembly process is required for both the fuel and oxidizer systems.

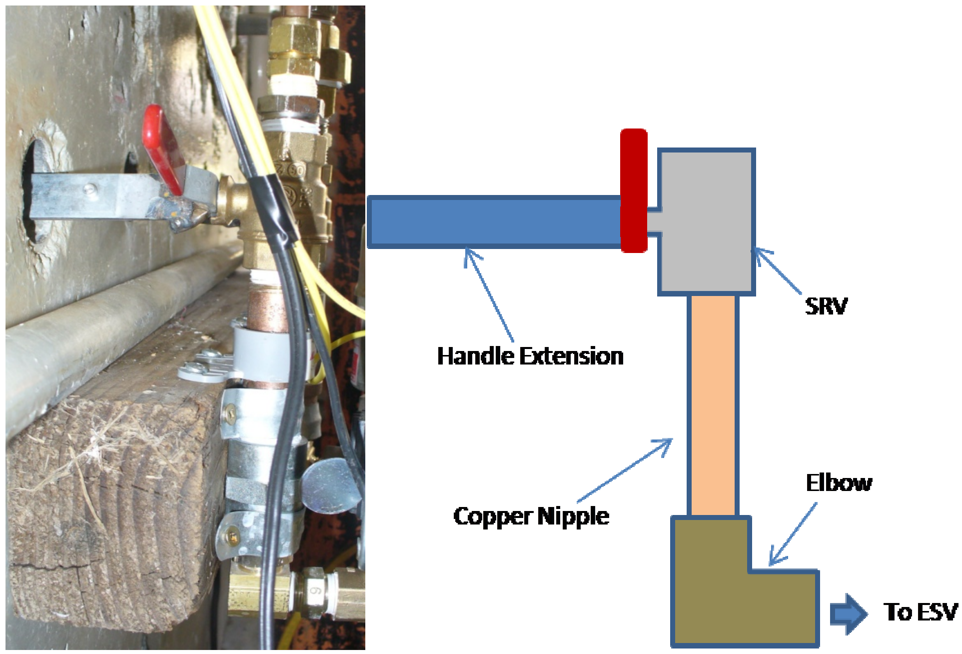


Figure 15: Main Valve Assembly (Non- Solenoid) & Valve Mounting

Once the ESV/SRVs are all mounted they should be connected to their respective switch inside the control room using proper wire nuts and electrical tape to seal off any possibility of an exposed arc. The valves are non-polarized, so either of the two wires can be connected to the hot power wire and the other to the neutral wire; a ground wire is also required and along with the power and neutral wires can be spliced off of the existing infrastructure wiring. Figure 16 is a simplified schematic of how the wiring is spliced and connected between infrastructure, switches, and ESVs. This part of the procedure is a phase 2 development and was performed by techs knowledgeable in the area of electrical wiring. If the lab operators are not comfortable with electrical wiring, then an experienced lab tech should perform the wiring.

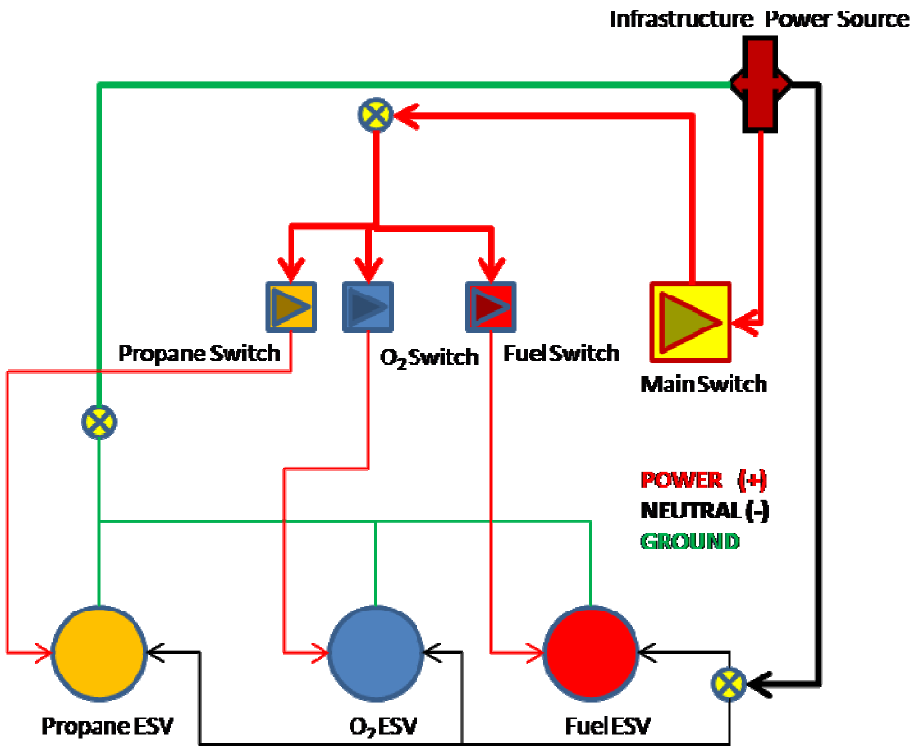


Figure 16: Electrical Wiring Schematic

Pressure Regulators, similar to the one shown in Figure 17, are attached to the nitrogen, oxygen, and propane tanks. All regulators are connected to their respective valves with the use of copper tubing and compression fittings. The nitrogen line differs from the other two in that the copper tubing from the regulator is connected to the top of the fuel tank rather than directly to the solenoid valve. The fuel tank and the fuel main valve assembly are then joined by a 1/2in. stainless steel braided hose with a quick-union-fitting used to easily assemble and disassemble the hose to the ESV. A similar hose and union fitting are used on the outlet side of the ESV to route the fuel to the fuel manifold/injector. The union fittings were implemented during phase 2 as an improvement in assembly and breakdown time. The decrease in time and complexity required to dismantle the system aides in troubleshooting the rocket because now it is possible to breakdown the entire apparatus system by system with relative ease compared to the older phase 1 design. A connection between the stainless steel fuel line and the 3/8in. copper propane line

occurs via two new T-fittings (one for a fuel pressure gauge and the other for the propane line) which form the fuel manifold and attach to the 1/2in. stainless steel pipe on the injector plate. The oxygen ESV is attached to the oxygen manifold in the same manner as it was done during phase 1 via a 3/8in. copper line. Although very unlikely, if the oxygen manifold is not already attached to the injector plate then the bored out brass cube manifold should be attached to the four 1/4in. lines built into the injector plate using the appropriate compression fittings.

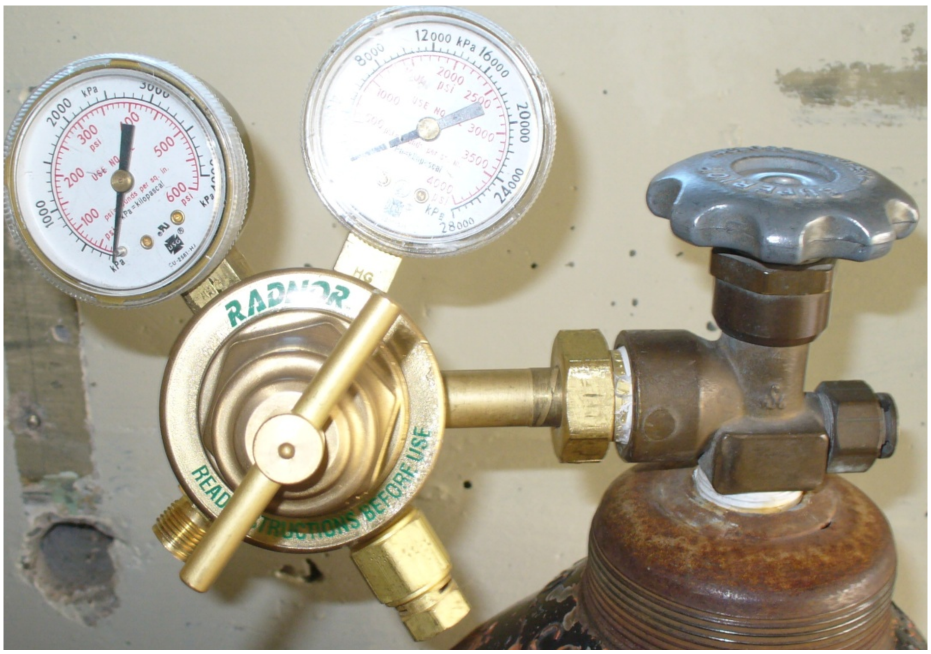


Figure 17: Typical High Pressure Gas Regulator

To keep the combustor walls cool, a copper coil with inlet and outlet hoses is submerged into an ice water filled tub and the outlet hose is connected to the lower port of the stainless steel sleeve surrounding the rocket engine. A third hose is connected to the upper port of the sleeve and is used as the outlet hose for the coolant flowing around the combustor. Figure 18 demonstrates the placement of the hoses relative to the rocket engine. The coolant inlet is at the bottom of the rocket to keep the throat cool at all times and divert the heat up and out in its natural convicting path. The initial SMORE testing had the pure water coolant released to the

outside ground, but in the future it should be placed into a holding tank and disposed of according to any regulations.

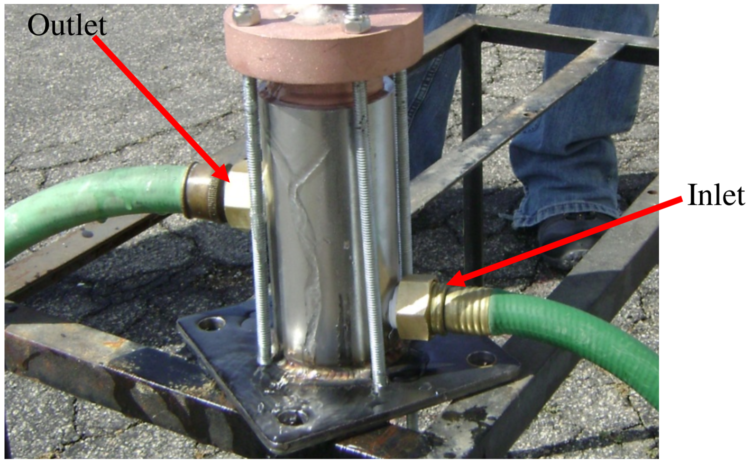


Figure 18: Coolant Hose Orientation

The phase 2 re-designed electrical ignition system is set up next; composed of an electric spark generator and 12 gauge insulated solid copper wire. The spark generator is and has always been kept inside the control room to diminish the possibility of having fuel or water contact. Its outlet cable is fed through the wall and into the test cell where an approximately 4 foot piece of 12 gauge wire is connected to the end. The two are connected by wrapping an exposed end of the copper wire into a small coil that fits inside the receiving end of the generator cable (a spark plug receptacle). The coil is inserted snugly into the spark plug receptacle and wrapped with electrical tape until the connection is fully sealed and the wire and cable held together securely. Using electric tape, the wire is attached to one of the rocket assembly rods, leaving about 6 to 7 inches of overhang past the attachment point. This attachment can be seen in Figure 19. A second piece of 8in. wire is cut and stripped about 1in. at one end. One of the bolts holing the rocket engine to the lever arm, opposite of primary ignition wire, is loosened and the 1in. exposed end of the 8in. wire is wrapped around the bolt and sandwiched between the nut and the bottom of the rocket cradle as shown in Figure 20.

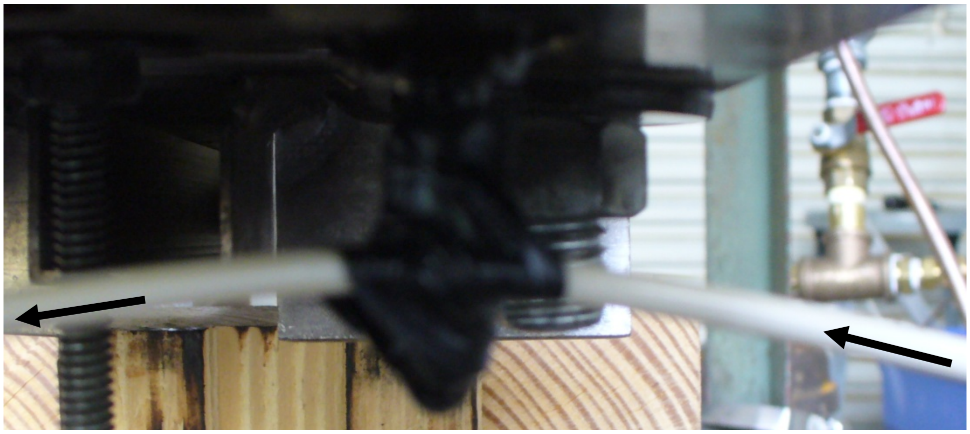


Figure 19: Igniter Wire From Spark Generator

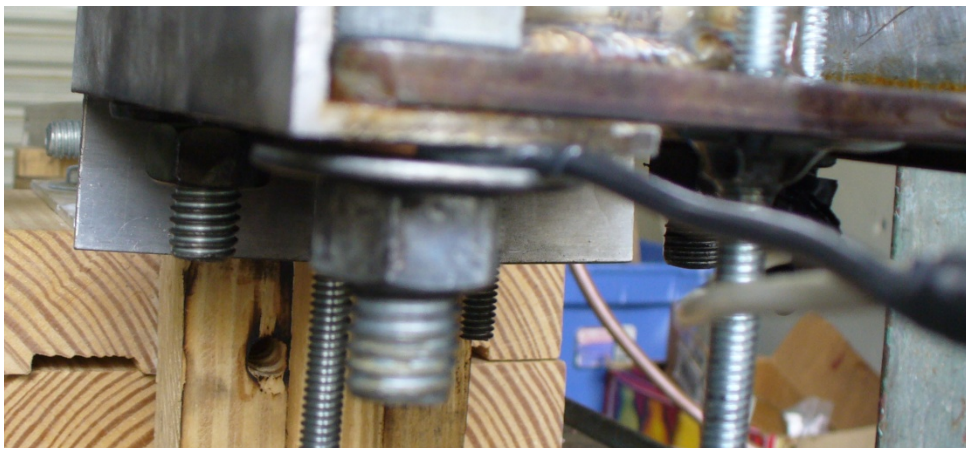


Figure 20: Secondary Grounded Igniter Wire

The loose ends of both wires are then stripped approximately an 1/8in. back, followed by forming and placing the wires side by side. It is necessary to align the two tips and then tape the wires together at two places (forward and rear) with a minimal amount of electric tape. It is important to maintain a gap between the two tips of the wires as shown in Figure 20, if not the ignition will not work. Before inserting the igniter into the rocket it should be tested and optimized during the systems testing procedure.

Figure 21: Igniter (Combined Wires)

Finally, the data acquisition system is setup using one of the aero propulsion lab's laptops, power supply, Datcom card, and load cell. For complete instructions on the assembly and calibration of the data acquisition system refer to the phase 1 SMORE senior project report by Josef Sanchez and Chaz Morantz[1]. The load cell should be calibrated prior to every new day of testing, because of changes that could occur to the placement of the load cell relative to the rocket.

Systems Testing

A series of system tests must be completed prior to initiating any live testing of the rocket engine. The systems tests are altered for the phase 2 apparatus setup with almost every system being affected. The tests are designed as a set of safety procedures designed to insure safe operation and should be performed each time after the rocket engine has been sitting for extended periods of time (between days) or if any part of the rocket engine system is altered; then that subsystem and any subsystem directly affected should be re-tested in the appropriate manner. Tests are composed of ESV testing, oxygen system testing, fuel system testing, and propane system testing. For all these tests and any live testing the manual back up SRVs attached to the wall inside the control room should be left on and used only as emergency shutoff valves in the rare case that the electric valves fail.

[1] (Morantz, Sanchez and Soria)

ESV testing consists of two parts; performed prior to and after line pressurization. First, each ESV system is assessed visually by checking that all of the components look tight and oriented in the correct manner. If needed, tighten and adjust any component that looks faulty. The switch board is checked to determine whether it is connected to working power source by flipping the primary switch and observing whether the power light turns on. If the power light is on, then each of the ESVs are tested by switching On/Off their respective switch and listening for their activation. However, unless there is a prior pressure difference between the inlet and outlet of the valves they may not activate, so a second test must be performed after the pressurized systems tests.

The entire oxygen system is tested for leaks by connecting the system to the pressurized nitrogen tank first; nitrogen's inert properties make it an ideal gas to safely test for leaks. It is important to insure that the male and female compression fittings are compatible between the oxygen line and the nitrogen regulator, so that there are no leaks. Once the line is connected and pressurized with nitrogen (with switches, valves, and tank shut off) it is necessary to check for leaks around all the connections between the regulator and the outlet of the oxygen valve. If there are no leaks then the two gauges attached to the regulator should stay constant once the nitrogen tank is shutoff (without opening the solenoid valves). If the gauges drop considerably at a fast rate then it is important to listen for major leaks from outside the test cell. Then if no major leak is heard, enter the test cell with a spray bottle filled with water and check the connections more closely (Safety attire should be worn at all times, including safety goggles and hearing protection). To depressurize the system, the nitrogen tank valve needs to be and should have already been closed, so that the regulator reads zero pressure coming from the tank. Back in the control room the ESV switch is turned on and left on until the pressure gauge at the rocket

engine reads zero. This test needs to be redone until there is no leak. A similar test is required for the other pressurized systems; testing both for leaks and to verify the correct operation of all the switches and ESVs.

A second pressure test should be performed occasionally and especially when the oxygen manifold is taken apart. The test involves a full system pressure test, including the manifold and combustion chamber. In order to perform this test, the ball valve attached to the oxygen manifold needs to be unplugged and a small aluminum plate needs to be placed inside, at the bottom of the cooling sleeve prior to inserting the combustor. The system is then pressurized in the same way as the previous pressure test, using nitrogen instead of oxygen, shutting off the tank after pressurization, and checking everything for leaks; this time including the rocket assembly past the ESVs (valves must be left on during this entire test). The pressure is then released slowly using the ball valve on the oxygen manifold (make sure that the ball valve is unplugged before pressurizing!!!). After the test has been performed and the necessary steps taken to fix any leaks, the ball valve should be plugged and the plate removed from within the rocket engine. A new crush gasket for the combustor should be used when reassembled for live testing.

The igniter is always tested prior to any live testing to ensure that it is functioning properly. There should be enough of a gap between the two bare ends, but not more than the separation caused by the insulation on the wires. The dual wire needs to be flexed in a direction which can be clearly observed from outside the test cell and from inside the control room. Everyone needs to step out of the test cell and into the control room, the electric generator is then plugged in, and the igniter is observed to ensure that there is a strong arc at the tip of the igniter. This test should only last a few seconds and not left on continuously during the systems test because the insulation will burn away and cause the strength of the arc to decrease. Once it is

verified that there is a strong arc at the tip of the igniter, the igniter needs to be bent and guided into the combustion chamber through the throat, assuring that the bare ends are not touching the throat or the chamber; it is very important that the wire is the correct size and that only the minimum amount of electrical tape is used to build the igniter.

Live Testing

Before performing any live testing it is important to have a print out copy of the live tests procedures summarized in appendix B. Use only the procedures of the appendix in this report because they have been completely redone and updated to incorporate the new design features. The phase 1 procedures are now obsolete. Live test should only be performed after the completion of a full systems test and completion of any required fixes. Only those that have taken the time to study the SMORE and its documentation, both the original report and this phase 2 report, should operate the rocket. The purpose of the phase 2 development and experiment is to produce a rocket with greater start up/shut off reliability and therefore safety, but during any lab, limited success is always possible and the proper steps should be taken to prepare for rare incidents. All personal working on or around the SMORE during systems or live testing should be wearing safety protection at all times. Also, there should always be a designated Range Safety Person or two that will be in charge of keeping people clear of the test cell during operation. The Range Safety Person should know what to do in case something goes wrong; whether it be shutting off the oxygen tank, or putting out a tiny flame. Another operator needs to be chosen to operate LabView and turn on/off the spark generator. The main operator is chosen to be in charge of turning the electric valves on/off during startup and shutoff.

At this point of the procedure everything should already be assembled and the system should be ready to be armed. The electric switches should be plugged in, and all the ESVs should

be turned off with the SRVs left open. Next, the lab instructor needs to ask all non-essential persons to exit the test cell and move on to an observation area; an area that poses no obstruction to safety. When everyone is cleared out, the operators should proceed to fueling the rocket. Prior to filling the fuel tank, a 1 liter container should be filled with methanol fuel. Then the ball valve on top of the fuel tank must be opened and a funnel placed in the opening. The fuel is then poured into the funnel, traveling through the ball valve and into the fuel tank. Pour slowly, because pouring too fast will cause the fuel to back up at the ball valve and spill. When all the fuel is in the fuel tank, the ball valve on the tank must be closed.

After fueling, only one person needs to be in the test cell to turn the nitrogen and pressurize the fuel. Before opening the nitrogen tank, the dial on the regulator should be screwed out so that it is not applying any pressure on the internal diaphragm. The nitrogen tank is then opened slowly until it is all the way open. Now the regulator can be honed in to the required pressure; this should be a predetermined pressure which when combined with the oxygen pressure will achieve the desired combustor pressure. These calculations are found in the previous phase 1 SMORE senior project by Josef Sanchez and Chaz Morantz[1]. The propane is turned on next and set to the max regulator pressure which is 60 psi. Oxygen is turned on last using the same procedure as the nitrogen; remember that the oxygen tank should be the most accessible, so that it can easily be turned on and off at any point without placing the operator in danger of any live fire from the rocket.

After the entire system is armed, the operators should once again listen for any leaks. If a leak is heard the operators should commence to close and turn off all the tanks beginning with the oxygen and continuing to the others. If leaks are non-present, then continue with the test by turning on the water for the cooling system and letting it run continuously. If video cameras are

[1] (Morantz, Sanchez and Soria)

being used to monitor or record the test, then the operators would begin the recording process at this point. All the remaining operators need to clear the entire area around the test cell and enter into the control room. The Range Safety Persons should be at their post making sure to keep any bystanders clear of the area, while also being ready to respond to an emergency following the lab safety protocol as required by the Cal Poly Aerospace Department.

When the safety persons assess that the first set of procedures is clear to go, then the revised phase 2 SMORE ignition sequence is ready to begin. Proceed by turning on LabView on the computer and opening the appropriate VI file; at the time of this experiment the file was 09_smore.vi. This file contains a GUI interface which controls the recording of data from the load cell below the rocket lever arm. To start recording turn on the “run continuously” function and flip the “switch” to the “start” mode. Next, turn on the main switch board control switch. Then plug in the electric spark generator followed by turning on the propane. As soon as the propane jet/flame is seen, the operator needs to turn on the fuel switch and immediately after, the oxygen switch, but not at the same time. At this point, the rocket should ignite, the generator should be unplugged, and the rocket left on for about 12 seconds; at which point the fuels should be shut off first followed by the oxygen once all combustion is done. If any flame persists in or around the chamber initially after shutoff, blow them out using the oxygen switch (in cycles of about 1-2 seconds until there is no more flame coming out of the chamber). Turn off the switch board using the main control switch, stop the LabView recording, and proceed to have the range safety persons turn off the oxygen tank (should always be outside of test cell) then assess the safety of entering the test cell. If a flame is still burning on the outside of the rocket and it is not severe then the range safety persons should enter the test cell, but only after having already turned off the oxygen, and proceed to turning the fire off with a water sprayer. If the fire is big

and out of control, the Range Safety Persons should immediately turn off the oxygen and yell out for everyone to clear the premises, while another immediately calls 911. If the ESVs fail to shut off the fuels or oxidizer, then immediately shut off the manual SRV. When testing is done, all the gaseous tanks should be disconnected and stored properly. The rocket engine should be disassembled and the combustor chamber inspected regularly after tests.

If for some reason the rocket ignition fails to occur instantly after flipping the switches on then the switches should be turned off immediately. A backup adhoc procedure has been developed during phase 2 testing to get the rocket to ignite even if it doesn't ignite instantly as it's supposed to. This method should really only be used during trouble shooting testing and development of the SMORE and not during lab demonstrations. The procedure differs to the regular procedure at the point of flipping the switches; when the fuel switch is flipped on it should be toggled on and off until a flame is seen exiting the rocket nozzle. Once a flame is seen the fuel switch should be flipped on followed immediately by the oxygen switch. Then if the rocket has still not ignited the fuel and oxygen switch should be toggled until choked flow is achieved at the nozzle throat. Then proceed with the regular shut down procedure.

Results & Discussion

The results of the experimental propane primed electric ignition system were successful, but not in the way that was hypothesized. The hypothesis consisted of using propane along with a redesigned electric igniter to light a propane fueled flame, which would then be used to ignite the oxygen and methanol; similar to the concept of having a pilot flame in a water heater. The first test was conducted using a pressure of 30 psi for propane, and 360 psi for oxygen and nitrogen/methanol. The propane was lit and then the oxygen was turned on, followed by the methanol. However, this method was faulty because the oxygen extinguished the propane flame

due to the oxygen's significantly higher pressure which caused the propane check valve to close instantly. Not being able to provide the oxidizer to the propane fuel caused the propane flame to light outside of the combustion chamber where it could burn with oxygen in the air. In this case, when the oxygen was turned on, it would simply blow through the throat and extinguish the propane flame. If the propane combustion could be maintained in the chamber and choked at the throat, then the oxygen and methanol would continue the combustion. Possible solutions to this issue would be to add an oxidizer source of equivalent pressure to the propane which could be used to choke combustion flow; or the pressure of the propane could be increased so that it could keep flowing even after the oxygen and methanol are turned on. The addition of a second lower pressure oxidizer was dismissed as it would be counter to the phase 2 main goal of simplification and improved consistency. Two more tests were performed with increased propane pressure; increasing the propane pressure to 40 psi and the max allowable propane regulator pressure of 60 psi. Both of these pressures were also not high enough to counter the two higher pressured fuel and oxidizer. Even if a propane pressure regulator with a higher working pressure were used, the max pressure of an average bbq style propane tank does not surpass more than 200 psi. This meant that the propane primer had to be taken out of the ignition process and that the start-up method needed to be rethought.

A solution to the propane ignition problem was derived by returning to the basics of the initial phase of the SMORE project. Initially, the rocket was designed for ignition to occur by lighting the methanol fuel using the spark generator in a similar way to the new method, but the igniter was under-designed and unreliable. The old design consisted of a single copper wire connected to the spark generator. The wire was taped to one of the clamp rods on the rocket and inserted into the rocket throat; bending the wire slightly so that the bare end didn't actually come

in contact with the throat. The gap between the wire and the throat caused the electric current to arc because of the electric potential difference and the proximity of the two metals. This phase 1 design was failure prone from the beginning because it depended entirely on a balance game of trying to keep the copper wire from touching the rocket. A new design for phase 2 was derived using the same methodology, but increasing the reliability and performance. By combining the two wires of the current design it was possible to achieve a consistent arc between themselves and not between the wire and the rocket. The insulation around each of the wires maintains the two bare ends insulated from the rocket when inserted in the combustor. The spark generated between the wires was hot enough to ignite the atomized fuel inside the combustor chamber, allowing the flow to choke at the throat instantly after ignition; compared to the older design where the fuel/oxidizer mix would ignite outside the chamber creating a flame thrower at first until the flame traveled back up into the chamber.

The limited success of the propane priming hypothesis was also not extended to the operation of the electric solenoid valves. The ESVs performed almost flawlessly, opening on time every time and shutting off without a problem. They virtually eliminated any "play" that was associated with starting up the phase 1 SMORE using the manual ball valves. All that was and is required to successfully operate the valves and the rocket is the flip of a switch for each valve. The valves didn't pose any issues, but the nature of their placement relative to the rocket was and continues to be less than optimal. They are placed approximately 4.5 feet away from the rocket. A distance which is too far and allows uncontrolled flow in the lines between the valve outlet and the combustor chamber, resulting in left over fuel during the shutoff period. The fuel could then spill out onto the ground and result in a potentially hazardous scenario. This spillage of excess fuel occurred occasionally during testing, until a shut off procedure was developed that

would decrease the amount of “free spilling” fuel. In the new procedure which can be found in Appendix B, the fuel is turned off first during shutoff and the oxygen is left on for a few seconds afterwards, allowing any extra fuel to be burnt off prior to total shutdown. When the rocket is shut down in this way, there is almost always a perfectly dry shutoff.

Over 20 tests were conducted, but unfortunately not all of them were full live tests and data was not collected for every successful live fire test. This was due to a combination of computer unavailability and test time conflicts. The phase 2 SMORE and the new ignition system ran perfectly fine the first five times that it was tested with the new modifications and procedure improvements. However, after a prolonged period of testing hiatus due to outside factors, phase 2 SMORE tests became consecutively unsuccessful (three testing sessions in a period of a month). A troubleshooting matrix was developed to address the possible factors that were impeding the rocket from operating properly, including: bad fuel, grounded igniter, spark not hot enough, clogged injector, and or faulty fuel valve. After new fuel was purchased and the igniter tested many times to ensure proper operation, the phase 2 updated SMORE was still not working, but with each test it became progressively apparent that something was wrong with the fuel system. When the ESVs were open for ignition, the fuel was observed to be inconsistently spurting out of the throat as if though the fuel line was clogged at some point or the flow was not under high enough pressure to atomize at the injector. Once the fuel system became the most probable cause of the ignition failures, a systems breakdown was performed starting at the rocket and working back to the nitrogen pressurized fuel tank. Fortunately, this system breakdown was short lived when the rocket was taken apart and the fuel injector was discovered to be loose to the point where it was dangling on its last threads. The loose non pressure holding injector could easily account for the sputtering of the fuel streams instead of a consistent emission of fuel mist.

The injector was reseated and the rocket was reassembled following standard procedure including the manufacturing of a new crush gasket. These tests were going to be the go/no go tests of this project due to time constraints. The igniter wire that was used for these last tests was not the same gauge size as the one that had been used for the previous successful tests. It was a #10 gauge wire instead of a #12 gauge wire. The thicker wire made it difficult to insert the igniter into the throat of the rocket and after a few tests, it was determined that the wire physically clogged the throat. This caused the startup transient pressure to build up in the chamber and pop the igniter out before any fuel/oxidizer mixture was ignited. Determined to test whether the injector was the culprit of the "pre- new wire" igniter failures, the igniter was adjusted so that the tip of it sat just outside the throat. The dual wire configuration made the igniter stiffer enabling it to be bent into a certain shape or position while maintaining its form. Doing so was jeopardizing the smooth start up, but could determine if the rocket could start up at all, and whether or not a smooth shut off was achievable.

Before running the two final tests, the data acquisition system was setup to gather more detailed information about the rocket's performance. The load cell was calibrated using the proper calibration method written out in full detail in reference 1. As recommended, a spring weight scale was used to apply a quantitative compression load on the load cell by hooking the scale onto the rocket cradle and pulling in consecutively increasing force steps. These loads were recorded on LabView in real time.

The recorded data was plotted in an Excel spreadsheet relative to the actual applied force values and a best fit line approximation was plotted to retrieve its equation and the R squared value. The calibration shown in Figure 22 showed that the approximation had an R squared value of .998, meaning that the equation of the trend line could closely approximate the actual applied

force value. The values of the equation were inserted into the new phase 2 SMORE's LabView GUI to serve as a multiplier and adder to the incoming data.

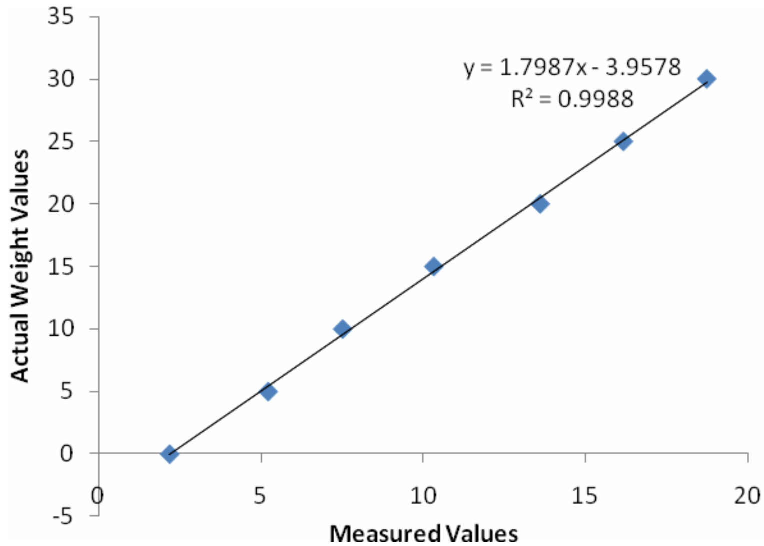


Figure 22: Load Cell Calibration Line

The first test was performed at an oxygen and nitrogen working pressure of 370 psi. This was done to produce an even mixture of fuel to oxidizer, while achieving the desired pressure in the combustion chamber. Following the procedural callout list, the spark generator was turned on and the fuel was flipped on first followed by the oxygen milliseconds later. The flow ignited initially as the fuel arrived, but due to the igniters position the flame was outside and not choked at the throat. Having the ignition inside the chamber and choked at the throat is crucial so that when the secondary oxidizer flow arrives, it doesn't extinguish the flame outside the throat, which was the case during the first few seconds of the test. With the spark generator still turned on, the valves were closed and then reopened, only this time the oxygen was delayed a little bit more. The fuel was then ignited and the flame entered the combustion chamber giving just

enough time for the oxygen to arrive and combust with a choked exhaust. This initial ignition delay and experimenting with valve operation sequence can be observed in Figure 23.

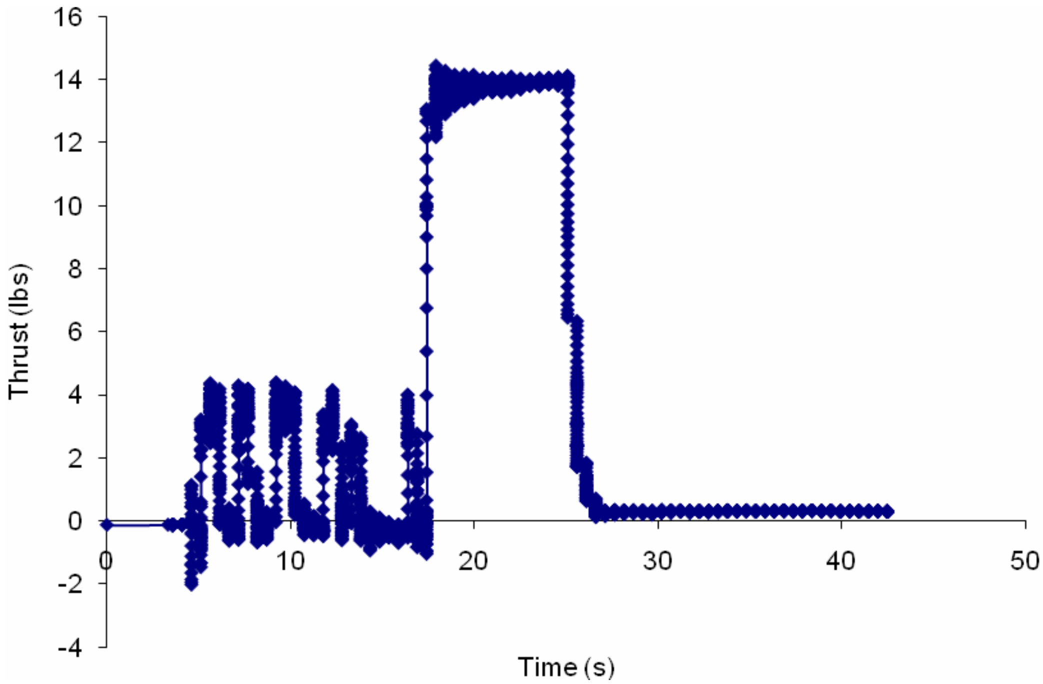


Figure 23: Test 1 Thrust Curve

The thrust spikes in Figure 23 represent the sudden and abrupt ignitions that were occurring during the startup process. A few seconds later the oxygen and methanol ignited in the chamber and produced a thrust curve that would be comparable to a theoretical thrust curve. A maximum thrust of 14.45 lbs was produced and sustained for approximately 10 seconds. It is important to note the shutoff portion of the test for two reasons; it shows a clean instant shutoff and captures the procedure of burning off the excess methanol in the fuel line after valve shutoff. At 24.5 seconds when the shutoff sequence began, the fuel was shut off and the thrust curve declined immediately, but not instantaneously. The thrust curve declines with a slight negative slope, descending to zero thrust proportionally to the decrease in remaining fuel. Figure 24 is the thrust

curve for a second test that was performed the same day. The same trend in characteristics is observed in the second thrust curve as in the first one, providing a consistent set of data legitimizing several of the improvements made to the SMORE rocket system under the phase 2 developments, including the ease of startup/shutoff operation, igniter reliability, and safety.

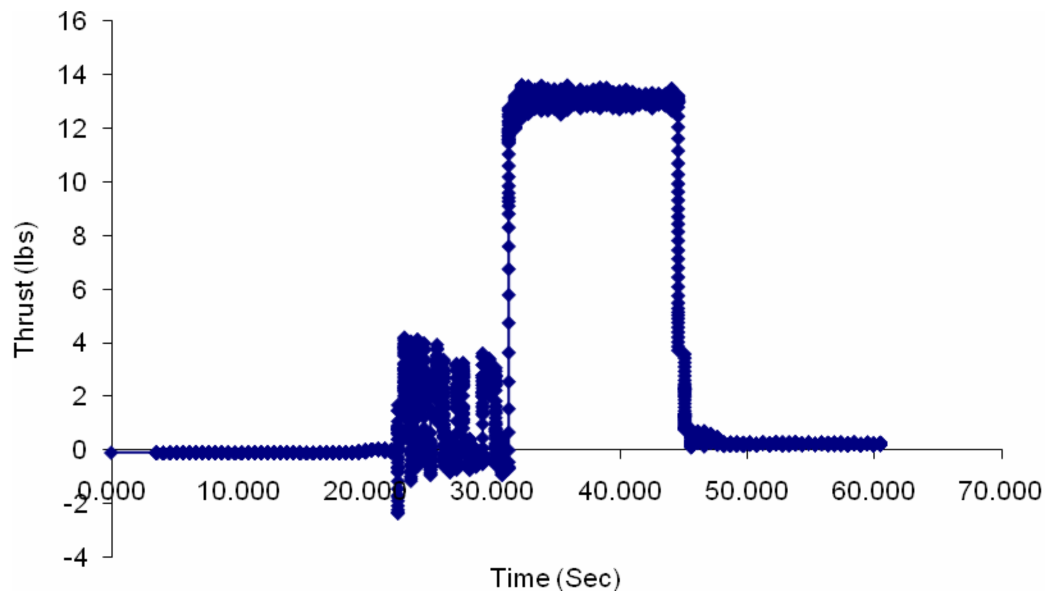


Figure 24: Test 2 Thrust Curve

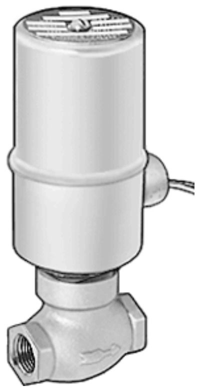
Conclusion

The SMORE phase 2 design upgrades were implemented to produce a liquid rocket system with a higher fidelity than the previous stage of the project. There was a need for an increase in consecutive ignition success and an overall simplification of operation and safety procedures due to valve operation and substance control. The initial phase 2 upgrade proposal for the SMORE employed (in theory) a propane primed ignition system, in which propane would be the primary flow ignited with an electric igniter to form a pilot flame and serve to instantly combust the methanol and the oxygen. The propane system was quickly shown through testing to be inadequate when paired with high pressures of the fuel and oxidizer because it wouldn't maintain

a choked combusted flow without a further increase in the complexity of project. Instead a new more robust electric igniter was designed and proven to work properly. The procedure followed in this report was the actual testing procedure written to incorporate the testing of the new propane ignition system. After discovering that the propane ignition theory was inadequate for the current setup, an updated live testing procedure had to be employed and can be found in Appendix B. Therefore the procedure in the early portion of this report should not be followed for future lab tests, as the propane system was proven obsolete. This report in general should be used as the most updated manual for the SMORE lab as of March 2010, but should not completely replace the previous report,[1] which still maintains the main source of the theoretical analysis for the development of small liquid rocket engines and a detailed calibration procedure required for every test. The results of this senior project have paved the steps for the next stages of the SMORE development. These steps include further testing and data acquisition using the new igniter design with the correct wire size, moving the project to the new propulsion lab, relocating the solenoid valves closer to the rocket engine to reduce residual line fuel, adding a combustor temperature reading device, and even developing a code that could operate the rocket from a computer.

[1] (Morantz, Sanchez and Soria)

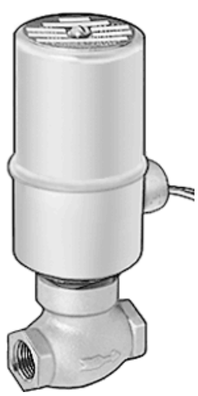
Appendix A: Apparatus Parts List



Propane Electrically Actuated Solenoid Valve

Description: Heavier duty and longer lasting than brass valves, a rugged bronze body and brass piston makes these valves great for frequent cycles

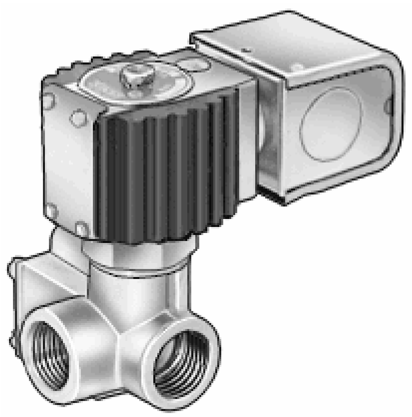
Part # and Manufacturer: McMaster-Carr #4809K112
Operation Frequency: 60 Hz and have a 1/2" conduit electrical connection; .32 amps @ 120V
Mounting: Horizontal to pipe
Temperature Range: -40° to +250° F
Minimum Differential Pressure: 5 psi
Max Pressure: 150 psi
Pipe Size: 1/4 in.



Methanol Electrically Actuated Solenoid Valve

Description: Heavier duty and longer lasting than brass valves, a rugged bronze body and brass piston makes these valves great for frequent cycles

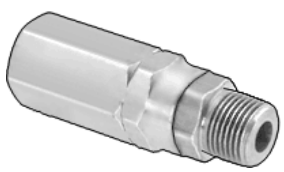
Part # and Manufacturer: McMaster-Carr #4809K314
Operation Frequency: 60 Hz and have a 1/2" conduit electrical connection; .32 amps @ 120V
Mounting: Horizontal to pipe
Temperature Range: -40° to +250° F
Minimum Differential Pressure: 10 psi
Max Pressure: 400 psi
Pipe Size: 1/2 in.



Oxygen Electrically Actuated Solenoid Valve

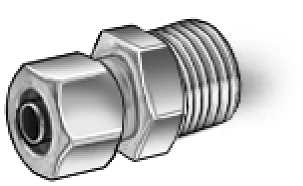
Description: Brass Space-Miser Solenoid Valve High-Pressure, 3/8" NPT Fem, Straight Flow

Part # and Manufacturer: McMaster-Carr #49895K32
Operation Frequency: 50/60 Hz and have a 1/2" conduit electrical connection; .24 amps @ 120V
Mounting: Horizontal to pipe
Temperature Range: 32° to 200° F
Minimum Differential Pressure: 10 psi
Max Pressure: 1200 psi
Pipe Size: 3/8 in.



Brass High-Pressure Spring-Loaded Ball Check Valves

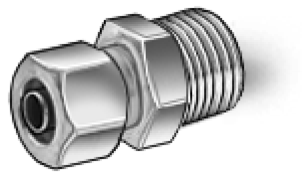
Description: High pressure rated brass valves, these are perfect for fluid and air applications where bubble-tight shutoff is required. They have a Type 316 stainless steel ball and a Type 302 stainless steel spring.
Part # and Manufacturer: McMaster-Carr 8549T18
Temperature Range: 33° to 180° F
Cracking Pressure: 1 psi
Max Pressure: 3000 psi @ 180° F



Compression Tube Fittings (3/8 in.)

Description: Body and nut with front and back sleeves (double ferrules). Yor-Lok Double-Sleeved Compression.

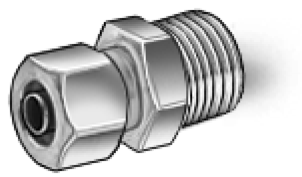
Part # and Manufacturer: McMaster-Carr 5272K195
Max Pressure: 1000 psi @ 72 F
Temperature Range: -40° to 400° F



Compression Tube Fittings (1/8 in.)

Description: Body and nut with front and back sleeves (double ferrules). Yor-Lok Double-Sleeved Compression.

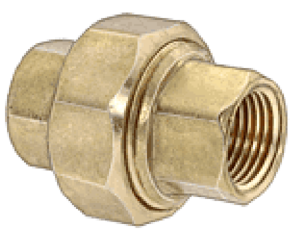
Part # and Manufacturer: McMaster-Carr 5272K291
Max Pressure: 2900 psi @ 73 F
Temperature Range: -40° to 400° F



Compression Tube Fittings (1/4 in. Propane)

Description: Standard Brass Compression Tube Fitting Adapter

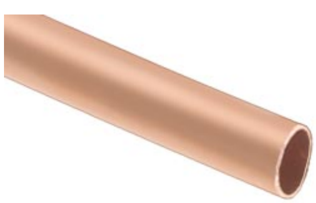
Part # and Manufacturer: McMaster-Carr 50915K224
Max Pressure: 200 psi @ 73 F
Temperature Range: -65° to 250° F
Compression Tube Fittings (1/4 in. Propane)



Union (1/2 in. for Quick Fuel Line Assembly)

Description: Standard brass union used with stainless steel fuel hoses at the solenoid valve and manifold. Used for quick break down of stainless steel hoses.

Part # and Manufacturer: McMaster-Carr 50915K224
Max Pressure: 200 psi @ 73 F
Temperature Range: -65° to 250° F



Copper Tubing (3/8 in)

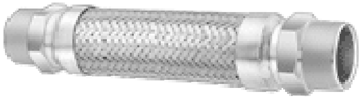
Description: General Purpose Copper (Alloy 122), .049" wall thickness

Part # and Manufacturer: McMaster-Carr 8955K14
Max Pressure: 1220psi @ 70F
Temperature Range: -425° to 400° F

Copper Tubing (3/8 in. for Propane)

Description: Copper Tubing W/ Yellow Polyethylene Coating, .03" wall thickness.

Part # and Manufacturer: McMaster-Carr 3089K13
Max Pressure: 912psi @ 100F
Temperature Range: -94° to 219° F



Braided Stainless Steel Hose (1/2 in. for Fuel)

Description: All-stainless steel construction makes this hose tough enough to handle high-temperatures as well as applications involving vibration. Also good when connections are misaligned. Hose interior is ribbed. Can be used indoors and out. Flexible hose with two male fittings.

Part # and Manufacturer: McMaster-Carr 5793K13
Max Pressure: 1186psi @ 72F
Temperature Range: -325° to 1250° f

Adjustable High Pressure Regulator (Propane)

Description: Suitable for liquid or vapor service, the 1200-00 series of high pressure (pounds to pounds) regulators are used for a variety of applications, torches, heaters, flame cultivators appliances. etc. All types within the series have a 1/4 inch FNPT side outlet in which a pressure gauge can be installed. The compact size of the 1200-00 makes it particularly useful on installations where space is limited. No special tools are required to service the units , and they can remain in the line should maintenance or repair work to be needed

Part # and Manufacturer: Gasngrills H1200-60
Max Pressure: 0- 60 psi
Capacity: 250,000 btu's

Adjustable High Pressure Regulator (Oxygen and Nitrogen)

Description: Brass Barstock Dual Stage Regulator. This type of regulator can be used with both the Oxygen and Nitrogen, therefore the Part number would differ only by the fitting options selected during purchase. The Oxygen and Nitrogen inlet fittings can be different depending on the tanks being used (refer to tanks before fitting alterations).

Part # and Manufacturer: Harris HP722-500-001-D
Max Pressure: 0- 500 psi

Load Cell

Description: All stainless steel construction. 5-Point calibration NIST traceable included. Small size for automation applications. 59 kOhm Shunt Cal Data Included.

Part # and Manufacturer: OMEGA LCFL-50
Max Load: 50 Lb's

Methanol (5 gal.)
Description: 5 gallon can of methanol
Part # and Manufacturer:
J.B. Dewar
Cardlock, Oil Store & Main Office
75 Prado Road
San Luis Obispo, CA 93401
(805) 543-0180

Nitrogen and Oxygen
Description: These two substances should be ordered by the department's lab technician. Always check pressure levels before planning any tests.

MISC: Any other parts not listed in this appendix, but found on the SMORE rocket setup are common standard parts found at most hardware stores or mcmastercarr.com. These parts might have been used based on availability and not so much functionality or efficiency; therefore they could be easily substituted by another similar or improved part. This encompasses any couplings, elbows, pipe extensions (pipe nipples), electric switches, or screws.

Appendix B: Procedure Checklist

Systems Test Checklist

1. Test Solenoid Valves: Assess visually checking that all of the components look tight and orientated in the correct manner

2. If needed tightened and adjust any component that looks faulty.

3. Check switch board to determine whether it is connected to working power source.

4. Pressurize the entire oxygen system with nitrogen then shutoff switches, valves, and tank.

   A. Check for leaks around all the connections between the regulator and the outlet of the oxygen valve (use water sprayer to check for bubbles).

   B. Depressurize the system; the nitrogen tank should already be closed, from step 4. Everyone clear test cell and turn solenoid valve on from control room until gauge at rocket reads zero.

5. Repeat for the fuel system, testing both for leaks and to verify the correct operation of all the switches.

6. Test the igniter:

   A. There should be a gap between the wires caused only by the interference of the insulation jacket.

   B. The dual wire needs to be flexed in a direction which can be clearly observed from outside the test cell and from inside the control room.

   C. Plug in the electric generator and observe for a strong spark

7. Bend and guided the igniter into the combustion chamber through the throat, assuring that the bare ends are not touching the throat or the chamber.

8. Open the water valve and insure that the coolant water flows properly through the system.

9. Calibrate data acquisition system per "Design, construction, and testing of a small static methanol/oxygen rocket engine (S.M.O.R.E.)."[1]

Live Testing Checklist

1. Make sure to perform Systems Test first.

2. All personal working on or around the K.O.R.E during systems or live testing should be wearing safety protection at all times.

3. Assign at least one Range Safety Person.

4. Assign operator to run LabView and turn on/off the spark generator.

5. Assign operator to control the valve switches.

6. Plug in electric switches, turn off all the electric valves, and leave open the backup shutoff valves.

7. Ask all non-essential persons to exit the test cell and move on to an observation area.

8. Fuel the rocket with 1 liter of methanol.

9. Open the nitrogen, but only after checking that the dial on the regulator is screwed out so that it is not applying any pressure on the internal diaphragm.

10. Set the desired nitrogen/methanol testing pressure.

11. Clear the test cell.

12. Turn on oxygen using same procedure as the nitrogen.

13. Once again listen for any leaks.

14. If anything is heard commence to close and turn off all the tanks beginning with the oxygen.

15. If leaks are non-present, then continue to turning on the coolant.

16. Begin the video recording.

17. Operators enter into the control room.

18. Range Safety Persons at their post making sure to keep any bystanders clear of the area.

19. Turn on LabView and start recording.

20. Turn on the main switch board control switch.

21. Plug in the electric spark generator.

22. Turn on the fuel switch.

23. Turn on the oxygen switch (immediately after the fuel switch, not at the same time).

24. Rocket Ignition.

25. Run for 10-20 seconds.

26. Shut off fuel.

27. Once no ignition is visible shutoff oxygen.

28. If flame is seen after oxygen shutoff, pulse oxygen on and off until flame is turned off.

29. Turn off main switch board and close redundant shut off valves.

30. Range Safety Persons check for hazards.

31. Close oxygen tank.

32. Enter test cell with water sprayer incase of unseen flame.

33. Purge the pressurized system.

    A. Place fuel collector below rocket engine.

    B. Everyone step outside the test cell and back into control room.

    C. Activate switch board and turn on oxygen solenoid switch to release remaining oxygen.

    D. Turn on fuel solenoid valve and wait for fuel/nitrogen to purge out.

    E. Turn off switch board.

34. If necessary begin disassembly.

Bibliography

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