2014-01-01

Evaluation Of A Torch Ignition System For Propulsion

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Dedication

I would like to dedicate this to my family.

EVALUATION OF A TORCH IGNITION SYSTEM FOR PROPULSION

by

ROBERT JOSEPH ELLIS, B.S. Mechanical Engineering

THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at El Paso

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE

Department of Mechanical Engineering

THE UNIVERSITY OF TEXAS AT EL PASO

August 2014

Acknowledgements

There are several people I would like to acknowledge by name for helping me throughout my time at UTEP. First I would like to acknowledge my teammates past and present: Jesus Flores, Luis Sanchez, Vanessa Dorado and Gabriel Trujillo who helped me with everything from test procedures, matrices, papers and tests. I would also like to acknowledge Dr. Choudhuri for giving me this opportunity as well as Jose Mena, and Juan Barragan for their help. Finally I would like to acknowledge the entire cSETR and NASA for everything they have done to make this lab what it is today.

Abstract

In recent years NASA has had a renewed interest in oxygen and methane as propellants for propulsion. The drive for this combination comes from several factors including ease of land-based storage, handling safety, in situ resource utilization, and a relatively clean burning process when compared with the widely used hypergolic propellants. This project is part of a larger goal of the Center for Space Exploration Technology Research (cSETR) to better understand all aspects of using LOX/CH4 propellants to create future hardware that is specially optimized for these propellants. This paper discusses the literature background and reasons that led to the design of a swirl torch igniter that uses a spark ignition system meant to be used as a main engine ignition source. The main goal is to create a flammability map for all phases of propellant inlet conditions to determine what temperature, pressure, and flow rate combinations will lead to reliable and repeatable ignition. This comes from the contemplation that the torch igniter will be fed from the main engine's tank boil off to eliminate the need for extra tanks and to reduce the overall weight of the propulsion system. The current data encompasses flammability maps for three out of six combinations as well as the discussion of design changes that lead to successful ignition of liquid propellants. Possible design changes as well as the goal of future tests are also discussed.

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Chapter 1

There are two main purposes to this document. The first is to detail the calculations, design, and testing of a swirl torch ignition system and the evaluation process used to determine its capabilities in terms of ignitability limits and combustion range from the beginning of the project until now. Hundreds of tests have been recorded and several flammability maps have been created and will be discussed as well as the design problems which were fixed in the second generation of the igniter design. The design of a second generation of igniter was created to ignite liquid propellants where the first generation could not. This document will try to discuss all of the work done with the igniter, why the old design failed to ignite cryogenic conditions, and why the design changes to this generation were able to successfully ignite where the first could not.

The second purpose is to be a guide for future reference. Included at the end of this paper are several appendices which detail how to operate various systems and the complete test procedures to aide in conducting future tests should there be no person of expertise around to explain. These projects were done during the time of this thesis but were either not part of a thesis themselves, or did not have adequate documentation to explain the intended purpose or use.

1.1 INTRODUCTION

The torch ignition system was designed as the ignition source for a series of experiments which purpose is to characterize the properties of methane that are involved in its performance as a rocket fuel and put it on par research-wise with other more widely used fuels, such as hydrogen or monomethylhydrazine[1]. This entails the use of GOX/LOX/GCH4/LCH4 as propellants and the observation of their behavior to create a flammability map. This map will be used to aide future designs that intend to use a torch ignition system. The second step is to use this igniter inside a Multipurpose Optically Accessible Combustor (MOAC). The torch ignition system is integrated to the MOAC and used to fulfill the important task of obtaining the ignition limits of

the system's operability to determine the conditions that will provide a stable and reliable ignition [2][3].

The propellant inlet conditions were chosen based on the requirement that this igniter should ignite at all phases of inlet conditions. This comes from the contemplation that the torch ignition system would be fed from the propellant boil-off generated in liquid oxygen and liquid methane tanks. This document discusses the experimental approach, testing procedure, and the measures taken to ensure that ignition was achieved and that data was accurately recorded and properly analyzed. An evaluation of the obtained data, recorded ignitability limits, and the impact of the ignition conditions on the characteristics of the produced flame are described as well.

The document also verifies the function of the modified torch ignition component developed for the LOX/Methane Ignition project. The tests will be conducted in the multi-purpose altitude simulation system (MASS) inside the bunker at the Goddard Laboratory at the University of Texas at El Paso. The investigation is meant to test different cryogenic inlet conditions for Methane and Oxygen. The torch ignition system will have pressure and temperature instrumentation to record the inlet conditions of the test article.

The described experiments in this document are the initial testing phases of the revised torch ignition system. The effects of three changes are being tested: The incorporation of unified igniter body assembly, an addition of a converging section, and the increase of the injection distance between the oxidizer and fuel. The previous igniter did not successfully ignite with cryogenic propellant inlet conditions for two reasons. First, CFD models showed that there was very ineffective mixing occurring in such a short distance (0.25"). The second was the increase in density and consequently increase in velocity of propellants which caused blowout without somewhere to anchor the flame. The changes to the design were made to increase the mixing and atomization of the propellants for better ignition with and to provide a converging section to create a place to anchor the flame with cryogenic inlet conditions. With these changes successful ignitions were seen and in the future wider, more complete flammability maps can be made.

1.2 METHANE AS A ROCKET FUEL

There are several characteristics which highlight methane as an excellent candidate for future rocket engines. Among these are energy density, high specific impulse, cryogenic storage temperatures similar to liquid oxygen, and possible in situ utilization [13]. However, most engines currently using LOX/CH4 are hydrogen engines that have been changed to accommodate methane. [5] The problem with this is that no research has been done to understand the characteristics of methane which can then be translated into designing optimized hardware specifically for LOX/CH4. The current process of modifying hydrogen engines by trial and error has a very high cost with little results. This is mainly due to the lack of fundamental understand of how the LOX/CH4 propellant combination works which has reduced the efficiency of these engines and made them undesirable when compared to much more understood propellants which have already been optimized for flight hardware. Organizations such as NASA have recently revived an interest in doing the fundamental research needed in order to fully understand methane as a rocket propellant. This project is part of a larger effort by the Center for Space Exploration Technology Research (cSETR) to take part in this research to understand many aspects of methane that apply to rocket engines such as the heat transfer characteristics, injector design, spray atomization, and specifically for this project the range and reliability of ignition at varying propellant conditions.

The current method of design is to create models using Computational Fluid Dynamics (CFD). However, these models do not have experimental data to validate the results. In order to get some of this data, visually accessible combustors have been manufactured and are currently using imaging techniques such as Schlieren, Particle Image Velocimetry (PIV), and Phase Doppler Particle Analyzer (PDPA) to understand how injector design affects the propellant break up and particle velocities to better understand the system as a whole to create more optimized hardware.

Another important aspect to consider is the ignition of a LOX/CH4 system which is considered as the greatest risk for the system. [5] The current consensus on the subject is to use a

spark torch ignition which is the method that is used in this paper and throughout the cSETR facilities. Several generations of sparking systems have been made with important parameters such as duty cycle analyzed.

1.3 Literature Review

1.3.1 LOX/Methane Literature

Several organizations have created LOX/CH4 engines including Aerojet USA[1] and NASA's project Morpheus [6]. The details of these engines is listed in table 1.

Table 1 Large Scale Projects Currently Using LOX/Methane

Company	Thrust	Chamber Pressure	MR
Aerojet, USA	870 lbf	111-190 psia	1.5-3.5
Aerojet, USA RCS	84-115 lbf	160-210 psia	3
NASA Morpheus	Up to 4300 lbf	-	-

The larger engine made by Aerojet was an adapted LOX/ethanol thruster that was originally used in the Kistler Program. While the main engine was modified to use methane, the ignition system used ethanol. During these tests it was noted that methane was not as good at film cooling as its predecessor. It is not known whether this is because of the design optimization for ethanol or a problem with the propellant itself. Another project at cSETR is exploring this issue. While the film cooling was a problem, the overall test was a success and produced an efficiency of approximately 97% throughout the entire testing process.

The RCS engine made by Aerojet was tested at atmosphere and at an altitude simulation of 130,000 feet with Isp values of 320s and 305s respectively. It was noted that colder propellants were more efficient while warmer propellants tended to give increased performance. The altitude test had a theoretical Isp of 315s showing that while methane does not meet the

same Isp levels as hydrogen (~430s) or Nitrogen Tetroxide/Hydrazine (~344) it is still a very practical propellant.

The most recent advancement in methane use as a propellant comes from NASA's project Morpheus. The project seeks to create a lunar lander which is operated by LOX/Methane. The reason for this is revitalized interest in moon colonization and manned mars exploration where it may be possible to produce methane from local sources. If this is true then it would drastically cut down on fuel costs for two reasons: having to bring less propellant, and creating propellant in a lower gravity well which would increase efficiency in getting the fuel into space. While there was a major setback where the entire vehicle was destroyed [7] an additional vehicle was already made so testing could resume and should be completed within the next few years.

The Morpheus program is testing the capabilities of methane in both main engine and RCS thrusters in a much shorter development cycle than is traditionally seen at NASA where the first major engine test was conducted less than a year after the project start date. [6] The Isp seen for this vehicle is similar to Aerojet at 321s. This project was a major factor in NASA's decision to fund LOX/Methane research and is a large part of the reason why this paper was written and why the torch igniter project was started.

1.3.2 Types of Ignition Sources

The first ignition type, and the one most similar to the design of this torch igniter, was done for an RCS thruster at NASA. [8] The reason for this was to get away from the very toxic and high cost hypergolic propellants which are typically used for these types of systems. Similar to the igniter described in this paper, it was designed to work over a range of mixture ratio inlet conditions and had 1402 ignition pulses before the ceramic surrounding the sparker failed. The oxidizer and fuel were injected using a series of doublets and an additional fuel inlet was created with a tangential swirl for film cooling. The mixture was ignited by a spark electrode using 20 kV to create an arc from the electrode to the wall of the thruster and the flame was anchored on a bluff body. The mixture ratios tested ranged from 1.08 to 1.88 which are both fuel rich due to the

additional fuel added for film cooling. The target thrust for this igniter was 44 N with chamber pressures varying from 1040 to 1720 kPa. Most of the testing was done in pulses with a 10% duty cycle and. A cross section of the injectors and spark plug can be seen in figure 1.

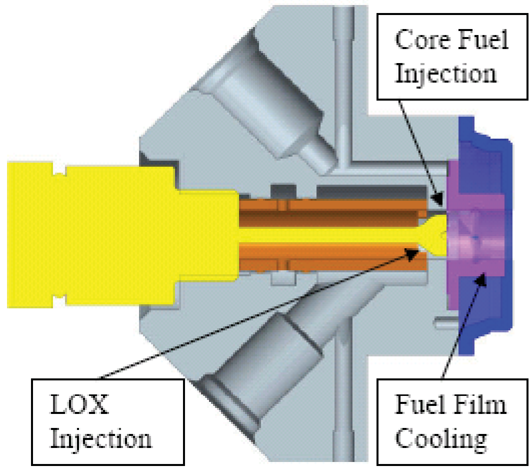


Figure 1 Cross section of the injector of an RCS thruster from NASA [8]

This igniter was especially important because many of the problems experienced were again found in the first generation of igniter testing. Many of the design parameters including the arc to the body, as well as chamber pressure and throat diameter were taken into account when redesigning the second generation of the igniter.

1.3.3 Literature Igniter Testing

The majority of the literature review on igniters came from NASA. Two igniters were designed and tested at the Glenn Research Center. [8][10] Each was made as an attempt to better understand LOX/CH4 interactions in hopes to use CH4 as an in situ resource for trips to mars and the moon.

One igniter is shown in figure 2 was studied to help with the design of the current torch igniter. The oxidizer is injected from the left as shown in the figure. The inlet feeds a ring which then goes to an impinging injector. The CH4 inlet on the right similarly feeds a ring and then into a swirl injector as well as impinging injectors. This combination is used to mix the propellant which is then ignited using a spark plug with variable spark energy of 0.007-0.55 J.

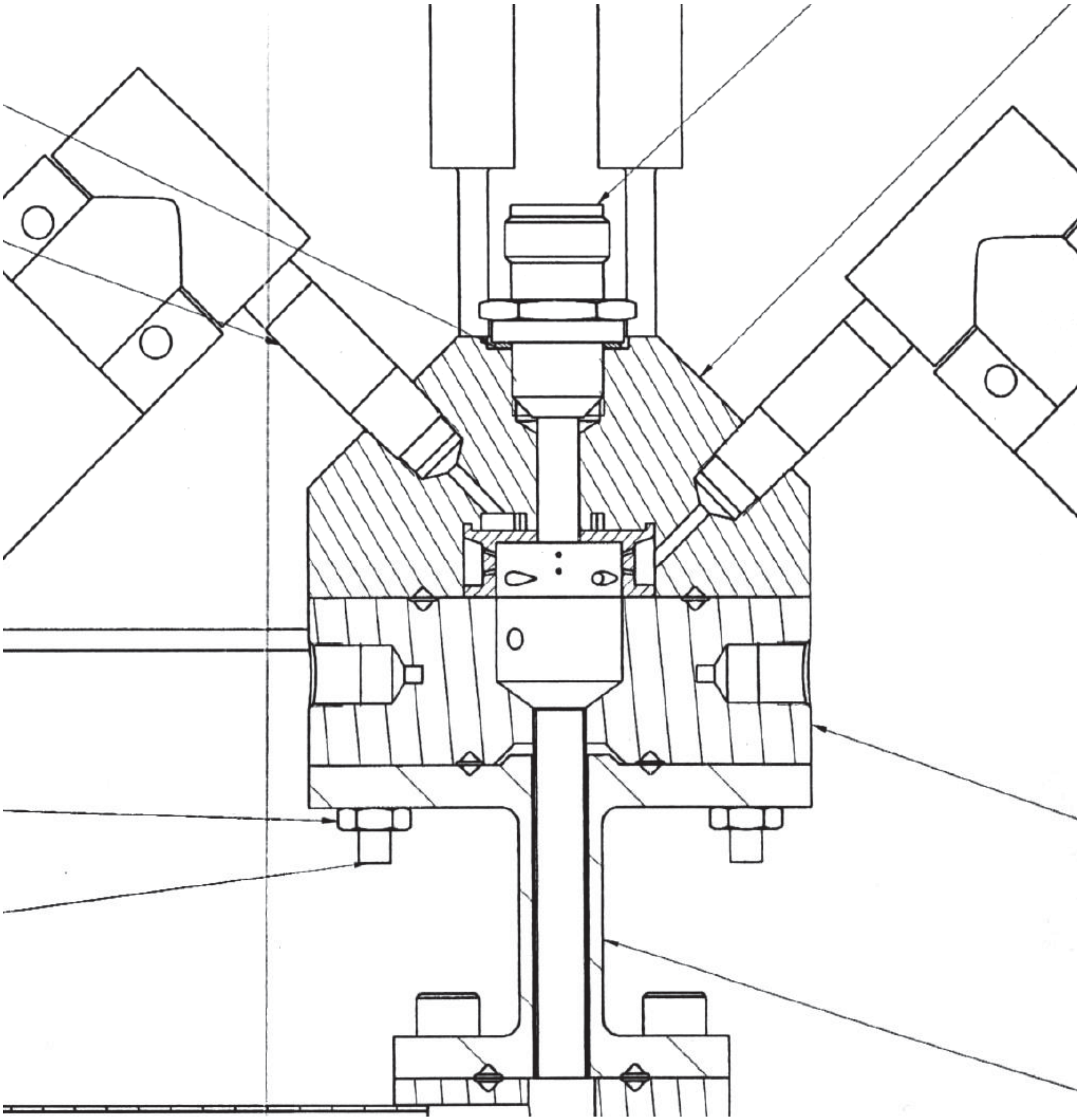


Figure 2 Cross Section of a Torch Igniter Developed by NASA [10]

The goal of the tests was to determine the ignitability limits in a lunar environment. Approximately 750 ignitions were performed with both gaseous and liquid propellants to determine fuel rich ignition limits as well as the effects of spark energy, power, spark plug recession and methane purity. Additionally, the effects of a cold igniter on ignition were tested to determine the amount of heating needed for this hardware to work. With these tests flammability maps were created.

1.4 Statement of the Problem

There are many common ways to ignite the main engines of rockets. Some of the current methods however are either too power heavy or require too much propellant which reduces overall system efficiency. Another consideration is the difficulty in storing and testing very volatile propellants. There are many dangers associated with hypergolics and hydrogen both in handling and in the impact of testing on the environment. This has led to more interest in green propellants which are far less harmful to the atmosphere and much less dangerous to store and test. With interest in a new propellant a large number of problems arise. Particularly the fact that no research has been done on the fundamental processes of storing, testing, burning, atomization, etc. This is where the cSETR plays a role. A large part of the research done is to understand these basic processes to better understand methane in particular. If these efforts are successful, a new generation of rocket engines can be made using this propellant.

The purpose of this paper is to provide information on the design, and all tests that have been done on the torch igniter since the project began. One of the main goals is to reduce the complexity of the system by having the torch igniter use boil off from the main tanks to ignite the main engines. This calls for an igniter that can reliably ignite at a large range of inlet conditions which includes any combination of gas, cold gas, or even liquid propellant. The previous design iteration was capable of igniting a large range of inlet conditions, however, could not ignite liquid propellants. The purpose of the newest igniter design was to maintain the previous ignitability range while also adding the ability to ignite liquid propellants. All of the results from every phase of testing the igniter are included in the document.

1.5 Previous Work

There are 6 propellant phase combinations that are of interest which are shown in figure 3. Of these 6 combinations, 3 have been completed and another has had a proof of concept. The results and discussion of these tests are located in the results section of this paper.

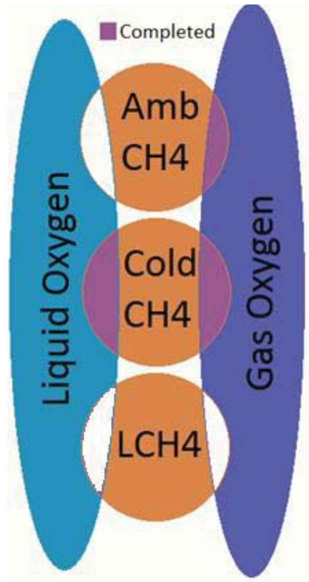


Figure 3 Propellant Combinations

1.6 Objectives

The functional purpose of the torch igniter is achieving reliable ignition inside the combustor. Its characterization involves determining its ignitability limits at different propellant inlet conditions. The obtained test data points will be classified by reliability depending on the igniter's response at a particular mass flow rate input and plotted accordingly to create a flammability map. The reliability criterion set will be the visual observation of three successful and consecutive ignitions out of three attempts. Different automatic sequence totaling 2-15 seconds were run where an ignition will be considered successful if it results in a visible flame that is stable enough to remain anchored to the torch igniter once the an electrical discharge in the sparker is turned off. The two factors associated that have been incorporated in the test matrices as variables are propellant temperature and mixture ratio. The time of the test depends entirely on the inlet propellants. Liquid propellants which have a higher heat release will be run for shorter periods of time until a form of active cooling can be made while tests incorporating gas propellants can be run for longer to study the flame characteristics.

These tests will add to data collected from tests conducted on the previous torch igniter hardware that included ambient temperature, cold gas, and liquid propellants at various mixture ratios. More precisely, among six phase interactions of interest, four were previously tested:

liquid oxygen in combination with cold gaseous methane and liquid methane, and ambient temperature gaseous oxygen in combination with gaseous methane at ambient and lower temperatures. These tests were successful and the data was used to create several flammability maps where the igniter was reliable and where the reliability goes down. The other propellant combinations remain to be tested however liquid/liquid tests have been successful but not enough have been completed to make a flammability map. Once the liquid/liquid map has been sufficiently populated (~50 firings) retesting of the old flammability maps will be done to ensure that the most recent igniter design can duplicate the findings of the previous ignitor or to change the maps to accommodate the ignitability ranges of the new hardware.

1.7 Relevance

LOX/CH4 research is a priority for NASA which has granted a large sum for it to be completed. Methane has many benefits over traditional propellants including storage, toxicity, clean burning, and even in situ resource utilization. The relevance of this project is in creating a reliable ignition source that reduces the complexity and cost of a rocket engine. Current technologies do not create hardware specifically for LOX/CH4 propellant combinations so this is a first step in creating hardware for future programs. All of the lessons learned through the iterative design process will help in the design of future igniter.

Chapter 2

2.1 Technical Approach

This section will cover the various systems that were used in completing testing such as the facilities, equipment, data acquisition, and measuring devices. One part in particular, the Multipurpose Altitude Simulation System, was tested to determine if the system met the original specifications and requirements. The data associated with those tests will be included in section 2.1.5 and are considered part of this thesis as a whole despite the lack of igniter testing at altitude conditions.

2.1.1 *Bunker and Control Room*

The bunker is a projectile proof room used to conduct all experiments. It is lined with ¼ inch Kevlar paneling and bullet proof glass in order to maximize the safety of test operators during testing sessions and allow optical access to monitor experiments. All of the hardware listed below is housed inside of the bunker along with all storage tanks which are separated from the testing location by additional Kevlar walls. The bunker also contains two separate ventilation systems powered by two 100 CFM fans. These ventilation systems are used to vent the burned and unburned propellants from tests as well as the boil off from propellant tanks. A CAD drawing showing the layout of the main components of the bunker is shown in figure 4.

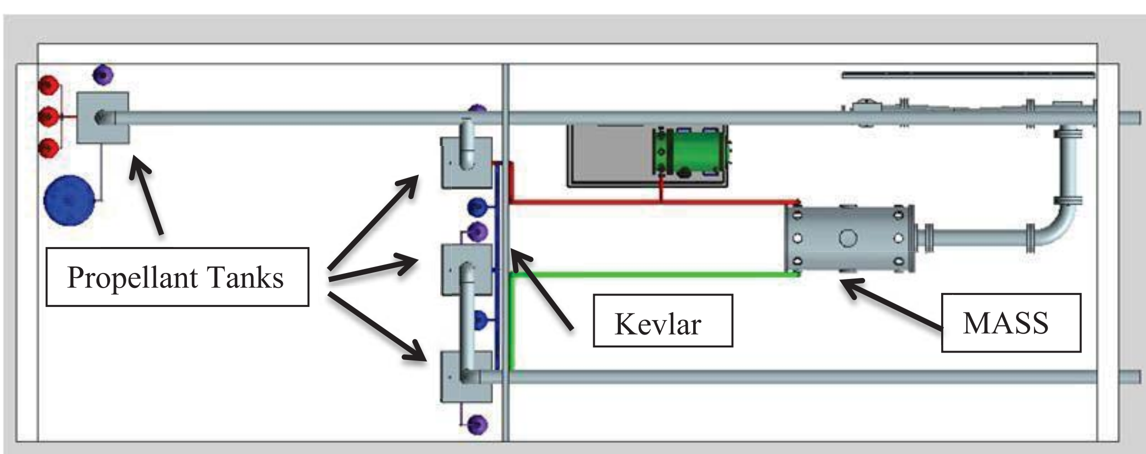


Figure 4 Layout of the Bunker Located at UT El Paso cSETR Facilities

One of the more important parts of the bunker is the patch panel shown in figure 5. The patch panel provides power for all of the devices inside and also receives the data from sensors and relays it back to the control room. A modular design using audio jacks was chosen in order to simplify troubleshooting and the changing of equipment. The first row provides power to in both 12V and 120V while the second row either receives data from the various sensors or outputs signals in order to actuate the valves. Each wire connected to the patch panel is run in overhead troughs to the control room where they are connected to a similar panel.

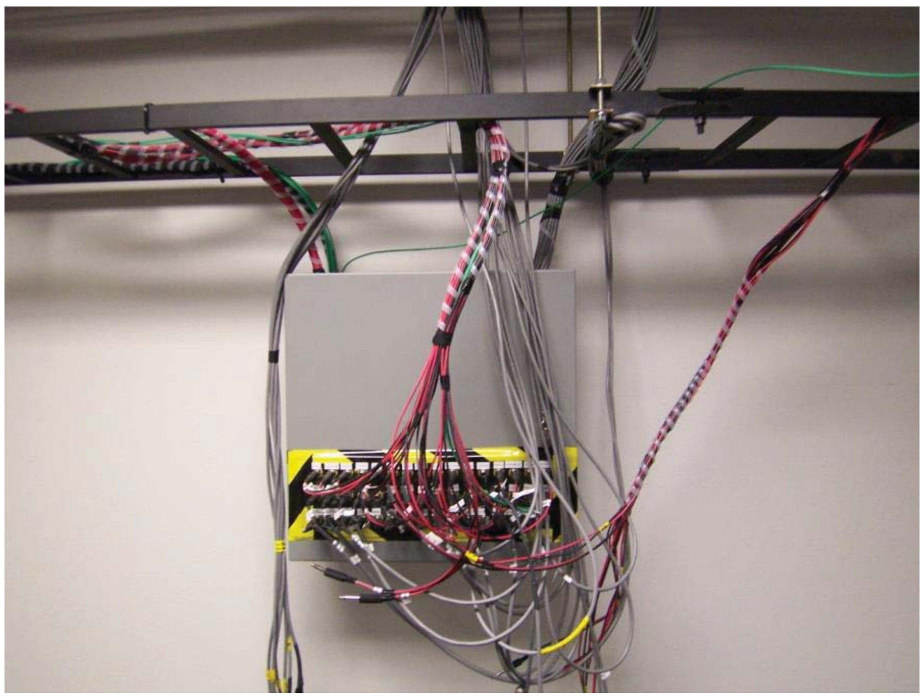


Figure 5 Patch Panel Showing Audio Jack Connections Used For Instrumentation

The control room is located directly next to the bunker and is where all of the power supplies and DAQ systems are contained. The patch panel inside the control room provides the connection from the controlling and power systems to the instruments inside the bunker. It also contains a computer running National Instruments LabVIEW and a server which records constant video feed from the bunker from four separate cameras and retains the video for up to two weeks.

2.1.2 *Cryogenic Delivery System*

The cryogenic delivery system was used extensively in conducting tests. A schematic of the LOX line is shown in figure 6. The lines were used primarily for the delivery of liquid oxygen but also contained lines for both cooling and purging between and after tests. In the interest of cost savings a line for liquid nitrogen was installed and used to chill most of the lines between tests to save the more costly liquid oxygen. An additional gas nitrogen line was used as a purge. The lines are located on a truss to allow for quick access for maintenance and reconfiguration. All lines were equipped with pressure relief valves to mitigate vapor lock and were insulated using cryogel to keep the lines from being heated by atmosphere too quickly. A cavitating venturi was installed on the line to control the flow rate of liquid oxygen.

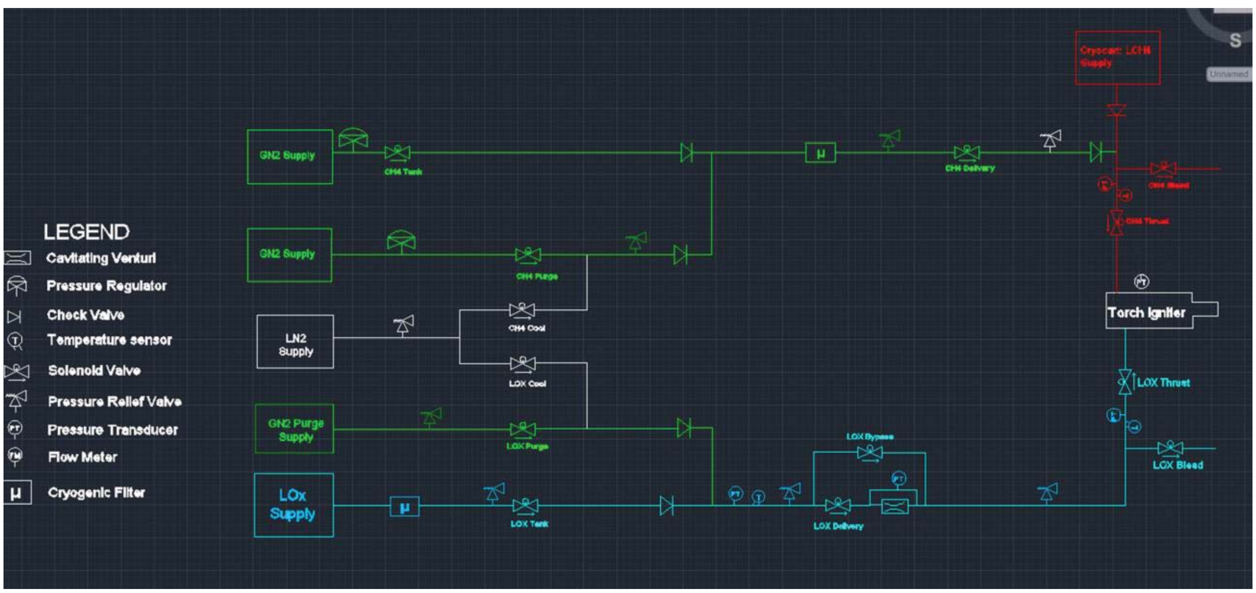


Figure 6 Schematic of the LOX Delivery System

The system also contains lines for liquid methane but was unable to be used because of the nature of purchasing liquid methane. The quantities involved in purchasing liquid methane in this geographic area make it impractical to buy. The line was then converted into a gas methane delivery system which was used in the previous work done on the igniter but was later converted to a GN2 purge line for all tests involving cryogenics.

2.1.3 *MASS-Multipurpose Altitude Simulation System*

This section is an overview of the MASS system and is more detailed than the other sections of this chapter. A detailed analysis of the entire system along with specifications and operation limits has never been done on this system so this section will try to incorporate all of the knowledge of the compressor and ejector system into one place. Shakedown testing of the system was also done and will be included in the results section as part of the overall thesis.

This system consists of two main components: a vacuum chamber and an ejector system. The vacuum chamber is 1.52 m (5 ft) long by 48 in 1.22 m (48 in) in diameter. It has visual ports in the middle that allow for optical diagnostics to be operated such as Particle Image Velocimetry (PIV), Schlieren imaging, and high speed cameras. Sixteen feed through ports are provided in the vacuum chamber to grant access to any electrical instrumentation and propellant delivery hardware needed for different experiments. Figure 7 showcases the two stage ejector system along with the vacuum chamber and a schematic of the system. The system is shown below however the pressure line is attached at the marked open port.

The MASS was used primarily as a test stand; however, recently a large compressor was purchased to elevate the MASS to its full potential. The ejector is a two stage system designed to create and maintain vacuum of 20 Torr (26 km simulation pressure) while operating a 15 lb LOX/LCH_4 thruster. The motive fluid for the ejector is air at 125 psig, and a compressor will deliver a total of 3828 kg/hr (8440 lb/hr); 508 kg/hr (1120 lb/hr) for the first stage, and 3320 kg/hr (7320 lb/hr) for the second stage. This provides the capability to pump 84.8 kg/hr (187 lb/hr) of Dry Air Equivalent (DAE) at 600 K (620 °F), while maintaining 20 Torr (0.39 psia) pressure. The MASS has a stainless steel plate with a grid of mounting holes in order to allow any type of instruments or experiments to be secured. The loads supplied by the propellant delivery system to the vacuum chamber must be compatible with the MASS in terms of ejector capability, material selection, and interface. There are still tests to be conducted at ambient conditions so no high altitude tests are currently planned. The second phase of testing will

include high altitude tests which will then be compared to the ambient conditions. At this time only shake down tests were conducted on the MASS to ensure that it is working properly.

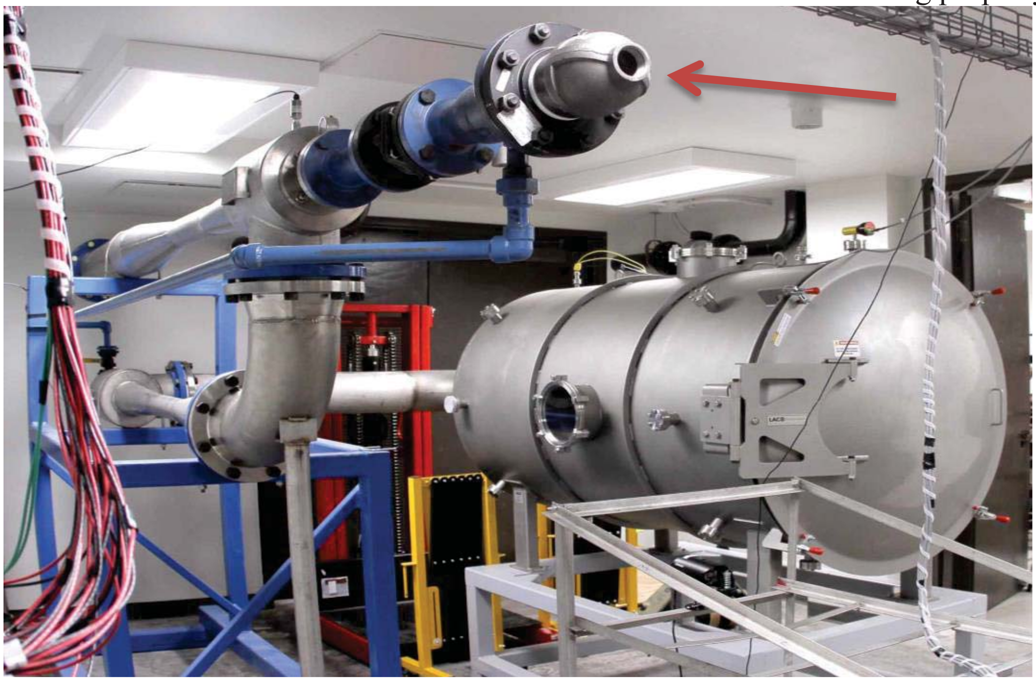


Figure 7 Two Stage Ejector and Vacuum Chamber Which Make the MASS

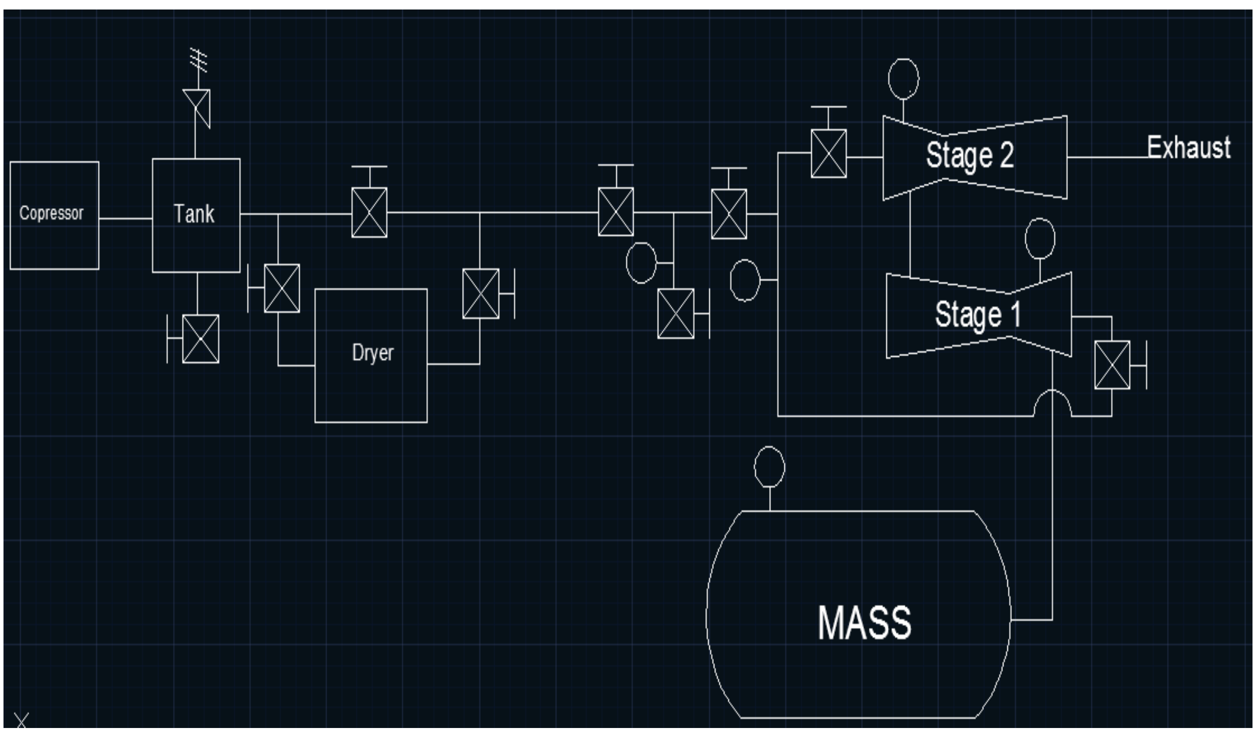


Figure 8 Schematic of the MASS Including Compressor

Table 2 Describes the specifications for each part of the compressor and ejector systems.

Table 2 Compressor Specifications

Ejector	
Total Air Flow	8,440 lbs/HR air @ 125 psig; 72 F
First Stage Consumption	1,120 Lbs/HR
Second Stage Consumption	7,320 Lbs/HR
Suction	65.96 lbs/HR CO2 +87.15 lbs/HR Water Vapor @ 20 Torr, 620 F (0.023 kg/s)
Discharge Pressure	14.7 psia (12.8 psia Ambient)
Compressor	
Capacity	
Maximum Operating Pressure	236 cfm @140 psig
Weight	2100 lbs
Connection Size	1.5 " NPT
Dimensions (LxWxH)	63.2" x 66.5" x 66.8"
Sound Level	75 dBA
Ambient Temperature Rating	115 F
Electrical Interface	460/3/60 69.3A
Control Interface	Build in Control Panel See Appendix 1*
Remote Control Interface	PC Compatible (Currently Not Integrated)
Dryer	
Capacity	25scfm
Dew Point	ISO Class 4, 39F
Refrigerant	R404A
Maximum Operating Pressure	300 psig
Maximum Inlet Temperature	120 F
Weight	340 lbs
Connection Size	1.5" NPT
Dimensions (LxWxH)	23" x 21" x 40"
Heat Exchantger Material	Stainless Steel
Electrical Interface	460/3/60 69.3A
Control Interface	Build in Control panel See Appendix 1

*The compressor is managed by the onboard electronic controller. The controller and drive system operate together to vary the speed of the compressor to deliver compressed air at the target pressure.

The ejector is designed to pull up to 0.023 kg/s (153.11 lb/hr) maximum ejection. Most of this will be exhaust gas from thrusters which must be cooled to under 600K (620 °F). This is higher than the current maximum flow rate of any thruster currently tested in these facilities. The current test article maximum is less than 0.015 kg/s. The exhaust consists of the combustion byproducts of LOX/CH_4, which are primarily CO_2 and water vapor. A heat exchanger was designed to be later added to the system between the vacuum chamber and the first ejector stage shown in figure 9 but was never manufactured. While shakedown did not use high temperature gases, the heat exchanger must be tested and installed before any high altitude firings are done. The heat exchanger is designed to cool 0.04 kg/s (317.5 lb/hr) from 775 C (1427 F) to 325 C (617 F) using water at room temperature as the cooling fluid. This is a low enough temperature to enter the ejector stages, where the gases will then be mixed with the incoming air from the compressor to a final exit temperature of ~100 C (212 F).

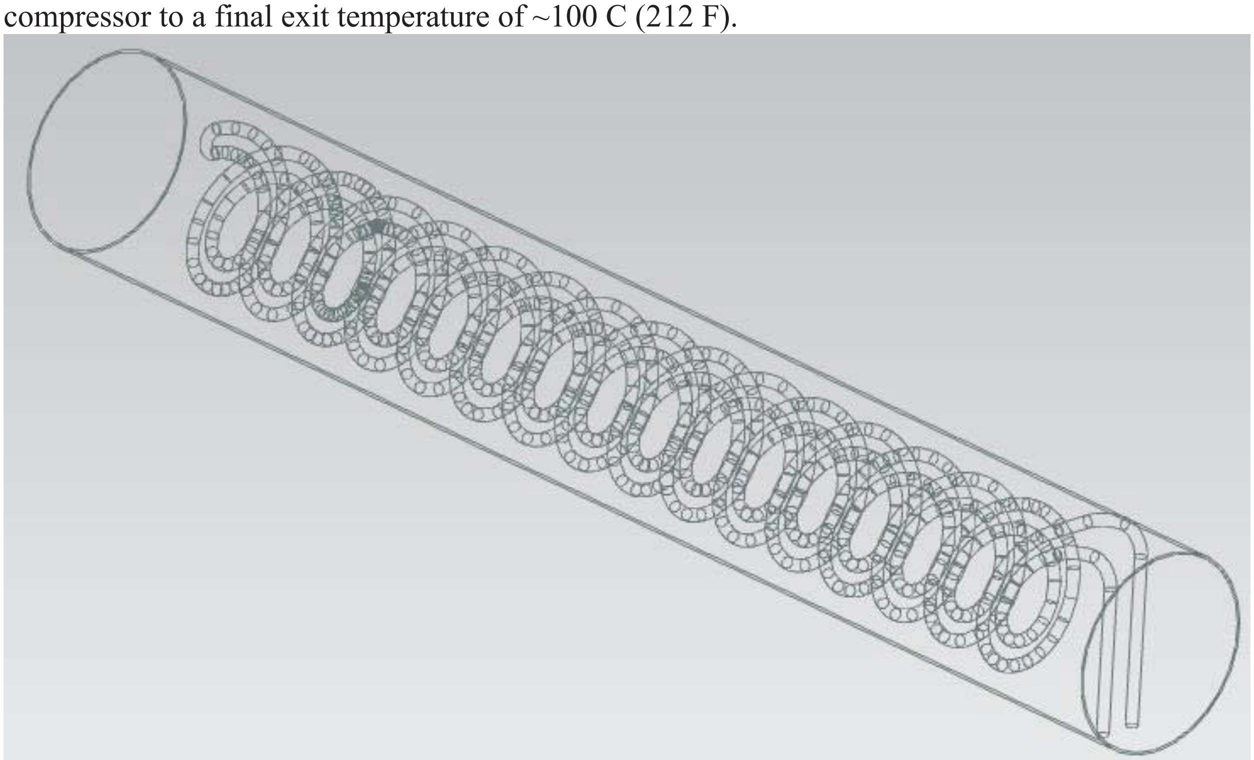


Figure 9 CAD Drawing of a Heat Exchanger to be Used with the MASS

For the ejector to maintain vacuum the inlet pressure must be maintained over 125 psi at all times to maintain optimum suction. If the pressure drops below 122 psig then the ejector will unchoke and lose suction potential.

The compressor is preprogrammed to supply air at 145psi. The compressor automatically turns on when the pressure drops below 125 and then off when it reaches 145 psi. During constant use when the ejector is on, the compressor will remain engaged supplying pressurized air until the flow rate stops. The line is fed to a tank and then into a dryer to remove excess water vapor.

The dryer uses a cooling system to condense the water vapor in the pressurized air. A separation system is integrated in the assembly, causing the air (post-condensation of the coolant) to be exhausted from the compressor through a moisture separator. All condensate is drained into facility drainage according to local policies. All of the dryer's operating limits are well within the specified limits listed above by the manufacturer's design. The safety considerations associated to this component are the following:

- Condensate drains must not be connected to other pressurized drains in closed circuit to ensure that the outflow is unimpeded
- The ambient air surrounding the dryer and compressor must not contain solid or gaseous contaminants. (Production of acids and chemicals by condensed gases is a possibility)

A tank was added to help maintain a constant pressure by adding volume to the system. The maximum operating pressure for the tank is 200 psig and has a relief valve with an orifice diameter of 0.5" that opens at 165 psig and allows flows of up to 382 CFM. The tank dimensions are 30" by 84" and can hold a maximum volume of 1.09 m^3 (240 gallons) of air. The tank along with the compressor were installed in the basement of the engineering building in order to reduce noise and avoid the heat from the compressor/dryer exhaust from disturbing others in the lab. The volume of the tank in comparison to the compressor operational output is very small.

The line used is 2" pipe with a pressure rating of ~1900 psig giving a factor of safety of ~14. Fittings and valves were tested for leaks by facilities but must be checked again before operation.

The vacuum chamber is equipped with connection ports for propellant lines and measurement device to work inside. Each port that does not use an o-ring seal has been treated with vacuum grease to help prevent leaks. For the purposes of the preliminary tests, all of the ports will be closed except for two inlets of CO_2 used to measure the effects of a load on the vacuum chamber's performance. The chamber cannot be pressurized above 20 psig. This pressure was calculated using the weakest point in the system, the Pirani Gauge. The compressor should be turned off if the chamber pressure goes over 20 psig to protect the measurement devices. This operation is not automatic and must be done manually via the e-stop button upstairs, or by pressing the stop or e-stop buttons on the compressor downstairs. No software for remotely controlling the compressor is available from the vendor.

Measurement Devices

The following devices are installed on the vacuum chamber:

1 Pirani Gauge: This gauge is used to measure pressure from 0.0001-1000 Torr (0.2E-6 – 19.3 psia) +/- 10% of reading, and is mounted at the front of the vacuum chamber.

InstruTech CVM-211 "Stinger"

It is recommended to never exceed 20 psia in presence of the sensor. Pressures over 35 psia can permanently damage the sensors heating element. While this value is set by the manufacturer they also state that there is a chance of permanent damage even between 20 and 35 psia.

1 0-250psia Pressure Transducer: This PT can be used in place of the Pirani Gauge to test the system is working correctly without endangering the Pirani Gauge from overpressuring.

4 **0-15 Psi Pressure Gauges**: One gauge is installed on each stage of the ejector to confirm that vacuum is being pulled at both locations.

2.1.4 *MMCU-Mobile Methane Condensing Unit*

The MMCU was designed in house in order to accommodate testing that requires liquid methane propellant. The need to create a condensing unit came from the inaccessibility of liquid methane in the region. Shown in figure 10, the currently used unit has a capacity of 15 liters and a maximum operating pressure of 350 psia. It works by first creating a vacuum inside the tank and then running liquid nitrogen in copper coils both inside and outside the tank in order to bring the metal to below cryogenic temperatures. Gaseous methane at 80 psia is then introduced into the tank which begins condensing on the pre-chilled copper coils until the desired amount of methane is produces. A schematic is shown in figure 11. The higher pressures allow for a higher condensing temperature which leads to a 50% decrease in condensation time when compared to condensation at ambient pressures. The entire system is well insulated to allow for a few hours of storage while the tests are performed. The tank is then pressurized using helium to the desired delivery pressure. Thermocuples were installed and welded into the side of the tanks to measure the current level of methane inside the tank. The system is equipped with quick connects for valves, pressure transducers and thermocouples to allow for very quick transition between various test setups in the lab. The total time to full disconnect and reconnect the cart to a different setup usually does not exceed 30 minutes.

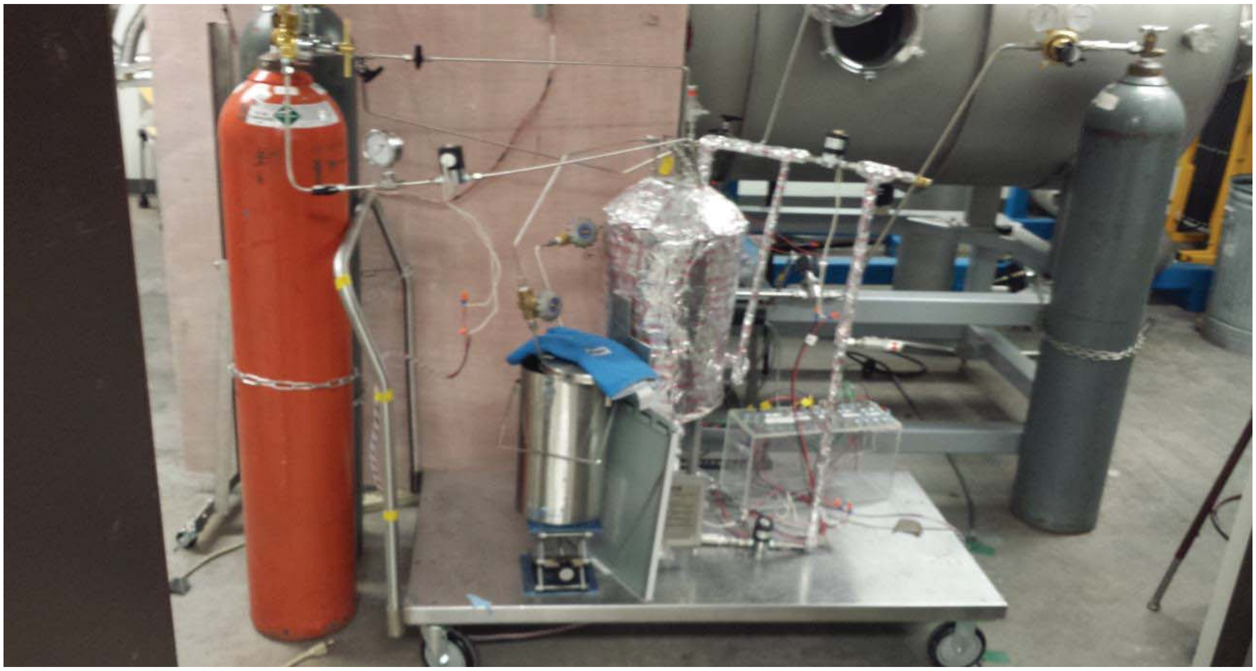


Figure 10 MMCU

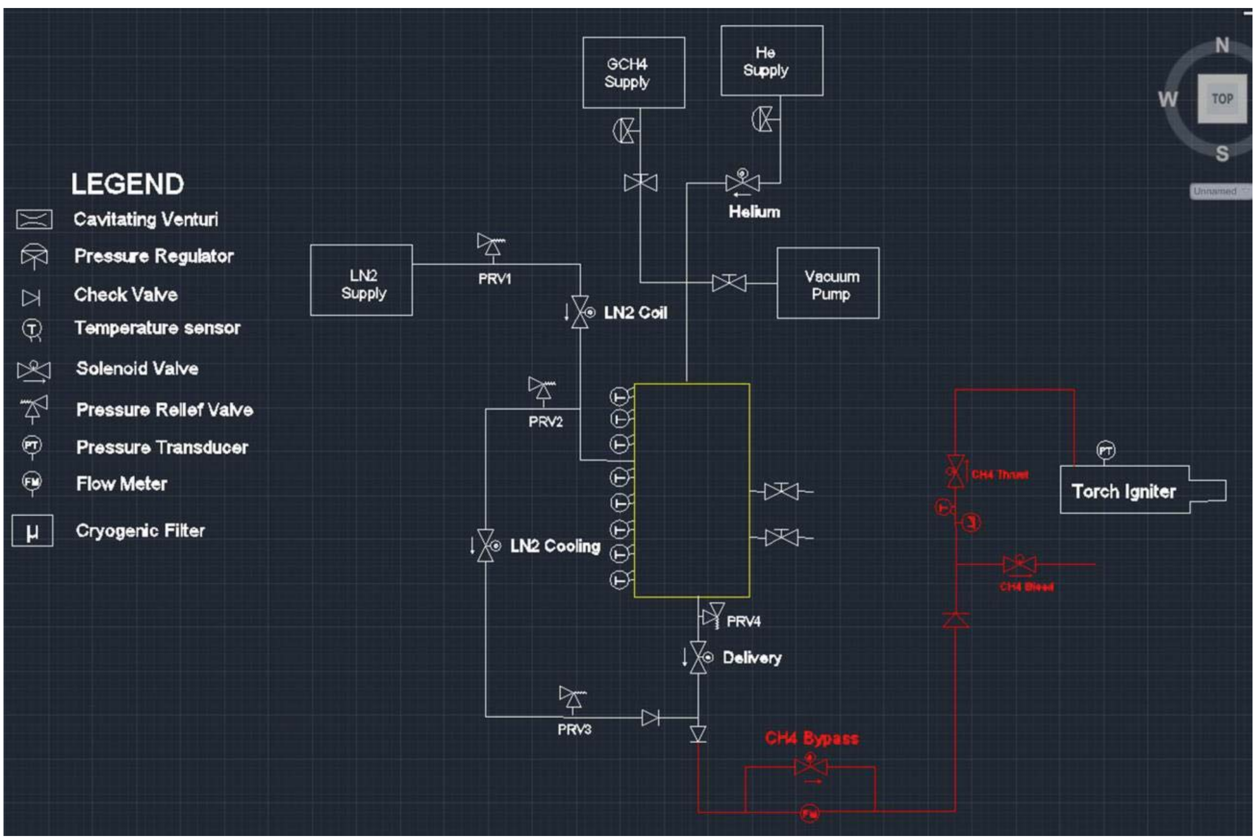


Figure 11 Schematic of the MMCU Which Doubles as the CH4 Delivery System

2.1.5 *DARCS-Data Acquisition and Remote Control System*

The DARCS system was originally created for a thesis by a previous graduate student [13] and has since been modified to accommodate additional instrumentation and testing needs. The system used for testing in this paper is National Instruments LabVIEW and is shown in fig 12. In the figure the front panel is shown which is essentially the graphical user interface. Here all the readings from the various pressure transducers, thermocuples, and flow meters can be readily seen. The program can operate in both manual and automatic modes which allows for manual control of the valves during system tests, chilling, and condensation phases. The automatic mode is used for conducting tests to control the consistency with each test. During this mode the valves are controlled with an input file where the timing is listed in the far left column and the ones and zeroes tell the program to either open or close a particular valve respectively. Several different NI LabVIEW programs were written throughout different stages of testing in order to accommodate the specific tests which are being done, however, consistency was maintained in the timing and duration of tests to help accuracy and consistency in data.

All testing and recording will be conducted using the NI LabView system installed in the control room. A program was written specifically for these LOX/LCH4 tests and is shown in fig 12. The program consists of two toggle switches. The first allows the user to switch between manual and automatic valve control modes, and the second tells the program whether or not to record data that is turned on during testing. Manual mode is used to initiate the lines' cooling, general maintenance, troubleshooting and in some instances testing. The automatic mode is used to control the valve opening and closing sequences during tests to ensure consistent testing parameters and is based on a text file containing a binary code.

This program was designed to give an approximate layout of the cryogenic delivery lines and Mobile Methane Condensation Unit (MMCU) setup. The valves, pressure transducers, and thermocouples are located in the GUI relative to where they are located on the actual line. It is also used to create a visual representation of the setup where the black lines indicate the

delivery lines and the buttons indicate and control the valves (control only in manual mode).

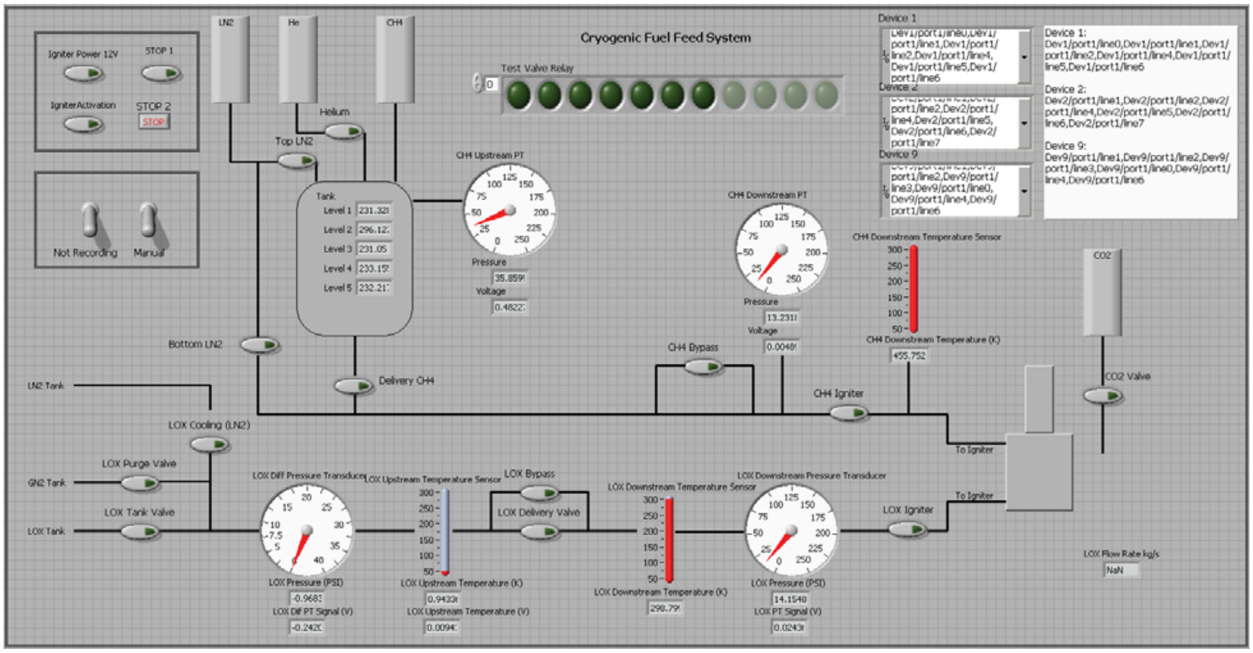


Figure 12 Graphical User Interface of the LabVIEW Program

All test data will be stored in the control room main computer upon completion for the test being conducted. A specified folder will be created where the raw data will be gathered to have an organized processing and to proceed without any inconsistency.

2.1.6 *Venturi Hardware*

Venturi hardware was installed on both lines as a form of passive flow control. Both venturis control flow by cavitating propellant at a throat and then recovering some of the pressure a drawing of which is shown in figure 13. The flow rate is controlled by the upstream pressure and is independent of downstream pressure. Flow controlling is detailed in chapter 3.

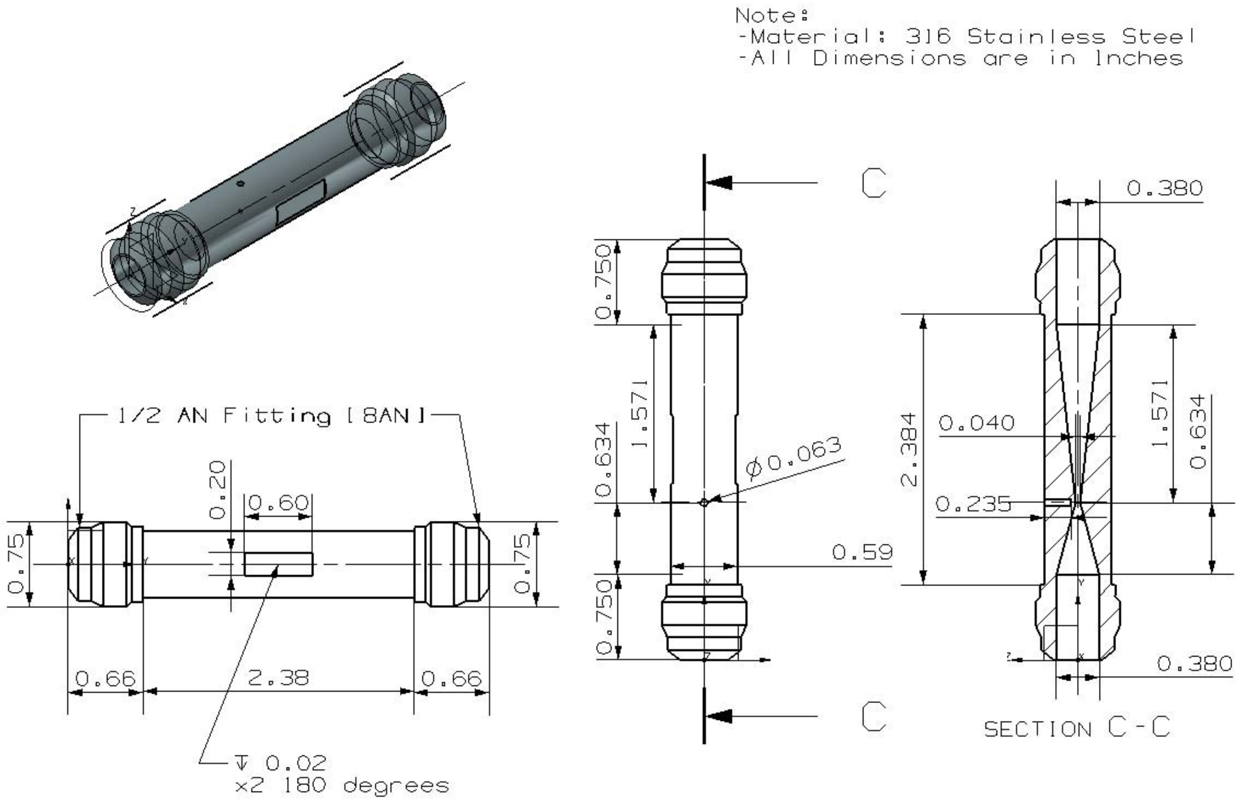


Figure 13 Venturi Hardware Used to Control Cryogenic Flow

Benchmark tests were conducted using water to determine the discharge coefficients. The next set of tests used liquid methane along with a turbine flow meter to determine the accuracy of the flow measurement. The results indicate that the venturis will control the flow accurately for downstream pressures below 67% of upstream pressure.

2.2 PREVIOUS IGNITER DESIGN

The overall purpose of the igniter is to be an ignition source for an optical combustor. The first iteration was designed with the following requirements [1]:

- The Torch Igniter should have a swirl co-axial injection design, similar to a mN class Thruster previously developed and investigated [4] This design allows a stable flame due to swirl mixing characteristics.

- The Igniter should be designed to fit into a threaded inlet port located on top of the MOAC. This port is designed for a ¼ inch NPT fitting.
- The Igniter should be feed with gas Oxygen and gas Methane as oxidizer and fuel.
- The Igniter should be made of a LOX compatible material to avoid fire and explosion hazards.
- The Igniter should be designed to withstand a maximum working pressure (MWP) of 100 PSI in both feed lines (Oxygen and Methane).

The sizing of the inlets was determined based on the desired swirl number of 0.04 which is the result of assuming a mixture ratio of 4. The swirl number is an indication of the amount of mixing between to propellants and is derived from the flow rates and injector geometry. [14] The swirl number S_g is calculated by the following equation.

$$S_g = \frac{r_o \pi r_e}{A_t}\left[\frac{\dot{m}_{Tan}}{\dot{m}_{Total}}\right]^2$$

Where r_o is the distance from the center of the tangential inlets to the center of the axial inlet, re is the radius of the exits and At is the area of the tangential inlets along with the flow rates tangentially and total.[15]

This igniter was used for all of the testing phases other than the liquid/liquid tests.

2.2.1 *Hardware*

The original design was to separate pieces of machined metal that were connected by tubing. The CAD models are shown in figure 14 and 15.

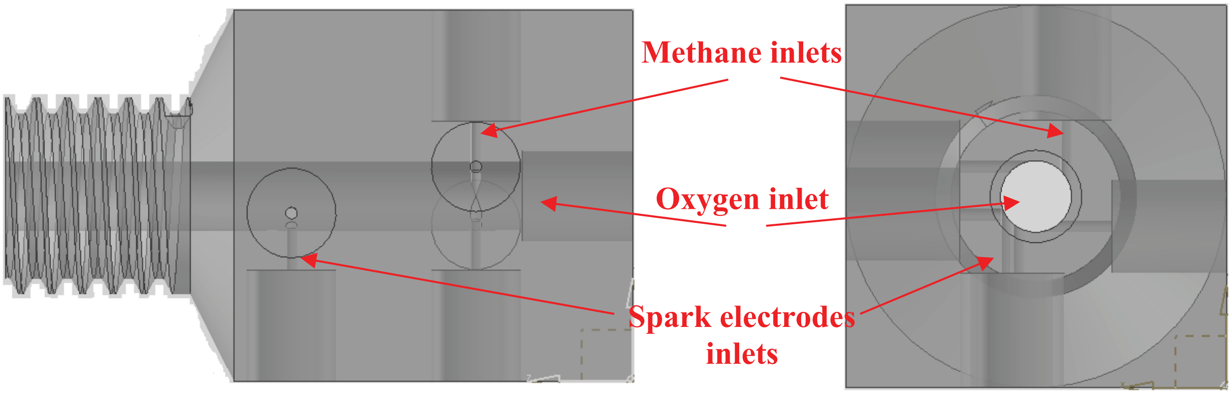


Figure 14 LOX Manifold with Methane Injection

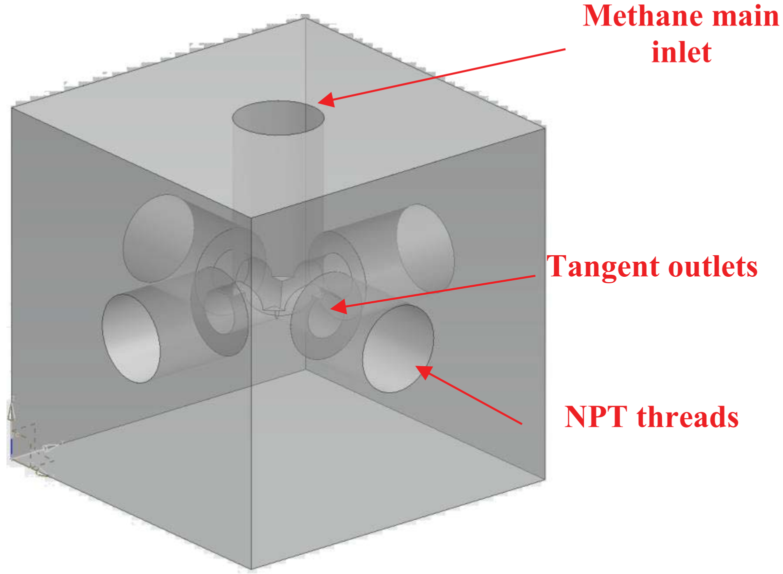


Figure 15 Methane Manifold

Both pieces were joined with Swagelok tubing, the complete hardware is shown in figure 16.

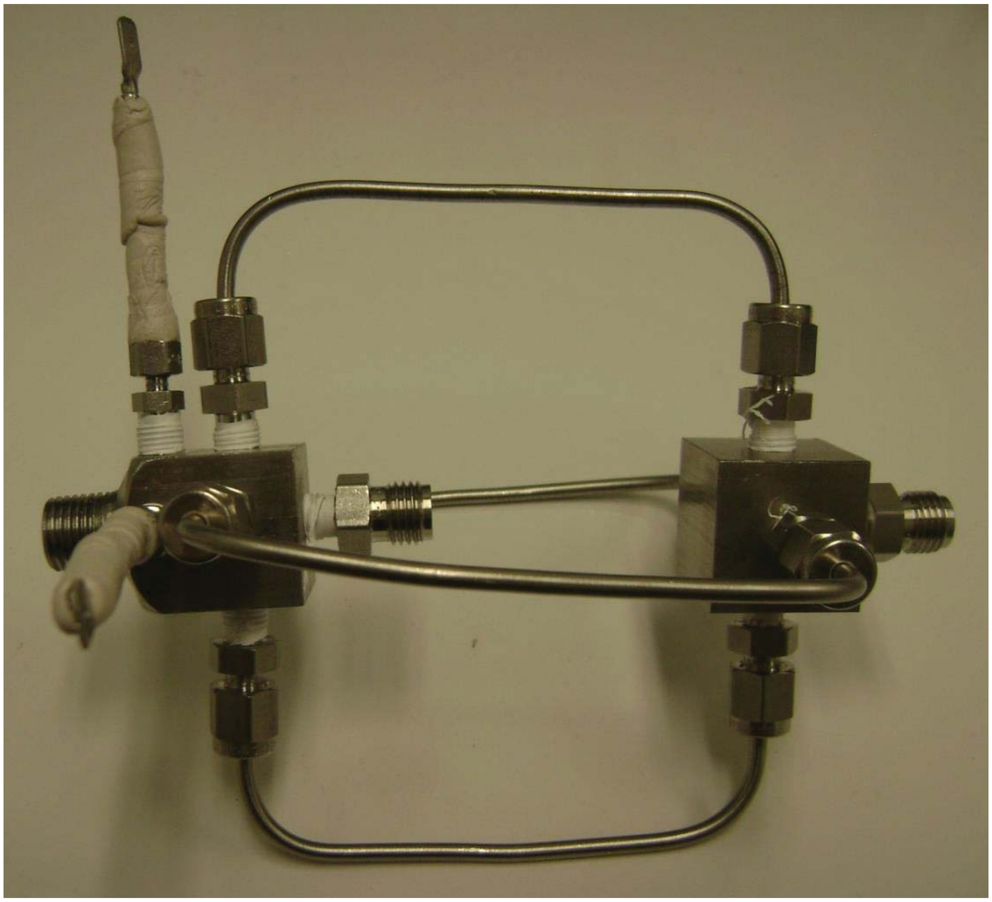


Figure 16 Completed Igniter

2.2.2 *Sparking System*

Several iterations of sparkers have been made. Each time there was a problem with the design a new design was made to fix the problem.

The original sparker is shown in figure 17. This sparker used two 90% platinum 10% rhodium wires to create a spark across a gap. There were several problems with the design, the integrity of the wires being the biggest.

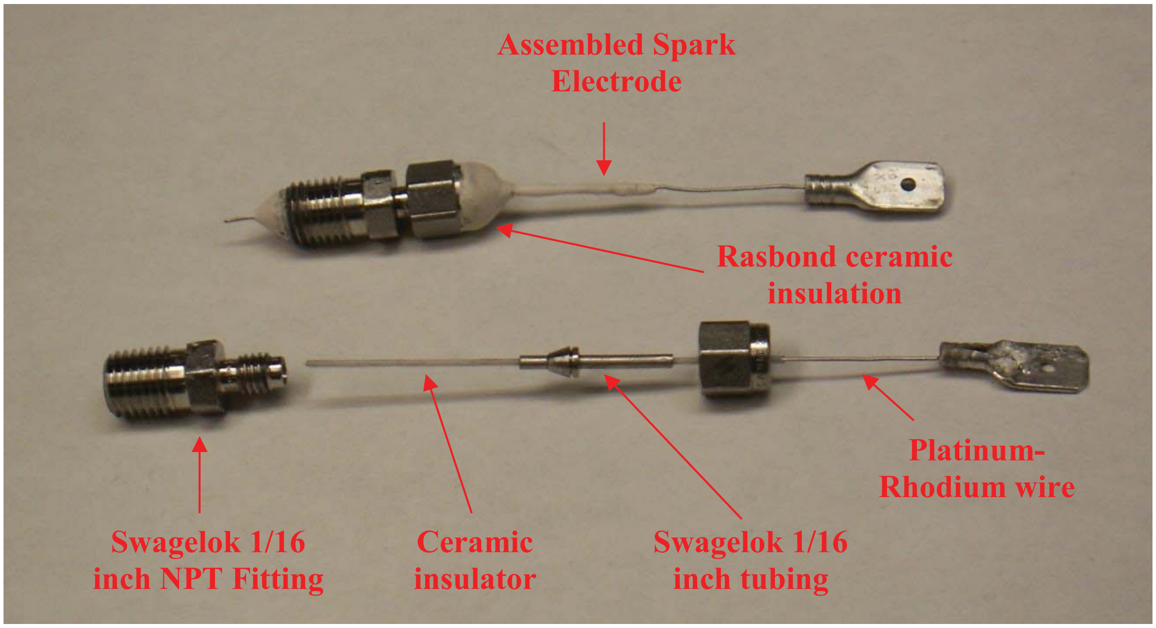


Figure 17 Original Sparking System

Several more iterations were done. The next sparker used two tungsten leads which took care of the integrity of the wire however the ceramic that was used began to crack after on a few tests so a more structurally stable ceramic was made but succumbed to the same problem. Eventually both leads were combined into one fitting but the problem persisted. The next step was to thicken the ceramic and fitting and use only a single lead which arced to the body of the igniter by connecting the negative lead of the transformer to a washer that was in contact with the fitting itself for firing. This is the current sparking method and is discussed under the new igniter design.

One part has stayed consistent throughout all testing which is the high voltage power supply. Essentially it is a step up transformer which has a 12V input and provides a 25 kV output. This causes a spark to propagate across the gap between the lead and the negative which ignites the propellants.

2.3 New Igniter Design

The torch ignition system uses an internal swirl where the mixing of propellants is governed by the momentum of colliding streams. The oxidizer flows down the main channel and meets four tangential methane inlets that form a swirl that causes the mixing of the propellants

prior to ignition. This configuration has remained unvaried throughout the test article's design iterations.

The torch igniter design was modified to improve the reliability and range of ignition of the last generation of the torch ignition system specifically liquid/liquid propellants. Main modifications where implemented to two aspects of the design: the injection/mixing zone and the body configuration. In the event of using liquid methane as a fuel the design of the igniter forces the fuel to cavitate inside of the injection lines. This causes the pressure to drop and the liquid to vaporize. The fuel which is now gas will cause the liquid oxygen to evaporate in a ring along the outside of the combustion chamber.

2.3.1 *Increased LOX Injection Distance*

The distance between the oxidizer and fuel inlets was increased to have more developed flow of the oxidizer before it comes into contact with the methane. This provides a less turbulent area for mixing which should lead to more consistent ignition.

2.3.2 *Injection Distance*

The injection distance between the oxidizer and the fuel was increased from ¼" to 1"; this is the distance that the oxidizer flows until coming in contact with the fuel. This distance was increased to provide better stability to the oxidizer flow before it comes into contact with the fuel thereby causing a more uniform mixing at the point of ignition. This increase in distance will allow the oxidizer to fully develop before coming in contact with the fuel. This will allow better mixing at the edge of the combustion chamber and consequently the ignition point.

The distance from the mixing to the sparker was also increased to 0.5" to allow more time for the propellants to mix before being ignited. Both of these distances were determined using CFD software. The inlet conditions chosen were liquid oxygen and gas methane at the vapor pressure. These were determined based off of the calculated inlet conditions determined by the injector geometry. The first model shown in figure 18 shows the velocity vectors at the point of methane injection. This shows what was expected, very large velocities in the swirl with a

LOX core coming out of the page. The momentum is dominated by the methane at the edge and the LOX at the center. This eventually becomes a typical flow through a channel at the end of the igniter body when assuming no ignition.

Figure 18 Vector Lines at Injection Point

The next two figures, 19 and 20, shows the mass fraction of O2 for a target overall mixture ratio of 2 and 4 respectively. These were the mixture ratios that were modeled because the optimal mixture ratios for LOX/Methane ignition are between 2 and 4 keeping the oxidizer flow the same and changing the methane flow rate. The figures show both the entire mixing zone

and cross sections at the methane injection, 0.5” downstream where the igniter is located, and the very end of the igniter.

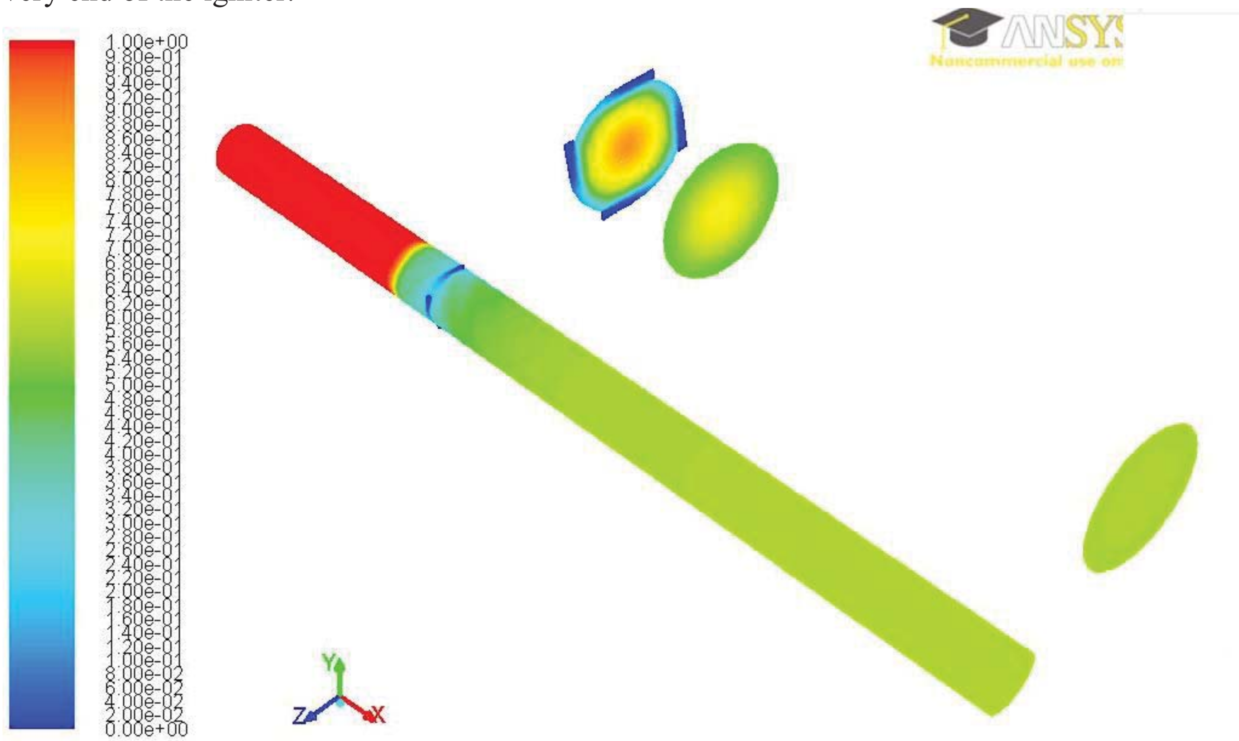


Figure 19 Mass Fraction of O2 for MR 2

The mixture ratio of 2 contains the largest amount of methane and therefore the best mixing. At the point of ignition a mixture ratio slightly over 2 is seen which is ignitable. As the mixture is allowed to mix without ignition the eventual mixture is exactly 2 at the very end of the igniter. This result is expected and the greater concern is when reducing the methane flow rate if the mixing will still be adequate for ignition.

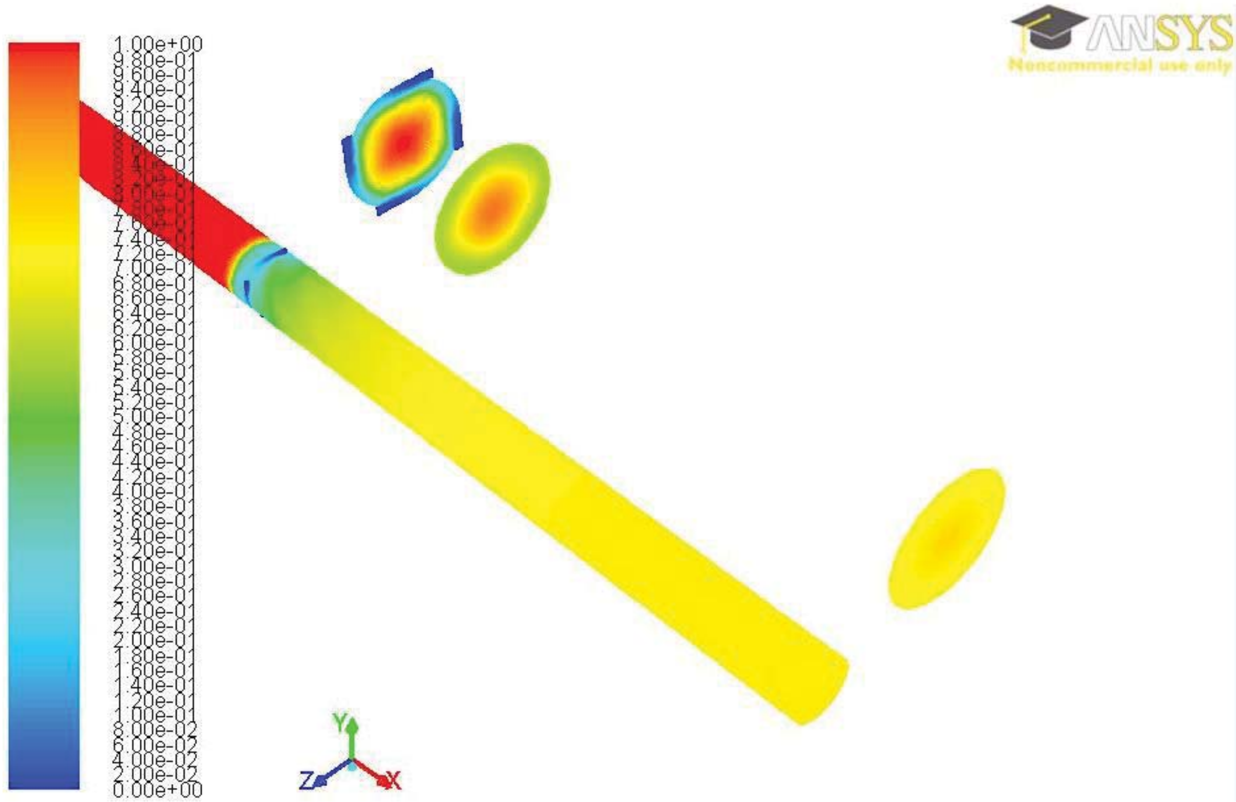


Figure 20 Mass Fraction O2 for MR 4

The CFD analysis was completed again for a mixture ratio of 4. Just like the previous model mixing is seen at the edges however since the total flow rate of methane is reduced the LOX core is still very dominant at the point of ignition. However the mixture ratio at the ignition point is much closer to 2. Using both of these models it was determined that 0.5" was adequate mixing length of propellants before ignition and was the basis for choosing the new mixing distance.

2.3.3 *Unified Body*

The body of the torch igniter was modified as well to a unified body; the first torch igniter design consisted of a separate configuration of the oxidizer and fuel injection manifolds. The unified body provides a more aesthetic and compact design. This design creates a more structurally sound piece with tubing that is laser welded to the body to reduce leakage from unnecessary threaded fittings to complete the fuel manifold. The redesigned model is shown in figure 21.

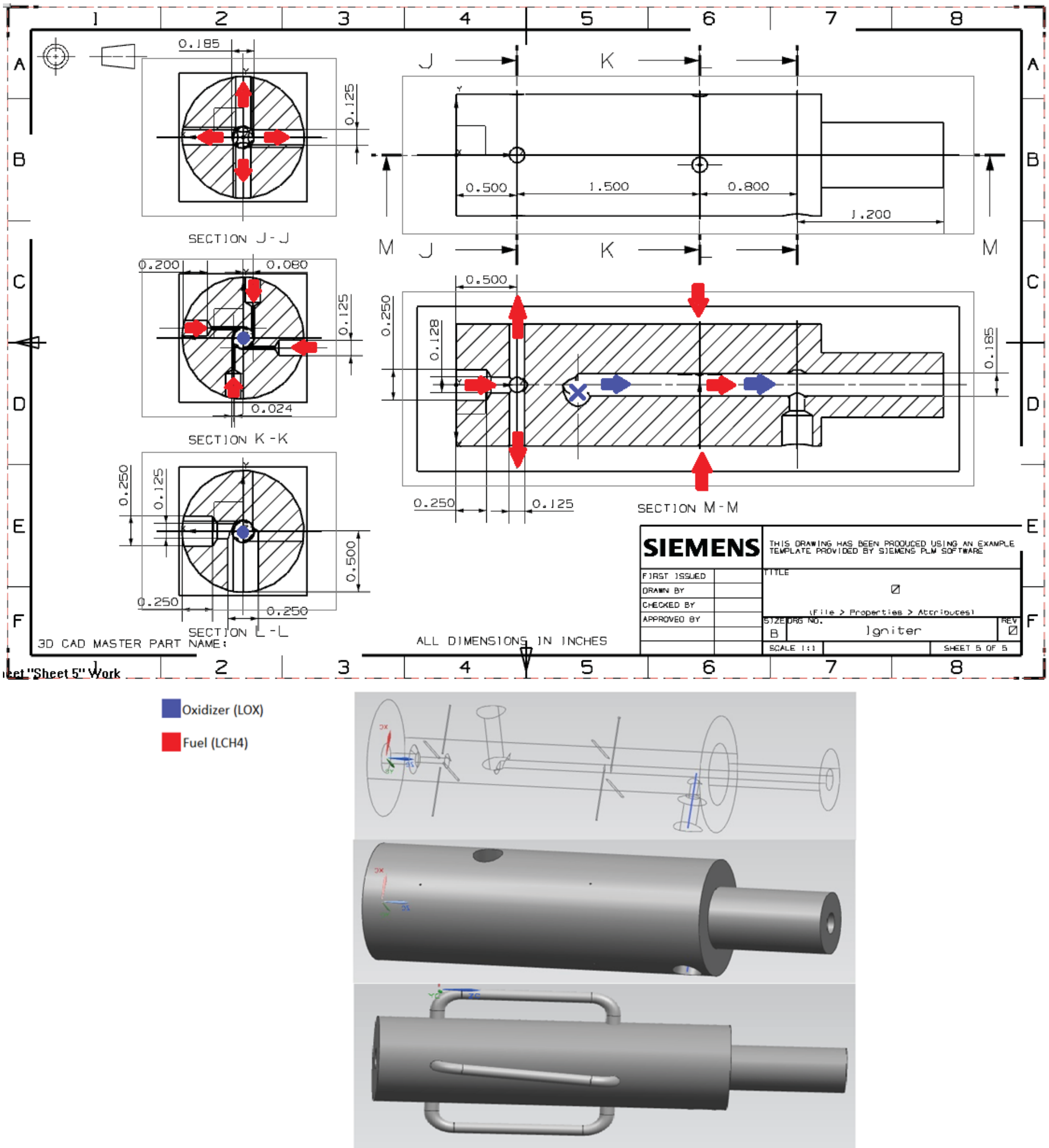


Figure 21 CAD Model of Latest Igniter With Incorporated Changes

Unified body: Incorporated for both aesthetics and to remove several threaded fittings making a more compact design with a lower probability and magnitude of leaking. The igniter can be seen in figure 22.

Figure 22 Completed Assembly

2.3.4 *Sparking System*

The diameter of both the fitting and ceramic were increased to reduce stress as well as provide better electrical insulation. The design was also modified to prevent the ceramic from blowing out under high transient pressures. The original sparker was held together solely by high temperature, nonflammable epoxy. This design incorporates a physical change to the ceramic to prevent blowouts. The larger bottom section creates a place for the pressure to be distributed and has a safety factor of 4 assuming 100 psia chamber pressure.

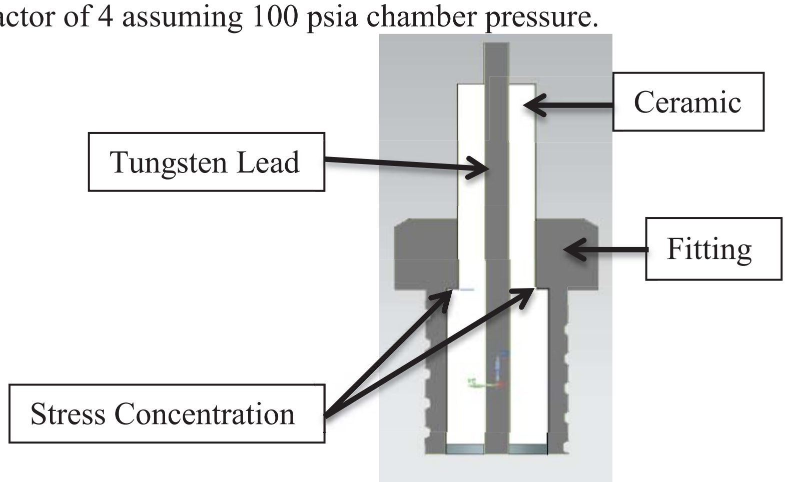


Figure 23 Cross Section of Igniter

These images show the spark paths for two different sparker configurations. During the last sets of testing it was unclear if the difference in sparking location affected the flow. The one on the right will be used first because it is not directly in the flow path which should increase the life of the part. If future ignitions with this sparker become problematic, then the sparker on the left will be used to create an arc through the flow path. Both use a step up DC voltage of 25 KV.

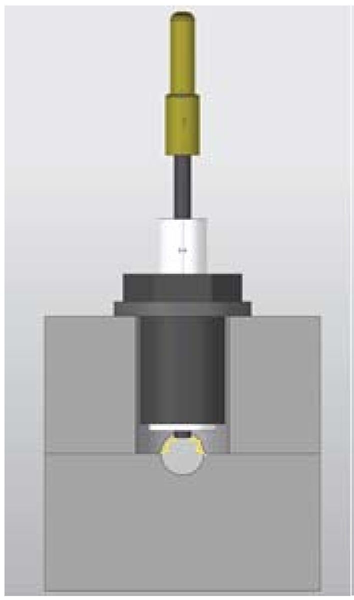


Figure 25 Sparking to the Wall (In Flow Path)

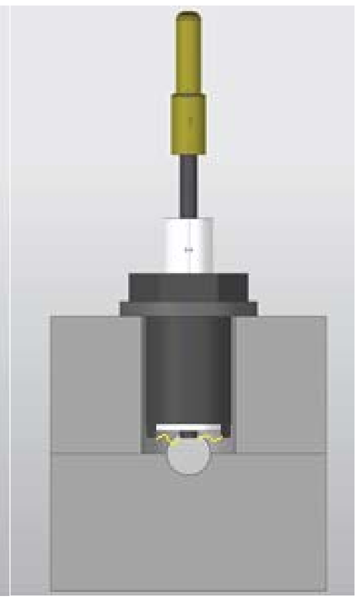


Figure 24 Sparking to Fitting (Not In Flow Path)

2.3.5 *Converging Section*

The converging section was added to create chamber pressure as well as provide a place for the flame to anchor. During previous liquid testing most ignitions were blown out because of the fast moving propellants. This provides a chamber where combustion can take place and help prevent the blowouts seen in the previous design where no significant chamber pressure was seen. The converging section takes the chamber diameter of 0.185” and reduces it to 0.145” which will give approximately 60-80 psia of chamber pressure for the desired flow rates of .0125-.015 kg/s. A CAD drawing can be seen in figure 26 and the converging section complete with the igniter in figure 27 and 28.

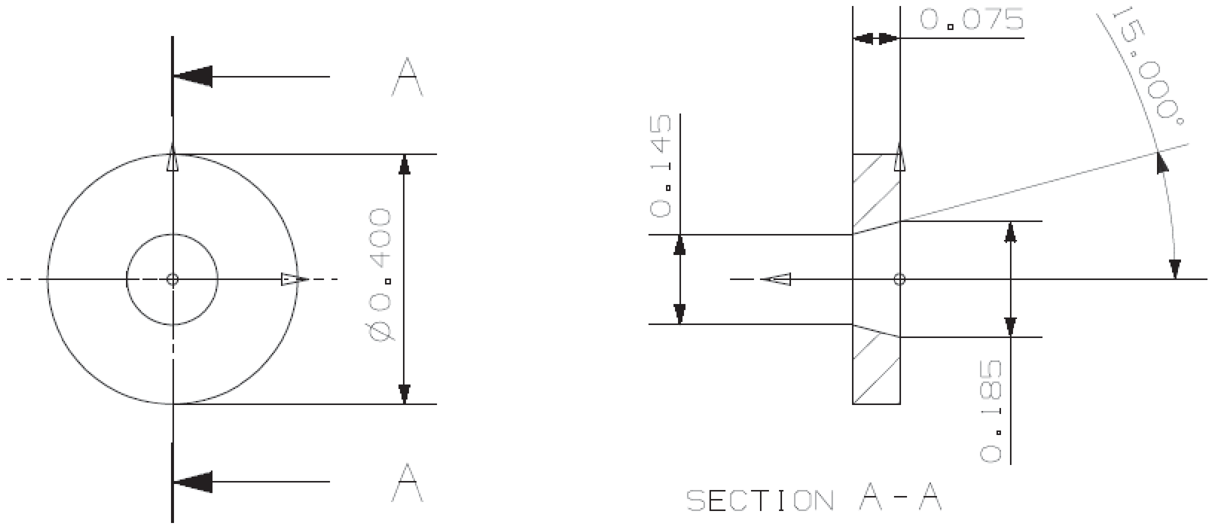


Figure 26 Converging Section

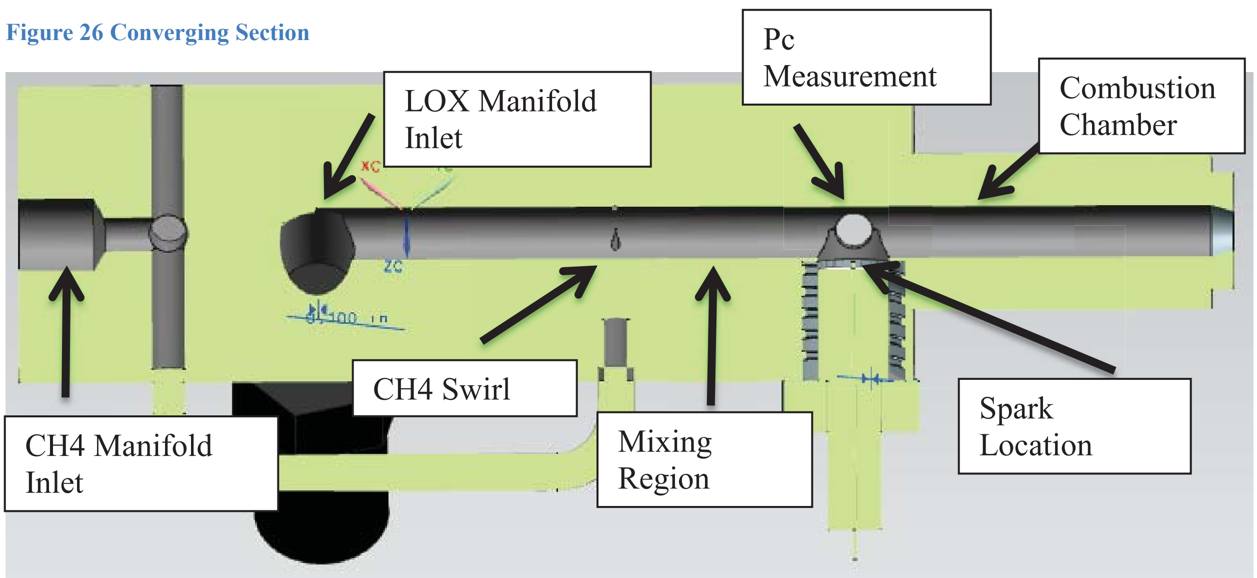


Figure 27 Cross Section of Torch Ignition System Labeling Major Parts

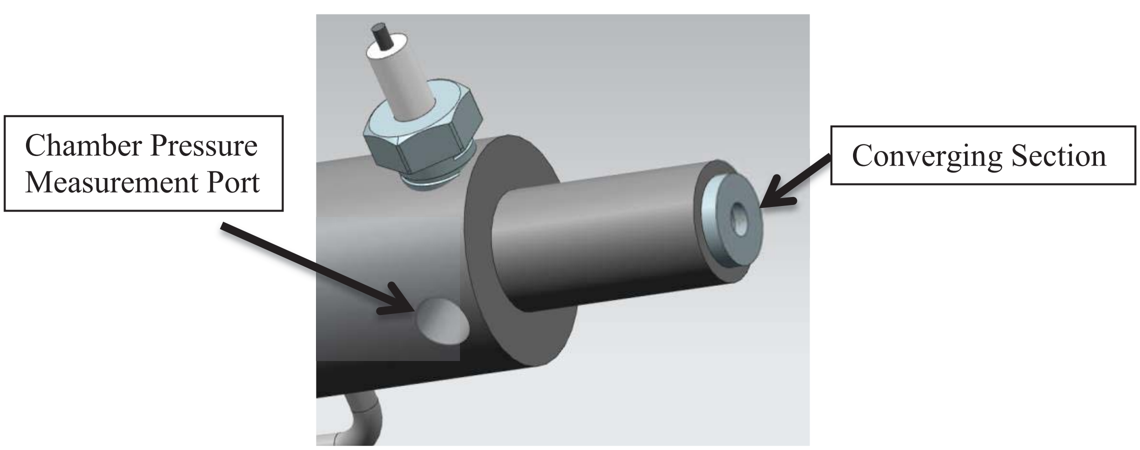


Figure 28 Converging Section and Pc Measurement Port

Chapter 3

3.1 Testing Setup

Due to the large differences in handling and measuring gas versus liquid propellants, several different methods were used for both testing and measuring data. These two methods of setup and measuring are broken into gas plus cold gas, and liquid propellants.

3.1.1 *Gas Measurement*

Both gas and cold gas are included under this section because both were measured very similarly. Gas is arguably a much easier medium to measure due to higher operation temperatures meaning less specialized equipment. For gas measurement, gas flow meters from Omega were used. A pressure transducer and thermocouple were placed on the line to obtain density measurements which were multiplied by the volume flow rates recorded by the flow meters to determine the flow rate.

3.1.2 *Liquid Measurement*

Each flow rate is controlled by the upstream pressure. The methane pressure is much more reliable while the LOX is not. So for each run, the LOX flow rate is to be kept constant at approximately 0.01 kg/s with a set 213 psia tank pressure and a helium tank was used to pressurize the liquid methane inside of the MMCU. The pressure of the helium was varied to obtain different flow rates to test various mixture ratios. The flow rate of LOX was controlled through the use of a cavitating venturi as well as a turbine flow meter, while the methane flow rates were controlled using another cavitating venturi.

For LOX at a given inlet pressure, the cavitating venturi will regulate the flow to a max flow, provided that the downstream pressure is maintained below the critical pressure ratio (Pcr=0.68). This will give accurate measurements as long as oxygen pressure is measured upstream and downstream of the pressure transducers and the critical pressure ratio is maintained. Knowing the dimensions of this venturi as well as the measured values such as the Cd obtained during validation we can calculate flow rates for given pressure drops across the

venturi. For downstream pressures below 68% of upstream pressures the Cd value remains 0.96 +/- .02 (figure 29) and the following equation can be used

$$\dot{m} = C_d A_{th} \sqrt{2\rho(P_1 - P_{th})}$$

Where it is assumed cavitation at the throat for pressure ratios below 0.68 and P_{th} will be set to the cavitation pressure (vapor pressure) at the inlet temperature of the propellant. Cd is taken from the calibration curve that was made during prove out testing of the venturi shown in figure 29.

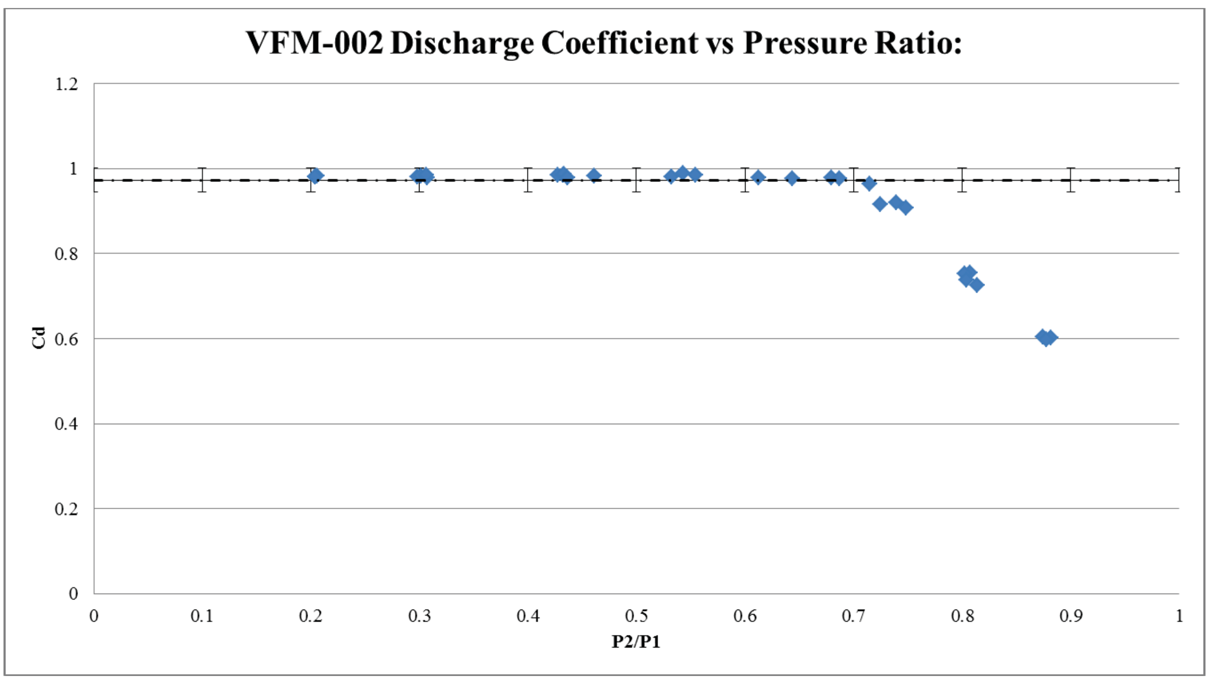


Figure 29 Cd Value for the Cavitating Venturi vs Pressure Ratio

The pressure of the liquid methane tank is maintained by pressurizing the entire tank from the top with helium. The helium pressure is kept constant by the regulator attached to the dewar and measured by a pressure transducer.

The methane flow rate is measured the same way as the oxidizer flow rate. The same equation will be used where P1 is set to the tank pressure and Pth is the cavitation pressure at the propellant inlet condition, these values are taken from Refprop and a summary is shown in figure 30 and 31 for both propellants. The flow is controlled by changing the tank pressure by manipulating the incoming helium pressure from the regulator.

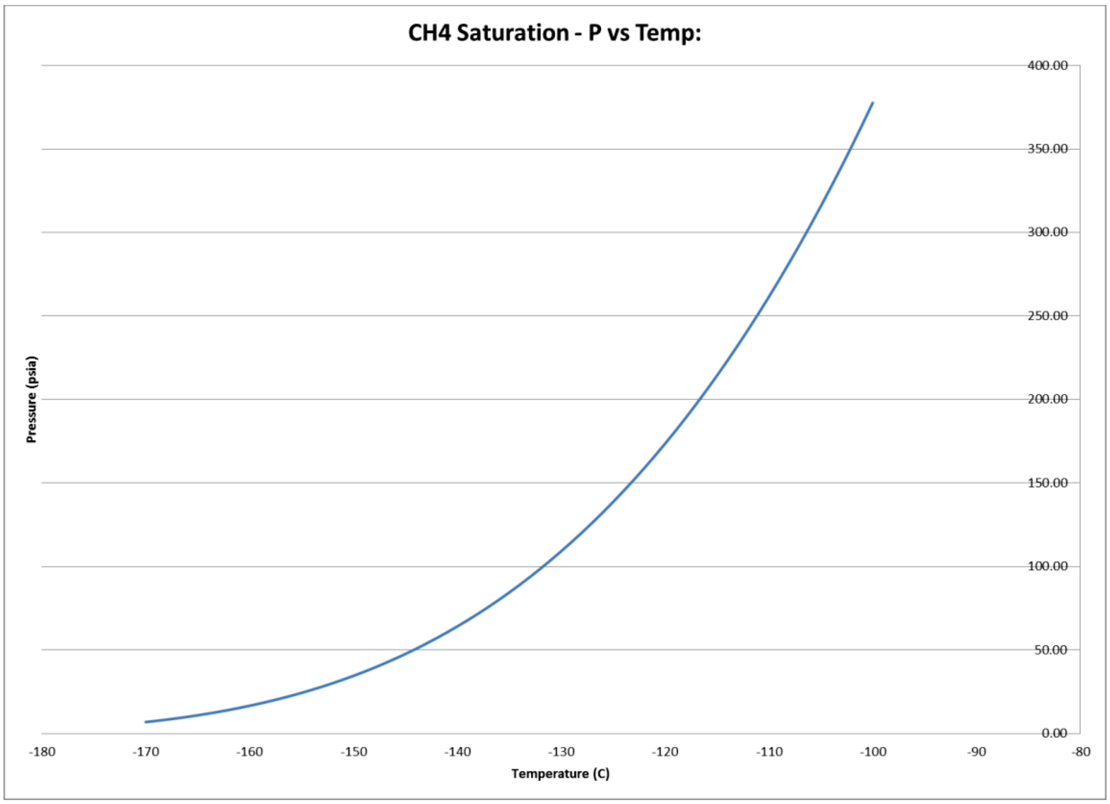


Figure 30 CH4 Saturation Pressure vs Inlet Temp

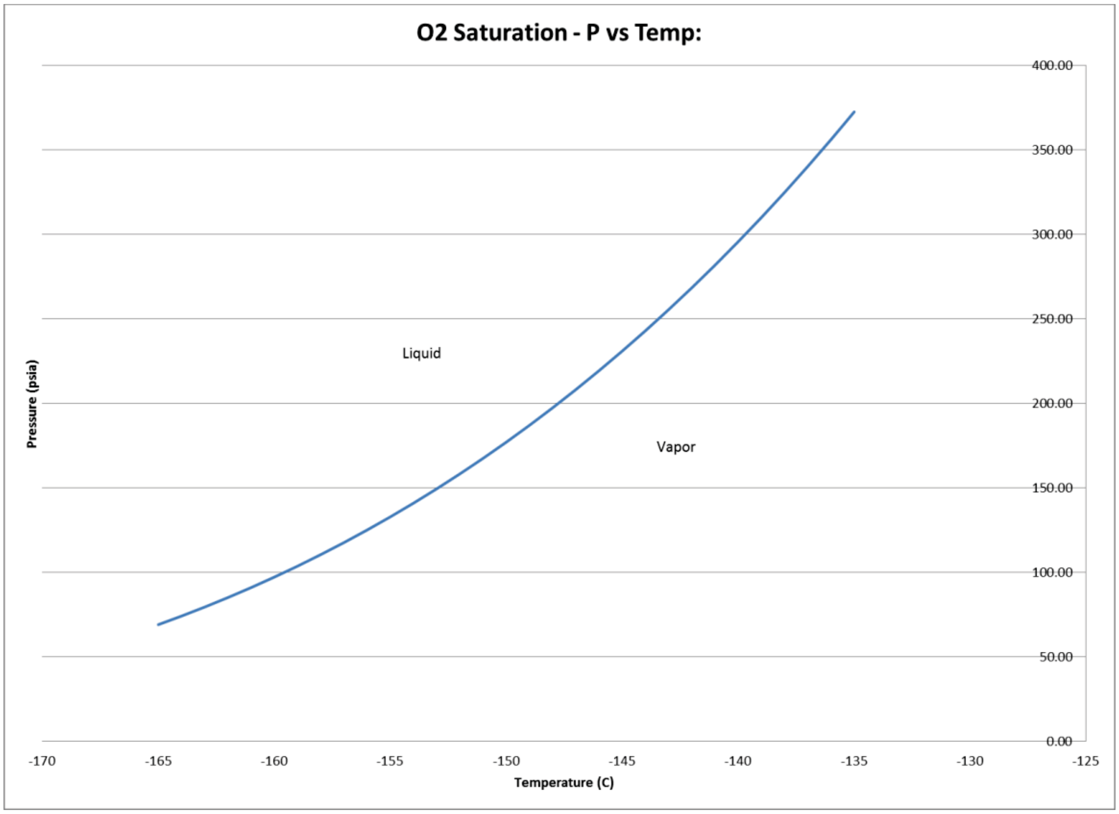


Figure 31 CH4 Saturation Pressure vs Inlet Temp

3.2 Instrumentation

A list of the instrumentation utilized for this test procedure is as follows:

- Omega Cryogenic Pressure Transducer
  - 0-250 psia
  - Used to measure upstream and downstream pressure as well as tank pressure when needed.
- Omega E-Type Thermocouple
  - 2 used inside the MASS to measure inlet temperature to the test article (one on each line)
  - 5 arranged vertically on the side of the methane tank to indicate the level of liquid methane inside
  - Used on various parts of the line to determine where liquid was currently flowing
- 2x Cavitating Venturis

    - As discussed previously, these were used to control the flow of liquid propellants
- 2x Omega Gas turbine flow meters
    - Used to measure the volume flow rates of gasses
- 1x Turbine Mass Flow Meter
    - Measures volume flow rates of 0.35-3.5 gal/min
    - Outputs voltages 1-5V
- 1x Liquid Nitrogen Dewar
    - Filled with LN2
    - Used to control the temperature of cold gas methane
    - Used a Heat exchanger in the form of a coil, the more line that was submerged, the lower the gas temperature

All instrumentation is used to record pressure and temperature data during testing. Pressure and temperature readings at the inlet of the torch igniter will provide the properties of both oxidizer and fuel at the inlet conditions. With this reading the propellant condition/phase can be determined to aid the analysis of the raw data recorded.

3.3 SEQUENCES

All tests were done using automated sequences similar to figure 32 where all data was recorded using LabVIEW and later analyzed to plot data and determine trends. These sequences consisted of a purge before and after testing as well as the tests. This is the most simple sequence which was used for gas oxygen and gas methane tests. With the addition of the cryocart as well as the cryogenic line the firing sequence begins to become very complicated, however, steps were taken to keep consistency. All sequences other than liquid/liquid had a total burn time of 15 seconds which was broken into 5 seconds with the sparker on and 10 seconds off to determine if sustained ignition had occurred. For the liquid/liquid tests a much shorter sequence was created due to hardware failure using the old sequence. The new sequence is similar but has a 2 second burn time where the sparker is on for one second and then turned off for the remaining second.

This was done to lessen the amount of heat transfer to the hardware which previously failed because of intense heat transfer. Without active cooling it is unsafe to use longer burn times.

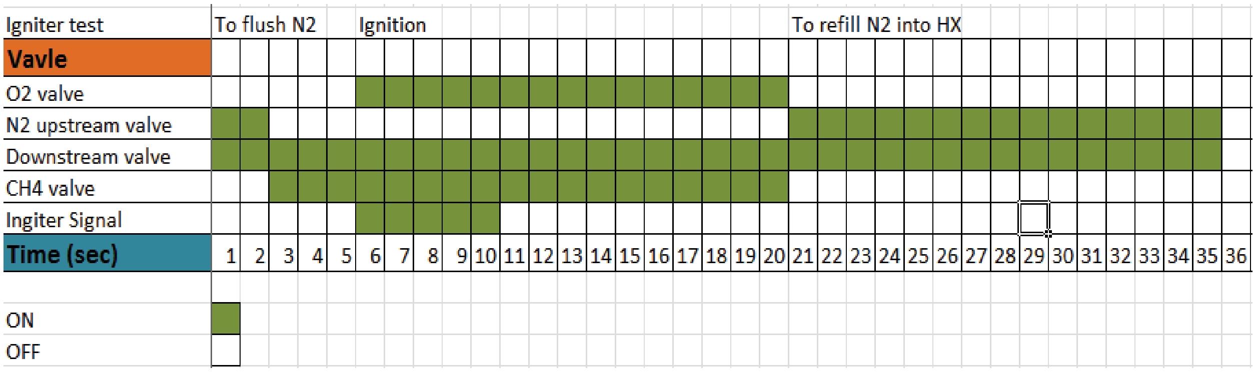


Figure 32 Automatic Firing Sequence

3.4 Results And Discussion

Some of this data was discussed as part of a dissertation done in 2013, several graphs and schematics were taken from that paper.[11] All of the data for the igniter is revisited here to have all testing in one document for future reference. Out of these 6 combinations only 3 have been tested extensively. The testing was halted with the previous igniter once the LOX/LCH4 combination was tested. This section will discuss the findings of the 3 completed test campaigns as well as the preliminary data for liquid testing using the new hardware.

3.4.1 Gas Oxygen/Gas Methane

This was the first propellant combination to be tested. All tests were conducted on an atmospheric aluminum test stand inside of the bunker at The University of Texas El Paso cSETR facilities. All flows were measured using volume flow meters which were converted into mass flow rates. Mixture ratios of approximately 2-4 where tested with the optimal mixture ratio being 2.7 for power and 3.5 for stoichiometric.[12] For these tests a total of 5 tests were conducted at each point and a reliable ignition was deemed if 4 out of the 5 successfully ignited. The

schematic shown in figure 33 shows the setup used for both the gas/gas and gas/cold gas tests. The only difference between the two is the omission of the HX in the gas/gas tests.

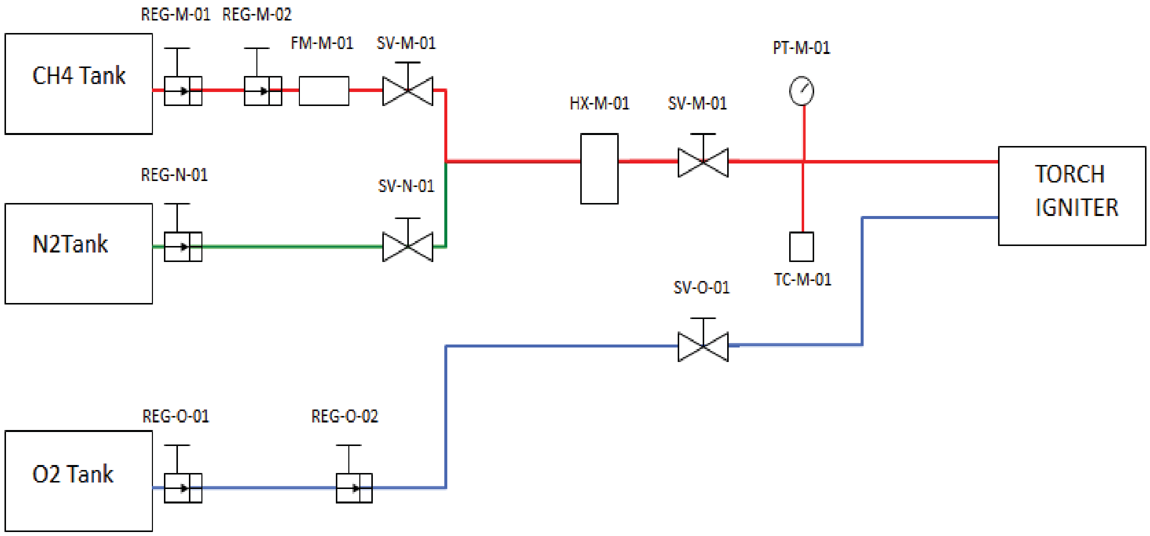


Figure 33 Schematic of Gas/Gas and Gas/Cold Gas Tests

It should be noted that the flow rates were set by hand before testing which could have caused them to shift shortly after ignition, because of this the data should not be considered completely accurate but instead should be used to visualize the region in which reliable ignition occurs, particularly between mixture ratios of 2 and 4. Another consideration is the accuracy of the flow meters which are accurate to within +/- 2 LPM where a typical test had measurements between 40-70 LPM.

Figure 34 shows the flammability map for the entirety of gas/gas testing plotting the mass flow rates of both propellants and the reliability. The lines on the graph indicate mixture ratios of 4, 3 and 2 in descending order.

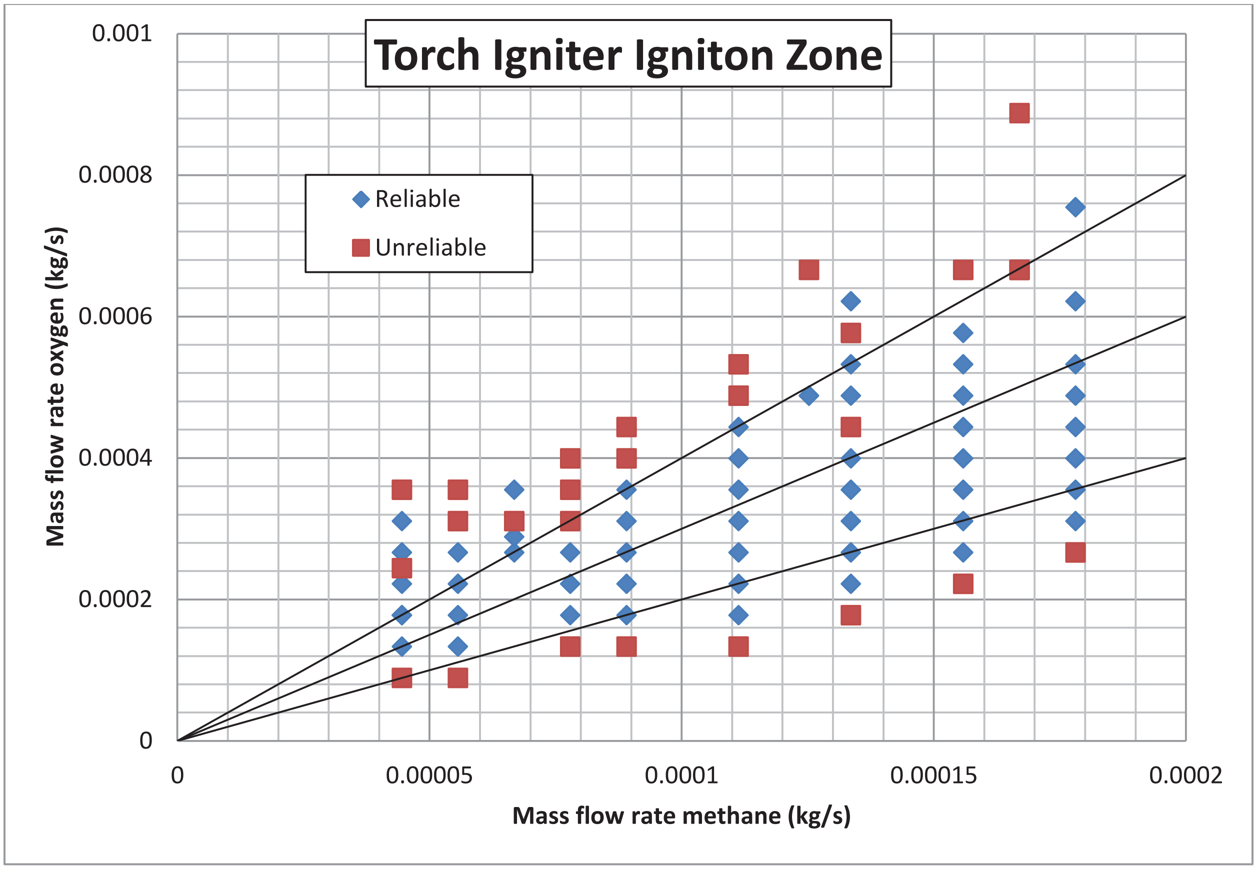


Figure 34 Flammability Map Gas/Gas

There is a clear correlation between mixture ratio and reliability. While a mixture ratio of 4 typically has successful ignition almost all ignitions between 2 and 3 were successful. While the stoichiometric MR is very close to 4, this graph indicates that there more reliable ignition in fuel rich mixture ratios. This agrees with previous torch igniters that were tested. The outliers in the data are attributed to the requirement of 4 out of 5 successful ignitions; because of this a test could have had 3 out of 5 successful ignitions and still be considered unreliable.

The purposes of these tests were to create a baseline for future tests and to see how the temperature and density of the propellants altered the original flammability map. A large part of these tests were to understand the test facility and systems to understand how to successfully conduct tests, obtain data, and operate safely.

Bulk velocity vs MR was also taken into consideration. The limitation of the previous igniter was the lack of an anchoring point for higher propellant flow rates and velocities. The

previous igniter would lose reliability around the 40 m/s bulk velocity region. When future tests are conducted with the new hardware with the converging section, a comparison will be done to better understand how the converging section affects the bulk velocity ignitability range.

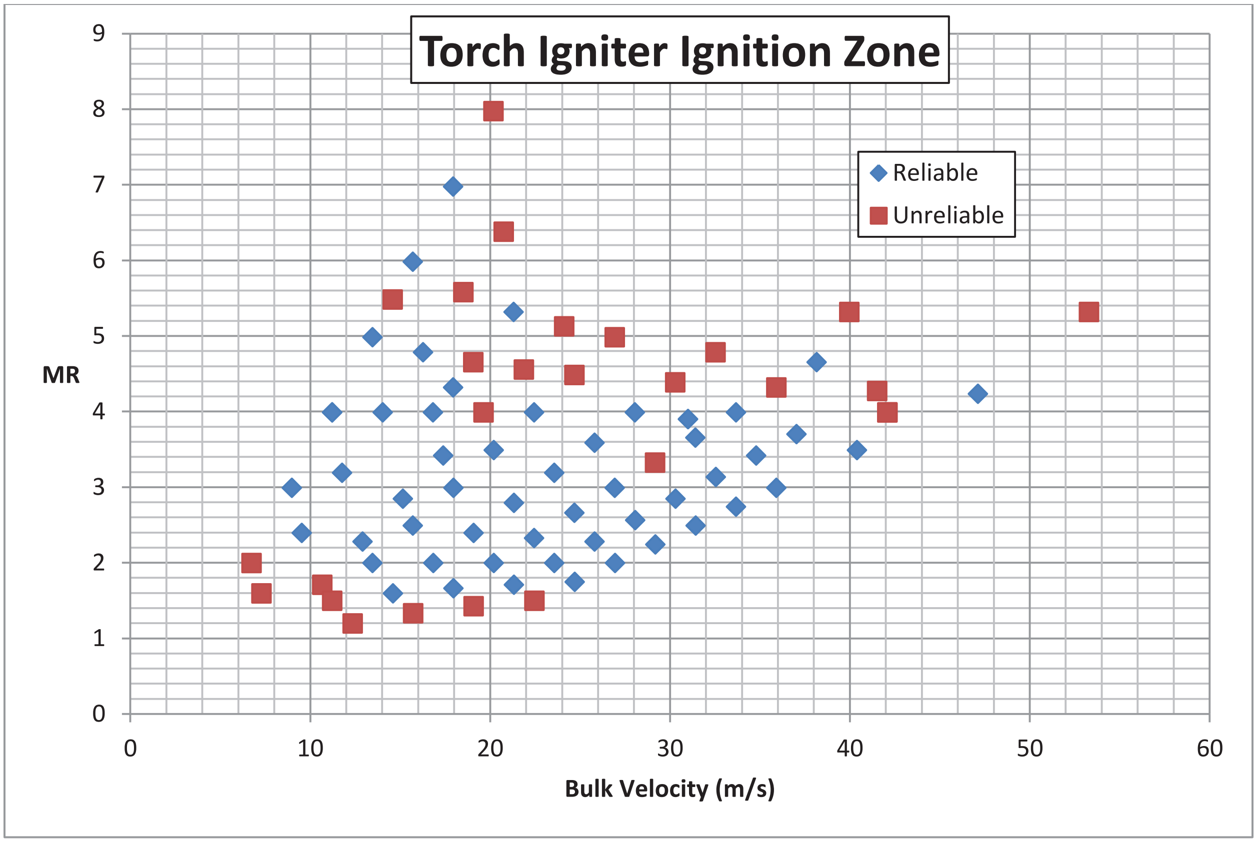


Figure 35 Bulk Velocity vs MR Flammability Map

Another very important aspect was the swirl number. The swirl number is an indication of the amount of mixing between the oxidizer and fuel in a swirl injection process. There was a very distinct trend in the swirl number plot as well. The lower limit of approximately 0.05 indicates that the propellants were not able to mix efficiently enough to produce a consistently ignitable mixture. The upper limit of 0.15 is caused by a combination of two things. When you increase the mass flow and velocity of each propellant blow out begins to happen just as with the bulk velocity limits. The second cause is the turbulence of the mixture. At higher swirl numbers the flow becomes very turbulent this produces irregularities in the mixture which makes ignition

difficult. The data shown in figure 36 is only applicable to the original igniter so future tests will need to include revisiting this region with the new hardware.

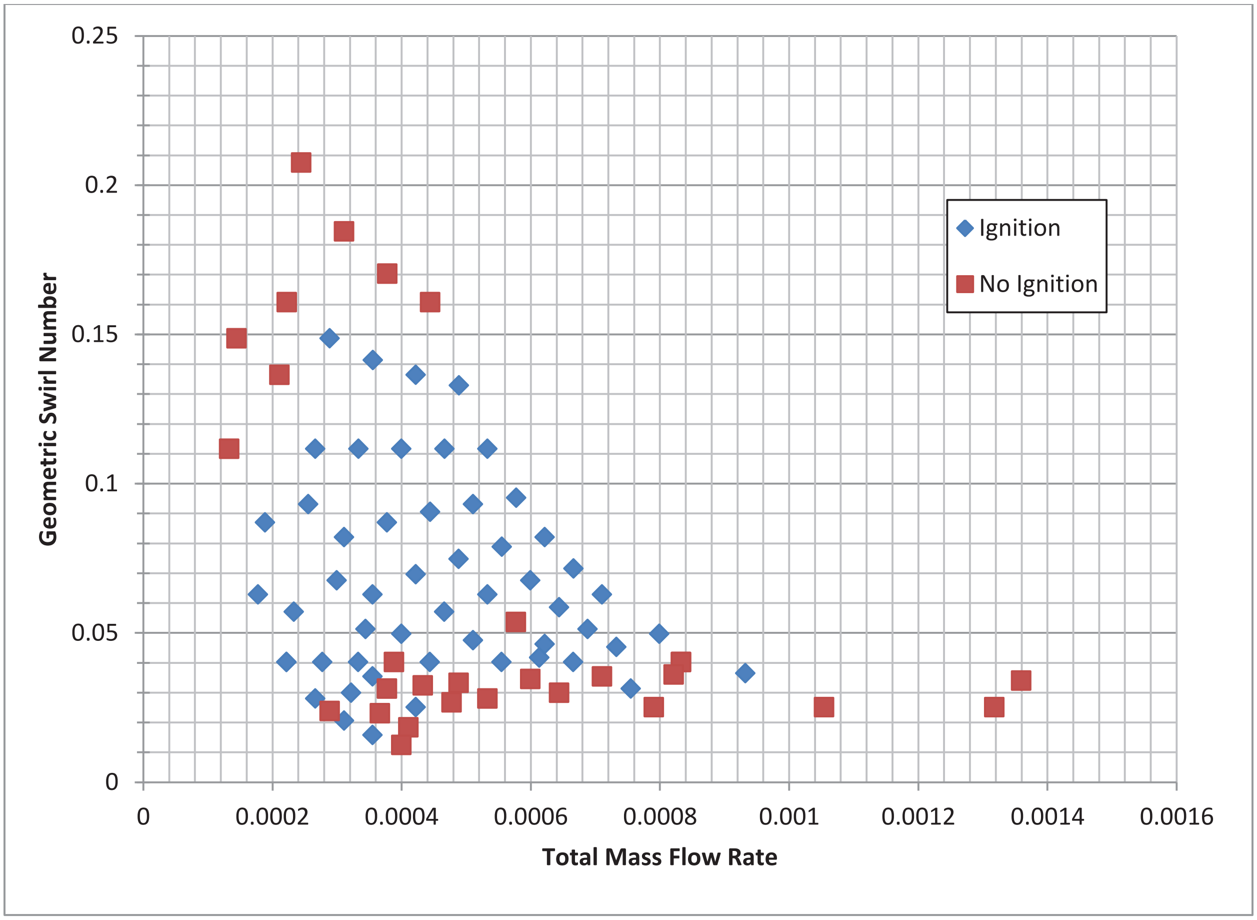


Figure 36 Swirl Number Flammability Map

3.4.2 *Gas Oxygen/Cold Gas Methane*

The tests involving cold gas methane were run in a very similar manner to those tests with room temperature propellants, the only difference being the addition of a coil bath heat exchanger which was used to produce methane temperatures between 190 and 275 K. The method used for cooling the methane was passing the methane through a coil that was submerged in a bath of liquid nitrogen. This method of cooling makes it difficult to accurately control the temperature of the methane at the inlet of the igniter but the amount of line submerged in the LN2 can control the temperature to a range of ~20K. However, this cooling

method is adequate to determine how the temperature affects the ignitability. The heat exchanger, shown in figure 37, uses a cryogenic dewar and 1/8” tubing to cool the methane.

Figure 37 Coil Heat Exchanger

Similar to the previous tests, a flammability map, shown in figure 38, was created to show where the igniter was reliable.

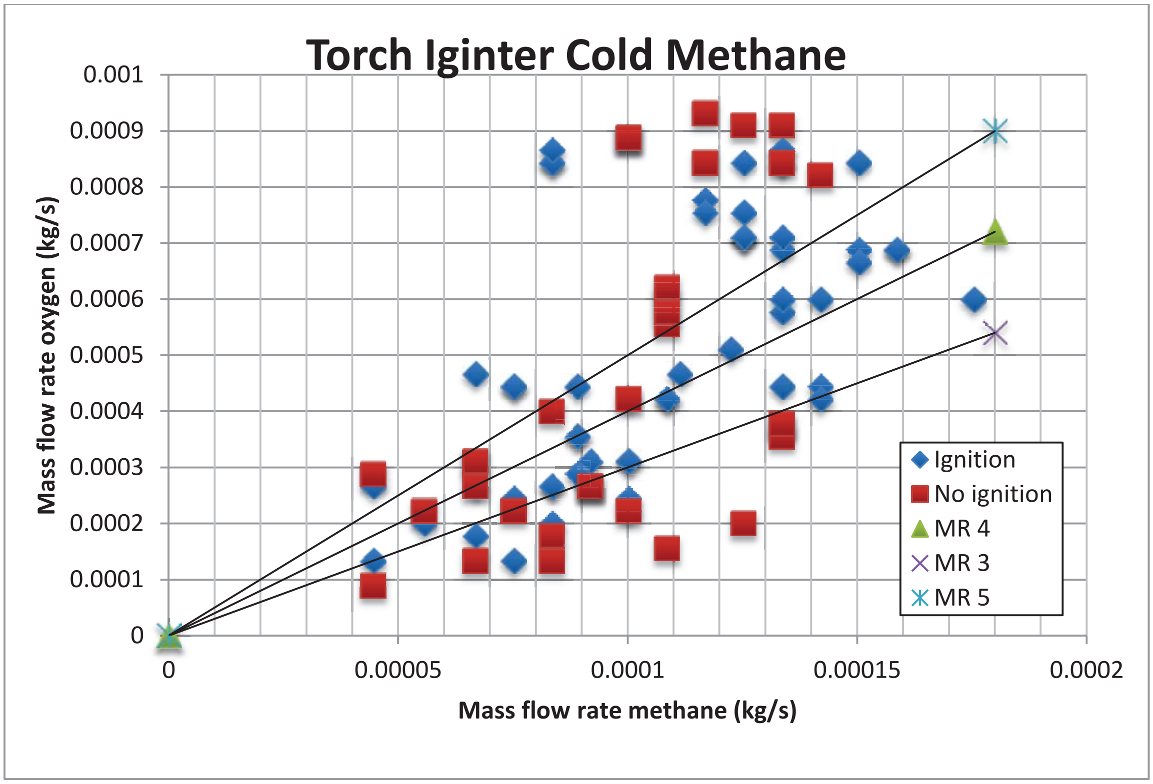


Figure 38 Flammability Map of Cold Methane and Warm Oxygen

The trend seen here is similar to the previous graph but shifted. Instead of igniting in the lower fuel rich mixtures, the more reliable ignitions tended toward the much higher lean mixture ratios of 3 to 5. Whereas there were almost no ignitions over a mixture ratio of 4 and none over 5, with cold gas there were several successful ignitions over a mixture ratio of 5.

The reason for the much more chaotic graph comes from controlling the flow rates. While the gas/gas flow rates were very easy to set before testing, the temperature of the cold gas and therefore the density were harder to predict before testing and were only know from analyzing the data once testing had been completed. Additionally, the increase in density from chilling the methane caused higher flow rates to enter the combustion chamber. While chamber pressrure was not recorded, calculations show a slight increase in pressure causing difficulty in setting the appropriate flow rates before testing. A graph showing the successful ignitions with the target flow rates is shown in figure 39; these are not the actual flow rates but the flow rates that were set prior to ignition. As before, the outlier data points come from the requirement to have 4 out of 5 successful ignitions. The data points within the ignition region did ignite but did not meet the criteria for reliability.

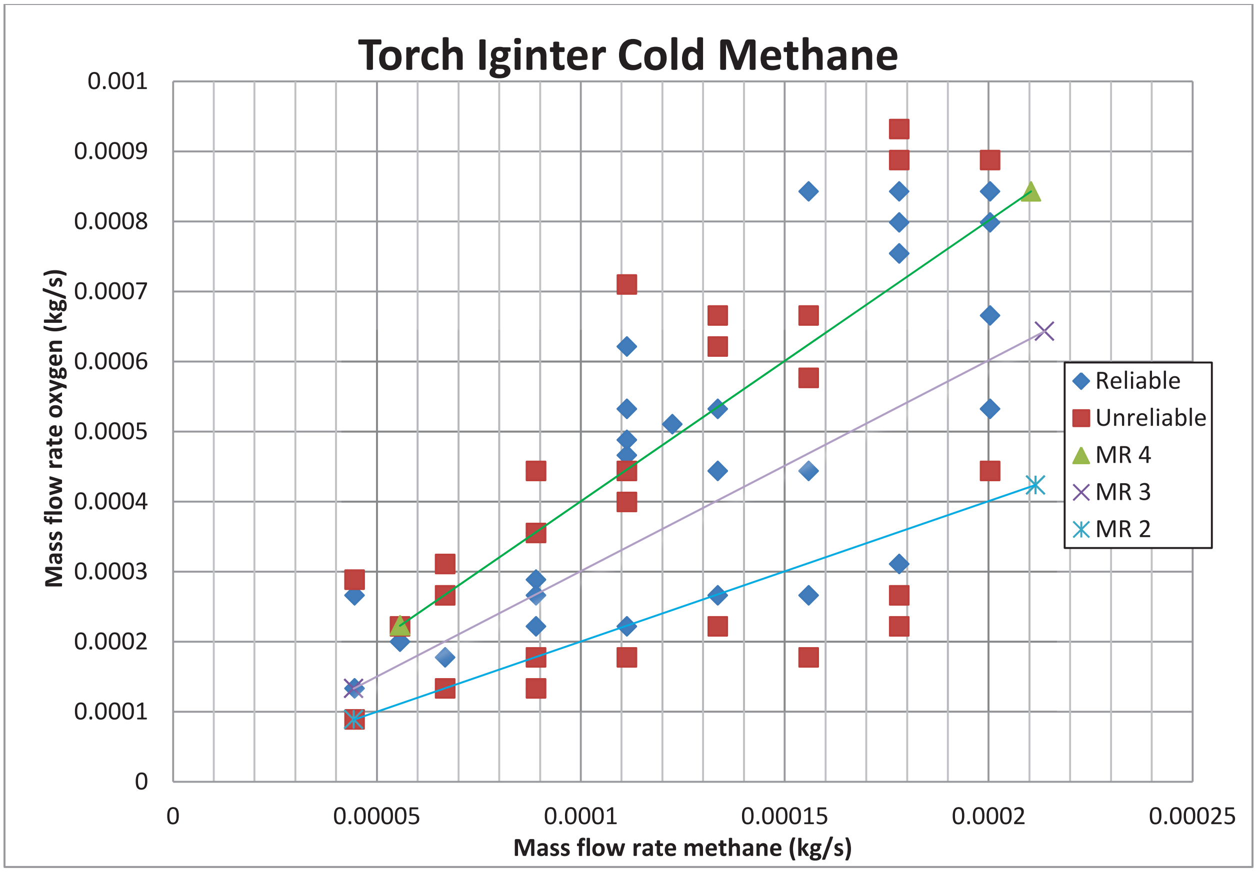


Figure 39 Flammability of Target Flow Rates

The goal of these tests was to understand how the limits changed, because of this the central region was not extensively tested only points near the boundaries.

Another difference with these tests is the unreliability at lower flow rates. This is quite interesting because low flow rates were ignitable with both room temperature propellants. The current explanation for this is the combination of two things: The low flow rate, and bad mixing. The low flow rates cause low velocities into the chamber; this coupled with the increased density of cold methane causes the methane to be injected very slowly. This would affect the mixing of the propellants prior to ignition. The oxidizer would have much lower momentum causing it to not break up the ring of methane causing very high mixture ratios on the wall. The increased

mixing length on the new igniter has yet to be tested for these conditions to determine if mixing is the problem or if it is mitigated by the larger mixing distance.

3.4.3 *Liquid Oxygen/Cold Gas Methane*

The next step was to test with liquid oxygen and cold gas methane. Several problems arose with this combination especially in getting the correct mixture ratios. The LOX has a very high density while cold gas methane is still in the gas region which causes it to have very low density. The problem arose when trying to obtain very high gas flow rate along with a very low liquid flow rate which also caused some cooling issues. Due to these restraints only a small range of tests could be completed.

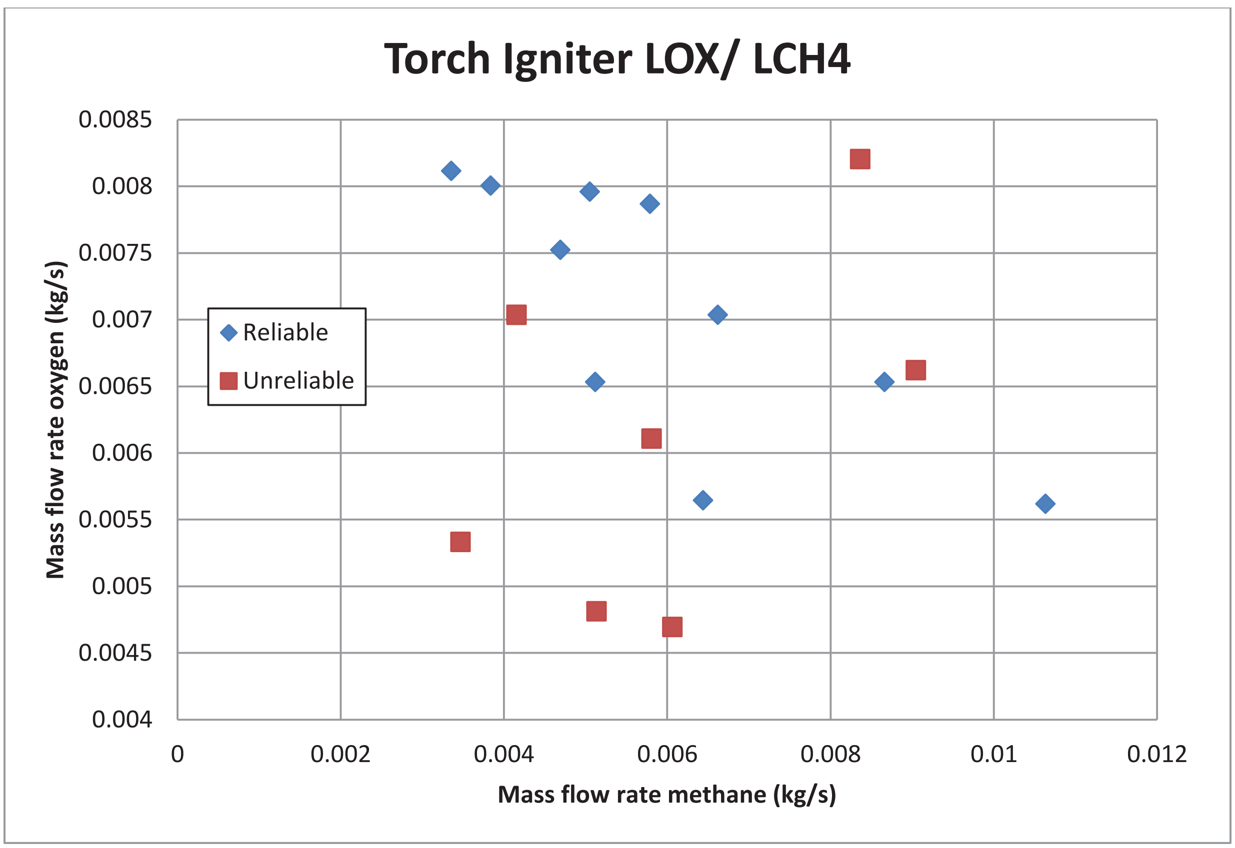


Figure 40 Liquid Oxygen Cold Methane

Difficulty in controlling the flow rate as well as measuring means this graph should not be considered completely accurate. Since these tests were conducted new more accurate liquid measuring equipment has been made and these tests should be redone with more data points.

3.4.4 *Liquid Oxygen/Liquid Methane*

During the first stage of testing the igniter was damaged. This damage is irrepairable and was caused by an error in the control system. The specified time for the igniter to be on is at most four seconds, however, during the first test a burn time of 10 seconds was sustained. This caused the igniter to melt starting at the nozzle and move back from there until the propellants were turned off. While the igniter was damaged, the goal of igniting liquid propellants was achieved. Another igniter is being fabricated and will be used to create a flammability map similar to previous ones that have been made for combinations of gas and liquid propellants.

Before the damage occurred useful data was acquired for approximately 4 seconds before the igniter failed. This is the only data available until the new igniter is fabricated and tested. This test was originally designed for a four second burn time with the igniter on for 2 seconds and then off for 2 seconds to determine if sustained ignition had occurred. Instead, an ignition of 10 seconds was seen with the sparker on for 2 seconds and off for the remaining duration.

The following pictures were taken from a video of the test. The camera's focus was disrupted by a glass pane between the testing and lense. However, the main points of each picture can still be seen. Figure 41 shows the liquid stream of propellants flowing out of the igniter just prior to ignition. The liquid out of the igniter demonstrates that liquid propellants were indeed injected and ignited.

Figure 41 Liquid Stream Prior to Ignition

Figure 42 shows the igniter during sustained ignition after the sparker had been turned off. The effects of the converging section can be seen from the shock diamond just after the nozzle. It should be noted that there is a second burn visible in the figure. This is the reflection of the flame on a glass pane.

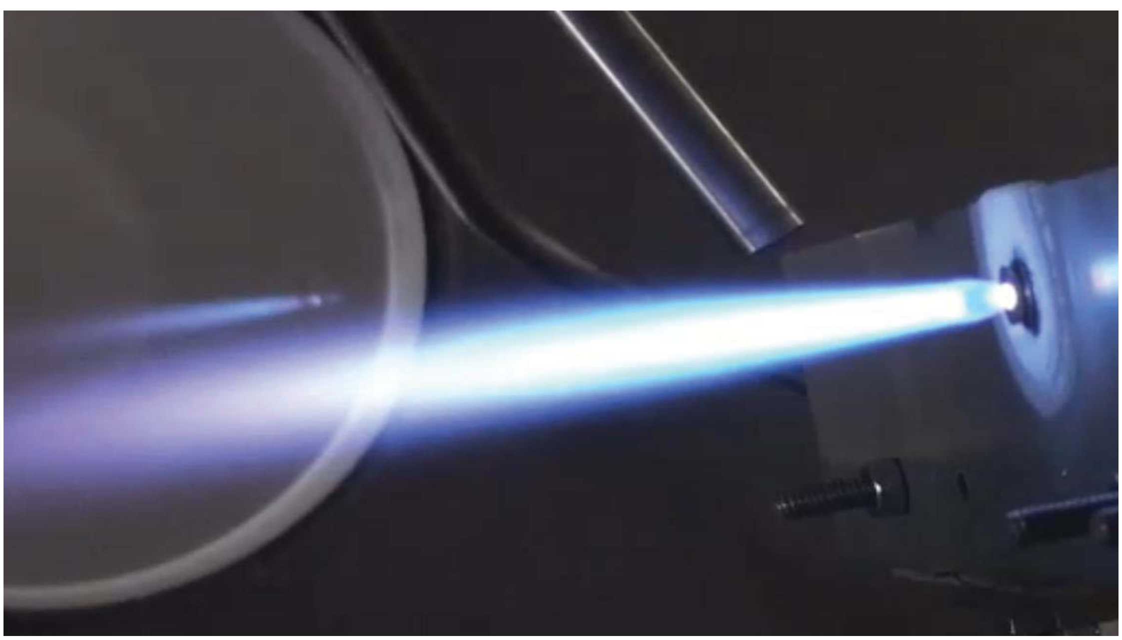


Figure 42 Ignition of Liquid Propellants

Figure 43 shows the igniter failure. The metal was hot enough to sustain melting for a short time after the propellants were stopped. Unfortunately, the igniter is unrecoverable and only this one test will be analyzed.

Figure 43 Igniter Failure

Figure 44 shows the flow rates that were calculated from measured values. The time for these graphs has been shortened to only show when LOX/CH4 is flowing and not the purging nitrogen. This particular test was aimed at a mixture ratio of 4; however, it is difficult to predict the effects of ignition on the flow rates. It was determined that the MR would increase after ignition but the increase was underestimated when the rise in chamber pressure caused a larger drop in methane flow rate than LOX flow rate, ultimately leading to a mixture ratio closer to 5. These would have been analyzed to better predict future tests and set tank pressures and needle valve positions more accurately to obtain better results. However, since the igniter was destroyed, the same process will be done on the next iteration.

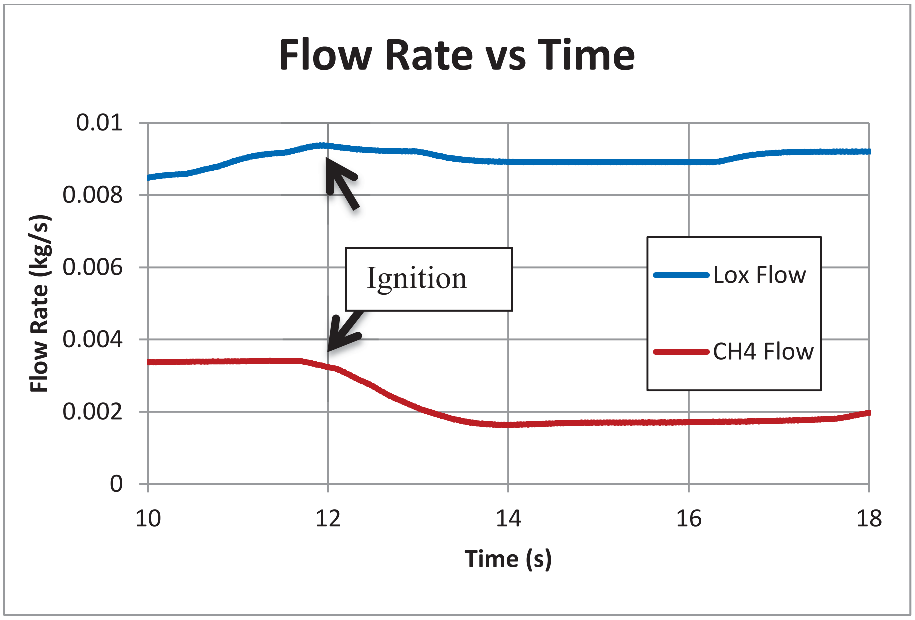


Figure 44 Flow Rates During Ignition

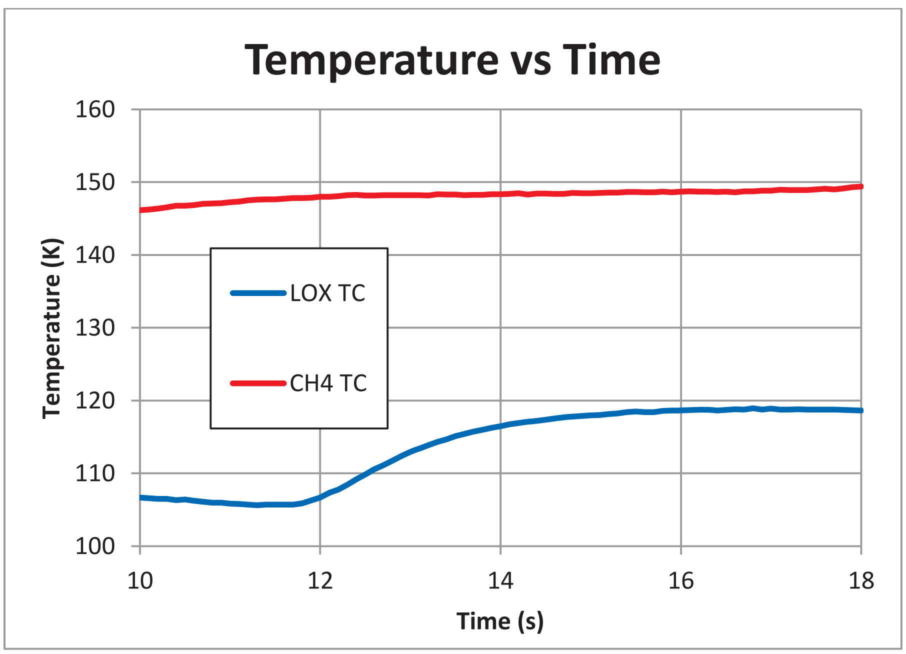


Figure 45 Temperature During Ignition

Lastly, the temperature profile throughout the test will be discussed. The temperatures at the measured point just before the valves tended toward steady state at the 12 second mark. During the remainder of the test there is liquid at both measuring points showin in Figure 45. The LOX temperature and pressure indicate that it is well within the liquid region while the methane

temperatures indicate that it is just under the line between liquid and gas at the ignition point. The higher temperature liquid methane heats up the oxygen to create a gas mixture around the liquid stream. This mixture is then ignited, which leads to vaporization of the propellants as they proceed into the ignition zone and a sustained ignition afterwards.

3.4 Limitations And Problems With Testing

A large part of the problems with testing were during the initial phases of gas/gas testing since these tests were the first. During these tests a very large iterative process took place with both flame anchoring and sparker design. The original sparker used was described in 2.2.2 however several iterations were done before a reliable sparking system was found which ended with a double lead tungsten electrode that was housed in a single fitting. Another problem that arose with flame anchoring at lower flow rates where the flame would tend to anchor on the electrode tips themselves instead of the edge of the igniter causing wear this was another reason the higher temperature tungsten was chosen to replace the original platinum electrode.

Once the integrity of the electrode was fixed, problems began to arise with the ceramic. The ceramic that was used was very brittle and susceptible to damage from vibration. This cause the ceramic to break often during testing which led to the decision to have a single tungsten lead accompanied by custom made ceramic piece similar to the one shown in figure 23. This new sparker design was the first in the design family of the current generation of sparkers. It provided excellent electrical resistance while withstanding all of the vibration of testing. This new sparker arced to the wall instead of between leads. This caused some grounding issues but was ultimately fixed when the entire system was grounded.

3.5 MASS Testing

The MASS was tested with the newly installed compressor for functionality. Unfortunately the compressor was undersized and vacuum was unobtainable. All

instrumentation, and hardware is working so future tests can be run on the system to determine functionality at a later time.

Chapter 4

4.1 Future Work Igniter

While a large number of tests have been completed to produce flammability maps the goal of testing all propellant combinations is only half finished. For future tests of the igniter two stages of testing must be completed: retesting previous flammability maps, and conducting the tests that have not been done.

The first part of retesting previous flammability maps will be slightly easier. Based on the previous tests done there are zones of good ignitability so to retest these areas is unnecessary. What is necessary however is to test the boundaries of the ignitability limits to determine if the boundaries are the same for the new hardware or if an updated boundary needs to be made.

The second part is a continuation of tests that have already been completed. Flammability maps still remain to be completed for several propellant combinations, liquid/liquid being the most difficult to conduct. Once these new tests have been completed as well as the retesting of previous maps the flammability maps will be complete for this torch igniter.

Some other things that could be completed are removing the piping altogether and testing different sparker configurations. The piping can be removed by adding a jacket that can be welded on or even a ring manifold. This would reduce the size of the igniter as well as the weight while making a completely sealed manifold with no pieces protruding. The igniter design has been through several iterations but there is always room for improvement. Both the configuration and required energy for ignition can be changed to produce more repeatable ignitions as well as reduce the power requirement. Another possible addition is a counter swirl. Preliminary CFD analysis has been done and predicted very good mixing using this injection method.

4.2 Future Work MASS

The MASS proof of concept has still not been completed. During testing it was determined that the compressor installed was not high enough capacity to run the two stage ejector at steady state. To mitigate this it is recommend incorporating the three large tanks

located in the basement of the engineering building. This would add several cubic meters of volume which could be pressurized above 125 psig which would allow for several minutes of ejector operation before the pressure dropped below 125 psig and thereby hurting the ejector performance.

Once the MASS has been tested for proof of concept, future high altitude tests can be conducted on many experiments at cSETR not just the torch igniter. It is important to understand how the effects of atmosphere affect the results of various projects.

There are several more additions to the system that would help with operation and safety. While the manufacturer does not provide any software that can be used to control the system remotely the compressor does have an IP address and can be connected to the UTEP network. With this, at the very least, we can monitor the status of the compressor remotely. Perhaps in the future a company will provide software that can be used to remotely start/stop the compressor which would help save time by allowing remote operation.

Another addition is adding a valve between the vacuum chamber and ejector. While the pipe is very large and it would be impractical to add a valve, it would help the overall system. If there were a way to add a valve between the two it would allow for the ejector to be run without having to worry about the MASS. Once the ejector is working properly the valve could be opened to start evacuating the mass. This would improve the safety of the system as well as add a way to test the ejector for leaks independently of the MASS.

The last suggestion is to protect the measurement equipment. A check valve or hand valve that could be placed between the MASS and the pirani gauge to better protect the gauge. This would prevent the gauge from becoming over pressured and damaged. Vacuum would be pulled before the gauge was allowed to read ensuring that it never reads above 20 psia.

4.3 FUTURE WORK WITH MOAC

The final stages of igniter testing are to incorporate it with the MOAC. The torch igniter was originally intended to be the ignition source for the MOAC and these tests will help to further the understanding of how methane combusts when injected coaxially. This will be the culmination of two current projects and will likely be a thesis itself. Several inlet conditions to the MOAC could be tested, similarly to the tests that are currently ongoing to determine what inlet conditions allow for ignition into a pressurized system.

Chapter 5

5.1 CONCLUSION

Several test campaigns have been completed and produced flammability maps. Extensive testing has created a baseline for future hardware designs showing the areas for which reliable ignition can occur. In addition to the flammability maps, the incorporation of design changes made ignition of liquid propellants possible. Future tests can now be conducted both in creating a flammability map for liquid propellants and incorporating the igniter into the MOAC. An incorporation of a nozzle along with chamber pressure has been tested and its functionality confirmed. A more structurally sound and robust sparker has been designed and tested as well. This configuration allows the support of many more firings, as well as the operation with transient pressure increases. In addition to data acquired, many test procedures and safe operation guides have been made for future reference in conducting tests. This will result in less time preparing and more time testing for future test campaigns.

Overall, a large amount of work has been done in creating an ignition system that works under a wide range of propellant inlet conditions including gas-gas at room temperature and chilled conditions and liquid propellants. This has been shown in all of the tests that have been completed. The proposed future tests will recreate previous flammability maps with the new hardware as well as explore the rest of the inlet conditions that remain.

References

[1] Betancourt-Roque J., "Instrumentation, Control and Torch Ignition Systems Development for Lox/Methane Propulsion Research". *Thesis*, University of Texas at El Paso, 2012.

[2] Navarro, C. D., Betancourt-Roque, J., Sanchez, L. E., Robinson, N., & Choudhuri, A. (2011). Development of a Multi-Purpose Optically Accessible Rocket Combustor for Liquid Oxygen and Hydrocarbons. 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit. San Diego, CA: AIAA.

[3] Navarro C., "Development of a High Pressure Optically Accessible Combustor and Shear Coaxial Injector". *Thesis*, University of Texas at El Paso, 2012.

[4] Flores, J. R. (2009). An Investigation of the Performance of mN Class Bipropellant Thrusters. El Paso: University of Texas at El Paso.

[5] Mark D. Klem "Liquid oxygen/ liquid methane propulsion and cryogenic advanced development." International Astronautical Congress

[6] Munday, Stephen R., Jennifer D. Mitchell, and Machael Baine. *Morpheus: Advancing Technologies for Human Exploration*. Tech. no. GLEX-2012.05.2.4x12761.

[7] Devolites, Jennifer L., Jon B. Olansen, and Stephen R. Munday. *Project Morpheus: Morpheus 1.5A Lander Failure Investigation Results*. Tech. N.p.: n.p., n.d. Print.

[8] Schneider, Steven J., Jeremy W. John, and Joseph G. Zoeckler. *Design, Fabrication, and Test of a LOX/LCH4 RCS Igniter at NASA*. Tech. no. NASA/TM—2007-215038.

[9] Chiara Manfletti, Joachim Sender, Michael Oschwald. "Theoretical and experimental discourse on laser ignition in liquid rocket engines" Institute of Space Propulsion, German Aerospace Center (DLR) Lampoldshausen, Germany. 2009.

[10] Breisacher, Kevin and Ajmani Kumud. "LOX/Methane Main Engine Igniter Tests and Modeling" 44th AIAA Joint Propulsion Conference & Exhibit. 21-23 July, 2006.

[11] Flores, Jesus. *DEVELOPMENT AND TESTING OF AN IGNITION PHYSICS TEST FACILITY AND AN OXYGEN/METHANE SWIRL TORCH IGNITER*. Thesis. University of Texas El Paso, 2013. N.p.: n.p., n.d. Print.

[12] Braeunig, Robert A. "Basics of Space Flight: Rocket Propellants." *Basics of Space Flight: Rocket Propellants*. N.p., 2008. Web. 16 July 2014.

[13] Sullivan, T.A., Linne, D. L., Bryant, L., and Kennedy, K., "In-Situ-Produced Methane and Methane/Carbon Monoxide Mixtures for Return Propulsion from Mars," *Journal of Propulsion and Power*, vol. 11, no. 5, 1995, pp. 1056–1062; also AIAA Paper 94–2846, June 1994

[14] Huang, Y., & Yang, V. (2009). Dynamics and Stability of Lean-Premixed Swirl-Stabilized Combustion. Progress in Energy and Combustion Science , 293-364.

[15] Claypole, T. C., & Syred, N. (1981). The Effect of Swirl Burner Aerodynamics on NOx Formation. Eighteenth Symposium (International) on Combustion .

Appendix 1: Igniter operation

The procedure outlined after its original development was followed. Some of the key parameters consistently followed in each condensing session are listed in appendix 2.

A test procedure was developed in detail to conduct the test in the safest manner possible. The procedure has been broken down into three parts (pretest, testing, and posttest). Three roles must be assigned before the testing session (Current role assignments and a description of each is listed in appendix 3).

Each role will fulfill their specific tasks and when needed will communicate via radio (ie during valve check the conductor will communicate with the hardware tech to test that each valve is working)

<u>Pretest</u>

1. Hardware technician must inspect the bunker and the testing area.
    a. Check the exhaust area of the torch igniter for foreign objects and remove any found
    b. Verify all tanks are closed
    c. Activate the ventilation system by turning on the ventilation fans
    d. Open the back doors of the bunker for additional ventilation
    e. Position the strobe light gate in the doorway to prevent people from entering the bunker from outside
    f. Perform a visual inspection to ensure the test article is in place and all instruments and propellant lines are installed correctly
    g. Position the Kevlar walls between the propellant tanks and the MASS
    h. Position all cameras to record tests
    i. Place high volume fan in such a manner that it pushes anything exiting the igniter from the facility to the outside.

j. Put on PPE (Cryogenic handling gloves, apron, and face shield/safety glasses)
k. Turn on the large fan to help prevent any gas buildup. Monitor the oxygen sensor to maintain appropriate oxygen levels. The sensor will begin to chime when unsafe levels are met (approximately 19.5%)
l. Open GN2 Tanks and set purge pressure of 50 +/- 5 psi
m. Ensure that the furthest valves downstream are closed and all others are open and pressurize the system using GN2. Leak check the system using snoop and fix any leaks found
n. Close the GN2 tanks and gas out the system until all PTs read 13+/- 1 psia.
o. Close all valves.

2. Test supervisor must complete the following data filing procedure for each session
    a. Create a folder for the type of testing being performed i.e. Liquid-Liquid Testing
    b. Create a document that lists the inlet conditions for the test session planned for that day (desired inlet pressure/temperature) and name it according to the folder created, i.e. Liquid-Liquid Testing 12-09-13 Record
    c. Leave a section in this document for comments that will contain the following information
        i. Changes done in the system configuration, i.e. part substitution
        ii. Renaming of channels if any
        iii. Troubleshooting procedures that might be useful for subsequent tests
        iv. A brief identifiable observation of the test, i.e. unsuccessful ignition

3. Test conductor must now activate the power supplies and monitor readings
    a. Each valve that will be used must be opened to ensure proper connection. The conductor will specify which valve will be opened and the hardware technician

will confirm that it was opened via visual/audio inspection. This process will be repeated for all valves

   b. Ensure that all pressure transducers and thermocouples are reading ambient conditions (13 +/- 1 psia and 297 +/- 3 K)
   c. Verify that the sparking system is functional. The hardware technician will enter the bunker and go within audio/visual range of the test article and will inform the conductor to test the sparker. The conductor will then turn on the power and signal for the sparker and the hardware technician will confirm that the sparker is arcing via audio confirmation.

4. Begin Methane Condensing (details of this procedure located in appendix C)

5. Test conductor now turns the bunker light from green to yellow indicating only the hardware technician is allowed to enter

6. Hardware technician must then set the components to required testing conditions
   a. Set cryogenic tanks to 213 +/-10 psia
   b. Open or confirm that all tanks that will be used are open. (2x LN2 1x LOX 1x GN2 2x GCO2 1x Helium) one LN2 tank and the helium tank should already be open per the condensing procedure.
   c. Close and latch ports of access to the bunker and return to the control room

7. Test conductor must turn the bunker light from yellow to red indicating no one is allowed to enter the bunker

<u>Testing Procedure</u>

8. Test session pre-conditioning

a. Purge the feed system using GN2 for 5 seconds

b. Open the cooling valves to cool down the delivery system of oxygen and methane. The cooling valves are closed once the temperature readings reach the desired system temperature (<110 K) in both the oxygen and methane lines and upon visual confirmation of a liquid stream exiting the test article.

c. Open the LOX delivery in order to cool the remainder of the LOX line not cooled by the LN2 cooling (same conditions must be met as in b)

d. Open the methane delivery system to ensure that downstream methane TC reads <116K

e. Both c and d can be cooled at the same time and liquid is confirmed by readings of the inlet thermocouples (LOX and methane downstream TCs read <110K and <116K respectively)

9. Test conductor now activates data acquisition program

    a. Begin the recording of data

    b. Commence test script

        i. Test script opens main delivery valves of oxygen and methane

        ii. The electrical discharge to the arc point located on the torch spark igniter body is remotely activated and set to maintain a constant spark for 1 seconds. This period of time is set to ensure ignition upon mixing of oxygen and methane

        iii. Delivery valves are closed after 2 seconds of the initiated test sequence

        iv. Purge the system with GN2 for 5 seconds which is enough time to fully purge the system's total volume.

    c. Restart and repeat automated sequence two more times to complete testing session for a single set of inlet conditions.

10. If no contingencies occurred during testing, the test conductor now turns the bunker light back to yellow

    Purge MASS system with CO_2 and allow at least 60 seconds for system to vent

11. Hardware technician then enters the bunker to visually inspect hardware
    a. Visually inspect hardware for damage
    b. From the CryoCart feed, set the desired helium pressure for the next test (determined by test matrix)

12. Steps 8-11 are repeated for the desired number of tests if more than one condition is to be tested, and after the last test, proceed to step 13

Posttest

13. Hardware technician may re-enter the bunker to shut down the system
    a. Change bunker lights from red to yellow
    b. Close all tank valves
    c. Open all hand valves on the MMCU
    d. Allow system to depressurize by opening all of the valves in the system (depressurization is defined as all pressure transducers reading 13 +/- 1 psi and all regulators indicating no pressure)

14. If any methane remains in the tank, follow the methane disposal procedure detailed in appendix D (Residual methane can be detected via the tank TCs reading <116K)

15. Test supervisor must now store the video recordings in the folder created in step 2 and rename them to indicate test order i.e. Testing Video 12-09-13 Test 1
16. Turn off all power supplies

17. Safety supervisor now turns off the ventilation system and turns the bunker light back to green

Emergency Procedure

Attached is the hazard analysis completed for the torch igniter test matrix. All safety considerations were taken and an emergency procedure was developed in case of an unwanted occurrence. Red lines are implemented in our test script to avoid a catastrophic failure of the hardware or facilities. Pressure and temperature redlines will stop the test script in case an overpressure of the system occurs or the temperature of an instrument surpasses it operational range.

Red Lines:

- Line pressure must remain less than 230 psia
- Methane tank pressure must remain less than 230 psia
- Temperature readings must remain between 75K<T<350K for all thermocouples

Appendix 2: Cryocart Role Assignments

(Current role assignments for testing – Scheduled for 06/09/14)

Test Supervisor – Jose Mena

Test Conductor – Robert Ellis

Hardware Technician – Vanessa Dorado

Test Supervisor

- Responsible for ensuring the test matrix is followed and informing the test supervisor and hardware technician of specific testing parameters for each test. (Tank pressures, desired flow rates, etc)
- Responsible for making sure the entire test procedure is followed by each of the three roles

Test Conductor

- In charge of operating the LabView program

Hardware Technician

- Responsible for inspecting hardware before testing and in between tests
- Changes helium pressure to the desired level between tests to change the methane flow rate

Appendix 3: Cryocart Procedure

Key parameters that must be followed for methane condensation:

- First, a vacuum must be achieved to rid the condensing tank of air which contains gasses which may freeze at liquid methane temperatures
- Time required to pull vacuum: 15 minutes (This is the time it takes the internal pressure to reach steady state with the current vacuum pump)
- Average final vacuum pressure: 3 psia (This is the approximate steady state vacuum pressure achieved)
- Methane tank pressure: 93 psia, higher pressures are allowed but not greater than 230 psia. The higher the pressure the higher the condensation temperature which leads to shorter condensation times.
- Average temperature to indicate methane's liquid state: 116 K (Temperatures hover a few degrees over 116 K during condensation but once the methane has become liquid each thermocouple that is submerged will read 116 K or less)
- As with projects using the MMCU, the liquid methane flow rate was calculated and controlled by manipulating the tank pressure that is pressurized using gaseous helium. (Detailed under "Methane flow measurement")

Methane condensing procedure:

a. Verify all instrumentation in the MMCU is reading ambient conditions (13 +/-1 psia 297 +/-3 K)
b. Verify all valves on the MMCU are working. This is done by the test conductor opening the valves one by one and the hardware technician confirming a successful opening. The conductor will indicate which valve is being tested and

the conductor will verify that it opens by audio/visual confirmation. (ie touching the valve and feeling it open)

c. Close hand valves to the methane and helium tanks

d. Attach the vacuum pump to the system and begin pulling vacuum in the lines and condensation tank. Vacuum is achieved when the pressure transducer reading the condensation tanks pressure reads 3 +/-1 psia

e. Methane and Helium tanks are opened and regulators are set to the correct pressure. Methane is set to 93 psia in order to increase the condensation temperature and helium pressure is set according to the test session conducted from the test matrix. Refer to "methane flow measurement" for details about helium pressure and methane flow rate.

f. Set the liquid nitrogen tank to 200 psia and open the tank regulator and cooling valves to begin cooling the MMCU.

g. Open the hand valve to the methane tank and allow methane to enter the condensation tank where vacuum was pulled in step d.

h. Ensure that the condensation tank pressure transducer is reading >90psia and maintain that pressure until the desired amount of methane is condensed.

i. Close the methane hand valve when the desired level is reached. Methane level can be inferred from the temperature readings of the thermocouples attached to the condensation tank (<116K indicates liquid at that level)

j. Once the desired level is achieved, close the methane hand valve and allow the remaining methane to condense. This will be seen by a drop in temperature and pressure in the tank.

k. Open the helium hand valve. The helium tank pressure can be changed in between test runs to provide various methane line pressures. It can be increased or lowered by using the dewar regulator. If a lower pressure is needed then gassing out through the top hand valve will relieve the helium pressure.

l. Close the liquid nitrogen cooling valves (LN2 tank valve remains open for cooling purposes during testing)

m. Use methane for testing and dispose of any remainder properly (proper disposal procedure in appendix 4)

Appendix 4: residual methane disposure

1. After test session is completed, the level of liquid methane will be reviewed to determine if any residuals exist. (indicated by tank thermocouples reading <116K)
2. If residuals do exist, the following steps must be followed
3. Turn on the high volume fan facing the MASS to push all propellants outside (the fan should already be on from the initial test procedure)
4. Open valves to allow liquid nitrogen to run through the system on the LOX side
5. After 5 seconds of purging, begin flowing methane, the diluted methane will be blown out of the MASS into the outside.
6. Do not flow for longer than 10 seconds. After this time of flowing a 5% methane mixture will be present, this is an ignitable mixture.
7. Wait 20 seconds for the entire MASS system to be removed and blown outside by the high volume fan
8. Repeat steps v through vii until all residual methane is gone indicated by a rise in temperature (>175K) in all thermocouples in the tank
9. Purge the methane system with nitrogen
10. Shut down the system by closing all tanks and venting the pressure in all of the lines

Appendix 5: hazards analysis

HA #	System	Hazard	Severity	Likelihood	HA Index	Mitigation
1	Methane Delivery	Regulator Failure	1 - Minor	1 - Unlikely	1	Open Valves and allow depressurizing
2	Methane Delivery	GN Regulator Failure	1 - Minor	1 - Unlikely	1	Open Valves and allow depressurizing
3	Methane Delivery	Manual Valve Failure	1 - Minor	1 - Unlikely	1	Close Tanks
4	Methane Delivery	Solenoid Valve Failure	2 - Moderate	2 - Infrequent	2	Close Tanks and allow depressurizing
5	Methane Delivery	Trapped LN2/CH4	1 - Minor	3 - Frequent	2	Pressure Relief Valve
6	Methane Delivery	Line Overpressure	3 - Significant	1 - Unlikely	2	Pressure Relief Valve
7	Nitrogen Delivery	Tank Regulator	1 - Minor	1 - Unlikely	1	Allow depressurizing and close tank
8	Nitrogen Delivery	Manual Valve Failure	1 - Minor	1 - Unlikely	1	Allow depressurizing and close tank
9	Nitrogen Delivery	Line Overpressure	3 - Significant	1 - Unlikely	2	Pressure Relief Valve
10	Controls	Program Failure	1 - Minor	2 - Infrequent	1	Close tanks allow for depressurizing and restart program
11	Controls	Power Failure	2 - Moderate	1 - Unlikely	1	Manual and pressure relief valves incorporated into system
12	Exhaust	Flammable	2 -	1 -	1	Low ch4/ox concentrations are diluted with air

	System	Mixture	Moderate	Unlikely		inside duct system
13	Exhaust System	Exhaust Failure	1 - Minor	1 - Unlikely	1	Close tanks and allow propellants to dilute in air

Appendix 6: MASS Procedure

Measurement Devices

The following devices are installed on the vacuum chamber:

1 Pirani Gauge: This gauge is used to measure pressure from 0.0001-1000 Torr (0.2E-6 - 19.3 psia) +/- 10% of reading, and is mounted at the front of the vacuum chamber.

InstruTech CVM-211 "Stinger"

It is recommended to never exceed 20 psia in presence of the sensor. Pressures over 35 psia can permanently damage the sensors heating element. While this value is set by the manufacturer they also state that there is a chance of permanent damage even between 20 and 35 psia.

1 0-250psia Pressure Transducer: This PT can be used in place of the Pirani Gauge to test the system is working correctly without endangering the Pirani Gauge from overpressuring.

2 0-15 Psi Pressure Gauges: One gauge is installed on each stage of the ejector to confirm that vacuum is being pulled at both locations.

Procedure

For operating the compressor control panel see appendix

This procedure is a generic operation manual for the MASS system. This procedure is only to pull vacuum. If any tests are to be completed while vacuum is pulled you must set up the test article before step 12 and evacuate the bunker after pulling vacuum but before firing the test article. Generic steps are added to the procedure to give an idea of where they should be done.

Pre Test

In order to ensure that no damage is done to the vacuum chamber, ejector system, or compressor the following steps must be taken before testing:

1. Ensure that all fittings are tight to prevent leaks. Flange bolts were tightened by facilities; this is to be sure that no fittings have become loose. If a fitting is found to be lose, contact facilities to have the flanges retightened.
2. Remove any loose material from the vacuum chamber.
3. Leak check all Swagelok lines feeding into the vacuum chamber. Only lines with a valve leading into the chamber can be tested using soap and water.
4. Make sure all pressure transducers are reading ambient conditions (13 +/-1 psia)
5. Initiate control system (Turn on power supplies, start Labview program, etc).
6. Ensure that all manual valves are in the appropriate position. See Appendix 2 for a guide.
7. Turn on the dryer and make sure the compressor is in the "ready" mode (Status listed under the home 1 tab on the compressor front panel) and set the compressor pressure to 115 on 125 off.

Testing

8. Two roles are needed for safe operation.
    a. One person who can enter the bunker to move the manual valves and access testing instrumentation between tests
    b. One person in the control room monitoring labview with access to the emergency shut off switch located next to the computer monitors.
    c. One person to go into the basement to turn on the compressor/dryer. Once the system is up and running this person may return to the lab upstairs.
9. Turn the bunker light from green to yellow.
10. Ensure all manual valves are in the correct position (Refer to Appendix 2)
11. Set up test articles (This is a generic step for reference when test articles are used)
12. Close the vacuum chamber door.

13. Turn the compressor on and communicate successful initiation to the control room. (This step is only needed for the first run through the procedure, if the compressor is already on then skip this step)
14. Wait for the compressor to pressurize the tank and line by gauge reading 125 +/- 2 psig (indicated by the pressure gauge located just before the yellow valve described in Appendix 2)
15. Begin recording data in the control room.
16. Open the manual valve to allow air flow into the ejectors
17. Monitor the pressure reading on the Pirani gauge and both ejector PT's
18. If there is an overload pressure on either ejector or a buildup of pressure in the vacuum chamber over 1000 +/- 10 Torr, then press the emergency stop button.
19. Allow steady state to be reached (Change of less than 20 Torr in 20 seconds)
20. If tests are to be completed evacuate the bunker and turn the light from yellow to red
21. The system should now be pulling steady vacuum. Since this is a generic operation of the ejector no specific tests are listed here. Any tests should now be conducted and once completed continue to step 22.
22. Turn the bunker light from red to yellow
23. Close the manual valve leading to the ejectors
24. Allow system to expend built up pressure in the ejectors.
25. Once all pressure transducers are again reading ambient (13 +/- 1 psia) turn bunker light from red to yellow.
26. Open vacuum chamber door and visually inspect the chamber for any damage.
27. Repeat steps 8-28 until all tests are completed.

Post Test

28. Shut down system (close tanks, turn off power supplies, save data, etc)
29. Turn off the compressor and dryer.

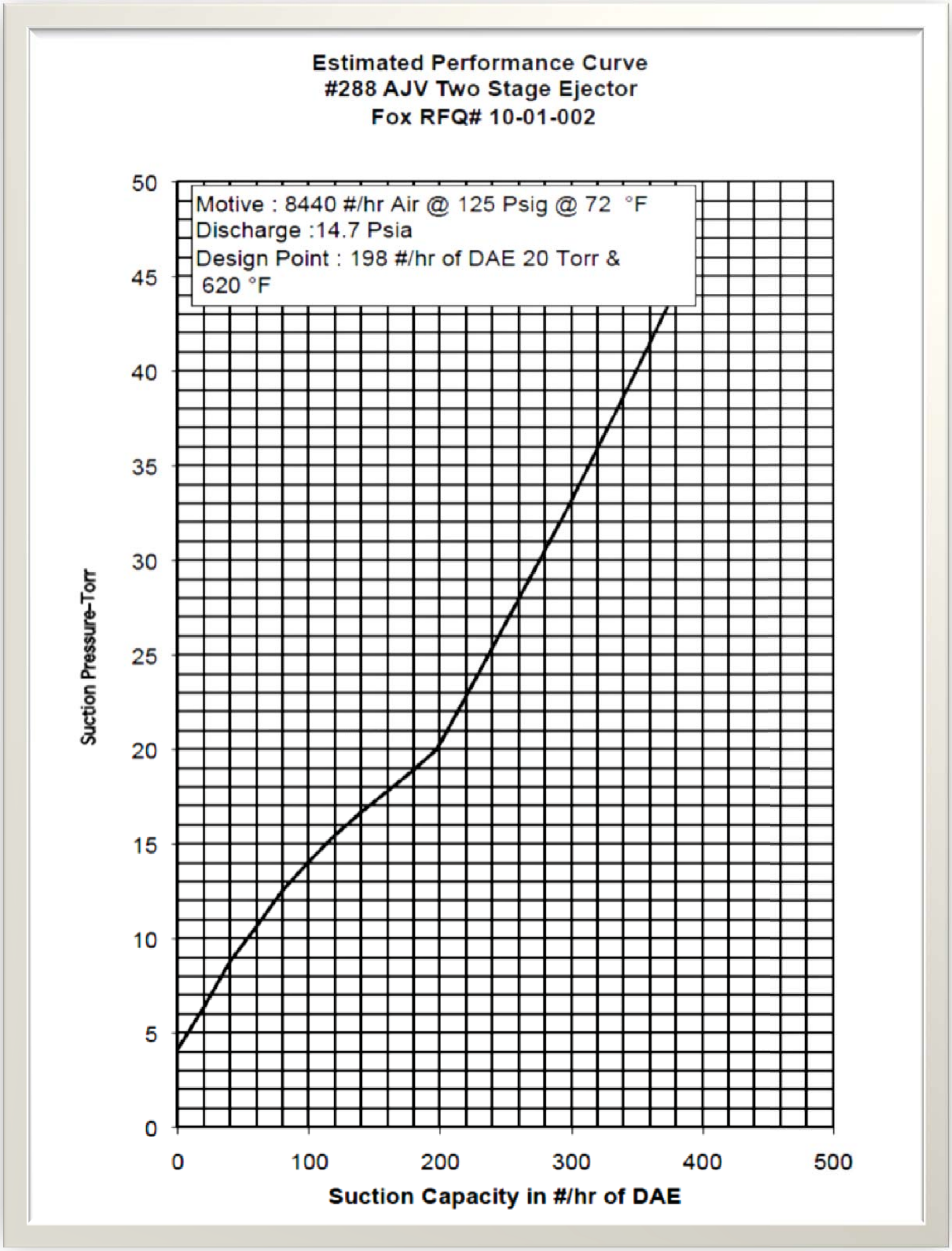
30. Release pressure from system using the valve at the bottom of the tank.
31. Turn bunker light from yellow to green.

The goal of these tests is to validate the system for use as a high altitude simulation system. This involves pulling vacuum in the chamber with no propellant input to establish a baseline vacuum pressure and then introducing varying mass flow rates to get a mass flow rate in versus vacuum pressure correlation. To do this, there are two CO2 tanks attached to the vacuum chamber along with flow meters. The flow meters will be used to determine the mass flow rate into the chamber. The steady state pressure with zero loads as well as with different mass flow rate inputs will be recorded and compared to the theoretical vacuum curve provided by the manufacturer. The following table will need to be completed when a fix to the compressor situation has been found.

Regulator Pressure Torr (psig)	Flow Meter (LPM)	Calculated Mass Flow (kg/s)
0	0	0
?	50	0.0063
?	100	0.0126
?	150	0.0188
?	200	0.025
?	250	0.031

POSSIBLE ADDITIONS TO THE SYSTEM

The following performance curve was given by the manufacturer and is what will be used to compare results



Estimated Performance Curve
#288 AJV Two Stage Ejector
Fox RFQ# 10-01-002
Motive : 8440 #/hr Air @ 125 Psig @ 72 °F
Discharge :14.7 Psia
Design Point : 198 #/hr of DAE 20 Torr &
620 °F
Suction Pressure-Torr
Suction Capacity in #/hr of DAE
0
5
10
15
20
25
30
35
40
45
50
0
100
200
300
400
500

Appendix 7: compressor operations

The only non-mechanical parts of the system are the measurement devices and the solenoid valve that controls flow into the chamber. These are controlled and monitored through Labview and have no part in pulling vacuum. The last, and most important, part is the compressor. The compressor is controlled by a control panel built into the unit itself. While it can be shut off from the lab using an emergency stop button, it can only be turned on using the panel downstairs. Facilities is currently in contact with the company to receive software to control the compressor remotely from the control room. Until then someone has to control it from the panel in the basement.

The purpose of this is for a basic understanding and a "must know" for operating the compressor. First this is the front panel:

The front panel contains a screen and 10 buttons that control the compressor and navigate the menus.

1. LCD Screen
2. Turns the compressor on

3. Turns the compressor off

4. Not sure

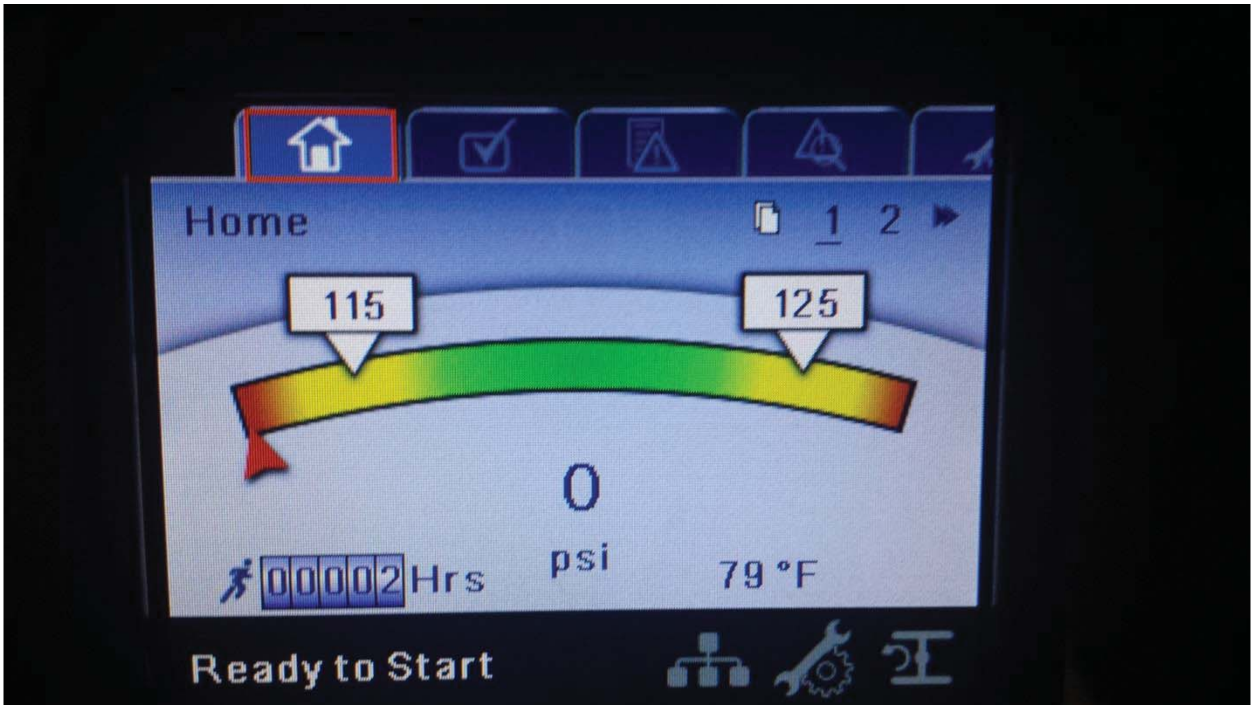
5. Opens the outlet of the compressor

6. Closes the outlet of the compressor

7. Acknowledges emergency stops

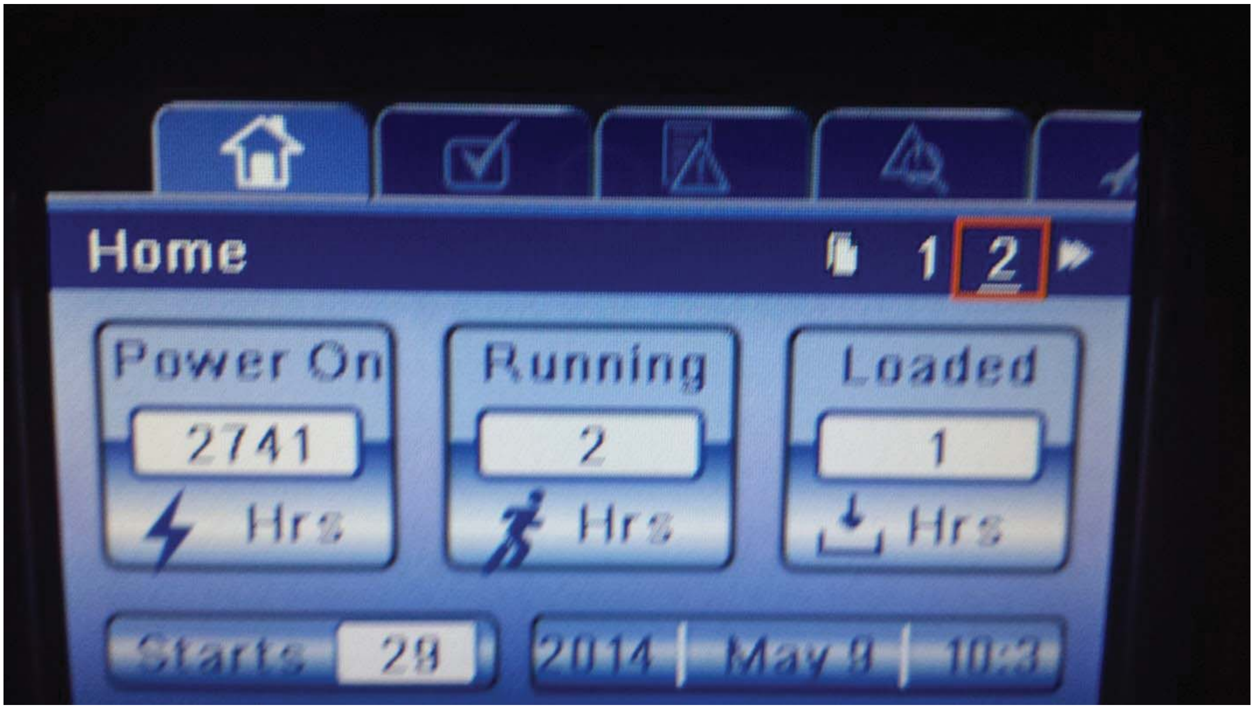
8. Used to navigate the menus

When controlling the more detailed aspects of the compressor you must navigate the menus. There are over 10 tabs but for everyday use I will only go over the more important ones.

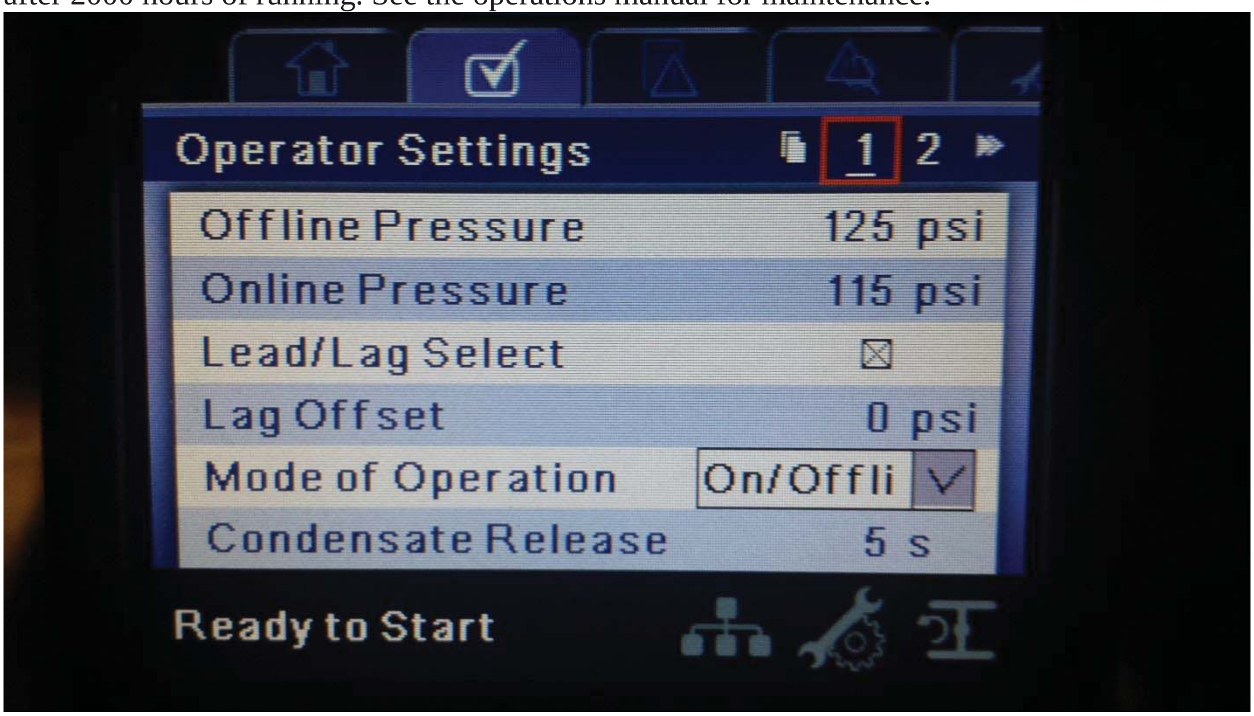


Home Tab

This tab shows the current operating conditions of the compressor. Here the current pressure inside is 0 psig. The 115 and 125 correspond to the pressure that the compressor turns on and off respectively. The compressor will turn on if the pressure is below 115 and stop when it reaches 125 psig. It is recommended that the range be set to 115-125 psig to avoid pressure dropping below 122 psig. This is the highest default setting.

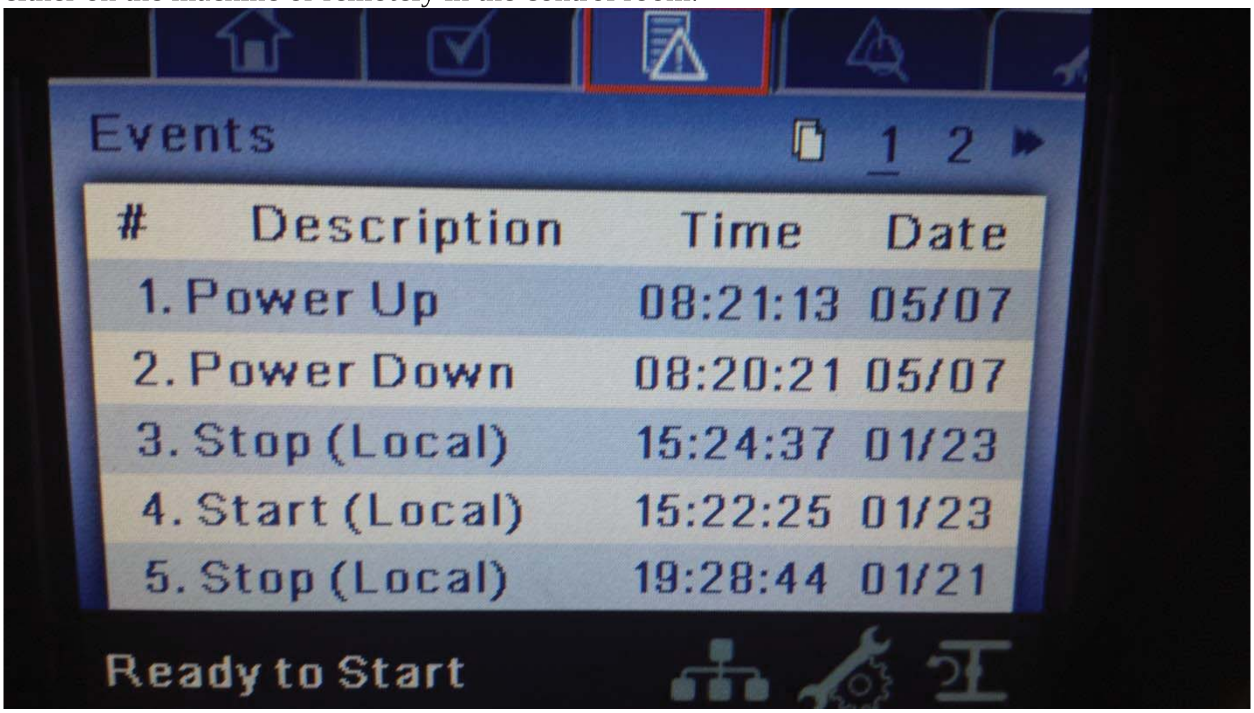


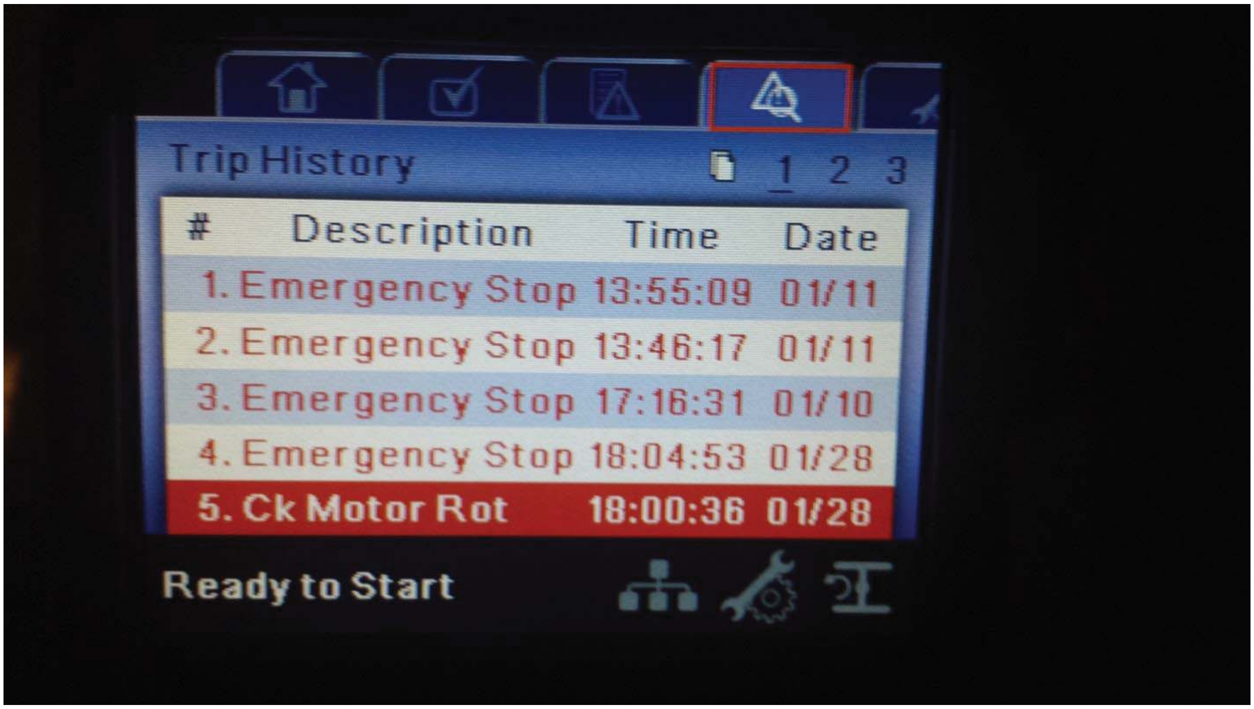
The second part of the home tab shows the total hours of operation so far. Maitenance is needed after 2000 hours of running. See the operations manual for maintenance.



The next tab controls the operation settings. Here you can change the pressures at which the compressor operates as well as how often to release the condensate, lag offset and mode of operation.

The next two tabs show the history of the machine, the first shows when it was turned on, off, powered on, off, etc. The second shows when the machine was stopped using the e-stop button either on the machine or remotely in the control room.





Vacuum is maintained as long as air at more than 125 psig is supplied to the ejectors at a rate of over 8440 lb/hr. The steady state operation of the compressor has a higher capacity than this so vacuum will be maintained until the compressor is turned off.

The dryer is used to take water vapor out of the air and also has a filter to remove particles above 3 microns. It removes the water by cooling the air to ~35 F and condensing the water vapor. Before operation, make sure the manual valves are oriented correctly. There are two that should be open (the ones leading into and out of the dryer) and one closed (the bypass overhead)

Two valves are located before each ejector and should remain open. There are two more manual valves futher down the line, one in the basement just before the line passes through the floor, and another just before the line splits to both ejectors inside the bunker. The one in the basement should remain open and the one before the piping splits will be closed when not in use and opened during operation to control flow into the ejectors.

The dryer is controlled from an integrated panel, all of the buttons are labeled and for operation the only thing that needs to be pressed is the on/off button. To change the settings of the compressor consult the user manual.


SYSTEM ENERGIZED
DRYER ON
REFRIGERATION COMPRESSOR ON
DRAIN OPEN
78
DEGREE F
DEGREE C
HIGH TEMP. ALARM
LOW TEMP. ALARM
ON
OFF
DRAIN OPEN
DRAIN CLOSE
EXCH. SET
% SAVINGS
DRAIN TEST
ALARM RESET
°F / °C
Ingersoll Rand

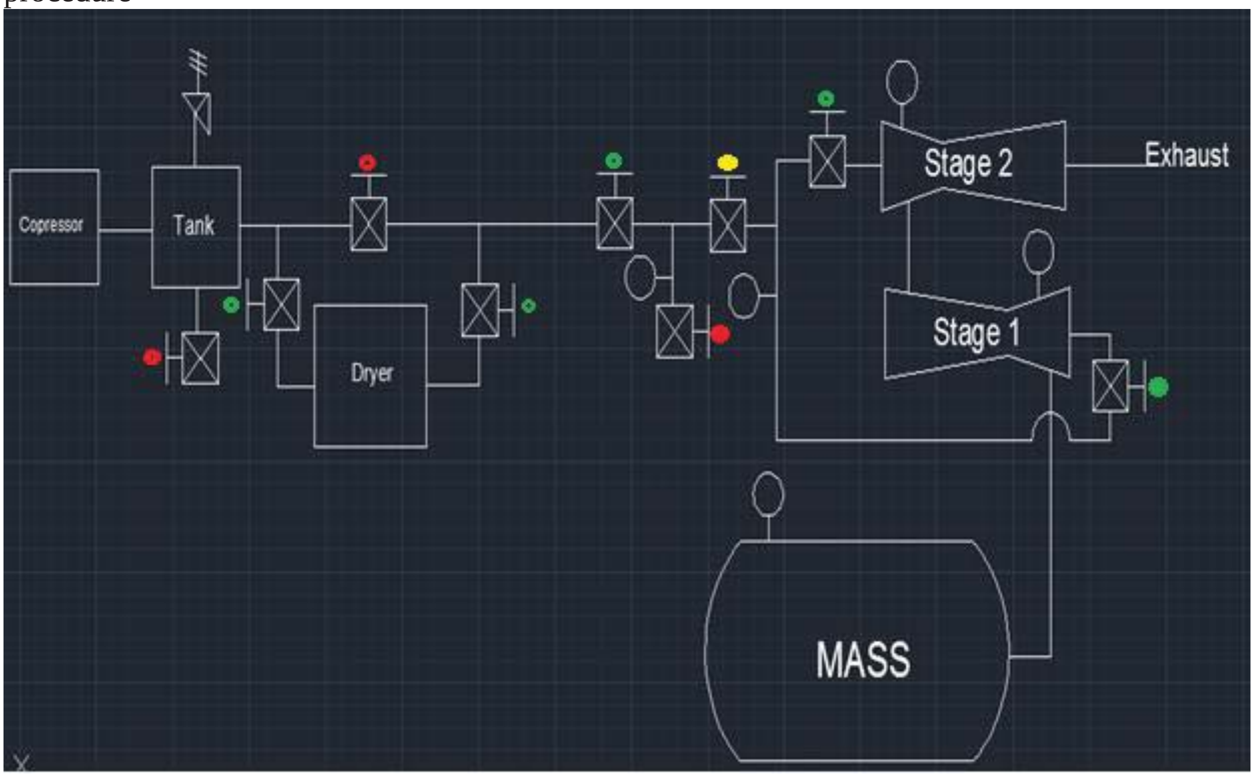
System Schematic

Pre Operation Valve Open/Close Positions

Green-Indicates Valves that should be OPEN before testing

Red-Indicates Valves that should be CLOSED before testing

Yellow-Indicates the valve that should be CLOSED before testing and then OPENED during the procedure



	System	Hazard Descritpion	Severity	Likelihood	F	Mitigation
1	Vacuum Chamber	Rupture from Over-Pressure	4- Catastrophic	1 - Unlikely	2	Monitor Pressure Remotely
2	Ejector	Exposure to compressed Leakage	2- Moderate	2 - Infrequent	1	Check bolt tightening of flanges
3	Ejector	Exposure to High Temp Gas	3 - Significant	4 - Imminent	**4**	No high temperature gases will be created during initial testing
4	Ejector	Exposure to High Velocity Gas	2 - Moderate	4 - Imminent	3	Ejector Area will be gated and off-limits
5	Compressor	Rupture from Over-Pressure	4 - Catastrophic	1 - Unlikely	2	Pressure Relief Valves on tank
6	Ejector	Rupture from Clogged pipeline	3 - Significant	1 - Unlikely	2	Visual Check and Preventative Maintenance

Vita

Robert Ellis was born and raised in El Paso Texas. He received a Bachelor of Science in Mechanical Engineering in the fall of 2011 and a Master of Science in Mechanical Engineering in the summer of 2014. He has helped write many publications for several conferences both here in the South West region (SESES) as well as National conferences such as the AIAA Joint Propulsion Conference. This thesis was written to provide as much detail about the project as possible so future generations working at cSETR would be able to reference it and know how to repeat the tests provided here or new tests by following the procedures in the appendix. If any questions arise please use the contact information provided below.

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This thesis/dissertation was typed by Robert Ellis.