2012-01-01

Cryogenic System Development For Lox/ Hydrocarbon Propulsion Research

Francisco Pineda
University of Texas at El Paso, fpineda@miners.utep.edu

CRYOGENIC SYSTEM DEVELOPMENT FOR LOX/ HYDROCARBON PROPULSION RESEARCH

FRANCISCO PINEDA

Department of Mechanical Engineering

APPROVED:

Ahsan R. Choudhuri, Ph.D., Chair

Norman Love Jr., Ph.D.

Eric MacDonald, Ph.D.

Benjamin C. Flores, Ph.D.
Interim Dean of the Graduate School

Dedication

To my family and friends

CRYOGENIC SYSTEM DEVELOPMENT FOR LOX/ HYDROCARBON PROPULSION RESEARCH

by

FRANCISCO PINEDA, B.S.M.E.

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 Department of Mechanical Engineering

THE UNIVERSITY OF TEXAS AT EL PASO

May 2012

Acknowledgements

I would like to extend my most sincere gratitude to my advisor Dr. Ahsan Choudhuri. His patience, guidance and teachings were invaluable to my development as an engineer. Thank you for giving me the opportunity to follow my dreams. I also want to thank Mr. Nate Robinson for his sound advice and supervision of this project. In addition, I want to recognize the entire staff of the cSETR because without their hard work, this project would not have been possible.

I want to thank my committee for their given time and contribution to this thesis.

Thank you NASA for providing the means to make all this possible.

Special thanks to Mr. Jesus Betancourt-Roque, his collaboration made this project a success. Jesus R. Flores, Chance P. Garcia, Chris Navarro and the rest of my colleagues at the cSETR, thank you. Finally, I would like to give a special recognition to my family and girlfriend, their support and motivation got me through challenging times, and for that I am grateful.

Abstract

A propulsion research facility is being developed at the Center for Space Exploration Technology Research (cSETR) at the University of Texas at El Paso (UTEP). These facilities were developed in order to meet new research demand for Liquid Oxygen (LOX)/Liquid methane (LCH_4) experiments. The main goal of this system is to produce in-house liquid methane and supply propellants to their respective test set up in a cryogenic state. The work presented describes the design, development, and operation of a liquid methane condensation system and a cryogenic delivery feed system. The condensation system design will allow for a production of methane of up to 25 L. The predicted performance is 71 N LOX/ LCH_4 thruster with a 368 Isp and a line pressure of 1310kPa.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

There is an extensive variety in today's propulsions systems and propulsion technology. In order to accomplish the goals of exploration, commercialization or defense, new technological advances are needed in order to ensure longer and more efficient missions. Current thruster technology utilizes toxic, expensive, and energy intensive propellants. The research that is currently being developed in propulsion technology revolves around safer, non-toxic propellants such as hydrocarbons. A prominent challenge presented by these propellants is the lack of understanding of the fundamental physics when utilized in propulsion systems. While some systems in industry have used hydrocarbons in heritage propulsion units, the performance advantages and drawbacks still need to be defined through fundamental research. Furthermore, developments made using in-situ research have shown the possibility of using or producing hydrocarbons in Mars or the moon [Linne, 1992] allowing for more convenient and efficient missions in space exploration.

Some of the current propellants being used in industry today include liquid hydrogen (LH_2)/LOX systems, monomethyl hydrazine (MMH), and nitrogen tetroxide (NTO). The use of these propellants offers favorable performance but at a high cost in safety and energy expenses. MMH and NTO propellants are highly carcinogenic and hypergolic with the added hazard of corrosion. In order to have a system that operates under these conditions, highly sophisticated operations are required to ensure the safety of the handling personnel and the astronauts on board a spacecraft. Some of the issues that are present with LH_2 and LOX systems are the storage temperatures of these propellants (20°K and 88°K, respectively). Hydrogen presents problems such as tank leakage, high flammability limits and low ignition energies. These issues create challenges such as a higher risk of explosion or leak issues. Liquid Oxygen creates problems related to contaminants in the system that might create sudden explosions but are manageable when compared to alternate oxidizers such as fluorine. Some of the advantages of methane include higher density, higher storage temperature (110°K), and low flammability limits. In addition, methane is relatively safe when compared to LH2, MMH, and NTO [Neill, 2009]. This allows for a system that consumes less energy and subsequent expense while being easier to maintain, making it a preferred choice for exploration missions [Crawly, 2008].

The cSETR at UTEP, under the direction of Dr. Choudhuri, has been researching and developing the next generation of propulsion systems. The Center has been conducting a series of tests that will use liquid methane for the characterization of methane heat transfer, ignition physics, injector design, propulsion, and combustion. The laboratory will require a cryogenic feed system in order to support all of the experiment needs, similar to other feed systems found in other universities or research facilities. This feed system must adapt to the needs and requirements of the respective experiments while meeting safety and budgetary constraints.

1.1 SCOPE OF THESIS

The purpose of this thesis is to develop a test facility in order to conduct propulsion and combustion research. This work will focus on two particular systems: the methane condensation system and the cryogenic delivery system. The methane condensation system needs to be designed to support the liquid methane needs of several experiments conducted at the laboratory. This design must be tested and evaluated for future development. The cryogenic delivery feed system needs to provide the propellants to the test article in a safe and metered way. The delivery feed system must be operated form a remote location and utilize the test facilities located at the Goddard laboratory at UTEP to full potential.

Chapter 2: Cryogenics Background

In order to design a successful system, a basic understanding of the physical properties of cryogenic substances is paramount beforehand. This chapter will describe some of the physical properties, hazards, and design considerations that must be taken when dealing with cryogenics.

2.1 IMPORTANT DEFINITIONS

- Cryogenic- A liquid that boils at temperatures of less than 114°K at atmospheric pressure. Some common cryogens are liquid hydrogen, helium, nitrogen and oxygen.
- Detonation: A combustion process where an exothermic reaction takes place at supersonic speeds.
- Deflagration: A combustion process which travels at subsonic speeds.
- Expansion Ratio: Volumetric ratio of vapor to liquid.

2.2 LIQUID OXYGEN

Most of the testing conducted in the laboratory will be done with oxygen as the oxidizer. Initial testing will be conducted with gas oxygen (GOx) and eventually with LOX. Any oxygen utilizing system faces challenges as a result of its strong oxidizing properties.

2.2.1 Properties

Oxygen is a powerful oxidizer that vigorously promotes combustion. Some of the physical properties of liquid oxygen are:

- Boiling Point = 90.2°K (-297.33°F)
- Expansion Ratio = 842:1
- Critical Temperature= 154.6°K (-181.4°F)
- Critical Pressure= 106,000 psia (5.06MPa)
- Chemically stable if stored under suitable conditions
- Mixable with liquid nitrogen
- Light blue transparent color, odorless
- Major impurity: Argon

2.2.2 Hazards

Physiological

Liquid oxygen is a non-toxic chemical, but breathing pure oxygen may cause symptoms such hyperventilation and coughing. Due to the low temperature of liquid oxygen, contact with the skin can lead to frost bite [Bell, 2006]. Liquid oxygen can become extremely unstable when mixed with other elements like hydrocarbons or organic materials. Personal Protective Equipment (PPE) such as safety goggles, safety shield, cryogenic apron, cryogenic gloves, and closed leather shoes should always be worn when dealing with cryogens. In the case of clothing becoming saturated with liquid oxygen, the clothing should be removed or aired out in a well-ventilated area.

Fire and Explosion

Liquid oxygen is not hypergolic when mixed with fuels but it supports combustion once it is ignited. A mixture of LOX and fuel should be treated as extremely dangerous and unstable. Fuel/LOX mixtures can be ignited by energy sources such as static electricity, mechanical shock, and electrical sparks. Fire and explosions are commonly present in cryogenic system due to overpressure and chemical reactions. Particulates over 2000 μm represent a detonation hazard [NASA WSTF, 2007] and a filtration system must be incorporated into any design of a LOX system.

An environment with oxygen content in excess of 21% represents a fire hazard. When facing a fire in an oxygen enriched environment, the optimal solution is to shut off the oxygen supply and allow the oxygen to evaporate. Any LOX/Fuel fire can be extinguished with class B firefighting agents.

Pressurization and ventilation

Liquid oxygen has an expansion ratio of 842:1. This poses a pressure hazard in the event of sudden phase change from liquid to gas. A pressure relief system needs to be incorporated into any cryogenic system design such as tanks and transfer systems.

Proper facility ventilation is required to prevent oxygen enriched environment or fuel/oxygen diffusion.

Material and equipment selection

Special material and equipment considerations are recommended when designing a cryogenic system. The extreme operating temperatures of cryogenics can create issues such as thermal expansion and ductility reduction. Materials usually found in valves such as O-rings and lubricants are usually not compatible with cryogenics. Oxygen service components require further criteria due to material compatibilities. Table 1 shows compatible materials for service with liquid oxygen and Table 2 shows prohibited materials for oxygen service. Appendix A shows the recommended nonmetals for oxygen service.

Table 1. Recommended materials for oxygen service [Flynn, 2005]

Application	Material low-moderate-pressure	High pressure-near sonic vel
Component bodies	Nickel alloy steel	Monel
	Stainless steel	Inconel 718
Tubing and fittings	Copper, stainless steel, steel aluminum and aluminum alloys	Monel
		Inconel 718
Internal parts	Stainless steel	Monel
		Inconel 718
		Beryllium copper
Springs	Stainless steel	Beryllium copper
		Elgiloy
		Monel
Valve seats	Stainless steel	Gold or silver
	Monel	Plated over Monel
	Inconel	Or Inconel 718
Valve balls	Stainless steel	Sapphire
	Tungsten carbide	
Lubricants	Everlube 812	Batch/lot tested
	Microseal 100-1 and 200-1	Braycote 3L-38RP
	Triolube 1175	Batch/lot tested
	Krytox 240AB and 240AC	Everlube 812
	Braycote 3L-38RP	Krytox 24DAD
O-seals and backup	TFE, Halon TFE	Batch/lot tested
	Teflon	Viton
	Kel F	Batch/lot tested
	Viton	Teflon
Pressure vessels	Nickel steel	Inconel 718
	Stainless steel	
	Steel	
	Aluminum alloys	

Operating pressure ranges as they are used in this section are defined as follows:

Low pressure	0–500 psia
Medium pressure	500–2000 psia
High pressure	2000–7500 psia
Very high pressure	7500–10,000 psia
Ultra-high pressure	10,000–15,000+ psia

Table 2. Prohibited metals in oxygen service [Flynn, 2005]

- Cadmium is not allowed because of its toxicity and vapor pressure
- Titanium and its alloys
  Impact sensitive
  Unsafe in liquid oxygen at any pressure
  Unsafe above 30 psi with air or gaseous oxygen
- Magnesium and its alloys
  Corrodes easily
  Reacts with halogenated lubricants
- Mercury
  Accelerated stress cracking of aluminum and titanium
- Veryllium is too toxic for use

System cleaning

In order to keep a clean and particle free oxygen system, a cleaning and maintenance procedure must be implemented. The system components need to be disassembled and individually cleaned. After which, the system can be reassembled and a leak test can be performed. The final step is to perform a purge with high purity gas nitrogen. Especial attention should be given to any kind of lubricant and its compatibility with oxygen. Table 3 shows a recommended procedure for effective cleaning of oxygen systems.

Table 3. This list shows the effective cleaning procedure of oxygen service items

1. Clean surfaces of films, greases, oils, and other organic materials
2. Prevent functional interference with components and the clogging of flow passages
3. Remove combustible contaminants
4. Avoid the accumulation of finely divided contaminants

- How is effective cleaning accomplished:
  Integrate with construction operations
  Plan for cleaning during all phases of development
- The cleaning process consists of several steps
  Solvent degreasing with methyl chloroform
  Detergent cleaning
  Acid pickling of stainless steel parts
  Final treatment consisting of steam and blow dry
  Seal in polychlorotrifluoro ethylene
- Good recordkeeping is required throughout the cleaning process

2.3 LIQUID NITROGEN

The physical properties of liquid nitrogen make this cryogen very versatile. LN_2 is widely used in research facilities, the medical field, food industry and others.

2.3.1 Properties

- Boiling Point = 77.6°K (-320°F)
- Expansion Ratio = 681:1
- Critical Temperature= 126.3°K (-232.3°F)
- Critical Pressure= 493.1 Psia (3400 KPa)
- Non-flammable, non-toxic, inert gas
- Odorless and colorless
- Major impurity: oxygen

2.3.2 Hazards

Physiological

The main physiological hazards related to liquid nitrogen are asphyxiation and frost bite. Nitrogen asphyxiation is the largest risk associated with the handling of liquid nitrogen [Crozier,2008]. Table 4 shows common physiological reactions to a nitrogen-enriched atmosphere.

Table 4. Respiratory hazards of nitrogen-enriched atmosphere [Flynn, 2005]

Percent oxygen in air	Physiological reactions
12–14	Respirations deeper, pulse up, coordination poor
10–12	Respiration fast and shallow, giddiness, poor judgment, lips blue
8–10	Nausea, vomiting, unconsciousness, ashen face
6–8	8 min, 100% fatal; 6 min, 50% fatal; 4–5 min, all recover with treatment
4	Coma 40 sec, convulsions, cessation of respiration, death
0	Death in 10 sec

Pressurization and ventilation

Over-pressurization issues are similar to the ones presented in the oxygen system. Proper ventilation should be implemented in order to avoid a low oxygen environment.

Material and equipment selection

The main concern when selecting components or materials for liquid nitrogen service is the extreme low temperature. Non-metal materials that are compatible with LN_2 include TFE Teflon, Kel-F, and selected types of graphite.

2.4 LIQUID METHANE

2.4.1 Properties

- Boiling Point = 112°K (-259°F)
- Expansion Ratio = 630:1
- Critical Temperature= 190.56°K (-116.66°F)
- Critical Pressure= 95,900 Psia (4.59 MPa)
- Stable and non-reactive under suitable conditions

2.4.2 Hazards

Physiological

Methane is a non-toxic cryogen, but extended exposure may cause respiratory irritation and asphyxiation. Frostbite is also a concern when in cryogenic form.

Fire and explosion

Liquid methane is a flammable cryogen, but relatively safe when compared to other fuels such as liquid hydrogen. The main concern when dealing with methane systems is diffusion with oxygen or other oxidizers thus becoming a fire hazard.

Pressurization and ventilation

LCH_4 has the same pressure hazards as the before mentioned cryogens. Proper ventilation must be implemented in order to avoid any oxygen diffusion and create a fire hazard.

Material and equipment selection

LCH_4 requires the same material and equipment considerations as liquid nitrogen.

Chapter 3: Methane Production System

The purpose of the methane production system is to supply the needs of liquid methane to the different experiments conducted in the laboratory. Experiments such as the Multipurpose Optically Accessible Combustor (MOAC) and Heat Transfer Rig were compared and at least 7 liters of fuel are required to conduct high demanding tests. Local suppliers of cryogens in the area were contacted but were only able to provide liquid methane in industrial quantities. The minimum quantities available were upwards of 1500 liters. Storing liquid methane in-site presents a safety hazard due to the location of the test facility being inside the university. After considering several options, condensing methane in-house became a viable option. This chapter explores the design and proofs of concept that have been developed for the methane condensation system.

3.1 Condenser Design

Several methods of condensation have been explored including cooling cycles similar to the Linde, Hampson, Claude, Collins, Joules-Thompson cycles [Cengel, 2007] and cryocoolers such as Stirling Cryocoolers. In these cycles it is common for a refrigerant to be recirculated through the system by means of condensation or other thermodynamic processes making them “closed loop”. These cycles usually have different types of heat exchangers such as cold plates or counter flow heat exchangers. The rates of condensation, cost, maintenance, and power requirements can vary from different cycles.

The second option explored was to have an open loop system where a cooling fluid flowed through a heat exchanger and was not recaptured. The difference in cost and complexity makes the latter option more practical. Several options were then considered for the cooling fluid selection. The condensation temperature of methane is between 110°K-130°K making cryogens such as oxygen, hydrogen, helium, and nitrogen potential options due to their boiling temperatures being lower than that of methane’s. Hydrogen and oxygen were not considered since they are highly reactive. Helium has a boiling temperature of 4.2 K and is non-reactive making it an ideal cooling fluid; however, its high cost at roughly $15 per liter makes it an expensive option. Liquid nitrogen then becomes the best option since

it has a boiling temperature of 77°K, at a cost of $0.15 per liter, is non-reactive, and is vastly available. Once the refrigerant was selected, it was possible to design the heat exchanger.

Several heat exchanger designs were evaluated such as shell and tube, counter flow, parallel flow, and cross flow heat exchangers. One of the biggest concerns when evaluating these designs was the possibility of clogging in the heat exchanger due to the formation of methane ice, making the counter flow and the cross flow heat exchanger not a good option. The best option was to design a heat exchanger similar to a cross flow or a shell and tube heat exchanger. The preliminary concept began with a dewar containing a coil inside. Two options were explored: the first would have the liquid nitrogen flowing through the coil; the second was to have the methane flowing through the coil in a bath of liquid nitrogen. By running the methane through the coil, solid methane could be formed and may clog the line, therefore this option was discarded. However, by dispensing the liquid nitrogen inside the coil and the methane into the dewar, the icing issue was not a concern. Any ice formation will reduce the performance of the heat exchanger but it will not disable it, making this option the most convenient design. Figure 1 shows a CAD model of the condenser design.

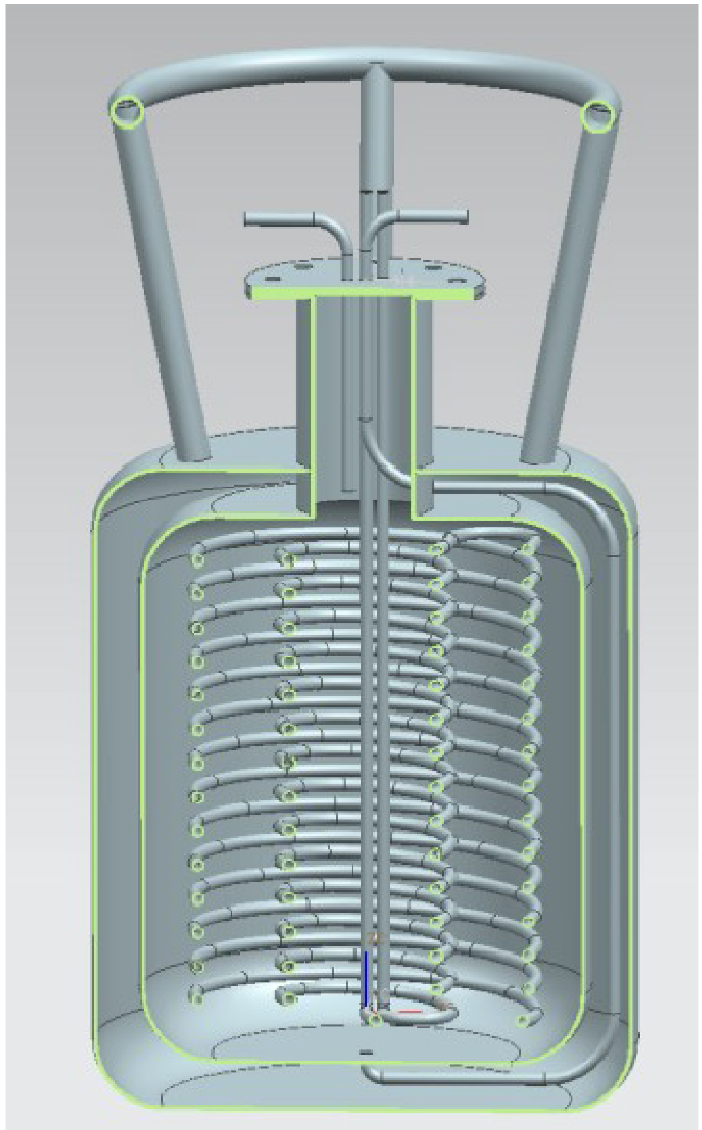


Figure 1. Crossectional view of the 25L methane condenser design.

As the temperature in the dewar decreases and the methane begins to condensate, the cryogen will begin to accumulate at the bottom. A manifold of gas methane connects to the dewar keeping the pressure constant. Figure 2 shows a possible arrangement of the manifold and the condenser. The condenser has a capacity of 25 L due to it being readily available in the cryogenic industry. This size of condenser provides enough capacity for operating all of the experiments that are currently being considered while being small enough to not present a significant liability to the laboratory. The condenser can also act as a long term storage vessel for the liquid methane. The methane used in the condenser will be a C.P. grade or high purity gas methane in order to avoid any kind of contaminants

fouling the condenser. It was determined that in order to supply the liquid methane demand for the cSETR experiments a condensation rate of 1.75 L/hr should be achieved.

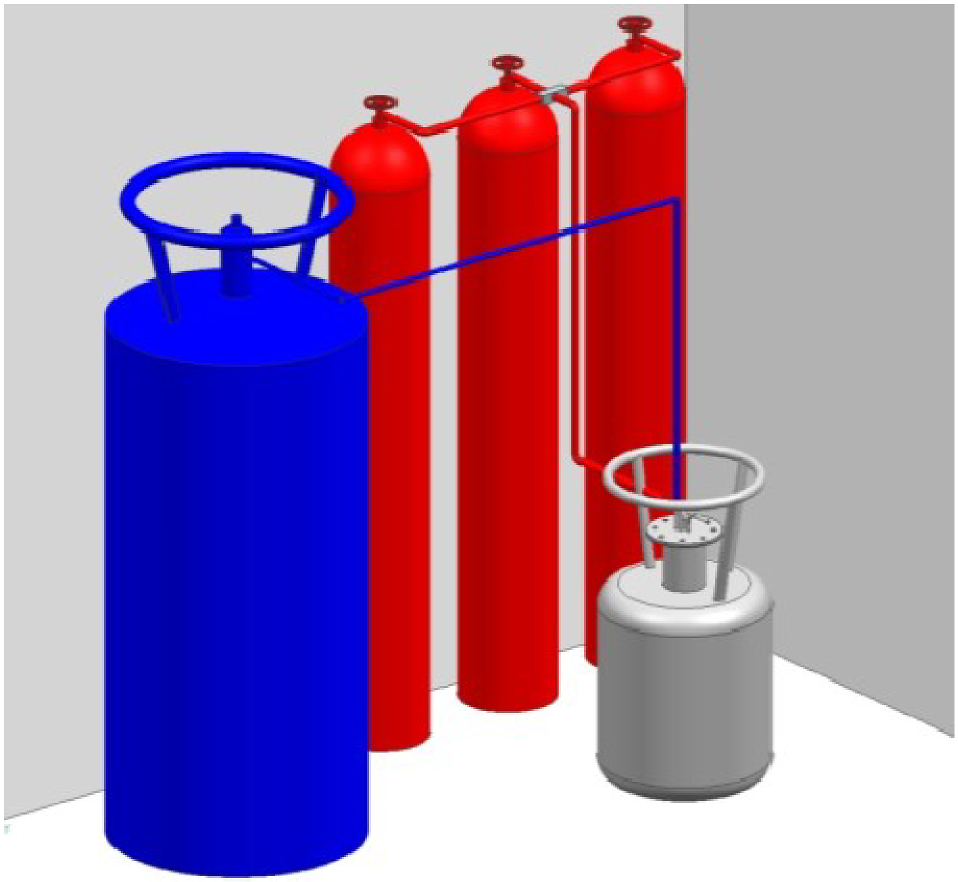


Figure 2. Methane condensation system with the gas methane in red and liquid nitrogen in blue.

One of the challenges encountered when designing the condenser was finding an effective way of measuring the condensate levels. The simplest method is by placing the condenser on a scale and measuring the weight change thus yielding the production amount. This method, while convenient, causes multiple errors due to the forces that the manifold exerts on the condenser. The cryogenic industry offers several solutions to this problem such as float level gauges, sonar level gauges, and laser level gauges. Even though these level gauges offer a low possibility of error, they also have high complexity and cost. A simple and practical solution then is to have a vertical thermocouple array. This array would measure the temperature change inside the dewar as methane condenses and based on the

position of the thermocouple it would provide an accurate level gauge. All of these solutions are valid and most likely a combination of some of them will be selected for the 25L condenser.

In order to calculate the parameters of the heat exchanger, an energy and heat transfer model was formulated. The first step was to calculate the mass and volume baseline between the condensed methane and the required liquid nitrogen. Utilizing the equation (3.1), it was determined the energy required to condense 10L (4.3kg) of liquid methane at 1Mpa.

$$Q = \dot{m}\int_{T_1}^{T_2} C_v dT \tag{3.1}$$

The pressure of 1Mpa was selected in order to operate in liquid phase of methane (see Appendix B for methane phase diagram). The amount of liquid methane necessitated for various experiments is shown in Table 5 along with the rates of demand for other propellants. The MOAC requires a maximum of 7L of liquid methane but to account for ullage and tank transfer losses, a 40% overproduction was included for a total of 10L.

Table 5. Propellant demand requirements for different test hardware or test stands.

	Liquid Methane			Liquid Oxygen		
Experimental System	Flow Rates		Max Pressure	Flow rates		Max Pressure
	Min (g/s)	Max (g/s)	(psi)	Min (g/s)	Max (g/s)	psi
Heat Transfer	0.337	3.37	190	--	--	--
MOAC	0.2	3.8	190	0.09	13.3	190
MASS	--	2.3	115	--	7.9	115

The energy determined from equation (3.1) was roughly 3800 KJ in the form of heat removed from the methane at room temperature. Reiterating the above equation but now solving for the mass of nitrogen, it has been calculated that roughly 17kg of liquid nitrogen are required to condense 10L of methane. Once the mass of both fluids was determined, a heat transfer model could be developed to calculate the geometry of the coil utilizing Newton's second law of cooling (equation 3.2).

$$Q = U\,A\,\Delta T \tag{3.2}$$

A is the outer surface area of the coil and U (equation 3.3) is the multi heat resistive term (Figure 3) that takes into account the different types of heat transfer that occur in the condenser. The ΔT term represents the log meant temperature difference which is commonly used in heat exchanger design [Cengel, 2007].

$$U = \frac{1}{\frac{1}{h_{natural}} + \frac{\ln\left(\frac{D_0}{D}\right)}{2\pi k l} + \frac{1}{h\,forced}} \tag{3.3}$$

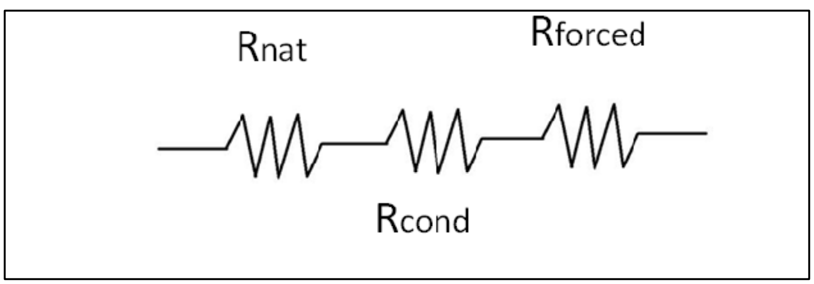


Figure 3. Multi resistive heat transfer displayed as electrical resistance

The coil line diameter was selected to be .635 cm (.25 in) since it will keep a high Reynolds number (>3000) when the nitrogen is in a liquid phase. In addition, this type of tubing is readily available through local vendors. One of the assumptions of the model was that the liquid nitrogen would go through a phase change. This phase change would create a choke point allowing the calculation of the mass flow of nitrogen possible. This calculation could be performed based on the tubing dimensions and upstream pressure of the coil. The phase change would also yield higher heat transfer due to the latent

heat of vaporization thus capturing more thermal energy. The challenge with this assumption was finding the point at which the nitrogen would phase change. Utilizing the heat transfer model, a simulation with all gas nitrogen was done. The same simulation was calculated for all liquid nitrogen in the coil. The all liquid line yielded a higher heat transfer resulting in a shorter coil. By choosing the worst case scenario, the all gas coil yielded a minimum length of 17 m.

3.2 Proof of Concept

3.2.1 Development

Once the heat transfer model and the parameters of the 25L condenser had been determined, it was necessary to create a small scale experiment in order to validate the model. The small scale system was constructed out of a 1L cryogenic dewar with a Stainless Steel lid, a 1 m coil that was manufactured in-house with a 3.175mm stainless steel line, an E-type thermocouple, a pressure relief valve, and a manifold to a methane tank and liquid nitrogen tank. Figure 4 displays the layout of the set up.

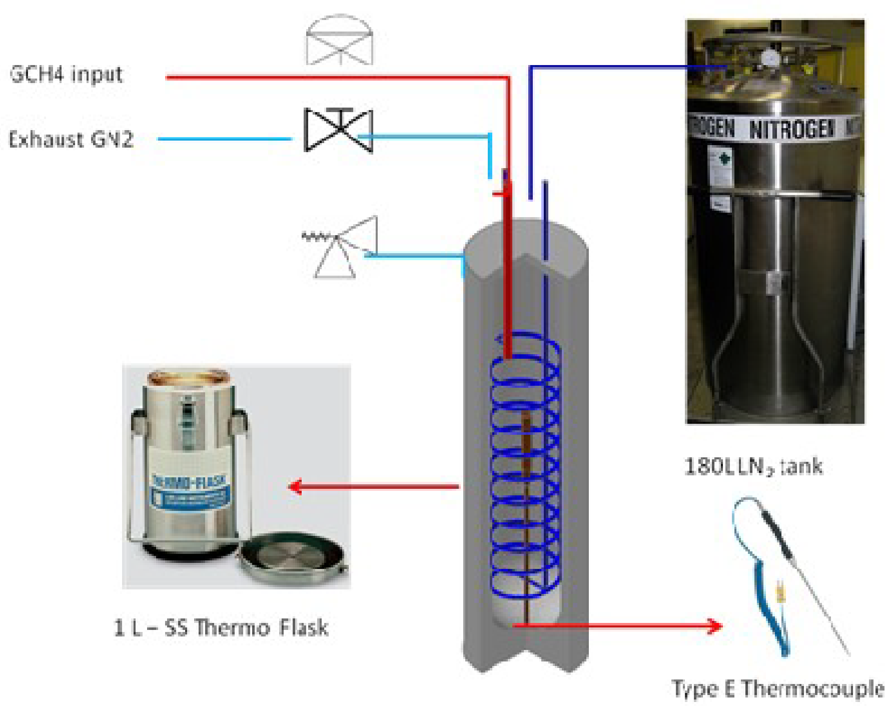


Figure 4. Proof of concept schematic. 1L dewar depicted with main components

The entire unit is placed under a scale to monitor the weight change and the thermocouple records the temperature of the methane as it is being cooled down by the nitrogen flowing in the coil. In addition, the exiting line of the coil is attached to a flow meter and a thermocouple in order to record the amount of LN_2 used and the respective temperature. The system was insulated by using aerogel cryogenic insulation. Figure 5 shows the actual test configuration.

Figure 5. Proof of concept 1L dewar test setup.

3.2.2 Test

The system was operated by first creating a vacuum in the dewar using a vacuum pump. Once vacuum was achieved, the dewar was pressurized to a constant 5psi. After pressurization, the liquid nitrogen line was then opened. The system was operated continuously for 35 minutes with data recorded each minute gathered from the thermocouple, the scale, and the flow meter.

3.2.3 Results and validation

In order to validate the heat transfer model it was first necessary to account for the errors and uncertainties of the system. Errors in the system are present in the measurement devices (flow meter, scale, etc.) and the components in the system affecting the measurement devices. The error for the measurement devices was provided by the manufacturer, but the error found in the components presented a challenge. The manifold line that connects the methane and nitrogen bottles to the dewar creates an error in the scale that had to be accounted for. An FEA model was created in order to calculate the stiffness of the line and the error that this created. After several models and calibrations, the error caused by the stiffness in the stainless steel line was calculated to be 1.13%. The final uncertainty of the measurement devices was found to be 10.06% (equation 3.4).

$$Bias\ Uncertanty = \sqrt{\sum (error^2)}$$

(3.4)

The overall effectiveness (ε) of the unit is 34.3% +/- 3.45% by considering the production target of 10L of methane in 3 hours under the 1L dewar production rate of 0.125Kg per 35min (equation 3.5).

$$Production_n = \frac{mass_{CH_4}}{mass_{N_2}}\ ;\ \varepsilon = \frac{Production_{Actual}}{Production_{Theoretical}}$$

(3.5)

The performance of the 1L dewar is at 15% of the target for the 25L dewar, but is important to note that this figure does not account for a non-dimensional parameter. However, this proof of concept was designed to show that the basic concept of the heat exchanger and the condensation process works as intended [Pineda, 2011]. Further work should focus on the study of the non-dimensional parameters and multiple measurement devices as to reduce the error present on the system. Future work should also include a system to safely dispose of the methane created either by means of a burner or boiled off into the atmosphere.

3.2.4 Simulation

A heat transfer simulation was performed on the 1L condenser in order to benchmark the model that was first developed. The simulation was performed with the ANSYS software and was done under the assumptions such as no phase change in the coil and constant wall temperature. Even though these assumptions do not represent the reality of the conditions present in the condenser, the simulation will yield a good benchmark for the hand calculations. Figure 6 shows the heat transfer model calculations compared to the simulation results. The simulation and the calculations were performed with a coil filled with all liquid nitrogen and again with all nitrogen gas. This simulation shows that the heat transfer coefficient from the simulation is close to the heat transfer model calculations.

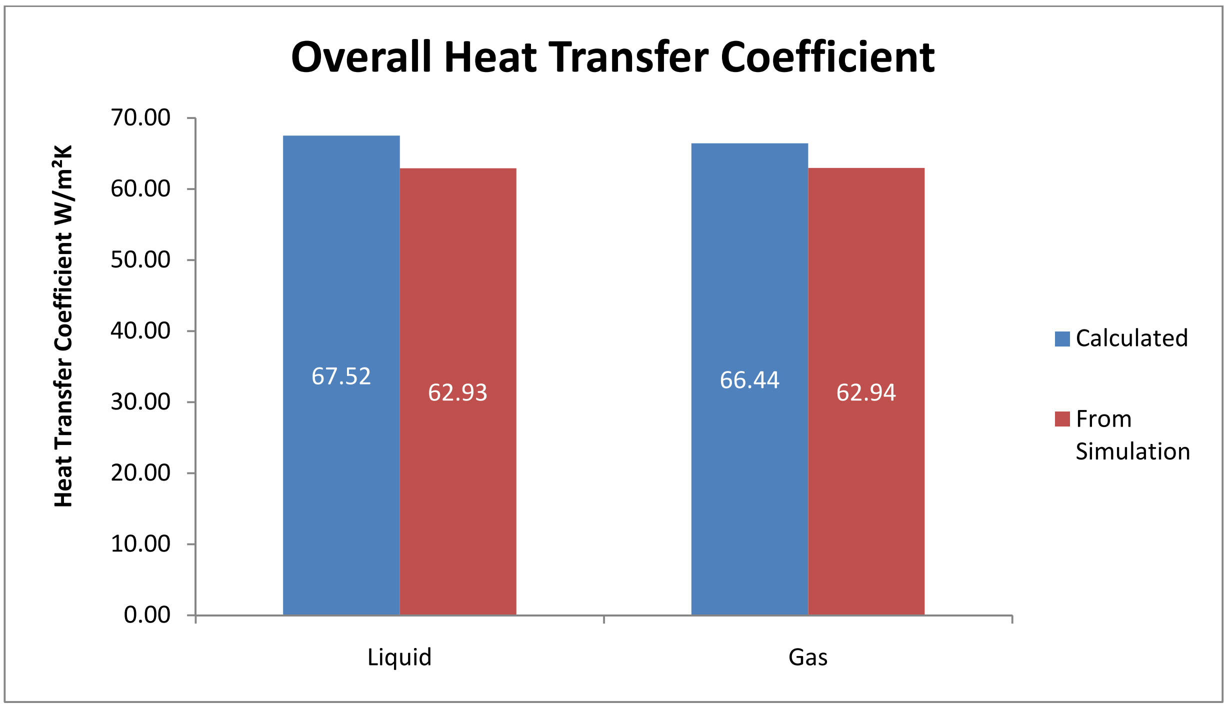


Figure 6. Compares a heat transfer simulation results to previously calculated heat transfer model.

3.3 Future development

A second generation condenser is currently being operated and a third generation condenser is being constructed. These condensers are 2.5L and 12L, respectively, and were designed utilizing the calculations and experiments that were conducted with the design of the 25L condenser and the proof of concept design. Different manufacturing techniques are being explored such as modification of existing

systems such as test tank modification or complete custom manufacturing. The full scale 25L dewar is scheduled to begin construction in Fall 2012. Figure 7 shows the 2L condensing unit.

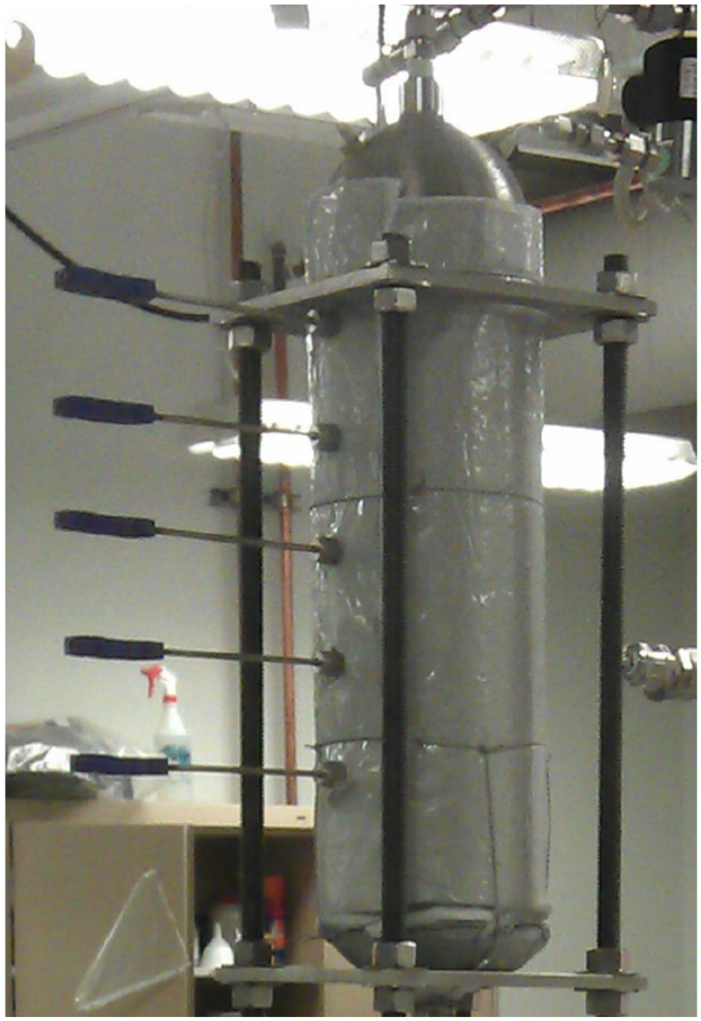


Figure 7. Second generation 2L condensing unit. A thermocouple array is used to measure the condensation levels.

Chapter 4: Cryogenic Delivery Feed System

A delivery system has been developed in order to be able to supply the experiments with their respective propellant supply. The challenges presented by this system include: test stand and hardware integration, delivery of propellants in a cryogenic state, remote operation of delivery system, and overall system safety. Furthermore, the system must support the feed requirements of the experimental hardware. This chapter will discuss the design, development, and operation of the cryogenic delivery feed system.

4.1 System Integration

4.1.1 Bunker

Due to the design and corresponding safety concerns, the cryogenic delivery feed system is located inside the Goddard's ballistic proof bunker. The bunker contains three separate ventilation shafts, double doors that open to the outside of the engineering building, double doors to the Goddard laboratory, and a single door that also opens to the laboratory. The bunker is insulated with ¼ inch Kevlar sheets and a bulletproof window making the facility ballistic proof and optimal for propulsion or combustion experimentation. The bunker has six 120V outlets, ventilation switches and a compressed air line. In addition, the bunker has two cable ports that allow for cables to be run from the bunker to the adjacent control room. The design of the delivery system must use these resources efficiently and allow for experiments and other hardware to operate inside the bunker. Figure 8 shows a CAD design top view of the bunker.

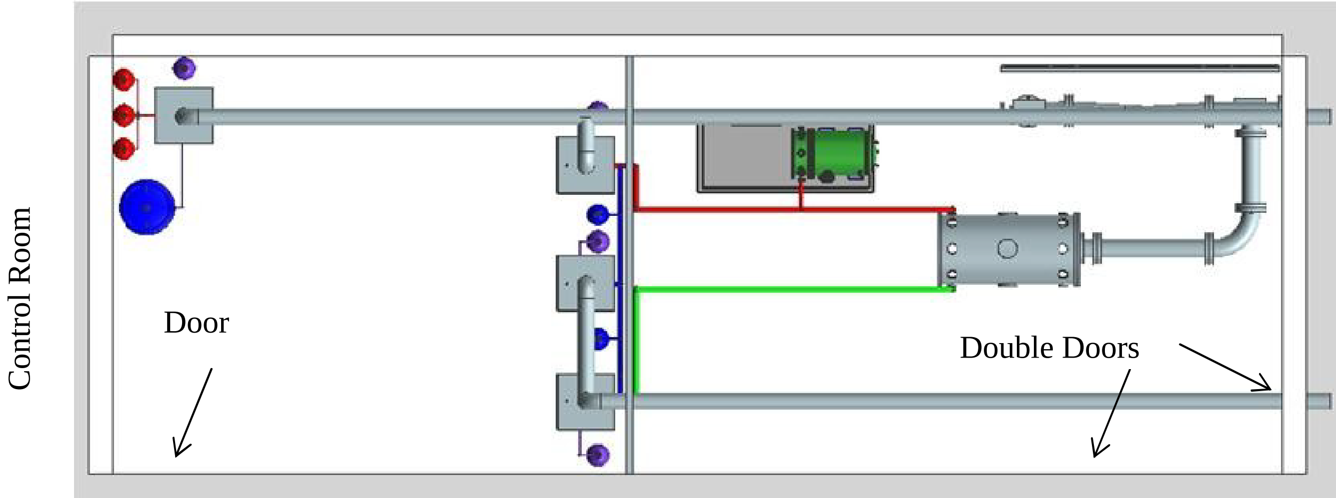


Figure 8.Early CAD design showing a top view of the bunker facilities. From left to right: Methane condensation system, tank storage, Kevlar separator walls, high heat transfer rig, and MASS system.

4.1.2 Methane production system

The methane production system will be stored in the bunker and must also operate remotely from the control room. The methane production system must integrate into a run tank that will be part of the delivery system. The run tank must be able to store the maximum production capabilities of the methane condensation system of 25L.

4.1.3 MASS System

The MASS (Multipurpose Altitude Simulation System) is a system where combustion and propulsion experiments can be conducted at a simulated altitude of 85,000 ft. (20 Torr). The MASS is composed of 2 main components: a 5 ft. long 48 inch wide cylindrical vacuum chamber and a 2 stage air ejector system Figure 9.

Figure 9. MASS system coupled with the two stage air ejectors.

The vacuum chamber has visual ports in the middle that allow visual instrumentation to be operated including high speed cameras, P.I.V. (Particle Image Velocimetry) systems, Schlieren units or monitoring cameras. Moreover, the vacuum chamber has 16 feedthroughs for any additional instrumentation or hardware that is needed. The two stage air ejector can create a vacuum of 20 Torr while operating a 15lb LOX/LCH_4thruster (368 Isp). The air ejectors will be powered by an air compressor. Currently the system is not operational due to the absence of the air compressor but is scheduled to be online by fall 2012. The MASS has a stainless steel plate with a grid of screw holes in the fashion of an optical table in order to allow any type of instruments or experiments to be secured. The delivery system needs to be compatible with the MASS and operate under such conditions.

4.1.4 Atmospheric Test Stand

In order to conduct testing at atmospheric conditions, a test stand was developed that could accommodate for different experiments to be conducted inside the bunker. The test stand was constructed out of 80/20 aluminum beams and is approximately 5ft long by 3ft wide. Figure 10 shows an

example of an experiment installed in the test stand. Due to the limited size of the bunker and the larger size of the test stand, special accommodations and modifications must be done in order to operate any experiment in the atmospheric test stand.

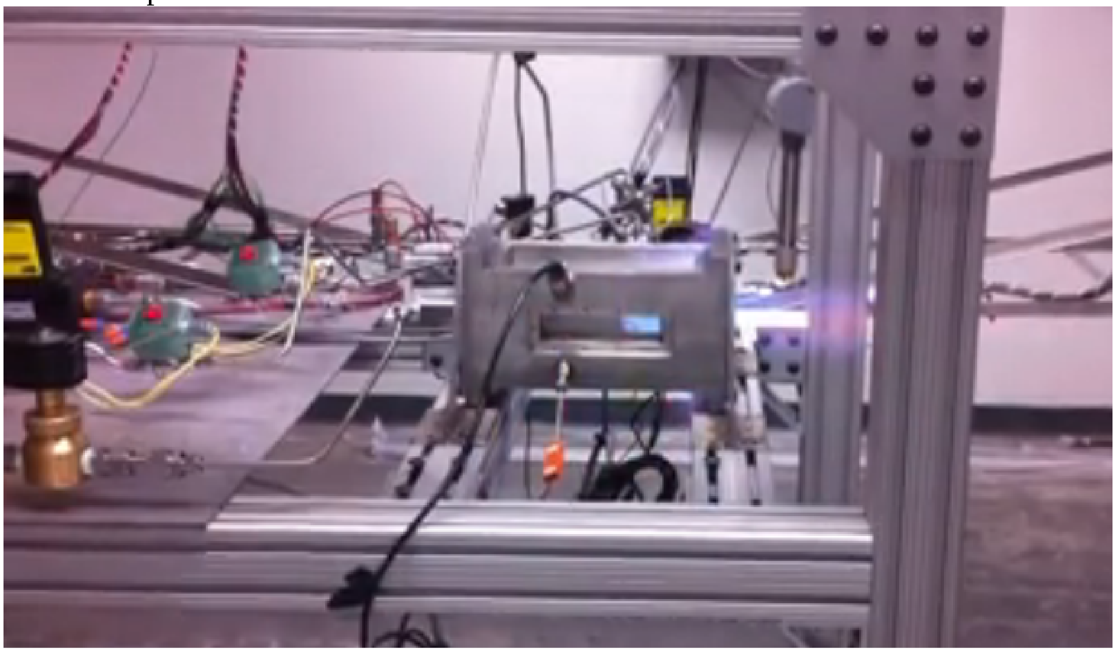


Figure 10. MOAC testing on the atmospheric test stand.

4.1.5 Experimental Hardware

MOAC

The Multipurpose Optically Accessible Combustor (Figure 11) is an experiment that studies the combustion characteristics of bi-propellant engines [Navarro, 2011]. This experiment was developed at the beginning stages of the delivery system design and at the time was the test article with the highest demand for propellants. The delivery system was developed with the operational capability of the MOAC. The demand for this experiment is 3.8 g/s of LCH_4 and 13.3 g/s of LOX both at 190 PSI. These values are the equivalent of a 15lb LOX/LCH_4 thruster at 368 Isp. The combustor would need to be capable of operating in the atmospheric test stand and the MASS.

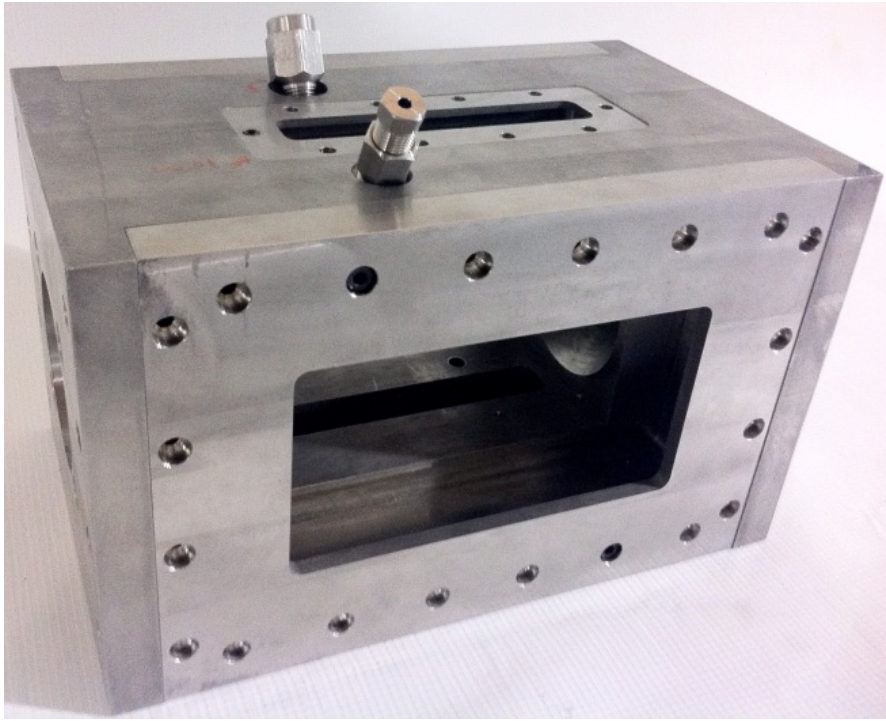


Figure 11. The MOAC experiment.

High Heat Transfer Rig

The high heat transfer rig is an experiment that studies the thermal properties of liquid methane. When the design process of the delivery system was started it was one of the objectives to provide support to this test article. Due to the small demand of propellant that the experiment required (0.03 g/s to 3.37 g/s of LCH_4, shown on Table 5) it was possible to operate this experiment with the proof of concept condenser, thus this experiment will no longer be considered as an objective for the delivery system.

Pencil Thruster

The pencil thruster is an experiment that attempts to characterize the performance of a Reaction Control System (RCS) thruster that utilizes LOX/LCH_4 as propellants. This experiment was brought to be coupled with the delivery system when the delivery system was in the final stages of assembly. Due to said circumstances, this experiment is not expected to be fully supported and will operate at the maximum performance of the delivery system.

4.2 DELIVERY SYSTEM DESIGN

The delivery system extends for more than half of the length of the bunker (15 ft. long) and divides the bunker into two sections: the tank compartment side and the experiment side. The tank compartment side holds all of the k-bottles and cryogenic tanks. On the experiment side is where the lines, components, and instrumentation are located. The lines are supported by a stainless steel support structure that holds the equipment and the lines in order to avoid unwanted vibrations and stress on the lines. The delivery system consists of 4 major parts: the oxygen delivery, methane delivery, chill system, and purge system.

4.2.1 Layout

The layout of the delivery system was created using an in-house convention for the symbols representing the instrument. Every component has an inventory tag that helps to keep the inventory and related information about each component in a database. The inventory tag also informs the reader about the position and location of the item in the system. The last term in the inventory tag represents the type of component (i.e. AV means Actuated Valve). The tags were of great aid when the system was programed in the DAQ and controls system.

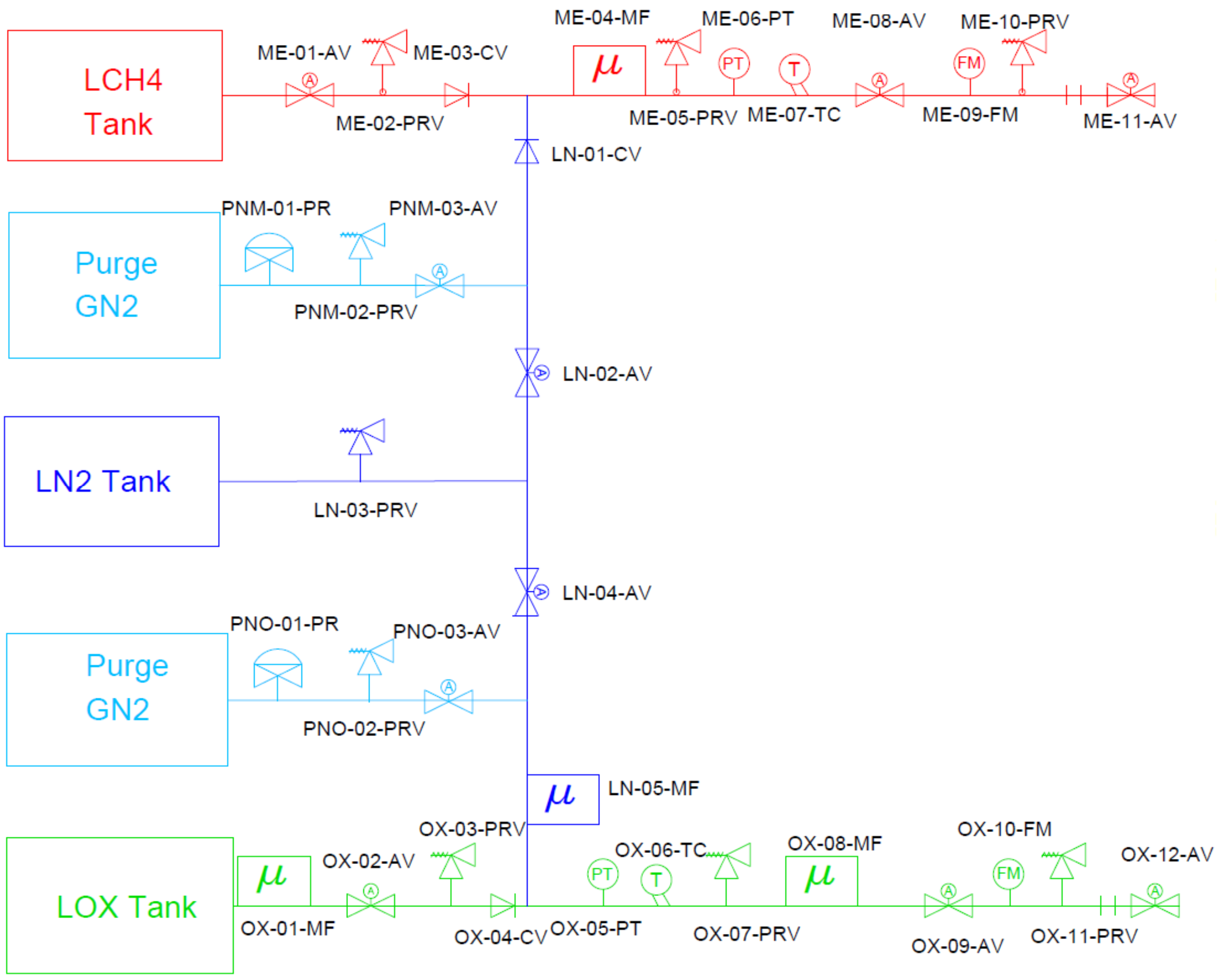


Figure 12. Cryogenic delivery system layout. The color codes are as follow: Green-oxygen, red-methane, light blue- gas nitrogen, navy blue- liquid nitrogen.

4.2.2 Liquid Oxygen

The LOX delivery system is different from the methane delivery system in a few aspects: There are two filters in the LOX line, and the purge and LN_2 lines pass through a filter before entering the LOX line. The components on this system are treated with special care and attention to avoid any type of contamination. The configuration of the valves allows for the system to be primed which is where the entire line is filled with the propellant and a delivery lag can be avoided. The system ends towards the test article, but it is important to note that there are two set ups in place: one that goes to the MASS and another line that goes to the atmospheric test stand. These lines are disconnected when one of the test stands is in use. This is shown in green on Figure 12.

4.2.3 Liquid Methane

The methane delivery system is similar to the oxygen but has only one filter. The methane delivery system also has the lines in place to operate in the MASS. and in the atmospheric test stand. Figure 12 depicts this in red.

4.2.4 Liquid Nitrogen

It was important for the design of to accommodate a pre-chill system in order to avoid boil-off and excessive gasified propellants in our ventilation system (Figure 12). The liquid nitrogen will be used before and in-between tests thus ensuring that the propellants will arrive in cryogenic state to the test article. In order to determine the amount of nitrogen required to cool down the system, Figure 13 shows the relationship between mass of nitrogen, mass of the lines and the temperature.

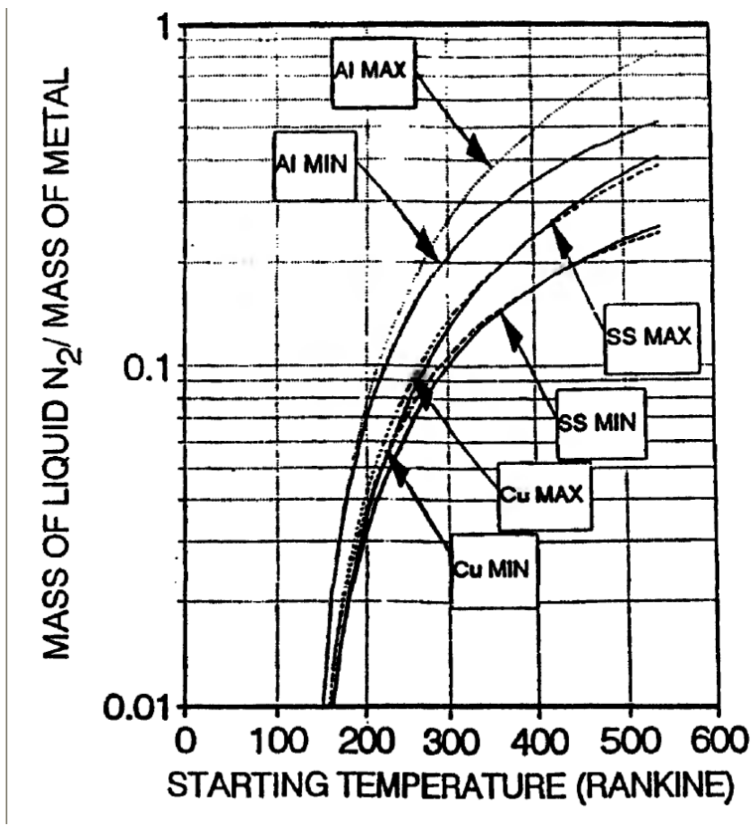


Figure 13. This graph allows for the approximate calculation of LN_2 required to perform a system cool down

For a 67.7 ft long stainless steel line with a ½ inch diameter and a temperature of 540°R, this relation yields approximately 26 kg or 32 L of liquid nitrogen for the initial cool down. If conducting four tests and an overshoot of 40%, a total of 151 L of LN_2 will be required.

4.2.5 Purge

The purge system utilizes gas nitrogen and is required in order to evacuate any nitrogen or trapped propellants between tests helping to clean the lines of any sediment or particulate that might be trapped in the line. In addition, the lines can be pressurized to perform leak and functionality checks. This is illustrated in light blue in Figure 12. This system is also necessary as a safety precaution in case of an emergency such as a fire or a similar event.

4.3 Components

Most of the components in the delivery system utilize NPT or Swagelok fittings. The high availability of NPT fittings in the cryogenic industry permit for the standardization of this type of fitting in our system. In addition, the laboratory has had training and experience handling Swagelok equipment and fittings, allowing for the convenient use of this fitting type between lines and some other components.

4.3.1 Lines

The lines of the delivery system consist of ½ inch high purity 304 stainless steel lines. For the flow rates that were required, a ½ inch line provides a low Reynolds number (<2000), thus reducing the heat losses and minimizing the risk of a sudden detonation in the LOX line. All of the bends in the system are at least 3 times the size of the line (1.5 inch radius) in order to avoid any instability in the LOX. Most of the components have an NPT fitting therefore a NPT to Swagelok fitting is used to connect the components to a section of line. At the end of the delivery system there is a cryogenic flexible stainless steel hose that connects to the MASS. This connection can be disconnected and attached to a line that redirects to the atmospheric test stand. All of the cryogenic lines are insulated using Cryogel Insulation. This insulation provides optimum insulation for cryogenic applications.

4.3.2 Tanks

Current testing does not involve the use of any cryogens thus most of the testing being conducted involves the use of gases. These gases come stored in K-bottles at a set pressure of 3000 psi. The flow rate is controlled by regulating the pressure out of the tanks. The k-bottles are stored in bottle holders that are specifically made for this purpose. The tanks will be acquired from local vendors once testing requires the use of cryogens. The tanks can be set by the distributor to the desired pressure dictated by the test. These tanks can be pressurized up to 250 PSI which is over the maximum operating requirement of 190 PSI for the M.O.A.C. The liquid methane run tank will be a 25L self-pressurized tank that will be able to be also pressurized up to 250 psi. The methane run tank will be able to couple with the methane production system and transfer the fuel from one tank to the other.

4.3.3 Valves

The delivery system is composed of a variety of valves such as: pressure relief valves, actuated valves, and check valves. The valves play an important role in the design of the system since they are the determining factor in the ceiling performance of the entire system. The actuated valves that have been found to be compatible in the system range in expense from hundreds of dollars to thousands. Ultimately, through our findings the increase in cost came with an increase of performance and features. Due to budget constrains the actuated valves that were chosen determined the performance of the entire system. The valves have the following specifications: 120V, brass body, FNPT connections, oxygen service ready, and a maximum pressure of 225 psi (figure 14).

Figure 14. Cryogenic solenoid valve.

The pressure relief valves are industry standard and are set with a burst pressure of 200 psi. The pressure relief valves have a brass body and a ½ inch MNPT fitting. Every pressure relief valve is located in a potential cryogenic liquid trap point and will potentially release any built up pressure that might be generated by the boil off of the cryogen. The check valves are also composed of a brass body with FNPT fittings and a burst pressure of 5 psi. The check valves are located in places where there could be a backflow issue, for example in the joints between the LOX feed system and the purge/cool down union. Both the pressure relief valves and check valves were purchased from the Ratermann manufacturing catalog. The valves have an important role in the safe and controlled delivery of the propellants to the test article.

4.3.4 Filters

The handling of LOX requires extensive safety precautions in order to avoid the risks associated with handling the cryogen. The delivery system has a series of filters that attempt to clear any particulates from the delivery system and avoid ignition sources in the LOX lines. The filters are cryogenic specific filters with a stainless steel body and ¼ inch FNPT fittings. The LOX system incorporates a total of 3 filters: one in the purge/chill down system and two on the LOX line. The filters in the LOX line are 25 μ while the rest of the filters in the delivery system are 40 μ. The filter size was determined by the desired cleanliness level.

4.3.5 Measurement devices

In order to monitor and record the delivery process to the test article, a series of sensors are located along the delivery system. These sensors such as temperature diodes, pressure transducers and flow meters are combined with a Data Acquisition system (DAQ) and a controls system.

Diodes

When the proof of concept condenser was developed an E-type thermocouple was used. The use of this thermocouple presented unforeseen issues like erratic readings and long term heavy cycle issues. These issues created the need to find a replacement sensor that could withstand the extreme

temperatures of the cryogenic propellants for long cycles. Said sensor was the Lakeshore cryogenic temperature diode, which is a sensor that is widely used in the cryogenic industry for temperature monitoring and offers a longer service life than a conventional thermocouple (figure 15).

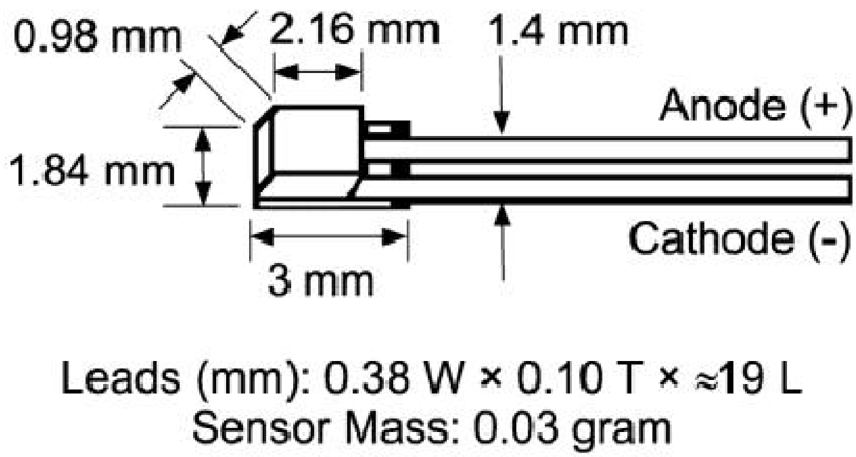


Figure 15. Lakeshore silicon diode.TD-400 series diagram

The diodes can be installed in different ways; but the selected method was to use a low temperature epoxy and attach it to the surface of the stainless steel line. By installing the diode in this way there will be a temperature lag however a fast temperature response is not necessary. The temperature diode has an excitation signal 10 µA and an output signal of 15V DC. These diodes are connected to a temperature monitor and the DAQ system for redundancy.

Pressure Transducers

Due to the requirement of remote operation, a cryogenic pressure transducer is accommodated in to the system. This pressure transducer is an Omega cryogenic thin film pressure transducer (Figure 16) that is designed to operate in a minimum temperature of 77K. The transducer requires a 10 V DC excitation and provides a 0-30 mV DC feedback signal. Since this sensor is considered critical it is also connected to the DAQ and a separate Omega pressure controller. The pressure transducer has a stainless steel body and it is supplied by the manufacturer as oxygen service ready.

Figure 16. Thin film cryogenic pressure transducer.

Flow Meters

There are many ways of monitoring cryogenic flow rates but the cost and complexity of the sensor can vary drastically. Some of the different flow meter varieties are: Ultrasonic, mass vortex, electromagnetic induction, turbine, and Coriolis flow meters. The flow rate in the system varied from 0.013 to 0.018 GPM in the LOX and 0.01 to .014 GPM for the LCH_4. These flow rates are the flow requirements for the MOAC system operational range of 1-17lb of thrust. According to several companies that were contacted, said flow rates were determined to be “small” thus limiting the selection of flow meters that could operate at this range. A Hoffer turbine flow meter for the LOX system was selected with an operational range of 0.017 to 0.12 GPM. Note that this flow meter will not provide the desired range of operations as dictated by the MOAC requirements. Figure 18 shows the cryogenic flow meter controller that is connected to the DAQ system. This flow meter will only provide a theoretical thrust measurement of 1 lb to 11 lbs. One of the drawbacks of a turbine flow meter is to avoid the overspinning of the turbine as it could lose the calibration or damage the turbine, therefore special attention must be given to the flow meter when running gases. Currently there is no LCH_4 flow meter installed in the delivery system. During the first stages of development only gas propellants were being tested and the cryogenic flow meters could not be operated, therefore gas flow meters were used. Omega FMA1800 gas flow meters were selected with a range of 0 to 500 LPM (liters per minute). These flow meters require an excitation voltage of 12V DC and yield a feedback signal of 0 to 5V DC back to the DAQ system. Figure 19 shows the gas flow meters.

Figure 17. Hoffer turbine flow meter.

Figure 18. Hoffer flow controller.

Figure 19. Omega Gas flow meters.

4.4 DATA ACQUISITION AND REMOTE CONTROL SYSTEM

In order to provide a safe remote operation and monitoring of the delivery system the Data Acquisition and Remote Control System (DARCS) was created by Jesus Betancourt (J. Betancourt-Roque). This system supports the test operations conducted in the bunker facilities of the Goddard laboratory. The DARCS integrates all of the instrumentation and components into an operable interface by means of a patch panel, a computer/DAQ, an array of relays and power supplies. Figure 20 shows the control room from where all testing is conducted.

Figure 20. The control room.

4.4.1 Patch Panel

To have a convenient interface between the bunker and the adjacent control room, a patch panel was constructed out of an electrical cabinet with an array of ¼ inch audio plugs installed in the front. One of the panels was placed in the middle of the bunker while the other was installed inside the control room. Connections were soldered from one array of the audio plugs to the other. By having these panels it was easy to connect an instrument such as a valve or a thermocouple from the bunker to the control room and rearrange it for different experiments. On the control room the panel was wired to a relay array and the computer/DAQ. This configuration allows the delivery system to be controlled through the computer interface (e.g. LabView) or a set of manual switches. In case the computer loses communication to the delivery system, the manual switches act as a redundancy to the operation. Figure 21 shows the patch panel with the connections in place.

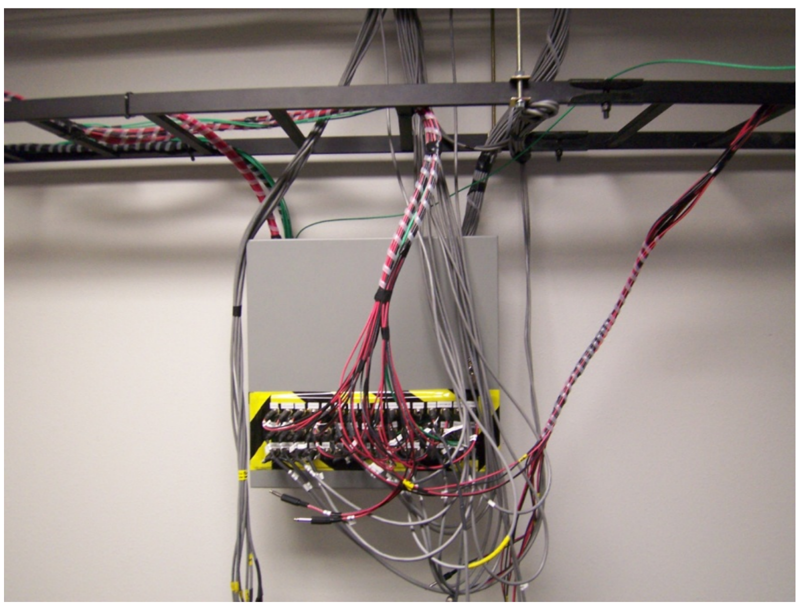


Figure 21. Patch panel located inside the bunker.

4.4.2 Computer/DAQ

An industrial computer equipped with PCI cards from National Instruments is used as the primary operations interface with the use of the LabView software. The PCI cards are connected to the patch panel and are able to control and record the experiments conducted in the bunker (Figure 22). Once the hardware was implemented, Virtual Instrument was developed to control the experiments

(Figure 23). This program allows for steady state or pulsed operation of the experiment, displays instant sensor information, and records the generated data.

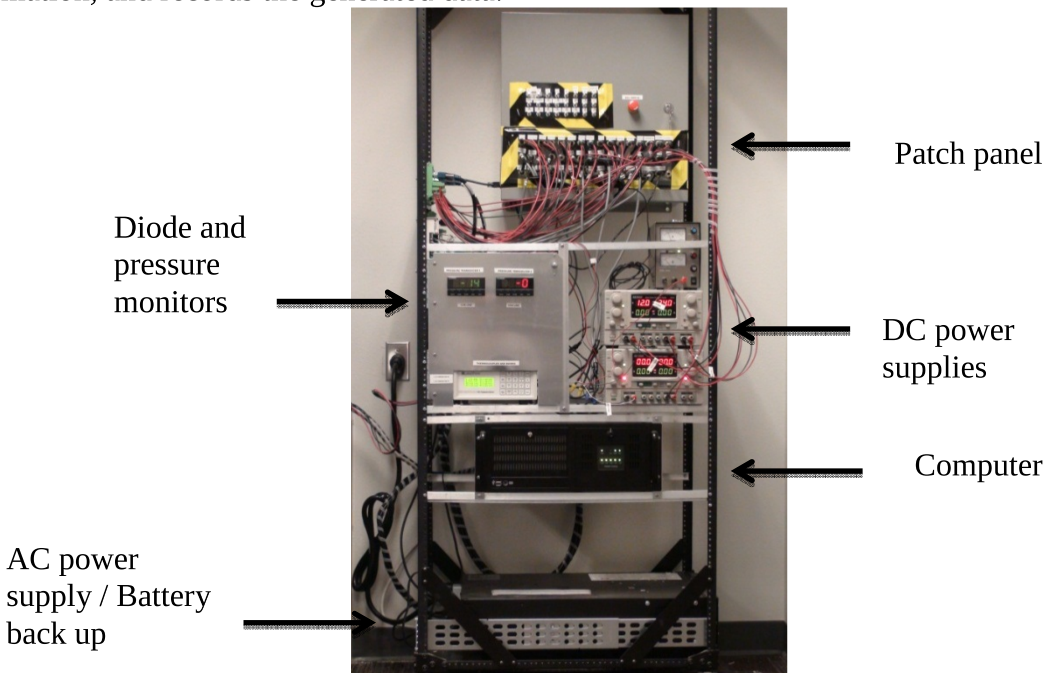


Figure 22. DARCS system on the control room. The patch panel (top), Pressure transducer monitor and diode monitor (center left), DC power supplies (center right), computer (center), AC power supply/back up system (bottom)

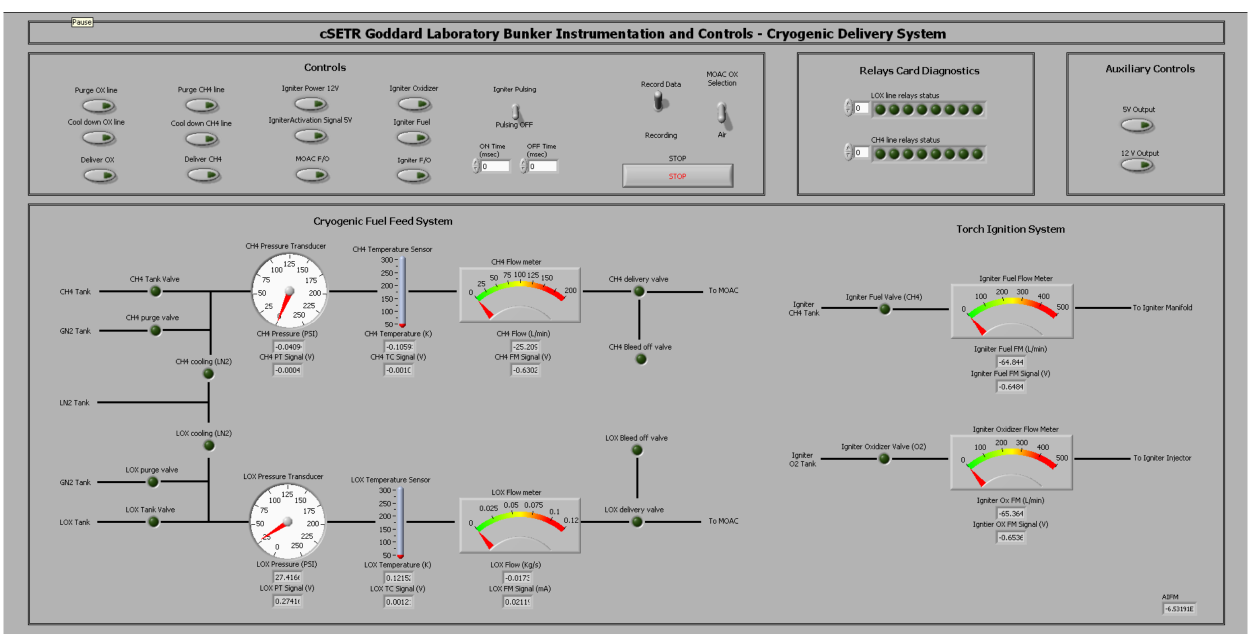


Figure 23. GUI of program that was developed to operate the DARCS

4.4.3 Power system

Due to the different components that must be powered, the DARCS has DC and AC power supplies (Figure 22). DC power is provided by two EXTECH power supplies. The DC power is provided by an APC power supply that also acts as a battery backup. This battery backup has enough power to provide the DARCS with 30 minutes of power in the event of a power outage.

4.4.4 Video monitoring

The entire operations that are conducted in the bunker can be monitored and recorded through a Digital Video Recording (DVR) system. This system is equipped with 4 cameras that can be positioned in most locations inside the bunker. The DVR system is displayed on a 55 in. TV that allows for the simultaneous display of the 4 video feeds (Figure 24).

Figure 24. Video monitoring being displayed on the TV

4.5 Safety

The delivery system is equipped with several safety features that are in place to maintain safe conditions for the facilities and the personnel.

4.5.1 Ventilation System

The ballistic proof bunker is equipped with three different exhaust ports. One of the ventilation ports is connected to an exhaust fan that services the exhaust ports for the entire Goddard laboratory. The other two ports are powered by separate inline exhaust fans. These fans provide approximately 100 CFM of air flow and are attached to separate 4 inch schedule 40 stainless steel pipes. These pipes or "exhaust vents" eject the exhaust gases to opposite sides in the east side of the bunker. By extending the stainless steel pipes with stainless steel ducting, a ventilation system was assembled and configured to capture any type of gases that might be ejected by the relief valves of the tanks or the delivery system. The ventilation system captures methane and nitrogen independently from the oxygen (Figure 25).

Figure 25. Stainless steel ducting on top of the delivery system.

4.5.2 Kevlar separator walls

Utilizing the same material that was used to insulate the bunker, kevlar sheets were modified and turned into 4 movable walls (Figure 26). These walls separate the bunker into two separate sides: the side that contains the tanks and the side where experiments are conducted. The tank storage side is then

separated into the fuel and oxidizer sections. All of these separations are meant to block any debris in case of an explosion and to slow the diffusion of any combustible gases that might not be captured by the ventilation system.

Figure 26. Modified movable Kevlar wall.

4.5.3 Safety Lights

A safety tree light was installed outside the bunker in order to inform all personnel of the status of the bunker. The light has three lights that can be activated from the control room: green, yellow, and red. The safety team assigned different codes to each respective color:

- Green: Proceed with caution, authorized personnel only.
- Yellow: restricted area except safety and test personnel. Proceed with extreme caution.
- Red: Area off limits to all personnel, test in progress.

4.5.4 Cleaning

All of the components in the delivery system are oxygen service ready. This allowed having a system that is fully-functional out of the box. Due to the required level of cleanliness of a LOX system, all components were cleaned separately and reassembled. Special attention was given to the stainless steel pipes in order to avoid any shavings that might have been created in the cutting process. The cleaning process includes soaking the component in nitric acid, sodium hydroxide, and then being rinsed in distilled (DI) water. Components with brass or copper were only rinsed with DI water. The components are then stored in a double sealed bag and installed when ready to use. As part of the test procedure, the system is purged for long periods of time to remove any contaminants that might still remain in the lines.

4.6 TEST AND PERFORMANCE

The initial tests were performed with the DAARCS as the control interface and the MOAC as the experimental hardware on the atmospheric test stand. The first set of testing was done with gas propellants in order to debug and correct possible issues that might arise. The delivery system has also been tested with the pencil thruster in the MASS system.

4.6.1 Procedures

All testing first needs to be approved by the center's director. The test application must contain the procedure and a Failure Mode Effects Analysis (FMEA) (see Appendix C and D). Once these forms are approved the team can begin the physical test. The control room is operated by a minimum of three operators: a test director, test operator, and safety supervisor. The role of the test director is to dictate the procedures and set the test parameters. The test operator is in charge of executing the test through either the LabView software or the switch panel. The safety supervisor is in charge of overlooking the test and ensuring the safety of the hardware and personnel. Before the testing of the hardware can be executed, a delivery systems check must be done first. The tests are divided into 3 major parts: functionality testing, pressure testing, and hot fire testing.

Functionality testing

Before a test is conducted a functionality test of the delivery system must be performed. This is done by checking that the cameras are functioning, the valves are opening, and the sensors are reading the correct information. Usually the test operator will activate the delivery system, while the test director will check the valves in the control room. Please note that during this step all propellant and purge tanks are closed.

Pressure testing

After the functionality test is executed and approved, a pressure test will be conducted. In this test the nitrogen tanks are opened and the system is pressurized at 30 PSI. The test operator will pressurize the system and then shut the tank valves. A leak will be detected as a constant decrease in pressure shown in the pressure transducer display. With the aid of a soap water solution, a leak check can be performed. Any leak check should be done with caution and an oxygen monitor to prevent asphyxiation or dizziness that may occur because of the leak.

Hot fire testing

Once the system is checked for any malfunctions and leaks, a dry run will be performed. This dry run will simulate the duration and operation of the system in order to prepare the test personnel for the hot test. After the system is approved for the hot test by the safety supervisor, the propellant tanks are set to the desired pressure and the test can commence. Depending on the type of test and the use of either cryogenic or gas propellants, the cool down process can be skipped or executed.

Post testing

After the tests have been completed the system must be purged for a set period of time, usually 30 seconds. After the bunker has been declared safe to enter by the safety supervisor, a system inspection must be performed. This system inspection should observe for any damage or loose equipment that might have occurred during the test. The shutdown procedure includes closing off all tanks and depressurizing the delivery system. Data can then be analyzed and processed. It is recommended that a test log or report be submitted to the center's director.

Maintenance

Most of the equipment used in the laboratory is either Swagelok or NPT. These fittings should be replaced when a seal is no longer possible or when fitting yields a persistent leak. All flow meters should be calibrated frequently to guarantee quality data. The delivery system is the first of its kind to be operational at UTEP and further experiences gathered by the operations of this system should dictate the life of the rest of the components on this system. Frequent cleaning or purging cycles should be scheduled for any time LOX testing is conducted.

4.7 RESULTS

4.7.1 Gas testing

Initial testing used the MOAC as the experimental hardware with gas oxygen and methane as primary propellants. The main objective of this testing was to determine the operability and performance of the delivery system, to achieve ignition of the MOAC, and sustain combustion. Flow control in the system is achieved by setting the tank pressure. Since the system was designed to operate with gas propellants, gas flow meters were installed and the cryogenic LOX flow meter was removed. By varying the propellant tank pressure, flow rates were determined in order to obtain the desired mixture ratio as depicted in Tables 5 and 6. The MOAC successfully sustained ignition at a mixture ratio of 4 by setting the oxygen line to 40 psi and the methane to 10 psi. The system was tested to a maximum pressure of 50 psi on gas nitrogen and 40 psi on oxygen/methane. The MOAC did not successfully sustain stable combustion at any other pressures above of what was stated.

Table 5. line pressure vs. flow rate of methane in the delivery system

Line Pressure [PSI]	**Methane mass flow rate [L/min]**
4	14
6	25
8	35
10	48
20	80
30	110
40	137
50	170
60	192

Table 6. Line pressure vs. flow rate of oxygen in the delivery system

Line Pressure [PSI]	**Oxygen mass flow rate [L/min]**
5	12
10	20
15	26
20	32
25	40
30	46
35	53
40	60

4.7.2 Liquid testing

Preliminary testing with liquid nitrogen shows promising results but currently there has been no need for liquid propellant testing on any of the experimental hardware. There are plans for liquid testing to occur during the summer of 2012 that will include chilled methane and eventually LOX/LCH_4.

4.7.3 Expected performance

The delivery system is expected to perform at a maximum pressure of 190 psi. The most limiting factor of the delivery system is the actuated valves. Said valves have a maximum pressure rating of 225 psi thus setting the system operation at a MWP of 190 psi. In addition, the maximum flow that the current liquid flow meter can read is 0.12 GPM. The system can operate under the current hardware to a theoretical maximum thrust of 11 Lbs. Changing key components such as the flow meters can bring the performance of the system up to 17 psi of theoretical thurst.

Chapter 5: Conclusions and recommendations

A propulsion facility has been developed at the cSETR laboratories at UTEP. The propulsion facility has the capabilities of researching the next generation of propulsion systems by trying to understand the physics and engineering behind LOX/LCH_4 engines. The work presented here was performed with an understanding of the physics of fluid mechanics, thermodynamics and heat transfer.

5.1 Conclusions

This project concludes that:

- A methane condensation system was designed and validated through several small scale experiments that showed that the mechanics of the design were valid.
- A cryogenic propellant delivery system was designed, developed, and operated with different experimental hardware and on different test stands
- The delivery system was operated from a remote location in the adjacent control room with the help of the DARCS system.
- The system has shown to be a safe design with design features such as the ventilation system and the DAARCS safety features.
- Experimental hardware has been successfully tested with the required conditions.
- Some of the experiments such as the MOAC will not be tested to the maximum design parameters due to low performance items (e.g. actuated valves, flow meters) in the delivery system
- Said items can be replaced and increase the maximum pressure or flow rating of the delivery system to accommodate higher demands.

5.2 Recommendations and future work

The cryogenic delivery system constitutes the first generation of feed systems that have been developed at the cSETR. The condenser design has been improving with every iteration of the small condensers. Future improvements should include:

- Further non-dimensional analysis should evaluate 1st, 2nd, and 3rd generation condensers and determine a more accurate predicted performance for the 25 L condenser.
- Build and test the 25L condenser.
- Test with liquid propellants and benchmark the system to maximum allowed performance.
- Upgrade the delivery system to allow for higher demand testing. This can be achieved by changing the key components that are currently limiting the performance.
- Change the feed lines from Swagelok fittings to AN 37° flare fittings since they provide higher operational cycles without leaking.
- Build a vacuum insulated delivery system

References

Flynn, T. M. (2005). Cryogenic Engineering. Second Edition, p. 773-871.

NASA White Sands Test Facility (2007). PDT-003 Cryogenics Handling. Power Point Presentation.

J. R. Delayen, R. A. Schlenker, K. W. Shepard, J. R. Specht, L. Y. Young (2001). Physics Division Cryogenic Safety Manual.

Bell, R. (2006). Short Course on Cryogenic Safety. Cryoco, Inc. Power Point Presentation.

Crozier, J. W. (2008). Safety Handling Procedures for Cryogenic Materials. Fulton School of Engineering, Arizona State University.

Brown, C. D. (1995). Spacecraft Propulsion. Washington, DC: AIAA.

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.

Pineda, F., Flores, J. R., Garcia, C. P., Navarro, C. D., & Choudhuri, A. (2011). Cryogenic System Development for LOX/Hydrocarbon Propulsion Research. 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit. San Diego, CA: AIAA.

Neill, T., Judd, D., Veith, E., & Rousar, D. (2009). Practical uses of liquid methane in rocket engine applications. Acta Astronautica 65 , 696–705.

U. Setzmann and W. Wagner. "A New Equation of State and Tables of Thermodynamic Properties of Methane Covering the Range from the Melting Line to 625 K at Pressures up to 1000MPa," *Institut fur Thermo-und Fluiddynamik, Ruhr-Universitat Bochum*. May 29, 1991

Cengel, Y. A. *Heat and Mass Transfer: a practical approach*, 3rd ed., Mc Graw Hill, New York, 2007, Chaps 7, 9, 10, 11.

Linne, D.D., and Meyer M.L. (1992) A compilation of Lunar and Mars exploration strategies utilizing indigenous propellants, NASA Technical Memorandum 105262.

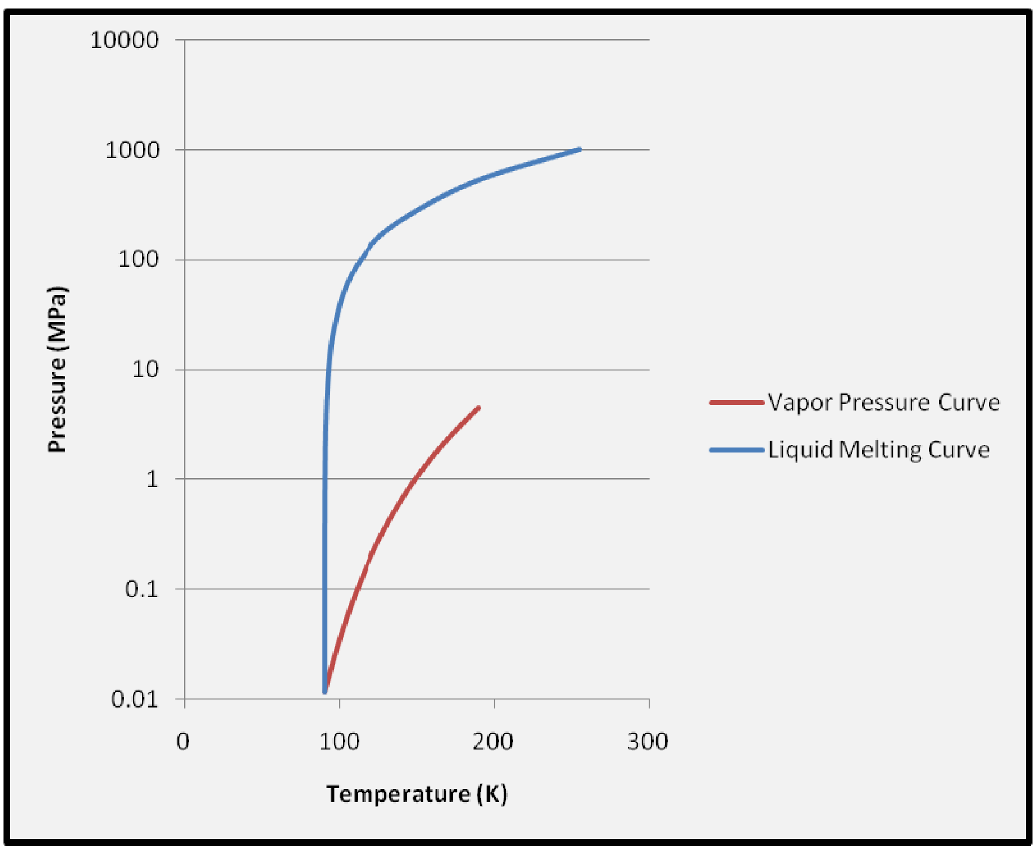
Crawley, E. et al. (2008) A constrained space exploration technology program: a review of NASA's exploration technology department program. Aeronautics and Space Engineering Board, Division on Engineering and Physical Sciences, National Research Council of The National Academies, The National Academies Press, Washington, D.C..

Appendix

Appendix A: Recommended Nonmetals for Oxygen Service [Flynn, 2005]

- Nonmetals have lower ignition temperatures, thermal conductivities, and heat capacities
- Acceptable nonmetals include
  - Tetrafluoroethylene polymer (TFE, Halon TFE, Teflon, or equivalent)
  - Unplasticized chlorotrifluoroethylene polymer (Kel F, Halon CTF, or equivalent)
  - Fluoro-silicone rubbers (Viton type), of a NASA tested compound
- Acceptable lubricants include
  - Kryotox (Dupont)
  - Tribolube 16 (Aerospace lubricants)
- The nonmetallic materials used should be based on data presented in the NASA Publication JSC 02681, *Non-Metallic Materials Design Guidelines and Test Data Handbook*, Latest Edition

Appendix B: Methane phase diagram [U. Setzmann and W. Wagner, 1991]



Appendix B: Testing procedure.

Procedural Actions: QC

#	Required Actions	Expected Results	Action Upon Adverse Result	☒
1	Complete pre assembly of combustor.	Combustor is assembled with all components. Sealed with gaskets and RTV. No smudges on windows. All bolts in place	Postpone test until completed	❑
2	Install Combustor on frame bracket with ceramic insulators	Combustor and bracket are secure to the testing frame. Insulators are installed below each leg. Bolts should not be lose	Postpone test until completed	❑
3	Ensure Bunker is free from foreign objects that pose a fire hazard	No lose parts in area. Area cleaned. No foreign flammable objects	Postpone test until completed	❑
4	Ensure MOAC chamber exhaust will not interact with any structure, wire, or foreign object	All Wires and structures should not be in front of the exhaust area. Any lose items to be secured	Postpone test until completed	❑
5	Connect Data instrumentation to MOAC chamber, thermocouples and pressure transducers	Instrumentation is connected to DAQ. Fittings to be Teflon tape wrapped and torqued to chamber	Postpone test until completed	❑
6	Ensure exhaust fans are on	Fans working and pulling air from vents	Postpone test until completed	☐
7	Ensure Kevlar barriers are in place	Barriers should be placed in front of test section and in between fuels and oxidizers	Postpone test until completed	☐
8	Via lab view, assure that all data transmissions is working properly	Labview monitors show proper data	Postpone test until completed	❑
9	Pre check to see all fluid connections are connected and tight	Connections should be tight to hand torque	Postpone test until completed	❑
10	Turn bunker light from green to yellow	Light should show yellow	Postpone test until completed	❑
11	Verify CCTV cameras are situated correctly	Cameras should show proper viewing angles and be secure	Postpone test until completed	❑
12	Verify Optical imagery equipment is working correctly and is focused on target	Optical equipment should work correctly and transmit remotely to computer	Postpone test until completed	❑
13	Prepare optical imagery for recording	Instrumentation should be ready to record with one click on computer	Postpone test until completed	❑
14	Verify test pressures for all tanks and bottles	Pre test preparedness should declare what pressures the system should be at	Postpone test until completed	❑

15	Ensure all regulators are set to close	Regulator should be turned to the left	Postpone test until completed	❑
16	Open testing bottles internal valve	Valve should be fully open	Postpone test until completed	❑
17	Regulate oxygen, methane, and nitrogen bottles to required pressures	Regulator displays should be at pressure	Postpone test until completed	❑
18	Regulate secondary regulators to testing pressures	regulator displays should be at pressure	Postpone test until completed	❑
19	Evacuate bunker and ensure that Doors are closed and latched	No personnel in bunker and doors do not open unless handle is activated	Postpone test until completed	❑
20	Turn bunker light from yellow to red	Light should show red	Postpone test until completed	❑
21	Personnel should be situated at testing stations	Testing teams should be situated at control, and video and data stations for test monitoring	Postpone test until completed	❑
22	Press Purge Ox and Purge fuel buttons in lab view	Purge valves should open	Stop test, trouble shoot	□
23	Igniter transformer voltage brought up to proper voltage by using switch on lab view 12V igniter	Transformer to be charged	Postpone test until completed	❑
24	Ensure Powersupplys are at correct voltage	Power supply should display correct voltages	Postpone test until completed	□
25	Ensure Killswitch is disengaged	Switch should be pulled out and ready to use in the event of abort	Postpone test until completed	□
26	Press Deliver fuel button to charge system for 1 second the turn off	Fuel system will be charged for test	Postpone test until completed	□
27	Begin optical recording	Computer and hardware to display in recording mode	Postpone test until completed	❑
28	Begin lab view recording	labview should begin recording data	Postpone test until completed	❑
29	Begin Countdown process	Count down leader will comense countdown	Postpone test until completed	□
30	Press Deliver Oxidizer and Fuel buttons on MOAC	Oxidizer and Fuel valves should open	Stop test, Trouble shoot	❑
31	Press Igniter O/F button to deliver ignition fuels to igniter	Valves should open	Stop test, Trouble shoot	❑
32	Engage igniter on via switch	Igniter should spark, pilot flame should begin to prorogate	Stop test, Trouble shoot once safe	❑

33	Close igniter O/F button after 3 seconds	Pilot flame should stop	Stop test, Trouble shoot once safe	☐
34	Turn igniter switch off after 3 seconds	Igniter should stop sparking, pilot flame should cease, flame should anchor in system.	Stop test, Trouble shoot once safe	❑
35	Monitor test carefully for test interval.	Observe to see if no anomalies occur	Stop test, Trouble shoot once safe	❑
36	After interval of testing close deliver Ox and deliver fuel buttons	MOAC flame should extinguish	Stop test, Trouble shoot once safe	❑
37	Press Purge Ox and Purge fuel buttons in lab view	MOAC system should be purged and ensure any flame system to be controlled	Stop test, Trouble shoot once safe	❑
38	Ensure via CCTV or windows that no anomalies have occurred	All hardware should be normal	Trouble shoot once safe to enter	❑
39	If additional tests are to be conducted repeat steps 19 through 33	Test should go as repeated	Stop test, Trouble shoot once safe	❑
40	Ensure bunker is safe to enter and switch light from red to yellow	No hazards pose risk, light to show yellow	Stop test, Trouble shoot once safe	❑
41	Close all fuel and oxidizer gas bottles from tank valve	Valves should be fully closed	Stop test, Trouble shoot once safe	❑
42	Close regulators on fuel and oxidizer lines	Regulators should be set to zero	Stop test, Trouble shoot once safe	❑
43	Exit bunker	No personnel in bunker and doors do not open unless handle is activated	Stop test, Trouble shoot once safe	❑
44	Run purge system	Nitrogen purge should occur	Stop test, Trouble shoot once safe	❑
45	Ensure via CCTV or windows that no anomalies have occurred	All hardware should be normal	Stop test, Trouble shoot once safe	❑
46	Close all nitrogen gas bottles from tank valve	Valves should be fully closed	Stop test, Trouble shoot once safe	❑
47	Close regulators on nitrogen lines	Regulators should be set to zero	Stop test, Trouble shoot once safe	❑
48	Open valves to ensure no gas is trapped	Valves should open	Stop test, Trouble shoot once safe	❑
49	Inspect hardware for damage	No damage should occur	Investigate and repair	❑
50	Save data and video recording	Data should be stored and immediately backed up	Do not proceed until completed	❑
51	Turn light from yellow to green	Light should show green	Trouble shoot	❑

52	Begin post test maintance	Cleaning assemblies and rechecking for damage	N/A	❑
53	Record events in test log	Log to be completed for testing	N/A	❑
54	Turn off Vent fans	Fans to be shut down by audio inspection	N/A	❑
				❑

Appendix C: Hazards Analysis

H#	System	Hazard	Severity	Likelihood	HA Index	Mitigation
1	Methane	Leak	1 – Minor	1 - Unlikely	1	Leak test system prior to operation with methane. Methane detector to be uitilzed for leakage
2	Methane	fire	3 - Significant	1 - Unlikely	2	minimize ignition sources, leak check system, Keep oxygen separate
3	Oxygen	leak	1 – Minor	1 - Unlikely	1	Leak test system prior to operation with Oxygen
4	Oxygen	fire	3 - Significant	1 - Unlikely	2	minimize ignition sources, leak check system, Keep fuel separate
5	MOAC	Overpressure ignition	2 - Moderate	1 - Unlikely	1	MOAC contained in bunker during testing, Ignition to not occur after 1.5 seconds of propellant build up
6	MOAC	fire	3 - Significant	1 - Unlikely	2	Clear bunker of all non essential objects. No items in flame path during testing.
7	MOAC	high temperature surface	2 - Moderate	1 - Unlikely	1	Allow proper cooling prior to post test handling. Proper PPE to be worn.
8	Methane / Oxygen	Overpressure	2 - Moderate	1 - Unlikely	1	two stage regulator systems installed on feed lines. Pressure relief valves installed in system. All components pressure rated above MWP
9	MOAC	flame or heat injury	3 - Significant	1 - Unlikely	2	All personal to be involved in testing to be evacuated outside of bunker during testing. All operations to be done remotely
10	MOAC	chamber fire	2 - Moderate	1 - Unlikely	1	Nitrogen purge to occur if conditions inside chamber require immediate shutdown

11	Methane / Oxygen	explosion	3 - Significant	1 - Unlikely	2	Propellants stored behind Kevlar walls to protect from damage. Propellants stored apart from each other. Video observation of tanks to ensure protection, all propellants stored inside bunker.
12	Methane / Oxygen	valve failure	2 - Moderate	1 - Unlikely	1	All valves are normally closed valves. Failure of valve closes valve completely and stops test
13	Methane / Oxygen	regulator failure	2 - Moderate	1 - Unlikely	1	Two stage regulator systems installed on feed lines. Pressure relief valves installed in system. Regulators set to pressures below MWP
14	Control system	Power outage/ power surge	2 - Moderate	1 - Unlikely	1	Battery back up to ensure systems stay operational for 30 mins. Proper grounding from electronic components used through out system.
	Control system	Computer failure	2 - Moderate	1 - Unlikely	1	Manual remote override switches are installed on control panel to shut down system.
	Feed system	Component fire	2 - Moderate	1 - Unlikely	1	Nitrogen purge to occur to attempt to quench fire. All components in bunker.
	Exhaust system	Fan failure	1 – Minor	1 - Unlikely	1	Fans to be checked prior to each test per test procedure. Exhaust system contains separate systems for fuel and oxidizer.
15	Ignition system	Transformer voltage	2 - Moderate	1 - Unlikely	1	Transformer is to be installed in a Plexiglas insulation chamber to prevent personnel from touching while charged. Warning signs to be present on chamber.

Vita

Francisco Pineda was born on June 29th, 1985. He is the eldest son of Luz E. Garcia and Francisco Pineda. During his time as an undergraduate at the University of Texas at El Paso, he participated in the Society of Automotive Engineers (SAE) as team captain for the 2008 season, worked as an engineering intern at El Paso Electric Company in the summer of 2008, and in 2009 was hired as a research assistant at the Center for Space Exploration Technology Research (cSETR). He graduated from the University of Texas at El Paso in December 2009 with a Bachelor of Science in Mechanical Engineering. Immediately after graduation, he began graduate school to in 2010 pursue a Master's of Science in Mechanical Engineering at UTEP under the supervision of Dr. Ashan Choudhuri. In the summer of 2011, he participated in an internship at NASA's Johnson Space Center (JSC) where he was awarded the best intern award. Mr. Pineda will continue to pursue a career as an aerospace engineer developing the next generation of propulsion systems.

Permanent address: 945 Chiricahua
El Paso TX, 70012

This thesis/dissertation was typed by Francisco Pineda.