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Design And Development Of A Delivery System For Green Ionic Monopropellants And Testing Of A 22n Thruster

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DESIGN AND DEVELOPMENT OF A DELIVERY SYSTEM FOR GREEN IONIC MONOPROPELLANTS AND TESTING OF A 22N THRUSTER

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Dedication

I want to thank my family, friends, and mentors for illuminating the path in higher education. You give me the strength, motivation, and guidance to persevere in this journey.

DESIGN AND DEVELOPMENT OF A DELIVERY SYSTEM FOR GREEN IONIC MONOPROPELLANTS AND TESTING OF A 22N THRUSTER

by

JACLYN MONA MEJIA, B.S. Mechanical Engineering

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Chapter1: Introduction

1.1 Project overview

LMP-103S and AFM-315E are emerging propellants that are less toxic to the environment than the propellants currently being used in spacecraft propulsion. Both propellants are a blend of liquid fuel, oxidizer and a majority percent of water. The diluted solutions enable the capability to handle and store the propellants with fewer requirements; for this reason, it decreases the overall cost of the propellants since it needs less precautions. The Missile Defense Agency (MDA) awarded the University of Texas at El Paso (UTEP) a contract to further research green propellants and eventually replace Hydrazide.

1.2 Project objectives

The project has three main objectives; the first objective is to design and develop both a gas and a liquid delivery system along with a program to control and record data from both feed systems. The second objective is to leak check both systems and run cold flow tests with nitrogen gas to verify pressure drop in facility. The third objective is to test a 22-N thruster. All tasks have been completed at this point.

1.3 Project approach

In order to reach the objectives, the project was divided into sections and each semester tasks within each section were completed. The project was approached in the following timeline. The first semester, the team designed both the gas and the liquid feed systems. The team created required documents, CAD models, hand calculations, computerized models, and literature review for material compatibility. The second semester, the team procured all components and assembled both delivery systems. The third semester, the lab view program was created along with all the electrical

connections needed to control and record data from all components. A fourth semester was utilized to finalize the project. The thruster was tested using the new capabilities of the laboratory.

1.4 Project relevance

The bunker in lab E-105 was not equipped to test green propellants. The need for an expansion was required to bring more green propellant research to the University. Currently, propulsion systems utilize hydrazine. This propellant has good performance and it meets all MDA requirements. On the other hand, this propellant is toxic to the environment and it is difficult to handle. The purpose of investigating new propellants is to reduce the burden on the environment and reduce issues caused to personnel storing and handling them. There are three green propellants currently being researched at the university. For this reason, the delivery systems were created. The liquid delivery system has three independent feed systems, one for each propellant. The gas delivery system has six independent feed systems to test six different gasses.

Chapter2: Literature Review

2.1 Monopropellant propulsion

Monopropellant thrusters create thrust by expelling hot and high-speed gasses from the chamber and across the nozzle. The gasses are created by a chemical decomposition that happens when the propellant passes through a catalyst bed. The catalyst bed enables the propellant to have a faster decomposition reaction rate that drives a faster energy release. The hot gasses generated by the energy release in the chemical decomposition flow through a converging-diverging nozzle where the exhaust gas velocity increases throughout the nozzle, resulting in thrust.

Monopropellant propulsion systems have several advantages compare to other propulsion systems. One of the advantages is the simplicity of the systems. This system does not require numerous of components. For example, since it is a monopropellant it only requires one tank. This advantage drives a second advantage which is weight savings. Another advantage is cost. Since the propulsion system requires a low number of components, the cost decreases. Ignition simplicity is another advantage of monopropellant systems. Monopropellant thrusters do not require an ignition source. The energy release is created by the propellant flowing through the catalyst. Lastly, the control system only requires valves to open and close. Oppose to bipropellants that require more functions in the propulsion systems.

Monopropellant propulsion systems have several disadvantages compare to other propulsion systems. The main disadvantage is the low specific impulse this rocket performs. Monopropellants are unstable in a storage environment. When the propulsion system is designed, it requires a pressure relief system. Monopropellants degrade with time inside the storage tank. The concentration of the propellant diminishes along with the performance of the rocket.

Illustration 2.1 shows a general idea of a monopropellant rocket. Monopropellant thrusters are composed of a tank to store the single propellant, a solenoid valve to drive the flow from the tank to

the catalyst bed, through the chamber, throat, and nozzle. Thruster response time is dependent on the valve control. A thermal standoff is between the valve and the injector plate. The function for this standoff is to reduce the amount of heat transfer from the heat released in the catalyst. The catalyst materials depend on the propellant. For example, the material used for hydrogen peroxide catalyst is Silver. The material used for hydrazine is granular alumina coated with iridium, also known under the commercial label Aerojet S-405 (previously made by Shell) [10]. These catalysts are efficient enough to create enough energy release in the rockets. No external energy source is needed to enable decomposition. There are monopropellants that need heaters to heat up the propellant before entering the catalyst bed. These propellants require high temperature for decomposition. As the chemical decomposition begins a mixture of hot and high-speed gasses drive to the chamber and a converging-diverging nozzle to produce thrust.

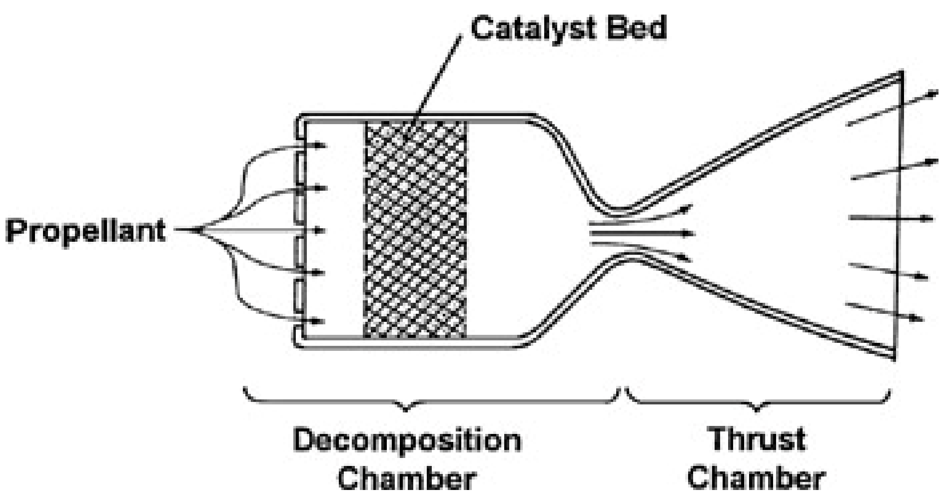

*Illustration **Error! No text of specified style in document.**1Monopropellant thruster*

Three monopropellants have been used for flight vehicles: hydrazine, hydrogen peroxide and propyl nitrate [3]. Hydrogen peroxide degrades 1% of its concentration per year. Propyl nitrate is shock sensitive [18]. Hydrazine is the best option out of the three, and most monopropellant propulsion systems use Hydrazine. There are two new bipropellants that behave like a monopropellant. These two propellants are composed of fuel, oxidizer, stabilizer, and solvent all in

one liquid solution. For this reason, the propellants can be characterized under monopropellants. These solutions have a large concentration of water to make the propellant safer to storage and handle.

Table 2.1 Comparison of four green propellants [3][7]

Chemical	Density (g/mL)	Isp, s	Vapor Pressure @ 293 K (psi)
Hydrazine	1.01	230	0.203
Hydrogen Peroxide	1.45	165	0.097
LMP-103S (Ammonium Dinatrimide-based)	1.24	252	???
AF-M315E (Hydroxyl Ammonium Nitrate - based)	1.46	266	???

2.2 Catalytic decomposition

A chemical decomposition is a process that transforms a chemical compound to another. The main study of a chemical decomposition process is to study the kinetics behind the breakdown of the initial chemical compound. The initial chemical compound can decompose to single elements or smaller species. The kinetics of the chemical reaction is the rate at which the chemical reaction is occurring at [18]. An equation used for chemical kinetic reactions is the Arrhenius equation. This formula relates the rate of reaction to temperature.

$$k = A_e^{\frac{-E_A}{RT}} \tag{2.1}$$

K is the rate constant; A is the frequency factor; R is the gas constant; T is the temperature in Kelvin and E_A is the activation energy [5]. The standard enthalpy of formation (or standard heat of formation) is a measure of the energy released or consumed when one mole of a substance is created under standard conditions from its pure elements [5]. The standard state condition is the ambient pressure of 1 atmosphere and ambient temperature 298.15 Kelvin. Another way of understanding standard enthalpy of formation is the measure of heat subtracted or added to the system ones the chemical reaction occurs. There are two temperature reactions that can occur in a standard enthalpy of formation an endothermic reaction which is losing heat and an exothermic reaction which produces heat.

Chemical reactions can take different chemical pathways depending on the environment of the reaction. The rate of a chemical reaction can be increased by the contribution of an additional substance called a catalyst [4]. Catalysts work by providing an alternative mechanism involving a different transition state and lower activation energy [18]. It should be known that there are two forms in which a catalytic reaction can occur; a heterogeneous and homogeneous reaction [8]. The catalyst typically is in a solid phase and the propellants in a liquid or gas state. In a homogeneous reaction, the reactants and the catalyst are in the same phase, whether that be a gas or liquid phase [18]. In a heterogeneous reaction, a phenomenon called adsorption between the reactants and the catalyst occurs [6]. Adsorption, not to be confused with absorption, allows the molecules from the reactants to "stick" on the surface of the catalyst. Diverse mechanisms for reactions on surfaces are known, depending on how the adsorption takes place [6]. The catalysts are reusable since the chemical decomposition does not change the catalyst composition.

In order for a reaction to occur, the molecules of the reactants must collide with the catalyst at a minimum energy called the activation energy [5]. This is the amount of energy required for a reaction to take place. Adsorbed molecules at an active site can then collide with molecules passing by; these molecular collisions have the energy needed to reach the transition state. For this reason, catalysts enable reactions that would otherwise be blocked or slowed by a kinetic barrier [6]. The catalyst increases the reaction rate by allowing the reaction to take place at a lower temperature. Illustration 2.2 explains the energy profile diagram.

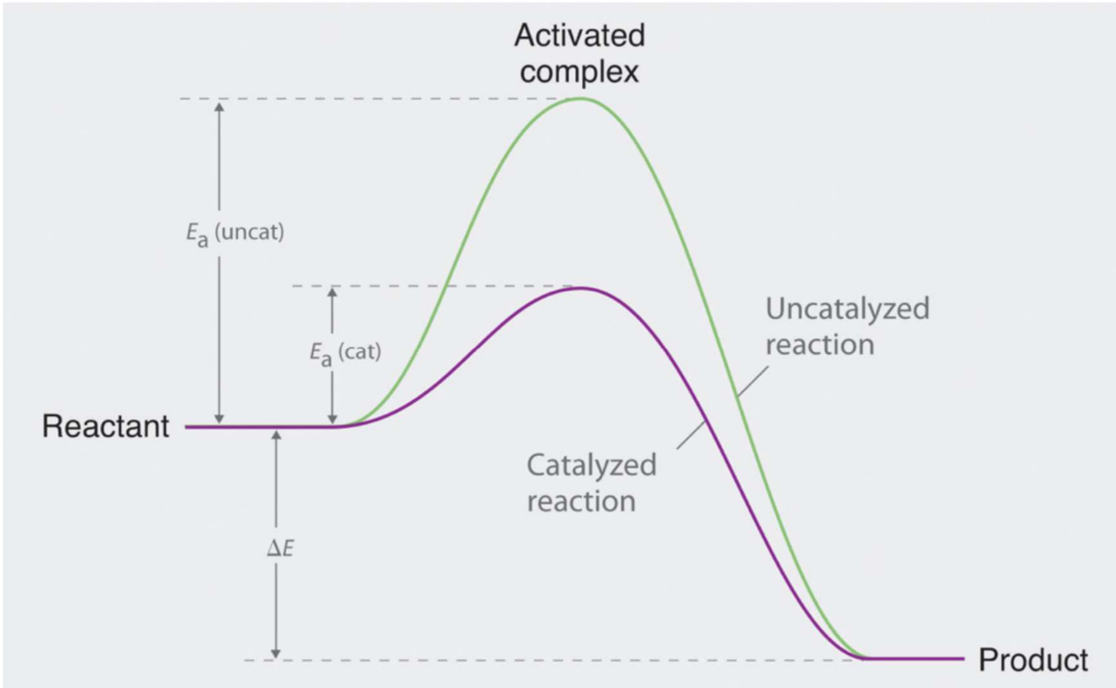

Illustration ***Error! No text of specified style in document.****2 Energy Profile Diagram*

When a slightly negative atom approaches a double bonded molecule that has a high negative charge, the atom and the molecule will repulse upon collision [8]. Illustration 2.3 represents the only collision that leads to a chemical reaction. Therefore, because it is not certain that a reaction will occur, the chances of reaction may be enhanced through an increase in catalyst concentration [8]. The surface area of the catalyst is important in the reaction. Increasing the surface of the catalyst will enable a large amount of positive collisions which increases the chance of a reaction.

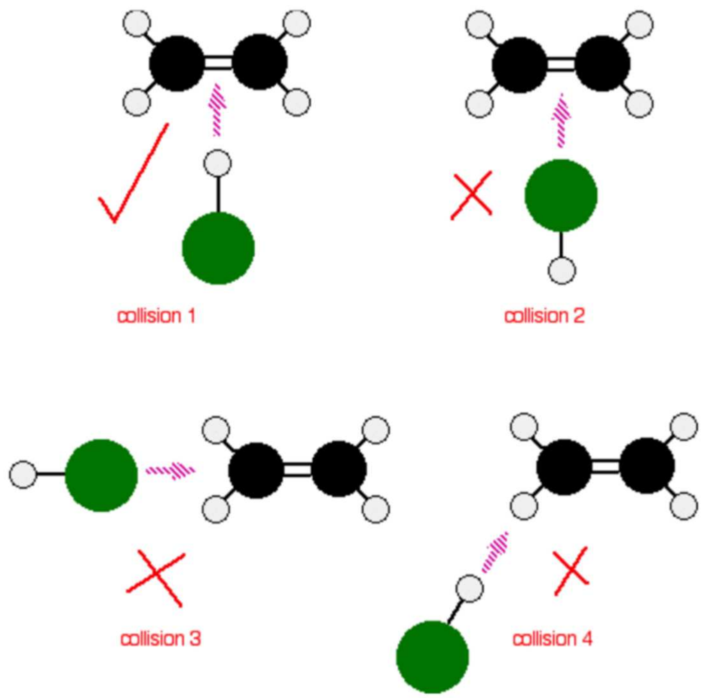

Illustration 2.3 Molecular Collisions [8]

2.3 Ammonium Dinitramide (ADN)

Ammonia Dinitramide (ADN) was discovered and produced in the Soviet Union during the 1970s and was strictly classified and unknown to the rest of the world until 1988 when SRI in the USA 8 "reinvented" ADN [5]. It was synthesized and patented in the United States by SRI International in 1991. It was then later discovered that ADN is highly soluble in polar solvents and could be used as an oxidizer in liquid propellants [5]. ADN is a high-energy, solid white inorganic salt of the ammonia cation (NH4)+ and the dinitramide anion (N(NO2)2-. It is hygroscopic and soluble in water and other polar solvents but not quite as soluble with non-polar solvents [7]. ADN crystals serve as the oxidizing agent in monopropellants and solid rocket propellants and dissolve in water which in turn acts as a stabilizer and moderates combustion temperature [18]. ADN has a high oxygen balance of +25.79 %, melts at 93°C and starts to decompose at approximately 150 °C at a heating rate of 10 K per minute [7]. Similarly, to ammonium nitrate, the density of ADN at solid state

is 1.81 g/cm3 molar volume, and corresponding density in the liquid state at 25.0 °C is 74.08 g/mol [2].

2.4 ADN based monopropellant (LMP-103S)

The new generation of green monopropellant scientist want to eventually replace Hydrazine since it is not environmentally friendly, is not safe to handle, it is an unstable propellant and the cost of storage it too high. One of the new propellants currently being studied is an ADN based monopropellant. This propellant is a blend of an oxidizer salt that is dissolved in a water-fuel blend. The development of ADN-based monopropellants started at FOI in 1997 on contract from the Swedish Space Corporation (SSC) and several different propellant formulations have been developed and tested. Two steps require the manufacturing of these types of monopropellants such as FLP-106; first, water dissolves the fuel and secondly, ADN mixes with the fuel/water blend [2].

In 1997, Ecological Advanced Propulsion Systems (ECAPS), a subsidiary of the SSC, developed the High-Performance Green Propellant (HPGP) ADN based monopropellant LMP-103S. Some advantages of LMP-103S includes its storability; compared to hydrazine it is safer to handle, has a higher performance level, and is environmentally benign [1]. It also greatly reduces the risk associated with toxicity, spacecraft contamination and operational handling complexity [18]. ECAPS claims that LMP-103S has a higher specific impulse by 6% and a higher density by 24% than that of hydrazine. This propellant is a light-yellow liquid with a discomforting odor. LMP-103S is a high-energy premixed bipropellant mixture composed of 60-65% ADN (NH4N (NO2)2), 15-20% methanol 3-6% ammonia (NH3) and (balance) water (H2O) that serves as a liquid mono-propellant [9]. The volatiles (fuel components) in LMP-130S are methanol and ammonia. Like water, ammonia serves for stabilizing the blend and helps dissolve the ADN crystals into the solution. Ammonia also helps balance the pH levels in the fuel [18]. Detonation test, large scale gap test, and critical diameter

test have been made with LMP-130S by the Swedish Defense Research Agency (FOI). The propellant has successfully passed performance, hazard, compatibility, radiation, storability, purity, transportability and handling testing. LMP-130S is considered to be an insensitive Division 1.3 substance [1]. Table 2.4 compares LMP-103S to hydrazine [1].

Table 2.2 Comparison of LMP-103S to hydrazine [1]

Comparison Parameter	Hydrazine	LMP-103S
Technology Readiness Level (TRL)	TRL9	TRL7
Stability	Dangerously unstable	Stable
Toxicity	Highly toxic	Low toxicity
Carcinogenic	Yes	No
Storable	Yes	Yes
Corrosive	Yes	No
Environmental hazard	Yes	No
Sensitive to air exposure	Yes	No
Sensitive to humidity exposure	Yes	No
Density @ 20oC (kg/L)	1.01	1.24
Melting point	1°C	- 6oC
Boiling point	114°C	120oC
Operating Temperature range (°C)	10 to 50	10 to 50
Blow down ratio – 1 N thruster performance typical	4 to 1	4 to 1
Cold start capability	Yes	No
SCAPE suites required	Yes	No
UN Transport class	8	1.4S
Approved for air transport	No	Yes

2.5 Hydroxylammonium nitrates (HAN) based monopropellant AFM-315E

The GPIM is a project that is on-going to develop these green propellant alternatives to Hydrazine and other propellants that have been proven to be toxic and that require several handling precautions [14]. HAN (hydroxyl ammonium nitrate) is a fuel/oxidizer blend mixed with HEHN (hydroxyethylhydrazinium nitrate) that forms the propellant AFM-315E. This propellant was developed by the United States Air Force a government company. The properties of this propellant overcome the properties of Hydrazine and Hydrogen Peroxide. This new propellant has a higher specific impulse (ISP) than the current propellants, which means better performance in the propulsion

system. Also, the density of AFM-315E is higher than Hydrazine and Hydrogen Peroxide enabling the ability to store more propellant in the same tank volume. Another advantage of this new propellant is that is safer to handle and stable while in storage.

AF-M315E composition is proprietary and the study of its decomposition it is still not well understood, but its main component, HAN, has been studied several times [12], [13], [15], [16]. Corthéoux's is a HAN researcher that studies the decomposition of HAN. He performed a thermic decomposition test. He heated up HAN and he found that when the blend reaches 135°C, the decomposition temperature rises exponentially, meaning that at this point the decomposition takes place.

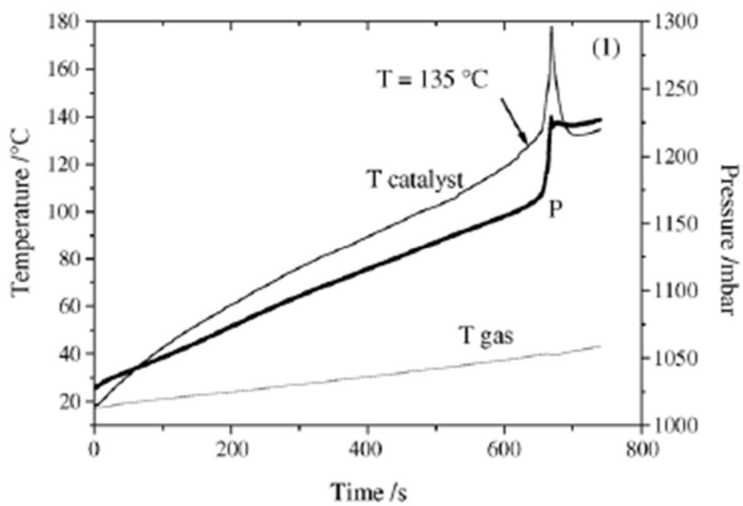

Illustration 2.4 Thermal decomposition of 40% HAN in a batch reactor [11] [12]

Corthéoux then performed a catalytic decomposition test. He combined platinum coated/alumina substrate catalyst with HAN to improve the overall performance of the decomposition. The results of this test were as predicted. The decomposition temperature decreased by 28°C and the time it took for the decomposition to take place was almost 600 seconds less.

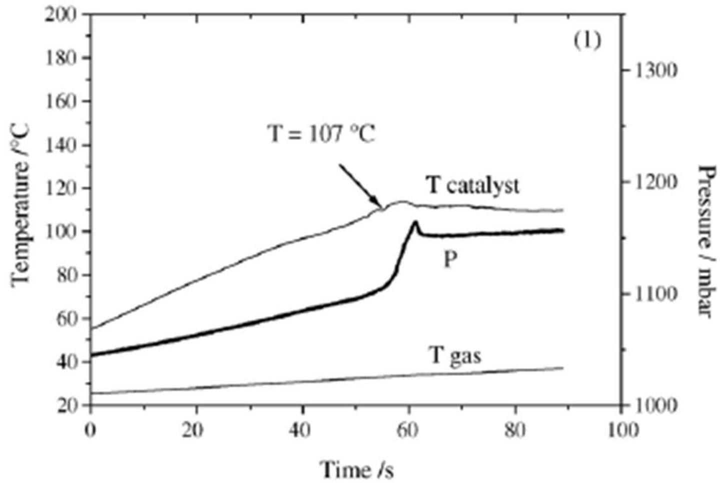

Illustration 2.5 Thermal decomposition of 40% HAN in a batch reactor with a 10% Platinum Coated/ Alumina Substrate catalyst added [11], [12]

Chapter 3: Bunker Delivery System

3.1 Introduction to chapter

Chapter 2 established the basic understanding of ADN and HAN including corresponding decomposition gasses and the ADN-based monopropellant LMP-103S and HAN-based monopropellant AFM-315E. Based on the information gathered from literature and CEA analysis a delivery system was expanded to be able to research all gasses and liquid propellants on a bigger scale. The new delivery system allows evolution and progressive maturity to test green propellants. Enabling formalization of development and testing strategies for future projects. Multiple independent thruster testing prevents component/system failure setbacks. Multiple independent decomposition gas testing prevents component/system failure setbacks. In this Chapter, the design of the delivery system will be explained in detail.

3.1.1 Introduction

LMP-103S is an Ammonium Dinitramide (ADN) base ionic liquid monopropellant that was developed by ECAPS, a Swedish Space Corporation (SSC) company. AFM-315E is an (HAN) based ionic liquid monopropellant that was developed by the air force, a United Stated government company. The decomposition of these propellants, in theory, will produce an ignitable mixture that would then combust to produce thrust. The combustion of these species is not fully understood, but it has been tested previously by studying different flames based on a combination of expected decomposition gasses.

The development of a delivery system inside the bunker is to be able to test green propellant capabilities for a range of 5 to 10-pound thrust requirement missions. This chapter will depict the fundamental capabilities of the delivery system design. The purpose of this project is to design a universal delivery system in the bunker for different teams to be able to test according to their

requirements. The bunker delivery system includes a gas feed system, liquid propellant feed system, an exhaust gas system and data acquisition program.

The liquid propellant feed system is capable of testing up to three green propellants, LMP-103S, AF-M315E, and HTP. The thrusters are mounted on a torsional thrust balance, which has the capability of measuring up to 15 pounds of thrust.

The gas feed system is capable of testing the decomposition gasses of the two green monopropellants. This system has the capability to test HTPB (Hydroxyl-Terminated polybutadiene) inside a MOAC (Multi Optical Access Combustor) to measure regression rate of the solid fuel.

Results will demonstrate the operation of the thrusters, and combustion systems of green propellants may one day support 5 to 10-pound thrust missions.

The purpose of designing and building a new delivery system is to expand testing capabilities for the facility. The team is ready to start testing in bigger scales. The first test for the research of LMP-103S is to test a 22 Newton thruster with the liquid propellant, and the first test for the research of AFM-315E is to run the expected decomposition gasses across a solid fuel slab shape and measure regression rate.

3.1.2 Test objectives

The objective is to design and build a delivery system that can test up to six different gasses and three liquid propellants. The delivery system must assure all components are working correctly, and no leaks are presented. Also, take a measurement of pressure drop across the system, and be able to ignite multiple thrusters.

3.2 Experimental approach

The test will be conducted in the bunker in the cSETR lab room E105. Personal protective equipment will be worn by the conductors to prevent flying projectiles and gas leakage causing

injury in case of a failure. The pressurized system will also be surrounded with Kevlar walls to prevent any damage to surrounding hardware and instrumentation inside the bunker.

3.2.1 Test 1. Check components are working correctly /System leak test

Turning on lab View and checking the display of each component to match ambient conditions for the pressure transducers and thermocouples, zero for flow meters, and listening to the solenoid valves when open, will approve the system components are working correctly.

The test will begin by attaching a ball valve at the end of the components to secure the pressurized gas. All components will be pressurized to 50 psig using nitrogen gas for the leak check test. The leak detecting fluid, snoop, will be applied to the perimeter of each fitting. All components will then be visually inspected to confirm no leaks are present. The components to be leak tested can be seen below in Illustration 3.2.

3.2.2 Test 2. Measuring pressure drop across the systems

The measurement for pressure drop process will begin by setting the Nitrogen K bottle to 100psi and recording the data from Pc (pressure transducer located at the thruster). This measurement will allow test conductor to set the K bottles to the right pressure when the hot fire test takes place. Pressure drop measurement will follow Illustration 3.2

Below is Table 3.1 summarizing the delivery system in two sections the gas and the liquid delivery systems

Table 3.1 Description of delivery system

Section	Characteristics	Purpose	Testing Capabilities
1	Green monopropellant liquid Delivery System	Test thrusters Component package Demonstrate capability Schematic of Components	Thruster integration Propellant Tank Integration Inert gas Tank Integration Data Acquisition and remote control
2	Green decomposition gas feed System	Test HTPB Test regression rate Component package Demonstrate capability Schematic of Components	Regression rate testing MOAC integration HTPB testing Multiple gas Tank integration Data Acquisition and control remote

3.3 Experimental test setup

The experiment test setup was designed, Assembled by the Green propellant team at the Center for Space Exploration Technology Research (cSETR) at the University of Texas at El Paso. The test setup is located inside the Goddard Laboratory on the first floor of the engineering building Room E105. Test procedures and hazard analysis were created by the team and approved by project managers, and the university's Environmental Health & Safety department.

3.3.1 System design

The requirements to fulfill the objective of expanding the delivery system are to design and build two delivery systems. One for expected decomposition gasses from both ionic propellants LMP-103S and AFM-315E and the other for the two propellants in the liquid stage.

3.3.1.1 Liquid propellant delivery system requirements

Design a liquid propellant delivery system for a 5-10-pound thruster, compatible with the green propellants. In order to test thrust. Along with the design of a remote-control system and data acquisition from the control room with a lab view program to control devices and record sensor outputs.

Each propellant requires having identical systems and at the same time individual systems, meaning each propellant has its own feed system and each system will only be used for the selected propellant. This is to prevent contamination of components and safety precaution. Propellant storability is required in a 1 gallon 316 stainless steel sample cylinder. The sample cylinders are required to have temperature and pressure measurement capability to ensure the propellant is stable. Both propellants are stable in ambient conditions. The system requires visibility such as a camera and windows to the system. An exhaust system is required to be able to expel the combustion gasses when testing due to the hazardous gasses expected. A lab view program is required to control the flow isolation in the system in case of emergency or part of the test procedure. An inert gas is required to pressurize the sample cylinder when testing. This gas will control the flow of the propellant. A pressure relief valve is required for safety precaution in case of the inert gas pressures the propellant too high during testing. Recording the temperature, pressure, and volume flow rate of the propellant is required for future calculations and testing precautions. A laser is required when testing a thruster. It will be the component measuring the force.

3.3.1.2 Decomposition gas delivery system requirements

Design a gas feed system compatible with the decomposition products of green propellants to perform regression rate analysis and test HTPB inside the MOAC. In addition, develop a remote-

control system and data acquisition program from within the control room with a LabVIEW program. This will allow for valve control and record data from pressure transducers, thermocouples, flow meters, and camera.

Each gas should have identical systems and at the same time individual systems, meaning each gas has its own feed system and each system will only be used for the selected gas unless purged for cleaning. This is to prevent contamination of components and safety precaution. All gas K bottles are required to be stored in a tank holder with straps for safety precaution. The system requires visibility such as a camera and windows to the system. An exhaust system is required to be able to expel the combustion gasses when testing due to the hazardous gasses expected. The premix of the gasses is required before the ignition component. A lab view program is required to control the flow isolation in the system in case of emergency or part of the test procedure. A pressure relief valve is required for safety precaution in case the gas is too high during testing. Recording the temperature, pressure, and volume flow rate of the gasses is required for future calculations and testing precautions.

3.3.2 Test setup sub-system development details

The delivery system was designed, and it took several iterations to make sure all requirements were met. In this section, the different sections of the delivery system will be explained in detail: Gas Delivery System, Liquid Propellant Delivery System, Exhaust System and Data Acquisition System. All systems are connected to the MASS (Multiple Altitude Simulator System). Below is a 3D CAD model of the delivery system.

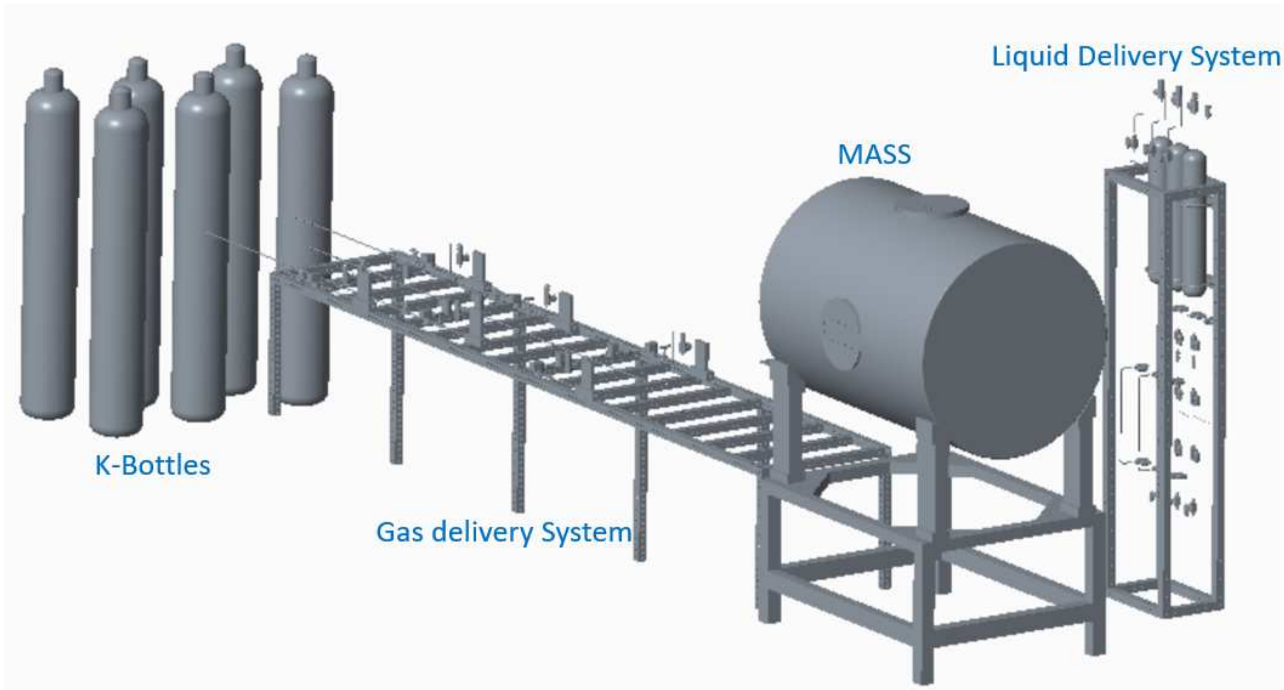

Illustration 3.1 Delivery system 3D CAD model

3.3.2.1 Gas delivery system

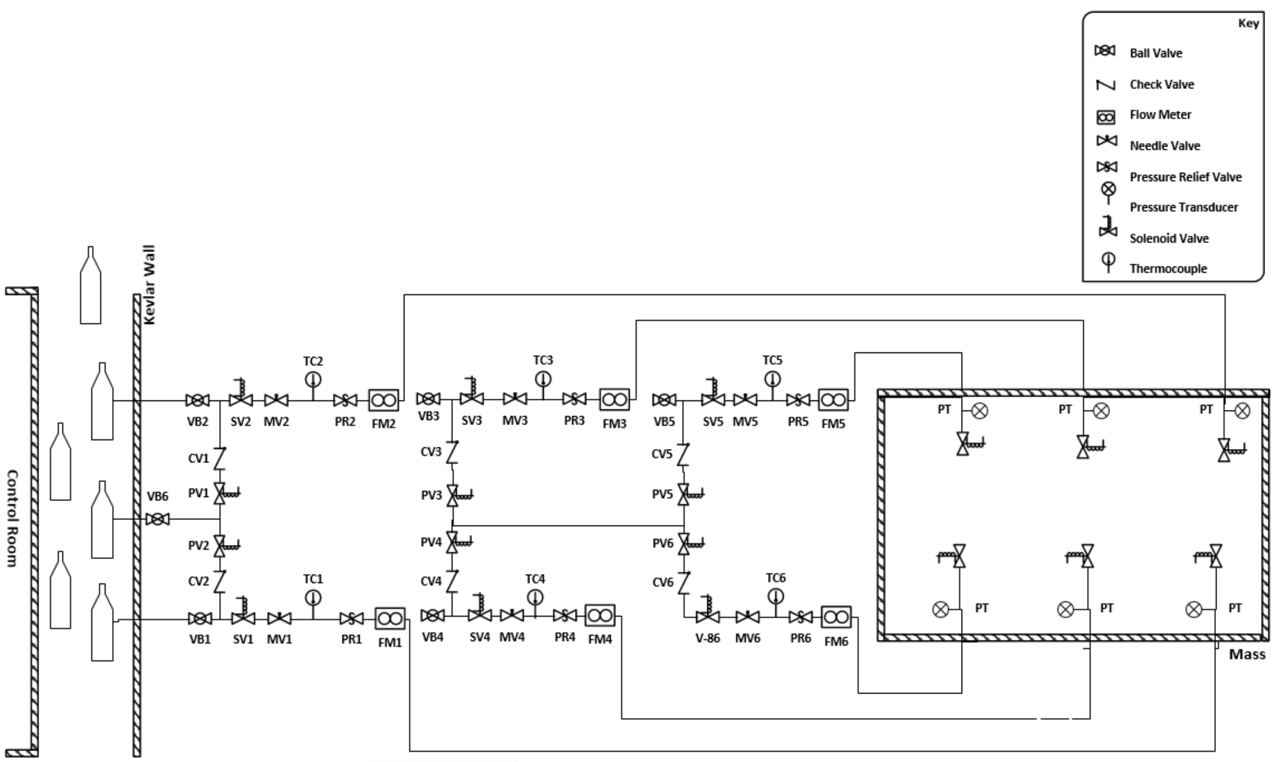

Illustration 3.2 Gas delivery system component schematic

The Engineering Test setup is a static test bed. Flexible interface for six propellant decompositions gas feed systems. The gasses are O2, N2, CO2, CO, H2O, NO, NO2, and N2O. Each decomposition gas has independent feed systems. Each gas has its own K bottle tank with its corresponding two stage regulator (Figure 3.1); regulates the pressure of the gas flow. The regulator connects to a ball Valve (Figure 3.2) with 1/4 compression fittings on both ends. It isolates the flow from the tank to the feed system. The ball valve connects to a solenoid valve (Figure 3.3); It is used as an automated valve actuation system control by a lab View program to isolate the flow while testing. The solenoid valve connects to a metering valve (Figure 3.4); which helps to control a more specific flow. The metering valve connects to a K-type thermocouple (Figure 3.5); It measures the flow temperature. The thermocouple connects to a Pressure Relief Valve (Figure 3.6); Set to open at 400 psig. The pressure relief valve connects to a flow meter (Figure 3.7) which measures volume flow rate of the gas. After the ball valve and before the solenoid valve there is a check valve (Figure 3.8); It opens with 1/3 of psi, and it prevents flow to pass in both directions. Followed by the check valve, there is a solenoid valve (Figure 3.3); It is used as a purge valve. After testing there is the need of purging all lines with nitrogen. After all components, there is a ¼ line that runs to the MASS port (Figure 3.9) where each gas has its own port. Inside the MASS each gas has a solenoid valve (Figure 3.3) to control flow while testing. The solenoid valve connects to a pressure transducer (Figure 3.10) that can read up to 500 psig. It measures the pressure of the gas flowing. The pressure transducer connects to the premix gas line system, which mixes the gasses before entering the test article.

Another capability is the data acquisition system; used for monitoring instruments, and making sure the hardware can manage/record all data; A necessary program was developed to interface data acquisition and remote control using lab view.

Figure 3.1 Two Stage Regulator

Figure 3.2 Ball Valve

Figure 3.3 Solenoid Valve

Figure 3.4 Rack with gas K bottles

Figure 3.5 K-Type Thermocouple

Figure 3.6 Pressure Relief Valve

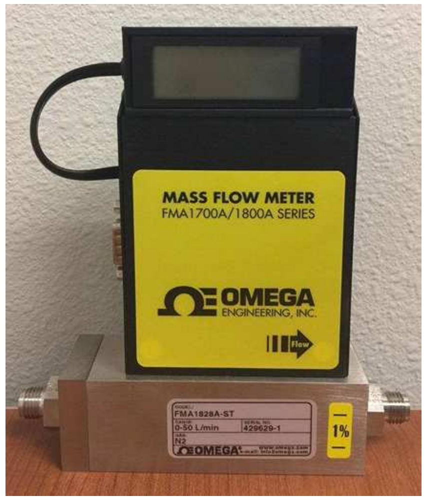

Figure 3.7 Omega Mass Flow Meter FMA 1700A/1800A Series


Figure 3.8 Swagelok Spring Loaded Check Valve


Figure 3.9 MASS Port

Figure 3.10 Pressure Transducer

Operating conditions for the gas feed system are shown below in table 3.2

Table 3.2 Operating conditions for the gas delivery system

Max Tank Pressure	400 Psi
Flow Meter Capability	50 LPM & 200 LPM
Thermocouple Type	K
Max Pressure Transducer Capability	500 Psi
Solenoid Valve Capability	AC & DC

The lab view front panel for the gas delivery system is shown below in Illustration 3.3. and a closer view in Illustration 3.4 and 3.5

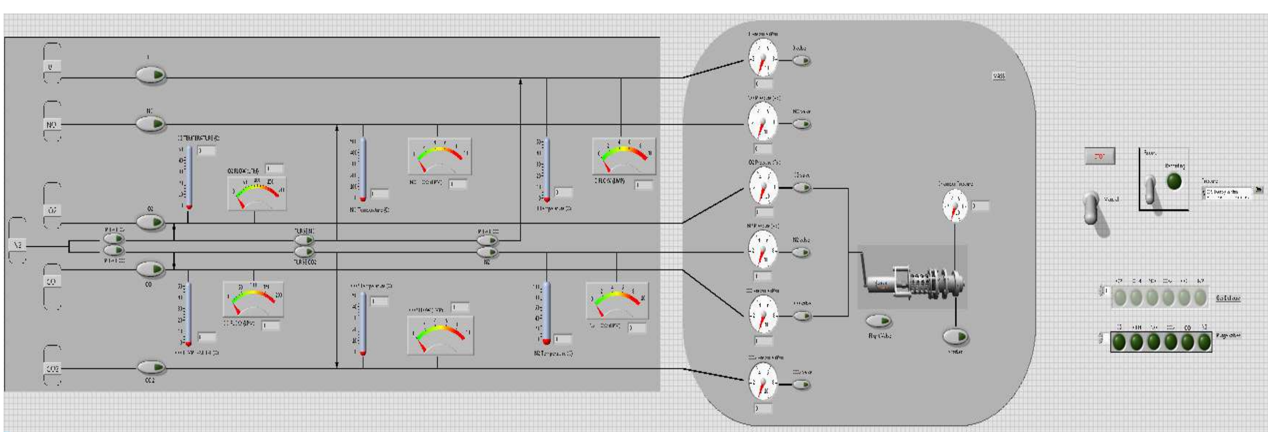

Illustration 3.3. Lab View front panel for the gas delivery system

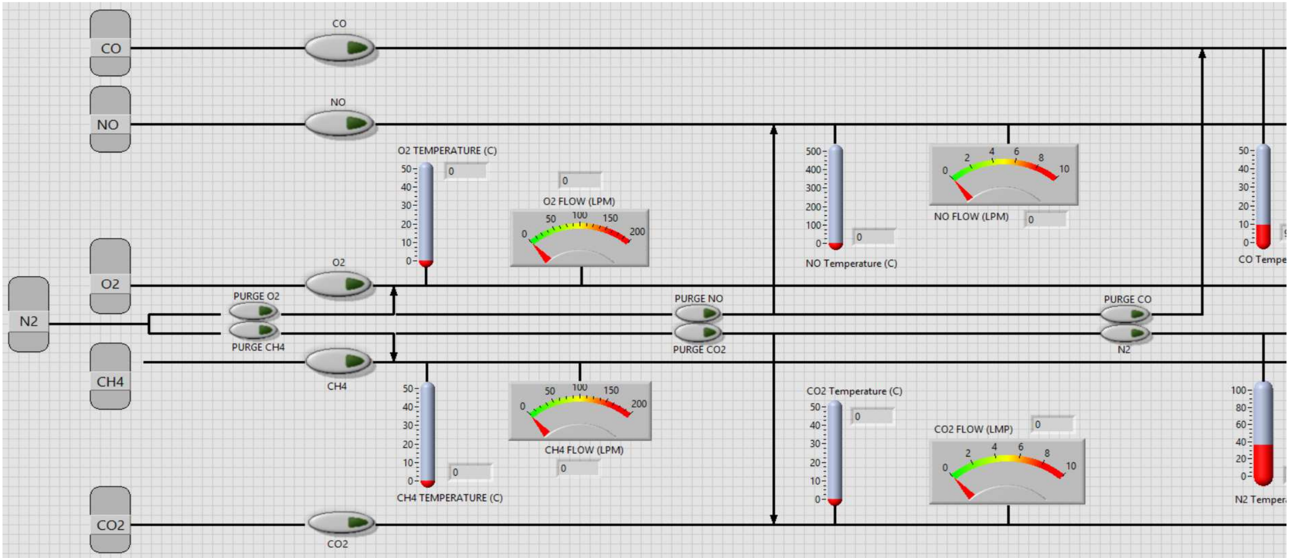

Illustration 3.4 Lab View front panel for the gas delivery system (closer look)

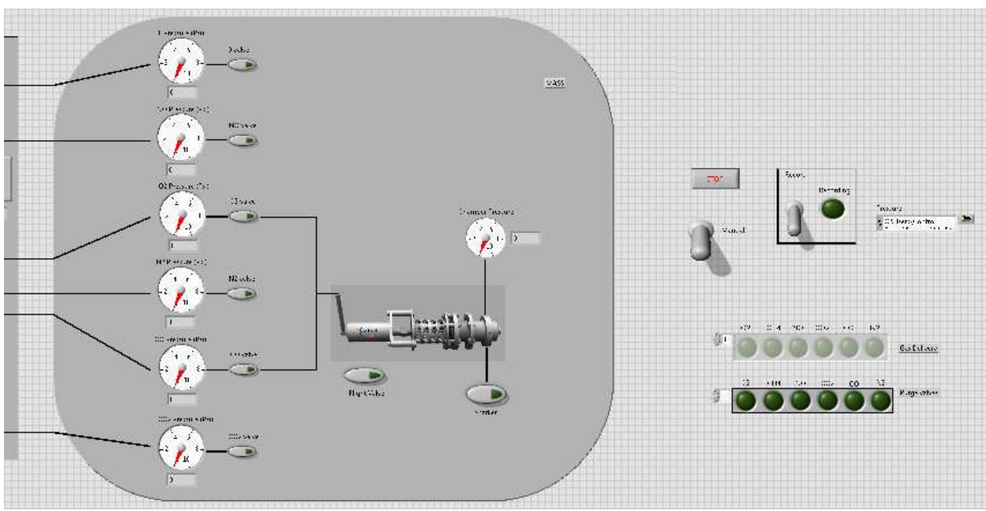

Illustration 3.5 Lab View front panel for the gas delivery system (closer look)

Below is a picture of the gas delivery system shown in Illustration 3.6

Illustration 3.6. Gas delivery system

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3.3.2.2 Liquid propellant delivery system

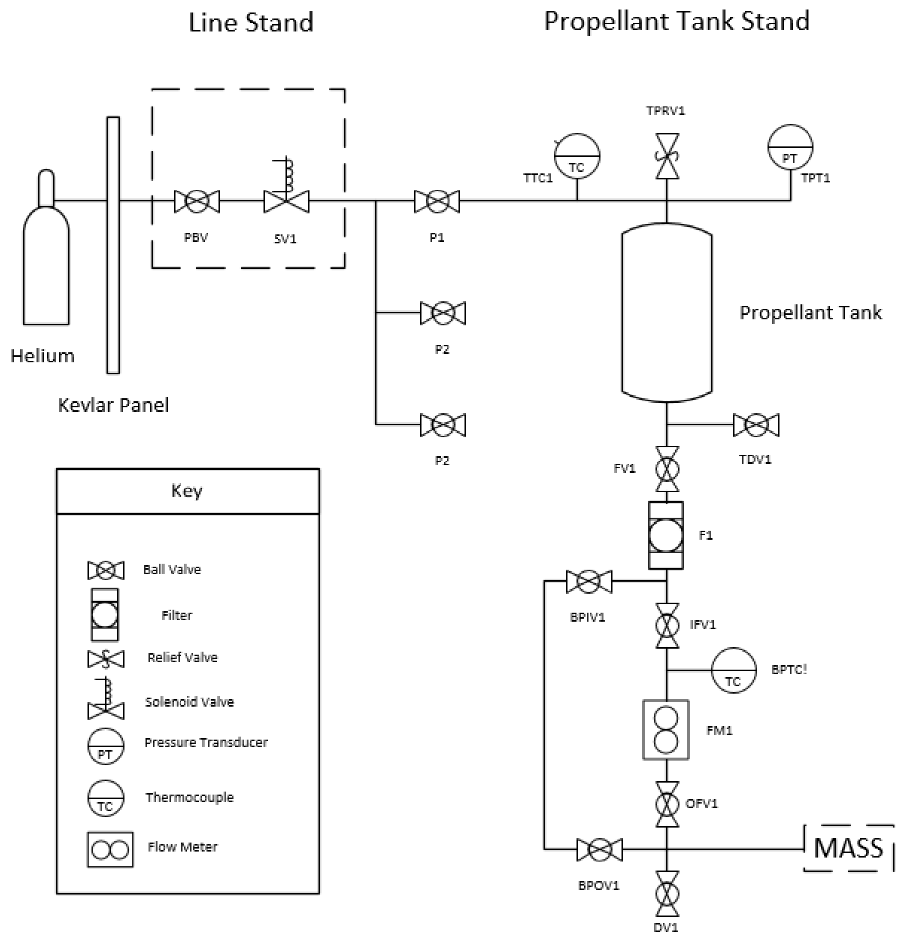

Illustration 3.7 Liquid propellant delivery system

The Engineering Test setup is a static test bed. Flexible interface for three liquid propellant feed systems. Two of the propellants are LMP-13S and AFM-315E. Each liquid propellant has independent feed systems. Each liquid propellant has its own sample cylinder tank (Figure 3.20) where the propellant is stored. A K bottle contains the inert gas to pressurize the system. The K bottle has its corresponding two stage regulator (Figure 3.11). It regulates the pressure of the inert gas flowing to the sample cylinder to pressurize the propellant when testing. The regulator connects to a ball Valve (Figure 3.12) with 1/4 compression fittings on both ends. It isolates the gas flow from the tank to the sample cylinder. The ball valve connects to a solenoid valve (Figure

3.13); It is used as an automated valve actuation system control by a lab View program to isolate the flow while testing. The solenoid valve connects to the sample cylinder where the propellant is stored. From the sample cylinder, there are three components up steam to have control of the stability of the propellant. First, a K type thermocouple (Figure 3.14); It measures the gas flow temperature and the temperature of the inner sample cylinder. Second, a pressure transducer (Figure 3.15) is able to read up to 500 psig; It measures the pressure of the gas flowing and the pressure inside the sample cylinder. Third, a pressure Relief Valve (Figure 3.16) set to open at 400 psig in case the sample cylinder pressurizes more that needed. Down stream of the propellant sample cylinder, there is a ball valve (Figure 3.12) to isolate the liquid flow. On the side of that, there is another ball valve (Figure 3.12) that is used to drain the tank after testing. Connecting the previous ball valves there is a micro-particle filter (Figure 3.17) to filter any particles collected from the sample cylinder. The filter connects to two ball valves (Figure 3.12); One the side there is the bypass which is used when purging to prevent overspin of the flow meter. On the other side, the ball valve (Figure 3.12) is used to manually open and close the flow path, (to test or to purge). This ball valve connects to a K-type thermocouple (Figure 3.14); It measures the flow temperature. The thermocouple connects to a turbine flow meter. (Figure 3.18); which measures volume flow rate of the liquid. The flow meter connects to 3 ball valves (figure 3.12). First is the end of the bypass. Second, the ball valve (Figure 3.12) is used to manually open and close the flow path, (to test or to purge). The third, is a drain valve for the components after testing. These three valves run one 1/8 line to the MASS port (Figure 3.19) where each liquid propellant has its own port.

Another capability is the data acquisition system used for monitoring instruments, making sure the hardware is able to manage/record all data. A necessary program was developed to

interface data acquisition and remote control using lab view. The testing duty cycle Operations of the thruster system will run from 2 to 10 seconds

Figure 3.11 Two Stage Regulator

Figure 3.12 Swagelok Ball Valve

Figure 3.13 Solenoid Valve

Figure 3.14 K-Type Thermocouple

Figure 3.15 Pressure Transducer

Figure 3.16 Swagelok Pressure Relief Valve

Figure 3.17 Swagelok Micro-Particle Filter

Figure 3.18 Turbine Flow Meter

Figure 3.19 MASS Port

Figure 3.20 Sample Cylinder

The lab view front panel for the liquid propellant delivery system is shown below in Illustration on 3.8.

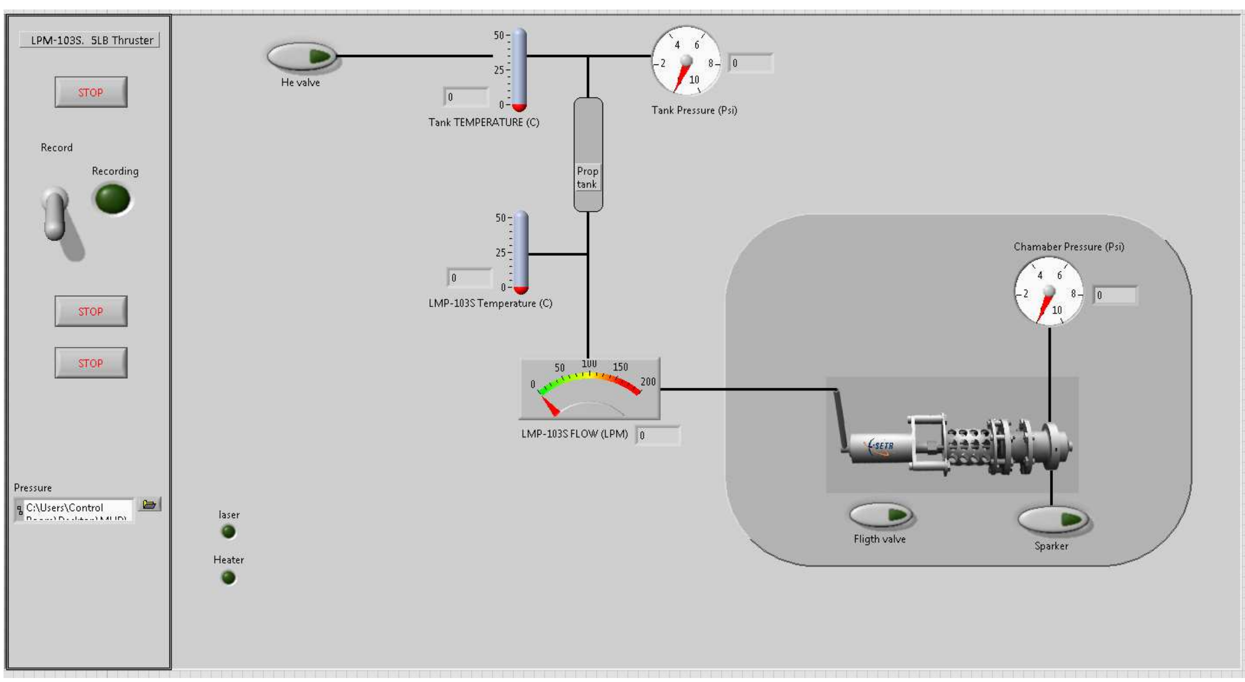

Illustration 3.8 LabView Front panel for the liquid delivery system

Operating conditions for the gas feed system are shown below in Table 3.3

The Propulsion parameters are full Thrust Range of 5-10lbf, flow rates of 0.9 to 9 LPM, ISP profile of 240 seconds for LMP-103S & AFM-315E, test times per gallon are 127 to 381 seconds, temperatures of 25°C to 1700 °C, and pressures up to 400 psi.

Table 3.3 Operating conditions for liquid delivery system

Size	Propellants	Operating Conditions	English Units	SI Units
Small thrusters	LMP-103S	Thrust	5-10 lbf	22-44 N
		ISP	240 sec	240 sec
		Volume Flow	6.4E-6 - 1.6E-5 ft3/sec	11-28mL/min
	AF-M315E	Temp	70-3092°F	21-1700 °C
		Pressure	0-400 Psi	0-2.75 MPa

Below are two pictures of the liquid delivery system shown in Illustration 3.9 and 3.10

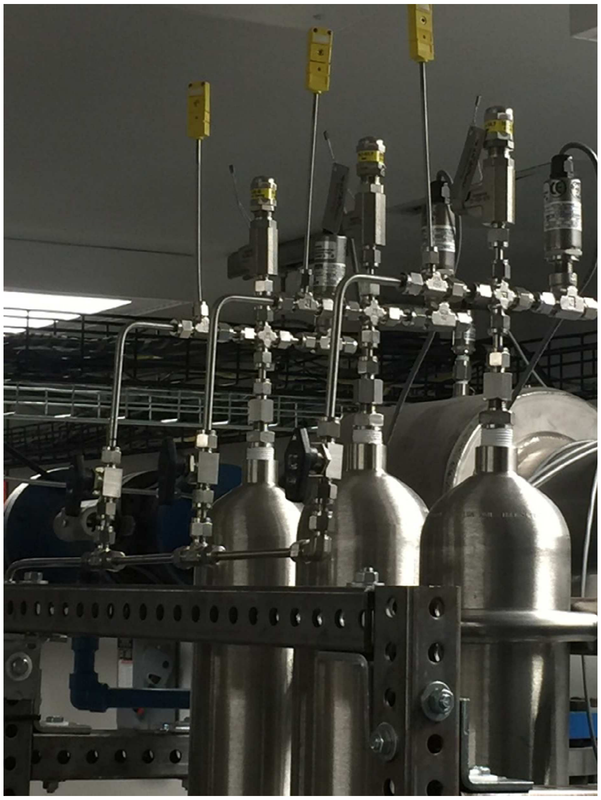

Illustration 3.9 inert gas feed system

Illustration 3.10 liquid propellant delivery system

3.3.2.3 Exhaust system

The exhaust system is used to expel the combustion decomposition gasses out of the MASS and out of the bunker. An exhaust duck is placed on the end port of the MASS shown in Figure 3.21 the duct connects to the exhaust system fan (Figure 3.22). The fan has an on and off switch. The fan expels the gasses to the outside environment as shown in Illustration 3.11.

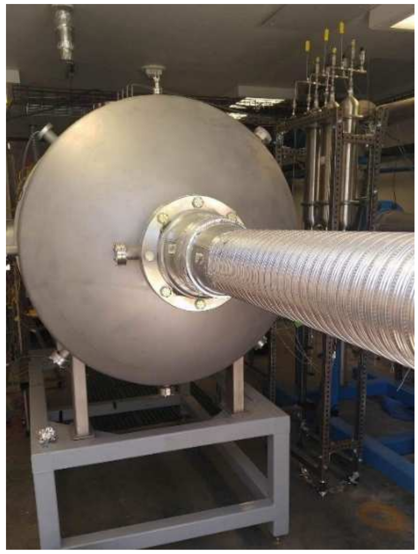

Figure 3.21 Exhaust duct

Figure 3.22 Exhaust system fan

Illustration 3.11 Exhaust fan setup with mass

3.3.2.4 Data acquisition

The data acquisition program was created to monitor, control and record data such as mass flow, temperature, and pressure of the delivery system. The mass flow rate is measured with the flow meters which have an input signal to record the data. The temperature is measured with thermocouples which have an input signal to record the data. The pressure is measured with the pressure transducers which have an input signal to record the data. A second capability of the system is to control the opening and closing of the valves and generate a voltage for the spark plug; these are controlled by an output signal from the program. The third capability of the system is to take measurements with a laser. The laser has a separate program ILD1402 Tool V2.03 where the data is recorded. A camera will record the test inside the MASS using an app on the mobile phone (play memory).

The signal data from the flow meters, static pressure transducers, and thermocouples (K type) will be acquired through a DAQ (NI SCB – 68A (4.29), NISCB -68A (4.30), and NI SCXI-1000 (4.31), respectively, and NI LabVIEW program. A program was developed to obtained signal data for all the measuring devices. Signal conditioners (Figure 3.28) shall amplify pressure transducers outputs. A connector block (model NI-SCB68) with 12 analog channels will transfer incoming signals to the program. Flow temperature and pressure data will be recorded and logged in an LVM file. The actions of opening and closing the gas valves will be done remotely, as designed for hot firing tests. Relays (Figure 3.25) will be used to send the signal to the valves. The spark plug utilizes a voltage generator (Figure 3.26) and a spark initiator (Figure 3.27). The laser (Figure 3.32) utilizes a DAQ (Figure 3.24) with high-speed USB carrier. Laser data will be recorded and logged in an excel file for data processing. The camera (Figure 3.33) will generate a

view for future reference of test and data processing. The power for the data acquisition system will be supplied by four power supply boxes (Figure 3.23).

For the data analysis, MS excel will be used to analyze the measurements data obtained from the tests. The LVM file will output to an XML file or text file for the static pressure, temperature, volumetric flow rates, and laser reading in the gaseous and liquid delivery system.

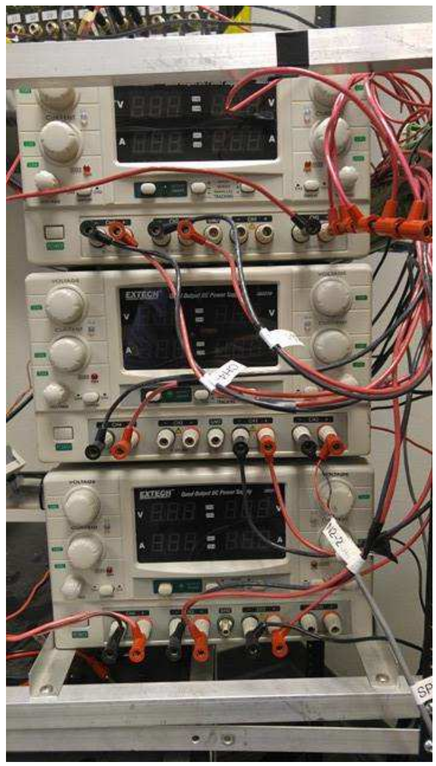

Figure 3.23 Power supply box

Figure 3.24 Laser DAQ

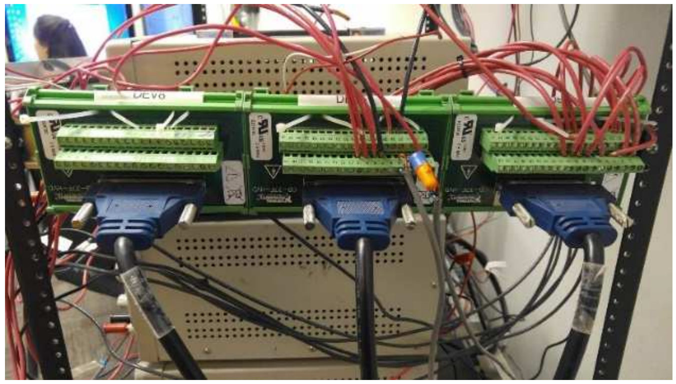

Figure 3.25 Relays for solenoid valves

Figure 3.26 Voltage generator

Figure 3.27 Spark plug voltage generator

Figure 3.28 Pressure transducer amplifier

Figure 3.29 DAQ flow meters

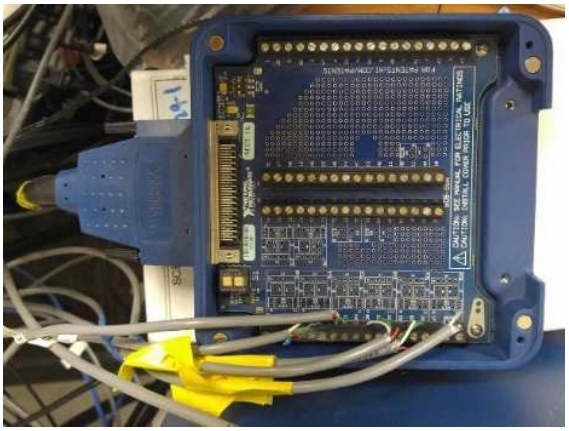

Figure 3.30 DAQ Pressure transducers

Figure 3.31 DAQ Thermocouple

Figure 3.32 Laser

Figure 3.33 Camera

Figure 3.34 PC & UPS

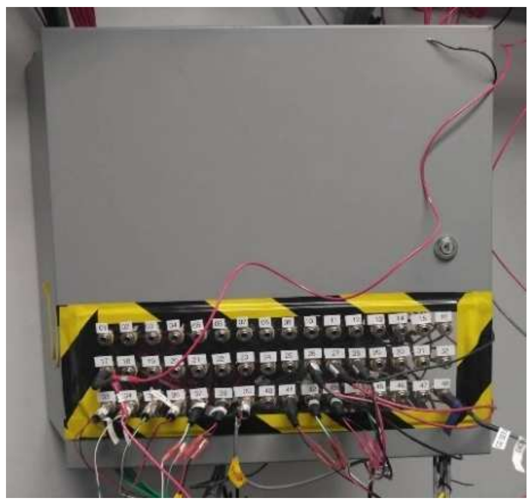

Figure 3.35 Bunker Patch panel

Figure 3.36 Control room patch panel

3.4 Chapter conclusion

3.4.1 Leak test:

The setup was pressurized to 50 psig with Nitrogen to check for leaks. The test matrix was based on previous leak check procedures. The test consists of closing the system and pressurizing it to 50 psig. Apply the snoop and visually look for any leaks. One of the requirements is to leak prove the system and the team met the requirement concluding that the delivery system is leak tested. Prior to a test, it is preferable the system is leak tested as part of the safety precautions. The step by step procedure is in Appendix A.

3.4.2 Pressure drop measurement

Nitrogen K bottle was set to 100 psig. and the nitrogen flow for 10sec. The test matrix was based on previous cold flow procedures. The test consists of setting the nitrogen tank regulator to 100 psig and reading the pressure on the pressure transducer (pressure chamber) installed on the thruster. One of the requirements is to measure the pressure drop across the system, and the team met the requirement. The step by step procedure for a measurement across the system is found in Appendix A.

Chapter 4: Gas/Gas - Thruster Test

4.1 Introduction to chapter

A 22-N class thruster was designed and developed to test the ADN based monopropellant LMP-103S. The thruster consists of 5 modules which include a solenoid valve, a thermal isolation standoff, an injector (distribution plate), propellant feed line, and finally the nozzle/combustion chamber which also houses the catalyst bed. By injecting the expected decomposition gasses into the thruster, the combustion of these gasses, in theory, will drive the exhaust gasses through the nozzle and produce thrust.

The previous chapter explained how the delivery system was designed and built to deliver the required decomposition gasses to the thruster for testing. Before hot fire testing is conducted with the thruster, a leak check and cold flow test with Nitrogen took place to ensure the system is fully functional and operational.

The first objective was to test the delivery system to ensure all components are properly working and assure no leaks in the system. Secondly, the pressure drop was measured across the system to validate calculations and know the pressure drop across the catalyst bed. In this chapter, the last objective will be described in detail. The last objective is to ignite the gas mixture with the ignition source within the thruster and record data with the lab view program during testing.

4.2 Test bed design and development approach (delivery system)

The test takes place inside the bunker in the cSETR E105 lab. Personal protective equipment is worn by test conductors to prevent injury in the event of an unexpected failure during testing. The pressurized system is also surrounded by Kevlar walls to prevent any damage to surrounding hardware and instrumentation inside the bunker.

The process starts by turning on the LabVIEW GUI and checking the channel for each component. The program should display ambient conditions for the pressure transducers and thermocouples. It should also display zero for flow meters. By clicking each valve and listening to the solenoid valves when open will prove the system components are working properly.

The process continues by attaching a plate to the heat bed of the thruster (the combustion chamber/nozzle module will be removed prior) followed by a ball valve and pressure transducer. This allows for the thruster to become pressurized. All components are now pressurized to 150 psig using nitrogen gas (N2) for the leak check. The leak detecting fluid, Snoop, is applied to the perimeter of each fitting. All components are visually inspected to confirm no leaks are present. The components to be leak tested can be found in blue below in Illustration 4.1

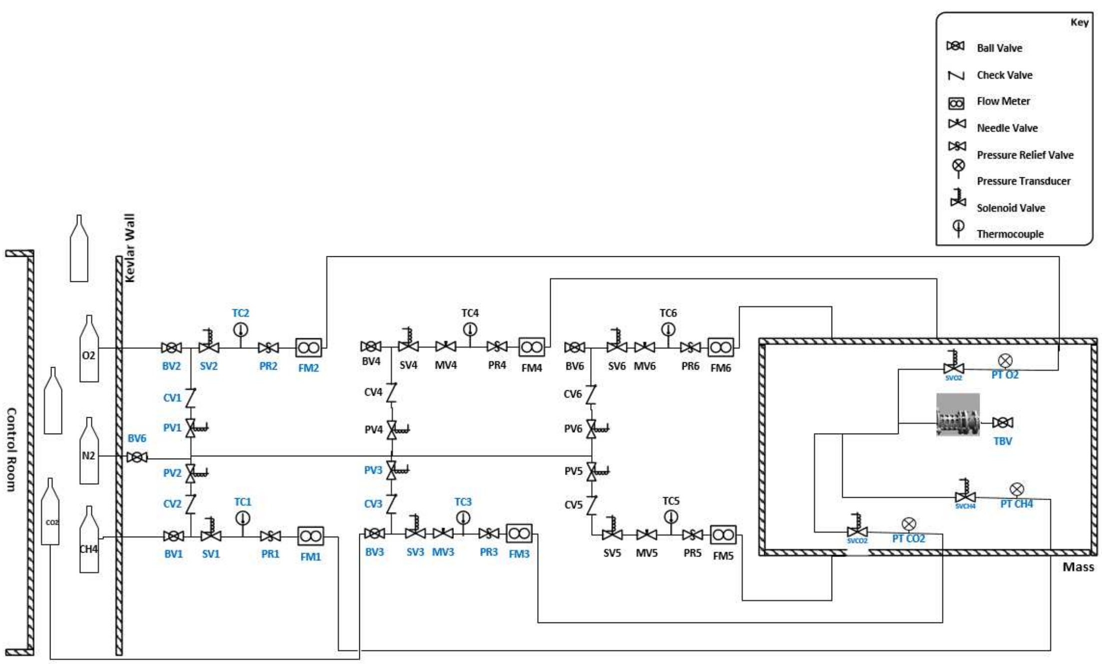

Illustration 4.1 Component schematic - leak check & pressure drop measurement

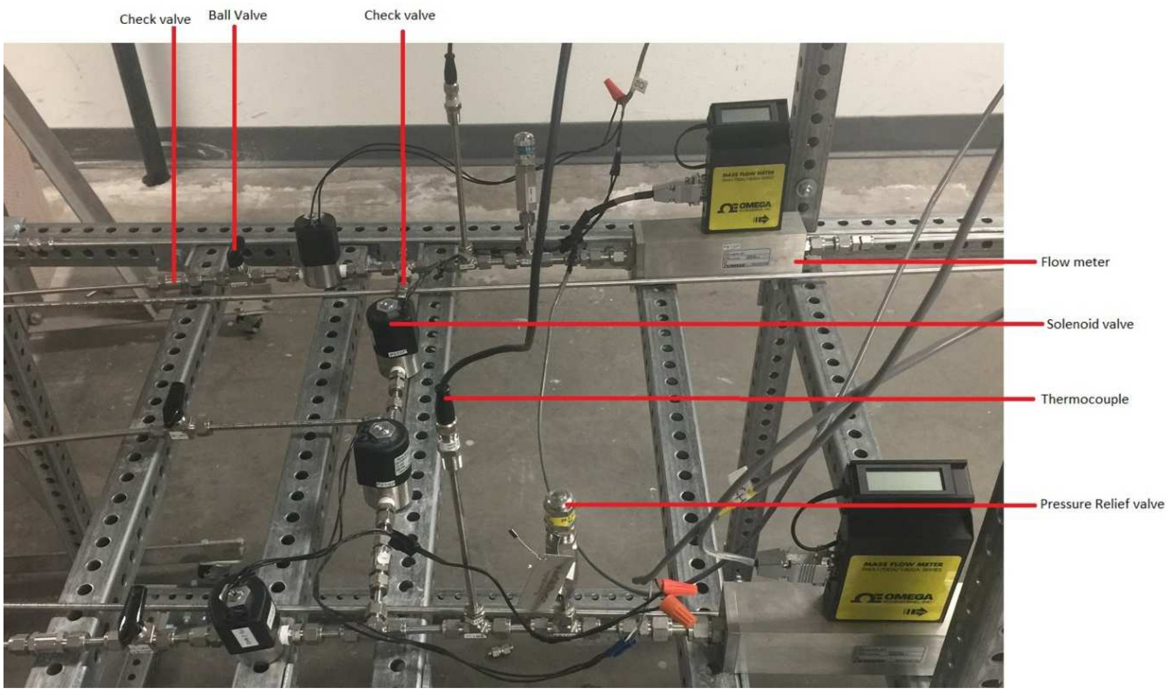

Illustration 4.2 Delivery System Components Outside of the MASS

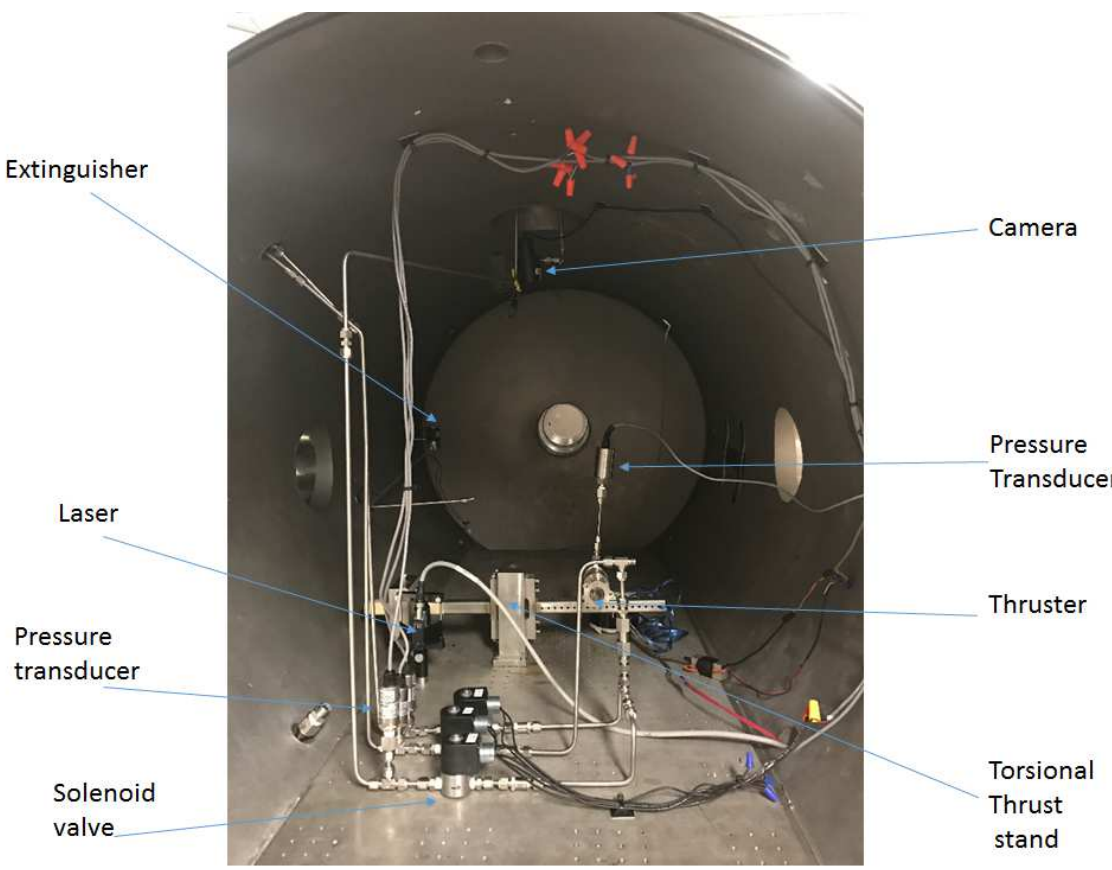

Illustration 4.3 Components inside MASS

The measurement for pressure drop begins by removing the TBV (thruster ball valve) and replacing it by the chamber nozzle section. A pressure transducer is located right before the thruster inlet. Another pressure transducer is located at the chamber and it reads chamber pressure. The Nitrogen K bottle is set to 100 psi. This pressure corresponds to a volumetric flow rate; This flow rate is shown in the flow meters. The flow rate is larger than what the test requires. The neddle valves outside the mass will be adjusted until the three flow meters read the correct flow rate according to the test matrix. The pressure drop across the delivery system and across the thruster will be recorded by opening the Oxygen purge valve, the Oxygen mass valve and let Nitrogen flow. The pressure transducer before the thruster will read pressure drop across the delivery system. The pressure transducer in the chamber will read the pressure drop across the inlet and catalyst of the thruster.

Performing this procedure allows test conductors to set the K bottles to corresponding pressures when hot fire testing takes place. The chamber pressure will be added to each tank after the cold flow with nitrogen.

4.4 Modular Thruster Parameters

The 22 Newton thruster was design and machined previously. The design requirements correspond to the testing for a liquid propellant (LMP-103S). For this matter, not all parameters chosen for the design of this thruster are the same for this test. This test only proves thruster ignition by combining three gases $CH4 + O2 + CO2$. Since there is only one inlet port to the thruster all bases are premixed in the lines before it enters the thruster.

Table 4.1 Thruster Parameters

Thruster Parameters	
Throat Cross-Sectional Area (in^2)	0.0253
Exit Nozzle Cross-Sectional Area (in^2)	0.053
Expansion Ratio (in^2)	2.075
L* Characteristic Chamber Length	30
Thruster Material	Inconel 625
Wall thickness (in)	0.055
Pressure Transducer port (in)	1/8
Pressure Transducer inside port (in)	0.03
Catalyst Diameter (in)	1
Catalyst Material	Silicon Carbide foam
Injector inlet diameter (in)	0.065
Injector expansion cavity (in)	0.9
Feed line (in)	1/8

4.5 Test matrix development

The test matrix was developed by establishing a set flow rate of CH_4, O_2, and changing the percentage of CO_2. Increase from 10% to 50% in the total mixture. The NASA program CEA (chemical equilibrium analysis) was used to obtain parameters. Parameters such as ISP, C*, Cf, and others are shown in Table 4.2. Also, the rocket equations were used to obtain other parameters. For example, Estimated thrust, and Total propellant weight.

Table 4.2 Test matrix calculations for hot fire testing

CO2 Dilution	C* (in/s)	Cf	Total Wp (lb/s)	Species	No. of Moles	Mole Fraction	MW (g/mol)	Total MW	Mass Fraction	Density @100 psi (kg/m^3)	mp (lb/s)	mp (kg/s)	Volume Flow Rate (m^3/s)	Volume Flow Rate (LPM)	Estimated Thrust (lbf) Using Cf	Isp (m/sec)	Isp (s)	Estimated Thrust (lbf) Using Isp
10%	61216.54	1.25	0.0158	**CH4**	1.00	0.30	16.04	4.81	0.169	4.522	0.00267	0.00121	0.000268	**16.078**	3.118	1939.2	197.7	3.118
				CO2	0.33	0.10	44.01	4.40	0.155	12.761	0.00244	0.00111	0.000087	**5.210**				
				O2	2.00	0.60	32.00	19.20	0.676	8.952	0.01066	0.00483	0.000540	**32.402**				
				Total				**28.41**	**1.000**									
20%	61519.7	1.2207	0.0157	**CH4**	1.00	0.27	16.04	4.28	0.142	4.522	0.0022	0.00101	0.000223	**13.404**	3.052	1907.4	194.4	3.051
				CO2	0.75	0.20	44.01	8.80	0.292	12.761	0.0046	0.00208	0.000163	**9.773**				
				O2	2.00	0.53	32.00	17.07	0.566	8.952	0.0089	0.00403	0.000450	**27.012**				
				Total				**30.14**	**1.000**									
30%	56267.717	1.2142	0.0172	**CH4**	1.00	0.23	16.04	3.74	0.117	4.522	0.00201	0.00091	0.000202	**12.109**	3.036	1735.3	176.9	3.035
				CO2	1.29	0.30	44.01	13.23	0.415	12.761	0.00712	0.00323	0.000253	**15.186**				
				O2	2.00	0.47	32.00	14.92	0.468	8.952	0.00803	0.00364	0.000407	**24.403**				
				Total				**31.89**	**1.000**									
40%	51090.5	1.2226	0.0189	**CH4**	1.00	0.20	16.04	3.21	0.095	4.522	0.00180	0.00082	0.000181	**10.857**	3.057	1586.5	161.7	3.056
				CO2	2.00	0.40	44.01	17.60	0.524	12.761	0.00990	0.00449	0.000352	**21.108**				
				O2	2.00	0.40	32.00	12.80	0.381	8.952	0.00720	0.00326	0.000365	**21.879**				
				Total				**33.61**	**1.000**									
50%	45385.8	1.234	0.0213	**CH4**	1.00	0.17	16.04	2.67	0.047	4.522	0.00099	0.00045	0.000099	**5.969**	3.085	1422.5	145.0	3.085
				CO2	3.00	1.00	44.01	44.01	0.767	12.761	0.01633	0.00740	0.000580	**34.815**				
				O2	2.00	0.33	32.00	10.67	0.186	8.952	0.00396	0.00179	0.000200	**12.029**				
				Total				**57.35**	**1.000**									

4.6 Testing

The test begins by setting the K bottles to 220 psi. Next, cold flow each line with nitrogen. This process is described step by step in the test procedure in a different document. Basically, it is finding the corresponding flow rate in each line by manually adjusting the ball valves outside the mass. The test runs for ten seconds (automatically). With the camera located inside the MASS, the test conductors can see the flame and record live footage.

The data was used to check the performance of the system (pressure readings in the thruster along with expected flow rate readings in the flow meters). The schematic in Illustration 4.1 was utilized for hot fire testing. Other components are shown below were also used during testing.

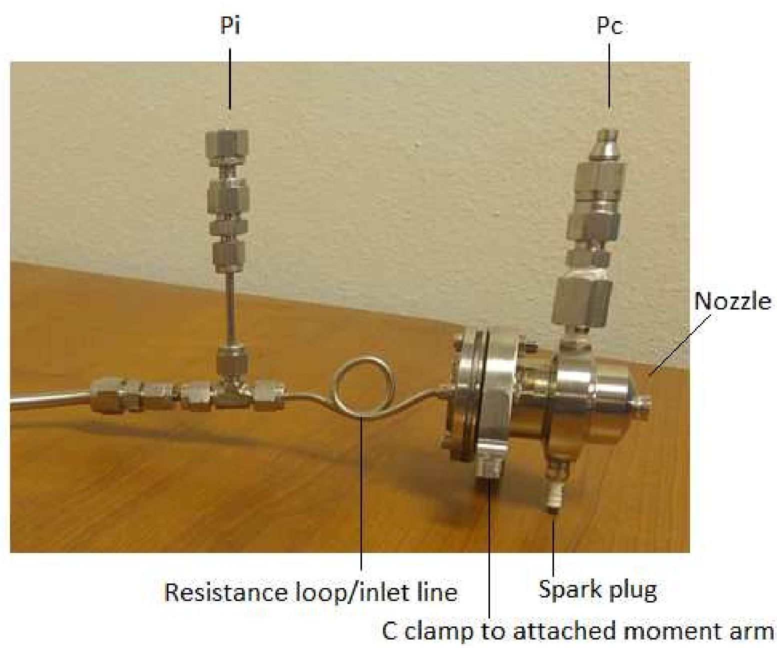

Figure 4.1 Thruster (Vertical fittings are the two pressure ports)

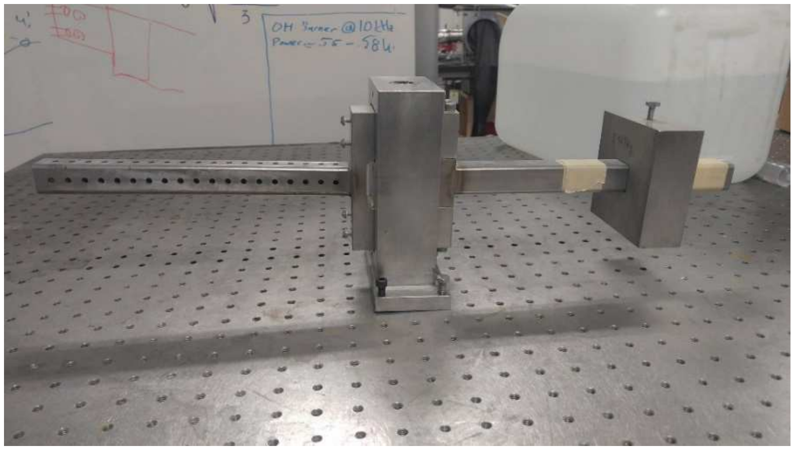
Figure 4.2 Torsional thrust stand


Figure 4.3 Precaution rail

Figure 4.4 Emergency button

Figure 4.5 Kevlar wall

4.7 Results

The testing lasted 4 full days. The objective of the test was to test different percentages of CO_2 in the total volume flow rate of the mixture. Table 4.3 summarizes the tests matrix having 8 different tests.

Table 4.3 Test Matrix

CO2	V flow rate O2	V flow rate CH4	V flow rate CO2
%	LPM	LPM	LPM
0%	12.48	9.56	0.00
4%	10.88	6.50	0.77
8%	10.86	6.94	1.59
9%	10.93	7.29	1.85
16%	12.18	9.56	4.15
35%	10.47	7.29	9.59
43%	10.44	6.87	12.93
49%	10.10	6.64	15.91

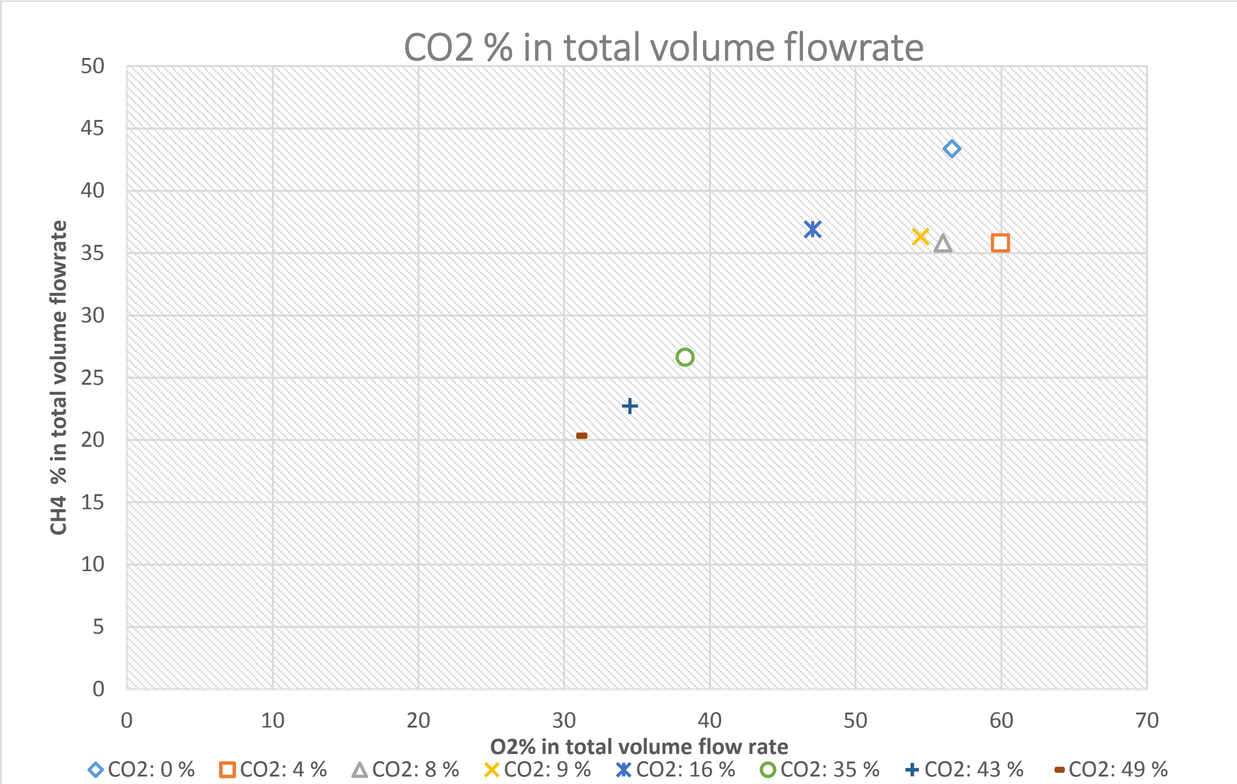

Illustration 4.4 Test matrix in a graph showing how CO2 increases

Illustration 4.5 to 4.13 show the data collected from the tests. All tests ignited.

Table 4.4 Test results

CO2	Volume flow rate O2	Volume flow rate CH4	Volume flow rate CO2	Pc max	Tank-Pc,max	Thruster,c wall
%	LPM	LPM	LPM	Psi	Pdelta Psi	Tmax C
0%	12.5	9.6	0.0	42.5	157.5	287.0
4%	10.9	6.5	0.8	43.3	156.7	287.7
8%	10.9	6.9	1.6	45.3	154.7	287.7
9%	10.9	7.3	1.9	46.6	153.4	287.7
16%	12.2	9.6	4.2	46.7	153.3	307.4
35%	10.5	7.3	9.6	47.4	152.6	355.2
43%	10.4	6.9	12.9	52.6	147.4	305.6
49%	10.1	6.6	15.9	47.9	152.1	244.5

Illustration 4.5 35% CO2 fire

Illustration 4.6   35% CO2 fire extinguishing

Illustration 4.7   46% CO2 fire

Illustration 4.8 46% CO2 fire extinguishing

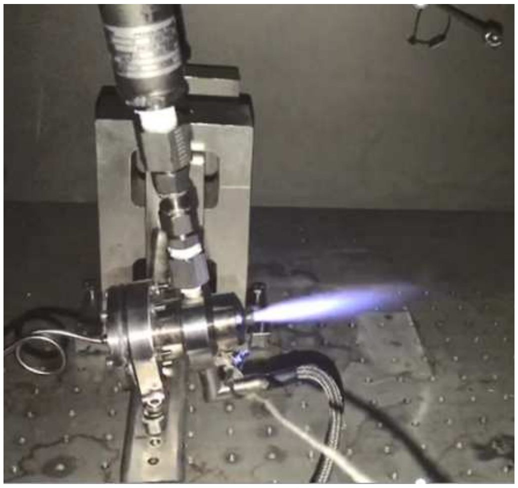

Illustration 4.9 49% CO2 fire

Illustration 4.10 49% CO2 fire extinguishing

Illustration 4.11 Catalyst failure

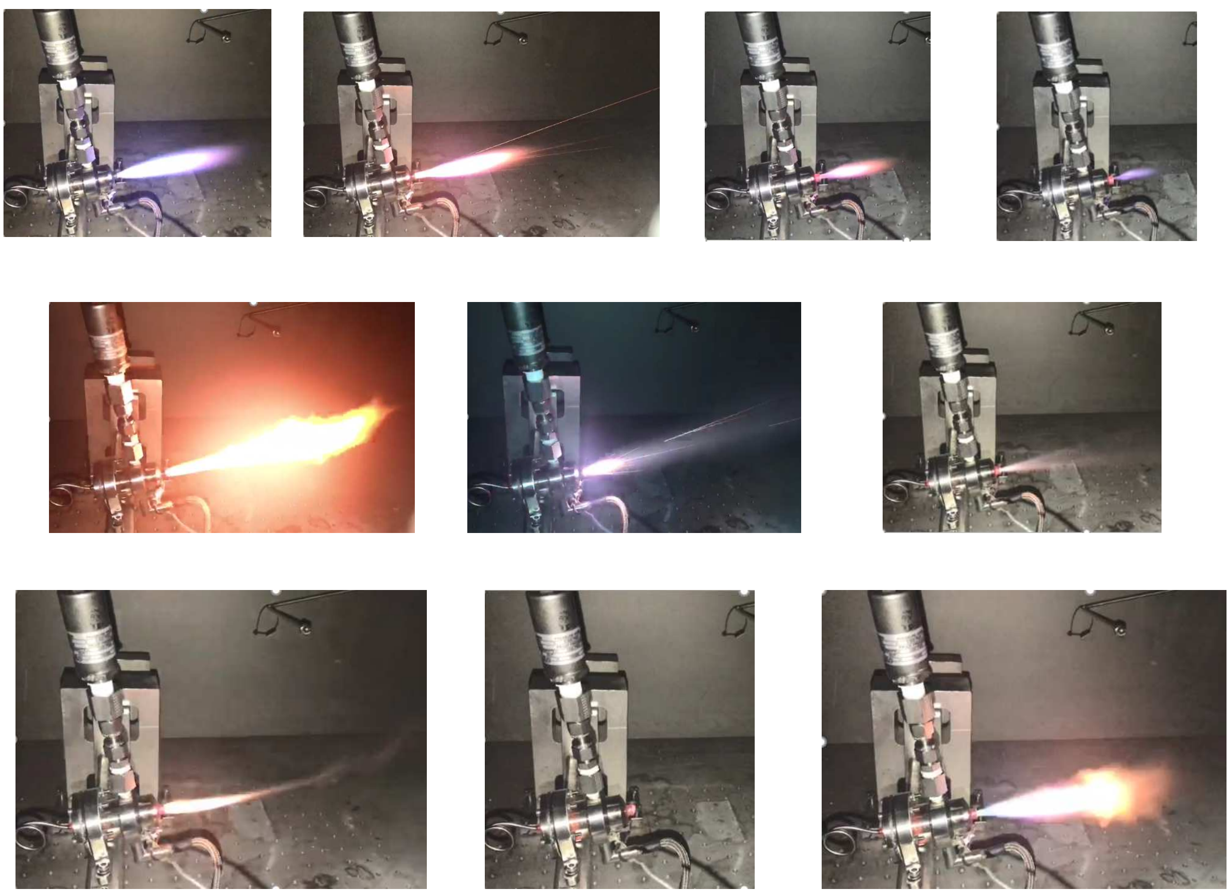

Illustration 4.12 (10 pictures) 0% CO2 fire

The last test performed was with no CO_2. The catalyst experienced failure after continuous test. Particles inside the chamber burned and started coming out on fire. Also, there was two ignitions in the last test. The first four pictures shown above are one ignition. After three seconds a second ignition started. The thruster started smoking from the middle and the entire thruster started turning red. This concluded the testing with this first modular thruster.

4.8 Future Work

The next step for this project is to prepare the testing of the 22 Newton thruster using the liquid delivery system. At this point, May 2017, the team is in the process of procuring liquid propellant from the Air Force, a US government agency. The propellant that will be used to test this thruster will be AFM-315E. The characteristics of both green propellants are very similar.

The second generation of thruster will be designed, manufactured and eventually tested. Another section of the green monopropellant effort team was to test flame lengths using the decomposition gasses of LMP-103S. This work enabled an idea of how long the flame length of this propellant. A model was created to have an input range of flame lengths and output range of chamber length. This model will help redesign the thruster using the new known parameter.

Chapter 5: Conclusion

5.1 Summary of work

The green team's main task was to develop a delivery system to further investigate new propellants. These ionic monopropellants LMP-103S and AFM-315E are being tested to understand the compound and create the next generation of the propulsion systems in rockets. The delivery system was designed and built. The system has a gas fed system and a liquid fed system. The delivery system was leak tested and a pressure drop measurement was taken. In parallel with the components, a data acquisition system was created to remote control the system and record information for data proceeding. The second part of this thesis was to test the 22 Newton thruster first generation; previously developed by the green propellant team. Based on the results of CEA, the mixture of Methane, Oxygen, and Carbon dioxide were chosen to test this thruster. Methane, Oxygen, and Carbon dioxide were delivered to the thruster by the new delivery system and with the help of the spark plug, the thruster was ignited. Based on this test, the team could assure the delivery system was working correctly and set requirements for future tests. The thruster provided useful information such as temperature, and pressure capabilities.

References

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Vita

Jaclyn Mona was born in El Paso TX on April 12, 1992. Her parents are both UTEP graduates, Carlos Mario Mejia, BS 1985 and Raquel Mejia, BBA 1985. Both with master degrees. She was raised as an ex-patriot while her father ran a Multinational Manufacturing company, Jaclyn was raised with community and family values in Chihuahua City, Chih., Mexico during her formative years. She attended Colegio Montessori de Chihuahua for her elementary and middle school education, which focused was on self-motivation, team work and creativity. Then, she attended Tecnologico de Monterrey, Campus Chihuahua, considered a highly demanding prep-school, for part of her high school years while actively participating in the soccer team. She returned home to El Paso, where all her extended family resides and completed high school at Franklin high school as part of the National Honor society, in June 2010. She selected to continue her higher education at the University of Texas at El Paso due to its' excellent engineering program and vast research opportunities. During her sophomore year, Jaclyn began working for Dr. Ahsan Choudhuri at the center for Space Exploration Technology Research. She began with cSETR February 2012 where she worked on several projects under NASA and MDA. In the summer of 2014, Jaclyn had an internship in Houston, NASA's Johnson Space Center. She obtained her Bachelors of Science degree in Mechanical Engineering in Spring 2015, also volunteering in various venues to motivate others to study STEM education. She was accepted into the Master of Science in Mechanical Engineering program where she graduated in spring 2017. Jaclyn decided to continue her education and now she is accepted into the Doctoral program in Mechanical Engineering at UTEP.

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