2012-01-01

Instrumentation, Control And Torch Ignition Systems Development For Lox/methane Propulsion Research

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INSTRUMENTATION, CONTROL AND TORCH IGNITION SYSTEMS DEVELOPMENT FOR LOX/METHANE PROPULSION RESEARCH

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Dedication

This thesis is dedicated to my family and all the support they gave me throughout my entire education and professional career.

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by

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THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at El Paso

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE

Department of Mechanical Engineering

THE UNIVERSITY OF TEXAS AT EL PASO

May 2012

Acknowledgements

I would like to extend my gratitude to all the people that helped me and made possible the accomplishment of the presented thesis. First, I would like to thank my advisor Dr. Ahsan Choudhuri for mentoring and giving me the opportunity of having a better education and improving my prospects toward a professional career. I would like to recognize Mr. Nathaniel Robinson for all his help and guidance provided over the entire time I worked at the Center for Space Exploration Technology Research. I would also like to thank my colleagues from the cSETR for sharing their knowledge, advising and especially their friendship. A special mention is extended to Mr. Francisco Pineda for his generous assistance and support in the completion of the present work.

I would to thank the staff of the cSETR for their time and effort to assist the students. Thank you to the members of my committee for the dedication, time and contribution to this thesis. Finally, I would like to extend a special recognition to my family and my girlfriend for providing me with their support and advice that inspired me to successfully accomplish this research work.

Abstract

A liquid propulsion research facility has been developed at the Center for Space Exploration Technology Research at The University of Texas at El Paso. This facility has capabilities for producing up to 25 liters of Liquid Methane, feeding LOX/Methane propellants to 100 N class thrusters and conducting automated steady state and pulsing combustion experiments. This work describes the design, development and testing process of the Data Acquisition and Remote Control System developed to integrate an Altitude Simulation System, a Cryogenic Delivery System, and multiple rocket combustors and thrusters. A Torch Ignition System development is detailed as well as the evaluation process to characterize optimum operation when integrated to a Multi-purpose Combustor Test Rig.

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Chapter 1: Introduction

The combination of Liquid Oxygen (LOX) and Liquid Methane (LCH_4) has been identified as a highly potential fuel option for the next generation of propulsion systems. The National Aeronautics and Space Administration (NASA) has identified a significant opportunity for mass reduction in future space vehicles if its main propulsion system and its auxiliary Reaction Control System (RCS) are integrated and both systems are fed with non-toxic LOX/LCH_4 propellants;. The advantage of a LOX/LCH_4 system (main engine and RCS) in mass reduction is produced by merging two common components into a single one, such as the pressurization system and the propellant tanks. However, LOX/LCH_4 propulsion technology is considered relatively new and more detailed investigations and risk reduction studies are required in order to manufacture integrated LOX/LCH_4 systems (Robinson, Veith, Hurlbert, Jimenez, & Smith, 2010).

There have been irregular periods of interest of using methane as liquid rocket's fuel since the 1960s. In the last thirty years the propulsion industry had been focused on the development of technology for fuels like hydrogen and kerosene, resulting in the slowed development of a complete propulsion system fed with Liquid Methane. However the increasing necessity of developing more efficient space vehicles has increased the interest in liquid methane as a rocket fuel. Liquid Methane application has multiple advantages in comparison with traditional fuels. Among these advantages, a cryogenic LOX/LCH_4 propulsion system has the storage systems working at a similar temperature[1]. Also, methane is considered to be relatively inexpensive to produce, easy to handle and a non-toxic propellant (Neill, Judd, Veith, & Rousar,

[1] Oxygen boiling point occurs at 90K, and for Methane at 111K (Flynn, 2005).

2009). However, the non-hypergolic characteristics of LOX/LCH_4 propellants drive the necessity of incorporating an external ignition source. This ignition system developed for LOX/Methane engines has to meet the requirements of high reliability, long durability and fast response (Rosenberg, 1983).

1.1 CENTER FOR SPACE EXPLORATION TECHNOLOGY RESEARCH

The Center for Space Exploration Technology Research (cSETR), established under the direction of Dr. Ahsan Choudhuri, promotes the research and education in propulsion and energy engineering. The cSETR conducts a wide range of research topics such as green propulsion, in-situ resource utilizations, structures, clean power generation, carbon monoxide sequestration, etc. As a University Research Center (URC) for the National Aeronautics and Space Administration (NASA), the cSETR performs fundamental research on ignition, heat transfer characteristics and injector dynamics for LOX/Hydrocarbon engines; focusing on LOX/Methane propellants due to the potential application on the lunar ascent engine (NASA Exploration Systems Architecture Study, 2005) and Mars in-situ resource utilization.

1.2 PROBLEM STATEMENT

The cSETR has built a propulsion research facility named the Goddard Laboratory at the University of Texas at El Paso (UTEP). In order to meet their research objectives on LOX/Methane propulsion systems, the cSETR researchers have implemented a specific plan of experimentation on heat transfer characterization, ignition physics and combustion phenomena; the hardware and equipment required to conduct such testing has been developed as well. A Multipurpose Optically Accessible Combustion Chamber (MOAC) was developed for optical diagnostics of ignition physics and combustion; the MOAC is modular to accommodate for

different injector designs (i.e. Shear Co-axial Injector) and nozzle components, such as converging section, throat area, etc. (Navarro, Betancourt-Roque, Sanchez, Robinson, & Choudhuri, 2011). A Multipurpose Altitude Simulation System (MASS) and a Cryogenic System were also developed at the cSETR. The Cryogenic system is configured in two major components; the first has the capabilities of producing in-house Liquid Methane, the second has the capability of supplying Liquid Oxygen (LOX) and Liquid Methane to different test rigs (i.e. the MOAC) and experimental set-ups (Pineda, Flores, Garcia, Navarro, & Choudhuri, 2011). In order to enable full testing operations, the systems need to be integrated and controlled in a safe manner; therefore, a remote control and data acquisition system needed to be developed. This system is required to provide the Goddard Laboratory staff with capabilities of controlling any experiment conducted and logging all data generated by any transducer or sensor required to conduct the experiment. In addition, a reliable ignition system is required to be developed and tested.

1.3 PROJECT PURPOSE AND OBJECTIVES

The purpose of this thesis is to design, implement and evaluate the performance of a Data Acquisition and Remote Control System (DARCS) to run multiple experiments with LOX/Hydrocarbons cryogenics in a safe, metered and remote manner. In addition, a Torch Ignition System has also been developed and evaluated to be implemented as the main igniter of the combustor (MOAC).

The objective of the DARCS is to serve as a modular control and data acquisition system to accommodate all the experiments testing cryogenics and combustion. The DARCS main objective is to be the permanent controller of the instrumentation and control hardware that integrate the Cryogenic Delivery System; as secondary objectives, the DARCS integrates the

controls and instrumentation hardware required to run the MOAC, the MASS and the Torch Igniter. The DARCS also provides the capacity of controlling different combustion experiments, such as other combustors, thrusters and delivery lines.

The objective of the Torch Igniter is to provide a reliable ignition source for testing and operation of the MOAC. The Torch Igniter design is based on a previous-tested micro thruster (Flores, 2009) that has proven to be reliable and stable. The Torch Igniter should incorporate to its design the manufacturing characteristics of the MOAC such that it is to be integrated.

1.4 PRACTICAL RELEVANCE

LOX/Methane engines can be designed to perform as booster engines, reaction control engines (RCE), orbital maneuvering engines (OME) as well as planetary descent/ascent engines (Neill, Judd, Veith, & Rousar, 2009). The development of this control and data acquisition system (DARCS) and the Torch Igniter will aid to conduct safe experimentation of LOX/Methane ignition physics and combustion characteristics. This experimentation will generate the data needed to increase the understanding of LOX/Methane combustion phenomena and its critical parameters, methane heat transfer behavior as well as related components life. This better understanding is required to develop the next generation of propulsion systems working with LOX/Methane propellants.

1.5 THESIS ORGANIZATION

This thesis is organized into six chapters. Chapter one gives an introduction of LOX/Methane propulsion technologies and potential applications in the space exploration industry as well as the objectives and the problem to be addressed in this project. Chapter 2 describes the importance of safety and a background of the systems to be controlled by the

DARCS. Chapter 3 details the design process, requirements and implementation; testing and integrating the DARCS is covered in Chapter 4. In Chapter 5, the Torch Igniter development is addressed covering background, requirements and testing performed to evaluate its operation and integration to the combustion experiments. Finally, in Chapter 6 the conclusion is covered and some recommendations for improvement are given as well.

Chapter 2: Instrumentation & Controls Background

In order to develop any automated control and instrumentation system, a set of requirements needs to be established. These requirements are delimited by the nature of the process to be measured and controlled. Processes that integrate various experiments and control operations are discussed below.

2.1 CRYOGENICS

A cryogenic is a liquefied gas with a normal boiling point below 183K (Flynn, 2005). Flammable cryogenic gases are extremely hazardous and require special handling for safe operations.

2.1.1 Hazards

Hazards associated with cryogenics handling may be categorized into two major types: physiological hazards and materials and equipment hazards. Possible physiological hazards affecting the personnel involved in cryogenics handling are frostbite, asphyxiation, hypothermia and death. Asphyxiation occurs due to Oxygen rich or an Oxygen deficient environment caused by the displacement of air due to boiling of cryogenic gases. The volumetric expansion ratio of boiling cryogenics (average 1 to 600) causes over-pressure hazards when a cryogenic is trapped without a relief path, causing bursting in the lines and damaging of components. Fire and explosions hazards are of concern when the combination of an oxidizer-fuel-ignition source is present. Any carbon-based material will ignite or explode when it is in contact with LOX (Flynn, 2005). LOX decreases the required ignition energy and triggers burning of materials even of those that are at room temperature.

2.1.2 Safety

In order to avoid said physiological hazards, all the cSETR personnel (staff and students) are extensively trained in handling cryogenic fluids. The cSETR's experimental protocol requires that prior to running any experiment a written procedure and a safety hazards analysis should be submitted to the director and safety committee. Once the procedure and safety analysis are reviewed and corrected, a dry run is performed several times to ensure every step is executed properly. After the dry runs are fully approved, the personnel are authorized to run the experiment with cryogenics. All the personnel involved in experimentation with cryogenics are required to use appropriate Personal Protective Equipment (PPE), e.g face shields, cryo-rated globes and aprons, glasses, etc.

2.1.3 Remote Operation

Safer operations in combustion and heat transfer experiments are achieved by conducting all experiments remotely and inside a projectile-proof bunker. The nature of these experiments requires the cryogenic system and test articles to be controlled from an external and risk-free control room to avoid injuries to students and personnel. Critical diagnostics as well as prevention systems, such as ventilation and relief paths should be incorporated in the design to minimize damage to components, equipment and facilities.

2.2 SYSTEMS INTEGRATION

Once the mechanical systems are developed (MOAC, MASS, Cryogenic Delivery System), these systems need to be integrated, tested and evaluated. In order to integrate each system to a remote control and instrumentation system, the electrical characteristics of each hardware component should be evaluated. These characteristics settle down the desired

performance for which the control and instrumentation system must be designed. In the following sub-sections, a brief summary of electrical components and requirements for the mechanical systems is presented.

2.2.1 Cryogenic Delivery System

Designed to deliver cryogenic propellants (LOX/LCH_4) in a liquid and metered state, the cryogenic delivery system incorporates pre-chill, purge and fed stages. Each stage of this system has specific control and metering components that operate and measure critical parameters, such as line pressure, temperature and flow rate. The schematic of this delivery system is shown in Figure 1; the Liquid Methane and LOX propellants, Liquid Nitrogen chilling down and gas Nitrogen lines are displayed.

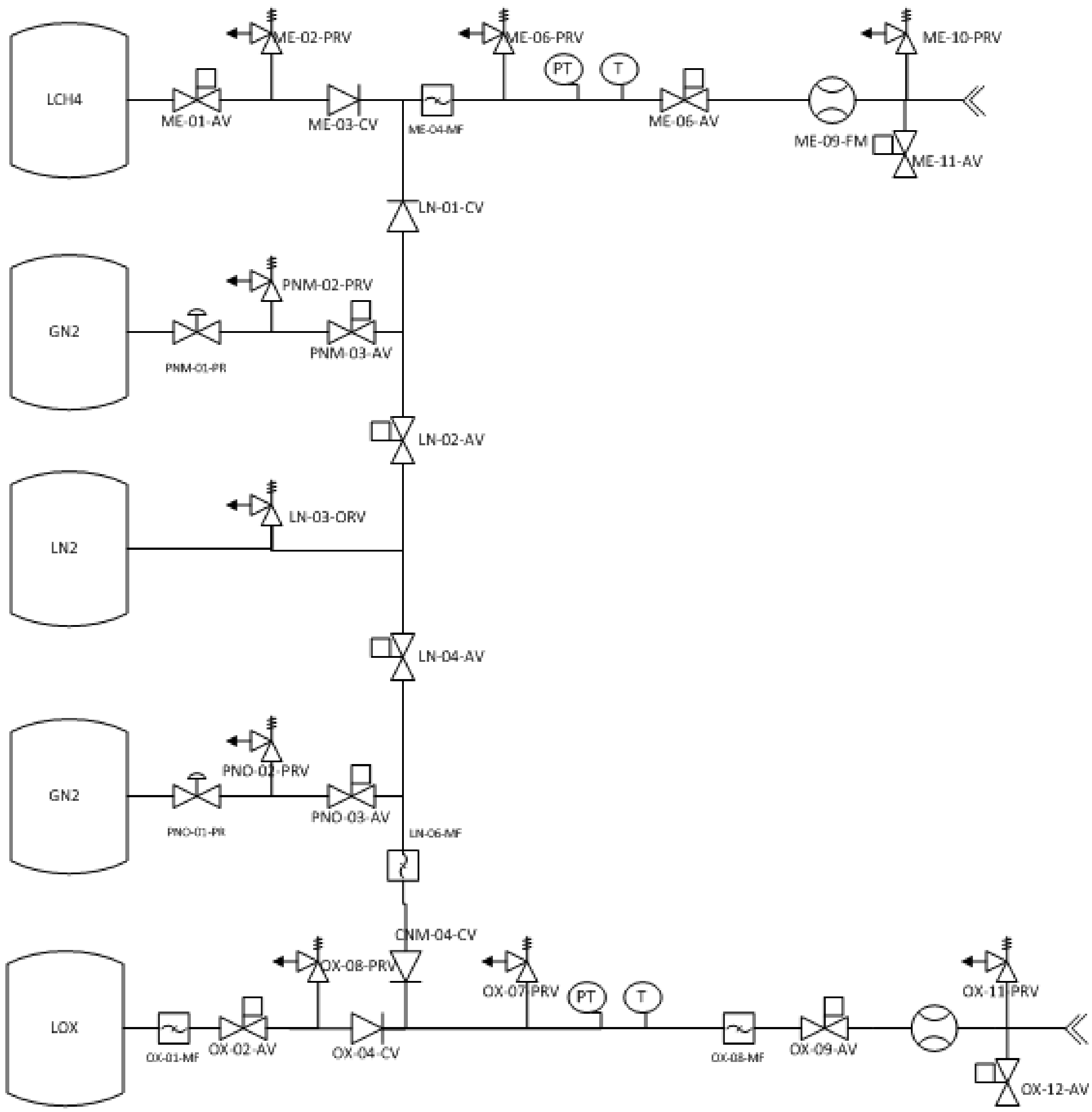


Figure 1 - Cryogenic Delivery System Schematic

Each component is labeled for reference and easier identification. The components with label ending in "AV" (i.e. ME-01-AV) are actuated valves: solenoid valves actuated with a 120 V AC signal (see Figure 2) from McMaster vendor. The system has a total of eight actuated valves with ½" NPT port connections.

Figure 2 - Cryogenic Brass Solenoid Valve #7902K43

Components with a circled “PT” symbol are cryogenic pressure transducers (see Figure 3) required to ensure normal pressure operating conditions and avoid bursts in lines. These pressure transducers from vendor Omega require a 10 V DC excitation signal and provide a feedback signal from 0 to 30 mV DC.

Figure 3 - Cryogenic Pressure Transducer PX1005L1-250 AV

Temperature measurements are achieved via two Silicon Diode Temperature Sensors from Lakeshore (shown in Figure 4). In the schematic, the sensors are represented with a circled

“T” symbol; these sensors require an excitation signal of 10 µA (micro amperes) and provide a feedback signal ranging from 0 to 1.5 V DC.

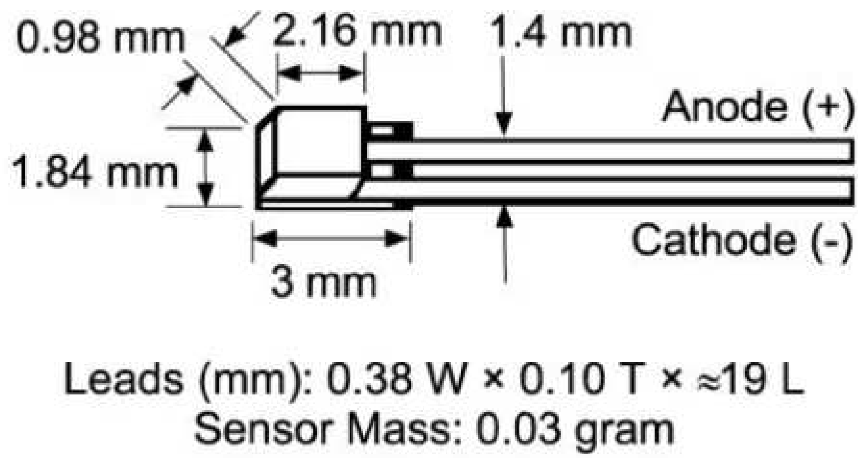


Figure 4 - Silicon Diode DT-670-SD-1.4L

Flow measurement devices have labels ending with “FM” (i.e. ME-09-FM) identification. A turbine flow meter from Hoffer vendor was selected (see Figure 5) for cryogenic fluids. This flow meter measures the flow and converts it to a pulsing output signal, where the frequency of the signal is directly related to the flow rate through a calibration curve.

Figure 5 - Hoffer turbine mini-flowmeter

The vendor incorporates a microprocessor-based transmitter to the flow meter as well. This device reads the pulsing output from the flow meter and traduces it to a current output of 0 to 20 mA (see Figure 6).

Figure 6 - CAT1 Flow Transmitter

For gaseous flow measurement, FMA1843 and FMA1845 flow meters from Omega vendor were selected. These flow meters require an excitation voltage of 12 V DC and provide a feedback signal of 0 to 5 V DC. These flow meters have a numeric display for redundant readings (Figure 7) as well.

Figure 7 - Omega FMA1800 Series Flow Meters

2.2.2 MOAC

With the purpose of studying combustion characteristics of bi-propellants engines, the Multipurpose Optically Accessible Combustor (MOAC) (Figure 8) is fitted with instrumentation for measuring chamber temperature and pressure.

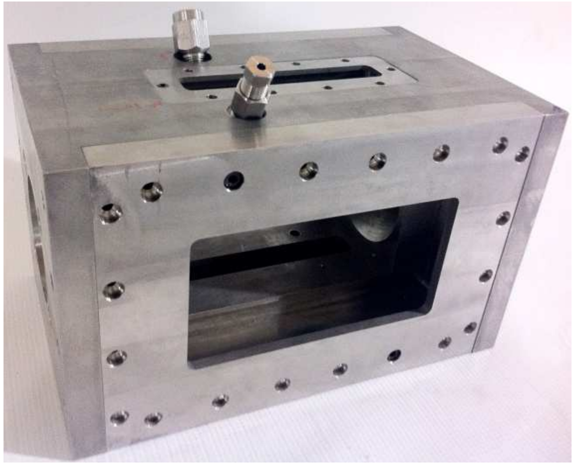


Figure 8 - MOAC with Thermocouple and Pressure Transducer ports

The chamber Pressure is measured by a PX309-500GV Pressure Transducer from Omega (Figure 9). This transducer requires an excitation signal of 5 V DC and generates a feedback signal of 0 to 100 mV DC. Outputs of this transducer are as follows: 20 mV for 1 psi (Need SI Unit), 40 mV for 2 psi and a linear 40 to mV signal for the range of 3 to 500 psi..

Figure 9 - Pressure Transducer PX309 Series

The MOAC has two N-Type thermocouples from Omega for temperature sensing. These sensors (Figure 10) require a dedicated thermocouple in the instrumentation system.

Figure 10 - Thermocouple KQXL-18G-12

2.2.3 Torch Igniter

The Torch Igniter was designed to serve as ignition source for the MOAC. This Torch Igniter is divided into three primary components: a fuel feed system, a spark generator system and an injector (for more details on the Torch Igniter, see Chapter 5). The feed system and the spark generator system require data acquisition and remote control capabilities (Figure 11).

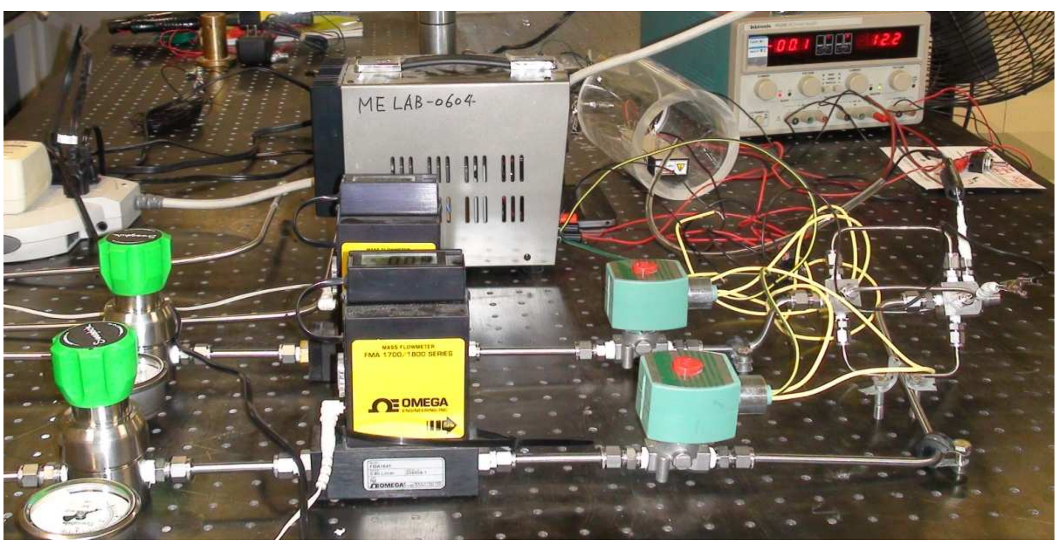


Figure 11 - Torch Igniter: Injector, Feed Lines and Spark Generator

The feed system utilizes two FMA1844 flow meters and two ASCO 8262H185-24/DC solenoid valves. The flow meters (Figure 7) require an excitation voltage of 12 V DC and

generate a feedback signal of 0 to 5 V DC. The solenoid valves (Figure 12) are actuated with a 24 V DC signal.

Figure 12 - ASCO 8262 Series Solenoid Valve

The spark generator system consists of two custom spark electrodes excited with a high voltage power supply. The power supply consists of a DC-DC high-voltage converter (shown in Figure 13) that supplies 25 kV at 0.16 mA.

Figure 13 - High-Voltage Converter 25A12-P4

This converter requires a 12 V DC primary power supply and a 0 to 5 V signal for proportional control of the output. Connections required to operate this converter are listed in Table 1.

Table 1 – High Voltage Converter Connections

CONNECTIONS	
PIN	FUNCTION
1	Input-Power Ground Return
2	Positive Power Input
3	Iout Monitor
4	Enable/Disable
5	Signal Ground Return
6	Remote Adjust Input
7	+5VDC Reference Output
8	HV Ground Return
9	Eout Monitor

Pins 2 and 1 are the connection for the 12 V power input signal; pins 6 and 7 are the connections for the remote adjust of output.

2.2.4 MASS

The Multipurpose Altitude Simulation System (MASS) provides capabilities for testing at altitudes up to 85000 ft. (25.9 km). The MASS consists of a 40x70 inch cylindrical Vacuum Chamber and a two-stage ejector (see Figure 14).

Figure 14 - MASS: Ejector and Vacuum Chamber

The MASS has two pressure transducers, one per each ejector stage and a Pirani Gauge in the vacuum chamber for monitoring the vacuum level of the system. The pressure transducers are Omega PX309-015AV (Figure 9) absolute pressure transducers. These transducers require an excitation voltage of 10 V DC and give a feedback signal of 0 to 100 mV. The vacuum chamber is fitted with a CVM211GFL Pirani Gauge (Figure 15).

Figure 15 - CVM211GFL Pirani Vacuum Gage

This sensor requires an excitation signal of 12 V DC and has an analog output range of 1 to 8 V (with a logarithmic linear scale of 1V per decade, Table 2). This range of output allows measuring a pressure range of 1 x 10^{-4} to 1000 Torr.

Table 2 - CVM211GFL Pirani Gauge Output Scale

Signal Range (V)	Pressure Range (Torr)
$1 \leq V < 2$	$0.0001 \leq P < 0.001$
$2 \leq V < 3$	$0.001 \leq P < 0.01$
$3 \leq V < 4$	$0.01 \leq P < 0.1$
$4 \leq V < 5$	$0.1 \leq P < 1$
$5 \leq V < 6$	$1 \leq P < 10$
$6 \leq V < 7$	$10 \leq P < 100$
$7 \leq V \leq 8$	$100 \leq P \leq 100$

Chapter 3: Instrumentation & Controls Implementation

The development of the control system involves design, implementation and evaluation phases. The following sections describe the steps and methodologies employed to implement the Data Acquisition and Remote Control System (DARCS).

3.1 DESIGN

The design phase defines the functional requirements, incorporates safety considerations and finalizes the components selection. The design of the DARCS integrates the multiple systems to facilitate fundamental experiments in liquid propulsion and evaluation of test articles.

3.1.1 Operational Requirements

Requirements for the present task are divided into three components centered on: operation, safety and integration. Operational requirements are established based on the nature of experimental parameters to be measured and controlled. In order to conduct combustion and cryogenic fluids experimentations, operational requirements are set as follows:

- The DARCS should have the capabilities to operate different propulsion experiments in an autonomous and metered manner from an external control room.
- The DARCS should incorporate an auxiliary operation mode capable of controlling the cryogenic feed system without an electronic controller.
- The DARCS should have sufficient recording capabilities for all the data generated by sensors and transducers.

3.1.2 Safety

Safety requirements are to ensure the physical safety for the operating personnel as well as the integrity of test facility. The safety requirements are identified as follows:

- The DARCS should have the capacity for redundant diagnostics of critical cryogenic parameters such as propellant line pressures and temperatures. In addition, DARCS should also have a battery backup to avoid hazards on power down conditions.
- The DARCS should incorporate an emergency procedure to abort any experimentation if the test article becomes unstable or represents a hazard.
- The DARCS should have the capabilities to visually monitor the experiments conducted inside the bunker facility.

3.1.3 Integration Requirements

An analysis of electrical characteristics (described in Chapter 2) is performed to define integration requirements. These requirements depend on electrical characteristics necessary to make the hardware function (e.g. excitation signals, feedback signals, control signal, etc). Table 3 summarizes these characteristics. These characteristics dictate the integration requirements and define the instrumentation hardware required to automate the process. DARCS requires automation hardware capable of controlling a minimum of 12 solenoid valves (both AC and DC voltages), reading 14 mV signals, measuring 2 mA signals and providing four different DC voltages (12, 24, 10 and 8 V) and one AC voltage (120 VAC) to power up all instrumentation and control components.

Table 3 - Electrical Characteristics of DARCS Components

System	Classification	Hardware	Electrical Characteristics
Cryogenic Feed System	Control	10 Solenoid valves	Excitation: 120 V AC
	Measurement	2 Pressure transducers	Excitation: 10 VDC
			Output: 0-30 mV
		2 Cryogenic Temperature sensors	Excitation: 10 µA
			Output: 0-1500 mV
		2 Cryogenic Flow meters	Excitation: 8 VDC
			Output: 4-20 mA
Multipurpose Optically Accessible Combustor	Measurement	1 Pressure transducer	Excitation: 10 VDC
			Output: 0-30 mV
		2 Thermocouples	Thermocouple data acquisition channel
		2 Gas Flow meters	Excitation: 12 VDC
			Output: 0-5 V
Multipurpose Altitude Simulation System	Measurement	2 Pressure transducers	Excitation: 10 VDC
			Output: 0-5 V
		1 Pirani Vacuum Gage	Excitation: 12 VDC
			Output: 1-8 V
Torch Igniter	Control	2 Solenoid valves	Excitation: 24 V DC
	Measurement	2 Gas Flow meters	Excitation: 12 VDC
Spark Exciter	Control	1 Voltage Transformer	Power: 12 VDC
			Output Control: 5 VDC

3.1.4 Components selection

The hardware components for DARCS are selected based on operational, safety and integration requirements. The automation hardware selected consists of three PCI cards from National Instruments (NI).

The NI PCI-6521 is shown in Figure 15. This card has eight mechanical relay outputs with maximum electrical ratings of 150 Volts AC or DC, 2 Amperes and, 60 Watts of power. The mechanical relays have an expected life of 100,000,000 cycles. To accommodate the total number of relay contacts, two PCI-6521 cards with a total of 16 relay outputs are used.

Figure 16 - NI PCI-6521 card

The NI PCI-6220 card is selected (Figure 17) for acquiring mV data. This card has 16 analog inputs capable of acquiring signals in the range of +/- 10 V with a resolution of 16 bits and a maximum sampling rate of 250 kS/s (10^3 samples per second).

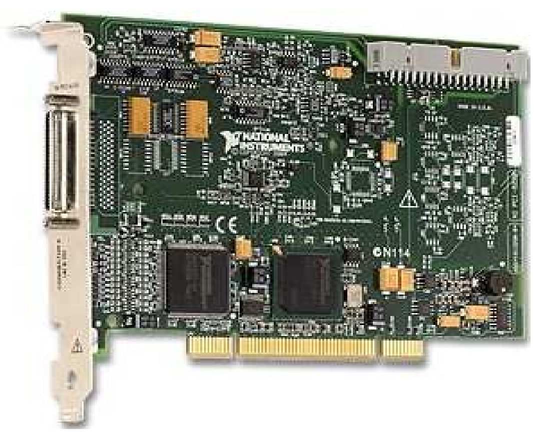


Figure 17 - NI PCI-6220 card

A NI PCI-6238 was selected (see Figure 18) to measure mA signals. This card has eight analog inputs with a measuring capacity of +/- 20 mA, a resolution of 16 bits and a sampling rate of 250 kS/s.

Figure 18 - NI PCI-6238 card

, A SYS-4U4000-4S58 ADVANTEC industrial computer (shown in Figure 19) with high storage capabilities for data recording has been as the primary control unit. This computer has two 500 GB hard drives, two ISA and ten PCI card slots. The computer uses Windows XP Professional SP3 as an operating system.

Figure 19 - SYS-4U4000-4S58 Computer from ADVANTEC

The auxiliary operation mode for the Cryogenic Feed System is achieved via manual toggle switches (see Figure 20).In case of any computer malfunction, these switches provide the system with independent control of each solenoid valve.; These switches control the selection between AUTO mode (operated by the computer and NI cards) or MANUAL mode (controlled by an array of switches) as well.

Figure 20 - MULTICOMP 98K4969 toggle switch

Power capabilities are provided by two components, a bench top power supply for DC voltage, and an uninterruptible power supply (UPS) for AC voltage. The model 382270 from EXTECH Instrument has been selected for the DC power supply unit (Figure 21). Each unit has a total of four outputs: two 0 to 30 V (and maximum current of 5 A), one 3 to 6.5 V (with 3 A of current), and one 8 to 15 V (and 1 A maximum output current) outputs.

Figure 21 - 382270 EXTECH Instruments Power Supply

The model SURTA30000RMXL3U smart UPS from APC (see Figure 22) is selected as an AC power supply. This UPS provides eight 120 V outputs and 2100 Watts of power.

Figure 22 - SURTA30000RMXL3U Smart UPS

In order to make the DARCS modular support multiple experiments, two patch panels (Figure 23) have been installed in the control room and in the bunker. These panels provide easy configuration and set-up changes for controlling various different experimental configurations.

Figure 23 - PP14M48 Patch Panel from One Visit Media

Connections to the patch panels are provided with ¼ inch audio plugs to standardize the wiring of multiple experimental configurations. These plugs (see Figure 24) have two soldering terminals and are implemented for the control hardware (e.g. actuator valves) as well as for instrumentation components (transducers, thermocouples, etc.).

Figure 24 - 7124PS ¼” Connector from One Visit Media

Wiring for DARCS is designed to cater toward two categories: for controls and for data acquisition/metering hardware. The wire for controls is selected to be gage 12AWG stranded wire from Grainger (Figure 25) due to the 120 V AC supply requirement. This wire is rated for a maximum of 600 Volts and 20 amps. The color code for power wiring is red for a positive signal, black for the negative signal and green for the ground.

Figure 25 - 2W285 Wire from Grainger

A Multi-paired wire (Model #566-9418-500) from Mouser Electronics is selected to power metering hardware and data acquisition. This wire, shown in Figure 26, is made of gage 18AWG wire with 4 shielded conductors and it is rated for a maximum of 300 Volts. As part of the standardization, the wiring convention is: red is for positive excitation, black is for negative excitation, white is for a positive signal, green is for a negative signal and shield is for ground.

Figure 26 - Multi-Paired Shielded Cable from Mouser Electronics

All the wiring connections are made inside a 20x20x10 inches (SI units) electrical cabinet to protect cables and terminals. These cabinets consist of a steel enclosure with a locking door shown in Figure 27. The patch panels are built-in the cabinet enclosure and the wires are soldered to audio connector terminals.

Figure 27 - Cabinet Enclosure from Omega

In compliance with safety requirements, components selected for redundant diagnostics include display monitors with signal conditioners. For pressure readings, two DP25B-E-A monitors from Omega are used (Figure 28): one monitor for the LOX line pressure and another

one for the LCH_4 line pressure. These monitors are capable of receiving voltage and current readings and provide transducer excitation output and one analog output for data acquisition devices.

Figure 28 - DP25B-E-A Pressure Monitor from Omega

Temperature measurements are sampled using a 218S monitor from LakeShore (Figure 29). This 8-channel monitor is compatible with diodes and RTD sensors . This monitor includes two analog outputs with a configurable routing to transmit data for the redundant sampling hardware.

Figure 29 - 218S Temperature Monitor from LakeShore

The emergency procedure is controlled by an emergency stop button. This button (shown in Figure 30) triggers a logic sequence that closes propellant tank valves and opens the purging valves of the delivery system.

Figure 30 - OMPBD7P-MT34PX10 Push Button

This logic sequence is operated with an array of solid state relays and a programmable timer to control logic signals (Normally Open and Normally Close contacts) for a user-configurable amount of time (Figure 31). Details of the emergency sequence and its configuration are presented in Section 3.2.1

Figure 31- 10M6579 Programmable Timer Relay from Magnecraft

The UPS provides about 30 minutes of backup power at 1100 Watts load and 14 minutes at full load (2100 Watts) to enable DARCS operational capabilities in the event of a facility power-down condition.

A 4-channel Digital Video Recording (DVR) system is installed for remote viewing of any bunker experiments. This system has four cameras (model SP301-C), a DVR(model SN502-4CH-X) with a 500 GB hard drive for video recording capabilities.

Figure 32 - Defender SN502-4CH-X DVR Security System

A 55 inch TV monitor displays video feeds from 4 cameras. The main computer has two 32 inch monitors for the control and monitoring operations.

3.2 IMPLEMENTATION

As part of the implementation phase, all hardware components are integrated and connected to power/data acquisition modules. The software for control is developed and the transducers calibrations are configured in the system. The functional testing is covered in Chapter 4.

3.2.1 Components integration

The components integration begins with setting up piping, actuator valves, pressure transducers and thermocouples of the Cryogenic Delivery System, MASS, MOAC and Torch

Ignition System. Figure 33 shows all systems and hardware components inside the bunker facility.

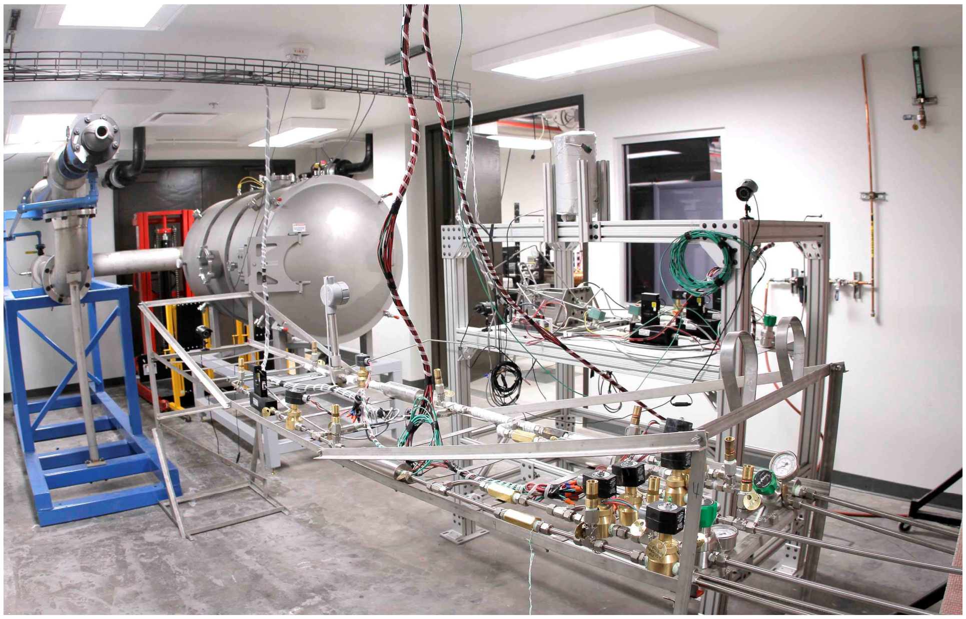


Figure 33 - Delivery, MASS, MOAC and Igniter systems integrated in the bunker

Figure 34 displays the patch panel and electrical cabinet of the bunker..

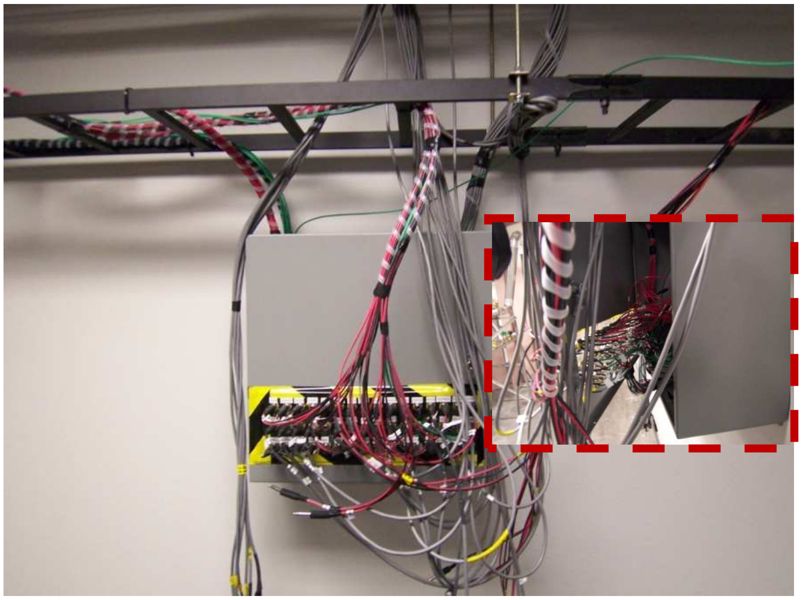


Figure 34 - Patch Panel installed inside the bunker

Cables running between the bunker and control room panels are installed in two cable trays. Figure 35 shows instrumentation and control cables separated by their corresponding cable trays.

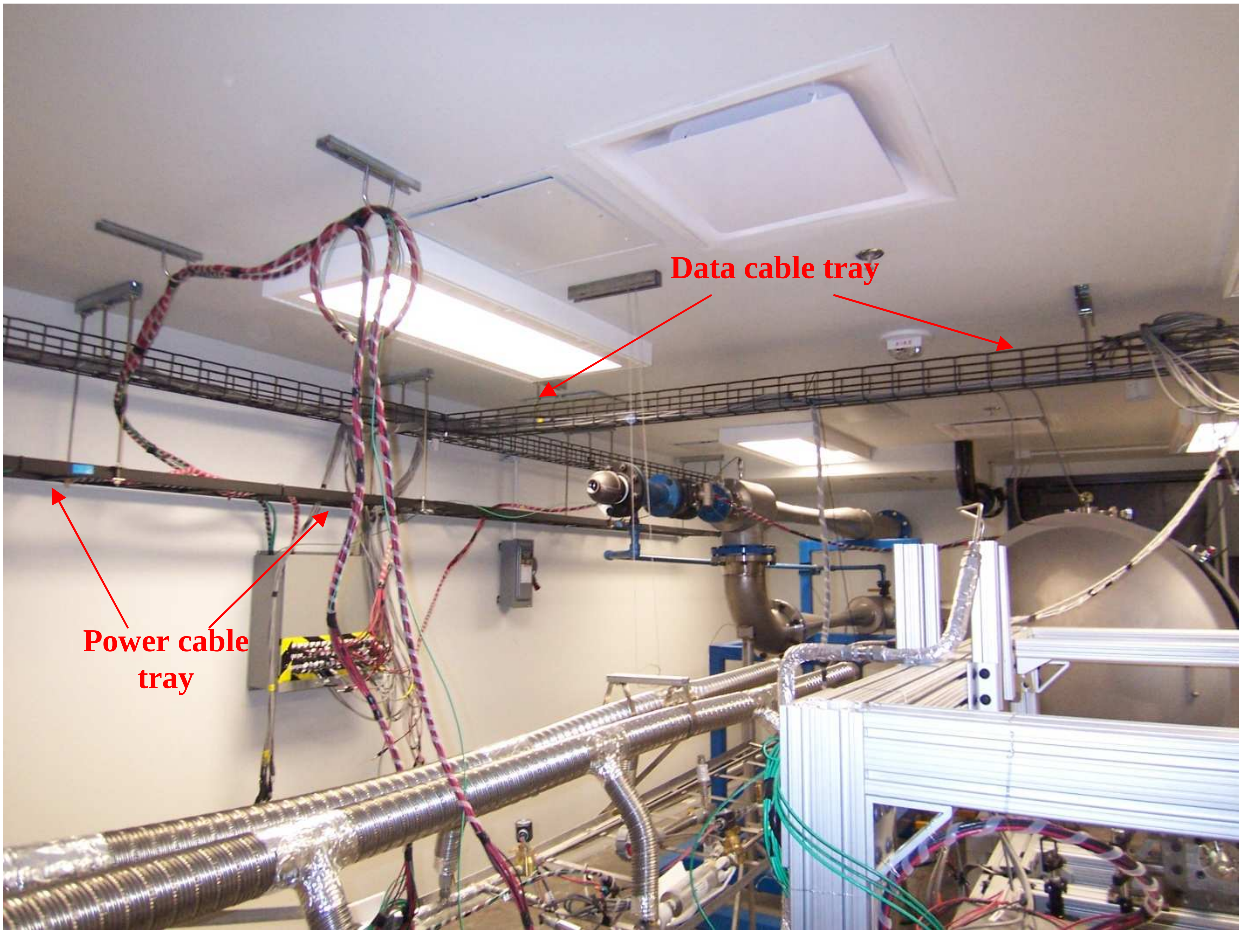


Figure 35 - Cable run for control and instrumentation separated in two cable trays

After all the components are set and the wiring from panel to panel is made, the wiring from components to bunker panel and from data acquisition modules to control panel is made. In this wiring configuration, all the wires are soldered to the ¼" connector plugs shown in Figure 24. Figure 36 shows the cable utilized for data acquisition; one plug is connected to the excitation signal (power supply) and the second one is connected to the data sampling module (transducer signal).

Figure 36 - Data cable with soldered ¼ inch plugs

Patch panel configuration allows for modular set-up configuration and multiple experimentation capabilities. Figure 37 shows the control panel where all the power and acquisition instruments are connected in addition to the auxiliary control modes.

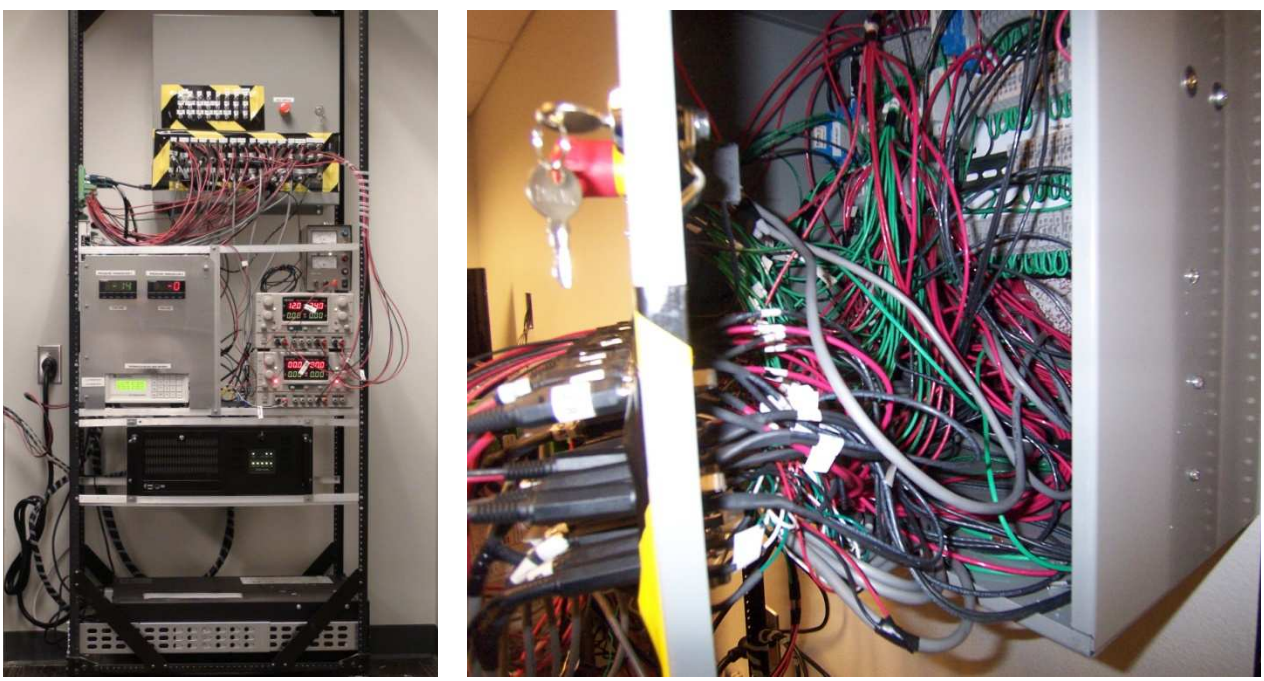


Figure 37 - Patch panel, data acquisition and power supplies installed in the Control Room

Data acquisition and control PCI cards were installed in the main computer in Slots 01 trough Slot 04; Slot 01 and Slot 02 for PCI-6521cards (relay outputs card), Slot 03 for PCI-6238 (mA sampling) and Slot 04 for PCI-6220 (mV sampling). The computer has eight extra PCI Slots for future expansions. PCI-6521 and PCI-6238 cards are connected to terminal blocks NI-CB-37F-HVD for wire connections; PCI-6220 is connected to terminal block NI SCB-68. Figure 38 shows the computer PCI Slots, PCI cards, terminal blocks and cables set-up.

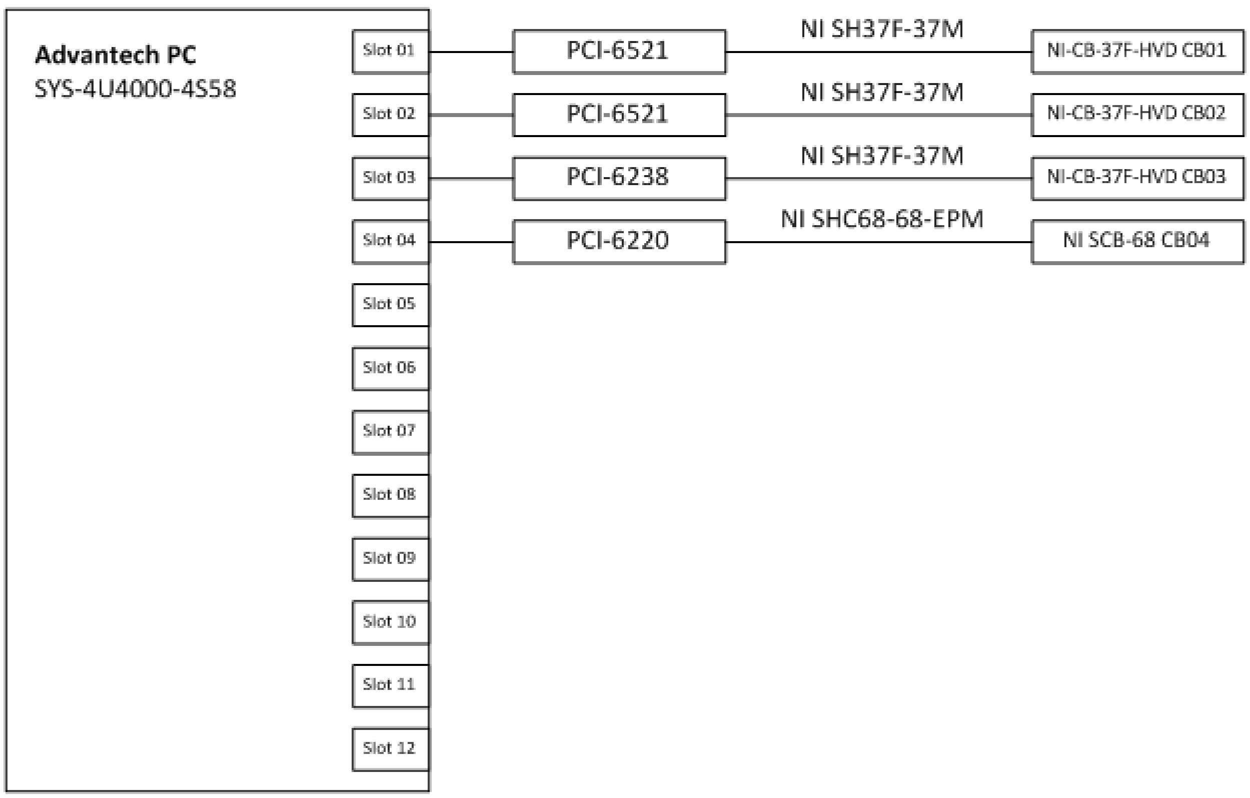


Figure 38 - PCI cards and connector blocks configuration

The connections between the four terminal blocks and the control panel are shown in Figure 39, Figure 40, Figure 41 and Figure 42. The connection name has a connection type, number of row and number of column. The type is differentiated with a P for power type wire and with a D data type wire. The name has also row number and column number, e.g. P1.06 means power type cable, raw 1, column 6 of the patch panels.

Figure 39 shows the connections for PCI-6521 connected to Slot 01.

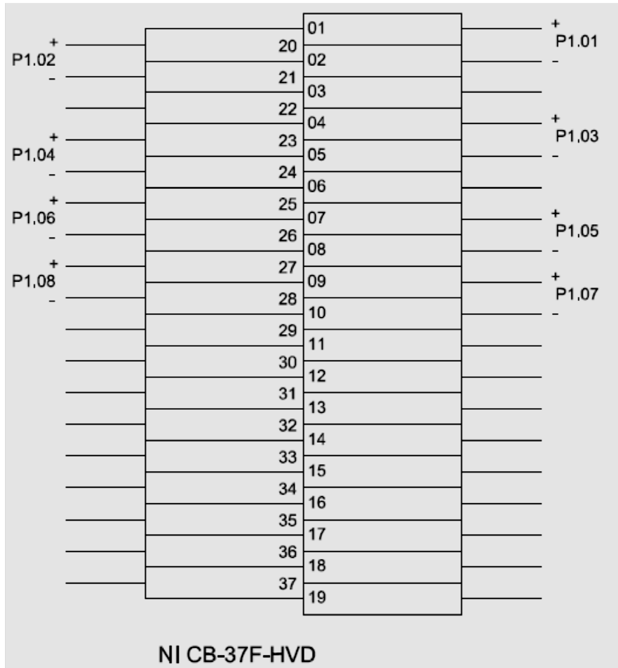


Figure 39 – NI PCI-6521 card on Slot 01 wiring

Figure 40 shows the connections of PCI-6521 connected to Slot 02.

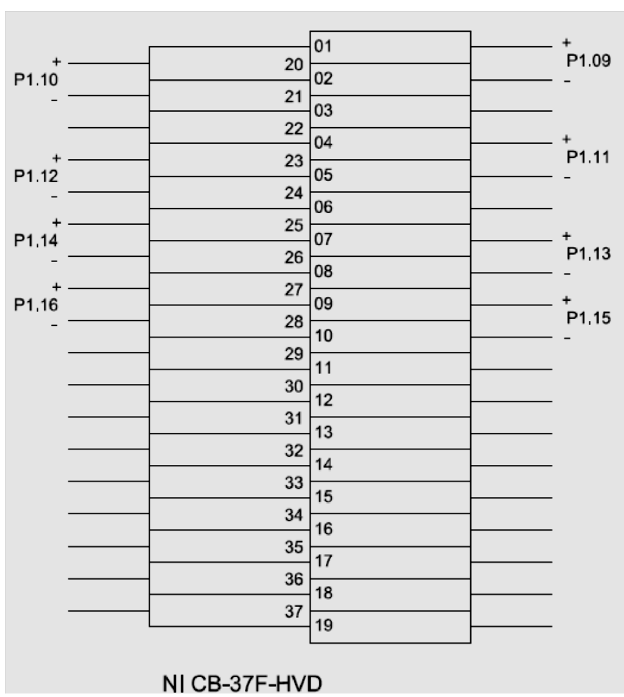


Figure 40 – NI PCI-6521 card on Slot 02 wiring

Figure 41 shows the connections of PCI-6238 connected to Slot 03.

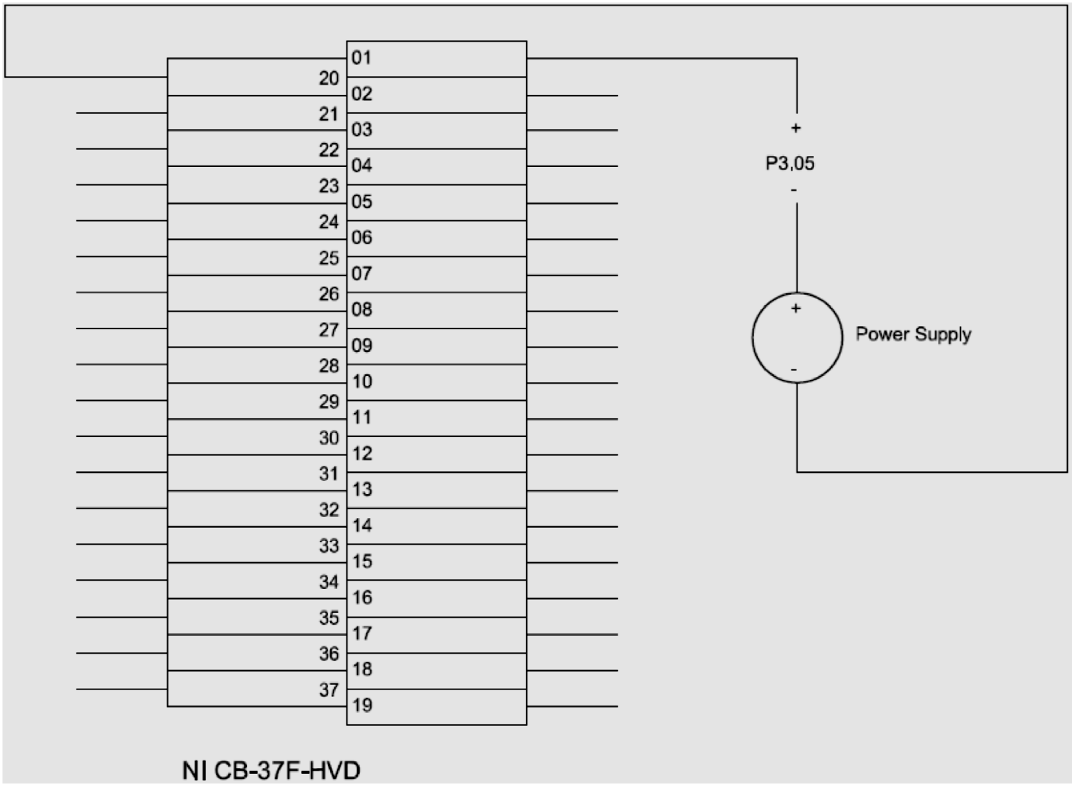


Figure 41 - NI PCI-6238 card on Slot 03

Figure 42 shows the connections of PCI-6220 connected to Slot 04.

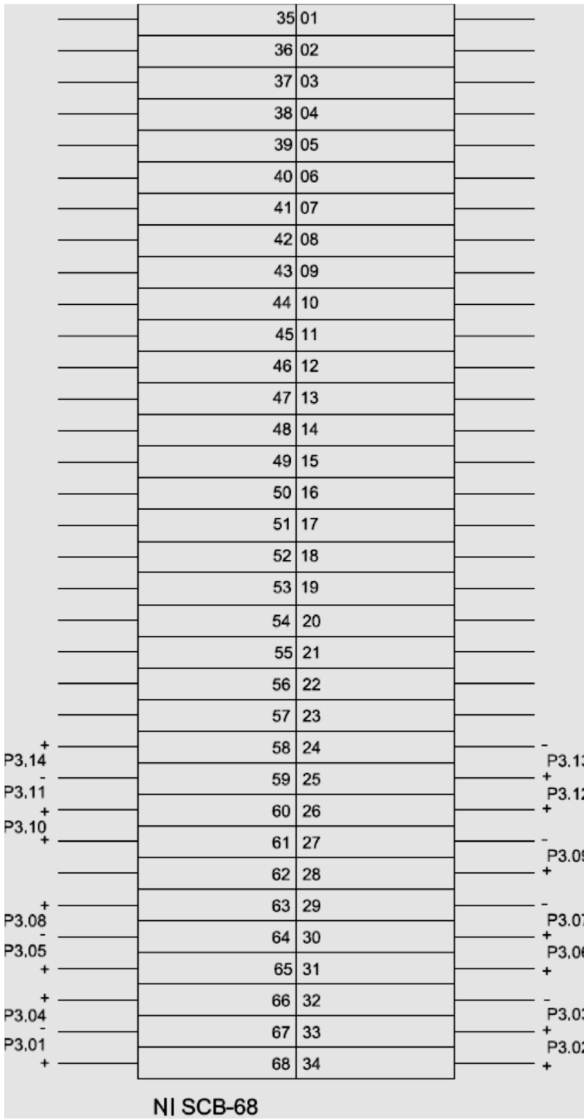


Figure 42 - NI PCI-6220 card on Slot 04

The connection from the terminal blocks to the control panel is shown in Figure 43. The connection from control panel to bunker panel is one to one matching every connection shown in Figure 43.

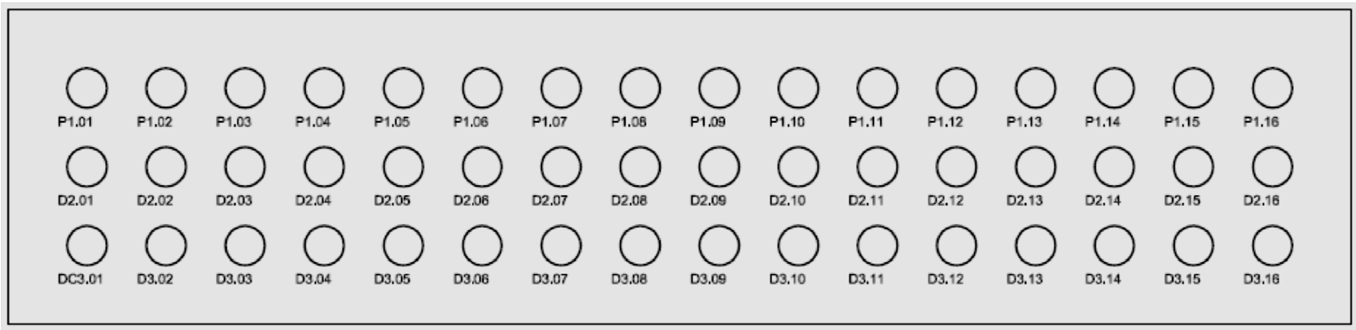


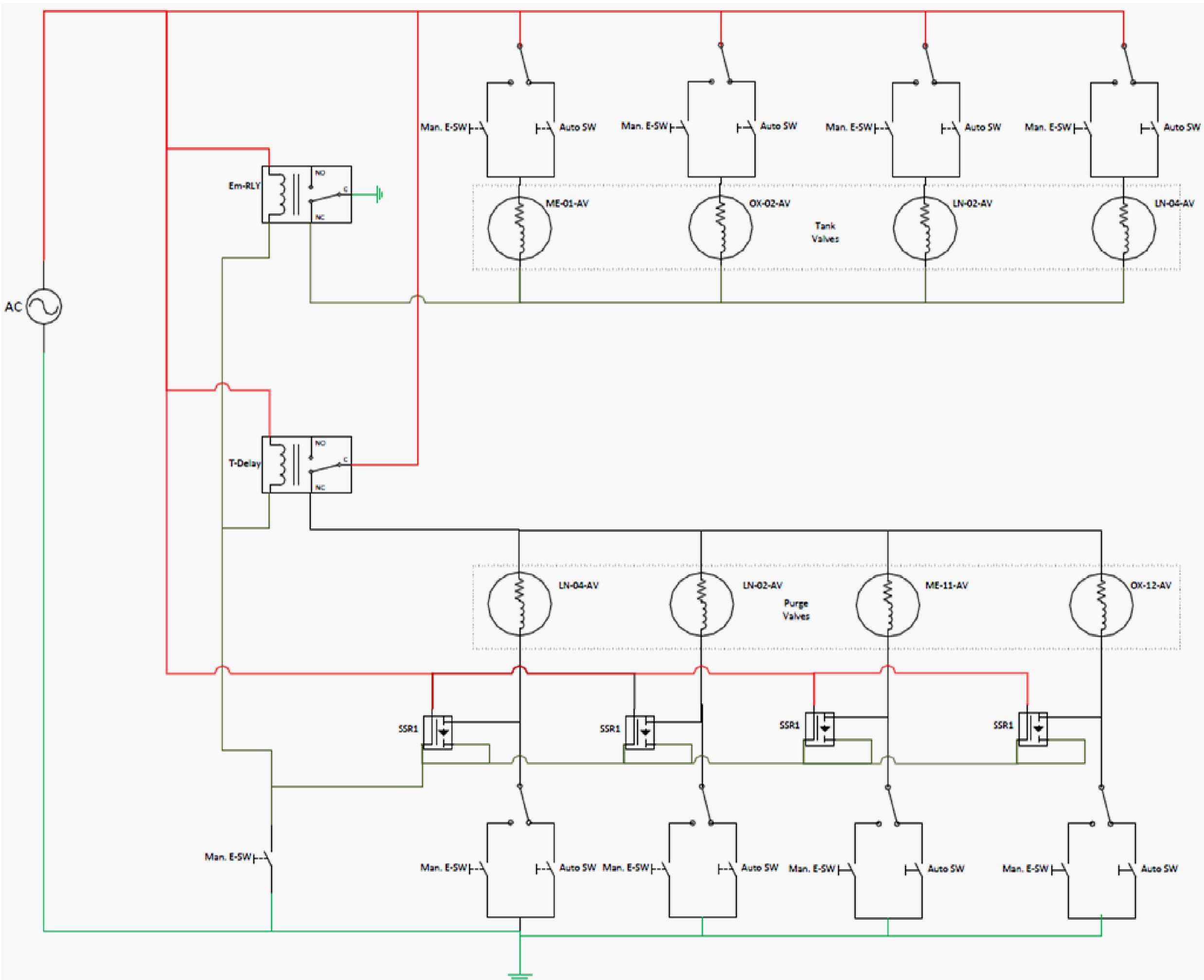
Figure 43 - Patch panel wiring configuration

The connections from the bunker panel to the control and instrumentation hardware are summarized in Table 4.

Table 4 - Bunker Panel Configuration

Bunker Panel Configuration					
Port	**Valves connected**	**Port**	**Power Connection**	**Port**	**Data Connection**
P1.01	LOX Tank Valve	D2.01	LOX Pressure Transducer	D3.01	LOX Pressure Transducer
P1.02	LOX Cooling Valve	D2.02	CH_4 Pressure Transducer	D3.02	CH_4 Pressure Transducer
P1.03	LOX Delivery Valve	D2.03	Not Connected	D3.03	LOX Temperature Diode
P1.04	LOX Bleed off Valve	D2.04	Not Connected	D3.04	CH_4 Temperature Diode
P1.05	LOX Purge Valve	D2.05	Not Connected	D3.05	LOX Flow Meter
P1.06	Igniter Oxidizer Valve	D2.06	CH_4 Flow Meter	D3.06	CH_4 Flow Meter
P1.07	Igniter Fuel Valve	D2.07	Pirani Gauge	D3.07	Pirani Gauge
P1.08	Spare Channel	D2.08	MOAC Flow Meter	D3.08	MOAC Flow Meter
P1.09	CH_4 Tank Valve	D2.09	Igniter Fuel Flow Meter	D3.09	Igniter Fuel Flow Meter
P1.10	CH_4 Cooling Valve	D2.10	Igniter Oxidizer Flow Meter	D3.10	Igniter Oxidizer Flow Meter
P1.11	CH_4 Tank Delivery Valve	D2.11	Not Connected	D3.11	MOAC Thermocouple 1
P1.12	CH_4 Bleed Off Valve	D2.12	Not Connected	D3.12	MOAC Thermocouple 2
P1.13	CH_4 Purge Valve	D2.13	MASS Pressure Transducer 1	D3.13	MASS Pressure Transducer 1
P1.14	MOAC Oxidizer Valve	D2.14	MASS Pressure Transducer 2	D3.14	MASS Pressure Transducer 2
P1.15	MOAC Fuel Valve	D2.15	Not Connected	D3.15	Not Connected
P1.16	Spare Channel	D2.16	Not Connected	D3.16	Not Connected

The automatic, manual and emergency stop control modes are coupled via a logic circuit integrated by an array of solid state relays, a configurable time delay relay (Figure 31) and an array ? or arrangement of toggle switches (Figure 44).



Emergency Switch Controls Ground Trip

time	Em-SW	Em-RLY	τ-RLY	Tank Vs	Purge Vs
0	0	NC	NC	Open	Open
0	1	NO	NC	Closed	Open
10	1	NO	NO	Closed	Closed
10+	1	NO	NO	Closed	Closed

Figure 44 – Circuit for Automatic, Manual and Emergency Stop control modes

This circuit displayed on Figure 44 enables Automatic or Manual control with the switch located at the top of each valve symbol. Once Automatic mode is selected, the relay contacts of the PCI-6521 control the actuator valves; otherwise, if Manual control is selected, the manual switches control the solenoid valves. If the emergency stop button is triggered, a solid state relay (shown at the top of Figure 44, next to the AC Power supply) closes the tank actuator valves and starts the purging procedure regardless of the operation control mode. This purging procedure is controlled by a programmable time delay relay, allowing the purging time to be programmable from 0.1 seconds and up to 10 days.

Due to hazards related with cryogenic fluids experiments, the manual and emergency stop control modes are implemented only for the Cryogenic Delivery System; additional hardware as the Torch Igniter is controlled only by the Automatic control mode.

3.2.2 Software development

Once all the hardware is configured the software to control the experiments is programmed as a LabVIEW Graphical User Interface (GUI) to provide monitoring capabilities from the control room. The first step is to configure the PCI cards with the DAQ Assistant tool from LabVIEW. Beginning with the PCI-6521 cards, the configuration of the first card (corresponding to Slot 01) is shown in Figure 45. This card controls the actuator valves from the Methane line (tank valve, chilling valve, purging valve and bleed off valve), the MOAC valves and has a spare relay output channel.

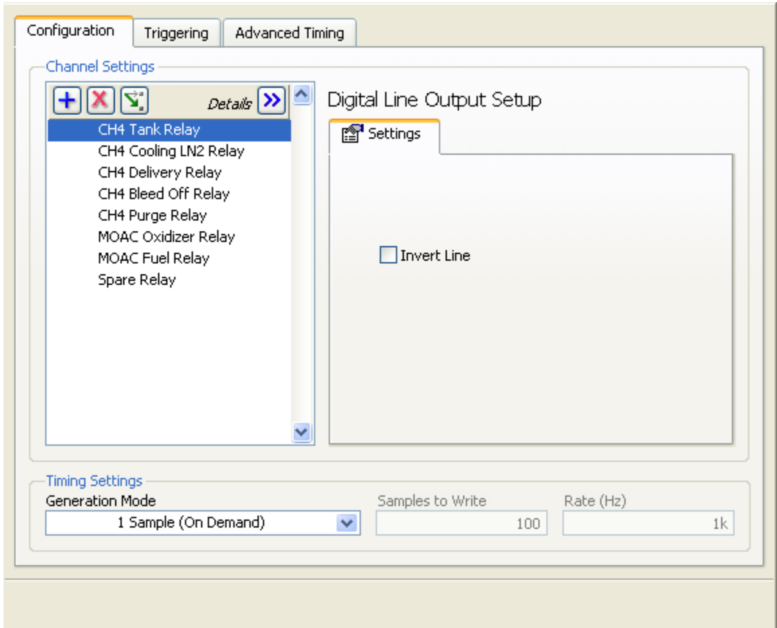


Figure 45 – PCI-6521 card 01 configuration

Figure 46 shows the configuration for card 02, this card controls the LOX line and Igniter actuator valves; in addition, the enabling signal for the high voltage transformer is controlled from this card.

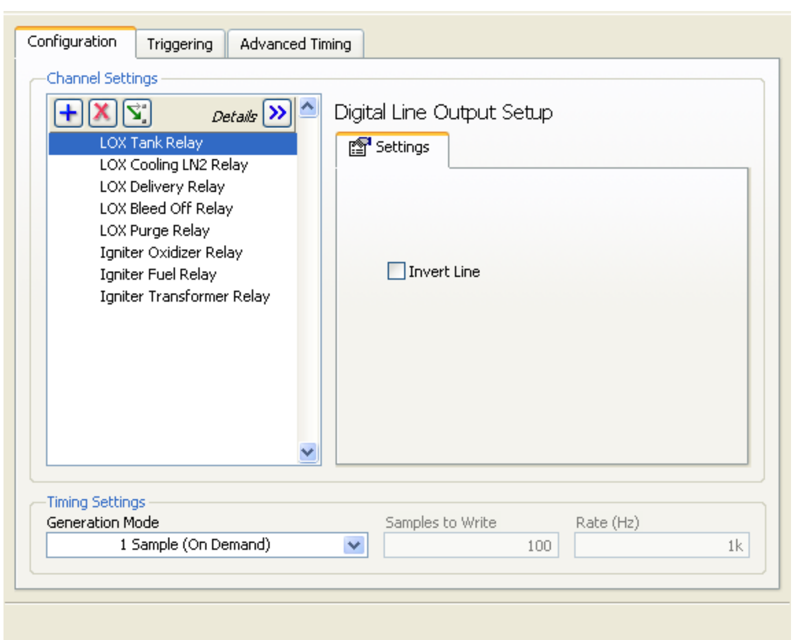


Figure 46 - PCI-6521 card 01 configuration

Figure 47 shows the configuration for PCI-6238; this card has configured one channel for sampling the mA signal from the cryogenic flow meter.

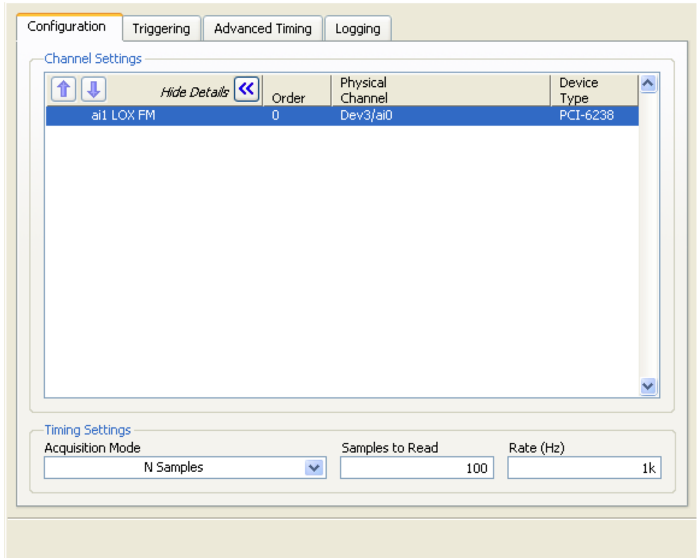


Figure 47 - PCI-6238 card 03 configuration

Figure 48 shows the DAQ Assistant configuration for PCI-6220 card; this card reads the signals from the pressure transducers, cryogenic diodes, gas flow meters, and thermocouples.

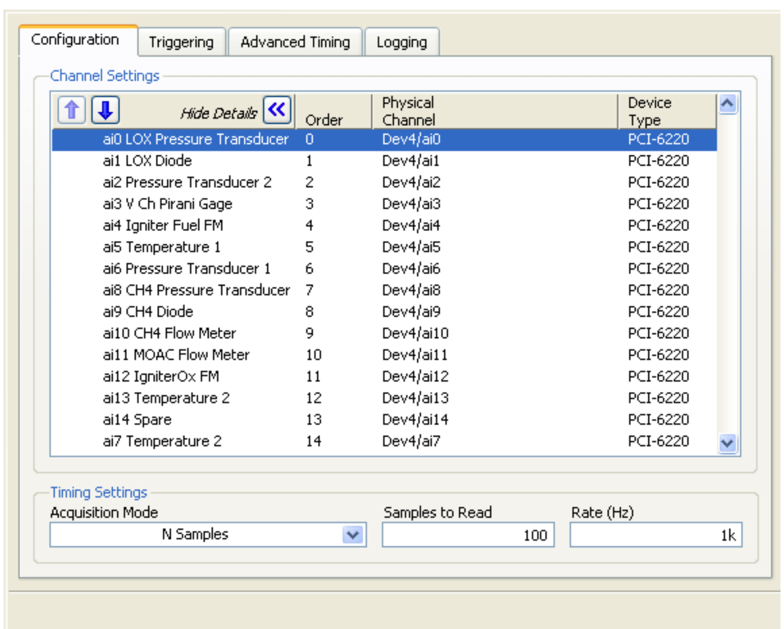


Figure 48 - PCI-6220 card 04 configuration

Data recording capabilities are accomplished with the “Write to Measurement File” tool from LabVIEW. In Figure 49, the set-up for multiple files is shown such that the name of the data files includes the date and time of testing.

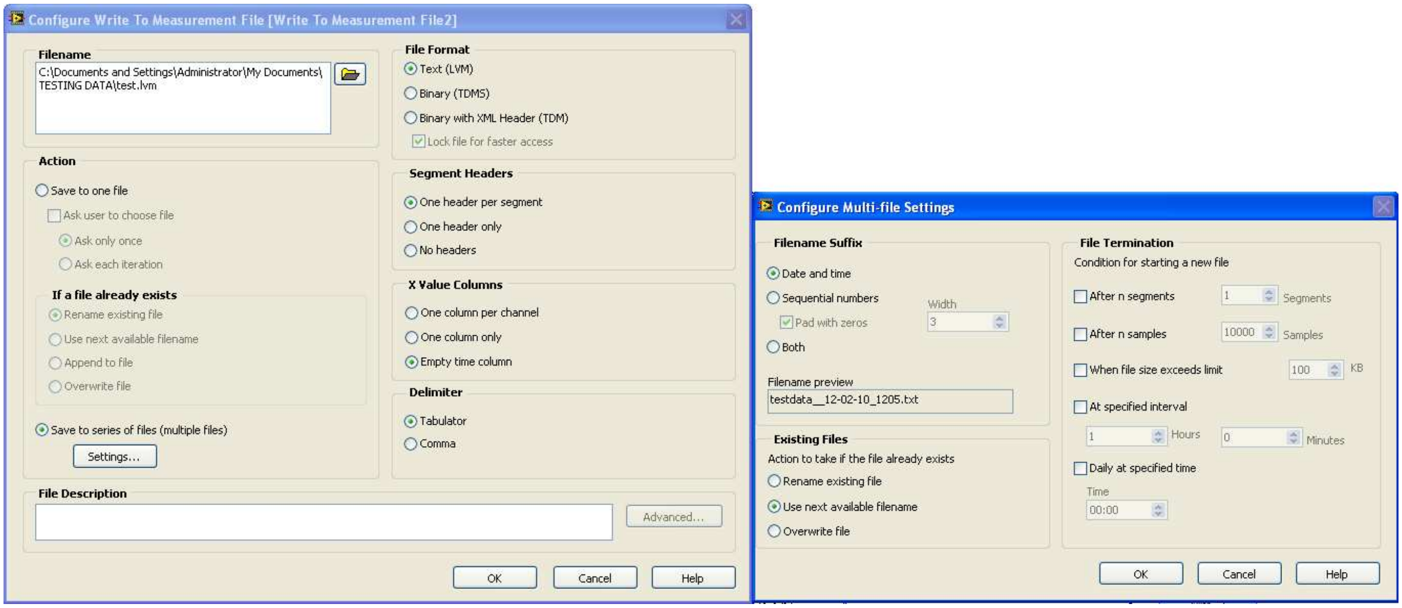


Figure 49 - Write to Measurement File tool configuration

Once the configuration of the hardware and data logging is done, the GUI code is written and all the sensor reading and actuator controls are integrated into two screens for better visual inspection and experiment control. Figure 50 shows screen 1 which displays the diagnostics of the Cryogenic Delivery System, the Torch Ignition System and the controls for steady state of pulsing test capabilities. Pulsing testing configuration requires input of “ON” and “OFF” time and steady state is controlled by latching buttons. This screen includes an “ON/OFF” switch for data logging start/stop and a switch for selection of the oxidizer to be fed. This oxidizer switch enables/disables the sequences to fed air, gas Oxygen or Liquid Oxygen into the system.

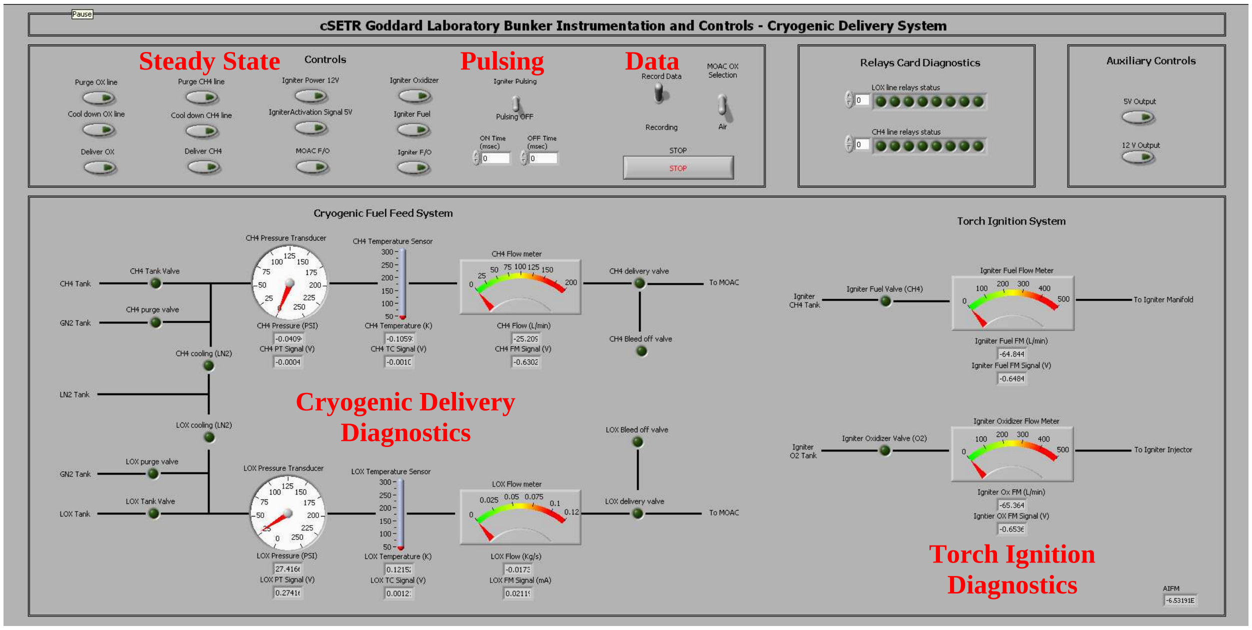


Figure 50 - GUI Screen 1, shows Cryogenic Delivery and Ignition System controls and data sensors

The Steady State controls have a safety setting to avoid multiple fluids in the delivery lines, e.g. only Methane or Nitrogen can be solely streamed into the system but not both at the same time. This setting is implemented for propellants, a Nitrogen purge and Liquid Nitrogen cooling down lines. If two controls are activated at the same time, all the actuator valves are closed until the second activation button is released. Figure 51 shows the logic circuit programmed for this safety setting on the Methane line.

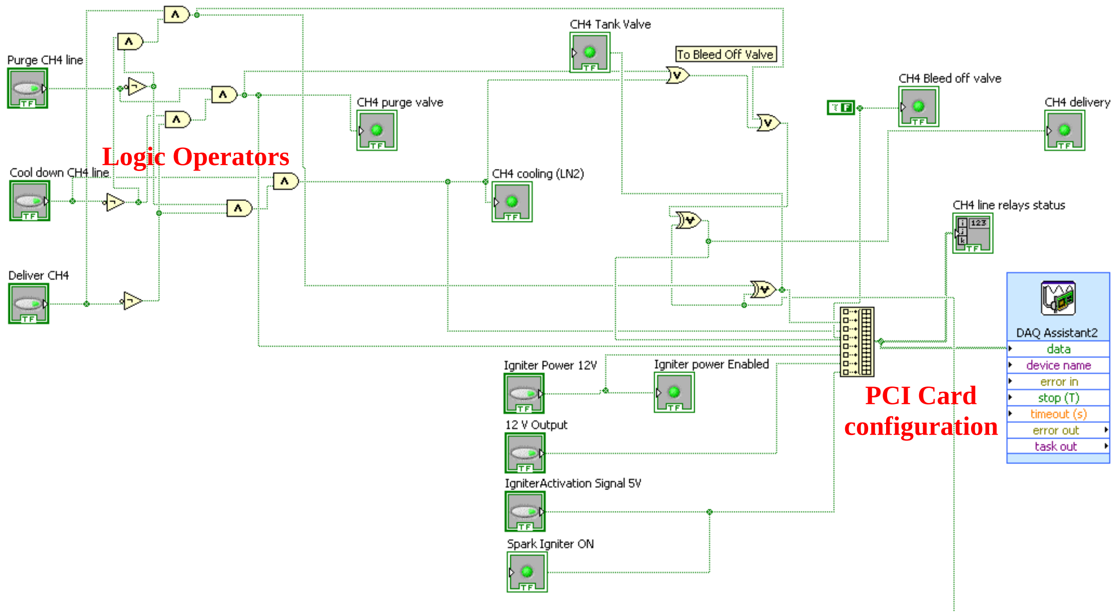


Figure 51- Logic operators for Safety setting on the CH_4 Delivery line

Figure 52 shows the logic operators (same as in the Methane line) for the LOX Delivery line. This figure also shows the selector switch for the MOAC oxidizer and the Pulsing code for the Ignition valves.

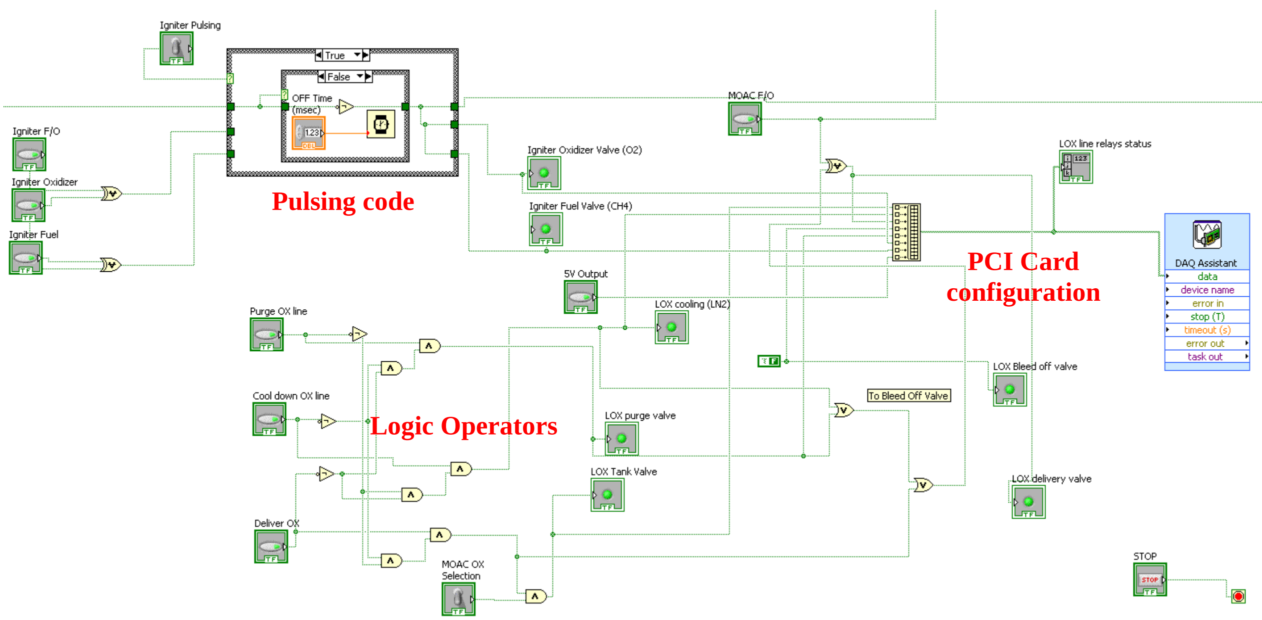


Figure 52 - Logic operators on the LOX Delivery line

The second screen (Figure 53) shows the instrumentation for the MOAC pressure and temperature diagnostics as well as the MASS pressure measurements. In addition, the status of the enabling and power signal of the Torch Ignition system is also displayed.

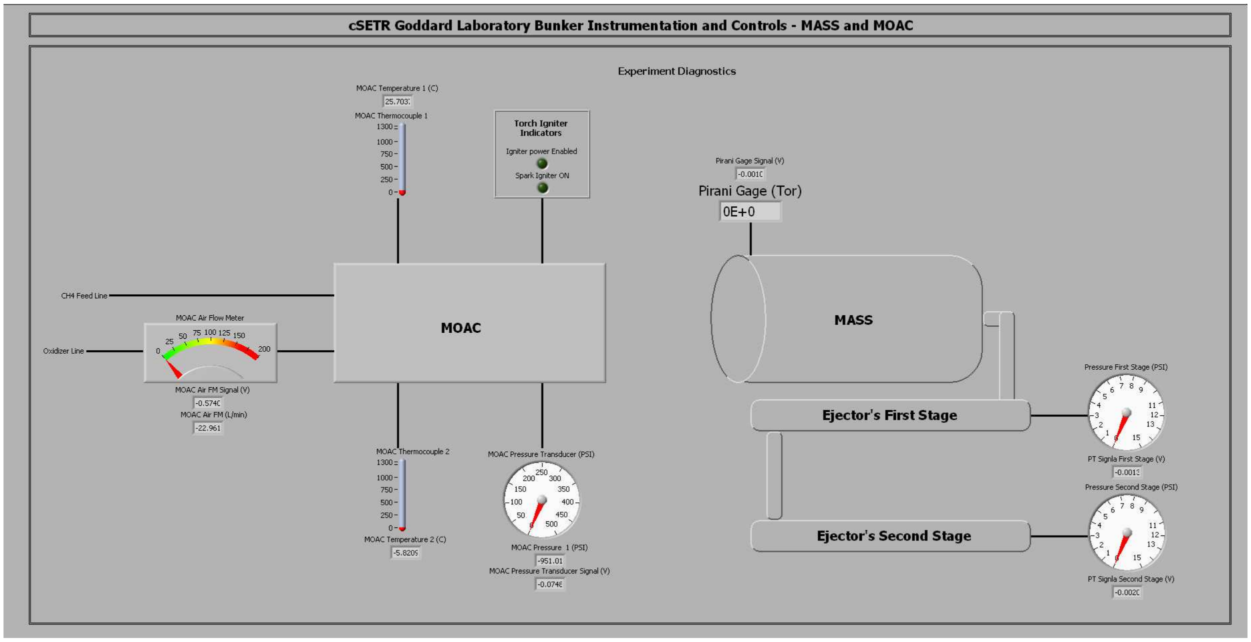


Figure 53 - GUI Screen 2, shows MOAC and MASS sensors

3.2.3 Transducers Calibration

In order to visually inspect the transducers reading in engineering units (PSI, K, Torr, Liters per minute, etc.) the GUI has three data displays: two text box and one graphical gauge. One of the boxes displays the signal being measured (i.e. voltage) and the other one displays the Pressure or Temperature in Engineering units. The gauge also displays the data in engineering units. MOAC temperatures are displayed only in a text box and a gauge because the Data Acquisition card provides direct temperature measurement. The Pirani gauge pressure is displayed in two text boxes, one for the signal and the second one for the measured pressure in Scientific Notation (i.e. 7.4 x 10^3 Torr).

Conversion of transducers signal to engineering units is made through the vendor calibration file. A slope and offset is applied to the raw signal of the transducers to display Engineering units. This slope and offsets configuration is shown in Figure 54.

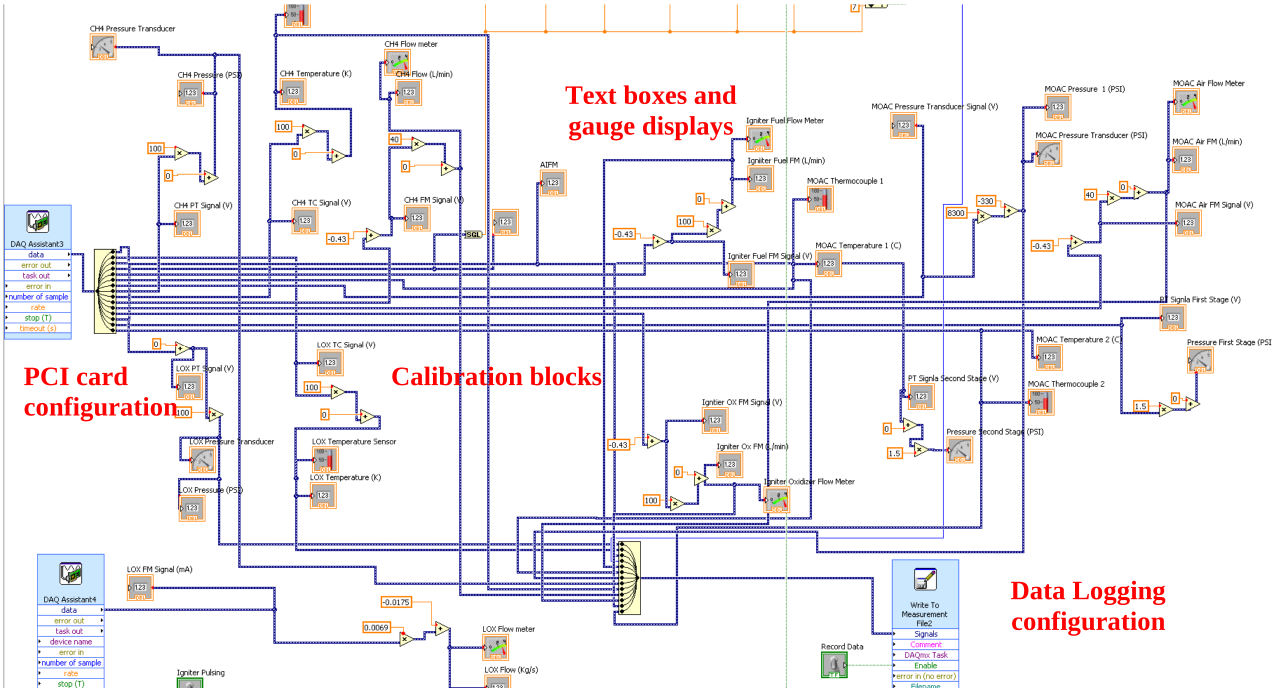


Figure 54 - Transducer calibration block

As the Pirani gauge outputs a logarithmic linear scale from 1 to 8 volts (see Table 2), the signal conditioning for measuring pressure level (in Torr) is filtered and calibrated through seven ranges of signal (1-2 V, 2-3 V, 3-4 V etc.) and displayed in Scientific Notation. Figure 55 shows the implemented code for the Pirani gauge data measurement.

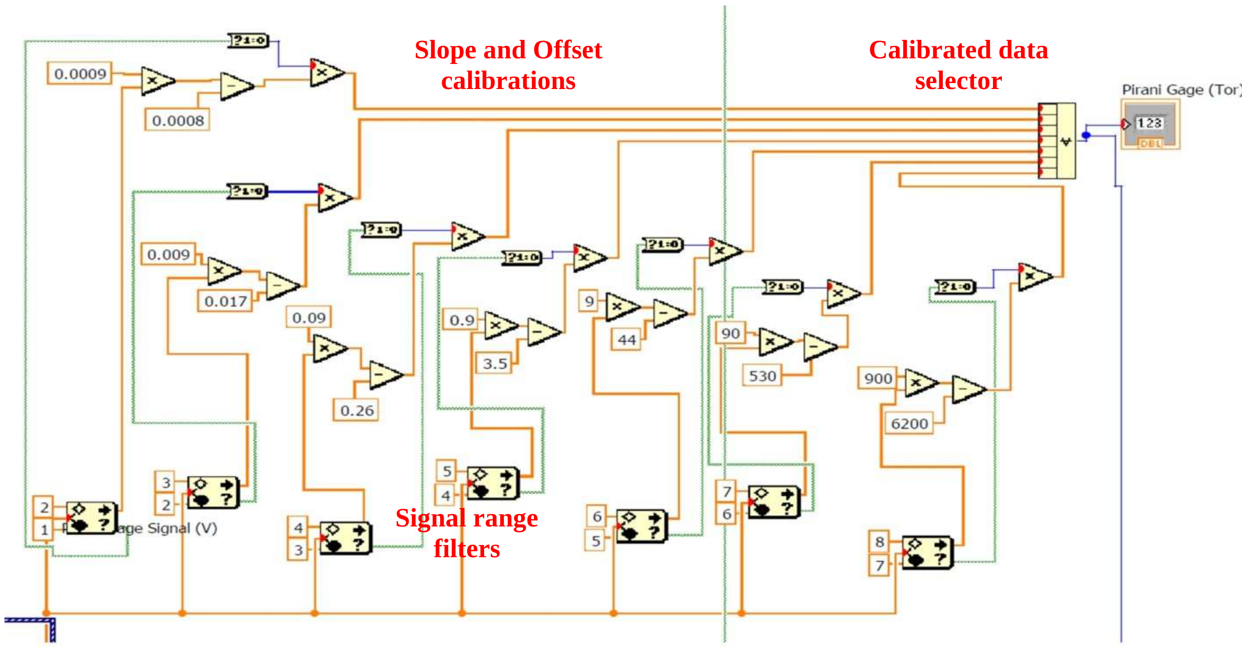


Figure 55 - Pirani gauge code for calibration and signal conditioning

Chapter 4: Instrumentation & Controls Testing

Testing and evaluation of DARCS is conducted concurrently with the Cryogenic Delivery System, MOAC and Torch Ignition System. The integration of the four systems allows for debugging and easier correction of possible failures or malfunctions.

4.1 TESTING PROCEDURES

All the testing is conducted from the control room. Safety procedure requires a minimum of three personnel to test any experiment. The three roles required are the Test Director, Test Operator and Safety Operator. The test director is responsible for running the experiment according to the Test Procedure and check list; the test director also supervises the Test Operator and the Safety Operator. The Test Operator follows the instructions from the Test Director and is in charge of the system controls and GUI; the Test Operator also monitors the critical parameters of the system and provides feedback to the Test Director. The Safety Operator overlooks the experiment to avoid hazardous situations and triggers the Emergency-Stop procedure if necessary. Figure 56 shows the control room facilities where all the experiments are conducted.

Figure 56- Control Room facilities

Testing of the system was executed in three phases. Functional testing, pressure testing and hot fire testing were conducted to evaluate the system performance and find improvement opportunities. All experiments including those of DARCS and the MOAC combustion experiment abide by a procedure and hazards analysis which is outlined in the Appendix.

4.1.1 Functional testing

All component functionality is tested in this section. The actuator valves are opened and closed one by one, pressure transducers are verified to read 0 PSI on the delivery lines, and lastly, the thermocouples are tested to be reading ambient temperature (~25 °C) while the flow meters are verified for readings of 0 L/min.

4.1.2 Pressure testing

The Cryogenic Delivery System is pressurized with gas Nitrogen at 30 PSI in order to test the system against leaks. The pressure transducer readings are verified to be 30 PSI. The thermocouples measurements are still ~25°C and the flow meters start to give flow rate measurements when the Nitrogen is flowing in the system.

4.1.2 Hot fire testing

The objective of this test is to maintain a stable combustion in the MOAC and in the Torch Igniter. Increments in pressure were related to measured flow rate in the feed lines for both Igniter and MOAC. Table 5 shows measured flow rate for Oxygen and Methane of the Igniter feed lines. The Torch Igniter maintained stable combustion and provided reliable ignition to the main injector with Igniter feeding pressures of 8 PSI for the Methane line and 15 PSI for the Oxygen line. With this pressure combination the propellants were fed to the Igniter at a mixture ratio of ~4.

Table 5 - Igniter Pressure vs. Mass Flow Rate Data

Line Pressure [PSI]	Oxygen mass flow rate [L/min]	Methane mass flow rate [L/min]
20	22	22
30	26	24
40	32	30
50	34	72
60	37	92
70	40	105
80	43	118
88	48	124

The main injector sustained the flame inside the MOAC with feeding pressures of 40 PSI for Oxygen and 10 PSI for Methane; this combination of pressures provides a mixture ratio of 4. Additional pressure vs. flow rate information for Methane is summarized in Table 6.

Table 6 - Injector Methane Pressure vs. Mass Flow Rate Data

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

Flow rates for Oxygen are shown on Table 7.

Table 7 - Injector Oxygen Pressure vs. Mass Flow Rater Data

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

Figure 57 and Figure 58 show a hot fire ambient test where the Igniter and the main injector were successfully ignited and maintained stable combustion. On Figure 57, the MOAC had not yet been installed with quartz windows.

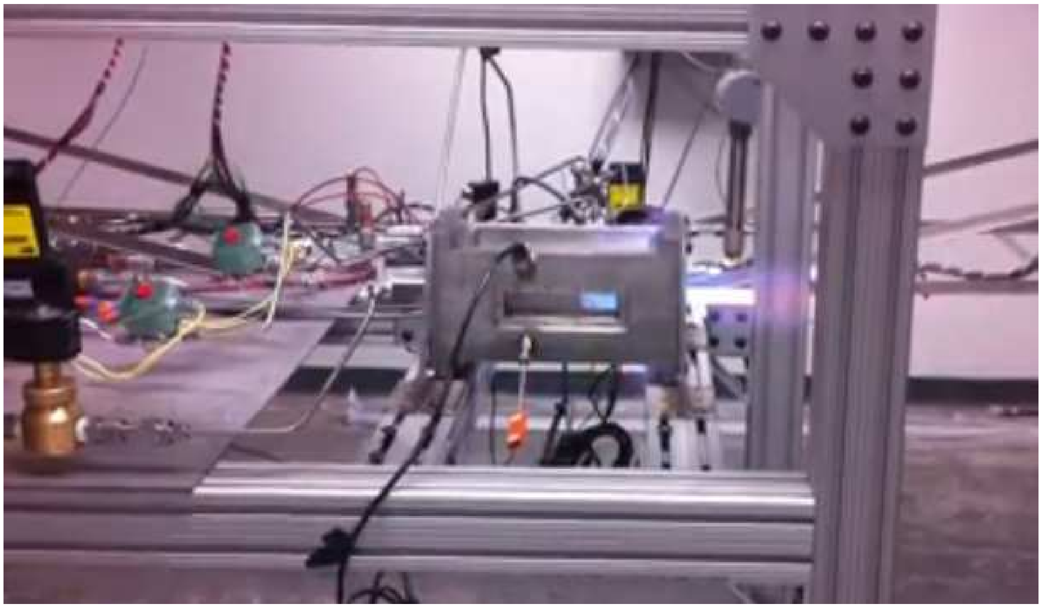


Figure 57 - MOAC hot fire testing at ambient conditions

Figure 58 shows the experiment from the monitoring DVR system installed in the control room. For this test, Quartz windows were installed and the Igniter and MOAC were fed with the optimum line pressures.

Figure 58 – MOAC Hot Fire testing with Quartz windows installed

4.1.3 Data logging

DARCS is configured to log measured data from all the sensors. Figure 59 shows an example of a log file and the recorded data.

Administrator										
12/7/2011										
29:23.8										
13										
100	100	100	100	100	100	100	100	100	100	100
12/7/2011	12/7/2011	12/7/2011	12/7/2011	12/7/2011	12/7/2011	12/7/2011	12/7/2011	12/7/2011	12/7/2011	12/7/2011
29:23.9	29:23.9	29:23.9	29:23.9	29:23.9	29:23.9	29:23.9	29:23.9	29:23.9	29:23.9	29:23.9
Volts	Volts	Deg C	Volts	Deg C	Volts	Volts	Volts	Volts	Volts	Volts
Time	Time	Time	Time	Time	Time	Time	Time	Time	Time	Time
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
ai0 LOX Pressure Transduc	ai1 LOX Diod	ai13 Temperature	ai4 Igniter Fuel Fl	ai5 Temperature	ai6 Pressure Transducer	ai8 CH4 Pressure Transduc	ai9 CH4 Diod	ai10 CH4 Flow Mete	ai11 MOAC Flow Mete	ai12 IgniterOx FM
27.026669	278.173776	-1.12E+14	8.407528	27.398271	-16418.38985	0.056535	300.594715	0.386548	8.04164	0.738912
27.091658	277.913823	-2.39E+10	9.414847	27.640017	-16272.75108	-0.040947	300.692197	-0.28933	10.641171	0.641429
27.221634	277.913823	1467.254802	8.440023	25.218814	-16264.66004	0.024041	300.659703	0.49053	3.88239	0.41397
26.994175	278.076294	1252.345348	7.855128	23.032585	-16558.6346	0.056535	300.594715	0.477532	6.15698	0.348982
27.124152	277.718858	-8.26E+11	9.999741	28.606175	-15806.1676	-0.040947	300.724691	0.152591	7.066816	0.901383
27.221634	278.076294	1405.831388	8.73247	27.156441	-16712.36441	0.056535	300.594715	0.672497	8.496558	1.096347
27.091658	277.978811	-3.33E+12	8.34254	26.672534	-16755.51664	0.056535	300.497233	0.659499	8.756511	1.323806
27.18914	277.978811	-2.43E+13	9.739788	21.327468	-16528.96744	0.121523	300.887162	0.594511	9.731335	0.966371
27.124152	278.0438	11.503409	9.6748	21.815067	-16636.84801	-0.040947	300.757186	0.997438	3.752413	0.41397
27.124152	277.978811	-6.26E+10	9.739788	28.123261	-16617.96891	0.024041	300.78968	0.178586	9.016464	1.096347
27.059163	278.011305	-1.51E+11	9.999741	26.914529	-15768.4094	-0.073442	300.887162	0.360553	9.666347	0.998865
27.059163	277.946317	1518.18752	8.017599	24.247996	-16763.60769	-0.073442	300.432244	0.152591	3.622437	0.478959
27.156646	277.816341	1236.95374	10.259694	27.156441	-16100.14216	-0.073442	300.757186	-0.133358	2.582624	0.316488
27.124152	277.913823	-2.36E+13	10.324683	27.88168	-15976.0795	-0.105936	301.017138	-0.354318	5.052179	0.933877

Figure 59 - Data Log Sample File

Chapter 5: Torch Ignition System

The Torch Igniter has been developed with the purpose of providing the MOAC with a reliable, durable and fast response Ignition Source capable of withstanding the pressure and temperature derived from LOX/Methane combustion. Requirements to develop this Torch Igniter are listed as follows:

- The Torch Igniter should have a swirl co-axial injection design, similar to a mN class Thruster previously developed and investigated (Flores, 2009). This design allows a stable flame due to swirl mixing characteristics.
- The Igniter should be designed to fit into a threaded inlet port located on top of the MOAC. This port is designed for a ¼ inch NPT fitting.
- The Igniter should be feed with gas Oxygen and gas Methane as oxidizer and fuel.
- The Igniter should be made of a LOX compatible material to avoid fire and explosion hazards.
- The Igniter should be designed to withstand a maximum working pressure (MWP) of 100 PSI in both feed lines (Oxygen and Methane).

As the design of this igniter is based on a swirl co-axial injector, an analysis of swirl mixing characteristics is conducted to properly gauge the size of the propellants' feeding ports. Standard Swagelok fittings were selected to simplify the manufacturing process. Once the Igniter is manufactured, the spark electrodes are fabricated with a custom design due to dimension restrictions? The Igniter is then integrated and tested in the MOAC with the objective of finding the correct feed pressures that allow a sustainable flame and stable combustion inside the MOAC.

5.1 BACKGROUND: SWIRL INTENSITY AND SWIRL NUMBER

Defined as "the ratio of the axial flux of the tangential momentum to the product of the axial momentum flux and a characteristic radius", the swirl number measures the intensity of a swirling flow (Huang & Yang, 2009). The swirl number calculation depends entirely on the injector geometry and flow profiles. For a radial injector with tangential inlets, the geometric swirl number Sg is approached and defined as:

$$Sg = \frac{r_o \pi r_e}{A_t}\left[\frac{\dot{m}_{Tan}}{\dot{m}_{Total}}\right]^2 \tag{5.1}$$

In the illustrated equation, r_o is the distance from the center of the tangential inlets to the center of the axial inlet, r_e is the radius of the exits and A_t is the area of the tangential inlets, $\dot{m}_{Tangential}$ is the tangential mass flow rate and $\dot{m}_{Total}$ is the total mass flow rate (Claypole & Syred, 1981).

5.1.1 Previous Swirl Co-axial Injector

The previous tested and validated Swirl Co-axial injector type consists of an axial oxidizer inlet of 5/64 inch in diameter with four tangential fuel inlets of 1/64 inch diameter. This injector has a 1/8 inch NPT fitting for the Oxygen input and four 1/16 inch NPT fittings for the Methane tangent inlets (Flores, 2009). Figure 60 shows the CAD model of this injector.

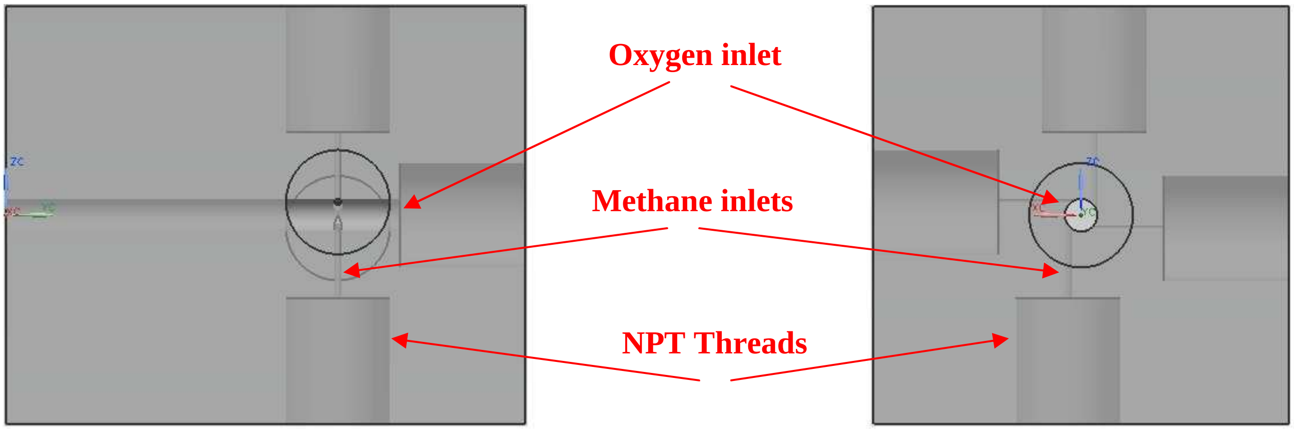


Figure 60 - Swirl Co-Axial Injector CAD model

5.1.2 Geometric Swirl number analysis

The geometric swirl number for the previous injector is calculated assuming a mixture ratio (the ratio of Oxidizer mass flow rate divided by the fuel flow rate) of 4. The result is a geometric swirl number Sg equal to 0.04. In order to increase this swirl number, a few iterations are made with the diameters of Oxygen and Methane inlets; as a result, a swirl number of 0.05 is achieved with a diameter of 3/16 inch for the Oxygen inlet and 1/16 inch for the Methane tangent inlets. This design increases the swirl intensity by 25%, with greater flame stabilization predicted.

5.2 SWIRL CO-AXIAL IGNITER DESIGN

Once the new dimensions for the Oxygen and Methane inlet ports are calculated, the the model for the Igniter body is designed in CAD to fulfill the requirements of assembly with the MOAC. A manifold for Methane distribution is also manufactured and integrated into the design.

5.2.1 Mechanical Design

The design of the Igniter body is made from a 1 inch thick square bar. A main center port is drilled with a Diameter of 3/16 inch and four tangential ports are sized to 1/16 inch of

diameter. A ¼ inch NPT thread was machined as connection to the MOAC. Two more ports were drilled to serve as spark electrodes inlet ports with a diameter of 1/32 inch. All the connections to these ports have NPT threads to connect Swagelok tubing to NPT adapters. For the center port, a 1/8 inch NPT port is drilled, and for the tangential ports 1/16 inch NPT thread is selected. The spark electrodes inlet ports have also 1/16 inch NPT threads. The final CAD model of the Igniter body is shown on Figure 61.

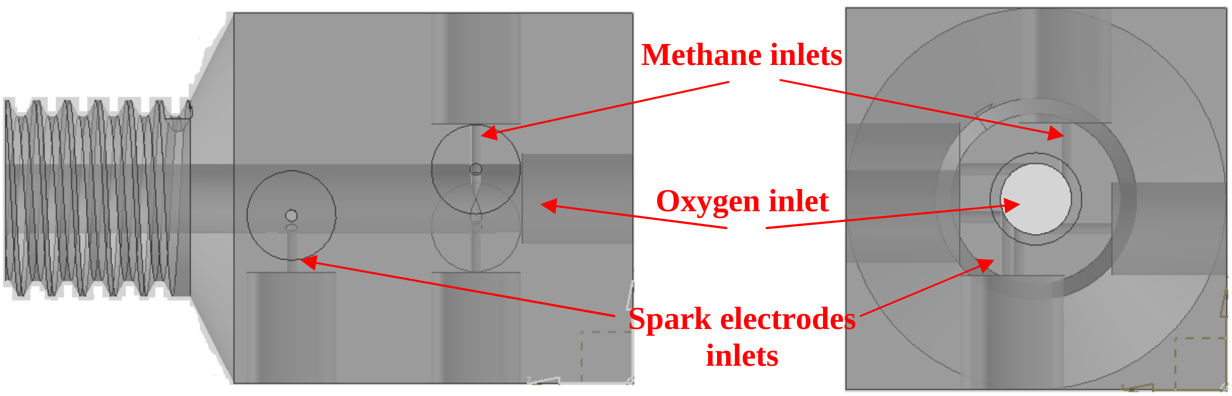


Figure 61 - Igniter Body CAD model

The manifold for Methane is also made from the 1 inch square bar; it consists basically of one centered port with a diameter of 1/4 inch and 1/8 inch NPT thread to feed the Methane; four outputs are drilled to be connected to the center port with a diameter of 1/8 inch and 1/16 inch NPT threads. Figure 62 shows the CAD model of this manifold.

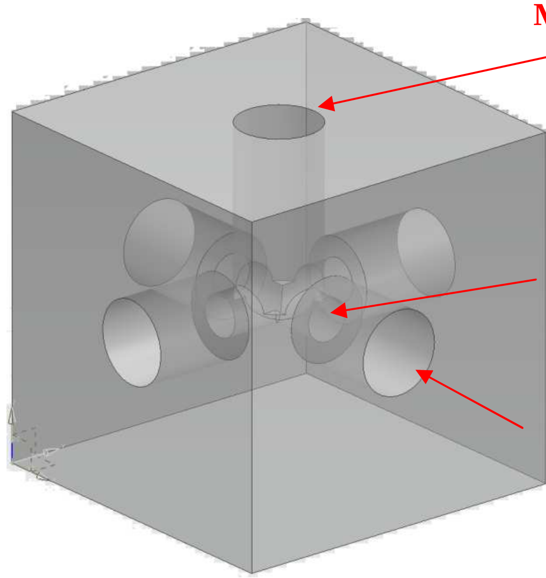


Figure 62 - Methane Manifold

5.2.2 Spark Electrodes

The spark electrodes are custom designed to avoid a discharge arch to the body of the igniter. These spark electrodes are composed of a 3 inch 90% Platinum 10% Rhodium wire insulated on a ceramic insulator with 1/32 outer diameter and a center port of 0.020 inch. The wire is inserted into the ceramic insulator and then the electrode is fitted onto a 1/16 inch Swagelok tube that engages to the 1/16 inch NPT to 1/16 inch Swagelok fitting (see Figure 63). Finally, the electrode is sealed with rasbond ceramic and allowed to cure for 24 hours.

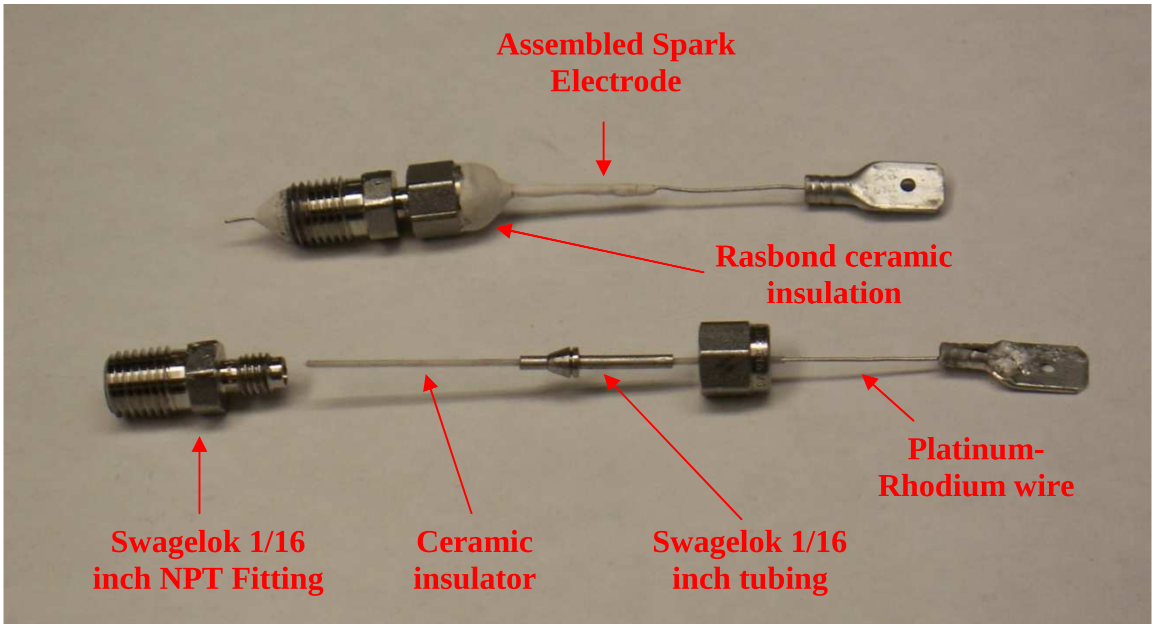


Figure 63 - Spark Electrodes Assembly

Figure 64 shows the Igniter body, Methane manifold, spark electrodes and 1/8 inch manifold tubing assembled.

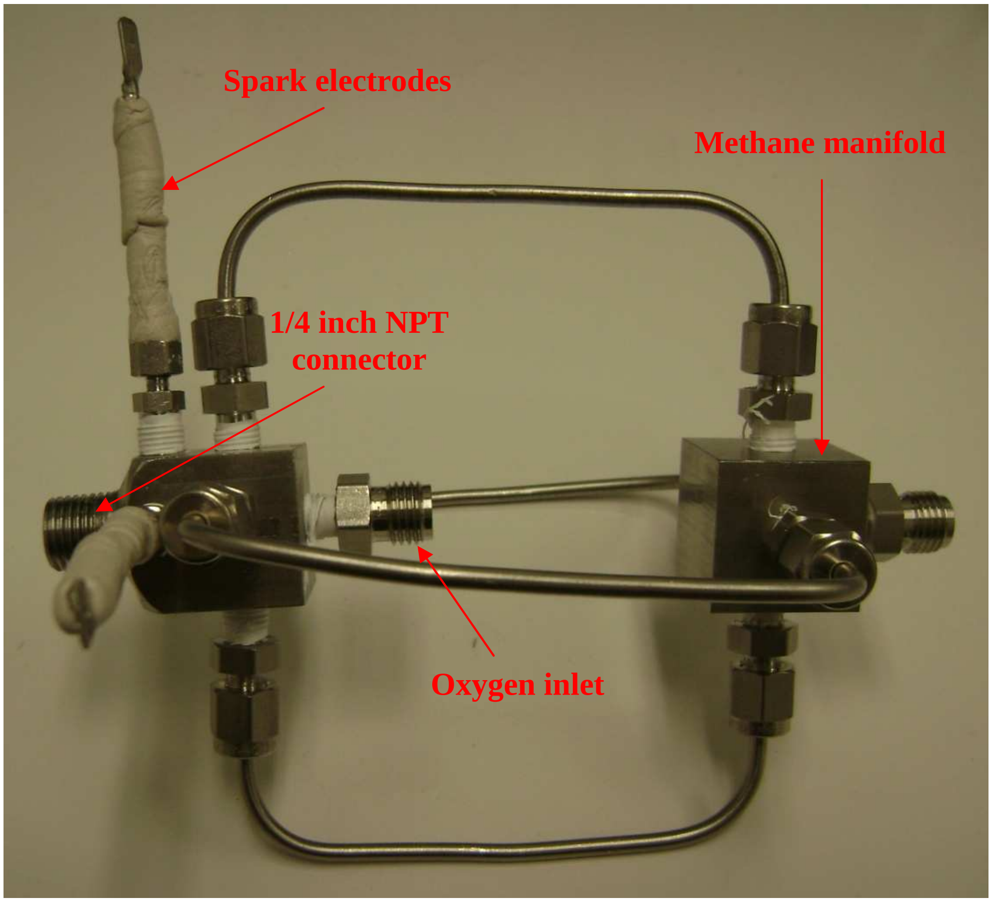


Figure 64 - Torch Igniter assembly

5.2.3 High Voltage Power Supply

The high voltage transformer (Figure 13) provides 25 kV to the spark electros thus allowing a spark discharge between both electrodes. To operate this high voltage power supply, two signals must be provided, a 5 V proportional control signal (5 V commands 25 kV and 4V commands 20 kV to the output and so on) and a 12 V power signal. The transformer has a red cable for the high voltage output and a high voltage return connection to ensure safe operation. The high voltage output is connected to one spark electrode and the high voltage return is connected to the second spark electrode.

5.2.4 Feed lines

To feed the Torch Igniter with gas Oxygen/gas Methane propellants, two separate delivery lines are developed. This lines are ¼ inch Swagelok tubing with a pressure regulator, a mass flow meter and a solenoid valve actuated with 24 V DC. Figure 65 shows the schematic for these feed lines.

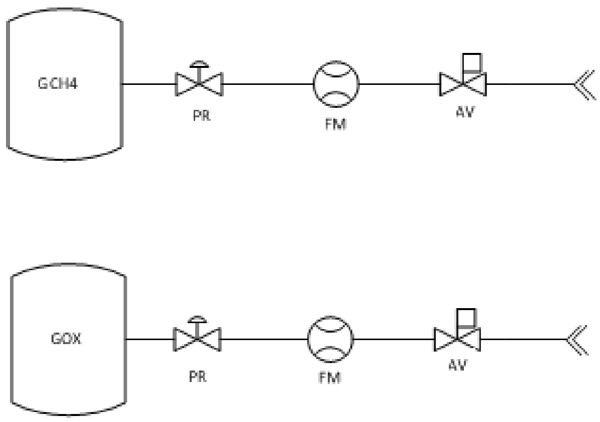


Figure 65 - Igniter Propellant Feed Lines Schematic

Figure 66 shows the Torch Igniter, High Voltage Transformer and Feed System integrated and the set up for initial testing.

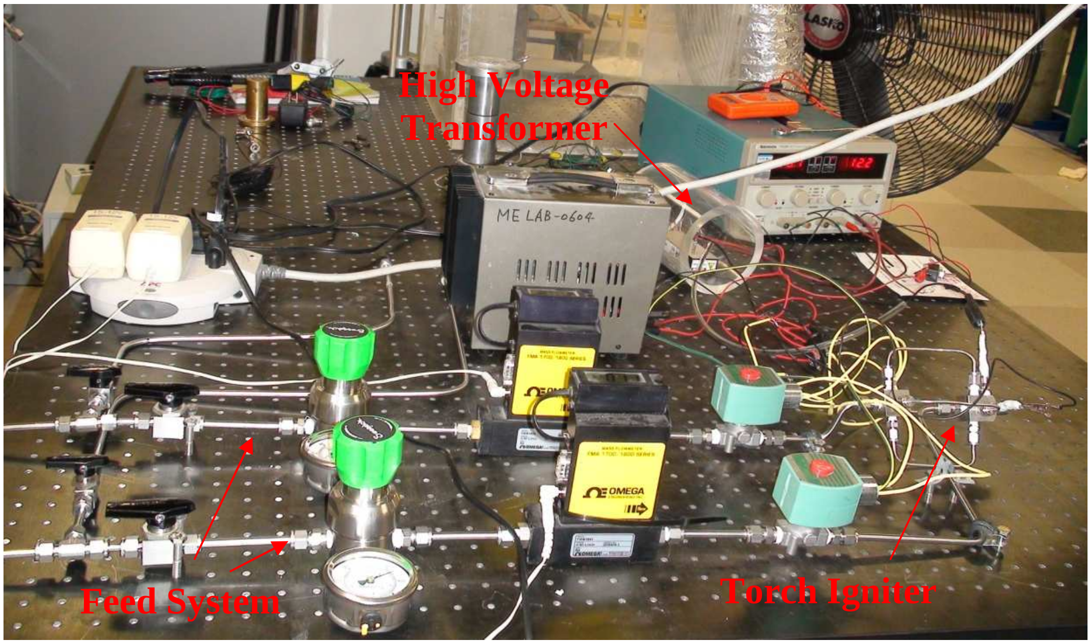


Figure 66 - Igniter Systems Integrated

5.3 IGNITER TESTING

Igniter testing is executed in a subsystems basis: in the first, the spark electrodes are verified to be working properly and repeatedly; during the second, the Igniter is pressurized to test against leaks; next, the Igniter is tested to fire without being installed in the MOAC and finally, the Igniter is integrated into the MOAC to fire the main Injector.

5.3.1 Spark Testing

The spark electrodes are assembled to the Igniter and the high voltage transformer is connected to the power and control signal; the transformer's high voltage output is connected to one electrode and the High Voltage return terminal is connected to the second electrode. Figure 67 shows the set up for the spark testing and the spark discharged is captured on the highlighted detail picture.

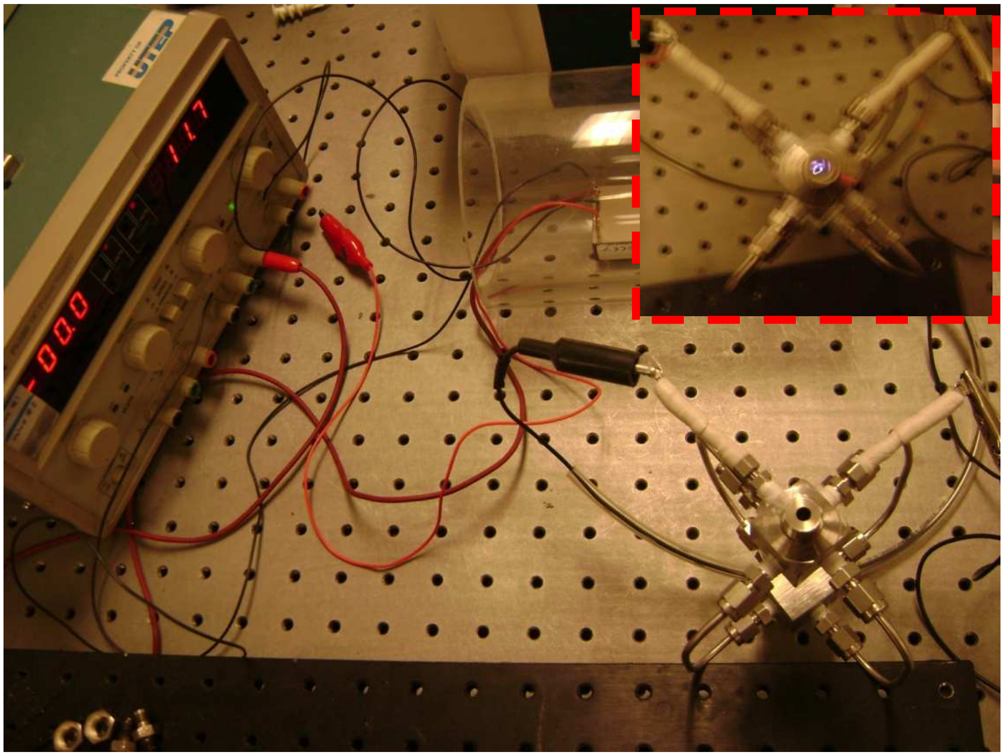


Figure 67 - Spark Test Set-Up

5.3.1 Pressure Test

Once the spark electrodes were verified to work properly, the Igniter assembly was pressurized and tested against leaks. Both inlets for Oxygen and Methane are pressurized with compressed air at 100 PSI until the system is leak free. The test was done in two parts: first, the Methane line was pressurized while the Oxygen line inlet is closed with a manual valve; secondly, part of the Oxygen line was pressurized and the Methane inlet was closed with the same valve. Figure 68 shows the set up for the Oxygen line pressure test.

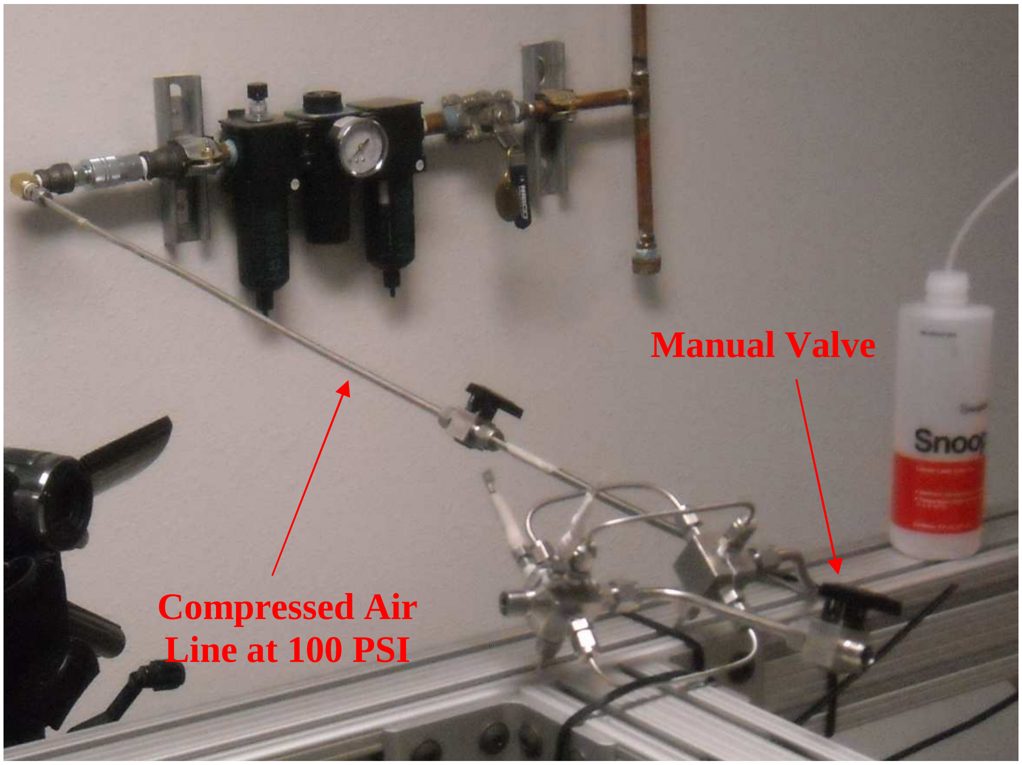


Figure 68 - Oxygen Line Pressure Test Set-Up

5.1.1 Hot Fire Test

After the pressure test, when the Igniter is determined to be leak free, the next test executed required is to integrate the Igniter, High Voltage Transformer and propellants feed lines to ensure the Torch Ignition System is capable of maintain stable combustion and providing the MOAC with a reliable torch flame that ignites the main injector configuration. Figure 69 shows a successful hot fire test with feeding pressures of 20 PSI for Oxygen and 18 PSI for Methane. The calculated mixture ratio in this test is 2.48 and the total mass flow measured is 1.65 g/sec.

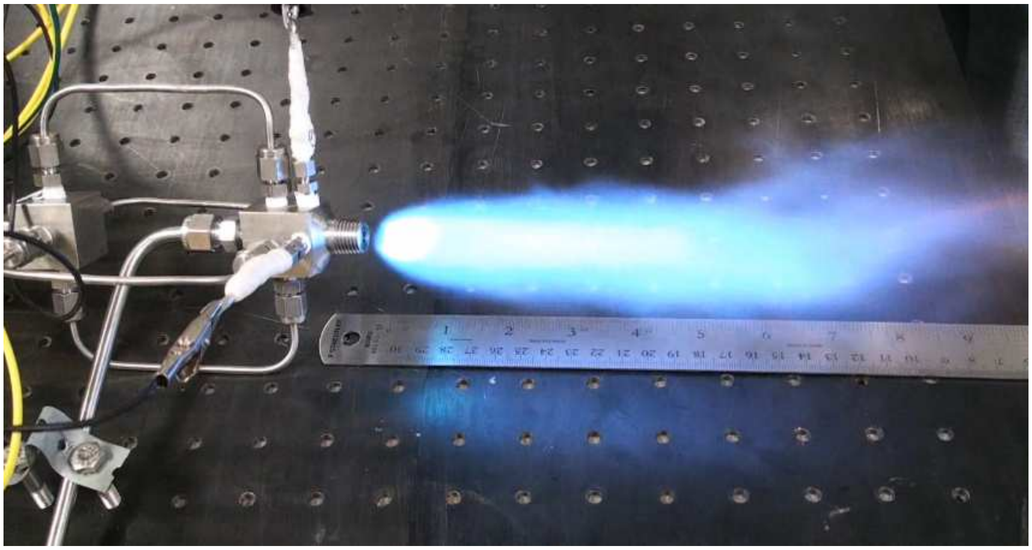


Figure 69 - Igniter Hot Fire Test

5.1.1 Combustor Integration Testing

Once the Igniter is tested and proved for successful ignition, it is integrated into the MOAC with the objective of testing the MOAC injector and maintaining stable combustion inside the MOAC assembly. Refer to section 4.1.2 for detailed results of these integration tests.

Chapter 6: Conclusion and Future Work

Integration of systems for experimentation of LOX/Methane engines requires a deep knowledge of the nature of the experiments and the engineering fundamentals of the components' phenomena. In addition, this work also required a deep understanding of cryogenics, fluid dynamics, heat transfer, combustion, propulsion, instrumentation and control systems. Ultimately, experimentally techniques and safe testing abilities were improved during the development of the presented work

6.1 CONCLUSIONS

The conclusions drawn from this project development and testing are:

- A Data Acquisition and Remote Control System has been developed at the Center for Space Exploration Technology Research; this system provides capabilities for automated testing of cryogenic and combustion related experiments.
- This system is modular and capable of remotely control of different testing set-ups, such as the MOAC, micro thrusters, Syngas combustors, and cryogenic systems while maximizing personnel safety and facilities integrity.
- The system allows for modular and permanent upgrades and modifications in order to serve new experiment requirement of current and future projects.
- A Torch Ignition System has been developed, tested and evaluated for optimum performance, in order to provide the MOAC with a reliable and consistent ignition device.

- System integration is executed in conjunction with the development of the component systems; every system is equally important and essential to produce the desired experimentation and gather high quality data.
- The development of this rocket engine testing facility provides performance capabilities to run steady state and pulsing tests of 100 N class LOX/Methane thrusters at a maximum pressure of 190 PSI.

6.2 FUTURE WORK

The area with greater opportunity for improvement is in the Torch Ignition system. A dimensions modification is required to provide an easier assembly to the MOAC; furthermore, a longer igniter body will eliminate assembly constraints and reduce the integration time of the Igniter to the MOAC. A bigger dimension for the Spark electrodes inlet is suggested in order to facilitate the assembly of the ceramic insulator. Finally, a circuit protection fuse is recommended to be implemented in the high voltage transformer power line- this fuse will provide protection to the instrumentation due to electrical discharge of the high voltage transformer.

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Appendix

Appendix A: 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 maintenance	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 B: 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.

Curriculum Vita

Jesus Betancourt-Roque was born on March 9, 1895 in El Paso, TX to Jesus Betancourt and Maria Guadalupe Roque Mora. He has lived and attended school in Juarez, Mexico for the majority of his life. He Graduated from CBTis #114 High School in 2003 and was awarded with an Associate Degree in Computer Programming. In May 2008, he graduated from ITESM Campus Ciudad Juarez with a Bachelors of Science degree in Mechatronics Engineering and two and a half years of experience in Software Testing working as a Co-Op at Delphi Automotive Systems. He then joined Cummins-Scania XPI manufacturing as a Test Engineer in April 2008. Beginning in Fall 2009, he entered the Graduate School at The University of Texas at El Paso pursuing the Master of Science degree in Mechanical Engineering. That same semester, he joined the Center for Space Exploration Technology Research under the supervision of Dr. Ahsan Choudhuri as a research associate. In addition, in the summer of 2011, he joined the prestigious NASA Marshall Space Flight Center Robotics Academy as an intern. Jesus will continue developing his career as an aerospace engineer focusing on commercial spaceflight industry.

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