LIQUID METHANE / LIQUID OXYGEN
PROPELLANT CONDITIONING FEED SYSTEM (PCFS) TEST RIGS

A. Skaff, S. Grasl, C. Nguyen, and S. Hockenberry
Sierra Lobo, Inc.
Milan, Ohio

J. Schubert, L. Arrington, T. Vasek
NASA Glenn Research Center
Cleveland, Ohio

ABSTRACT

As part of their Propulsion and Cryogenic Advanced Development (PCAD) program, NASA has embarked upon an effort to develop chemical rocket engines which utilize non-toxic, cryogenic propellants such as liquid oxygen (LO2) and liquid methane (LCH4). This effort includes the development and testing of a 100 lbf Reaction Control Engine (RCE) that will be used to evaluate the performance of a LO2/LCH4 rocket engine over a broad range of propellant temperatures and pressures. This testing will take place at NASA-Glenn Research Center's (GRC) Research Combustion Laboratory (RCL) test facility in Cleveland, OH, and is currently scheduled to begin in late 2008. While the initial tests will be performed at sea level, follow-on testing will be performed at NASA-GRC's Altitude Combustion Stand (ACS) for altitude testing.

In support of these tests, Sierra Lobo, Inc. (SLI) has designed, developed, and fabricated two separate portable propellant feed systems under the Propellant Conditioning and Feed System (PCFS) task: one system for LCH4, and one for LO2. These systems will be capable of supplying propellants over a large range of conditions from highly densified to several hundred pounds per square inch (psi) saturated. This paper presents the details of the PCFS design and explores the full capability of these propellant feed systems.

INTRODUCTION

Based on various past studies, the National Aeronautics and Space Administration (NASA) has identified liquid oxygen (LO2)/liquid methane (LCH4) propulsion systems as promising options for some future space vehicles. Specifically, it is believed that an integrated main and reaction control propulsion system utilizing LO2/LCH4 propellants can provide substantial savings in overall systems mass when compared to conventional hypergolic systems. To address the necessary risk reduction, the NASA Exploration Technology Development Program (ETDP) has formed the Propulsion and Cryogenics Advanced Development (PCAD) project. The PCAD project is managed by the NASA Glenn Research Center (GRC) in Cleveland, Ohio, and is supported by the NASA Johnson Space Center (JSC) in Houston, Texas and the NASA Marshall Space Flight Center (MSFC) in Huntsville, AL.

The charter of PCAD is to identify and fund programs that develop and expand the maturity of candidate technologies considered to be important for future cryogenic space vehicles. These programs focus on components or subsystems that are deemed lacking in technical maturity but are considered to be essential to successful design, development, and fabrication of an integrated LO2/LCH4 propulsion system. Consistent with the PCAD charter, NASA awarded a contract to Aerojet to develop a 100-lbf LO2/LCH4 Reaction Control Engine (RCE) aimed at reducing the risk of utilizing a cryogenic reaction control systems (RCS) on a space vehicle.

To test the RCE over a full range of propellant conditions, NASA has contracted with Sierra Lobo Inc. (SLI) to design, develop, and fabricate a stand-alone portable Propellant Conditioning and Feed System (PCFS). The PCFS consists of two test rigs; one for LO2 and one LCH4.

Although the main purpose of this paper is to describe the PCFS test rigs, a brief description of the RCE will first be provided. The prime objectives of the PCFS test rigs will then be discussed. Finally, a detailed description and analysis of the test rigs will be given along with their unique capabilities.

100 lbf REACTION CONTROL ENGINE (RCE)

RCE DESIGN

The RCE designated for this test was developed under contract by Aerojet[1] to utilize LO2 and LCH4 as the propellants. The engine assembly consists of four major components including the combustion chamber, injector plate, spark plug, and propellant valves. The assembled engine is illustrated in Figure 1 below.

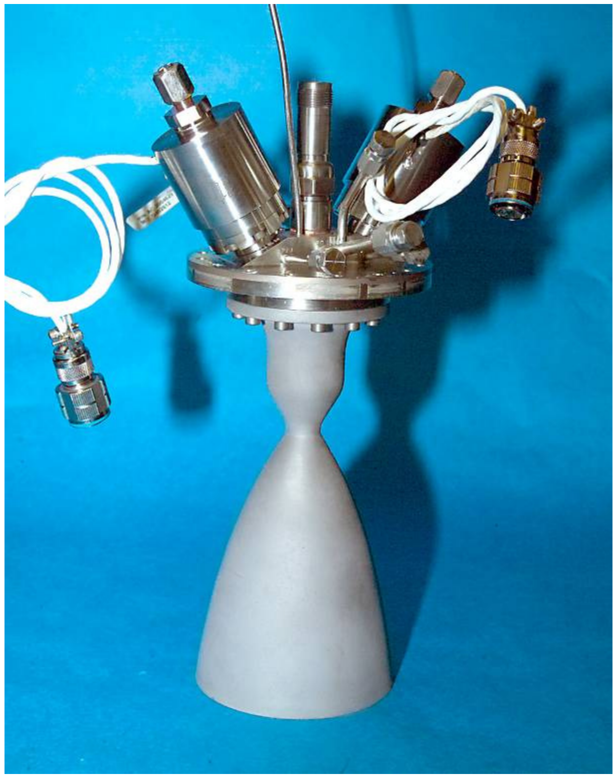

Photo Courtesy of NASA and Aerojet

Figure 1. 100 lbf LO2/LCH4 Engine.

For the initial sea level testing phase, the divergent section of the combustion chamber will have an optimal area expansion nozzle. The sea level chamber will be similar to the 45:1 nozzle shown with Figure 1. The RCE was designed to meet the performance specified in Table 1 below using cryogenic propellants. Acceptance testing of the engine has demonstrated that it met or exceeded the initial design requirements.

Table 1. 100 lbf engine design specifications and acceptance test results.

Parameter	Design Specification
Nominal Chamber Pressure	175 psia
Thrust	100 lbf ± 10 lbf
Mixture Ratio	2.3 - 2.5
Isp @ 80:1 AR, Steady State	320 seconds
Minimum Impulse-Bit (Ibit)	4
Ibit Repeatability	< ± 5%
Thermal Heat Leak to Feed System (Non Solar Load)	< 1 Btu/hr
Electric Pulse Width (EPW)/Any DC (1, 5, 15%)	< 80 msec

<u>RCE TEST REQUIREMENTS</u>

The primary objectives for the sea level testing of the 100 lbf engine will be to verify operation of the propellant conditioning and feed system during hot fire engine tests, identify the ignition range over a wide variation of propellant conditions, investigate ignition repeatability, and characterize the combustion performance of the engine. A subsequent test series will characterize the thrust performance of the engine and measure the heat flux at the wall of the combustion chamber. A schematic of the test section is shown in Figure 2.

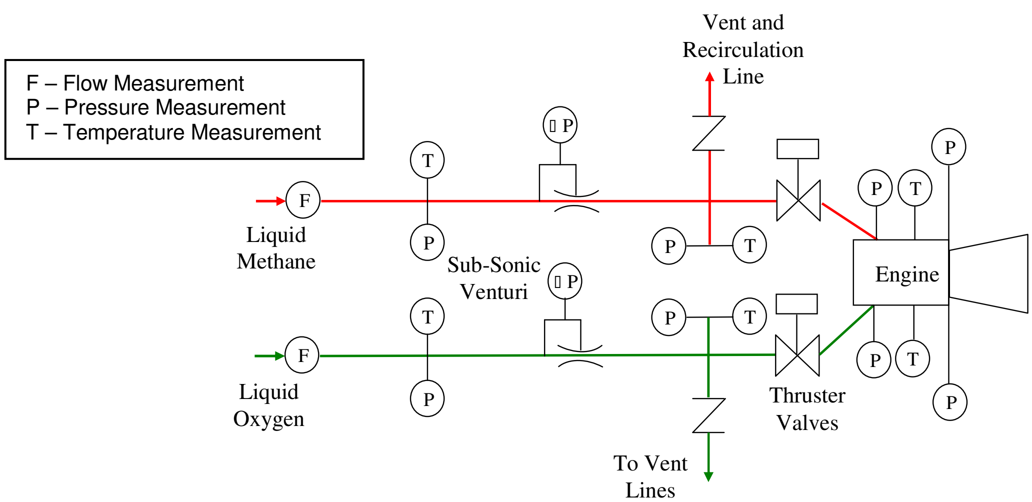

Figure 2. RCL-32 Test Section Schematic.

Propellant Ignitability

Engine testing shall begin upon completion of the PCFS operational tests. This will be the first series of tests to utilize the delivered hardware in the sea level test configuration. The purpose of this test is to verify that ignition is possible over a portion of the operating range of the PCFS. This test series will define the ignitable region of methane based on varying propellant properties and mixture ratios. There will be no pulsed engine operation during this test and will be comprised of steady state hot fires.

Ignition Repeatability

Upon full characterization of the ignitability range of the propellants, testing will then focus on the repeatability of the engine hot fire pulses. This test will consist of multiple test runs of pulsed operation at various duty cycles. The purpose of the test will be to demonstrate consistency of ignition pulses at various propellant conditions.

Combustion Performance

The final component in the initial phase of engine tests will be to characterize the combustion performance of the engine. A thrust measurement stand (TMS) will be designed and built for the second phase of testing. This portion of the test plan will be conducted after the initial series of tests but prior to altitude testing at the Altitude Combustion Stand (ACS).

Run Time & Duty Cycle

The maximum, cumulative firing time during any one hot fire profile for this engine will be 120 seconds; however individual ignition pulses will range from 0.080 up to 30.0 seconds. The duty cycle for the test article will vary depending on the specific test being conducted. It is expected that the duty cycle will vary from 0.1% to 100%, which corresponds to a total profile run time of 0.080 to 1200 seconds. The maximum coast time between main engine pulses will be 240 seconds with a 0.1% duty cycle, while the minimum coast time will be 0.080 seconds with a 75% duty cycle. The system is required to maintain propellant conditioning from this maximum run profile time.

PROPELLANT CONDITIONING AND FEED SYSTEM (PCFS)

To support the above RCE testing, NASA-GRC contracted with Sierra Lobo, Inc. (SLI) in Milan, OH for the design, development, and fabrication of two independent test rigs that make up the PCFS to condition the propellants supplied to the RCE or other similar rocket engines. Skid/pallet fabrication, assembly and installation of the test rig components, and subsystem checkouts occurred at the SLI-Milan facility. System validation will occur at GRC.

PCFS REQUIREMENTS

The specific design parameters for the PCFS test rigs are given as follows:

- Provide conditioned LO2 and LCH4 to a 25-100 lbf rocket engine over the full range of delivery requirements specified in Table 2 below
- Be capable of conditioning batches of LO2 and LCH4 within 1-2 hrs and hold values for up to 4 hrs
- Each system to operate as a self contained unit to generate conditioned propellants
- Provide accurate instrumentation in the run tank to precisely measure both propellant liquid level and propellant temperatures throughout the liquid using SLI's proprietary Cryo-Tracker® measurement probe.
- Each system must be skid-mountable and transportable
- Design and fabricate all hardware to ASME B 31.3, ASME Boiler and Pressure Vessel Code Section VIII
- Design and fabricate electrical installations to NEC Class I, Division 2 , Group B location, and NFPA 496 Type Z Purged and Pressurized Systems
- Spatial and consumable constraints/interfaces for NASA-GRC Research Combustion Laboratory (RCL) Cell 31/32 and Altitude Combustion Stand (ACS).
- Sighting according to design considerations in accordance with DOD 6055, NFPA 55

Table 2. Propellant delivery requirements.

Propellant	Flow Rate (lbm/s)	Working Pressure (psia)	Saturated Pressure (psia)	Temperature (°R)
LO2	0.060 - 0.40	275 – 400	4.7 – 322.7	145 – 243
LCH4	0.016 - 0.16	275 – 400	2.7 - 323.4	170 – 304

PCFS SYSTEM DESIGN

The propellant conditioning and feed system was designed to deliver cryogenic liquid propellants to the test article over a broad range of propellant conditions. The point of reference for the propellant conditions was the inlet of the thruster valves. The PCFS was also designed to ensure that the cryogenic liquids at the target propellant conditions could be delivered to the engine for the entire duration of a test run.

The PCFS consists of two separate, but similar propellant systems which are designed to supply conditioned propellants to various size rocket engines at the NASA GRC RCL. Each system as described below is mounted on a steel skid/pallet structure that has a footprint of approximately 8 ft x 12 ft, and can be relocated by "crane" or "forklift". Each skid weighs approximately 10,000 lbs and is capable of being transported to any region of the country.

As previously stated, one of the test rigs is designed for the LCH4 propellant; the other is for the LO2. The primary difference in the schematic of the two systems is that the LCH4 system includes a cryogenic submersible pump and piping which allows the propellant to be recirculated from the run tank back to the upstream side of the propellant conditioning system so that its temperature can be re-modified, if necessary. A simplified schematic of the LCH4 system is shown in Figure 3 below.

The PCFS was designed to control the propellant temperature conditions up to the inlet to the thruster valves in a consistent manner. The PCFS will condition the propellants to a specified temperature in less than one hour. The system will be able to maintain the set point temperature to within +/- 5°R up to the thruster valve inlet. The system will also be able to maintain propellant conditions within the temperature tolerance for the entire duration of the test, including holding periods up to 4 hours. In addition, a trace cooling system has been incorporated into all the cryogenic vessels and vacuum jacketed (VJ) piping to pre-chill the entire test rig prior to initiating the flow of any propellants. The LCH4 test rig utilizes liquid argon (LAr) for pre-chilling and the LO2 test rig utilizes LN_2.

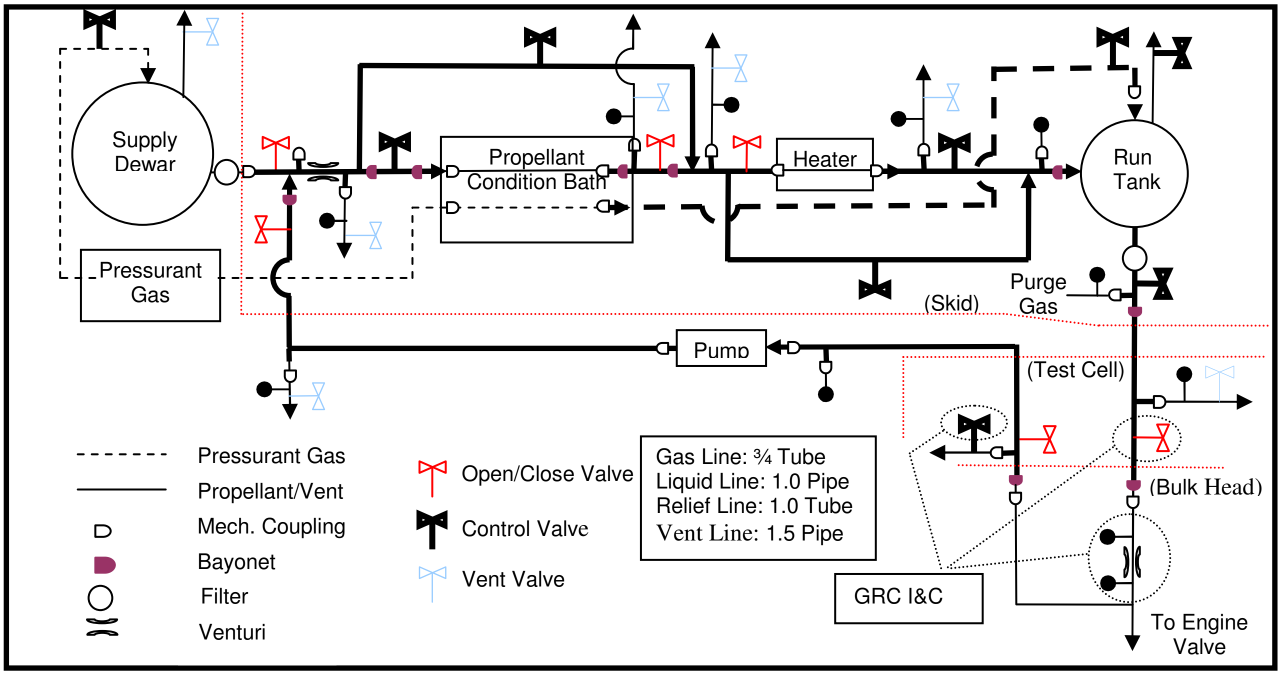

Figure 3. LCH4 propellant conditioning and feed system schematic

PCFS COMPONENT DESIGN

In order to meet all the required objectives of these tests, many of the components in the PCFS rigs had to be custom designed and fabricated. All components were specified to not only operate continually in the outdoors, but also had to meet the requirements of operation in a hydrogen rich environment due to nearby test activity. In addition, all LO2 components were cleaned and inspected to either KSC 123 or ASTM G93-96 G. A photograph of the completed LO2 test rig is shown in Figure 4. Each of the two rigs contains the following subsystems:

1. Supply Dewar
2. Propellant Conditioning Bath
3. Heater
4. Run tank
5. Recirculation Pump (LCH4 system only)
6. Stand-Alone PLC and Data System

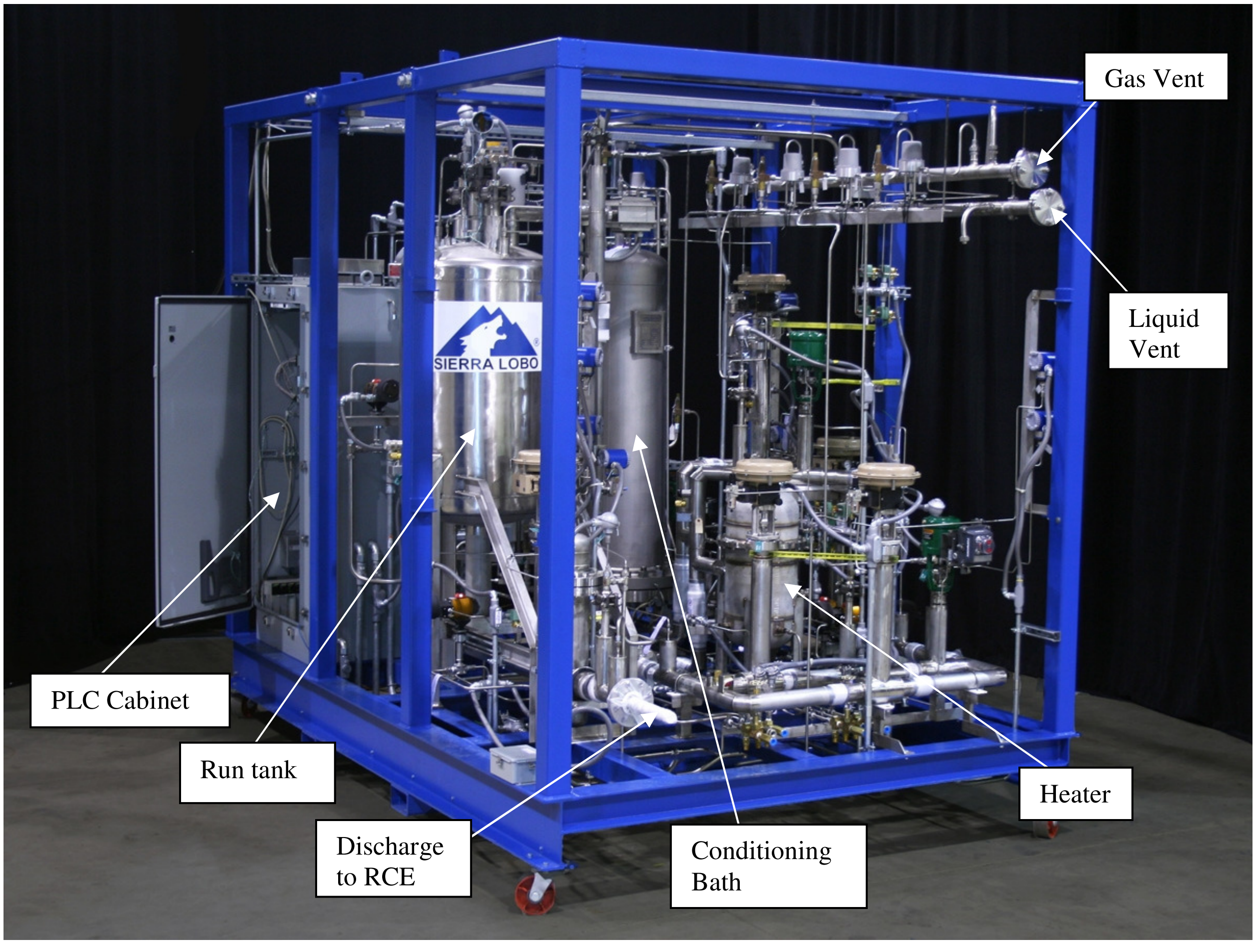

Figure 4. Picture of LO2 Skid Post-Assembly, Pre-Installation

Supply Dewar

The supply dewar stores and provides liquid propellant at saturated temperatures (from 0 to 50 psig). One dewar is used for the methane system, and one for the LO2 system. Once the system has been adequately chilled down, the supply dewar will be pressurized as high as 475 psig using an external GHe supply. The liquid propellant will then be expelled out of the dewar through the conditioning system, and into the run tank. The dewar pressure will be maintained at a constant level during this expulsion to help keep a constant flow rate of the liquid propellant through the conditioning system.   Each supply dewar is made of vacuum-jacketed stainless-steel, rated for a maximum allowable working pressure of 500 psig and a liquid storage capacity of approximately 428 liters (113 gallons). A commercially available Department of Transportation (DOT) certified dewar was utilized for the LO2 system, while a custom

ASME certified dewar had to be purchased for the LCH4 system. The dewars are located off the skid and have an integrated frame with fork pockets to allow it to be easily moved. The pressurant and vent valves are located on the skid and plumbed to the supply dewar. The dewars can be easily disconnected as needed for relocation.

Propellant Conditioning Bath

The Propellant Conditioning Bath is used for three purposes:

- To reduce the temperature of the liquid propellant as low as possible without freezing.
- To provide a partial chill-down of the helium pressurant gas that will be used to pressurize the run tank (to reduce the heat input from the pressurant gas into the conditioned liquid propellant).
- To reduce the temperature of the liquid propellant during recirculation of the LCH4.

The propellant will flow through cooling coils submerged in the bath liquid. For the LO2 system, this bath will be filled with liquid nitrogen (LN_2) and open to the atmosphere. For the LCH4 system, it will be filled with liquid argon (LAr) and saturated to approximately 10 psig to keep from freezing the LCH4 propellant. The bath size will be 60 gal for LCH4 and 60 gal for LO2, both rated at 400 psig.

Electric Heater

The heater is used to heat the propellant from either saturated temperature (from the supply dewar), or from sub-cooled temperatures (from the conditioning bath). The electrical input power of the heater will be adjusted to achieve the propellant temperature desired, without causing any nucleate boiling. The heater consists of coiled tube encompassed in cast aluminum. The heater elements are also encompassed in the same aluminum casting, but do not physically contact the propellant tubing. Heat is then conducted from the elements, through the casting, and into the tube wall. A separate trace cooling coil will be used to pre-chill the entire casting. This entire assembly is then encased in a vacuum jacket with 10 layers of multi-layer insulation (MLI) installed.

To operate the heater over the required range of conditions, a 208V 3-phase power circuit controlled with a zero-cross power controller through a PLC which provides variable power input to a maximum of approximately 3.0 kW for LO2, and 4.25 kW for LCH4.

Run tank

The run tank will contain the conditioned propellant at the temperatures, pressures, and flow rates required for the test engine. The 60 gallon liquid capacity of the tank is sufficient to allow approximately six minutes of run time for each test, with an extra 60 seconds for run line conditioning. Run tank pressures will vary up to a maximum of 500 psia. Similar to the supply dewar, the run tank is a vacuum-jacketed stainless-steel vessel with a maximum allowable working pressure of 575 psig. The inner vessel is 24" nominal diameter and is wrapped in 30 layers of MLI. The outer vessel is 30"- 32" outer diameter. The entire vessel is trace cooled to allow prechilling of the run tank prior to fill.

Recirculation Pump / Sump

A recirculation piping "loop" is utilized for the LCH4 system only. The purpose of this loop is to allow for the re-conditioning of the LCH4 in the run tank and engine circuit without venting. When re-conditioning is needed, the LCH4 will be expelled from the tank and will flow into a sump. A submersible cryogenic pump will be fully submerged in this sump and will pump the propellant back through the conditioning bath and/or heater to obtain the propellant conditions desired.

The cryogenic pump requires a power input between 10 – 140 watts (depending on the desired flow rate), and operates on 208v, 3-phase power. The pump speed is controlled by a Toshiba® variable frequency drive via the human-machine interface (HMI) control computer.

Vacuum Jacketed Lines

All propellant lines and valves in this system are 1-in schedule 5, product line with a 2 ½-in schedule 5 vacuum-jacket. In addition, they are also traced with either LN_2 (for the LO2 system) or LAr (for the LCH4 system). At least 10 layers of MLI have been added to limit the amount of heat leak into the propellant and also allow the system to be chilled down as quickly as possible.

Pressurant and Purge Gas

The pressurant gas for the supply dewar and run tank will be supplied by a GRC facility gaseous helium (GHe) tube trailer. The pressurant gas will be at 800 – 2,400 psig. As described above, the GHe pressurant gas for the run tank will be partially chilled down using the conditioning bath. The same GHe supply will be used to purge out the lines and components prior to flowing propellants. The skids contain multiple regulation stations for gas.

Valve Operator and Programmable Logic Controller (PLC) Enclosure Purge Gas

Gaseous Nitrogen (GN_2) will be used for valve operator operations and to purge the PLC enclosure to meet NFPA 496 requirements, and will be provided by the GRC facility at 800 – 2,400 psig.

PCFS CONTROLS & INSTRUMENTATION

Human Machine Interface (HMI),PLC control and Data Acquisition

The HMI software used is "Wonderware InTouch®" Version 8.0., running on Microsoft Windows XP Professional (Ver. 2002) platform, a Dell Dimension 8300 3.00 GHz, Pentium 4, personal computer, which will be integrated into the test facility Control Room at NASA GRC. Wonderware InTouch® receives commands via the control computer which in turn will command appropriate PLC functions through the Modicon "Concept" program described below. PCFS System Tags and Alarms will be acknowledged through Wonderware InTouch®.

The Modicon Quantum PLC system software is Concept Version 5.2 SR1/2 software, resides on the personal computer mentioned above; all I/O and programming functions are carried out through the PLC program. PLC programmatic scan time is calculated to be 10mS.

Data collection will be compiled using Software Toolbox's® OPC Datalogger Version 3.5 (Text) software via Software Toolbox's® Topserver software V4.102.251-U with InTouch Client Driver V4.10.8-U, and using the Wonderware® Modicon Modbus Ethernet I/O Server driver for communicating with the Modicon Quantum PLC system. The Data will be stored on the personal computer,

A photograph of the LCH4 and LO2 HMI control interface screens is shown below in Figure 5.

Instrumentation

Various instruments are field-mounted throughout the methane and oxygen conditioning skids, as well as on each of the run lines and recirculation lines to and from the engine. These include absolute and delta pressure transmitters, control valve position indicators, thermocouples, resistance temperature detectors (RTD's), and liquid level transmitters. Limit switches are provided on all isolation valves. The Sierra Lobo Cryo-Tracker ® will be used to monitor tank propellant conditions as well as provide level indication.

The PCFS control system is independent of the facility's RCL-32 facility data acquisition and control system (DACS) with the sole responsibility of conditioning the propellants to the desired set points. The pressurant gasses required to operate the PCFS test rigs will be delivered from and controlled by the test facility. The facility does have full abort control over the entire PCFS.

During engine firing, the RCL-32 DACS at NASA-GRC's RCL shall be used to control all facility valves including the fire valve, bleed valve and thruster valves while the PCFS control system will control the run tank pressurant and isolation valves on the skid. Liquid level and propellant temperature along with engine cutoff off will be performed by Sierra Lobo's Cryo-Tracker® system which is installed in the Run tanks.

Figure 5. HMI Control System for operation of the PCFS test rigs

Devices Monitored and Controlled by GRC PLC

The fire valve, recirculation valve and bleed valve will be controlled by the GRC PLC. The skid PLC will share a permissive high signal to the GRC PLC for engine firing readiness and receive an abort high signal from the GRC PLC. The Sierra Lobo Cryo-Tracker® will also transmit two discrete level indications from the run tank for engine approach cut-off and engine cut-off.

GENERAL DESCRIPTION OF OPERATIONS

Prior to generating the conditioned propellant, the run tank, transfer lines, bath coils and heater coils will be purged and then pre-chilled via trace cooling. The bath will also be filled. The required volume of propellant will be pressure-transferred from the unconditioned dewar through the conditioning system. For temperatures below normal boiling point, the propellant is flowed through the bath alone. If the propellant is to be conditioned around normal boiling point, it will pass through both the bath and heater. For higher temperatures, the propellant will flow through the heater alone. Once the required amount of product has been accumulated in the run tank, testing may begin.

The propellant may then be used for final conditioning of the run line via the prime vent bleed valve, or in the case of LCH4, the recirculation pump can be used. At appropriate conditions, the pump or prime bleed valve will be isolated and the engine control system will command the isolation valve open for testing to begin. A Cryo-Tracker® cryogenic liquid level indication system and the run tank delta pressure transmitter will provide indication when the product propellant has been nearly depleted from the run tank. This will ensure that testing ends in a controlled manner. The system has been designed to support up to 300 seconds of engine testing per batch.

TEST PLANS

NASA Research Combustion Laboratory Cell 32

Both PCFS test rigs are installed in RCL-32 and have experienced full system cold shock using LN_2. The control systems for both skids have been validated, and all operational check-outs completed. A photograph of RCL-32 is shown below in Figure 6. Initial testing at this location will evaluate the capabilities of the PCFS utilizing reserve hardware until the system has demonstrated that the propellants can be delivered in cryogenic, liquid phase, across the full range of temperatures desired. The RCE test article will then be installed for subsequent sea level testing. The outcome is expected to show that the PCFS can condition and deliver propellants to the engine across a wide range of propellant conditions and operational duty cycles.

RCL-32 is capable of providing gaseous and cryogenic liquid propellants, and kerosene type fuels to a sea level test stand and can measure 2000 lbf axial thrust. An air conditioned room immediately adjacent to the test cells is designed to support laser based optical diagnostic equipment with access ports to each test cell.

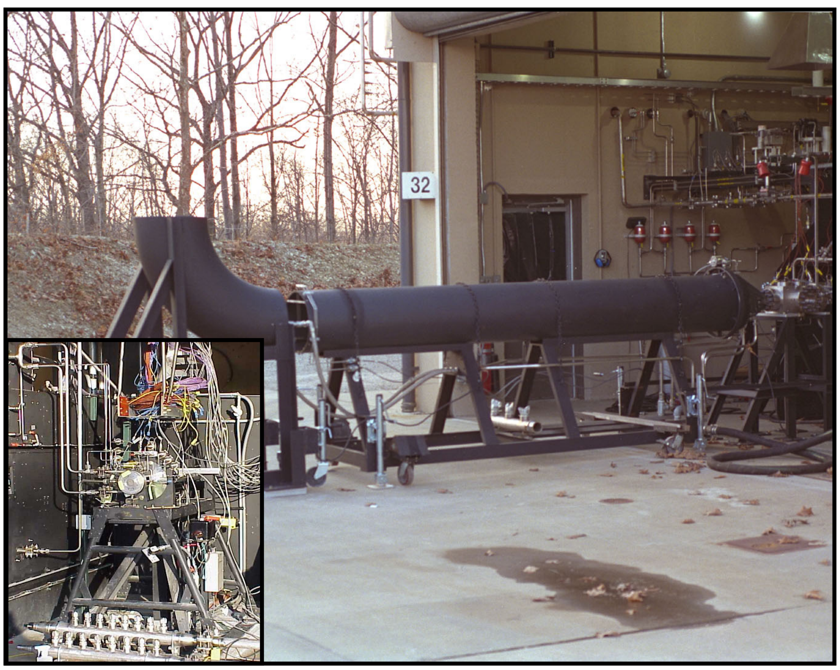

Figure 6. Cell 32 at NASA-GRC's RCL facility

Altitude Combustion Stand (ACS) Facility

After completion of sea-level testing in RCL-32, the PCFS test rigs and RCE test article will be moved to the ACS altitude facility at NASA-GRC. A photograph of this facility is shown below in Figure 7. This facility provides the capability of testing combustion components at a simulated altitude of 130,000 feet (0.03 psia). The facility is equipped with a 2000 lbf axial thrust stand, gaseous and cryogenic liquid propellant feed systems, water-cooled diffuser, data acquisition system, facility control system, spray cooler and multi-stage ejector system.

Figure 7. ACS facility at NASA-GRC

SUMMARY AND CONCLUSIONS

Sierra Lobo, Inc. (SLI) has designed, developed, and fabricated two separate portable propellant feed systems under the Propellant Conditioning and Feed System (PCFS) task: one system for LCH4, and one for LO2. The propellant conditioning and feed system was designed to deliver cryogenic liquid propellants to the test article over a broad range of propellant conditions. The point of reference for the propellant conditions was the inlet of the thruster valves. The PCFS was also designed to ensure that the cryogenic liquids at the target propellant conditions could be delivered to the engine for the entire duration of a test run. Each system as described below is mounted on a steel skid/pallet structure that has a footprint of approximately 8 ft x 12 ft. The PCFS system has integrated seamlessly into RCL-32. The facility systems and the PCFS rigs are currently undergoing subsystem and full system validation required to support RCE testing. All validation testing has performed according to design. Propellant conditioning and delivery results are scheduled to be completed by the end of 2008 in support of RCE testing. Concurrent build-up of the ACS facility for RCE testing is progressing rapidly to meet the aggressive test

schedule. SLI wishes to acknowledge the PCAD project office and GRC operations personnel for their valued input and review of this presentation.

[1] Robinson, P.J., Veith, E.M., Hurlbert, E.A., Jimenez, R., and Smith, T.D.: 100-LBF LO_2/Reaction Control Engine Technology Development for Future Space Vehicles, 59th International Astronautical Congress – Glasgow, Scotland, September 29-October 4, 2008.