Vehicle-Level Oxygen/Methane Propulsion System Hot-Fire Testing at Thermal Vacuum Conditions

Robert L. Morehead[1], J.C. Melcher[2], Matthew J. Atwell[1], Eric A. Hurlbert[1], Pooja Desai[1]
NASA Johnson Space Center, Houston, TX, 77058, United States

Rudy Werlink[3]
NASA Kennedy Space Center, Titusville, FL 32899, United States

A prototype integrated liquid oxygen/liquid methane propulsion system was hot-fire tested at a variety of simulated altitude and thermal conditions in the NASA Glenn Research Center Plum Brook Station In-Space Propulsion Thermal Vacuum Chamber (formerly B2). This test campaign served two purposes: 1) Characterize the performance of the Plum Brook facility in vacuum accumulator mode and 2) Collect the unique data set of an integrated LOX/Methane propulsion system operating in high altitude and thermal vacuum environments (a first). Data from this propulsion system prototype could inform the design of future spacecraft in-space propulsion systems, including landers. The test vehicle for this campaign was the Integrated Cryogenic Propulsion Test Article (ICPTA), which was constructed for this project using assets from the former Morpheus Project rebuilt and outfitted with additional new hardware. The ICPTA utilizes one 2,800 lbf main engine, two 28 lbf and two 7 lbf reaction control engines mounted in two pods, four 48-inch propellant tanks (two each for liquid oxygen and liquid methane), and a cold helium system for propellant tank pressurization. Several hundred sensors on the ICPTA and many more in the test cell collected data to characterize the operation of the vehicle and facility. Multiple notable experiments were performed during this test campaign, many for the first time, including pressure-fed cryogenic reaction control system characterization over a wide range of conditions, coil-on-plug ignition system demonstration at the vehicle level, integrated main engine/RCS operation, and a non-intrusive propellant mass gauging system. The test data includes water-hammer and thermal heat leak data critical to validating models for use in future vehicle design activities. This successful test campaign demonstrated the performance of the updated Plum Brook In-Space Propulsion thermal vacuum chamber and incrementally advanced the state of LOX/Methane propulsion technology through numerous system-level and subsystem experiments.

Nomenclature and Acronyms

APU	=	Avionics and Power Unit
CFM	=	Cryogenic Fluids Management
COP	=	Coil on Plug
COPV	=	Composite Overwrap Pressure Vessel
CRIO	=	Compact RIO
DAQ	=	Data Acquisition
EMI	=	Electro-Magnetic Interference
FFT	=	Fast Fourier Transform
FRF	=	Frequency Response Function
HEX	=	Heat Exchanger
HF	=	Hot-Fire Test Day (e.g., HF6 is "Hot-Fire Day 6")
ICPTA	=	Integrated Cryogenic Propulsion Test Article
IPSTB	=	Integrated Propulsion Systems Test Bed
ISP	=	In-Space Propulsion (test chamber)
ISRU	=	In-Situ Resource Utilization
K	=	MPG system stiffness
LEO	=	Low-Earth Orbit
M	=	MPG system modal mass
MAWP	=	Maximum Allowable Working Pressure
MIB	=	Minimum Impulse Bit

[1] Propulsion System Engineer, Propulsion Systems Branch EP4, AIAA Member
[2] Propulsion System Engineer, Propulsion Systems Branch EP4, AIAA Senior Member
[3] Advanced Engineering Development Branch NE-L6

MLI = Multi-Layer Insulation
MPG = Propellant Mass Gauging
PCAD = Propulsion and Cryogenics Advanced Development
PZT = Lead Zirconate Titanate
RCE = Reaction Control Engine
RCS = Reaction Control System
RTD = Resistive Thermal Device
TC = Thermocouple
TCA = Thrust Chamber/Nozzle Assembly
TRL = Technology Readiness Level
TTS = Thrust Termination System
TVS = Thermodynamic Vent System
$\pm Z$, $\pm Y$ = Tank Identification Nomenclature

I. Introduction

SPACECRAFT trade studies planning our future flights to Mars and other places frequently recommend the oxygen/methane propellant combination as the right combination of specific impulse, density, propellant storability, and In-Situ Resource Utilization (ISRU) compatibility[1,2,3,4]. NASA, US industry, and numerous other spacefaring nations have invested in oxygen/methane engine and propulsion system development, though to date no oxygen/methane engine has flown in space nor has a vehicle reaction control system with cryogenic propellants. Although manageable, these are notable technology readiness level (TRL) hurdles to the general acceptance of oxygen/methane propulsion for spacecraft.

In 2017, a multi-center NASA team conducted a hot-fire test series of a small prototype lander with a liquid oxygen (LOX) / liquid methane (LCH4) propulsion system at simulated high altitude conditions both at ambient temperature and at deep cryogenic thermal vacuum conditions – a first for this propellant combination. The goal of this campaign was twofold: exercise the renovated test facility, and collect model validation data on the vehicle-level oxygen/methane propulsion system for the benefit of similar landers in the future. The hot-fire test article was named the Integrated Cryogenic Propulsion Test Article (ICPTA) (Fig. 1), and was based on the hardware assets developed during NASA Johnson Space Center (JSC) Project Morpheus[5,6,7] from 2012 to 2014 and cold helium pressurization experiment in 2015[8].

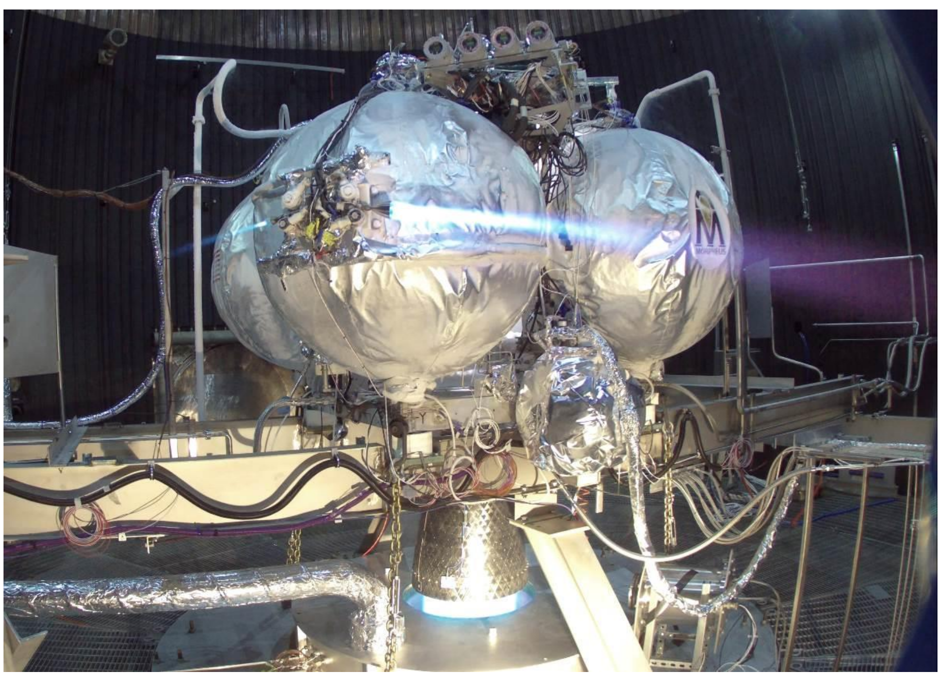


Figure 1. Integrated hot-fire test of the ICPTA in the Plum Brook ISP Thermal Vacuum Chamber: 2800 lbf-vac main engine (bottom), 7 lbf-vac RCE (left), and 28 lbf-vac RCE (right).

Numerous experiments were conducted both on the test article and facility to maximize the overall benefit of the test campaign. Vehicle Reaction Control System (RCS) experiments were performed at a variety of thermal conditions and included water-hammer characterization with varied propellant quality, vacuum priming, gas/gas to liquid/liquid self-conditioning under hot-fire conditions, and thermal vacuum ignitions. Main engine hot-fire testing was performed for the benefit of the facility and for vehicle test objectives. Notable other experiments included vehicle heat transfer characterization during cryogenic thermal vacuum exposure, novel propellant mass gauging, a multi-rocket engine ignition system, cold helium pressurization, and propellant tank spray-chilling.

A future spacecraft propulsion system based around oxygen and methane propellants will likely have numerous reaction control engines on the periphery of the vehicle, all plumbed to common tankage via long manifolds. In contrast with every other spacecraft reaction control system flown to date, these remote engines may have to manage multiphase propellants in the normal course of operation. In Low Earth Orbit (LEO) or in the Earth/Moon system, heating of the spacecraft may increase the propellant temperature in these remote manifolds above the vaporization point resulting in either gas or liquid at the engine inlets depending on the RCS engine duty cycle. The ICPTA test campaign demonstrated the following mission architecture: minimum impulse bit firings operated using gaseous propellants (such as during long coast phases), and high thrust/high impulse bits (such as during critical mission phases) performed by pre-conditioning the cryogenic feed system to liquid conditions using an efficient thermodynamic vent system. This is a simple and robust solution for a cryogenic reaction control system.

The ICPTA system also demonstrated the capability of the RCS system to naturally transition from gas/gas to liquid/liquid operation under continuous use (self-conditioning), which is a hybrid architecture that could be employed by a flexible guidance and control system. Additionally, performing minimum impulse bit firings with gaseous propellants is advantageous for producing clean pulses and for minimizing propellant consumption by the spacecraft.

Several other cryogenic RCS architecture options are available: continuously condition the RCS lines to a liquid state using recirculation pumps, resort to very high manifold pressures to maintain the propellants in a liquid or supercritical state (high pressure tanks or pumps), or add gasification systems for the propellants to ensure a gaseous state at the engine. These are more complicated approaches which have higher dry mass, higher complexity, lower reliability, and are less efficient.[9,10,11] However, much of the data from these tests and the individual technologies can be applied to other RCS architectures.

A. Hot-fire Test Campaign Background

During the NASA Propulsion and Cryogenic Advanced Development (PCAD) program[2], several oxygen/methane engines were tested in simulated altitude conditions at NASA White Sands Test Facility (WSTF) and Glenn Research Center (GRC), including some RCE in multi-engine test stands. PCAD main engine altitude testing was only conducted on stand-alone test articles (i.e. not integrated with common RCEs). An Integrated Propulsion System Test Bed (ISPTB) with propellant tanks, RCS, and a main engine was designed during PCAD for altitude testing at WSTF, but was never built or tested before PCAD program completion in 2010. Project Morpheus was a vehicle-level implementation of an oxygen/methane propulsion system, with many hot-fire tests and vehicle free-flights demonstrating the robustness of the propellant combination at sea level[5]. Numerous technical challenges remain for the progression of oxygen/methane propulsion from its current state of ~TRL 5 to a robotic or manned space mission. For example, at the end of the PCAD program, thermal-vacuum testing for RCS was identified as a key area that was still untested.

Figure 2: ICPTA test article suspended over the ISP test cell at NASA Glenn Research Center Plum Brook Station.

A key asset in the development of future propulsion systems is the NASA Glenn Research Center Plum Brook Station In-Space Propulsion (ISP) Thermal Vacuum Chamber (formerly known as the B2 facility). This one of a kind facility is capable of hot-fire testing complete upper stage spacecraft at altitude conditions while simultaneously thermally conditioning the spacecraft with solar lamps or walls flooded with liquid nitrogen (LN2). A hot-fire test was last performed in the ISP facility in 1998. After recent renovation, a hot-fire test at that facility was determined to be necessary to characterize its performance and to make the ISP facility ready once again to provide its unique space simulation environment for spacecraft testing and propulsion system development.

An opportunity was identified to both advance the state of oxygen/methane propulsion and to characterize the renovated Plum Brook ISP thermal vacuum chamber. A test article based on evolved Morpheus hardware would not only enhance the capabilities of the ISP facilities, a thermal vacuum hot-fire at the vehicle level would also provide an opportunity to incrementally advance oxygen/methane propulsion - since the assets of Project Morpheus were available for use by new projects, and all previous ISP facility hot-fire experience centered around oxygen/hydrogen propulsion. Therefore, a NASA intercenter collaboration team was assembled to perform this experiment, with NASA Plum Brook readying and operating the ISP facility, and the NASA Johnson Space Center (JSC) team assembling and operating the oxygen/methane test article. Additional NASA personnel from Glenn Research Center, Stennis Space Center, and Kennedy Space Center contributed expertise and research projects to the test campaign.

II. ICPTA and Plum Brook Facility Hardware

A. Test Article Overview

The ICPTA is a liquid oxygen/liquid methane propulsion test bed in the configuration of a small planetary lander in approximately the correct scale to land a 1,000 lbm payload on the moon. Built by NASA JSC for this experiment, the ICPTA was configured specifically for this thermal vacuum hot-fire test series using repurposed hardware from previous NASA projects (Morpheus, others) and new components where necessary. The ICPTA consists of four oxygen/methane Reaction Control Engines (RCE) mounted in two pods, a central oxygen/methane main engine, four spherical aluminum propellant tanks containing up to 4,700 lbm of LOX and 1,700 lbm of LCH4, and a spherical Composite Overwrap Pressure Vessel (COPV) with ~8 lbm of helium gas at 3,600 psi and -250F or below (Fig. 1).

Figure 3: The ICPTA in the NASA Plum Brook ISP (B2) thermal vacuum chamber

In the Plum Brook ISP test cell, the ICPTA rested on an I-beam structure, suspended over the 32-inch duct separating the 60,000 ft^3 thermal test cell from the 350,000 ft^3 nozzle exhaust spray chamber (Fig 3). The vehicle was positioned so that the main engine nozzle exit plane was located either 3 inches submerged into this duct or 3 inches above the duct entrance, depending on the test conditions of the day.

The ICPTA was instrumented with more than 320 sensors monitoring numerous subsystems, with data recorded by the vehicle flight computer or the Plum Brook facility systems. The facility test cell contained additional instrumentation for its functional operation and oxygen/methane heat transfer experiments. Numerous electrical and fluid interfaces attached the ICPTA to the facility. With the exception of insulation purges, a backup LN2 chill system for the helium COPV, and the five engines on the vehicle, all fluids/gases entering the vehicle vented back to the facility for safe disposal (i.e., all the overboard vents were captured and not released into the test cell).

A simplified propulsion system schematic of the ICPTA is shown in Fig. 4. The LOX and LCH4 systems provide a common feed to the main engine and RCS. Pressurization during hot-fire is supplied by helium stored in a COPV that is chilled with LN2 pre-test. The high-pressure helium is warmed via a heat exchanger mounted in the diverging section of the main engine nozzle before entering a regulator panel and then the propellant tanks. RCS feedline conditioning is accomplished via bleed flow through a thermodynamic vent system (TVS) on the RCS manifolds. All of these major components are described in more detail in the following sections.

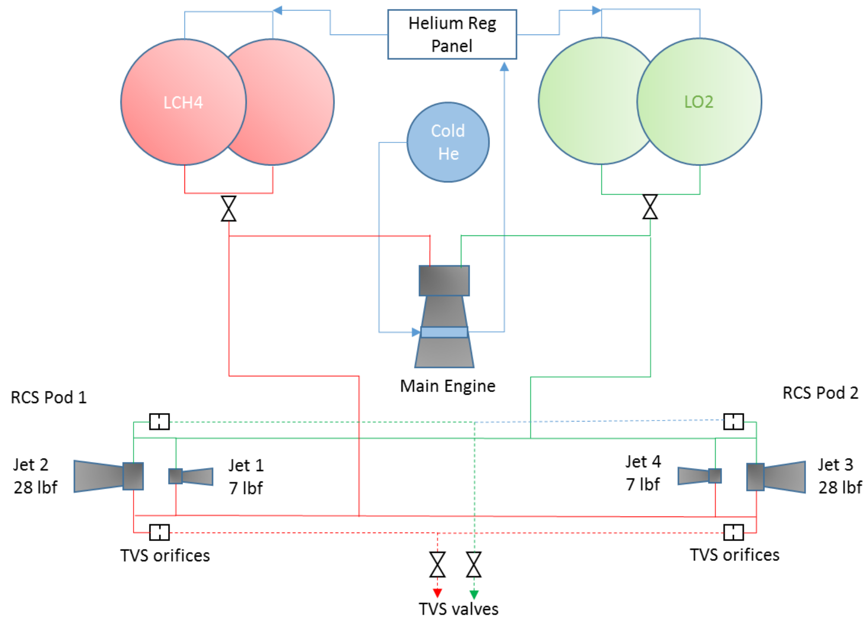


Figure 4. Simplified propulsion system schematic of the ICPTA showing major functional components.

B. Test Article Control and Instrumentation

A primary purpose of the ICPTA test campaign was collecting system level performance and model validation data. More than 320 sensors on the vehicle provide temperature, pressure, thrust, flowrate, strain, etc under static and dynamic conditions, enabling research on a variety of propulsion topics by researchers at multiple NASA centers. The data was recorded by multiple systems; ~25% by the ICPTA flight computer, and the remainder by Plum Brook facility systems. Fig. 5 is a schematic of the control and data systems used during ICPTA testing at Plum Brook B-2. Tables 5-9 summarize all of the instrumentation and control channels used across the various systems for ICPTA testing.

The ICPTA flight controller was developed during Project Morpheus as the Avionics and Power Unit (APU). This computer functionally executes the core software needed to operate the ICPTA, and also includes the data acquisition (DAQ) and control systems for ICPTA function (e.g., solenoid valves, throttle actuator, igniter power). The APU has two data recording rates: a slow-rate mode at 10 samples/sec for all channels and a higher rate 100 samples/sec for all channels. The 10 sample/sec rate is used for nominal ops during loading, chilling, etc., and the 100 samples/sec rate is using during main engine or RCS hot-fire. The APU was not vacuum-rated, so for ICPTA testing at Plum Brook the entire APU was housed outside of the B-2 vacuum test cell in a purged avionics cabinet. The APU is remotely operated via Ethernet from the B-2 Control room.

The APU harness carried all of the APU-to-ICPTA command and data channels, and was ~50 ft length. A single common vacuum chamber feedthrough connector was built into the APU harness, bundling 342 wires through a 3-inch port. The common harness and its length was an auxiliary experiment in electro-magnetic interference (EMI) because along with low power data signals from thermocouples and pressure sensors, the harness also included five Coil-On-Plug (COP) igniter wires which could operate at ~7 to 9 amps each with 100 hz switching and other high-current wiring for thruster solenoid valves, etc. The COP electronics were also housed in the avionics cabinet with the APU since the COP igniter electronics were also not vacuum rated. Extensive functional ground testing was completed at JSC prior to vehicle shipment to Plum Brook, including fully-integrated hot-fire test demonstrations, to verify that the harness bundle design did not introduce excessive EMI in the data. All data analysis conducted to date has shown no significant EMI issues caused by the common harnessing, even during thruster hot-fire operations.

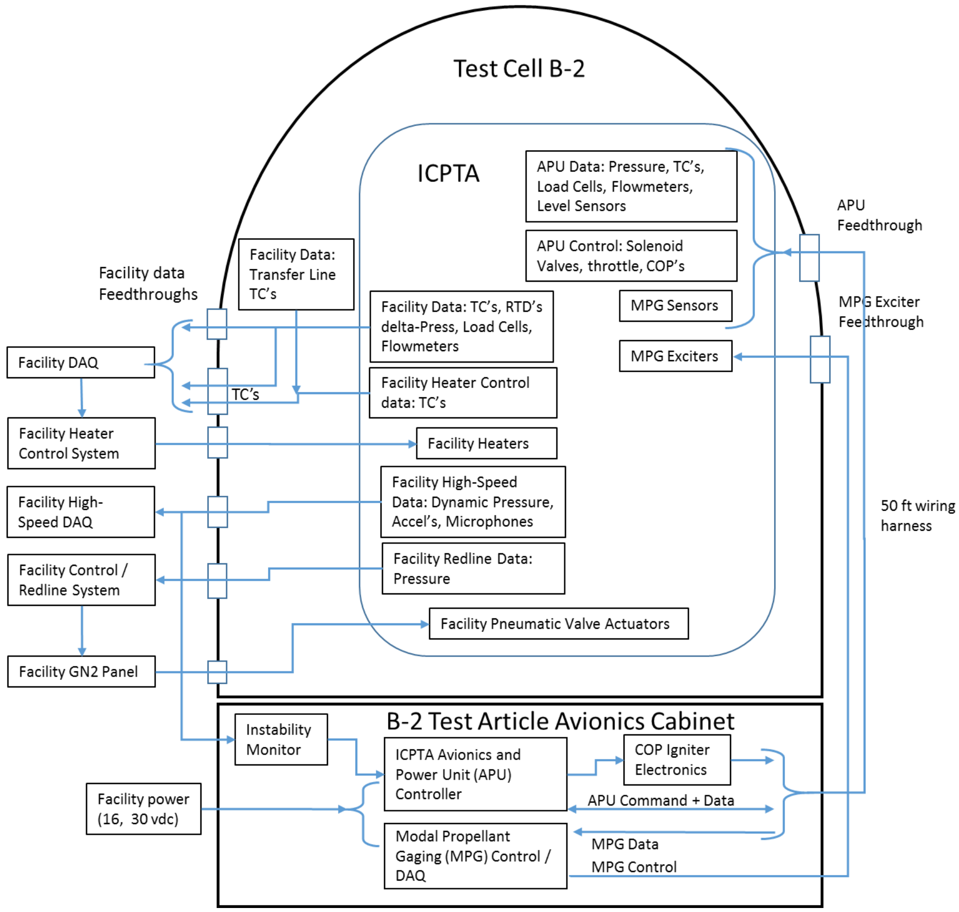


Figure 5. ICPTA Control and Data Overview for testing in B-2

The Modal Propellant Mass Gaging (MPG) DAQ and control systems were also included in the test article APU cabinet (Fig. 5). Similar to the APU, the MPG control and DAQ systems were remotely operated from the B-2 Control Room via Ethernet. The two MPG actuators were connected to the ICPTA in the test cell via dedicated vacuum feedthrough connectors since these circuits utilized considerably higher voltage (0-200 vac) than the APU (16 vdc, 30 vdc). However, the ten MPG return signal data channels (at 0-10 vac) were included in the APU harness.

The APU utilizes a secondary avionics box to generate a main engine combustion stability redline from the integrated signal of two of the main engine dynamic pressure transducers. This secondary box was similarly mounted in the APU avionics cabinet, shown in Fig. 5. A pass-through circuit in the box transmitted the raw signal from these two transducers to the facility high-speed instrumentation system for recording.

The facility data and control systems are not fully described in this manuscript, but a simplified overview is shown in Fig. 5. The facility instrumentation and controls can be functionally described in a four categories: 1) data recording system, 2) high-speed data recording system, 3) heater control system, and 4) facility redline control system. First, the primary facility instrumentation system was used to record ICPTA instrumentation such as thermocouples, load cells, flowmeters, delta-pressure transducers, etc. Details of the instrumentation recorded by the facility are shown in Table 5. The facility data recorders operated at two modes: a low-speed mode at 6.25 samples/sec (all channels), and a higher speed mode at 100 samples/sec (all channels). Similar to the APU, the lower rate mode was using during tanking and chilling operations, and the high-rate mode was used during hot-fire operations. As shown in Fig. 5, the facility instrumentation was connected from the ICPTA to the facility DAQ system via separate vacuum feedthroughs than the APU. For example, large thermocouple feedthrough connectors were used to connect the extensive amount of temperature measurements on the vehicle to the facility DAQ. 157 channels of ICTPA data were recorded by the facility DAQ (not including the high-speed or heater control systems described below).

The second functional segment of the facility data system was the high-speed recording system. This system was used to record data at 25,000 samples/sec (all 26 channels) from dynamic pressure transducers, accelerometers, and microphones. Table 6 lists the high-speed instrumentation recorded, including dynamic pressure transducers on the RCS manifolds used for understanding water hammer and transducers installed on the main engine to monitor combustion stability.

Third, the facility provided power and control for heaters installed on ICPTA actuators and instrumentation that were not cryogenically rated for the cold-thermal environment testing. For example, the pneumatic valve actuators on the ICPTA (e.g., vent valves, isolation valves, and fill valves) were wrapped in resistive heater tape to ensure operation during cold-thermal testing. This resistive heater method was used similarly on pressure transducers, camera housings, and other sensitive instruments in the test cell. To monitor performance of the heaters, the facility team installed Type E thermocouples on all heated components, totaling 39 channels as outlined in Tables 5-9.

Lastly, dedicated instrumentation was added to the ICPTA for facility-based redline control (in addition to the APU redlines that monitor vehicle parameters). The ICPTA propellant isolation valves and vent valves were pneumatically-actuated so that the facility could safety isolate the engines or vent the propellant tanks in the event of an emergency such as if the APU lost command capability. Similarly, a facility-controlled solenoid vent valve was added to the ICPTA on-board helium tank. Four dedicated pressure transducers, shown in Table 8, were added to the ICPTA for redline monitoring. These were redundant pressure transducers, installed in parallel with the APU instrumentation, typically on the same hardware port. Additionally, watchdog hand-shake bits (e.g., "facility ready" and "engine ready") were required in both the APU and the facility control systems for activation and redlines.

Additional instrumentation was included on the facility-to-ICPTA transfer line as part of a cryogenic fluids experiment. Twelve channels of thermocouples were added on both the LOX and LCH4 transfer lines to monitor during filling operations. For most of the test operations, this data was recorded by the facility control system at 1 sample/sec. For one dedicated LCH4 tanking test, the 12 channels were recorded in a stand-alone National Instruments Compact RIO (CRIO) at 20 samples/sec (all channels).

Testing of the ICPTA was conducted using a hybrid scheme whereas the Plum Brook facility provided the test cell environment and loaded commodities onto the vehicle and the JSC test article team operated the vehicle to perform testing. The ICPTA was controlled remotely from consoles set up in the Plum Brook facility control room. Continuous status communication between the facility and ICTPA computer and detailed combined operations procedures were used to mitigate risks of this shared operations and control scheme.

C. Plum Brook Facility Overview

The Spacecraft Propulsion Research Facility (formerly known as test cell B2) is a one-of-a-kind test stand capable of performing steady state hot-fire testing of entire spacecraft upper stages in various thermal conditions. The facility supports testing of engines up to 400 klb thrust at 100 kft simulated altitude conditions while maintaining the spacecraft at temperatures ranging from deep cryogenic to hot solar cycling conditions. Figure 6 shows computer models of the ICPTA in the Plum Brook ISP test cell.

For ICPTA testing, the Plum Brook ISP facility operated using a single train of the auxiliary ejectors. This approach allowed the facility to evacuate the test cell atmosphere using a 3rd party rental boiler system (note that the facility-based steam generation system was inactive for ICPTA testing). For the majority of test days, the test cell and spray chamber were not isolated, so vacuum operations required the steam ejectors to evacuate the large common volume of both chambers. During main engine operation, the main engine nozzle diffuser duct separating the test cell from the spray chamber choked, facilitating steady-state or higher

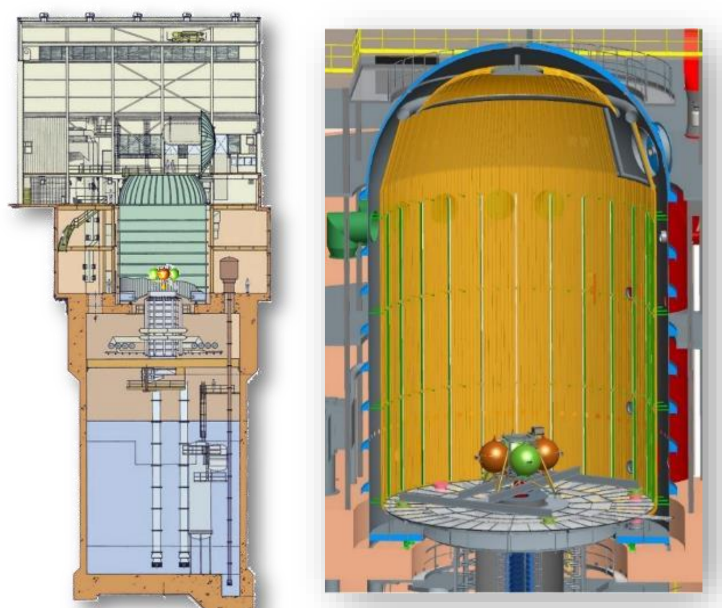


Figure 6. Computer models of the ICPTA in the NASA Plum Brook ISP (B-2) thermal vacuum chamber test cell.

simulated altitude conditions in the test cell during main engine operation. However, due to leaks in both the ICPTA and the facility systems, combined-volume tests were only conducted at pressures of ~30 torr.

For thermal-vacuum testing, the cold wall shroud in the test cell was flooded with liquid nitrogen (LN2), and the wall temperatures measured down to -305ºF after reaching thermal-steady state. The LN2 cold-wall was active in the entire cylindrical section of the test chamber and the concave cap at the top of the test chamber. As seen in Fig. 3, the lower 20 ft of the copper walls were painted black to improve radiative heat transfer with a measured emissivity of ~0.84 at 77K. The unpainted oxidized copper emissivity was measured at ~0.24 at 77K. During thermal vacuum testing of the ICPTA, the 11-foot diameter flapper door between the test cell and spray chamber was closed, allowing vacuum levels to achieve 0.02 Torr, which then increased to ~6 Torr prior to RCS hot-fire testing.

As seen in Figures 3 and 6, the main engine plume was centered over a 32-inch diffuser duct, which was water-cooled during main engine hot-fire testing. The water system was a 7,000 gal gravity-fed water supply located outside the test cell, operating at ~1,200 GPM. The facility team activated the cooling water and verified flow prior to hand-off to the ICPTA test team to begin the main engine test sequence. The duct cooling water run time could have been an operational limiting factor on engine run time, but that constraint never materialized since engine run times tested were less than one minute. The cooling water also became an entrained fluid during shut-down blow-back at the end of main engine test operation, significantly adding moisture to the test cell. Mitigation options were available but not employed due to cost and schedule limitations.

The facility provided the fluid commodity interfaces to the ICPTA for propellants (LOX and LCH4) and helium pressurization. In addition to these primary commodities, the facility also provided LN2 for COPV cooling and gaseous nitrogen (GN2) for pneumatic valve actuators and purges. The propellants were isolated to the vehicle using pneumatically-actuated fill valves, mounted integral with the ICPTA. In addition to the supply commodities, the facility also provided vent / relief capability from the ICTPA to outside of the test cell (eventually vented outside the facility). The fluid interfaces from the ICPTA to the facility are seen in Fig. 7.

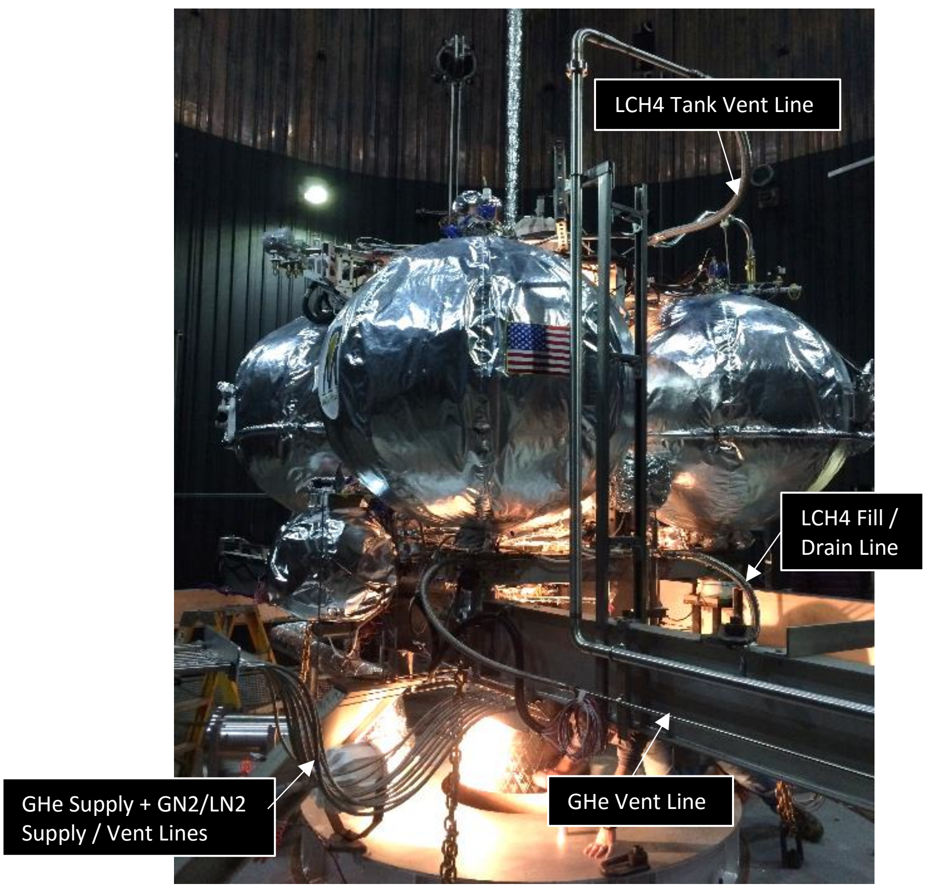


Figure 7. Fluid Interfaces from the facility to the ICPTA
Note: LOX tank fill/drain, and vent lines not shown

The facility provided power to the ICPTA Avionics and Power Unit (APU) located outside of the test cell in a dedicated test article avionics cabinet. The APU was not vacuum rated for testing, and was located in a purged enclosure outside the vacuum wall. Further details on the ICPTA controls and instrumentation interfaces with the facility are described below.

D. Verification Testing at Johnson Space Center

Prior to shipping the ICPTA to Plum Brook, a short hot-fire test series was conducted at NASA JSC to verify the performance of the rebuilt vehicle plumbing, controls, software, and instrumentation as closely as possible to the intended operation at NASA Plum Brook. Additionally, this was the inaugural test series of a newly fabricated main engine injector and the first opportunity to test the MPG system under rocket engine vibration loads/noise. These tests were conducted on the JSC on-site antenna range where previous Project Morpheus and Cold Helium ICPTA hot-fire testing was conducted from 2011-2015 (Ref.'s 5, 8). The vehicle was suspended from a crane in a static position over a flame trench, allowing main engine hot-fire durations up to ~5 seconds.

The vehicle-level tests included the Plum Brook configuration avionics using the ICPTA controller (APU) and the ~50 ft vacuum feedthrough connector. Additionally, vehicle-to-ground interfaces were built to mimic the Plum Brook facility where practical. For the JSC testing, the APU was powered by JSC-provided 16 and 32 vdc power supplies powered by a gasoline generator whereas the APU was powered by facility 16 and 32 vdc power supplies at Plum Brook.

Generally, the sea level checkout hot-fire testing successfully met the test objectives. Some COP development issues were identified and corrected (Ref. 12), and the testing activity itself was an effective forcing function to improve procedures, training, and team dynamics prior to the test campaign at NASA Plum Brook.

The team performed 88 RCS tests and 9 main engine tests (some integrated with the RCS) over the course of 6 test days. Sea level checkout testing not only verified the function of the vehicle prior to the Plum Brook test campaign, but also provided a reference data set to help bridge the analysis gap between previous sea-level LOX/Methane test programs and the altitude and thermal vacuum testing of this program.

Figure 3. System checkout hot-fire test of the ICPTA at NASA Johnson Space Center

In addition to system verification, component level qualification and acceptance testing was performed on certain hardware prior to installation on the ICPTA. For example, the RCS engines and main engine igniter were hot-fire tested individually in a small vacuum chamber at the JSC Energy Systems Test Area to demonstrate acceptable performance of the new COP ignition devices.

III. ICPTA Test Campaign at Plum Brook Overview

Integrated testing of the ICPTA and Plum Brook facility began following a series of ICPTA and facility functional checkouts, leak checks, procedure walkthroughs, cryo-shock leak tests, and a wet run with LOX and LN2 loading. Hot-fire testing began on Feb 3, 2017 and continued through March 9, 2017. Table 1 outlines the operational test days, their primary objectives, and some major results summaries.

Table 1: Operational Test Day History of ICPTA at Plum Brook ISP

Date	Test Operation	Test Cell Conditions	Major Results
Nov. 16 - Dec. 6, 2016	Sea-level Wet-Run and Hot-Fire	n/a	RCS and Main Engine Sea-level hot-fire tests complete at JSC
Dec. 16, 2016	n/a	n/a	ICPTA structural installation complete at Plum Brook
Jan. 9, 2017	Cryo-Shock leak test	Ambient pressure and temp.	LCH4 system loaded with LN2
Jan. 13, 2017	Cryo-Shock leak test	Ambient pressure and temp.	LOX system loaded with LN2
Jan. 27, 2017	Dry Run, Vacuum checkout	Simulated Altitude, Ambient Temp	Vacuum checkout with dry ICPTA in test cell
Jan. 31, 2017	Wet Run	Simulated Altitude Ambient Temp	LOX loaded, LN2 loaded in LCH4 system
Feb. 3, 2017	Hot-Fire Day 1	Simulated Altitude, Ambient Temp	RCS and Main Engine testing
Feb. 14, 2017	Hot-Fire Day 2	Simulated Altitude, Ambient Temp	RCS and Main Engine testing
Feb. 17, 2017	Hot-Fire Day 3	Simulated Altitude, Ambient Temp	RCS testing only. Main engine not tested due to valve leaks.
Feb. 21-23, 2017	~30 hr Thermal-Vacuum checkout	Cold-Thermal Vacuum	Facility-only test with dry ICTPA in test cell
Feb. 28, 2018	Hot-Fire Day 4	Simulated Altitude, Ambient Temp	RCS and Main Engine testing
Mar. 2, 2017	Hot-Fire Day 5	Simulated Altitude, Ambient Temp	RCS and Main Engine testing
Mar. 7-8, 2017	~40 hr Thermal-Cold Soak	Cold-Thermal Vacuum	LOX and LCH4 loaded
Mar. 9, 2017	Hot-Fire Day 6	Cold-Thermal Vacuum	RCS testing only. Main engine not tested due to ICPTA valve leaks
Mar. 10, 2017	LCH4 tanking test / CFM experiment	Simulated Altitude, Ambient Temp	Transfer line data recorded on JSC-CRIO

The bulk of vehicle testing was conducted under ambient temperature conditions and test cell pressures of ~30 Torr, which was the typical lowest pressure attainable of the combined test cell plus spray chamber volume – as limited by the vapor pressure of the cooling water in the spray chamber and underground spray chamber leakage. At these conditions, dozens of RCS test sequences were conducted, adding up to nearly 1,000 engine pulses. These tests included a range of minimum impulse bit (MIB) pulsing sequences with low duty cycle, analogous to a coast phase in which the RCS is primarily used for station keeping. Higher duty cycle pulsing tests were also performed, analogous to an ascent or landing mission phase (Fig 8). Lastly, tests with longer pulses and multiple engines firing either in series or simultaneously were performed to gather transient system response data.

Additionally, specific tests were performed to demonstrate the potential for the RCS engines to self-condition their propellant through nominal operation, especially under warm conditions. Numerous thermocouples on each leg of the RCS system provided real-time indications of the state of propellant in the system. Surface thermocouples at three locations in each leg of the RCS manifold and submerged thermocouples at the thruster valve inlets indicated the propellant temperatures at those locations, with real-time plots indicating gaseous, two-phase, or subcooled propellants. Various tests were run with different duty cycles/pressures/etc to stress the system’s ability to self-condition.

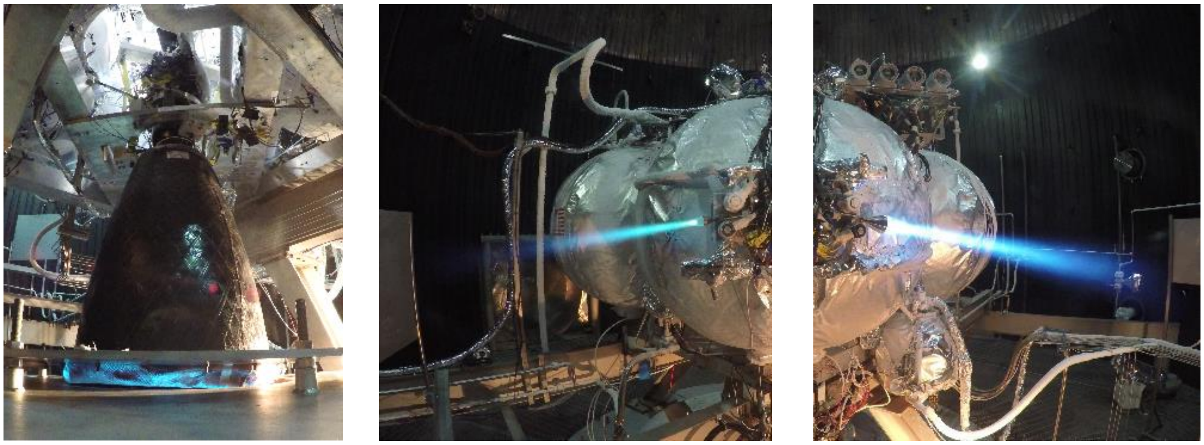


Figure 8. ICPTA Standalone Engine Tests: 2800 lbf-vac main engine with nozzle boot (Left), 7 lbf-vac RCE (middle), and 28 lbf-vac RCE (right).

Main engine standalone testing occurred at these conditions and included igniter-only tests, very short duration ignition-only tests, and mainstage full-thrust tests from 1 to 56 seconds in duration (Fig 8). Integrated tests were also performed to demonstrate simultaneous main engine and RCS operation (Fig. 1).

The final series of tests were performed with the test cell cold wall active, flooded with liquid nitrogen. The vehicle was first loaded with propellants and then exposed to the deep cold soak for more than ~40 hours. The average test cell temperature was ~-305°F during this cold soak, and pressures began at around 0.02 Torr but rose to ~ 6 Torr by the time RCS testing began. Vacuum system performance was limited by facility ejector capacity, test cell and ICPTA leakage. By the start of testing, RCE jet body temperatures, including the COP, reached ~-200°F to -225°F. The RCE jet body temperatures dropped below -300°F in some cases as the RCS was conditioned for hot-fire.

Several "quenched lights" occurred on the RCE under the extreme cold thermal conditions that were successful with warmer thruster body temperatures. In these cases, the propellant conditions upstream of the thruster valves were in-family with previous successful ignitions performed on the thrusters but the thruster body temperatures were much colder. A facility camera on one engine revealed that the core of that RCE injector flow lit during all of these ignition attempts, but the main flow of the RCE did not light and passed through the nozzle unburned, obscuring the view of the core combustion. It is unclear from imagery or RCE temperature/pressure sensors whether the core flow was extinguished by the surrounding flow or continued to burn despite the unburned propellant flowing around it and out the nozzle. A similar camera view was not available for the other two engines that were operated in these conditions, so is not known if this same phenomenon was occurring for every no-light.

Two successful RCE ignition pulses at cold thermal conditions were demonstrated after a gaseous nitrogen purge flow was introduced to warm the jet bodies to approximately -160°F before the ignition attempt (Fig 9b). One RCE coil mechanically failed during these cold thermal conditions due to inadequate plastic-to-metal bonding of the coil body housing (Ref. 12). Further RCS hot-fire testing was not attempted within the test campaign time remaining. The main engine was not tested under the cold thermal conditions due to other system leakage on the ICPTA.

a. **b.**

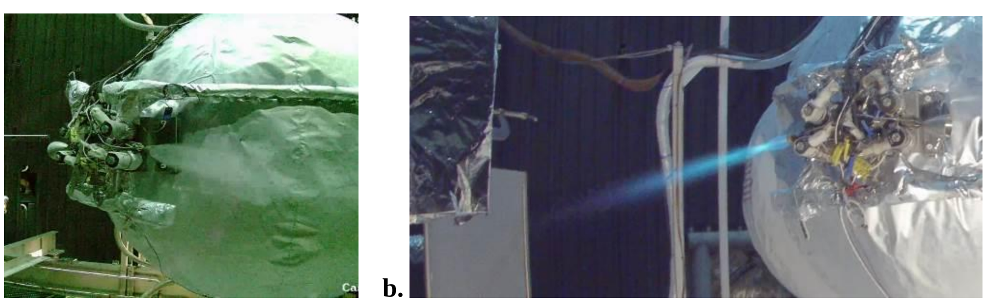


Figure 9. Cold Thermal Wall Test Imagery of ICPTA RCS testing. a) No-light cold-flow (quenched flow) at cold temperature extremes. b) Successful jet hot-fire after warm gaseous nitrogen purge flow.

In addition to the prime test events, numerous minor system tests were scattered across the 6 weeks of integrated testing. For example: each propellant loading event provided the opportunity to perform another priming test of the RCS propellant manifolds, simulating post-launch priming. Numerous ambient temperature priming tests were performed with propellant tank pressures from 50 to 250 psi. Thrust termination system valves remained closed during propellant loading for each test (maintaining the main engine and RCS manifolds dry and at ambient pressure and at test cell temperature), and were opened midway through tank pressurization, thereby providing a range of oxygen and methane water-hammer data at different driving pressures.

IV.Detailed Subsystem Design and Test Results

A. Reaction Control System

The ICPTA reaction control system is composed of two 28 lbf and two 7 lbf reaction control engines (RCEs). The RCEs utilize a coil-on-plug (COP) ignition system designed for operation in a vacuum environment, eliminating corona discharge issues associated with a high voltage lead. There are two RCE pods on the ICPTA, with two engines in each pod. One of these two engines is a heritage flight engine from Project Morpheus. Its sea level nozzle was removed and replaced by an 85:1 nozzle of machined Inconel 718, resulting in a maximum thrust of 28 lbf under altitude conditions. The other engine is a scaled down version of the 28 lbf engine, designed to match the core and overall mixture ratios as well as other injector characteristics. This engine produces a maximum thrust of 7 lbf with an 85:1 nozzle that was additively manufactured using Inconel 718. The 7 lbf thrust level was chosen because it is a more reasonable thrust level for a spacecraft (and propellant manifolds) of this size. Both engines are film-cooled and capable of limited duration gas-gas and gas-liquid operation, as well as steady-state liquid-liquid operation. Each pod contains one engine of each version, such that two engines of the same thrust level can be fired as a couple on opposite pods. The RCS feed system is composed of symmetrical 3/8 inch lines that tap off of the main propellant manifold to send LOX and LCH4 outboard to the RCS pods (Fig 10).

A Thermodynamic Vent System (TVS) is used to condition propellants at each pod by venting small amounts of propellant through an orifice at the end of the feedline and then venting the cold expansion products overboard through tubing that is welded to the main RCS feedline along the majority of its length, thereby removing heat from the incoming propellants. A single TVS system was used to condition both RCS pods and although trimmed individually, a slight imbalance was observed between the pods potentially resulting in some of the observed no-lights.

The RCEs in each pod are mounted to plates connected to the tank wall via click bond struts. Since the RCEs are mounted on the periphery of the tank, exposed to the cold test cell wall with without heaters or insulation, the bodies of the thrusters were very cold following the deep thermal vacuum conditioning, likely at lower temperatures than a typical RCE would experience in a spacecraft application.

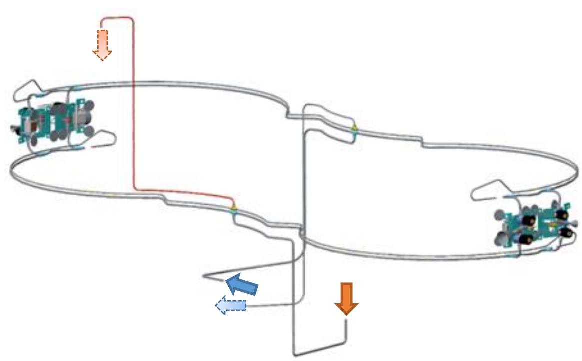


Figure 10: ICPTA RCS propellant manifolds, with inlets and TVS outlets indicated

Major RCS test objectives for Plum Brook were focused on system dynamics, and included characterization of fluid transients, manifold priming, manifold thermal conditioning, Thermodynamic Vent System (TVS) performance, and main engine/RCS interaction.

Data was collected for 40 different RCS tests across the 6 test days, consisting of 1,010 individual thruster pulses. Of these pulses, 987 were performed at ambient test cell temperatures with 961 ignitions and 23 were performed at deep cryogenic test cell temperatures with 2 ignitions. The engines experienced significant ignition problems during testing under extreme cold thermal conditions. Successful ignition was demonstrated only after warming the thruster bodies with a gaseous nitrogen purge to an intermediate temperature. The root cause of the no-lights/quenched-lights in the cold thermal conditions is under review; potential causes include low spark energy for the local conditions, inadequate propellant vaporization due to the low temperature (a propellant ice ball was observed exiting the nozzle of one thruster following a no-light), poor mixture ratio control, etc.

Peak surge pressures from valve opening and closing events were examined. It was determined that the observed pressure levels were a function not only of the injector manifold volume between the valve poppet and injector orifices but also by a vapor cavity of unknown volume upstream of the RCE propellant valves caused by local propellant vaporization during ambient temperature testing. In most cases, the valve opening transient was more severe than the valve closing. Peaks that resulted from valve closing after steady engine operation agreed well with analytical predictions, but peaks that followed valve *opening* were typically much higher with amplitudes as high as 600 psid during ambient-thermal testing. In all cases, system transients were more severe during thermal vacuum testing, with results comparable to a hard-fluid system with no propellant vapor to dampen transients.

Under thermal vacuum conditions, TVS operation was unnecessary to maintain liquid conditions at the thruster inlets. However, under higher heat leak environments, it was demonstrated that the RCS could be operated either in a TVS active mode to force liquid propellants to the engine inlets without engine interaction or in a self-conditioning mode utilizing the RCE hot-fire operation to draw propellants from the tanks without overboard TVS venting. In a flight application, the self-conditioning mode would require a wide engine inlet condition operating box and a GNC system capable of managing a changing MIB. Additionally, a TVS system may still be desired for contingency operation or preparation for a known dynamic event.

Lastly, simultaneous RCS and main engine hot-fire testing was performed to determine any integrated impacts. No notable performance impacts were observed on either the RCEs or Main Engine, although RCE shutdown transients caused ~4psid oscillations at the main engine inlets during ambient temperature testing and up to ~10psid during cryogenic temperature environment testing.

A detailed discussion on the RCS design, operation, and test results may be found in Ref [13].

B. Propellant tanks and Feed System Thermal Performance

A primary objective of the testing in the thermal vacuum chamber is to obtain thermal performance data on an insulation system designed to be capable for use in space and also for ground use in humid ambient environments. The insulation system was design to provide a low enough heat leak to allow a vehicle sized similarly to the ICPTA to complete transit to the moon in 4 days without boil-off and without exceeding required tank propellant conditions for the engine. In addition to the cold-thermal conditions, the ambient-temperature boil-off data provides useful information of ground loading of a LOX/LCH4 spacecraft.

The ICPTA consisted of four spherical 48-inch propellant tanks manufactured from 5083 aluminum with an MAWP of 325 psia and each capable of storing 250 gallons of propellant. The ICPTA propellant tanks and propellant manifold lines were insulated with a hybrid aerogel/multi-layer insulation scheme providing insulation for both sea-level and vacuum operation. This included an aluminized cover, 9 layers of 1 mil polyester Polyethylene Terephthalate (PET) film perforated with a 0.125-inch hole diameter (0.08% area) with two layers of RFB4A polyester B4A netting separating each layer of PET film, and a 6 mm layer of Pyrogel XT consisting of a quartz fiber infused with aerogel (faced with aluminum foil), as shown in Fig. 11. The Gentex 1299-074 Fiberglass Dual Mirror Aluminized cover provided a fire resistant and radiant outer cover and created a volume that could be purged with gaseous nitrogen (GN2) to keep moisture out. This allowed use in a humid ambient environment (e.g., for sea-level testing at JSC), but also provided some advantages for use in the vacuum chamber since spray chamber cooling water condensed and in some cases impinged on the tanks during many of the test days. Lastly, the aerogel provides reduced heat leak at higher pressures when the multilayer insulation (MLI) is not effective.

Figure 11. Installation sequence of propellant tank insulation

Table 2. Predicted Heat Leaks for the Each Propellant Tank at 5x10-6 Torr and 298K boundary condition

Element	Heat Leak Per Tank	
	LO2	CH4
Tank Insulation	14.9 W	14.2 W
Structure	12.3 W	11.0 W
Propellant Lines	11.3 W	10.0 W
Total	38.5 W	35.2 W

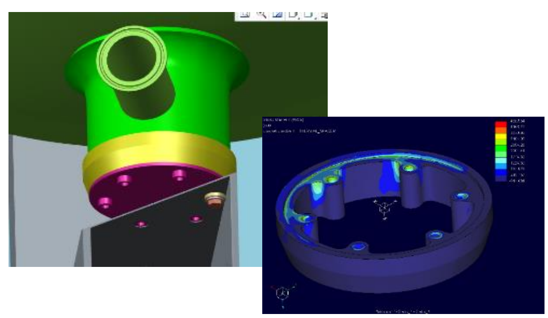


Figure 12. Propellant tank hollow thermal spacer

The tanks were supported by a G10 fiberglass thermal isolator on the bottom and two lateral steel struts at the top of the tanks. The heat leak through these are estimated to total 15 watts at ambient 298K boundary conditions. The propellants lines also contribute heat leak to the tank. A predicted performance of the complete system at high vacuum (5x10-6 Torr) is shown in Table 2.

The main feed system was insulated with the same approach and layering of the aerogel, purge tubing, MLI, and Gentex 1299-074 Fiberglass Dual Mirror Aluminized cover (shown in Fig. 13). The RCS lines had a similar insulation system but included a thermodynamic vent system (TVS) consisting of an orifice near the thrusters connected to return-line tubing welded to the RCS 3/8-inch lines from the RCS pod back to the main propellant manifold tap-off. The vented propellant expanded in the return line thereby providing more efficient cooling of the RCS lines. Cycling of the TVS valve at the end of the vent tubing controlled the temperature and thus propellant quality and level of sub-cooling in the RCS lines to the desired test conditions for the RCS engines.

a) b)

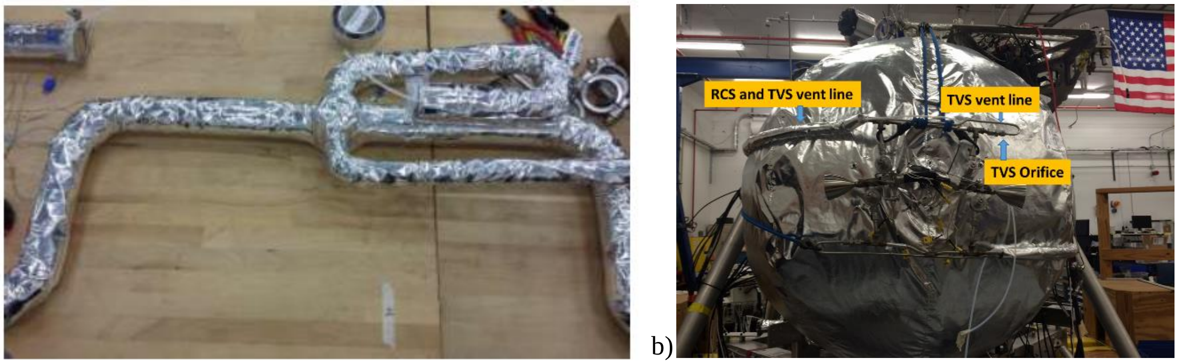


Figure 13. a) Main oxygen feedline, B) RCS lines wrapped around tank

Two cryogenic thermal vacuum cycles were performed on the ICPTA during this test campaign, with and without propellants onboard. The data set with propellants onboard is the prime resource for vehicle thermal response modeling activities, which include the vehicle tanks, propellant feedlines, vehicle structure, and test cell structure/thermal wall. This thermal vacuum test occurred over ~60 hours and included ~40 hours with the thermal wall active. Propellants were loaded prior to cold wall activation and offloaded during cold wall warm-up. The ICPTA response to this environment is shown in Figure 14. Note that the cold wall surrounds the sides and top of the vehicle, but the ICPTA was smaller in diameter than the primary 11-foot nozzle duct so the floor of the cold wall did not extend under the vehicle.

Tank boil-off rates and the thermal performance of the liquid oxygen tanks are shown in Table 3 for tests done outdoors at NASA KSC and JSC and at Plum Brook in the vacuum chamber (MLI was not installed for the outdoors tests but would not have provided significant insulation in that environment). Oxygen boil-off rates were calculated from the vehicle weight load cell readings during a quiescent period after the LOX tanks were filled. Tank heat leaks were then calculated from the boil-off rates and include tank struts and propellant lines. The oxygen tank heat leak significantly decreases at lower chamber pressures and during cold-thermal vacuum testing when the wall is at -305°F. The total boil-off from all four tanks decreases by a factor of approximately 2.5 between the no cold wall and cold wall case for Hot-Fire 6 (HF6).

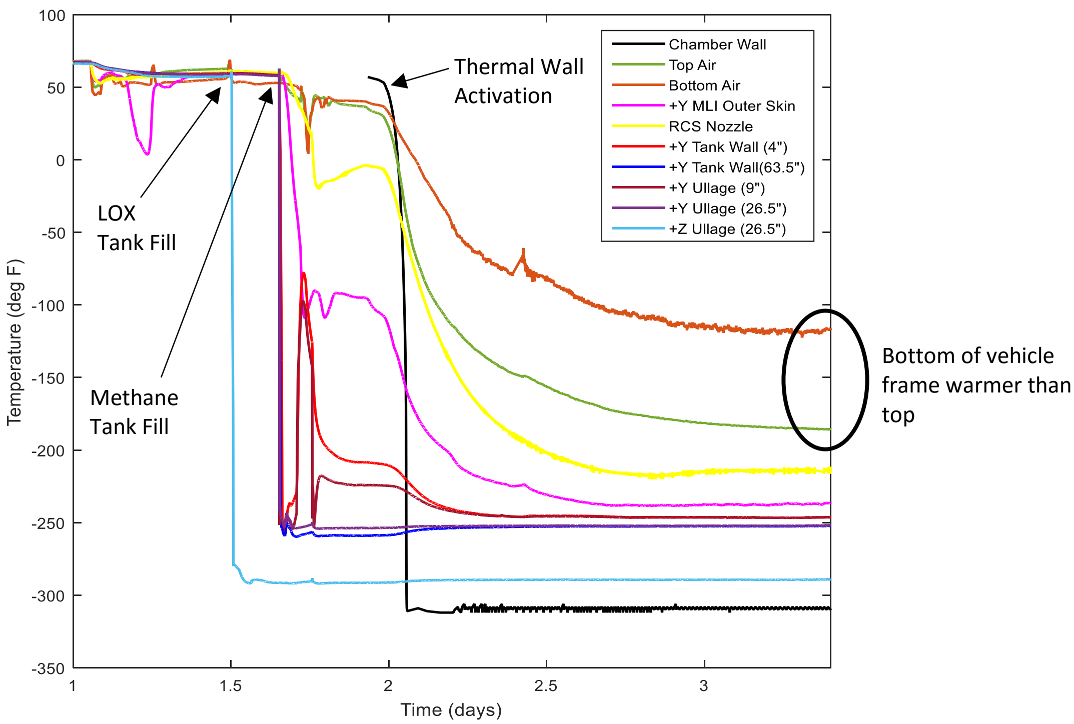


Figure 14. ICPTA thermal response to Plum Brook facility cold wall activation

Table 3. ICPTA Propellant Tank Heat Leak Rate Comparison for Plum Brook Tests and Sea-level Tests at JSC and KSC.

Test Location	Test	Conditions	LOX Boiloff after LOX Fill (lb/min)	Heat Leak per LOX tank (W)	Heat Leak per LOX tank (W/m^2)	Total Boiloff after LOX and LCH4 Fill (lb/min)
KSC	FF6	ambient, outdoors	-2.8	-2270	-485	**-5**
JSC	Cold Helium	ambient, outdoors	-1.9	-1540	-329	
Plumbrook	HF2	30 torr, no cold wall	-1.3	-1054	-225	-2.25
Plumbrook	HF3	35 torr, no cold wall	-0.9	-730	-156	-1.3
Plumbrook	HF4	35 torr, no cold wall	-0.7	-567	-121	-1.95
Plumbrook	HF5	30 torr, no cold wall	-0.85	-689	-147	-1.9
Plumbrook	HF6	0.2 torr, no cold wall	**-0.25**	-203	-43	-0.6
Plumbrook	HF6	0.3 torr, cold wall (-305 F)	**-0.15**	-122	-26	-0.25
	*In Red are estimated values					

Table 3 also shows that the thermal performance of the insulation system was never tested in a high vacuum such as 1×10^{-6} Torr. The measured heat leak values from Table 3 are plotted against a modified Lockheed-Martin (LM) MLI performance equation[14] (modified to account for interstitial pressure) from ambient to 1×10^{-6} Torr to determine if the measured data fits the predicted values for the insulation and to extrapolate to space flight conditions. Note that this equation does not account for the aerogel insulation layer. As shown in Fig. 15, the measured ICPTA heat leak performed much better than predicted at higher ambient pressures. This points to the benefit of having aerogel insulation at higher ambient pressures.

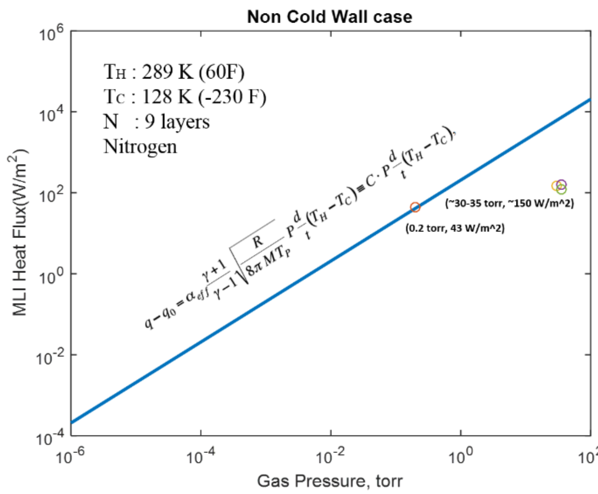


Figure 15. Performance Prediction for ICPTA MLI compared to measured ICPTA heat flux, demonstrating benefit of aerogel insulation at higher ambient pressures.

The RCS oxygen feed system heat leak is estimated by the observed temperature rise in the RCS manifold lines between cycles of the TVS valves. A representative segment of RCS tubing that has a constant insulation cross section and the same view factor to the external environment is selected. A skin temperature sensor at the center of this section gives the temperature rate. That rate is used along with the thermal mass of the section to estimate the approximate heat leak. These values are shown for representative ambient and cold soak test segments in Table 4.

Table 4. Heat Leak in the RCS Oxygen Manifold During Ambient and Cold-Thermal Testing

Test Conditions	Local Heat Leak (over 35” of line section)	Local Heat Flux	Estimated Total Heat Leak
Ambient	11 W	366 W/m^2	123 W
Cold Soak	1.4 W	46 W/m^2	15 W

An estimate for total heat leak can be made if this heat leak is extrapolated to apply to the entire RCS. This translates to approximately 123 watts for the entire oxygen manifold during ambient testing and approximately 15 watts during cold soak testing. If all of this heat leak energy is used to vaporize the oxygen, then that would amount to 5.4 lbm/hr for the ambient case and 0.6 lbm/hr for the cold soak case.

Previously, a similarly sized RCS feed system was tested in a thermal vacuum chamber using thruster flow simulators with LN2 as the fluid (Ref. 15,16) Tests were conducted across pressures ranging from 1×10^{-2} Torr to 1×10^{-4} Torr with ambient walls, and the TVS controlled to a temperature band of 190 ºR to 200 ºR. Approximately 0.85 lbm/hr of propellant consumption was required to maintain this set point at a test pressure of 2×10^{-3} Torr. At a lower test pressure of 2×10^{-4} Torr, 0.35 lbm/hr was required.

Overall, this test data and analysis suggests that meeting the required heat leak is achievable for a zero-boil off LOX/LCH4 lander for a lunar mission with minimal amount of insulation at $1x10^{-6}$ Torr space vacuum levels. Future analysis of the test data will attempt to refine the split between tank supports, fluid line penetrations, and the tank surface insulation. The tank wall and ullage stratification temperatures recorded should allow for a three-dimensional modeling of the system.

C. Modal Propellant Mass Gauging System

A new type of propellant mass gauging system was included in this test campaign, taking advantage of the ICTPA configuration and test environment. The modal propellant mass gauging system is non-intrusive, utilizing piezoelectric patch sensors affixed to the exterior of fluid tanks. This system monitors the modal response of the tank to a white noise stimulation to interpret propellant mass inside the tank and can be used with or without a gravity field[17].

The Propellant Mass Gauging (MPG) technology is based on the characteristic frequencies of vibration which are unique to any object depending on its mass stiffness and geometry. These characteristic frequencies may be excited by applying a consistent range of frequencies (i.e., white noise) and collecting responses. Changes in stiffness and mass can be detected by comparison to a baseline. By applying the same excitation and maintaining the same stiffness, the frequencies will change only due to the mass changes thus allowing the mass of fluids in tanks to be detected with a non-invasive and accurate method. This method may also be used in zero-gravity as the fluid ullage typically settles to the central of the tank volume middle with the fluid mass on the inner walls (in the settled condition). The basic equation is represented by Eqn. 1.

$$\text{Frequency} = \sqrt{\frac{K}{M}} \tag{1}$$

Where K is the system stiffness which is affected by the type, geometry, temperature of the material, and external stress such as pressure. Changes in stiffness, which may be also be caused by a structural defect, causes a corresponding change in frequency thus allowing detection. M is the modal mass of the system. In the case of MPG, the varying fluid mass changes the frequency.

In this experiment, multiple identical lead zirconate titanate (PZT) piezoelectric patch devices were bonded to the external surface of the metal propellant LOX tanks. One of these devices acts as an actuator and the others act as sensors. Broadband white noise was introduced to the tank through the actuator and this input signal was measured with one "monitor" sensor placed adjacent. The Frequency Response Function (FRF) is computed from the Fast Fourier Transforms (FFTs) that are derived from the monitor signals and from sensors placed in other locations on the tank. By dividing the FFT responses from pairs of sensors only the differences are measured by these FRF's, which simplifies the modes and lowers noise by cancellation, thus allowing much greater detection of only the wanted responses (Fig. 16a). The resulting peak frequencies may then be translated into fluid mass through Eqn 1.

For the ICPTA, the non-intrusive propellant mass gauging system utilizes piezoelectric patch sensors with high sensitivity to strain whose flexibility and thin profile enables them to be affixed to the exterior of the two spherical

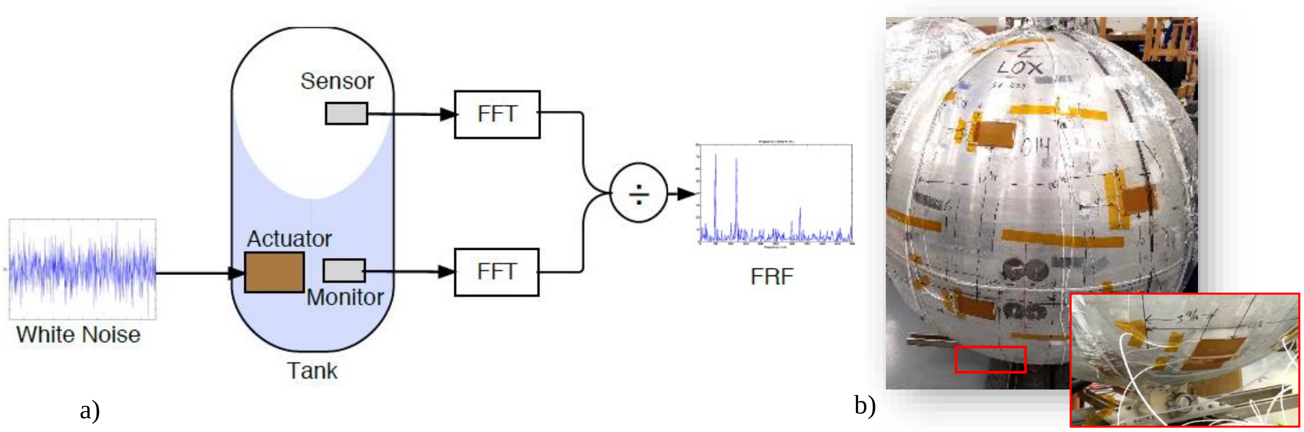


Figure 16: a) Schematic of Modal Propellant Mass Gauging system, b) PZT sensors installed on the –Z LOX tank including the monitor/actuator (top/bottom) pair (inset image)

liquid oxygen tanks (Fig. 16b). These patches are bonded to the metal surface using a two-part cryogenic adhesive, with the insulation applied over the sensors. By applying a random voltage (useful frequency ranges 10-3,000 Hz for example) through an amplifier, typically 175-200 volts is applied to one of the sensors (called an actuator) which responds and consistently stimulates the tank/fluid system modes. For the ICPTA, one actuator and four response PZT sensors were used for each on the LOX tanks. The data system monitors the modal response of the tank to piezoelectric sensor stimulation or engine-induced broad spectrum noise to interpret propellant mass inside the tank. This was the first test of the technology on a vehicle during hot fire testing and demonstrated that the MPG can measure propellant mass during an engine firing. During the 30 second hot-fire, as an example, the engine vibration added 40-50% to the output of the MPG actuator level but most of that energy was below 300 HZ which did not interfere with the MPG data which was typically at higher frequencies. Frequency shifts due to propellant mass consumption were clearly visible.

Shown below in Fig. 17 are FRF plots showing Frequency changes detected during the 30 second Hot-fire for both LOX tanks (blue lines for tank 101 and red lines for tank 102) with the same 7.8 Hz delta. This is the expected result since the tanks are changing fluid mass at the same rate as they drain in parallel. Based on other LOX Drain data, the sensitivity of a 1 HZ frequency shift is about ~10 lbs. of fluid mass. In addition, the test data also showed that the sensor responds to the fluid level directly, similar to a point sensor that is external to the tank, which has some significant advantages. In this case, the raw sensor output decreased ~linearly as the ullage/fluid interface passed by the 2-inch tall sensor.

The ICPTA testing at JSC and Plum Brook provided much data showing the effectiveness of the NASA MPG technology. This data obtained during main engine firing in the test chamber low pressure environment is unique and valuable for future applications on the Orion service module. Further MPG testing is planned for 2017 and 2018 on propellants tanks more representative of the Orion Service Module Main Engine Testing

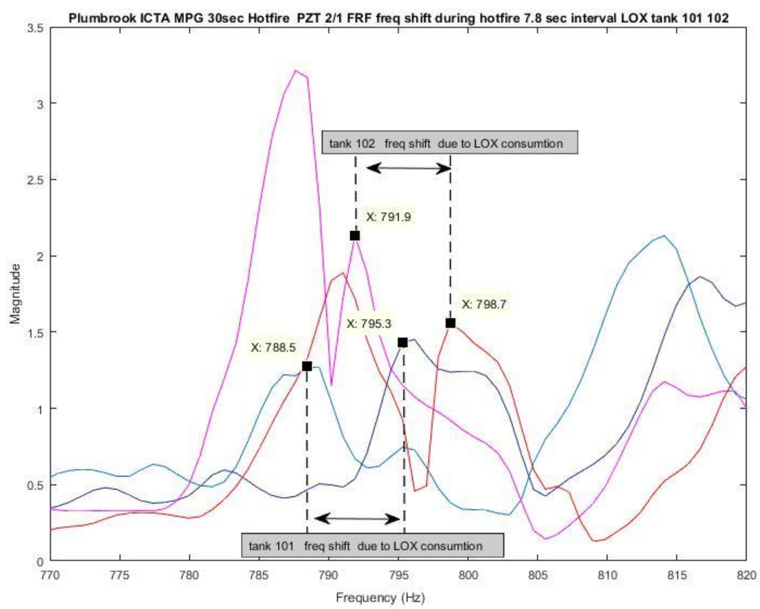


Figure 17. FRF plots showing Frequency changes detected during the 30 second Hot-fire for both the LOX tanks

D. Main Engine Testing

The ICPTA main engine produces 2,800 lbf (vac) max thrust and is centrally mounted in a thrust measurement system (TMS) that is attached to the vehicle lower frame. This engine was developed at JSC in 2014 as workhorse engine for basic LOX/Methane propulsion systems. The engine utilizes an impinging element injector, 15 L-shaped quarter wave acoustic cavities, a spark torch igniter plumbed off the main propellant feedlines, and a carbon composite overwrapped ablative thrust chamber/nozzle assembly (TCA) with nozzle mounted heat exchanger (HEX). Two combustion chambers were produced for this test series, a two-part TCA with detachable nozzle extension and metallic flange mount for the helium HEX at the AR=10 position, and a single part TCA with an embedded HEX at AR=10. Only the two-part TCA (Fig 18) was tested during this test series due to schedule.

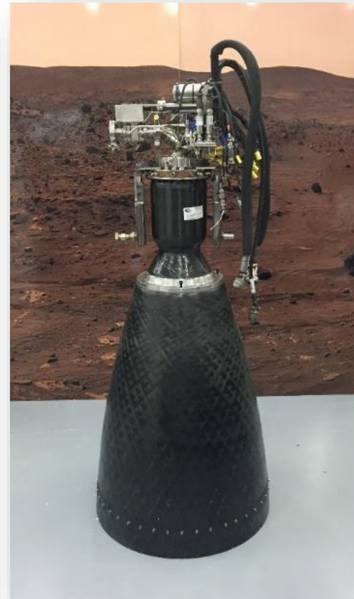


Figure 18: 2,800 lbf thrust JSC2kb-Vac Engine

The TMS utilizes three evenly-spaced load cells in tension and includes an in-place calibration system for use before and after each hot-fire test. An alternate thrust measurement was obtained from the real-time ICPTA weight measurement provided by the four vehicle/facility interface load cells.

The main engine was developed after the completion of Project Morpheus and the main engine described in Ref. 7. The ICPTA main engine was an evolution of the impinging element design, with major injector changes focused on improved performance by using an ablative chamber with reduced film cooling (note that Project Morpheus main engine was metal-chamber with broad film cooling). The acoustic cavity approach was also redesigned to correct combustion instabilities observed in Ref. 7. The 2,800 lbf-vac engine was designed, developed, and fabricated at JSC. Stand-alone engine testing was conducted at SSC, and integrated vehicle test demonstrated were conducted as part of the JSC cold-helium pressurization experiment in 2015, detailed in Ref. 8. The engine has demonstrated >5:1 throttling using a linear-actuator ball-valve throttle mechanism.

Main Engine testing involved 4 igniter-only tests, 4 short duration ignition tests, and 9 mainstage hot-fire tests over a range of throttle levels from 1 to 56 seconds in duration. Two injectors were tested during the campaign. The initial injector suffered an injector overheating event during a 27 sec test requiring replacement with a lower performing backup injector. This overheating event was not traced to a facility or test environment cause.

Notably, neither injectors showed indications of combustion instability across the entire test campaign, either in sea-level testing at SSC and JSC, or altitude testing Plum Brook. An analog high speed redline system was installed on the main engine for protection from instabilities if they were to occur and consists of two piezoelectric dynamic pressure sensors, a standalone integrator circuit, and the ICPTA flight computer which monitors the circuit output. The system is capable of initiating a shutdown within 40 ms of the onset of instability. Near the end of the test campaign, degradation of the high speed sensors caused excessive noise on the system and to avoid false positives the redline was eventually turned off since no indications of instability had been observed on this engine.

The vehicle propellant manifolds were primed with subcooled propellants up to the last few feet of plumbing near the main engine inlet during pre-ignition preparations. In some cases, the propellant near the inlets warmed to the saturation prior to ignition; in other cases, the propellant was subcooled up to the engine inlets at the time of ignition. The manifold and inlets were cooled using an overboard bleed system which drew propellant from the main engine ball valves located at the inlets and then routed the bleed flow back to the facility vent system. An injector chill system was not included on this engine (unlike the Project Morpheus main engine), thus the injector body temperatures were relatively warm compared to the engine inlets.

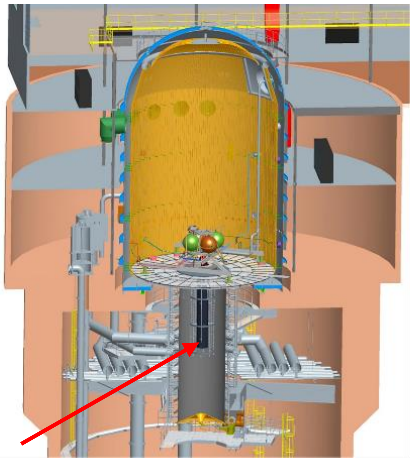


Figure 19: CAD Model of the 32-inch nozzle diffuser (installed in the 11-foot diffuser), located between the test cell and spray chamber

The main engine portion of the test campaign was the primary interest of the Plum Brook facility team. Since the facility steam ejectors were not operational, the facility was operated in “accumulator mode”, which used the main engine exhaust to provide physical (if temporary) separation between the atmospheres of the two chambers. The auxiliary ejector system could pull ~0.1 lb/sec from the combined test cell/spray chamber volume, however this was nearly two orders of magnitude less than operational ICPTA main engine mass flow rate. The accumulator mode of operation was accomplished using a 30 ft long by 32-inch diameter main engine nozzle diffuser duct which hermetically isolated the upper test cell and lower spray chamber (Fig 19). This 32-inch duct was placed inside an 11-foot diameter diffuser duct, still in place from previous large engine test programs. The 32-inch duct was backside-cooled with dozens of water nozzles and also contained numerous thermocouples and pressure sensors to measure plume-duct interaction and cooling performance for model validation.

The main engine nozzle exhaust traveled down the duct into the spray chamber during engine operation, forming a standing wave in the duct. This isolated all exhaust products to the spray chamber while also actively reducing test cell pressure. A differential pressure between the spray chamber and test cell up to ~2.5 psia could theoretically be achieved with this method before that pressure differential would overwhelm the diffuser performance resulting in a diffuser unstart and forced repressurization of the test cell (while the main engine was running). The highest differential pressure achieved during this test campaign was ~1.2 psia during the longest 56 second hot-fire, which was a lower delta-pressure than predictions.

The spray chamber contains a grid of spray bars near the ceiling capable of flowing 250,000 gallons per minute of water as rain pumped up from the spray chamber floor located ~150’ below ground level. This torrential rain comingles with the main engine exhaust entering the spray chamber through the diffuser, cooling the exhaust and condensing a large fraction of the exhaust into liquid water, thereby reducing the volume and pressure of gas trapped in the spray chamber. This system was more effective than anticipated, resulting in longer allowable main engine run times than predicted. A downside of this mechanism, however, is the concentration of non-condensable exhaust products (such as methane) in the spray chamber.

Two different ICPTA nozzle/test cell configurations were tested during the test campaign, an elevated position with the nozzle exit plane ~3 inches above the chamber floor, and a lowered position with the nozzle submerged into the duct by ~3 inches as shown in Fig 20a&b. The elevated position provided optical access to the nozzle plume for high speed plume imagery but resulted in a very high test cell repressurization rate. At the end of each main engine hot-fire event, the remaining gas in the spray chamber immediately repressurized the test cell via reverse flow up the diffuser duct, impinging on the nozzle of the main engine. For tests longer than a few seconds, the spray chamber/test cell differential pressure was high enough that the repressurization flow reached sonic speeds with the choke point at the radial nozzle/duct interface. No nozzle damage was observed due this flow, however the spray chamber gas carried significant quantities of cooling water with it which drenched the nozzle and ICPTA after hot-fire tests when the ICPTA/nozzle was in the elevated position.

To reduce the repressurization flowrate, the ICPTA was operated in the lowered position and a fabric “boot” was attached to both the main engine nozzle and an aluminum disk near the test cell floor thereby creating a flexible barrier that directed the spray repressurization flow away from the ICPTA and into a 360° open area near the floor of the test cell (Figure 20b), protecting the nozzle and vehicle from the repressurization flow. The nozzle-side attachment mechanism was a series of “T” nuts woven into the carbon composite overwrap ~4 inches upstream of the nozzle exit plane. On the facility side, the fabric was bolted to the aluminum disk. The fabric and disk created a much smaller radial choke point between the disk and the test cell floor (perpendicular to the diffuser axis) resulting in much slower test cell repressurizations and far less spray chamber cooling water being drawn up the diffuser. The water that did enter the test cell in this configuration was sprayed away from the vehicle.

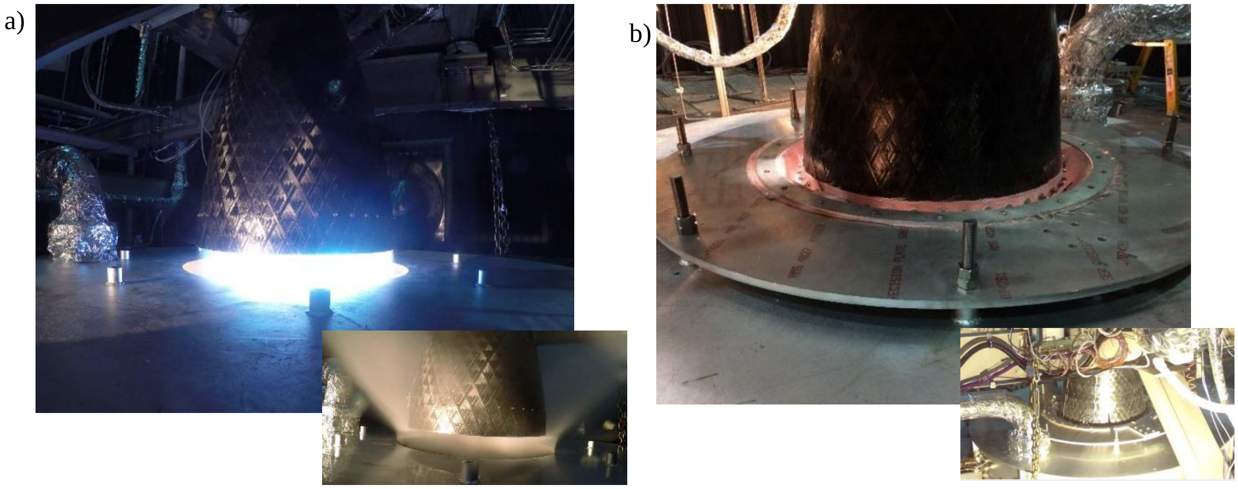


Figure 20. Main engine duct interface conditions tested: a) "elevated" for high-speed plume imagery, b) "submerged" and "booted" for optimized run-time and "blow-back" prevention. Inset images show (a) the dynamic test cell repressurization without the boot, and (b) the gradual repressurization with the boot

It should be noted that although the ICPTA avoided direct spray water impingement with the boot, the resulting spray chamber environment was humid enough to become foggy after certain tests and condensed heavily on the cold vehicle. In all cases the vehicle was quite wet following main engine hot-fire testing. Tests were performed with and without the boot to determine the effects on test articles. It was determined that testing longer than a 2 seconds would result in spraying the vehicle with cooling water if the boot was not installed (Figure 20a). A tri-axial accelerometer located at the tip of the nozzle indicated a ~20% reduction in vibration during mainstage and post-shutdown blowback.

At the end of the 56 second duration main engine test, the test cell was repressurized with gas from the spray chamber that contained enough free methane to combust immediately after entering the test cell when exposed to the residual air in the cell (the ignition source was likely a hot surface such as the main engine nozzle). This unexpected combustion event increased the chamber wall temperature by ~10ºF and singed a small amount of facility camera MLI insulation and the tips of a few cable ties but was otherwise uneventful. The test cell atmosphere was preemptively replaced with GN2 for subsequent tests, to prevent a repeat of that event. During previous hot-fire events in the Plum Brook B2 test cell (e.g., low mixture-ratio RL-10 testing), the facility steam powered ejector systems were capable of maintaining altitude conditions in both the test cell and spray chamber, and the fuel-rich test cell repressurization event was avoided.

E. Coil-On-Plug Ignition System

The ICTPA included five spark ignition devices for the four RCS thrusters and the main engine igniter, and these ignition devices used coil-on-plug (COP) electrical systems. Details of the COP igniters for the ICPTA can be found in Ref. 12. The COP ignition system eliminates the use of a high-voltage lead between a conventional exciter coil and the spark plug, as used in current space craft hardware utilizing spark ignition. Conventional exciter coils with high-voltage leads are at risk of corona discharge in the high-voltage components, which can lead to loss of spark energy at the igniter electrode and damage to propulsion system hardware. By moving the coil directly to the spark plug, the high-voltage components sensitive to corona discharge are removed, mass of the exciter hardware is reduced, and the igniter electronics (e.g., timing and voltage flyback protection) can be co-located with centralized avionics, away from the cold environments at the thruster pods.

The Project Morpheus system used a conventional coil system for its sea-level testing, including external exciters and high-voltage leads at each of the four RCE and the main engine igniter. A COP system was integrated into the vehicle for ICPTA testing at simulated altitude and vacuum conditions. WeaponX Performance Products, LTD fabricated the coils (Fig. 21a), and the vendor custom-modified the coil to be vacuum-potted into a threaded interface nut to mount into the existing spark plug ports on the ICPTA RCE and main engine igniters (Fig. 21b). The vacuum potting prevented pressure/vacuum leakage into the coil body and maintained the spark location at the electrode tip.

Subsequent testing at NASA showed that additional modifications for the potting and electrode thermal and electrical insulation were needed to increase COP life in the hot-gas main engine igniter environment. For example, the hot-gas environment inside the igniter could lead to epoxy erosion and arc-tracking along the exposed epoxy surface, which resulted in the loss of spark at the electrode tip. A combination of ceramic insulators, high-temperature potting, and the elimination of Kapton tape was required to produce a long-life COP.

a) 

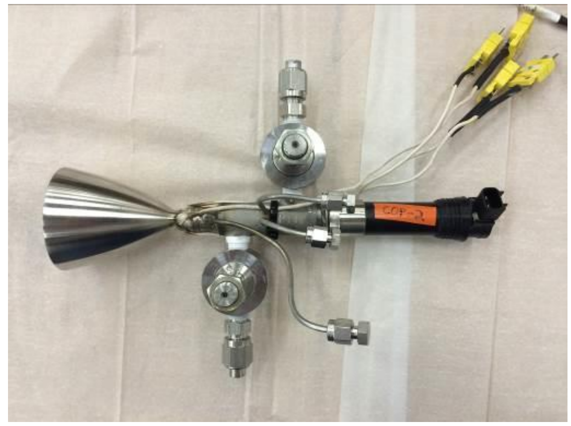
b) 

Figure 21. a) Coil-on-plug (COP) igniter and electrode. b) COP igniter installed in 28 lbf-vac RCE

The coils integrated into the ICPTA were originally designed for 12 vdc automotive systems, but they were operated at 16 vdc using facility power supplies. The ICPTA trigger command for all the igniters is 100 sparks per second at 50% duty cycle, which was the heritage command output of the ICPTA controller from Project Morpheus. Bench-top testing on the 12 vdc coil with 16 vdc power supply demonstrated ~22-24 mJ spark energy at 50% duty cycle.

In the ICPTA configuration that was tested in 2016-2017, the coil body did not include the electronics (e.g., transistors) to produce a high frequency spark using the 16 vdc power and the 5 vdc Transistor-Transistor Logic (TTL) trigger. Instead, the ICPTA testing included a vendor-supplied ignition electronics device to perform the switching, accepting a continuous 16 vdc input and then sending a 16 vdc pulse to the COP transformer for each 5 vdc trigger signal at 100 Hz. This device was not vacuum-rated prior to testing, however, requiring the igniter electronics module to be installed outside of the vacuum test cell during ICPTA testing. In addition to the switching electronics, a vendor-supplied “condenser” was included to help reduce voltage flyback from the igniter to the APU controller.

Prior to ICPTA testing at Plum Brook, tests at NASA JSC demonstrated the performance of the COP igniters at a component level. First, electrical tests were conducted in a vacuum bell jar and demonstrated no corona discharge external to the coil during electrical operation from 50 to 10^{-4} Torr. Next, component-level hot-fire testing was performed on the ICPTA 28 lbf-vac RCE, 7 lbf-vac RCE, and the main engine igniter. The test series was conducted on the NASA JSC CryoCart test bed (Fig. 22a), both at ambient and vacuum conditions. A new “vacuum pipe” test fixture was designed and fabricated to facilitate ignition testing at vacuum conditions. The vacuum pipe included an intrinsically safe flapper door designed to open when the pipe pressure rose to ambient pressure, but would allow for short-duration ignition demonstrations of the RCE and main engine igniter (Fig. 22b). Tests demonstrated vacuum ignition at 50 to 0.03 Torr with zero “no-lights” due to COP failures. The final test series at NASA JSC for the coil-on-plug included fully integrated hot-fire testing of the ICPTA, with tests demonstrating simultaneous main engine and RCS operation at sea-level conditions. The integrated vehicle hot-fire tests successfully proved that the integrated electronics could operate all five of the coil-on-plug igniters simultaneously and in test sequence (e.g., main engine with RCS pulsing) without significant EMI problems or voltage fly-back problems into the ICPTA avionics and power controller.

a)  b) 

Figure 22. a) JSC Cryo-Cart LOX-LCH4 test cart and vacuum-pipe test article for vacuum ignition demonstrations. b) ICPTA main engine igniter vacuum demonstration with COP igniter.

At Plum Brook B-2 testing during the ambient temperature vacuum testing, successful RCE hot-fire tests were completed without any COP failures during hot-fire test. No vacuum corona discharge was observed in any of the test conditions external to the coil bodies. One RCE COP failure was identified during electrical/command functional checkouts (i.e., not during hot-fire) that was attributed to arc-tracking epoxy issues. Similar to sea-level integrated testing, the main engine igniter COP demonstrated one failure to provide spark energy at the electrode during the ambient-temperature altitude testing, possibly due to arc tracking at an internal ceramic/epoxy joint. Subsequent replacement of the electrode ceramic insulation was required and the final configuration COP performed as designed for the remainder of testing, becoming the fleet leader. During the test campaign, 19 successful main engine igniter lights were demonstrated in igniter-only testing, main engine testing, and integrated testing. During cold-thermal environment testing, several RCE non-ignition/quenched ignitions were observed, followed by one mechanical failure of the COP (see Ref. 12), however two RCE ignitions did prove vacuum ignition function under cold-thermal conditions.

F. Cold Helium System

A cryogenic gaseous helium system on the ICPTA provides real-time pressurization of the propellant tanks by passing stored cold helium gas through the main engine nozzle mounted heat exchanger at high pressure, then regulating that pressure down to tank conditions. The helium is stored on the ICPTA in a 19-inch diameter, spherical, aluminum lined COPV. Helium loading was accomplished using ambient temperature gas from the facility. The gas was chilled in the COPV using LN2 which passed through additively manufactured aluminum heat exchangers that were mounted on the upper and lower COPV bosses. This thermal vacuum hot-fire test of the cold helium system was a follow-up to the sea-level ambient temperature test series on the same vehicle in 2015 (Ref. 8). This iteration of the same experiment was significant due to much higher propellant fill fraction (smaller ullage volume), and much colder initial conditions for the entire helium system, thereby simulating an in-space application of the system. A diffuser was added for this test campaign to reduce the helium inlet velocity into the tank, reducing the gas/liquid impingement velocity, heat transfer and ullage recirculation. Additional instrumentation was also added to this iteration of the experiment, including helium flowmeters for each propellant commodity and numerous additional thermocouples.

Performance variation between previous atmospheric testing (in a high heat leak environment with low propellant fill) and Plum Brook testing can be quantified by comparing the instantaneous and cumulative collapse factors CF_i and CF_c. CF_i is the ratio of actual measured pressurant mass flow rate to the mass flow rate required under ideal (zero heat transfer) conditions for a given steady main engine flow rate. CF_c is the average performance over a set time, typically a flight segment or mission duration. A perfectly efficient system would have a value of 1.

$$CF_i = \frac{\dot{m}_{Pressurant,\ actual}}{\dot{m}_{Pressurant,\ ideal}} \approx \frac{\dot{V}_{Pressurant}}{\dot{V}_{Propellant}} \qquad CF_c = \frac{Total\,Mass_{Pressurant,\ actual}}{Total\,Mass_{Pressurant,\ ideal}} \tag{2}$$

Previous testing of the ICPTA in 2015 resulted in values of CF_i and CF_c close to 1 (within measurement error) due to the high ullage fraction (greater than 75%) and warm upper section of the tank. Five main engine tests during the 2017 Plum Brook campaign, ranging from 10 to 56 seconds in length, provided steady flow rate data for the pressurization system over a long enough period to evaluate CF_i. All of these tests occurred with an ullage fraction of less than 20% and colder propellant tank walls. The measured values for CF_i range from 1.2 to 1.9. For the 56 second main engine test, the averaged CF_c value was 1.44. These values indicate the reduction in efficiency as the warm pressurant collapses due to heat transfer to the cryogenic propellant and cold tank walls. Because no main engine tests were performed under the cold-thermal environment, data was not obtained for this condition. It is anticipated that the value of CF_i in the cold-thermal environment will be even higher since all of the plumbing and components between the COPV and propellant tank inlet will be cold, thus causing further collapse in the pressurant specific volume.

G. Methane Heat Transfer: Tank and Feedline Chill Experiments

In support of enhancing the knowledge base of methane heat transfer, numerous thermocouples were added to the ICPTA and Plum Brook ISP facility feedlines to collect propellant line quench/chill data. Facility and vehicle data was collected (at 10 hz and 1hz respectively) during each propellant loading event, and involved liquid oxygen, liquid nitrogen, and liquid methane commodities. Additionally, one dedicated propellant line heat transfer experiment was performed during the last liquid methane loading event. During this experiment, 12 thermocouples on the main liquid methane transfer line, located in the test cell immediately upstream of the vehicle interface, were monitored at 20 hz using a standalone data system to measure the rapid quench and chill down of this transfer line under well characterized conditions. These thermocouples were located on the top, side, and bottom of four locations along the liquid methane feedline. This set and a similar array on the liquid oxygen transfer line were monitored at 1hz for all other propellant loading events.

For future in-space cryogenic propellant transfer operations (especially in zero-g) an internal tank spray system may be used to more efficiently chill the tank mass, reducing commodity loss and theoretically facilitating zero boil-off propellant transfer. Spray bar systems have been previously tested in ground applications, but little data is available for liquid methane. Therefore, a tank chill experiment was added to the ICPTA prior to the Plum Brook test campaign to measure the effectivity of this type of system. The tank chill experiment included an additively manufactured spray injector (with 360° spherical coverage) that was attached to a capacitance probe in the middle of one oxygen and one methane tank and then connected to a through-port fitting on top of the tank via Teflon tubing. A solenoid valve was placed between the tank fitting and the propellant feedline (upstream of the main vehicle fill valve) to allow flow through the injector and spray onto the tank wall. The tank was vented nominally to ambient pressure. The spray injector is shown in Figure 23. Multiple skin temperature sensors were instrumented along the tank walls and the propellant transfer lines for data collection during the tests.

Figure 23. Tank Chill Spray Injector

The tank chill experiment test was performed twice during the Plum Brook testing campaign. The first attempt was prior to normal tank loading operations during HF5. On both tanks, single phase liquid flow was not achieved from the spray injectors due to limitations on propellant storage tanks pressures and facility plumbing heat leaks but two-phase tank chill data was collected. The experiment was performed again on the methane tank after HF6 at a higher storage tank pressure of 40 psi. This worked quite well and delivered subcooled methane to the spray injector at a known flowrate. The entire tank wall and propellant manifold chilled down in approximately 15 minutes from 60°F to -256°F. Since the opposite methane tank did not have a spray chill system, a zero-boil off-loading was not attempted.

V. Summary/Conclusions and Open Work

A wide variety of LOX/Methane and general propulsion experiments were performed on the Integrated Cryogenic Propulsion Test Article in the NASA Plum Brook In-Space Propulsion facility, creating a valuable data set that continues to be explored. The test campaign met or exceeded all requirements and was a positive example of NASA inter-center collaboration. Hardware overviews and preliminary results were reported in this paper.

Notable Results:

- The primary objective of the testing campaign was Plum Brook facility characterization. The ICPTA provided sufficient main engine thrust and duration to characterize the facility performance in accumulator mode and with methane fuel, demonstrating its readiness for future spacecraft testing. Facility performance results will be reported in the future.
- RCS priming, chill, and hot-fire tests were performed under a variety of environmental conditions including ignitions a cryogenic thermal vacuum conditions.
    - Cryogenic, pressure-fed RCS performance was demonstrated at two thermal extremes and specifically demonstrated the system capability to self-condition the engine propellant from gas/gas to liquid/liquid operation.
    - Repeated no-light events were observed at cryogenic thermal vacuum conditions that were resolved through warming the thruster. Root cause has not been identified.
- The thermal-vacuum testing portion of this campaign was truncated due to schedule and cost limitations for the overall ICPTA test effort.
- The non-intrusive MPG system demonstrated the ability to detect propellant tank fluid level under main engine vibration and showed improved clarity in the low pressure environment. This technology will next be tested on the Orion service module.
- The novel COP ignition system performed well at the system level, having no electrical issues or EMI. Some mechanical spark plug integration issues were encountered but resolved for the test campaign. Improvements have been identified and will be tested.
- Methane and oxygen heat transfer data was collected for transfer lines, tank chill, and propellant feedlines.
- Additional data points were collected for the cold helium pressurization system, showing a much different result than the previous sea-level/high ullage tests. Detailed results from this experiment will be reported in the future.

Thermal-vacuum RCS ignition testing identified a key issue that needs further investigation for operating a cryogenic RCS in very cold space conditions; specifically, no-lights/quenched lights observed at the extremes of the cold-thermal environment testing. Additional component and/or system level testing is needed to identify root cause and corrective measures, and modifications to the CryoCart Vacuum Pipe test apparatus at JSC are under consideration to conduct cryogenic thermal-vacuum ignition testing at the component level. In practice, this extremely cold thruster environment may not be representative of a flight vehicle application since engine components will potentially be protected from thermal extremes by vehicle body panels or other insulation. Lastly, operation in warmer space environments such as Earth orbit will pose less of a design challenge for this issue than deep space operation.

Acknowledgments

ICPTA vehicle development was funded by the JSC Engineering Directorate, Laurie Hansen, director. Plum Brook Hot-Fire facility testing was funded by the NASA Rocket Propulsion Test Management Board, Roger Simpson, chair, and Glenn Research Center Plum Brook Propulsion Test Facility, Jerry Hill, lead. JSC qualification and verification testing of the ICPTA and subsystems was also funded by the JSC Engineering Directorate, Propulsion and Power Division, Edgar Castro, chief. Additional travel required for hot-fire testing at Plum Brook was funded by NASA Advanced Exploration Systems, Jason Crusan, director, and Jon Olansen at JSC.

Numerous Propulsion and Power Division engineers contributed to the effort: Nehemiah Williams, Mark Villemarette, Jacob Collins, Brian Banker, John Applewhite, Christina Deoja, Bill Holten, Hector Guardado, Robert Fulmer, Marty Mclean, and Mike Reddington. The NASA Pathways interns who supported this test include Michael O'Donnell, Joseph Sparta, and David Hoffman. University of El Paso students Daniela Aguilar, Mariano Mercado, Luz Bugarin, Mariana Chaidez, Pedro Nunez, and Armando Sandoval provided engineering and test support at JSC and Plum Brook.

Hal Weaver, Brian Jones, John Zang, Nicolas Connelly, Chris Maloney, Wes Sallee, Brad Weisenberger, Jeremiah Folds, Sage Amato, and numerous technicians and engineering staff conducted testing at Plum Brook Testing. Ben Stiegemeier of NASA Glenn Research Center and Andrew Guymon of NASA Stennis Space Center provided additional test engineering support.

Integrated ICTPA vehicle testing at JSC was conducted with the efforts of Jim Rice, Ian Young, Jennifer Devolites, Steve Daniel, Jessie Zapata, Fred Shetz, Robert Hirsch, Ronnie Gambrel, Kent Dekome, Dave Swartwout, Randy Wade, and the JSC riggers and technicians.

Table 5. Primary Experiment Instrumentation on-board the ICPTA

Subsystem	Sensor Description	Sensor Type / model	Number of sensors	Total number channels	DAQ system
Propellant Tanks (2 LOX tanks, 2 LCH4 tanks)	Ullage Temps, 6 axial depths	Exposed Tip TC, Type T	6 each on 4 tanks	24	22 to Facility, 1 LOX and 1 LCH4 into APU
	Skin Temps, 10 axial locations	Weld-on TC, Type T	11 on -Z LOX, 10 on +Y LCH4, 4 on +Z LOX, 5 on –Y LCH4	30	28 into Facility, 1 LOX and 1 LCH4 into APU
	Liquid RTD (at tank bottom)	Probe RTD	1 each on 2 tanks (LOX and LCH4)	2	Facility
	Tank Pressures	Omega PX-329	1 each on 2 tanks (LOX and LCH4)	2	APU
	Delta-Pressure Sensors	Omega custom	1 on each tank pair (LOX and LCH4)	2	Facility
	Level Sensors	Capacitance Probe	1 each on 4 tanks	4	APU
	MPG PZT sensor	Piezoelectric patch (cement-on)	4 each on 2 LOX tanks	8	MPG Control/DAQ
	Strain Gages	Vishay WK-13-125BT-350/W	8 each on 1 LOX tank	8	Facility
	Strain Gage Temps	Cement-on TC, Type T	4 each on 1 LOX tank	4	Facility
Helium COPV	Ullage Temps, 6 axial depths	Multi-point probe, grounded tip TC, type T	6 each	6	5 to Facility, 1 to APU
	Skin Temps, 6 axial locations	Cement-on TC, type T	6 each	6	5 to Facility, 1 to APU
	LN2 cooling delivery temps	Grounded tip TC Type T	1 each	1	Facility
	Tank Pressure	Omega PX-429	1 each	1	APU
Helium Pressurization System	Heat Exchanger Body Temps	Weld-on TC, type K	4 each	4	APU
	Heat Exchanger Inlet/Outlet Temps	Probe, exposed Tip TC, Type K	1 each inlet and outlet manifolds	2	APU
	Heat Exchanger Pressures	Omega PX-429	1 each inlet and outlet manifold	2	APU
	Regulator Outlet Pressures	Omega PX-429	1 each manifold (LOX and LCH4)	2	APU
	Regulator Outlet Temps, inlet temp	Probe, Exposed tip TC, Type T	1 each outlet manifold (LOX and LCH4), 1 inlet	3	2 to APU, 1 to facility
	Helium Flowmeters	Hoffer Turbine	1 each manifold (LOX and LCH4)	2	Facility
RCS	Nozzle Temps	Weld-on TC, Type K	3 each on 4 jets	12	8 to Facility, 4 to APU
	Pod Inlet Temps	Probe, Exposed tip TC, Type T	2 each (LOX and LCH4) on 2 pods	4	APU
	Jet Inlet Temps	Probe, Exposed tip TC, Type T	2 each (LOX and LCH4) on 2 pods	4	Facility
	Chamber Pressure	Omega PX-309	1 each on 4 jets	4	APU
	Tank Plume Impingement	Stick-on TC, Type E	4 each	4	Facility
Main Engine	Igniter Inlet temps, Injector Temps	Stick-on and probe, exposed-tip, Type T	2 each manifold (LOX and LCH4)	4	APU
	Igniter and Injector Body Temps	Weld-on TC, type K	2 each on igniter and injector	4	APU
	Nozzle Extension Temps	Stick-on TC, type K	5 each	5	Facility
	Gimbal Ring Temp	Stick-on TC, Type T	1 each	1	Facility
	Throttle Actuator Position	Linear Hall Effect Sensor	2 each	2	APU
	Inlet and Manifold Pressures	Omega PX-329	2 each manifold (LOX and LCH4)	4	APU
	Igniter Pressure, Chamber Pressure	Omega PX-429	2 each	2	APU
	Burn-through wire	n/a	1 each	1	APU

Table 5 (Continued). Primary Experiment Instrumentation on-board the ICPTA

Subsystem	Sensor Description	Sensor Type / model	Number of sensors	Total number channels	DAQ system
Propellant Feed Systems	Main feedline manifold Temperatures	Stick-on TC, Type T	6 each manifold (LOX and LCH4)	12	8 to Facility, 4 to APU
	Propellant Flowmeters	Hoffer Turbine Flowmeters	1 each manifold (LOX and LCH4)	2	APU
	Main Engine Inlet Temps	Stick-on TC, Type T	1 each manifold (LOX and LCH4)	2	APU
	RCS Manifold Temps	Stick-on TC, Type T	3 each manifold (LOX and LCH4)	6	Facility
	RCS TVS outlet temps	Cement-on TC, Type T	1 each manifold (LOX and LCH4)	2	Facility
	Tank Chill Experiment inlet Temps	Probe, exposed tip TC, Type T	1 each manifold (LOX and LCH4)	2	Facility
	Facility-Vehicle Transfer line	Stick-on TC, Type T	12 each manifold (LOX and LCH4)	24	Facility, 12 into JSC-CRIO
Vehicle Structure	Vehicle Load Cells	Transducer Techniques SWP-3K	4 each	4	APU
	MPG PZT sensor	Cement-on piezoelectric patch	2 each	2	MPG Control/DAQ
	Vehicle Structure Temps	Stick-on TC, Type T	5 each	5	Facility
	Ambient Pressure Gage	Omega PX-429 (0-5 psia)	1 each	1	APU
	Ambient Temperature	Exposed-tip TC, Type T	2 each	2	Facility
Thrust Measurement System	Thrust Load Cells	Transducer Techniques LPO-2K	3 each	3	Facility
	Thrust Calibration	Interface 1210-BE-10K	1 each	1	Facility
	TMS structure temps	Stick-on TC, Type T	1 each	1	Facility
APU	APU Body temps, cold junction reference temps	Type T TC, Thermistors	3 various	3	APU
	Main Engine Instability Monitors	Integrated dynamic pressure	2 each	2	APU
	Bus and H-Bridge current and voltage monitors	n/a	16 various	16	APU
				Total: 257	

Table 6. ICPTA high-Speed Instrumentation

Subsystem	Sensor Description	Sensor Type / model	Number of sensors	Total number channels	DAQ system
RCS	Pod dynamic pressure	Kulite CTL-190-1000A	2 each (LOX and LCH4) on 2 pods	4	Facility High-Speed
	Manifold dynamic Pressure	Kulite CTL-190-100BarA	1 each (LOX and LCH4)	2	Facility High-Speed
Main Engine	Injector Flange Accelerometer	Endevco 2221F	1 each axis	3	Facility High-Speed
	Chamber Pressure	Omega DPX-101 or PCB 113B24	3 each	3	Facility High-Speed
	Acoustic Cavity Presure	Omega DPX-101 or PCB 113B24	3 each	3	Facility High-Speed
	Nozzle Extension Accelerometer	Endevco 2221F	1 each axis	3	Facility High-Speed
Vehicle Structure	Accelerometers	Endevco 2221F	1 each axis on lower and upper deck	6	Facility High-Speed
	Microphone	Rockwell MC449-0191-0002	1 each on lower and upper deck	2	Facility High-Speed
				Total: 26	

Table 7. ICPTA Instrumentation for Facility-Provided Heater Control

Subsystem	Sensor Description	Sensor Type / model	Number of sensors	Total number channels	DAQ system
Pneumatic Valves	Propellant Tank Vent Valve Actuators, Fill Valve actuators	Stick-on TC, Type E	1 each on 4 valve actuators (LOX and LCH4)	4	Facility, Heater Control
	Thrust Termination System Actuators	Stick-on TC, Type E	1 each on 2 valve actuators (LOX and LCH4)	2	Facility, Heater Control
Pressure Transducers	Propellant Tank pressure and delta-pressures	Stick-on TC, Type E	2 each on 2 prop tanks (LOX and LCH4), 1 on COPV	4	Facility, Heater Control
	Helium pressure transducers	Stick-on TC, Type E	1 for COPV, 1 for heat exchanger, 1 for regulator outlet	3	Facility, Heater Control
	RCS Pressures	Stick-on TC, Type E	1 each on 2 pods	2	Facility, Heater Control
	Main Engine Pressures	Stick-on TC, Type E	2 each on inlets (LOX and LCH4), 1 each for chamber pressure	3	Facility, Heater Control
Load Cells	Vehicle Load Cells	Stick-on TC, Type E	4 each	4	Facility, Heater Control
	Thrust measurement Load cells	Stick-on TC, Type E	4 each	4	Facility, Heater Control
Linear Actuators	Main Engine Throttle actuator and sensors	Stick-on TC, Type E	1 for actuator, 1 for sensor	2	Facility, Heater Control
Accelerometers	Main Engine Accels	Stick-on TC, Type E	1 each flange black and nozzle extension	2	Facility, Heater Control
	Vehicle Structure Accels	Stick-on TC, Type E	1 each lower and upper decks	2	Facility, Heater Control
Dynamic Pressures	Main Engine high-speed Press	Stick-on TC, Type E	1 each	1	Facility, Heater Control
Regulators	Helium Regulators	Stick-on TC, Type E	1 for both regulators	1	Facility, Heater Control
Flowmeters	Helium Flowmeters	Stick-on TC, Type E	1 for each flowmeter	2	Facility, Heater Control
Solenoid Valves	Helium isolation/ bleed/ vent valves	Stick-on TC, Type E	1 for isol valves, 1 for bleed valve, 1 for vent valve	3	Facility, Heater Control
				Total: 39	

Table 8. ICTPA-provided instrumentation for Facility Redline Monitoring

Subsystem	Sensor Description	Sensor Type / model	Number of sensors	Total number channels	DAQ system
Propellant Tanks	Tank Pressure	Omega PX-329	1 each on 2 tanks	2	Facility Redline Control System
Helium COPV	Tank Pressure	Omega PX-429	1 each	1	Facility Redline Control System
Main Engine	Chamber Pressure	Omega PX-429	1 each	1	Facility Redline Control System
				Total: 4	

Note: APU-Facility “ready” hand-shake bits not shown. APU monitored and controlled redlines not shown.

Table 9. ICTPA Control Systems/Actuator Channels

Subsystem	Sensor Description	Sensor Type / model	Number of sensors	Total number channels	Control system
Propellant Tanks	Vent Valves	Jefferson Solenoid Valves	1 each on 2 tanks (LOX and LCH4)	2	APU
	Facility Vent Valves Pneumatic Actuators	Triad Radius Series A	1 each on 2 tanks (LOX and LCH4)	2	Facility Control/Redline System
	Fill Valves pneumatic Actuators	Triad Radius Series A	1 each on 2 tanks (LOX and LCH4)	2	Facility Control
	Tank Chill Experiment Fill Valves	Jefferson Solenoid Valves	1 each on 2 tanks (LOX and LCH4)	2	APU
	MPG PZT exciters	Cement-on piezoelectric patch	1 each on 2 LOX tanks	2	MPG Control System
Helium System	Propellant Tank ground pressurization	Jefferson Solenoid Valves	1 each tank (LOX and LCH4)	2	APU
	Tank isolation valves	Marotta solenoid valve	1 each tank (LOX and LCH4)	2	APU
	COPV fill and vent valves	Clark Cooper Solenoid Valve EH-30	1 fill and 1 vent	2	APU
	Facility vent valve	Clark Cooper Solenoid Valve EH-40	1 each	1	Facility Control/Redline System
	Heat Exchanger Bleed Valve	Clark Cooper Solenoid Valve EH-40	1 each	1	APU
RCS	LN2 cooling valves	Gems Solenoid Vavle	2 each	2	APU
	Igniter Power	WeaponX COP	1 channel each on 4 thrusters	4	APU
	TVS Valves	Gems Solenoid Valves	1 each manifold (LOX and LCH4)	2	APU
	Main Engine / RCS GN2 purge	Gems Solenoid Valves	1 command for two valves	1	APU
Main Engine	Igniter Power	WeaponX COP	1 each	1	APU
	Igniter Valves, Bleed Valves (LOX and LCH4)	Gems Solenoid valves	2 igniter valves, 2 bleed valves	4	APU
	Throttle Actuator	Linear Actuator	1 each	1	APU
Thrust Termination System (TTS)	TTS valves pneumatic actuators	Avco Type C Actuator	1 each manifold (LOX and LCH4)	2	Facility Control/Redline System
Thrust Measurement System	Calibration Air Cyinder	Norgren A1633C1-Rev 3	1 each	1	APU
APU	Igniter Trigger Timing	n/a	1 each igniter	5	APU
	APU-Facility ready handshake bits	n/a	3 various	3	APU, Facility Control/Redline System
Facility Heaters	Pressure Transducers, Actuators, Load Cells, etc.	n/a	~25 various heaters in 6 channels	6	Facility Heater Control System
				Total: 54	

Note: Camera Power not shown (GoPro or high speed camera). GoPro Trigger not shown. Camera Housing heaters not shown.

References

[1] Hurlbert, E., Morehead, R., Melcher, J.C., and Atwell, M., "Integrated Pressure-Fed Liquid Oxygen/Methane Propulsion Systems – Morpheus Experience, MARE, and Future Applications," AIAA-2016-4681, 52nd AIAA/SAE/ASEE Joint Propulsion Conference, Salt Lake City, UT, July 25-27, 2016.

[2] Smith, T.D., Klem, M.K., and Fisher, K., "Propulsion Risk Reduction Activities for Non-Toxic Cryogenic Propulsion" AIAA-2010-8680, AIAA Space 2010 Conference and Exposition, Anaheim, CA, August 30 – September 2, 2010.

[3] Hurlbert, E., Applewhite, J., Nguyen, T., Reed, B., Baojiong, Z., and Yue, W., "Nontoxic Orbital Maneuvering and Reaction Control Systems for Reusable Spacecraft", Journal of Propulsion and Power, Vol. 14, No. 5, pp.676-687, September-October 1998.

[4] Hurlbert, Johnson, Ueno et Al, "International Space Exploration Coordination Group Assessment of Technology Gaps for LOx/Methane Propulsion Systems for the Global Exploration Roadmap", AIAA 2016-5280, AIAA Space 2016, Long Beach, CA, September 13-16, 2016

[5] Olansen, J.B., Munday, S.R., and Devolites, J.L., "Project Morpheus: Lander Technology Development", AIAA 2014-4314, AIAA Space 2014 Conference and Exposition, Sand Diego, CA, August 4-7, 2014.

[6] McManamen, J.P., Hurlbert, E.A., and Kroeger, D.J., "Development and Flight Operation of a 5 lbf to 20 lbf O2/CH4 Roll Control Engine for Project Morpheus," AIAA-2014-3589, 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cleveland, OH, July 28-30, 2014.

[7] Melcher, J.C., and Morehead, R.L., "Combustion Stability Characteristics of the Project Morpheus Liquid Oxygen / Liquid Methane Main Engine", AIAA-2014-3681, 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cleveland, OH, July 28-30, 2014.

[8] Morehead, R.L., Atwell, M.J., Melcher, J.C., and Hurlbert, E.A., "Cold Helium Pressurization for Liquid Oxygen / Liquid Methane Propulsion Systems: Fully-Integrated Initial Hot-Fire Test Results", AIAA-2016-4682, 52nd AIAA/SAE/ASEE Joint Propulsion Conference, Salt Lake City, UT, July 25-27, 2016.

[9] Pohl, Henry O., Chester A. Vaughan, and Darrell Kendrick, NASA JSC, "Space Shuttle Reaction Control System", Society of Automotive Engineers SAE, Paper # 700802, Los Angeles, Ca., October 5-9, 1970.

[10] Orton, G.F., Lox/Hydrocarbon Auxiliary Propulsion System Study, NAS9-16305, MDAC E2548, NASA JSC, July 1982.

[11] Applewhite, J, Hurlbert, E. "Non-Toxic Orbital Maneuvering and Reaction Control for Reusable Vehicles", p676, JPP Vol 14, Number 5, Sep-Oct 1998

[12] Melcher, J.C., Atwell, M.J., Morehead, R.L., Hurlbert, E.A., Bugarin, L., and Chaidez, M., "Coil-on-Plug Ignition for Oxygen/Methane Liquid Rocket Engines in Thermal-Vacuum Environments" (submitted for publication), 2017 AIAA Propulsion and Energy Forum, Atlanta, GA, July 10 -12, 2017.

[13] Atwell, M.J., Hurlbert, E.A., Morehead, R.L., and Melcher, J.C., "Characterization of Pressure-Fed LOX/LCH4 Reaction Control System Under Simulated Altitude and Thermal Vacuum Conditions," (submitted for publication), 2017 AIAA Propulsion and Energy Forum, Atlanta, GA, July 10 -12, 2017.

[14] Feller, J.R., and Johnson, W.L., "Dependence of Multi-Layer Insulation Thermal Performance on Interstitial Gas Pressure," American Institute of Physics, Vol.1434, 2012.

[15] Flores, S., Collins, J., and Hurlbert, E., "Characterization of propellant distribution for a cryogenic Attitude Control System," AIAA-2011-5775, 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, San Diego, CA, July 31- August 3, 2011.

[16] Jimenez, R., Flores, S., Romig, K., and Hurlbert, E., "Characterization of a Thermodynamic Vent System (TVS) for an On Orbit Cryogenic Reaction Control Engine (RCE) Feed System," AIAA-2008-4553, 44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Hartford, CT, July 21-23, 2008.

[17] Crosby, K.M, Rundle, T., LeCaptain, K., Werlink, R., "Modal Propellant Gauging in Low Gravity", AIAA 2016-5533, AIAA 2016-5280, AIAA Space 2016, Long Beach, CA, September 13-16, 2016