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Testing of a Liquid Oxygen/Liquid Methane Reaction Control Thruster in a New Altitude Rocket Engine Test Facility

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Abstract

A relocated rocket engine test facility, the Altitude Combustion Stand (ACS), was activated in 2009 at the NASA Glenn Research Center. This facility has the capability to test with a variety of propellants and up to a thrust level of 2000 lbf (8.9 kN) with precise measurement of propellant conditions, propellant flow rates, thrust and altitude conditions. These measurements enable accurate determination of a thruster and/or nozzle's altitude performance for both technology development and flight qualification purposes. In addition the facility was designed to enable efficient test operations to control costs for technology and advanced development projects. A liquid oxygen-liquid methane technology development test program was conducted in the ACS from the fall of 2009 to the fall of 2010. Three test phases were conducted investigating different operational modes and in addition, the project required the complexity of controlling propellant inlet temperatures over an extremely wide range. Despite the challenges of a unique propellant (liquid methane) and wide operating conditions, the facility performed well and delivered up to 24 hot fire tests in a single test day. The resulting data validated the feasibility of utilizing this propellant combination for future deep space applications.

Introduction

In 2009 the NASA Glenn Research Center activated a relocated rocket engine test facility, the Center's Altitude Combustion Stand (ACS). ACS has the capability to test with a variety of propellants and up to a thrust level of 2000 lbf (8.9 kN) with precise measurement of propellant conditions, propellant flow rates, thrust and altitude conditions. These measurements enable accurate determination of a thruster and/or nozzle's altitude performance for technology development. Recently, liquid oxygen-liquid methane ($\text{LO}_2\text{-LCH}_4$) has been considered as a potential "green" propellant alternative for future exploration missions. The Propulsion and Cryogenic Advanced Development (PCAD) project was tasked to develop systems to use this propellant combination to enable safe and cost effective exploration missions (Ref. 1). Prior to this activity, limited experience with this propellant combination existed, and as a result a comprehensive test program was critical to demonstrating the viability of implementing such a system. The NASA Glenn Research Center conducted tests of a 100-lbf (445-N) reaction control

engine (RCE) at the ACS facility, focusing on altitude testing over a wide variety of operational conditions. In addition to altitude test conditions, the ACS facility includes a unique propellant conditioning feed system (PCFS), which allows precise control of propellant inlet conditions to the engine over a wide range of temperatures. Engine performance as a result of these inlet conditions was examined extensively during the test program. Three test campaigns were conducted over the period of a little more than a year and included over 300 separate hot-fire tests (see example firing in Figure 1), and the ACS facility achieved as many as 24 tests in a single run day.

Each test campaign for this project focused in on a unique objective. The first campaign captured extensive data on steady-state performance of the thruster over the full range of propellant inlet conditions. The second campaign investigated the thruster's performance in pulsed operation mode and characterized the minimum impulse bit, a critical parameter for precise maneuvering. Finally the third campaign allowed deeper investigation into a primary concern of customers for the $\text{LO}_2\text{-LCH}_4$ propulsion system, the ignition process and its reliability. One goal of the ignition test program was to explore ignition performance and reliability versus delivered spark energy. The other goal was to examine the sensitivity of ignition to spark timing and repetition rate. Three different exciter units were used with the engine's augmented (torch) igniter to assess the impact of ignition system electronics on ignition reliability.

This paper will describe the ACS facility and its operational performance capability. The facility was highly effective and its operation and performance will be illustrated through a summary description of the $\text{LO}_2\text{-LCH}_4$ RCE thruster test program, data reduction and interpretation of the results.

ACS Facility Background

Testing of the 100-lbf Aerojet (PCAD) engine took place in the recently activated Altitude Combustion Stand, ACS, at the NASA Glenn Research Center. The stand was originally designated "B-Stand" when it was built back in the mid-1980s for altitude testing rocket nozzles for in-space applications with area ratios of 1000:1 (Refs. 2 and 3). The sister stand, "A-Stand", had been built in the 1950s to test engines up to 50,000 lbf (220 kN) thrust at sea level. As a result of an expansion project by the City of Cleveland at the airport adjacent to the facility, A-Stand was demolished and B-Stand was moved to its new location and renamed. Much of the

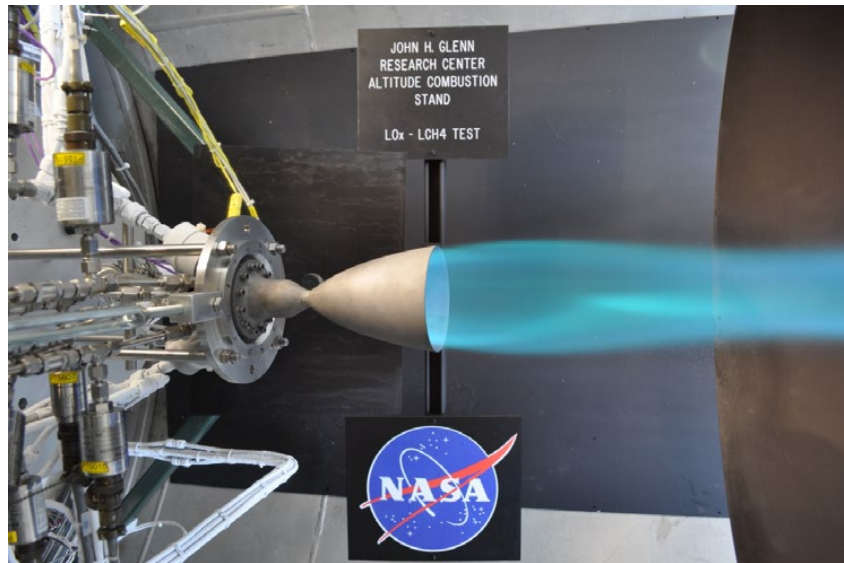


Figure 1.—Liquid oxygen-liquid methane RCE thruster firing at altitude.

original infrastructure, test capsule, diffuser, spray capsule, ejectors and pressure vessels, was refurbished and reutilized at the new location. The original propellant capabilities of B-stand were duplicated. Finally, the facility relocation was validated by checkout tests with an existing workhorse gaseous hydrogen/gaseous oxygen in-house combustor in the spring of 2009. These tests were of short duration ~ 1 sec performed at sea level, and provided confirmation of facility systems and controls functionality. The first programmatic test was the PCAD engine and involved testing the 100-lbf (445-N) engine through a wide variety of tests, from the fall of 2009 until the fall 2010. Special propellant requirements for testing this engine necessitated the addition of several systems to the facility capabilities.

The test stand consists of a test capsule for mounting and operating the test hardware, a diffuser for capturing and compressing the engine exhaust and a spray capsule for quenching and condensing the rocket exhaust. The cylindrical test capsule is approximately 8 ft (2.4 m) in diameter by 14 ft (4.3 m) long. One end of the capsule is stationary through which the mounting system for the thrust stand is permanently fixed to the test cell floor. The stationary end contains all the feed-through connectors for propellants, instrumentation and controls (Figure 2). The cylindrical section of the test capsule and the diffuser are rolled back away from the stationary end to allow access to test hardware and the thrust stand. The diffuser moves independently of the test capsule and allows for flexibility in positioning the inlet of the diffuser relative to an engine nozzle exit plane of up to 2-1/2 ft (0.8 m) diameter. The diffuser exits into the spray capsule, which has five water nozzle spray arrays that are used to cool the rocket exhaust. Inflatable seals at the capsule exit and spray cart inlet provide the sealing surfaces against the diffuser inlet and exit for the vacuum. The entire test stand (Figure 3) is evacuated to altitude conditions using a variety of nitrogen ejector trains, an air ejector train, or a roughing pump.

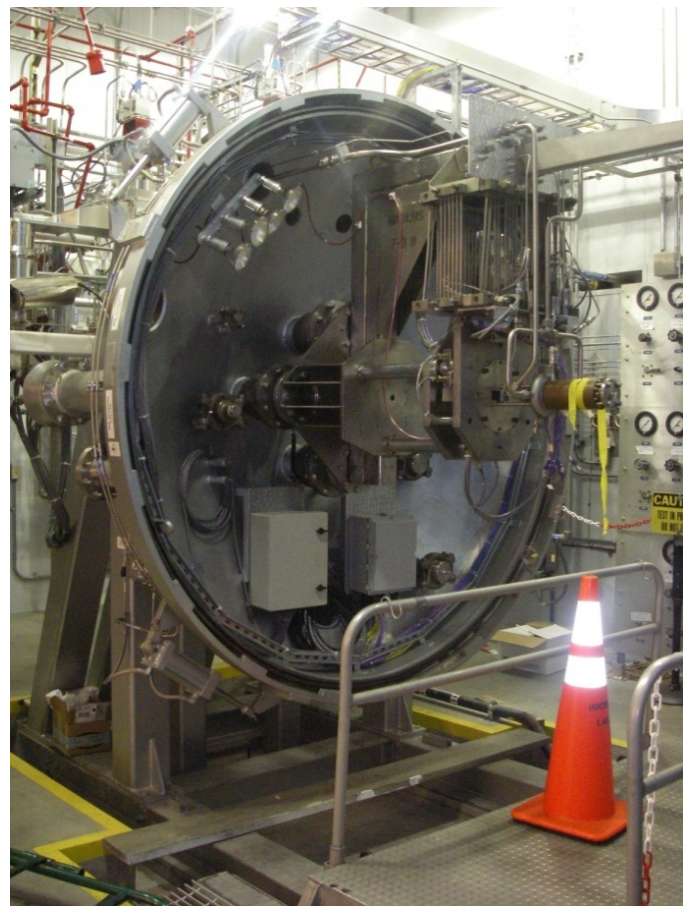


Figure 2.—Test Capsule bulkhead with feed-throughs and thrust stand.

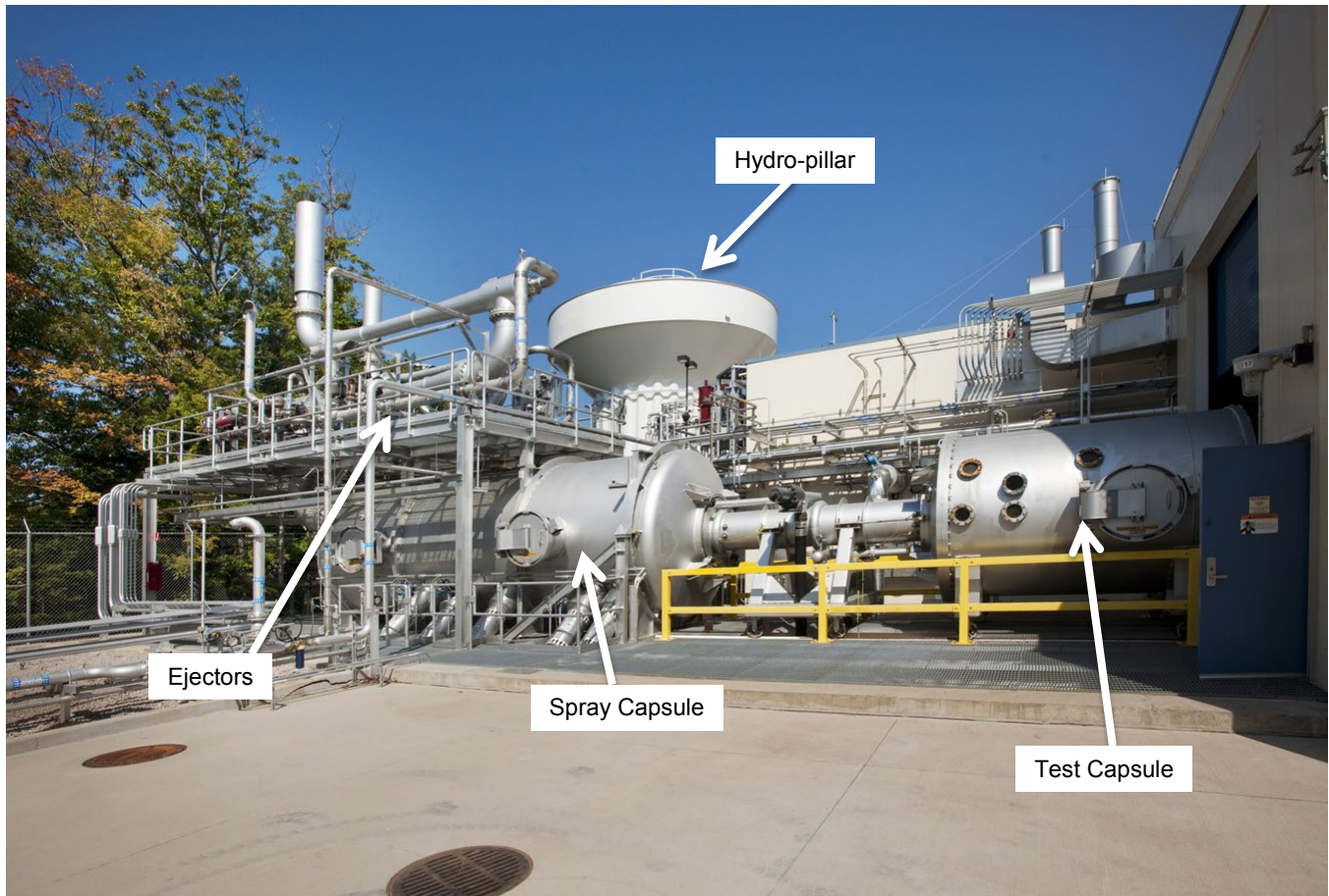


Figure 3.—Major facility subsystems of the Altitude Combustion Stand.

The facility's basic capabilities include testing with gaseous hydrogen, gaseous oxygen, liquid hydrogen, and LO_2 , in rocket engines up to 2000 lbf (8.9 kN) thrust and combustion chamber pressure from 40 to 1000 psia (275 to 6900 kPa). The engines can be fired for short durations at sea level or into the test capsule that is evacuated up to altitudes as high as 130,000 ft (39.6 km). Other support systems available in the facility include gaseous nitrogen, gaseous helium, liquid nitrogen, liquid argon, hydraulic, service air and water. The nitrogen system provides valve actuation pressure, purge gas, and motive fluid for the ejectors that provide the vacuum for the test capsule. The helium can be used for liquid propellant tank pressurant, and purges. The liquid nitrogen system supplies fluid to the vaporizers to replenish the gaseous nitrogen storage vessels. The hydraulic system provides valve actuation pressure to propellant fire valves for increased actuation response. The service air system supports one small set of ejectors for capsule vacuum. There are two water systems. One is a high pressure water system for engine cooling and the other is a closed loop system that is used to quench and condense the engine exhaust during testing.

The testing for the PCAD engine required LCH_4/LO_2 . The test requirements were to condition propellants by controlling

both pressure and temperature at the engine inlet. Due to the addition of a new propellant type, LCH_4 , and the need to control temperature, two independent propellants systems were developed to enable precise control of propellant inlet temperatures.

Propellant Capabilities

Table I provides a capability summary of the various propellant systems in ACS. Both the gaseous oxygen and gaseous hydrogen system have two subsystems that can provide independently controlled flows to both an injector and an igniter within an engine. They are also used to pressurize the comparable liquid propellant run tanks. The two gaseous propellant systems and the two larger liquid systems provide propellant to the engine at near storage temperature conditions. The two smaller liquid propellant systems are designed to allow control of propellant temperature to an engine. These systems use a liquid argon or liquid nitrogen bath, respectively, to subcool propellants or with the use of an in-line heater warm propellants above saturation temperatures.

TABLE I.—PROPELLANT CAPABILITIES

Propellant	Supply capacity, (scf/m ³)	Maximum supply pressure (psi/kPa)	Maximum flow range	Temperature range
Gaseous oxygen (trailer)	50,000 to 70,000 scf (1400 to 2000 m ³)	2400 psi (16,500 kPa)	7 lbm/sec (3.2 kg/sec)	Ambient
Gaseous hydrogen (trailer)	50,000 to 70,000 scf (1400 to 2000 m ³) (x2)	2400 psi (16,500 kPa)	2.65 lbm/sec (1.2 kg/sec)	Ambient
Liquid oxygen	200 gal (760 l)	1800 psi (12,400 kPa)	7 lbm/sec (3.2 kg/sec)	Saturated
Liquid hydrogen	200 gal (760 l)	1800 psi (12,400 kPa)	1.5 lbm/sec (0.7 kg/sec)	Saturated
Liquid methane	60 gal (230 l)	500 psi (3450 kPa)	0.16 lbm/sec (0.073 kg/sec)	170 to 304 °R (121 to 217 K)
Liquid oxygen (conditioned)	60 gal (230 l)	500 psi (3450 kPa)	0.5 lbm/sec (0.23 kg/sec)	145 to 243 °R (104 to 173 K)

Support Fluid Systems

The gaseous nitrogen can be separated into two systems supplied by independent bottle farms. The higher pressure, 2750 psi (18,960 kPa), and greater storage volume system is used for the motive fluid in two parallel ejector systems. The two larger ejector trains evacuate the test capsule during rocket firing and remove the rocket exhaust to atmosphere. Both trains can be run independently or together depending on load requirements with a maximum single run duration of 3 to 9 min. During operations, the ejectors provide a vacuum in the capsule of less than 0.5 psia (3.5 kPa). Additional pumping is achieved when an engine nozzle is sized for the diffuser.

The second nitrogen system is pressurized to 2400 psi (16,500 kPa) and has smaller storage capacity. It provides fluid for valve actuation, dome loaded regulators and purge gas for the propellant lines. Part of this system also provides propellant line purges. There are two levels of purges, trickle purges which flow continuously at slightly above ambient pressure to keep hydrogen and oxygen from accumulating in the rocket engine between tests, particularly during sea level testing. The other purges are higher pressure and capacity to inert propellant lines and primary thruster purges.

The service air system is provided by Glenn's Central Services at 150 psig (1,000 kPa) and 2 lbm/sec (0.9 kg/sec) of service air is needed to operate a smaller ejector train. The service air driven ejector train for is used for initial evacuation of the test capsule prior to transition to the larger nitrogen driven ejector trains during a test. Between tests, during the no-load periods, the service air ejector train is used to maintain altitude conditions in the test capsule.

Electrical

The facility is automated with a Programmable Logic Controller (PLC), controlled by Human Machine Interface computers (HMI), and uses a Data Acquisition System (DAS) to record data. All systems are powered by an Uninterruptible Power Supply (UPS) that uses batteries to provide backup

power during an external power outage. The UPS utilizes a "double conversion" topology to eliminate power dropouts during transfer between external power and battery power. This topology ensures a clean, constant power supply that is free from the uncertainty of the external power source. All control room electrical devices including the PLC, HMI, DAS, video, and lighting are powered by the UPS. This allows for uninterrupted control of testing even during an external power failure.

The PLC contains eight chassis, 100+ modules, 500+ discrete I/O points, and 500+ analog I/O points. There are five dedicated operator control HMI's and two engineering HMI's that can be configured for operator control as needed. The DAS contains six chassis, 70 modules, 200 channels of bridge transducer signal conditioning, and 400 channels of analog input.

Optical Access

Both video and still camera capability are provided within the test capsule to monitor the engine hardware. Still photos are generally taken during testing and video is monitored between tests and recorded during a test sequence. In addition, the test capsule has access ports for more detailed optical diagnostics.

LO₂-LCH₄ Reaction Control Engine Tests in ACS

The PCAD RCE test program in the ACS facility occurred between fall 2009 and 2010. A 100-lb_f LO₂-LCH₄ engine, developed by Aerojet, was used to study propellant performance in a reaction control engine (RCE) (Refs. 4 and 5). Cryogenic hydrocarbons, such as methane, are appealing due to their high performance, storage requirements, and local availability at various exploration destinations (such as Mars). The replacement of the current toxic hypergolic propellants in reaction control systems would also reduce overall mission cost and risk. This engine was intended for use on a lunar

ascent vehicle and in-space applications, so testing at reduced pressure (high altitude) conditions was critical to performance evaluation. Additionally, wide temperature fluctuations at these destinations can affect engine performance. Propellant temperature conditions were therefore varied in an effort to bound the capabilities of the supporting cryogenic systems. A schematic of the RCE feed-system in ACS is shown in Figure 4.

Propellant temperatures in the tank were controlled within ± 5 °R using propellant conditioning feed systems (PCFS). Figure 5 shows the propellant temperatures at the inlet of the thruster valves for all test runs. The boxes represent the three target temperature conditions, which were achieved for the majority of the runs.

Under this RCE test program, over 300 hot-fire tests were conducted in 30 test days spread over 1 years' time. This does not include checkout tests (cold flow and/or sea level nozzle tests) or the thrust stand calibration tests, which were performed at vacuum at the beginning and end of each test day. As many as 24 tests were performed in a single test day. This efficiency was largely enabled by the streamlined data acquisition system. The entire test dataset was output to a file immediately after the run. Using the facility network, this file could be accessed by the researchers and reduced using commercial software. In this way, the test results could be displayed within 5 min of each hot fire. Test condition changes and corrections could be made in real time based on these results, enabling a more complete and valuable test program.

The project encompassed a series of three test campaigns, all performed in ACS at altitude conditions. In the first test campaign, the engine was fired for durations between 3 and 7 sec to determine specific impulse performance values. Mixture ratio was set at values between 2 and 3 (based on model projections) to determine engine performance at off-nominal conditions. Mass flow rates could be adjusted prior to each hot fire to obtain the desired value. Propellant temperature was also varied during the campaign but was held constant during each test day.

The average vacuum specific impulse over all mixture ratios and propellant temperatures was 305 sec. Propellant temperatures in the higher end of the liquid regime showed better performance with a vacuum specific impulse of 323 sec. This was likely due to improved injector mixing characteristics and to a lesser extent, a higher enthalpy of the incoming propellants. The second set of tests involved firing the engine in pulsed mode (short bursts), which is more representative of RCE operation. One goal of this program was to achieve minimum pulse duration of 80 ms, which was regularly achieved without issue. Several runs were performed at 40 ms, but these were limited since some system aborts had to be disabled to achieve the short pulse duration. Duty cycle, the ratio of burn time to the total pulse time, could also be easily varied, though this did not have a significant impact on performance. Each test consisted of up to 30 consecutive pulses.

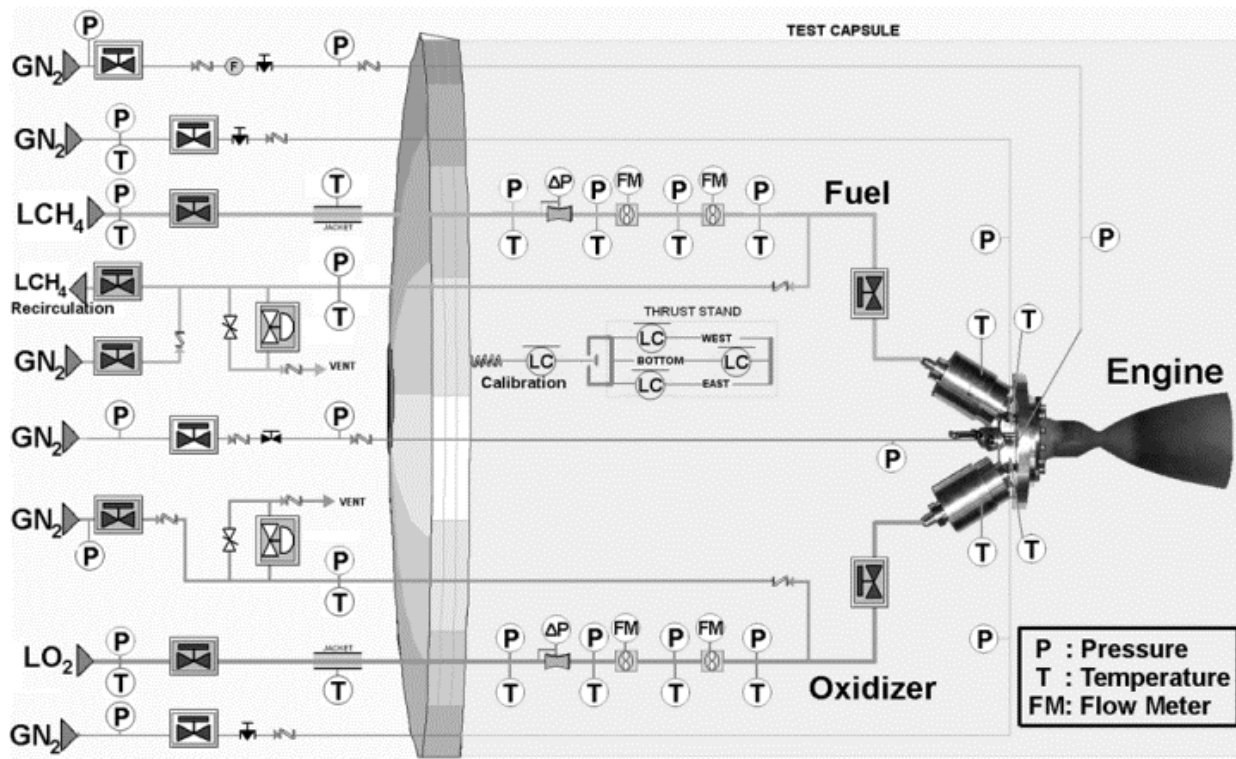


Figure 4.—A schematic of the RCE feed system in the ACS facility.

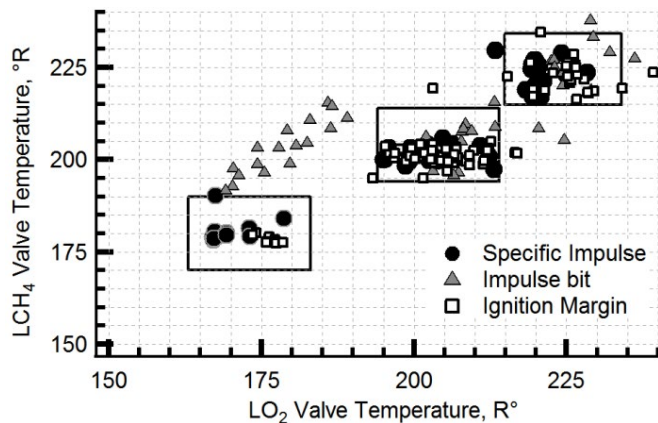


Figure 5.—The propellant conditions achieved for all three RCE test campaigns.

Like the first test series, the pulse test program also indicated improved performance (lower Impulse bit) at higher propellant temperatures. The target impulse bit goal of 4 lb_r-s (17.8 N-s) was successfully achieved using the 40 ms pulse durations. It was also observed that LO₂ could become trapped in the manifold at lower propellant temperatures. This liquid would then volatilize after the oxygen propellant valve had closed. Since the fuel valve closed after the oxygen, this volatilization could trigger a reaction in the heated chamber. This resulted in a secondary flame plume, or “double pulse”. This unique phenomenon resulted in a perceived increase in I-bit values. The test series also clearly demonstrated repeatable and reliable ignitions.

In the final test program, several different exciter units were used with the augmented torch igniter to examine ignition performance and reliability as a function of delivered spark energy. This test program was developed in response to the perceived LO₂-LCH₄ drawback of high ignition energy. The exciter units were instrumented with a high speed digital storage oscilloscope (DSO) to obtain delivered spark current and voltage waveform information. Using the oscilloscope, the data rate could be tailored within the region of interest, i.e., the ~60 ms in which the igniter was active. This data (~250 kHz) was then synchronized with the 1 kHz facility data, so that individual spark behavior could be correlated to engine pressure and flow conditions, such that the spark that triggered ignition could be identified. As with the other test series, an automated data reduction allowed for near real time feedback of the results.

It was shown that spark discharges in a hot fire environment were less repeatable and more susceptible to quenching or dropouts than sparks in room condition “dry sparks”. While higher energy discharges would help overcome the pressure and flow effects of the engine environment, appropriate spark timing can be an effective alternative. The optimum ignition

time was early in the combustible flow environment, when the propellant flow rates and igniter cavity pressure were still low. The facility permitted timing adjustments down to 10 ms to resolve this phenomenon. An exciter with a high spark rate concentrated during this time period increased the ignition probability.

Summary and Conclusions

A high fidelity altitude rocket engine test stand, the Altitude Combustion Stand, has been activated at the NASA Glenn Research Center. This stand, with both cryogenic and ambient temperature propellant capability, can test engines up to 2000 lbf (8.9 kN) thrust at altitudes up to 130,000 ft (39.6 km). The first test program in ACS was a technology development effort evaluating LO₂-LCH₄ RCE performance. Over 300 hot fire tests were successfully conducted to investigate steady state performance, pulsed mode performance, and ignition robustness. A large body of high quality data was collected that illustrated the feasibility of utilizing this high-performance non-toxic propellant for deep space missions. In conducting this test program the ACS facility proved to be an effective and efficient location for achieving the project objectives.

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