

GREEN PROPELLANT TEST CAPABILITIES OF THE ALTITUDE COMBUSTION STAND AT THE NASA GLENN RESEARCH CENTER

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ABSTRACT

The NASA Glenn Research Center (GRC) is committed to providing simulated altitude rocket test capabilities to NASA programs, other government agencies, private industry partners, and academic partners. A primary facility to support those needs is the Altitude Combustion Stand (ACS).

ACS provides the capability to test combustion components at a simulated altitude up to 100,000 ft. (~0.2 psia/10 Torr) through a nitrogen-driven ejector system. The facility is equipped with an axial thrust stand, gaseous and cryogenic liquid propellant feed systems, data acquisition system with up to 1000 Hz recording, and automated facility control system. Propellant capabilities include gaseous and liquid hydrogen, gaseous and liquid oxygen, and liquid methane. A water-cooled diffuser, exhaust spray cooling chamber, and multi-stage ejector systems can enable run times up to 180 seconds to 16 minutes. The system can accommodate engines up to 2000-lbf thrust, liquid propellant supply pressures up to 1800 psia, and test at the component level. Engines can also be fired at sea level if needed.

The NASA GRC is in the process of modifying ACS capabilities to enable the testing of green propellant (GP) thrusters and components. Green propellants are actively being explored throughout government and industry as a non-toxic replacement to hydrazine monopropellants for applications such as reaction control systems or small spacecraft main propulsion systems. These propellants offer increased performance and cost savings over hydrazine. The modification of ACS is intended to enable testing of a wide range of green propellant engines for research and qualification-like testing applications. Once complete, ACS will have the capability to test green propellant engines up to 880 N in thrust, thermally condition the green propellants, provide test durations up to 60 minutes depending on thrust class, provide high speed control and data acquisition, as well as provide advanced imaging and diagnostics such as infrared (IR) imaging.

INTRODUCTION

Chemical propulsion research and testing has had a rich history at the NASA John H. Glenn Research Center (GRC) since the 1940's. The first rocket engine test cells, which were the first structures of the now Chemical Propulsion Research Complex (CPRC), were built in the mid-1940's with the balance of the original complex being built from the late 1940s to the mid-1950's and an additional sea level test facility (Cells 31/32) built in the early 1990's.

The Rocket Engine Test Facility (RETF) was completed in 1957 at what was then NACA Lewis Flight Propulsion Laboratory. The RETF was a chemical rocket test facility capable of testing engines up to 20,000 pounds thrust. The focus of the research at that time was on high-energy liquid propellants. For 30 years research at RETF contributed to the field of rocket propulsion especially related to cryogenic and liquid propellants.¹

In 1984, a second thrust stand was added to the RETF complex. It was designated as B-stand, while the original 20,000-lb stand was designated A-stand. B-stand allowed testing of engines with lower thrust, up to 2,000 pounds; however, it had the unique capability to test such engines in a vacuum or simulated altitude representative of upper atmosphere conditions.¹

Testing at B-stand continued through the 1980's and early 1990's. B-Stand was instrumental in providing test data on high-area ratio nozzles, and helped to provide data to anchor modern design codes like TDK.² In 2003, RETF was demolished to allow for the expansion of Cleveland Hopkins International Airport. Much of the critical B-stand altitude hardware was preserved including the test chamber, water condenser chamber, water cooled diffuser, high pressure nitrogen storage bottles and vacuum ejectors. This equipment was refurbished and relocated to its present location for use at the Altitude Combustion Stand Facility at Glenn Research Center's Lewis Field.

Construction of the ACS facility started in the summer of 2006 and finished in the spring of 2008. Formal building occupancy of ACS was obtained in March, 2008. Between March, 2008 and March, 2009, activation and checkout of ACS's systems were completed culminating with a sea-level gaseous hydrogen-oxygen checkout test, shown in Figure 1. The Altitude Combustion Stand was located adjacent to the then existing Research Combustion Lab (RCL). The entire area, including the ACS facility, was renamed the Chemical Propulsion Research Complex (CPRC) in 2016.

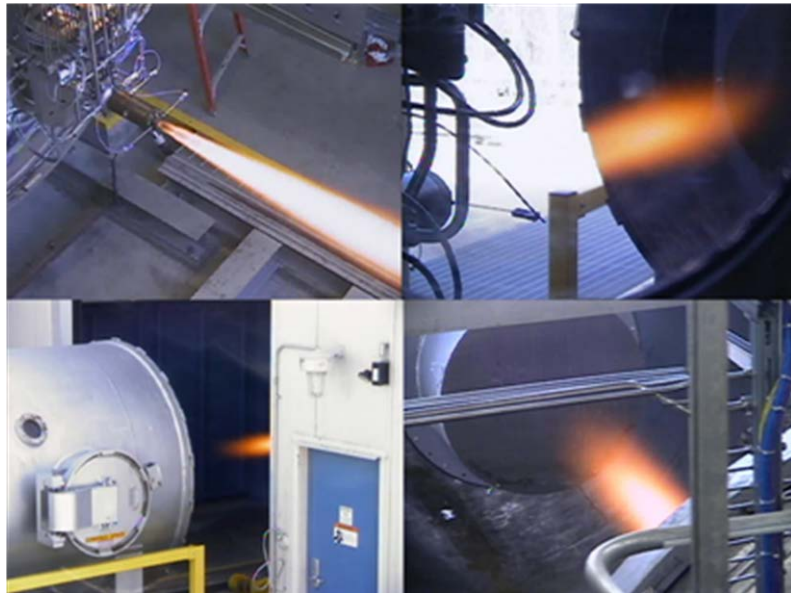


Figure 1: Sea-Level Testing of 1000-lbf Hydrogen-Oxygen Engine, 2009.

The first customer at ACS was the Propulsion Cryogenic Advanced Development (PCAD) program. This extensive LOX/LCH₄ test program of a 100-lbf_r reaction control engine (RCE) began in November of 2009 and concluded in November of 2010. Propellant Conditioning and Feed Systems (PCFS) were used to control the desired temperature of the main propellants. During this test campaign, a total of 400 tests were completed that included 3 sub-series of tests. The facility also demonstrated the capability of achieving 24 hot fire tests within a single day.^{3,4,5,6,7} At the conclusion of this test campaign, the facility was placed in an inactive test state. Figure 2 shows a photograph of the 100-lbf_r RCE operating in the ACS test capsule.

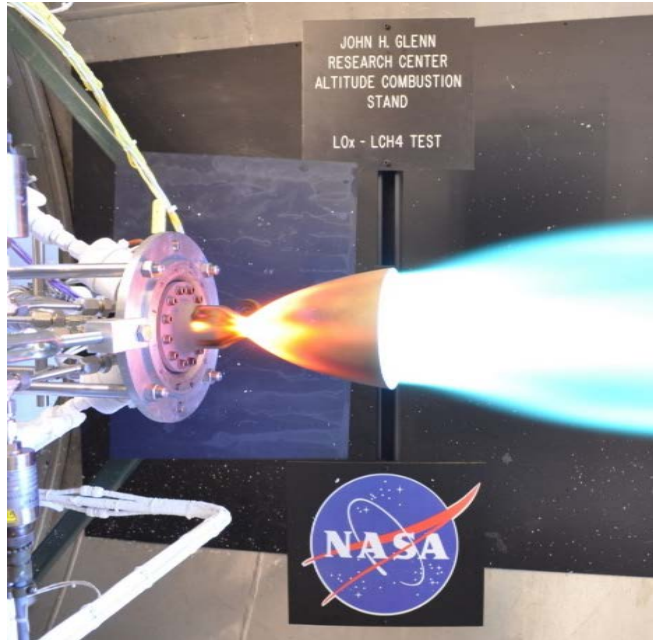


Figure 2: Altitude Testing of 100-lbf Liquid Methane-Liquid Oxygen Reaction Control Engine (RCE) for the Propulsion and Cryogenic Advanced Development (PCAD) Project, 2010.

Recognizing chemical propulsion is a core competency of the NASA GRC, in July of 2015 GRC Center management made a commitment to reactivate ACS to an active testing status. By June of 2016, the test facility was successfully reactivated as demonstrated with a successful hot fire of the 100-lbf PCAD engine. Upon completion of this reactivation, a test program for Igniter-only testing under the Lander Technologies Project was performed. A total of 119 tests over the course of 3 weeks were completed. The test series included two exciter configurations, using liquid oxygen and liquid methane⁸. This test series was completed within 3 months of the facility reactivation and Figure 3 shows a photograph of the igniter tests. ACS is currently active and available for testing.

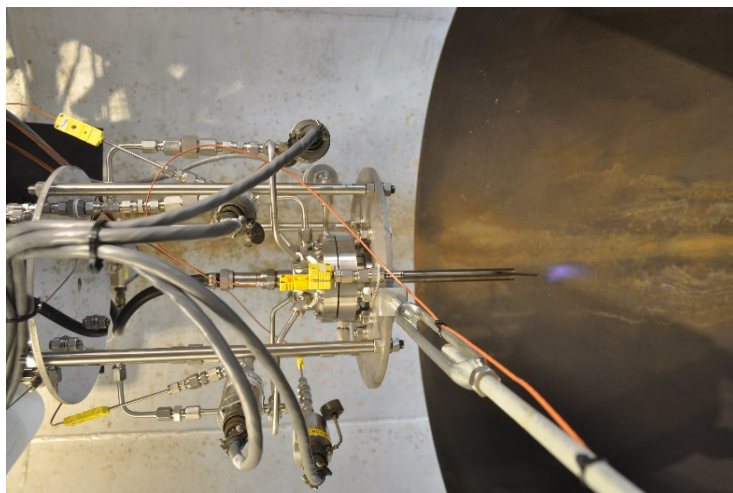


Figure 3: Altitude Testing of Methane-Oxygen Igniter, 2016.

CURRENT TEST FACILITY OVERVIEW

ACS is a highly adaptable test facility and can be reconfigured to support many different testing needs. ACS provides the capability to test combustion components at a simulated altitude up to 100,000 ft. (~0.2 psia/10 Torr) through a nitrogen-driven ejector system. The facility is equipped with an axial thrust stand, gaseous and cryogenic liquid propellant feed systems, data acquisition system with up to 1000 Hz recording, and automated facility control system. Propellant capabilities include gaseous and liquid hydrogen, gaseous and liquid oxygen, and liquid methane. A water-cooled diffuser, exhaust spray cooling condenser, and multi-stage ejector system can enable run times up to 180 seconds to 16 minutes. The system can accommodate engines up to 2000-lbf thrust, liquid propellant supply pressures up to 1800 psia, and test at the component level. Engines can also be fired at sea level if needed. Methods to further extend test duration have been identified and are being explored. The external systems of ACS are shown in Figure 4.



Figure 4: Exterior photo of the Altitude Combustion Stand's translating test chamber, water cooled diffuser, spray cooling condenser, and vacuum ejector systems.

The vacuum chamber consists of three major components. The movable test chamber, the water cooled diffuser, and the spray cooling condenser. The test chamber consists of a fixed bulkhead with a movable tank. The test chamber measures approximately 8 ft. in diameter by 14 ft. long. It is designed to ASME Code, Section VIII, Division 1 for pressure vessels ranging from full vacuum to 15 psig. Connecting the test chamber and spray cooling condenser is a water cooled convergent-divergent diffuser. When the engine nozzle exit ratio is properly matched to the diffuser, greater vacuum pumping is achieved. In the spray cooling condenser a series of five spray bar assemblies are positioned internally to thermally quench and condense the rocket

exhaust flow to reduce the gas load on the ejectors. Figure 5 shows a simplified schematic of the ACS vacuum chamber.

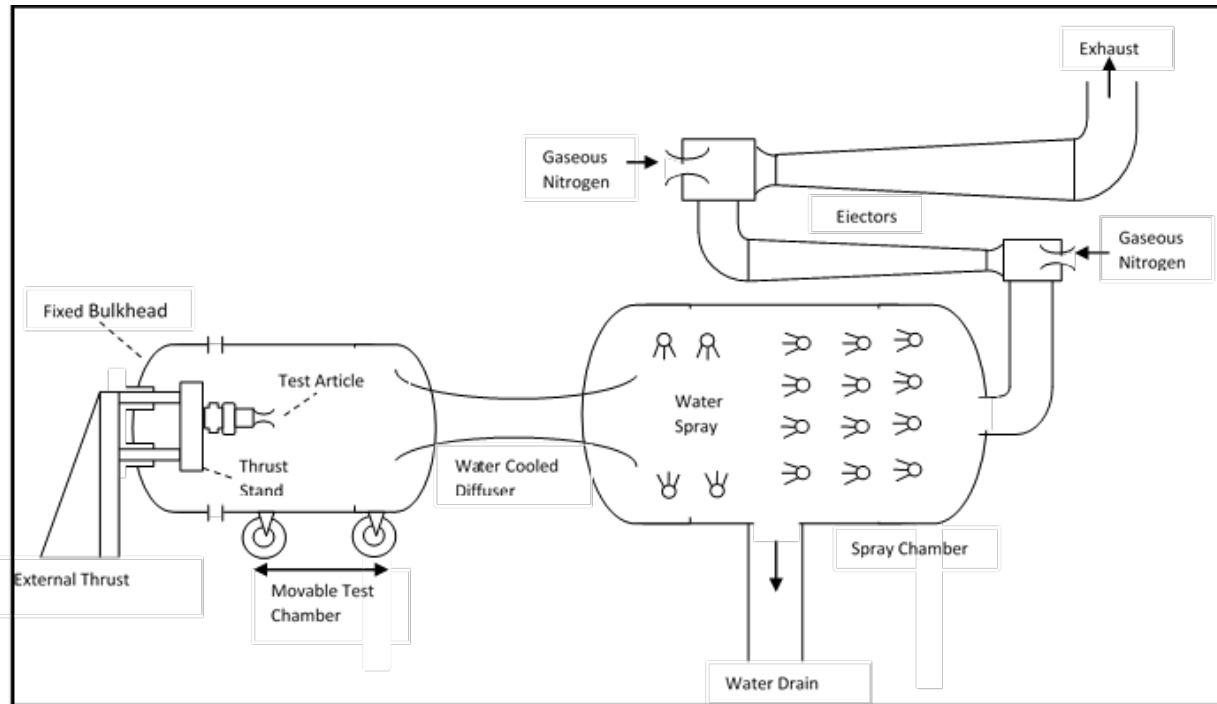


Figure 5: ACS Vacuum Chamber Schematic

Rocket hardware is installed on the thrust stand which is fixed to the thrust take-out structure anchored to the test cell floor. The test chamber stationary head is positioned around the thrust take out structure where a series of steel isolation baffles allows the thrust load to transfer through the stationary head. During an altitude test, the test chamber is closed against the fixed bulkhead to form a vacuum seal. The diffuser is positioned between the test chamber and fixed spray cooling condenser. Inflatable seals ensure the vacuum between the diffuser, test chamber and spray cooling condenser. Engine exhaust is pulled by vacuum ejectors through the water cooled diffuser into the spray cooler where it is quenched and condensed. Non-condensable gas species flow through the ejectors and exhaust to atmosphere.

Other facility support systems available include gaseous nitrogen, gaseous helium, hydraulic, liquid nitrogen, liquid argon, service air, and water. The nitrogen system provides valve actuation pressure, purge gas, and motive fluid for the ejectors that create the vacuum for the test chamber. The helium can be used for liquid propellant pressurant and purges. The hydraulic system provides valve actuation pressure to propellant fire valves for increased actuation response. The service air system supports one stage of the ejectors for roughing down the chamber vacuum levels. There are two water systems. One is a test article high pressure water system for engine cooling and the other is a closed loop facility system that is used to cool the diffuser and quench the engine exhaust during testing.

PROPELLANT TEST CAPABILITIES

Table 1 below contains the current ACS propellant test capabilities. The table outlines the volume, supply pressures, flowrates, and temperature capabilities of these systems. Thermal conditioning is defined as control of the propellant temperature at the conditioning system run tanks. Vacuum jacketed lines and trace cooling provide maintenance of the thermal conditioning up to the test article.

Propellant	Volume	Maximum Supply Pressure, psi (MPa)	Flow Rate, lb_m/s (kg/s)	Thermal Conditioning, °R
Liquid Hydrogen* (LH₂)	200 gal (757 L)	1,800 (12.4)	1.5 (0.68)	N/A
Gaseous Hydrogen (GH₂)	140,000 scf	2,400 (16.5)	3.0 (1.36)	N/A
Liquid Oxygen* (LO₂) – unconditioned	200 gal (757 L)	1,800 (12.4)	7.0 (3.18)	N/A
Liquid Oxygen (LO₂) – conditioned	60 gal (227 L)	525 (3.6)	0.5 (0.23)	145 to 243 (+/- 5)
Gaseous Oxygen (GO₂)	60,000 scf	2,400 (16.5)	7.0 (3.18)	N/A
Liquid Methane* (LCH₄) – unconditioned	200 gal (757 L)	1,800 (12.4)	1.2 (0.54)	NA
Liquid Methane (LCH₄) – conditioned	60 gal (227 L)	525 (3.6)	0.16 (0.07)	170 to 304 (+/- 5)

*Systems installed and certified but yet to be verified

Table 1: Current ACS Propellant Test Capabilities

VACUUM TEST ENVIRONMENT AND DURATION

Three methods are used to achieve simulated altitude pressures during rocket engine testing: Nitrogen-driven ejectors, pumping through the diffuser, and condensing of water vapor/condensable species in the rocket exhaust. Water in the system exits the spray cooling condenser through a vertical drain, which forms a barometric leg. This leg provides a vacuum seal of the spray chamber such that spray cooling water continues to drain while maintaining vacuum in the spray chamber. Four trains of nitrogen driven ejectors, each with two stages, can be used individually or in tandem to pull vacuum and exhaust non-condensable gases to atmosphere. Vacuum run time is a direct function of nitrogen gas storage capacity and spray cooler water usage. Base vacuum pressure of trains 1, 2, and 3 is ~0.5 psia. It is possible to achieve higher vacuum levels during steady state operation of a thruster through the addition of diffuser inserts of contraction ratios appropriately matched to the engine and colder water temperatures. For example, the primary 33" inlet, 24" throat diffuser when paired with the 100 Lbf PCAD engine provided ~0.3 psia vacuum pressures in the test chamber.

Vacuum test duration is directly related to the nitrogen gas storage capacity. Based on current capacity and the motive requirements of the ejector trains test duration ranges from ~5 minutes using ejector train 1 to ~40 minutes with ejector train 3. Table 2 summarizes the vacuum levels and durations for high capacity ejectors. The fourth train is used to maintain the steady ~0.5 psia background pressure while not firing the engine.

Estimated Vacuum Test Duration by Ejector Train			
Ejector Train	Base Vacuum Pressure (psia)	Capacity (Lbm/s)	Duration (min)
3	0.5	0.16	40
2	0.5	0.5	9
1	0.5	1.1	5

Table 2: Vacuum Environment and Test Duration

TEST HARDWARE COOLING CAPABILITIES

There are three commodities that can be supplied to actively cool hardware components at ACS depending on the need: water, liquid nitrogen, and liquid argon.

High pressure water can be supplied for cooling test hardware. This system is ASME coded and rated for 1800 psi. It has a volume of 673 gallons of water and can accommodate cooling flow rates of up to 200 GPM. Based on its capacity and maximum flow rate, it can accommodate cooling hardware for ~200 s with longer test durations being possible with lower flowrates.

Cryogenic liquids are also available for hardware cooling support. Liquid nitrogen can be supplied via a roadable dewar. Liquid argon is supplied via a stationary dewar. Separate remotely operated controls allow liquid nitrogen and liquid argon to be flowed to trace cool lines in the test chamber with returns to a flash tank. Relative hot and cold set points can be adjusted via HMI to control the desired temperature of the main propellants. Liquid nitrogen is used to thermally condition liquid oxygen in the liquid oxygen Propellant Conditioning and Feed System (PCFS) and liquid argon is used to thermally condition liquid methane in the liquid methane PCFS.

THRUST STAND

The Altitude Combustion Stand is equipped with an Ormond, Inc. Single Component Thrust Stand, with a thrust rating of 1000 lbf, and yield safety factor of 2. Figure 6 is a photograph of the thrust stand. Originally manufactured in 1984 for RETF B-stand, the thrust stand was updated with a new live bed, flexures, and PLC controls for remote calibration in 2009. The thrust stand uses three thrust load cells spaced at 120 degrees apart for measuring thrust and off-axial thrust performance. Each load cell is of dual bridge design for thrust measurement redundancy. In-situ thrust calibration is made possible by way of a pneumatically motorized screw and calibration load cell connected with mechanical linkages to the live bed and can be performed at simulated altitude and temperature conditions. Since the main test chamber head is capable of much higher thrust loads, customer supplied thrust stands of higher or lower thrust rating are easily adapted to the thrust mounting flanges as needed.

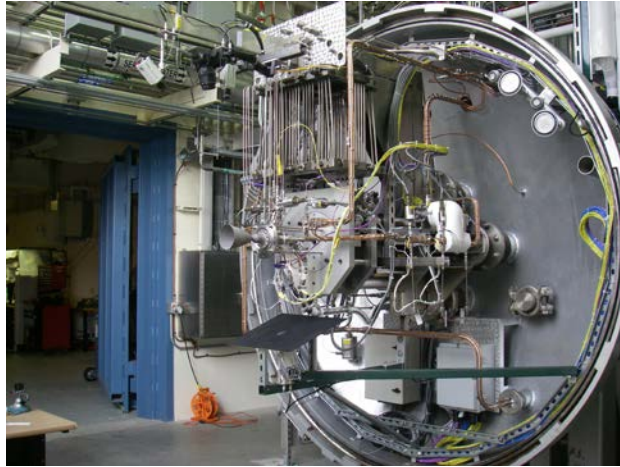


Figure 6: ACS Thrust Stand

DATA ACQUISITION AND CONTROL SYSTEM CAPABILITIES

National Instruments hardware forms the basis of the data acquisition system. Labview software together with SCXI signal conditioning modules provide 1,000 Hz sample rate nominally. Currently 198 temperatures and 208 pressures channels are available. Test sequence timing is achieved through use of Modicon Quantum PLC hardware. There are 256 discrete outputs, 96 discrete inputs and 256 intrinsically safe inputs available. There are also 320 analog input and 40 analog output channels that are available. ACS is also sensitive but unclassified (SBU) compliant.

GREEN PROPELLANT TEST CAPABILITY

NASA GRC is in the process of modifying ACS capabilities to enable the testing of ionic liquid propellants, also known as “green propellants” (GP), for thruster and component level testing. Green propellants are actively being explored by NASA, government partners, and members of industry as a non-toxic replacement to hydrazine monopropellant for a variety of future applications.⁹ These applications may include use as main propulsion systems, or reaction control systems for anything from CubeSats to launch vehicle upper stages. These propellants offer increased performance and cost savings over hydrazine. The facility modifications are intended to enable the testing of a wide range of green propellant engines, for research and qualification-like testing applications.

Currently planned facility modifications for green propellants include but are not limited to:

1. Providing a green propellant feed system, with the capability to test 1-N to 22-N thrusters for a test duration of approximately 60 min., with extensibility up to 880-N thrusters.
2. Providing conditioning of the green propellants from +10 to +50 °C.
3. Providing advanced imaging and diagnostics techniques such as infrared (IR) imaging and laser diagnostics.
4. High speed valve control and high speed data acquisition of key performance data.

Integration of green propellant testing capabilities is projected to be complete by August 2017.

The following sections present the expected capabilities of the facility according to plan. Certain intended capabilities are still in design and under development.

GREEN PROPELLANT CONDITIONING SYSTEM

The green propellant conditioning system is currently in the process of being fabricated at Sierra Lobo, Inc. in Milan, Ohio. Presented in this paper are the capabilities of the system as designed. Validation tests are scheduled to be performed in March 2017 prior to delivery.

Figure 7 provides an overview of the Green Propellant Conditioning System (GPCS).

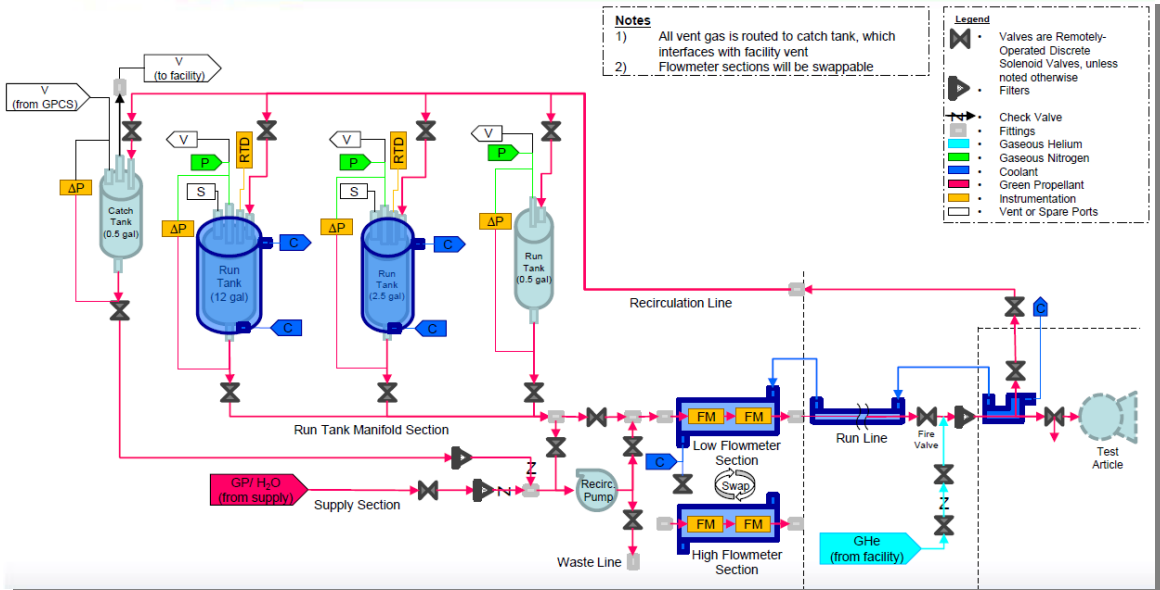


Figure 7: Basic process flow diagram of the green propellant conditioning system. (Credit: Sierra Lobo, Inc.)

The GPCS has been designed to provide the broadest range of green propellant testing possible, including a variety of different propellant formulations. A market research study was performed to anchor the requirements and perceived future customer needs based on available development plans and historical research of hydrazine thrusters. The conclusion of the market study was that the primary area of development for green propellant engines is centered on the 1-N to 22-N thrust range, with development of thrusters of up to 220-N is on the near horizon with some in the industry already developing. The system has been designed to test green propellant engines in the 1-N to 22-N thrust class range for up to 60 minutes at steady state with the ability to support higher thrust class engines of up to 880-N at varying run durations according to the tank volumes selected for the 1-N to 22-N range.

Thermal conditioning of the propellant is accomplished with a recirculator capable of heating or cooling a 50/50 water/glycol mix running through jacketing surrounding the main lines, as well as jackets surrounding the two larger run tanks on the system. The system was designed to thermally condition propellant to a temperature range of $50\text{ }^{\circ}\text{F} \pm 2\text{ }^{\circ}\text{F}$ to $122\text{ }^{\circ}\text{F} \pm 2\text{ }^{\circ}\text{F}$ ($10\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$ to $50\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$). Extensive thermal modeling was conducted by Sierra Lobo, Inc. and validation testing with water was performed to anchor the model. The models predict that a bulk propellant temperature of approximately $26\text{ }^{\circ}\text{F}$ ($-3\text{ }^{\circ}\text{C}$) may be possible.

Primary mass flow measurement and totalization will be provided by Coriolis flowmeters for steady state and pulse mode testing. The Coriolis flowmeters selected are capable of achieving the required accuracy needed during steady state and pulse testing in a totalizing mode. Two flowmeter models will be required to provide acceptable accuracy over the thrust range. One model will cover the 1N-22N range, with another model covering the 50N-880N thrust range. Secondary propellant mass measurement will be provided by differential pressure transducers.

Table 3 outlines expected flowrates in g/s (lb/s) anticipated for green propellant testing (non-propellant specific) as specified in the foundational requirements.

Flow Regime	Thruster Size							
	1 N (0.22 lbf)	5 N (1 lbf)	22 N (5 lbf)	50 N (11 lbf)	100 N (22 lbf)	220 N (50 lbf)	440 N (100 lbf)	880 N (200 lbf)
Low	0.035 (7.7E-5)	0.400 (8.8E-4)	3.00 (0.007)	10.0 (0.022)	27.0 (0.06)	55.0 (0.12)	115 (0.25)	230 (0.50)
Nominal	0.440 (9.7E-4)	2.10 (0.004)	10.0 (0.022)	21.0 (0.05)	48.0 (0.11)	87.0 (0.19)	185 (0.41)	370 (0.81)
High	1.02 (0.002)	4.50 (0.009)	16.0 (0.035)	36.0 (0.08)	80.0 (0.18)	130 (0.29)	280 (0.62)	510 (1.12)

Table 3: Anticipated Non-Propellant Specific Flowrates for Green Propellant Testing.

The green propellant conditioning system was sized to accommodate a thruster in the range of 1-N to 22-N for a duration of approximately 60 minutes. The system provides multiple tank options to minimize the amount of propellant loaded into the system for a given test series, while providing a sufficient quantity of propellant for testing before tanks require refilling. The tank volumes were sized to accommodate the needed volume of propellant for flowrates expected for a 22-N, 5-N, and 1-N thruster for at least 60 minutes of run time with some additional for filling run and recirculating line volumes.

Table 4 outlines the expected test durations of the green propellant conditioning system according to anticipated flowrates for given thruster sizes.

Tank Volume (gal)	90% Fill (gal)	Thruster Size							
		1 N (0.22 lbf)	5 N (1 lbf)	22 N (5 lbf)	50 N (11 lbf)	100 N (22 lbf)	220 N (50 lbf)	440 N (100 lbf)	880 N (200 lbf)
12	10.80	135,655	28,423	5,969	2,842	1,244	686	323	161
2.5	2.25	28,262	5,921	1,244	592	259	143	67	34
0.5	0.45	5,652	1,184	249	118	52	29	13	7

Table 4: Estimated Test Durations of the Green Propellant Conditioning System (s)

Multiple tanks are used to satisfy operating requirements while addressing the required quantities of propellant. The tanks were sized to accommodate the immediate target thrust range of 1-N to 22-N with a minimum duration of 60 minutes for a single steady-state burn. For shorter pulse-tests or smaller thrusters, one of the smaller tanks can be used, limiting the amount of propellant in the system. Smaller tanks also provide a more accurate secondary liquid level measurement utilizing differential pressure transducers and faster conditioning times are achievable, reducing turnaround time. Propellant can also be stored in either the 2.5 gallon or 12 gallon tanks and transferred to one of the smaller tanks as needed to reduce pauses in test series to have test personnel refill the system. The design allows for the 0.5 gallon tank to be swapped for another tank size in the future.

HIGH SPEED DATA AND VALVE CONTROLLER CAPABILITY

In addition to the current number of 1000 Hz data channels, a 16 channel, High Speed Dewetron data system, capable of up to 200 kHz sampling rate, is in the process of being added to the facility in order to capture high frequency data from such instrumentation as high frequency pressure transducers and load cells, to provide high resolution of data during short pulse widths.

A PLC-Based Valve Driver was developed using a Modicon Momentum PLC. It is capable of independently actuating up to three high speed pulses (fuel valve, oxidizer valve, spark) simultaneously with pulses as fast as 20.0 ms with 2.0 ms of resolution. It is also capable of variable duty cycles. Each of the three channels may be programmed with a user-defined delay and each channel may have different pulse widths. Ethernet and I/O ports on the Momentum PLC allow for easy integration into the facility control system. Design options to support 10 ms pulsing with 1 ms resolution are currently being explored.

THRUST STAND

A new axial thrust stand designed for thrusters in the 1-N – 30-N range, with in-situ thrust calibration, is in the process of being procured in parallel with internal development of a torsional thrust stand.

VACUUM TEST ENVIRONMENT AND DURATION

It is planned to have the necessary capability to support a 1-N green propellant test for up to 30 min in test duration by August of 2017. Modifications to the supporting water cooling systems and nitrogen storage capacity are in process.

Based on recently conducted vacuum ejector and water flow tests, the facility currently has the capability to provide approximately 13 minutes of simulated altitude conditions for thrusters of up to 100-N (22 lbf), approximately 9 minutes for thrusters up to 440-N (100 lbf), and approximately 5 minutes for thrusters up to 880-N (200 lbf). The ultimate goal is to maintain environment for a 22-N thruster for 60 minutes once facility modifications are complete.

A base vacuum pressure of approximately 0.5 psia is currently possible with the ejector systems. Options are being explored in order to support higher simulated altitude.

SUMMARY

The NASA Glenn Research Center (GRC) is committed to provide simulated altitude rocket test capabilities to NASA programs, other government agencies, private industry, and academic partners. The Altitude Combustion Stand (ACS) is a primary facility at NASA Glenn Research Center to support those needs.

Once complete, modifications to the GRC's Altitude Combustion Facility will enable capability to test thrusters using ionic liquid propellants conditioned from 10 – 50 °C in the 1-N to 22-N thrust range for a test duration of approximately 60 minutes, with extensibility up to 880-N at shorter durations. A high speed valve driver will be capable of reliably driving valves for 20 ms pulses with 2 ms resolution.

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