Integrated Cryogenic Propulsion Test Article Thermal Vacuum Hotfire Testing

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Abstract

In support of a facility characterization test, the Integrated Cryogenic Propulsion Test Article (ICPTA) was hotfire 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). The ICPTA utilizes liquid oxygen and liquid methane propellants for its main engine and four reaction control engines, and uses a cold helium system for tank pressurization. The hotfire test series included high altitude, high vacuum, ambient temperature, and deep cryogenic environments, and several hundred sensors on the vehicle collected a range of system level data useful to characterize the operation of an integrated LOX/Methane spacecraft in the space environment – a unique data set for this propellant combination.

The ICPTA vehicle was purpose-built at NASA Johnson Space Center for this experiment using components from previous lander development projects. The vehicle is similar in size and form factor to a planetary lander, approximately the correct scale to land a 1000 lbm payload on the moon. Four 48” diameter spherical propellant tanks on the ICPTA held up to 4800 lbm liquid oxygen and 1800 lbm liquid methane (two tanks for each propellant), and one 19” spherical COPV held 9lb of helium at 3600 psi and -250F. The vehicle utilized one downfiring 2,800lbf main engine with 5:1 throttling and four side-firing reaction control engines (RCEs), two at 28lbf thrust and two at 7 lbf thrust. Each engine was lit using a coil-on-plug spark ignition device, incorporating the high voltage transformer needed to produce the spark into the body of the spark plug, thereby eliminating high voltage cabling and associated risk for corona discharge. Additional information on the design and operation of the COP ignition device may be found in *Coil-On-Plug Ignition System Development for LOX/Methane Engines in Thermal Vacuum Conditions*, AIAA JPC 2017.

Figure 1: CAD model of the ICPTA in the NASA Plum Brook B2 thermal vacuum chamber

This hotfire test series is particularly interesting due to the propellant combination and distributed engines. A 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 LEO or in the Earth/Moon system, heating of the spacecraft will likely increase the propellant temperature

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in these remote manifolds above the vaporization point, forcing the spacecraft to prime the engines prior to each use (very cumbersome for an on-demand reaction control system), resort to very high manifold pressures to maintain the propellants in a liquid state, add gasification systems for the propellants (such as the DC-X vehicle), or design the engines and guidance systems to accommodate multiphase propellants and the associated varying minimum impulse bit (MIB). A prime experiment of this test campaign was a deep examination of the last option – designing the system to accommodate a variable propellant state. We feel this is the most reliable and simplest solution for a cryogenic reaction control system

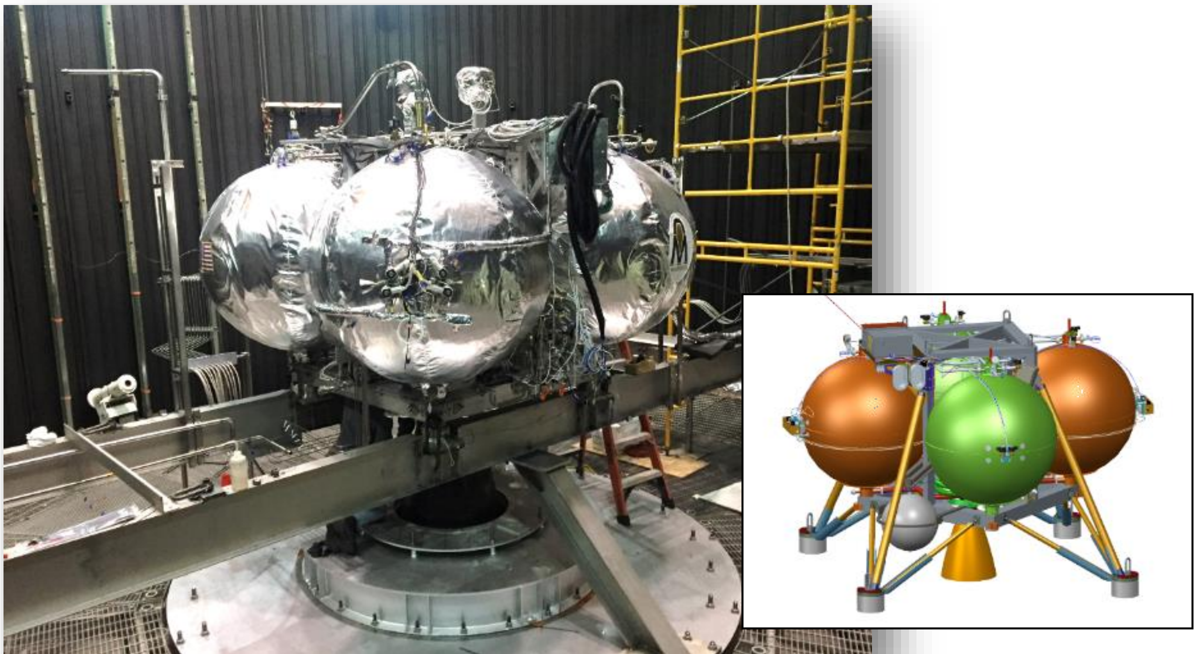

Figure 2: Integrated Cryogenic Propulsion Test Article (ICPTA) installed in the NASA Plum Brook In-Space Propulsion Thermal Vacuum Chamber, with inset CAD model picture of vehicle

The ICPTA RCEs are mounted in pods on the farthest outboard point of each methane tank, with one 28lbf and one 7lbf engine in each of the two pods. These engines are plumbed on long manifolds with close-coupled thermodynamic vent (TVS) cooling lines providing a means of conditioning the propellants in those manifold feeding the RCEs if necessary. Multiple conditioning states of the LOX/Methane propellants were hotfire tested in the thermal vacuum chamber, demonstrating gas/gas operation, gas/liquid transients, and liquid/liquid operation; at both ambient temperature and deep vacuum starting conditions. Data was collected on propellant feedline dynamics, thruster minimum impulse bit (MIB) shift, and TVS demand. Propellant waterhammer was especially interesting, showing the gradual shift from squishy two-phase soft waterhammer to single phase operation with hard waterhammer. A detailed discussion on the Reaction Control Engines design, operation, data analysis and transient modeling may be found in *Pressure-Fed Cryogenic Reaction Control System for Spacecraft: Transient Modeling and Hotfire Test Results,* AIAA JPC 2017.

The ICPTA main engine produces 2,800 lbf (vac) max thrust and is mounted in a thrust measurement system (TMS) 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. Two combustion chambers were produced for this test series, a two-part version 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. Both nozzles were tested with TBD results. The TMS utilizes three evenly-spaced load cells in tension with three backup “catch bars” to protect for load cell failure. An in-place calibration system for the TMS was also installed in the ICPTA and used before and after each hotfire test. An alternate thrust measurement was obtained from the real-time vehicle weight measurement provided by the four vehicle/facility interface load cells. During this test campaign, the main engine was operated at thrust levels between 2,800 and 500 lbf with durations up to one minute (limited by the facility diffuser for the main engine nozzle).

A cryogenic gaseous helium system on the vehicle 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” aluminum lined COPV. Helium loading was accomplished using ambient temperature gas from the facility which was chilled in the COPV using liquid nitrogen which passed through additively manufactured aluminum heat exchangers mounted on the upper and lower COPV bosses. This thermal vacuum hotfire test of the cold helium system was a follow-up to the sea-level ambient temperature test series on the same vehicle in 2015 (insert ref). This iteration of the same experiment was significant due to much higher propellant fill fraction (smaller ullage volume), and deep cryogenic initial condition for the entire helium system, simulating an in-space application of the system. The following paper contains a more detailed description of the experiment, hardware, modeling, and results: *Cold Helium Gas Pressurization For Spacecraft Cryogenic Propulsion Systems*, AIAA JPC 2017.

The vehicle propellant tanks were insulated with a hybrid aerogel/multi-layer insulation scheme providing insulation for both sea-level and vacuum operation. The tanks were tightly covered in a ¼” sheet of aerogel-based “Pyrogel” insulation, faced on both sides with aluminum foil. Ten layers of perforated aluminized Mylar MLI with interstitial Dacron netting was applied over the aerogel insulation, with a perforated purge line in-between. Covering the MLI was a single layer of Gentex aluminized fireproof fabric. The MLI provided negligible insulating benefit during sea-level checkout testing, a minor improvement at high altitude, and a notable improvement at high vacuum conditions. The tanks were further insulated using G10 fiberglass standoffs from the vehicle frame. Overall heat flux data for the hybrid insulation scheme will be reported in the final paper for all environmental conditions.

The ICPTA was instrumented with ~200 thermocouples, 30 static and 12 dynamic pressure sensors, strain gauges, flow meters, etc. totaling over 300 instruments supporting numerous prime and secondary experiments. A notable addition was a non-intrusive propellant mass gauging system utilizing piezoelectric patch sensors affixed to the exterior of the two liquid oxygen tanks. This 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 and can be used with or without a gravity field. This was the first test of the technology on a vehicle during hotfire testing, and additional information about the system and results can be found in *Non-Intrusive Propellant Mass Gauging System for Spacecraft using Piezoelectric Sensors Demonstration Hotfire Test*, AIAA JPC 2017.

During the exposure to ambient/deep cryogenic temperature and simulated 100kft pressure/simulated high vacuum environmental conditions, multiple main engine hotfires and hundreds of RCE hotfire tests were be conducted. The main engine tests ranged from 1-60 seconds duration covering the 5:1 throttle range of the engine, and the RCE hotfire durations ranged from 80 msec to 5 seconds. One of the verification tests conducted on the ICPTA prior to the thermal vacuum hotfire test series was a successful ambient sea-level hotfire test of the main engine and RCEs, conducted at NASA Johnson Space Center in December 2016.

Figure 3. System checkout hotfire test of the ICPTA at NASA Johnson Space Center prior to shipment to NASA Plum Brook Station