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Development Project Overview for MEP Engine Propulsion System for Small Satellites

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ABSTRACT

Ball Aerospace (Ball) and the Electric Propulsion Laboratory, Inc. (EPL) are in partnership to develop a high specific impulse electric propulsion system. The propulsion system is based on EPL's Magneto-gradient Electrostatic Plasma 650-Watt (MEP 650) engine technology. The goal of the MEP 650 project is to develop a flight-like, engineering model (EM) MEP 650 system that can meet future Ball Small Satellite (SmallSat) mission requirements. These requirements are met by an engine that operates at a discharge power of 650 W in self-heating mode, attains a specific impulse of 1,500 seconds, a thrust of 29 mN, and processes about 7.0 kg of xenon propellant at full power.

To support the project efforts, two laboratory engines (EM1 and EM2), a power conditioning unit (PCS), a xenon flow system (XFS) and a MEP command, control, and telemetry (MCCT) unit have been built and tested. Laboratory engine EM1 is dedicated to endurance testing and has completed a 947-hour endurance test at 684 W, at an average discharge voltage of 258 volts. The EM2 engine is dedicated to support continued performance optimization and plasma plume investigations. EPL has completed the MEP system component design, structural and thermal testing, fabrication, and have extensively tested all components, including full system level "end-to-end" performance testing. Characterization of the EM2 engine has been conducted for discharge power levels up to 1 kW (any power level beyond 700 W requires the use of facility power supplies). The results to-date have exceeded the Ball (SmallSat) mission requirements and indicate a total MEP 650 engine efficiency of 35.5%, thrust of 30 mN, and specific impulse of 1,581 seconds at a discharge power of 650 W in self-heating mode. The MEP 650 system has completed all testing identified to achieve a Technology Readiness Level (TRL) 6.

INTRODUCTION

The use of electric propulsion (EP) for multiple mission profiles such as station keeping, spiral orbit maneuvers, orbit repositioning, interplanetary transfers, drag compensation and constellation phasing has grown steadily. These opportunities have encouraged the space community to explore novel EP solutions while continuing to improve on well-established technologies such as Hall Effect thrusters (HET). MEP engine technology has been in development by the Electric Propulsion Laboratory (EPL) since 1990 to address the need for a low cost, high specific impulse EP solution for both small and large satellites as shown in Figure 1.

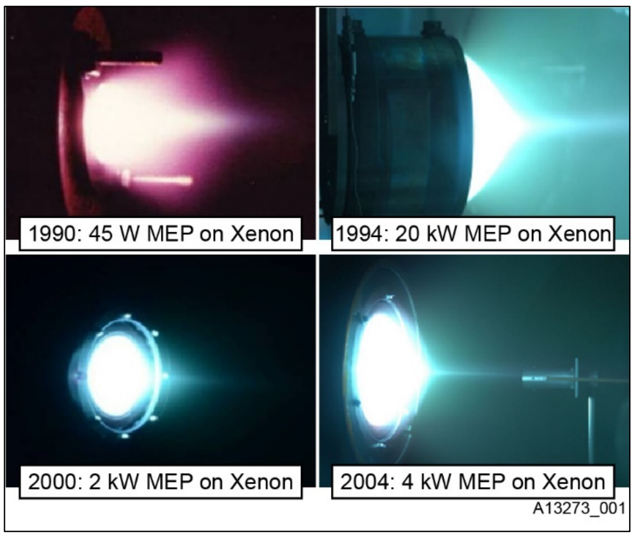

Figure 1: Several Laboratory Model MEP Engines at Various Operating Points

In 2018, Ball found that the performance characteristics of the MEP 650 engine provided substantial cost and performance benefits in SmallSat applications and tasked EPL with the design, build, test, and integration of the MEP 650 system. The goal of the development activity is to evolve the MEP 650 system to a Technology Readiness Level (TRL) of 6, and demonstrate an engineering model (EM) MEP system that outputs a thrust of > 29 mN at a discharge power level of 650 Watts, has a total efficiency > 0.30 and specific impulse > 1,500 seconds, and has a xenon throughput capability of about 7.0 kg corresponding to an operational lifetime of 1,000 hours while operating at full power.

Several tasks were performed co-operatively between Ball and EPL to ensure the specific hardware design, operation, structural integration and command and control features of EPL's MEP propulsion systems will meet the operational objectives listed above and fit well with the Ball Configurable Platform (BCP-100) spacecraft structure.

A key enabler of the effort is the availability of EPL's three large cryo-pumped vacuum test facilities: Tank H (volume of 10.5 m^3), Tank M (volume of 36.6 m^3) and the BAT (volume of 96.4 m^3), which have extensive plasma diagnostic instrumentation and thrust stands. The facilities are manufactured from non-magnetic stainless steel and have demonstrated xenon pumping speeds of 35,000 L/s, 90,000 L/s and 130,000 L/s respectively. All three have base pressures in the very low 10^{-8} Torr range.

This paper further summarizes the MEP 650 propulsion system physics and technology, heritage, architecture, component description and development activity including the functional, performance, environmental, and testing plans. Finally, evaluation and integration of the MEP system to a Ball SmallSat is described.

MEP 650 ENGINE PHYSICS AND TECHNOLOGY

It is important to note the physics of MEP engine operation and fundamental differences between MEP engine technology and traditional Hall Effect Thrusters (HETs). Unlike HETs, which use a narrow, annular discharge chamber operating at relatively high plasma pressures, MEP engines have a large discharge volume which operates at relatively low pressures. No insulator channels are required in the MEP engine since the large discharge plasma volume is contained by careful design of the magnetic and electric fields. These fundamental design differences are highlighted by the schematic drawings in Figure 2.

As with HETs, most of the engine physics is embodied in the design details, shape, and strength of the magnetic field distribution. The MEP engine uses magnetic mirrors to establish a diverging closed mirror, magnetic field. Electrons from the embedded upstream hollow cathode are trapped on this diverging mirror while rotating azimuthally due to $J \times B$ forces. This same hollow cathode produces an electron plasma jet extending along the engine axis. Gas is injected directly through the anode/manifold electrode located upstream of the diverging magnetic flux distribution. This gas is ionized rapidly, and the ions are acted on by equipotential surfaces created by electrons trapped on the magnetic flux lines. These potential gradients are much weaker than in a HET and extend over an acceleration zone much greater in volume than in a HET acceleration channel as shown in Figure 2. The ions created in the MEP engine discharge chamber are accelerated towards the electron plasma jet emerging along the engine axis. This jet is generally close to space or zero potential. Neutralization of the accelerated ions is by electron current leaving the axial electron jet to form a downstream-directed plasma exhaust plume with the ions. A significant fraction of the ion acceleration zone is downstream of the MEP engine exit plane and has a bell shape. This feature creates a much better impedance match to the downstream vacuum of space than achieved with a HET. Consequently, MEP engines operate without any discharge plasma current oscillation, or breathing modes. Permanent magnet circuits are used throughout the MEP engine and therefore no power must be expended to provide this magnetic distribution function. The ion beam divergence of a MEP engine is like the HET engine but with a different distribution of ion flux. However, ion energy distribution scans show an absence of errant high energy ions at large angles in the MEP plume. Those ions present at large angles are facility-induced low energy charge exchange ions.

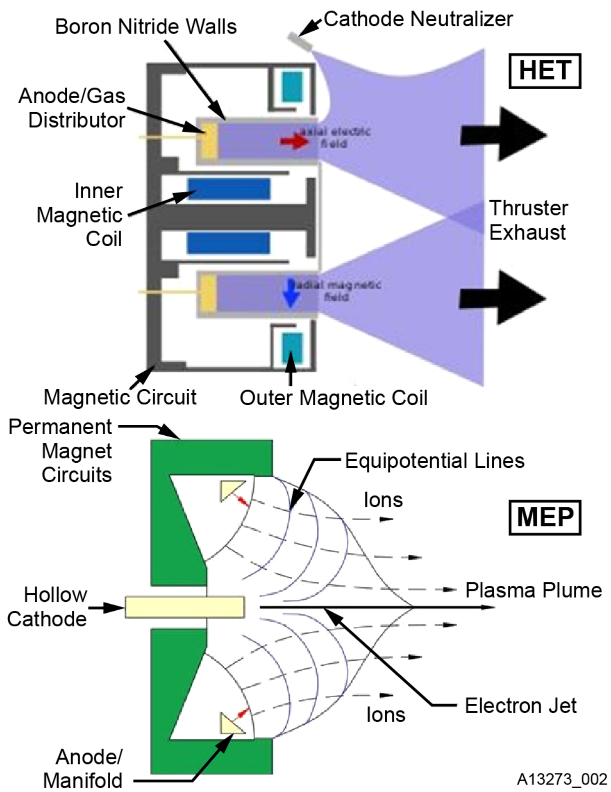

Figure 2: Side-by-Side Cross Section Comparison of the HET vs. MEP

The open discharge chamber structure of the MEP engine means that it is primarily forward radiating to space which aids in thermal control of the engine. Due to the location of the engine hollow cathode, all gas flow to operate the cathode is used to further support the discharge plasma ionization processes. Moreover, since the cathode gas flow enters the large volume discharge chamber, changes in this flow, along with changes in the flow leaving the anode/manifold, can be used to significantly alter the MEP engine plasma impedance distribution and the engine thrust-to-power ratio. Specifically, MEP engines can operate stably at discharge voltages much lower than 100 V to achieve very high thrust levels for certain applications.

MEP 650 SYSTEM HARDWARE HERITAGE

As part of the United States Air Force (USAF) FalconSAT-8 spacecraft mission, EPL developed a 180 W MEP system operating on Krypton. The MEP 180 system was delivered to the USAF on October 1, 2017. The FalconSAT-8 spacecraft was launched in May of 2020. EPL's MEP 180 propulsion system has successfully fired multiple times and as of the publication of this paper, the mission is on-going. Figure 3 shows EPL's MEP 180 propulsion system and Table 1 lists the flight qualified components on this system which are shared with the MEP 650 propulsion system under development.

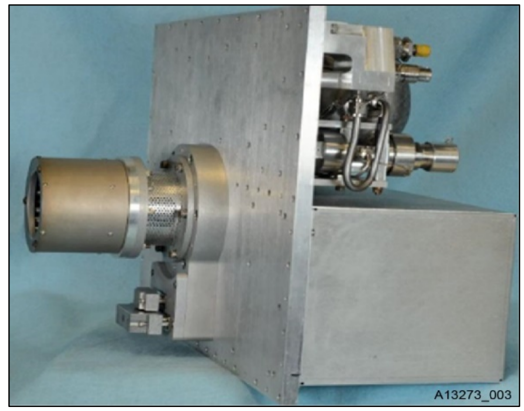

Figure 3: MEP 180 System Built on a Pallet to Accommodate an Existing Slot on the Spacecraft

Table 1: Shared MEP 650 Components with the Flight Qualified MEP 180

PCS	The 250F cathode heater DC-DC converters and associated circuits and outgassing/heating software
	The PCS isolation diodes, heat sinking material, wiring type and cabling techniques
	The current sensing transducers and temperature sensors and associated calibration circuits and telemetry software
	All circuit board design approaches/manufacturing and conformal coating material
	The PCS anode discharge DC-DC converters are of the same Interpoint family-with the MEP 650 PCS having higher power and more efficient units but still of the form factor/bolt pattern etc.
	The Keeper discharge start circuit
	All fasteners
XFS	The two-stage regulator
	The gas flow isolators
	The fill and drain valve
	The solenoid valve driver circuit
	The flow restrictors
	The DOT certified carbon composite tank
	The use of Swagelok gas line fittings and stainless-steel propellant tubing
	All fasteners
MCCT	> 50% of the overall control/telemetry software
	All circuit board design approaches/manufacturing and conformal coating material
	All fasteners
	The RS 422 communication interface
Engine	The 250F hollow cathode
	All fasteners
	The general build principles of the two MEP engines, such as the pole pieces and general magnetic circuit design

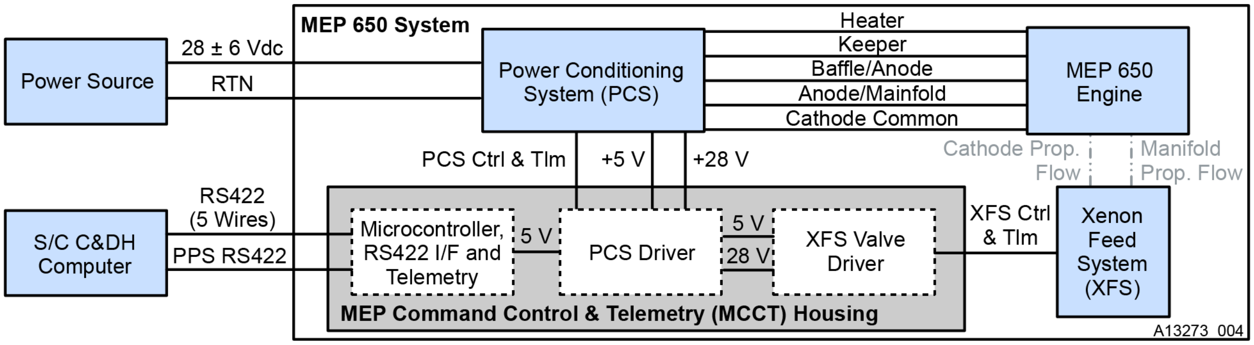

Figure 4: MEP 650 Architecture

MEP 650 ARCHITECTURE AND COMPONENT DESCRIPTION

As shown in Figure 4, the MEP 650 system is comprised of four sub-modules: PCS Figure 5, XFS Figure 6, MCCT Figure 7 and MEP EM engine Figure 8.

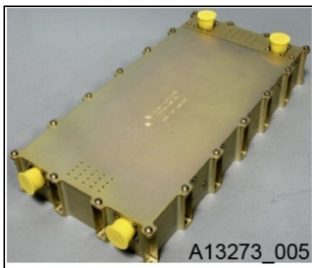

Figure 5: EM PCS Box

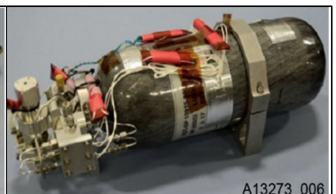

Figure 6: EM XFS w/ DOT Certified 3.3 Liters COPV Tank

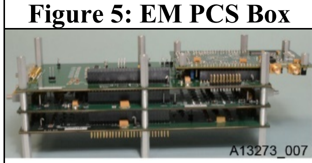

Figure 7: EM MCCT without Enclosure

Figure 8: MEP 650 EM Engine

The boxes provide structural support for the components, as well as protect against the space environment and for use as a radiator. The XFS stores high pressure xenon gas in a composite overwrapped pressure vessel (COPV) and uses regulator-based flow control components to enable constant flow to the engine. The main XFS function of the MCCT is to operate the XFS valves. The temperature of the PCS is monitored via thermocouples attached at several critical points. High voltage and power are needed to ionize xenon gas, and therefore the PCS supplies the needed power to the engine and provides necessary voltages to the MCCT.

The mass of the PCS is 3.7 kg, the XFS (less tank) is 1.1 kg, the MCCT is 1.4 kg and the MEP engine mass is 2.4 kg. The total MEP 650 system mass with electrical cabling and tank not included, is approximately 8.6 kg.

PCS: The PCS main subsystems are inrush current limiter, system and engine filters, system component housekeeping power, engine cathode heater power, engine keeper discharge power and anode discharge power. The heater and keeper power supplies are only used during engine startup and are shut off during normal operations so that only the anode power supply is used to operate the engine. The architecture of the PCS includes multiple DC-DC converters arranged to achieve the nominal 270 Vdc required for the anode discharge. This modular converter approach allows for various converter series and parallel combinations. Specifically, if a future mission application requires very high engine thrust-to-power operation, the PCS could be configured to support a 90 Vdc discharge at 650 W.

The PCS enclosure is fabricated from aluminum. Heat transfer is accomplished by thermal conduction from the PCS base plate to the spacecraft bus radiator. The baseline PCS operates at a single set-point and provides a plasma discharge current of 2.4 A. Total efficiency of the PCS is 83% over an input bus voltage range of 28 ± 6 Vdc at 650 W to the engine discharge plasma. The DC-DC power converters and filters used in the PCS are well suited for multi-year LEO missions and are relatively low cost, flight proven, MIL-STD-883 level components from Interpoint/Crane Aerospace and Electronics. Figure 9 shows the internal arrangement of the components in the PCS. It should be noted that these 883 converters have drop-in 100 krad replacements should the mission require this level of protection. Finally, the PCS can be upgraded to a nominal power of 1 kW using 883 or 100 krad components using the same enclosure, while incurring only a 10% mass penalty.

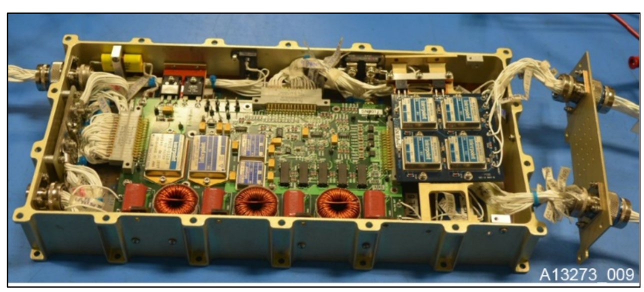

Figure 9: PCS Internal View

XFS: The XFS includes high and low-pressure transducers, a two-stage pressure regulator (with 5-micron filter), a high-pressure isolation latch valve, low pressure isolation valve, low pressure solenoid valves, flow restrictors/orifice and a service fill/drain valve as described in Table 2. Heaters are fitted to the propellant tank to maintain the xenon at approximately +35°C. Similarly, the two-stage regulator has heaters and a thermostat to keep the regulator at or above +35°C. No welding is used in the XFS to minimize cost and footprint size. Figure 10 shows, schematically, the feed system layout of the XFS.

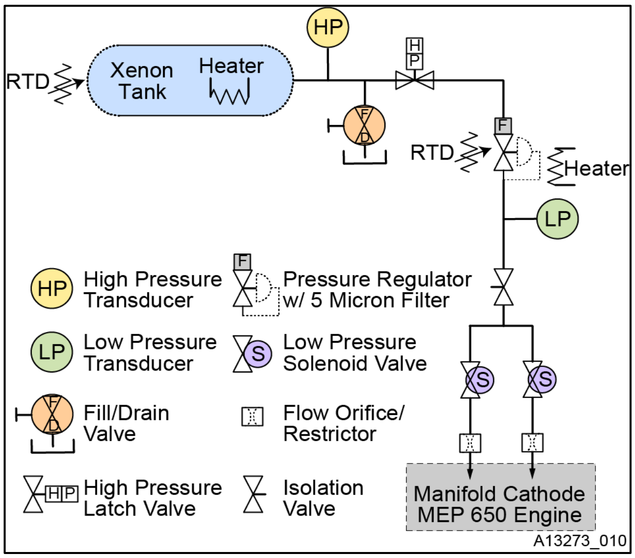

Figure 10: MEP 650 XFS Layout

Table 2: XFS Components

Component	Value
COPV Xe Tank	DOT Certified Volume: 11.1 liters Service Pressure: 3,000 psi Proof Pressure: 4,500 psi Burst Pressure: 9,000 psi
High Pressure Transducer	Working Range: 0 to 2,500 psi
Fill/Drain Valve	Working Range: 0 to 5,000 psi
High Pressure Latch Valve	Working Range: 0 to 3,000 psi
Pressure Regulator w/ filter	Dual Stage; 5-micron filter
Low Pressure Transducer	Working Range: 0 to 250 psi
Isolation Valve	Working Range: 0 to 120 psi
Low Pressure Solenoid Valves	Working Range: 0 to 815 psi
Flow Restrictors/Orifice	Sintered Stainless-Steel
Discharge Tubing	Stainless-Steel; 1/16” and 1/8” in diameter
Flexible Heaters	5 Watt Kapton
Resistive Temperature Device (RTD)	Working Range: -55 to 150°C

MCCT: The MCCT is a multipurpose control and data handling system that supports MEP engine operation and ensures correct PCS and XFS function. Using existing and proven in-house custom circuit designs, EPL designed and built an MCCT made up of three circuit card PCBs shown in Figure 7 above. The first card houses a Cobham UT32M0R500 microcontroller and a standard 4-wire RS485/422 serial communications interface for receiving commands and sending telemetry to the BCP-100 flight computer. The UT32M0R500, used in the current TRL 6 MCCT, has an upgrade path to support up to 50 krad qualified parts. Taking advantage of existing in-house coding structures, EPL developed the firmware to perform all MCCT functions. In addition, bootloader code was developed for uploading new flight software, in case it is needed, while operating the MEP propulsion system on orbit. The firmware programmed into the UT32M0R500 is a part of the firmware that has been flight proven on the MEP 180 propulsion system. Card number two supports the proper valve timing operation to the XFS along with receiving telemetry from the XFS transducers and temperature sensors. Correct power control and sequencing, and conditioned telemetry to and from the PCS, are provided via card number three.

MEP Engine: The MEP engine is manufactured from various grades of stainless steel and soft iron. The permanent magnet circuits provide a clamping action to the engine structure resulting in a relatively low-mass engine. A boron nitride cover is used to mitigate ion sputter erosion on the downstream pole piece, while a boron nitride cover protects the upstream pole piece assembly. The engine is attached to an aluminum mount including ceramic-to-metal standoffs to isolate the engine electrically and thermally from the spacecraft. Two rings/discs at the up and downstream ends of the primary magnet assembly provide additional radiative heat rejection for the engine, adding to the engine’s inherent forward radiation cooling. The MEP 650 engine uses samarium cobalt permanent magnet circuits which undergo an EPL-demonstrated magnetic field strength reduction of ~1% at t = +350°C. However, the MEP 650 engine typically operates at magnet temperatures of 270°C which indicates that there is increasing power margin for this engine size. EPL’s 250F flight hollow cathode is used in the MEP 650 engine. Multiple units of this hollow cathode have flown on various EPL plasma engines for both unclassified and classified mission applications. The 250F hollow cathode was endurance tested in a diode configuration for 12,500 hours on xenon at an emission current of 2.0 A (25,000 Amp-hours). The 250F hollow cathode is part of a family of EPL flight cathodes, the smallest of which is the 175F which currently supports operation of two HET’s in-flight on the Venus spacecraft. EPL’s largest flight cathode, the 500F unit was endurance tested in a diode configuration where it demonstrated a nominal lifetime of 120,000 Amp-hours (3,000 hours at 40 A).

All design, analysis, manufacturing, and testing of the MEP 650 EM engines is performed in-house by EPL where the flight qualified MEP 180 engine and system was built. All tasks for the MEP 650 EM engines development project leveraged the experience, knowledge, and lessons learned during the development of several laboratory model MEP engines, as well as EPL's experience in manufacturing, testing and integration of the flight-qualified MEP 180 engine.

EPL manufactured two dimensionally identical engines for the MEP 650 development project. EM1 is dedicated to endurance testing, while EM2 is dedicated to performance testing and environmental testing.

One of the key temperature parameters specific to the MEP 650 engine is the permanent magnet assemblies. High temperatures above +350°C would demagnetize the permanent magnets and therefore they must be kept below about +325°C. To alleviate this thermal challenge, copper titanium-carbide coated thermal fins were installed at the rear and front of the engine. Thermal testing confirmed that the thermal fins were effective in keeping the permanent magnet temperatures at +270°C.

MEP 650 ENGINE TEMPERATURE LIMITS

The MEP 650 engine has been operated over equilibrated temperature ranges from +260°C to +350°C depending on the discharge power set points being investigated. Hundreds of re-starts have occurred at these equilibrated temperatures since EPL takes thrust measurements by switching off all power and flow to the engine and then going through a hot re-start. Regarding cold soaking, the engine has been cycled down to -30°C repeatedly in support of TVAC tests. The critical engine component, the EPL 250F hollow cathode, was cold soaked to -136°C without part breakage in support of a DoD program and all 250F hollow cathodes are considered cold-soak verified by similarity with these earlier program tests.

MEP 650 PROPULSION SYSTEM COMPONENT TESTING TO DATE

The purpose of the MEP 650 propulsion system test plan is to demonstrate a Technology Readiness Level (TRL) of 6. The following sections document the extensive testing performed by EPL for each of the MEP 650 subsystems.

PCS Simulated Load Testing (in air): As part of initial functional testing, EPL operated the PCS in air using a MEP engine resistive load simulator and demonstrated high in-rush current suppression during power-up. Test periods were short and only a few minutes in duration since the PCS was not connected to a thermally controlled base plate. These initial bench tests demonstrated operation of the PCS over the expected BCP-100 bus voltage range of 28 ± 6 Vdc. End-to-end efficiency measurements were taken during these bus voltage excursions and indicated a PCS total efficiency of about 83% over this input voltage range. EPL also quantified line noise emissions from the PCS during its various operating modes and bus voltage conditions. All of these in air resistive load tests were performed using a nominal 28 Vdc Li-ion battery pack manufactured by EPL as shown in Figure 11.

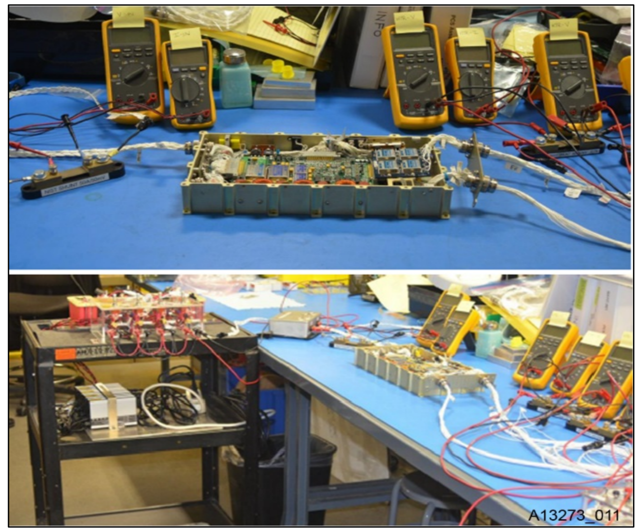

Figure 11: The PCS was Operated, Under Load, in-Air, Using a 28 Vdc Li-ion Battery for Input Power

PCS Simulated Load Testing (in vacuum): Following in-air load testing, the PCS was mounted on a temperature-controlled plate in a cryo-pumped vacuum test facility while operating an out-of-vacuum MEP engine resistive load simulator. These functional vacuum tests covered the full range of temperature extremes (-20°C to +50°C) described in the BCP-100 mission scenarios provided by Ball to EPL. The Figure 12 photos show the PCS mounted to a temperature controlled base plate, this assembly was fitted inside EPL's Tank B vacuum facility, and the external resistive loads and metering were placed outside Tank B. Background pressures during testing were less than 1×10^{-5} Torr. These thermal cycle tests were hours in duration which required operating the PCS off a laboratory power supply rather than the Li-ion battery pack.

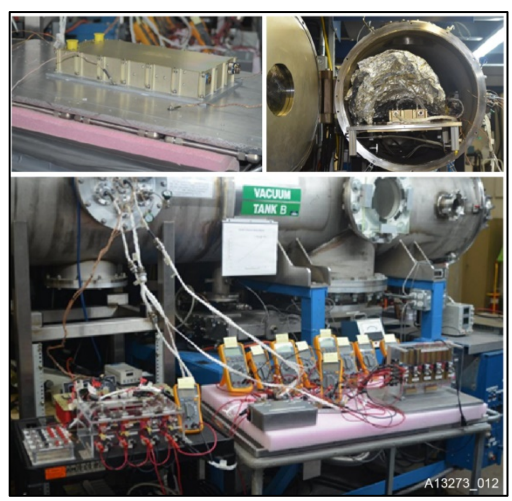

Figure 12: PCS Attached to a Temperature Controlled Plate and Placed in EPL's Vacuum Tank for Load Testing

Figure 13 documents the heat transfer between the PCS and temperature controlled base plate, and shows relatively low PCS internal component temperatures after several hours of full power operation at a base plate temperature of +50°C.

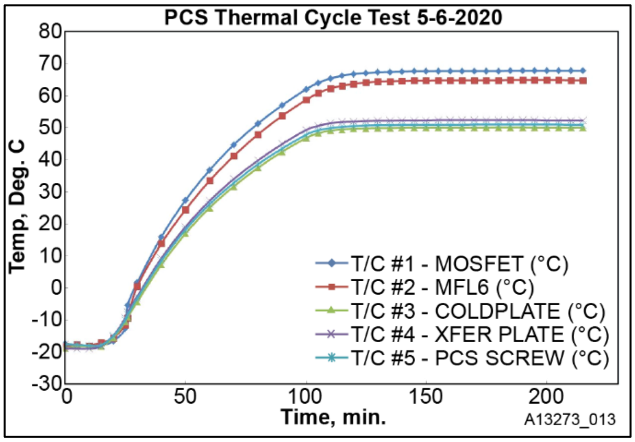

Figure 13: Heat Transfer Between the PCS and Temperature Controlled Base Plate

PCS Testing in Vacuum with the MEP 650 Engine: After successful completion of in-vacuum load testing at mission relevant thermal environments, the PCS was used to operate the EM2 MEP engine in EPL's Tank H cryo-pumped vacuum test facility, as shown in Figure 14. The PCS was attached to a heat dissipation plate in EPL's vacuum tank facility. The PCS was then used to operate the MEP engine at the nominal 650 W condition as shown in Figure 14. Engine startup procedures using the PCS were also established. These engine load tests successfully validated PCS operations under typical mission operations including startup, discharge current ramp-up, response to transient xenon flow changes, worst case shutdown events, and line noise emission characteristics. The PCS efficiency during these in-vacuum MEP 650 engine tests remained unchanged at 83%. Similarly, there was no discharge current oscillation (breathing modes) observed during engine operation.

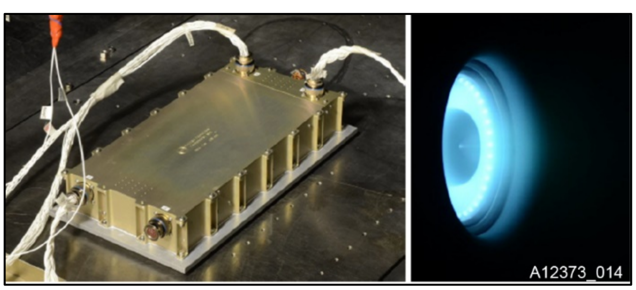

Figure 14: PCS Attached to a Heat Dissipation Plate in Vacuum Tank (Left) and Operating at 650W (Right)

PCS Deep Thermal Cycling: EPL operated the PCS part fit-up (PFU) over ten deep thermal cycles. EPL's PFU hardware meets the form, fit, and function of a qualification unit with components which meet the mission environmental specifications.

Ten deep thermal cycles were accumulated over a four-day period, with the PCS installed in EPL's Tank B cryo-pumped vacuum test facility. This non-magnetic stainless-steel chamber has a diameter of 24" and a length of 108" and is pumped by a single CTI 400 cryo-pump. Base chamber pressures during thermal cycling varied from 2×10^{-6} Torr to 2×10^{-7} Torr, from Cycle #1 to Cycle #10, over this four-day period.

Several thermocouples were placed outside and within the PCS to record temperatures during the ten cycle excursions from -20°C to +50°C. In particular, the previously known hottest internal electronic components, the MOSFET on the bus input current soft-start circuit, and the Interpoint/Crane MFL DC-DC Converter #6, were monitored, with peak temperatures of +64°C and +60°C recorded respectively at the +50°C condition.

The PCS performance/efficiency behavior of 83% did not change beyond data experimental error over the ten thermal vacuum cycles from -20°C to +50°C.

PCS Testing Milestone: EPL has completed the extensive PCS tests required for TRL 6 and has validated the unit for a wide range of future Ball spacecraft mission applications and environments. Milestone completion criteria is supported by both load testing and engine testing data documenting the full range of MEP engine operations and demonstrated mitigation of any likely power transfer interactions with the BCP-100 bus.

XFS: EPL upgraded an existing XFS to support BCP-100 mission scenarios. The XFS was upgraded to EPL's PFU levels. This XFS upgrade included an EPL flight qualified COPV tank as a representative XFS and tank assembly for future BCP-100 spacecraft.

XFS Flow Rate Verification (at room temperature): The XFS was operated at room temperature in air with all flows passing into the cryo-pumped Tank B vacuum facility to calibrate flow rates for the BCP-100 mission scenarios. This test environment was used to adjust the cathode flow and anode/manifold flow to the levels required to support operation of the MEP 650 engine. To support this test, a partial fill of xenon was put in the XFS tank. This flow adjustment is enabled in the XFS by small mechanical adjustments to the two-stage regulator used in this system. As shown in Figure 15, calibrated commercial gas flow meters were used to set the correct regulator adjustment.

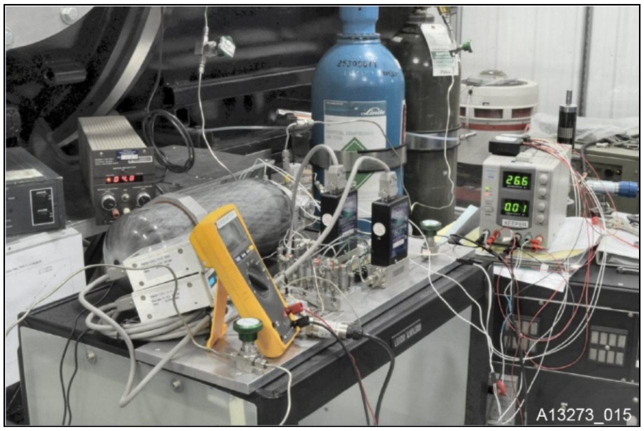

Figure 15: Calibrated Commercial Gas Flow Meters Used to Set Appropriate Regulator Adjustment

XFS Flow Rate Verification (with thermal control): Following flow rate verification, 40 W of thin Kapton film flexible heaters were attached to the XFS tank and 5 W of resistive heating were placed on the regulator as shown previously in Figure 16. These feed system heating functions will be controlled in flight to ensure the xenon is at +35°C, well above its critical temperature of 16.6°C. However, for this test the XFS bottle was filled with nitrogen to support the entire XFS testing down to -20°C with no active heaters. The upgraded XFS was mounted to a temperature-controlled plate within EPL's Tank B vacuum facility which maintained a background pressure less than 1×10^{-5} Torr. Figure 16 and Figure 17 document this test set-up in Tank B.

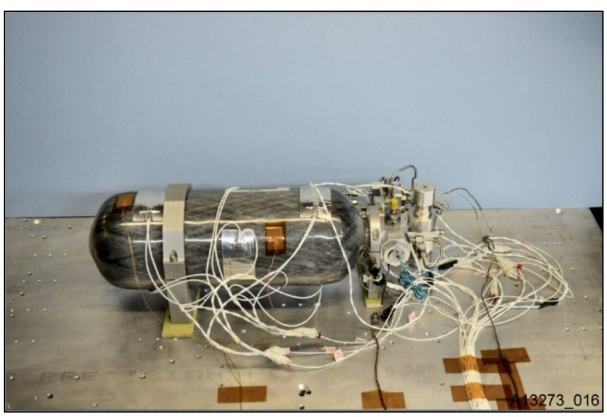

Figure 16: Thin Strips of Flexible Kapton 40 W Heaters Attached to the XFS Tank & 5 W Resistive Heating Placed on Regulator

Figure 17: XFS in Tank B Mounted to a Temperature Controlled Plate

XFS Thermal (Vacuum Testing): During thermal cycling, the base plate temperature was varied from -20°C to +50°C which represents the temperature extremes typical of the BCP-100 integration/mission environments. At a base plate temperature of -20°C, the entire XFS and tank were allowed to equilibrate to this temperature after which the XFS heaters were turned on. With the heaters operating, the XFS and tank could be brought back up to +25°C rapidly. As expected, there was no change in the XFS flow rates from the non-heated room temperature baseline. The baseplate was then raised to +50°C after which the XFS and bottle eventually reached a similar temperature. At this temperature, the flow rates dropped by 5% to 7%. This drop reflected the high gas viscosity at this temperature which resulted in a greater pressure drop across the flow restrictors. The results of these tests enabled the correct sizing of the tank heaters and feed system regulator heaters for future BCP-100 missions.

XFS Vibration Testing: Upon completion of the XFS flow and thermal cycle tests, the XFS and tank assembly were subjected to proto-flight random vibration levels of 9.76 Grms typical of BCP-100 spacecraft launch requirements. Figure 18 documents the XFS orientations on EPL's vibe table. After the successful completion of the XFS vibration testing with the tank empty, the tank was filled with 4.1 kg of sulfur hexafluoride (SF_6). EPL uses this gas to simulate flight loads of xenon since the filled density is very similar. Again, the XFS and tank assembly were subjected to proto-flight launch levels in all axes without damage or leakage.

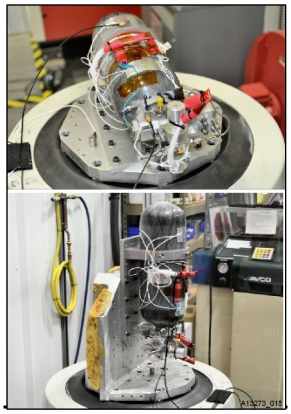

Figure 18: XFS Orientations of EPL's Vibration Table

XFS Testing Milestone: Functional testing of the XFS and tank assembly validated the overall feed system design approach, and component selections, for a range of BCP-100 missions. Milestone completion criteria are supported by flow rate and control data over a wide range of thermal environments typical of spacecraft temperature extremes. Based on the above-described test results the XFS is TRL 6.

MCCT: EPL transitioned from a commercial off the shelf (COTS) based controller design found in the MEP 180 system to a more robust space qualified parts and design using a COBHAM UT32MOR500 microcontroller development board in the EM MCCT development unit. The firmware currently used in the MCCT was taken from the propulsion system controller found in the MEP 180 system and modified to add the additional control and telemetry support required for the MEP 650 system. This transition required modifying the firmware from PIC embedded code to ARM Cortex 0 code used in the UT32MOR500 microcontroller. This updated firmware included additional valve and heater control for the XFS, and support for the higher power of the MEP 650 PCS outputs. The development board used for testing has a direct replacement part chip set to support up to 50 krad for a future build. EPL developed in-house software to simulate host BCP-100 computer control and validate all command functions and telemetry. EPL used previously developed subsystem load simulators and procedures and successfully validated all MCCT functions. See Figure 19, Figure 20, and Figure 21.

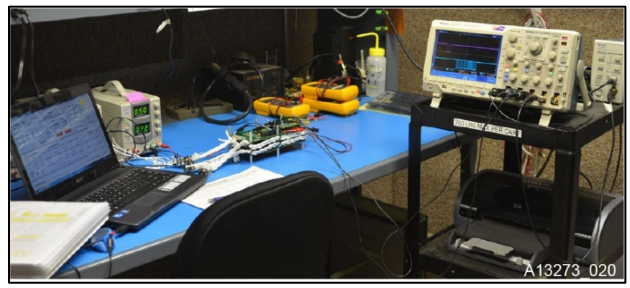

Figure 20: Bench Validation of the MCCT Timing and Control Functions

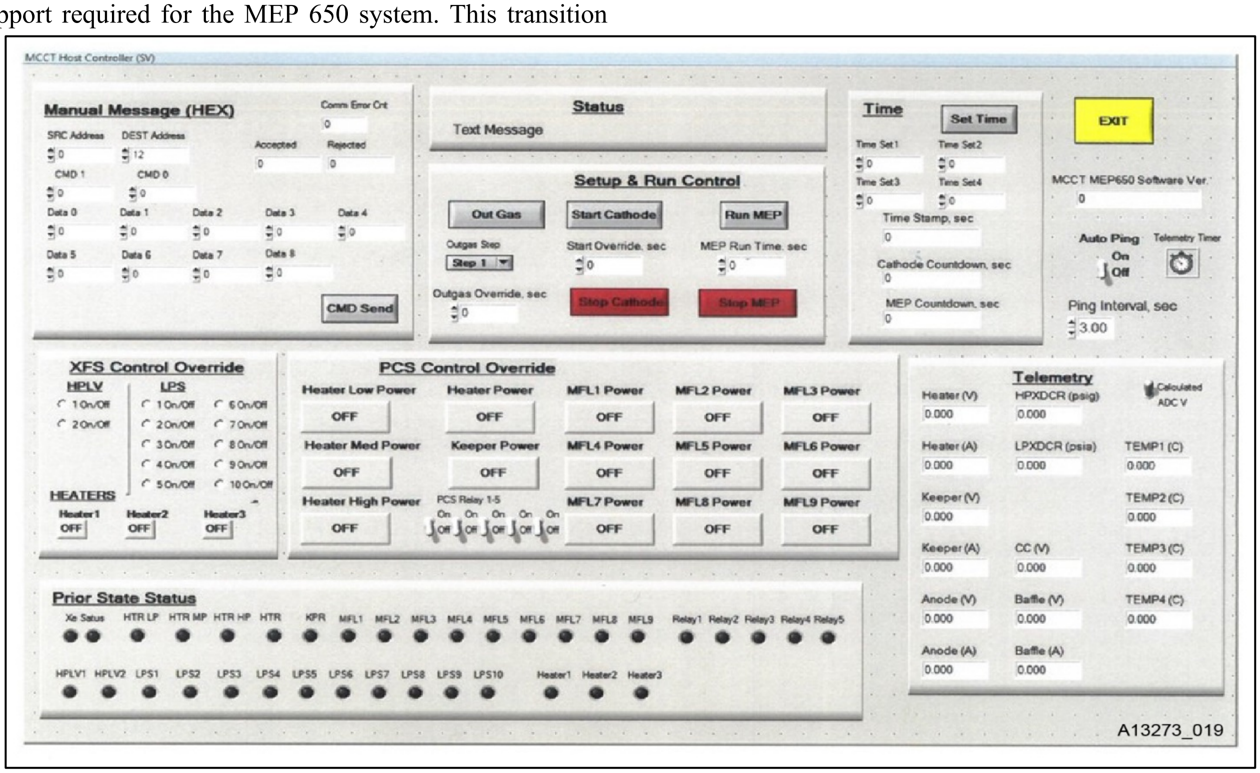

Figure 19: EPL Developed Host Control Interface

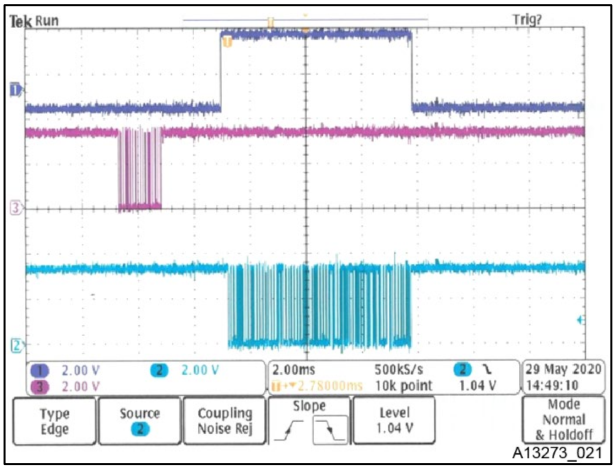

Figure 21: Example of the Communications Interface Command and Response Timing

MCCT Testing Milestone: Fabrication of the various controller boards enabled full functional testing of the MEP system. A milestone completion criterion was documented and a validation of all control signals and communication protocols in an end-to-end propulsion system simulator was completed. The MCCT is at TRL 6.

MEP 650 EM Engine Testing: EPL built two MEP 650 engines, EM1 and EM2. The MEP EM1 engine was built to EPL's PFU level to support endurance testing. The MEP 650 EM2 engine was also built to EPL's PFU level and is used to characterize the performance of the engine in EPL's large Tank M and BAT vacuum test facilities.

MEP 650 EM1 Endurance Testing: EPL built EM1 to support endurance testing in EPL's cryo-pumped Tank H vacuum test facility. In preparation for EM1 engine endurance testing, EPL assembled existing laboratory power supply systems, gas feed systems, and data acquisition systems to support long term engine operations in a dedicated vacuum tank. EPL also installed GRAFOIL liners, to mitigate tank wall ion sputtering during extended MEP engine testing.

The EM1 MEP 650 engine has been operated extensively in EPL's Tank H facility to investigate regions within the engine which are susceptible to long term ion sputter erosion and to quantify the expected lifetime of these various engine components. These component durability tests have comprised a total of 1,200 hours of accumulated engine operation with the longest test period being 427 hours. During these tests different internal component design iterations were undertaken as the various wear mechanisms were understood and appropriate upgrades implemented.

From these investigations, the principal life-limiting component within the engine was determined to be the boron nitride cap covering the upstream magnetic circuit components.

Various design modifications have been implemented by EPL to enable a more robust boron nitride cap component on EM 1. This engine completed 947 hours of operation at 684 W discharge power to verify the durability of this modified component.

The Tank H facility is fitted with ten CVI Torr Master 500 cryo-pumps and maintains a xenon corrected back pressure in the high 10^{-6} Torr range during engine operation. Figure 22 shows the EM1 engine during endurance testing in Tank H.

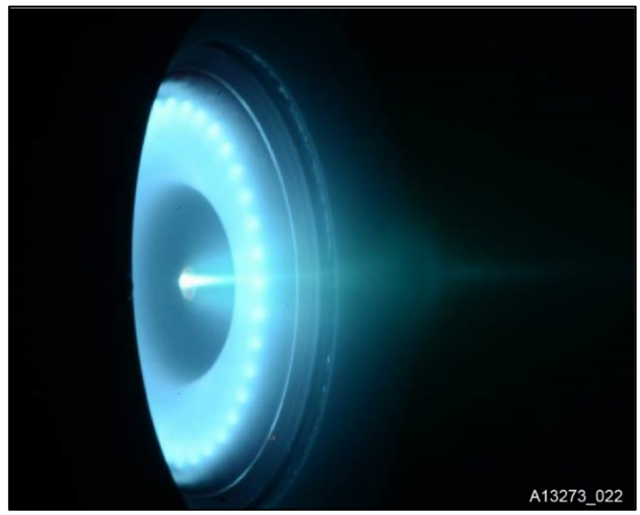

Figure 22: EM1 Engine Operating in Tank H

Figure 23 outlines the MEP 650 EM1 and EM2 engine testing roadmap. The objective of maturing and qualifying a MEP 650 engine to TRL 6 has been completed. This includes all the functional, performance and environmental testing of EM2, the short duration testing (to verify the engine internal component erosion rates can support long duration endurance testing) and 947 hours at 684 W endurance testing of the EM1 engine.

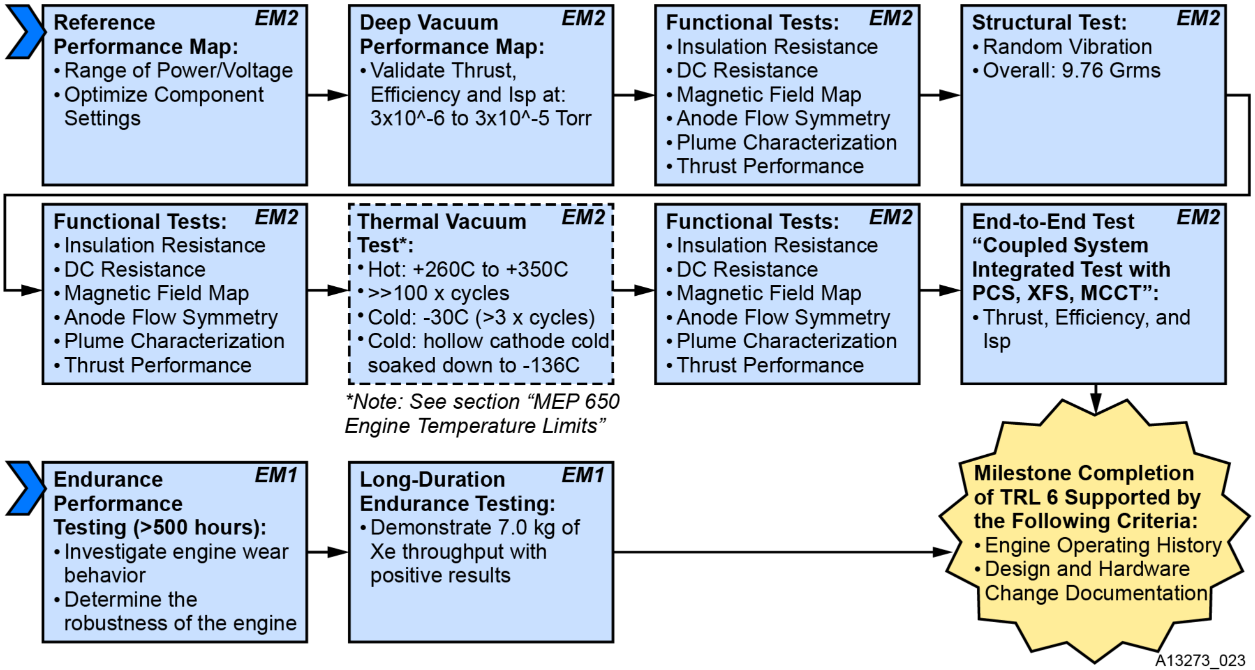

Figure 23: MEP 650 Engine Testing Roadmap

Deep Vacuum Performance Mapping: EPL uses its much larger Tank M and BAT vacuum facilities to perform plasma engine performance characterization. EPL has operated the EM2 MEP 650 engine in the Tank M vacuum tank test facility and performance was documented with varying background pressures. The Tank M facility is fitted with 26 CVI Torr Master 500 Cryo-pumps and has a base pressure of 2×10^{-8} Torr with a xenon pumping speed of 90,000 L/s. Engine performance data were taken for a total of ten different vacuum chamber background pressures over a test period of several days. Tank M was fitted with several STBL ion gauges to perform these measurements. The engine was mounted to an EPL-developed thrust stand, with a heritage of EP flight engine testing spanning back to the year 2000, shown in Figure 24. Thrust data was consistent at 30.2 ± 0.5 mN, at near the nominal engine input power of 650 W, over the background pressure range of 3.45×10^{-6} Torr to 1.02×10^{-5} Torr. Engine performance decreased as the background pressure increased to 3.11×10^{-5} Torr. These data are presented in Figure 25. This MEP engine behavior is important since it suggests that the MEP engine technology will always have higher performance in space.

Engine EM2, with performance enhancement modifications, was operated in Tank M at power levels up to 1 kW to investigate the performance capability of the unit at very low background pressures. These data are reproduced in Figure 26 and show that the engine thrust-power increases with increasing input power to a level of 50 mN/kW at 1 kW and 270 Vdc. The specific impulse (corrected for facility back flow) shows levels up to 1,725 seconds. Concurrent with these performance measurements, the exhaust plume of EM2 was analyzed with an EPL swing arm diagnostic system, shown in Figure 27, which enabled quantification of the engine plasma production efficiency, beam energy efficiency, beam divergence and total engine efficiency. The total engine efficiency results correlated well with the total engine efficiency obtained from the thrust stand readings. Figure 28 shows the EM2 engine operating at 1 kW in Tank M.

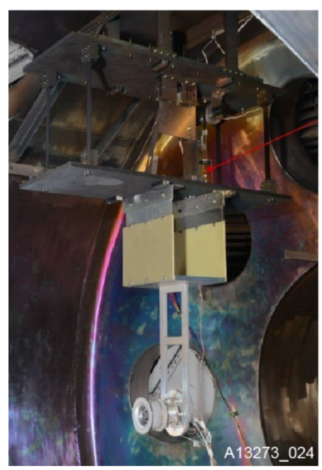

Figure 24: EPL Thrust Stand

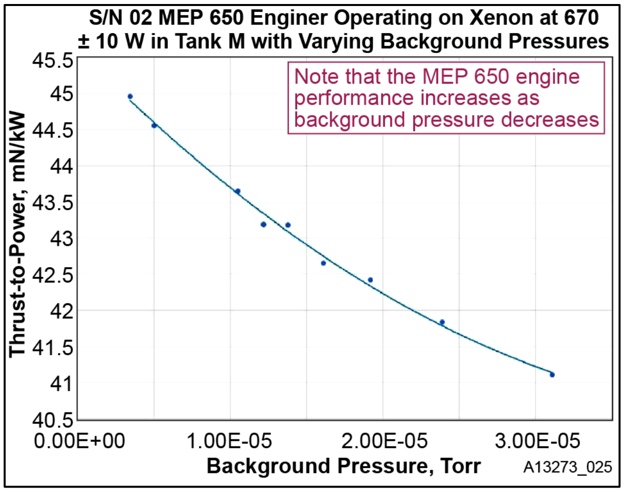

Figure 25: MEP Engine EM2 Performance with Varying Background Pressures

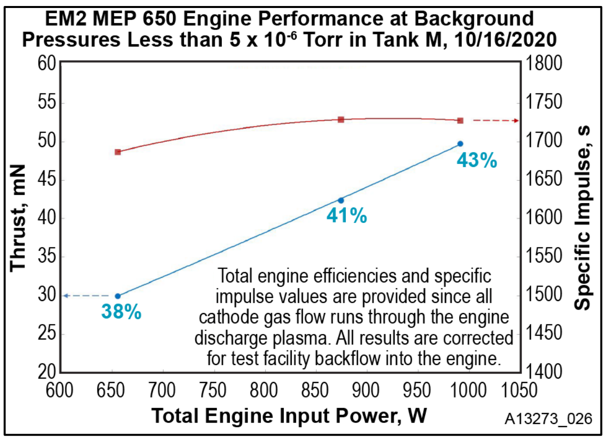

Figure 26: EM2 Engine Showing Performance Up to 1 kW

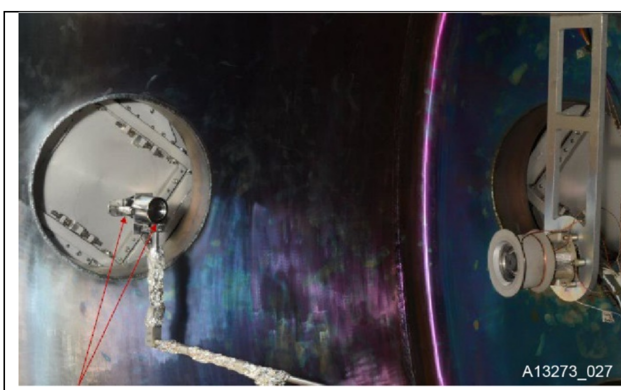

Figure 27: Ion Flux Probe (Left Arrow) and Ion Energy Probe (Right Arrow). EM2 Engine on Far Right.

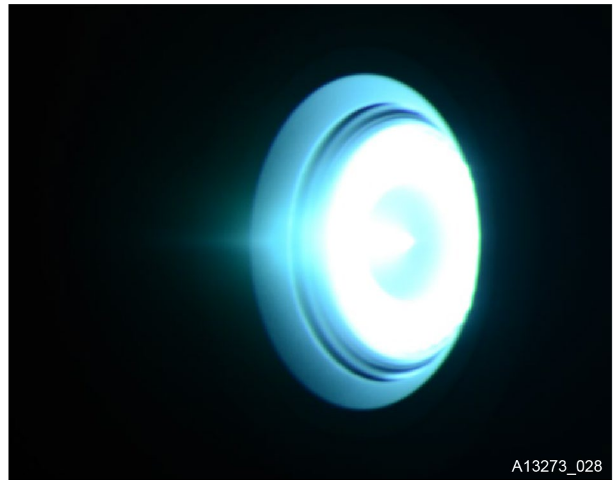

Figure 28: MEP 650 EM2 Engine Operating at 1 kW

Structural Test: EPL developed a proof-of-concept MEP 650 engine from which the EM1 and EM2 engines were designed and fabricated. An important feature of the MEP 650 engine is that the magnet circuits act to hold together the various engine structural elements. To demonstrate the robustness of this design approach, the proof-of-concept engine was run through sinusoidal and random vibration testing at EPL. Figure 29 documents one of the random vibration axes tested on EPL's vibe stand with the proof-of-concept engine. The vibration level tested was 9.76 Grms. This was the proto-flight level associated with qualifying EPL's MEP 180 krypton propulsion system presently flying on the USAF FalconSAT-8 spacecraft. No structural failures or part misalignment was noted after these 3 axes tests.

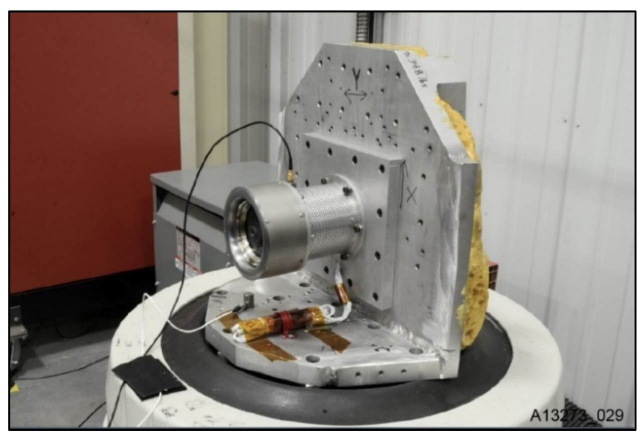

Figure 29: Proof-of-Concept Engine Random Vibration Axes Tested on EPL's Vibration

Magnetic Field Characterization Test: The EM2 engine was placed in EPL's fixture for measuring the far field magnetic intensity around a plasma engine, shown in Figure 30. This apparatus uses a Lake Shore three-axis probe mounted on a multi-axis probe positioning system. This apparatus allows EPL to characterize the magnetic field distribution around its plasma engines and thus provide critical information for spacecraft payloads regarding possible adverse interactions. These field measurement campaigns were performed several weeks apart with the EM2 engine operated extensively during these data collection runs. Figure 31 shows the far field magnetic strength behavior in contour plots before and after these EM2 test runs. There was no appreciable difference in the magnitude of the magnetic field intensity around EM2. This result shows that the EM2 MEP 650 engine design and construction is stable.

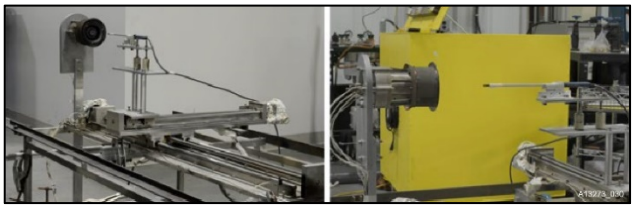

Figure 30: The Precision X-Y Table Which is Used to Position an Accurate 3-Axis Gauss Meter Probe Around EM2 Engine (Left). Probe Positioned to Take an On-Axis Magnetic Field Measurement (Right)

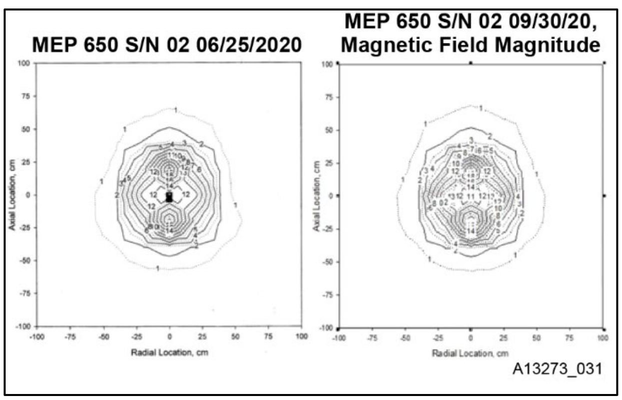

Figure 31: MEP 650 EM2 Engine Data Output Magnitude Field Contour Map

Plume Characterization Test: Plume Characterization is performed as part of functional testing and post-system integrated end-to-end testing. The intent of the plasma plume measurements is to determine whether the plume features, shape, density, position, etc., change between operations of the engine. Specifically, any changes in the plume between operating conditions where the engine is fully temperature equilibrated, shut down, and then run through multiple startups, temperature equilibration and shutdown cycles.

Following completion of successful MEP 650 system operations, the EM2 engine was operated using laboratory power supplies over several days to characterize the plasma plume features. The xenon background vacuum chamber pressure during engine operation was 4×10^{-6} Torr. The MEP 650 system XFS and tank, along with the MCCT, were placed out of vacuum to support these tests. Each campaign comprised a total of 250,000 loop Langmuir probe data points divided into eight axial locations as the probe rake assembly moved from close to the engine exit plane, to EPL's large BAT vacuum chamber north bulkhead as noted in Figure 32.

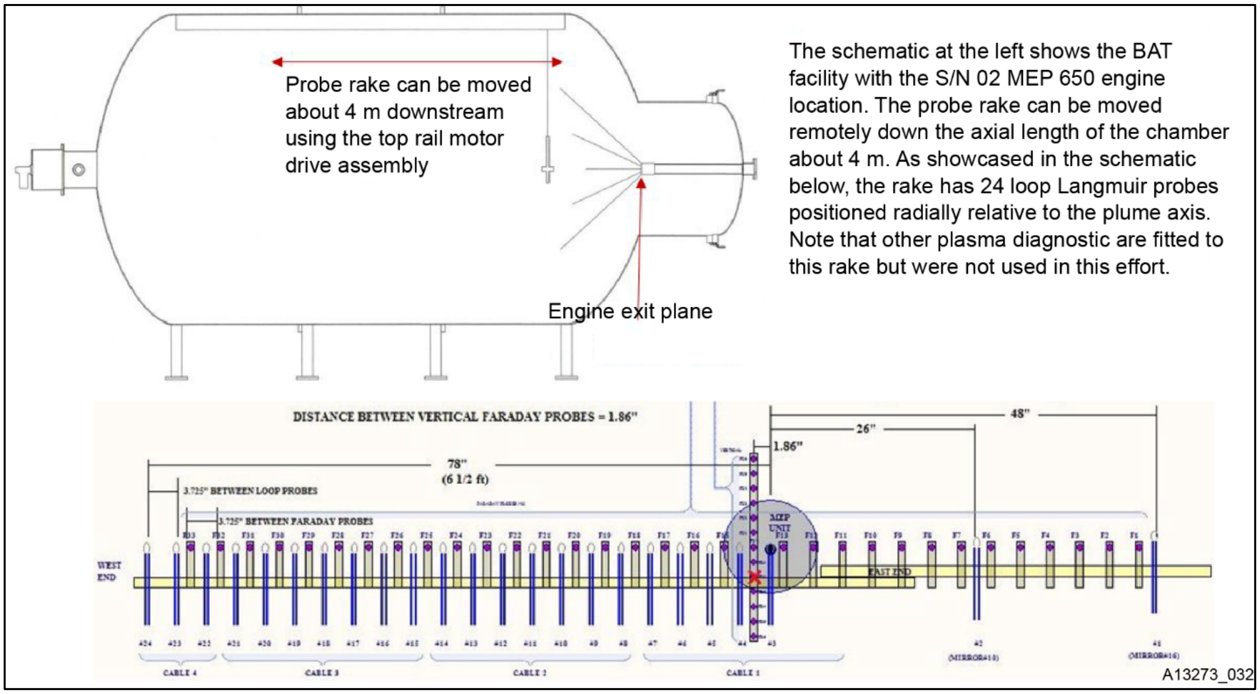

Figure 32: EPL's BAT Facility Plume Diagnostic System

These raw data were analyzed using EPL's proprietary Langmuir probe trace analysis algorithms. The EPL loop Langmuir probe trace analysis algorithms have been verified by comparing data taken of the plume of a HET operated in EPL's large vacuum chamber and in the USAF SPEF vacuum chamber. Both EPL's loop Langmuir probe analysis programs, and the USAF needle Langmuir probe analysis programs provide similar results.

The plume plasma parameters, electron number density (n_e), plasma potential (V_p), and electron temperature (T_e), are of fundamental importance in integrating the MEP 650 engine to a user spacecraft. EPL's analysis included the calculated electron number density, plasma potential and electron temperature in the engine plume at the relevant location. The error/uncertainty associated with each of these parameters are: ± 30% of the n_e value stated, ± 0.25 volt of the V_p value stated, and ± 0.1 eV of the T_e value stated.

While an uncertainty of ± 30% for n_e may appear large, accurately measuring plasma electron density in an engine plume is very difficult and often a factor of two is considered acceptable. For each run, the n_e, V_p, and T_e results were put into curve fit routines which were used to formulate equations to populate large data tables from which contour plots could be created. The final product of these efforts, the respective contour plots for n_e, V_p, and T_e were presented to Ball by EPL.

Note that the local ion density is equal to the local electron density in a plasma such as the engine exhaust plume. However, while the electron motion is somewhat random, the ions are streaming downstream with a velocity of order 15,000 m/s.

The XFS xenon flow set points were identical for each run at a cathode flow rate of 1.2 sccm and an anode/manifold flow rate of 22 sccm.

For Run 1, the discharge plasma was operating at 269 Vdc at 2.64 A for 710.2 W, while for Run 2 the discharge plasma was operating at 270.4 Vdc at 2.76 A for 746.3 W. Operational engine data collected during the plasma plume campaigns was recorded by hand using EPL Log Sheets.

The run-to-run operation of the MEP 650 engine during the test campaigns was very repeatable, resulting in clear plasma parameter contour plots for easy comparison. A large amount of data was collected, analyzed, and plotted for each of two plasma plume loop Langmuir probe campaigns of the MEP 650 engine plasma exhaust plume over the extent of most of the internal volume of EPL's BAT vacuum chamber.

Comparing the contour plots of the n_e, V_p, and T_e results showed no significant differences in these parameters from run-to-run, or any plume distortion. These comparisons validate the operational and mechanical stability of the MEP 650 engine, and the geometrical consistency of its plasma exhaust plume features. By association, these results also point to the stability of the thrust vector associated with the MEP 650 engine.

The Run 2 plasma parameters tended to result in contour plots which extended slightly farther downstream than the contour plots for Run 1.

This behavior was due to the slightly higher discharge current and beam power for the Run 2 campaign which resulted in these features extending slightly farther down the vacuum facility.

Additionally, the slightly lower facility background pressure in Run 2 resulted in slightly smaller charge exchange ion production rates along the plume axis which tended to extend the plasma slightly farther down the chamber.

These comparison plots are shown in Figure 33, Figure 34 and Figure 35.

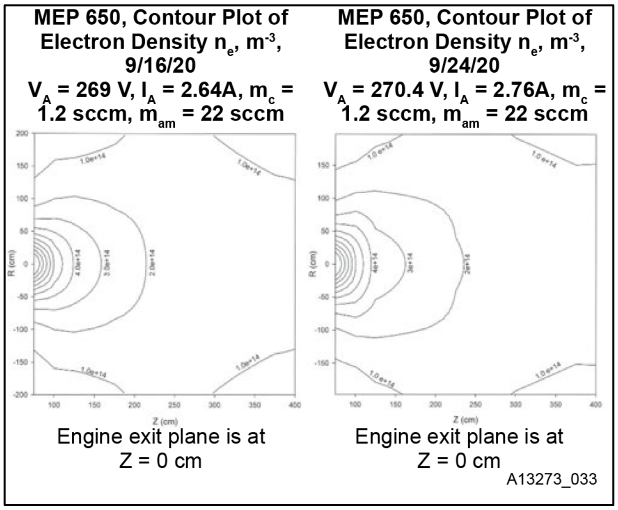

Figure 33: Comparison of Entire Plume Electron Density Features for Run 1 and Run 2

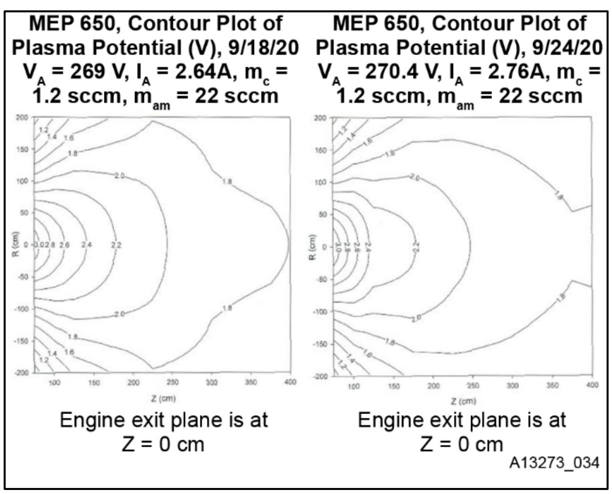

Figure 34: Comparison of Entire Plume Plasma Potential Features for Run 1 and Run 2

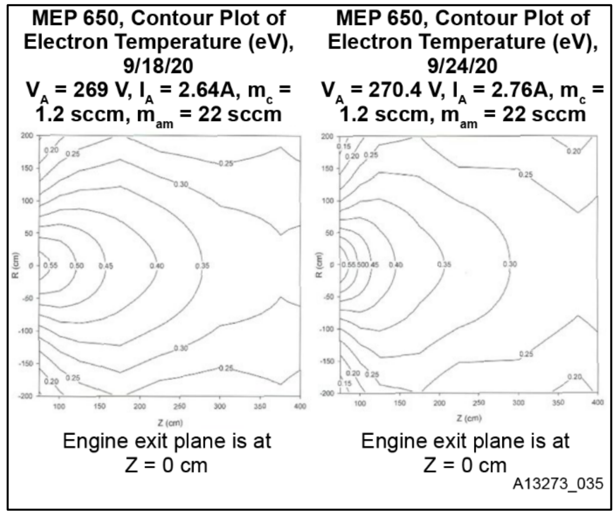

Figure 35: Comparison of Entire Plume Electron Temperature Features for Run 1 and Run 2

MEP 650 Engine Performance Testing: At different times, the EM1 engine operated on laboratory power supplies at an input discharge power of 650 W in Tank M to measure its performance prior to being installed in Tank H to support endurance testing. A specific impulse of 1,581 seconds and thrust efficiency of 35.5% were demonstrated during Tank M operations. Figure 36 shows a photograph of the engine during testing in Tank M after 500 hours of cumulative operation. Figure 37 documents the lack of discharge current operation, or breathing modes, associated with EM1 MEP 650 engine operation.

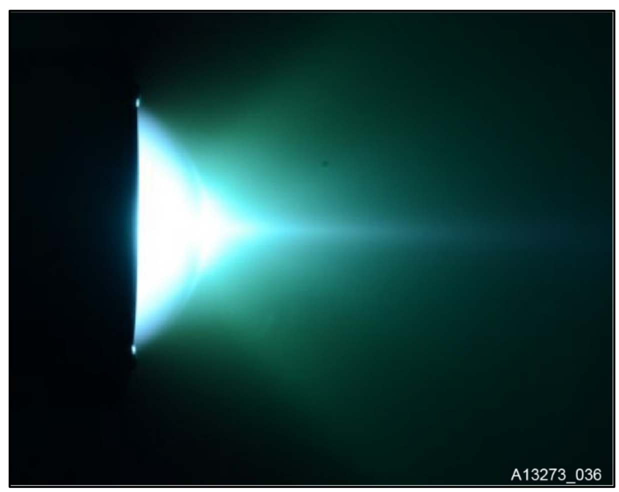

Figure 36: EM1 Engine After 500 Hours

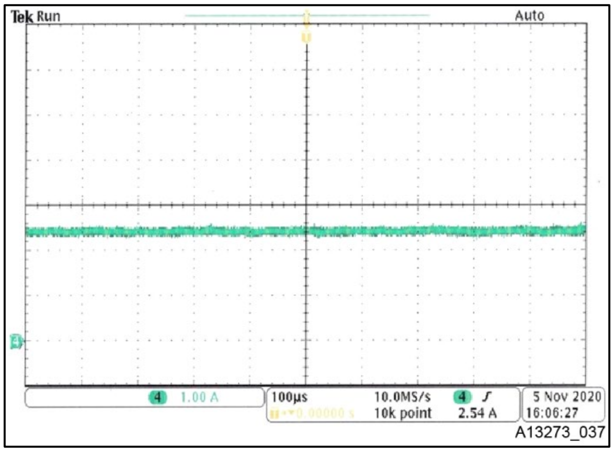

Figure 37: EM1 Showing No Breathing Mode Oscillations at 270V and Discharge Current of 2.33A

Facility Effects on Long Duration MEP Engine Testing: Two times during long duration endurance testing, at a discharge power of 684 W for 947 hours, the EM1 engine was shut down, cleaned of back-sputtered carbon using a vacuum cleaner (leaving the engine otherwise untouched) as shown in Figure 38, inspected, and photographed. During these shutdown events, the cryo-pumps in Tank H were regenerated, the xenon reclaimed, cleaned, and re-bottled to support further testing. Unlike HETs where the anode/manifold is located upstream in a rather narrow insulator channel, the MEP 650 engine anode/manifold is completely open to the test facility with a large view factor for the ready accumulation of sputtered carbon backflow. Nevertheless, the life/component tests to date have demonstrated that cleaning approximately every 500 hours using a vacuum cleaner only, is sufficient to address this facility issue. The goal of the engine endurance testing of accumulating a lifetime of 1,000 hours (or 7.0 of Xe throughput) at a discharge power of 650 W has been completed.

Milestone significance: The MEP engine performance testing has validated the unit for BCP-100 mission applications. Milestone completion criteria is supported by engine operating history data, design, and hardware change documentation. The MEP 650 engine is at TRL 6.

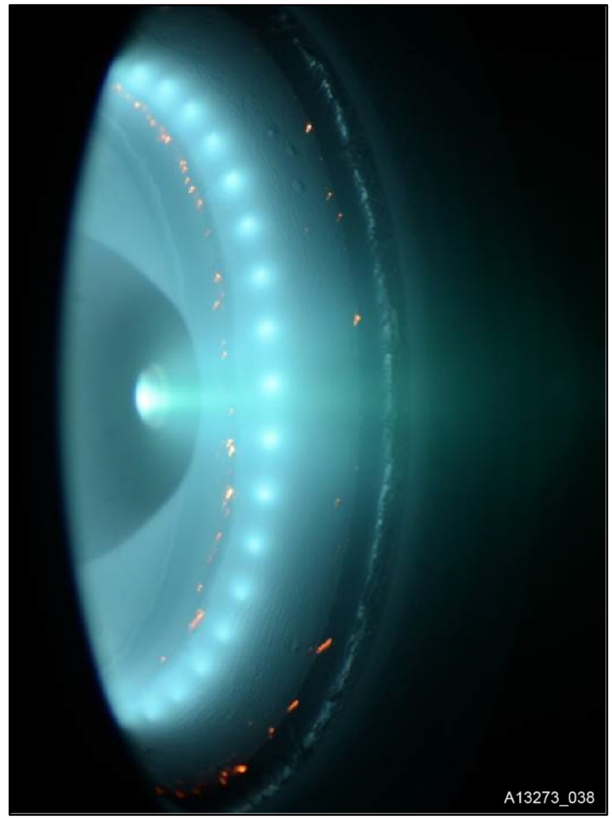

Figure 38: Back-sputtered Carbon from the GRAFOIL Target/Beam Dump

MEP 650 SYSTEM "END-TO-END" INTEGRATED TEST

Operation of the MEP 650 system "end-to-end" was demonstrated over three days of testing. System operation was consistent from day-to-day, with outgassing, gas valve settings, startup and run, controlled by a laboratory computer through the MCCT system that was placed in-vacuum.

System startup and operation was demonstrated from an out-of-vacuum EPL manufactured Li-ion battery pack that was like that of a typical SmallSat class spacecraft. See Figure 39, Figure 40 and Figure 41.

The MEP 650 system showed stable and reliable operation powered by a Li-ion battery pack down to a voltage of 22 Vdc. Dozens of system startups were performed over the three-day period with 100% reliability. Multiple runs in excess of one hour were performed using a laboratory power supply in place of the battery pack with all system component temperatures nominal. The XFS flow rate set points were calibrated and set to provide nominal operation of the EM2 MEP engine.

CHALLENGES AND MITIGATIONS

Background pressures in EPL's larger BAT vacuum facility were initially in the very high 10^{-5} Torr range due to tank contamination from a thermal shroud that was being high temperature tested in support of a separate activity.

A single scan was taken of the engine plasma plume using EPL's vacuum chamber Langmuir probe rake assembly after initial system startup on the first day, but results were dominated by noise due to the excessive vacuum chamber background pressure.

Nevertheless, as the system was operated over these three days, the energetic plasma plume from the MEP 650 engine gradually cleaned contaminants from the interior vacuum chamber wall surfaces and the background pressure steadily decreased.

This plume cleaning of the chamber walls was augmented by intensive cleaning by EPL personnel prior to the last test day.

During system operations on the third day, the vacuum chamber background pressure had reduced to the low 10^{-5} Torr range which is considered nominal for testing of other plasma engines such as HETs.

Due to the vacuum chamber background pressure starting out high and gradually reduced over the three days of system testing, the PCS was affected by this high background pressure. Specifically, internal pressure induced Paschen breakdowns knocked out the voltage telemetry chip from the engine shortly after the start of testing on day one.

Additionally, pressure-induced spurious transient arcs around the engine wiring caused some of the series connected DC-DC converters in the nine-converter anode power system to shut off periodically. This necessitated a controller shutdown of the engine, a system reboot, and an engine restart.

As cleaning of the vacuum chamber walls by the engine plasma plume continued, and the chamber background pressure decreased, these spurious arcs and converter shutdown events gradually decreased also.

During the final test day, the chamber pressure had reduced to a level where no spurious arcing occurred and, consequently, no spurious PCS converter shutdown events occurred. However, after achieving this condition, and while preparing for a complete plasma plume scan, the PCS filter/control board failed due to a previous voltage stress arcing event which shut down all testing using the PCS. After these system level tests in the BAT, EPL completed upgrades of the EM PCS based on design changes from lessons learned coming out of the end-to-end MEP 650 system test. This upgraded EM PCS was operated in Tank M with the EM2 MEP 650 engine and demonstrated multiple-engine start and run periods.

To further mitigate the converter shutoff concerns in future builds, EPL will add Schottky diodes across the outputs of each of the nine series connected Interpoint/Crane MFL DC-DC converters. These converters can shut off if they receive a transient negative back-bias in excess of 0.6 Vdc. EPL performed a worst-case converter transient output voltage test of 350,000 on/off cycles to validate this future build change.

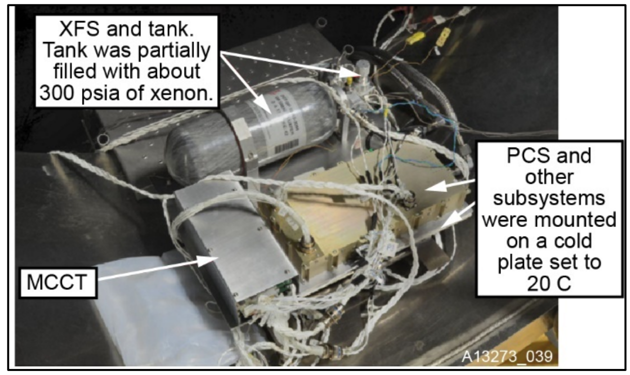

Figure 39: MEP 650 System Installed in EPL's Vacuum Chamber Prior to Covering with Aluminum Foil

Figure 40: MEP 650 EM2 Operating During End-to-End Testing on Li-ion Battery Power

Figure 41: EPL's Li-ion Battery Used in MEP 650 System End-to-End Test

EPL completed the MEP 650 component testing and demonstrated a MEP 650 propulsion system which was successfully operated end-to-end. Testing met the tasking objectives but was hindered somewhat by high facility pressures compromising PCS operation due to contamination from previous work for a separate program. Part failures in the PCS were addressed under an EPL IR&D effort which brought the PCS back to its original operating specifications. The MCCT, XFS and EM2 engine met the performance metrics established before testing.

INTEGRATING A MEP 650 SYSTEM TO BALL SMALLSAT

Successful integration of the MEP 650 propulsion system to a Ball SmallSat requires accommodating the requirements of the propulsion system to the requirements and limitations of the spacecraft.

Although attaining a TRL-6 status for the MEP 650 system is a useful yardstick and the goal of this development effort, it does not address the integration and architecture tasks which must be completed before a successful Ball SmallSat can be flown with a MEP system.

EPL has a complete MEP 650 propulsion system which is fully operational to support the various design integration tasks identified as necessary to demonstrate integration capability:

Heat Flux: EPL in conjunction with Ball, will quantify the heat flux from the MEP 650 engine back to the spacecraft using operational temperature data to calibrate a thermal model which can then be used to optimize the engine attachment structural design to the spacecraft.

Plume Impacts: EPL will use operational plume data to develop an empirical model describing the distribution of ion flux and ion energy at the plume edge which could impact the SmallSat. Keep-out zones will be quantified to guide payload/instrument placement for future mission applications.

Diagnostic Port: EPL will work with Ball engineers to define in-situ functional and continuity tests of the MEP 650 system which can reduce risk and cost during assembly and qualification testing. Testing functions will be implemented by including a diagnostic port to the MEP 650 propulsion system and verifying functionality.

Power, Control and Grounding: EPL will work with Ball engineers to develop a complete end-to-end power distribution and control architecture to support operations of the MEP 650 propulsion system. Additionally, the correct spacecraft grounding scheme and plasma grounding scheme suitable for a Ball (SmallSat) will be defined.

Tank Structure: EPL will work with Ball engineers to develop effective xenon propellant tank mounting options with consideration to tank thermal conduction isolation, tank thermal blanketing, tank heating, and tank temperature control.

Box Location: The PCS and MCCT are separate boxes which must be assigned locations within the SmallSat bus. The MCCT is quite small and requires very little heat rejection (3 W). EPL will work with Ball engineers to properly locate the larger PCS and to quantify the expected heat transfer (up to 140 W) and to design the necessary thermal interface and structural mounting.

Soft Start: EPL will use the existing MEP 650 propulsion system to develop an effective soft start technique which minimizes the SmallSat bus power draw during engine startup.

Magnetic Moment: EPL will use its Helmholtz coil system to measure the magnetic moment for the MEP 650 engine in all three axes to help Ball engineers quantify potential guidance and navigation effects in different flight environments. If required, EPL will work with Ball engineers to mitigate these magnetic moments.

Engine Gimbal: EPL will work with Ball engineers to explore the need for gimballing a single MEP 650 engine on a SmallSat to ensure proper center of mass thrusting and thrust vector/attitude adjustments. This work will focus on use of the existing EPL gimbal system developed by EPL under an EPL IR&D effort.

Plasma/Solar Array: EPL will work with Ball engineers to establish likely interactions between the MEP 650 engine plasma exhaust plume and the SmallSat solar array. Using the extensive literature on this subject, EPL and Ball will establish design/build guidelines for the solar array and spacecraft Faraday shielding.

CONCLUSION AND PLANNED FUTURE WORK

Demand for low cost, high performance EP systems continues to increase for small satellite applications. Ball identified EPL's MEP 650 system as an EP system with potential to meet Ball SmallSat requirements and tasked EPL with its development, design, manufacture, and test.

All development tasks are completed and verified, including an endurance test that demonstrated 947 hours at a discharge power of 684 W (equivalent to 997 hours at 650 W) identified to demonstrate TRL 6 status. An integrated "end-to-end" system level test was also successfully completed. The MEP engine exceeded development activity performance goals: total engine efficiency up to 35.5%, thrust of 30 mN and specific impulse of 1,581 seconds while operating at a discharge power of 650 W.

Before the MEP system is integrated to a Ball SmallSat, a series of activities will be performed by EPL to demonstrate integration readiness.

ACKNOLWEDGEMENTS

The authors would like to acknowledge the commitment and expertise of the EPL Team in advancing the MEP 650 propulsion system to TRL 6 and for advancing the integration of the MEP 650 system to Ball (SmallSat).

REFERENCES