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CONSIDERATIONS FOR OPERATION OF A DEEP SPACE NANOSATELLITE PROPULSION SYSTEM

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A distinguishing feature of deep space CubeSats is that they require some form of propulsion system, either for orbital maneuvering operations, spacecraft momentum management, or both. However, the comparatively short lifecycle for these missions, combined with the mass and volume restrictions that are attendant with the CubeSat form factor, make the integration of propulsion systems one of the highest-risk aspects of the entire mission. There are a limited number of facilities around the country that can support accurate testing of thruster systems that generate milli-Newtons of thrust, and the cost associated with handling and transportation of traditional propellants can be prohibitive for many CubeSat mission budgets. As a result, many deep space CubeSats are considering propulsion systems that are either at a fairly low technology readiness level or which will be integrated after a truncated test campaign. This paper will describe the propulsion system architecture selected for the BioSentinel mission, a six-unit CubeSat under development at NASA Ames Research Center. BioSentinel requires a propulsion system to support detumble and momentum management operations, and this paper will discuss the integration of a third-party propulsion system with an Ames-built CubeSat, as well as the test campaign that is underway for both quality control and requirements verification purposes.

INTRODUCTION

The promise of a new wave of heavy-lift launch vehicles capable of transporting secondary payloads to geostationary transfer orbits or beyond has resulted in a recent spike in the development of CubeSat-class spacecraft targeted for operation in deep space. One challenge that must be overcome for successful operation in deep space is the development of a range of reliable propulsion systems. Such systems are required for both orbit maintenance and reorientation maneuvers, however a relatively small field of solutions conform to the mass, volume, and power constraints of CubeSats. Moreover, CubeSat programs often have smaller budgets and shorter development lifecycles than traditional spacecraft, making the testing and integration of propulsion systems even more challenging. The combination of relatively few viable vendors and short development times means that the propulsion system can be one of the higher-risk elements of the overall spacecraft, which is an untenable position for deep space operations. This paper will describe the propulsion system architecture selected for the BioSentinel mission, an upcoming CubeSat-class spacecraft under development at NASA Ames. BioSentinel will be the first deep space CubeSat

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flown by NASA Ames, and great care is being taken to ensure that the propulsion system will perform as desired on orbit.

For the purposes of this work, a CubeSat (also known as a nanosatellite) will refer to any spacecraft that adheres to the CubeSat standard[1], whereby a 10 cm x 10 cm x 10 cm cube comprises one unit of volume, abbreviated as 1U. In contrast to the 6U volume of the BioSentinel spacecraft, traditional CubeSats are ssmaller than 3U in total volume, with an overall size of no more than 10 cm x 10 cm x 30 cm. This volume constraint allows the spacecraft to be compatible with the various deployment mechanisms that are available, such as the Cal Poly P-POD[2] or the UTIAS/SFL X-POD[3]. NASA Ames has a rich history of building 3U CubeSats to research topics in fundamental space biology, such as the GeneSat-1, O/OREOS, and PharmaSat spacecraft[4]. More recently, NASA Ames developed a fleet of eight 1.5U CubeSats for the Edison Demonstration of SmallSat Networks (EDSN) mission, which was to demonstrate multi-point science operations in LEO[5]. Unfortunately, EDSN suffered a launch vehicle failure prior to deployment.

BioSentinel is a unique mission in that it combines Ames heritage related to fundamental space biology with a wide range of cutting-edge CubeSat-class subsystems, while operating in deep space[6]. BioSentinel will launch on the first flight of the Space Launch System (SLS), a heavy-lift rocket being developed by NASA to enable future human missions to deep space. On the maiden launch of SLS, known as Exploration Mission 1 (EM-1), the rocket will place the Orion Multi-Purpose Crew Vehicle on a Lunar orbit trajectory prior to deploying a number of secondary payloads, including BioSentinel.

The spacecraft bus must provide a stable thermal environment for the science payload, and also be capable of pointing body-mounted patch antennas to ensure communications with the ground. In contrast to typical CubeSats, momentum management must be performed using an array of thrusters, since there is insufficient magnetic field at the target orbit to allow for magnetic torquers to be of use. Similarly, the operational distance from the Earth is such that the spacecraft will rely upon the Deep Space Network (DSN) to close the communication link, something that has not yet been attempted by a CubeSat. Additionally, a Field-Programmable Gate Array (FPGA) has been selected for the main Command and Data Handling (C&DH) computer. While more robust to radiation-induced faults, such a processor has not yet been used for CubeSat C&DH operations at Ames. Thus, the BioSentinel mission managers must not only oversee the integration and test of a collection of heterogeneous subsystems, but must also accommodate a test plan for a propulsion system. Typical monopropellant reaction control systems cannot be used on CubeSats due to safety restrictions levied on secondary payloads, meaning that the mission managers must look beyond established deep space technologies to meet the mission requirements.

The BioSentinel project team has selected a 3D-printed cold gas propulsion system for use on the spacecraft. This system, under development by Lightsey Space Research (LSR) in Atlanta, GA, has already been shown to be capable of adhering to the stringent mass, volume, and power requirements levied on CubeSats[7]. By 3D-printing the majority of the structure, it is possible to accommodate the extreme volume limitations of the BioSentinel spacecraft while still ensuring the system will have sufficient control authority for both detumble and momentum management operations. This paper will describe the current design of the cold gas propulsion system for BioSentinel, and will also describe the test regime that has been planned for qualification and verification/validation purposes. A series of tests will take place at LSR’s facilities in Atlanta, at NASA’s Glenn Research Center (GRC) in Cleveland, OH, and at NASA Ames. Such a distributed test campaign adds a certain measure of complexity to development of the system, but also ensures that the very best facilities are being used to test each aspect of the propulsion system's design.

The remainder of this paper is organized as follows. First, the science objectives and hardware requirements for the BioSentinel mission will be described. With this context established, the propulsion system selected to satisfy the mission requirements will then be detailed. The test plan to verify the performance of the selected propulsion system will subsequently be presented, highlighting work that will be carried out at all three test sites. A discussion of the next steps and potential challenges facing development of both an Engineering Development Unit and a Flight Unit will follow, and the paper will end with some conclusions about the development of deep space CubeSat systems.

THE BIOSENTINEL MISSION

The objective of the BioSentinel mission is to assist in mitigating risks to humans during future long-term space exploration missions beyond low Earth orbit (LEO). This will be achieved by studying the impact of the deep space radiation environment on genetically modified yeast cells. Specifically, BioSentinel will utilize the monocellular eukaryotic organism *Saccharomyces cerevisiae* (yeast) to report DNA double-strand-break (DSB) events that result from ambient space radiation. Yeast was selected due to its similarity to cells in higher organisms, the well-established history of strains engineered to measure DSB repair, and the spaceflight heritage from past NASA Ames missions. DSB repair in yeast is strikingly similar to humans, and BioSentinel will provide critical information about what impact deep space radiation may have on future manned missions. BioSentinel will also include physical radiation sensors based on the TimePix sensor, as implemented by the RadWorks group at NASA's Johnson Space Center. This sensor records individual radiation events, including estimates of linear energy transfer (LET) values. Radiation dose and LET data will be compared directly to the rate of DSB-and-repair events as indicated by *S. cerevisiae* cell population numbers.

The yeast cells are dehydrated prior to launch, and then are rehydrated and kept alive in deep space using a microfluidics system and heaters. The payload container itself is maintained at 1 atm pressure throughout the mission life, and the overall size of the science payload is approximately 4U (10cm x 20cm x 20cm). The reaction of the yeast cells to the deep space radiation environment is monitored using optical measurements inside the payload container. The yeast is cultured in multiple independent culture microwells, which are built into a 96 well plate, depicted in Figure 1 below. Optical measurements are performed using LEDs shining through the culture wells, allowing for measurement of DSB-triggered cell growth and metabolism. It is noteworthy that unlike many deep space missions, there are no specific pointing requirements levied on the spacecraft by the science payload, beyond ensuring thermal stability. Provided the yeast does not get too hot or too cold, the experiment simply requires access to the deep space environment, as opposed to being pointed in a specific direction to take measurements.

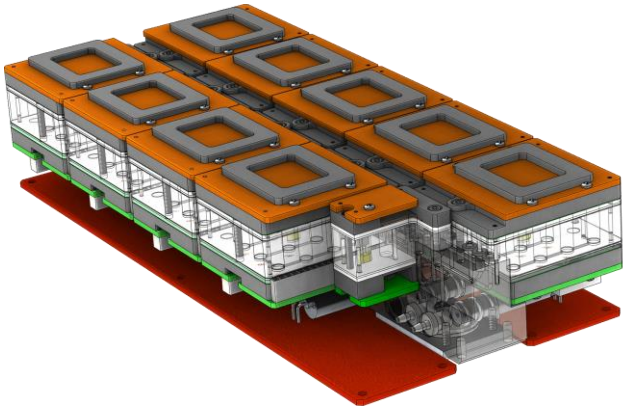

Figure 1. The fluidics array which supports the science payload for the BioSentinel mission.

All spacecraft bus systems, including C&DH, communications, attitude determination and control, and propulsion must occupy no more than 2U of volume in order to conform to the volume restrictions of the spacecraft dispenser. As can be seen in Figure 2, these systems occupy the "rear" portion of the spacecraft along the $\mathbf{b}_x$-axis, including a small volume allocation for the propulsion system of approximately 10cm x 20cm x 4cm. A thin slice of volume on the front of the spacecraft is allocated for the gimbal of the deployable solar arrays. The nature of the Earth-leading, heliocentric orbit that BioSentinel will occupy is such that for the majority of the mission it will be necessary to slew the spacecraft up to 90 degrees in order to establish a communications link with the DSN. This slew maneuver will be undertaken using a set of three reaction wheels integrated within the spacecraft. These reaction wheels will also have to counteract the effects of a solar radiation pressure torque, and current estimates are that the wheels will saturate approximately every three days. Furthermore, early estimates for the tip-off conditions from SLS indicate that the reaction wheels may also saturate during detumble. Spacecraft detumble and reaction wheel momentum management over the 12 month nominal operating life will be accomplished using the propulsion system.

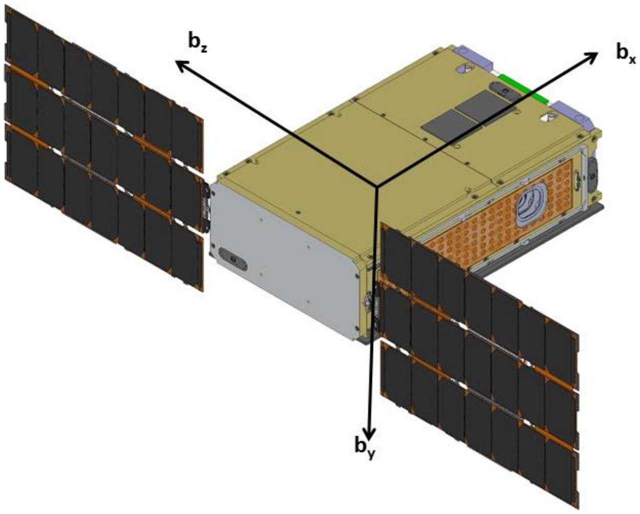

Figure 2. The BioSentinel spacecraft, shown with solar panels deployed and the body-fixed reference frame overlaid for clarity.

In general, the pointing requirements levied upon the spacecraft are quite loose. The ADCS must keep the solar panels oriented towards the sun and periodically point the medium gain antenna (MGA) at the Earth. Both of these activities require no better than 5 degrees of pointing accuracy. However, coarse attitude determination methods employed in LEO that leverage a magnetic field or Earth vector measurement cannot be used in this environment; a star tracker is necessary for 3-axis attitude determination. BioSentinel will also utilize sun sensors for coarse attitude determination when the star tracker is not enabled and a gyro for rate information. Recall that reaction wheels will control the attitude of the spacecraft while the thrusters will be responsible for removing momentum from the system. The star tracker, reaction wheels, and inertial measurement unit are all integrated into a stand-alone module provided by Blue Canyon Technologies (BCT). The spacecraft C&DH processor must manage communications between the BCT unit and the propulsion system provided by LSR, while also executing high-level attitude determination and control activities. A block diagram of the software architecture can be seen in Figure 3.

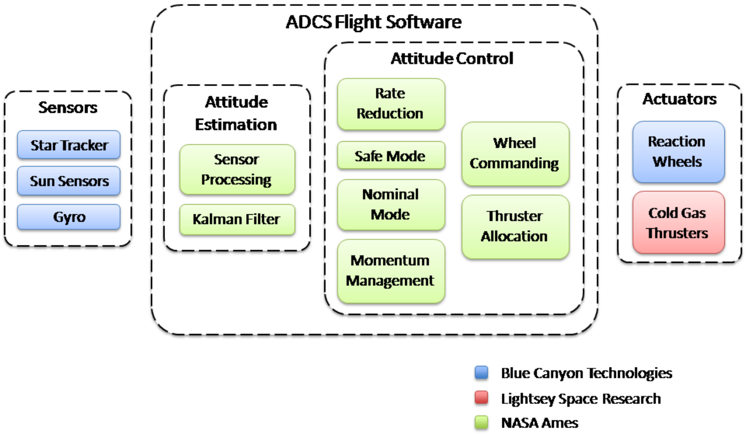

Figure 3. The software architecture for the BioSentinel attitude determination and control subsystem.

Based on the volume limitations of the spacecraft and the safety restrictions imposed from flying as a secondary payload on SLS, the field of candidate propulsion systems for BioSentinel was fairly small. A number of vendors make cold gas systems that meet the safety restrictions for SLS, but not many of these could fit inside the available volume envelope. Microelectrospray propulsion (MEP) technologies were also examined for the mission[8], although these systems were deemed to not be at a sufficient technology readiness level based on the project schedule. Thus, a unique cold gas propulsion system was selected as the baseline design for BioSentinel. This thruster system is unique in that the main tank, plenum, nozzles, and tubing are all 3D-printed in a single, monolithic component. This design approach allows the developers to maximize the volume allocated to the main tank and plenum using non-traditional internal geometry, which is very important for the minimum 12 month mission life. Mechanical valves and drive electronics are affixed to the 3D-printed structure, and as shown in subsequent sections a very fine level of impulse control is achievable. Greater detail on the baseline propulsion system design is provided in the next section.

PROPULSION SYSTEM DESIGN

The BioSentinel thruster is a cold gas system that is primarily 3D-printed. 3D-printing is an additive manufacturing process in which a part is built up layer by layer by adding material, rather than removing material, as is done in traditional machining. The propellant tanks, pipes, and nozzles are all printed into a single piece of high strength composite material. This piece also serves as the structure of the thruster, and provides mounting locations for the valves, sensors, and fill ports, as well as attachment points for mating with the spacecraft.

There are several advantages to using a 3D-printed structure in a propulsion system. The main advantage is the increased versatility in using the allotted volume. The 3D-printing process does not become more difficult or expensive with increasing geometric complexity. This allows parts to be made that would be prohibitively expensive or impossible with removal machining. This flexibility allows the propellant tanks to utilize all available volume, which increases the maximum propellant load, and thus the total delta-velocity (ΔV) impulse available to the spacecraft. The use of 3D-printing also reduces the number of pressure seals required, which reduces the potential for leaks in the system. Figure 4 shows a computer rendering of the BioSentinel thruster system, showing the printed structure (blue), the electronics (green) and metal interfaces (grey).

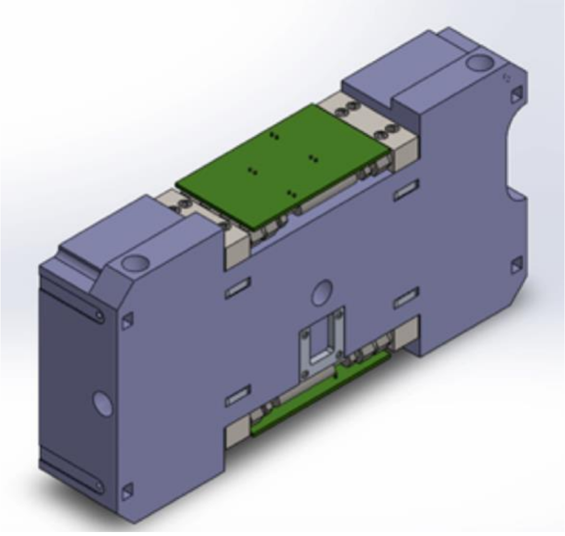

Figure 4: CAD rendering of the BioSentinel thruster.

The thruster uses R-236fa, an inert chemical which is stored as a saturated liquid-vapor mixture, as its propellant. R-236fa is a commercially available refrigerant, chosen for its high density and relatively low saturation pressure. The high density allows for a larger propellant loading, which is important for systems with tight volume constraints like CubeSats. The low saturation pressure reduces the consequences of a structural failure of the thruster. While it would still be a serious failure for the BioSentinel mission, the thruster would not pose a safety hazard to the primary payload. This eases the process of approval to fly with a propulsion system as a secondary payload.

The BioSentinel thruster has two propellant tanks, called the “main tank” and the “plenum”. Eight solenoid valves control the flow of propellant between the tanks and seven nozzles. Figure 5 shows a block diagram of the thruster. The majority of the propellant (approximately 245 grams) is stored in the main tank as a saturated liquid-vapor mixture. A saturated mixture allows more propellant to be stored than a vapor alone, due to the higher density of the liquid component. The main tank is equipped with pressure and temperature sensors to determine the state of the propellant. Although the pressure of a saturated mixture can be determined from its temperature alone (and vice versa), both sensors were included to detect when the propellant is almost exhausted. At this point, the main tank will contain vapor alone, and the pressure and temperature will be independent. In this phase, the propellant state would not be observable with a single sensor, so both temperature and pressure sensors are needed.

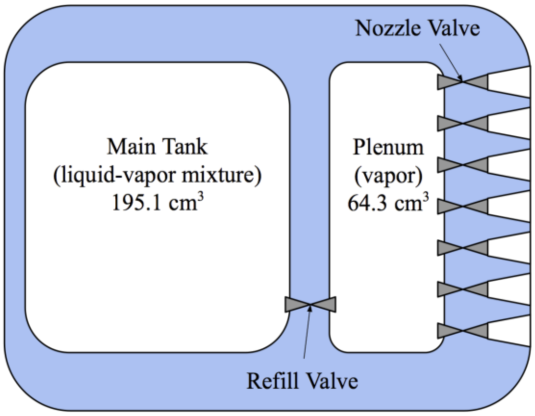

Figure 5: Block diagram of the BioSentinel thruster.

Rather than drawing from the main tank directly, the nozzles are fed from the plenum. The plenum is a smaller tank that stores propellant as a vapor only, and is refilled from the main tank as propellant is exhausted. This serves three purposes. First, it protects the spacecraft against a single valve failure. If any of the nozzle valves fail open, only the small amount of propellant in the plenum would be expelled, rather than the entire propellant load. Second, it allows the nozzle backpressure to be controlled by regulating how often the plenum is refilled. The main tank pressure cannot be controlled without changing its temperature. Finally, the density of propellant in the plenum is uniform, unlike the main tank, which has droplets of liquid floating amongst the vapor. These droplets may be ingested by the feed pipes, causing unpredictable behavior in the nozzles. Feeding the nozzles from a uniform vapor tank mitigates this concern.

The system's thrust is a function of the backpressure of each nozzle, which is approximately equal to the plenum pressure. While firing, the plenum pressure decreases as propellant is consumed, leading to a corresponding loss of thrust. The plenum must then be refilled from the main tank to increase the pressure. In order to prevent a scenario in which the refill valve and a nozzle valve could fail open simultaneously due to a software problem or other issue, all nozzle valves are closed before the refill valve is opened. Thus, the thruster must operate on a fire-refill cycle, in which a nozzle fires until the plenum pressure drops to a certain threshold, then stops firing until the plenum is refilled from the main tank. The BioSentinel team determined that a decrease in plenum pressure below 80% of a full charge would begin to degrade performance unacceptably. Figure 6 shows the simulated plenum pressure during 5 firings, each one lasting approximately 2 seconds before the plenum must be refilled. In this figure, the plenum pressure initially rises to its nominal value, after being evacuated prior to launch. The sawtooth pattern that is seen from approximately 12 seconds onwards corresponds to the plenum pressure dropping from a thrust nozzle being opened, and then increasing when the refill valve is opened.

The thruster has seven nozzles, positioned to provide torque about all three principal axes of the spacecraft, as well as a single ΔV nozzle for orbit adjust. BioSentinel does not have any direct requirements to perform a ΔV maneuver, however the project team decided to include a thruster nozzle that could impart linear velocity as a possible technology demonstration during later phases of BioSentinel's operational life. One consequence of the location of the thruster array in the spacecraft is that torques about the y- and z-axes are uncoupled and will result in center of mass translation. There are no specific station-keeping requirements levied on BioSentinel in order to complete its science objectives, so these small translations are considered to be acceptable. The thrust vectors generated by the thruster system are depicted, along with the spacecraft body frame axes, in Figure 7.

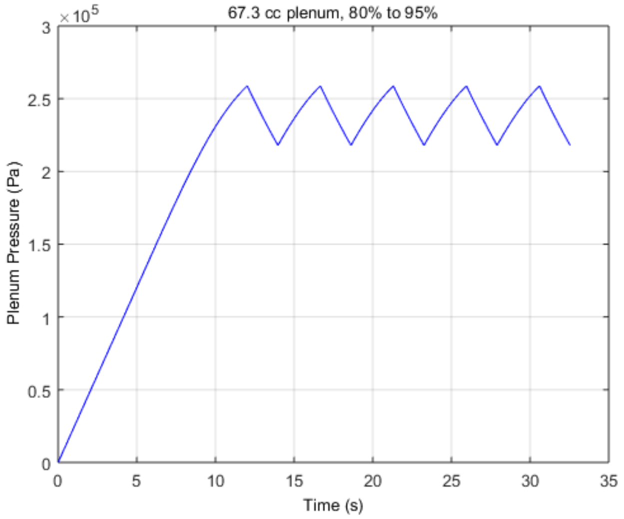

Figure 6. Plenum pressure as a function of time when a refill threshold of 80% nominal pressure is imposed.

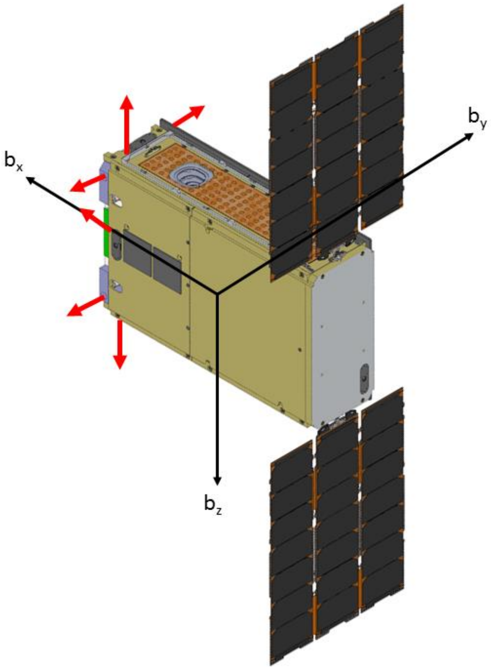

Figure 7. Six of the seven thrust vectors generated by the cold gas propulsion system (seventh thrust vector not shown).

The thruster system described above is expected to produce approximately 40 milli-Newtons of thrust at room temperature, with a specific impulse (I_{SP}) of approximately 50 seconds. This thrust and I_{SP}, along with minimum firing time and multi-nozzle firing operations, all must be tested prior to launch. Additionally, basic safety considerations such as the main tank leak rate and burst pressure must also be checked prior to integration with the SLS. The test campaign for this thruster system will involve Lightsey Space Research, NASA Glenn Research Center, and NASA Ames Research Center. This workflow, and some of the major tests, are described in the sequel.

PROPULSION SYSTEM TEST PLAN

As was described in the introduction, a major challenge for CubeSat-class missions that require a propulsion system is developing a test plan that meets both the cost and schedule limitations of the program. For the purposes of the BioSentinel mission, NASA Ames has teamed with the Liquid Propulsion Systems branch at Glenn Research Center (GRC) to develop a test plan that will allow for verification and validation of the major system requirements in a relevant test environment. Prior to the test campaign at GRC, the LSR team will perform a number of tests in-house to verify basic performance capability. Similarly, the BioSentinel integration and test team at NASA Ames will conduct a wide array of tests, both on the propulsion system itself and on the integrated spacecraft. The overall workflow, color-coded by organization, can be seen in Figure 8 below.

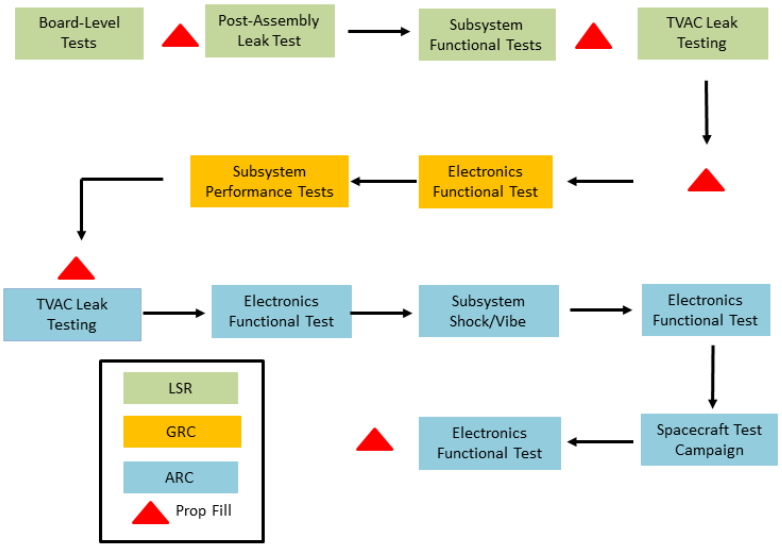

Figure 8. Testing flow for the BioSentinel Cold Gas propulsion system.

One challenging aspect of testing the thruster system is that a number of different modalities of tests must be developed. The mechanical assembly requires multiple tests to verify nominal performance (such as a maximum leak rate of the sensor manifolds), the electrical system must be tested to ensure proper interaction with the spacecraft bus, and the overall liquid propulsion system must be tested in a vacuum chamber to verify the high-level performance requirements. As can be seen in Figure 8, these various testing responsibilities are shared by all three institutions. A basic electronics functional test will be performed at all three locations to ensure consistent performance, but no "hot fire" tests will be carried out at NASA Ames, since that Center lacks the facilities required for a meaningful test. Similarly, leak testing will only be conducted at LSR and

NASA Ames in an effort to speed up the overall test workflow at GRC. One challenge that is common to all three tests facilities is loading propellant into the system. R-236fa is available in standard industrial-sized dewars, and the LSR team has extensive experience handling the propellant and loading it into the propulsion system. However, the nature of the test campaign is such that multiple refills will likely be required at each test site, meaning that a certain amount of propellant (and the attendant loading hardware) must be shipped to each site.

An important facet of the BioSentinel propulsion test plan is software testing. The propulsion system will use its internal pressure and temperature sensors to monitor the state of the plenum and main tank, and the on-board microcontroller will control valve opening and closing commands. However, these low-level tasks must interface with the BioSentinel C&DH, which will be operating at 5 Hz. As can be seen in Figure 9 below, the internal software operations of the propulsion system are somewhat involved, and these operations must be tested along with the high-level exchange of commands and telemetry. Verification of commands and telemetry will be the central focus of the electronics functional test described previously.

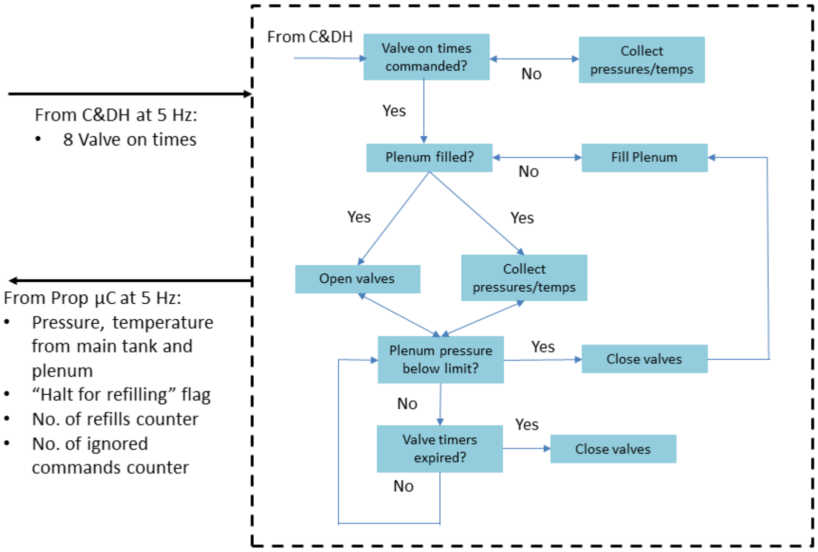

Figure 9. Concept of operations for the cold gas propulsion system.

"Hot fire" tests, in which the thruster nozzles are opened for some period of time in order to generate thrust, will be carried out in a vacuum facility at GRC. The vacuum facility currently under consideration is evacuated with four oil diffusion pumps and can attain a base pressure of $5x10^{-7}$ Pa. The pumps are equipped with cold traps to prevent diffusion pump oil from backstreaming to the chamber. To measure and assess the performance of the thruster a torsional-type micro-Newton (µN) thrust stand is used. The thrust stand can be used to determine impulse bit and thrust as a function of thrust stand deflection, spring stiffness, and natural frequency. In-situ calibration weights are used to apply a known force to determine the deflection of the thrust stand. The thrust stand can measure thrust levels as low as 5 µN and has a resolution of ~0.5 µN. Both steady-state and single pulse operation can be used to determine impulse bit size. The µNewton thrust stand has been extensively used to measure the impulse bit size and thrust for various energy level pulsed plasma thrusters (PPTs).

To test the BioSentinel system in a flight-like manner, NASA Ames is developing a small avionics package that is comprised of a BeagleBone Black single-board computer, the electrical/power system (EPS) card under development for BioSentinel, and a set of the batteries that will be used in the spacecraft. As can be seen in Figure 10, these elements will interact with the LSR propulsion system when it is mounted in the GRC vacuum facility to demonstrate flight-like command and operations. Both regulated voltages and unregulated battery voltage will be supplied to the propulsion system (as would happen on orbit), and commands will be sent using the RS-422 protocol. Thrust outputs will be measured by the aforementioned thrust stand, and I_{SP} can be verified by weighing the system before and after a set of thrust operations. By using Ames-developed flight software and BioSentinel hardware components in a vacuum chamber that provides a relevant operating environment it should be possible to verify the majority of the propulsion system performance requirements.

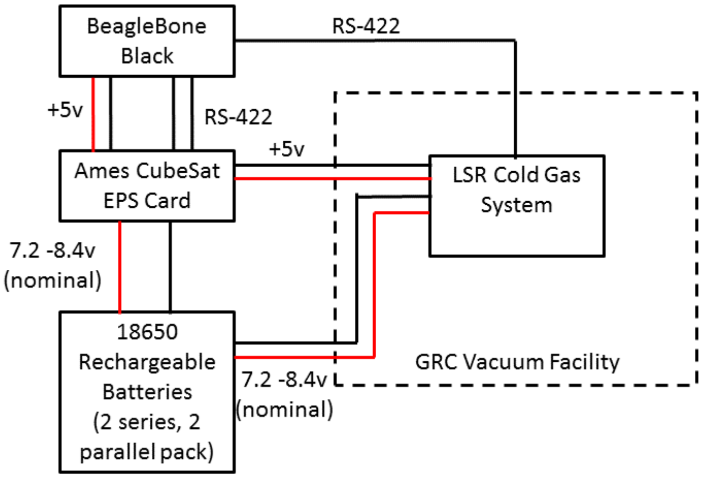

Figure 10. Block diagram representation of the test set-up at Glenn Research Center.

DISCUSSION

It should be noted that the testing work flow described in the preceding section has thus far only been concerned with the Engineering Development Unit (EDU). A Flight Unit will also be built by LSR for the BioSentinel mission, but it is not yet clear what portion of these tests will be replicated on that unit. There is some concern about using the same vacuum facility for testing the Flight Unit as for the EDU, given that there is evidence of the oil diffusion pumps used for that chamber leaving a small amount of oil residue on the test article. It is unlikely that this oil would negatively impact the operation of the propulsion system on-orbit, but there is some concern regarding this oil outgassing and then being redeposited on the lens of the star tracker, which is located very close to the propulsion system on the rear end of the spacecraft. It is unknown what impact a smudged lens would have on nominal star tracker operations. The vacuum facilities at Glenn Research Center that do not use oil diffusion pumps are much larger, so switching to these facilities is not desirable due to the increased time and cost required to pump the larger facilities down to vacuum. This trade remains open, and will likely require additional study of the performance of the star tracker under off-nominal conditions.

One topic not directly addressed in this paper is failure mode testing. A distinct advantage of 3D-printing the vast majority of the system is that it minimizes mechanical connections, which would normally be one of the main areas of concern regarding on-orbit failures. Instead, one of the major failure concerns that merits future study is the possibility of the valves failing in either the open or closed position. As described previously, the software operations of the system are such that the refill valve and nozzle valve can never be open at the same time, so if one of the nozzle valves fails in the open position it will only result in the plenum being evacuated, as opposed to the entire main tank. There is still the problem of that nozzle always being “on” during firing operations, but it does not result in immediate loss of the mission. One failure mode that could result in loss of mission is the refill valve failing in the closed position. While this modality appears to be highly unlikely, if the valve were to fail closed the system would only operate for one “charge” of the plenum, which is not sufficient for spacecraft detumble or momentum management. A number of valve stress tests are planned during EDU testing to study the likelihood of these failures modes.

It is not uncommon for spacecraft subsystems to have their nominal operations verified “by analogy”, and the same philosophy will be applied to the BioSentinel propulsion system. The test stand in the vacuum facility measures thrust along one axis, but there are obviously a number of configurations of detumble or momentum management in which thrusters about multiple axes will be commanded to fire. The test campaign envisioned for BioSentinel will only ever conduct “hot fire” tests about a single axis, although electronics tests will be run about multiple axes. Consequently, the BioSentinel team will need to develop test protocols that provide a sufficient level of confidence that multi-axis rotational maneuvers can be successfully accomplished in space. This is not an uncommon approach for propulsion systems, given the lack of test facilities that supply both a vacuum environment and multiple degrees of translational or rotational freedom. The BioSentinel mission managers are working closely with both the LSR team and collaborators at Glenn Research Center to adopt testing principals that have been applied to previous multi-axis thruster system test campaigns.

CONCLUSION

The BioSentinel mission represents an important step forward in the use of CubeSats for scientific exploration. The spacecraft science payload will provide critical information for future manned deep space missions, but its success is dependent upon reliable operation of a number of advanced subsystems, including the propulsion system. The 3D-printed cold gas propulsion system provided by Lightsey Space Research conforms to the stringent mass and volume budgets levied on the spacecraft, and the comprehensive test plan detailed in this paper should significantly reduce operational risk. While there is a certain amount of uncertainty surrounding the exact operating temperature for the propulsion system on-orbit, characterizing the minimum impulse bits and firing thrust at room temperature should help mission operators plan out thruster operations with a sufficient level of confidence. Near term work for this project includes writing and testing the software driver for the propulsion system, and testing low-level electronics interfaces with representative hardware from the BioSentinel C&DH system.

ACKNOWLEDGMENTS

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