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PERFORMANCE CHARACTERIZATION OF A COLD GAS PROPULSION SYSTEM FOR A DEEP SPACE CUBESAT

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One challenge facing the developers of CubeSats that operate in deep space is that magnetic torque rods cannot be used for unloading the momentum stored in reaction wheels. Rather, this task is performed by a system of thrusters. While a wide variety of attitude control thrusters have been deployed on larger spacecraft, there remain very few examples of such systems being used on CubeSats. The upcoming BioSentinel mission, under development at NASA Ames Research Center, is an example of a CubeSat-class spacecraft that requires thrusters for momentum management. A new 3D-printed cold gas thruster was developed for this application. This paper will describe the test campaign that was completed for the engineering development unit (EDU), and will present a variety of preliminary results describing the performance characteristics of the thruster. The test campaign for the propulsion system EDU was carried out in partnership with members of the In-Space Propulsion Branch at Glenn Research Center in Cleveland, OH.

INTRODUCTION

Universities and government agencies have been developing spacecraft that adhere to the CubeSat Standard[1] for over a decade, yet there still remain very few examples of CubeSats that have implemented some form of propulsion system onboard[2]. Propulsion technologies can be challenging to miniaturize, and the typical budget and schedule allocated to CubeSat programs makes comprehensive testing and risk-reduction challenging. This paper describes the test campaign that is underway for the propulsion system of the BioSentinel spacecraft, a six unit (6U) CubeSat in development at NASA Ames Research Center. This is the first example of a propulsion system that has been manifested in a NASA Ames CubeSat, and the test campaign seeks to characterize all aspects of system performance, including thrust levels, specific impulse, software performance, and fault management.

A CubeSat is defined as any spacecraft that adheres to the CubeSat Standard[3], whereby a 10 cm x 10 cm x 10 cm cube comprises one unit of volume (abbreviated as 1U). The majority of CubeSats that have been launched to date have ranged in size from 1U to 3U, with an overall volume of no more than 10 cm x 10 cm x 30 cm. 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 would have demonstrated multi-

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point science operations in LEO[5]. Unfortunately, EDSN suffered a launch vehicle failure prior to deployment.

The BioSentinel mission represents a unique opportunity for NASA Ames in that this spacecraft not only requires a wide range of advanced technologies for successful operation, but will also operate in an environment that has not yet been encountered by CubeSats. 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 flight 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. Over the 12-18 month mission life, BioSentinel will characterize the radiation environment encountered beyond the Van Allen belts, which will help to inform the development of radiation countermeasures for future manned missions[6]. While the science payload itself doesn't levy stringent pointing requirements on the spacecraft, it is necessary to point the spacecraft antennas towards Earth for communication, which in turn necessitates an active attitude determination and control system (ADCS). The BioSentinel propulsion system will be used for rotation rate reduction after tip-off from the upper stage of SLS, and for reaction wheel momentum management throughout the life of the mission.

As described in Reference 7, the BioSentinel project has selected a 3D-printed, cold gas propulsion system produced by the Georgia Institute of Technology (Georgia Tech) for use in this mission. One advantage of 3D-printing the main tank, expansion tank, piping, and nozzles is that the overall shape can be custom-designed for the mission at hand, allowing the spacecraft to maximize the amount of propellant stored within the system. BioSentinel will be the second spacecraft to make use of the 3D-printed propulsion technology from Georgia Tech, but this will be the first time it is used in a 6U CubeSat. Thus, a rigorous test campaign has been planned for both the engineering development unit (EDU) and the flight unit. This paper describes the test campaign that was performed for the EDU, and presents a variety of preliminary results describing the performance characteristics of the thruster.

The EDU test campaign was conducted at both Georgia Tech and Glenn Research Center (GRC) in Cleveland, OH. In both cases, fundamental propulsion system performance characteristics such as minimum impulse bit, thrust level, and total impulse were verified experimentally using a thrust stand mounted in a vacuum chamber. Testing of the system must be carried out in a vacuum chamber to obtain the proper pressure ratio across the nozzles. While thermal control is not strictly required for testing, certain tests were undertaken at the anticipated temperature extremes for the mission. Both thrust stands are capable of resolving thrusts in the milliNewton range required for BioSentinel, although their basic construction differed some. The performance results collected on both thrust stands are in good agreement with each other, and all results so far indicate that the propulsion system will operate as required during the mission.

The remainder of this paper is organized as follows. First, the BioSentinel mission and specifics of the spacecraft design are briefly introduced. Next, a detailed description of the propulsion system design is presented, and performance targets are reviewed. The overall test campaign is then outlined, and a number of test results are provided. This is followed by a discussion of the test results to date, and an overview of what tests remain. The paper concludes with a description of the future work facing the BioSentinel propulsion team.

THE BIOSENTINEL MISSION

The BioSentinel mission will address a Strategic Knowledge Gap associated with long-duration manned missions in deep space by more fully characterizing the radiation environment beyond the Van Allen Belts. 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 remarkably 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 interested reader is directed to References 6 – 8 for more information about the BioSentinel mission.

All spacecraft bus subsystems, including the ADCS and the propulsion system, must occupy roughly 2U of volume within the BioSentinel spacecraft. As can be seen in Figure 1, 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. 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 Deep Space Network. 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 solar radiation pressure torque during station-keeping, 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. Thus, spacecraft detumble and reaction wheel momentum management over the 12 month nominal operating life will be accomplished using the propulsion system.

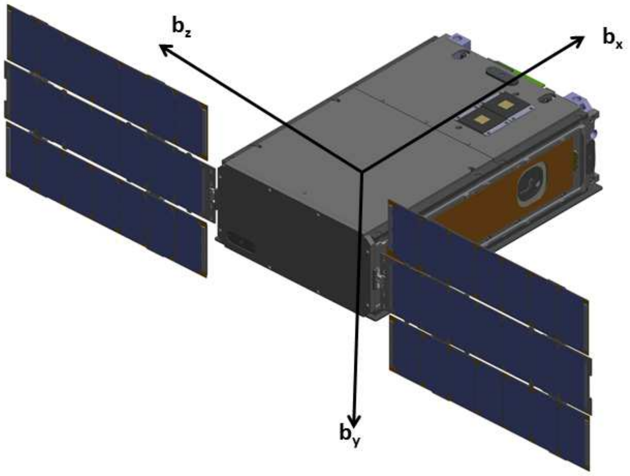

Figure 1. The BioSentinel spacecraft, shown with solar panels deployed and the body coordinate system overlaid.

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[9], although these systems were deemed to not be at a high enough technology readiness level based on the project schedule. Thus, a 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.

COLD GAS PROPULSION SYSTEM

The majority of the BioSentinel thruster is made from a single piece of printed composite material. The propellant tanks, feed pipes, and nozzles are contained within a single continuous additively manufactured component. This approach has several advantages over a more traditional design. It greatly reduces the number of pressure seals that must be made, reducing the number of potential leak sites. The design also allows the tanks to be made in unusual shapes to take advantage of the entire allocated volume. This is especially important in the case of the BioSentinel spacecraft, with its strictly limited volume. A CAD image of the entire thruster can be seen in Figure , wherein the light blue component is the printed structure.

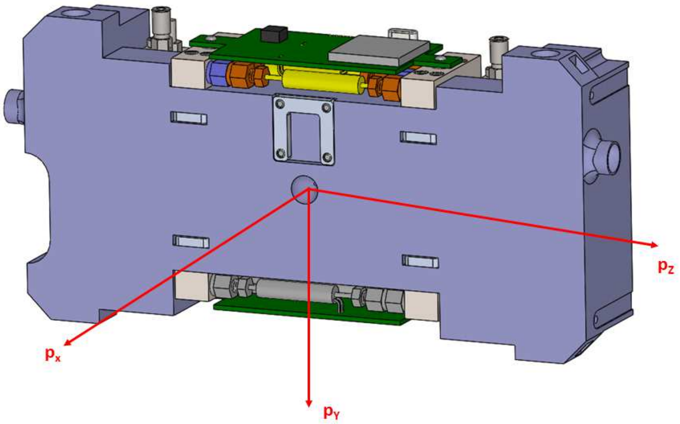

Figure 2. A 3D rendering of the BioSentinel cold gas propulsion system, shown with the propulsion coordinate frame overlaid.

The thruster has two propellant tanks printed into its structure. The larger "main tank" stores the majority of the propellant as a saturated liquid-vapor mixture. The saturated mixture is a relatively high-density state, which allows a larger propellant loading than a vapor alone in the same volume. However, as this state contains a mixture of vapor and liquid, it is not an ideal state to feed the nozzles directly, since the inlets of the nozzle feed pipes might experience sudden changes in propellant density, which may impact performance. To mitigate this, a smaller tank, the plenum, stores propellant as a vapor alone. The nozzles are fed from the plenum, which is depleted as the thruster fires. When the pressure in the plenum drops below a user-specified threshold, it is refilled from the main tank. Each of the two tanks is outfitted with a pressure transducer and thermistor, so the state of the propellant in both tanks is known.

The thruster has seven nozzles, six of which are oriented to provide attitude control, and the seventh is oriented to provide a delta-V maneuver. The locations of these nozzles, as well as the two tanks, are shown in Figure . In the figure, the plenum and main tank appear to be separated into segments. This is a result of the cutaway plane location and complex tank geometries. All areas marked as part of the plenum are in fact connected, as are both areas marked as part of the main tank.

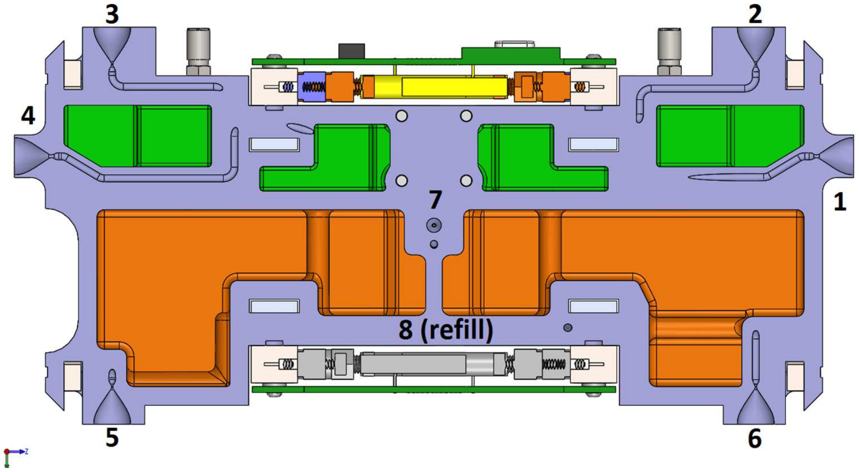

Figure 3. A cross-section of the propulsion system, showing the numbering convention used for the nozzles. The plenum is shown in green, and the main tank in orange.

Propellant flow is controlled by eight solenoid valves, installed in two manifolds with four valves each. Each manifold has a corresponding circuit board, which contains the power switches necessary to drive each valve. One of the circuit boards also contains an LPC1549 microcontroller and a low-drift oscillator. The microcontroller communicates with the flight computer over an RS-422 serial connection. The flight computer sends timing commands to the microcontroller, which opens the specified valves for the commanded duration. The microcontroller also reports the sensor telemetry and various heath data to the flight computer as part of each command response. Finally, it automatically monitors the plenum and main tank pressures, and refills the plenum if the pressure drops below the threshold. This circuit board can be seen integrated into the EDU thruster in Figure 4.

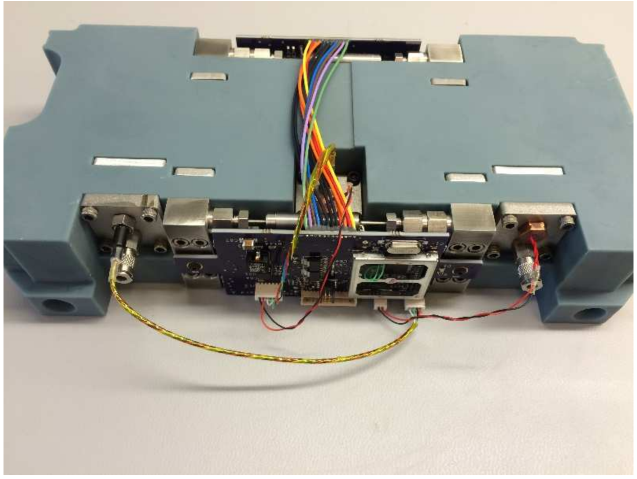

Figure 4. The fully assembled propulsion system EDU, in this case with the -x side of the system facing up.

The propellant used in the thruster is the refrigerant R-236fa (1,1,1,3,3,3-hexafluoropropane). It is a non-toxic, non-flammable gas that has a relatively low saturation pressure of 584 kPa at 50 °C. These low-risk properties are advantageous to the mission, since no special safety precautions beyond those for low-pressure vessels must be taken. The low saturation pressure also allows the thruster to store the propellant as a saturated mixture without prohibitively thick tank walls.

R-236fa is a relatively large molecule, with a molecular weight of 152.04 grams/mol. This reduces the speed of sound in the vapor, and thus the exit velocity of the propellant and the specific impulse of the system compared to lighter molecules like CO_2 (M=44 g/mol) or butane (M=58 g/mol). However, the high liquid density of the refrigerant allows a larger mass to be stored in the same volume, so while R-236fa is not an ideal cold gas propellant on a mass basis, it outperforms CO_2 and butane on a volume basis. Since the BioSentinel thruster is more constrained by its volume limits than its mass limits, R-236fa was chosen as the best available propellant.

PROPULSION SYSTEM PERFORMANCE REQUIREMENTS

As with all spacecraft subsystems, one challenge facing the BioSentinel propulsion system is developing a test and analysis plan that allows for verification of all system (also known as Level 4) requirements. This is particularly challenging for the propulsion system, given that the nominal thrust at a typical room temperature is approximately 40 mN, and observing this thrust on any sort of test apparatus requires the test stand and thruster to be in a vacuum. As such, it was understood from the early concept stage of the propulsion system that validation testing in a specialized environment would be necessary. With that in mind, the NASA Ames team worked to identify the minimum set of requirements that had to be verified via test, as opposed to those which could be verified through analysis or inspection. Ideally all requirements will be verified through testing, but this is not always possible with certain spacecraft systems or subsystems. As can be seen in Table 1 below, a total of six Level 4 requirements were identified as needing verification by way of testing in a relevant environment.

Table 1. BioSentinel Propulsion System Requirements Verified by Testing[*]

Requirement No.	Title	Description	Associated Test
Prop-7	Operating Pressure	The Freeflyer propulsion system maximum operating pressure shall be less than 100 PSI.	Prop-SFT-TVAC
Prop-15	Maximum Temperature	The Freeflyer propulsion system shall be capable of operating at a maximum ambient external temperature of no greater than 50°C.	Prop-SFT-TVAC
Prop-16	Minimum Operating Temperature	The Freeflyer propulsion system shall be capable of operating at a minimum ambient external temperature of no less than 0°C.	Prop-SFT-TVAC
Prop-21	Nominal Thrust	The Freeflyer propulsion system shall be capable of generating a nominal thrust of 18 mN ± 5 mN from each nozzle at the nominal spacecraft operating temperature.	Prop-SPT
Prop-22	Total Impulse	The Freeflyer propulsion system shall provide a total impulse over the life of the mission of 36 N-sec.	Prop-SPT
Prop-23	Minimum Impulse Bit	The Freeflyer propulsion system shall be capable of generating a minimum impulse bit of 120 microN-sec from all thrusters.	Prop-SPT

Examining the right hand column of Table 1, it is first necessary to define the testing nomenclature adopted by NASA Ames. The BioSentinel team chose to identify two separate test campaigns: the System Functional Tests (SFTs) carried out at Georgia Tech, and the System Performance Tests (SPTs) conducted at GRC. The Georgia Tech team has access to a thermal vacuum chamber, so it is also possible to carry out some of the SFTs at controlled operating temperatures, hence the "SFT-TVAC" label in the last column of Table 1. All tests that were run at GRC were also run at Georgia Tech. There was good agreement between the results of both test campaigns, as shown in the next section.

An interesting challenge associated with this project is that a number of requirements (and their attendant uncertainties) are inherited from the Space Launch System itself. For example, the SLS team has stipulated that all secondary payloads cannot be pressurized beyond 100 PSI prior to deployment in space, hence the limit in Prop-7. Similarly, the initial orbit parameters of the secondary payload is still unknown, which means that the distance from the sun is also unknown. This in turn impacts the upper and lower limits on the expected operating temperature range. For now, the BioSentinel team is assuming a worst-case operating temperature of 0 °C, which informs the nominal thrust that can be generated using R-236fa (see Prop-16 and Prop-21). The propulsion system team has levied a firm upper temperature limit of 50 °C, since beyond this temperature the Factor of Safety requirement on the burst pressure (as imposed by the project) is violated. The performance of the propulsion system EDU with regard to these requirements is presented in the next section.

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[*] Please see the Notation table at the end of this paper for all engineering units used throughout this work

TEST CAMPAIGN

Testing of the BioSentinel propulsion system EDU was carried out in two phases: first at Georgia Tech's Space Systems Design Lab in spring of 2016 and then at Glenn Research Center in summer of 2016. Some additional testing was also undertaken at Georgia Tech during the fall of 2016, largely to better quantify the specific impulse of the system. Testing at both facilities made use of a torsional test stand inside a vacuum chamber, as seen in both images of Figure 6 below. All tests were run using a LabView interface connected to a data acquisition card, which collected displacement data from the test stand and telemetry from the propulsion system. MATLAB© was used for additional data processing after all test runs. The Georgia Tech thermal vacuum chamber test volume measures 60 cm x 55 cm x 60 cm, and can achieve a base pressure of 1x10^{-6} Torr. In contrast, the GRC vacuum chamber (Vacuum Facility 8) is a cylindrical chamber 1.5 meters in diameter and 4.5 meters long. The GRC vacuum level is controlled using four oil diffusion pumps, and the chamber is capable of reaching a base pressure of 4x10^{-7} Torr.

Both test stands use a torsional pendulum design to measure thrust, with a long aluminum arm allowed to pivot within a welded frame. The Georgia Tech test stand (seen in the left-hand image of Figure 5) very closely replicates the GRC design. The arm is attached via two flexural pivots, which provide nearly frictionless rotation, in addition to a restoring force to the arm. The GRC test stand can resolve thrusts at the microNewton level, and can be seen in the right-hand image of Figure 5. This test stand was originally designed to test pulsed plasma thrusters, which produce low levels of thrust in short pulses. As the BioSentinel thruster is also designed to produce short, low thrust pulses, the stand was used with little modification.

The GRC stand is calibrated by use of a series of test masses, suspended from a thread that attaches to the thrust stand arm. The other end of the thread is wrapped around a pulley, which is used to raise and lower the masses. When fully lowered, all three of the weights are supported by the arm, leading to a constant offset in the arm deflection. As the pulley is raised, the weights become supported by the pulley one by one, causing the constant offset to change, until none are supported by the arm. With the magnitude of the deflections and the masses of the test weights, the restoring force from the flexural pivots can be determined. Using the measured restoring force and the natural frequency of the stand, the impulse response of the stand can be determined.

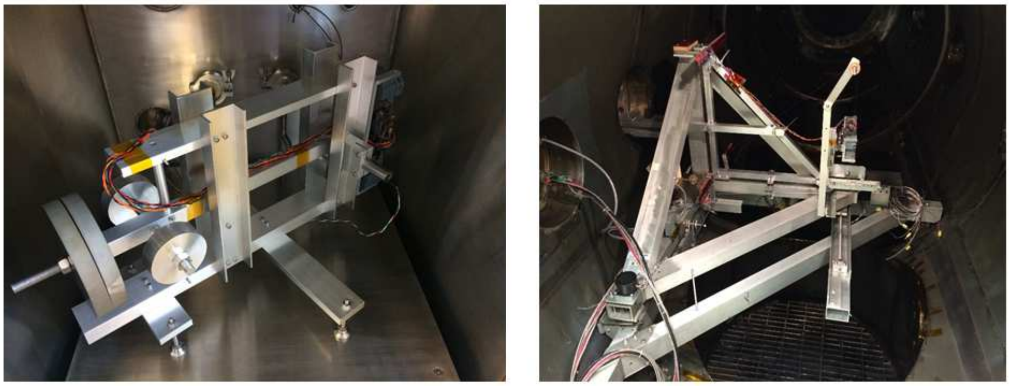

Figure 5. The BioSentinel thruster mounted to the thrust stand in the vacuum chamber at Georgia Tech (left image) and the thrust stand at Glenn Research Center (right image).

Referring back to Figure 3, all seven nozzles on the propulsion system were tested in the vacuum chamber. Tests were conducted at pulse widths ranging from 3 msec to 200 msec. Testing initially focused on the thrust generated by each nozzle for a given pulse duration, thrust dependency on pressure in the plenum, and system specific impulse (derived by measuring the change in mass over a series of thruster firings). The range of firing times (3 msec to 200 msec) was motivated by the operational conditions of BioSentinel. The spacecraft operates at 5 Hz, which means that the propulsion system could theoretically be commanded to fire for a full operating cycle (200 msec). The fastest that the valves can respond when commanded to fire is approximately 3 msec, so this lower bound was tested as well. MATLAB/Simulink simulations of the spacecraft operating modes that utilize the propulsion system indicate that the vast majority of the commanded firing times are greater than 100 msec, so more recent testing has largely focused on longer pulse durations. Nozzle thrust as a function of pulse time for one nozzle on each face of the propulsion system is shown in Figures 6 – 8 below. This data was collected during the first round of testing at Georgia Tech. Note that Nozzle 2 is on the –y face of the propulsion system, Nozzle 4 is on the –z face, and Nozzle 7 is on the x face.

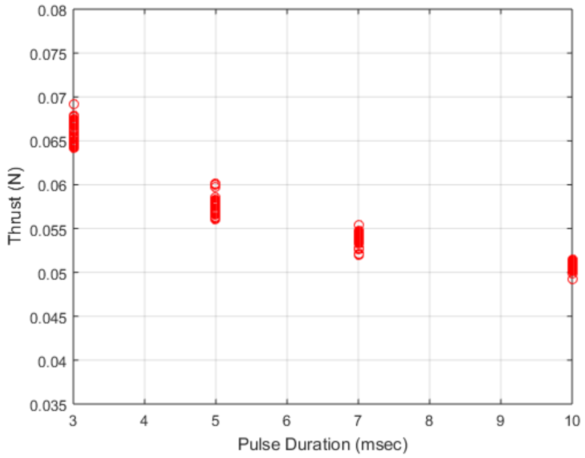

Figure 6. Nozzle thrust as a function of pulse width for Nozzle 2 (-y face) of the BioSentinel propulsion system.

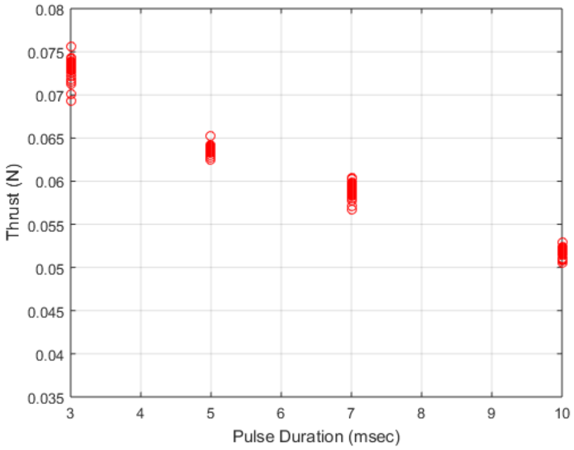

Figure 7. Nozzle thrust as a function of pulse width for Nozzle 4 (-z face) of the BioSentinel propulsion system.

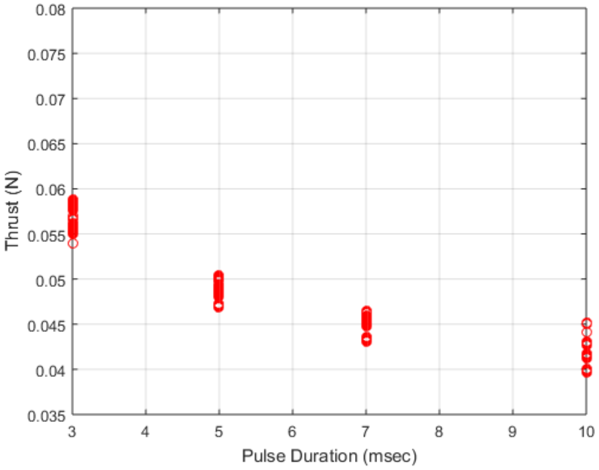

Figure 8. Nozzle thrust as a function of pulse width for Nozzle 7 (x face) of the BioSentinel propulsion system.

It is important to note that the temperature of the test chamber was not strictly controlled during data collection in Figures 6 – 8, and thus the expected nominal thrust varies between tests. The variance seen in the thrust level achieved at a particular pulse width is due to changes in the plenum pressure. That pressure decreases with each firing, and hence the thrust that is achieved also decreases. That said, it is interesting to observe that for all three nozzles in Figures 6-8 the measured thrust systematically decreases as a function of pulse time. Upon examination, the propulsion system team concluded that at these very short pulse times the thrust stand is observing the effect of the solenoid valve closing. This effect is illustrated in Figure 9 below, in which thrust curves produced by a short pulse and a long pulse are represented graphically. An ideal valve would open and close instantly, producing a square thrust profile, but real valves take a finite time to open and close, leading to a trapezoidal shape. The area underneath the thrust curve is the impulse provided by that pulse. The dark red area at the beginning of each pulse corresponds to the impulse lost due to non-instantaneous valve opening, while the orange area at the end of each pulse shows the additional impulse gained from the non-instantaneous closing of each valve. If the valve is slower to close than to open, each pulse gains a fixed amount of impulse. This additional impulse is proportionally more significant to shorter pulses, as is apparent in Figure 9.

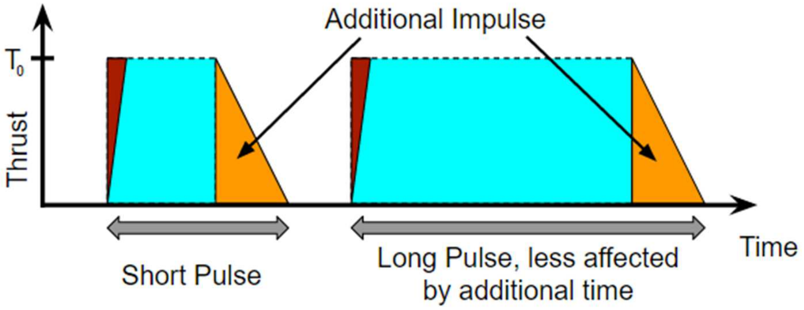

Figure 9. A graphical representation of the command valve action as compared to the actual valve action.

As mentioned earlier, it is anticipated that the BioSentinel spacecraft will largely request pulse widths of 100 msec or greater for both detumble and momentum management operations. The theory presented in Figure 9 is borne out by tests performed at longer thrust durations, which were tested specifically for BioSentinel. As can be seen in Figure 10 below, the drop in thrust resulting from the effect of the solenoid valve taking a non-zero amount of time to close is asymptotic. The average thrust achieved by the thruster is nearly constant beyond approximately 100 msec. Note that the data points below the trendline are the result of the propulsion system software halting a firing operation to refill the plenum. This occurs automatically whenever the plenum pressure drops below the user-specified set point. The BioSentinel attitude control software has been designed to accommodate the discontinuities that are injected into the control signal by virtue of this “halt for refill” behavior.

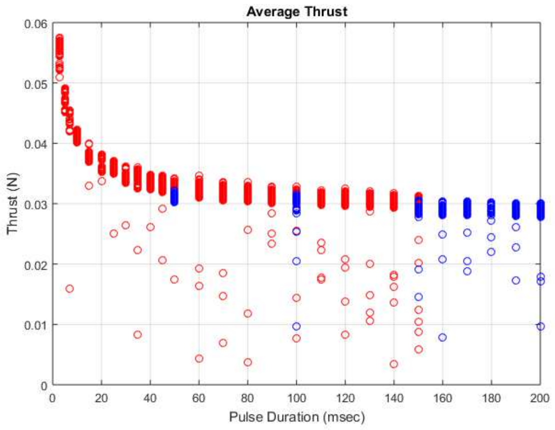

Figure 10. Nozzle thrust as a function of pulse duration for durations from 3 msec to 200 msec.

As stated at the beginning of this section, the thrust stands at Georgia Tech and Glenn Research Center are very similar in design. Each vacuum chamber was also able to produce about the same vacuum level inside the chamber. The only major difference in testing conditions between the two test sites was the temperature in the chamber during testing. The thrust generated by the R-236fa is strongly correlated to this operating temperature, meaning that the thrust levels recorded at each test site will be different. The majority of the Georgia Tech testing was conducted at a lower temperature than the GRC tests, although some limited tests were conducted at higher temperatures (explicitly controlled by the TVAC chamber). Figure 12 below shows the average thrust as a function of pulse time for Nozzle 6 during three different tests. The red points are data collected at Georgia Tech during high temperature testing at 32 °C. The blue points were measured at GRC at approximately 30 °C, and the black points were measured at Georgia Tech at 26 °C. As expected, the higher temperature tests result in uniformly higher thrust levels, but retain the same shape.

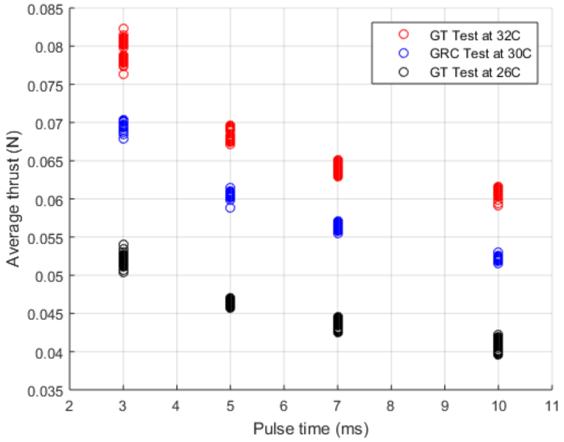

Figure 11. Comparison of the average thrust level at three different testing temperatures for data collected from Nozzle 6 at both GRC and Georgia Tech.

DISCUSSION

The experimental results presented in the preceding section indicate that the BioSentinel propulsion system is performing as expected. Nominal trust values hover in the range of 40 – 70 mN, which agrees with the theory for R-236fa. The "lag" in the solenoid valve response seen for shorter pulse durations (as depicted in Figure 9) is a very interesting result, but not a terribly troubling one given that in flight pulse durations lower than 100 msec will rarely be commanded. This is reinforced by the result of Figure 10, which shows that the thrust generated as a function of pulse duration levels out for longer firing times.

An important parameter than can be determined from these results is specific impulse (I_{sp}). Specific impulse is a measure of propulsive efficiency, and is used to determine how much propellant is required to produce a certain amount of impulse. Specifically, that relationship is:

$$I_{sp} = \frac{J}{g m_p}$$

Where J is the total impulse produced, g is the standard acceleration due to gravity (9.806 m/s2), and m_p is the mass of the propellant. A thruster with a higher I_{sp} will expend less propellant to achieve a certain impulse than a thruster with a lower I_{sp}. This is an important parameter for mission planning, since it informs how much propellant is required over the life of the mission to meet the 36 N-s total impulse requirement (see Table 1). It is also necessary for propellant consumption tracking; the applied impulse can be measured directly by the ADCS, and propellant mass consumption can be computed from that known impulse and the thruster's specific impulse.

During the design of this thruster, the expected specific impulse was calculated to be 47.3 seconds, using the published properties of the propellant and the thruster's nozzle geometry. During the test campaign, it was also determined experimentally. In order to determine specific impulse, using Equation 1, a total impulse and a propellant mass change must be measured. In practice, a large number of firings are needed to produce a measurable change in mass, due to the low thrust of the system. During testing the thruster was commanded to produce a large number of firings at various pulse widths, and the impulses measured from each firing were added to determine the total impulse. The mass change was measured simply by weighing the thruster before and after the test. Table 2 summarizes these test results.

Table 2. Specific impulse calculations for the BioSentinel propulsion system, derived from thrust stand data.

Description	Total Impulse (N*s)	ΔM (g)	Isp (s)	Thrust avg (mN)	$\dot{m}$ (mg/sec)
3500 firings, 10 ms each	1.4118	3.26	44.2	40.35	93.08
1200 firings, 5 ms each	0.2749	0.69	40.6	45.82	115.08
1200 firings, 10 ms each	0.4912	1.1	45.5	40.94	91.74
1200 firings, 50 ms each	1.8956	4.04	47.8	31.59	67.39
720 firings, 200 ms each	3.7278	8.2	46.4	25.89	56.89
1200 firings, 5 ms each	0.271	0.68	40.7	45.18	113.19

Note that the 5 millisecond pulse tests showed substantially lower Isp than the longer tests. We hypothesize that this is due to the finite valve opening effect described above. While the valve is opening, the flow is forced through a smaller aperture than when the valve is fully open. This may be causing frictional losses as the flow is choked inside a non-smooth section of the valve. These losses, in turn, may be reducing the specific impulse of the thruster. Even if one selects an average value from Table 2 (say, for example, 43 seconds) as the I_{SP} for the BioSentinel propulsion system, the full 200 g propellant load still is more than sufficient for the needs of the mission. It is predicted that a worst-case detumble maneuver will require approximately 1 g of propellant to complete, and a typical reaction wheel momentum management maneuver requires 0.07 g of propellant. Assuming the reaction wheels need to be desaturated three times a day (which is itself conservative), this translates to 115 g of propellant consumed over an 18 month mission. Thus, the total propellant budget for BioSentinel is 116 g of propellant, and the spacecraft will fly with 200 g.

The results seen in Figure 11 of the previous section show good agreement between the Georgia Tech and GRC thrust stands when measuring the response of the propulsion system. This is not terribly surprising—the thrust stands are of a very similar design—however it is an encouraging result for the development of the flight unit, which will need to happen over a shorter period of time than the EDU. Given the similarity of the results plotted in Figure 11, the BioSentinel team will likely only use the Georgia Tech thrust stand for verification and validation of the flight unit. Examining Figure 11 more closely, it is interesting to see the strong relationship between thrust performance and operating temperature. Six degrees Celsius of temperature difference between the upper and lower bound tests results in greater than 30% difference in the thrust level achieved. Recall that for the purposes of planning the BioSentinel team has been assuming a worst-case operating temperature of 0 °C, and even at this very low temperature the thruster has sufficient control authority for both detumble and momentum management operations. However, it will be important to collect as much temperature data as possible on orbit so that mission operators can know what nominal thrust level to expect from the propulsion system.

CONCLUSION

The engineering development unit of cold gas propulsion system selected for the BioSentinel mission was tested on thrust stands at both Georgia Tech and Glenn Research Center to verify system-level performance. The test results presented herein show that the design does meet the major operational requirements stipulated by the project team, including nominal thrust and nominal specific impulse. The test results obtained at Georgia Tech show good agreement with those obtained at Glenn Research Center, and in the future the BioSentinel project team does not anticipate it will be necessary to repeat tests at GRC. Important future work for the project includes further testing between the propulsion system and flight software system, with a particular emphasis on fault management and off-nominal cases. The Georgia Tech team also plans to continue characterizing the performance of the thruster at pulse durations of 100 msec and larger, since those pulse durations appear to be of greatest interest to end-users.

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NOTATION

ΔM	Change in propellant mass
g	gravitational constant (meters per second squared)
I_{SP}	Specific impulse (in seconds)
J	Total Impulse
kPA	Pressure (in kilo- Pascals)
M	Molecular weight (in grams/mol)
$\dot{m}$	Mass flow rate
m_P	Propellant mass
mN	Thrust (in Newtons)
Ns	Total Impulse (in Newton-seconds)
PSI	Pressure (in pounds per square inch)

REFERENCES

[1] Puig-Suari, J. et al., “Development of the Standard CubeSat Deployer and a CubeSat Class Picosatellite”, *Proceedings of the 2001 IEEE Aerospace Conference*, Volume 1, 2001 pp. 347-353.

[2] Mauthe, S., Pranajaya, F., and Zee, R., “The Design and Test of a Compact Propulsion System for CanX Nanosatellite Formation Flying”, *Proceedings of the AIAA/USU Small Satellite Conference*, Logan, UT, August 2005.

[3] Nugent, R. et al., “The Cubesat: The Picosatellite Standard for Research and Education”, *Proceedings of the AIAA Space Conference and Exposition*, September 2008, San Diego, Ca.

[4] Diaz-Aguado, M.F., et al., “Small Class-D Spacecraft Thermal Design, Test, and Analysis-PharmaSat Biological Experiment”, *Proceedings of the IEEE Aerospace Conference*, Volume 1, 2009, pp. 1-9.

[5] Sorgenfrei, M., Nehrenz, M., and Shish, K., “Operational Considerations for a Swarm of CubeSat-Class Spacecraft”, *Proceedings of AIAA SpaceOps Conference,* Pasadena, CA, May 2014.

[6] Lewis, B., et al., “BioSentinel: Monitoring DNA Damage and Repair Beyond Low Earth Orbit”, *Proceedings of AIAA/USU Small Satellite Conference*, Logan, UT, August 2014.

[7] Sorgenfrei, M., Stevenson, T., and Lightsey, G., “Considerations for Operation of Deep Space Nanosatellite Propulsion System”, *Proceedings of AAS Guidance, Navigation, and Control Conference*, Breckenridge, CO, February 2016.

[8] Nehrenz, M. and Sorgenfrei, M., “On the Development of Spacecraft Operating Modes for a Deep Space CubeSat”, *Proceedings of AIAA Space Conference,* Pasadena, CA, August 201

[9] Sorgenfrei, M., Nehrenz, M., and Thomas, R., “On the Implementation of Microelectrospray Propulsion Systems in a CubeSat-Class Spacecraft”, *Proceedings of AAS Guidance, Navigation, and Control Conference,* Breckenridge, CO, February 2015.

[10] Arestie, S., Lightsey, E.G., and Hudson, B., “Development of a Modular, Cold Gas Propulsion System for Small Satellite Applications”, *Journal of Small Satellites*, Vol. 1, No. 2, pp. 63-74, 2012.