Development and Testing of a 3D-Printed Cold Gas Thruster for an Interplanetary CubeSat

E. Glenn Lightsey, Terry Stevenson, and Matthew Sorgenfrei

This paper describes the development and testing of a cold gas attitude control thruster produced for the BioSentinel spacecraft, a CubeSat that will operate beyond Earth orbit. The thruster will reduce the spacecraft rotational velocity after deployment, and for the remainder of the mission it will periodically unload momentum from the reaction wheels. The majority of the thruster is a single piece of 3D-printed additive material which incorporates the propellant tanks, feed pipes, and nozzles. Combining these elements allows for more efficient use of the available volume and reduces the potential for leaks. The system uses a high-density commercial refrigerant as the propellant, due to its high volumetric impulse efficiency, as well as low toxicity and low storage pressure. Two engineering development units and one flight unit have been produced for the BioSentinel mission. This paper describes the design, development, and test campaign for the thruster system.

I. Introduction

Universities, government agencies, and commercial entities 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 onboard propulsion system [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 design and related test campaign that was recently completed for the propulsion system of the BioSentinel spacecraft, a six unit (6U) CubeSat currently in development at NASA Ames Research Center (Ames). This is the first example of a propulsion system that has been manifested in a NASA Ames CubeSat. Due to the extremely challenging size, weight, and power requirements, a new 3D-printed implementation of a cold gas thruster was selected for the spacecraft. This paper is both a description of the design and development activity that was conducted for this new technology and a demonstration of how innovative manufacturing techniques may be used to create new capabilities on small satellites.

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

The BioSentinel mission presents 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 a space environment that has not yet been encountered by CubeSats. BioSentinel is a 6U CubeSat that 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 6 - 12 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 does not 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). Three mutually-orthogonal reaction wheels will be used for science and communications mode reorientation maneuvers. A propulsion system will be used for rotation rate reduction after tip-off from the upper stage of SLS (also called detumble) and for reaction wheel momentum management throughout the life of the mission.

As described in [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 of the device 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.

Cold gas thrusters have been previously demonstrated on CubeSats[8]. The first CubeSat-sized spacecraft known to employ a cold gas thruster in space was the

Microelectromechanical System-based PICOSAT Inspector (MEPSI) [9]. This mission involved a pair of spacecraft, deployed in 2006, one of which was equipped with a miniature cold gas thruster. The thruster was used to maneuver the first spacecraft relative to the second spacecraft, and achieved a total ΔV of 0.4 m/s. In 2014, two cold gas attitude control thrusters were created for the Jet Propulsion Laboratory's Interplanetary Nano-Spacecraft Pathfinder in Relevant Environment (INSPIRE) mission, a pair of 3U CubeSats developed by the Jet Propulsion Laboratory to demonstrate small satellite capabilities beyond Earth orbit [10]. At the time of this writing the INSPIRE satellites have not flown, although spacecraft integration and testing was successfully completed. In 2015, a cold gas thruster was demonstrated in Low Earth Orbit on the POPSAT-HIP1 spacecraft [11]. This propulsion system used pressurized Argon to provide between 2.25 and 3 m/s of ΔV. The BioSentinel thruster draws on heritage from the previous INSPIRE attitude control thrusters, and employs the same solenoid valves and propellant that were used in that design.

Because of the mission risk associated with flying new technology on BioSentinel, a rigorous test campaign was completed for two engineering units and the flight unit. The campaign sought to characterize all aspects of the performance of the thruster, including thrust level, specific impulse, software performance, fault management, leak rate, thermal performance, and longevity. The first engineering development unit (EDU1) was tested in Georgia Tech's Space Systems Design Lab in the spring and summer of 2016 to determine leak rate and demonstrate electronics performance, as well as to measure preliminary thrust and specific impulse values. A second round of testing at NASA Glenn Research Center confirmed the initial thrust level findings, and a third and final test sequence at Georgia Tech focused on refining the specific impulse estimates. The second engineering development unit (EDU2) underwent a shorter test campaign, entirely at Georgia Tech, before being delivered to Ames for spacecraft fit checking and system-level testing. Testing of the flight unit was conducted at Georgia Tech in summer 2017 to demonstrate acceptable performance.

The remainder of this paper is organized as follows. First, the BioSentinel mission is introduced in Section II. Next, the driving requirements and project schedule are presented in Section III. The physical system design is described in Section IV, and the electronics design is described in Section V. The test facilities used to verify the performance of the thruster are detailed in Section VI, and test results are presented in Section VII. A discussion of the test results and the work that remains for the BioSentinel program is offered in Section VIII, and the paper closes with concluding remarks in Section IX.

II. 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 [6].

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 **Fig. 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. All reorientation maneuvers must satisfy a pointing requirement of ±5 degrees. The 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 6 month nominal operating life will be accomplished using the propulsion system.

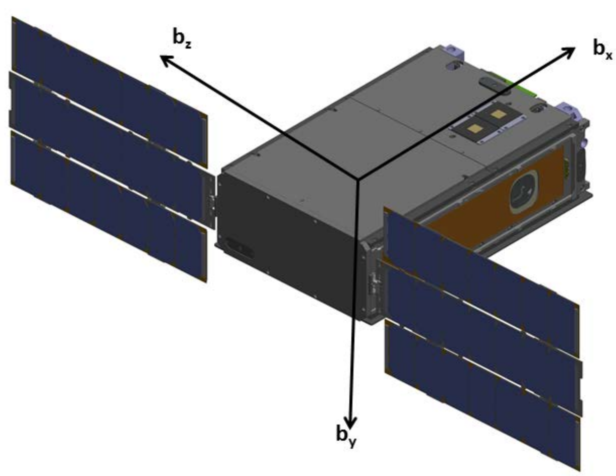

Fig. 1 The BioSentinel spacecraft shown with solar panels deployed and the body coordinate system overlaid.

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 [12], 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 in order to satisfy the mission operating life.

III. System Architecture

A. 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 development that verification 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.

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 later in this paper.

An interesting challenge associated with the BioSentinel program 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 all secondary payloads are 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 the selected propellant of 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 requirements outlined in Table 1 drove the design of the BioSentinel propulsion system.

Table 1. BioSentinel propulsion system requirements that are 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

B. Development Schedule

Three thrusters have been built for the BioSentinel mission. The first engineering development unit (EDU1) was built in the spring of 2016. It was tested to determine thrust, specific impulse, leak rate, electronics performance, and thermal performance. EDU1 was tested at NASA's Glenn Research Center to confirm the thrust measurements taken at Georgia Tech, and was used at NASA Ames for software interface development.

A second engineering development unit was built in fall of 2016, and was also tested at Georgia Tech, although the thrust characterization was not as extensive as the campaign for EDU1. EDU2 underwent a full range of environmental tests, including thermal cycling and shock/vibration testing, at NASA Ames while integrated with the BioSentinel spacecraft EDU.

The flight thruster was built and tested in the summer of 2017, with delivery to the project completed in August 2017.

IV. System Design

A. Propellant Selection

One of the most important metrics when selecting a propellant for the BioSentinel application is volumetric efficiency, or impulse [N s] per unit of propellant volume [m^3]. This volumetric impulse, or I_{vol} [kg s^{-1} m^{-2}], is defined as the amount of impulse gained per unit volume of propellant expelled:

$$I_{vol} \triangleq \frac{J}{V_p} \quad (1)$$

where J is the impulse produced and V_p is the volume of propellant expended. This can be restated in terms of specific impulse:

$$I_{vol} = g I_{sp} \rho \quad (2)$$

where g is the standard acceleration due to gravity at sea level [9.81 m s^{-2}], I_{sp} is the specific impulse [s], and ρ is the propellant density [kg m^{-3}].

The thruster, like many CubeSat subsystems, is highly volume constrained. The final design is significantly under the mass requirement of 1.4 kg, but uses nearly all of the available volume. The use of 3D-printing mitigates this somewhat by allowing more creative tank geometry, but the driving requirement for the propellant is still the impulse provided per unit volume. Table 2 shows a comparison of several candidate propellants with a wide range of molecular masses. The general trend is for lighter molecules to have higher specific impulse, which represents a higher mass efficiency. However, these propellants also tend to have a lower storage density, so the lightest and most mass-efficient propellant, helium, also has the worst volumetric efficiency.

As seen in Table 2, ammonia has the highest volumetric impulse rating, although the I_{vol} of R-236fa was less than 1% lower. R-236fa is a commercially available refrigerant that is used in fire suppression systems and exists as a liquid at room temperature and pressure.

Table 2: Properties of some candidate propellants. Note that since nitrogen and helium cannot be stored as a liquid at room temperature, the densities given here are vapor phase densities at 10 MPa.

Name	*M* [g/mol]	I_{sp} [s]	Density [kg/m^3]	I_{vol} [N-s/m^3]
R-236fa	152.04	46.9	1360	625 721
R-134a	102.03	49.3	1207	583 600
Butane	58.12	73.1	564	404 832
CO2	44.01	67.6	711	471 172
Ammonia	17.03	106.7	603	630 967
Nitrogen	14.00	77.6	113 *	85 641
Helium	4.00	177.3	16.4 *	28 525

Ultimately ammonia was rejected due to its high storage pressure and safety concerns. The saturation pressure of ammonia at 25 C is 1003 kPa, versus 272 kPa for R-236fa. This allows an R-236fa tank to have thinner walls than an ammonia tank, which allows for more volume to be devoted to propellant. Additionally, ammonia is a toxic gas, and would require more stringent safety precautions when handling and loading the propellant than R-236fa, which is nontoxic.

B. Printed Structure

The largest component of the thruster is a single piece of 3D-printed material, encompassing the propellant tanks, propellant feed pipes, nozzles, O-ring grooves, and attachment points for the spacecraft. The printed structure, without any other components attached, is shown in Fig. 2. The structure is made from Accura Bluestone, which is a high stiffness nano-composite material which is 3D-printed using stereolithography at a resolution of 0.1 mm.

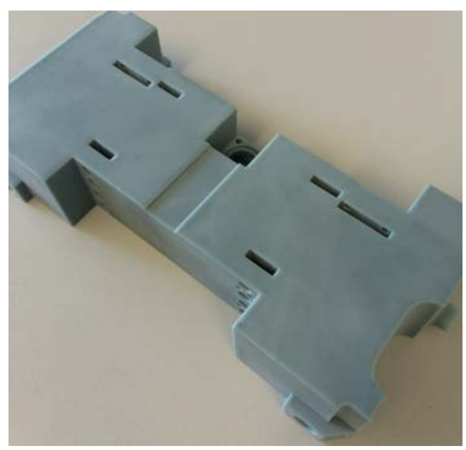

Fig. 2 The 3D-printed structure of the BioSentinel thruster, with no other components attached.

There are two propellant tanks contained inside this printed structure. The larger tank, called the main tank, has a volume of 176 cm^3 and holds the majority of the propellant as a saturated liquid-vapor mixture. This state has higher density than a vapor, which improves the volumetric efficiency of the system. However, this state is not suitable as a feed for the nozzles, since liquid droplets may be ingested into the nozzle. To prevent this, a second tank, called the plenum, is used to store propellant as a vapor alone. The plenum has a volume of 67.3 cm^3, and is used to feed all seven nozzles. The plenum pressure decreases as propellant is consumed. Once the pressure drops below a user-defined fraction of the main tank pressure, a refill valve is opened, and the plenum is re-pressurized from the main tank. This repressurization boils some of the propellant in the main tank, and decreases its temperature, so continuous operation will result in thrust losses due to the lower propellant temperature. A cutaway view of the thruster is shown in Fig. 3, with the plenum colored in green and the main tank is colored in orange. Note that the plenum segments are connected, however the tank geometry is complex enough that one cutaway plane cannot show this.

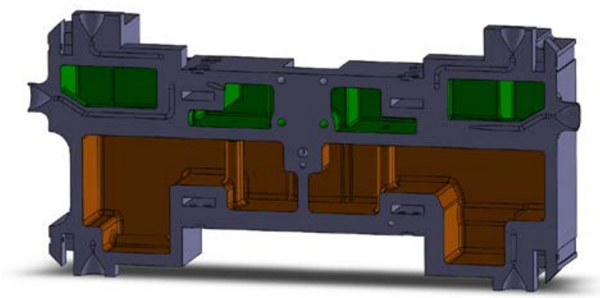

Fig. 3 Cutaway view of the 3D-printed structure, showing the main tank (orange) and the plenum (green).

V. Electronics Design

The thruster electronics are contained on the two printed circuit boards (PCBs) attached to the valve manifolds. These boards are fastened to the manifold with locking screws, and then soldered to the leads of the valves. The boards are labeled “PCB-A” (negative Y face) and “PCB-B” (positive Y face). The spacecraft cable is connected to PCB-A, and PCB-A is connected to PCB-B via a ribbon cable.

A. Valves

Propellant flow is controlled by eight two-way axial flow solenoid operated valves, installed in two manifolds of four valves each. The valves are rated to 250 million cycles, far more than the expected 800,000 cycles they will experience during the BioSentinel mission life.

B. Valve Control Circuits

The valves require a “spike/hold” voltage profile, consisting of a high initial voltage of 9-16V for 3 milliseconds, then a low sustaining voltage of 1.8V. The valves are spring-loaded and normally closed, so when the 1.8V supply is disabled, the valve closes automatically. This means that a loss of power can never result in uncommanded thruster actuations, since the valves cannot remain open without power. Each PCB contains four sets of actuation circuits, so each valve can be operated independently.

C. Sensors

The main tank and plenum are both equipped with temperature and pressure sensors so that the state of the propellant is known at all times. The sensors are installed on steel manifolds, which are sealed to the surface of the printed structure with O-rings. The manifolds are removable, allowing testing and replacement of the sensors, if necessary.

D. Microcontroller

PCB-A contains a low power microcontroller and a 12 MHz reference oscillator. The microcontroller communicates with the spacecraft’s flight computer via a serial interface, accepting commands and returning telemetry. The thruster receives valve timing commands-for example, a command to open valve 1 for 50 milliseconds. The microcontroller controls the timing of this pulse, using the reference oscillator. The system also monitors the four propellant sensors, updating its measurements at approximately 100 Hz. Every command from the flight computer is answered with a full telemetry frame, containing the state of all eight valves, the accumulated opening time of each valve, and the pressure and temperature of both tanks.

The system is designed to perform plenum refilling autonomously, although it is possible to manually refill the plenum by commanding the refill valve to open. In the nominal operating mode, the thruster continuously monitors the pressure ratio between the tanks, and when the plenum pressure drops to 80% of the main tank pressure, valve opening is halted, and the plenum is refilled. In the case that one of the pressure sensors has failed, the system can be placed into a “dead reckoning mode”. In this mode, the refill decision is based on the total accumulated opening time of the valves. After the total opening time exceeds the defined limit, the plenum is refilled, also for a set amount of time.

VI. Test Facilities

The first engineering unit underwent three separate test campaigns, first at Georgia Tech to evaluate general performance, then at NASA Glenn Research Center to verify that performance, and again at Georgia Tech to investigate longer duration actuations and specific impulse [13]. Testing at both facilities made use of a torsional test stand inside a vacuum chamber. All tests were performed 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 were completed.

A. Glenn Research Center

The vacuum chamber used at Glenn Research Center is a cylindrical chamber 1.5 meters in diameter and 4.5 meters long. It is pumped by four oil diffusion pumps, and is capable of reaching a base pressure of $4x10^{-7}$ Torr.

The GRC test stand, shown in the right hand side of Figure 4, is a torsional pendulum design that can either measure steady state thrust or short impulses. This test stand was originally designed to test pulsed plasma thrusters, which produce relatively low levels of thrust for short periods. As the BioSentinel thruster has a similar operating paradigm, the stand was used with little modification. A long aluminum arm is allowed to rotate on flexural pivots within a welded aluminum frame inside the vacuum chamber. The flex pivots provide nearly frictionless rotation as well as a small restoring force to the arm. When the thruster actuates, the arm begins to oscillate, and the amplitude of that oscillation is recorded by a linear variable displacement transducer (LVDT). The amplitude of this oscillation is proportional to the impulse transferred to the arm.

The GRC stand is calibrated by use of a series of three 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.

B. Georgia Tech Space Systems Design Lab

The Georgia Tech vacuum chamber has a cubic test volume, with a usable volume of approximately 60 cm x 55 cm x 60 cm, and can achieve a base pressure of 1×10^{-6} Torr using a 300 L/s turbomolecular pump. The chamber is capable of limited thermal testing via a heated/cooled platen on the floor of the chamber, with an operating temperature range of -40 to +60 C.

The thrust stand used at Georgia Tech was based on the GRC design, and closely resembles it. It is also a torsional pendulum design, with flex pivots and an LVDT to measure displacement. It is physically smaller, in order to fit in the SSDL vacuum chamber. The two stands are shown side by side in Fig. 4.

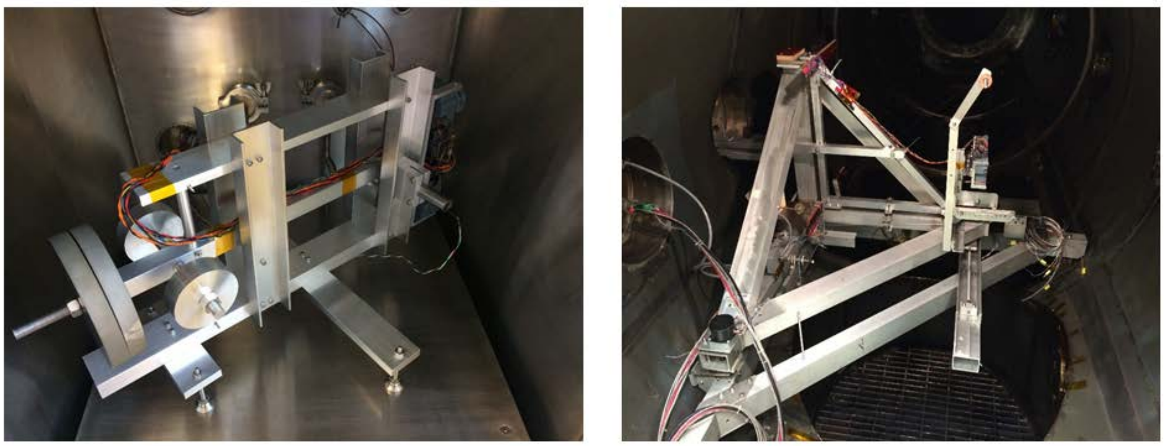

Fig. 4 The BioSentinel thruster mounted to the test stand in the vacuum chamber at Georgia Tech (left) and at the NASA Glenn Research Center (right).

VII. Test Results

A. Thrust Measurements

All seven nozzles on the propulsion system were tested in the vacuum chamber. Tests were conducted at pulse widths ranging from 3 ms to 200 ms. 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 actuations).

The range of actuation times (from 3 ms to 200 ms) 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 actuate for a full operating cycle (200 ms). The minimum time the valves can be opened is 3 ms, since the valves receive a 3 ms spike voltage at the beginning of every actuation, 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 actuation 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 Fig. 5 – 7 below. These measurements were collected from the flight unit during its qualification 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.

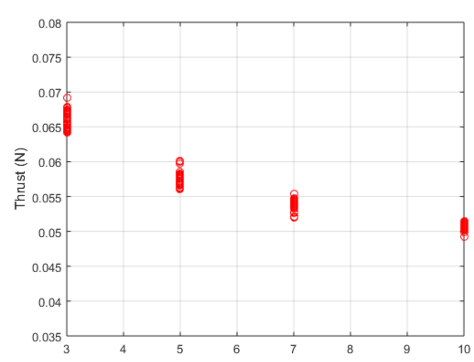

Fig. 5 Average thrust as a function of pulse duration for Nozzle 2 (-Y).

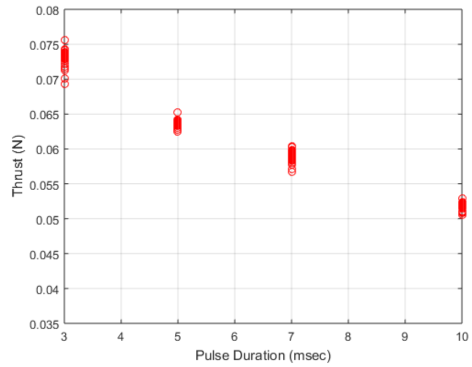

Fig. 6 Average thrust as a function of pulse duration for Nozzle 4 (-Z).

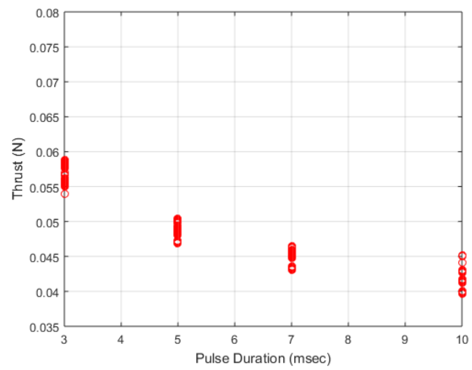

Fig. 7 Average thrust as a function of pulse duration for Nozzle 7 (+X).

It is important to note that the temperature of the test chamber was not strictly controlled during data collection in Fig. 5 – 7, 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 actuation, and hence the thrust that is achieved also decreases.

B. *Time Dependence of Average Thrust*

From the thrust plots shown in the preceding section, it is clear that the average thrust is dependent on pulse duration, with shorter pulses producing higher average thrust. 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 Fig. 8, 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 on shorter pulses, as is apparent in Fig. 8, since the impulse is averaged over a shorter time period, resulting in a higher measured thrust.

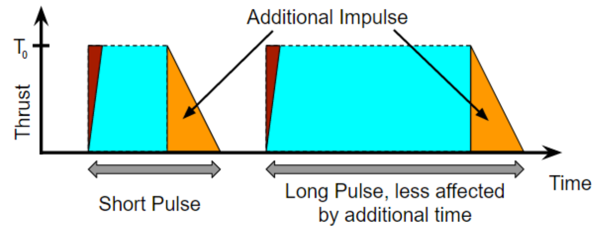

Fig. 8 Notional diagram of instantaneous thrust throughout a pulse, note that valve closing takes more time than valve opening.

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 Fig. 8 was confirmed by tests performed at longer thrust durations, which were tested specifically for BioSentinel.

As can be seen in Fig. 9, 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 scatter of data points below the main group are the result of the propulsion system software halting an actuation 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.

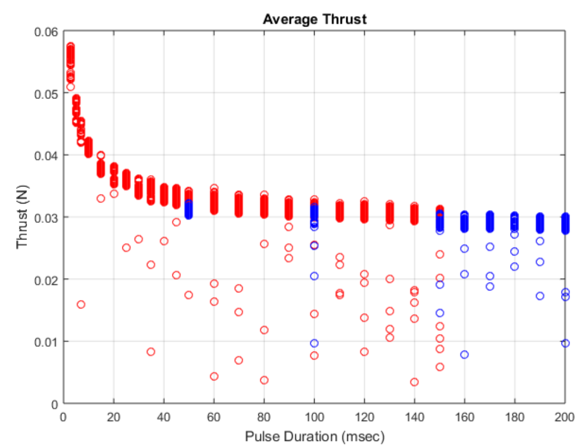

Fig. 9 Nozzle average thrust as a function of pulse duration over a range of 3-200 ms. The blue and red points were collected during different tests, but at the same temperature.

C. *Specific Impulse*

The specific impulse of the thruster must be known in order to determine the proper propellant loading for a given mission. Specific impulse can be predicted using the isentropic flow equations. These equations simplify the system to a quasi-one-dimensional, isentropic expansion through a nozzle. The specific impulse of the system can be computed with:

$$I_{sp} = gV_e \tag{3}$$

Where I_{sp} is the specific impulse [s], g is the standard acceleration due to gravity [9.81 m s^{-2}] and V_e is the velocity of the exhaust at the exit plane of the nozzle [m s^{-1}]. The exit velocity can be determined by calculating the speed of sound and the Mach number at the exit plane. The speed of sound in an ideal gas is:

$$a = \sqrt{\gamma RT} \tag{4}$$

Where a is the speed of sound [m s^{-1}], γ is the ratio of specific heats of the gas, R is the specific gas constant [kg m^2 s^{-2} K^{-1} mol^{-1}], and T is the absolute temperature [K]. The Mach number of the exit gas can be calculated, although not explicitly, using:

$$\frac{A}{A^*} = \left(\frac{\gamma+1}{2}\right)^{-\left(\frac{\gamma+1}{2(\gamma-1)}\right)} \frac{1}{M}\left(1+\frac{\gamma-1}{2}M^2\right)^{\left(\frac{\gamma+1}{2(\gamma-1)}\right)} \tag{5}$$

Where A/A^* is the area ratio between the exit plane of the nozzle and the throat of the nozzle, γ is the ratio of specific heats, and M is the exit plane Mach number.

The BioSentinel thruster has an area ratio of 204, and the ratio of specific heats of the R-236fa propellant is 1.069. From these values the specific impulse was predicted to be 46.9 seconds when operating the thruster at 25 C. Since this assumes no viscous losses, the actual value is expected to be somewhat lower.

In order to measure specific impulse, the thruster must be weighed before and after an actuation to determine the amount of mass lost. With an I_{sp} of 46.9 seconds, a typical 10 millisecond pulse only consumes 870 micrograms of propellant, too small of an amount to detect on available mass scales. Instead, the thruster was actuated thousands of times at the same pulse width, and the impulses from each actuation were summed to obtain a total impulse for a large amount of total actuation time. The average specific impulse across all of the actuations could then be calculated using:

$$I_{sp} = \frac{\sum J_i}{g\Delta M} \tag{6}$$

where J_i are the impulse measurements from each actuation [N s], g is the standard acceleration due to gravity [9.81 m s^{-2}], and ΔM is the mass change across all of the actuations [kg]. The number of actuations is chosen to yield a large enough mass change that it is measureable with low relative uncertainty on the available 0.01 gram resolution mass scales.

Several of these actuation series were completed to characterize the specific impulse of the thruster at a variety of pulse widths. Each sequence involved an initial starting propellant load of at least 50 grams, and an interval of 65 seconds between pulses to allow the test stand to settle. The results of these tests are shown in Table 3.

Table 3: Specific impulse test summary

Pulse width [ms]	Number of pulses	Total Impulse [N s]	Mass Loss [g]	Specific Impulse [s]
5	1200	0.271 ± 0.010	0.68 ± 0.01	40.7 ± 1.93
5	1200	0.275 ± 0.010	0.69 ± 0.01	40.6 ± 1.91
10	3500	1.412 ± 0.048	3.26 ± 0.01	44.2 ± 1.53
10	1200	0.491 ± 0.018	1.10 ± 0.01	45.5 ± 1.87
50	1200	1.896 ± 0.071	4.04 ± 0.01	47.8 ± 1.79
200	720	3.728 ± 0.147	8.20 ± 0.01	46.4 ± 1.82

D. *Total Impulse*

The total impulse requirement of 36 N s can be verified with the specific impulse test results. The total impulse of the system is:

$$J_t = gI_{sp}m_p \tag{7}$$

where J_t is the total impulse of the system [N s] and m_p is the total propellant mass [kg]. Using the worst-case specific impulse number of 40.7 seconds, and the nominal propellant loading of 200 grams, the total impulse is calculated to be 79.8 N s, which much larger than required. This excess margin will be retained to support potential mission extensions.

VIII. Discussion

The experimental results presented in the preceding section indicate that the BioSentinel propulsion system is performing as expected. Nominal thrust values operate in the range of 40 – 70 mN, which agrees with the theory prediction for R-236fa. The "lag" in the solenoid valve response seen for shorter pulse durations (as depicted in Figure 8) is a very interesting result, but not a troubling one given that in flight pulse durations lower than 100 msec will rarely be commanded. This is reinforced by the result of Figure 9, which shows the thrust generated as a function of pulse duration levels for longer actuation times.

It is important to acknowledge that the test campaign described here, while detailed, does not fully encompass all of the testing requirements for any spacecraft mission. In particular, system-level testing between the propulsion system and other spacecraft elements (such as the flight computer) is not included, nor is any environmental testing. Shock and vibration testing and thermal vacuum mission simulation testing will be undertaken at NASA Ames when the propulsion system has been integrated into the full spacecraft. Preliminary vibration testing with the engineering development unit indicates that the thruster will meet its structural requirements.

One challenge facing any spacecraft mission is determining a test program for a given subsystem that is reflective of the environment that will be encountered on orbit. This is particularly challenging for the BioSentinel mission, since so much is unknown about the operating environment. NASA has not yet finalized the trajectory of the Space Launch System, making it difficult to predict what the exact thermal environment will be during nominal BioSentinel operations. As such, the propulsion system design team was required to prepare against a wide range of possible temperatures, as reflected in the operating requirements presented in Section III. However, it should be noted that the BioSentinel propulsion system has sufficient control authority for both detumble and momentum management operations.

The BioSentinel mission poses unique requirements for the propulsion system, given the strict volume limitations of the 6U form factor and the safety constraints that must be considered to fly as a secondary payload on SLS. Using R-236fa as a propellant allays safety concerns, and taking advantage of 3D-printing technology allows for the available volume to be used with maximum efficiency. The results presented herein indicate that no loss of performance is seen as a result of using these novel design approaches. The propulsion system presented in this work has significant design margin for the anticipated 6 – 12 month mission life of the BioSentinel spacecraft.

IX. Conclusion

A novel propulsion system for spacecraft attitude control and momentum management has been developed at Georgia Tech for NASA's BioSentinel mission. The majority of the thruster was manufactured using stereolithography, a type of 3D-printing. This allowed much greater design flexibility relative to conventional fabrication methods, especially in the design of the internal tank geometry which is well suited to small satellites. Standalone testing of the flight unit is complete, and further testing will focus on integration with the BioSentinel spacecraft. The results presented here, collected from testing both at Georgia Tech and at NASA Glenn Research Center, confirm that the thruster is capable of meeting the mission requirements.

Acknowledgment

The authors would like to thank their collaborators at NASA Ames Research Center and Glenn Research Center. In particularly, the inputs of Dr. Robert Thomas, Dr. Tom Haag, and Dr. Jon Mackey of NASA Glenn's In-Space Propulsion branch are much appreciated. Development of the BioSentinel propulsion system is being funded under NASA SBIR Contract NNX15CA06C.

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] J. Mueller, J. Ziemer, and R. Hofer, "A survey of micro-thrust propulsion options for microspacecraft and formation flying missions," *5th Annual CubeSat Developers Workshop*, San Luis Obispo, CA, 2008, pp. 1–19.

[9] D. Hinkley, "A Novel Cold Gas Propulsion System for Nanosatellites and Picosatellites," *Proceedings of AIAA/USU Small Satellite Conference*, Logan, UT, 2003.

[10] T. K. Imken, T. H. Stevenson, and E. G. Lightsey, "Design and Testing of a Cold Gas Thruster for an Interplanetary CubeSat Mission," *Journal of Small Satellites*, vol. 4, no. 2, pp. 371–386, 2015.

[11] G. Manzoni and Y. L. Brama, "SSC15-IV-5 Cubesat Micropropulsion Characterization in Low Earth Orbit," *Proceedings of AIAA/USU Small Satellite Conference*, 2015.

[12] Sorgenfrei, M., Nehrenz, M., and Thomas, R., "On the Implementation of Microelectrospray Propulsion Systems in a CubeSat-Class Spacecraft", *Proceedings of AAS Guidance, Navigations, and Control Conference,* Breckenridge, CO, February 2014.

[13] Sorgenfrei, M., Stevenson, T., and Lightsey, G., "Performance Characterization of a Cold Gas Propulsion System for a Deep Space Cubesat", *Proceedings of AAS Guidance, Navigation, and Control Conference*, Breckenridge, CO, February 2017.