SSC23-VI-06

Design to Delivery of Additively Manufactured Propulsion Systems for the SWARM-EX Mission

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ABSTRACT

Recent progress in miniaturized spacecraft propulsion technology has allowed for the development of complex, multi-vehicle missions which enable the cost-effective realization of science goals that would previously have been prohibitively expensive. The upcoming NSF-funded Space Weather Atmospheric Reconfigurable Multiscale EXperiment (SWARM-EX) mission leverages these swarm techniques to demonstrate novel autonomous formation flying capabilities while characterizing the spatial and temporal variability of ion-neutral interactions in the Equatorial Ionization Anomaly and Equatorial Thermospheric Anomaly. SWARM-EX will fly a trio of 3U CubeSats in a variety of relative orbits with along-track separations ranging from 3 km to 1300 km.

To achieve the required orbital variability, the mission uses a novel hybrid approach of differential drag and an onboard cold gas propulsion system. Mission requirements necessitate a propulsion system that provides each spacecraft with 15 m/s of ΔV and a maximum thrust greater than 5 mN in a volume of roughly 0.7U (7 cm x 10 cm x 10 cm). Unlike many other CubeSat-scale cold gas propulsion systems which are used to provide attitude control and perform reaction wheel desaturation burns, the primary objective of the SWARM-EX propulsion system (SEPS) is to provide ΔV during maneuvers.

The Georgia Institute of Technology Space Systems Design Laboratory (SSDL) is conducting the design, assembly, and testing of three identical SEPS. By leveraging additive manufacturing technology, the propellant tanks, nozzle, and tubing are combined into a single structure that efficiently utilizes the allocated volume. The propulsion system uses two-phase R-236fa refrigerant as a propellant, which allows for the storage of the majority of propellant mass as a liquid to maximize volumetric efficiency. The final design allows for 17 m/s of total ΔV per spacecraft and a measured maximum thrust of approximately 35 mN for short pulse lengths at room temperature. Each individual propulsion system has a volume under 0.5U (489 cm^3), making them among the smallest formation-flying CubeSat-scale propulsion systems developed thus far. Owing to their two-phase propellant storage and single nozzle, the SEPS have a high impulse density (total impulse provided per unit of system volume) of 176 N-s/L. Additionally, process improvements to mitigate known failure modes such as propellant leaks and foreign object debris are implemented.

This paper describes the entire design-to-delivery life cycle of the SWARM-EX propulsion units, including pertinent mission requirements, propulsion system design methodologies, assembly, and testing. Major lessons learned for future small satellite propulsive endeavors are also detailed.

Introduction

Multi-vehicle formations of small spacecraft and CubeSats are increasingly being proposed as a method of facilitating complex science missions.[1] The success of these missions hinges upon the ability to precisely deliver small impulses to enable attitude control and relative orbit adjustment. Several upcoming CubeSat science missions will leverage two-phase cold gas propulsion systems developed by the Georgia Institute of Technology (Georgia Tech) Space Systems Design Laboratory (SSDL) to perform maneuvers central to mission operations. These missions include the Sun Radio Interferometer Space Experiment (SunRISE), VIrtual Super Optics Reconfigurable Swarm (VISORS), and the Space Weather Atmospheric Reconfigurable Multiscale EXperiment (SWARM-EX).[2–4] This paper details the design, assembly, and testing of propulsion systems for the SWARM-EX mission.

0.1 The SWARM-EX Mission

SWARM-EX is an upcoming NSF-funded mission that will launch a trio of identical 3U CubeSats into low Earth orbit (LEO) to investigate the equatorial ionization anomaly and equatorial thermospheric anomaly. It will also demonstrate novel formation flying capabilities utilizing both onboard propulsion and differential drag. SWARM-EX serves as a pathfinder mission for a proposed global constellation of CubeSat swarms making in-situ real-time atmospheric measurements.[4] The project is a collaboration between the University of Colorado Boulder (CU Boulder), Stanford University, Georgia Institute of Technology, Western Michigan University, University of Southern Alabama, and Olin College. Georgia Tech is supplying the propulsion systems for all three CubeSats. A computer-aided design (CAD) rendering of a single SWARM-EX CubeSat is shown in Figure 1.[5]

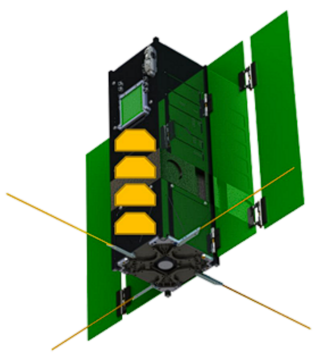


Figure 1: CAD rendering of a single SWARM-EX CubeSat[5]

The Concept of Operations (CONOPS) for SWARM-EX involves all three spacecraft maneuvering in a variety of relative orbits with along-track separations ranging from 3 km to 1300 km. The principal propulsion system requirements to support the mission CONOPS are as follows:

- The volume of the propulsion subsystem shall be less than 0.7U.
- The mass of the propulsion subsystem shall be less than 700 g.
- Each propulsion subsystem shall be capable of providing a ΔV of greater than or equal to 15 m/s.

Subsequent subsystem requirements were then derived from these principal requirements.

In support of the SWARM-EX mission, a total of five SEPS were assembled and tested at the Georgia Tech SSDL. Two engineering development units (EDUs), designated EDU1, and EDU2, were built first in late 2022. This allowed for the concurrent environmental and performance testing of EDU2 at Georgia Tech while EDU1 was delivered to CU Boulder to support preliminary spacecraft integration work. Three flight modules (FMs), denoted FM1, FM2, and FM3, were then assembled and tested at the SSDL in Spring 2023.

Two-phase Cold Gas Propulsion

Cold gas propulsion systems produce thrust by expelling propellant gas through a converging-diverging nozzle. The propellant is typically stored as a pressurized gas or as a saturated liquid. Cold gas systems have the advantage of being relatively low cost and low complexity while providing fine control over impulse imparted for precise maneuvering.[6]

The Georgia Tech SSDL has developed several cold gas propulsion systems utilizing the non-toxic, high-vapor-pressure refrigerant R-236fa as a propellant. These propulsion systems generally follow the functional block diagram shown in Figure 2, in which a main tank stores the propellant as a saturated liquid to maximize volumetric efficiency. A solenoid refill valve allows for the release of some propellant into a secondary plenum tank, in which the propellant vaporizes. When commands are received from the spacecraft, the system opens another solenoid valve to allow the now-gaseous propellant to flow from the plenum through a diverging nozzle into space, delivering an impulse to the spacecraft. These valves are mounted in traditionally machined sub-assemblies and soldered onto a controller board which operates the system in response to commands received from a spacecraft flight computer.

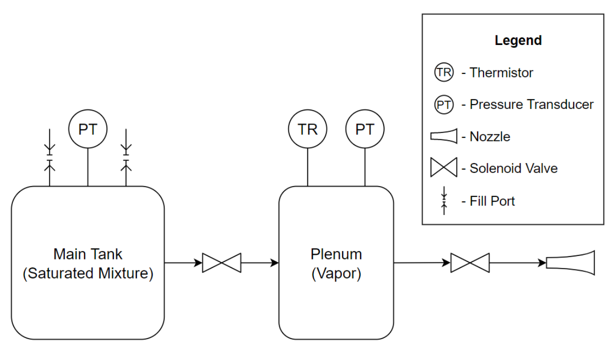


Figure 2: Functional block diagram of the SWARM-EX two-phase cold gas propulsion system.

Additive manufacturing in the form of stereolithography (SLA) resin 3D printing is leveraged to allow for maximum use of the limited, irregular volume envelopes available within typical CubeSat buses. Integrating the propellant lines and mounting points into the tank structure forms a monolithic primary "flight structure". Sensors, valves, valve subassemblies, and controller boards are subsequently attached to the flight structure. Temperature and pressure sensors allow for monitoring of the subsystem via telemetry and give input for closed-loop control of the refill valve during long fires.

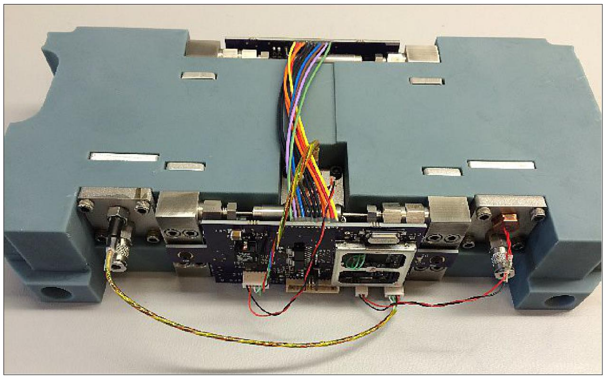


Figure 3: BioSentinel propulsion system.[7]

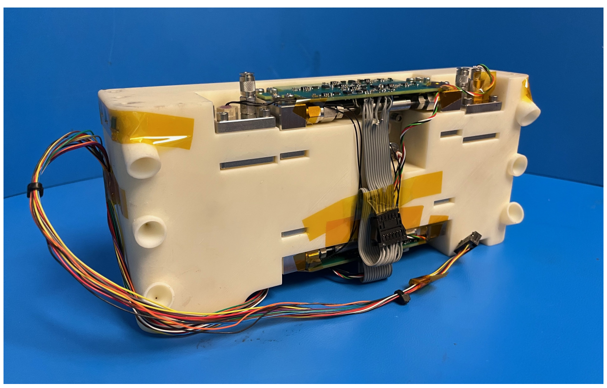


Figure 4: SunRISE propulsion system EDU.[8]

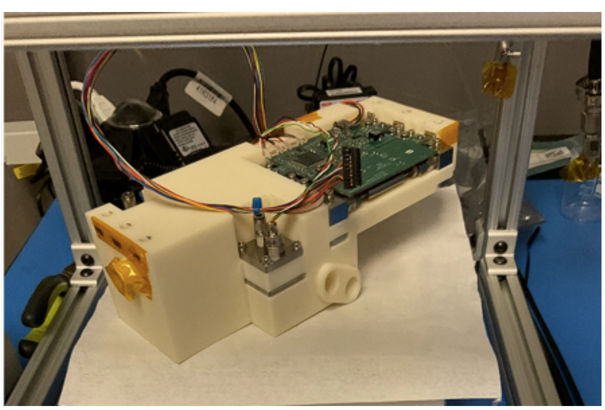


Figure 5: VISORS propulsion system EDU.

As of April 24, 2023, three systems of this general type have successfully flown, with six additional systems awaiting spacecraft integration.[9] An additional five flight systems are currently undergoing subsystem assembly and environmental testing, including the three SWARM-EX flight propulsion systems.

The first cold gas propulsion system developed by the Lightsey Research Group using the aforementioned general plan was for the University of Texas at Austin's Bevo-2 satellite in 2015.[10] Continued improvements were made before another system was delivered for the NASA Ames Research Center's BioSentinel mission. BioSentinel was launched on November 16, 2022, on Artemis I and successfully used its cold gas propulsion system to de-tumble and perform a lunar avoidance maneuver on its way into an Earth-trailing heliocentric orbit.[7,9] See Figure 3 for a view of the BioSentinel propulsion system before spacecraft integration. A derived system was also flown on the AFRL Ascent mission in 2021.

The next major cold gas propulsion system to be developed was for the NASA SunRISE mission. Major changes included the repositioning of nozzles and internal flow paths for spacecraft system requirements and the replacement of the Accura Bluestone material used for the structure of BioSentinel with SOMOS PerFORM on all subsequent systems. A total of six flight units and one flight spare have been delivered and are currently awaiting spacecraft integration.[2,8] Figure 4 shows the SunRISE propulsion system before spacecraft integration.

As of June 2023, the VISORS propulsion system is currently in the initial stages of assembly in the SSDL. The VISORS propulsion system, shown in Figure 5, is similar to the SunRISE system but notably provides the ability to produce an impulse along all six translational directions in the spacecraft body frame.

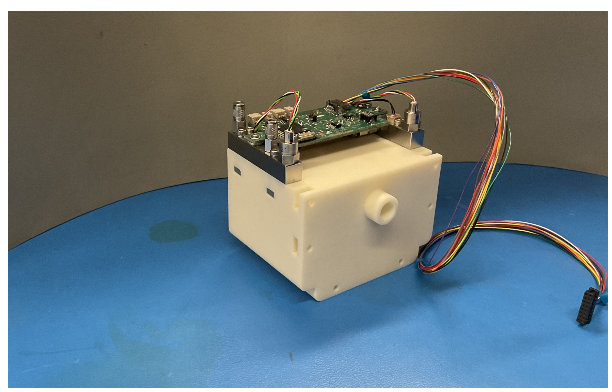


Figure 6: SWARM-EX EDU2 fully assembled.

Meanwhile, the SEPS is somewhat distinct from the previous systems in being a purely ΔV thruster mounted on 3U CubeSats, as opposed to the 6U spacecraft into which the previously mentioned systems are integrated. The SEPS contains an improved valve sub-assembly structure that features integrated sensor and valve manifold plates to enable the system to fit within the 0.7U volume envelope while still achieving the 15 m/s ΔV requirement. The system also only contains a single nozzle due to there being no attitude determination and control (ADCS) component of its mission, with all of the reduced complexity of internal flow paths entailed.[11] These major components are called out in the CAD model shown in Figure 7.

Design

Mechanical Design

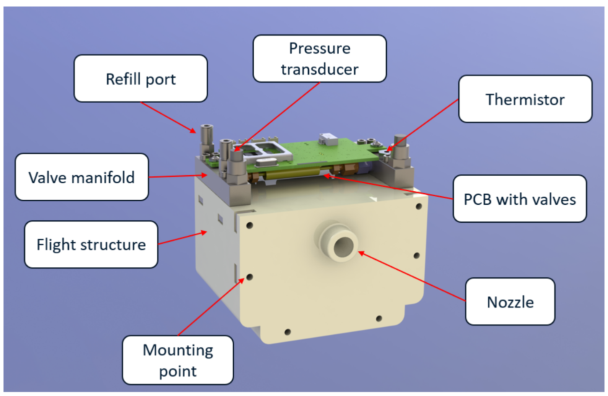


Figure 7: CAD model of the SEPS, with examples of major components called out.[11]

The SEPS design is driven by mass efficiency. The system is limited by the mass requirement, rather than the volume, so volumetric efficiency is not prioritized. This fact has led to a simplified and unique thruster that improves upon the choices made in past systems.

SEPS inherited its system architecture and major design features from the BioSentinel propulsion system. From this baseline, mass was first cut by mounting all sensors and fill ports directly to the valve sub-assemblies. This approach eliminates the need for separate sensor plates and mounting hardware, which have traditionally been used. Additionally, the integrated sub-assemblies also reduce the number of sealing surfaces in the system, thereby decreasing the risk of leaks.

Eliminating dedicated sensor plates consequently removes the large ports that these plates mount onto. In past systems, these ports have facilitated the cleaning of the tanks before assembly. In their absence, the largest access point into the tanks is decreased to just 2 mm in diameter. This was identified as a problem during the cleaning of EDU1. A 2.5 mm diameter piece of debris from the manufacturing process was found in the tank and could not be removed due to its size. This issue was remedied in flight units by increasing the diameter of the pressure transducer mounting ports. With this change, debris was more easily removed from the flight units.

Additional mass is removed from the system by eliminating one of the two thermistors used to sense tank temperature. Previous designs allocated a thermistor to each tank, but in reviewing the system software and requirements, it was determined that the temperature of the main tank is not a required measurement. Eliminating this sensor allows for a shortened valve sub-assembly and additional mass savings.

Software Design

The SEPS uses an updated version of the controller, electronics, and software developed for the BioSentinel propulsion system. Minor changes were made to the electronics to reduce power usage and nonlinearities in sensor readings. Despite relatively unchanged electronics, the performance and reliability of the system have seen significant improvements thanks to progressive iteration in the software implementation.

The most significant improvement is the operational change in the closed-loop refill strategy. The closed-loop refill relies on the sensor readings to determine whether or not the plenum is filled. The system uses a saturated liquid-vapor mixture of propellant so plenum pressure is maintained between a high and low fraction of the main tank pressure. When the high refill threshold pressure is met, the refill is complete. When the pressure drops below the low refill threshold, a refill is automatically triggered to return the plenum to the high refill threshold pressure. The plenum is typically depleted after several separate thrust maneuvers. During the testing of the cold gas systems, it was determined that the flow between the tanks injects liquid into the plenum. As this liquid evaporates, the plenum pressure rises when the refill valve is closed. The liquid in the plenum introduces operational risks. These conditions produce large thrust that is difficult to model and predict. To combat this issue, the propulsion systems went through refill characterization testing. The results of this testing enable the prediction of the refill valve opening time to inject the necessary mass of propellant in the plenum to raise the pressure to the high refill threshold. This function is implemented in software along with logic to wait for the plenum pressure to reach a steady state before the operation can continue.[12] The refill logic changes are an improvement on the previous system performance in terms of the system operation predictability and consistency. Waiting for the plenum pressure to reach a steady state, though, has increased the refill time from 5-10 seconds to 30-60 seconds.

The implementation of refill logic in software is unit tested along with other propulsion system software functionality. A software unit testing framework has been developed using serial communication between Matlab and an Arduino Mega running a modified build of the flight firmware. Additional command operational codes are included in the command processing logic of the modified software build to read in pressure and temperature values for the main tank and plenum. This approach allows the unit test writer to set the current state of the propulsion system in software without needing any flight hardware in the loop. Unit tests are conducted by sending commands and monitoring the resulting telemetry to ensure that the software is behaving as expected. Examples of requirements satisfied by unit tests are listed below.

- The flight software shall command a valve or combination of valves open for a time specified by the operator between 1 ms and 65,533 ms.
- The flight software shall command the refill valve open until the plenum pressure reaches the current high refill threshold.
- The flight software shall be able to pause and resume a 1 Hz telemetry stream

Assembly

The SWARM-EX propulsion units were assembled in the SSDL's Flight Hardware Lab (FHL). The FHL is a class 100,000 clean room and components brought into the space undergo a detailed cleaning process with foam-tipped clean swabs and isopropyl alcohol (IPA). As the primary structures and ancillary components arrived, inspections and fit checks were performed prior to cleaning and the parts being brought into the clean room. All mechanical fasteners were thread-locked with vacuum-safe epoxy. While EDU1 and EDU2 were assembled in series, all three FMs were assembled in parallel to take advantage of more efficient workflows associated with batch production.

Pre-assembly preparation for the SEPS consists of modifications to off-the-shelf components and gathering data for calibration. Valves and sensors are cut down from their original lengths to fit within the tight volume of the SEPS. Calibration curves are produced for the temperature and pressure transducers using custom-built ground support equipment (GSE). The pressure calibration GSE controls temperature using a commercial thermoelectric cooler while the sensors are pressurized in a sealed container with nitrogen gas. This allows for precise control of the temperature and pressure experienced by the sensors, and the creation of a temperature vs pressure vs sensor signal curve. These calibration curves are subsequently used to scale the raw analog signals of the sensors into meaningful system telemetry by flight software.

Finally, the additively manufactured flight structures were cleaned of internal foreign object debris (FOD) from the printing process. The cleaning process consisted of multiple cycles of IPA rinsing, followed by detailed observation of the resultant debris under a microscope. A major takeaway from the cleaning process during both the EDU and FM assembly was that it is extremely difficult to adequately clean self-contained additively manufactured structures sufficiently to ensure that particulates left over from the manufacturing process do not flow downstream during operation. Concerns regarding the cleaning process in fact led to additional cleaning cycles being performed prior to FM assembly.

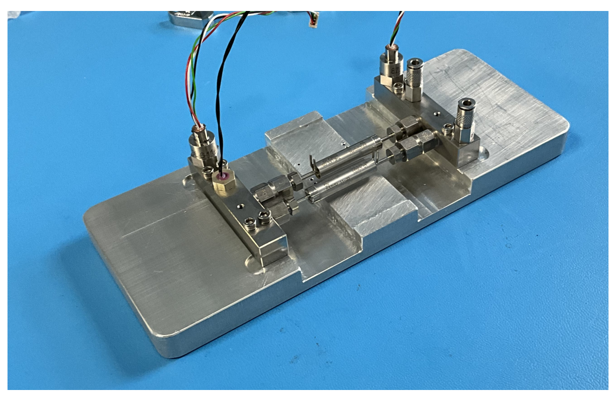


Figure 8: SWARM-EX FM1 valves, compression fittings, filters, and valve sub-assemblies mounted in a swaging stencil.

After component-level preparations were completed, the mechanical assembly of the systems commenced. The joining of the valves to the subassembly blocks involved the use of Swagelok-type tube compression fittings. Five-micron filters were installed upstream of the valves along the fluid flow path to catch any remaining FOD from the interior of the propellant tanks. Prior to installation, the built-in O-rings on the filters and compression fittings were lightly coated in vacuum-safe silicon O-ring grease to lubricate them and prevent abrasive damage.

The valves, filters, compression fittings, and valve sub-assemblies were subsequently installed together in a stencil to keep all the parts in place before the fittings were "swaged" or torqued down to specification, crushing the front and back metal ferrules together to form a seal.

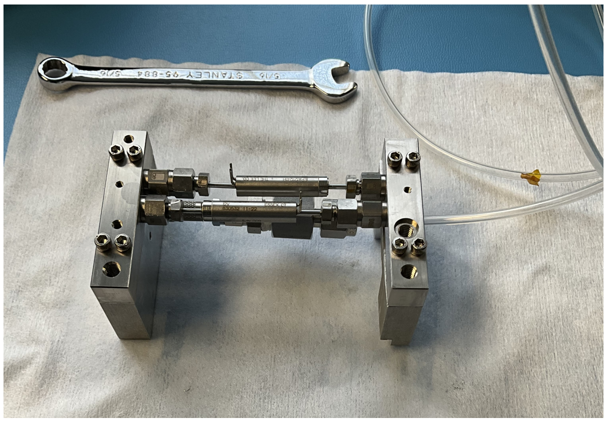


Figure 9: FM1 valve sub-assembly mounted to leak check GSE.

Following the initial swaging, the valve sub-assemblies were bolted onto leak check GSE as shown in Figure 9 which mimic the O-ring groove patterns of the flight structure and allow for the flow of clean N_2 gas through the valve and sub-assembly structure. Swagelok Snoop® Liquid Leak Detector was then applied to the compression fittings to check for leaks. If leaks were detected on compression fitting joints, the leaky joint was then re-swaged by torquing an additional quarter turn. This process was repeated until no leaks were detected in the system. The pre-assembly leak check process allowed for the detection of leaks associated with the valve sub-assembly early in the process, before system assembly and the standard 72-hour full system leak check. Potential leaks due to insufficiently tight compression fittings were detected and resolved on all three FM valve sub-assemblies at this stage.

After leak checking and re-swaging, the thermistors, pressure transducers, and quick disconnect (QDC) fill valves were installed. The O-ring grooves in the flight structure were then filled with lubricated O-rings in preparation for the joining of the valve sub-assembly and primary structure. The completed valve sub-assemblies were secured to the flight structures via through-hole bolts into small stainless steel back plates slotted into the additively manufactured structure.

Concurrently with the assembly of the valve sub-assemblies and flight structure, preparation work began on the controller boards for the propulsion systems. This process consisted of board functional checkouts, followed by sensor staking and conformal coating.

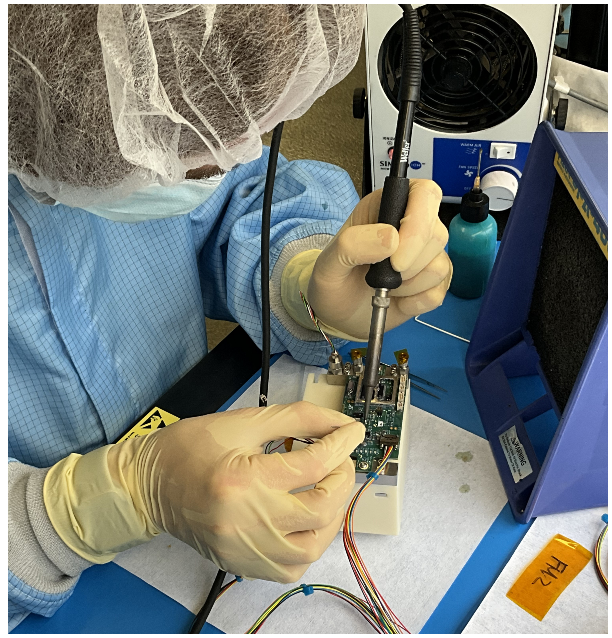


Figure 10: FM2 valves being soldered onto the controller board.

After conformal coating, the boards were then mounted onto the flight structure and the vertical pins of the solenoid valves slid into through-holes on the boards. The valves were soldered into place, as shown in Figure 10. The flight software was then flashed onto each board at this stage to close out the assembly process.

Testing

EDU2 went through an extensive environmental and performance test campaign. The following tests were performed:

- Proof Pressure Testing
- Initial Leak Rate Check
- Performance Testing (Hot, Cold, and Ambient)
- Vibration Testing
- Post-Vibration Leak Rate Check

Each SWARM-EX FMs also underwent an abbreviated test campaign, with the main omissions being hot and cold performance tests and vibration testing. These decisions were arrived at following discussions with the SWARM-EX systems engineering team. The SEPS FMs will undergo vibration testing integrated with the rest of the spacecraft, and hot and cold performance estimates for each FM can be derived from the EDU test results and ambient performance testing data.

Proof Pressure Testing

Each SEPS underwent nitrogen proof-pressure testing, in which the pressure transducers were tested to ensure correct readings against a calibrated pressure sensor attached to the regulator of the nitrogen source. The proof-pressure testing is a final verification step to ensure that the systems hold up to the design pressure with margin. Then, the systems were filled with a flight load of Rf-236fa propellant to allow for further testing under flight-like conditions.

Initial Leak Rate Check

The primary purpose of the initial leak check is to verify that the SEPS meets leak rate requirements. The test provides a worst-case leak rate, and the leak rate on the ground will be no worse than the result obtained under a vacuum. First, a 24-hour bakeout is performed in the GT SSDL thermal vacuum chamber (TVAC). During bakeout, the propulsion unit is heated under a high vacuum (1e-6 torr) to reduce the impact of off-gassing on the results of the leak rate test.

Leak check testing consists of a measurement of system mass before and after it is placed in the TVAC for 72 hours, during which thermal cycling between +50 °C and 0 °C is performed. The average leak rate over the duration of the test is then found using the following equation, where m_f and m_i refer to initial and final masses, and t_f and t_i refer to the start and end times of the test:

$$\dot{m}_{leak} = \frac{m_f - m_i}{t_f - t_i} \tag{1}$$

Table 1: Final Leak Rate Measurements

System	Measured Leak Rate
EDU2	6.62 mg/hr
FM1	0.356 mg/hr
FM2	0.393 mg/hr
FM3	0.481 mg/hr

The measured initial leak rate of SWARM-EX EDU2 is 6.62 mg/hr. The min-max range with measurement error, accounting for +/- 5 mg of precision on the calibrated scale used in the test, is 6.48 mg/hr to 6.76 mg/hr. This leak rate is above internal GT guidelines, which had been based on the mission requirements of BioSentinel, but below the SWARM-EX systems requirements.

The propulsion team subsequently noticed that the SWARM-EX leak rate requirement was not reflective of mission needs. At the original project guidelines of maintaining a leak rate under 24.4 mg/hr, up to 211 g of propellant would have been lost each year, greater than the SWARM-EX nominal propellant load of 200 g. Since SWARM-EX expects to wait roughly 6 months after integration for launch and then spend 2 months after launch commissioning the spacecraft, the leak rate requirement as initially set was unacceptably high and would potentially have led to a major loss of propellant prior to the end of the mission. Even the measured preliminary leak rate of 6.62 mg/hr is equivalent to a loss of 57.2 g of propellant per year, which would be close to the maximum amount tolerable by the mission.

A new leak rate requirement based on system propellant needs has therefore been proposed and is currently under review by the SWARM-EX systems engineering team. The new leak rate is the maximum allowable propellant loss rate based on the propellant load required after 6 months of waiting for launch and 2 months of commissioning to achieve 15 m/s of ΔV. This has been calculated to be 6.77 mg/hr. All SEPS FMs now are below this updated leak rate.

Performance Testing

Performance testing was conducted at Georgia Tech using a torsional pendulum test stand inside the SSDL TVAC chamber originally constructed to support the development of the BioSentinel propulsion system. Due to the very small impulses produced by the SEPS, traditional thrust stand designs based on reaction spring force or load cells are insufficiently sensitive, which led to the development of the test stand currently used. EDU2 is shown mounted to the stand in Figure 11. When the SEPS is fired, the thrust stand's arm oscillates, and the amplitude of the oscillation is recorded by a linear variable differential transformer (LVDT). The amplitude is proportional to the impulse transferred to the arm. During the test, the SEPS is controlled via a custom MATLAB GUI that simulates spacecraft telemetry. LVDT data are recorded via a LabView interface connected to a data acquisition card that is then transferred to and logged by the MATLAB program that runs the test. Post-processing is then accomplished via a series of separate MATLAB programs. Manual removal of outliers may then occur, with additional post-processing work performed as required.[7,13]

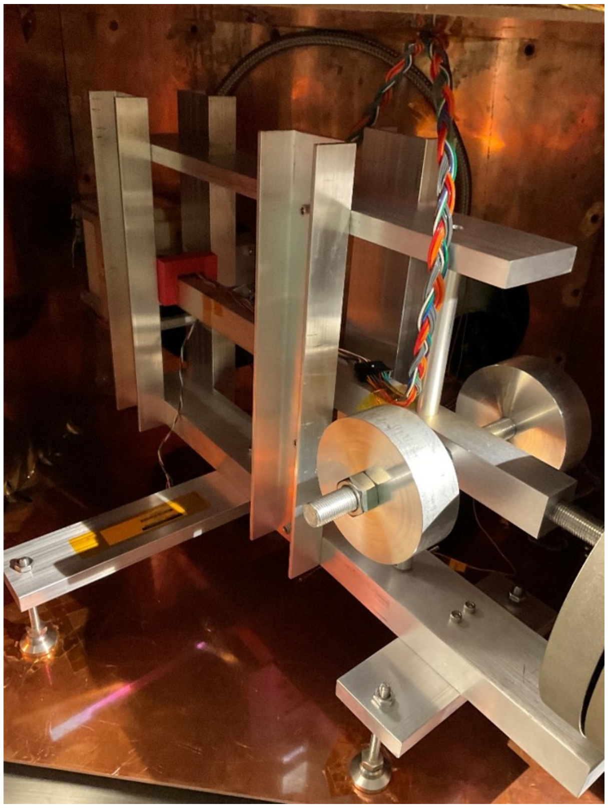


Figure 11: SWARM-EX EDU 2 mounted on the GT SSDL torsional thrust stand.

The test sequence consists of multiple fires at each pulse length, with pulse lengths logarithmically scaling up towards the maximum pulse length measurable before saturating the thrust stand at a given temperature. Saturation occurs when a pulse generates a sufficient impulse to cause the thrust stand arm to hit the limit of its travel bounds, generating inaccurate data. The thrust stand saturates with pulse lengths of approximately 100 ms at ambient conditions, and with pulse lengths of approximately 40 ms when the system is at hot temperature conditions. This is due to the higher pressures achieved in the plenum at higher temperatures, which means that larger impulses are achieved for each given pulse length.

EDU performance testing was undertaken at three separate temperature set points, a hot condition of 46 °C, a cold condition of 1.5 °C, and ambient conditions of 23 °C. As previously noted, the abbreviated testing for the FMs was only conducted at ambient conditions.

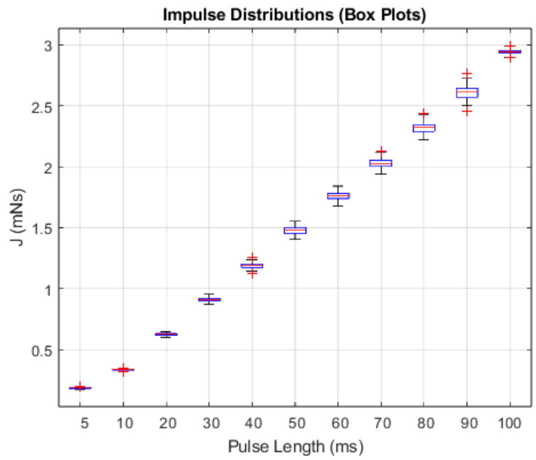


Figure 12: SWARM-EX FM1 Ambient Performance Test Impulse Data.

During performance testing, bulk I_{sp} measurements are also produced. These tests consist of measuring unit mass before and after individual performance tests during which large pulse times are used to burn off enough propellant to get a sufficient mass difference to ensure that scale precision does not dominate the results (typically 1.5-2g). Bulk I_{sp} is then determined using the following equation, where each of the J_i are impulse measurements from each discrete pulse command sent and $g = 9.81 m/s^2$ is gravitational acceleration:[7]

$$I_{sp} = \frac{\sum_{n=1}^{n} J_i}{g(m_i - m_f)} \tag{2}$$

Figure 12 shows the thrust impulse measured as a function of commanded pulse length for FM1. Box-and-whisker plots for each pulse length group represent the distribution of impulses recorded for each commanded pulse length. The measured Isp of FM1 at high vacuum and under ambient temperature conditions is 40.6 s, which leaves a significant margin towards fulfilling the required 15 m/s of ΔV. Similar data was generated for EDU2 at hot and cold conditions in addition to the ambient test conducted on FM1. As of June 1, 2023, performance testing is still underway for FM2 and FM3.

Vibration Testing

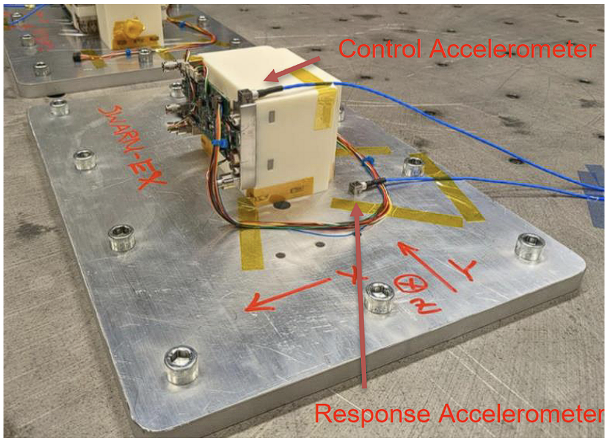
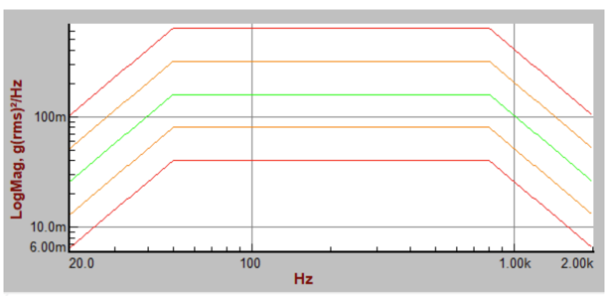


Figure 13: EDU 2 placed on an aluminum vibration plate and bolted to the GTRI horizontal vibration table. Axes of vibration and accelerometer placements are called out.

Vibration testing of SWARM-EX EDU2 to verify the design was performed at the Georgia Institute of Technology Research Institute (GTRI) vibration testing facility in Cobb County, Georgia.



	Freq (Hz)	Ref	Unit
1	20	6	dB/Oct
2	50	0.16	(g)²/Hz
3	800	0.16	(g)²/Hz
4	2000	-6	dB/Oct

Acceleration (g rms): 14.125

Figure 14: SWARM-EX EDU2 random vibration testing profiles. Green denotes the target curve, with orange and red denoting margin within which the test may continue.

The test consisted of a functional checkout and sine sweep conducted before and after a random vibration load was applied to each axis of the propulsion unit to determine whether it would survive launch. The functional checkout was performed before and after each axis vibration test, consisting of the actuation of all valves. The random vibration load applied was consistent with the NASA Goddard Space Flight Center's General Environmental Verification Standard (GEVS) GSFC-STD-7000 Version B Table 2.4-3 for the Qualification Level Prototype Qualification.[14] The vibration duration in each axis was 2 minutes. See Figure 14 for the random vibration profile.

The system passed functional checkout in all three axes, x, y, and z. The sine sweep responses before and after random vibration in each axis are shown in Figure 15. The shift in pre- and post-random vibration sine response in the y and z axes is not considered subjectively significant. However, the shift in pre- and post-random vibration sine response in the x-axis was considered subjectively significant and may be attributed to the settling in of some components which previously were not as tightly packed, or the shifting of propellant inside the system. As the EDU passed the functional checkout after the x-axis random vibration test, it is not considered a significant fault requiring rework. Overall, the vibration testing of EDU2 was sufficient to verify system function under expected launch loads.

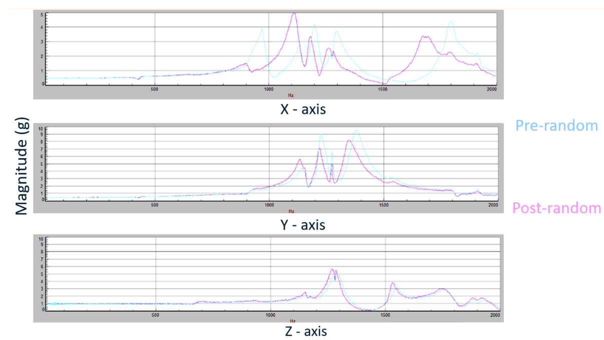


Figure 15: EDU 2 sine response plots in all three axes. The x-axis denotes the frequency and the y-axis denotes the response magnitude in g.

Post-Vibration Leak Rate Check

After vibration testing, EDU2 was put through another leak rate test to check if leaks had developed due to the modal load. Surprisingly, the system had a significantly lower leak rate post-vibration test. The overall leak rate of 0.46 mg/hr meets even the updated 6.77 mg/hr. Potential hypotheses for this change include the longer leak check time causing out-gassing to be a less significant factor in the leak rate calculation, systematic error inherent in the testing methodology, such as scale precision or an inconsistent leak rate, or the vibration process having shaken closed a passage through which propellant had previously been leaking. As of the time of writing, there has not yet been vacuum chamber time available to test any of these hypotheses against control cases in the TVAC, although these tests are planned for the future.

FM1 Anomaly

A particularly notable anomaly was encountered during FM1 testing and required significant rework to FM1, although no other systems were impacted. This experience is detailed here as a lesson learned for other projects.

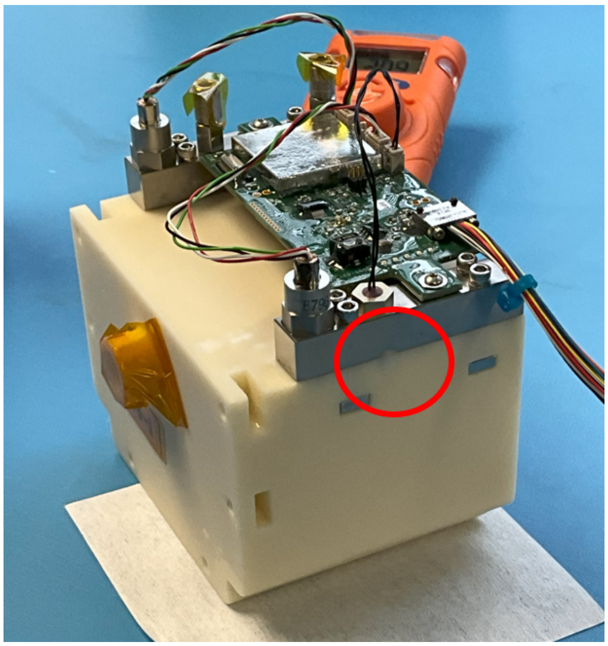


Figure 16: SWARM-EX FM1 plenum flight structure - valve sub-assembly interface leak.

During the initial mass measurement post-bakeout of FM1, it was noticed that FM1's mass was dropping after the plenum was first filled. Through analysis of telemetry data, it was discovered that the plenum pressure was consistently dropping noticeably throughout a subsequent 30-minute window. All three SWARM-EX flight units were then placed in the vacuum chamber at pressure overnight to gather additional data.

By the next morning, the plenum of FM1 was fully at vacuum and the propulsion unit had lost 1g of mass, while FM2 and FM3 had only minimal differences in mass compared to the previous night. This was a leak that was very obviously above the SWARM-EX maximum leak rate requirements. Subsequent investigation found a major leak between the plenum-facing valve sub-assembly and the flight structure. In Figure 16, the location of this leak is circled in red, with the bubbles generated by gas leaking through a film of Snoop visible.

The FM1 sub-assembly was unbolted from the flight structure and a visual inspection was performed on the interface in the area surrounding the leak, finding no obvious defects. The O-rings were unseated and examined under a microscope and no visible defects were found. The system was then re-assembled with a different set of personnel, but no change was observed in the leak.

A root-cause analysis was subsequently performed to search through the problem space, resulting in the fishbone diagram shown below in Figure 17.

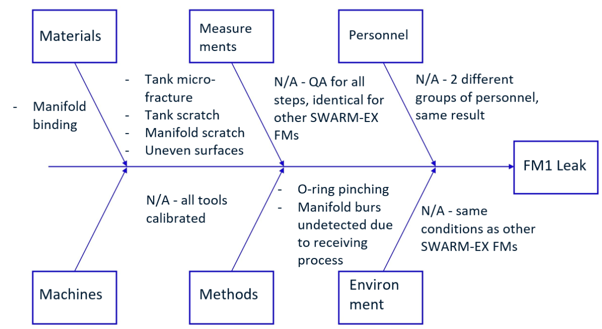


Figure 17: Fish-bone diagram showing the results of the FM1 leak root cause analysis.

Additional investigations were then performed in an attempt to eliminate potential root causes. The valve sub-assembly was reattached with a different torque pattern and higher torque specifications to no visible effect, eliminating the potential root causes of sub-assembly binding. New O-rings were installed, resulting in no change in the leak rate. These O-rings were then examined under a microscope and no damage was found, eliminating O-ring pinching or damage as a potential root cause. The flight structure and valve sub-assembly were also examined both under a microscope and with a tactile inspection for irregular surface finishes without any evidence of irregularities being found, leaving damage to the flight tank or sub-assembly too small to discern under a microscope the only remaining root causes.

After receiving approval from the SWARM-EX systems engineering team, the SWARM-EX EDU2 flight structure was upgraded from an engineering unit to a flight component. The EDU2 valve sub-assembly was unbolted from the flight structure, and the EDU2 flight structure and cleaned to flight standards to minimize the amount of FOD remaining inside. After replacing the O-rings on the flight structure, the FM1 sub-assembly was attached to the EDU2 flight structure. Testing with Snoop revealed that after the flight structure swap no major leak was observed at the interface between the flight structure and valve sub-assembly.

However, a leak in the FM1 plenum fluid system was still observed, as a test using nitrogen at RF-236fa's nominal pressures revealed a pressure drop over time in the plenum telemetry, albeit at a much slower rate. The source of this second leak was investigated and found to be the swage joints between the valves and sub-assembly. An in-place reswaging procedure was developed and executed, after which FM1's 72-hour leak test was conducted. The final leak rate was experimentally found to be 0.356 mg/hr, significantly below the project requirement of 6.77 mg/hr. After the leak check, FM1 continued on to ambient performance testing.

In this instance, the existence of EDU2 was extremely important in the ability of the project to rapidly recover from this anomaly. The importance of EDUs which have undergone pre-qualification testing as available flight spares for projects which may not have the resources to outright build additional flight units is a major takeaway for the SSDL.

Future Work

As of June 1, 2023, assembly is complete on all SEPS units - 2x EDUs and 3x FMs. A complete testing campaign has been completed on EDU2 and the abbreviated testing campaign is complete on FM1, while performance testing is underway for FM2 and FM3. After the completion of FM2 and FM3 performance testing, all three FMs will be delivered to CU Boulder for spacecraft integration.

Conclusion

This paper describes the design, assembly, and testing of two-phase cold gas propulsion systems for the SWARM-EX mission. The SEPS draws upon the architecture and design features of previous cold gas propulsion systems while introducing improvements in both mechanical and software features. A total of five units, two EDUs and three FMs, were assembled at the GT SSDL. These systems represent the state of the art in compact cold gas propulsion. The three FMs will be delivered in the coming months and enable the SWARM-EX spacecraft to maintain relative formation and ultimately perform their scientific mission.

Acknowledgments

The authors would like to thank Dr. Kristina Lemmer and Nathaniel Allwine of Western Michigan University, as well as Dr. Scott Palo and Maggie Zheng of the University of Colorado Boulder for their work on the SWARM-EX propulsion system in collaboration with the GT SSDL team. This material is based upon work supported by the National Science Foundation under Award No. 1936550 and by the National Science Foundation Graduate Research Fellowship under Grant No. DGE-2039655.

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