

Development of ASCENT Propellant Thrusters and Propulsion Systems

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ABSTRACT

Since the 1960s, hydrazine technology has dominated the market of propulsion technology by providing reliable performance on a wide variety of spacecraft. Efforts to replace hydrazine with a higher-performance and safer alternative have engaged numerous emerging technologies in the industry to mature. ASCENT propellant, also known as AF-M315E, is an example of one such green propellant. Initially developed to provide a safer handling environment than hydrazine, ASCENT offers higher overall performance than a hydrazine equivalent by creating more heat during ignition. The next generation of propulsion technology, based on ASCENT propellant, produces a higher impulse and energy density, expanding the realm of applicable missions from LEO to GEO and beyond. Building on a strong background in small satellite technology and expertise in thermal and oxidation resistant materials, Plasma Processes began several thruster programs for variety of small satellite applications using ASCENT-based technology. Plasma Processes' background expertise in thermal and oxidation resistant materials provides the necessary foundation to create ASCENT-based technology hardware.

INTRODUCTION

In 2016, Plasma was awarded funding to develop a 100 mN thruster. This thruster was later selected by NASA for the Lunar Flashlight Propulsion System. With support from AFRL, Plasma Processes is currently developing a 1N thruster for use on multiple missions, to be flight qualified in 2023. NASA's additional support of the 5N thruster program aids the advancement towards a flight-ready version in late 2022. In coordination with Georgia Tech, Plasma Processes' thrusters are being incorporated into a full propulsion system. The quick maturation of the 100 mN, 1N, and 5N thrusters were possible by an extensive list of in-house capabilities and an industry-leading rapid development cycle. Thruster development begins with the process of EL-Form[®] deposition; major components such as the thrust chamber, injector, and a monolithic metal catalyst are additively manufactured using Plasma's EL-Form[®] technology to ensure a uniform and superiorly dense material coating. Thrusters are then assembled,

tested, and verified in-house. Performance characteristics for each thruster are determined during hot fire testing in vacuum, which allows real-time monitoring and test feedback. Plasma Processes' thrusters have outstanding efficiency and remarks of groundbreaking performance, lifetime, and capability. This increasing array of small-sized ASCENT thrusters signifies the advancement of green propulsion technology. This paper and subsequent presentation will discuss the development efforts for ASCENT-based, small-sized thrusters and propulsion systems within their respective programs.

BACKGROUND

Temperature and Oxidation Resistant Materials

Existing rocket engines burn much hotter than the operating temperature of most traditional metals. To conquer this issue, Plasma Processes employs several thermal resistance strategies to preserve substrate material. One such option is the addition

of a thermally protective coating to a substrate in order to increase its heat resistance. Most commonly in aerospace applications, this takes the form of throat inserts, inner diameter coatings, and heat shield coating. Another option to increase thermal resistance is changing the material entirely.

Plasma Processes utilizes EL-Form[®] electrodeposition or electrochemical forming methods to deposit refractory metals and platinum group metals on a substrate to form a coating or a removable mandrel for a net-shape-formed component, which are better suited to handle higher temperatures. Key advantages of the process include the ability to meet tight tolerances and the high density in the as deposited condition. Plasma Processes' material capabilities cultivate the perfect conditions to manufacture temperature-resistant thrust chambers and injectors for ASCENT propellant with in-house capabilities.

Green Propulsion

Although developed nearly two decades ago, green propulsion still occupies only a small minority of in-space propulsion as of 2022 despite several key benefits over hydrazine. ASCENT monopropellant was developed to be safer to store, handle, and use without the need for self-containing atmospheric pressure suits, respiratory wear, or costly storage facilities. The propellant itself is primarily odorless and creates less toxic byproducts than hydrazine when in fired. During mission use, ASCENT produces a higher specific impulse than hydrazine and is more thermally efficient. Hydrazine still makes up the majority of space monopropellant systems due to its extensive flight heritage and reliability over the past sixty years.

Several green monopropellant thrusters exist on the market today. Bradford ECAPS offers a 1N thruster size using LMP-103S, another green monopropellant, which has flown on numerous missions in low Earth orbit (LEO) since its development.¹ Aerojet Rocketdyne and Ball Aerospace offers a 1N ASCENT thruster, which previously flew on the Green Propellant Infusion Mission (GPIM) in 2019.² Busek offers the BGT-X1, which uses ASCENT propellant.³ Several other companies have reported their development of green propulsion thrusters that are not currently available on the commercial market.

NASA 100 mN THRUSTER

Early Development

Beginning in 2016, the first efforts to develop an ASCENT-based thruster at Plasma Processes began in conjunction with NASA. Plasma agreed to develop and manufacture major thruster components such as the thrust chamber, catalyst bed heater, injector, and catalyst based on their expertise in high temperature and oxidation resistant materials. The thrust chamber and injector were both manufactured by EL-Form[®] deposition, a highly efficient process that additively deposits refractory metal onto a mandrel base to create a layered structure. This process is extremely effective for ASCENT technology as it provides the structural integrity and the thermal resistance required to sustain the propellant reaction to steady-state. Various feed tube designs were flow-rate tested. Metal catalysts were created and sampled using scanning electron microscopy (SEM) and surface area analysis. After full assembly, the thruster was ignition tested at NASA MSFC to define performance characteristics. Though testing was unsuccessful due to electrical issues, the thruster itself verified manufacturing processes to create thruster components and provided a base design for follow-on commitments.

Mid Development

Reflecting on the first design, a series of design changes were proposed to enhance the thermal balance of the thruster. A new prototype was manufactured with improvements in the design to enable better propellant flow within the thruster, shown in Figure 1.



Figure 1: Mid Development 100 mN Thruster

This development included a 1N size test reactor, shown in Figure 2, to determine catalyst properties, verify bed configuration for the 100 mN thruster,

and improve on the early development prototype design. This test reactor was assembled using machinable metals that enabled short duration firing of ASCENT propellant. Seven instrumentation ports were used along the test reactor, including five thermocouple ports and two pressure transducers. The test reactor verified the hot fire test system and the catalyst bed configuration to be used within the 100 mN thruster.

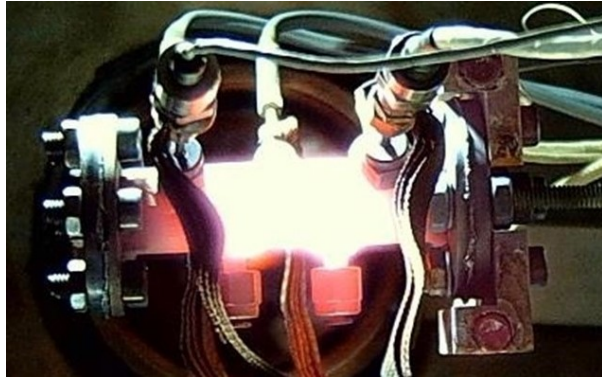


Figure 2: 1N Test Reactor

Late Development

The next phase of the program prioritized necessary implementations that would allow the Plasma Processes thruster to best suit a flight opportunity. Parameters were explored to create a more consistent and quality deposition of iridium when creating thrust chambers and injector heads that would allow for consistency across the thrusters. Furthermore, the graphite mandrels were manufactured in-house to allow for full control over electrodeposition parts.

A flight prototype thruster was built and tested in-house following the COVID19 outbreak and a series of test facility modifications. After determining the proper preheating settings and troubleshooting the valve, the first thruster firing resulted in flooding of the catalyst bed. Initial characteristics obtained from hot fire testing towards the end of the development period showed promising results for the Lunar Flashlight mission, a flight opportunity presented by partners at NASA Marshall. After all hot fire data was gathered from the thruster, a random vibration test was done to determine the environmental effects on hot fire performance. The thruster operated nominally after the random vibration test, and ideas were gathered for points of improvement.

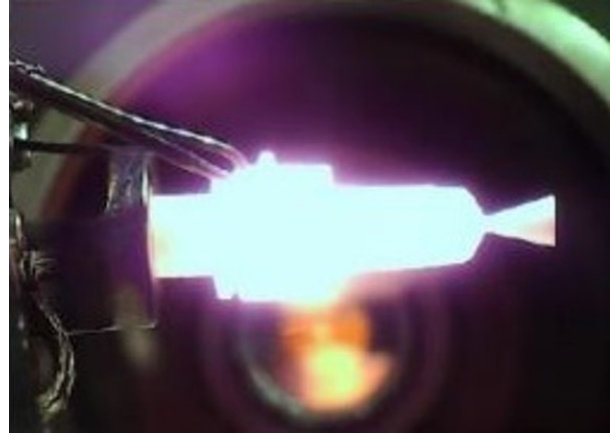


Figure 3: Late Development 100 mN Thruster

Flight Qualification

Following development, the thruster was adapted to better fit the Lunar Flashlight mission profile. This included flight-like modifications to the thermal standoff and feed tube that would better suit the space environment. A total of twelve flight thrusters were delivered to the Lunar Flashlight program, which served as articles for the Lunar Flashlight module, the backup Lunar Flashlight module, test articles, and two qualification articles.

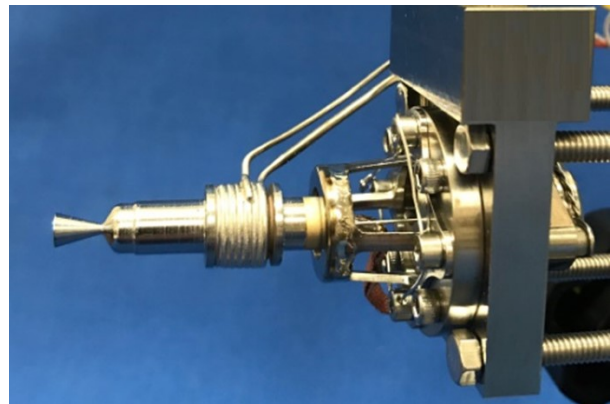


Figure 4: Flight 100 mN Thruster

Every thruster completed hot fire testing as part of the acceptance program prior to delivery. First, a thermal vacuum test was conducted to determine pre-heating power and corresponding catalyst bed temperature for the thruster. During hot fire testing, steady-state mode and pulse mode thrust, flow, rise time, and decay time were analyzed. After ensuring the thruster was responsive to propellant, the acceptance hot fire test sequences alternated

between steady-state and pulse mode. The steady-state mode performance was determined by a 30-second, single pulse sequence, shown in Figure 5. Pulse mode was determined within a reference cycle (500 ms on, 500 ms off) that typically lasted 400-500 pulses, or until the thruster reached quasi steady state, shown in Figure 6. For all thrusters, rise time was observed to be approximately 65-80 ms and decay time was observed to be 100-110 ms. Further metrics were obtained during the qualification program.

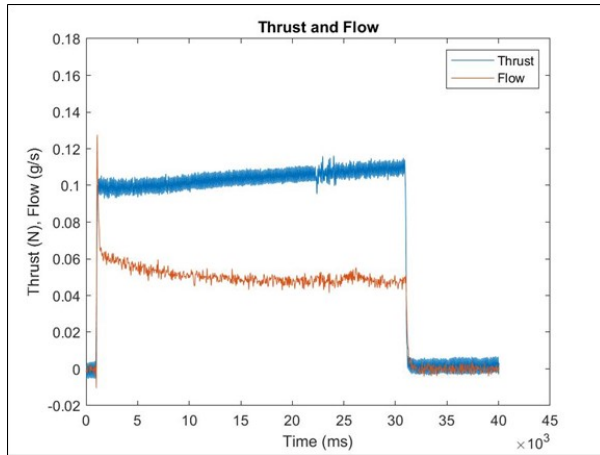


Figure 5: 100 mN Steady State Performance

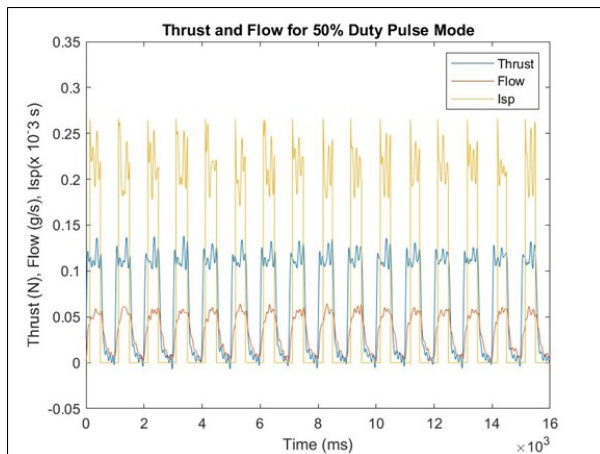


Figure 6: 100 mN Pulse Mode Performance

This thruster completed an in-depth qualification program using two test articles. The first test article, QA-1, surpassed expectations and performed 152% of the mission required, 12,000 hot fire pulses, thereby firing a total of 18,258 pulses and producing 2,430 Ns of total impulse. This

thruster also demonstrated a total ontime of 22,140 seconds, or 6.15 hours, before it was put into storage. Ongoing plans to extend this qualification program may increase the total throughput from 1.25 kg to 2.5 kg, well over the mission requirement of 530 g, as this thruster is completely operational and shows no signs of degradation as a result of testing. Additionally, QA-1 sustained a steady state firing for 101 minutes, which is the longest single pulse firing of a 100 mN thruster to date.

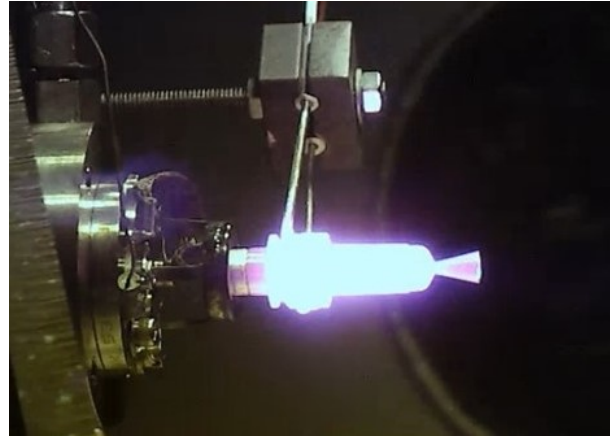


Figure 7: 100 mN Thruster during Hot Fire Test

The second test article, QA-2, verified performance repeatability and was used to verify additional requirements such as random vibration, pre-heating power, response time, steady state and duty cycle performance, and propellant throughput requirements. Additional data was obtained to obtain metrics such as minimum impulse bit, thrust roughness, and impulse repeatability. A full list of thruster performance values are in Table 1, below.

Table 1: 100 mN Performance

Parameter	Requirement	Value
Thrust Range	> 90 mN	30-220 mN
Pulse Mode Thrust	> 90 mN	100 mN
Steady State Isp	> 190 sec	235 sec
Pulse Mode Isp	> 190 sec	214 sec
Min. Impulse Bits	< 5 mNs	3.6 mN
Response Time	< 150 ms	70 ms
Decay Time	< 300 ms	100 ms
Throughput	> 530 g	1250 g
Acc. Burn Time	> 3.5 hours	6.15 hours
Longest Burn	N/A	101 mins
Heater Power	< 10 W	7-9 W

1N PROGRAM

1N Prototype Thruster

Plasma Processes worked on an independent research and development campaign to develop an early 1N green propellant prototype. As the first ASCENT 1N thruster to be produced at Plasma, many of the processes used to manufacture the prototype were demonstrative based on a theoretical approach. This design would establish experience for later programs by leveraging thermally resistant materials with a demonstrative thruster design. Due to independent funding, several components had a limited lifetime and thus reduced the operational limits of the thruster.

The thruster was functional tested by electrical, leak, and pressure tests to verify the integrity of the as-built hardware. A thermal vacuum test verified pre-heating capabilities inside the reactor bed within the thermal capacity of other components. During hot fire testing, shown in Figure 8, the thruster fired 637 pulses at a range of 2% to 100% duty. As expected, the thruster looked visibly good during firing but lacked exceptional performance due to the lower quality materials used.

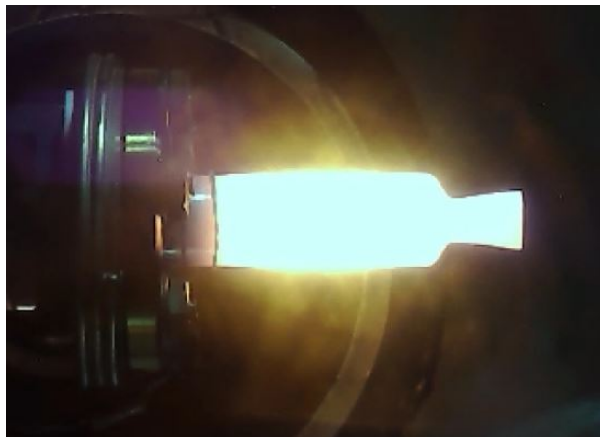


Figure 8: 1N Prototype during Hot Fire Test

AFRL 1N Sprint BAA

From knowledge acquired from developing a 100 mN and 1N prototypes, Plasma had a strong advantage when awarded the Sprint BAA contract from the AFRL to develop a 1N thruster. Initial modeling began with an up-scaled version of the 100 mN thruster and followed many of the same design processes. Due to its higher thermal loads, the

heater carrier of the 1N was reworked for better thermal performance. Beyond minor modifications and the addition of instrumentation ports for the prototype, the Sprint BAA 1N design reflected that of the mid-development 100 mN thruster.

The first thruster assembled for this program, named the forerunner, demonstrated the assembly processes and initial test characteristics. This thruster, shown in Figure 9, completed functional tests, a thermal vacuum test, and five days of hot fire testing. The thermal vacuum test revealed the appropriate heater power required to bring the catalyst to nominal firing temperature and the approximate relationship between heater temperature and catalyst bed temperature.

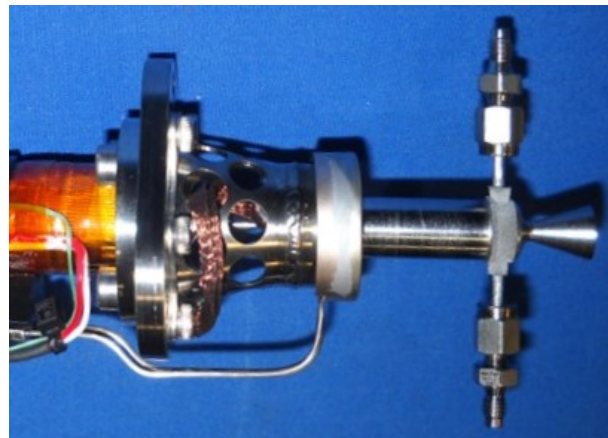


Figure 9: 1N Instrumented Thruster as Assembled

After successfully determining the thermal characteristics necessary for firing, hot fire testing (Figure 10) characterized steady-state and pulse mode performance for the thruster at various feed pressures. The first day of hot fire testing was used as a fact-finding session to determine if the thruster could be fired to steady-state without overheating. Subsequent days of hot fire testing analyzed thruster performance in both steady-state and pulse mode firing. To demonstrate steady-state behavior, the thruster was fired manually for individual pulses that increased in length up to 30 seconds. This information justified the existing configuration for subsequent thrusters as the thermal performance of the forerunner remained within tolerance at steady-state.

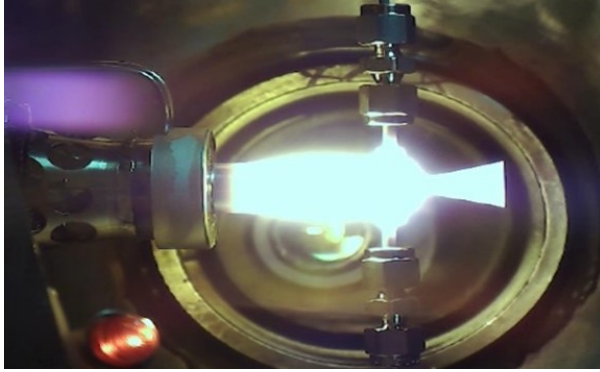


Figure 10: 1N Instrumented Thruster during Hot Fire Test

Additional firing included single pulses up to 240 seconds in length and a wide range of duty cycles to further characterize the thruster's performance. Other than oxidation effects, the thruster performed without noticeable degradation. Early on the fourth day of testing the hot fire test matrix, a propellant leak was detected inside the thermal standoff, which did not trigger noticeable differences in flow rate or thrust. After 5768 pulses fired and over 77 minutes of total firing time, the thruster burned over 2.3 kg of propellant. In steady-state, the thruster produced 1.03 N of thrust with a flow rate of 0.47 g/s, as shown in Figure 11. In pulse mode, the thruster produced 0.86 N of thrust with a flow rate of 0.51 g/s.

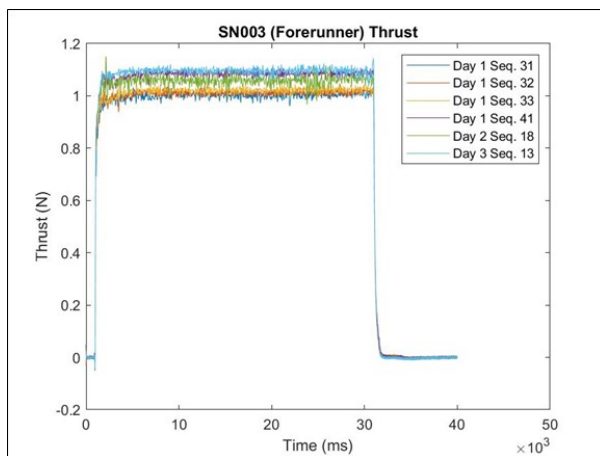


Figure 11: Thrust Produced by 1N Instrumented Thruster

Two additional instrumented thrusters were built to further test the design. Both thrusters completed the same tests as the forerunner leading up to hot fire testing and were characterized nearly

identical to the forerunner. For the hot fire portion, the thrusters saw an abbreviated acceptance matrix to preserve life before further testing at the AFRL that consisted of only single pulses at various feed pressures. The extended matrix yielded promising results and a strong belief that a flight version of the 1N thruster would succeed.

NASA 5N THRUSTER

Early Development

Beginning in 2019, Plasma's effort to develop a 5N thruster began with a redefined approach to more rapidly prototype the thrusters. Initial characteristics defined by project requirements led to an optimized bell-shaped nozzle with the correct throat diameter, expansion ratio, and cost-effective nozzle length. Readily machined and integrable parts also made it easier to disassemble the thruster for inspection, which aided the knowledge base gained from testing each thruster. After an initial prototype was designed, manufactured, and assembled, initial testing gained critical information about the performance of the thruster assembly. A brief functional test yielded no abnormalities and hot fire testing followed. Thermal balance was verified within 30 seconds of firing by the stable position of the reaction zone. After a total throughput of 1.13 kg, the thruster had a reported thrust level of 5 N and a steady-state specific impulse of 250 seconds.



Figure 12: Early 5N Prototype

Late Development

The next program goal aimed to develop both a low throughput and a high throughput design of the 5N thruster, which allows the end user to pick the thruster that fits their mission profile. Key differences are noted in Table 2, below.

Table 2: 5N Throughput Differences

Parameter	Low	High
Acc. Firing Time	30 min	6 hr
Acc. Throughput	2 kg	50 kg
Longest Duration Burn	30 min	6 hr

The first series of changes implemented in this program aimed to lower the preheating power necessary from almost 75 W to 15 W to get the 5N thruster from room temperature to adequate firing temperature, thereby heating the catalyst to approximately 420 °C. Changes in the design improved the thermal capabilities of the thruster to achieve this effect. Two prototype thrusters of the low throughput design were assembled and tested for their performance characteristics by a series of functional and hot fire tests. Similar changes in the high throughput design were determined following prototype tests.



Figure 13: 5N Thruster

The first prototype thruster completed three days of hot fire testing. Despite the first two days of testing not being incredibly valuable to the test due to a valve error, the thruster was fired to steady-state and limited pulse mode. The cost-effective prototype catalyst failed midway through the third day of testing after an accumulated throughput of

1.4 kg; the bed was flooded with propellant early in a low duty cycle sequence. Overall, this thruster performed very well with a reported steady-state thrust of 5.6 N at a feed pressure of 18 bar A and provided a steady-state specific impulse of 259 seconds.

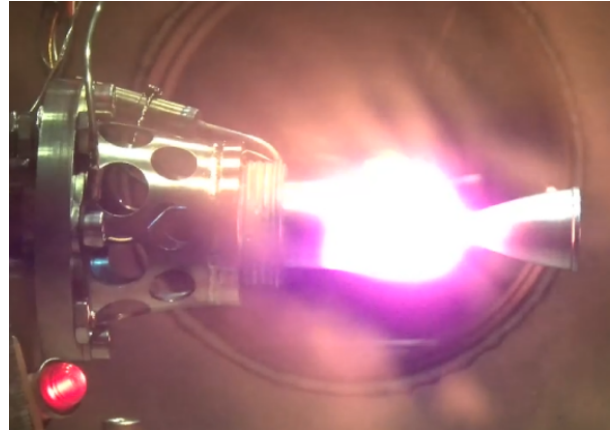


Figure 14: 5N Thruster during Hot Fire Test

The second prototype thruster completed two days of hot fire testing and accumulated over 3 kg of total throughput. With over 24 minutes of accumulated firing time, the thruster outperformed expectations. This prototype thruster was made with a higher strength catalyst than the first prototype, but other components of the assembly remained unchanged. The thruster verified a steady state thrust of approximately 5.4 N at 18 bar A feed pressure and a specific impulse of 261 seconds.

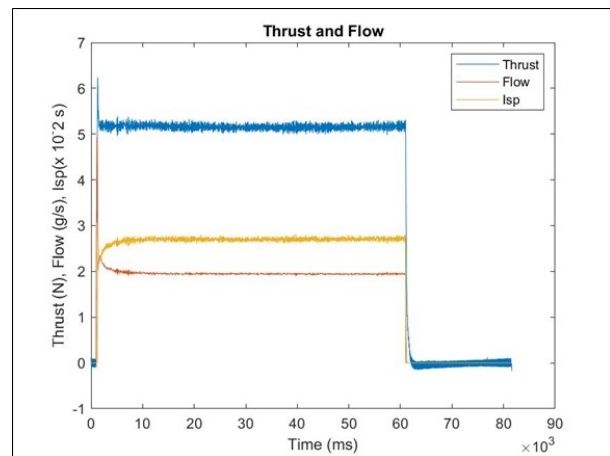


Figure 15: 5N Steady State Performance

100N Prototype Thruster

Plasma Processes has previously developed a 100N thruster prototype which reached TRL 4 during development. Heat sensitive components of the 100N thruster prototype were made by electrodeposition of metal onto graphite. Both an in-atmosphere test and an in-vacuum test were conducted. During hot fire testing, the thruster completed a 60-second burn nominally.



Figure 16: 100N Thruster



Figure 17: 100N Thruster during Hot Fire Test in Ambient Pressure

CURRENT STATUS

100 mN Thruster

Four 100 mN Plasma Processes thrusters were integrated on Lunar Flashlight Propulsion System,

which is expected to launch in 2022. This will be the first flight mission for this thruster design. The 100 mN thruster is commercially available for purchase. A total of twenty 100 mN thrusters have been produced and tested as of 2022 and there are currently plans to incorporate 100 mN thrusters into a dual mode propulsion system, in partnership with NASA and Georgia Technical Institute.

1N Thruster

The instrumented thruster tested as part of the Sprint BAA is being modified into a flight design. Verification tests within the current contract period hope to qualify this thruster for flight by the end of 2023.

5N Thruster

Both the low and high throughput configurations of the 5N thruster are being modified towards more flight-worthy models based on the hot fire test results produced by the two prototype thrusters. The thrusters are expected to be available by early 2023 and are ideal for multiple propulsion systems as a mid-range option between 1N and 100N for attitude adjustment.

100N Thruster

The 100N thruster has not made advancements in the recent year due to focus on other programs. Additional development may take place on this thruster for use on a propulsion system, which would require the thruster to be in a flight qualified maturation state.

ADDITIONAL PROGRAMS

Catalyst Development

Plasma Processes has developed several catalysts that are ideal for use with ASCENT propellant. Plasma catalysts are ideal for a variety of extreme conditions. These metal catalysts withstand the high temperatures of ASCENT and provide consistent performance throughout thruster or reactor lifetime.

Systems Development

Testing equipment was procured to enable hot firing in-house, including a data acquisition system, vacuum chamber, pressure panel, and control panel. Thrust is monitored during firing via a force sensor integrated into the thrust stand. The flow rate is measured by a flow meter and redundantly checked by a scale to measure the amount of propellant used for each sequence. Eight thermocouple inputs, including five type-K and three type-B inputs monitor temperature data from the thruster at a sample rate of up to 5 kHz. The precision is typically within 5 °C for thermocouple inputs due to small voltage amplifiers within the system. Four pressure transducer inputs monitor the system pressures during testing at the same sample rate. Additionally, one channel is dedicated for a pyrometer input, which enables an understanding of the thruster reactor. A video system allows monitoring of the thruster during firing.



Figure 18: Early Hot Fire Test Facility

Small satellites are most limited in power consumption and available space. To operate a thruster in a space environment, ample volume would be occupied within a system in addition to the thruster itself to maintain steady operation. To mitigate this effect, testing with a micropump began that would lower the amount of power and volume use of a propulsion system. First, a miniature breadboard propellant feed system was built which incorporated the micro-pump to test its operational capacity. This breadboard imitated a CubeSat propulsion system, which could be pressurized using a micro-pump in space. Besides the micro-pump, the system was outfitted with valves, pressure regulators, a propellant tank, pressure sensors, and a pressure relay system for redundancy.

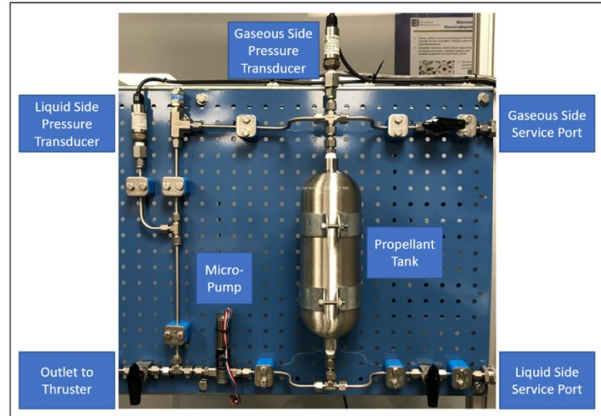


Figure 19: Breadboard CubeSat Propulsion System

Following a successful test, the micro-pump was incorporated into the hot fire test facility. There, it would supply feed pressure within the vacuum chamber to a thruster during hot fire testing. The pump enhanced the capabilities of the thruster over a traditionally fed system by providing a consistent laminar flow to the thruster. Due to the extremely low flow rate of the 100 mN thruster tested, this is critical in operation to maintain a smooth thrust curve, fast response time, and wide operational capability.



Figure 20: Incorporated Micro-Pump CubeSat Propellant System

Lunar Flashlight is a NASA-developed system that aims for the moon's south pole in search of water ice in preparation for future Artemis missions. Four Plasma Processes 100 mN thrusters are in use on NASA's Lunar Flashlight Propulsion System (LFPS), shown in Figure 21, which provides delta V of up to 250 m/s to a 6U craft. This two year effort exhibited collaboration from multiple

companies to provide the thrusters, valves, micro-pump, structure, and more to the system. Lunar Flashlight is expected to launch in late 2022.

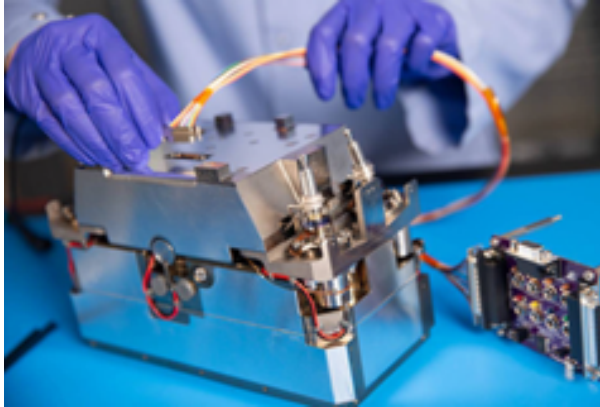


Figure 21: Lunar Flashlight Propulsion System

Plasma Processes is developing a successor to Lunar Flashlight with NASA and Georgia Tech. This 12U variant, double the size of LFPS, allows for a larger payload and wet mass, which extends the mission parameters for this module. The Phantom Propulsion System is adorned with four, 100 mN ASCENT thrusters from Plasma Processes and can produce over 500 m/s in delta V. Phantom is expected to be completed no earlier than FY2023. This system features a newly designed controller, propellant tank, and manifold that allow a wide range of maneuverability and performance. Within the controller design, up to eight valve drivers, eight heater drivers, twelve thermocouples, and four pressure sensors can be in use at various times, which allow any mix of 100 mN, 1N, and 5N thrusters to be used. The propellant tank with integrated manifold fits within a standard CubeSat envelope, allowing integration with other CubeSat components.

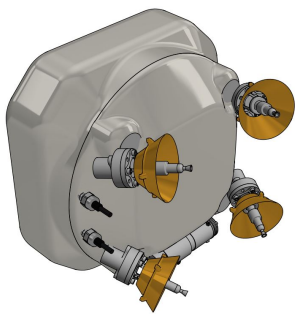


Figure 22: Phantom Propulsion System

CURRENT CAPABILITY

Manufacturing

Thruster and system manufacturing take place primarily in-house using a large array of state-of-the-art equipment and capabilities. After initial designs have been created, long lead items such as the catalyst, thrust chamber, and injector head are additively manufactured using Plasma's EL-Form[®] technology. This process utilizes an electric current to deposit metal onto a substrate material, therefore building each component from the inside radially outwards. Though electrodeposition takes a variable amount of time to complete depending on manufacturing parameters, its benefit comes from the ability to control deposit configuration. Following deposition, components are EDM cut to profile and ready for assembly. Most assembly processes take place in-house within a laboratory environment. Using an induction furnace, brazing processes can be carefully manipulated to achieve several joint configurations. Flight hardware is assembled within an in-house clean room environment.

Testing

Since the award of the 100 mN thruster program, Plasma has made a number of improvements to its testing facilities to facilitate all thruster testing regimes in-house. The first of these included building a test control panel, which enables real time control and monitoring of thruster firing and firing parameters. A small, two by three-foot vacuum chamber and vacuum pump system was purchased under the award that enabled firing of 100 mN and 1N thrusters to steady-state.

Initially, testing took place within existing facilities such as within a fume hood or within vacuum booths that lacked the control and data acquisition mechanisms necessary to obtain reliable data. Later on, a larger vacuum system (Figure 23) was purchased that featured a three by ten-foot vacuum chamber and increased pump capacity to enable steady-state firing of thrusters in the 22N range. Each thruster is individually analyzed for physical condition, pressure and leak tested, and checked for electrical functionality. Acceptance hot fire tests can take place extremely quickly due to the availability of in-house facilities.



Figure 23: Hot Fire Test Vacuum Chamber

FUTURE CAPABILITY

Plasma Processes aims to push its propulsion technologies further into the space realm by developing fully adaptable propulsion systems. With at least three flight qualified thruster programs by the end of 2024 and a full CubeSat propulsion system, Plasma has proposed multiple larger propulsion systems for development in the coming years. To supply these systems, Plasma continues to increase manufacturing and testing capabilities. Additional testing capability will include in-house vibration testing, expanded hot fire testing, and expanded methods of non-destructive evaluation. As Plasma pushes into systems development, these additional capabilities will allow more control over qualification test programs.

ACKNOWLEDGEMENTS

Plasma Processes would like to acknowledge the NASA Marshall Space Flight Center Green Propulsion team and the Air Force Research Laboratory at Edwards Air Force Base for their critical contributions and support of multiple thruster programs.

CLOSING

Plasma Processes is developing multiple ASCENT thruster and system alternatives to existing

hydrazine technology. From experience in high temperature materials, Plasma Processes has a key advantage to creating highly efficient ASCENT-based technologies with long life and throughput capabilities. These thrusters are ideal for any range of fine adjustment to orbital insertion, depending on the configuration, orbit, and payload. With continued improvements to manufacturing and testing capabilities, Plasma Processes propulsion systems will be commercially available in the near future.

REFERENCES

1. Bradford, 100 mN HPGP Thruster, 2020.
2. Aerojet Rocketdyne, Aerojet Rocketdyne Thruster System on NASA Green Propellant Infusion Mission Passes Major Test, 2022.
3. Busek, BGT-X5 Green Monopropellant Thruster, 2021.
4. Hasanof, T., et al., "100 mN Green Monopropellant ASCENT Thruster Development," Proceedings of the 8th Space Propulsion Conference, Estoril, Portugal, 2022.
5. Shchetkovskiy, A., Etenko, A., & V. Sikin, "Electroforming of Near-Net Shapes of Iridium," Proceedings of the International Symposium, Nashville, TN, January 2000.
6. Toenshoff, D., R. Lanam, J. R., Shchetkovskiy, A., & A. Smirnov, "Iridium Coated Rocket Chambers Produced by Electroforming," AIAA, July 2000.
7. Toon, J., Lunar Flashlight, January 2022.