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Sprite, a Modular Template of In-Space Propulsion

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ABSTRACT

Huntsville, AL is home to Plasma Processes, a materials company that creates high temperature material solutions for aerospace and defense applications. Their capabilities include several thermal spray coating techniques, near-net shape refractory metal fabrication, and an array of government and commercial customer entities. A Small Business Innovation Research (SBIR) contract received in 2016 pushed the development of Plasma's first fully integrated thruster assembly using component processes for thrust chambers, injector heads, and high temperature parts that Plasma creates daily for various entities. The thruster assembly used the ASCENT, or AF-M315E, propellant, which was first demonstrated on the Green Propulsion Infusion Mission (GPIM) that featured thrust chambers made by Plasma Processes. Plasma's SBIR thruster assembly gained the attention of a NASA flight project after demonstrating the viability of the thruster. In 2021, twelve thrusters were delivered to the Lunar Flashlight mission, of which four thrusters launched in December 2022.

The successful development of the 0.1N thruster thruster was a catalyst for new developments and growth. Rubicon Space Systems, a division of Plasma Processes LLC, was formed in mid-2022 to become the premiere manufacturer of ASCENT thrusters and propulsion systems.

In development since early 2022, the Sprite propulsion system is a 1.5U fully enclosed, plug-and-play solution for SmallSats. Sprite targets missions in need of space propulsion, collision avoidance, and de-orbit capabilities while providing over 1200 Ns of total impulse, the equivalent of 100 m/s of delta V to a 12U CubeSat. The system utilizes the green monopropellant ASCENT, or AF-M315E, to improve system performance and reduce propellant handling costs when compared to other industry-standard monopropellants. Sprite features a flight qualified 0.1N with space heritage, a fully integrated flight controller, heritage components such as valves that have been demonstrated on previous missions, and a fully additively manufactured structure. Commands and telemetry are transmitted over RS-422 to the spacecraft, and RS-485 communication allows up to 8 modules to be networked together for systems that require multiple thrusters. The Sprite propulsion system passed its Critical Design Review (CDR) in December 2022 and its first four engineering development units (EDUs) are expected to complete qualification efforts in Q3 2023. A Protoflight article will be delivered to NASA in Q1 of 2024.

INTRODUCTION

Small satellites are quickly expanding in resourcefulness, compactness, and overall capability as world class missions carry them to orbit to perform science, communications, and technology missions. With a transforming market of ridesharing to reach low Earth orbit (LEO), and more opportunities becoming available to reach higher orbits, propulsion capability remains a challenge for small satellite developers. Rubicon Space Systems, a division of Plasma Processes LLC, was formed in mid-2022 to become the premiere manufacturer of thrusters and propulsion systems that use the "green" fuel, ASCENT.

ASCENT, formerly known as AF-M315E, is a chemical monopropellant that has been acknowledged for the push for more sustainable propulsion, primarily its non-toxic handling. The monopropellant functions in the same way hydrazine does, without the need for a separate oxidizer by creating a high temperature reaction within the combustion chamber. ASCENT also offers an advantage in storability by eliminating the need for inert gases, and the propellant is more energy efficient than other common monopropellants, which permits a smaller volume of propellant to be carried onboard to achieve the same total impulse capability that hydrazine would. The challenge of ASCENT is that it owes its high performance to its high combustion temperature. Most traditional thruster chamber and catalyst materials cannot withstand the ASCENT flame temperatures for long. Rubicon's solutions employ high temperature materials to create higher performing thrusters.

BACKGROUND

What We Do

Rubicon's expertise in green propulsion extends into thruster and propulsion system design, development, integration, and test activities. Formed in the summer of 2022, Rubicon Space Systems began its mission to develop ASCENT-based propulsion solutions for satellite developers. As a division of Plasma Processes, a materials based company focused on high temperature material solutions and the forefront of green propulsion components, Rubicon developed its line of thruster products including 0.1N, 1N, and 5N thrusters. Furthermore, Rubicon is developing lower cost versions of these products aimed at missions with lower lifetime requirements. This allows satellite developers to better meet their mission scope and budget for propulsion capabilities.

Using these thrusters, Rubicon is developing a line of propulsion systems to provide a fully integrated module with propellant tank, controller, and "plug-and-play" capability to a satellite. These solutions are based on a "variation on a template" design approach, where particular capabilities are configurable towards customer requirements, but non-recurring engineering costs are minimized. Sprite, being the first of these propulsion modules, will demonstrate this approach through its development, qualification, and production practices.

FCC De-Orbit Rule

In 2022, FCC adopted a new requirement for satellites in LEO to deorbit within five years after mission end, which would enact as early as 2024 for current satellite developers. For currently in development programs, this means that the inclusion or effectiveness of propulsion systems may need to be reevaluated before flight, easily adding cost and schedule risks to any program. The goal of this guidance is to slow the ever-crowding environment of LEO that end of life (EOL) satellites are consuming under former rules. Sprite was designed to serve as a self-contained bolt-on propulsion module to add primary propulsion, collision avoidance, and de-orbit capabilities to a satellite.

WHAT IS SPRITE?

Single Module

Sprite is a 1.5U-sized ASCENT propulsion module that provides "plug-and-play" propulsion capability to a spacecraft. Weighing just under 2 kgs as fueled, Sprite fits in a 10cm x 10cm x 15cm envelope (plus tuna can). Sprite mounts into or outside of a spacecraft by eight mounting points located on the exterior of its tank. A wired RS-422 protocol connection from the spacecraft connects to Sprite's internal controller, where its thruster and valves are commanded from. In blowdown operation, Sprite delivers 1200Ns of total impulse by a single 0.1N thruster. On the protoflight unit, an auxiliary port located on Sprite's valve side will allow connection of a dual mode propulsion system from the same isolation valve and propellant supply.

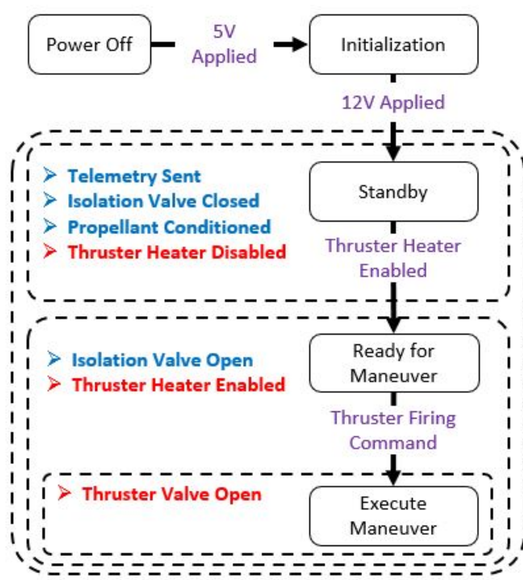

Figure 1: Simplified concept of operations of Sprite's startup

Multi Module

By RS-485 protocol, up to eight Sprite units can be networked together to provide additional propulsion capability to a spacecraft. Mounting Sprite units on various points around the spacecraft configures total impulse attainable, attitude control, and maneuverability. Sprite's controller commands all units such that additional units will be timed precisely along with the primary Sprite unit in operation.

Inside Sprite

An additively manufactured propellant tank and manifold are welded together and make up Sprite's primary structure. Inside, the thruster, valves, controller, propulsion system sensing, and propellant are housed and piped together. Internal flow passages carry propellant through an isolation valve before reaching the thruster valve, as commanded by the spacecraft. The thruster is hooked up to a 12V power line, which supplies power to its catalyst heater prior to firing commands.

Parts for four Sprite modules can be built from one laser powder bed fusion (L-PBF) build plate, and additional material specimens are printed to verify per build material properties, weld certification, and process control. Each module is then assembled, verified, and delivered per the qualified process approach.

HERITAGE AND COMPONENTS

Sprite owes its design maturity to the individual qualification campaigns of its primary components, including the 0.1N thruster, micro-solenoid valve, and controller framework. A significant amount of the controller components, sensing, and mechanisms gained flight heritage on Lunar Flashlight's propulsion module.

Thruster

The 0.1N thruster was designed and developed under SBIR contracts with NASA. As it demonstrated a high level of technical maturity and thorough hot fire test performance, it was selected and used for the Lunar Flashlight mission (2022-2023). Twelve 0.1N thrusters were delivered as part of a SBIR Phase III award, and flight qualification was completed. Since then, the thruster has demonstrated over eight times its qualification throughput with ongoing test campaigns that further explore the thruster's capabilities. As of early 2023, one article has demonstrated over 17 hours of continuous firing and over 3 kg of total throughput.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	> 3 kg
Acc. Burn Time	> 3.5 hours	17+ hours
Longest Burn	N/A	101 mins
Heater Power	< 10 W	7-9 W

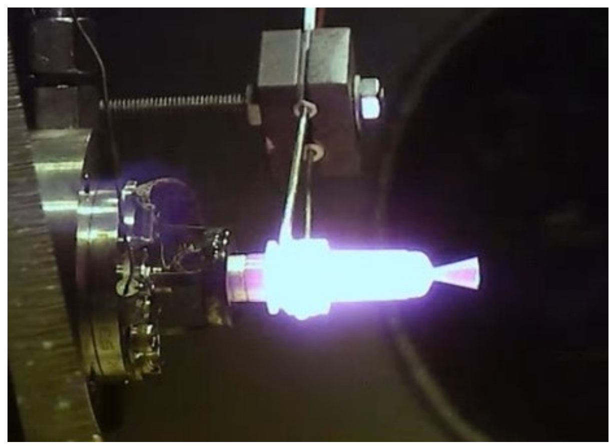

Figure 2: 0.1N Thruster during Hot Fire Test

Controller

Our Foxglove Model 2 controller will run all of Sprite's valves, sensors, and thruster. The controller design is based on lessons learned from Lunar Flashlight's propulsion system controller, which shares its partnership with Georgia Tech's Space Systems Design Lab with the Foxglove design. Three prototype controllers were built in early 2023 and environmentally tested for workmanship and qualification. One of these controllers will be used to hot fire test a front end version of Sprite later this year, and another will be integrated with Sprite's protoflight unit.

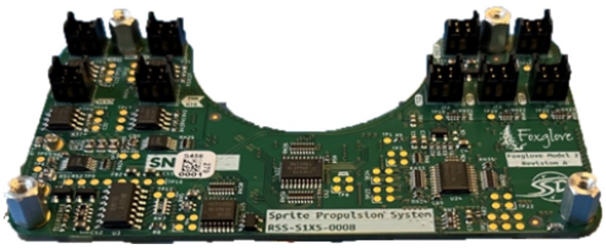

Figure 3: Foxglove Model 2 Controller

Valves

Sprite's valve heritage comes from the Lunar Flashlight program as well. The qualification effort done by NASA is being observed for Sprite's development. Newly built units will be acceptance tested per the specification. NASA's micro-solenoid valve is being used for the isolation valve and the thruster valve. A service valve also qualified by NASA is being used for the fill and drain valve.

Figure 4: Solenoid valve (top) and service valve (bottom) to be used on Sprite

Additively Manufactured Structure

Nearly every industry worldwide continues its march towards adoption of additive manufacturing as the new baseline manufacturing process for complex and unique components. While more traditional manufacturing processes may hold prominence in large volume manufacturing for the ages to come, it is very common to see AM components in the space industries of the world. Additive manufacturing offers a high level of design freedom while incorporating non-recurring engineering cost in different places than traditional manufacturing. For example, parameter development for qualifying the print process may add a significant portion of non-recurring engineering, although additive manufacturing does not require traditional tooling until it gets post-machined. Rubicon's choice to employ L-PBF for structural components is to maximize the integrated interface area within a small form factor. The largest challenge with additive manufacturing for propulsion system development remains proving that the structure meets design load criteria established by government and commercial entities for certification of materials. Qualification efforts for the additive manufacturing components of Sprite included developing a Manufacturing Control Plan (MCP), detailing fracture critical component quality controls, and working closely with a vendor to establish Additive Manufacturing Requirements (AMRs) and Equipment and Facilities Control Requirements (EFCPs). Thermal processes, non-destructive testing, and witness specimens were also controlled via the MCP.

Figure 5: Additively manufactured propellant tank, manifold assemblies

Electron Beam Weld

A common approach to space hardware includes weld development for assembly level qualification. For Sprite, this entails a circumferential electron beam weld that connects its propellant tank to the manifold after part of the integration process is completed. Rubicon provided weld coupons that were printed alongside the assembly parts to develop a Welding Procedure Specification (WPS) and weld parameters that would adhere the printed material best. A non-destructive testing approach was implemented to verify the weld, which included visual inspection, fluorescent dye penetrant testing, and x-ray. For the module, weld coupons were welded before and after the module weld to be sectioned and verify the module weld. If the coupons passed examination, the article is assumed to have a sufficient weld as well.

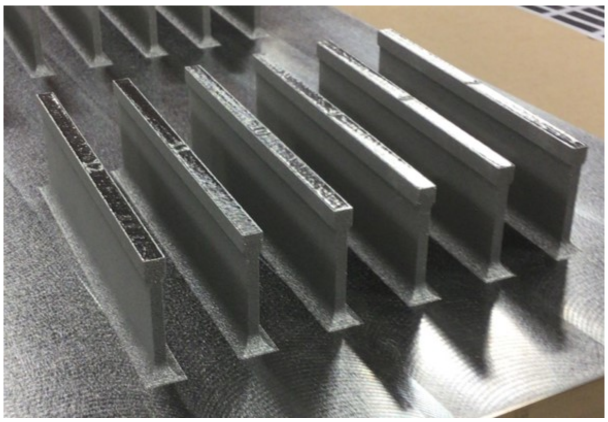

Figure 6: L-PBF printed coupons used for electron beam weld development

Flow Passage Improvements

Attention is being given to address challenges imposed by powder removal and interior surface finish of additively manufactured components. Small propulsion systems are especially vulnerable to foreign object debris (FOD), specifically within flow passages and small components. Attention to cleanliness and propellant filtration along the flow passage reduces the associated risks imposed by FOD. Additionally, processes such as extrusion honing, chemical etching, and micro-CT scanning were explored to gain further confidence in the flow passage surface finish. Micro-CT data before and after surface modification allowed the team to evaluate the effectiveness of the process and explore each area of the flow passages visually and quantitatively.

DEVELOPMENT AND QUALIFICATION APPROACH

To demonstrate and qualify the new module, four units of Sprite began development to pioneer assembly and integration processes, perform structural testing, demonstrate performance characteristics, and support a protoflight article. Taking inspiration from the original Pac-Man game, the four Sprite development units were named 'Inky', 'Blinky', 'Pinky', and 'Clyde' after the ghost sprites.

Inky

Inky is the name of the manufacturing pathfinder, which will be used to validate the assembly and integration processes. As the first module to be welded, Inky will not be used for flight, but it will inform five assembly, integration, and test (AI&T) procedures for the various components of Sprite. These processes include the propellant management device installation, weld certification, sensors and actuators installation, thruster installation, and controller installation.

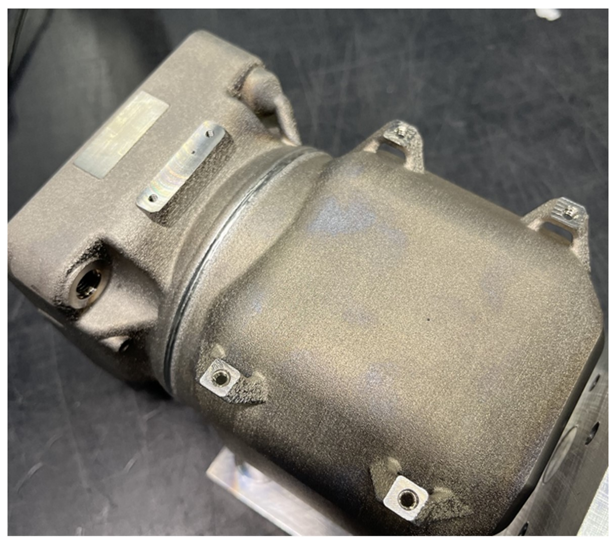

Figure 7: Inky, the manufacturing pathfinder

Blinky

Blinky is the name of the burst test unit, which will be used to verify the structural integrity and design of Sprite by completing a destructive test of the pressurized vessel. This unit is completely representative of what will be the flight unit by having identical pressurized interfaces, mass simulators, and configuration. The sensors and actuators, thruster, and controller will be simulated on the unit with blank off plates with identical interfaces and masses. A burst test, performed at a much higher pressure than Sprite will operate at, will verify the structural design margins and operational loading conditions through its structure, joining, and sealing.

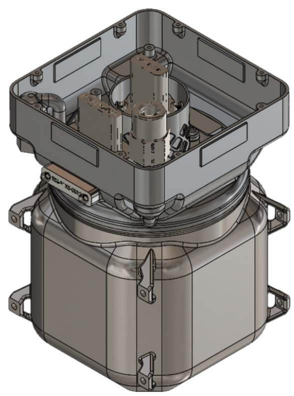

Figure 8: Blinky, the burst test unit

Pinky

Pinky, named subtly for the pinkish color of the propellant, will be a front-end hot fire test unit to verify the performance and temperature profiles of Sprite during operation. The unit will consist of a manifold with integrated thruster, valves, and controller while connected to an adaptor for pressure-fed operation of the unit in a vacuum chamber. The propellant tank and PMD will be simulated with resistances within the adaptor, and Sprite's pressure sensor and thermocouples will be integrated to obtain information throughout the module during test. After test, the data will be evaluated to validate assembly procedures and controller operation for the unit while also validating the effectiveness of the manifold design with the qualified thruster and valves.

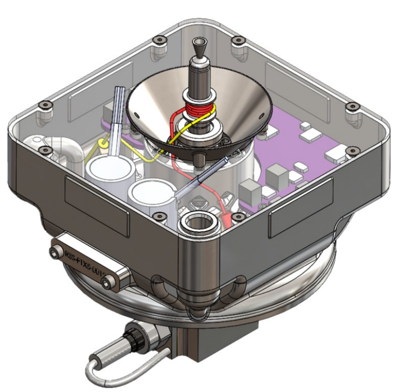

Figure 9: Pinky, the hot fire test unit

Further testing of the 0.1N thruster was conducted in fall 2022 to validate the thermal model of Sprite. This hot fire test, although just a precursor to the capability of Pinky, provided meaningful insight into thermal configuration and performance for Sprite's operational envelope.

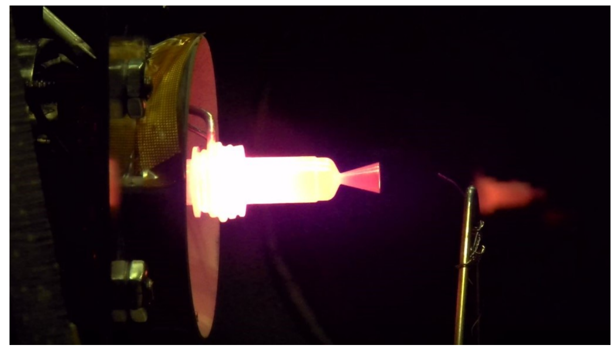

Figure 10: 0.1N thruster with demonstration Sprite hardware in hot fire test

Clyde

Clyde, being the odd one out in the Pac-Man ghost names, will take practices learned from Inky, Blinky, and Pinky to demonstrate the system on a protoflight mission. The unit will be acceptance tested, including a full environmental testing regime, before delivery to NASA.

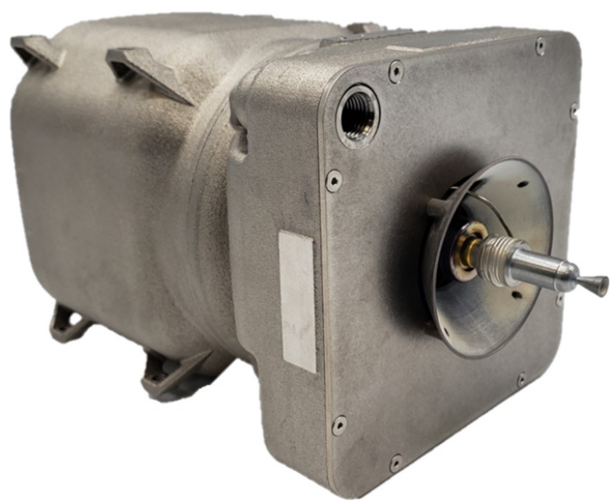

Figure 11: Clyde, the protoflight unit

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CLOSING

Sprite, a chemical propulsion system that operates in blowdown mode, can be easily integrated onto small satellites to provide 1200 Ns of total impulse for a 12U CubeSat, or up to 9600 Ns if eight modules are linked together. Its design is backed by component flight heritage, qualification programs, and government certified material processes. AI&T of the module is being conducted with four development units, which include a structural pathfinder, burst test unit, hot fire test unit, and protoflight unit. Qualification of the Sprite propulsion system is expected to complete by fall of 2023. In doing so, Rubicon's first designed-in-house propulsion module will be ready for a demonstration flight. Sprite is only the first of Rubicon's line of propulsion system designs, where larger and more powerful modules are in development. One such system will feature approximately four times the propellant tank volume and four 0.1N thrusters.

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