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On-Orbit Commissioning of High Performance Green Propulsion (HPGP) in the SkySat Constellation

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ABSTRACT

In late 2012 Skybox Imaging selected HPGP technology for implementation on their second generation (propulsive) SkySat small Earth observation satellite platform. During 2013 ECAPS worked to design a complete, compact and 'modular' HPGP propulsion system; the first (protoflight) version of which was delivered in 2014. A total quantity of nineteen SkySat HPGP propulsion systems have been ordered thus far, and 'assembly line' manufacturing is ongoing at ECAPS – with multiple deliveries accomplished in 2015 & 2016, and continuing into 2017.

The first five SkySat satellites with HPGP propulsion systems were launched during 2016 and an additional six SkySat satellites with HPGP systems are scheduled for launch in 2017 from Vandenberg AFB on Orbital ATK's Minotaur-C. SkySat-3 was launched in June 2016 from the Satish Dhawan Space Centre on Antrix's PSLV and SkySat-4 through SkySat-7 were launched in September 2016 from the Guiana Space Centre on Arianespace's Vega. Each satellite's HPGP system has been successfully commissioned and is now being operated in-orbit.

This paper will begin by providing a brief introduction to HPGP technology; with a more in-depth description of the SkySat HPGP propulsion system design. A summary of the PSLV and Vega launch campaign fueling operations will also be provided, followed by the process and results of the post-launch propulsion system commissioning activities, and a performance overview of nominal on-orbit maneuvers executed to-date.

Finally, a short update will be provided regarding the continued progress and improvement of HPGP technology, including maturation of the 5N & 22N HPGP thrusters to TRL-6 and the development of a new lower-cost 'next generation' 1N HPGP thruster.

I. INTRODUCTION

Benefits of HPGP to Small Satellite Missions

HPGP provides a number of important benefits to small satellite missions, including increased performance over monopropellant hydrazine, simplified handling and transportation, and reduced mission life-cycle costs as compared to hydrazine. Some additional details regarding each of these benefit areas include:

<u>Increased Performance</u>: As successfully demonstrated in-space on the PRISMA mission (2010-2015), HPGP has been shown to provide a 32% mission average performance increase over monopropellant hydrazine [1-6]. As a result, a smaller tank is able to provide an equivalent overall delta-v to that of a larger hydrazine system.

Simplified Handling and Transportation: Unlike hydrazine, which requires a rigorous regime of safety procedures, HPGP handling does not require any specialized safety equipment (such as SCAPE suits) or facility-related precautions. This is due to the fact that HPGP has very low toxicity, is extremely stable (insensitive to mechanical shock, air and humidity) and non-flammable. Additionally, HPGP has received a transport classification of UN and U.S. DOT 1.4S; thus allowing it to be transported on commercial passenger aircraft.

Reduced Costs: HPGP propellant is able to be shipped to launch sites by air, together with all of the Fueling Ground Support Equipment (FGSE), and satellite fueling activities have been declared to be "non-hazardous operations" by multiple Range Safety authorities. As a result of the simplified transport and handling, cost savings are able to be realized for transportation and fueling activities as compared to an equivalent set of activities being performed for a hydrazine system [7-10].

SkySat Overview

Via its SkySat satellites, Planet (previously Skybox Imaging and Terra Bella) provides commercial high resolution Earth observation imagery, high definition video and analytic services. The first two SkySat satellites, SkySat-1 and SkySat-2, were launched in 2013 and 2014 respectively. Although the first generation SkySat platform (shown in Figure 1) did not include propulsion, it successfully demonstrated the ability to deliver high resolution imagery and high definition video; thus paving the way for deployment of the full constellation.

Figure 1. SkySat-1 and SkySat-2

In order to enhance mission flexibility and increase on-orbit life, the SkySat platform was upgraded to allow the incorporation of a propulsion subsystem. Based on the results of a propulsion trade study [11], HPGP technology was selected for implementation on the second generation (propulsive) SkySat satellite platform.

II. SKYSAT PROPULSION SYSTEM DESIGN

Following the selection of HPGP technology for implementation on the SkySat constellation, ECAPS worked to design, manufacture and test an initial protoflight propulsion system for the SkySat-3 satellite.

System Architecture

A hydraulic schematic and the mechanical layout of the complete HPGP propulsion system developed by ECAPS for the SkySat platform are shown in Figures 2 and 3, respectively. The propulsion system design consists primarily of four 1N HPGP thrusters, three propellant tanks, two service valves, a latch valve, a pressure transducer and a system filter. All of the fluid control components selected had flight heritage from previous missions.

The three propellant tanks, which are connected in series and each of which has a Propellant Management Device (PMD), hold a combined total of 10.5 kg of LMP-103S with sufficient ullage for the Helium pressurant. The system operates in blowdown from a Beginning of Life (BOL) pressure of about 18.5 bar (absolute) at 21°C and is capable of delivering approximately 21 kN-s of total impulse.

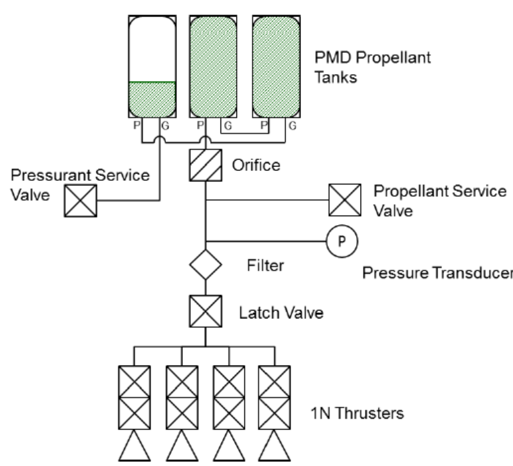

Figure 2. SkySat HPGP System Architecture

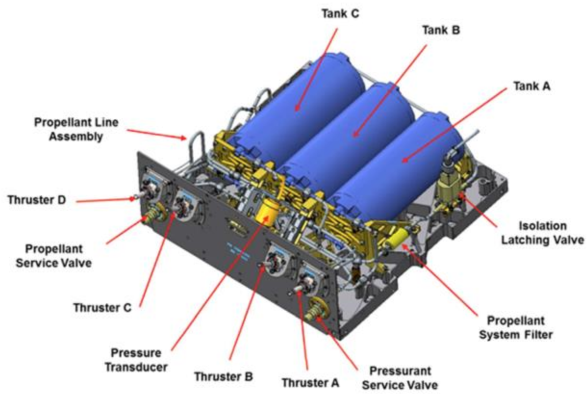

Figure 3. SkySat HPGP System Layout

Propellant

The SkySat HPGP propulsion system utilizes the first ‘green’ storable monopropellant qualified for space flight, which is the ADN-based LMP-103S.

LMP-103S propellant is a blend of Ammonium DiNitrimide (ADN), water, methanol and ammonia. The most harmful chemicals in LMP-103S are methanol (in significantly lower concentration than what is used in typical camping stoves) and ammonia (in lower concentration than regular household cleaning agents). Unlike hydrazine the LMP-103S propellant is not sensitive to air or water vapor. The LMP-103S blend has low toxicity, is non-carcinogenic and environmentally benign. Satellite propellant loading therefore does not require the use of SCAPE suits.

LMP-103S has undergone extensive ground testing with respect to performance, sensitivity, thermal characterization, compatibility, radiation sensitivity and storability. The propellant has been stored for more than 11 years (and ongoing) in a ground propulsion system end-to-end test; without any indication of degradation or pressure build-up.

Despite its high energy content, LMP-103S is classified as an insensitive substance (NOL 1.3) and further classified for transportation as a UN 1.4S and U.S. Department of Transport (DOT) 1.4S article (when stored in its designated transport container), which allows for shipment as air cargo on commercial passenger aircraft.

Thrusters

Each SkySat propulsion system includes four 1N HPGP thrusters, shown in Figure 4. The thruster is comprised of two major assemblies, the propellant Flow Control Valve (FCV) and the Thrust Chamber Assembly (TCA). The FCV is a normally closed series redundant valve with independent dual coils. The FCV implemented on ECAPS’ 1N HPGP thruster is manufactured by Moog and has extensive flight heritage. The TCA is further broken into multiple subassemblies, including: Propellant Transfer Assembly, Thermal Standoff, Thrust Chamber, Reactor Heater, and Reactor Thermocouple.

Figure 4. 1N HPGP Thruster

In HPGP thrusters, the propellant is thermally and catalytically decomposed and ignited by a pre-heated reactor. Nominal pre-heating is regulated between 340-360ºC. For thermal control, the thruster is equipped with redundant heaters and thermocouples.

The design and function of the thrusters developed for ADN-based propellant blends have several similarities with monopropellant hydrazine thrusters. The combustion temperature of LMP-103S (1600˚C) is however significantly higher than for a hydrazine thruster. The Thrust Chamber Assembly (TCA) is therefore made of Iridium/Rhenium and other high temperature resistant materials.

III. PROPULSION SYSTEM MANUFACTURING & INTEGRATION

To date, a total of nineteen (19) SkySat HPGP propulsion systems of the design described above have been ordered. In light of the constellation-driven quantities, ECAPS’ production capability has been scaled up to allow ‘assembly line’ manufacturing.

Thruster Production & Testing

The nineteen SkySat propulsion systems ordered correspond to a total quantity of seventy-six (76) 1N HPGP thrusters. In order to achieve the necessary production rates, ECAPS has worked to increase its capabilities in the areas of both manufacturing and hot-fire acceptance testing of HPGP thrusters.

In support of increased thruster manufacturing rates, ECAPS has invested in additional vacuum braze stations. Additionally, in order to enable an improved thruster acceptance testing timeline, ECAPS' Test Stand #2 (TS-2) has been modified to support multiple thrusters simultaneously. The new TS-2 configuration, shown in Figures 5 and 6, permits four 1N HPGP thrusters to be mounted in parallel.

Figure 5. TS-2 with multiple 1N thrust balances mounted

Figure 6. Four 1N HPGP thrusters mounted in TS-2

Although the thrusters are still hot-fired individually, as shown in Figure 7, the resulting efficiency improvement allows four thrusters to be tested in the same overall amount of time that was previously required to test just one thruster.

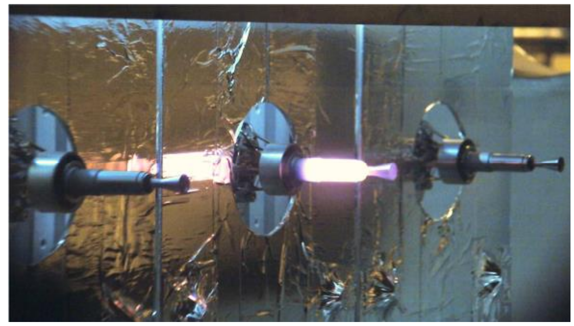

Figure 7. 1N HPGP thruster hot-firing in TS-2

Prior to hot-fire testing, all thrusters are subjected to thermal vacuum (TVAC) testing, random vibration testing, and radiographic (X-ray) inspection. ECAPS then performs acceptance hot-fire testing of each 1N HPGP thruster at three different inlet pressures prior to integration into the SkySat propulsion systems. The results of the 100% duty-cycle acceptance test runs for all HPGP thrusters delivered to Planet thus far are shown in Figure 8. At 22 bar(a) inlet pressure the average thrust is 1.03N (with an average Isp of 224.9 seconds), while at 5.5 bar(a) inlet pressure the average thrust drops to 0.26N (with an Isp of 205.6 seconds). During ground test acceptance hot-firings at 22 bar(a) (for 30 seconds) and 12 bar(a) (for 60 seconds) the thrusters only reach quasi-steady state temperatures; the measured Isp is therefore somewhat lower than true in-space steady-state performance. However, the ground test acceptance hot-firings at 5 bar(a) (for 120 seconds) matches the in-space performance data.

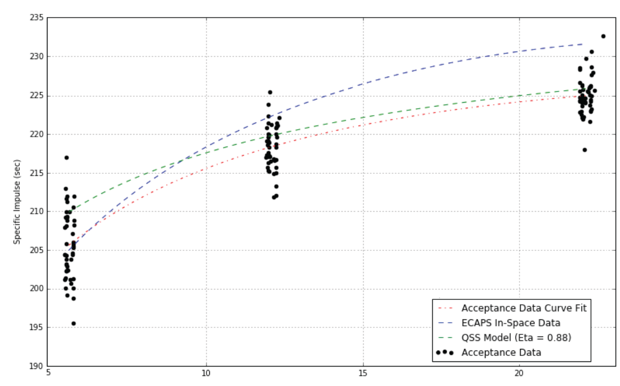

Figure 8. 100% Duty-Cycle Acceptance Test Results (Isp) for 1N HPGP thrusters integrated into SkySat propulsion systems

System Assembly & Testing

As shown in Figure 9, the SkySat HPGP propulsion systems are being manufactured in an 'assembly line' manner. By implementing standardized procedures and support equipment, multiple systems are able to exist in various stages of production simultaneously – thus streamlining the flow of incoming components into their respective systems, and minimizing the likelihood of key tooling sitting 'idle' due to the individual integration schedule of any particular system.

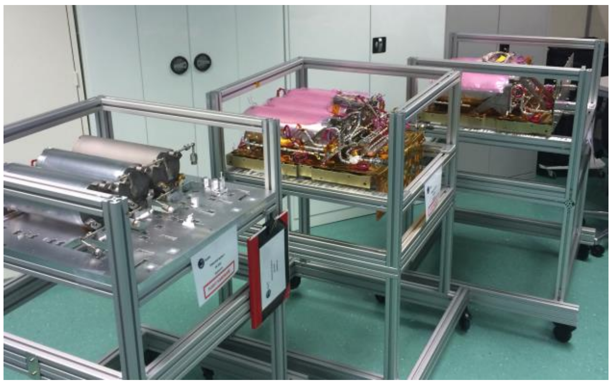

Figure 9. Multiple SkySat HPGP systems in different stages of production

Before delivery by ECAPS, each SkySat HPGP system is subject to proof pressure, external and internal leak checks, and electrical and functional checks. The initial SkySat propulsion system (for SkySat-3) was also random vibration tested to acceptance levels.

Satellite Integration

The first SkySat HPGP propulsion system, shown in Figure 10, was delivered by ECAPS in 2014. To date, a total of thirteen complete HPGP systems have been delivered and the remaining six systems currently on order are scheduled to be delivered during 2017.

Figure 10. The SkySat-3 HPGP Flight System

Following delivery of each HPGP system, integration of the propulsion module into the SkySat bus is performed by SSL. The HPGP modules are electrically connected to the satellite bus avionics and electrical verifications are performed. After the module harnessing is complete, it is integrated into the SkySat bus, as shown in Figure 11. The full bus is then exposed to satellite-level vibration testing.

Figure 11. HPGP propulsion system (circled) integrated into the SkySat-3 satellite

IV. LAUNCH SITE OPERATIONS

Five SkySat satellites with HPGP propulsion systems were launched in 2016, from two different launch sites (the Satish Dhawan Space Centre in Sriharikota, India and the Guiana Space Centre in Kourou, French Guiana). Importantly, neither launch site required the use of SCAPE suits during SkySat fueling operations.

Sriharikota

SkySat-3 was shipped to the Satish Dhawan Space Centre in May 2016 and launched on 22 June 2016, on PSLV-C34. Shipment of all FGSE and LMP-103S propellant to India was accomplished as commercial air cargo, via the Chennai International Airport (MAA).

The SkySat-3 propulsion system checkout testing and propellant loading operations were performed by ECAPS personnel on 1-2 June. The checkouts consisted of pressurization up to a MEOP of 22 bar(a) with both high and low pressure internal leakage measurements of the service valves, isolation latch valve, and individual (upstream & downstream) FCV seats.

Following the successful checkouts, the isolation latch valve was closed for launch with the downstream manifold filled with Helium at 2 bar(a). LMP-103S propellant was then pushed into the SkySat-3 propellant tanks via ECAPS' loading cart, shown in Figure 12.

After the required liquid load was completed, the system was pressurized for flight to approximately 18.5 bar(a) and subjected to a 12 hour pressure hold before further satellite processing operations were resumed.

Figure 12. LMP-103 Fueling Set-up

Kourou

SkySat-4 though SkySat-7 were shipped to the Guiana Space Centre in August 2016 and launched on 16 September 2016, on Vega-VV07. Shipment of all FGSE and LMP-103S propellant to French Guiana was accomplished as commercial air cargo, via Paris (CDG & ORY) to the Cayenne Airport (CAY).

The fueling campaign was very similar to what had been performed in India three months earlier, but with a few notable differences (in response to customer requests). Firstly, as shown in Figure 13, the ECAPS team processed two SkySat satellites at a time (in parallel) for both the system checkouts and the propellant loading operation. Secondly, the system checkout procedure was streamlined to eliminate the low pressure leak check of the valves. And finally, the total internal leak rate of the FCVs was verified rather than each individual seat being checked.

Figure 13. SkySat-4 and SkySat-5 Fueling Operations

V. ON-ORBIT OPERATIONS

Thermal Management

The LMP-103S propellant blend will begin to saturate and precipitate ADN at temperatures around -7°C. Therefore, patch and line heaters are employed to keep the entire propulsion system in the range of 10-50°C. Thermal control of each SkySat HPGP system is divided into four ‘zones’, with each zone controlling its own heater circuit via one of two control thermistors. All zones are currently set to maintain 19-21°C. However, if desired, each zone can also be set to individual temperature setpoints.

Propulsion System Commissioning

Following separation from the launch vehicle upper stage, the same propulsion system commissioning activities were performed on each SkySat. Depending on ground station contact scheduling, the process took approximately 8 hours per satellite. First, the thruster catalyst bed heaters were activated and allowed to operate within their pre-heating temperature setpoints of 330-370°C for 1 hour in order to thoroughly drive off any residual moisture and ensure complete and uniform heating of the entire reactor assembly. Then the 2 bar(a) Helium downstream of the isolation latch valve was vented by opening all four thruster FCVs for two minutes, leaving the manifold in vacuum. After the FCVs were closed again, the isolation valve was commanded open to fill the manifold with liquid propellant down to the upstream FCV seat. Finally, a manual firing sequence of 50 pulses with 100 ms on-time at 1% duty cycle was used to prime the FCVs with liquid, expel any Helium gas that may have been trapped in the propellant feed lines (due to the tanks not being vacuum loaded) and to begin smooth and repeatable combustion.

Experience has shown that it takes approximately 5 pulses for propellant to reach each thruster’s reactor and for combustion heating to be observed on the reactor thermocouples. The entire system priming operation requires approximately 7.5 grams of propellant. With the system primed and successful combustion demonstrated, the last step of propulsion system commissioning is to perform a 20 second closed-loop burn with the firing commands issued by the satellite’s Attitude Control System (ACS) controller. The intention here is to verify system performance and demonstrate that the controller converges to steady-state, and can maintain attitude during propulsive maneuvers.

Recurring Propulsive Operations

The SkySat propulsion systems are used to maintain proper station keeping, maintain inclination and compensate for drag. As of the date of publication, a total of forty (40) propulsive maneuvers have been executed across the entire fleet, for normal operations and both propulsion and other subsystem tests. A summary for each SkySat is shown in Table 1.

Table 1. SkySat propulsive maneuver summary

Satellite	# Maneuvers	Total Impulse (as of 1 Jun 2017)
SkySat-3	13	1,732 N-s
SkySat-4	3	57 N-s (*)
SkySat-5	5	150 N-s
SkySat-6	5	269 N-s
SkySat-7	14	317 N-s

(*) Note: SkySat-4 is currently being used as the 'reference' for maintaining constellation phasing (and has thus required fewer maneuvers than all of the other satellites)

SkySat propulsion maneuvers are executed via an automated sequence with a pre-defined start time and duration. Prior to opening the FCVs, the maneuver sequence configures the satellite state and enables the required 30 minutes of thruster catalyst pre-heating. When the satellite time reaches the programmed maneuver time, the sequence allows the ACS algorithm to slew the satellite to the firing attitude and then dynamically control the individual thruster duty cycles to maintain satellite orientation throughout the bun. Following a successful maneuver, the sequence cleans up the satellite state and slews the attitude back to the nominal cruise orientation.

System Performance

The on-orbit performance of the SkySat HPGP propulsion systems corresponds well with the pre-flight predictions. Figure 14 shows the as-measured performance of "Thruster B" (which is fired at 100% duty cycle) on the SkySat-3 satellite for all closed loop maneuvers performed to date.

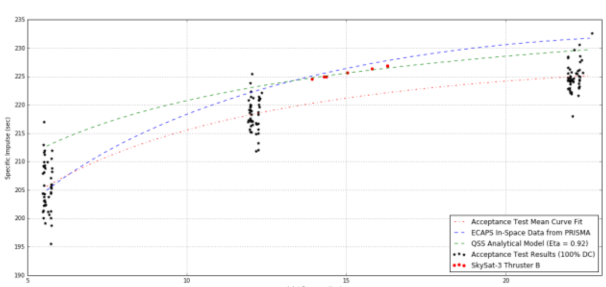

Figure 14. Comparison of On-Orbit Steady-State Performance vs. Pre-Flight Predictions

As seen in Figure 14, the steady-state Isp achieved in orbit is higher than the thruster acceptance test data (due to the thrusters only reaching quasi-steady state temperatures during ground testing at higher feed pressures) and is consistent with the analytical model.

A comparison plot showing the reactor temperature of Thruster B on SkySat-3 during regular orbit maintenance maneuvers is provided in Figure 15, with the end of each maneuver indicated by a sharp decrease in reactor temperature.

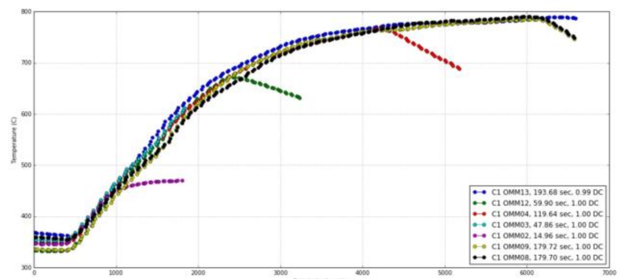

Figure 15. SkySat-3 Thruster B

Additional information regarding SkySat HPGP system on-orbit performance, post-maneuver calibration, and propellant tracking methodology is presented in Reference 12.

Thruster Non-Fire Anomaly and Resolution

In December 2016, SkySat-7 experienced an aborted propulsive maneuver due to a fault indicating that the satellite had insufficient torque to maintain the burn attitude. Telemetry review indicated Thruster B did not achieve the expected temperature rise associated with propellant combustion and further analysis by the satellite GNC team confirmed the as-measured body rates matched a simulated maneuver with little or no thrust generated by Thruster B.

A collaborative investigation was performed by Planet and ECAPS to determine the cause of the non-fire and develop mitigation options. Multiple on-orbit test maneuvers were executed, in conjunction with ground testing performed at ECAPS, to further characterize the anomaly. The investigation team determined that the most likely cause of the thruster non-fire was a leaking downstream FCV seat that caused ADN precipitation (due to long term exposure of the inter-seat propellant volume to vacuum) and resulted in the downstream valve or feed tube becoming clogged.

The issue was ultimately resolved with a new flight software command which allowed for an increase to the FCV pull-in (opening) voltage application and duration.

Following implementation of the modified software, Thruster B on SkySat-7 has performed nominally during multiple maneuvers and the satellite has been released back to the flight team for normal operations.

Although the non-fire anomaly was obviously an undesirable event, its rapid and successful resolution demonstrates the effectiveness of the investigation team's collaborative efforts to both identify and address the root cause of unanticipated issues on-orbit.

VI. CONTINUING PROGRESS

SkySat Satellites

SkySat-8 through SkySat-13 are scheduled to be launched on a Minotaur-C from Vandenberg AFB during the second half of 2017. All of the associated HPGP propulsion systems have been delivered by ECAPS for integration into the satellites by SSL and preparations for the launch campaign (which is currently expected to begin in the Aug/Sep timeframe) are underway.

1N 'GP' Thruster

With the objectives of reducing thruster manufacturing costs and enabling increased production volumes, ECAPS has developed a 1N 'Green Propellant' (GP) thruster with the same general form, fit and operational characteristics as the existing 1N HPGP thruster that is currently being implemented on the SkySat satellites. This is achieved by using a new propellant blend (with the same constituent ingredients as LMP-103S) which has a lower combustion temperature; thereby allowing the thrust chamber components to be fabricated from a lower cost refractory metal that can be conventionally machined. The thrust chamber is subsequently coated to improve its high-temperature endurance.

The 1N GP thruster has comparable steady-state specific impulse as compared to similar size hydrazine thrusters, but with a density impulse that is more than 20% higher than hydrazine. The 1N GP thruster can be used as a drop-in replacement for the 1N HPGP thruster without any modifications to the overall propulsion system design.

The first 1N GP thruster, shown in Figures 16 and 17, was successfully hot fired in December 2016.

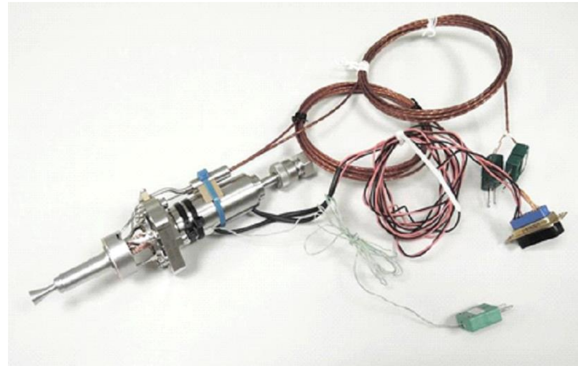

Figure 16. 1N GP Thruster

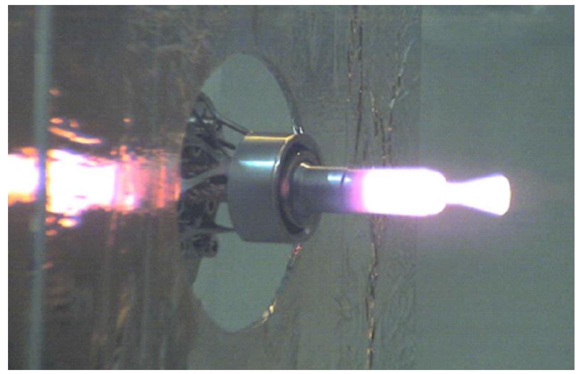

Figure 17. 1N GP Thruster Hot-Firing

Scaling of HPGP Thrusters (both down & up)

Successful hot-firing demonstrations of a 100 mN HPGP thruster development model have been performed and testing of a qualification model has begun. This size thruster is intended to be used primarily on CubeSats and other micro-satellites.

Flight representative (TRL-6) designs have been completed for both the 5N and 22 NHPGP thrusters. The 22N Engineering Qualification Model (EQM) thruster is currently in assembly and the environmental and hot-firing life tests (to qualification levels) are planned to be completed in September 2017. Assembly of the 5N EQM thruster is scheduled to begin in September 2017, with environmental and hot-firing life tests (to qualification levels) planned to be completed in the second quarter of 2018.

The design of a 50N HPGP thruster, intended for an in-space flight demonstration, has also been completed.

And finally, the Swedish Space Corporation and ECAPS have been awarded a contract for the development phase of a satellite orbit raiser based on HPGP technology; including the initial design of a 200N-class apogee thruster.

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