SSC21-XI-06

# Flight Qualification of a Water Electrolysis Propulsion System

Allison Porter, Mason Freedman, Richard Grist, Conlan Wesson, Mark Hanson
Tethers Unlimited, Inc.
11711 N Creek Pkwy S, Suite D113, Bothell WA 98011; 425-486-0100
aporter@tethers.com

## ABSTRACT

The successful operation of the HYDROS® propulsion system on NASA's Pathfinder Technology Demonstration (PTD)-1 mission is the first flight demonstration of a water electrolysis thruster. This hybrid electrical/chemical propulsion system was launched in January 2021 on PTD-1, and testing of the HYDROS propulsion system was carried out over the first half of 2021. HYDROS electrolyzes liquid water into gaseous hydrogen and oxygen, which are then combusted in a bipropellant rocket nozzle. The PTD-1 flight demonstration characterized the performance by performing a series of thrust events at varying operational parameters. The results show that this system delivers a relatively high thrust compared to electric propulsion and high specific impulse compared to a typical monopropellant thruster. The HYDROS propulsion system addresses a growing mission need for high maneuverability spacecraft. With the success of the on-orbit demonstration, HYDROS increases the practicality of using liquid water as the primary fuel and feasibility of refueling using resources commonly found in the solar system.

## INTRODUCTION

The HYDROS propulsion system uses a "hybrid" electrical/chemical architecture in which the propellant is launched into orbit as liquid water and then electrical power supplied by the spacecraft is applied to an electrolysis cell to add energy to that propellant by splitting the water into oxygen and hydrogen. The gases are stored in separate plenums, and when thrust is desired the systems combusts the gases in a traditional bipropellant rocket nozzle.

### *Overview of Water Electrolysis Thrusters*

Water electrolysis using solid polymer electrolytes (SPE) was first developed by General Electric Company in 1959 with a vision of reducing carbon-dependent fuel sources in terrestrial applications[1-2]. Shortly after this development, the concept of electrolysis thrusters for space applications was identified and underwent laboratory testing[3]. Recent increased interest in high capability propulsion technologies suitable for CubeSat and 'small' satellites reinvigorated interest in water electrolysis thrusters for space propulsion. Electrolysis thruster are a better alternative to cold gas thrusters, which have low specific impulse, and compared to electric propulsion, which requires substantial power input, which necessitates large solar arrays.

Water electrolysis is appealing because the combustion of a hydrogen and oxygen mixture yields a high energy output. In traditional hydrogen-fueled bipropellant thrusters, the hydrogen and oxygen are separately stored under high-pressure as liquids, which requires a cryogenic thermal management system. Water electrolysis is appealing because the fuel and oxidizer can be stored together in a low-pressure state. The electrolysis process allows for the fuel and oxidizer to be generated on-demand. Using water as non-toxic and inexpensive fuel increases the feasibility and accessibility of highly capable small satellites for companies that cannot afford the expensive of safely handling toxic chemicals. Additionally, water can be found off-world, opening up the possibility of farming fuel in-situ and further broadening the applicability of small satellites for advanced space exploration missions beyond Earth orbit.

Electrolysis uses an applied current to breakdown the input molecules. Electrolysis of liquid water results in hydrogen and oxygen gas. From the overall electrolysis electrochemical reaction, the following is split into two-half reactions:

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \tag{1}$$

Where hydrogen half-reaction is:

$$2H^+ + 2e^- \rightarrow H_2 \tag{2}$$

and the oxygen half-reaction is:

$$O^{2-} \rightarrow 2e^- + \frac{1}{2}O_2 \tag{3}$$

The reaction equations show the electron transfer that the current through the electrolyzer is proportional to the gas generation rate of the electrolyzer cell.

### *HYDROS Development Heritage*

Initial development of the HYDROS thruster at Tethers Unlimited, Inc. traces back to a prototype water electrolysis thruster for PowerCube™, a 3U small satellite platform under a NASA SBIR. PowerCube™ showed that a catalytic membrane could be used to generate hydrogen and oxygen, and that the gas products could be used in a 1U propulsion module[5].

Following PowerCube, the thruster architecture was scaled up for use as primary propulsion for a microsatellite. This version, named HYDROS-M, included the full tank, avionics controller, and thruster as an integrated propulsion unit. The propulsion unit was specifically designed to fit within a lightband separation system for deploying of ESPA-class spacecraft as shown in Figure 1.

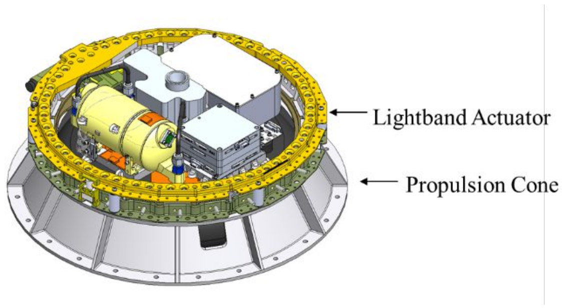


**Figure 1: HYDROS-M propulsion unit in the launch configuration**

The HYDROS-M propulsion unit underwent a full qualification program, including extensive laboratory performance and environmental testing. At the end of the qualification program, HYDROS-M achieved TRL 6. Three flight units were delivered to a customer program. The maturation of HYDROS under this microsatellite propulsion product was the foundation of the CubeSat-variant, HYDROS-C.

## DESIGN ARCHITECTURE & CONOPS

The HYDROS propulsion system has a basic architecture of water management, gas management, and the thruster. The system also includes an integrated controller for providing power and data to the lower-level components. The following section describes the HYDROS-C protoflight unit. This unit was configured to fit within a 2U volume with an approximate size of 2U x 1U (orthogonal to thrust vector) and 1U height (aligned thrust vector) as shown in Figure 2. Water storage was divided into two equal tanks arranged in a saddlebag configuration so that the 1U core that consists of the electrolyzer, gas management, thruster, and avionics.

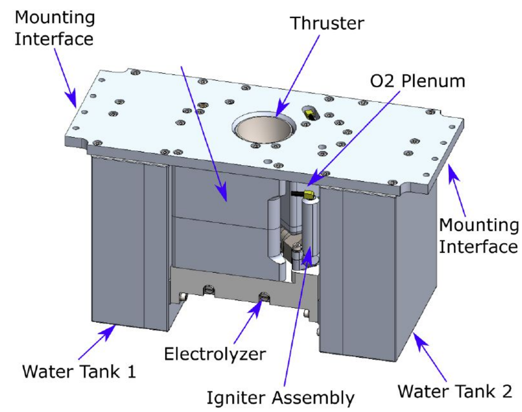


**Figure 2: Primary components of the HYDROS-C Propulsion Unit**

The concept of operation (CONOPS) is a cyclic operation of gas generation followed by gas combustion and expulsion. In this way, HYDROS operates like a pulsed-thruster, where the pulsed event is bipropellant chemical combustion. Liquid water is drawn from the tanks into the electrolyzer. Current is applied to split the water into the hydrogen and oxygen gases. The electrolyzer separates and routes the gases into plenums until a target gas pressure is reached. Once the plenums are charged, the gases are injected in the combustion chamber, ignited, and expelled out of the nozzle. This combustion event has a blowdown pressure profile to a chosen pressure floor. This completes the electrolysis-thrust cycle and additional water is electrolyzed to recharge the plenums for the next operation cycle. The operational pressures during the standard electrolysis-thrust cycle, such as the plenum charge and thruster blowdown pressures, are configurable set points.

## GROUND TESTING

The HYDROS-C underwent an extensive performance and environmental testing program on a protoflight unit before integration to the host spacecraft. The prototoflight unit is shown in Figure 3.

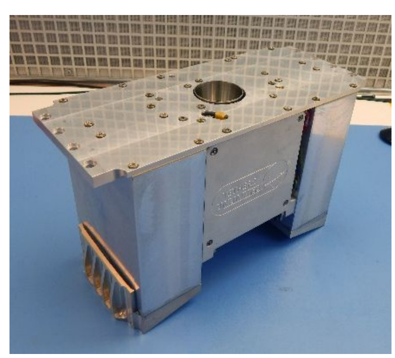

**Figure 3: HYDROS-C protoflight unit**

### *Electrolysis Ground Testing*

The electrolyzer for HYDROS-C is a single-celled electrolyzer, but much of the design was based on the development of the qualified HYDROS-M dual-celled electrolyzer. The two versions use the same catalytic membrane and fluid management features for water retention and gas separation. The HYDROS-M electrolyzer underwent a component-level throughput test that showed over 4 kg of processed water. Following the validation of the electrolyzer design, the electrolysis cell for the protoflight HYDRO-C unit underwent a throughput test of 34.9 grams to exceed 5% life as a burn-in minimum. The water consumption over time of the burn-in testing is shown in Figure **4**. The slopped sections of the graph show the water consumption/gas generation. The flat regions are breaks in the testing, but the data acquisition continued to log telemetry.

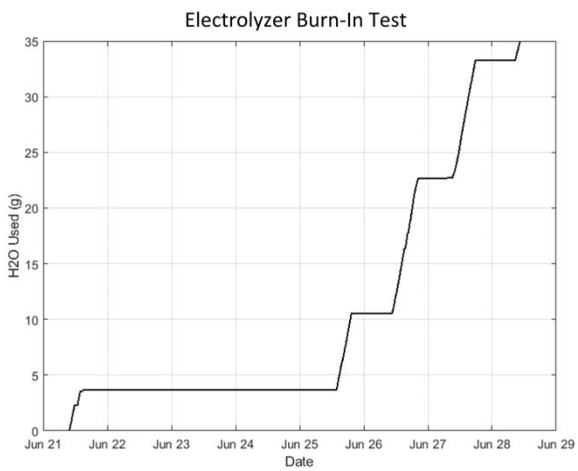


**Figure** 4**: Water consumption during burn-in testing**

### *Thruster Ground Performance*

As part of the protoflight test program, the thruster was fired in a vacuum chamber with each full functional test. These functional tests were conducted before and after environmental testing and used to establish the performance baseline. The thrust stand held the propulsion unit on a swinging arm with a force sensor on the opposite arm from the pivot. As such, this test setup resulted in minor oscillations in addition to the bulk force response from the thrust event.

Figure 5 shows an example thrust event from one of the functional tests. Combustion was confirmed by observing a temperature rise of the nozzle. In contrast, a failure to ignite or cold gas event resulted in a drop in the nozzle temperature due to the expulsion of expanded gases. The initial force reading is slightly clipped from showing the true peak value due to a limitation in the thrust stand design.

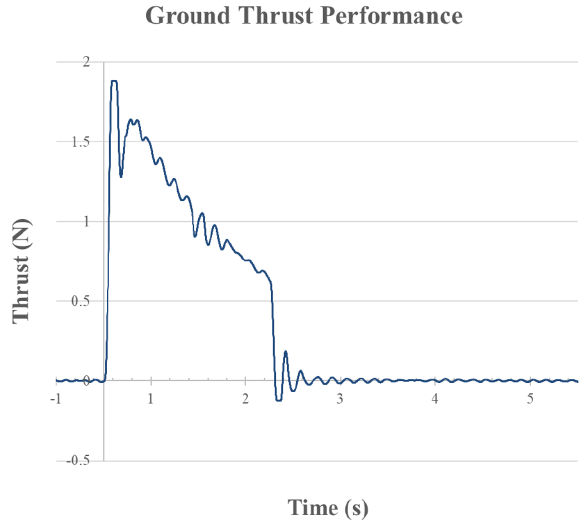


**Figure 5: Baseline thrust event during ground testing**

For the thrust event shown in Figure 5, the thrust duration was a commanded parameter such that the plenum pressures were not allowed to fully decay to zero. Table 1 shows example ground test data for three primary cases. ‘Trial 1’ was performed with an elevated pressure floor. This resulted in the maximum plenum pressure, $P_i$, and maximum differential, $\Delta P$, when compared to the final pressure following the combustion event. The table shows the average pressures between the hydrogen and oxygen gas pressures. Ideally, these plenums would be the same pressure, but slight variance in the as-built interior volume resulted in a minor difference in the respective gas pressures. ‘Trial 2’ was performed at a lower plenum pressure, but still resulted in a combustion event. In contrast, ‘Trial 3’ was performed with the lowest initial pressure and smallest pressure drop, which did not result in combustion, so the event was a cold gas blowdown. All thrust durations were 1.75s.

**Table 1: Example of Ground Thruster Data**

| Trial | Avg $P_i$ (psi) | Avg ΔP (psi) | I (Ns) | Isp (s) |
|---|---|---|---|---|
| 1 | 198 | 111 | 1.96 | 309 |
| 2 | 113 | 63 | 0.99 | 269 |
| 3 | 51 | 27 | 0.15 | 91 |

Using the force data from the thrust stand, the total and specific impulse were calculated for each trial. For the protoflight unit, the allowable volume for the combined nozzle and combustion chamber constrained the nozzle geometry. This drove a throat and expansion ratio selection that was not solely optimized for thruster performance, and in turn, resulted in a specific impulse that is under the theoretical maximum for a hydrogen-fueled bipropellant thruster.

## DEMONSTRATION MISSION

### *Mission Description*

HYDROS-C was integrated to the PTD-1 CubeSat as the first payload in a series of demonstration missions under the Pathfinder Technology Demonstrator project. The common PTD spacecraft bus has a 6U total volume with the HYDROS-C occupying approximately 2U's.

**Figure 6: PTD-1 being loaded into the CubeSat deployer[7]**

PTD-1, shown in Figure 6, was launched in January of 2021 into a sun-synchronous orbit. The first portion of the mission included commissioning of the spacecraft bus followed by checkout and commissioning of the propulsion unit. The first several weeks of the payload mission focused on characterizing electrolysis and refining the on-orbit operational parameters before proceeding with a series of thrust firings.

### *Electrolysis Flight Data*

For the on-orbit demonstration, the electrolyzer operated with a commanded set point for the voltage input. As noted previously, the electrolyzer was operated in a constant current with varying voltage mode during ground testing. Per the standard operating procedure, the bulk of the water was stored in separate tanks so water was periodically deposited into the electrolyzer.

Initial electrolysis was stepped up from 1.45 V, but most of the flight operations were performed at a commanded set point of 1.8 V. Over multiple electrolysis sessions, the electrolyzer dried and so the current data along the given voltage set point level decreased. In addition to membrane dryness, the electrolyzer efficiency varied with component operational temperature. During the mission demonstration, the electrolyzer temperature varied from 5 to 45°C with the bulk of the operations between 17 and 32°C as shown in Figure 7. This graph shows multiple electrolysis sessions over the course of the on-orbit electrolyzer characterization. Each electrolysis session includes multiple data points so over the course of sequential sessions, the current draw started out at a peak value and as the electrolysis continued, the current draw decreased until additional water was deposited.

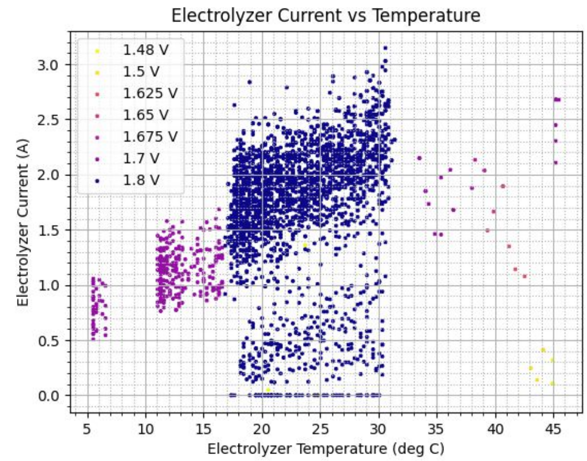


**Figure 7: Electrolyzer performance with temperature**

For warmer temperatures, the electrolyzer operates at a higher efficiency. Recall that in the constant voltage operating mode, the electrolyzer current draw is directly proportional to the gas generation rate from Equations (1-3); so a larger current draw for a given input voltage indicates a higher gas production efficiency.

The resultant pressure in the respective gas plenums is the primary telemetry for determining the amount of gas produced. Figure 8 compares on-orbit gas generation rates to the expected trend based on the applied voltage and current draw of the electrolyzer. Each data point is the average gas generation for a particular session to go from the initial plenum pressure to the target plenum pressure.

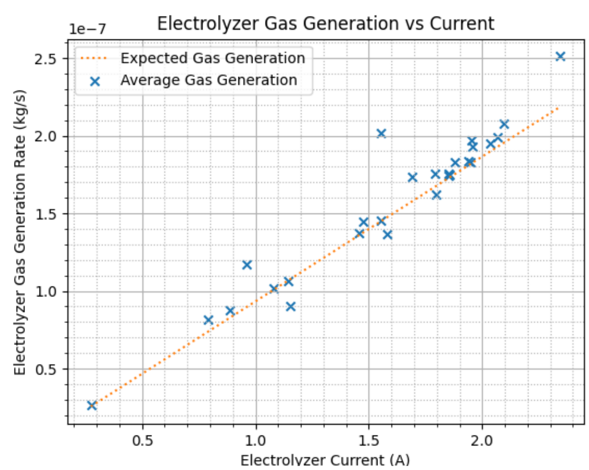


**Figure 8: Comparison of electrolyzer performance with theoretical prediction**

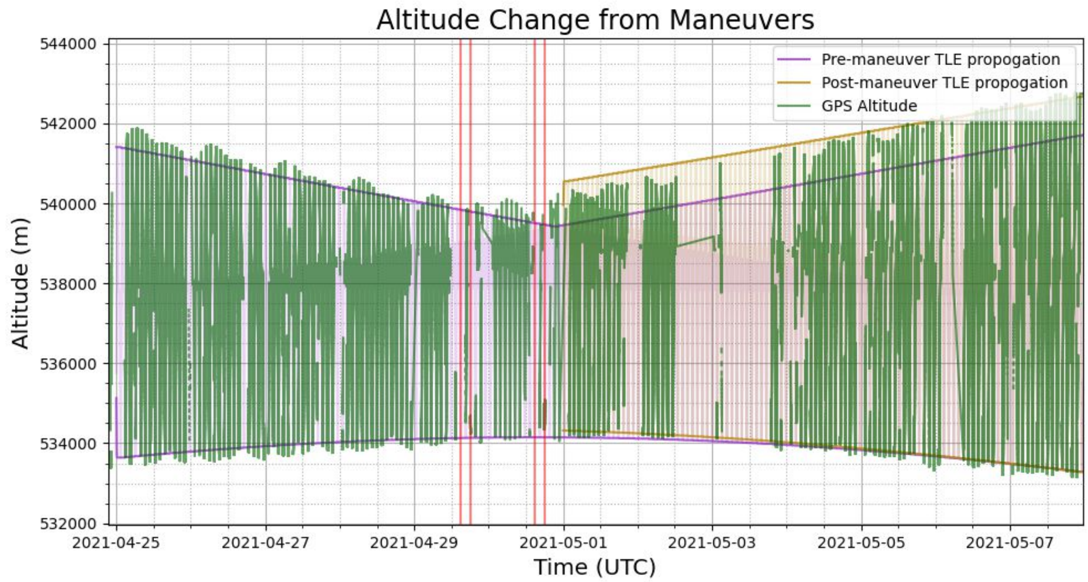


**Figure 9: Altitude change due to thruster firings**

***Thruster Flight Data***

As described in previous sections, the HYDROS-C operates as a blowdown pressure vessel. This blowdown occurs when the separated gas plenums that hold the hydrogen and oxygen products are released into the combustion chamber, ignited, and expelled from the nozzle.

Unfortunately, the spacecraft bus did not provide sensors that could instantaneously read acceleration responses from a single thrust event. For this reason, the estimated thruster performance was determined by tracking a combination of the spacecraft GPS telemetry and the NORAD two-line element sets (TLE) over time. Multiple thruster events over many orbits were performed so that the bulk orbit change could be observed.  shows the orbit change as the result of four thrust events. The red vertical lines indicate the times when the thrust events were executed. The first pair of thrust events were separated by a day from the second pair of thrust events. The spacecraft GPS data is shown in green with occasional gaps in the telemetry capture. The purple line and shaded region propagate the NORAD TLE from a time shortly before the first thrust event. The propagation backwards across the days leading up to the thrust events aligns well with the pre-maneuver spacecraft GPS data over that time. The gold line and shaded region propagate the NORAD TLE from a time shortly after the fourth thrust event and similarly aligns well with the post-maneuver spacecraft GPS data.

The change in the orbit from the series of four thrust events is the difference in the purple and gold shaded regions after the maneuvers. The orbit apogee is noticeably raised when comparing the pre and post-maneuver TLEs while the orbit perigee did not have a significant change.

Due to the natural minor variations in the orbit, the orbit change due a single thrust event cannot be discerned. The plenum pressure and nozzle temperature indicated whether the blowdown and combustion occurred for each thrust event, respectively. For the four thrust events shown in , the temperature sensors throughout the propulsion unit varied and fluctuated between 5 and 15°C. A typical combustion event had nozzle temperature rise of 30-40°C. The thruster temperature did not affect the temperature of the rest of the system significantly since the thruster is thermally isolated from the rest of the system. The first thrust event resulted in a slight decrease in the nozzle temperature, indicating an unsuccessful ignition due to the cold gas flow dropping in temperature as it expands out the nozzle. The large temperature rises in the later three thrust events indicated successful combustion.

From the orbit data, the performance of the thruster can be estimated. The spacecraft GPS data are qualitative well-matched to the NORAD TLEs. The NORAD TLEs are also updated at a much lower frequency than the spacecraft GPS data. The spacecraft GPS data also shows minor oscillations in the altitude that are not present in the NORAD TLEs so both the high and low values of the post-maneuver GPS data were examined. For these reasons, the thruster performance is summarized by looking at both the NORAD TLEs and spacecraft GPS data to determine the orbit change as listed in Table 2.

**Table 2: Summary of on-orbit thruster performance**

| Description | NORAD TLE | GPS |
|---|---|---|
| Pre-maneuver perigee (m) | 533318 | |
| Pre-maneuver apogee (m) | 541670 | |
| Post-maneuver perigee (m) | 533314 | 533339 |
| Post-maneuver apogee (m) | 542640 | 542721 |
| Total maneuver impulse (N-s) | 3.12 | 3.38 |
| Specific impulse, Isp (s) | 223 | 241 |

The first thrust in the series was a cold gas event so only the later three thrust events are considered to substantially contribute to the orbit change. Taking into consideration, the GPS data compared to the NORAD TLE set, the measured on-orbit specific impulse is likely between 223 and 241 s. Given the differences in the mission demonstration, this performance is within expected values when compared to ground data as shown in Figure 10.

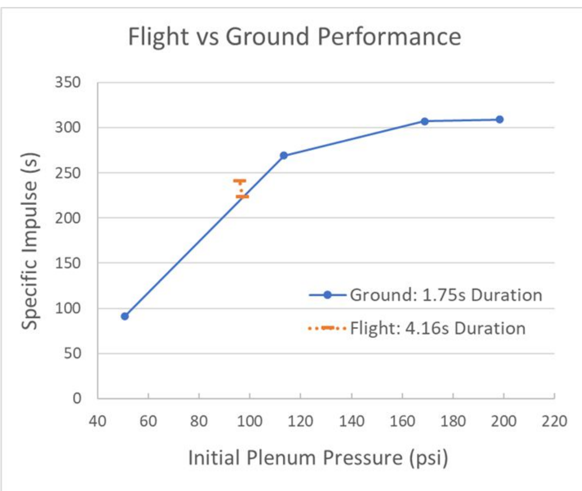


**Figure 10: Specific impulse with varying operational set points**

Compared to the ground testing, the on-orbit demonstration was performed with lower target plenum pressures and allowed to blowdown to a lower final pressure. The demonstration target plenum pressure was around 100 psi and the blowdown pressure was typically between 40 and 20 psi. Additionally, the thrust event durations were over twice as long for the mission demonstration.

With these differences in operational set points, the closer comparison to the mission demonstration data is the 'Trial 2' results in Table 1. The starting and final pressures are much closer (though still slightly higher) to the mission demonstration. The force contribution from the tail of the longer thrust durations also lowers the specific impulse of the mission demonstration compared to the 'Trial 2' results. With these differences in mind, the specific impulse of 223-241s from the mission demonstration is within the expected range when compared to the 269 s from ground testing under more favorable operating conditions. Future HYDROS testing is expected to be performed at higher plenum pressures in order to push the specific impulse above 300s.

## CONCLUSION

The HYDROS-C propulsion system is the first water electrolysis thruster to operate in space. Even though this mission is currently on-going, the early electrolysis demonstrations showed that the on-orbit performance was consistent with the expected behavior for gas generation rates for given input power. This electrolyzer performance assessment validated the fluid management of the propulsion system, including the water tank, electrolyzer, and gas plenum design. Using the on-orbit telemetry, additional analysis can be performed to refine the characterization of the electrolyzer, including a more detailed assessment of the efficiency given the in-space, operational thermal environment.

The demonstration mission telemetry clearly indicated a change in the host spacecraft orbit due to the thruster operation. An approximation of orbit determination and mission data showed the on-orbit performance was consistent with ground testing trends. This performance trend was a rough comparison that took into account the changes in the thruster operational parameters for gas pressures and thrust event duration. These preliminary results provide confidence that the thruster was working as expected and capable of operating at a variety of operational set points. Additional analysis is in-work to refine this performance evaluation.

The on-orbit performance along with the extensive environmental and performance testing on the ground shows the feasibility of highly-capable propulsion systems suitable for CubeSats and other classes of small satellites. HYDROS-C successfully utilized liquid water as the fuel for a bipropellant thruster. This is an attractive green propellant alternative that also has options of being farmed and processed in-situ as part of advanced space exploration missions.

### *Acknowledgments*

Authors would like to acknowledge NASA Glenn Research Center for technical guidance during the NASA Tipping Point Partnership and continued support with NASA Ames for selecting HYDROS® as the first payload in the series of Pathfinder Technology Demonstration CubeSats through the Small Spacecraft Technology program. This work is funded under NASA contract NNA16BD36C.

***References***

1. Grubb, W.T., “Batteries with Solid Ion Exchange Electrolytes”, Journal of The Electrochemical Society, Vol. 106, No. 4, 1959.
2. Nuttall L.J., Fickett A.P. and Titterington W.A., “Hydrogen Generation by Solid Polymer Electrolyte Water Electrolysis. Hydrogen Energy. Springer, Boston, MA, 1975.
3. Chapman, H. G., and Stechman, R. C., “Water Electrolysis Propulsion System Testing," Air Force Rocket Propulsion Laboratory, AFRPL-TR-74-72, 1974.
4. Groot, W., Arrington, L., McElroy, J., Mitlitsky, F., Weisberg, A., Charter, P., Myers, B. and Reed, B., “Electrolysis Propulsion for Spacecraft Applications”, 33rd Joint Propulsion Conference and Exhibit, Seattle, WA, July, 1997.
5. Wrobel, J.S., Hoyt, R.P, Slostad, J.T., Storrs, N.D., Cushing, J.I., Moser, T.J., St. Luise, J.L. and Jimmerson, G.J., “PowerCube™ Enhanced Power, Propulsion, and Pointing to Enable Agile, High Performance CubeSat Missions,” AIAA SPACE 2012 Conference & Exposition, Pasadena, CA, September, 2012.
6. Middlebrook, L., “NASA CubeSat to Demonstrate Water-Fueled Moves in Space,” January, 2021, website: https://www.nasa.gov/feature/ames/ptd-1.