

Electrolysis Propulsion for CubeSat-Scale Spacecraft

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As CubeSats grow in both numbers and capability, the need to extend their reach with integrated propulsion systems is becoming clear. A water-electrolysis propulsion system for 3U CubeSats is proposed that could fill the gap in the available propulsion systems at this scale. Combining the advantages of electric propulsion with those of chemical rockets, the system is safe both to handle and to launch; it is lightweight, and it is capable of providing roughly 1000 m/s, enough ΔV to reach lunar orbit from GTO. The efficiency of the proposed technology is at least 75% for Cornell's prototype system, consisting of Ni electrodes and 0.5 M KOH as electrolyte. With over 1 km/s of ΔV from 1 kg of water as propellant, sample missions include compensating for drag, orbit raising and lunar exploration.

I. Introduction

CubeSats have been a popular platform for in-orbit flight demonstrations for over a decade, and their success has shown that standardization can open the doors for low-cost access to space. The standard introduced in 1999 by CalPoly was meant primarily as a way of lowering the schedule and cost of a satellite from concept to launch.¹ The CubeSat standard helps achieve this goal in two ways. First, a standardized mechanical interface and deployment technology make CubeSats readily launched as secondary payloads. Since the deployment mechanism, the P-Pod, is a high technology-readiness, COTS subsystem, it reduces risk for the primary payload to well below what a typical secondary payload offers. Second, CubeSats can exploit other COTS components for bus and payload.² For university researchers, using this third-party hardware reduces risk and minimizes demands on project resources, allowing the researcher to focus on the custom-built or experimental sections. The original standard specified satellites with a volume of 1 L and dimensions of 0.1 m per side (a 1U CubeSat).³ However, many recently developed satellites have the size of two (2U) or three (3U) of the original satellite specification.

For the most part, CubeSat missions have been confined to low Earth orbit (LEO), their small volume and mass precluding the use of any sort of propulsion system. New, more complex missions will be possible if these small, affordable satellites can perform significant orbit raising. Previously implemented propulsion systems at the CubeSat scale have been low specific-impulse technologies. For example, the CanX-2 mission, a 3U CubeSat, flew a liquid sulfur hexafluoride cold-gas thruster, which attained an I_{sp} of 50 s and a total ΔV of 2 m/s.^{4,5}

Miniaturized solid-propellant rockets barely fit in a 3U CubeSat, with little space for payload or other hardware. ATK's Star 3 motor, with a diameter of 8 cm, a length of 29 cm, and a loaded mass of 1.16 kg, can provide a 4 kg satellite with just over 330 m/s of ΔV .⁶ Solid rockets are also difficult to throttle and usually expend all their propellant at once. Such propulsion systems severely limit the type of orbital maneuvers possible, precluding multiple burns.

New developments in electric propulsion will soon make a small hall thruster, ion engine, or similar system viable, with the constraint that enough propellant for a significant ΔV will require heavy pressure vessels to contain the gaseous propellant. Since in most cases not enough power is available to operate an electric propulsion engine continuously, a burst-operation strategy must be used, where the system is on for only a fraction of the orbit. Throughout the rest of the orbit, the spacecraft uses its solar panels to charge batteries. When this operations concept is taken into account, the total mass of the propulsion system, batteries, power distribution system and propellant storage tanks can in many cases become restrictive for CubeSat applications.⁷

Using electricity to electrolyze water into hydrogen and oxygen gases, and then using these gases for propulsion is not a new concept. It is the subject of a 1973 report by Stechman, et al., which focused on spacecraft with a mass on

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the order of 1000 kg. In this 1973 system, the hydrogen and oxygen gases produced by the electrolysis unit are stored separately in order to avoid accidental ignitions seen in previous designs.⁸ Subsequent versions, such as that proposed by de Groot et al., followed the approach of storing the hydrogen and oxygen separately.⁹ By using a regenerative fuel cell, their system can also convert the chemical energy stored in the gas back to electrical energy, operating like a battery.¹⁰ However, the extra mass of the separate hydrogen and oxygen tanks as well as the necessary number of valves makes this design impractical for smaller spacecraft. A CubeSat's mass and volume limitations demand a less complex, lighter design, one that scales to exploit the benefits of small size.

Electrolysis propulsion combines the qualities of electric and chemical propulsion systems that are desirable for small-scale satellites. Like electric propulsion, an electrolysis system obtains its energy from solar cells and operates on inert propellant—an extremely safe one in the case of water electrolysis. However, unlike electric propulsion, the electrolysis propulsion system proposed here can scale down its power usage to the satellite's needs and does not require heavy propellant tanks. It also does not require batteries for storing electrical energy because the propellant itself provides energy storage. Like chemical propulsion, each burn is impulsive, but unlike traditional chemical propulsion schemes, the operation is in small bursts and does not need to be continuous. It therefore offers much more versatile orbit control and avoids the thermal issues associated with sustained high-temperature operation. In addition, there is no need for cryogenic storage of propellant and oxidizer. This paper evaluates the promise of this technology through experiments and analytical results. It describes a likely propulsion-subsystem architecture, outlines a spacecraft bus architecture that accommodates it, and offers some CubeSat mission concepts that take advantage of this solution.

II. Electrolysis Propulsion

Electrolysis propulsion works by capturing energy from the sun and converting this energy into chemical energy which can be used to propel the spacecraft. The first step in the process is to convert the energy from the sun into electrical energy using photovoltaic cells. The electricity generated is used to electrolyze liquid water into hydrogen and oxygen gas. Water is a good propellant choice because, among other useful properties, it has a high enthalpy of formation per unit mass, 15.86 kJ/g.¹¹

The technology described here is based on a 3U CubeSat that spins about its maximum axis of inertia during orbit raising, which provides passive attitude stability and momentum stiffness for managing the effect of thrust-induced torque. The spin also virtually eliminates thrust-direction errors due to mechanical misalignment. At least as important, these kinematics provide a spin field that conveniently collects the electrolyzed gases, due to centrifugal effects, at the center of the spacecraft. They are then passed into a combustion chamber when enough gas has been electrolyzed. The flight software then commands a spark that combusts the gas mixture, which expands through a small nozzle located approximately on the spin axis, generating thrust.

There are several possible modes of operation, depending on the mission. The most likely is for the satellite to electrolyze water while it is in sunlight and then combust the gases only once per orbit. This approach helps ensure that enough gas has accumulated for a successful firing, and the satellite's orbit can be raised efficiently, with thruster impulses only at perigee (for example). The process repeats, each time combusting about 1.5 g of water in the case of a 90 minute LEO orbit.

A. System Overview

For this study, it is assumed that the solar cells are at least 30% efficient in converting solar energy to electrical energy and that the satellite is a 3U CubeSat with solar cells on all faces. Deployable solar panels are not considered, although these would certainly

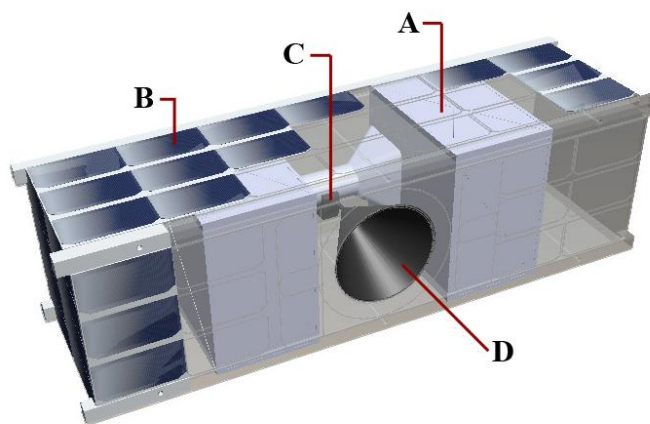


Figure 1. Electrolysis propulsion system for a 3U CubeSat. *The water tanks (A) store propellant and generate H₂ and O₂ through electrolysis using power from solar cells (B). The gases are combusted in the chamber (C) and expanded through a nozzle (D) to generate thrust. The spacecraft spins passively about an axis parallel to the thrust direction. For clarity, some solar cells are shown only as outlines.*

increase the power available significantly. The solar cells supply power to a set of electrolyzers, which convert the electrical energy to chemical energy by splitting the liquid water from the fuel tank into hydrogen and oxygen gas.

The electrolyzers to be used are composed of an anode and a cathode, both made of strips of nickel mesh, separated by a thin layer of non-conductive mesh. The electrodes are within the liquid water tank, which contains water as well as potassium hydroxide as an electrolyte. The non-conductive layer allows for the passage of ions between the two electrodes while preventing them from coming into direct electrical contact. The electrodes are then tightly rolled so that the separation distance between the anode and cathode is minimized. Each of the rolls operates at the same voltage. Several of these electrode rolls are to be used in parallel so that as much power as possible goes toward electrolysis of the water. The number of electrolyzers that are operational at any point changes the amount of power devoted to electrolysis.

A spacecraft spin rate of about 2 rad/s frees the gas bubbles from the electrolysis device. Rotation can be achieved either initially at de-spin or through a later maneuver, perhaps with magnetic torque rods. Alternatively, reaction wheels can counter-spin the bus of a zero-momentum spacecraft, but the resulting system would not have the beneficial momentum stiffness of a true momentum bias. When the pressure is sufficiently high and a burn is desired, an actuated valve opens to allow gas to flow into a combustion chamber, where the mixture of hydrogen and oxygen is ignited. A small nozzle is connected to the far side of the combustion chamber. The hot gases expand in the nozzle and are expelled to provide an impulse. The process is repeated once every orbit or as soon as enough gas has been electrolyzed, for the example of missions that require aerodynamic-drag compensation. Figure 1 is a schematic of the propulsion system inside a 3U CubeSat.

B. Efficiency experiments using nickel electrodes

The proposed method for electrolyzing water into hydrogen and oxygen is one that involves an alkaline solution. Preliminary tests on prototype electrolyzers operating under 0.1 M and 0.5 M solutions of potassium hydroxide (KOH) indicate that the efficiency of a nickel electrolyzer increases with concentration of potassium hydroxide. Added efficiency allows more of the solar energy to be converted into chemical energy, speeding up the mission and/or saving cost and weight associated with the solar cells. Tests conducted so far at different power settings show that the electrolysis device is about 60-65% efficient in 0.1 M KOH, and 70-75% efficient in 0.5 M KOH. Figure 2 shows the results of these tests. Future tests using a higher concentration of potassium hydroxide are expected to increase the efficiency to about 80%. While the exact concentration of potassium hydroxide is something that can be tailored to the specific mission, these recent experiments indicate that an initial concentration of 0.5 M yields a satisfactorily high efficiency.

Electrodes were constructed from nickel mesh, spaced at 150 wires per inch, for an open-area fraction of 37%. I.e. for every square mm of geometric area, the mesh has about 2.5 square mm of reacting surface area. The two nickel electrodes were separated by a thin sheet of fiberglass cloth (0.005 inches), and wound tightly so as to decrease the space between the two electrodes without causing them to be in electrical contact. The fiberglass cloth is porous so that water can fill the gap between the electrodes and so that gases can escape easily. Figure 3 shows the device used in tests. This mechanical separation presents a tradeoff between efficiency and simplicity. Tests similar to those above indicate that polymer electrolyte membrane (PEM) electrolyzers achieve efficiencies in the 85-95% range.

While using a polymer electrolyte membrane as a separation between the electrodes would permit the use of distilled water as well as increase efficiency, using a mechanical, chemically inert separation membrane is a lower-cost option that also does not suffer from mechanical failures. PEMs can crack if not maintained at the proper moisture level and can then cease to function properly. While during normal operations it is not expected that the

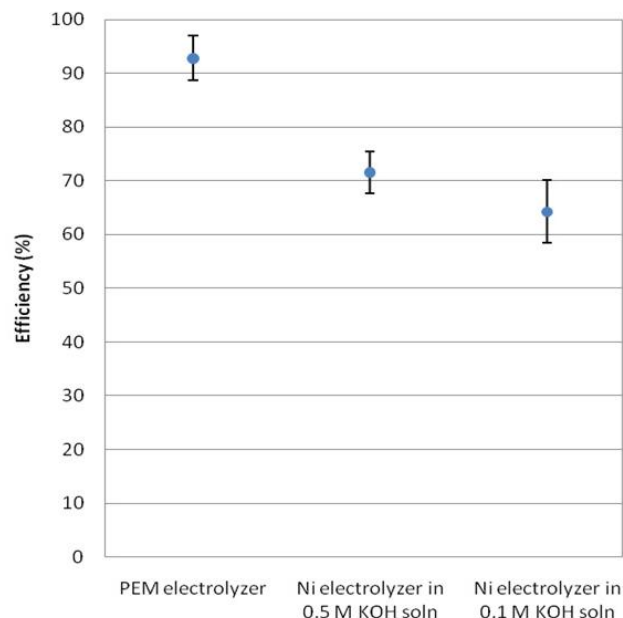


Figure 2. Efficiency of electrolyzers tested. *The off-the-shelf PEM electrolyzers attained an average efficiency of 92.8%. The nickel mesh electrolyzers were 64.2% efficient in 0.1M KOH and 71.5% efficient in 0.5 M KOH.*

electrolyzers would dry out, when the water level in the tank is low the electrolyzers can spend large amounts of time in the part of the tank filled with the gas mixture. Using a mechanical separator therefore causes the electrolyzers simply to stop operating when immersed in gas, since the fiberglass cloth acts as an electrical insulator. When the space between the electrodes once again is in contact with in water, the resistance would drop and electrolysis would proceed.

In order to measure the efficiency of the electrolyzers, the electrodes were immersed in the KOH solution and a known voltage was applied. The current drawn by the electrolyzer was measured in order to quantify the amount of electrical energy applied to the system. The gas produced by the electrolyzer was captured and the volume of gas then measured in order to compute how much of the electrical energy was converted to chemical energy. Each test runs for ten minutes. Each data point in figure 2 represents between five and ten tests, and the error bars represent ± 1 standard deviation.

In the flight version of the electrolyzers, the electrodes would be placed inside the water tank. The number of electrodes and size would be determined based on the power available and time between successive firings. Since the electrolyzers are tuned to operate most efficiently at a set voltage, the amount of power used by the electrolysis process can be controlled by operating only some of the electrolyzers. In this manner, the spacecraft is able to accommodate power-intensive payloads by taking more time to electrolyze the water while using less power.

C. System Performance

A 3U CubeSat with 30% efficient solar panels can provide approximately 14 W of power while in sunlight in low Earth orbit without the use of deployable solar panels. Due to the geometry and spin of the spacecraft, the actual power available in one orbit fluctuates between 4.1 W and 17.8 W, as shown in figure 4. The electronics and instruments not dedicated to the propulsion system are estimated to consume 4 W from the power provided by the spacecraft. The rest of the power available is used to electrolyze water into its constituent gases. Using the 75% efficient electrolyzer described above, a 3U CubeSat could electrolyze about 1.5 g of water during the sunlit portion of a LEO orbit.

This 1.5 mL volume of water, now broken down into hydrogen and oxygen gas, is separated from the remaining liquid water by the centrifugal effect of the spacecraft's spin. When the pressure is high enough and a burst is desired, the valve between the water tank and combustion chamber opens. This valve allows the gas to enter the combustion chamber, where a firing is triggered and the gases are combusted. The chamber is directly attached to a divergent-convergent nozzle which expands the flow, imparting thrust. Analysis of the combustion and flow through the nozzle using both theoretical equations and finite-volume CFD modeling shows that the specific impulse of the system is in the 350 s to 390 s range. At this efficiency, and using the Tsiolkovsky rocket equation, the ΔV produced by the system for a 4kg spacecraft with 1kg of propellant is between 987 m/s and 1100 m/s. For context, consider that Earth escape from GTO requires no more than 800 m/s. As discussed below, exploiting the weak stability boundary in the Earth-Moon system may enable a transfer to Lunar orbit with significantly less ΔV , leaving significant propellant for design margin or for circularizing the resulting lunar orbit.¹²

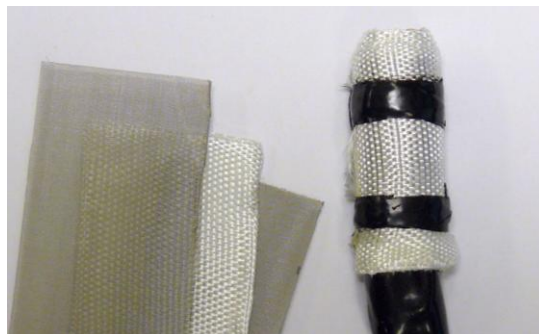


Figure 3. Prototype electrolyzer. The electrolyzer is composed of a Ni mesh anode and cathode with a fiberglass separating layer (left). The layers are then rolled (right) to reduce separation distance.

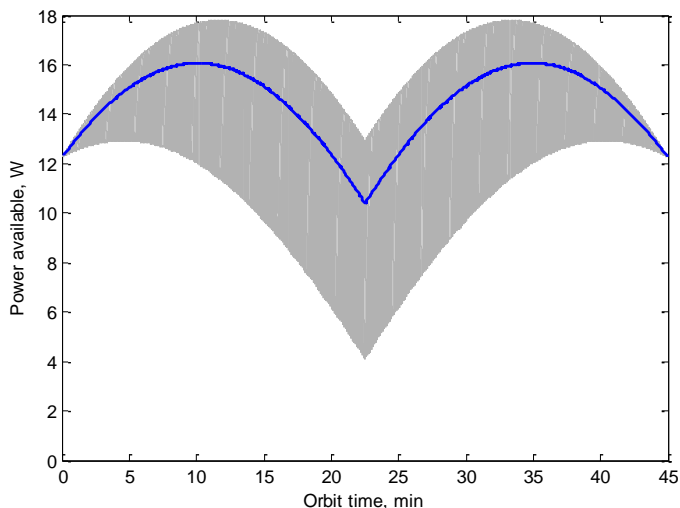


Figure 4. Power available for a 3U CubeSat during sunlit portion of LEO orbit. The gray line represents the electrical power generated by 30% efficient solar cells in LEO. The high frequency variations are caused by the spacecraft's spin about the thrust axis. The blue line shows the power available, averaged in order to remove the effects of rotation.

D. Benefits of Electrolysis Propulsion

The CubeSat standard specifies what can be launched as a CubeSat. Adhering to these requirements makes the launch of a CubeSat far easier and less expensive than the more general requirements for secondary payloads. Electrolysis propulsion at the CubeSat scale has several important benefits over competing systems, especially when considered in light of the CubeSat standard. Pressure vessels over 1.2 atmospheres are not permitted in CubeSats.³ Electrolysis propulsion systems do not have high pressure storage tanks: the fuel is stored as liquid water, and therefore no heavy tanks are needed for containing the propellant. In turn, light tanks allow more propellant to be loaded. Not having a pressurized tank can also be a benefit in terms of safety and reliability during integration and launch, which of course are among the reasons for the CubeSat standard's requirement.

The CubeSat standards disallow the use of hazardous materials and limit the total amount of chemical energy stored at launch to 360 kJ.³ The water is not combustible while on the launch pad. Since the system begins producing hydrogen and oxygen gas only when powered (and that occurs after launch, per the CubeSat standard), there is no risk of an explosion caused by the propellant inside the CubeSat. There is also no risk to personnel associated with the accidental release of propellant. An accidental leak of hydrazine or other hypergolic propellants, by contrast, would cause a critical safety hazard to both personnel and flight hardware. During flight, the presence of 1 kg of sloshing water should represent a negligible effect to the rocket's flight dynamics given that the primary spacecraft very likely contains hundreds if not thousands of kg of liquid propellant.

Electrolysis propulsion at this scale also has the advantage that it is mechanically simpler than liquid hydrogen/liquid oxygen propulsion as used in a larger rocket but for comparable specific impulse. The absence of cryogenics saves considerable mass and cost in the plumbing and tank design. It also vastly simplifies propellant loading at the launch site. In flight the propellant is already pre-mixed and in the gaseous state, so it requires no atomizer or similar mechanism as an injector. This perfect pre-mixing also increases overall efficiency because the propellant is not attempting to combust as macroscopic droplets of liquid but as a mixture of gases. Unlike gaseous propellant propulsion at a large scale, at a CubeSat scale the gases can be stored in the water tank between bursts and ignited at relatively low pressures, once again reducing the need for strong (and heavy) propellant tanks.

III. Missions and Applications for Electrolysis Propulsion Systems

Once CubeSats are enabled with propulsion systems that are reliable, safe to work with, and provide sufficient ΔV for relevant orbital maneuvers, the possibilities for missions increase greatly. The cost of a lunar mission, an earth escape mission or even a LEO to GTO mission decreases considerably if the whole spacecraft can conform to a CubeSat standard. Including an electrolysis propulsion system among the off-the-shelf tools available to researchers and CubeSat designers will be an important step in the low-cost, private exploration of space. While an electrolysis propulsion system is an enabling technology open to many possible missions, a few of them are described here.

A. Drag Compensation

CubeSats are usually launched to low Earth orbit and therefore have a lifespan limited by aerodynamic drag. A CubeSat with an integrated propulsion system would be able to extend that lifetime and allow the CubeSat to maintain its altitude for longer so that it may continue normal-mode operations. An electrolysis propulsion system would be particularly well-suited for this type of mission. The power with which it operates can easily be varied. So, the propulsion system can provide just enough ΔV for maintaining altitude while accommodating the payload's power requirements.

An electrolysis propulsion system would be able to extend the lifetime of a satellite in a 250 km altitude orbit by about six months at worst, even more if solar activity is low. As the orbital altitude increases (and drag losses decrease), the propulsion system would provide even longer lifetime. At 350 km, the propulsion system would increase the lifetime by at least 3.5 years.¹³ This mode of operation can be very useful for low-budget Earth-observation missions where data is needed over a long period of time or when a constant altitude is necessary.

B. Orbit Raising and Lunar Exploration

The full capabilities of an electrolysis propulsion system become apparent when it is used to continually operate at full power in order to increase the altitude of the satellite's orbit. In this mode of operation, the satellite would electrolyze water the entire time it is in sunlight. Each time the satellite crosses perigee, the system would fire once, raising the satellite's orbit slightly. Repeated firings at perigee would further raise the satellite's orbit. In this modality, the satellite would be able to achieve between 1.4 and 1.85 m/s of ΔV per orbit. The total ΔV provided by 1 kg of propellant is 1070 m/s. So, the satellite would be able to raise its orbit significantly. For example, from a

300 km LEO, the satellite would be able to raise its apogee to an altitude of 5550 km in under 670 orbits. This maneuver would take the spacecraft 55 days to complete if it fires once every orbit. If the initial orbit is a geostationary transfer orbit (GTO), then the spacecraft would have enough ΔV to achieve Earth escape.

Perhaps more interesting than LEO orbit raising is the prospect of sending a CubeSat to another celestial body. The moon would be a prime target, and an electrolysis propulsion system would have just enough ΔV to make it to the moon. To do so, the spacecraft would have to use a low energy transfer, since a traditional patched-conics approach would require too much ΔV in too little time for the current design. A low energy transfer, also known as a Weak Stability Boundary transfer, uses the four-body dynamics of the Sun-Earth-Moon-spacecraft system in order to save significant amounts of propellant. However, the spacecraft would take longer to reach its destination than it would using a traditional transfer. In the context of electrolysis propulsion, however, a longer time of transfer is not necessarily a drawback, as the spacecraft needs the extra time to electrolyze enough water into component gases. Without time spent in eclipse, the spacecraft would be able to electrolyze all of its water in a little over 20 days. A typical Weak Stability Boundary transfer between the Earth and Moon takes 138 days and requires 695 m/s of ΔV after the initial burn in low Earth orbit provided by a launch vehicle.^{12, 14, 15} It is therefore within the capabilities of the electrolysis propulsion system to provide enough ΔV in the required time to perform a lunar insertion and circularization maneuver. Such a maneuver might even motivate a less-capable power subsystem, saving the cost of some solar cells, since they're not necessary for propulsion. If the desired orbit is one that is not circular, the required ΔV would be even lower.

C. Near Earth Asteroid/Lunar Explorer

An electrolysis propulsion system has the ability to be on standby for months and return to operation quickly. A lack of volatile or explosive components adds to the safety and reliability of the system. An ideal application for such a propulsion system would be for the spacecraft to remain parked at a high LEO or GTO, where the orbital decay rate is small, and wait for a target of opportunity. Such a target could be a Near Earth Asteroid (NEA), which a propulsion-enabled CubeSat could photograph closely as well as deliver a payload of dozens of tiny ChipSats.¹⁶

NEAs are usually identified only months before they pass near the Earth and, in some cases, can pass within 36000 km of Earth (the GEO belt). Near Earth Asteroids frequently make close approaches to Earth. As of this writing, in 2011 there have been two NEAs that have passed within 20000 km of Earth (2011 CQ1 and 2011 MD), both within 6 degrees of the ecliptic.¹⁷ A CubeSat in a GTO orbit would have time on the order of a few months to reposition itself to the proper orbit. Once there, the ChipSats would be deployed directly in the path of the NEA. These would impact the asteroid and send back data from their onboard sensors.

The NEA mission described above can be seen as a precursor to a lunar exploration mission. For the latter mission, the CubeSat would use the electrolysis propulsion system to attain a lunar impact trajectory. To minimize onboard propellant requirements, the spacecraft would follow a Weak Stability Boundary trajectory. A lunar insertion from this orbit leads to a highly eccentric orbit, which would require a minimal ΔV for lunar impact. The CubeSat would release its payload of ChipSats before impact, and the surviving ChipSats would then send back data on their location and, if equipped with the proper sensors, about lunar composition.

IV. Conclusion

A propulsion system capable of imparting CubeSats with hundreds of meters per second of ΔV can transform the way CubeSats are viewed and used. No longer will CubeSats be seen only as testbeds for microgravity experiments or neat educational projects. Instead, with a capable, safe and reliable propulsion system, CubeSats will become devices for exploration. Electrolysis propulsion systems allow university researchers to develop and launch them safely and provide CubeSats with much more ΔV than any CubeSat technology to date.

The development of an electrolysis propulsion system for CubeSats still requires several key technology-development activities. The first and possibly one of the most critical aspects of this is to test the lifetime of the electrolysis mechanisms. As described above, efficiency tests have been run that show that the process is feasible and yields sufficient gas in reasonable amounts of time. However, it is unclear how the nickel electrodes will corrode in extended electrolysis operation. Over the lifetime of the propulsion system, and as the water in the water tank is exhausted, it must be clear that the efficiency is not significantly reduced by corrosion, operation in the gas bubble, or extended use.

Several tests were run in which electrodes were operated in a manner similar to the one described in section II, but at much higher voltage, for 120 continuous minutes. In these tests increased voltage led to very fast corrosion of the

electrodes. However, it is not clear that this is true if the electrodes are operated near their optimal, much lower, voltage. In this circumstance, the nickel in the electrodes is far less likely to participate in the reaction and will therefore not corrode significantly. In the electrolysis tests run at lower voltage, no significant corrosion was observed, despite cumulative operation time comparable to the tests at higher voltage. However, more work needs to be done to assure that the electrolyzers will survive for the lifetime of the mission without critical corrosion.

The second aspect on which future work will focus is the performance testing of a prototype integrated propulsion system. The prototype will include the electrolysis mechanism as well as the combustion chamber and nozzle. Testing the system in a vacuum chamber will lead to measurements of the impulse per burst, the specific impulse, and the thrust time-history for the prototype system. These tests are expected to occur in late fall of this year.

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