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## Hydrolytic space propulsion: a new opportunity for CubeSat missions

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Water propulsion is receiving strong interest in the recent years in the field of small thrusters. Negligible toxicity and risk are appealing properties of a flexible propellant that can be used as is (e.g., resistojets, microwave electrothermal thrusters) or as a reserve of chemical reactions (e.g., electrolysis and combustion). Typically, propulsion systems using water need power input to heat up, vaporize, or split chemical the H<sub>2</sub>O molecule. The present paper describes a new propulsion technique based on hydrolysis of metals. In principle, this concept does not need energy: the hydrolytic chemical reaction is spontaneous and exothermic. The amount of water involved in the process as well the chemical and physical nature of the metal used for the reaction dictates the thermodynamic outcome and the kinetics. This reaction is water-driven: it can be regulated, stopped, and restarted on command. The concept is still quite naive but preliminary tests (presented in other papers in this same conference) demonstrated the concept. In this paper the discussion will be about the principle of application.

### Nomenclature

$C_v$	: Specific heat at constant volume, J mol <sup>-1</sup> K
$C_p$	: Specific heat at constant pressure, J mol <sup>-1</sup> K
$g_0$	: Gravity acceleration at sea level, 9.81 m s <sup>-2</sup>
$H_{r,298}$	: Enthalpy of reaction at standard state, kJ mol <sup>-1</sup>
$\gamma$	: Specific heat ratio
$I_s$	: (Gravimetric) specific impulse, s
$I_v$	: (Volumetric) specific impulse, kg s m <sup>-3</sup>
$M_0$	: Initial mass of satellite, kg
$M_f$	: Final mass of satellite, after the firing of the rocket, kg
$M_{gas}$	: Mass of expelled gas mixture, kg
$M_{mol}$	: Molar mass of exhaust gases, g mol <sup>-1</sup>
$M_0$	: Initial mass of satellite, kg

$P_{jet}$	: Power of the jet, W
$T$	: Temperature, K
$v_e$	: Exit velocity, m s <sup>-1</sup>
$\bar{\rho}$	: Propellant average density, g cm <sup>-3</sup>
$\dot{m}$	: Propellant mass flow rate, kg s <sup>-1</sup>

### Acronyms/Abbreviations

DART	: Double Asteroid Redirection Test
GEO	: Geostationary Transfer Orbit
LEO	: Low Earth Orbit
MET	: Microwave Electrothermal Thruster
MarCo	: Mars Cubesat One
TDO	: Technology Demonstration Orbiter
TRL	: Technology Readiness Level

### 1. Introduction

Satellite market is evolving towards the commercial and scientific exploitation of small space platforms. Statis-

tics state 2068 nanosats (up to 10 kg and CubeSats up to 27 U) were launched in 2022. Out of this number, 1893 were CubeSats [1]. It has been estimated that about 5000 cubesat platforms have been launched in total. About 50 % are 3 U, followed by 1 U, 6 U or larger. Since 2020, historical trends show a tendency to move towards 6 U or larger configurations, and towards picosats smaller than 1 kg. Typically, these satellites are secondary payloads, most of them without primary propulsion. The typical lifetime of these LEO items is 2 years, unless specific design choices are done. About 1100 operating satellites are active while about 250 CubeSats are no more operative, but still in orbit. Constellations play a very important role. For example, the company *Planet* launched about 1000 satellites in total. Currently, the active constellation is made by 400 satellites with the configuration called *Dove*, a 3 U CubeSat having mass of 3 kg.

The global CubeSat market was valued at 178 M\$ in 2020 and is projected to reach 631 M\$ by 2027. CubeSats are being designed targeting a large number of space missions, such as observation, reconnaissance, communication network construction through cluster satellite technologies, as well as space exploration. Additionally, they may be a means to demonstrate novel technologies for formation flying, close inspection or rendezvous and docking, orbit change and raising as well as deorbiting capabilities to comply with orbital debris mitigation requirements. Originally, the absence of propulsive solutions strongly constrained CubeSat missions. For this reason, the interest of Agencies, research institutes, and industries is currently focusing on in-orbit CubeSat mobility and respective technology enablers.

Since 2018, CubeSats have been under consideration also for higher orbit and interplanetary missions. The MarCO has demonstrated the use of CubeSats for interplanetary exploration, performing a fly-by of Mars. The Light Italian CubeSat for Imaging of Asteroids (LiciaCUBE) has been designed to perform a fly-by of a comet, carried as a secondary payload by the DART probe. In 2019 the US Air Force launched the first Technology Demonstration Orbiter (TDO), a 12 U CubeSat in GTO orbit while Ascent was launched in GEO in 2021 [2, 3]. In 2022, the number of “beyond-LEO” mission was 79, with typical mass in the range 3 U to 12 U, engaged in GEO, GTO, lunar, and interplanetary missions.

Propulsion systems are vital to facilitate CubeSat in-orbit relocation, to obtain accurate mission execution, to perform collision avoidance maneuvers based on both early and late warning, to handle efficiently the end-of-life of the spacecraft, to perform (relatively) generic high  $\Delta V$  maneuvers even for long time and, in general, to widen their space missions operation capabilities. Innovative so-

lutions must consider primary constraints deriving from their size, mass and power constraints, and should also adhere to general guidelines and development trends deriving from the CleanSpace initiative and, more in general, from the new European Green Deal (limited toxicity of propellants and exhaust, compliance with debris mitigation guidelines, etc.) . So far, both chemical and electric propulsion have been investigated for CubeSat applications, but the limited on-board power restricts the use of highly fuel-efficient electric systems, whereas the chemical ones have scaling-related issues. Moreover, there are some common problems such as low thrust performance or higher dry mass fraction because of high-pressure gas systems such as tanks, feed lines and valves.

Water hydrolysis as a means of power and propulsion generation may represent an innovative opportunity. Water is already considered a potential propellant thanks to its low cost and negligible toxicity. Hydrolysis is a spontaneous exothermic chemical process which is triggered by the contact of metals, hydrides, or alloys with a water molecule. The exploitation of hydrolysis and alcoholysis of light metals for hydrogen generation in connection to fuel cell technology is under study for ground applications, because the reachable storage density is superior to compressed gas or cryogenic technology [4]. This paper explores the use of water hydrolysis for space rocket propulsion. The paper describes the general strategy for the technology application and presents some preliminary performance computations. The reader will find in Section 2 a review of water-based propulsion applications, in Section 3 the concept description of hydrolytic propulsion, in Section 4 a simple model approach and a description of attainable ideal performance. Section 6 will discuss the results and will explore the obstacles for the application of the hydrolytic propulsion. Conclusions and future works will close the paper in Section 7

## 2. A brief review of water-based propulsion

Water answers to the need for a propellant characterized by low cost, easy to obtain, simple handling during both testing and operating phase, and with negligible environmental impact. all these things lead to a reduction of global costs. Water can be a constituent of propellant mixtures, such as the ionic liquid LMP-103, where different ingredients are dissolved and kept stable. These promising monopropellant are characterized by high specific impulse, but the need of catalysts and high reaction temperature make the development complex, especially for miniaturized solutions.

In the market, several options to use water as is are under development or testing. The following examples represent only a limited number of the existing uses of water,

currently under consideration.

**Resistojets** These propulsion systems exploit the technological flexibility of resistojets. Water is used as propellant, vaporized thanks to Joule effect heating. Saturated water vapor is expanded in the nozzle. Relatively high thrust, flexibility of propellant type, and simplicity represent the advantages of such technology [5]. Power needs and low specific impulse are drawbacks derived by, respectively, high specific heat and high molar mass of the propellant. Just as an example, the Pale Blue PBR-20 is a milli-newton level water resistojet reportedly capable of 220 N s of declared total impulse with a wet mass of less than 1.5 kg. The specific impulse is 70 and these performance figures are obtained at the operating power of 20 W. The system can fit a 1 U size and is considered a good option for 6 U to 8 U CubeSats [6]. In the same propulsion category, Aurora Propulsion Technologies is proposing the ARM product family. It is also a millinewton-level water resistojet array, which is supposed to power a range of CubeSats from sub-U to about 6 U. In the largest implementation officially documented, the propulsion system is up to 2 U large and weights less than 1.5 kg, with a specific power consumption of about 3 W mN<sup>-1</sup> to 5 W mN<sup>-1</sup> and a specific impulse of about 100 [7].

**Microwave Electrothermal Thrusters** These propulsion systems perform a gas dynamic expansion, similar to resistojets. They are characterized by more advanced method of propellant heating, based on the exploitation of water molecule polarity and its microwave excitation. Flexibility of operating power range and of thrust are features of this technology. In this respect, the Japanese company Pale Blue exploits Electron Cyclotron Resonance (ECR) to transfer power to the vaporized propellant. This company developed systems which can be integrated inside CubeSats. For example, the model PBR-9 has a size of 0.5 U, a mass of 0.6 kg and grants a thrust of 1 mN, with a specific impulse slightly higher than 45 s and a power need of about 9 W [6]. Also, URA Thrusters is developing a family of MET propulsion systems in the range of tens to hundreds of millinewtons, fed by different propellant types. AQUAMET version is expected to reach the market in 2025. It supplies a thrust up to 150 mN with an expected specific impulse in the range 500 s to 1000 s. The power consumption is less than 1 kW [8]. The maturity is reaching a good level, as demonstrated by the successful in-orbit demonstration performed by the company Momentus. In 2023, its propulsion unit performed an orbit raising using a water-fed MET [9].

**Bipropellants with electrolyzer** This solution typically considers the use of a Proton Exchange Membrane (PEM) cell to perform the electrolysis of water into hydrogen and

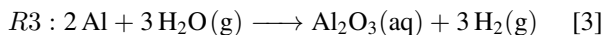
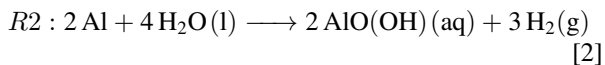
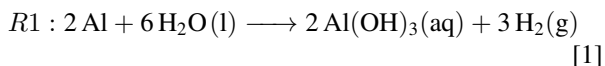
Table 1. Properties of hydrolysis reactions

Id.	$H_{r,298}$	Temp. range, K
R1	$H_{r,298} = -839 \text{ kJ mol}^{-1}$	$T < 553 \text{ K}$
R2	$H_{r,298} = -862 \text{ kJ mol}^{-1}$	553 K to 753 K
R3	$H_{r,298} = -950 \text{ kJ mol}^{-1}$	$T > 753 \text{ K}$

oxygen, in stoichiometric proportions. These reactants can be used in a combustion chamber to obtain replicate the performance of a typical bipropellant rocket engine. Tether Unlimited, now part of Arka group, has developed the *Hydros* family. The version *C*, reportedly a TRL 9 product, grants a thrust up to 1.2 N with a specific impulse higher than 310 s. The unit fills the propellant tanks before each propulsion action. The impulse granted for each firing cycle is 1.75 N s. The preparation takes 25 W of power and 800 s of time [10]. Other companies are working at this type of solution. The Italian *Miprons* has patented and is developing a propulsion unit based on water hydrolysis, targeting a size of 0.3 U (without propellant) and supply a gravimetric specific impulse of about 350 s [11].

### 3. Hydrolysis and propulsion

Hydrolysis is a convenient method for generation of heat and hydrogen by cleavage of water molecule. In a typical configuration, a metal is used as reducing agent that captures the oxygen of the water molecule, releasing hydrogen. The reaction also releases energy, being an exothermic oxidation process. Among the different metals that can combine with water, aluminum generates twice the heat of reaction per unit of fuel volume, when compared to kerosene [12]. Aluminum and pure water, ideally, can generate three stoichiometric reactions.



Despite each reaction leads to 1.36 L of hydrogen at standard conditions (1 bar and 298 K), they are active in different temperature ranges and lead to different reaction enthalpy, reported in Table 1.

There are two possible strategies for exploitation of this reaction: excess of water or poverty of water.

**Water-rich reaction: vapor mode** If the amount of water available is above the one needed for the respective stoichiometric reaction, the product will be a mixture of saturated water vapor and hydrogen. If a simplified equilibrium thermodynamics model is used, all the metal avail-

able will be consumed and the excess of water will be converted into vapor. The temperature of the vapor depends on the amount of enthalpy released, and so by the oxidizer-to-fuel ratio (namely, the ratio between the mass of water and metal). If the amount of water grows, the produced volume of vapor also increments, although its temperature will decrease, till condensation conditions are reached (see Fig. 1). Ideally, it can be reached a temperature above 2000 K, but this is only a virtual condition. In fact, aluminum melting temperature would prevent the cartridge from being consumed properly, and the system would stop operating nominally. Moreover, the metal bulk would disperse the majority of the heat, thanks to the high heat conductivity of aluminum. In any case, thermodynamic data are assuring that the spontaneous and exothermic reaction taking place in proximity of the metal can act as a heater for the excess of water. In this way, the vapor-mode can elaborate a significant amount of propellant (water) which will be available for thrust generation. Rather, the evolved gas will be mainly water, mixed with some hydrogen, reducing the expected gravimetric specific impulse.

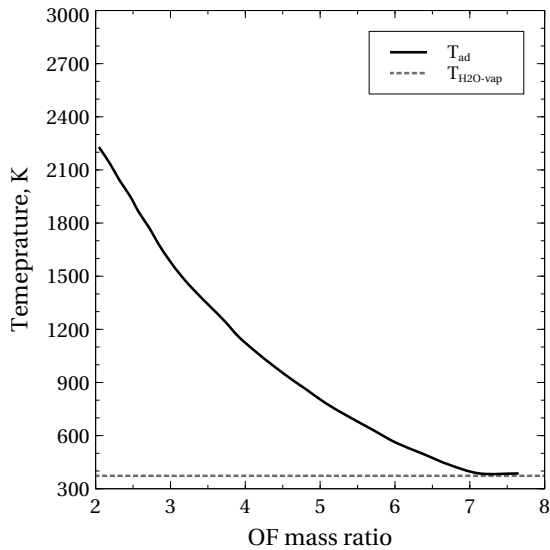


Fig. 1. Adiabatic flame temperature for vapor mode

**Water-lean reaction: hydrogen mode** If the amount of water is below the stoichiometric threshold, computations show a strong increment of the temperature. According to thermodynamics, a fraction of the metal is reducing all the available water, capturing the oxygen and releasing hot hydrogen. The rest is still in the combustion chamber and participates in the reaction heat sink. The temperature as a function of the OF ratio is reported in Fig. 2. The lower the water, the lower the temperature. For  $OF \approx 0.049$  the temperature of the reaction products overcome the melting

temperature of aluminum and, as already briefly discussed in the vapor-mode condition, this event would impair the correct operation of the metallic cartridge. Under the thermochemical equilibrium assumption, the available water is fully consumed, and the reaction product is made by hydrogen. The heating of the metallic leftover consumes part of the heat evolved from the reaction. Ideally, the gas produced by the reaction is molecular hydrogen, if the temperature constraint to prevent aluminum melting is maintained. The specific impulse is expected to rise sensibly with respect to the vapor-mode, but few mass flow rate will be generated, reducing the thrust available.

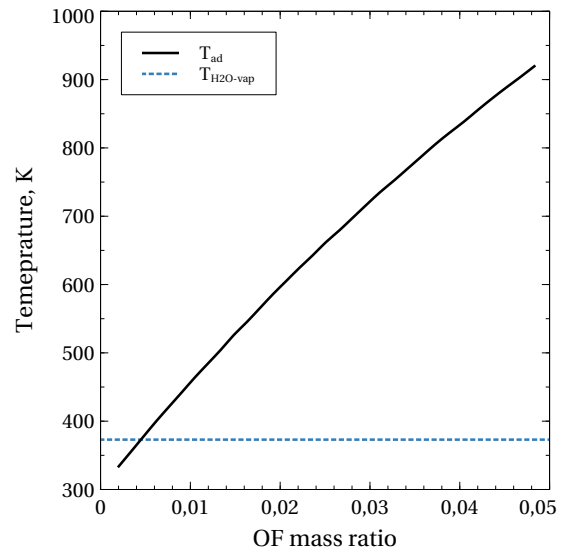


Fig. 2. Adiabatic flame temperature for hydrogen mode

#### 4. Architecture

The architecture concept has to take into account the fact that the two elements are in two distinct phases. Aluminum is in solid form, while water is handled liquid. The reaction between the two components is heterogeneous, making modeling and performance prediction difficult. Knowledge of reaction rate becomes of paramount importance and, currently, has not yet been established.

##### 4.1 Operating modes

**Vapor mode** The vapor mode approach is simpler. An aluminum bulk is fully consumed. Part of the water oxidizes the metal, while the leftover is vaporized by the reaction enthalpy. This configuration can be implemented by arranging aluminum in a unique cartridge or in a pellet form. The use of free-flowing powder is also possible, although its management is complex, since a dedicated feeding system has to be considered. The control of the oxidizer-to-fuel ratio is a matter of regulating the

water mass flow rate, defining the fuel surface exposed to the oxidation, and of characterizing carefully the water-metal reaction. This configuration has strong similarity to the one of a chemical-hybrid rocket combustion chamber, with a dissimilarity: solid reaction leftovers (aluminum oxide) are generated and should be handled, in a currently unclear manner. Their expulsion from the nozzle can contribute to thrust generation, but specific impulse would be decreased. Then, risk of clogging, erosion, and debris generation have to be carefully considered and evaluated.

**Hydrogen mode** In hydrogen mode, water is supplied in quantity insufficient to complete the reaction. The excess of metal absorbs part of the released heat, working as a sink. Only hydrogen is generated, producing a higher specific impulse, because of the molar mass of the exhausted products. Most of the metal may maintain its consistency, depending on compaction technique, and oxide generation is much less important. In this configuration, heat transfer capacity of the metal cartridge towards the external case can be one cause of losses.

#### 4.2 Metal fuel considerations

In both forms, aluminum reactivity is fundamental. Shaping controls the surface exposed to the liquid flow. In this respect, the faster the reaction, the lower the heat transferred through the metal bulk towards the outside of the engine. The increment of reactivity can be granted by the use of a metal with high specific surface area. Nanometric particles or mechanically activated powders can represent a viable solution [Patent Reactive]. Shaping of the metal charge imposes a constraint on the maximum allowed temperature, which has to stay below its melting point. In the examined case, the maximum temperature of 933 K is assumed, being aluminum the metal.

#### 5. A use case: vapor mode in a 3 U CubeSat

We are now considering the case where a CubeSat having size 3 U and a total mass of 6 kg. The satellite mass includes 1 kg of propellant mix (water and aluminum). We place the assumption that the propulsion unit operates in vapor mode. The constraint of 933 K is enforced. The model assumes that all the material, at the end of the reaction and (for evolved gases) at the inlet of the nozzle, have a temperature 1 K. The stagnation pressure in the heating chamber  $1.12 \text{ g cm}^{-3}$ . The respective amounts of water and aluminum are derived by using the plot in Fig. 1 and imposing the maximum operating temperature constraint. In the present case, reading from the plot brings an OF mass ratio of about 4.75 (which becomes 7.1 molar ratio). In this step, thermochemical equilibrium is assumed. The chemical equation may be rewritten according Eq. 5, splitting the water in two parts: for each mole

Table 2. Properties of gas mixture evolved

Symbol	Value
$M_{mol}$	14.62 gram/mol
$C_p$	37.85 joule/mol/K
$C_v$	29.54 joule/mol/K
$\gamma$	1.281

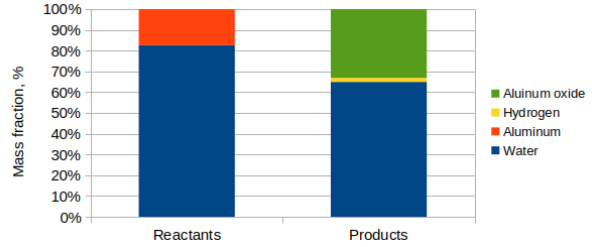
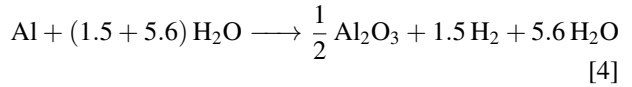


Fig. 3. Reactant and product mass fraction

of aluminum, there are 1.5 moles for metal oxidation and 5.6 moles for vaporization.



In this preliminary development step, aluminum oxide is considered trapped inside the engine and only the gaseous mixture of water and hydrogen expands through the nozzle. Molar-weighted properties of the mixture are addressed in Table 2.

If a frozen expansion model at constant specific heat is imposed, the specific impulse  $I_s = 207 \text{ s}$  can be computed analytically [13]. When mass fractions are retrieved, out of 1 kg of propellant loaded in the system. The mass  $M_{gas} = 669 \text{ g}$  of gaseous mix is generated, leaving only 331 g of metallic oxide. The mass fraction of reactants and products is reported in Fig. 3.

When the CubeSat performance is considered, the standard Tsiolkovsky equation has to be adapted to the fact that part of the initial propellant budget is not expelled and acts as an inert (see Eq. 6).

$$\begin{aligned} \Delta v &= I_s g_0 \log \frac{M_0}{M_f} = \\ &= I_s g_0 \log \frac{M_0}{M_0 - M_{gas}} = 240 \text{ m s}^{-1} \quad [5] \end{aligned}$$

As the weighted density of the propellant is  $\bar{\rho} = 1.12 \text{ g cm}^{-3}$ , the volumetric specific impulse is  $I_v = 232 \text{ 400 kg s m}^{-3}$ .

Finally, the quantification of the total energy stored in this propulsion solution is based on the conservative assumption of evaluating the power delivered to thrust, with-

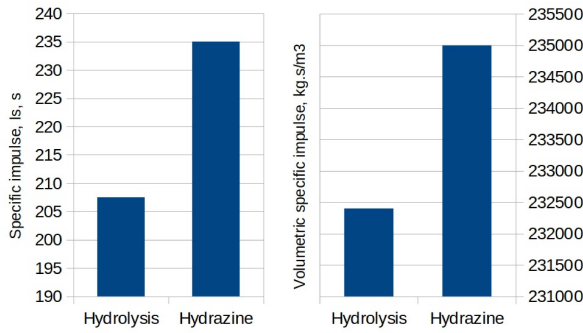


Fig. 4. Comparison between vapor mode and hydrazine

out accounting for losses. The jet power can be computed by using the ideal specific impulse and the total propellant mass, if the instantaneous jet power  $P_{jet} = 1/2\dot{m}v_e^2$  is integrated in time.

$$\begin{aligned}
 P_{jet} &= \int \frac{1}{2}\dot{m}v_e^2 dt = \int \frac{1}{2}\dot{m} (I_s g_0)^2 dt = \\
 &= \frac{1}{2}M_{gas} (I_s g_0)^2 dt = 1.39 \text{ MJ} \quad [6]
 \end{aligned}$$

## 6. Discussion

A comparison with a hydrazine-based monopropellant system, characterized by the same properties, has been performed. The hypothesis of pressure and expansion ratio is maintained, while temperature and performance are retrieved through NASA CEA equilibrium code. Whereas the specific impulse of hydrazine is consistently higher than the one of this water-based technology, the volumetric specific impulse is comparable. This is a benefit of water as an oxidizer.

An interesting comparison can be also obtained between the power content of this metal-based propulsion package and a lithium-polymer power pack. If it is assumed from the literature a value of 288 kJ for a pack having a mass of 670 g (values of Optimus-80 lithium polymer battery [14]). Assuming a single use of a battery that has to power the same maneuver, its mass should be about 3.2 kg. The reader should note that the assumption is underestimating the mass of the battery, as the jet power does not include any thruster efficiency of a generic electric propulsion unit.

## 7. Final remarks

The paper has presented the concept of hydrolytic propulsion, an innovative configuration which exploits the natural and exothermic reaction between some metals and water. Two main operational modes have been identified, being the vapor-mode the easiest to be implemented. A

case study of a 3 U CubeSat containing 1 kg of metal-water propellant has been presented and ideal performance as well as energetic content have been estimated. Despite the lower  $I_s$ , this kind of propulsion performs quite well when we come to analyze the energy density of the system. This solution compares with hydrazine in terms of  $I_v$  and can supply at least 3 times the power that could be obtained by using a battery as energy storage system.

With respect to other water-based applications, this one does not need power. As long as we can flow water inside the metal cartridge, the reaction propagates spontaneously, vaporizing the rest of the water. The reaction rate depends on the metal configuration and quality, so a relatively high thrust and short time pulse can be developed as a collision avoidance system. The technology is still at laboratory scale, however, demonstration experiments have been already performed successfully. Two more papers are presented at this same conference.

## 8. Acknowledgements

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## References

- [1] *Nanosatellite Launch Forecasts - Track Record and Latest Prediction*, SSC22-S1-04, pp. 1–17.
- [2] G. D. Krebs, *Tdo 1,2,3,4*, Gunter’s Space Page. Retrieved September 19, 2024, from [https://space.skyrocket.de/doc\\_sdat/tdo.htm](https://space.skyrocket.de/doc_sdat/tdo.htm).
- [3] G. D. Krebs, *Ascent*, Gunter’s Space Page. Retrieved September 19, 2024, from [https://space.skyrocket.de/doc\\_sdat/ascent.htm](https://space.skyrocket.de/doc_sdat/ascent.htm).
- [4] L. Ouyang, J. Jiang, K. Chen, M. Zhu, and Z. Liu, “Hydrogen Production via Hydrolysis and Alcoholysis of Light Metal-Based Materials: A Review,” *Nano-Micro Lett.*, vol. 13, no. 134, pp. 1–30,
- [5] W. MORREN and J. A. M. E. S. STONE, “Development of a liquid-fed water resistojet,” American Institute of Aeronautics and Astronautics, 1988. doi: 10.2514/6.1988-3288.
- [6] “Pale Blue, website,” <https://pale-blue.co.jp/product/>, 2023.

- [7] *ARM-O: Resistojet module for orbit control, aurora propulsion technologies website*, <https://catalog.orbitaltransports.com/arm-o-resistojet/>, last accessed sept. 2024.
- [8] *Met propulsion*. <https://www.urathrusters.com/met/>, URA Thrusters website, Last accessed sept. 2024.
- [9] J. Foust, *Momentum tug raises orbit with water-fueled thruster*, <https://spacenews.com/momentum-tug-raises-orbit-with-water-fueled-thruster/>, 2023.
- [10] *High-Performance Water-Based Propulsion for Small Satellites, Hydros TM datasheet*. Tethers Unlimited, 2023.
- [11] *Miprons: The project*. <https://www.miprons.com/the-project/>, Miprons website, last accessed sept. 2024.
- [12] Y. Yavor, S. Goroshin, J. Bergthorson, and D. Frost, “Comparative reactivity of industrial metal powders with water for hydrogen production,” *International journal of hydrogen energy*, vol. 40, no. 2, pp. 1026–1036, 2015.
- [13] N. Kubota, *Propellants and Explosives: Thermochemical Aspects of Combustion*, second. Weinheim, Germany: Wiley-VCH, 2007.
- [14] *Optimus battery*, <https://www.aac-clyde.space/what-we-do/space-products-components/cubesat-batteries>, Clyde Space Website, accessed sept. 2024.