Photovoltaic Electrolysis Propulsion System (PVEPS)

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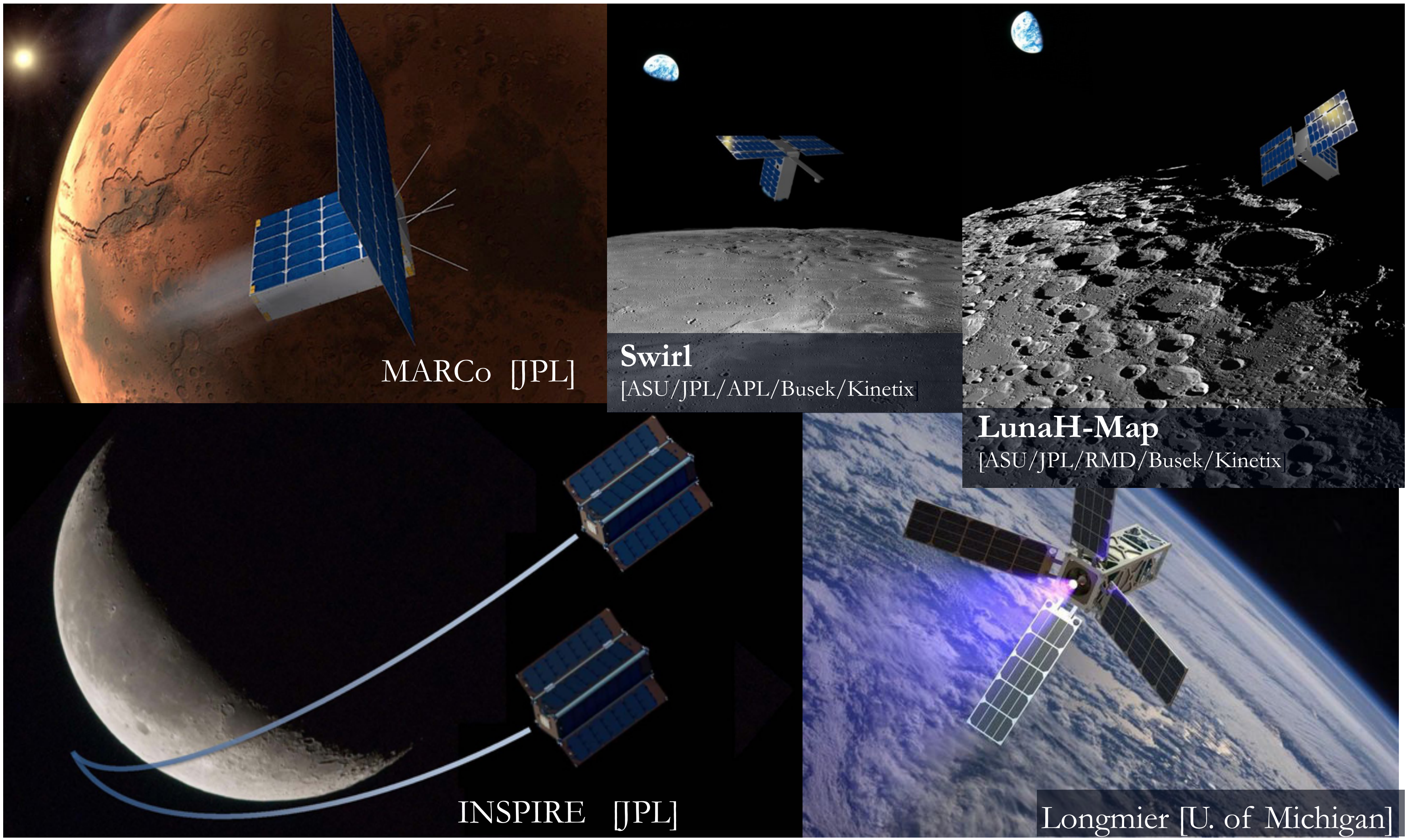
ASU
SpaceTREx

Motivation


MARCo [JPL]
Swirl
[ASU/JPL/APL/Busek/Kinetix]
LunaH-Map
[ASU/JPL/RMD/Busek/Kinetix]
INSPIRE [JPL]
Longmier [U. of Michigan]

Challenges

- Small volume and mass
- Extreme temperature
- Pressure restriction in storage tanks
- Limited power for electric propulsion

Objective

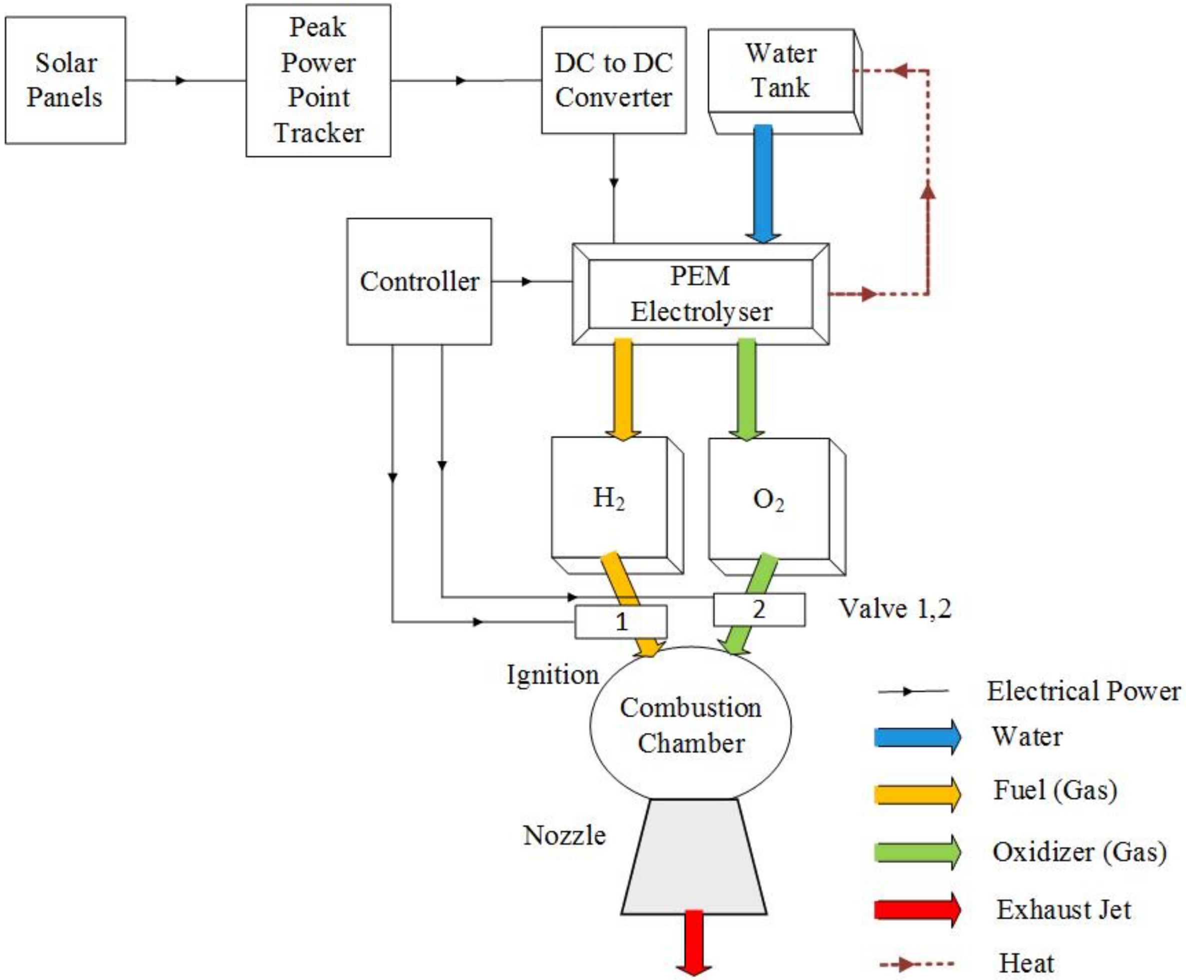
Evaluate the feasibility and preliminary design of Photovoltaic Electrolysis Propulsion System (PVEPS) for interplanetary CubeSat missions.

Methodology

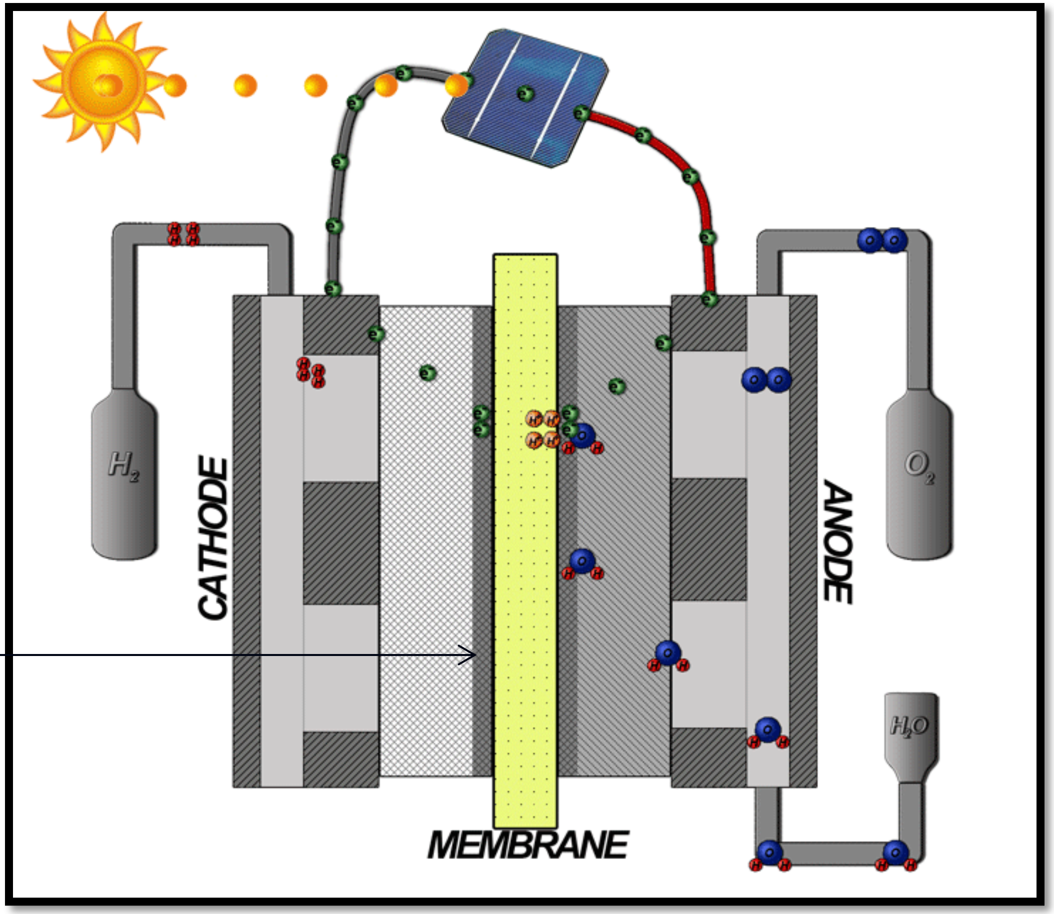
- Preliminary Feasibility analysis of PVEPS

- Analytical calculations
- Physical Experiments
- Preliminary propulsion system design

Schematic of PVEPS



PEM Electrolyzer

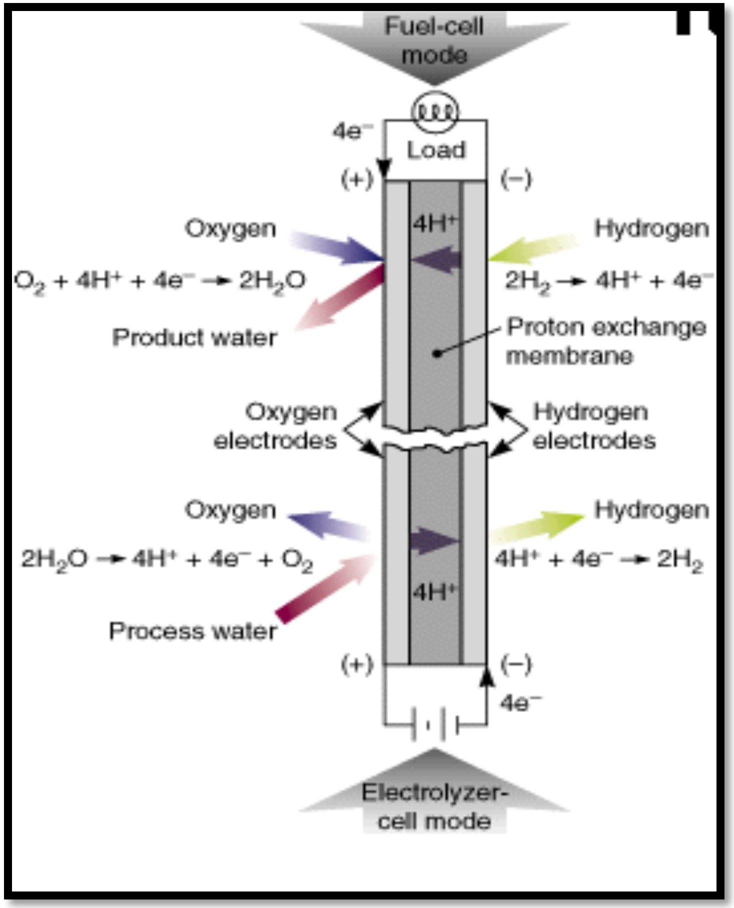


Platinum
Catalyst

Fritz, David L. *PEM Electrolyser.* Digital image. Web

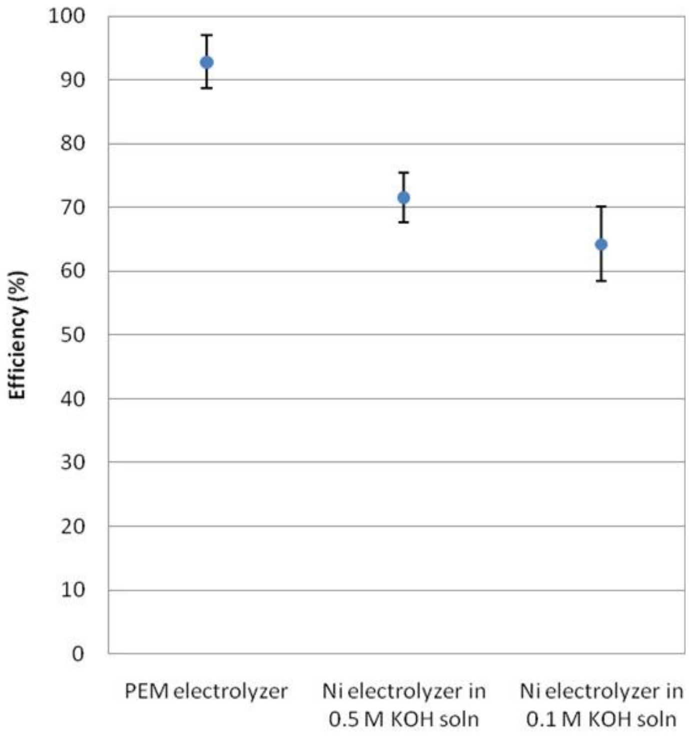
Previous Research

- Water Rocket (Militksy , Weisberg et al., 1999)
  - Zero ‘g’ Electrolyzer
  - 50, 100, 200W Variants
  - Flexible H_2 thrusters
  - Use of Unitized Regenerative Fuel Cell (URFC)



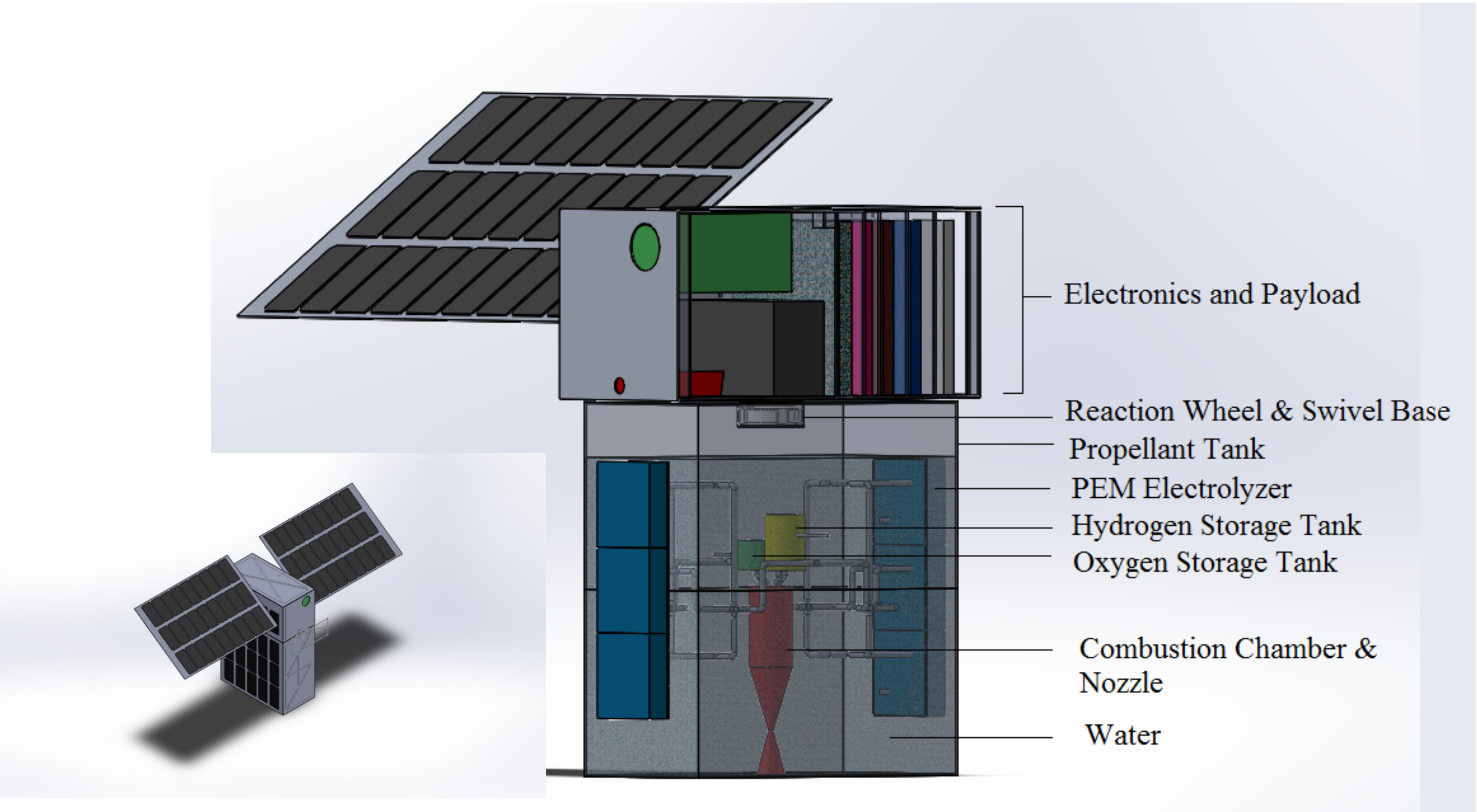
Previous Research

- Electrolysis Propulsion for 3U CubeSat (Peck and Zeledon, 2011)
  - Orbit raising
  - Experiments on various electrolyzers
  - Separation of gas from water

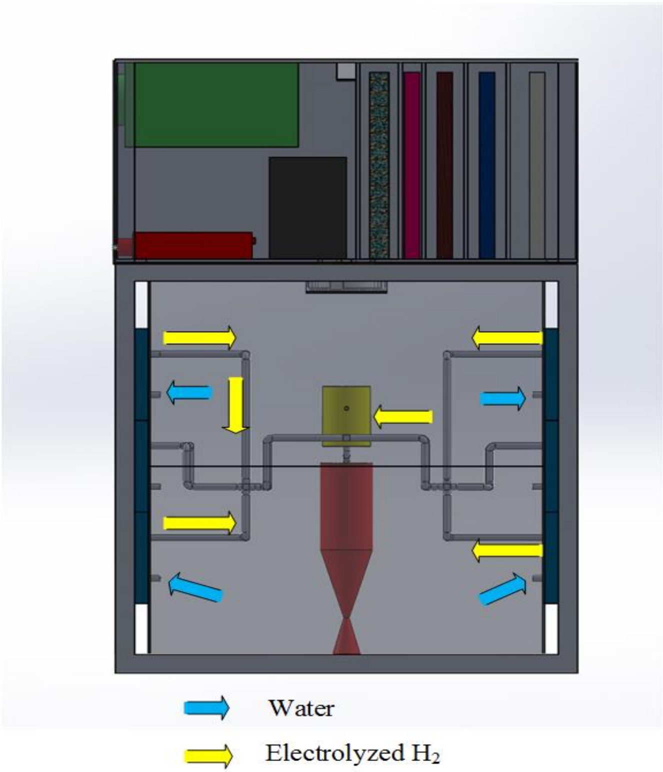


<u>Efficiency Comparison</u>

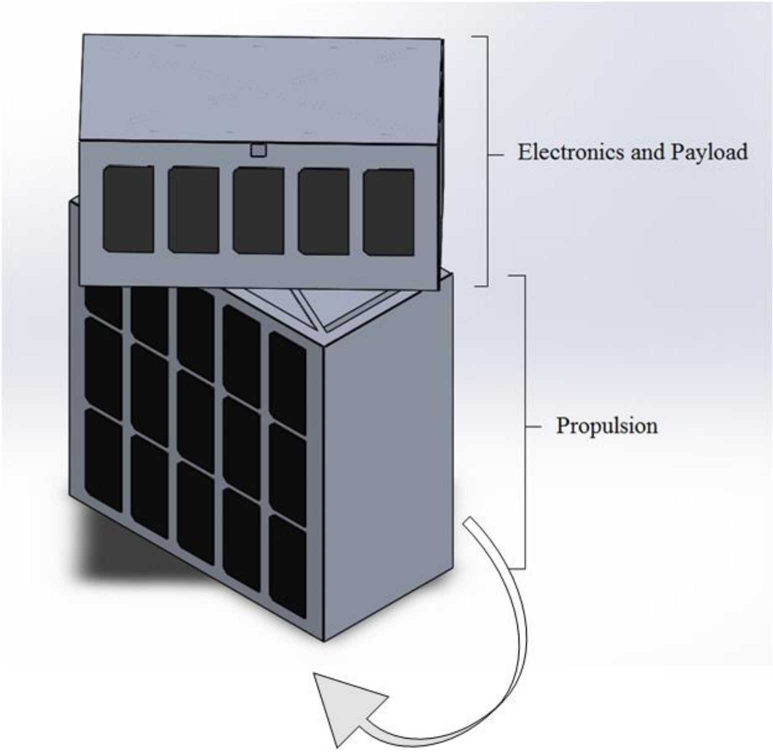
System Concept



System Operation



Side View of PVEPS



Lower segment rotates to separate water from reactants

System Performance

- For short pulses

  $I_{sp} = 360s$

- For a 6U CubeSat
  - Total Mass – 14 kg
  - Dry Mass – 4.5 kg
  - $\Delta V = 4000$ m/s

To	Required ΔV
Low Lunar Orbit	4040 m/s
EML – 1	3770 m/s
EML - 2	3430 m/s

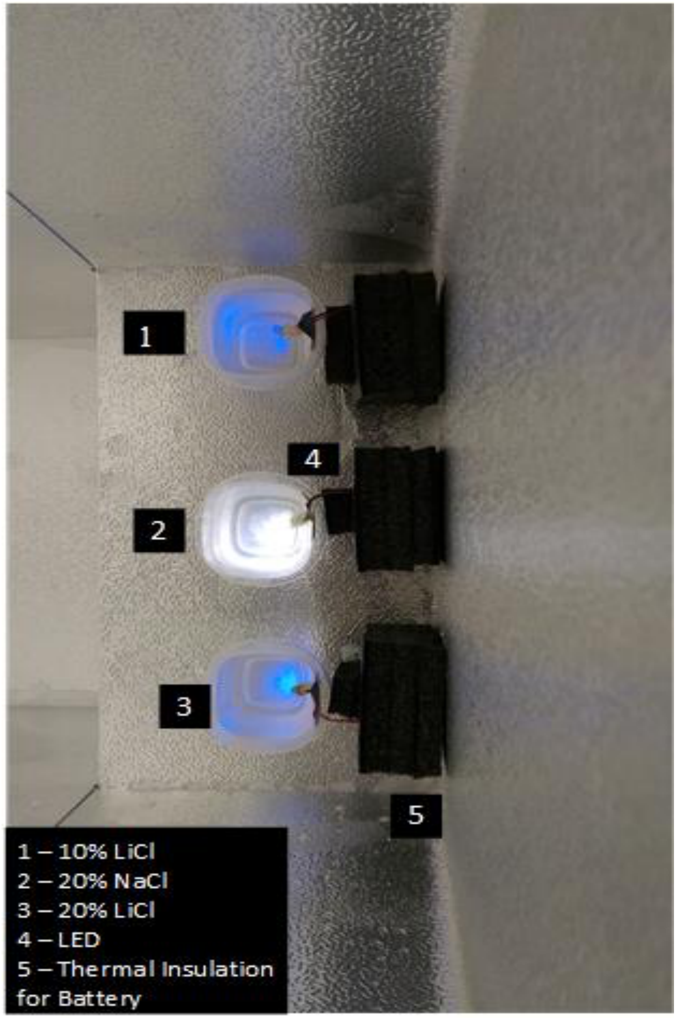
Sutton, George P., and Oscar Biblarz. "Thrust Chambers." Rocket Propulsion Elements. 8th ed. Wiley. 301-305. Print.

Thermal Requirements for 6U CubeSat in LEO

Condition	Tank Temperature (K)	Heat Energy Required(J)
One Side Illuminated	260	25
Three Sides Illuminated	290	1
Three Sides Illuminated, Albedo and Infrared	320	-18
Eclipse	170	80

Freezing Point Depression

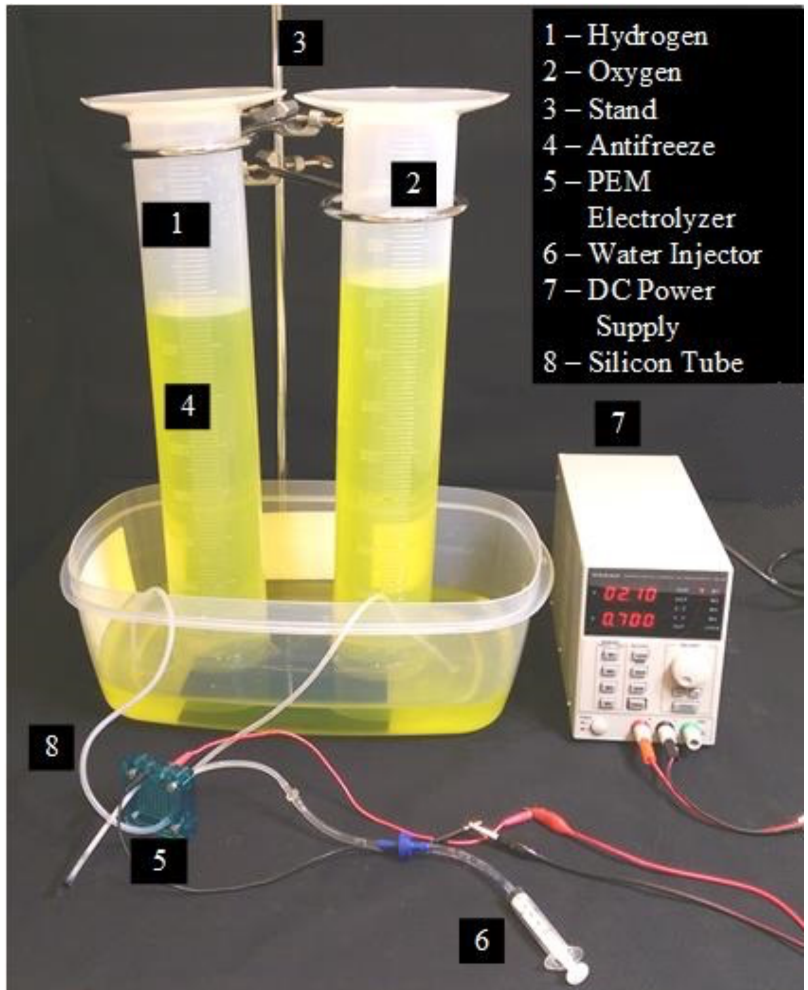
- Electrolytes Chosen (Meewisse and Ferreira, 2001)
  - 10% LiCl Solution
  - 20% LiCl Solution
  - 20% NaCl Solution



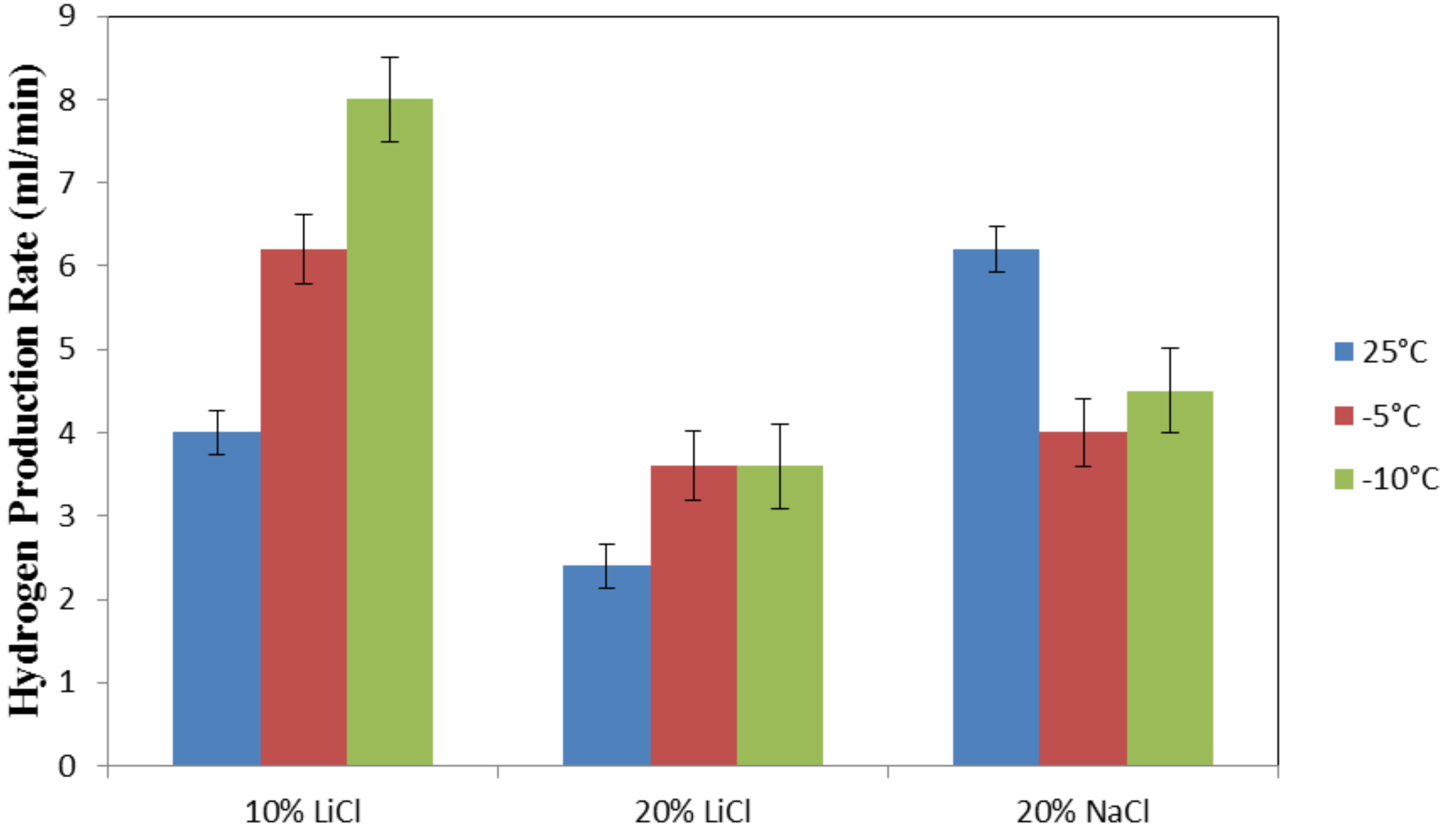
List of Experiment

- Hydrogen Production Rate for PEM Electrolyzer
  - Distilled Water at STP
  - 10% LiCl, STP, -5°C and -10°C
  - 20% LiCl, STP, -5°C and -10°C
  - 20% NaCl, STP, -5°C and -10°C

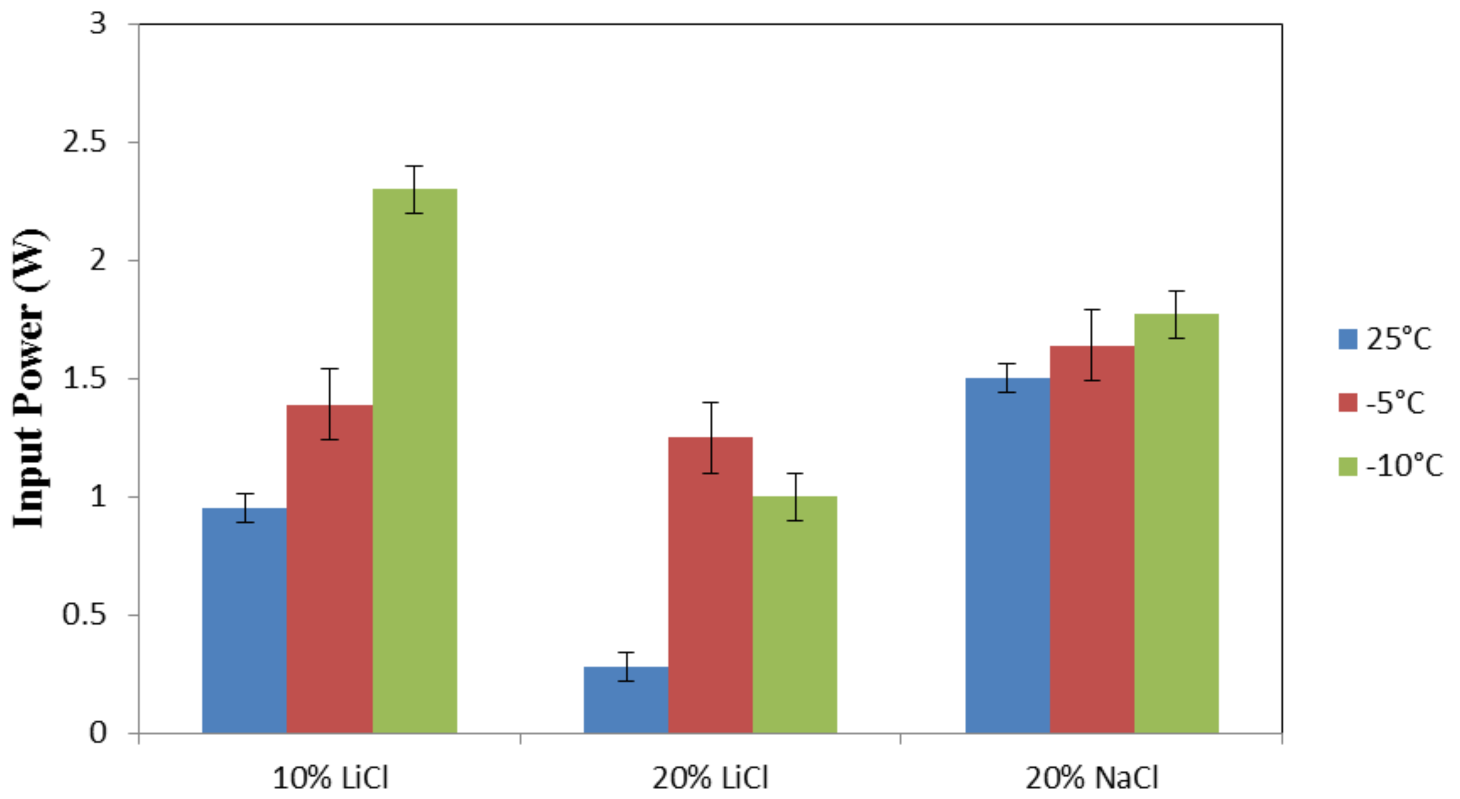
Experimental Setup



Results – Maximum Hydrogen Output



Results – Input Power For Peak Performance



Summary

System	ΔV (m/s)	Thrust (N)	Thermal Insulation	Safety	Restrictions
PVEPS (H_2O)	4000	8.5	Void	Separation of H_2 &O_2.	Propellant Mass
Zeldon & Peck (H_2O)	850	5	Needed	H_2 and O_2 stored as Mixture	Earth's gravity well
AeroJet RocketDyne (Hydrazine)	550	4	Needed	Highly toxic propellant	Operating Temperature
Cold Gas Thruster (N_2)	20	1.5	Needed	Inert Propellant	Pressure dependent

Conclusion

- Electrolysis Propulsion offers highest ΔV compared to current commercial systems for CubeSats.
- PVEPS offers increased operational flexibility due to its design.
- Freezing point depression requires much less power than thermal insulation.
- In scenarios of extreme cold temperature, freezing point depression will remain the only viable solution.

Future Work

- Thrust Chamber Evaluation
- PEM Electrolyzer Evaluation at lower temperatures to the tune of -200°C
- Additive Materials Evaluation to decrease rate of corrosion on electrodes.

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Questions …. !?

Specific Impulse

- For a control volume in case of Rocket Motor

$$\frac{\dot{Q} - \dot{W}_e}{\dot{m}} = \left(h_e + \frac{{V_j}^2}{2} + gz_e\right) - \left(h_c + \frac{{V_c}^2}{2} + gz_c\right) \quad (1)$$

$$\frac{{V_j}^2}{2} = h_c - he \quad (2)$$

- For short pulses, estimated Isp :

$$361.66 < I_{sp} < 424.35$$

Sutton, George P., and Oscar Biblarz. "Thrust Chambers." Rocket Propulsion Elements. 8th ed. Wiley. 301-305. Print.

Nozzle Design Analysis

$$P_t = P_c \left(1 + \frac{k-1}{2}\right)^{\frac{-k}{k-1}} \quad (4)$$

$$T_t = \frac{T_c}{\left(1 + \frac{k-1}{2}\right)} \quad (5)$$

$$A_t = \frac{q}{P_t}\sqrt{\frac{R \times T_t}{M \times k}} \quad (6)$$

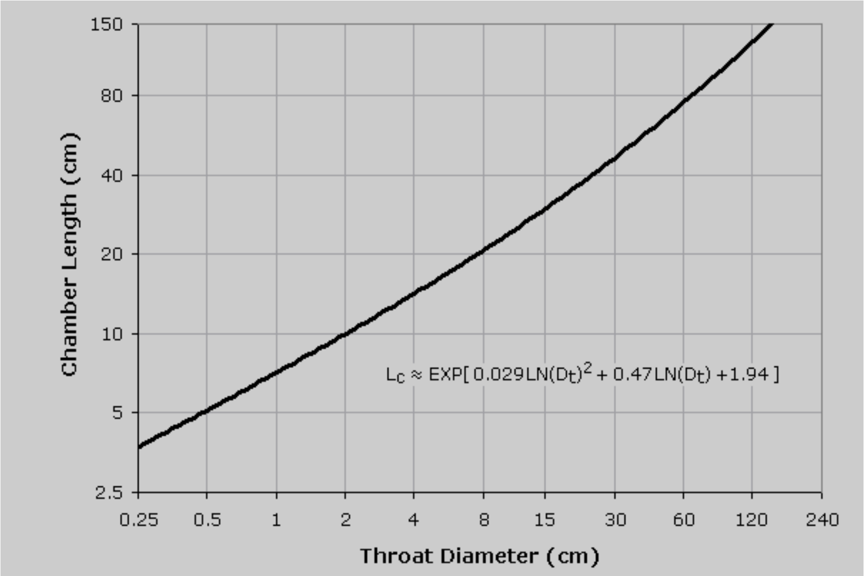
Calculations	
Mass Flow Rate (g/s)	1
Specific Heat Ratio	1.32
Chamber Pressure (N/m^2)	6×10^5
Nozzle Throat Pressure (N/m^2)	3.2×10^5
Chamber Temperature (K)	1300
Nozzle Throat Temperature (K)	1120
Nozzle Throat Area (m^2)	1.9×10^{-6}
Nozzle Throat Diameter (mm)	0.78

Braeunig, Robert A. "Rocket Propulsion." Rocket and Space Technology. 1 Jan. 2012. Web. <http://www.braeunig.us/space/propuls.htm>.

Combustion Chamber Design Analysis

$$L^* = \frac{V_c}{A_t} \quad (7)$$

$$V_c = A_1 L_1 + A_1 L_c \left(1 + \sqrt{A_t/A_1} + A_t/A_1\right) \quad (8)$$



Calculations	
Volume of Chamber (kg/m^3)	4.5×10^{-5}
Diameter of Cylindrical Chamber (cm)	2.5
Area of Cylindrical Chamber (m^2)	4.9×10^{-4}
Length of Cylindrical Chamber (m)	0.05
Nozzle Throat Diameter (mm)	0.78
Nozzle Throat Area (m^2)	4.8×10^{-7}
Length of Converging Cone Frustum (m)	0.041

Braeunig, Robert A. "Rocket Propulsion." Rocket and Space Technology. 1 Jan. 2012. Web. <http://www.braeunig.us/space/propuls.htm>.

Mass And Volume Budget

Component	Mass (kg)
Propellant	9. 5
PEM Electrolyzer(6 Units)	0.2
Structure	2
Payload and Electronics	2

Component	Volume (kg/m^3)
Propellant Tank	7×10^{-3}
Thrust Chamber	4.5×10^{-5}
PEM Electrolyzer	2.5×10^{-5}
Payload and Electronics	3×10^{-3}

Energy Comparison

- Energy required to electrolyze 1g of water = 13.5 J
- Energy required to keep water in liquid state for 6U at LEO = 80 J
- Heat Energy Released = 1.5 J
- Heat transferred by thrust chamber = 6 J
  - Ablative Material (k) = 0.5 W /m-K

Spin Rate Calculation

- Choice of Spin Rate decided by Bond Number

$$B_o = \frac{\Delta\rho\ a\ L^2}{\sigma}$$

- Minimum Spacecraft Spin

$$\omega = \left(\frac{B_o\,\sigma}{\Delta\rho\ r\ L^2}\right)^{\frac{1}{2}}$$

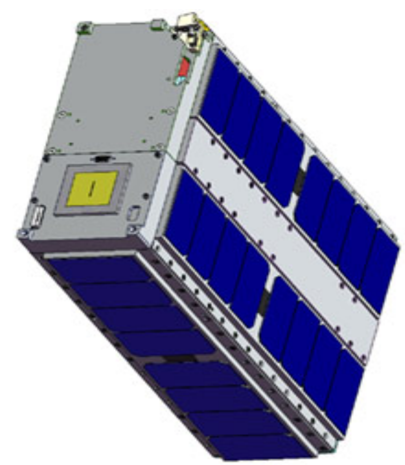
- $\omega = 1.3$ rad/s

Introduction

- **What is a CubeSat ?**

- **Spacecraft**
- **Discrete but scalable**
- **1U – 1.33 kg**

  10cm × 10cm × 10cm



[1] Gunter, Derik. Cubesat. Digital image. Gunter's Space Page. 2008. Web.

Motivation

- Lower schedule and cost
- Advances in satellite development
- Low cost launch opportunities
- Reduced risk for primary payload
- Secondary payloads for interplanetary trajectories

Nozzle Design

Mass Flow Rate (g/s)	1
Specific Heat Ratio	1.32
Chamber Pressure (N/m^2)	6×10^5
Nozzle Throat Pressure (N/m^2)	3.2×10^5
Chamber Temperature (K)	1300
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Nozzle Throat Area (m^2)	1.9×10^{-6}
Nozzle Throat Diameter (mm)	0.78

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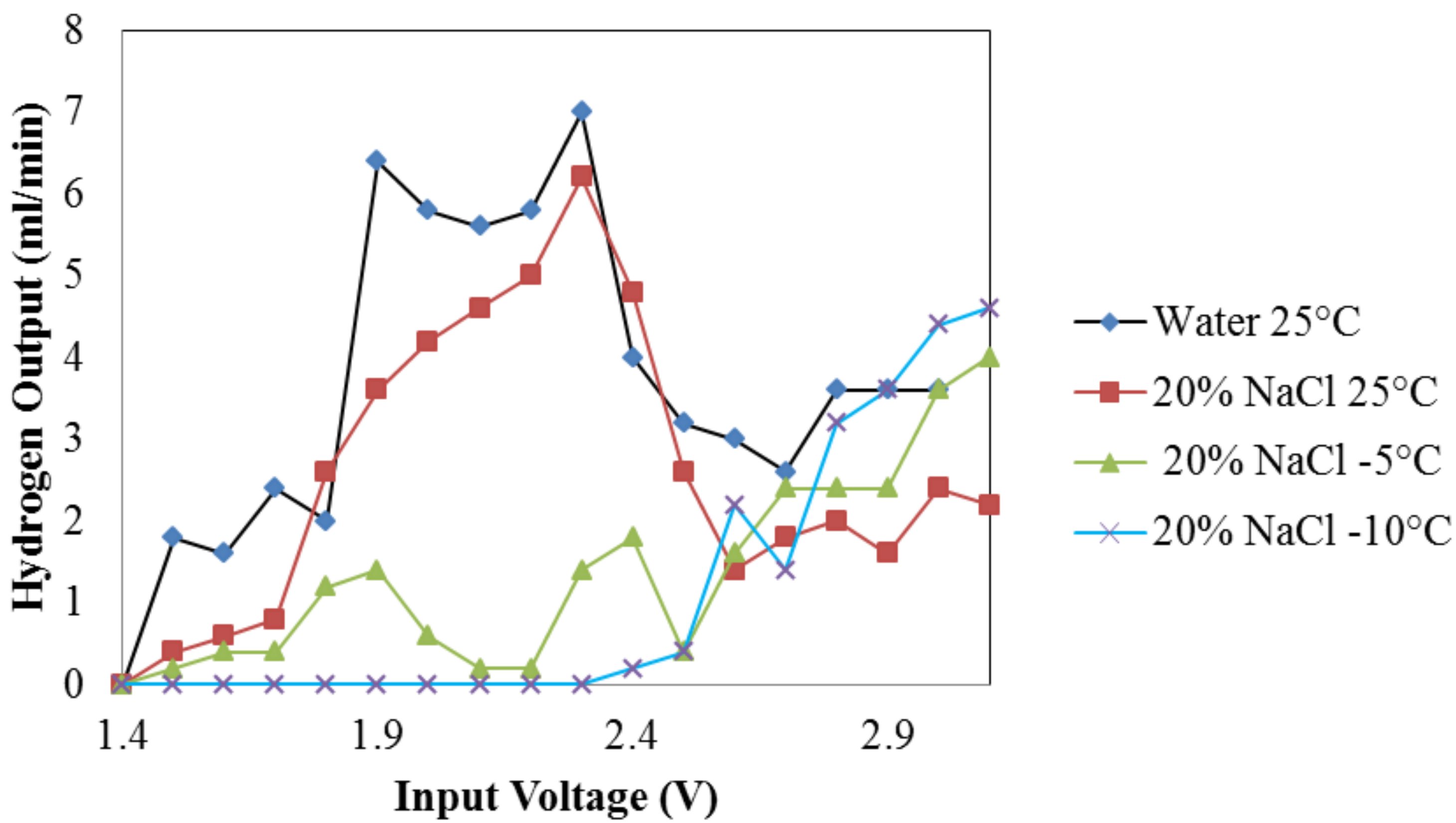
Combustion Chamber Design Analysis

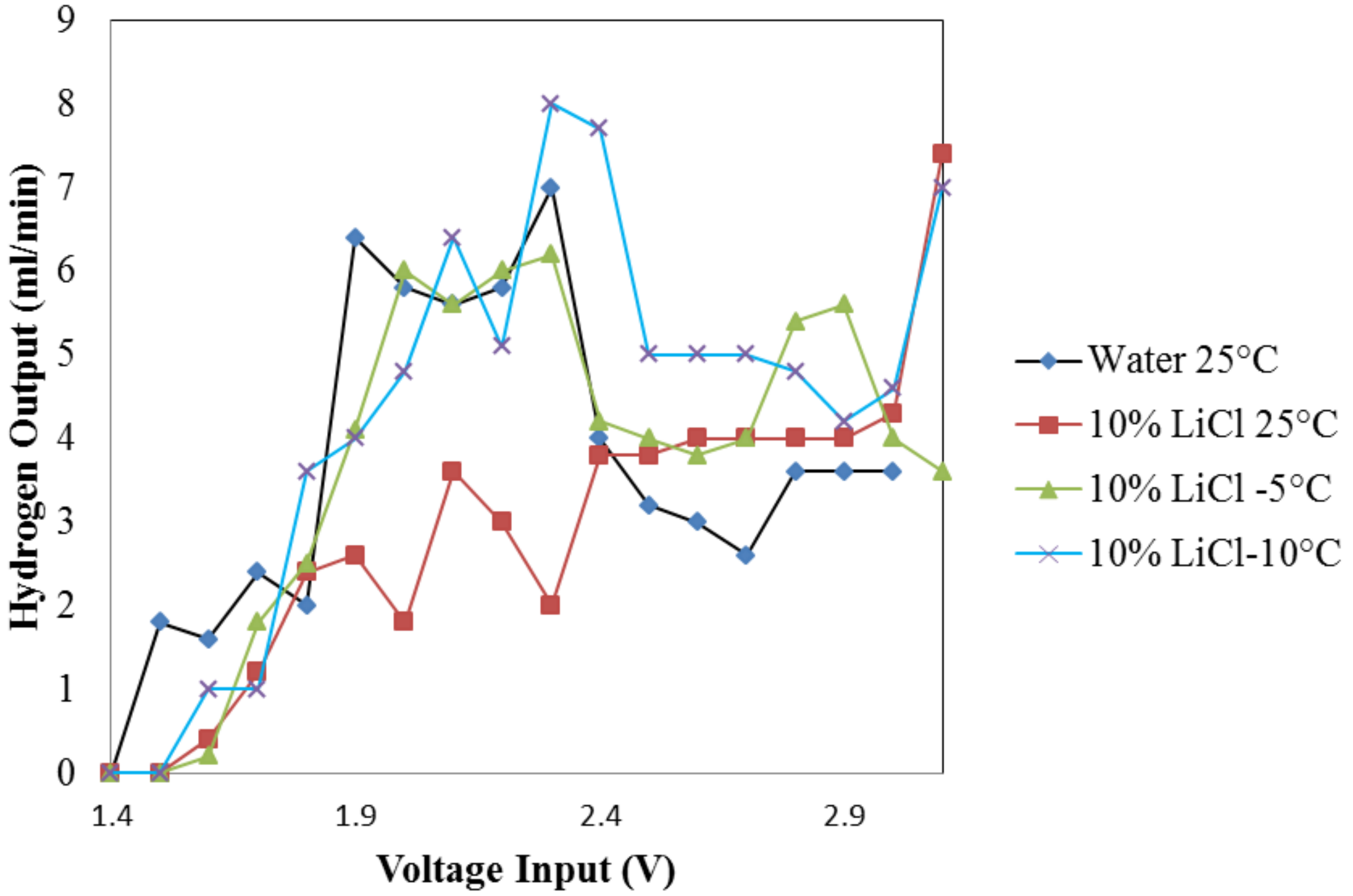
Volume of Chamber (kg/m^3)	4.5×10^{-5}
Diameter of Cylindrical Chamber (cm)	2.5
Area of Cylindrical Chamber (m^2)	4.9×10^{-4}
Length of Cylindrical Chamber (cm)	5
Length of Converging Cone Frustum (cm)	4.1

Braeunig, Robert A. "Rocket Propulsion." Rocket and Space Technology. 1 Jan. 2012. Web. <http://www.braeunig.us/space/propuls.htm>.

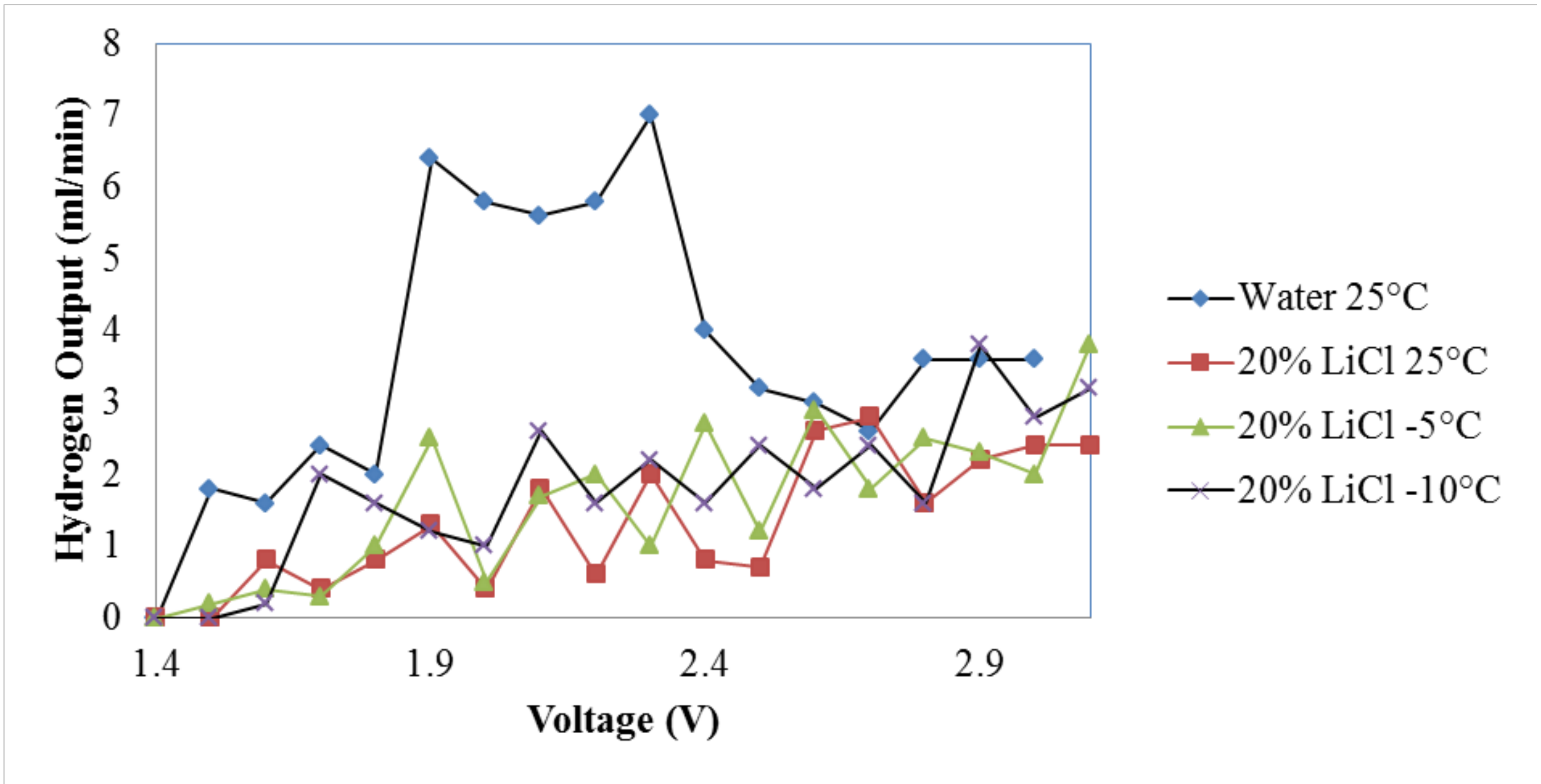
Results – 20% NaCl Solution



Results – 10% LiCl Solution



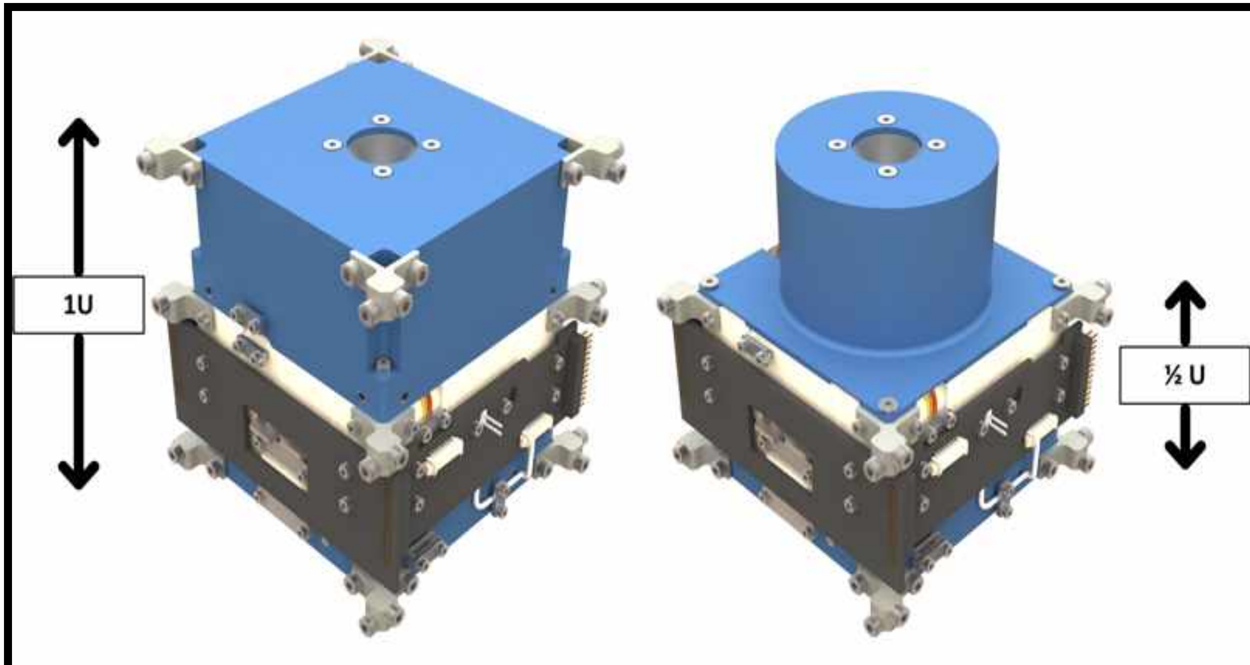
Results – 20% LiCl Solution



Contributions

- Showed electrolysis can be performed below 0 °C using LiCl and NaCl brine solutions.
  - Tradeoffs in propulsive performance and thermal mgmt
- Came up with a design of an electrolysis propulsion system for current state of the art 6U CubeSat
- Proposed electrolysis propulsion offers 5-8 fold advantage over current methods
  - Enabling technology
    - Moon Orbiter mission from low earth orbit.
    - Mars Orbiter mission from an earth escape trajectory

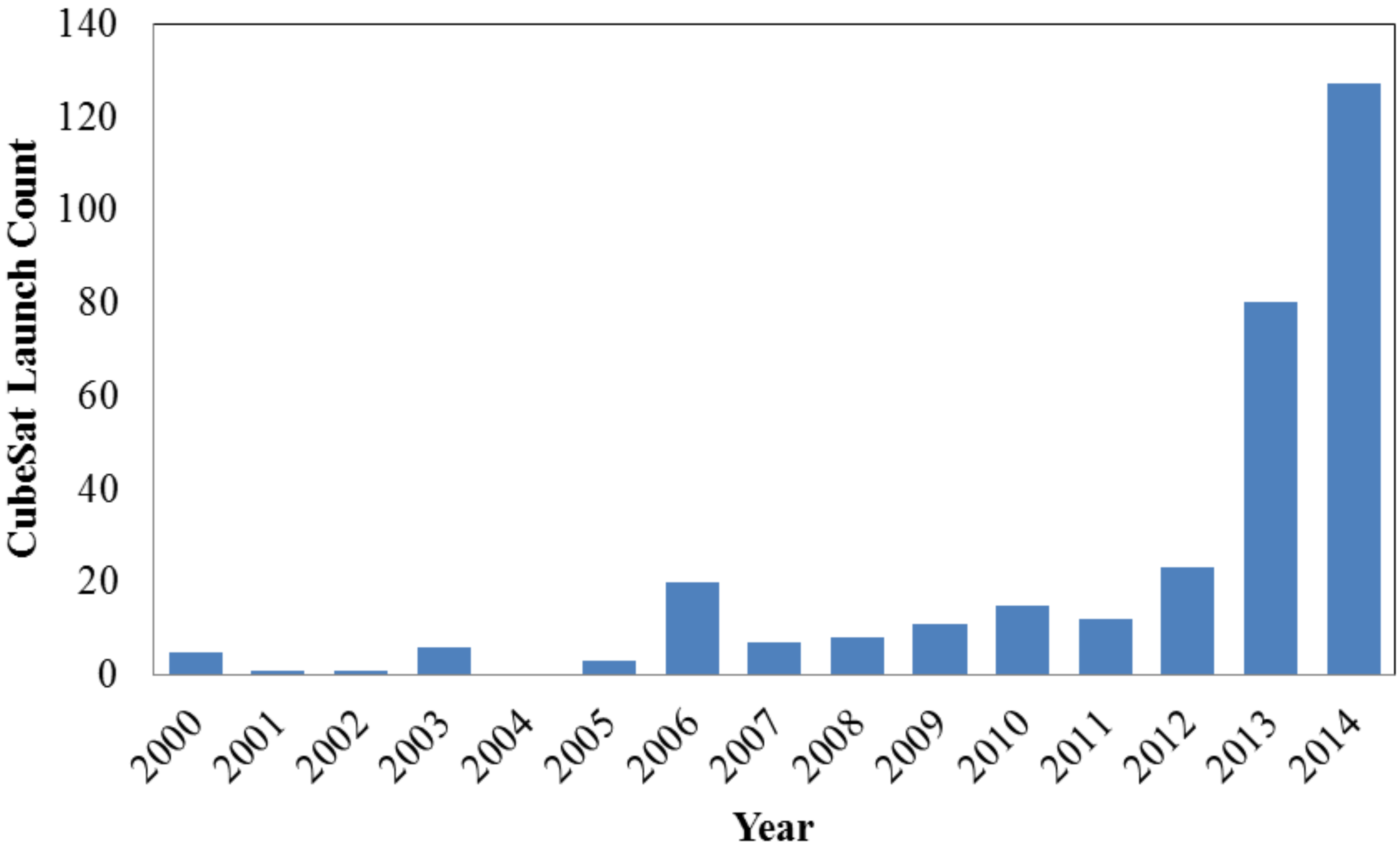
Previous Research



- 0.8N Thrust
- 300s I_{sp}
- Attitude Control Module Included

Hydros – Tether's Unlimited Inc.

Motivation



CubeSat Launch Count
140
120
100
80
60
40
20
0
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
Year