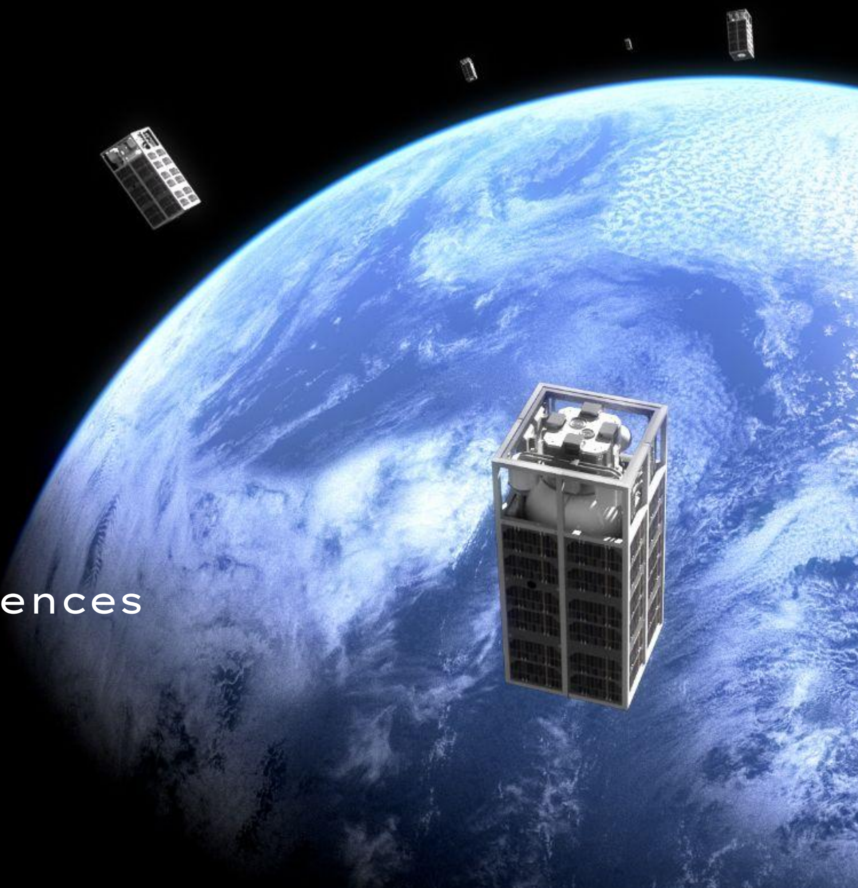
GAS STATIONS IN SPACE™

Planetary and Terrestrial Mining Sciences Symposium
6/10/2021



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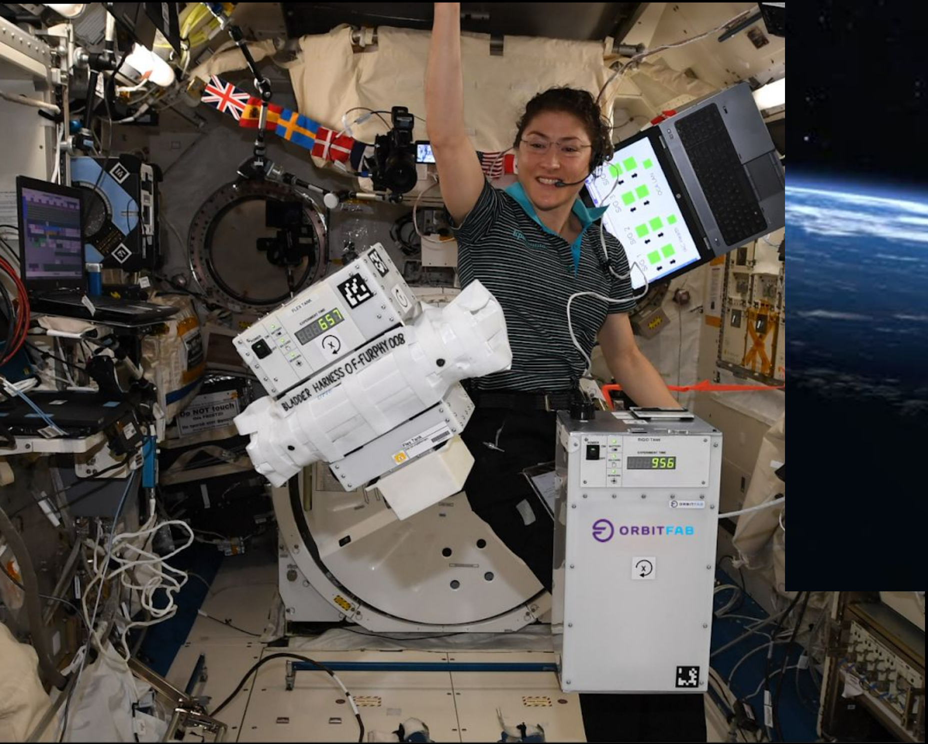
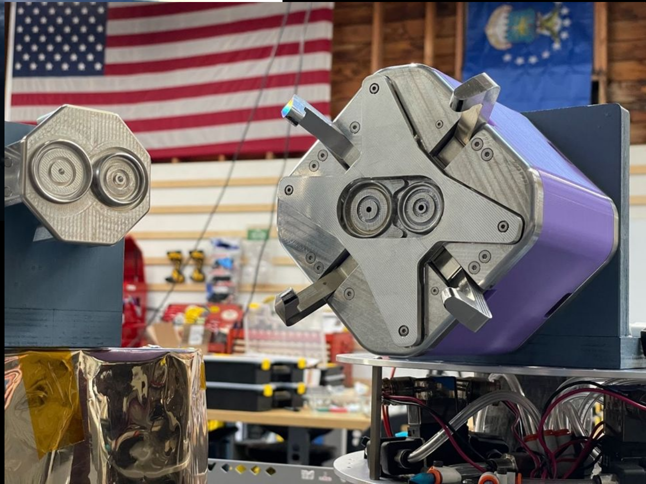
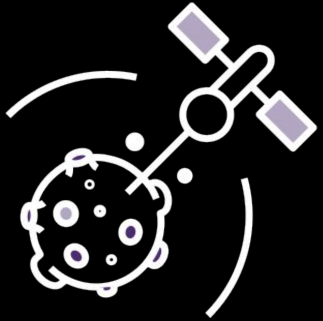


First commercial water refueling of the ISS

Tanker-001 Tenzing
launching late June 2021



RAFTI:
Rapidly Attachable Fluid
Transfer Interface



High-Test Peroxide Production System for In-Situ Propellant Manufacture from Extraterrestrially Mined Water

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NASA’s Artemis Priorities

NASA's Plan for Sustained Lunar Exploration and Development (2020):

“ISRU will enable the production of fuel, water, and/or oxygen from local materials, enabling **sustainable surface operations with decreasing supply needs from Earth**.”

The Propellant Market

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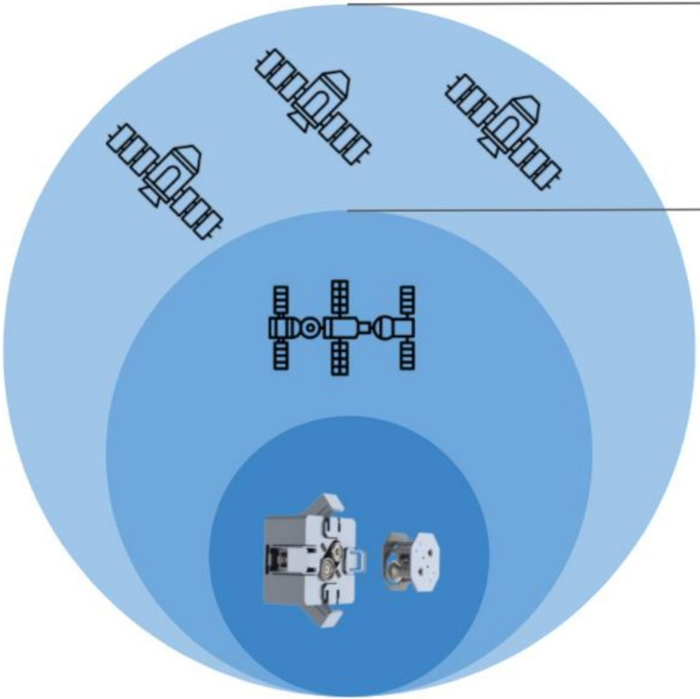

$3B Total Market

Total in-space value of all propellant launched to space last year

$1.5B Addressable Market

Total in-space value of all propellant launched on potentially refuelable satellites

The Challenge

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→ Off-Earth propellant production is critical to the long-term success of the bustling in-space economy.

→ But, there is no complete system that could be deployed today to produce and store propellant from mined extraterrestrial resources.

What is the most cost- and time-effective pathway to produce a useful propellant on the surface of the Moon?

Lunar Propellant

Figure: Kutter et al. 2008

Lunar ISRU resource availability:

- Ice may comprise up to ~30 wt% of lunar regolith in some areas. (Sanders 2018)
- Oxygen comprises up to 40 wt% of lunar regolith. (Sanders 2018)
- Nitrogen and carbon in lunar samples are present at ppm levels. (Sanders 2006)

In-Situ Propellant Options

Cryogenic:

- **Hydrolox:** can be produced from water alone. But, despite much funding, cryogens need more time before fluid management and storability technology is ready.

Chemical storable:

- **Hydrazine:** widely used but needs nitrogen (non–ISRU). Toxic.
- **High–test peroxide (HTP):** can be produced from water alone. Storable and nontoxic with enough specific impulse for lunar and small body ascent.

HTP is the only high-impulse storable monopropellant and oxidizer that can be created from lunar resources.

Photo by NASA

High-Test Peroxide for ISRU

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- **HTP can be stored, but is there a way to produce it in a compact form factor?**

Biggest hurdle: turn water into low-concentration hydrogen peroxide.

Peroxide Anthraquinone Process

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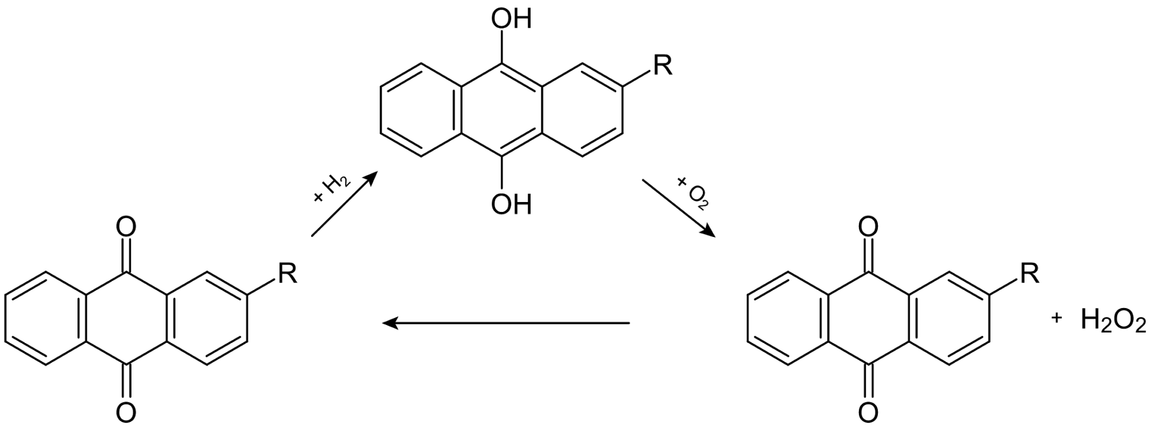


Most widely used process to produce hydrogen peroxide.

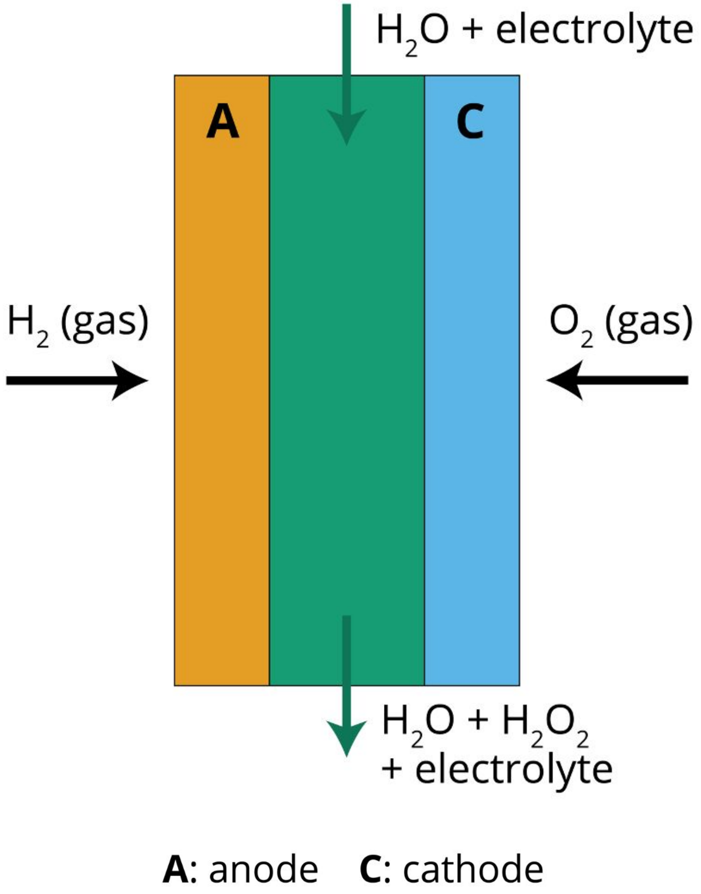
Drawbacks: wasteful, resource intensive, and challenging to scale for ISRU.

Peroxide: Electrosynthesis

Benefits

- Little to no waste.
- Less energy intensive.
- Scalable form factor.
- Not dependent on gravity to function.

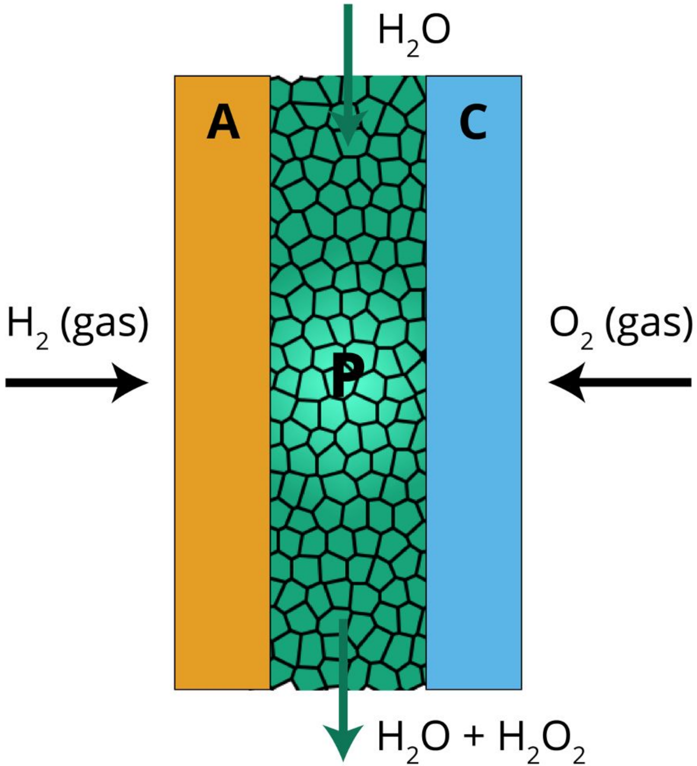
Drawback: step of electrolyte separation required.



Peroxide: Solid Electrolyte Electrosynthesis

Replace liquid electrolyte with a porous solid to get the **benefits of electrosynthesis without the intermediate step** of electrolyte separation.

Thus, water, oxygen, and hydrogen are turned directly into high-purity low-concentration hydrogen peroxide.



A: anode **C**: cathode
P: porous solid electrolyte

Peroxide: Solid Electrolyte Electrosynthesis

PEM cell reaction equations:

Anode hydrogen oxidation reaction:

$$H_2 \rightarrow 2H^+ + 2e^-$$

Cathode oxygen reduction reaction:

$$O_2 + H_2O + 2e^- \rightarrow HO_2^- + OH^-$$

Overall PEM cell reaction:

$$HO_2^- + H^+ \rightarrow H_2O_2$$

Peroxide: Solid Electrolyte Electrosynthesis

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- TRL 6 cell produces 130 L of 1% peroxide per hour per square meter of membrane.
- When coupled with a concentrator, only 0.69 m^2 area cell is needed to produce 1 L/hr of 90% HTP.
- Resulting PEM cell energy consumption is about 850 W.

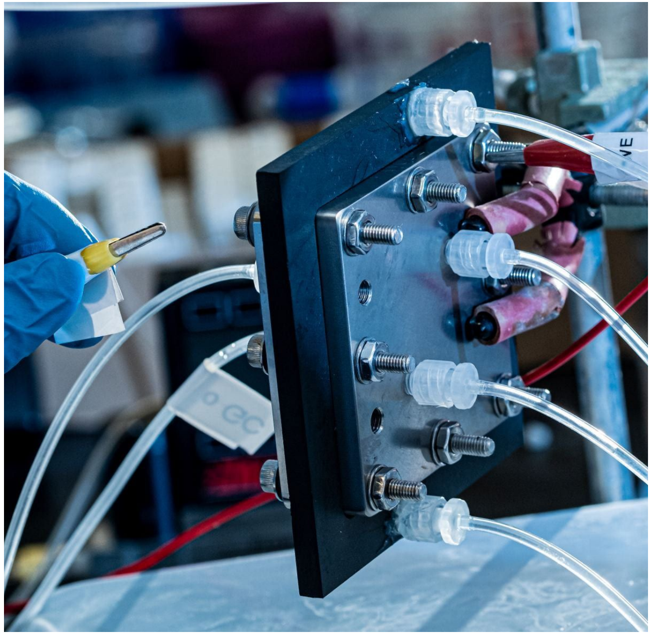

Figure: Haotian Wang

HTP Production System Architecture

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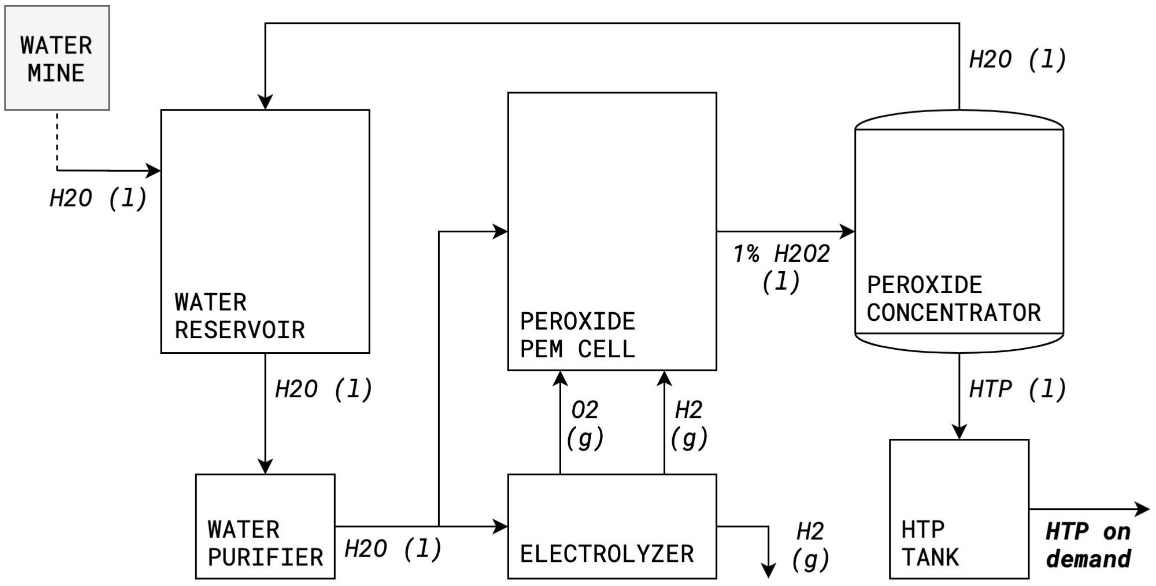
The **new solid electrolyte peroxide cell**, coupled with **mature concentration technology**, enables several architectures with inputs of:

1. hydrogen, oxygen, and water
2. oxygen and water
3. air and water
4. water

HTP Production System Architecture



Minimum Viable Product system weighing on the order of 100 kg will output liters per hour.

Conclusions

- A benchtop prototype could be built in a year's time.
- A system could be ready to fly in 2023 and deployed on the lunar surface soon after.
- Capital requirements for fully operational space production system: single digit millions.
- The HTP system will build operational expertise and enable rapid iteration for future propellant diversification.

References

NASA. NASA's Plan for Sustained Lunar Exploration and Development. 2020.

Kutter, Bernard, et al. "A Practical, Affordable Cryogenic Propellant Depot Based on ULA's Flight Experience." AIAA SPACE 2008 Conference & Exposition, American Institute of Aeronautics and Astronautics, 2008.

Sanders, Jerry, et al. NASA In-Situ Resource Utilization (ISRU) Research & Development. 2006

Sanders, Jerry. In-Situ Resource Utilization (ISRU) Planning and Update. NAC Technology, Innovation, and Engineering Committee Meeting. 2018

Xia, Chuan, et al. "Direct Electrosynthesis of Pure Aqueous H_2O_2 Solutions up to 20% by Weight Using a Solid Electrolyte." Science, vol. 366, no. 6462, Oct. 2019, pp. 226–31.