Exploring Venus with Electrolysis (EVE)

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What's so great about a balloon on Venus?

The rocky planets Earth, Mars, and Venus are as different as solar system siblings can be. Thriving, biodiverse, and geological active Earth stands in contrast to Mars, a largely dead relic of rapid evolution. But mysterious Venus ranges from a roiling cloud-veiled hellscape to a benign CO_2-dominated middle atmosphere at 50-60 km.

Compared to Mars, we know little about Venus and it has been largely ignored as a human destination. Yet **exploration of Venus from a balloon platform** promises to help us complete the puzzle of planetary evolution, extend the search for life, inform our understanding of climate change, teach us to recognize "exoVenuses," and perhaps let us feel the wind on our face as we "sky cruise" on another planet. As a bonus, the prevailing winds at 50-60 km carry a balloon around the planet every ~100 hrs, allowing robust exploration of the entire planet from a single platform.

In the near term, EVE offers a scientific platform-in-the-clouds to investigate both the surface of Venus (radar and IR imaging, seismology with infrasound), and the atmosphere (in situ dynamics, chemistry, biology). In the longer term, EVE may enable powered atmospheric flight, surface sample return, or floating cruise ships.

What is EVE?

EVE uses Solid Oxide Electrolysis, as demonstrated on Mars by MOXIE, to replenish buoyant gases in a Venus balloon and enable long-duration exploration. The initial helium is gradually replaced by CO and O_2 derived from the ambient CO_2. CO and O_2 also power the night-time traverse and potentially provide rocket propulsion.

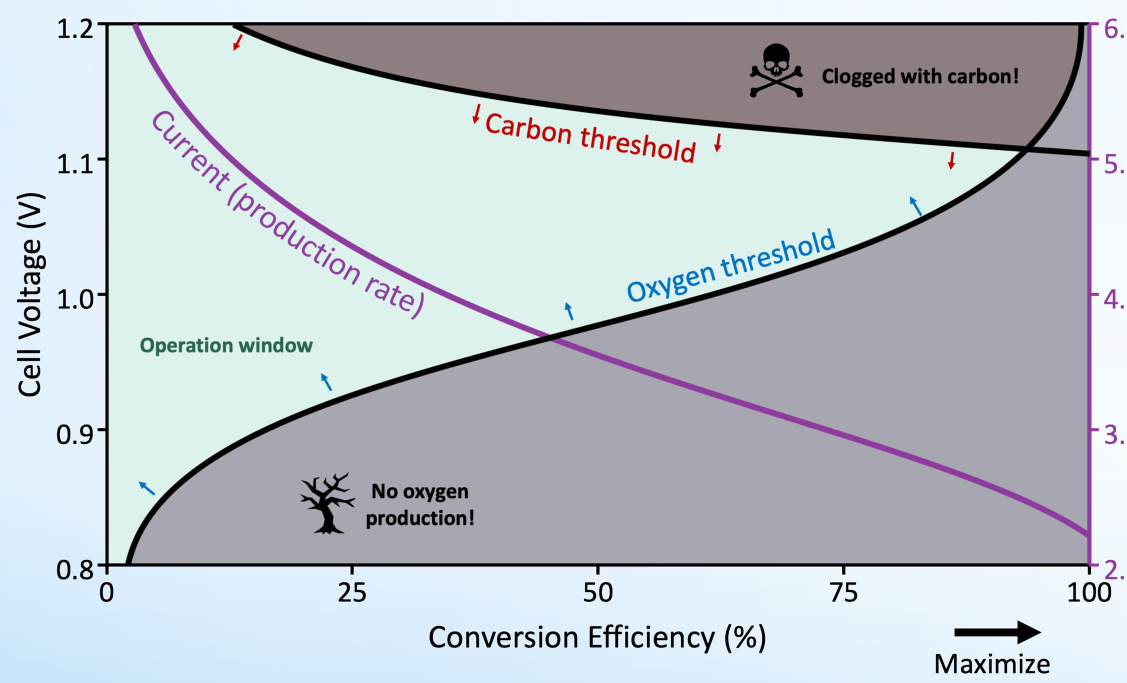
Open questions & challenges addressed in Phase 1:

- Can we make the CO, which is mixed with unreacted CO_2, pure enough?
- Can EVE survive SO_x exposure (~150 ppm)? Can the same system generate power in the night-side traverse using some of the gases produced on the day-side?
- Can we achieve 10-year balloon lifetime with reasonable resources? What is the best starting gas? Is there a role for plasma processing?

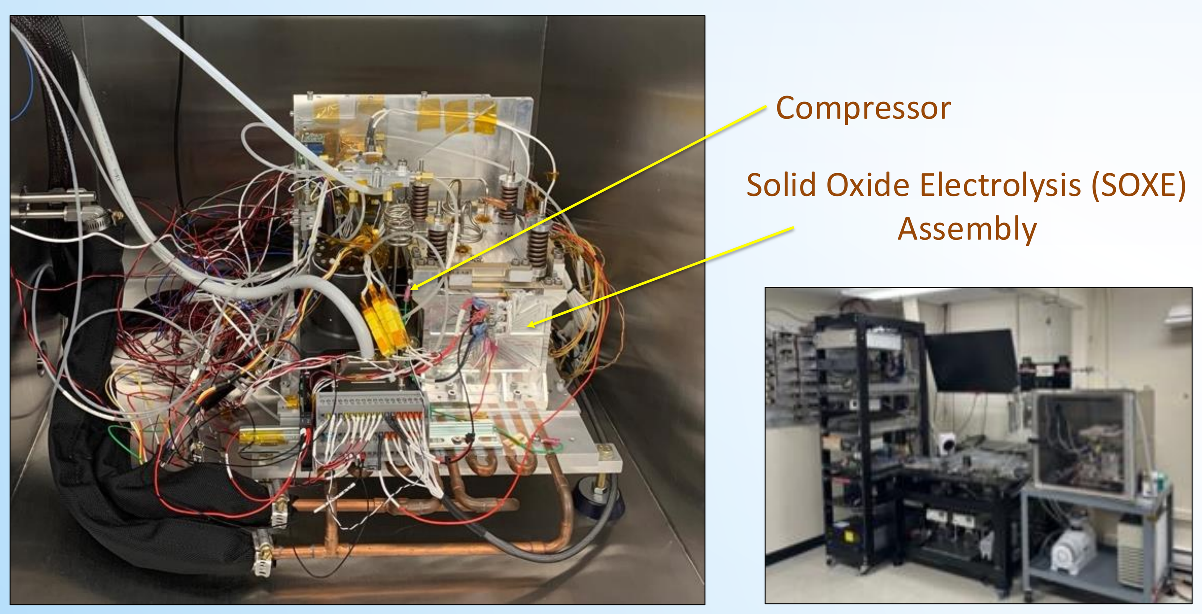
Demonstration mission

- Balloon Exploration of the Atmosphere of Venus with Electrolytic Replenishment (BEAVER) demonstrates longevity and achieves landmark science. It uses gases generated on the day-side traverse to provide electrical power on the night-side.
- Future missions might add mobility, powered flight, or surface sampling.

Task 1: Modeling of high conversion efficiency. Extending the MOXIE model to Venus has taught us how to safely produce concentrated CO as well as ultrapure O_2 and has shown us what new pressure, flow and voltage control capabilities are needed. The cost of high conversion efficiency is low production per unit cell area, so larger stacks will be needed.



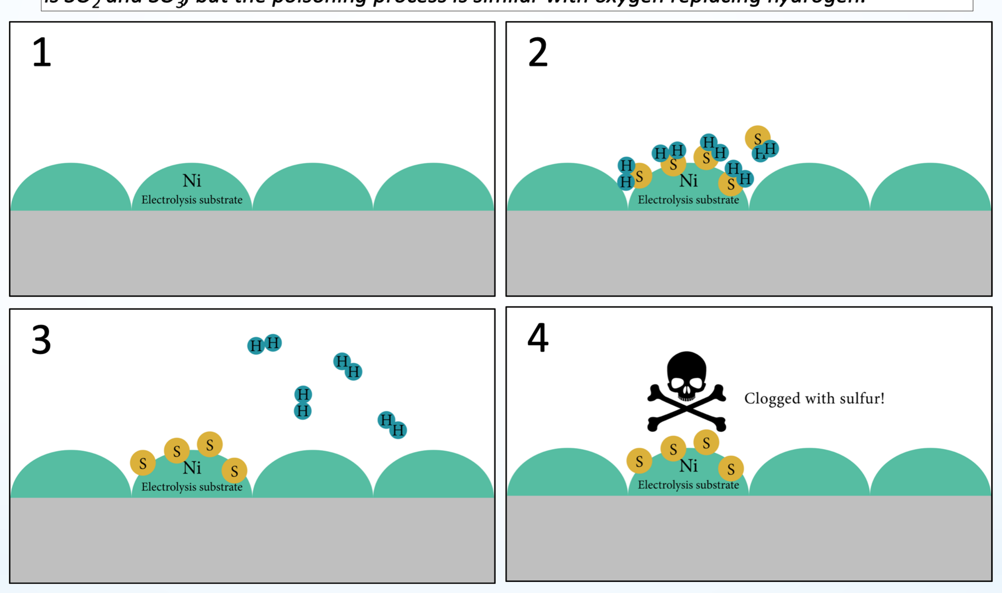
Task 2: High conversion efficiency demo. We have recommissioned the MOXIE "FlatSat" and added pressure regulation, flow control, and precise voltage control. This will allow us to validate the model, even though the output will be low. We have also demonstrated the ability to operate the cathode at a pressure below the ambient, which adds safety margin. The high efficiency test is planned for early September.



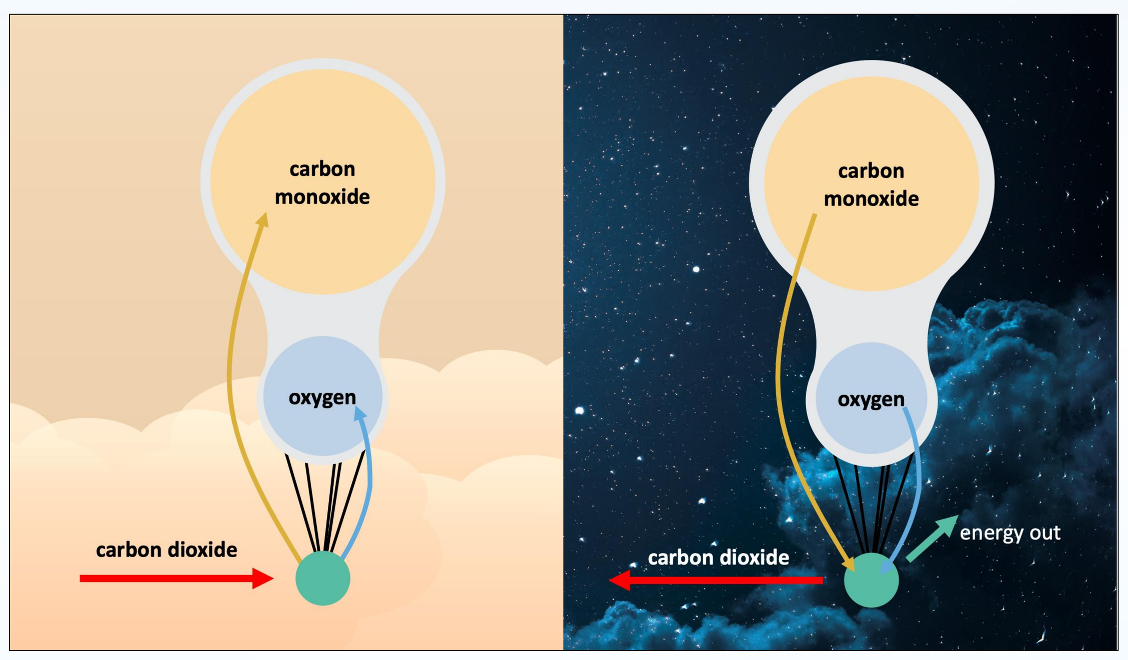
The MOXIE FlatSat at MIT Haystack Observatory

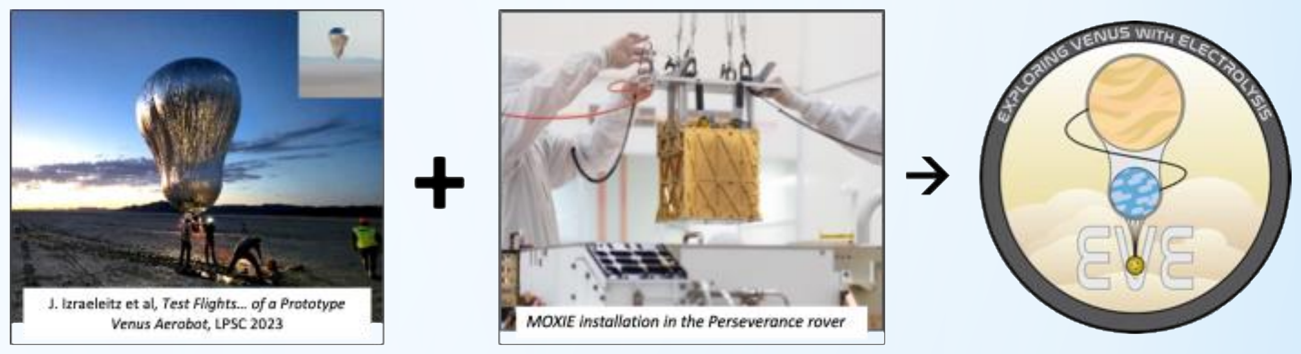
Task 3: Assessment of sulfur compound sensitivity. The Venus atmosphere is expected to have ~150 ppm SO_2, and up to 10 ppm SO_3 will be introduced as sulfuric acid aerosol is heated. Sulfur compounds are known to degrade certain electrolysis materials but it is not known if the MOXIE design is susceptible. Testing is underway at OxEon Energy with small "button cells" that use the same materials as the MOXIE stacks, as well as a set with a novel surface composition.

Sequence below is for hydrogen sulfide, which was tested on other programs. The Venus risk is SO_2 and SO_3, but the poisoning process is similar with oxygen replacing hydrogen.



Task 4: Demonstration of reversible SOE/SOFC. The prevailing Venus winds will carry a balloon around the planet in about 4 Earth days. To continue operation during the night side transit, EVE will operate as a *fuel cell*, consuming some of the gases produced on the day side to produce electrical power. This capability will also be demonstrated with button cells at OxEon Energy.



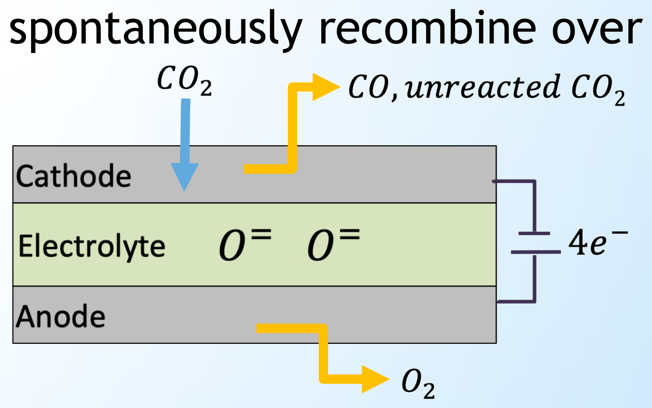


Task 5: System optimization. EVE merges JPL's existing Venus balloon mission designs and MOXIE-derived technology to create an entirely new system concept. Optimization studies are addressing questions such as what the starting gases should be, what the MVP implications of different mission lifetimes are, and the relative merit of using fuel cell technology. In the chart below:

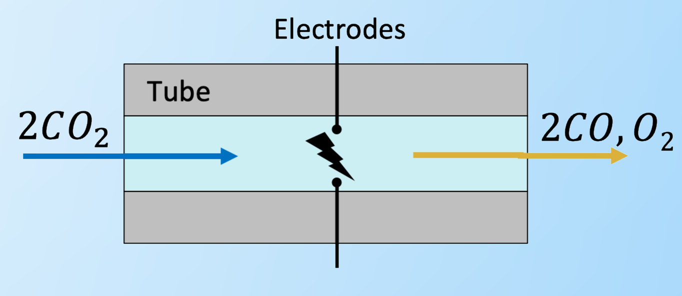
- All architectures deploy 10kg science payload at 54km altitude and provide 10W power
- Starting overpressure is 2x factor-of-safety to bursting
- End-of-mission with replenishment occurs when balloon drops below 50 km altitude

Architecture	Mass (kg)	Power (W)	Life (years)
Helium balloon Tanks only	123	25	0.21
EVE balloon Forward $2CO_2 \rightarrow 2CO + O_2$ for lift	261	181	1.96
EVE balloon with power Reversable $2CO_2 \leftrightarrow 2CO + O_2$ for lift and power	429	150	10.00

Task 6: Technology trades. For Phase I we focus on solid oxide electrolysis technology, as used in MOXIE, vs plasma technology. Plasmas have an advantage of long life and tolerance to being frequently turned on and off, but the disadvantage that the products stay mixed and spontaneously recombine over time.



SOE Reactor (MOXIE)



Plasma Reactor