Exploring Venus with Electrolysis: Atmospheric ISRU for Long Duration Aerial Missions

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Introduction: Earth, Venus, and Mars are similar planets that have followed radically different evolutionary paths. Earth is rich and complex, but the dynamic nature of its surface frustrates attempts to look deep into its past. With its relatively clear skies and traversable surface, Mars is an open, if static book that has preserved its early history over much of its surface. Venus has a rich and dynamic surface and atmosphere, but thick clouds limit our view of the surface to narrow bands in the long wavelength end of the electromagnetic spectrum, and hostile surface conditions (90 bar, 465˚C) restrict the lifetime of a lander to a few hours.

Above the Venus clouds, however, some 50-70 km above the hellish surface, are found mild temperatures, Earth-like atmospheric pressure, and super-rotating winds [1] that allow a floating platform to survey the entire planet that circle the planet every ~100 hrs, compared to the planetary rotation period of 5,832 hours. Building on technology from the Mars Oxygen ISRU Experiment (MOXIE) [2,3], EVE enables such a long-lived floating platform, in turn enabling *in situ* studies of the dynamic atmosphere and surface seismicity (*via* infrasound waves) and providing an operational base from which to dispatch probes of the lower atmosphere or sorties to sample surface materials.

The use of short-lived buoyant vehicles in the Venus atmosphere is not new, having been demonstrated by Russia's Vega mission in 1986, and conventional balloons are currently on the threshold of adoption by NASA by virtue of recent development programs [4]. These modern ballooning concepts offer the promise of somewhat longer life, up to a few hundred days, but eventually fall victim to helium leakage by diffusion and through pinholes [5,6]. On Earth, for example, CNES has been flying 13-m balloons with a design lifetime of 3 months [7]. In comparison EVE platforms will have virtually unlimited lifetime, as well as power reserves to operate on both the day and night side of the planet and the ability to generate propellant for mobility and for independent probes to harsher environments.

EVE achieves robust and long-lived operations with a deceptively simple concept: Using electrolysis to split the molecules of CO_2 that make up 97% of the atmosphere into lighter-weight CO and O_2 molecules that replace lost buoyancy gases and also serve as feedstock for fuel cells, reducing dependence on batteries for night-side operation (Figure 1).

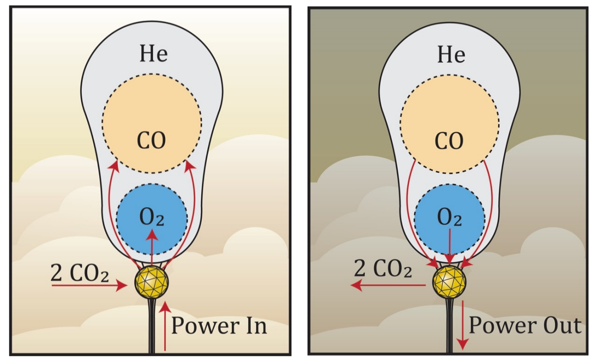

Figure 1. This conceptual design for EVE uses 3 bladders; one for O_2, a second (2x as big) for CO, and one for helium. Electrolysis of the CO_2 atmosphere of Venus provides lifting gas during the day (left), and ~10% of the produced gas is utilized for power generation during the night (right).

Adapting MOXIE to Venus: The enabling technology for EVE is solid oxide electrolysis (SOE) using the reaction $2CO_2 \rightarrow 2CO+O_2$, converting two moles of CO_2 into two moles of CO and one of O_2. While MOXIE emphasized O_2 production, EVE will utilize *both* the CO and O_2 products for buoyancy, directing the CO/CO_2 mix and the O_2 either into flexible bladders internal to the balloon or into storage vessels for later use.

MOXIE takes in martian atmosphere through a dust-trapping HEPA filter, compresses the atmosphere with a scroll pump, heats it to 800˚C, and sends it through the SOE assembly where CO_2 flows over a nickel-based cathode and decomposes into O^{2-} and CO. The anode releases pure O_2 while the cathode exhaust is a mixture of CO_2, CO, and inert atmospheric gases. The molar ratio of CO flow (f_{CO}) to the sum of (f_{CO} + f_{CO2}) in the cathode outlet is termed the utilization fraction (UF).

Since the cathode stream represents a waste product for MOXIE, it typically operated at UF ~30% in order to optimize O_2 production without poisoning the cathode with carbon (coking). For the EVE cathode exhaust stream to achieve sufficient buoyancy without costly and complex separation of the CO and CO_2 will require increasing UF to ~75%. Models show this is feasible with increased cell area and low driving current density. In that mixture both the O_2 and the combined CO/CO_2 gas streams would have a mean molecular weight of 32, compared to 44 for the CO_2-dominated ambient, and hence provide the same buoyancy (though less than the initial helium with molecular weight 4).

MOXIE as implemented for Perseverance could reliably produce 10 g/hr O_2, which, at 75% UF, is accompanied by 26.7 g/hr of the CO_2/CO mixture emitted from the cathode, for a total of 36.7 g CO_2 processed into 36.7 g of buoyant gases or a diurnal average of 18.4 g/hr at 50% duty cycle.

Mission concept: Complete replacement of the initial He, which occurs in ~4 Earth years, causes the 12-m balloon in our point design to descend 8.7 km from an initial altitude of 62 km to a final altitude of 53.3 km. The minimum balloon size is constrained by the need to stay above the base of the cloud layer, ~48 km, below which the atmospheric temperature rises precipitously beyond 100˚C, while retaining a reasonable payload mass capacity.

Estimating the leakage as <3% of the inflation gas in 1000 hrs requires the SOE to process an average of 24.4 g/hr of CO_2 for replenishment. A nominal diurnal average of 55 g/hr gas production at 75% UF allows 10% overage for regeneration (see below) and a factor of 2 overall margin. Eventually, the initial 30.5 kg of helium [8] is replaced by O_2 and a CO/CO_2 mix with a total mass of 813 kg, reflecting a factor of x8 for the increased molecular weight and a factor of 3.3 for the higher atmospheric density at the lower altitude.

We baseline a 3x increase in MOXIE production capability to meet the diurnal average of 55 g/hr production. Since high UF is achieved at the expense of the quantity of generated product for a given electrochemical cell area, the scale-up will require ~5x the cell area to meet those production rates at the specified 75% UF.

From a mass perspective, scaling up MOXIE to these requirements is expected to result in a net mass *reduction*. On Mars large volumes of the thin atmosphere had to be drawn in, protected from pebbles, filtered for dust, and compressed up to 100-fold. For EVE, operating at an atmospheric pressure near 1 bar, the filter/compressor assembly will be replaced by a lightweight blower. Despite requiring larger cell area, the SOE stack *assembly*, which includes a compression system and a structure to contain the insulation, can be substantially reduced in size and mass due to the decreased differential pressure relative to the ambient.

The proposed production rate requires a diurnal average 105W electrochemical energy, and 210W total power if we assume a modest 50% system efficiency (we expect ~75%). This corresponds to approximately 20% of the production of a 5 m^2 solar array.

Regenerative (fuel cell) operation: A 5 m^2 solar array deployed from an aerobot circling the planet in the equatorial regions will generate 49 kWh of solar energy per circuit of the planet at 52 km altitude, or ~500W average over the orbit. Assuming a typical value of 100 Wh/kg for a battery package, continuous day/night operation at constant power would require storing up to ~30 kW-hr, equivalent to ~300 kg of battery pack. Instead of battery packs, EVE will operate the SOE as a fuel cell (SOFC) using the reaction $2CO+O_2 \rightarrow 2CO_2$. During the ~50-hr night side traverse, overpressure in the balloon bladders will feed gases back into the SOFC to produce electricity and to provide heat to maintain the SOE at or near its operating temperature (810˚C) on the night side. Converting up to 10% of the produced gas to energy at night will generate up to ~15W electrochemical power, which can be used in support of survival avionics and/or night-side scientific observations.

Atmospheric chemistry challenge: while the middle atmosphere consists of predominantly CO_2, the clouds consist of sulfuric acid droplets that collectively represent from several ppm up to 30 ppm by mass of the atmosphere [9,10]. In addition, the atmosphere at balloon altitudes contains up to ~100 ppm SO_2 [9]. The balloon envelope itself can be protected from corrosion with appropriate coatings, but the sulfur compounds pose a potential problem for the electrolysis system that will need to be mitigated. The intake and preheating system will need to be non-metallic to tolerate the H_2SO_4 droplets, which will be converted to SO_3 and harmless H_2O during the process of preheating to the SOE operating temperature of 810˚C. In the SOE stack itself. SO_x molecules may be toxic for the chemical half reactions that occur during SOE [11], or may attack components including the electrodes and the metallic interconnects between cells. Assessment and mitigation of this risk is under study.

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References: [1] Esposito, L.W. *et al.* (1983), in *Venus*, The University of Arizona Press, Tucson. [2] Hecht, M.H *et al.* (2021), *Space Sci Rev* **217:**9. [3] Hoffman, J., *et al.* (2022), *Science Advances* **8**:35. [4] Cutts J. A. *et al.* (2023) 54th *LPSC* #2806. [5] Hall, J.L. *et al.*, *AIAA 2021 Aviation Forum* [6] Widemann T. et al. (2023) *Space Sci. Rev.* 219: 7. [7] Center National d'Etudes Spateiale (CNES), *Strateole 21,* https://strateole2.aeris-data.fr/long_duration_balloons/. [8] Cutts, J.A. *et al.* (2022), *IEEE Aerospace Conference.* [9] Mills, F. P. *et al*. (2007), AGU Geophysical Monograph Series 176. [10] Baines, K.H. *et al.* (2021), Astrobiology 21(10), p. 1316. [11] Skafte T.L. *et al.* (2018) *J. Power Sources*, 373, p. 54.