

Scientists propose adapting a Mars ISRU system to the changing Mars environment

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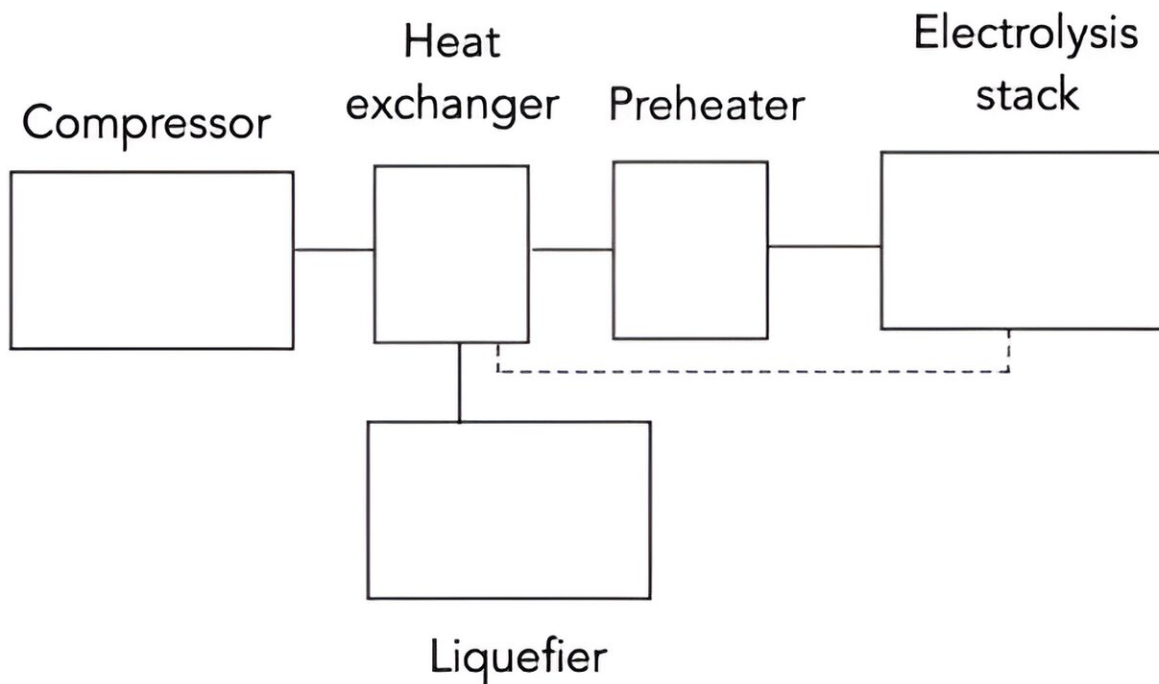


Fig. 1: Major subsystems for oxygen production. Credit: *Space: Science & Technology*

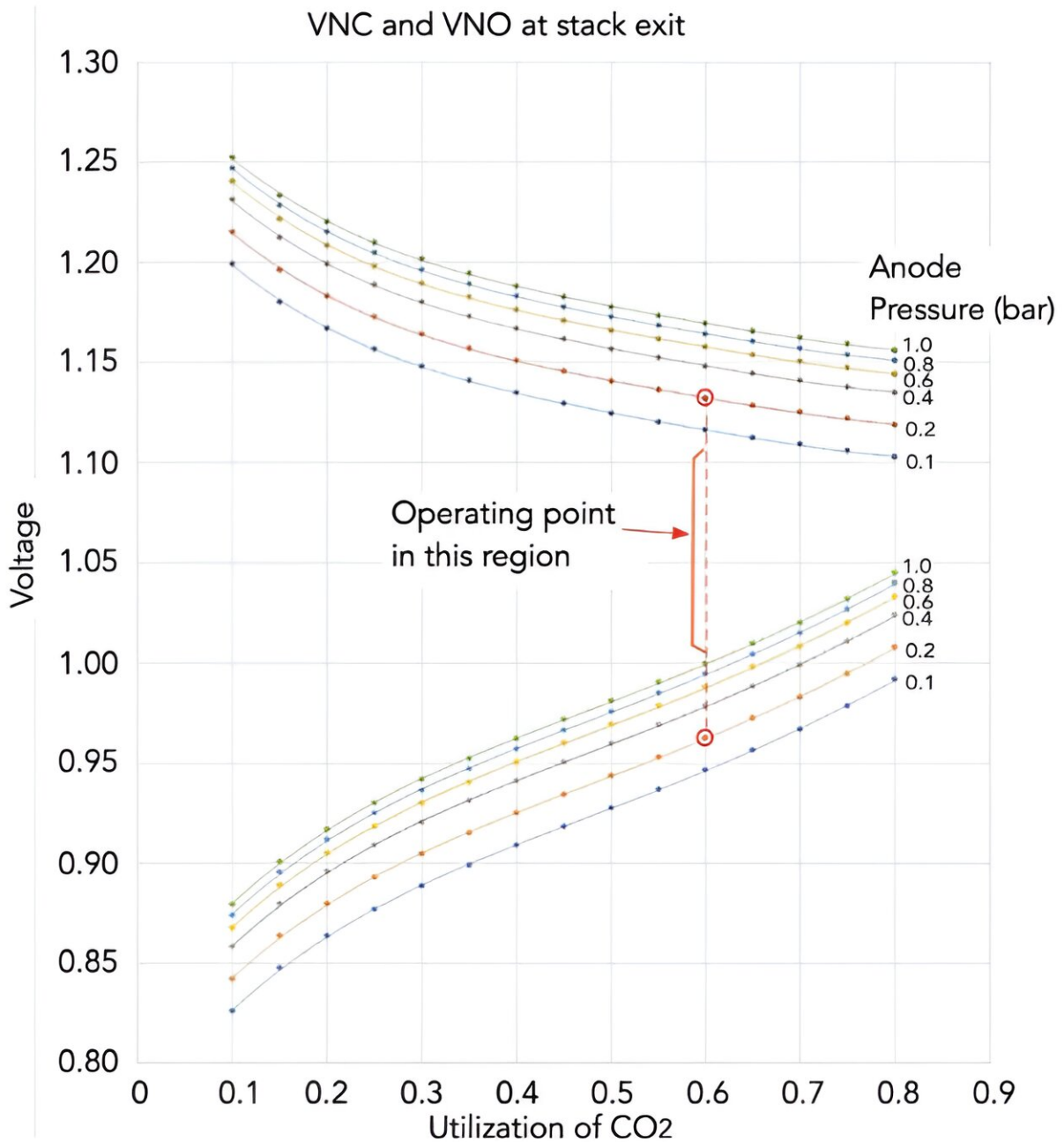
Human missions to Mars will require a substantial launch vehicle to ascend from Mars to rendezvous with a waiting Earth return vehicle in Mars orbit. For an ascending crew of 6, the current best estimate of oxygen propellants required for ascent is about 30 metric tons.

Producing oxygen for ascent propellants and possibly life support from the indigenous CO₂ on Mars, rather than bringing oxygen to Mars from Earth, is of significant benefit.

The oxygen production is accomplished through a process known generically as in situ resource utilization (ISRU). Since the Mars Oxygen ISRU Experiment (MOXIE) Project demonstrated operation of a prototype electrolysis system for converting Martian CO₂ to O₂ on Mars with great success, it is now appropriate to investigate scaling up this prototype to a full-scale system.

In a [research paper](#) recently published in *Space: Science & Technology*, Donald Rapp and Eric Hinterman modeled the performance of a full-scale Mars in situ resource utilization (ISRU) system to produce 30 metric tons of liquid O₂, operated for 14 months as the Mars environment changes diurnally and seasonally.

First, the authors introduce the ISRU system layout, requirements, and settings. The simplified layout of the ISRU system is shown in Fig. 1. The heart of the system is the stack (or, more likely, a set of stacks) of electrolysis cells, producing a flow of O₂ out of the anode and a mixture of CO, CO₂, and inert gases in the cathode exhaust. While the process operates, a compressor first pulls Mars atmosphere into the system and compresses it from Mars pressure to stack pressure.



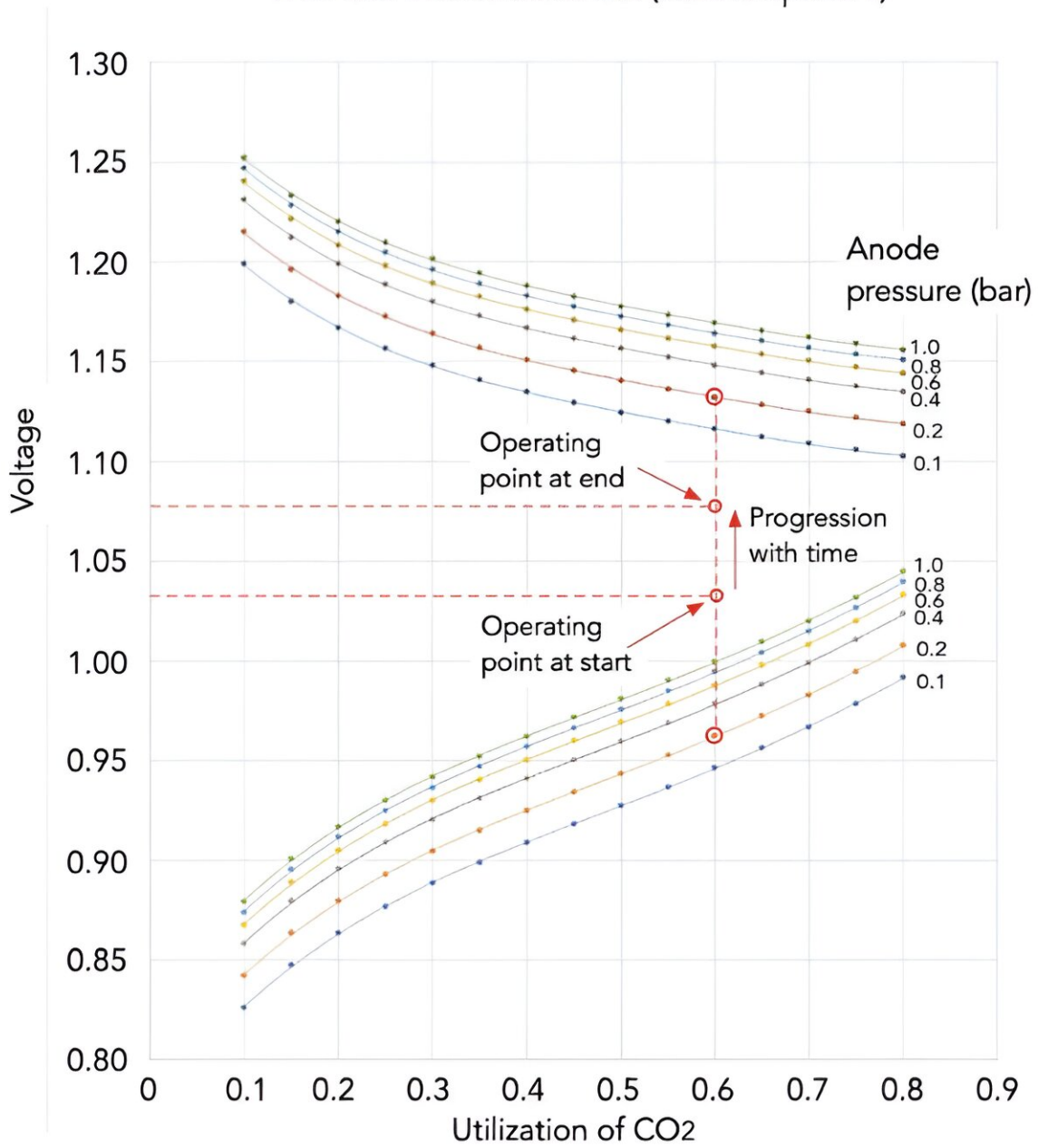
Allowable range of average cell voltage for anode pressure = cathode pressure = 0.2 bar and 60% utilization of incoming CO₂. Credit: *Space: Science & Technology*

A heat exchanger recuperates some heat from the [exhaust gases](#) to incoming gas from Mars, and this gas is preheated to stack temperature before entering the stack. After the electrolysis in the stack, the effluent from the stack is fed back to the [heat exchanger](#) to prewarm incoming Mars gas, and the cathode exhaust is vented, while the anode exhaust is fed to the liquefier.

Moreover, it is critical that the voltage across the electrolytic cells of the stack(s) must be greater than the Nernst voltage for the oxygen production reaction (0.96 V) and less than the Nernst voltage for side reaction that deposits carbon (1.13 V). The system is required to be on a 14-month (420-sol) run with an average [oxygen production](#) rate of 3.0 kg/h to produce a total of 30240 kg of oxygen over this period. There are also several control schemes.

In option 1, the electrolysis stacks and the liquefier are operated at constant flow rate 3.0 kg/h, while the compressor revolutions per minute (RPM) is controlled to be greater when the Mars density is lower, and vice versa. In control option 2a, the RPM is always maintained at 3325, and the compressor is the same size as in control option 1, but the number of cells in the stacks is reduced.

VNO and VNC at stack exit (control option 1)



Nernst potentials near the cathode exit in control option 1. Credit: *Space: Science & Technology*

In control option 2b, the RPM is always maintained at 3325, and the number of cells is the same as in control option 1, but the size of the compressor is reduced. In control option 2c, the number of cells and compressor size are the same size as in control option 1, but the RPM is always maintained at 2705.

Then, the authors examine the intrinsic area-specific cell resistance (iASR), current density (J), and flow rate in different control options. The basic relationship: $V_{op} = + V_{other} + (iASR)(J)$ is used, in which V_{op} is the average operating voltage applied to a cell; V_{other} is the Nernst potential for O_2 production, averaged across a cell; V_{other} is a voltage added to balance the equation.

In addition, anode pressure = cathode pressure = 0.2 bar, utilization = 0.60, and iASR is assumed to start at 1.00 ohm-cm^2 and increase to 1.20 ohm-cm^2 after 420 sols of operation. In control option 1, the required cell area to produce 3 kg/h of oxygen is $A_T = 83750 \text{ cm}^2$.

Table 1. Characteristics of run control options.

		Reduce number of cells	Reduce compressor size	Reduce RPM
	Control option 1	Control option 2a	Control option 2b	Control option 2c
FO ₂ O ₂ production rate	Constant	Variable	Variable	Variable
FM Mars gas flow rate	Constant	Variable	Variable	Variable
RPM	Variable	Constant	Constant	Constant
Number of cells	840	678	840	840
RPM	Variable; less than 3,325	3,325	3,325	2,705
Relative compressor size	1.000	1.000	0.814	1.000

Characteristics of run control options. Credit: *Space: Science & Technology*

Table 3. Comparison of control options.

	Adjust compressor constant flow rate	Reduce number of cells	Reduce compressor size	Reduce RPM
	Control option 1	Control option 2a	Control option 2b	Control option 2c
FO ₂ : O ₂ production rate	Constant	Variable	Variable	Variable
FM Mars gas flow rate	Constant	Variable	Variable	Variable
RPM	Variable	Constant	Constant	Constant
RPM	Variable	4,000	4,000	2,705
Number of 100-cm ² cells	840	678	840	840
Relative compressor size	1	1	0.814	1
FO ₂ : Maximum O ₂ production rate (kg/h)	3	3.542	3.614	3.614
FO ₂ : Average O ₂ production rate (kg/h)	3	3	3	3
FO ₂ : Minimum O ₂ production rate (kg/h)	3	2.393	2.441	2.441
FM: Maximum Mars gas flow rate (kg/h)	14.25	16.83	17.17	17.17
FM: Average Mars gas flow rate(kg/h)	14.25	13.99	14.27	14.27
FM: Minimum Mars gas flow rate (kg/h)	14.25	11.37	11.60	11.60
Minimum current density (A/cm ²)	0.12	0.120	0.098	0.098
Average current density (A/cm ²)	0.12	0.148	0.120	0.120
Maximum current density (A/cm ²)	0.12	0.178	0.145	0.145
iASR (start/finish)	1.00/1.20	1.00/1.20	1.00/1.20	1.00/1.20
Minimum of average cell voltage	1.036	1.037	1.014	1.014
Average of average cell voltage	1.048	1.078	1.048	1.048
Maximum of average cell voltage	1.060	1.114	1.077	1.077

Comparison of control options. *Credit: Space: Science & Technology*

With cells of area 100 cm² each, this requires 840 cells. The span of cell-operating voltages is Max $V_{op} = 1.060$, Avg. $V_{op} = 1.048$, and Min $V_{op} = 1.036$. The RPM varies from 3325 at minimum density, to 2706 at average density, to 2251 at maximum density. In control option 2a, Max $V_{op} = 1.114$, Avg. $V_{op} = 1.078$, and Min $V_{op} = 1.037$.

The maximum average cell voltage is perilously close to the Nernst voltage for carbon formation, and considering the uncertainties in estimating iASR, this option is unacceptable. In control option 2b, Max $V_{op} = 1.077$, Avg. $V_{op} = 1.048$, and Min $V_{op} = 1.014$. In control option 2c, Max $V_{op} = 1.077$, Avg. $V_{op} = 1.048$, and Min $V_{op} = 1.014$, which are essentially the same as for control option 2b.

Finally, authors discuss the results and draw conclusions. As for the solid oxide electrolysis (SOXE) system, the electrochemical power is 14.6 kW for control option 1 and $4.87 \cdot FO_2$ kW for control option 2. The preheat power is estimated to be ~ 0.5 kW. The heat loss is approximately 0.35 kW, although it depends on atmospheric conditions. The total SOXE power for any control option is the sum of the electrochemical power, preheating power, and heat loss power.

The runs for the various control options yield the results shown in Table 4. As for the compressor, the adiabatic efficiency is a function of inefficiencies of its components, including motor losses, seal friction, and bearing friction. Table 5 summarizes power requirements for compression in various control options. The rate of heat removal from the system by the cryocooler is calculated as the cooling required to lower the temperature of the gaseous oxygen to its boiling point and liquefy it. The result is shown in Table 6. Total power including all contributions is concluded in Table 7. All tables can be viewed in the open access paper.

More information: Donald Rapp et al, Adapting a Mars ISRU System to the Changing Mars Environment, *Space: Science & Technology* (2023). [DOI: 10.34133/space.0041](https://doi.org/10.34133/space.0041)

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