Mars Oxygen ISRU Experiment

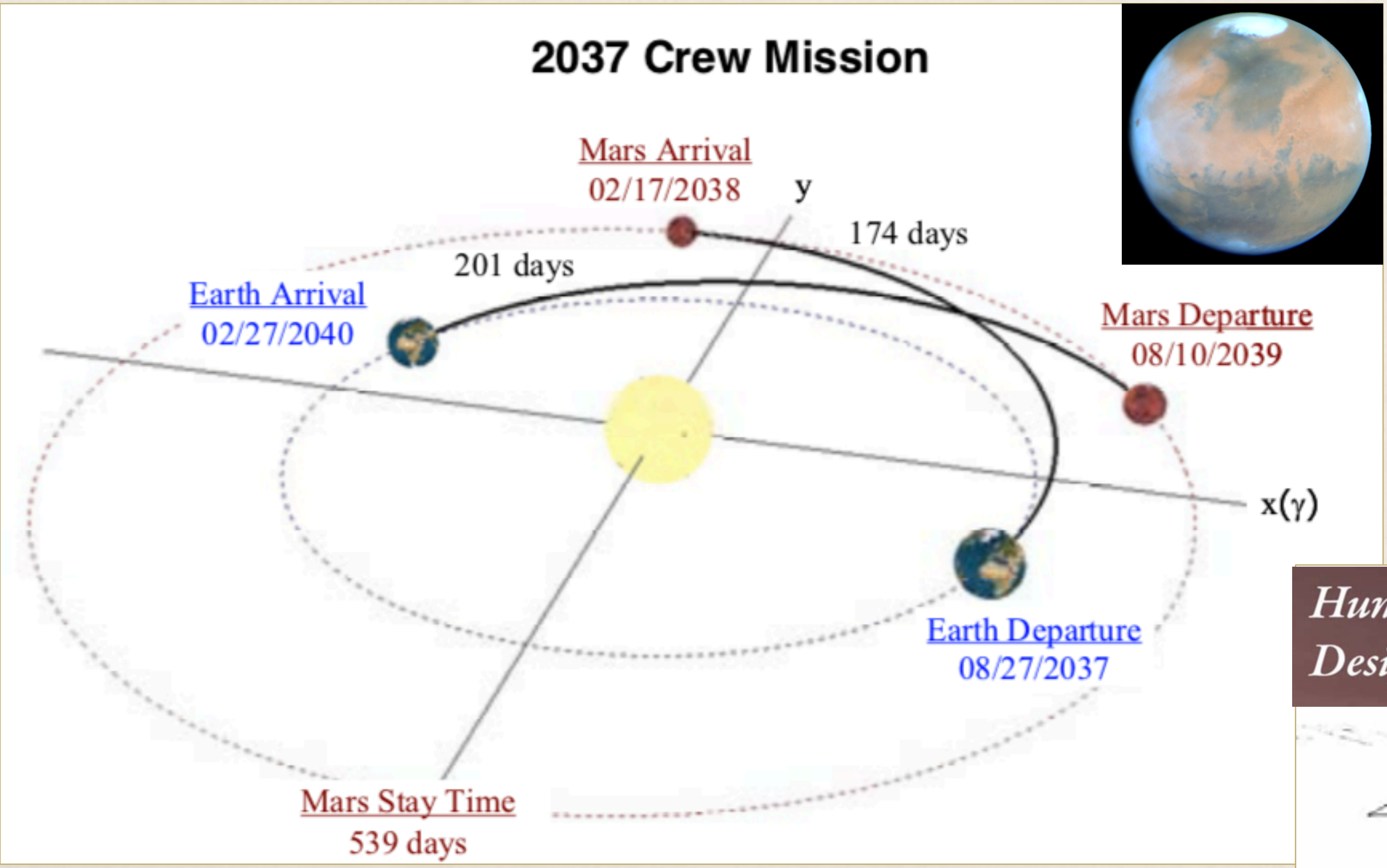
Michael Hecht (for the MOXIE Team)
Lexington Computer Group
October 26, 2022

MOXIE: A chemical factory on Mars

#JOURNEYTOMARS

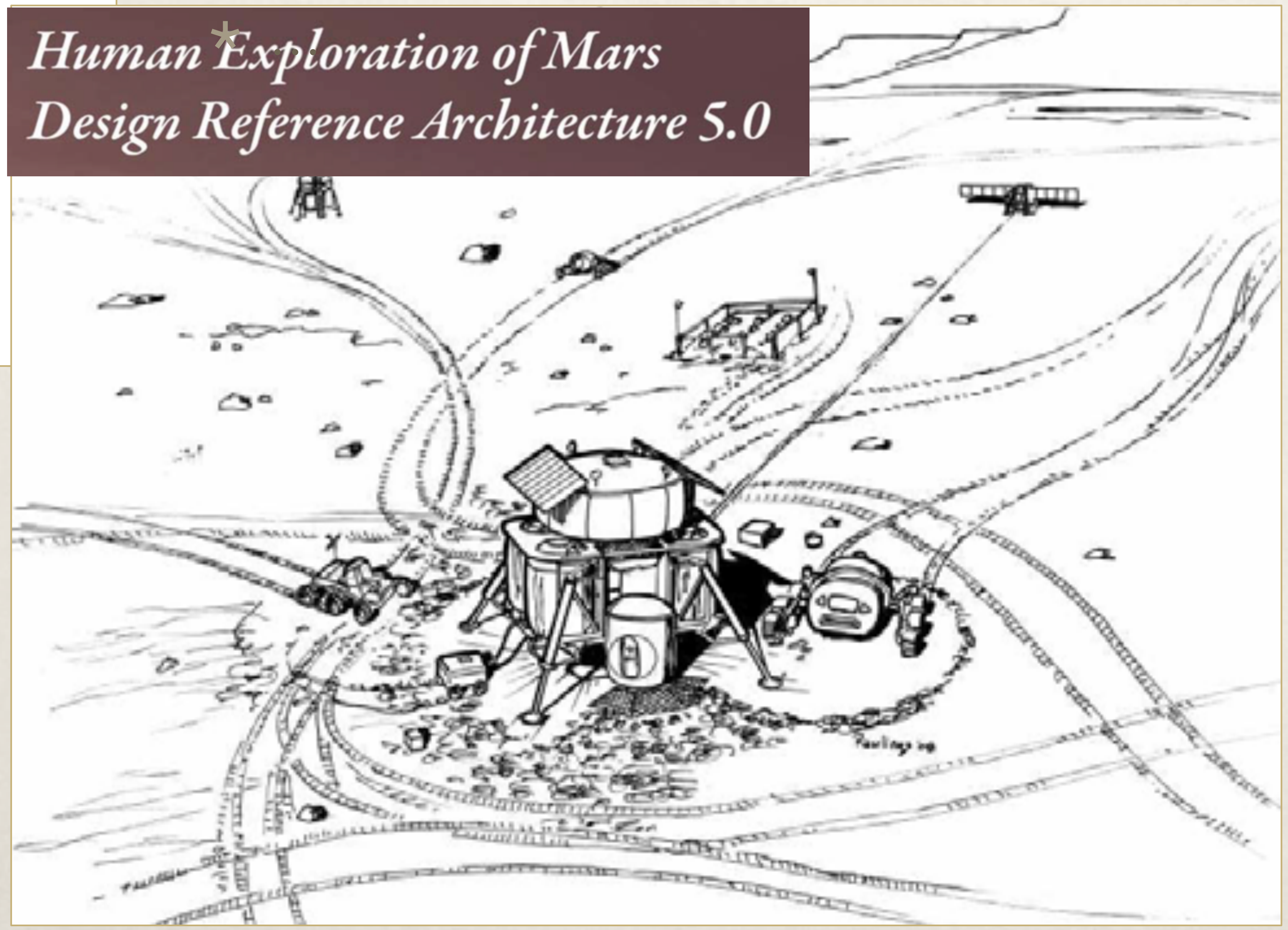
How to go to Mars

MOXIE
Mars Oxygen
ISRU Experiment



Cargo mission

- HABitat
- Descent/ Ascent Vehicle (DAV)
- Rovers (pressurized & unpressurized?)
- 25-30 kW power plant (Kilopower? Photovoltaic?)
- 32 tons propellant (7 for fuel & 25 for oxidizer) plus ~2 tons O_2 for breathing… ***or ISRU plant***



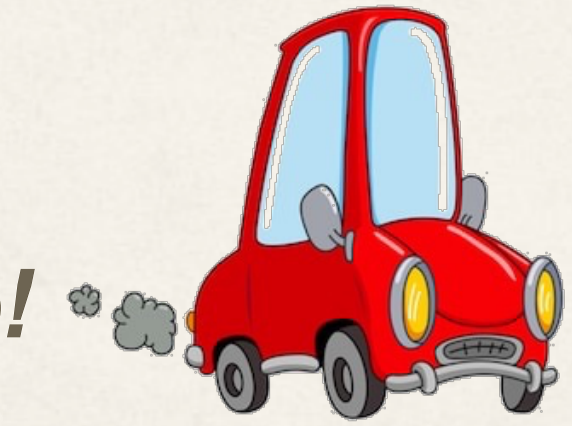
Human mission

- Mars Transfer Vehicle
- The Crew
- Toothbrush, etc.

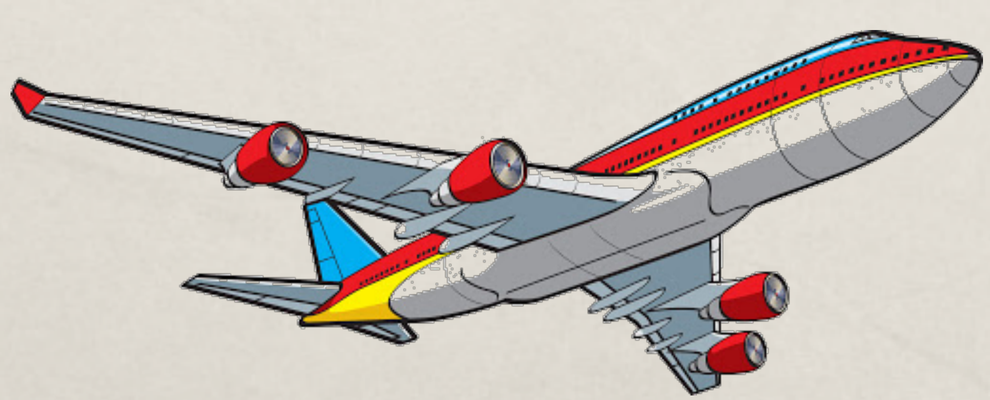
Why we need an “oxygenator” on Mars

MOXIE Mars Oxygen ISRU Experiment

Everything that “burns” fuel needs to breathe!

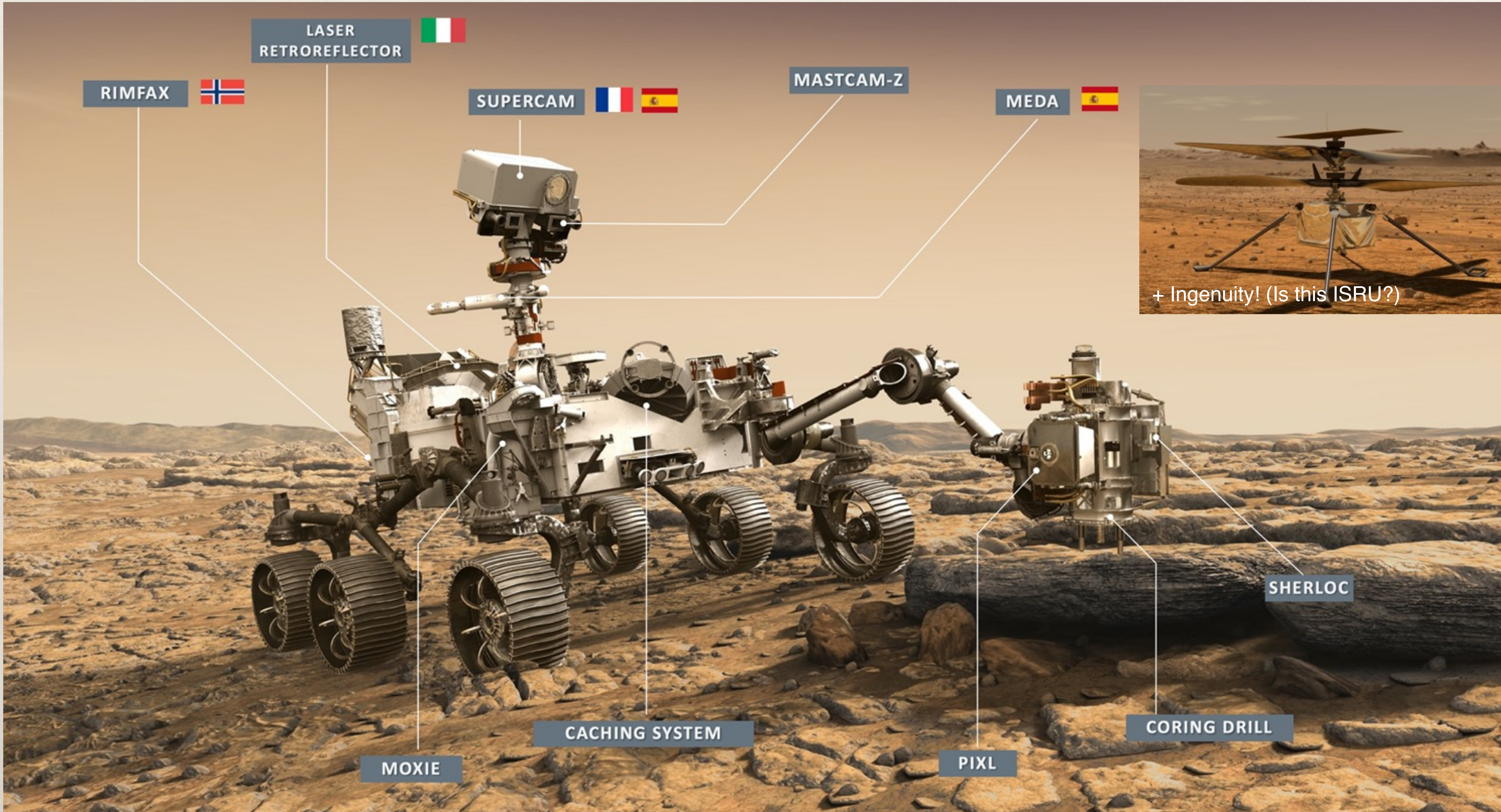


* Oxygen weighs several times the weight of the fuel
* The biggest fuel burner on Mars? The ***Ascent Vehicle!***
* The single heaviest thing we need to bring with us to Mars? A full oxygen tank for the ascent vehicle.
* To launch a crew of 4 takes **~25 tons** of O_2 & 7 tons of fuel
* By comparison, the crew breathes **~1.5 ton** O_2 / year

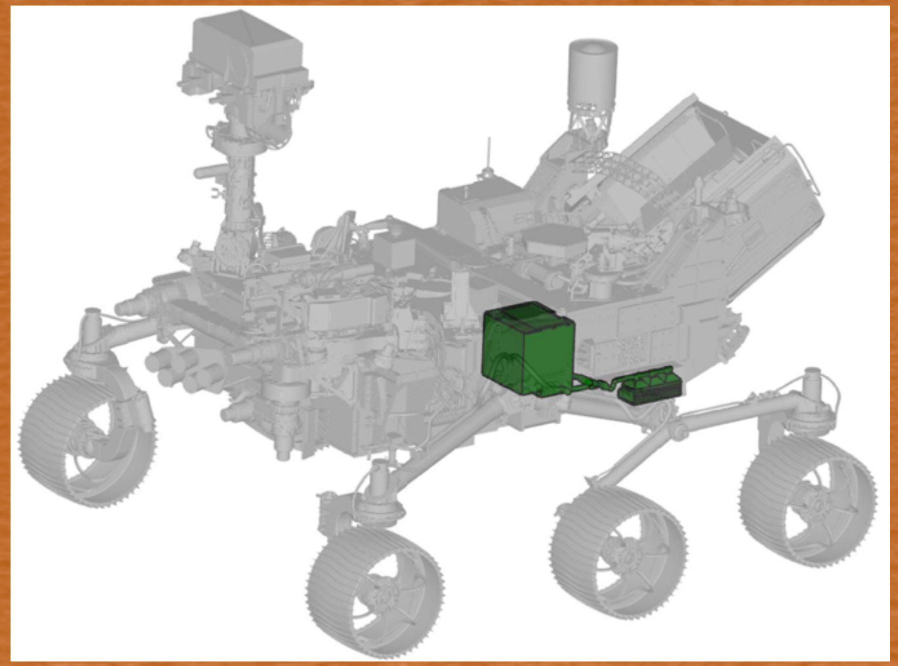


The Perseverance science mission

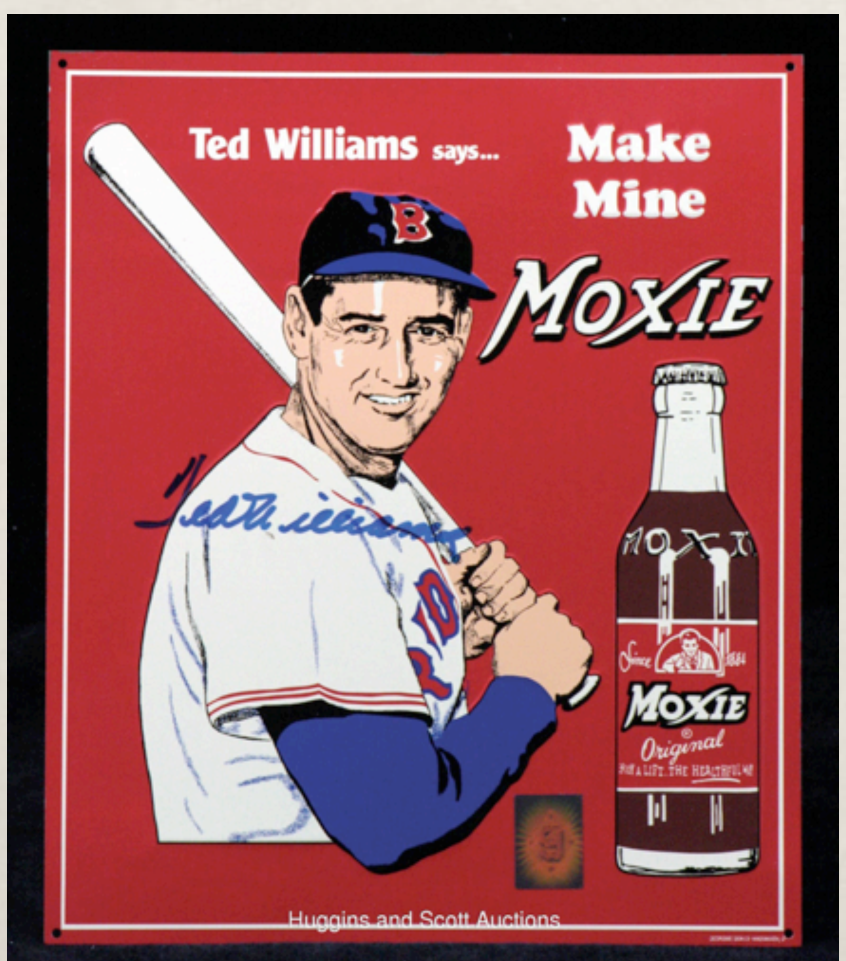
MOXIE
Mars Oxygen ISRU Experiment



* MOXIE is a scale model of an In Situ Resource Utilization (ISRU) plant for a human mission.
* MOXIE will make 6-10 g of propellant-grade O_2 per hour from CO_2, which makes up most of the thin air on Mars
    * Like a smallish tree, or ~50% of what a person breathes
    * Production is limited by available power to about 1:200 full scale



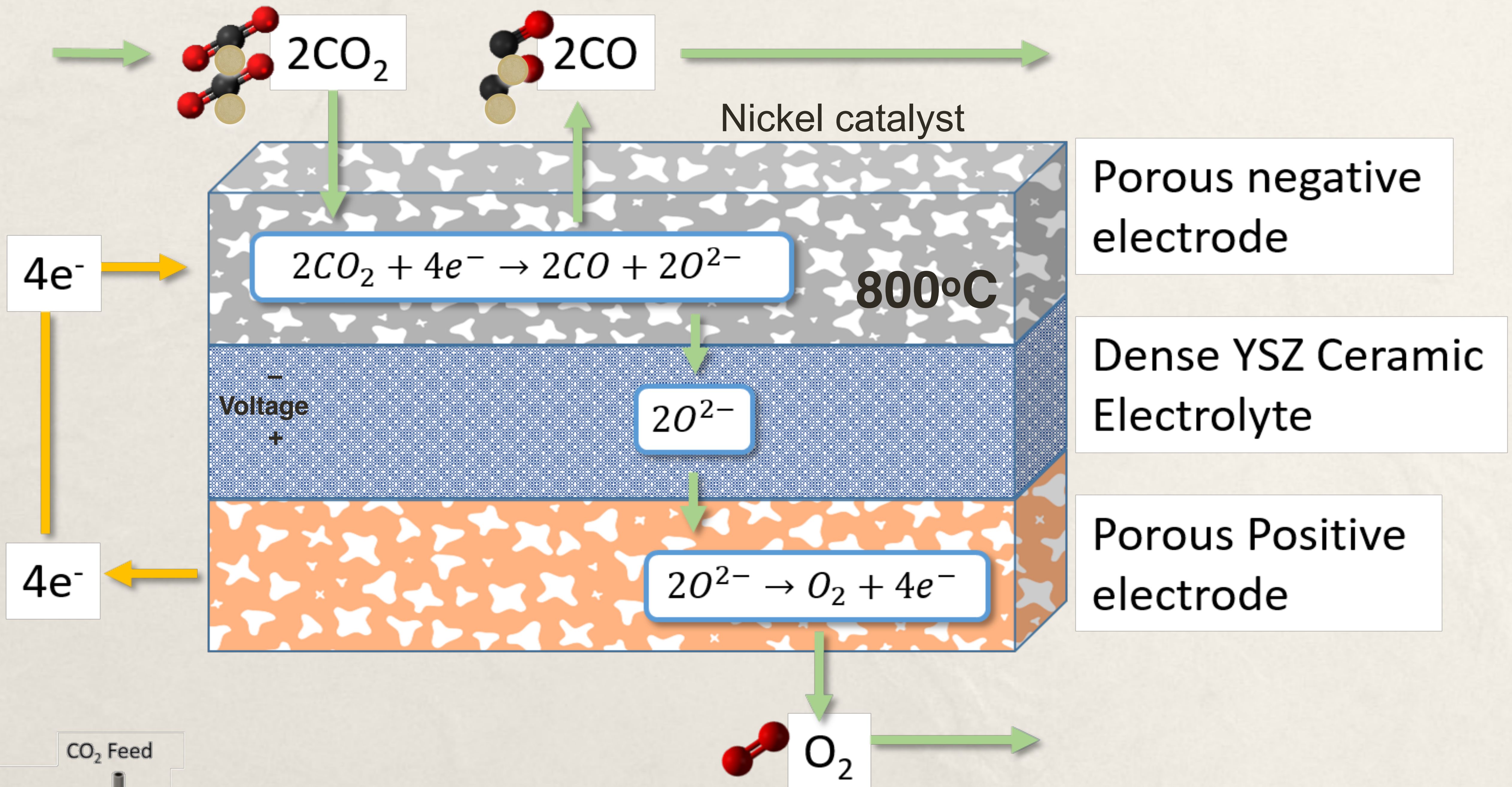

HE'S GOT
MOXIE
5¢

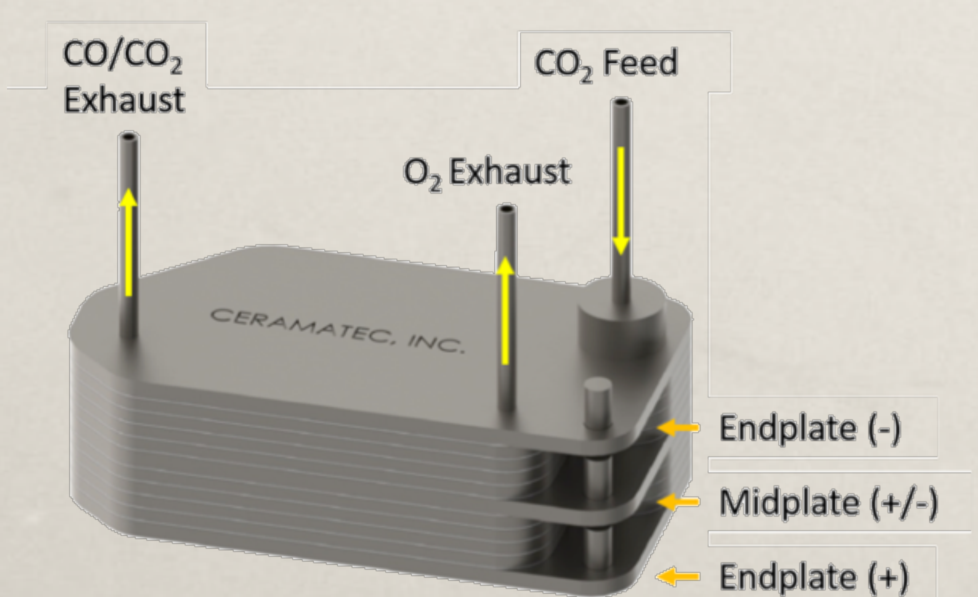

Ted Williams says...
Make Mine
MOXIE
Huggins and Scott Auctions


MOXIE
Secret Ingedient—
Gentian Root:
Cures anything caused by nervous exhaustion.
Stops the appetite for intoxicants in old drunkards.
Stops insanity, blindness from overtaxing, paralysis, and loss of manhood from excesses.
Makes you able to stand twice the usual amount of labor with less fatigue.
Neither a medicine, nor a stimulant.
Harmless as milk.


E

The Solid OXide Electrolysis (SOXE) cell





SOE: $CO_2 \rightarrow CO + O$

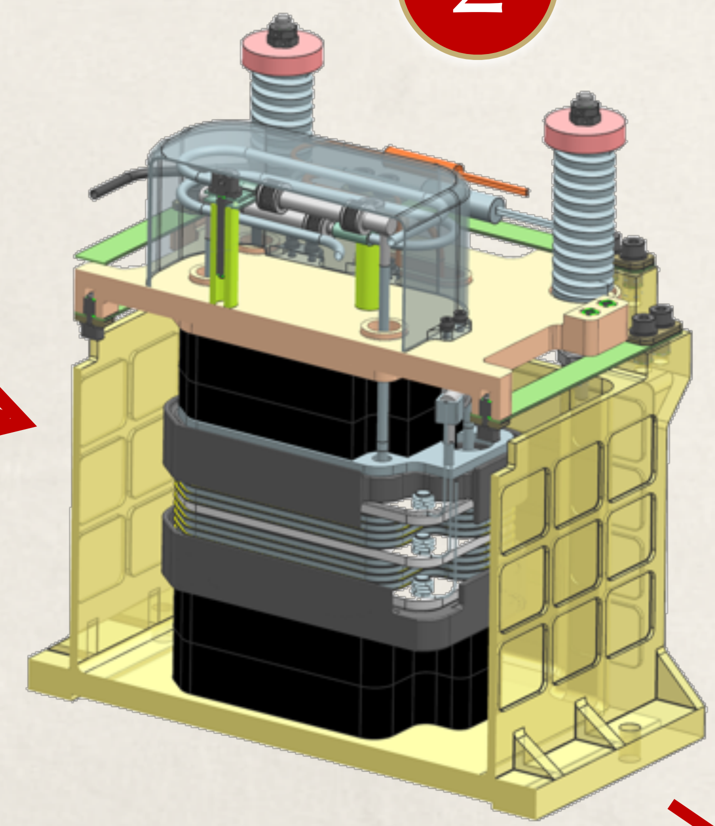
SOFC: $CO + O \rightarrow CO_2$

Putting it together

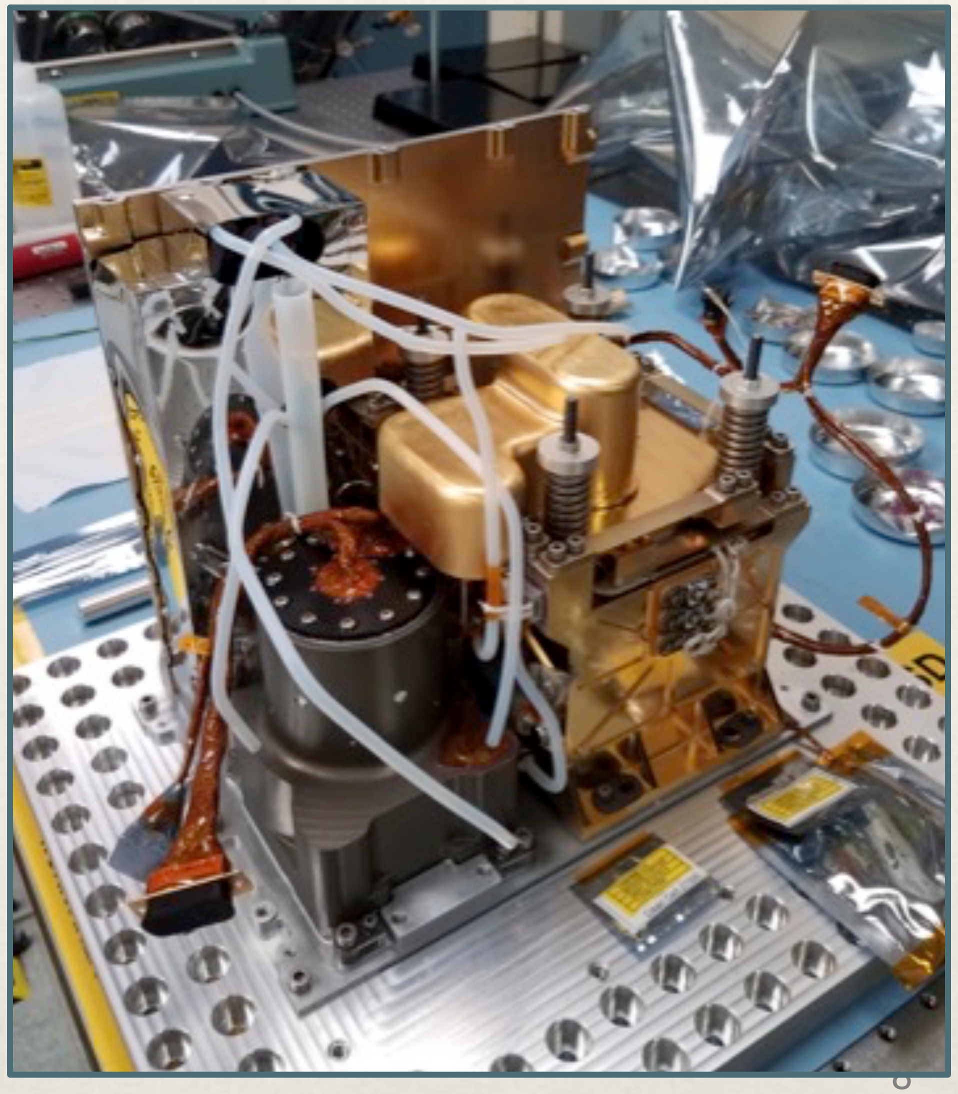
MOXIE
Mars Oxygen
ISRU Experiment

1

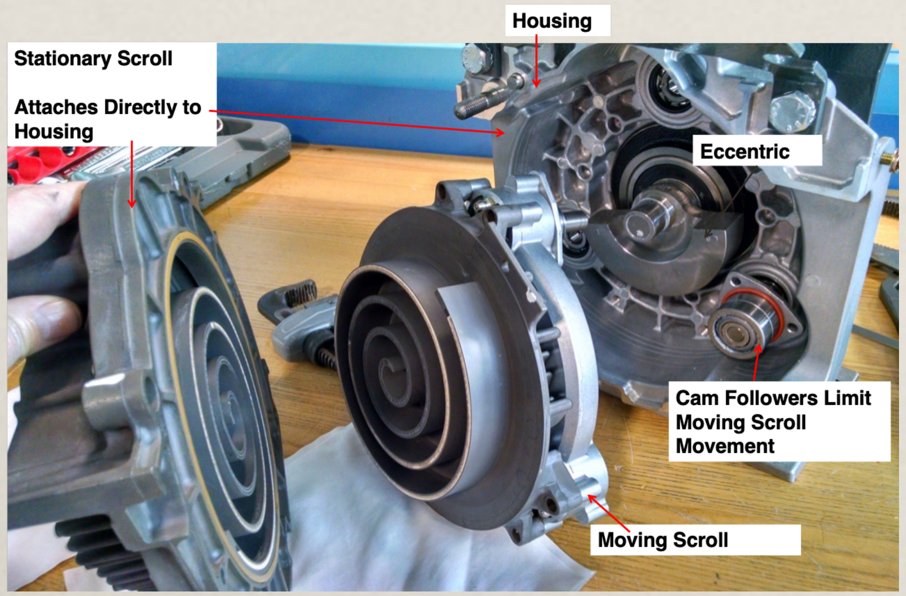
2



4



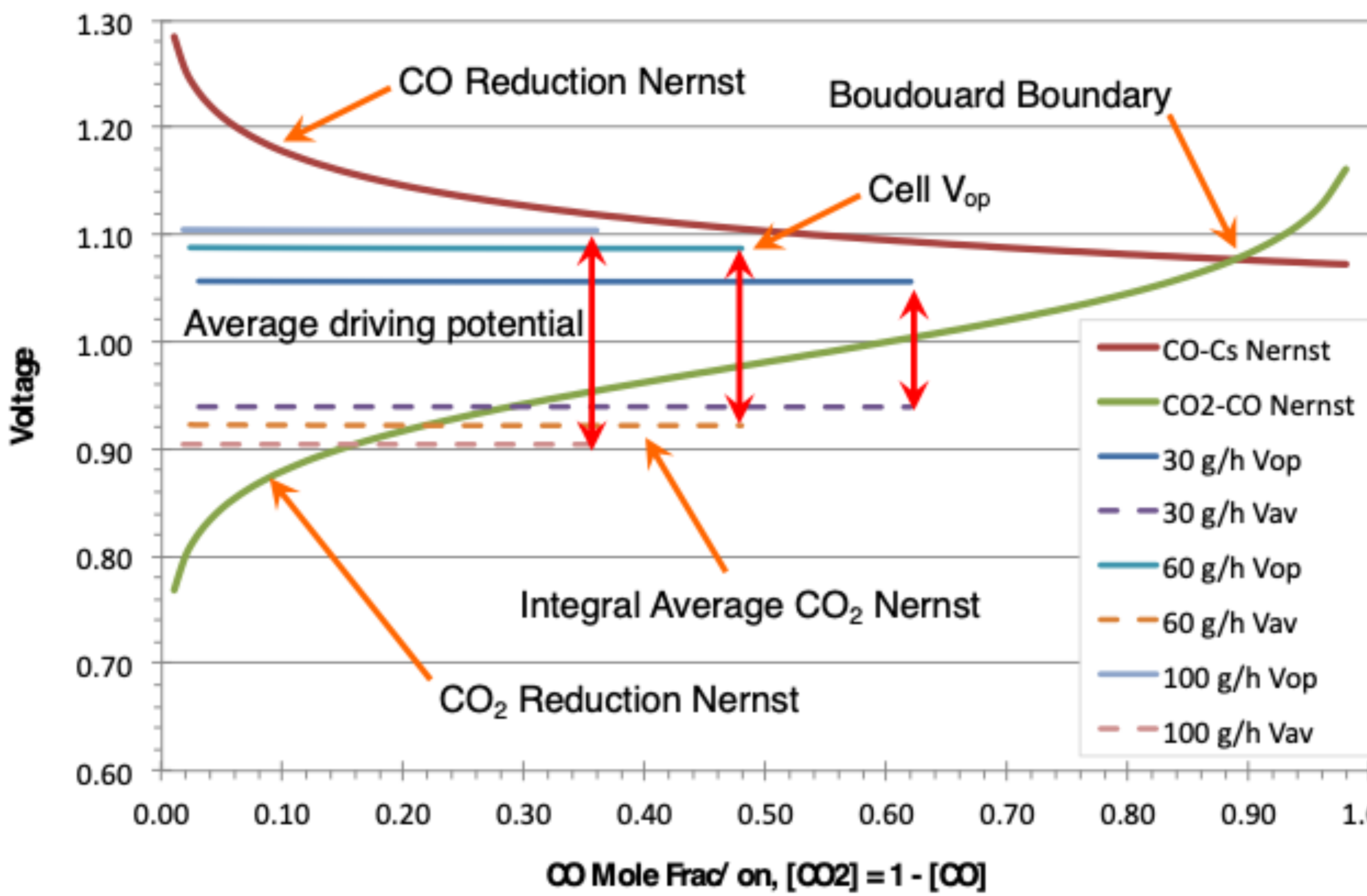
3



air squared

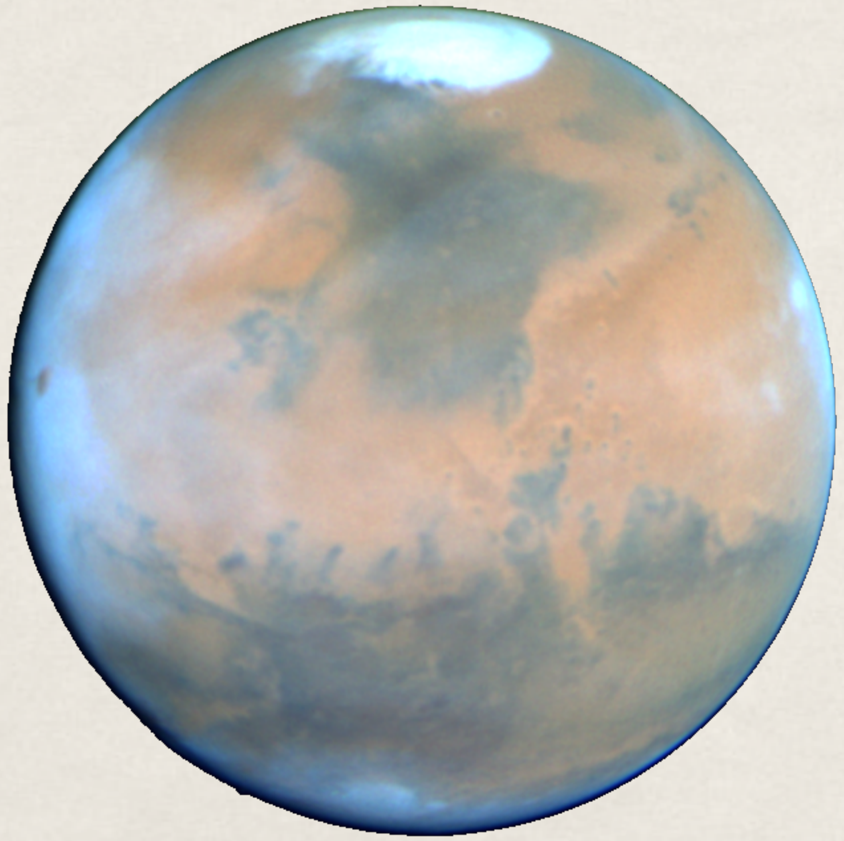
Staying in safe range from inlet to outlet

Operating Window - Driving Performance



Thermodynamic Constraints on SOXE Operation From Mars Atmosphere

International Conference on Electrolysis, Copenhagen, Denmark, June 2017



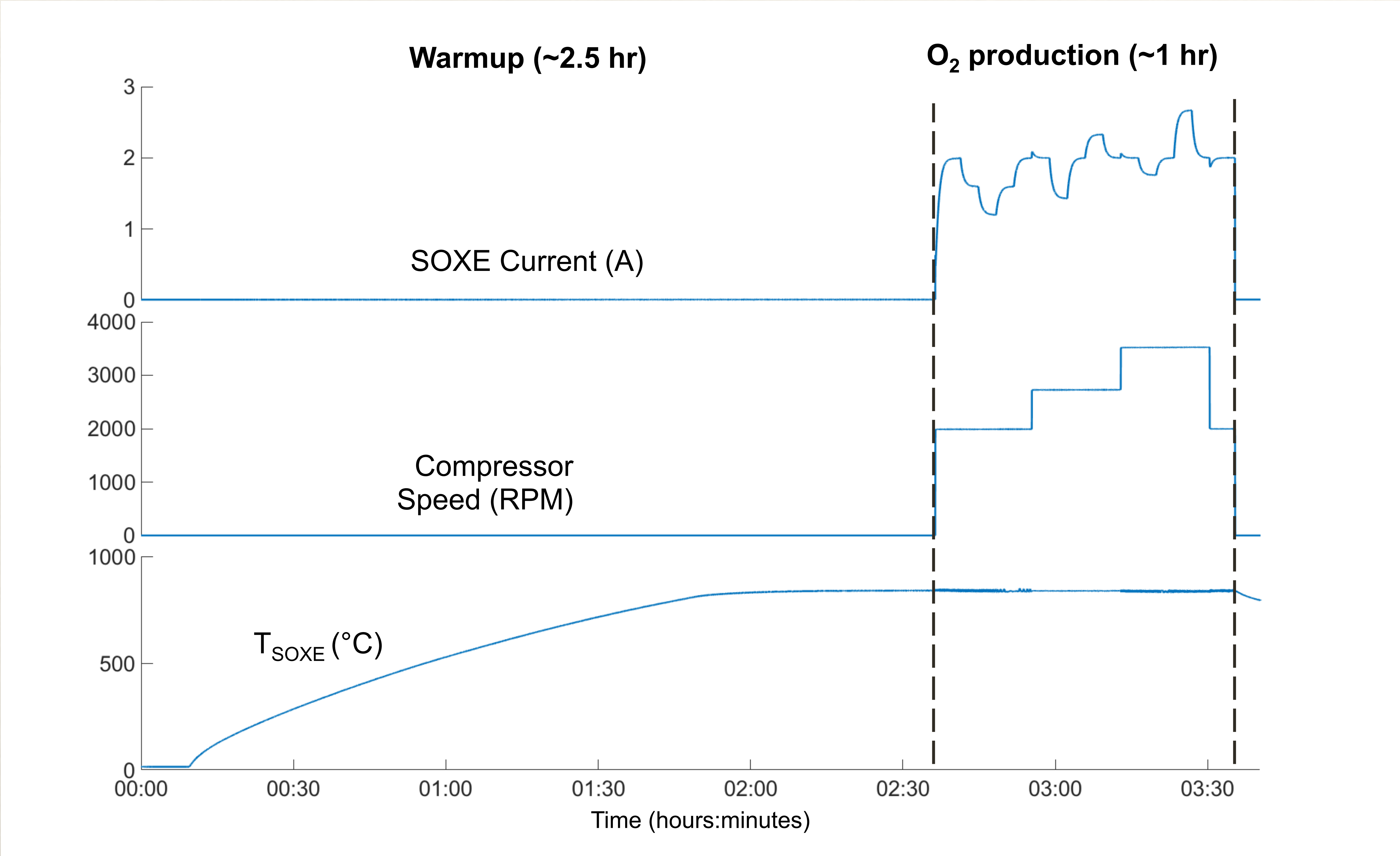
Operating on Mars

The first year

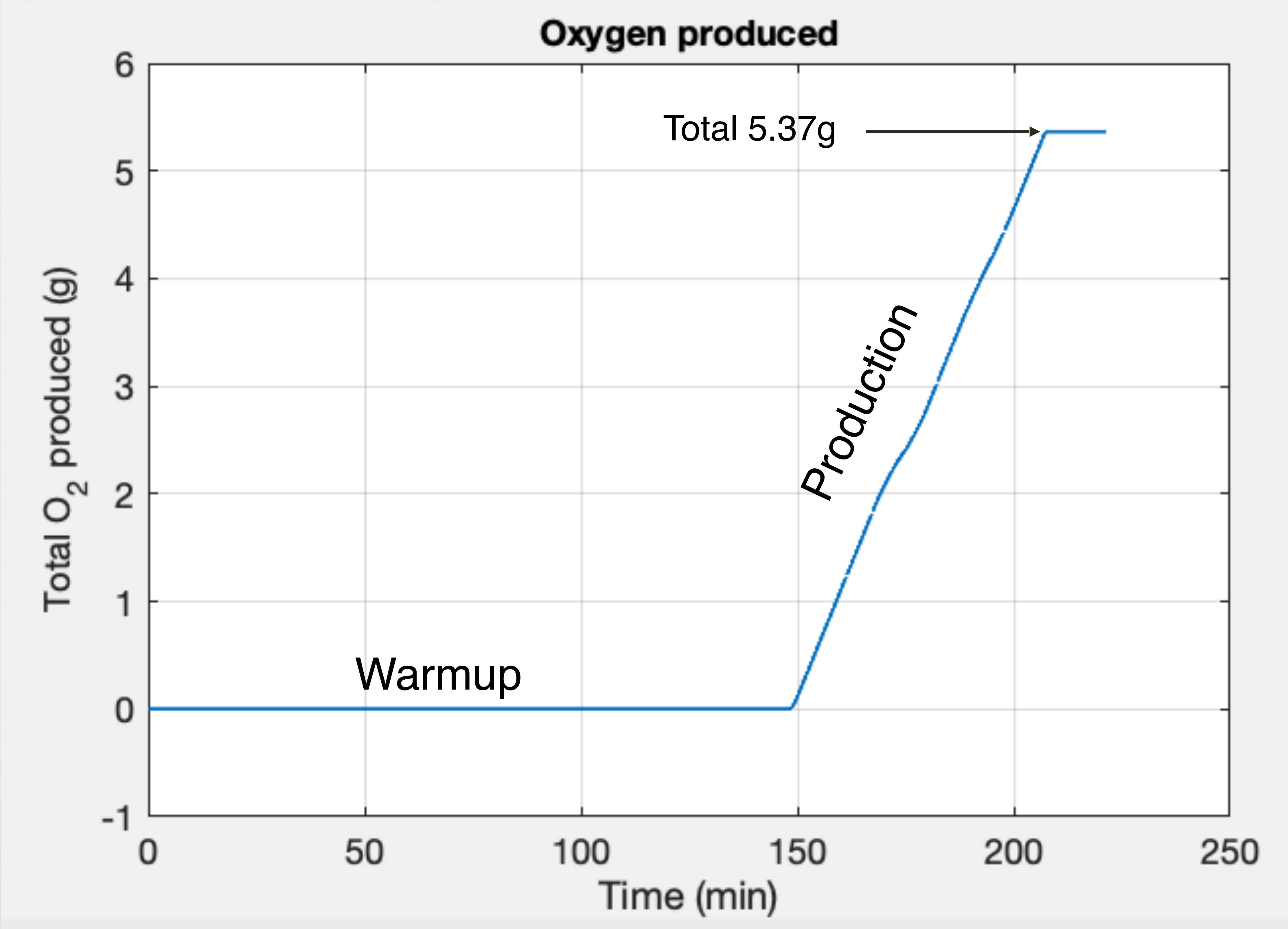
Safe arrival on Mars: February 18, 2021

Typical MOXIE run

MOXIE Mars Oxygen ISRU Experiment



Cumulative O_2 produced

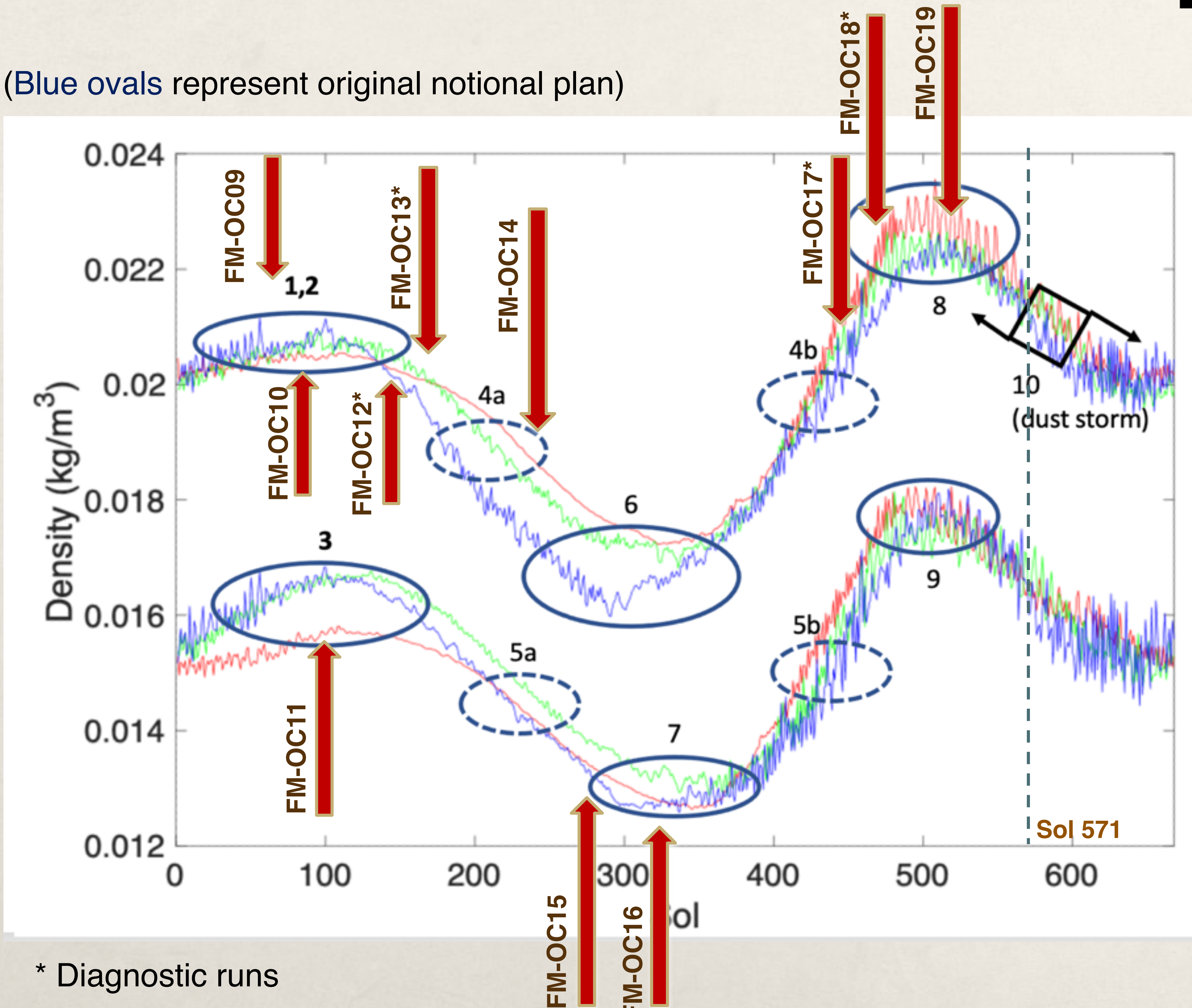


Atmospheric density variations on Mars

(Blue ovals represent original notional plan)

Daily maximum

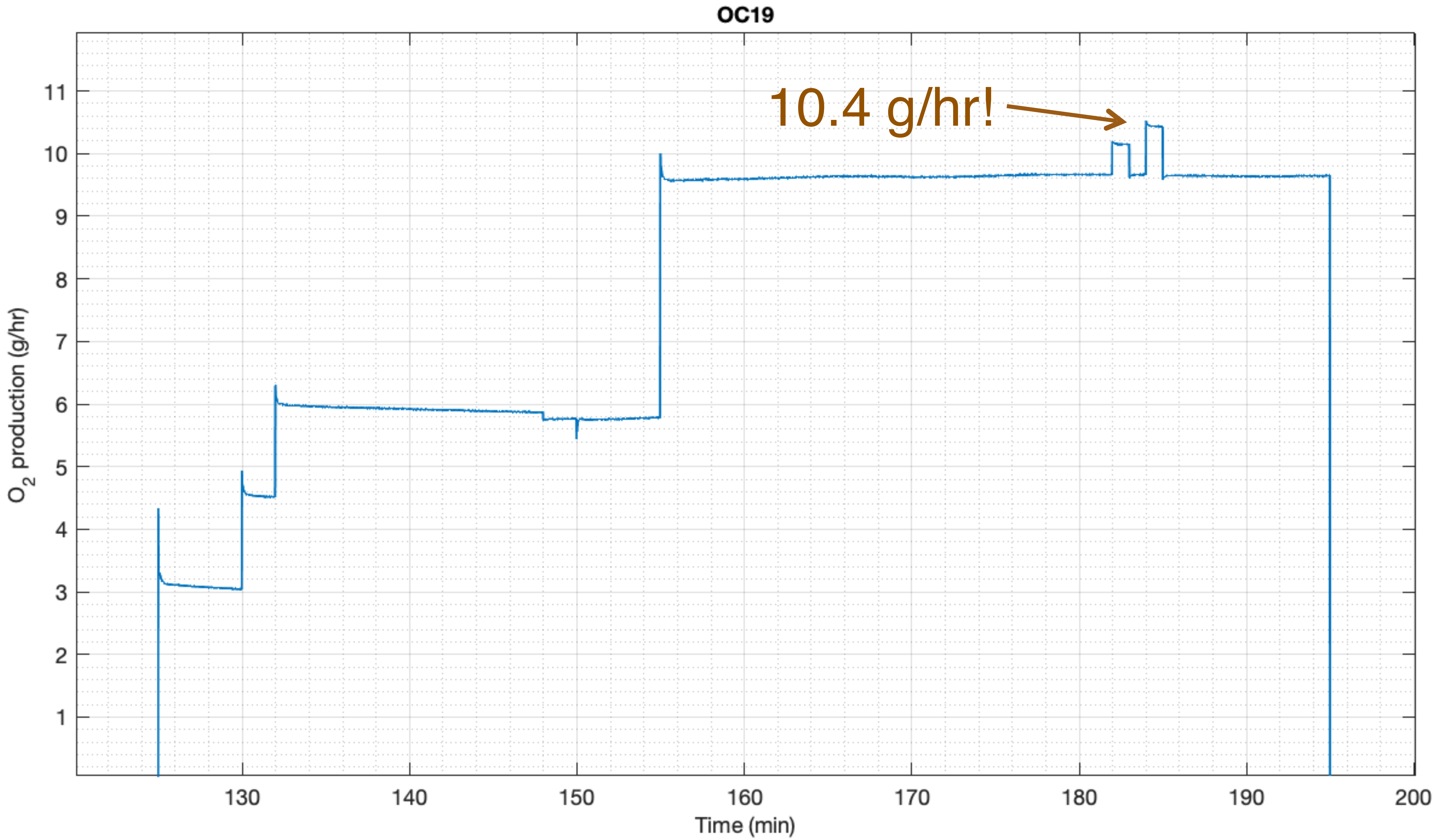
Daily minimum



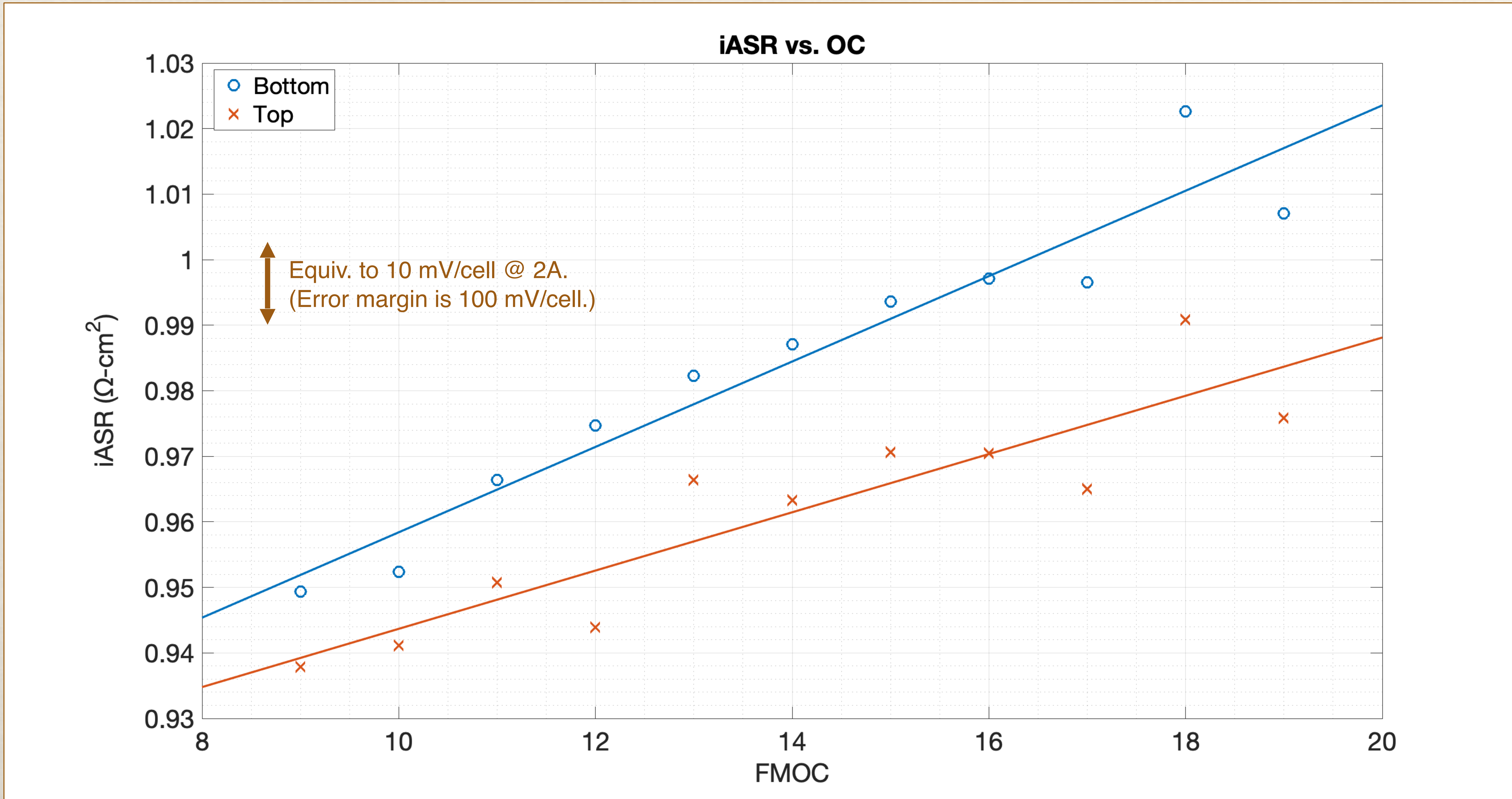
* Diagnostic runs

TOTALS
11 runs
82.69 grams O2
856.15 total minutes

FMOC-19: Maximum density

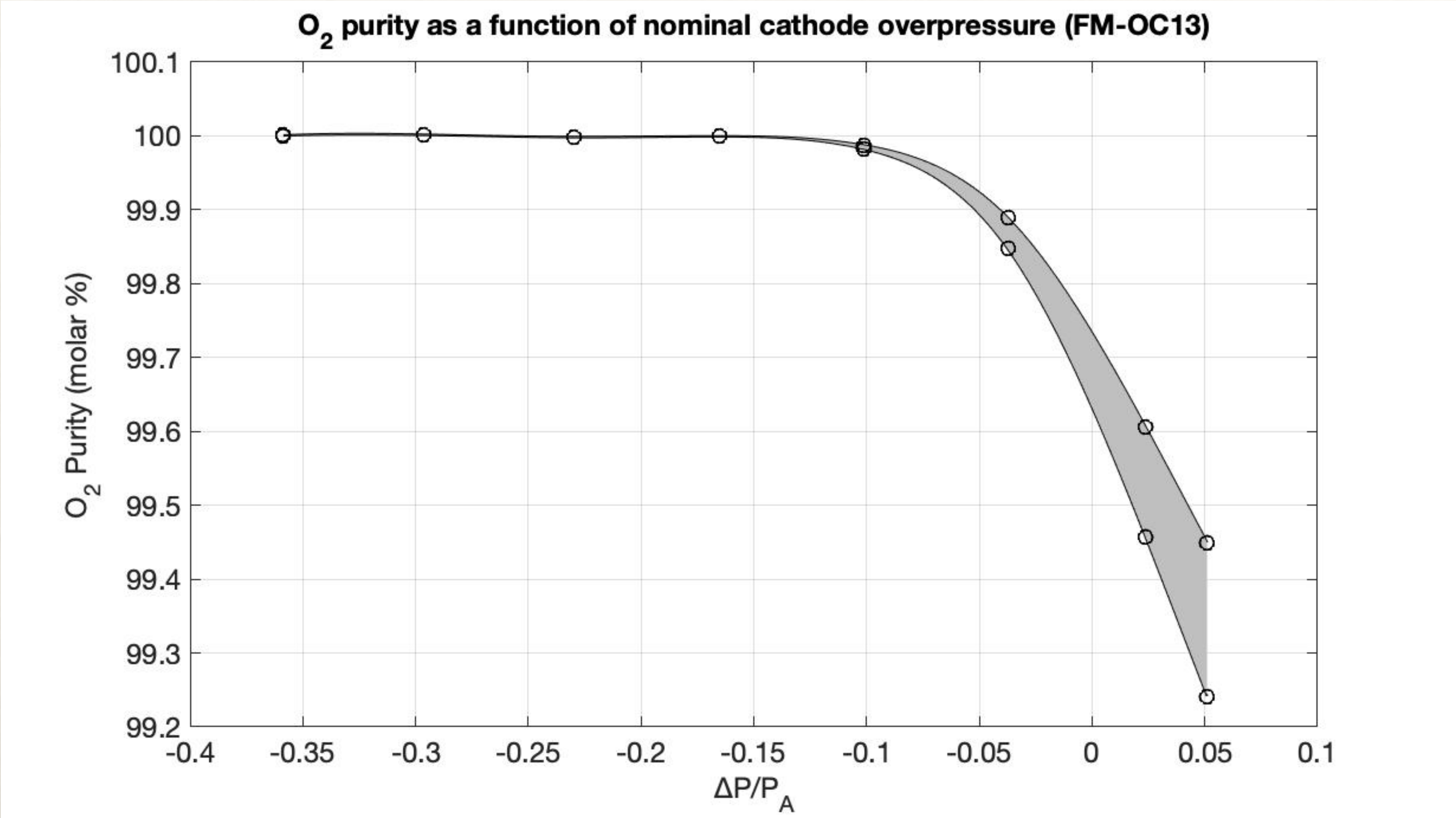


Robustness (iASR) – looking good!

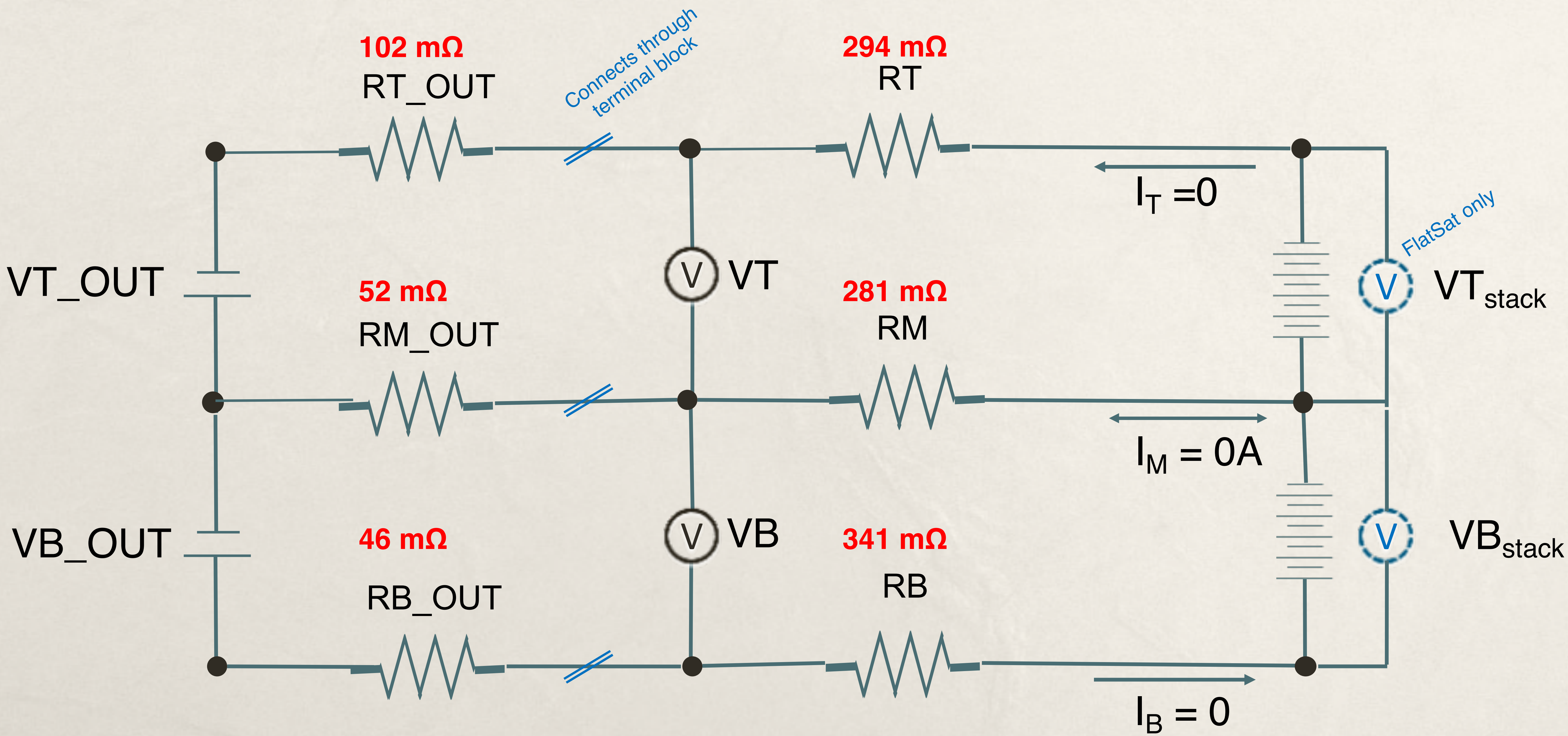


O_2 purity for FM-OC13 (molar)

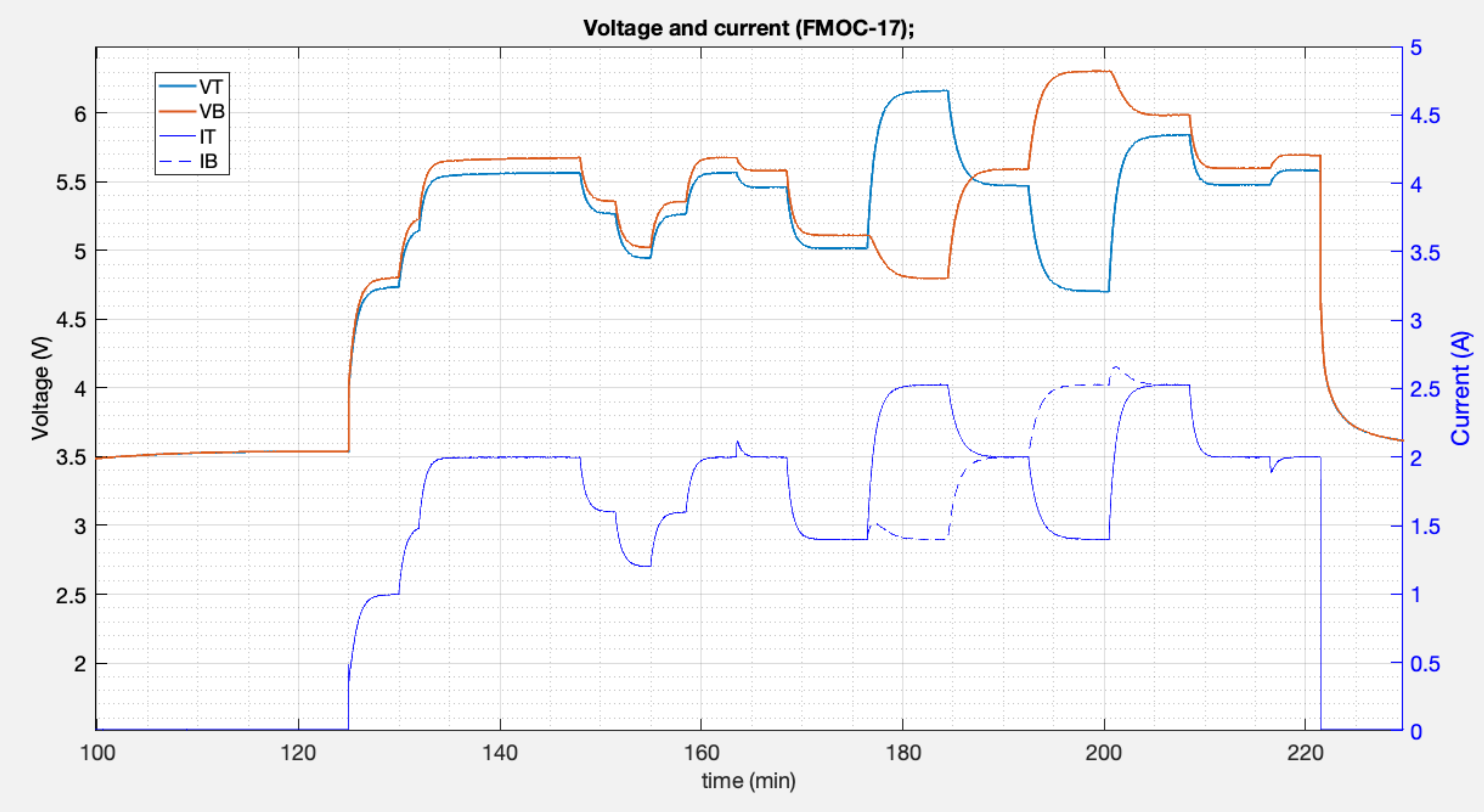
Purity = 1 – CS2 / P5



Resistance summary
(values in red were derived in situ, on Mars):



Example: finding RM with unbalanced current

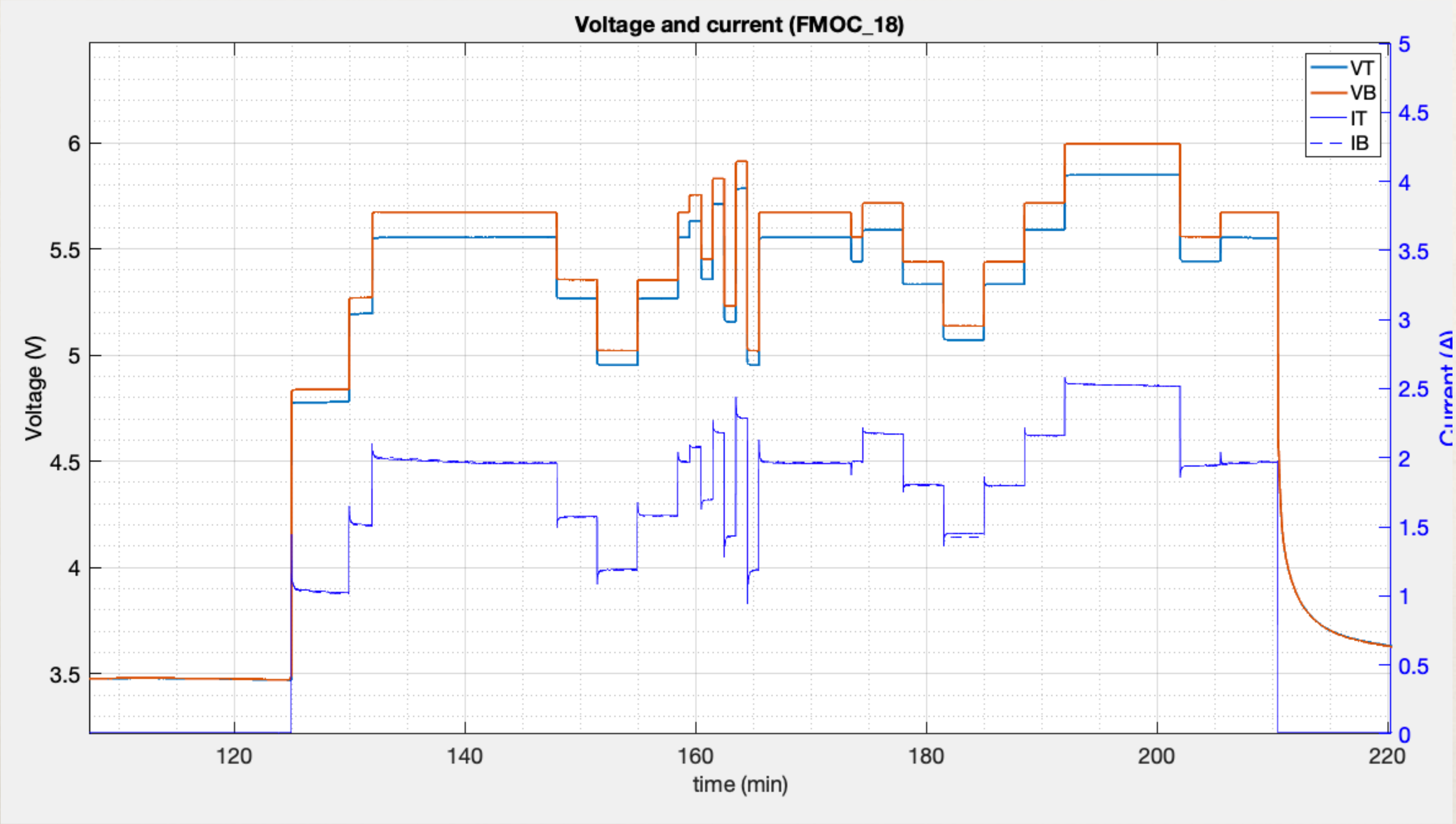


The latest experiment: Voltage control (vs. the standard current control)

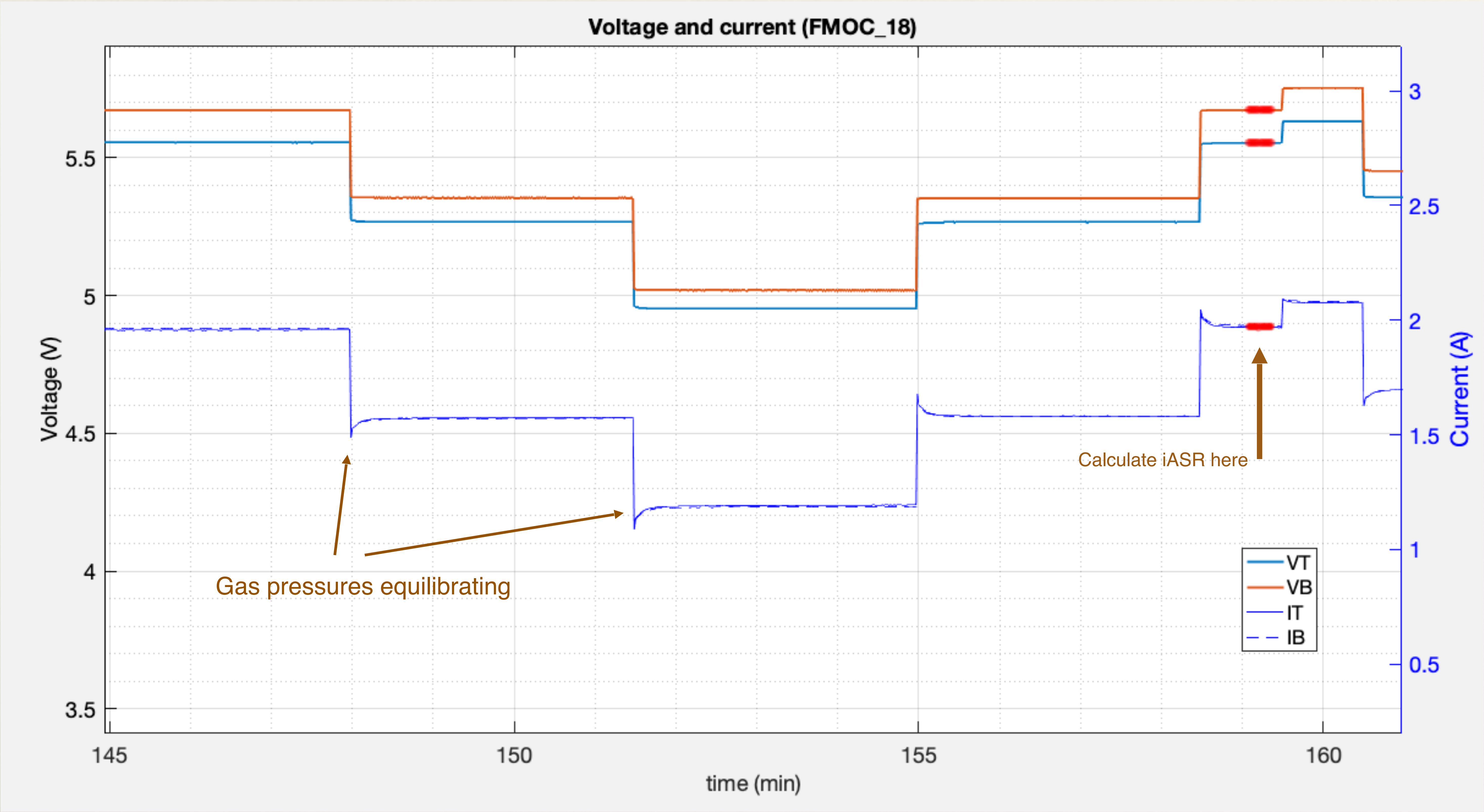
MOXIE
Mars Oxygen ISRU Experiment

* Eliminates current control loop lag (~4 minutes)
* *Fixing* the voltage reduces risk of exceeding the coking voltage threshold
* Onset of coking won't cause the voltage to increase, which would exacerbate the problem

Current and voltage



Details we can see with no control circuit lag



The next experiment: Pressure feedback

* We now carefully plan our combination of current/voltage and compressor speed to stay within the safe operating boundaries, using predictions of atmospheric density
* We plan to test a feedback mode, first on the ground and then on Mars, which will regulate the cathode pressure by adjusting the compressor speed.
* This will allow us to use a single run design for all times of day.

Where to find MOXIE data

PDS: The Planetary Atmospheres Node

- NASA Portal

HOME | ABOUT US | DATA AND SERVICES | EDUCATION | CONTACT US | EXTERNAL LINKS

Data Catalog | ADS NASA Astrophysics Data System | NASA Research Solicitations | Abstracts of Funded NASA Proposals

Atmospheres data and related services

- Atmospheres data
- Software

PDS Nodes

- PDS
- Atmospheres
- Geosciences
- Cartography and Imaging
- Navigation & Ancillary Information Facility (NAIF)
- Planetary Plasma Interactions (PPI)
- Ring-Moon Systems
- Small Bodies

Mars Summary Page

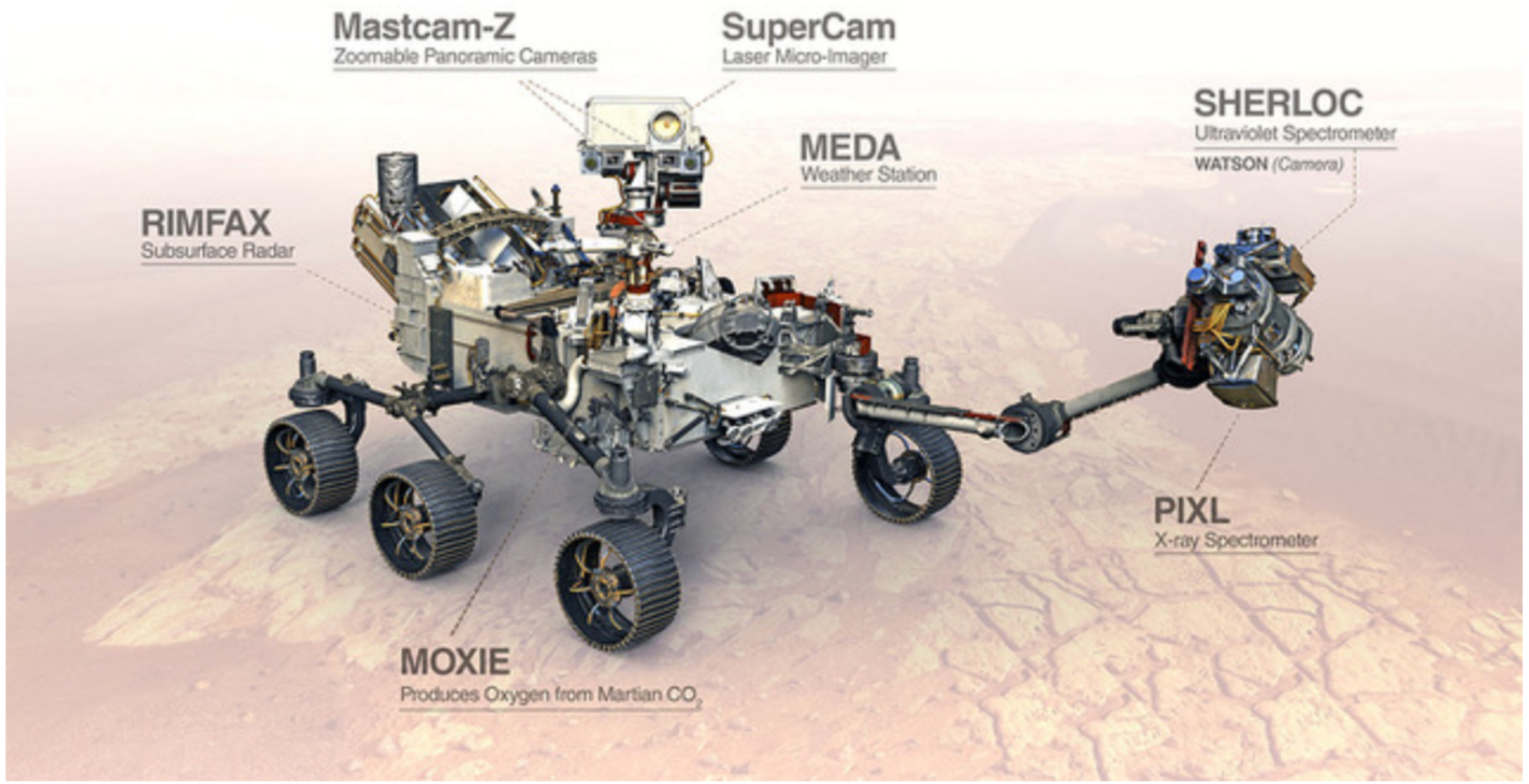
Mars Orbiter
- Mariner 9
- Viking Orbiter 1
- Viking Orbiter 2
- Mars Global Surveyor
- Mars Odyssey
- Mars Express
- Mars Reconnaissance Orbiter
- MAVEN

Mars Lander
- Viking Lander
- Mars Pathfinder
- Mars Exploration Rover
- Mars Phoenix Lander
- Mars Science Laboratory - Curiosity

Welcome to the Mars 2020 Perseverance Archive

MOXIE Mars Oxygen ISRU Experiment - CERTIFIED

Feb 22, 2021 (Ls 8.0 MY 36) to [ongoing]

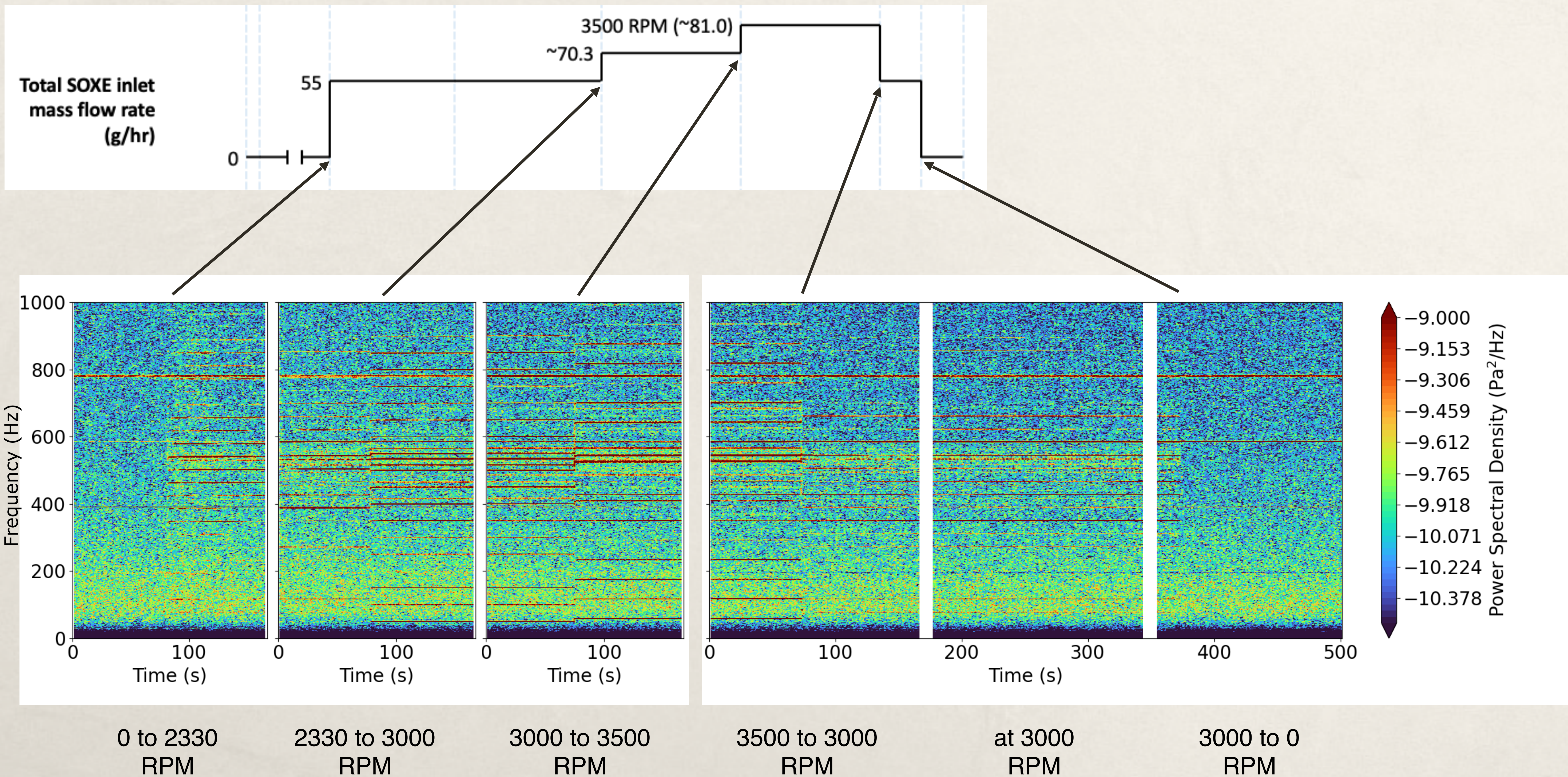


A schematic showing the location of MOXIE and other major instruments. Credit NASA/JPL-Caltec

Experiment Overview

MOXIE is a demonstration of In-Situ Resource Utilization (ISRU) technologies to enable propellant and consumable oxygen production from the Martian atmosphere. This demonstration is a precursor to developing the

Listening to the MOXIE compressor

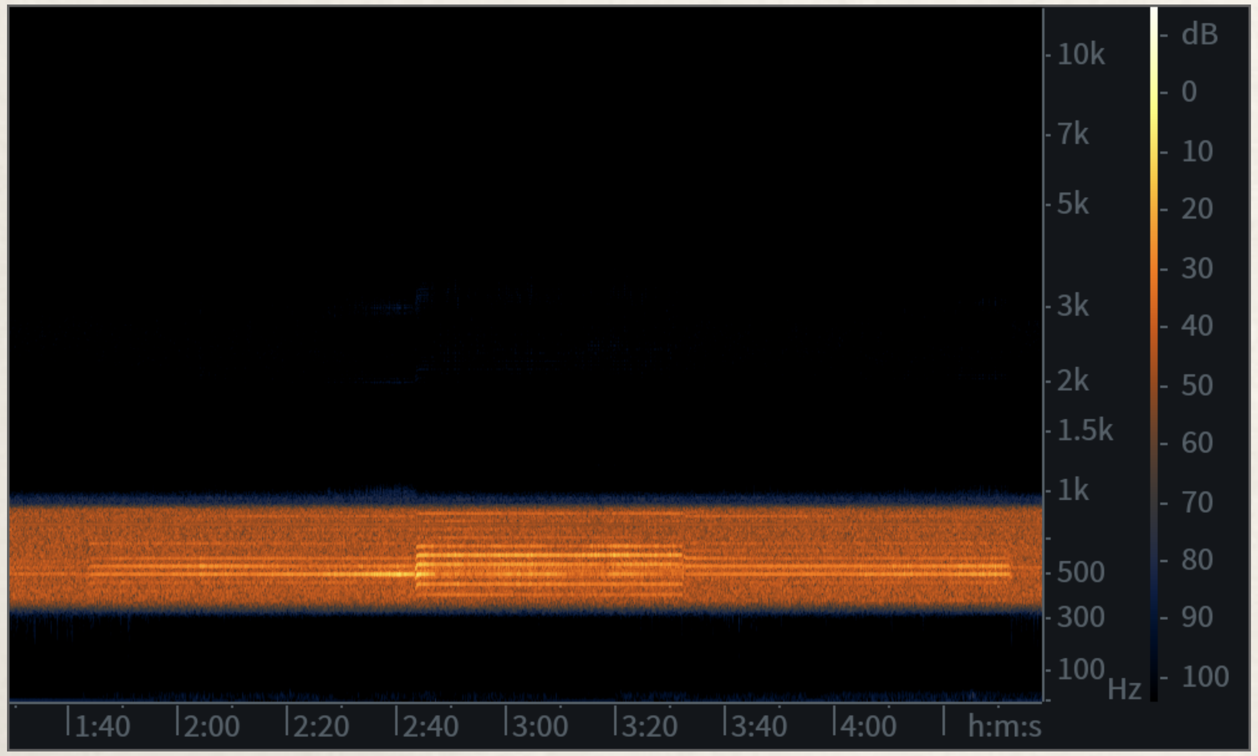


Supercam microphone spectrograms (courtesy Chide et al.)

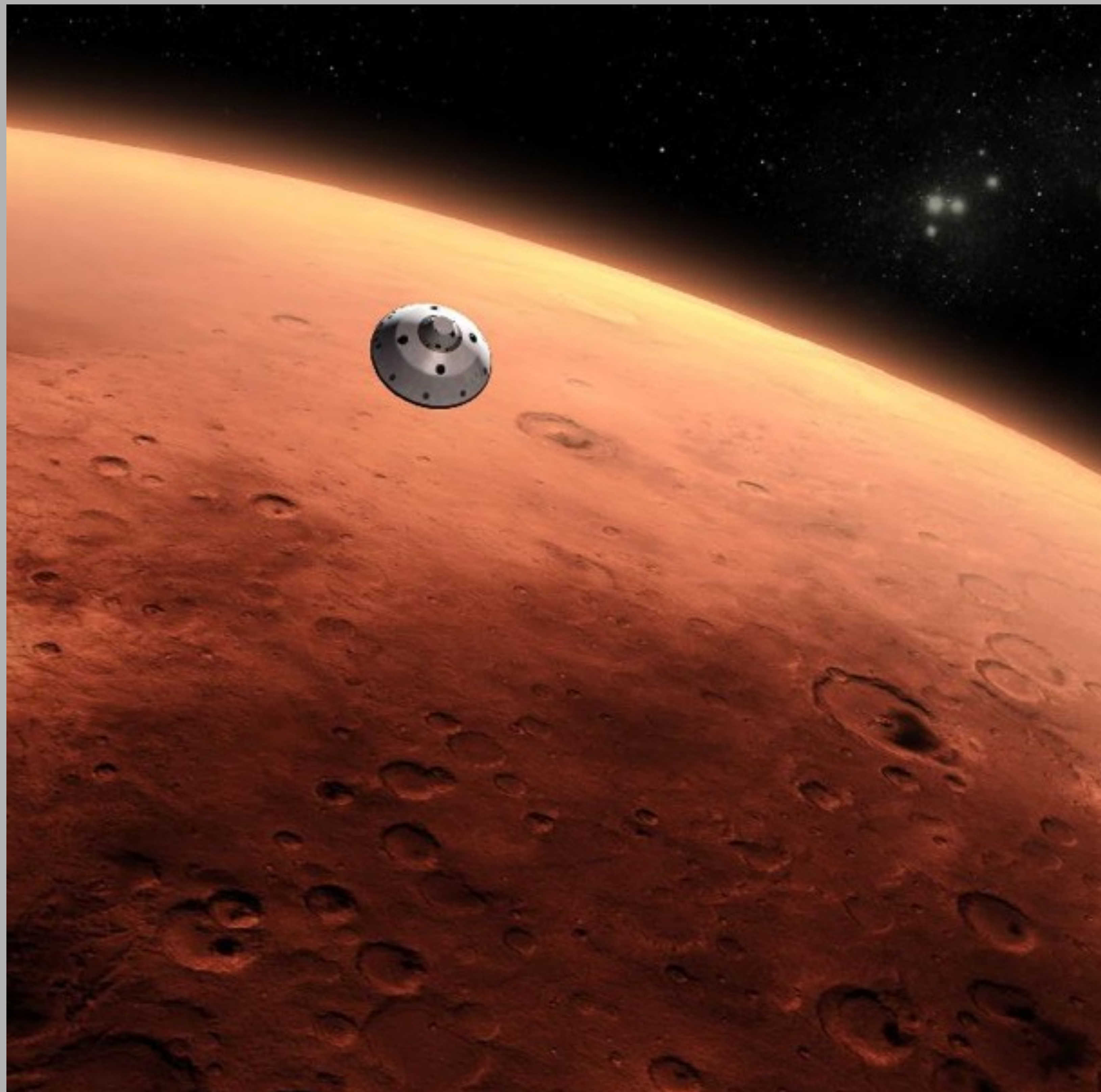
MOXIE compressor recorded by SCAM mic

Sol 276 (turn-on)

Sol 96 (RPM change)



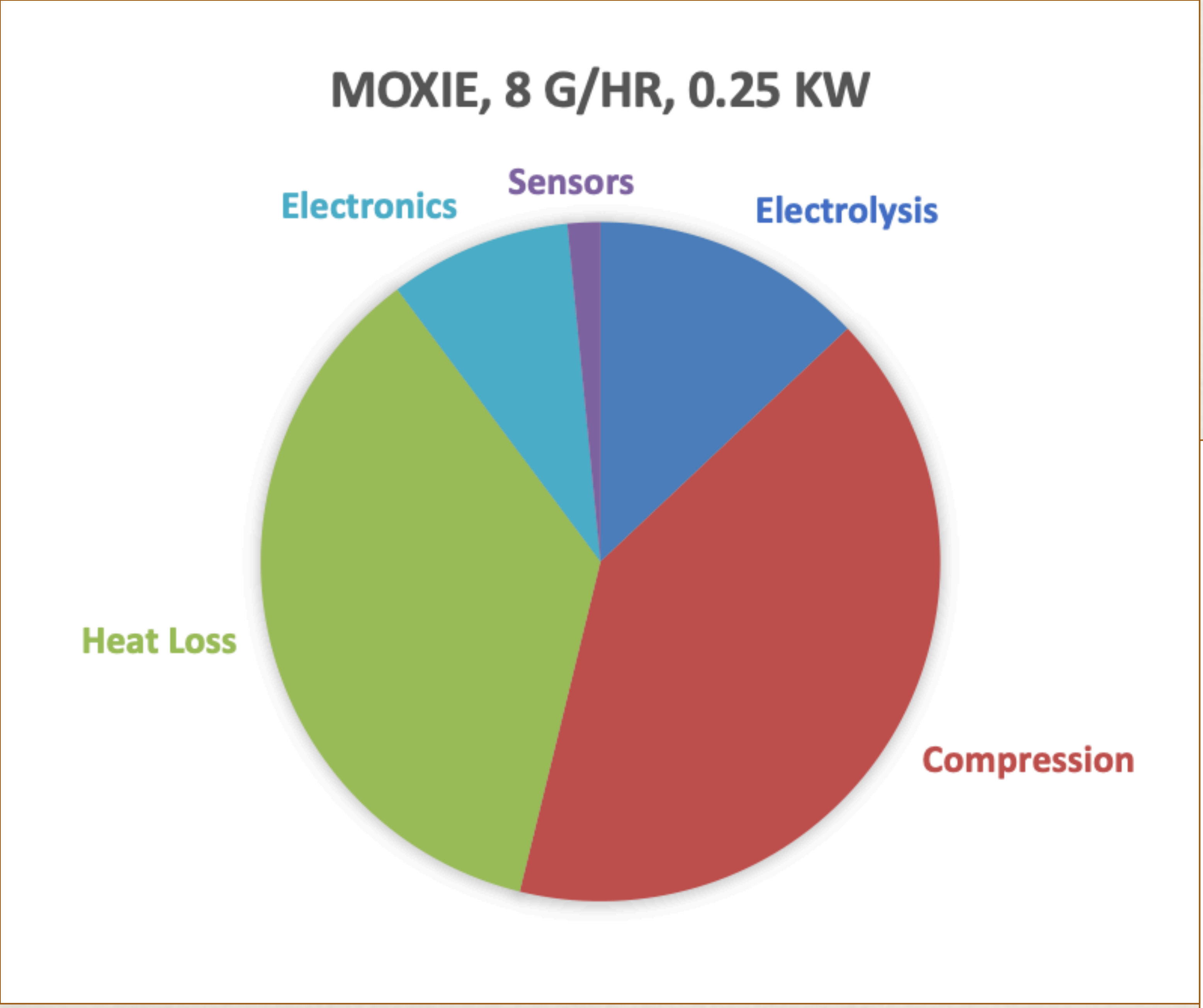
Credit: Sam Hoffman

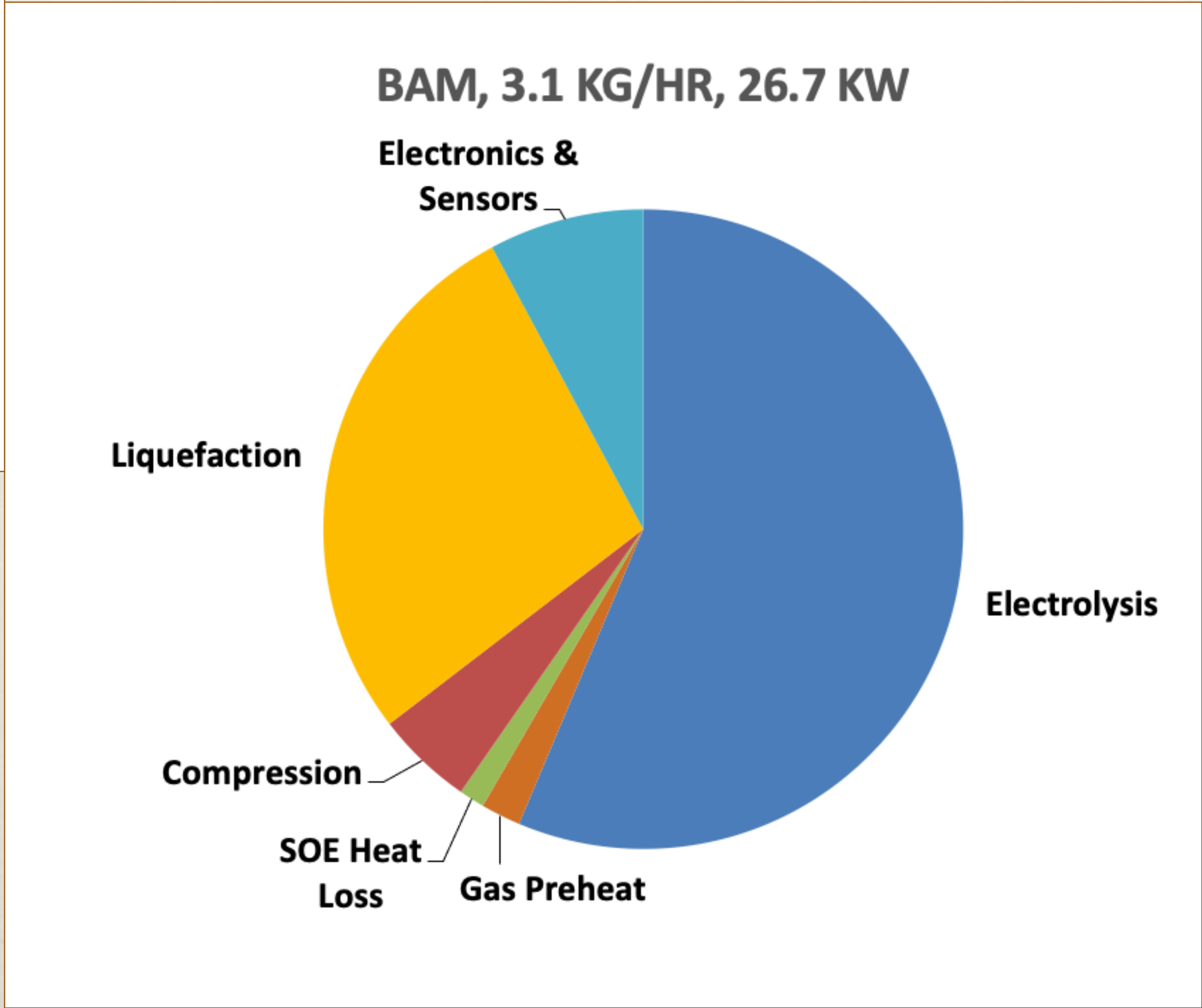


BAM!

MULTI-OBJECTIVE SYSTEM OPTIMIZATION OF A MARS ATMOSPHERIC ISRU PLANT

Eric Hinterman | Thesis Defense | 05.03.22





Full-system design, modeling, and analysis by Eric Hinterman, PhD

Longer-term applications

MOXIE
Mars Oxygen
ISRU Experiment

* Evolution to co-electrolysis for fuel & oxidizer
* Custom applications (e.g. habitat or pressurized rover oxygen replenishment)
* CO fuels
* Energy storage?

Sponsors and Partners

MOXIE
Mars Oxygen
ISRU Experiment

Massachusetts Institute of Technology

NASA Jet Propulsion Laboratory
California Institute of Technology

OxEon energy

CERAMATEC

air squared

DTU

University of Copenhagen

ASU Arizona State University

Imperial College London

NASA Johnson Space Center

MOXIE
MARS OXYGEN
ISRU EXPERIMENT

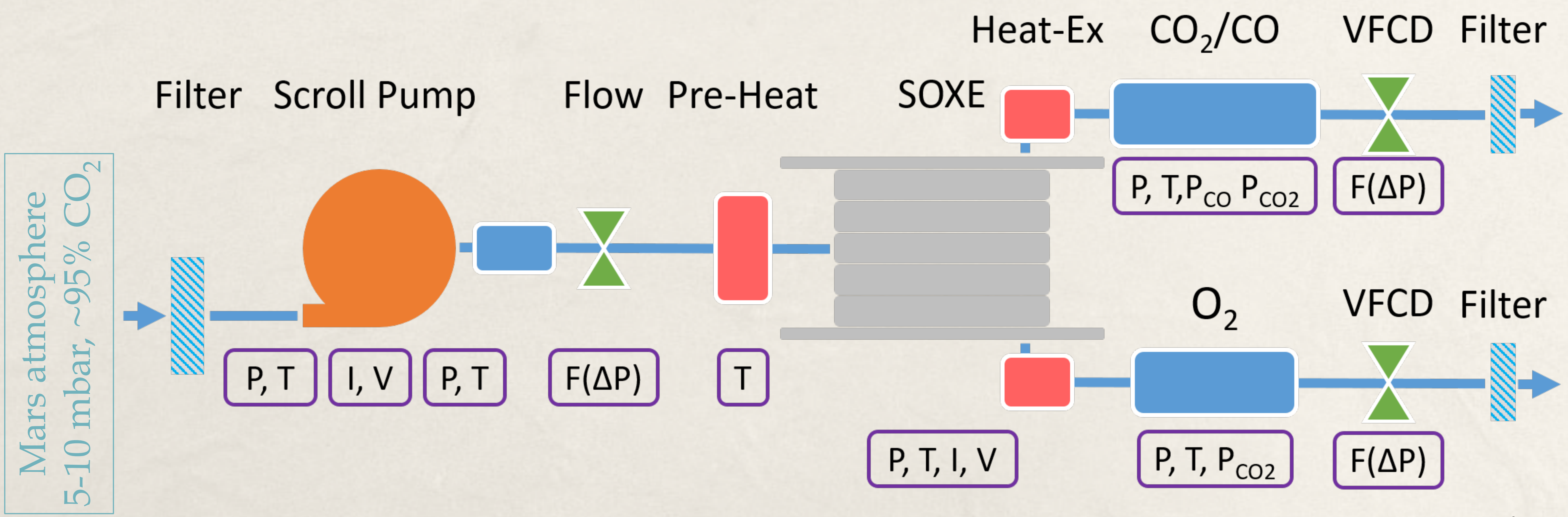
* Supported by HEOMD and STMD
* Mars 2020 Project managed by SMD

MOXIE
Mars Oxygen
ISRU Experiment

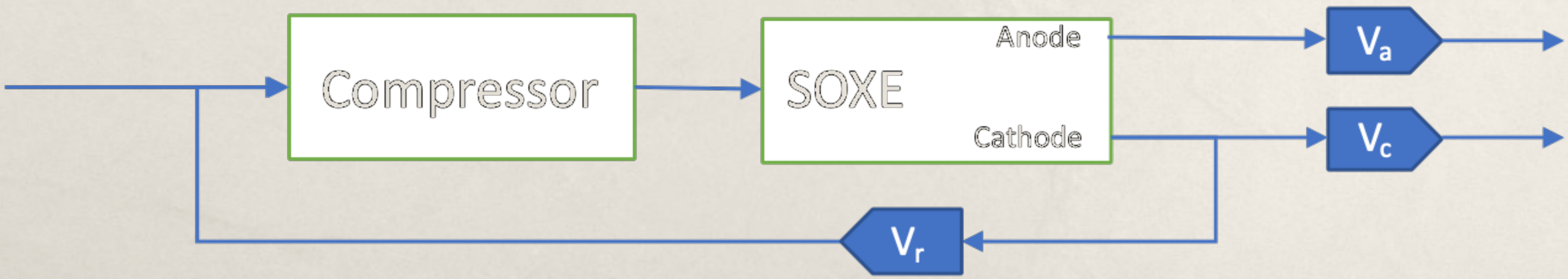
Backup

To be updated

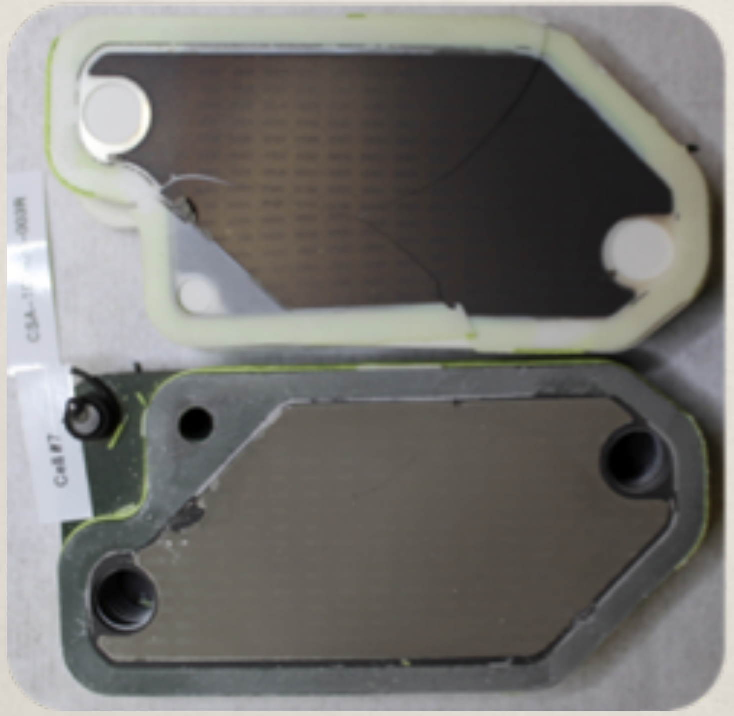
How MOXIE works

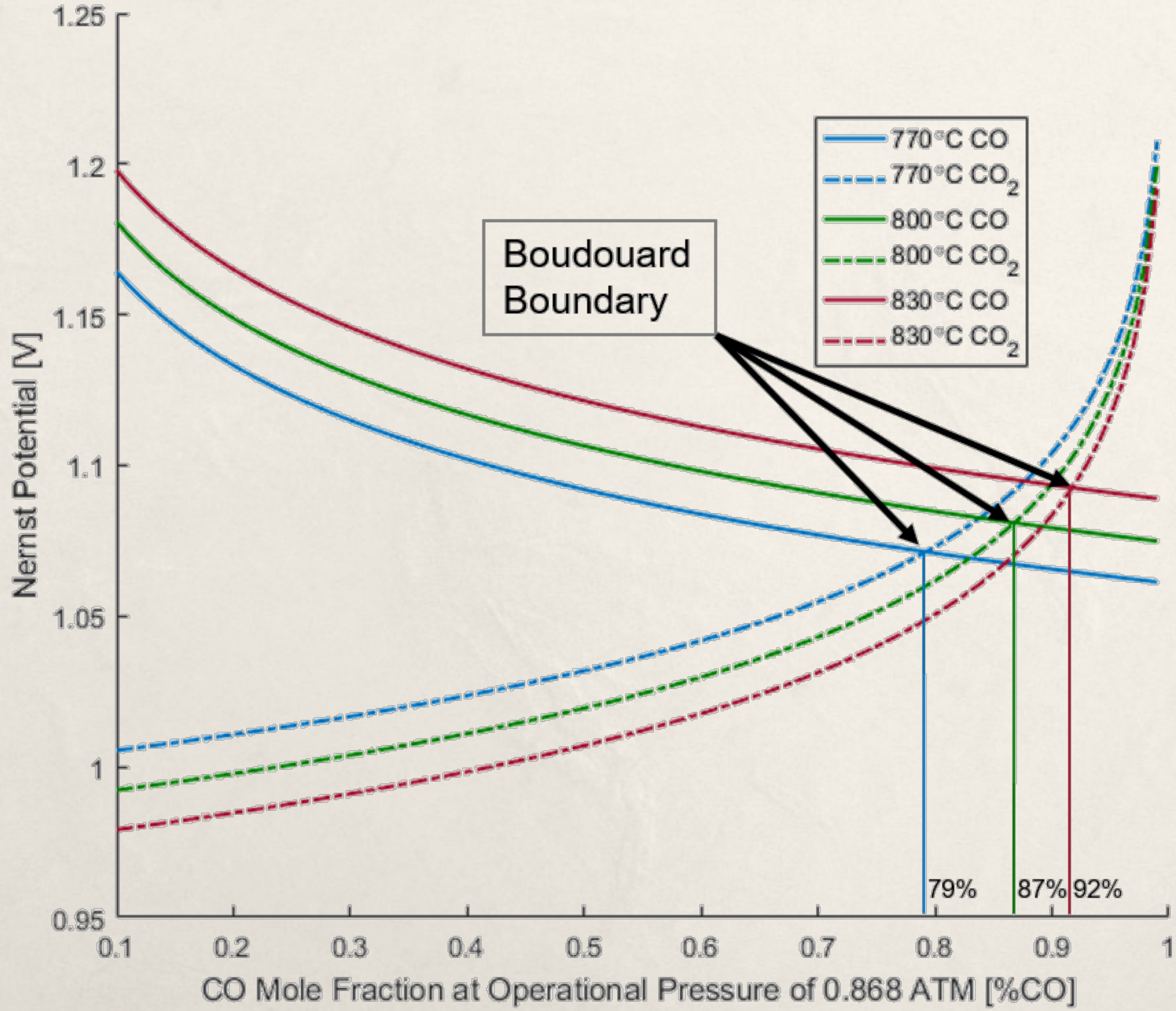


Meyen (2015)



Boudouard and Ni Oxidation Limits

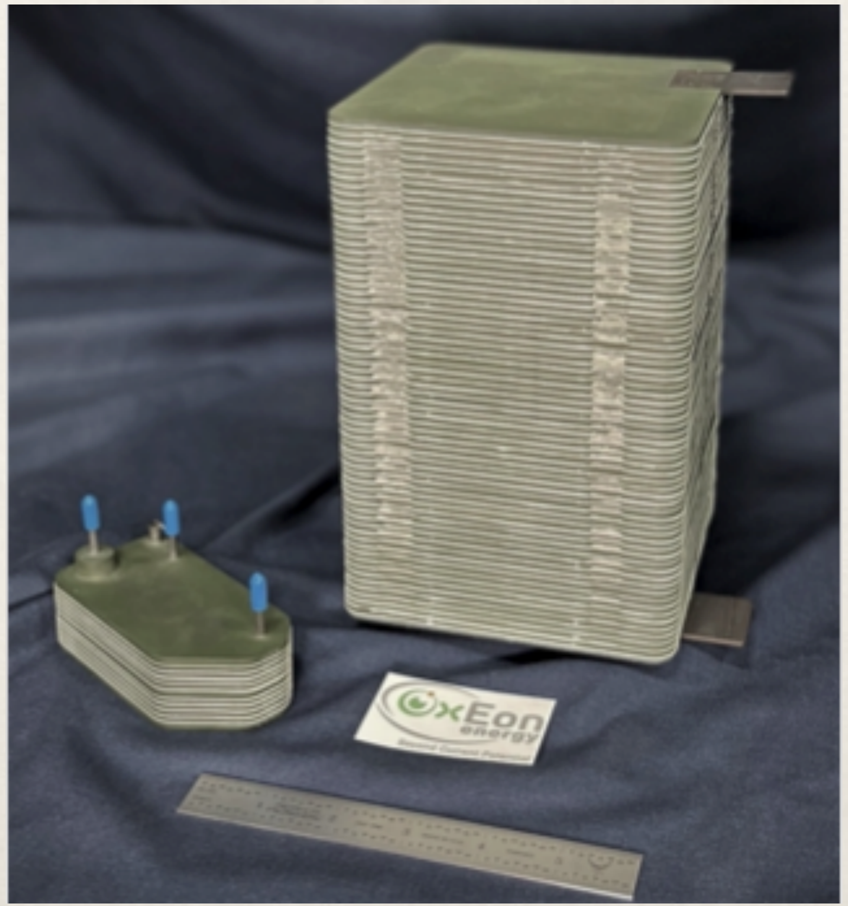




What we've learned, where we're going

MOXIE
Mars Oxygen ISRU Experiment

* MOXIE is a rugged and reliable system that can be scaled to meet human exploration needs in a straightforward way.
* The path to a full-scale MOXIE (BAM) is clear, if not without challenges. BAM needs to:
  * Produce >200x more oxygen
  * Operate continuously for over a year!
  * Be smarter and more adaptive



Things to improve for the next generation

* Power efficiency
  * Low density operation
  * Reduced heat loss
  * Gas heat exchange
  * Minimizing inlet tube heating
* Fault mitigation and recovery
  * Carbon (coking) avoidance
  * Preventing cathode oxidation
* Extended operation
  * e.g. launch-tolerant compressor bearings
* Dust mitigation
  * Most entrained dust will not follow airflow through a baffle!
  * We need a filter material that is less resistant to flow
* Monitor & control
  * Voltage sense leads (to eliminate series resistance errors)
  * Flow control and measurement
* Balance of Plant

SOXE robustness

* Carbon deposition is avoidable by careful selection of operating voltages, temperatures, and flow rates
* Cathode oxidation has been mitigated by recirculating CO to the inlet
* Cycle-to-cycle (cool-heat) variation is significant but acceptable
  * ASR roughly doubled after 60 cycles in first test; New test underway.
  * Will get better as we learn about mechanisms and improve protocols
  * Not really relevant to full-scale system, which won't generally cycle
  * **Compensating by increasing cell area has little impact on overall M, V, P**
* Degradation from continuous long-term operation needs to be verified but expected to be low.

Run summary

OC #	FM-OC9	FM-OC10	FM-OC11	FM-OC12	FM-OC13	FM-OC14	FM-OC15	FM-OC16	FM-OC17	FM-OC18	TOTALS
Comment	1st oxygen!	1st microphone	1st daytime run	1st Temperature sweep (to determine series resistance)	1st flow sweep (to determine oxygen purity)	Generic nighttime run (intermediate density)	Generic nighttime run (low density)	Generic daytime run (lowest density, just after dust event)	Unbalanced stack current to determine middle lead resistance	Voltage Mode (summer night)	**10 runs**
Sol	60	81	100	155	176	241	276	317	444	467	
Total O2 (g)	5.4	6.9	6.9	8.9	8.1	6.9	6.8	6.7	9.0	8.0	**73.64 grams O2**
eak rate (g/hr)	6.0	8.0	8.0	6.0	6.9	7.6	7.2	7.0	7.6	7.6	
Duration (min)	59	74	71	96	82	74	74	74	97	86	**786.11 total minutes**
Time of day	Night	Night	Day	Night	Night	Night	Day	Day	Night	Night	
Microphone	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Predecessors	Aliveness test (Sol 4) RCT check (sol 13) Full health check (sol 14) Compressor sweep (sol 55)	Compressor sweep w/ microphone (sol 79)	Daytime compressor sweep w/ microphone (sol 96)	None	None	None	None	None	None	None	