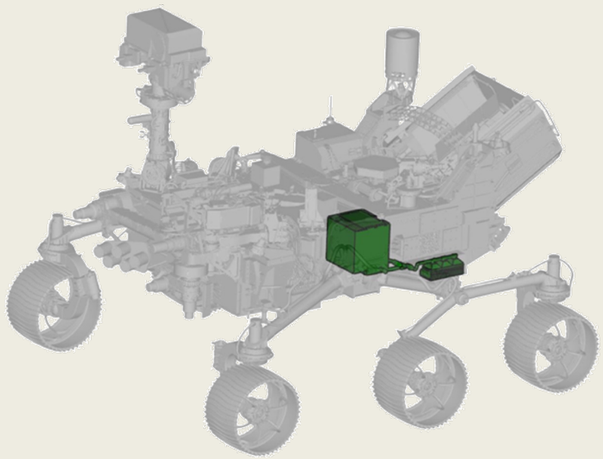
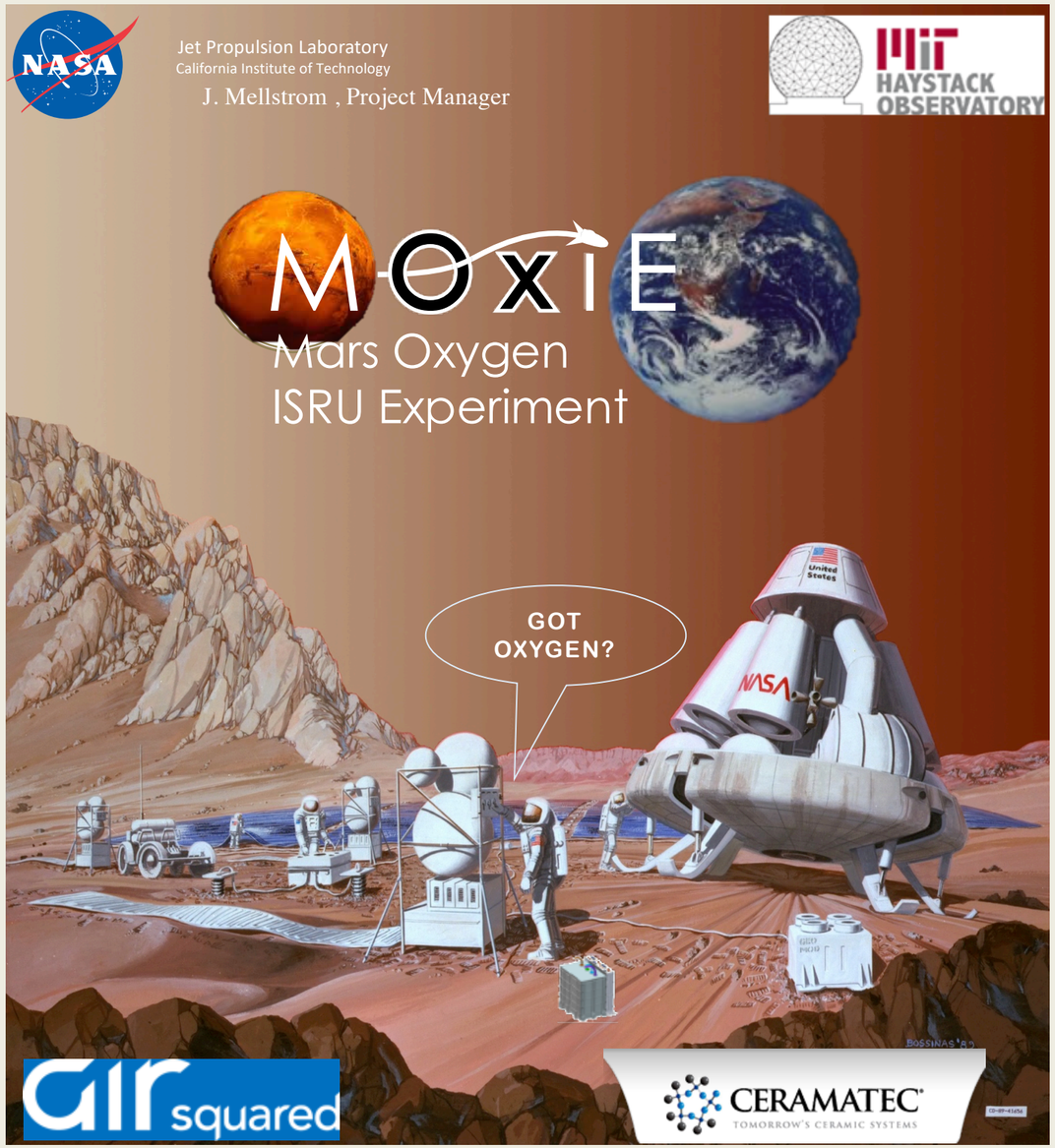
Michael Hecht for the MOXIE team
Space Resources Roundtable
June 7, 2024



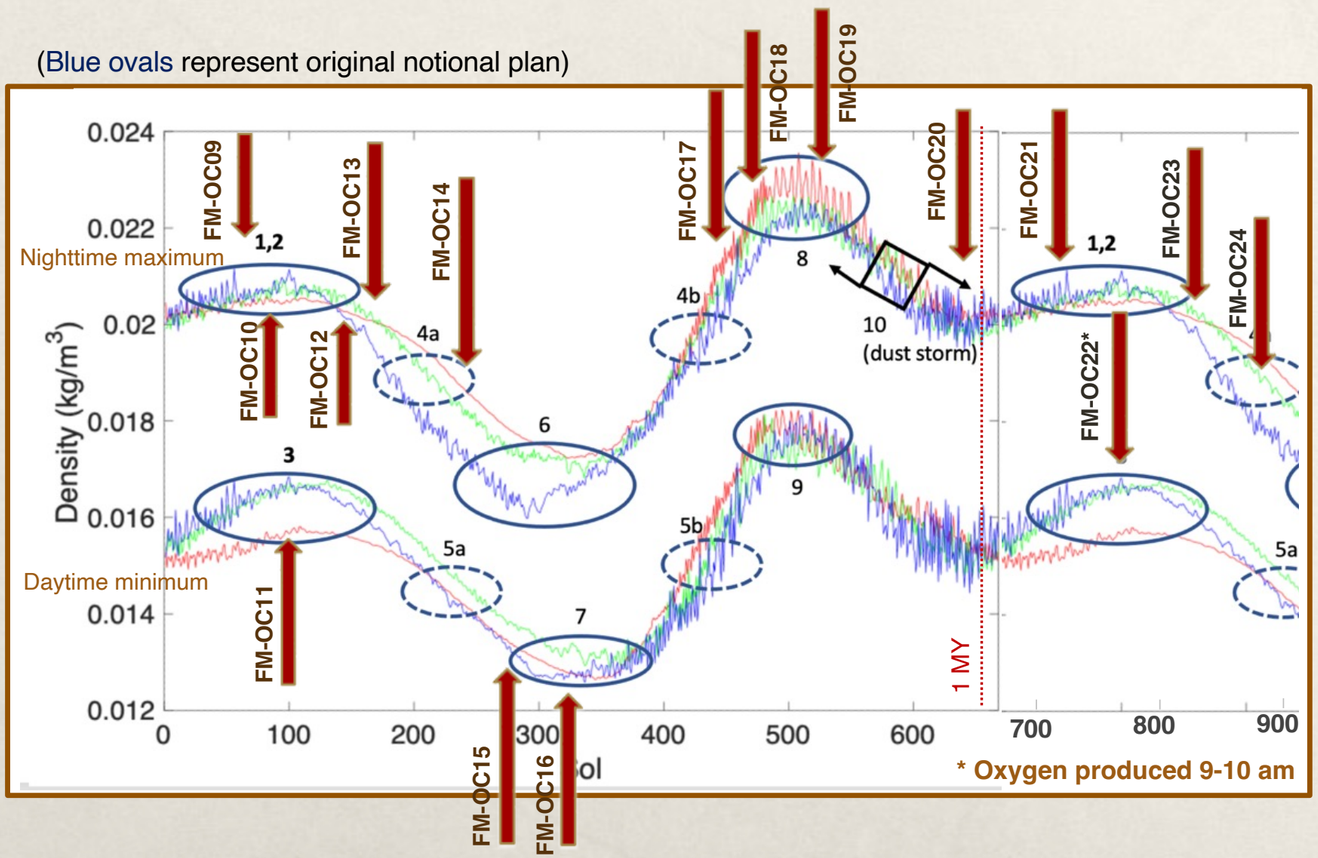


MOXIE: Epilogue

Operations summary

* 16 O_2-producing runs on Mars
* 122 g O_2 produced in 1213 minutes operation (average 6.1 g/hr)
* MOXIE mission ended programmatically as of Sept. 30, 2023

(Blue ovals represent original notional plan)



Accomplishments

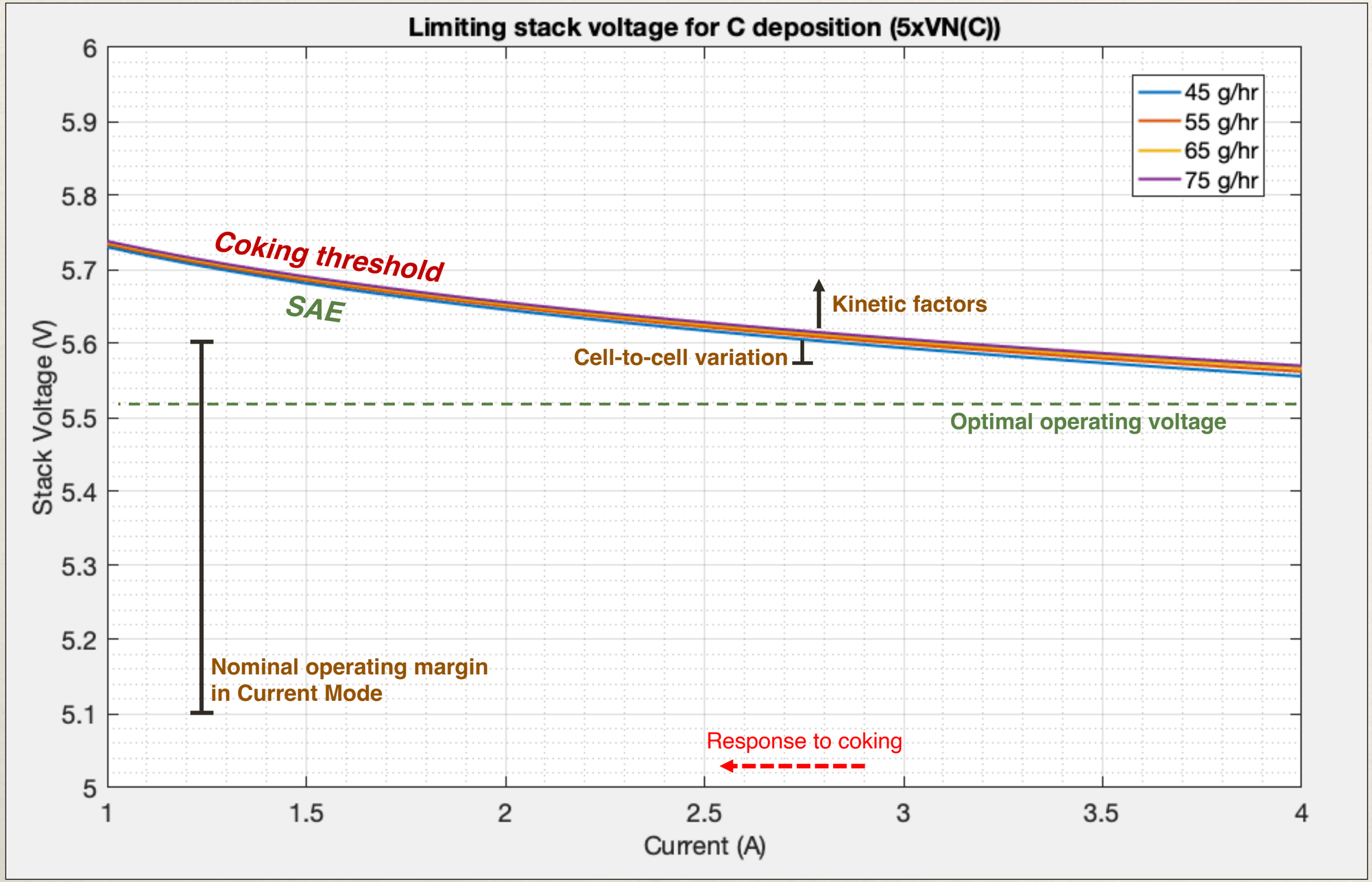
- Demonstrated
  - Operation over full range of environmental conditions (P, T, dust)
  - Tolerance to SOE heat-cool cycles without significant degradation
  - High production rate, 2x requirement (12 g/hr O_2)
  - High O_2 purity
  - Constant voltage mode
  - Constant pressure mode
  - Low pressure operation
  - High fidelity predictive performance model
  - Excellent agreement with lab results
- Determined
  - Lead resistances and other unknowns
  - Inlet tube warming
  - Dust penetration is negligible with baffle alone

The path to full-scale

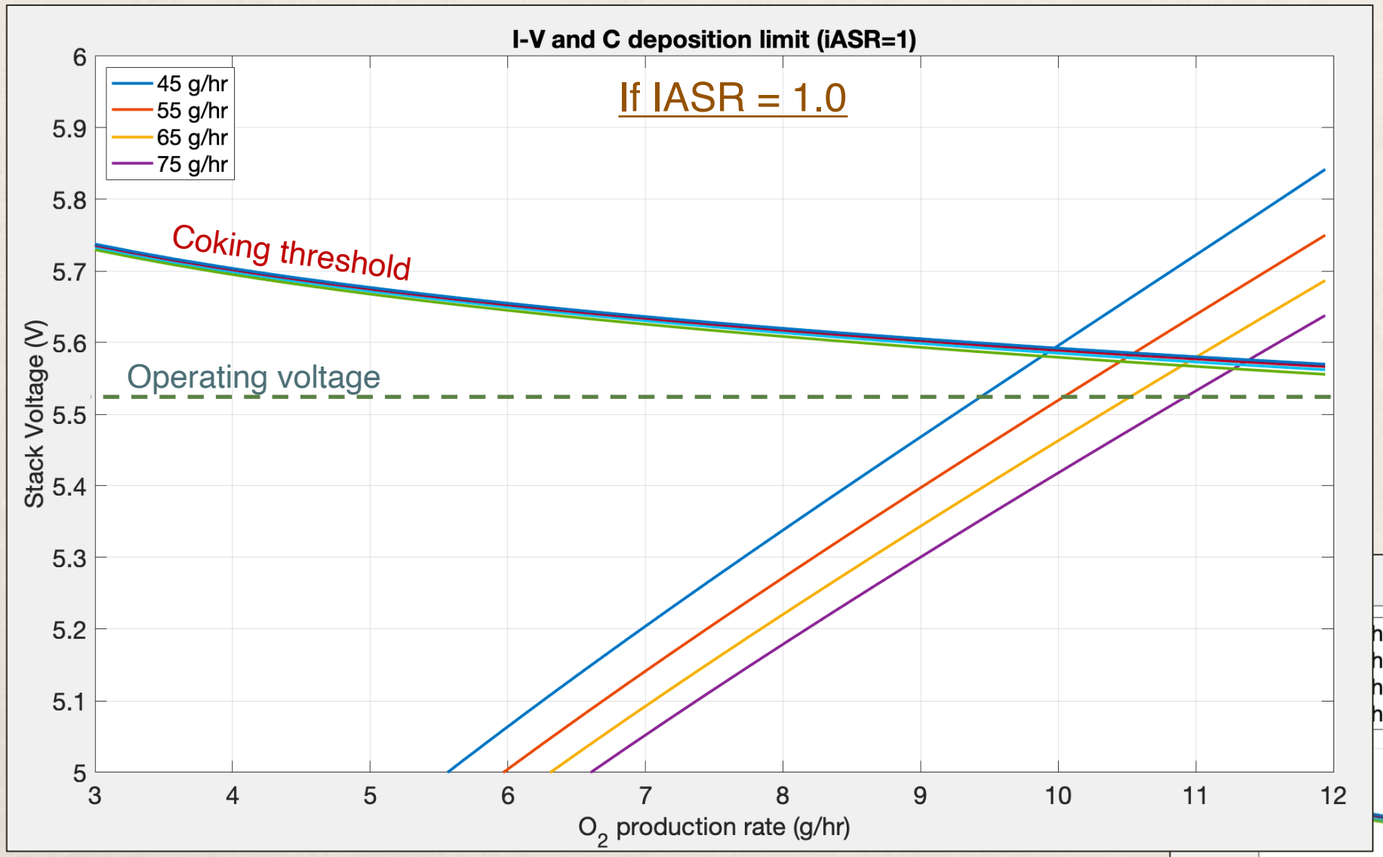
- System level
  - Operate continuously for over a year
  - Improved sensing & control
  - Lower resistance dust filtering
- Scaled-up SOE
  - Produce >200x more oxygen
  - Curtail heat loss with a better oven, heat exchange between inlet & outlet gas
- Scaled-up compressor
  - Dramatically reduce compression power with low density operation, controlled inlet temperature
  - Larger, lower speed for power efficiency
- Operations options
  - Constant voltage to safely maximize O_2 production
  - Fixed current, system design to constant production

A 60-cell stack developed by OxEon Energy offers 30x the active area of the MOXIE stack

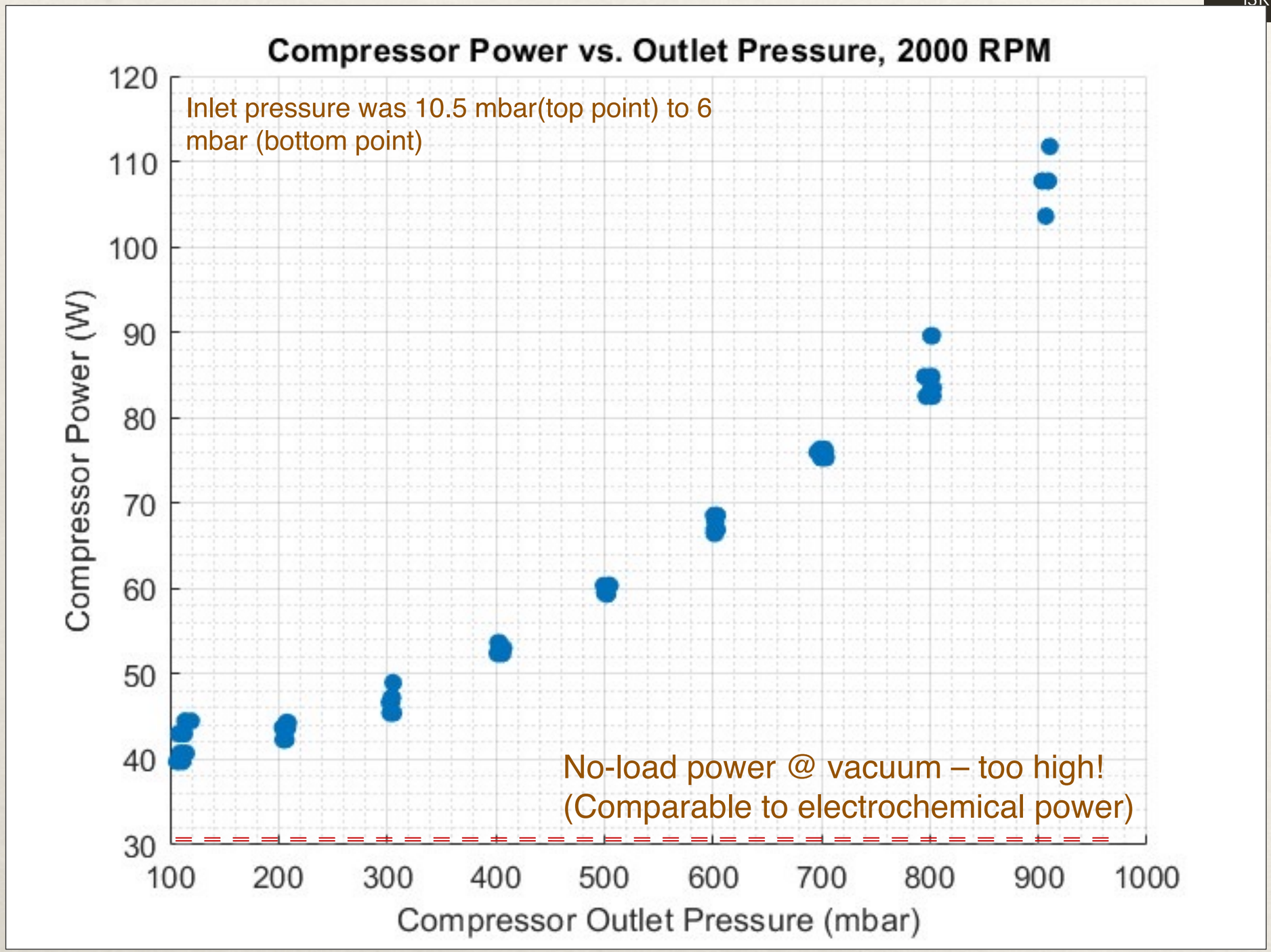
Why operate at fixed stack voltage?



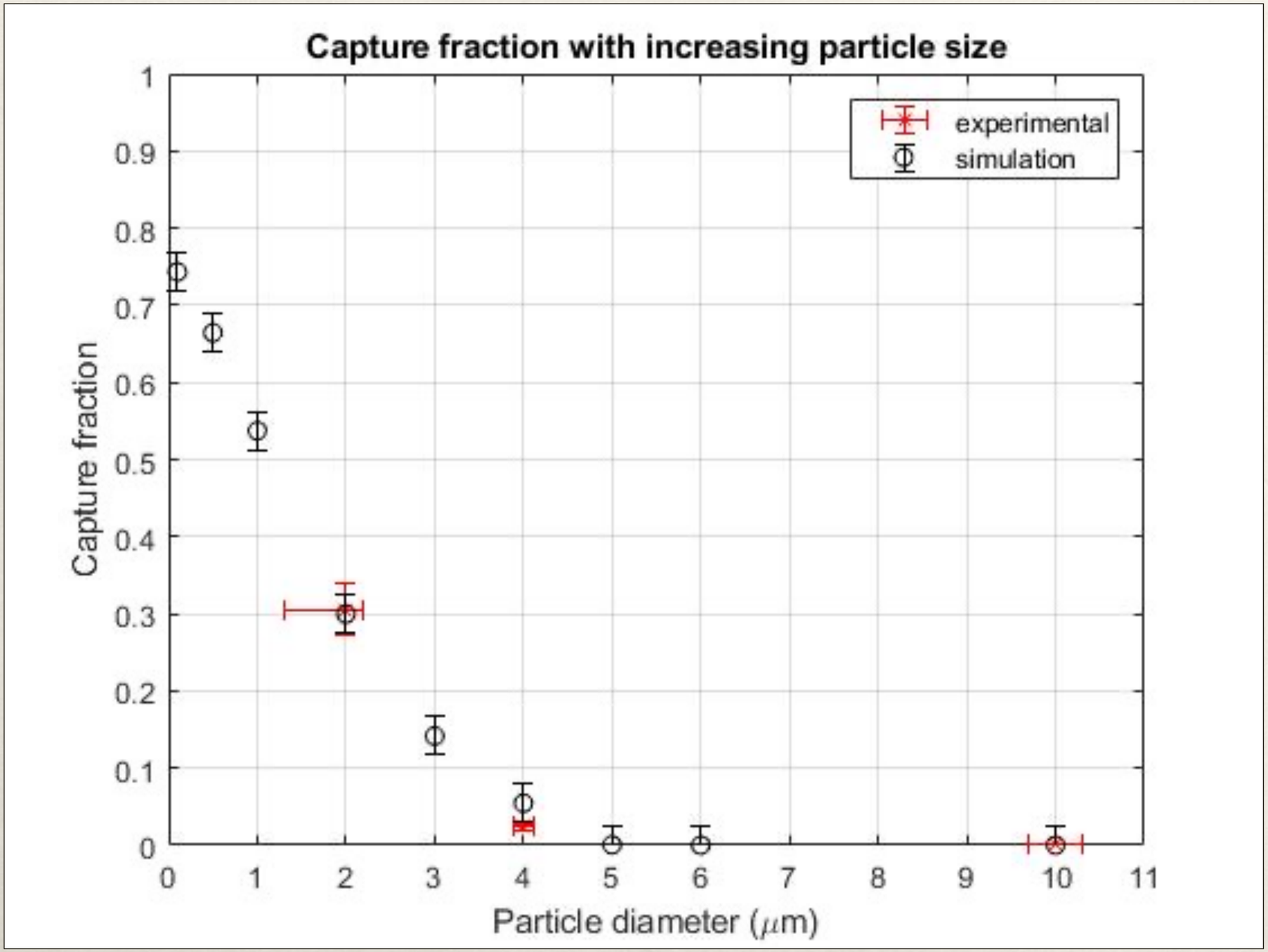
Variable production rate at fixed voltage



Operation at low pressure



Avoiding dust with a simple baffle



Longer-term applications

Mars Oxygen ISRU Experiment

* Evolution to co-electrolysis for fuel & oxidizer
  * Follow by methanation reactor or Fischer-Tropsch for liquid/solid fuels
* Custom applications (e.g. habitat or pressurized rover oxygen replenishment)
* CO fuels (e.g. for hopper)
* Energy storage?

What's next for MOXIE?

A proposal from Jim Cutts, JPL

J. Izraeleitz et al, *Test Flights… of a Prototype Venus Aerobot,* LPSC 2023

Sponsors and Partners

Massachusetts Institute of Technology

Jet Propulsion Laboratory
California Institute of Technology

OxEon energy

CERAMATEC
TOMORROW'S CERAMIC SYSTEMS

GIR squared

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Lunar Outpost

UNIVERSITY OF COPENHAGEN

ASU Arizona State University

Imperial College London

NASA Johnson Space Center

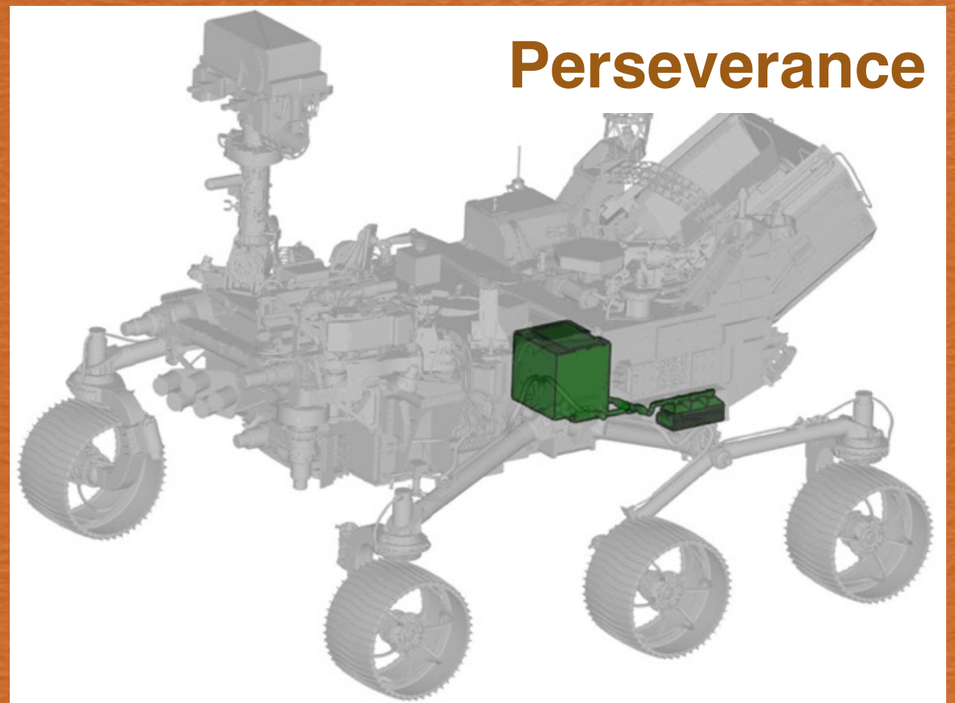
MOXIE
MARS OXYGEN
ISRU EXPERIMENT

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

Backup

More MOXIE

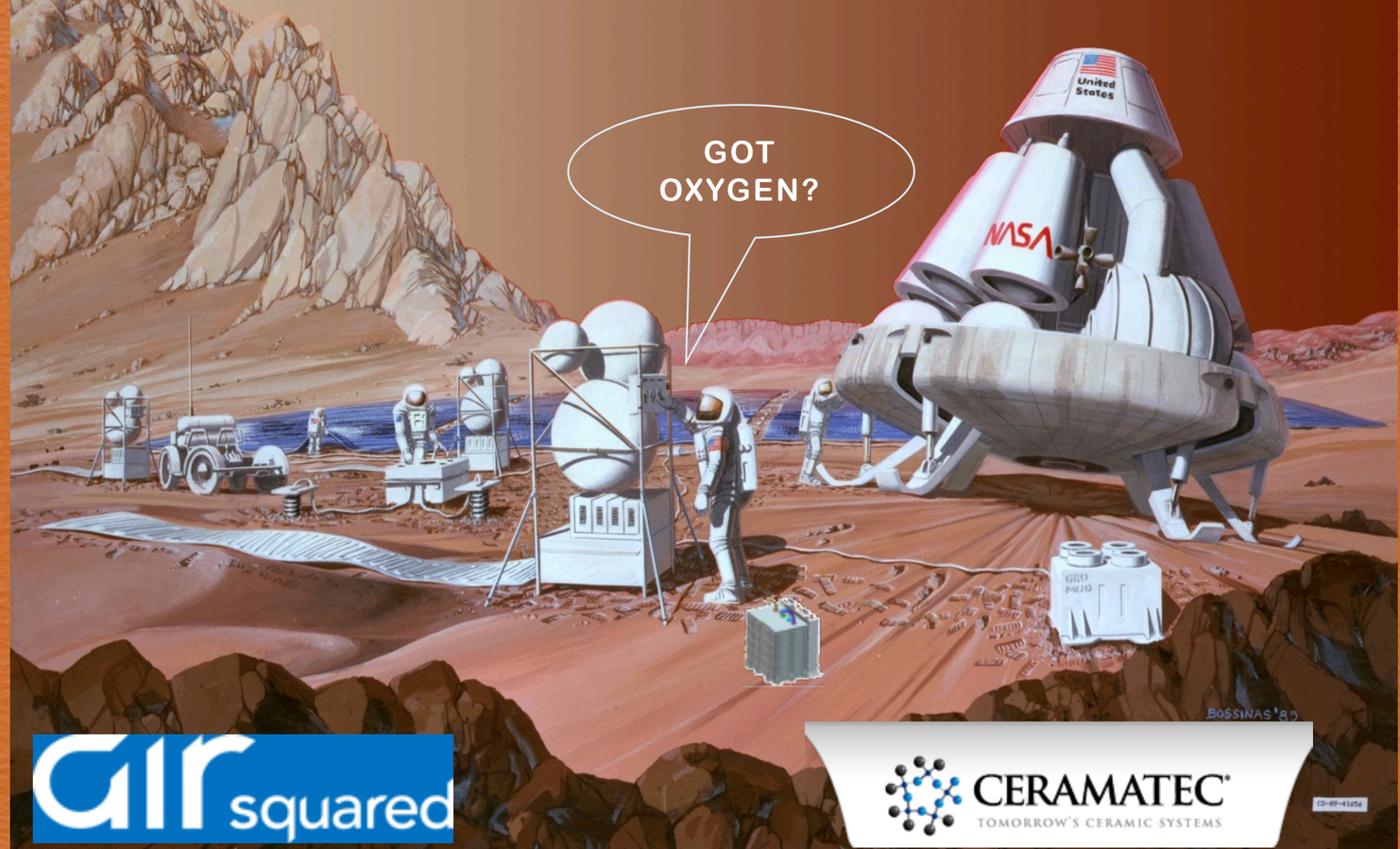
- **A scale model of an In Situ Resource Utilization (ISRU) plant for a human mission.**
- **Makes 6-12 g of O_2 per hour from atmospheric CO_2**
  - Like a small tree, or ~50% of what a person breathes
  - Limited by available power to ~1:200 full scale production



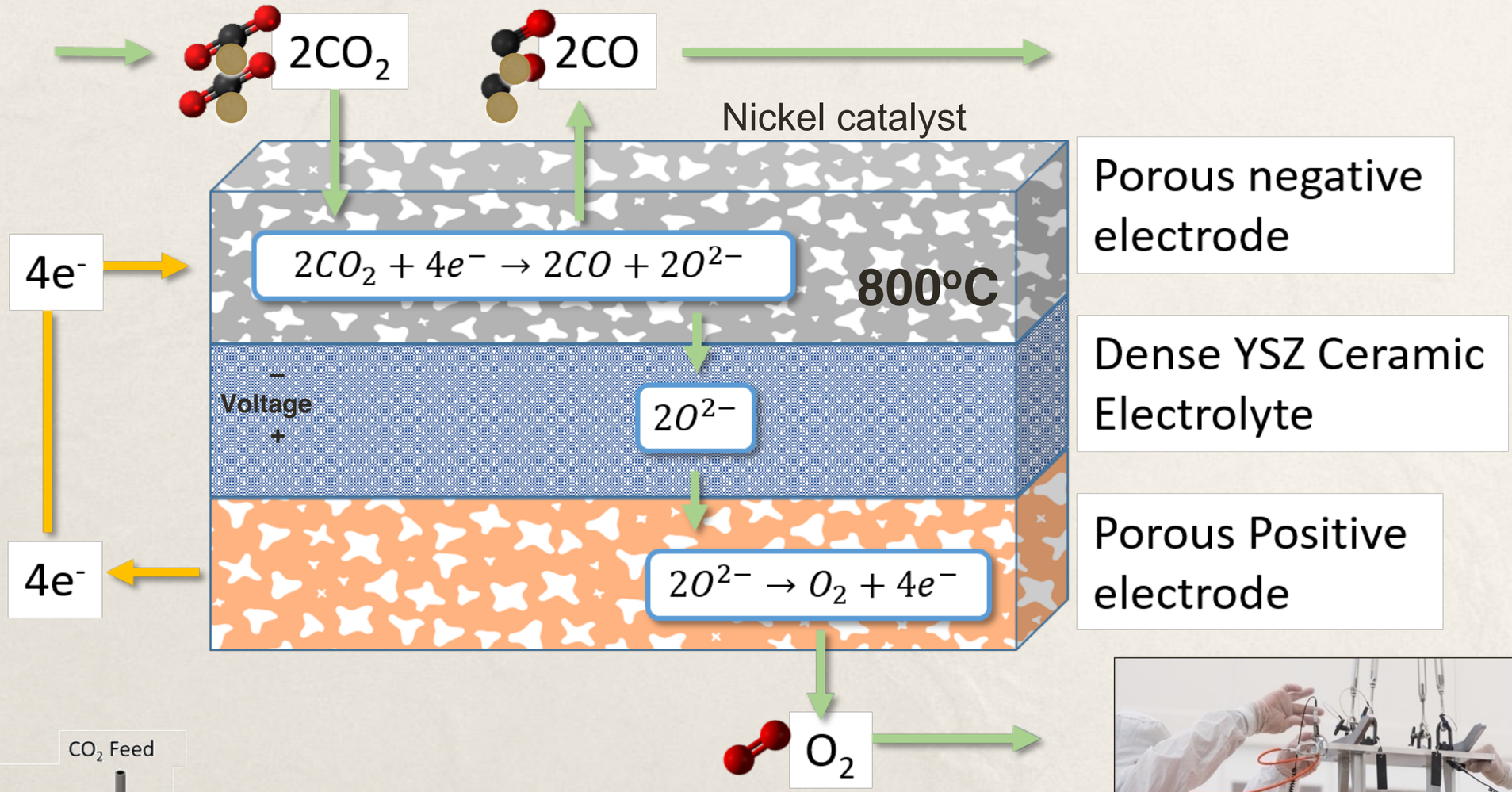
Jet Propulsion Laboratory
California Institute of Technology
J. Mellstrom , Project Manager

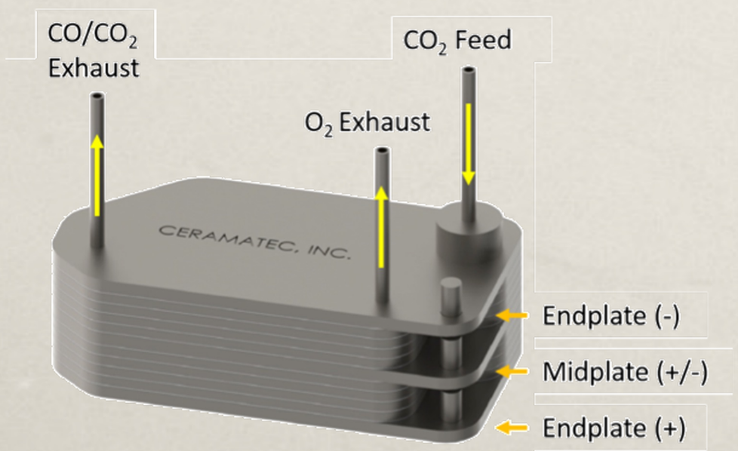
HAYSTACK OBSERVATORY

MOXIE
Mars Oxygen ISRU Experiment



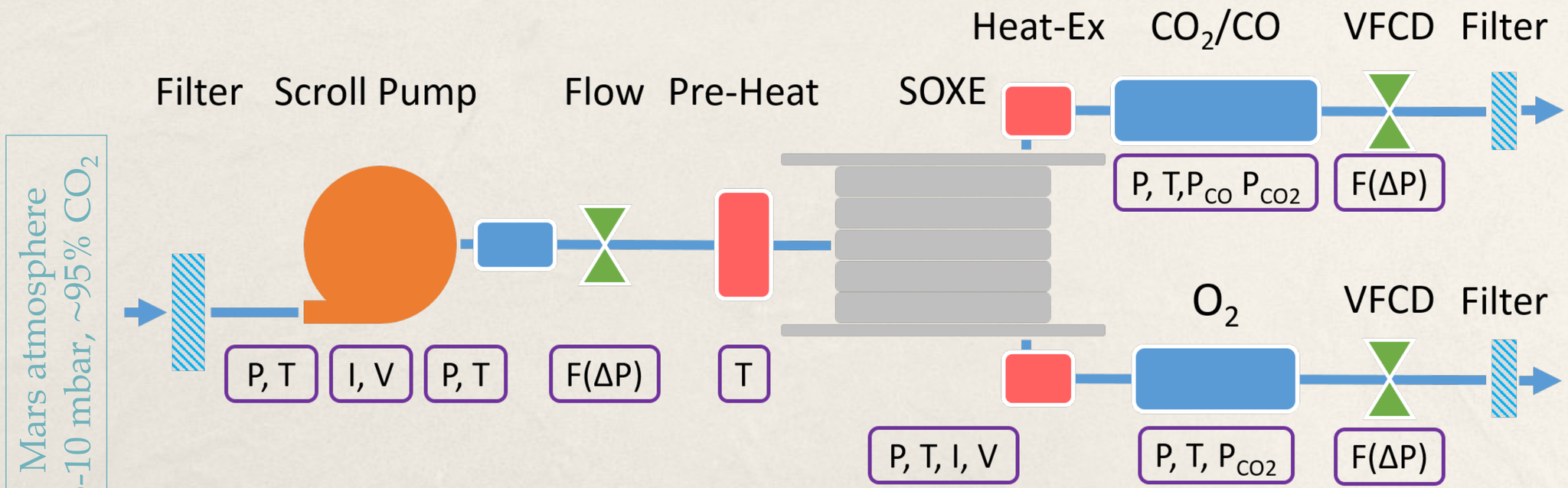
The Solid OXide Electrolysis (SOXE) cell



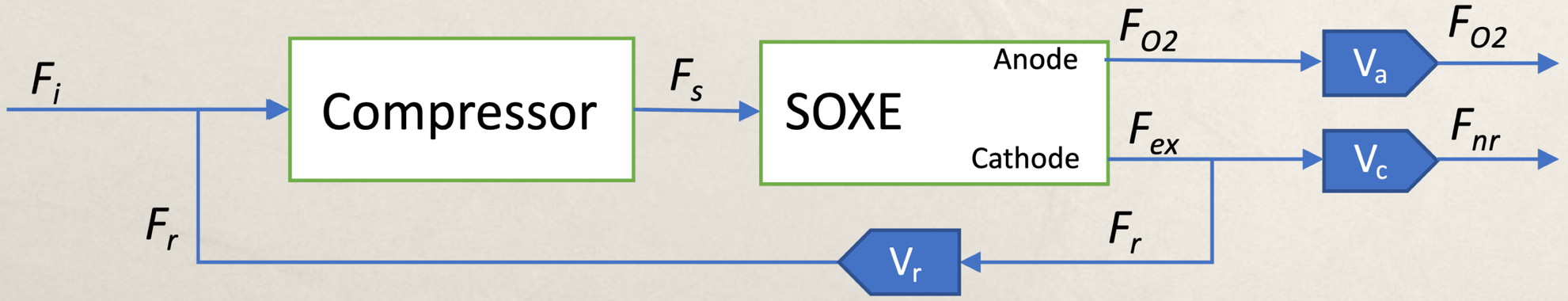


SOE: $CO_2 \rightarrow CO + O$
SOFC: $CO + O \rightarrow CO_2$

General architecture



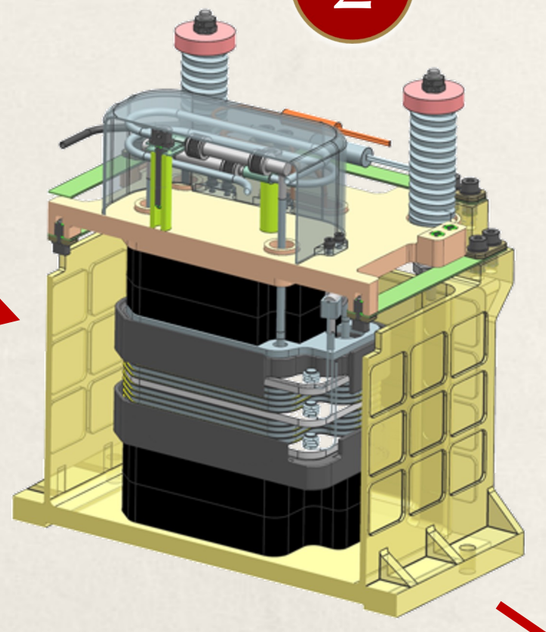
Meyen (2015)



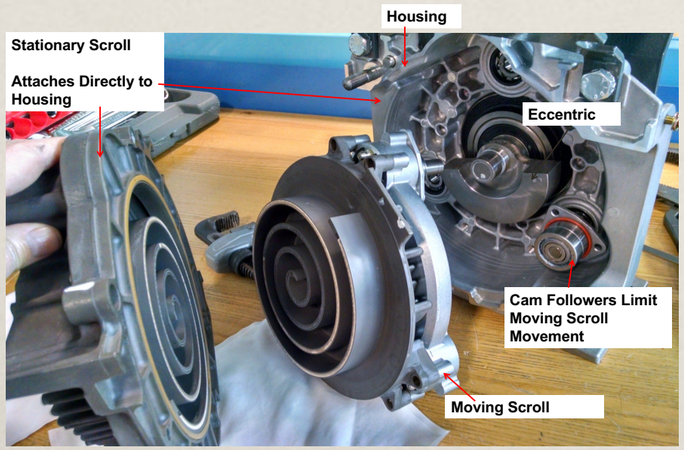
Putting it together

1

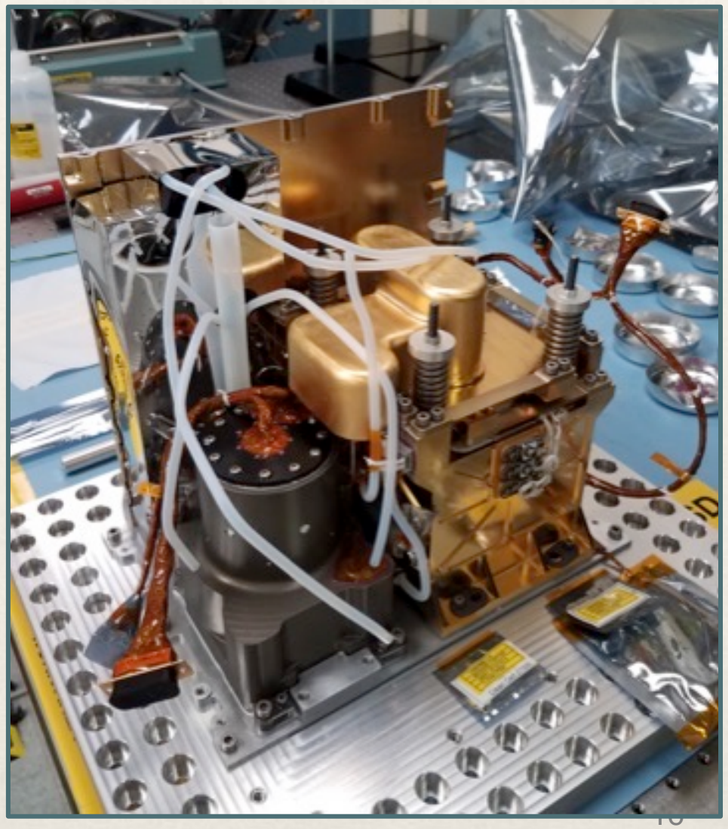
2



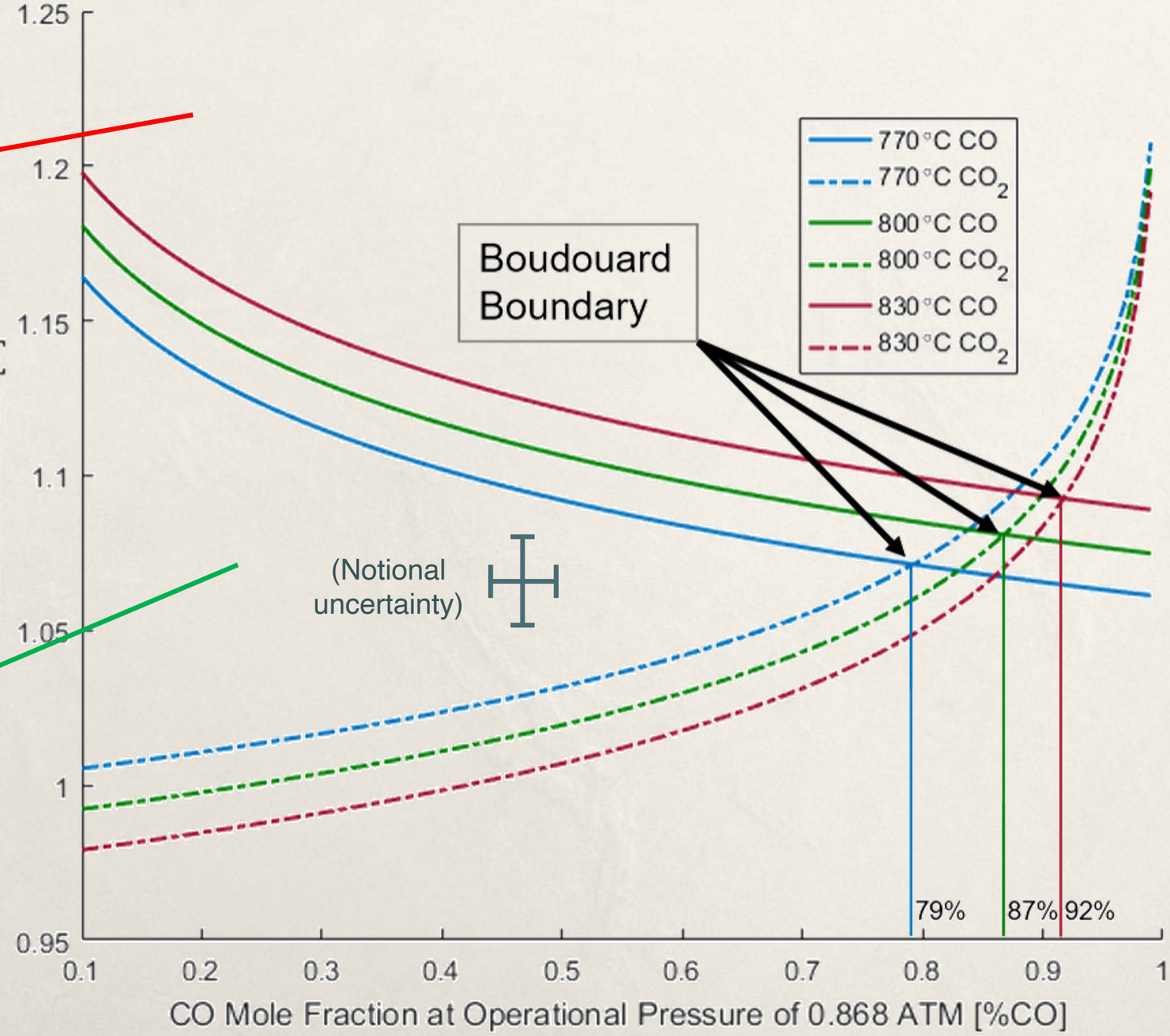
3

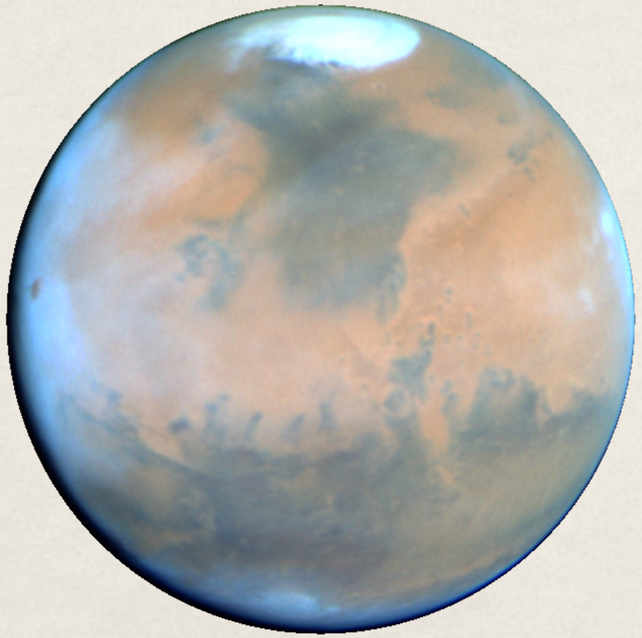


4



What makes this hard? *Uncertainties* affecting efficiency and safely.





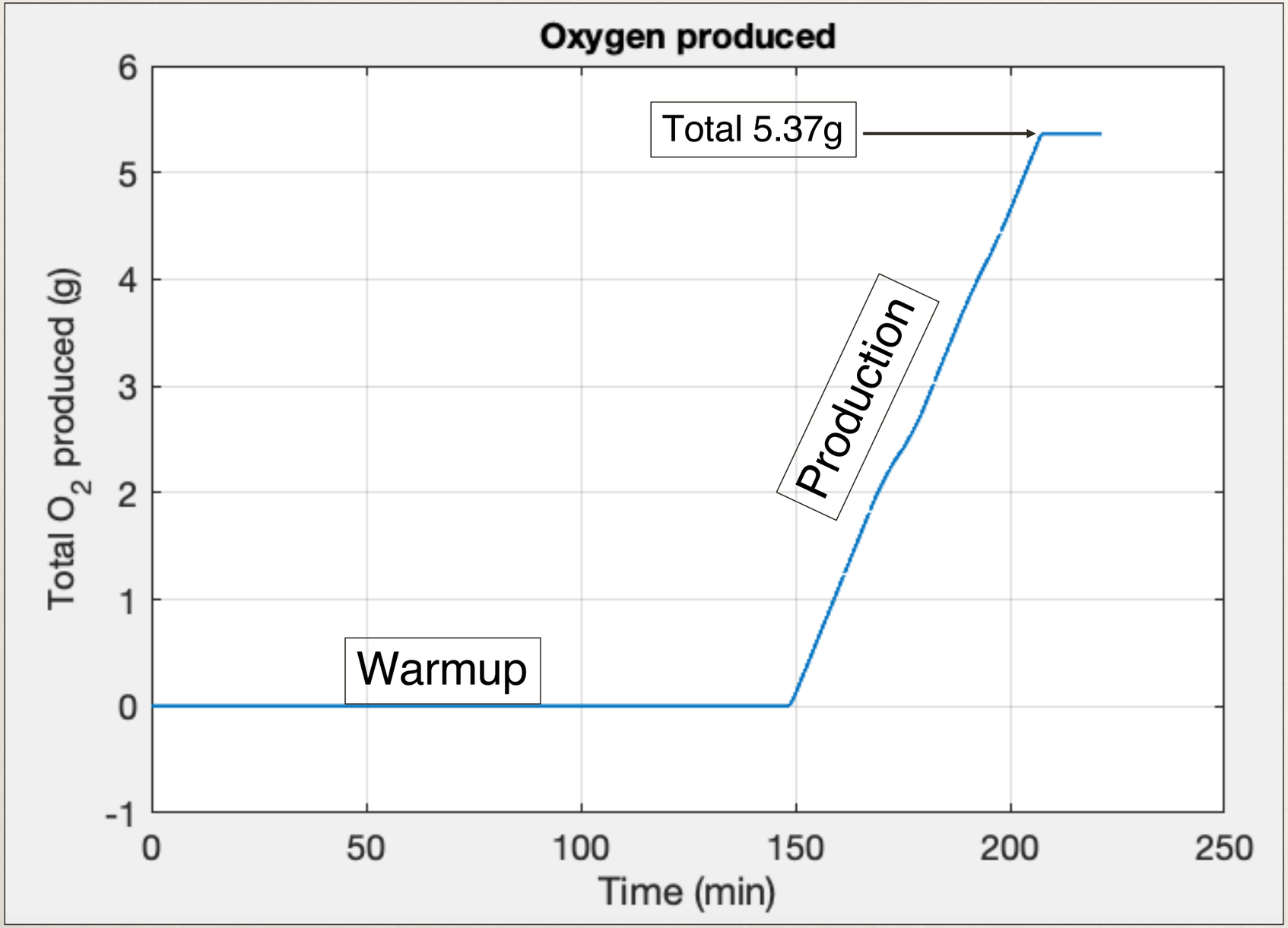
MOXIE
Mars Oxygen
ISRU Experiment

Going To Mars!

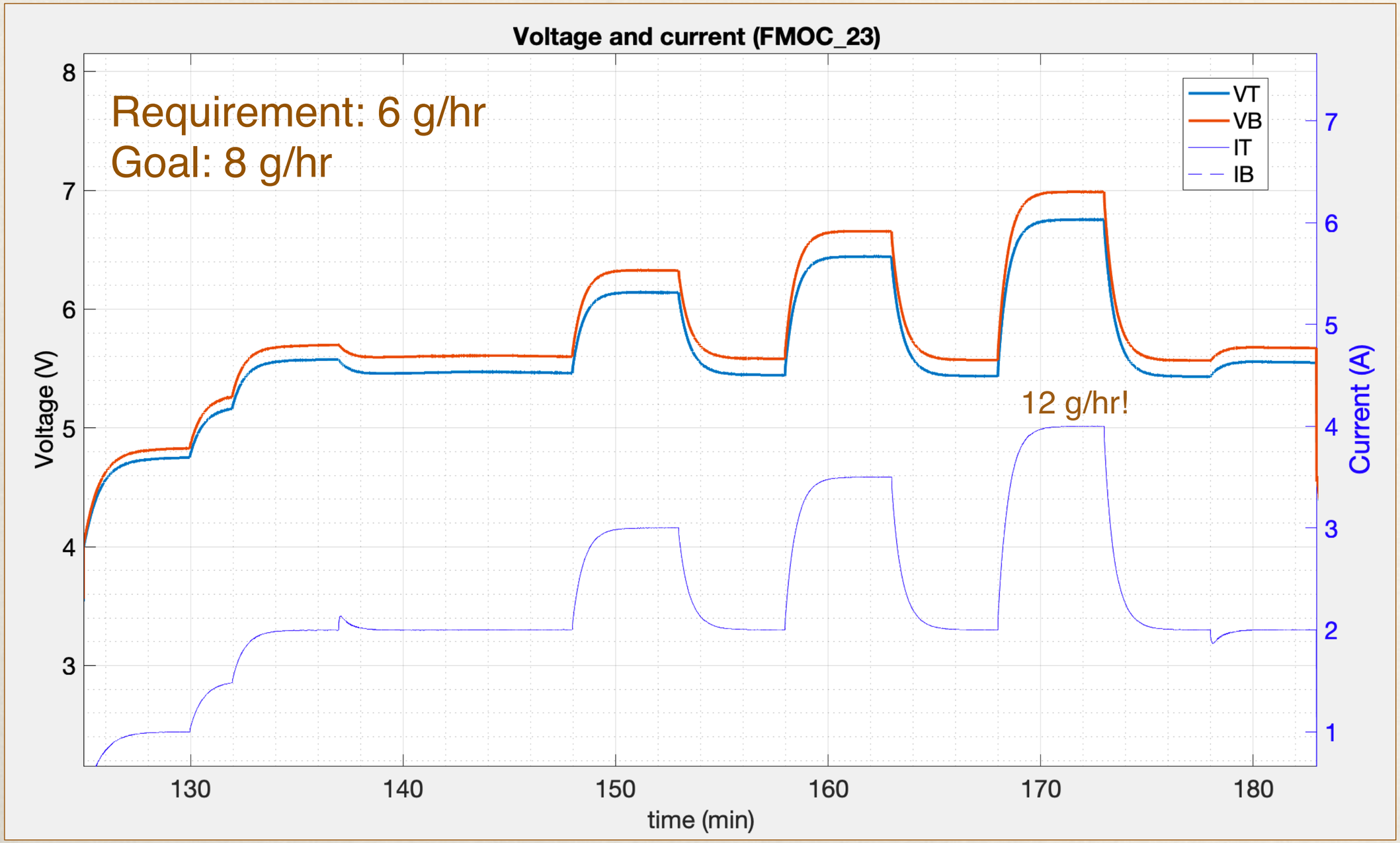
Operation summary

- 7 oxygen-producing runs in CY'21 (starting April 20)
  - General demonstration of capabilities
  - Operation over full range of environmental conditions
- 5 oxygen-production runs in CY'22
  - Demonstrating safer, more capable modes of operation (Voltage Mode)
  - Probing performance limits (high production rate)
  - Targeting specific unknown characteristics (O_2 purity, lead resistance updates)
- 4 oxygen-production runs in CY'23
  - Demonstration that MOXIE still meets purity and production requirements after >10 cycles on Mars
  - Validation of *pressure control* and *low pressure* operation → first morning run.
  - Demonstration of maximum oxygen production rate allowed by current supply (12 g/hr) – over twice the initial requirement
- **MOXIE mission was ended as of Sept. 30, 2023** ☹

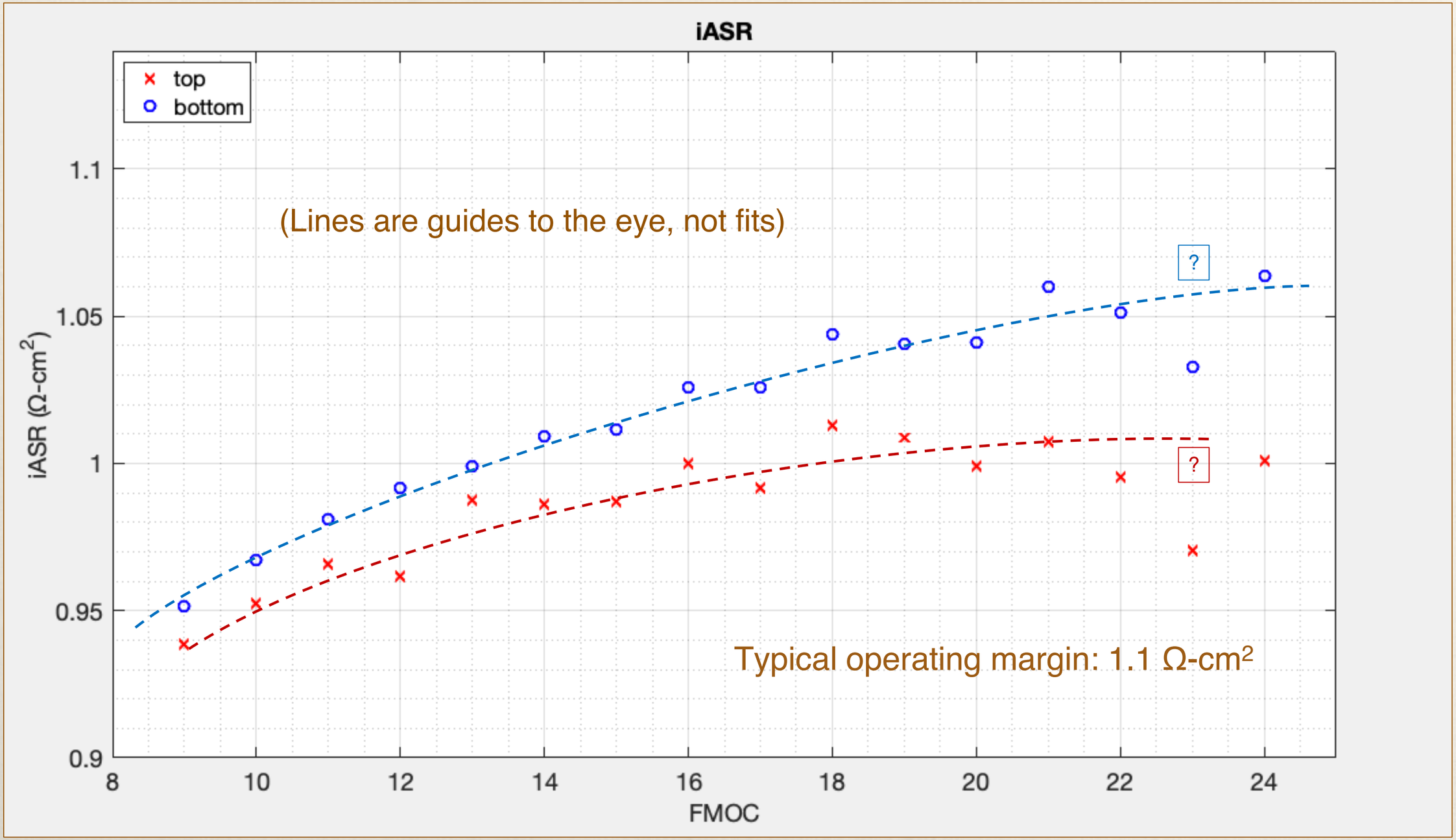
O_2 production in our first run



Record production in our 15th run

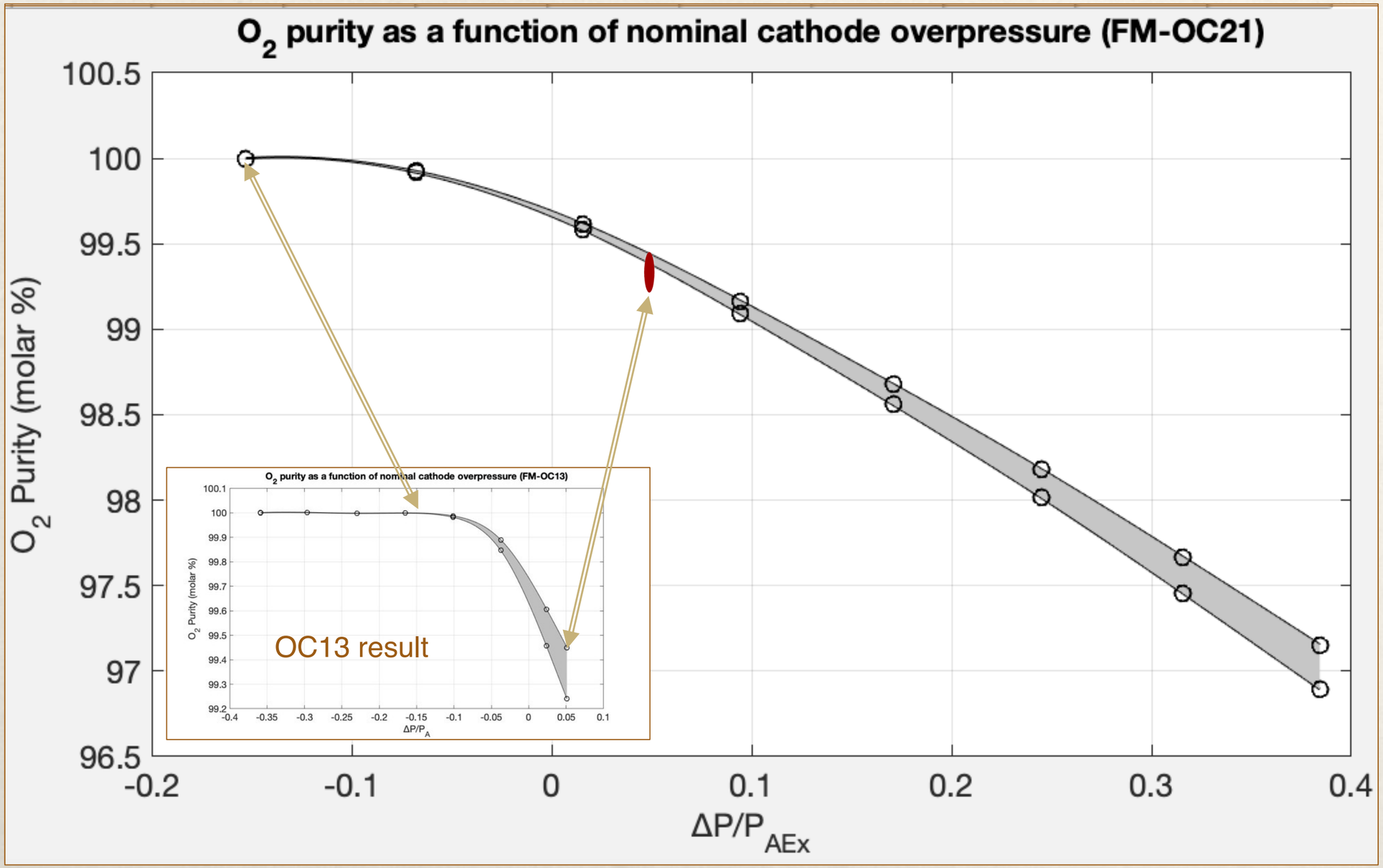


Robustness (iASR)

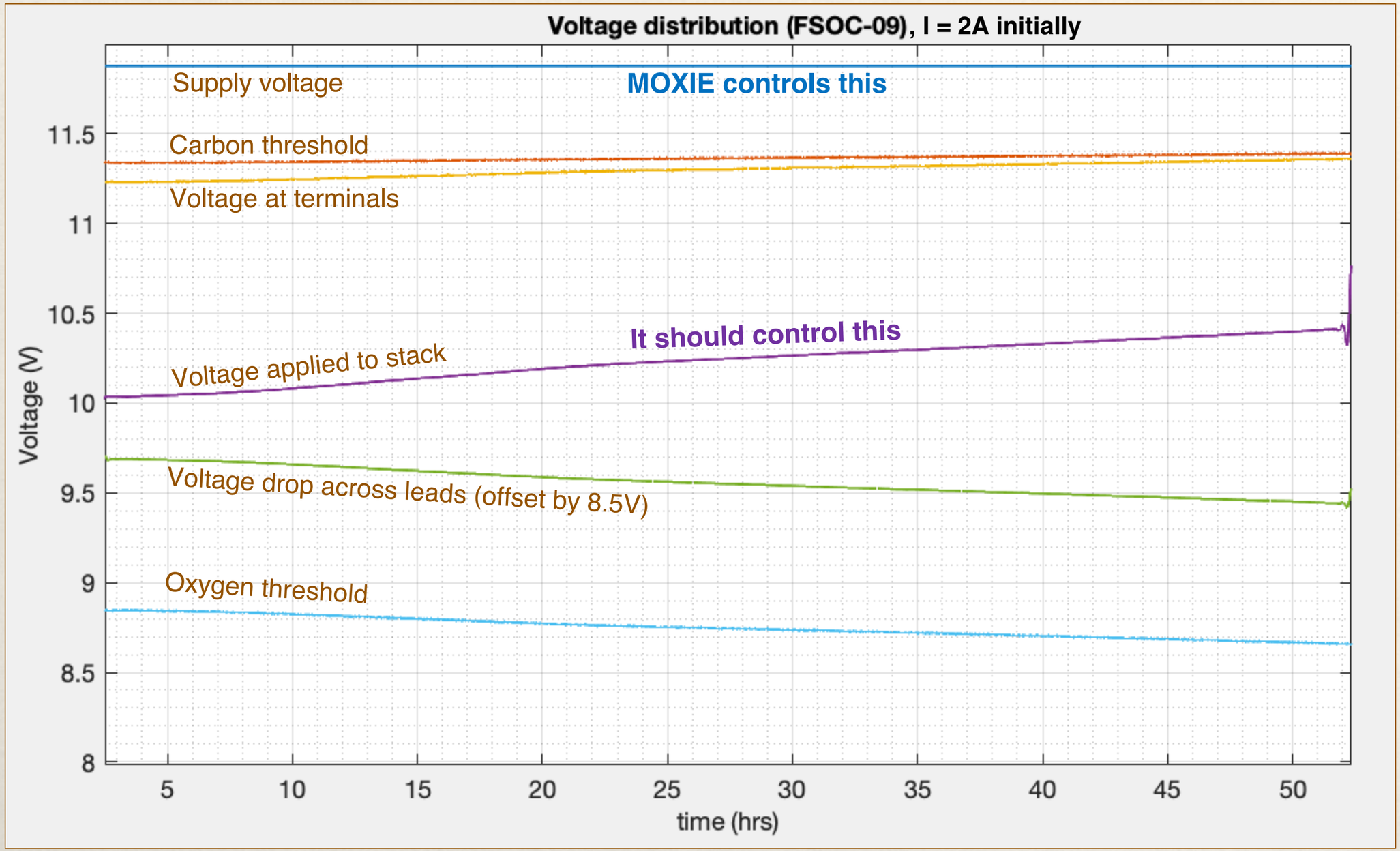


O_2 Purity

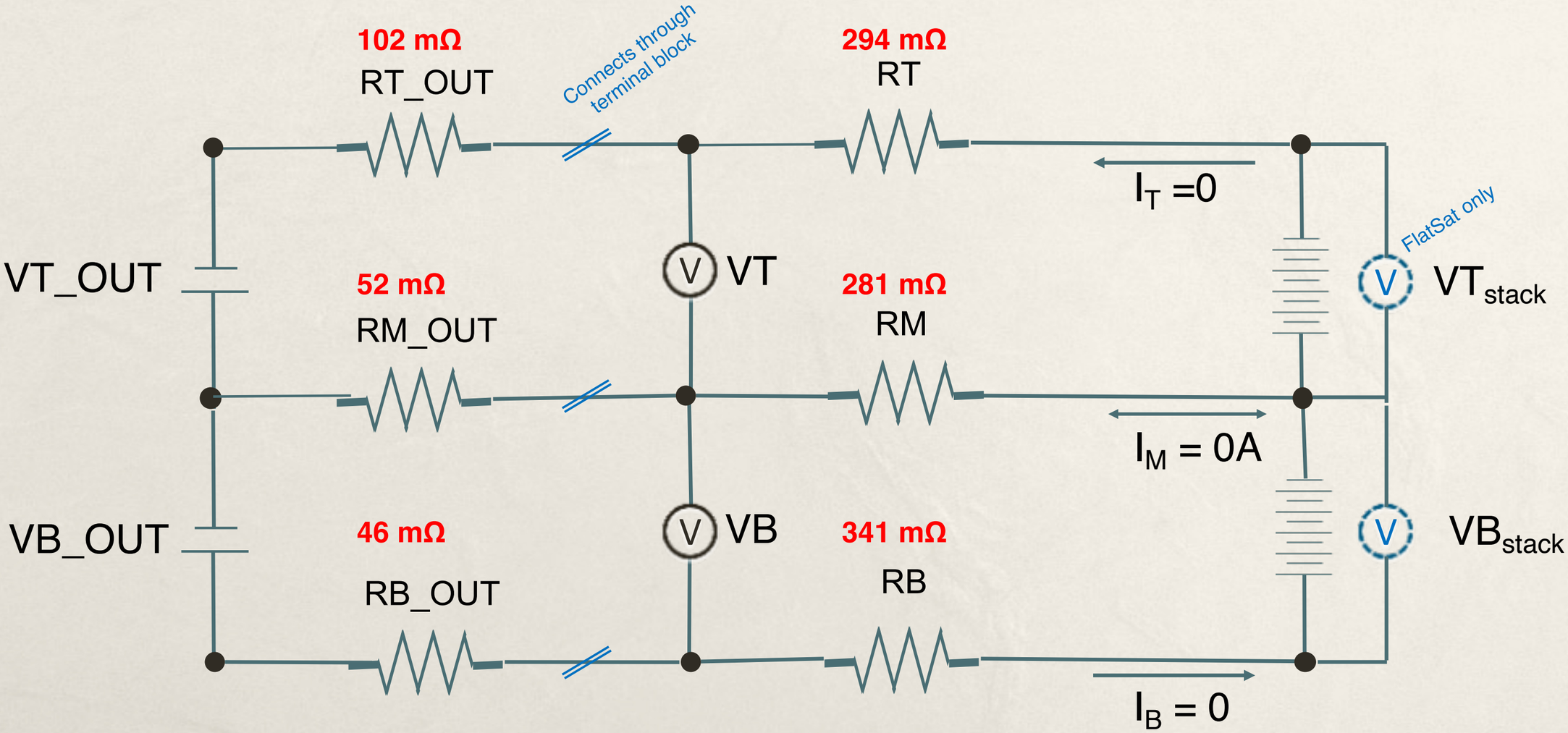
* Essentially 100% as long as there is an anode (O_2) overpressure



Stack voltage control: FSOC-09

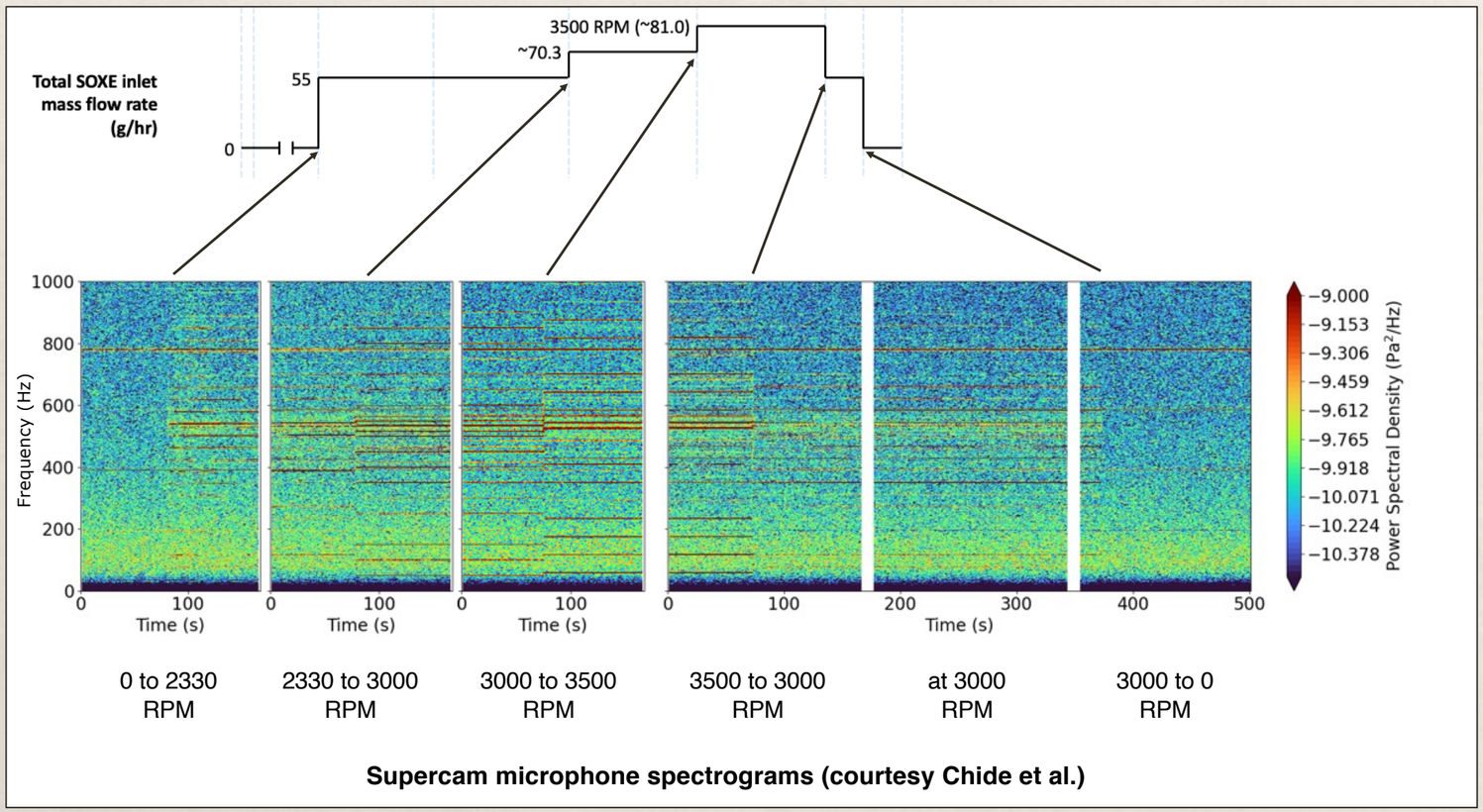


Resistance summary
(values in red were derived in situ, on Mars):

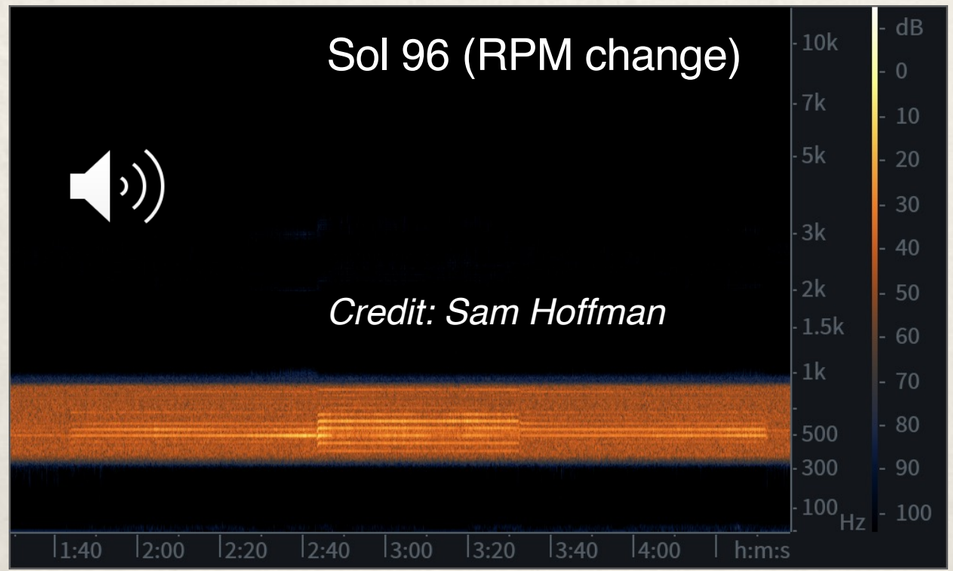


MOXIE compressor recorded by SCAM mic

* Intended as diagnostic of compressor changes
* Also useful as probe of acoustic transmission on Mars

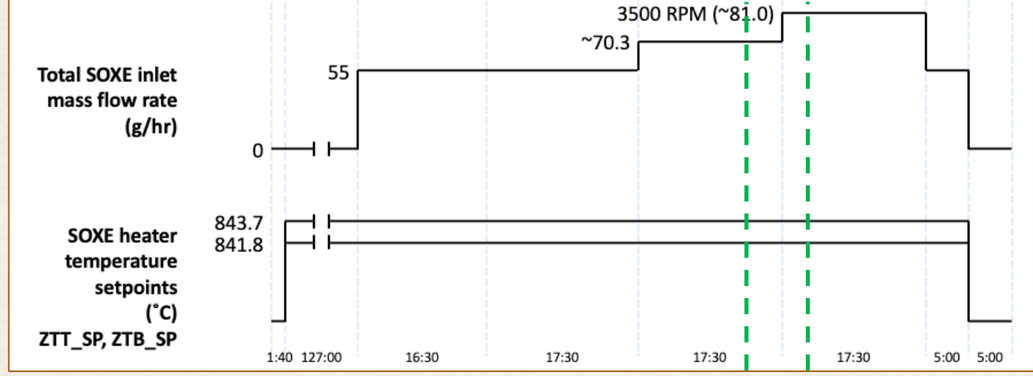


Supercam microphone spectrograms (courtesy Chide et al.)



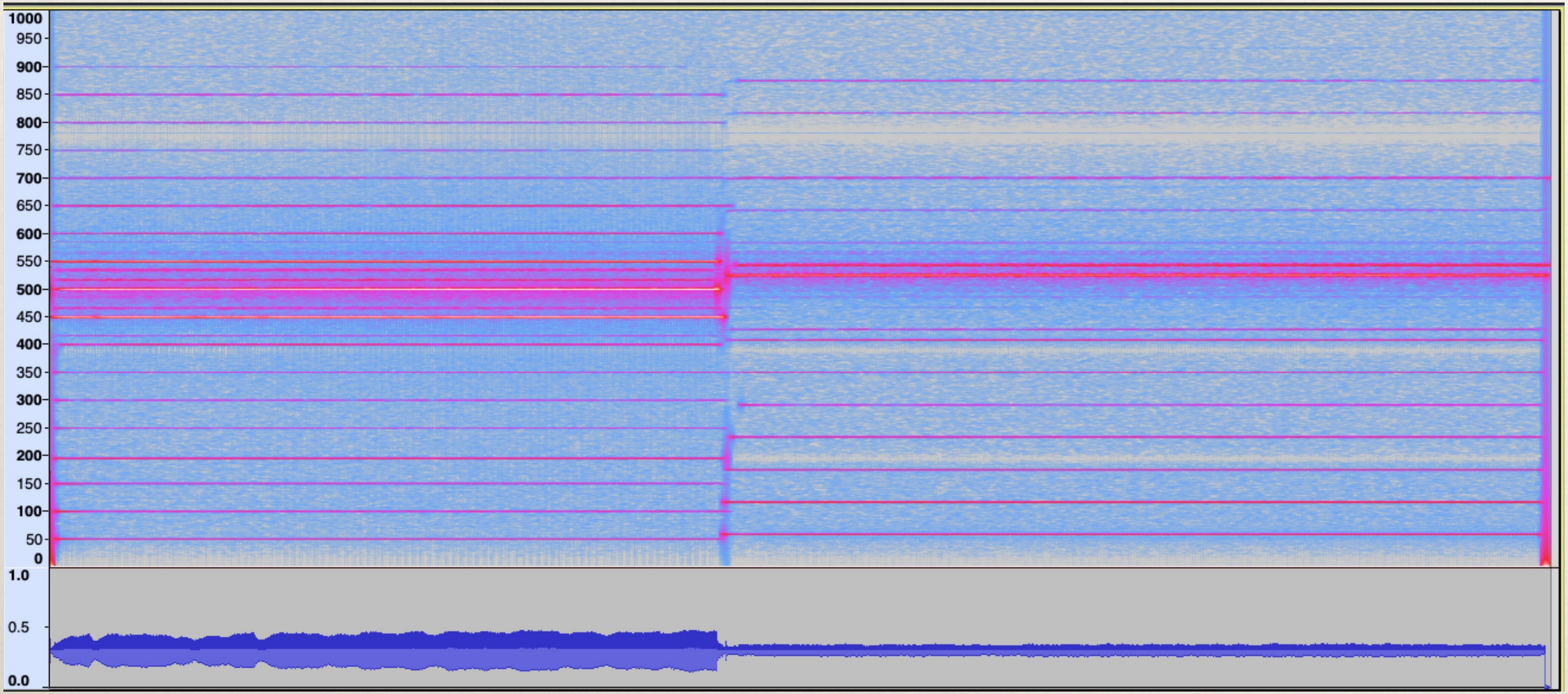
A useful frequency comb?

OC10 (sol 81) ~ 0522 LST



3000 RPM

3500 RPM

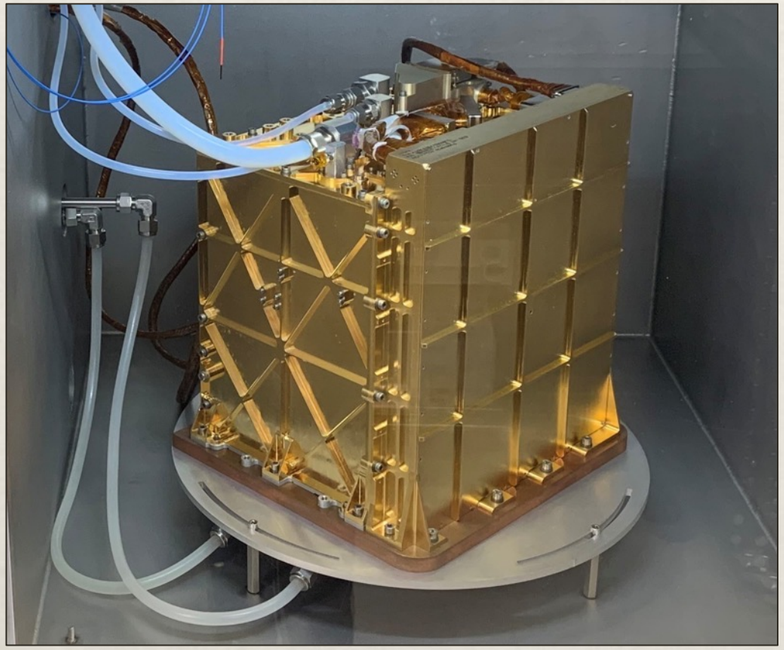


What have we learned about MOXIE?

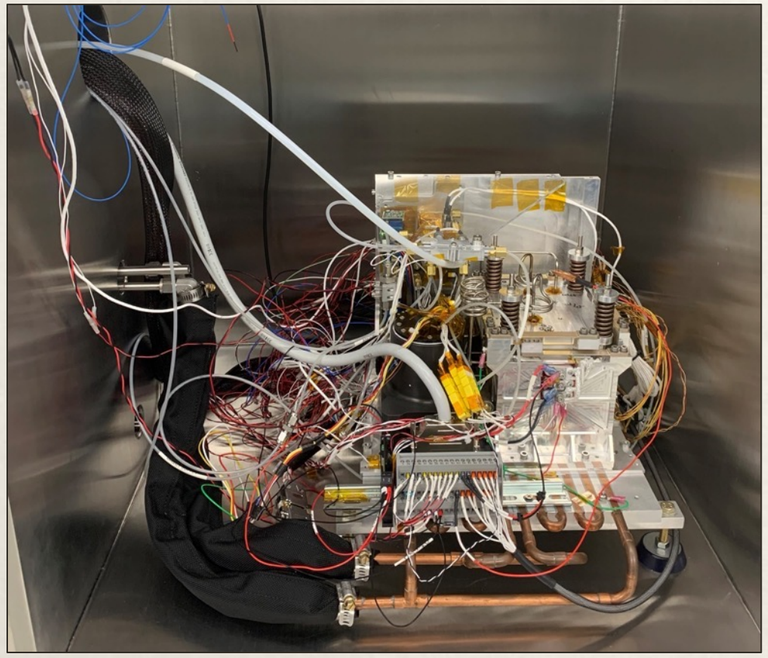
* With careful operation, MOXIE is surprisingly robust against thermal cycling, dust, changes in atmospheric density and temperature
* A few simple changes will greatly improve power efficiency to ~90%:
  * Operation at much lower cathode pressure
  * A well-insulated surrounding oven
  * Heat exchange from gas input to gas output
* A few more will greatly improve autonomy and safety
  * Separate voltage sense wires (instead of sensing through power wires)
  * An accurate flow meter and composition sensor
  * A capable processor with dynamically tunable control algorithms
  * Materials improvements to enhance resistance to carbon deposition
* Dust mitigation will be straightforward
  * Dust is not well entrained in the air and won't go around corners!
* Models show full system < 1000 kg and <25 kW **including liquefaction**

Laboratory operations

* Pre-validate Mars operations
* Develop and test techniques for safer, more efficient operation on Mars
* Perform experiments that can't be done on Mars (e.g. long lifetime tests)
* Explore new technologies, subsystems, and configurations



The MOXIE engineering model (EM) is packaged like the FM, with minor differences in fabrication.



The MOXIE FlatSat (FS) is an open assembly using the same subsystem components as the EM.

Laboratory activities

* Accomplishments included:
  * Compressor power characterization vs outlet pressure
  * Low cathode pressure operation for power efficiency
  * Cathode pressure (P4) feedback operation for safety and stability
  * Lead resistance measurement and validation of “thermal sweep” technique
* Recent developments:
  * Remote operation capability (for long-duration tests)
  * Flight electronics emulator running flight software with commercial modules (to buffer against future board failures and provide more testing flexibility)

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

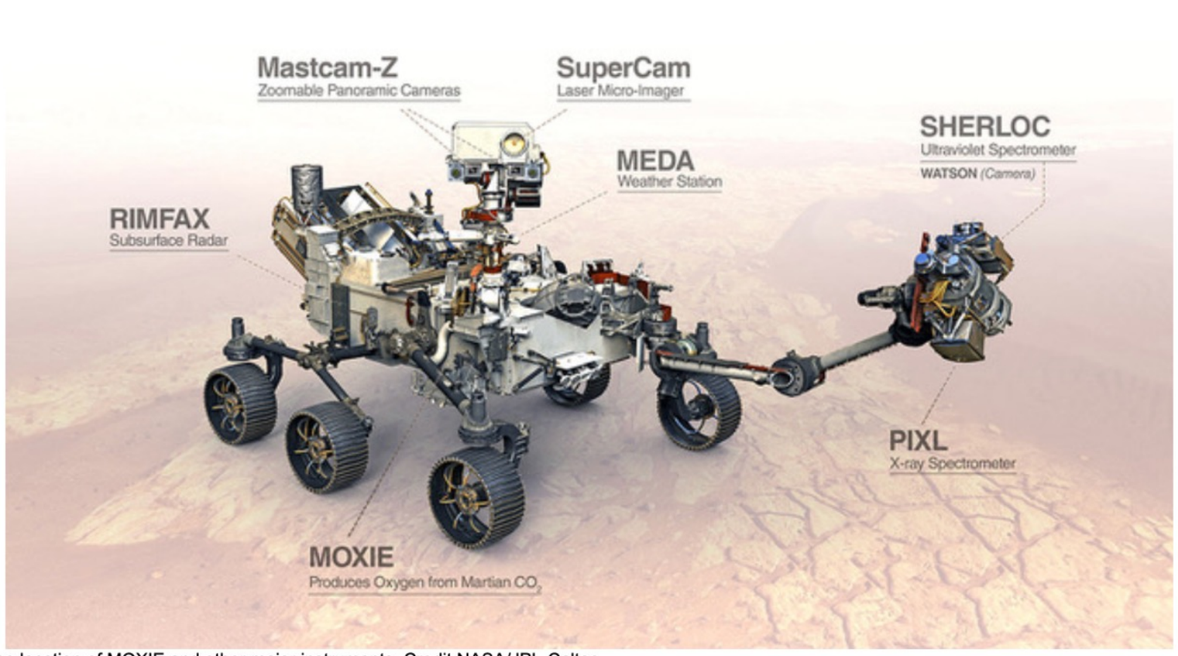
Mars Lander

- 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