MOXIE
Mars Oxygen
ISRU Experiment

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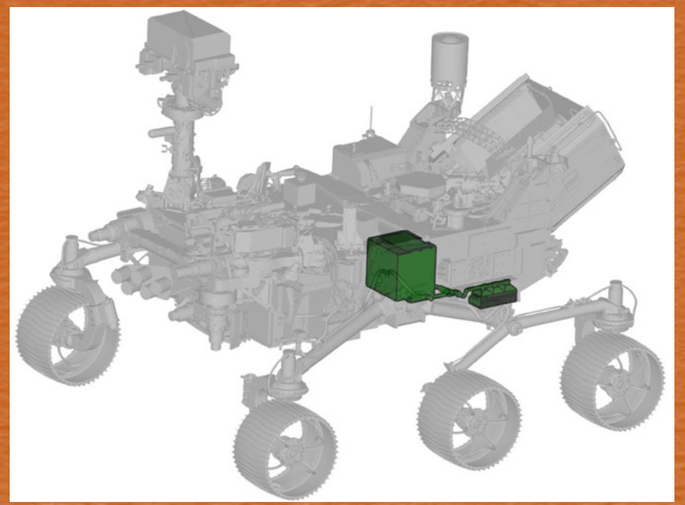
Space Resources Roundtable
June 10, 2022

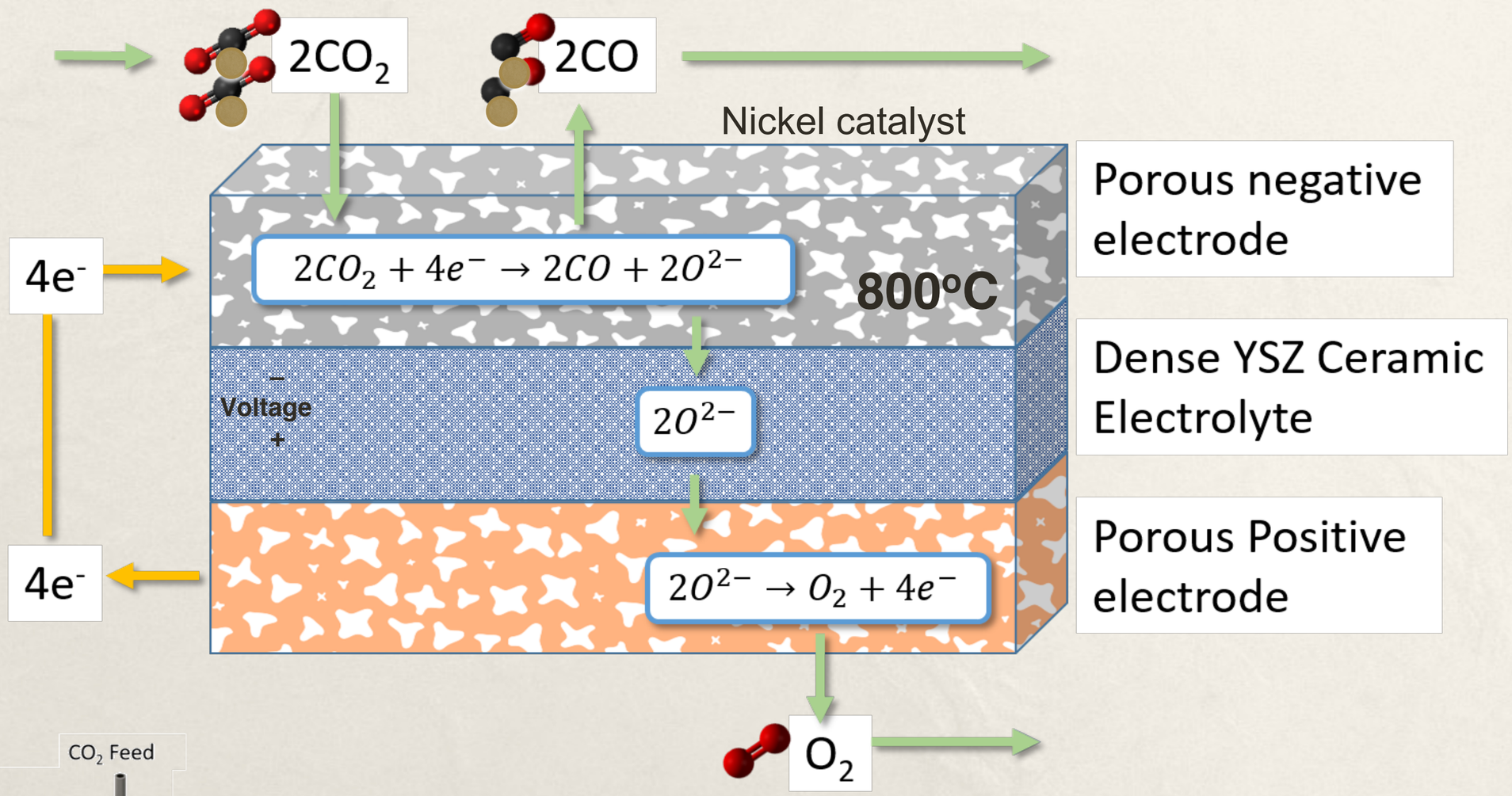
MOXIE: A year of ISRU on Mars.

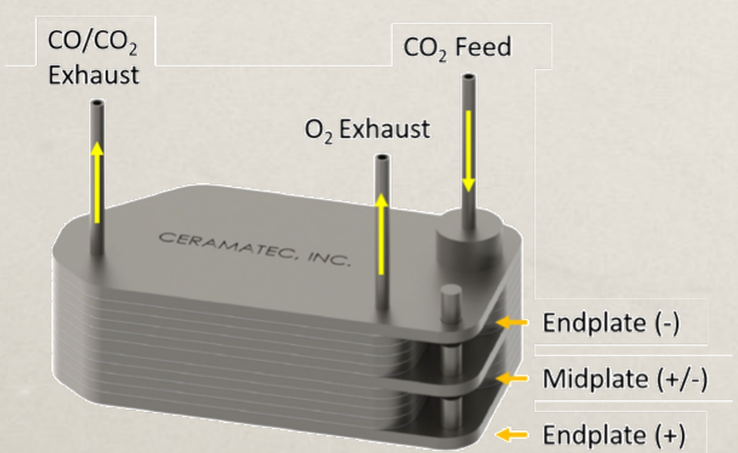
#JOURNEYTOMARS

* **MOXIE is a 1:200 scale model of an In Situ Resource Utilization (ISRU) plant for a human mission.**
  * The size is limited by available power
* **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



The Solid OXide Electrolysis (SOXE) cell





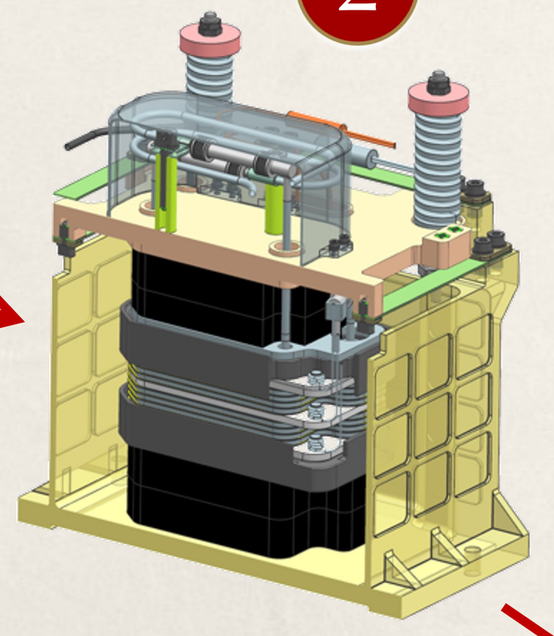
SOE: $CO_2 \rightarrow CO + O$

SOFC: $CO + O \rightarrow CO_2$

Putting it together

1

2



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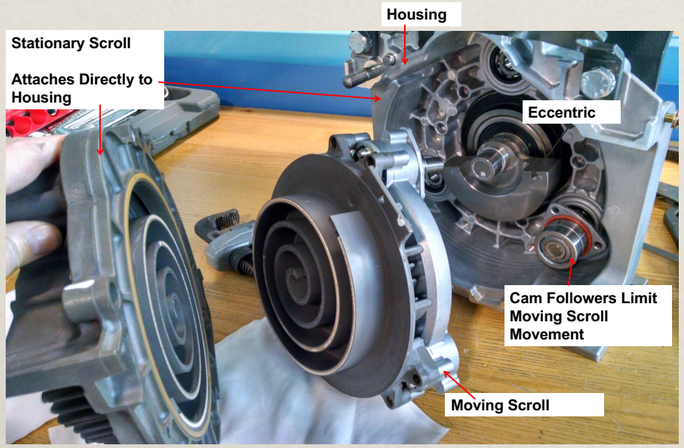

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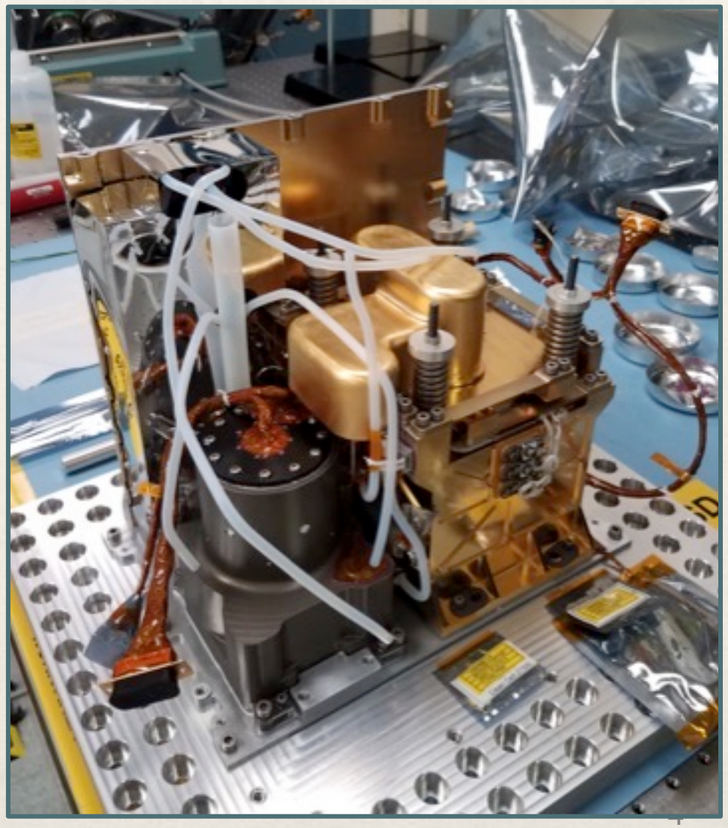
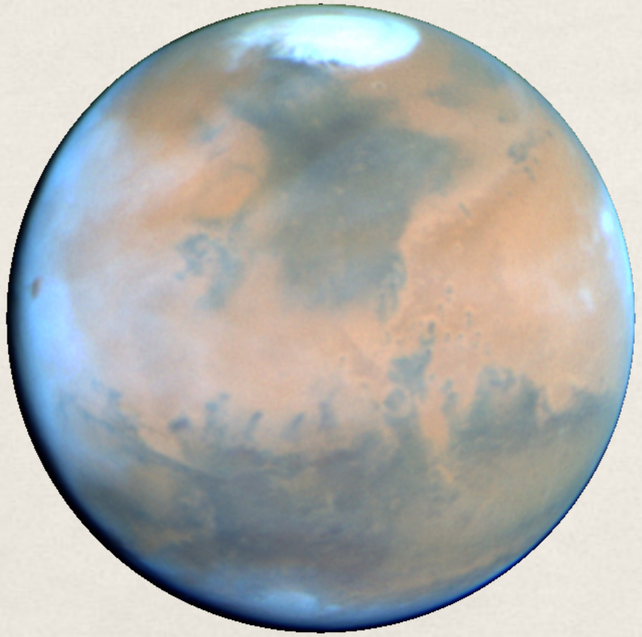




On Mars

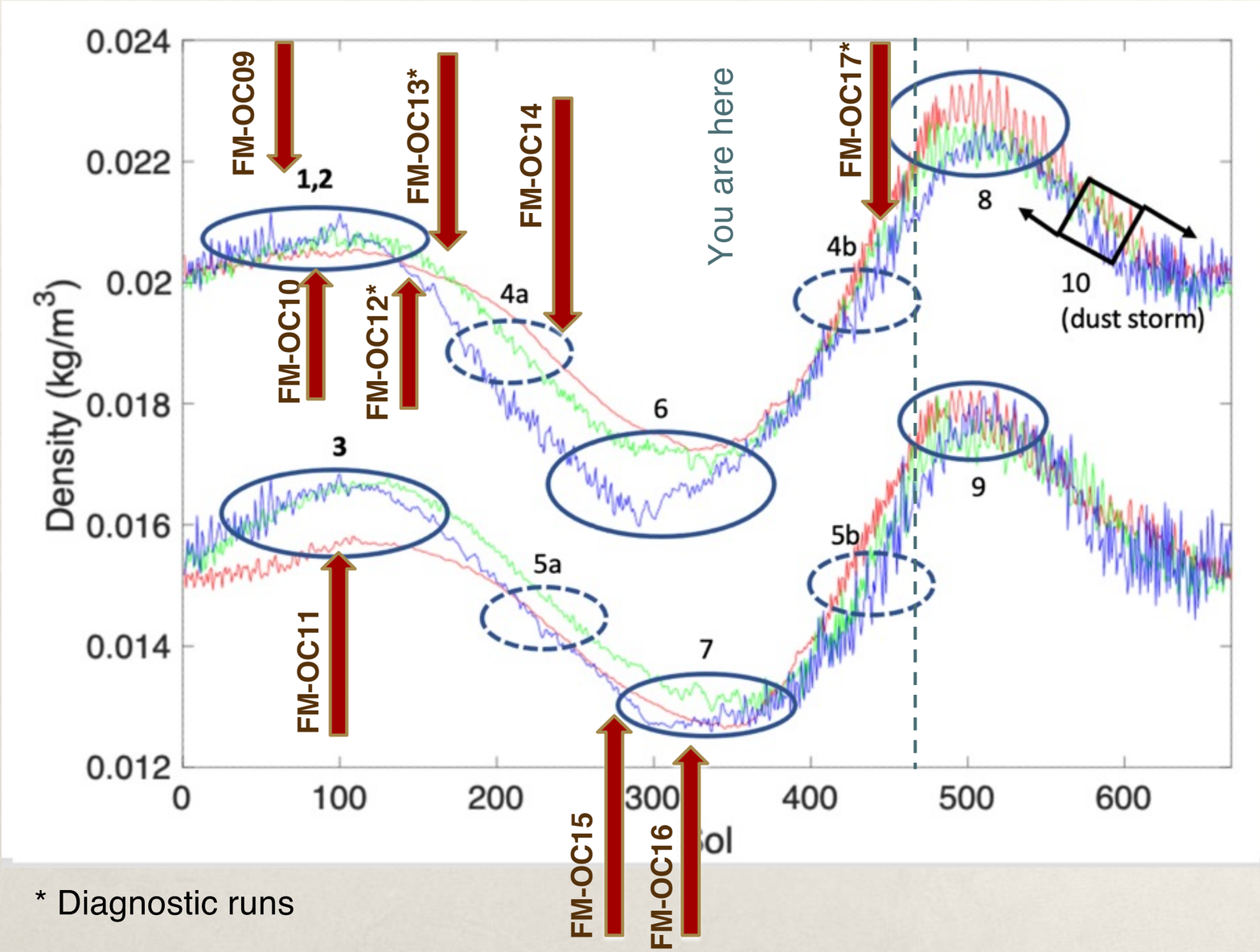
The first year

Atmospheric density variations on Mars

(Blue ovals represent original notional plan)

Daily maximum

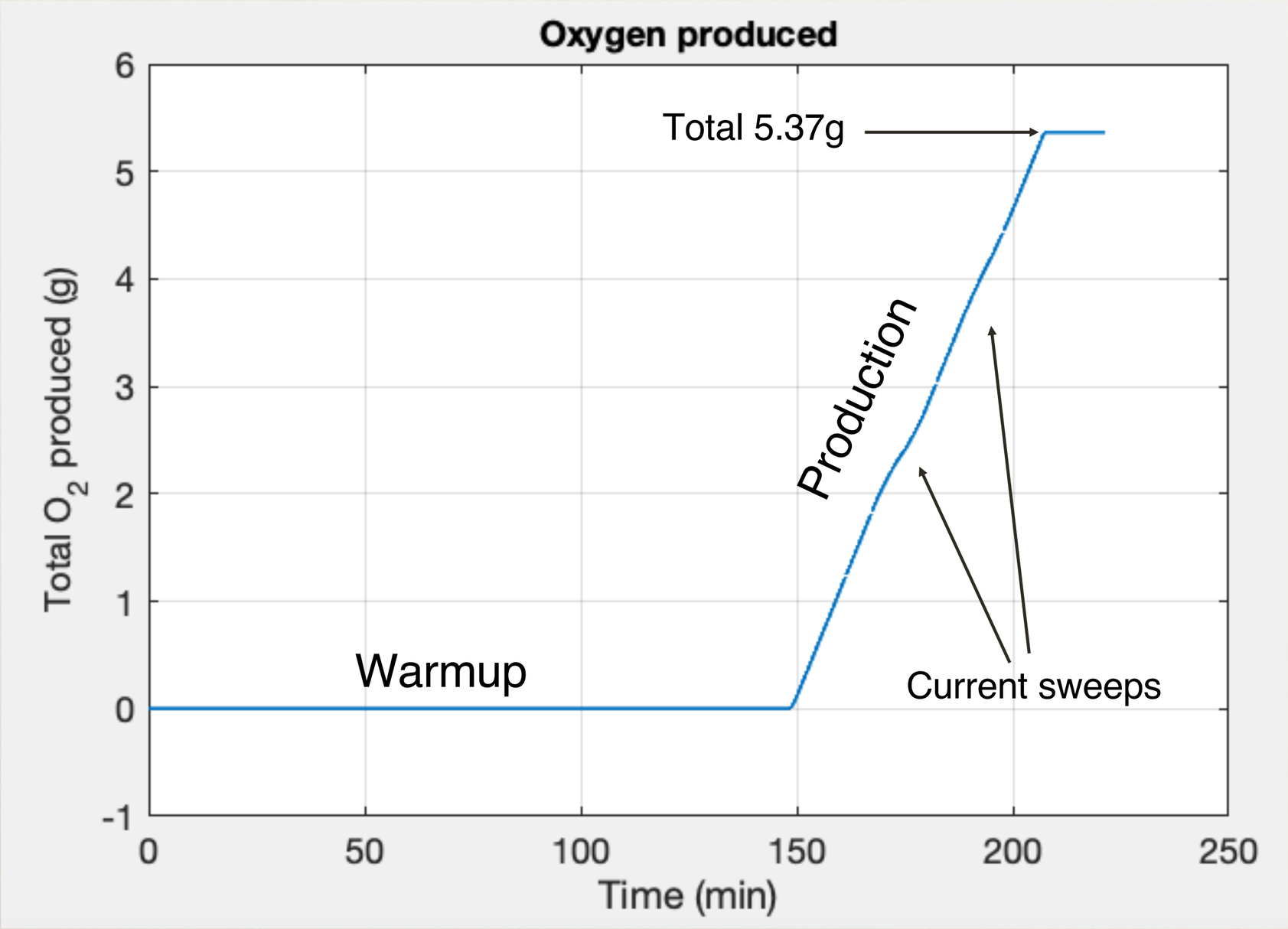
Daily minimum



TOTALS
8 runs
65.61 grams O2
700.55 total minutes

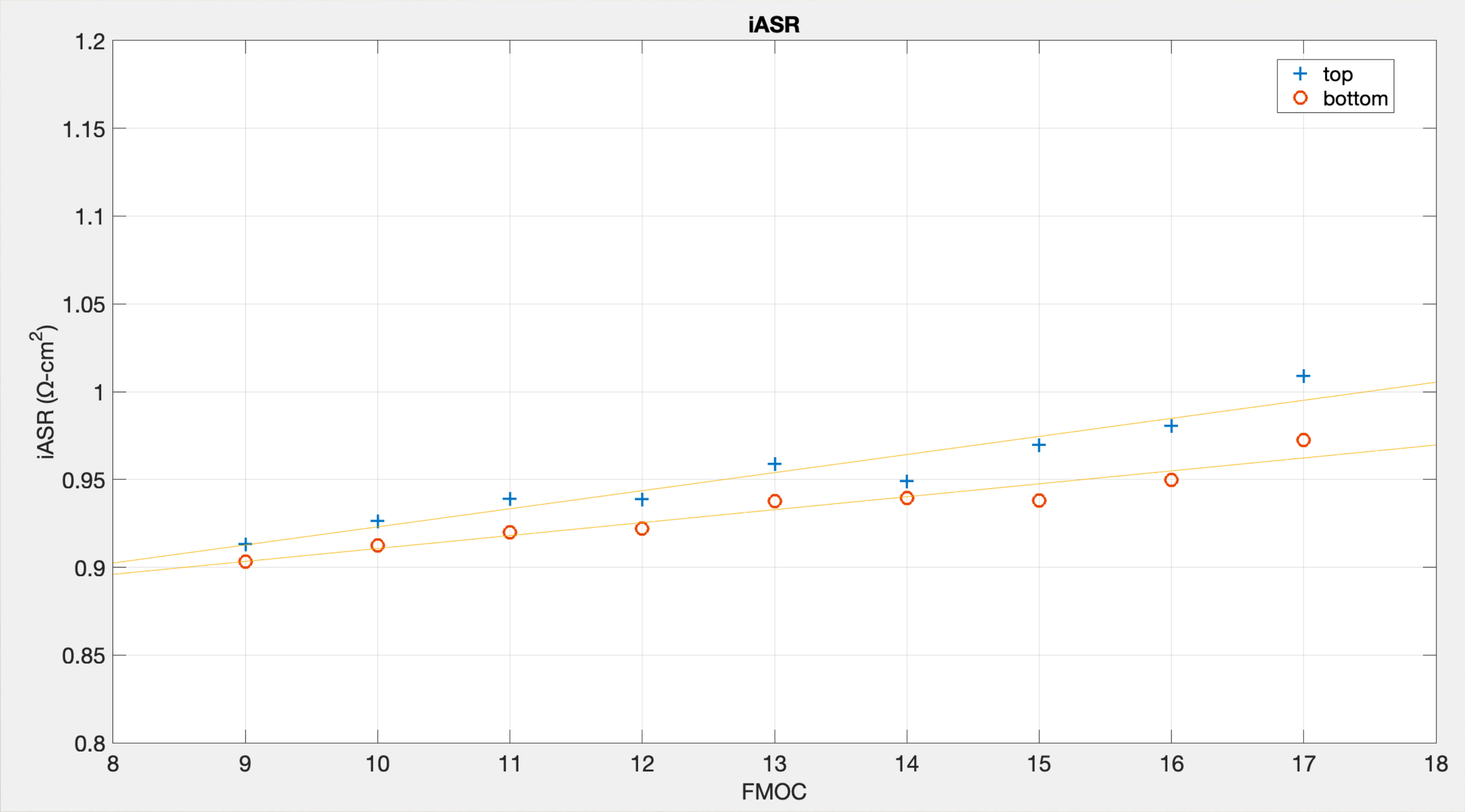
* Diagnostic runs

Cumulative O_2 produced



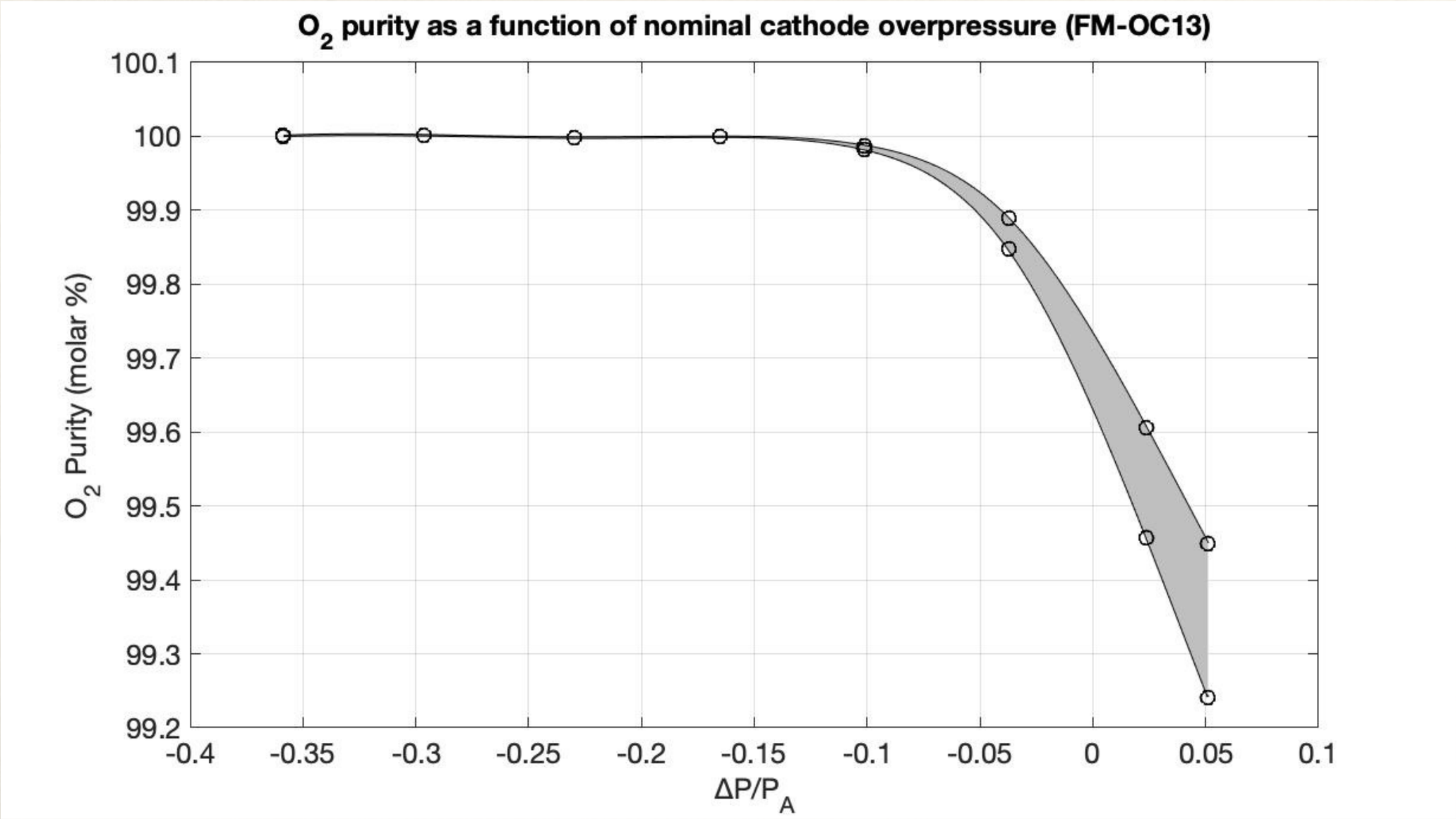
Energy (MOXIE only): 623 W-hr + RMCA (94% to 52% SoC)

Robustness (iASR)

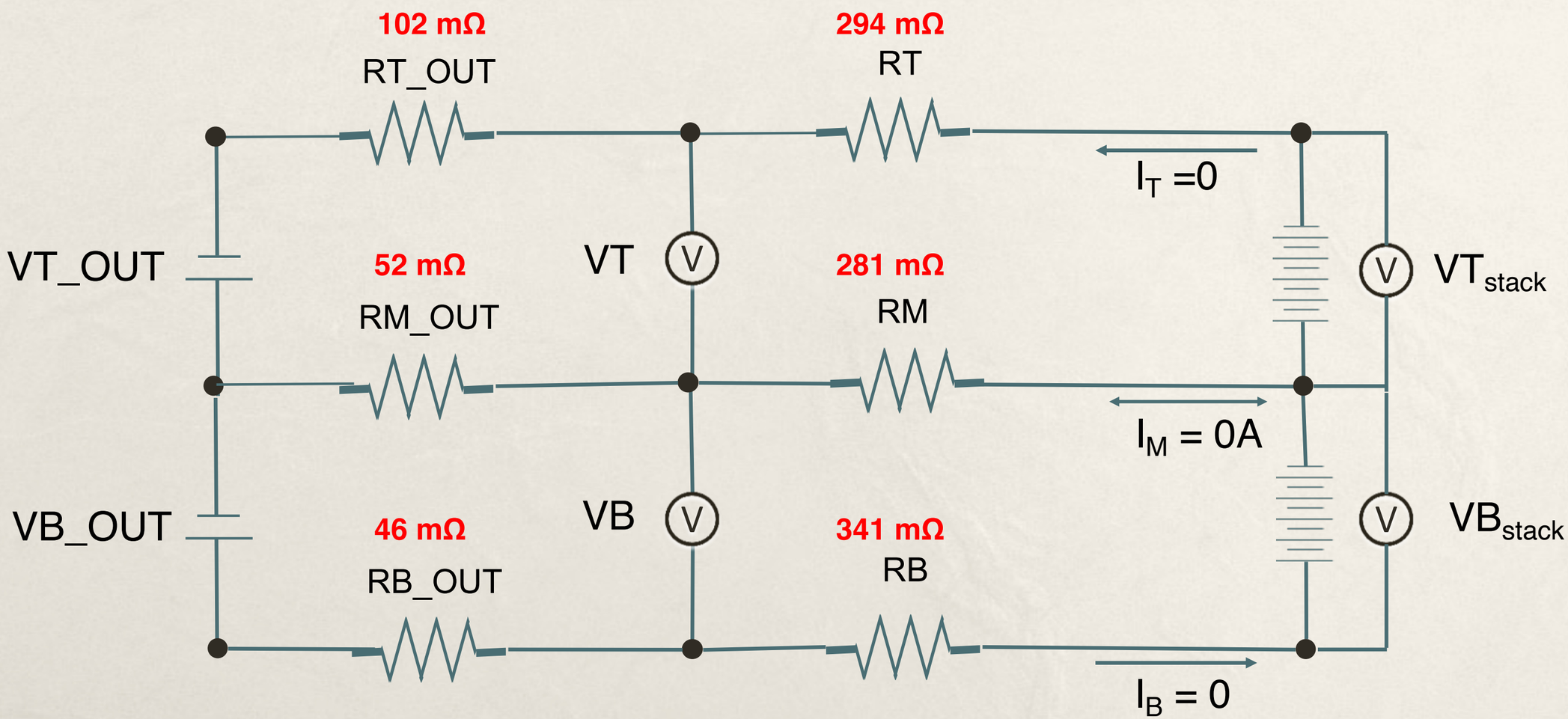


O_2 purity for FM-OC13 (molar)

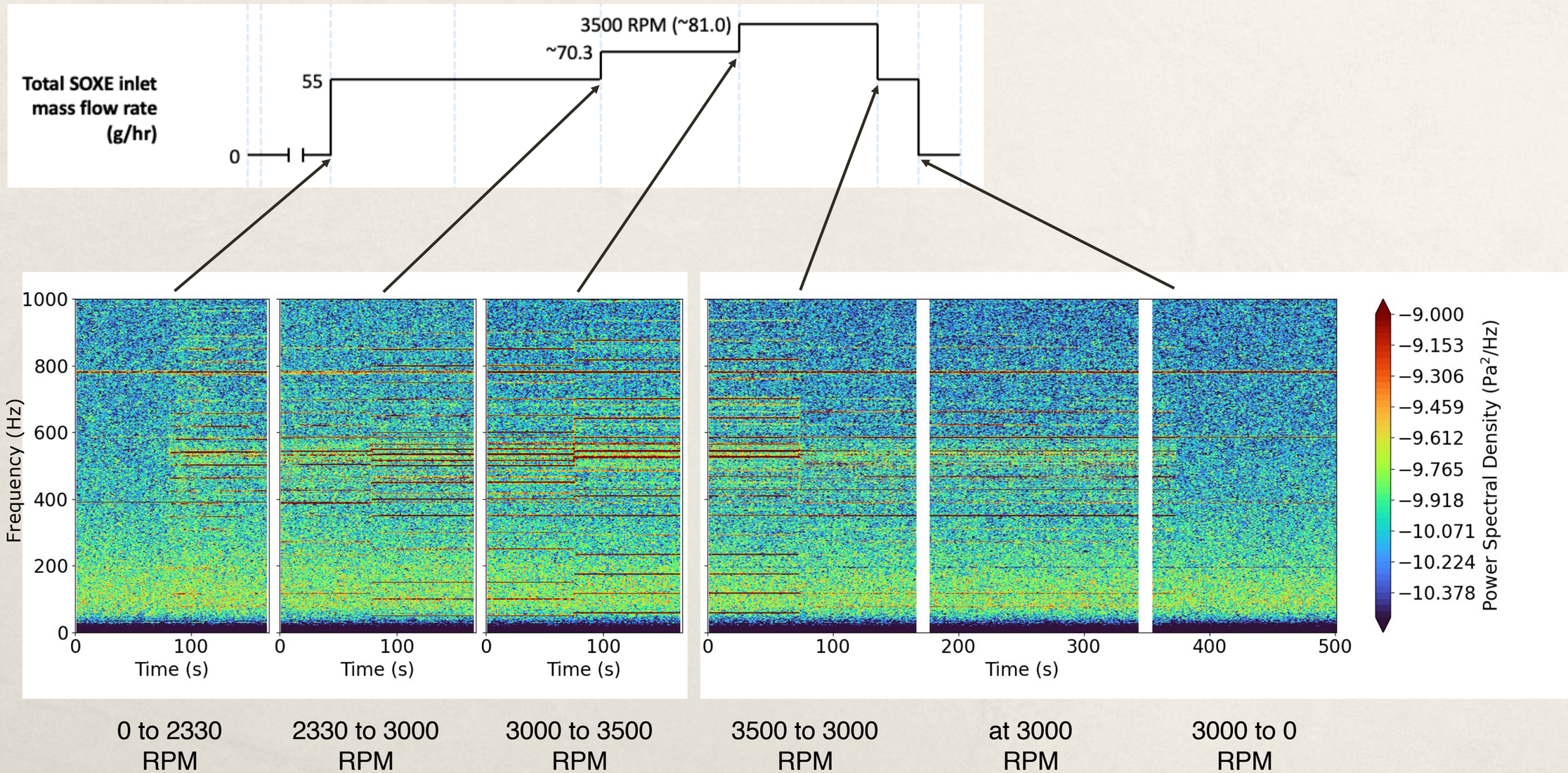
Purity = 1 – CS2 / P5



Reverse engineering on Mars



Listening to the MOXIE compressor



Supercam microphone spectrograms (courtesy Chide et al.)

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

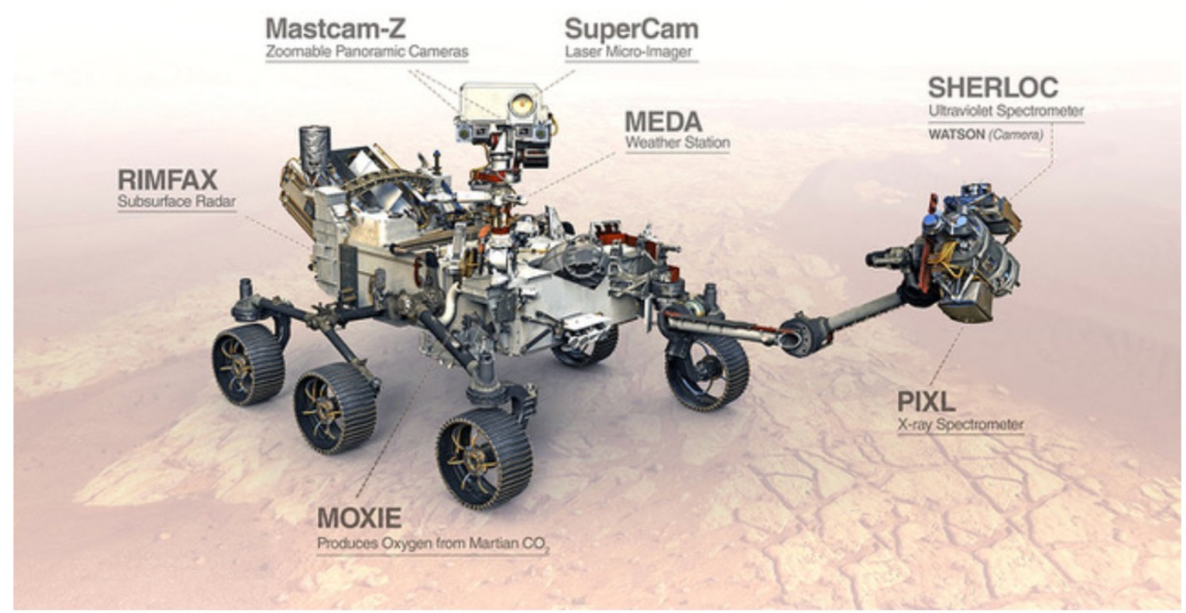
Mars Lander

- 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

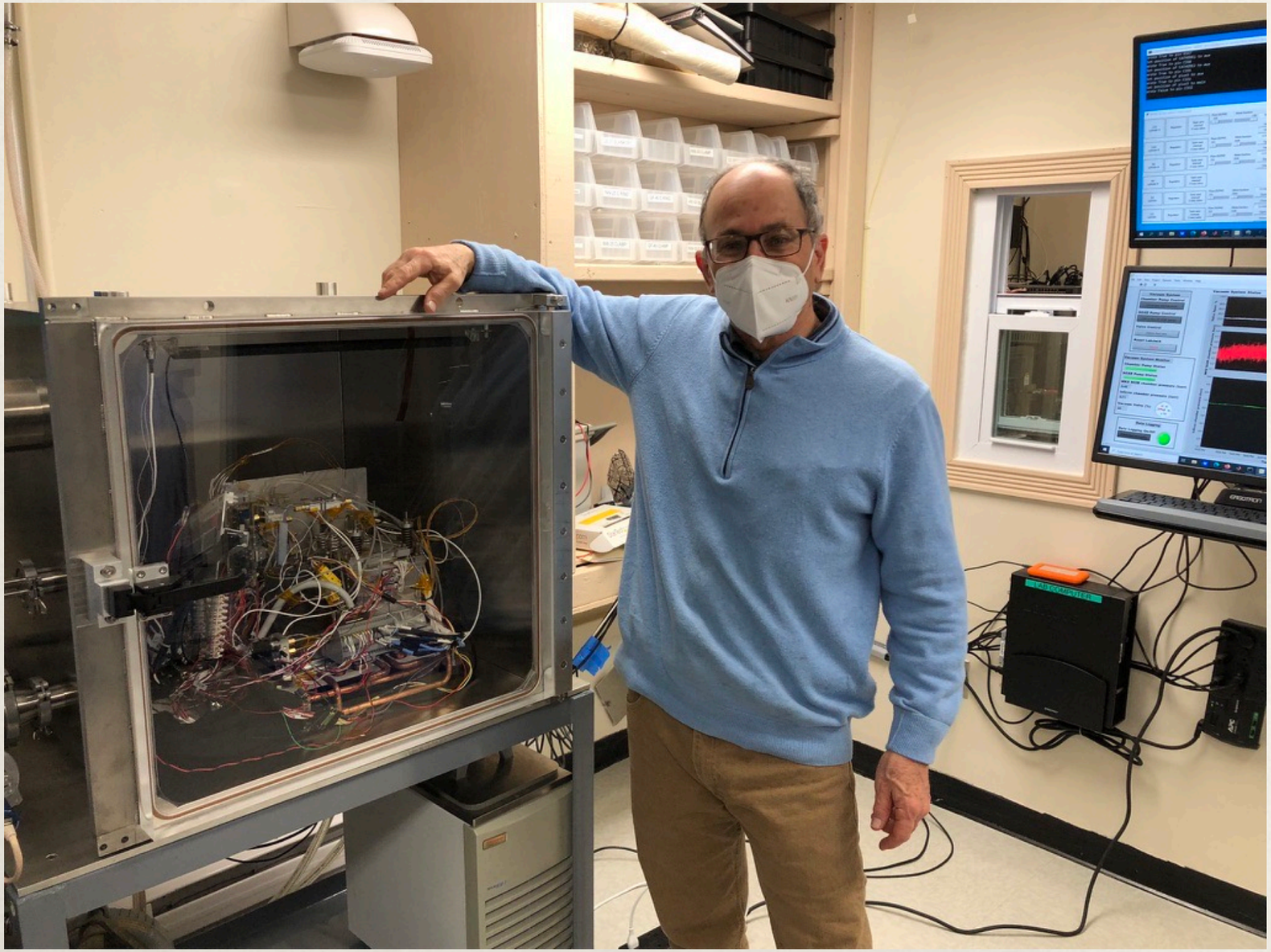
Experiment Overview

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

The Lab

EM, FlatSat, and ?

The “FlatSat”

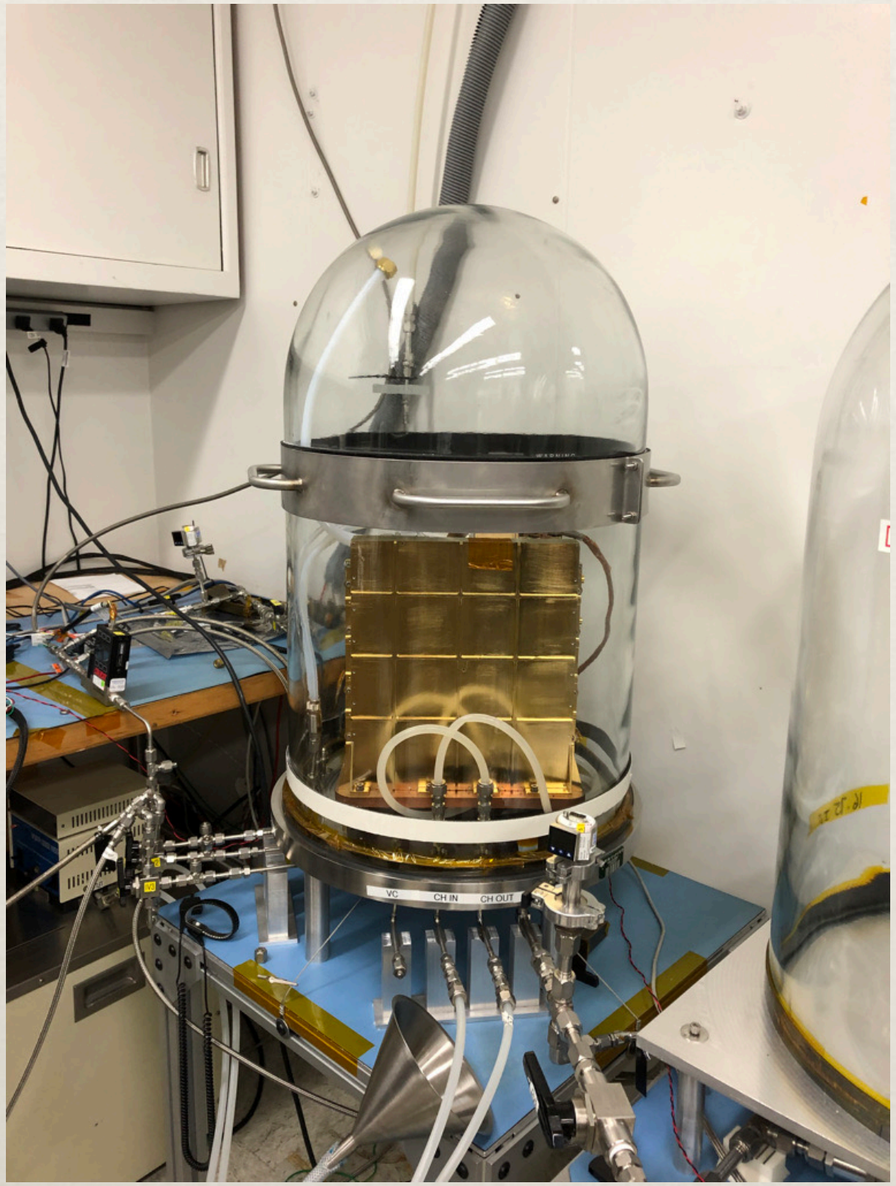


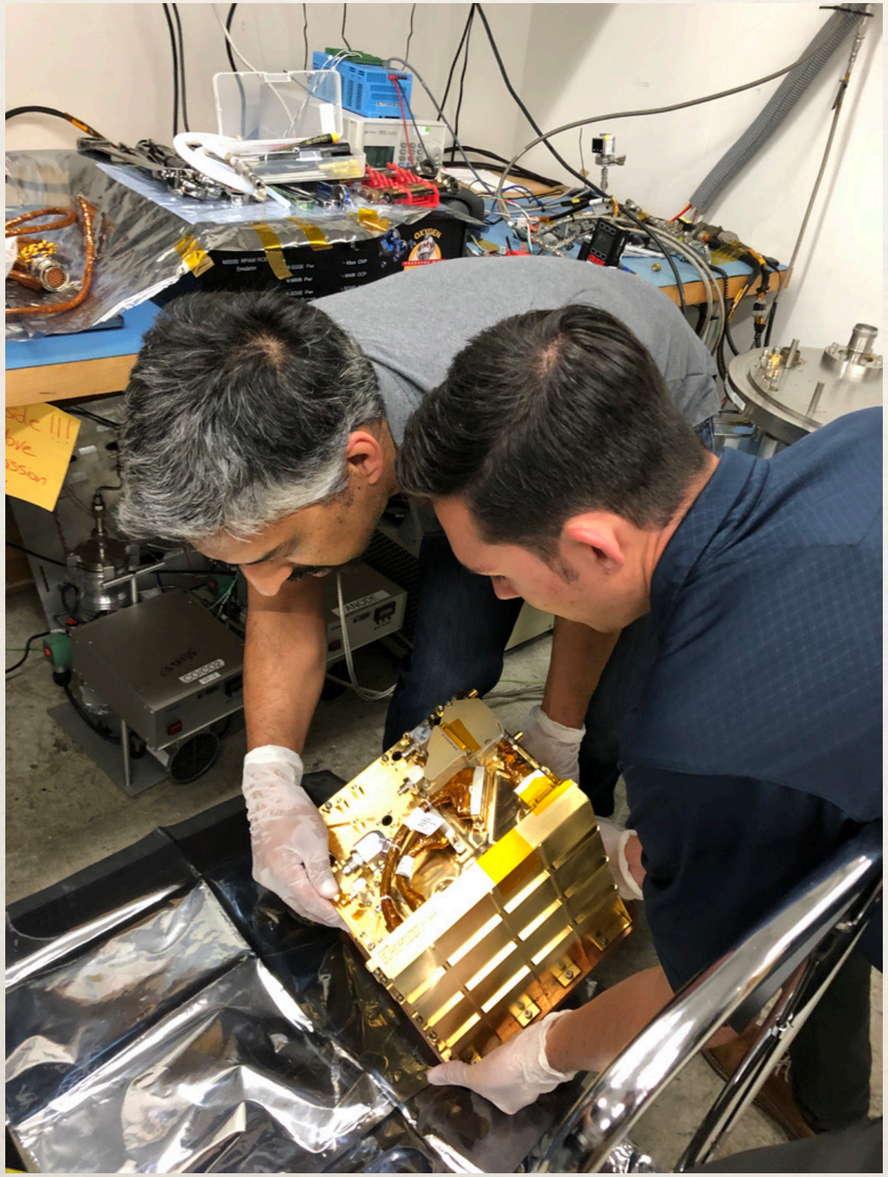
* We have now run two operational cycles…

Plans for the FlatSat

- SOXE
  - Lifetime test (continuous ops)
  - Low cathode pressure operation
  - Relationship of T(heater) and T(cells), ΔT across cells, V(I)
  - Coking threshold, weakest cell
  - ASR as function of T, P, V, I, f
- Compressor
  - Lifetime tests
  - Power vs. inlet & outlet pressure
  - Volumetric efficiency vs T, P
- Packaging
  - Measure lead resistance
  - Characterize inlet tube warming
- Controls & operation
  - Validate mass flow determination from P4 and P4-controlled flow
  - Optimize PID settings for I-V loop, stack temperature
  - Software to optimize step-wise controllable vs. table parameters
  - Autonomy (dissertation topic)

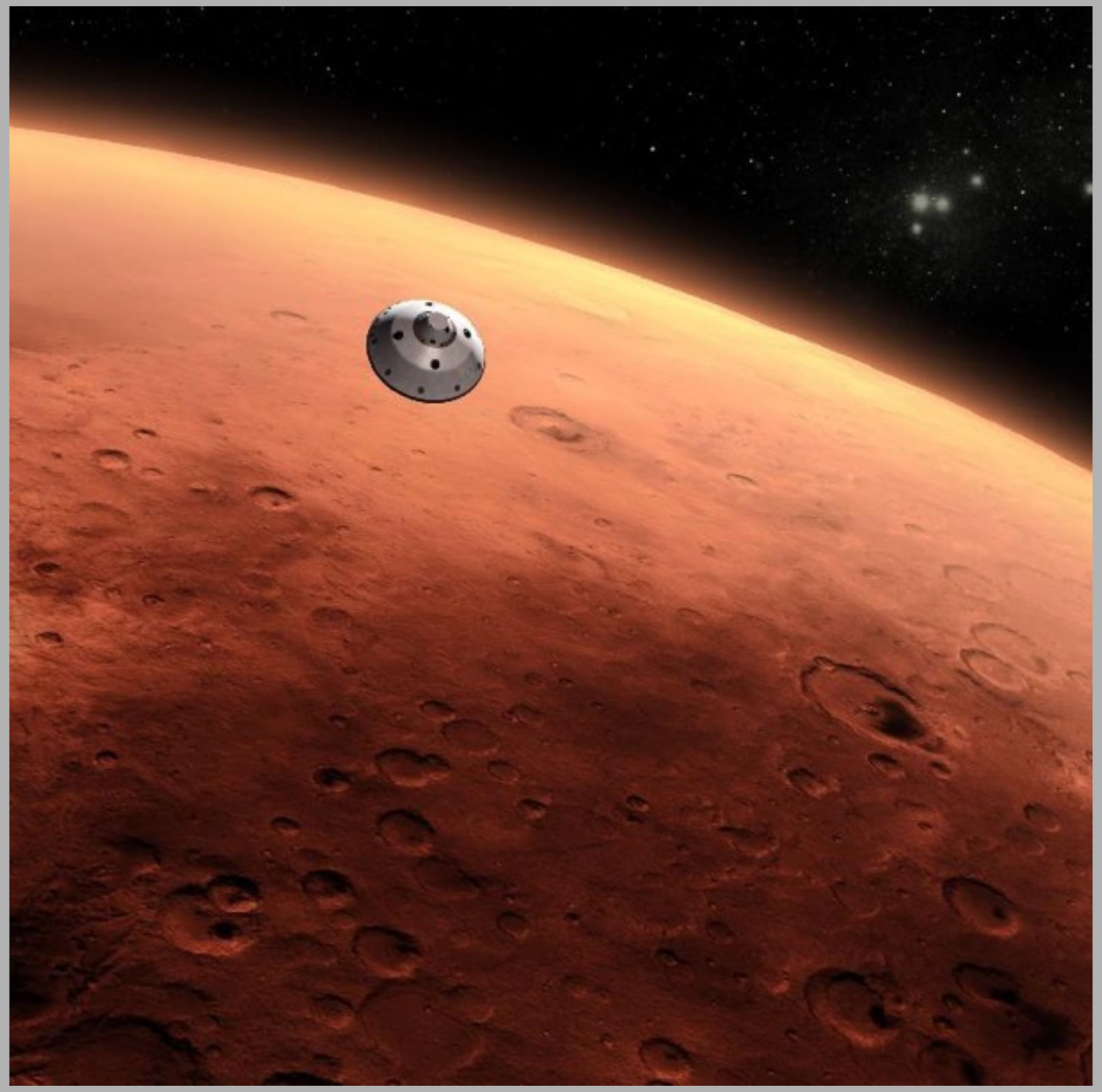
The EM is coming to MIT





The Future

BAM!



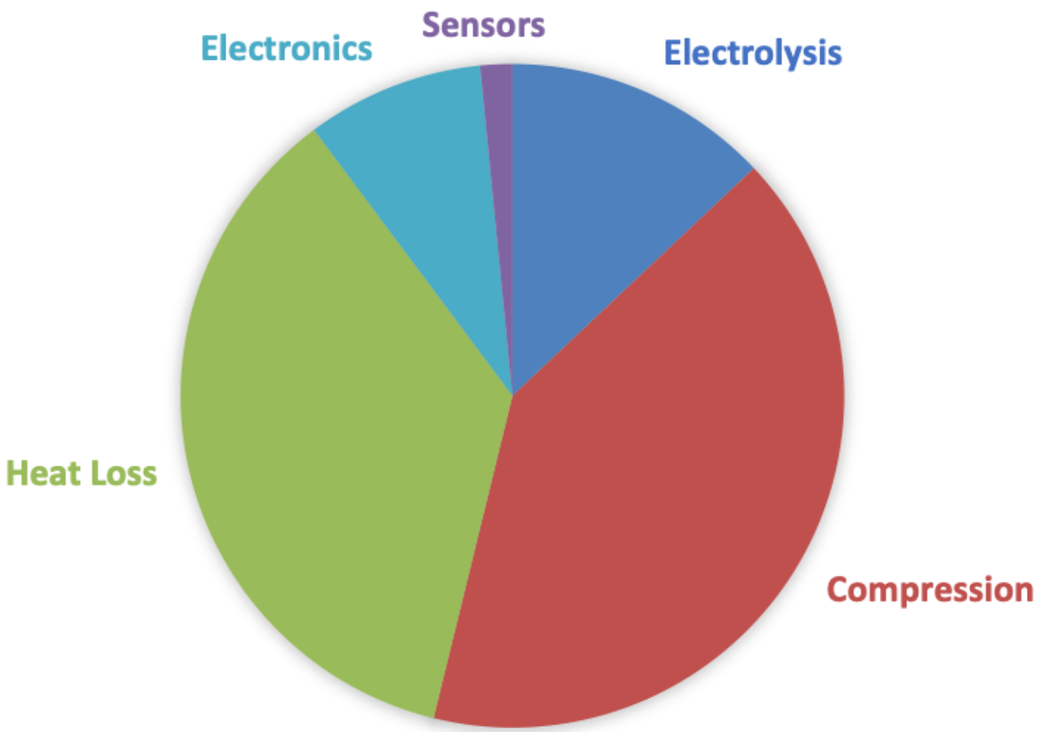
MULTI-OBJECTIVE SYSTEM OPTIMIZATION OF A MARS ATMOSPHERIC ISRU PLANT

Eric Hinterman | Thesis Defense | 05.03.22

What we've learned, where we're going

* MOXIE works remarkably well, we see hardly any differences from laboratory operation
* 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 (i.e. autonomous)!

MOXIE, 8 G/HR, 0.25 KW



MOXIE
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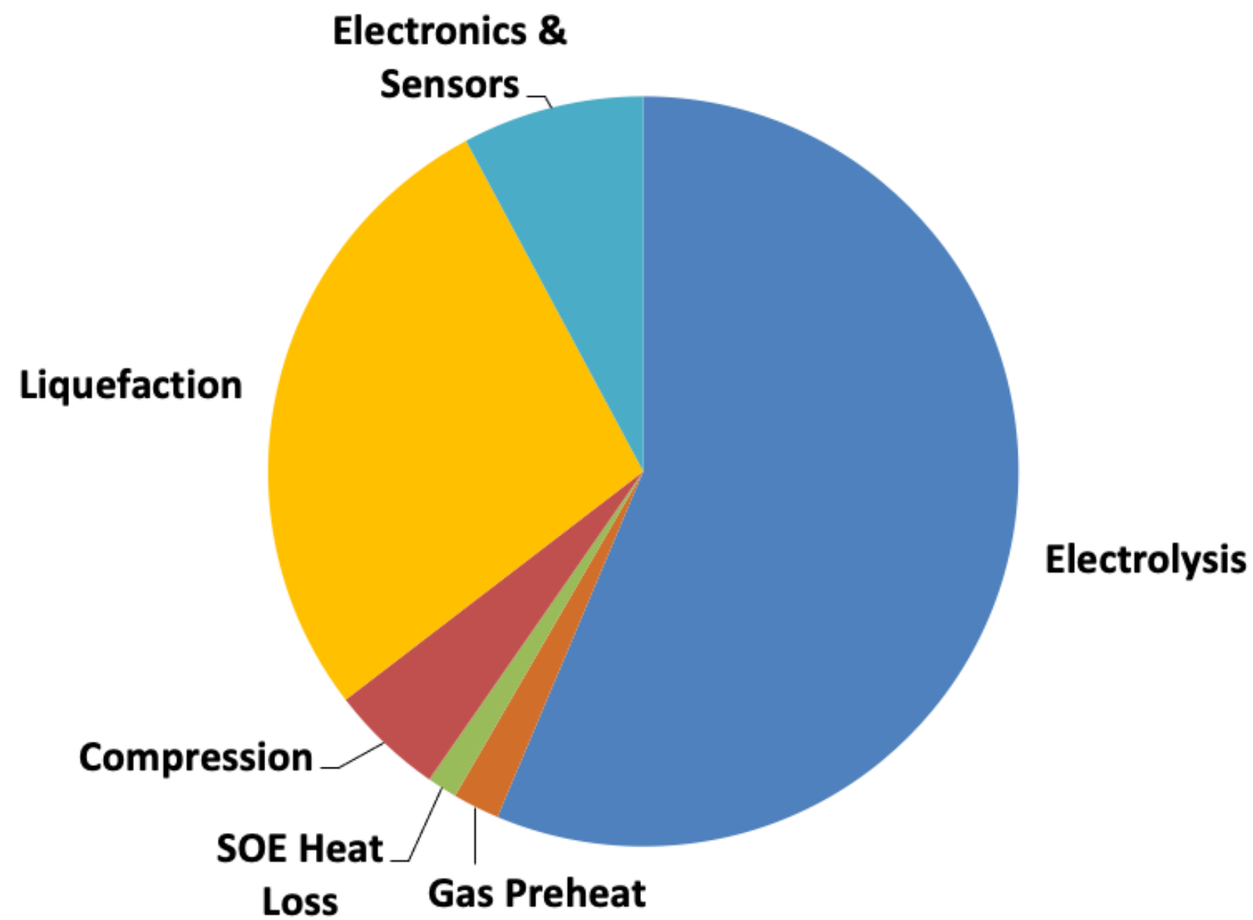
ISRU Experiment

BAM, 3.1 KG/HR, 26.7 KW



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

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

Longer-term applications

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

Sponsors and Partners

Massachusetts Institute of Technology

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

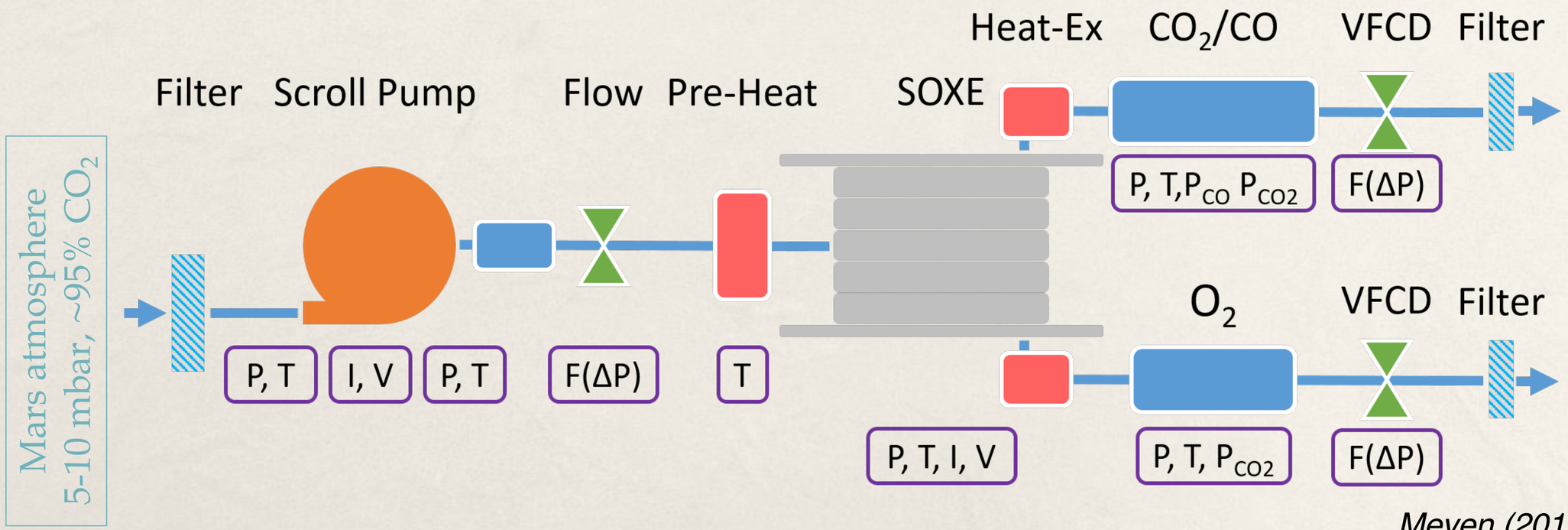
* Supported by HEOMD and STMD
* Mars 2020 Project managed by SMD

MOXIE
Mars Oxygen
ISRU Experiment

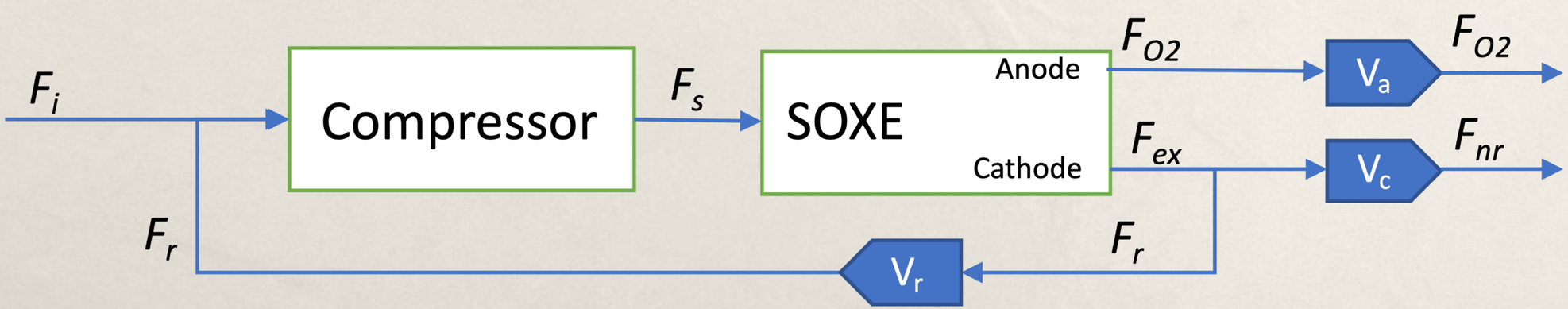
Backup

To be updated

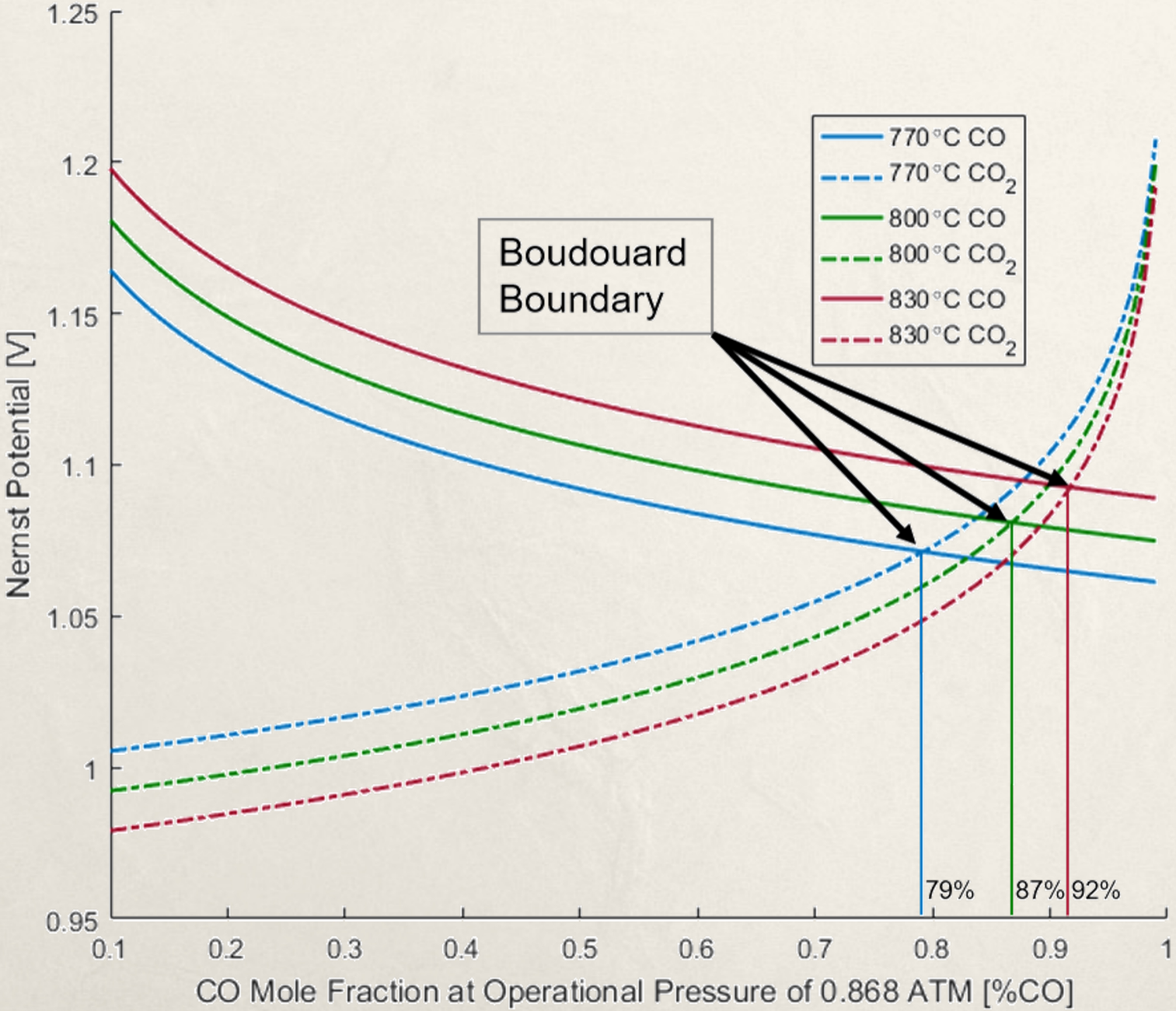
How MOXIE works



Meyen (2015)



Boudouard and Ni Oxidation Limits



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.

Runs to date

OC #	FM-OC9	FM-OC10	FM-OC11	FM-OC12	FM-OC13	FM-OC14	FM-OC15	FM-OC16	FM-OC17	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	**8 runs**
Sol	60	81	100	155	176	241	276	317	444	
Total O2 (g)	5.4	6.9	6.9	8.9	8.1	6.9	6.8	6.7	9.0	**65.61 grams O2**
Peak rate (g/hr)	6.0	8.0	8.0	6.0	6.9	7.6	7.2	7.0	7.6	
Duration (min)	59	74	71	96	82	74	74	74	97	**700.55 total minutes**
Time of day	Night	Night	Day	Night	Night	Night	Day	Day	Night	
Microphone	No	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	