Mars Oxygen
ISRU Experiment

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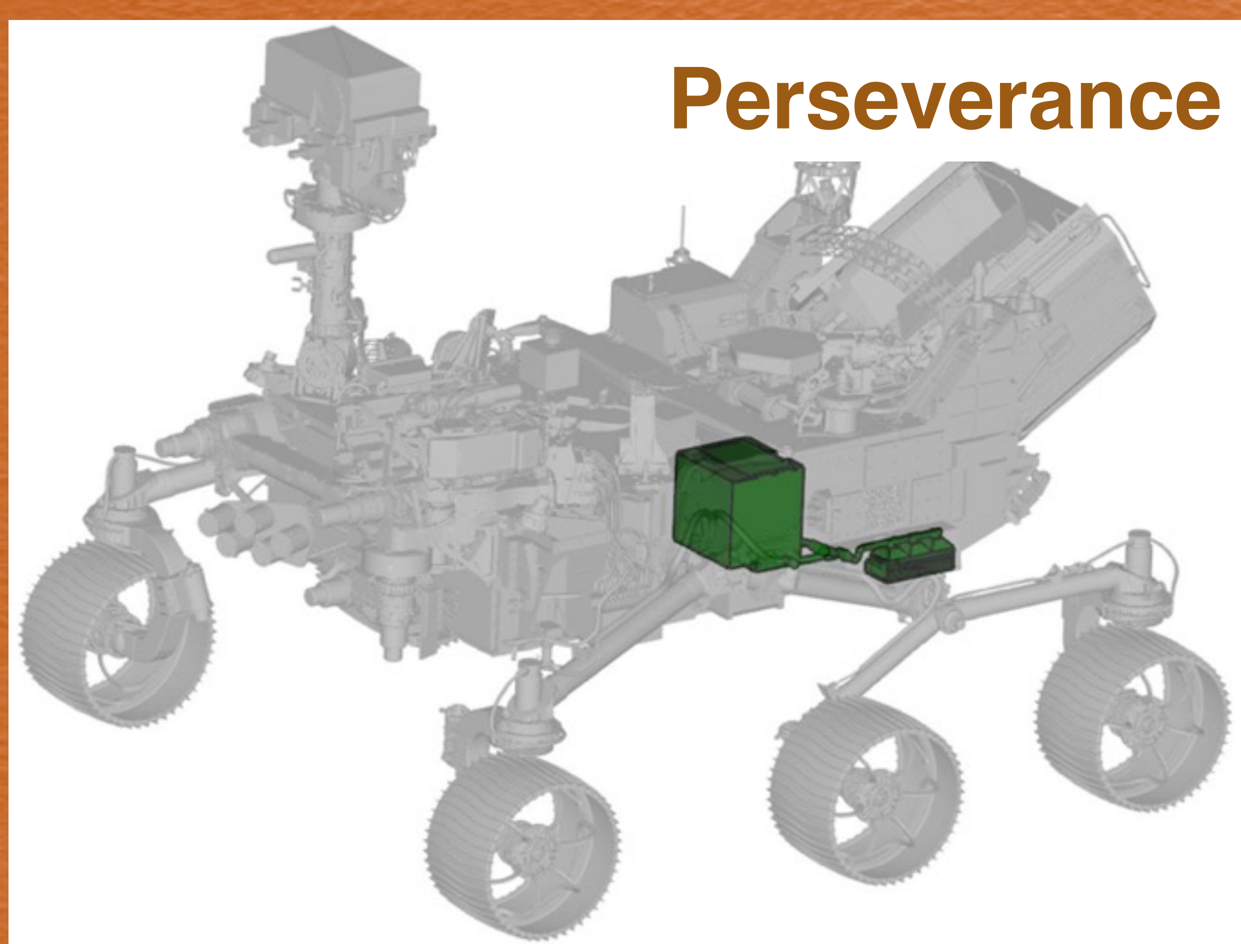
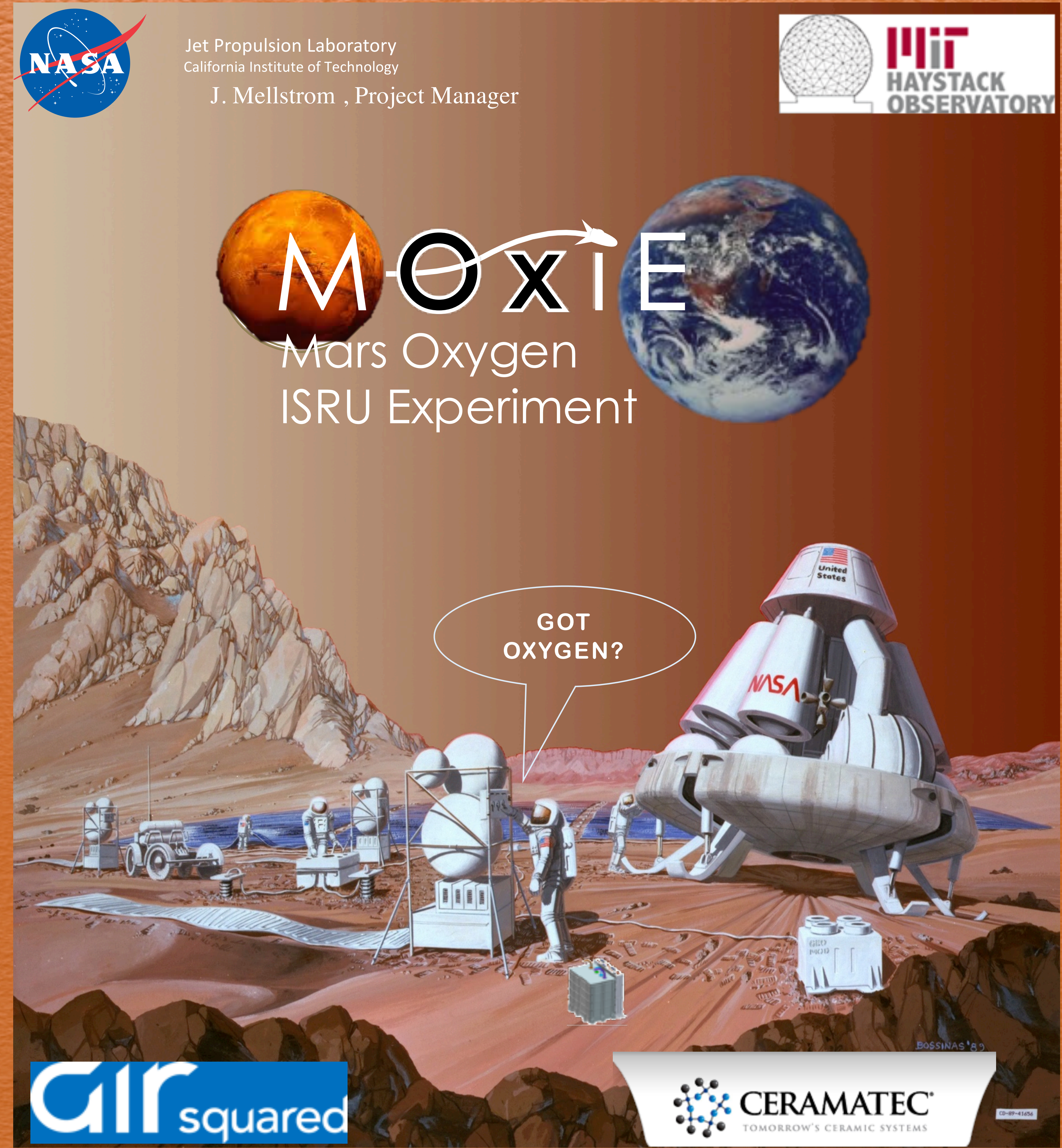
Space Resources Roundtable
June 6, 2023

MOXIE: What makes it hard, what would make it easy.

#JOURNEYTOMARS

* A scale model of an In Situ Resource Utilization (ISRU) plant for a human mission.
* Makes 6-10 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



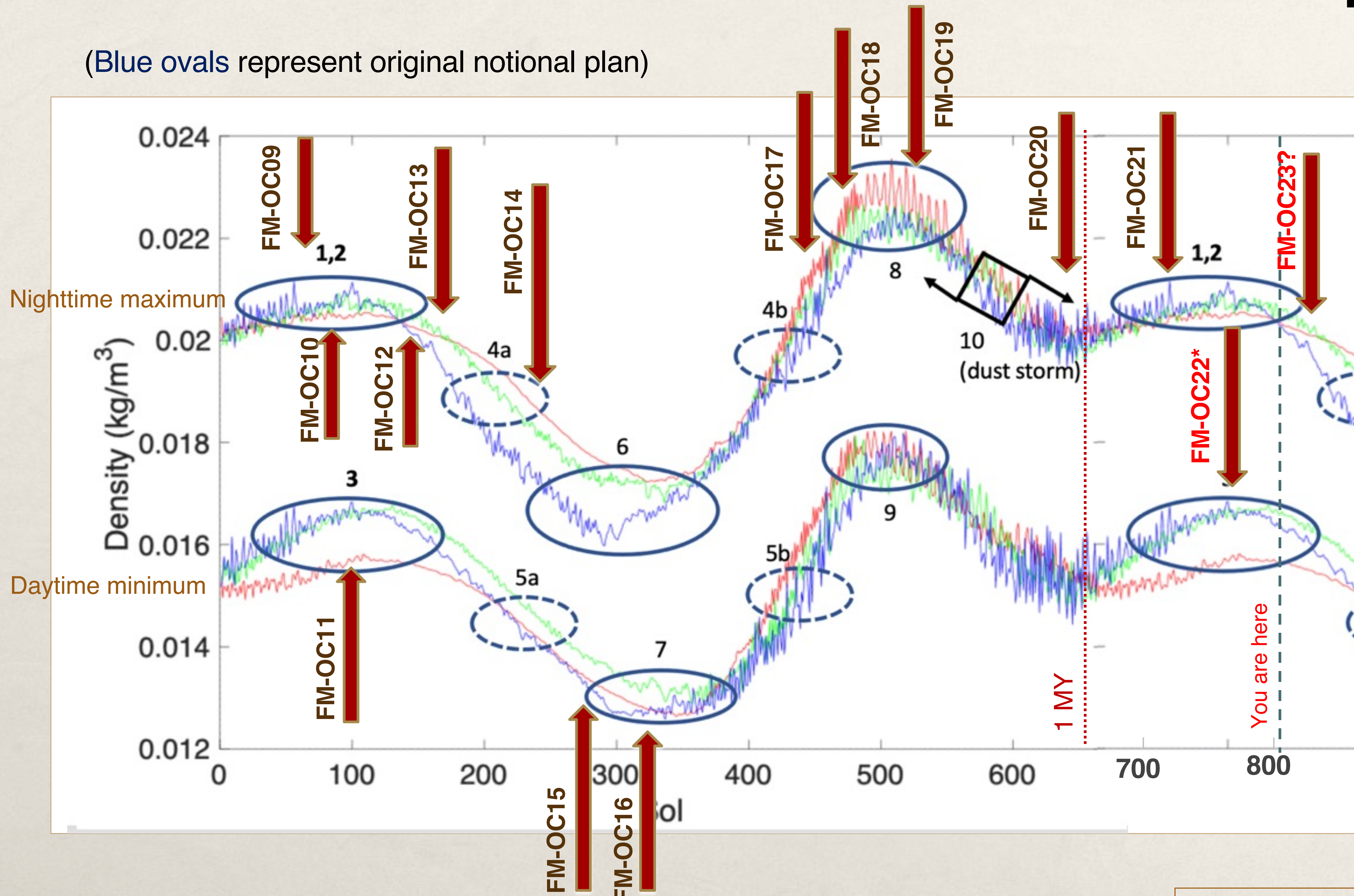


Operation summary to date

- 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)
- 2 oxygen-production runs in CY'23 so far
  - FMOC-21 on sol 710 in February, 2023
    - Purity test by varying CO_2 flow rate (i.e. cathode pressure) over wide range while holding current (i.e. anode pressure, production rate) constant
  - FMOC-22 on sol 771, April 21, 2023
    - Validation of *pressure control* and *low pressure* operation.
    - This enabled the first *morning* run (i.e. not at diurnal density extrema)

Operations to date

(Blue ovals represent original notional plan)

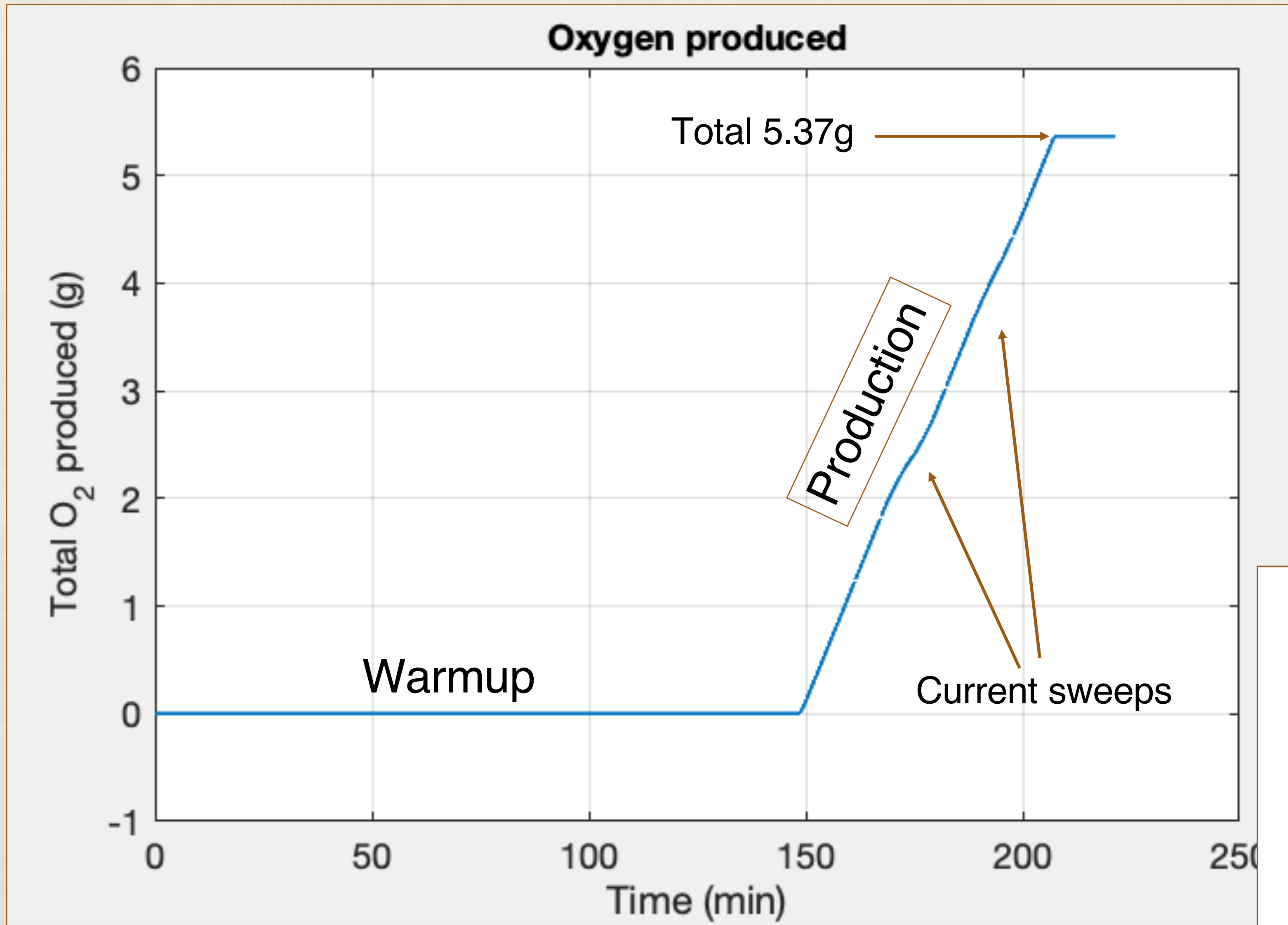


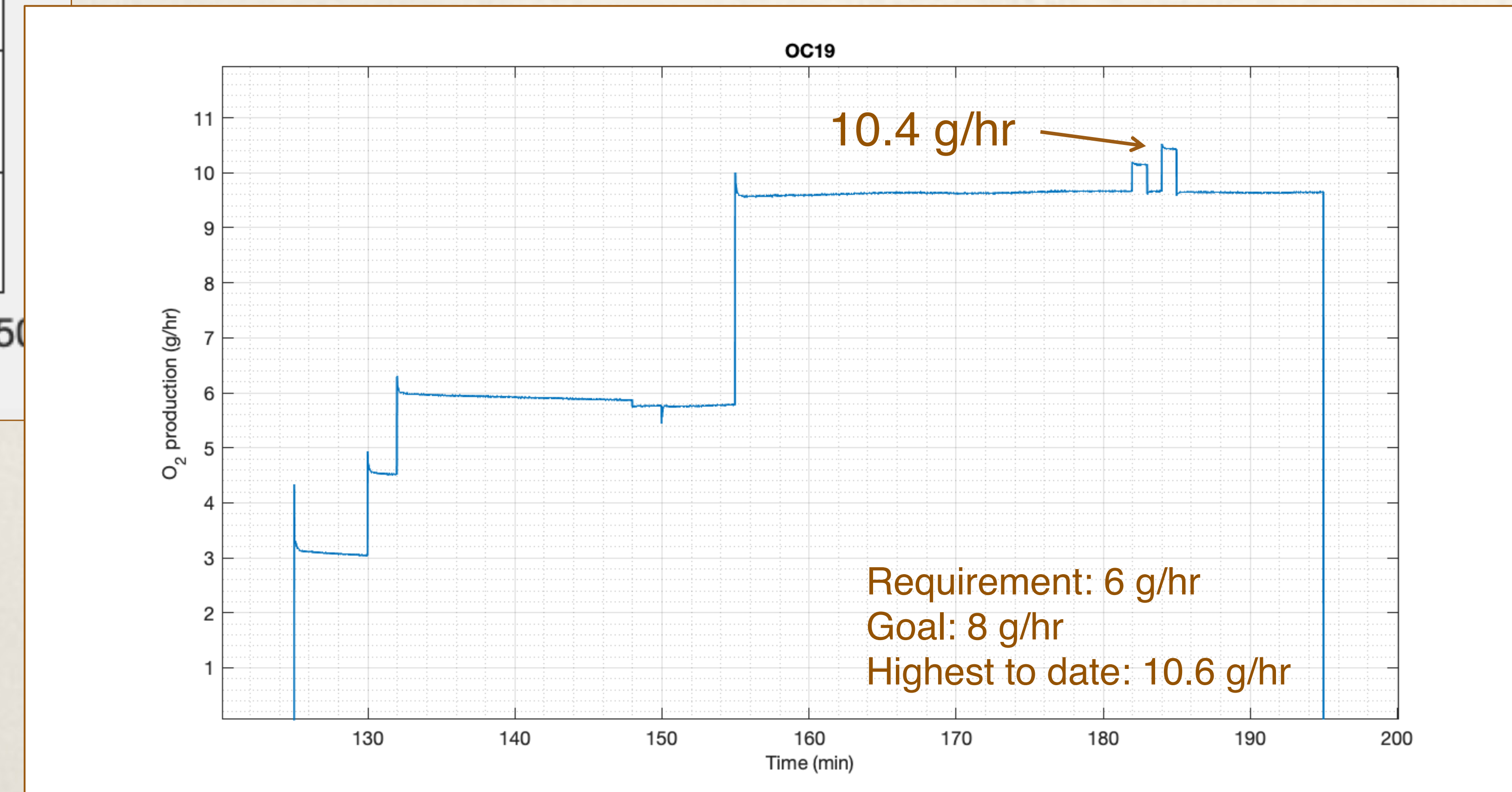
TOTALS
13 runs
106.054 grams O2
1083.15 total minutes
5.90 g/hr (average)

* Oxygen produced 9-10 am

Running MOXIE efficiently and safely

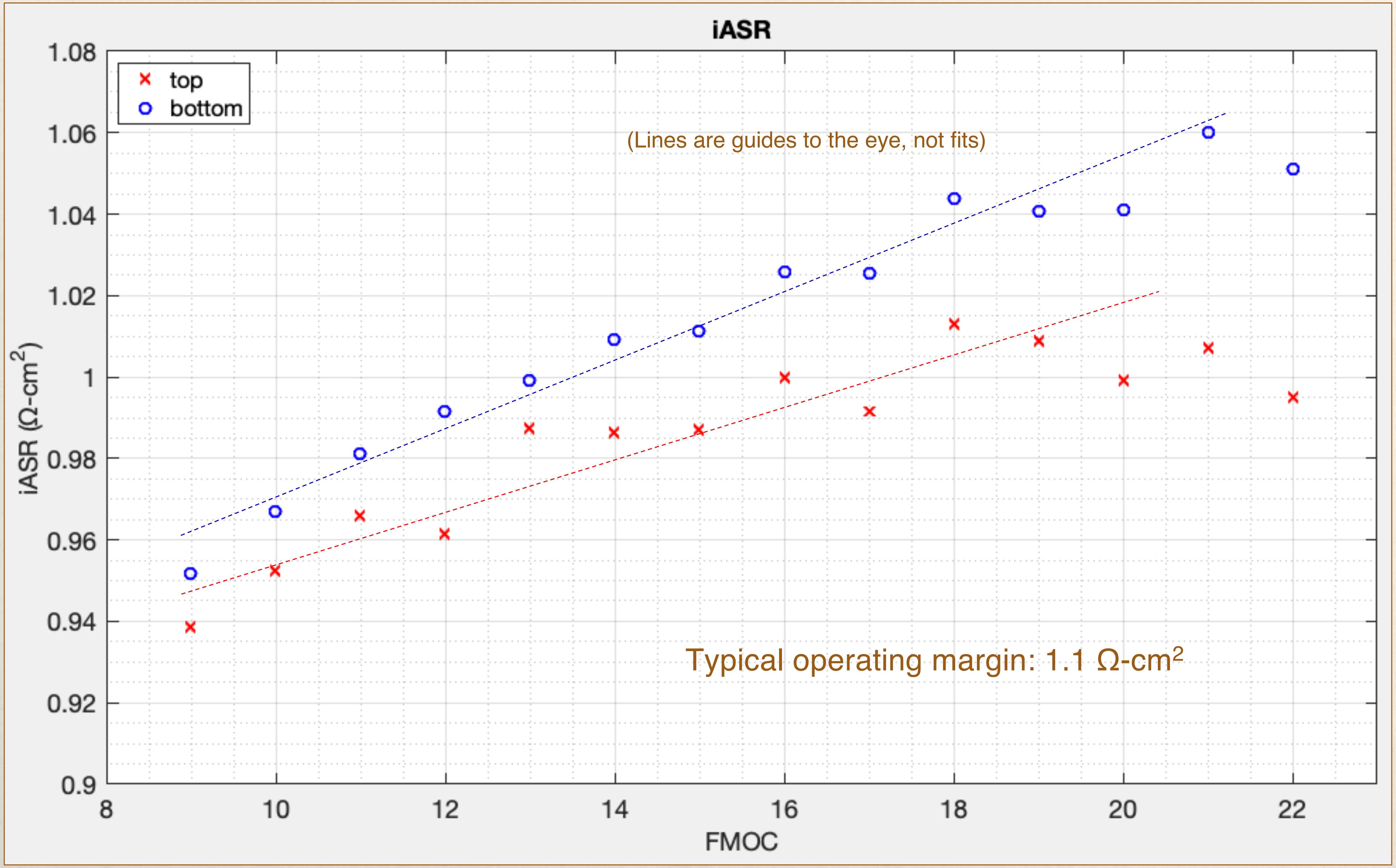
MOXIE
Mars Oxygen
ISRU Experiment





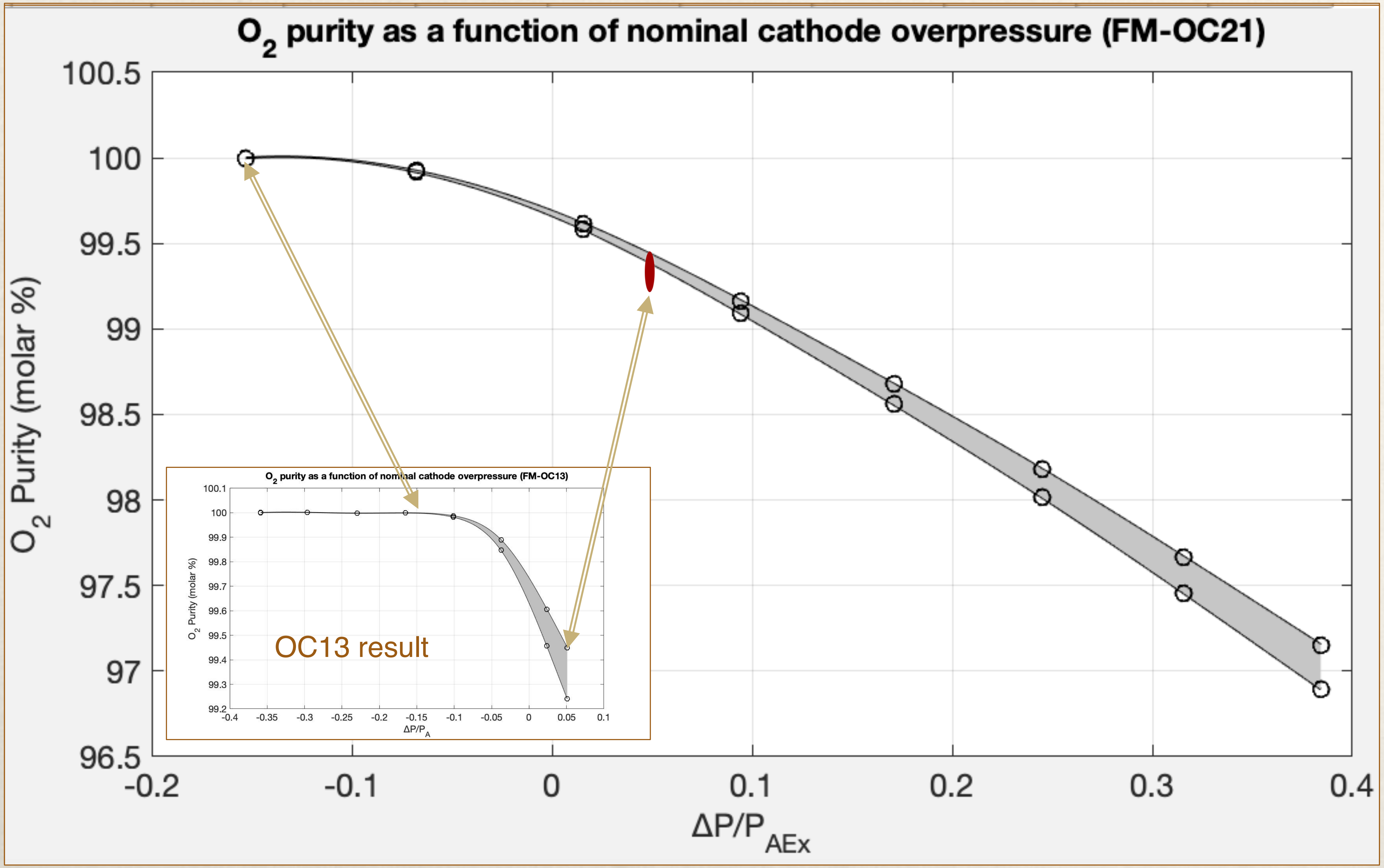
iASR (current and flow compensated)

* Are we starting to see the power law behavior, or just scatter?

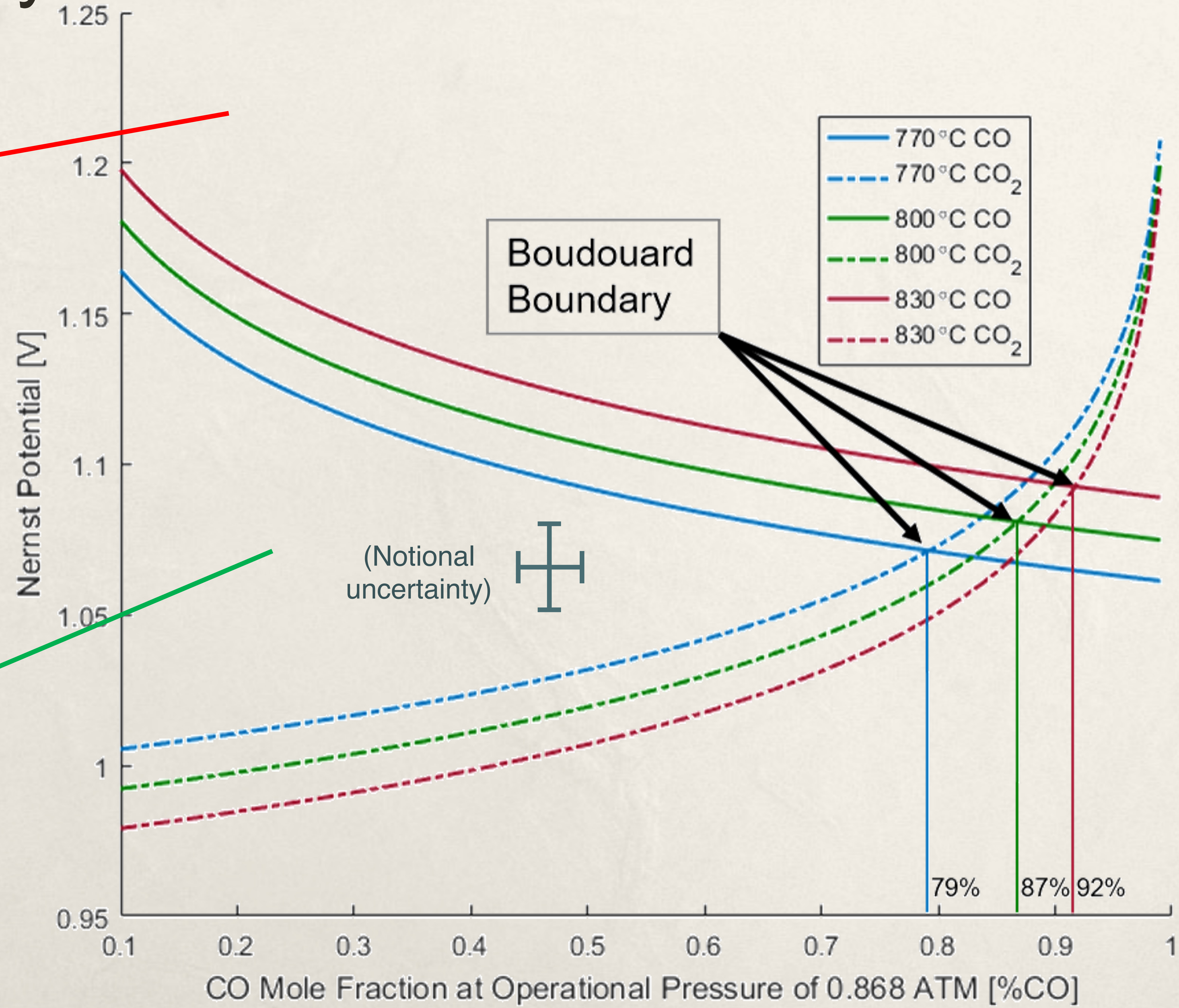


O_2 Purity

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



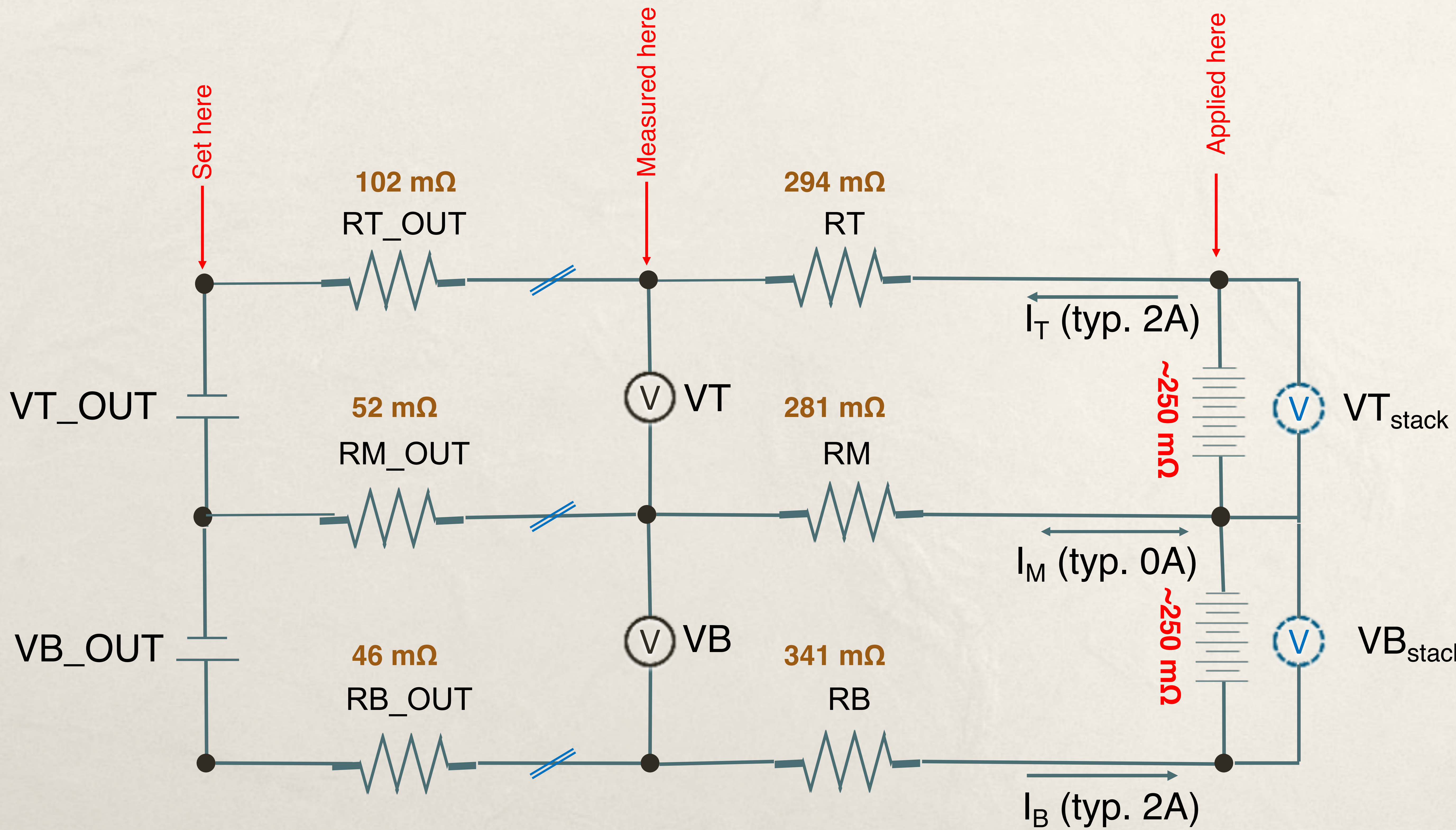
What makes this hard? *Uncertainties* affecting efficiency and safely.



1. Voltage measured through current-carrying wires across poorly known resistances

- The problem:
  - Stack connections need to be low thermal conduction and high temperature tolerant → fine Inconel.
  - Wire resistance is high compared to stack, and poorly known (especially windings).
- MOXIE solution
  - Voltage control mode offers partial solution (See #2)
- Future solution
  - Non-current-carrying voltage sense wires
  - Coking-resistant technologies (in development)

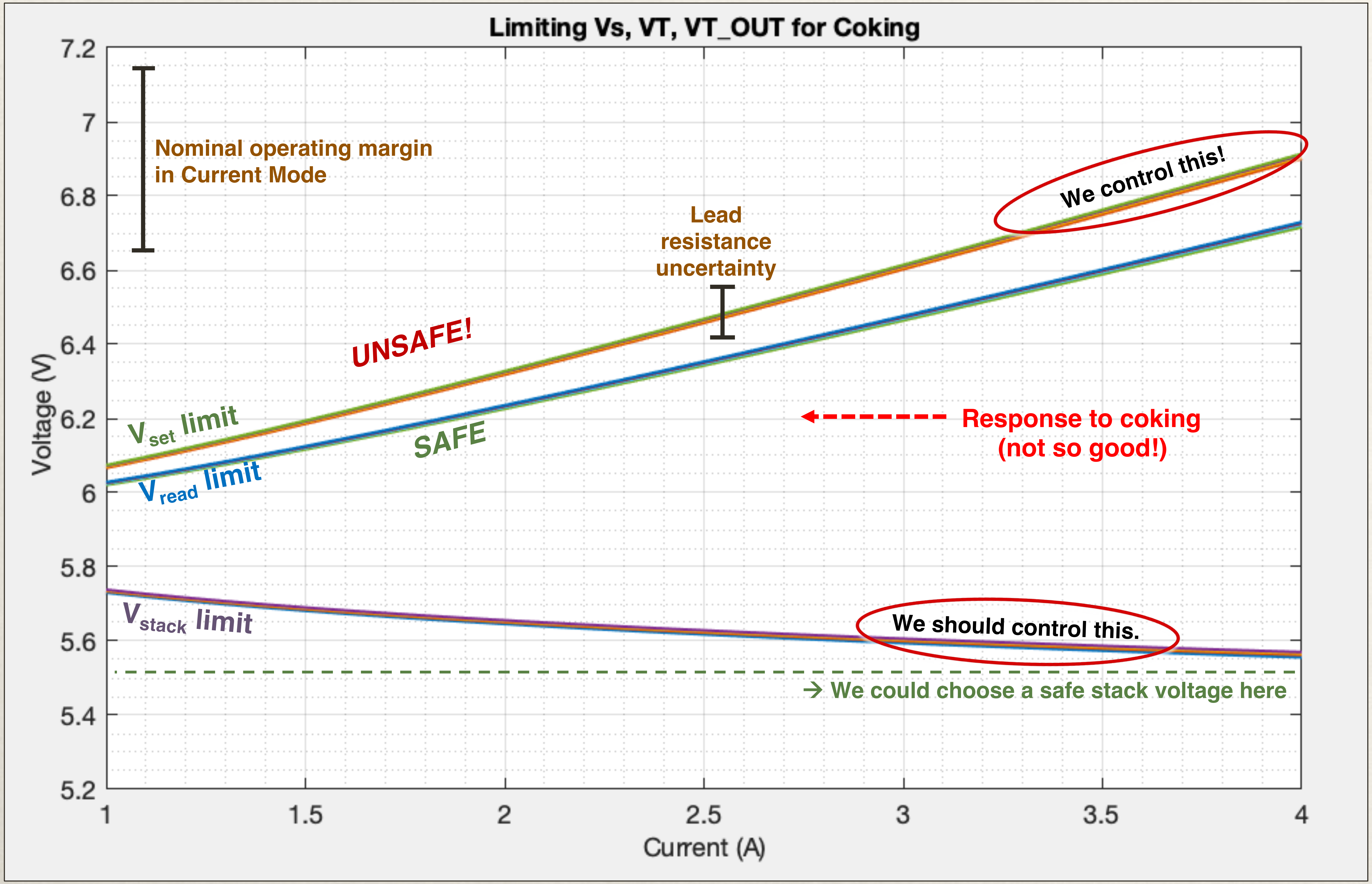
1. (cont.)


Set here
Measured here
Applied here
102 mΩ
RT_OUT
294 mΩ
RT
I_T (typ. 2A)
VT_OUT
52 mΩ
RM_OUT
VT
281 mΩ
RM
~250 mΩ
VT_stack
I_M (typ. 0A)
VB_OUT
46 mΩ
RB_OUT
VB
341 mΩ
RB
~250 mΩ
VB_stack
I_B (typ. 2A)

2. Voltage uncertainty

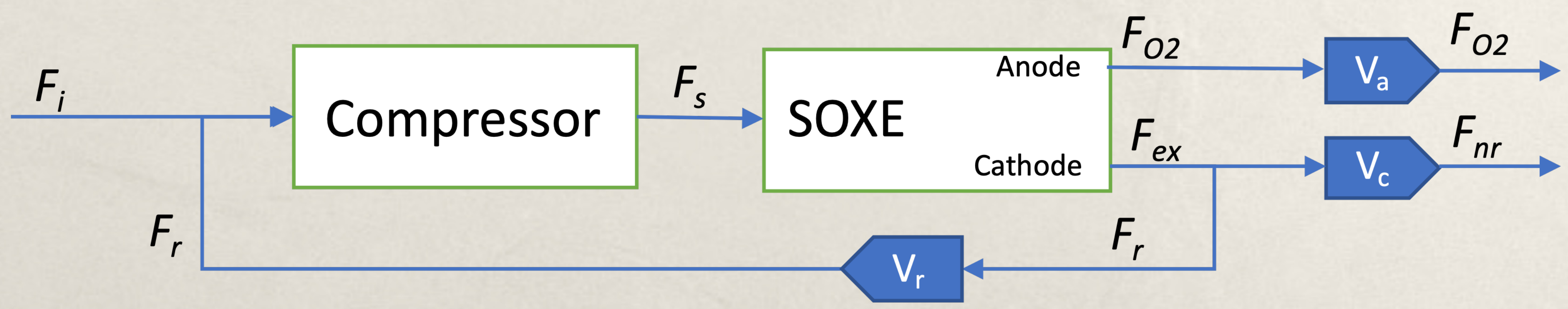
- The problem:
  - We would like to set *stack voltage* relative to the coking threshold, which is only weakly dependent on flow and current.
  - MOXIE was validated in constant *current* mode. Uncertainty in I-V relationship (iASR and resistances) → uncertainty in stack voltage.
- MOXIE solution:
  - Constant *power supply voltage* mode is now validated, but voltage *at stack* is still current-dependent (see item #1)
- Future solution:
  - Constant *stack voltage* operation, adaptive setpoint for utilization variations
- *See next slide*

2. (Cont.) Maximum safe voltages



3. Flow control is through fixed aperture with volumetric compressor

* The problem:
  * Molar flow uncertainty from varying external air density
  * Poorly known gas temperature rise in inlet tube
  * Poorly known and evolving compressor volumetric efficiency
* MOXIE solution:
  * We have validated a pressure-feedback mode in zone with accurately-measured temperature
* Future solution
  * Pressure regulation and true mass flow control (explored in lab setting)



4. Stack temperature variations and gradients

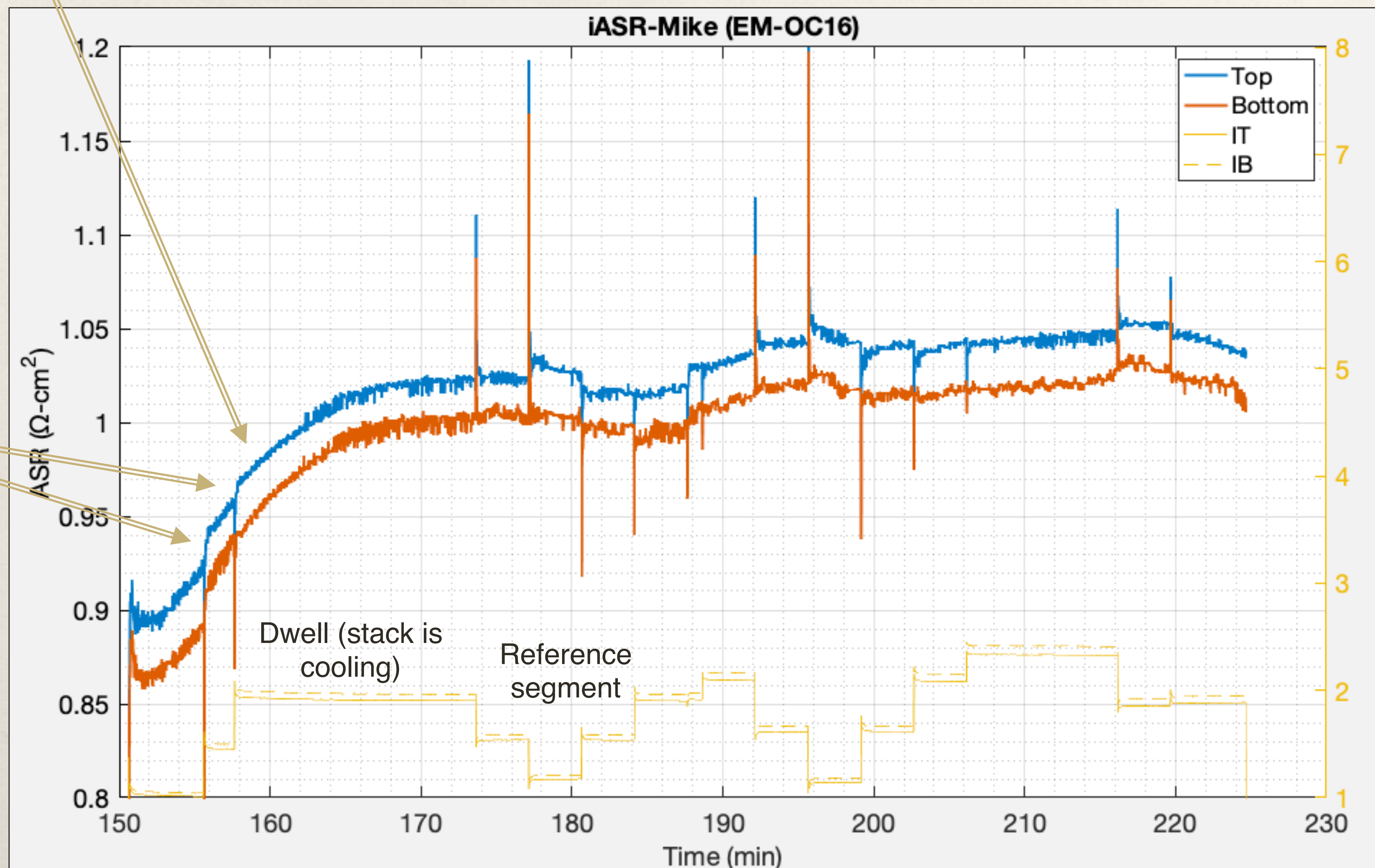
- The problem:
  - ASR (i.e. I-V relationship) is strongly temperature-dependent
  - There are poorly-understood 5-10K gradients across the stack (vertically and laterally)
  - Temperature is modified by endothermic reaction rate as well as flow rate
    - T changes are evident from voltage/current drift (depending on mode) as well as Nernst potential changes manifested as apparent ASR "jumps"
    - T is only measured near heaters, poorly coupled to stack
    - Internal response time constant ~10-15 minutes (compare 1-hr runs)
- Possible MOXIE solution:
  - A high-fidelity dynamic internal thermal model (a major effort).
- Future solutions
  - A more uniform oven to minimize gradients
  - Sustained operations, made possible by dedicated operations
- *See example next slide*

4. (Cont.). iASR variation in typical run

Mars Oxygen ISRU Experiment

Stack is cooling due to endothermic reaction (time constant 10-15 min.)

"Jumps" due to current change (compensated at nominal temperature)



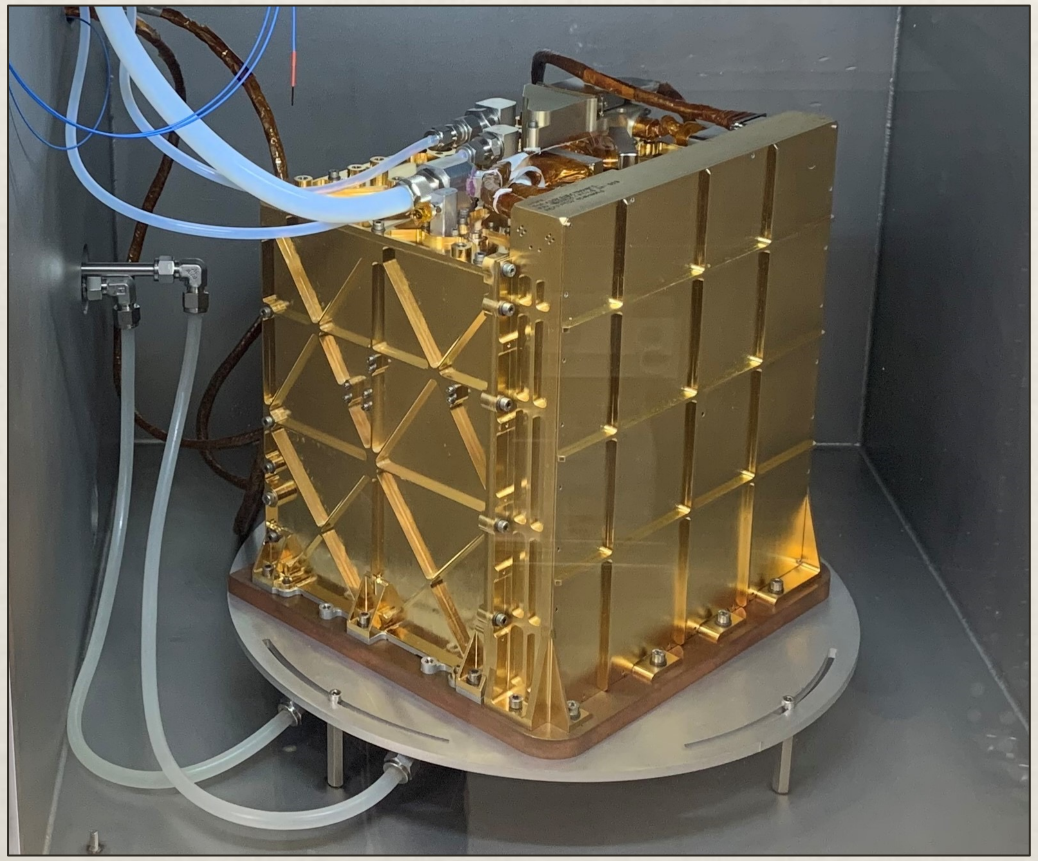
Summary: What have we learned?

MOXIE
Mars Oxygen
ISRU Experiment

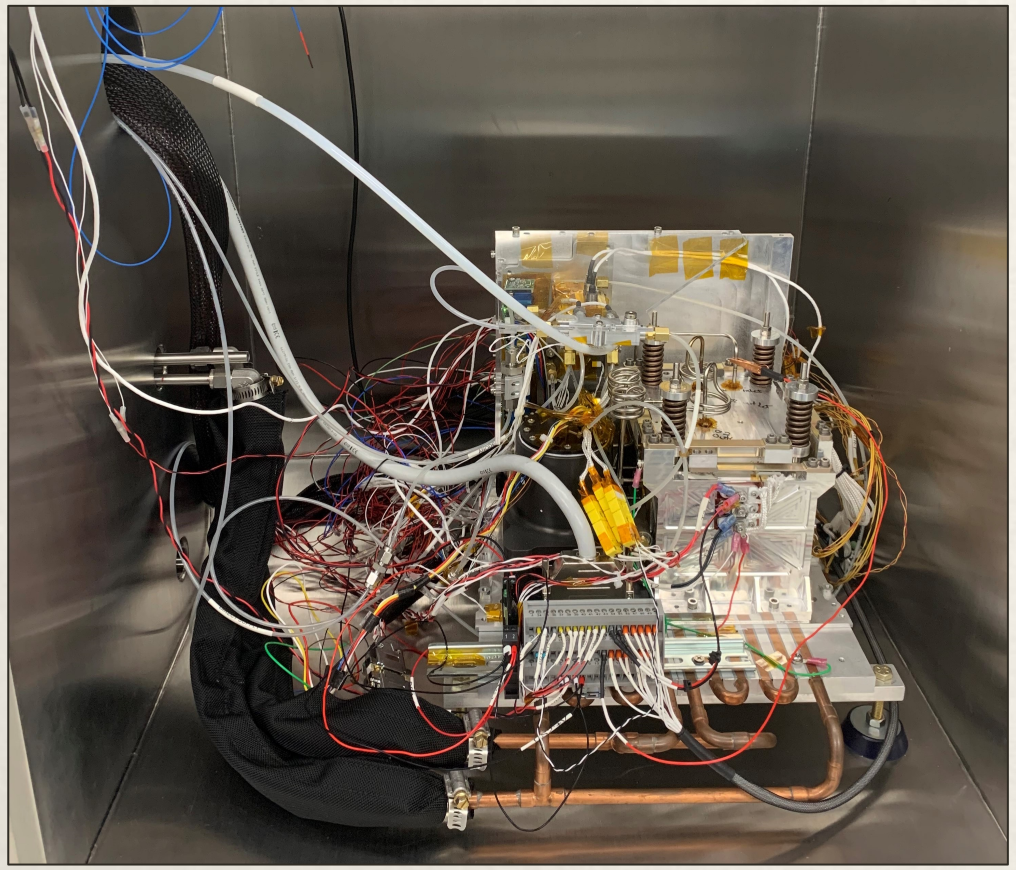
* With careful operation, MOXIE is surprisingly robust against thermal cycling, dust, changes in atmospheric density and temperature
* A few simple changes will greatly reduce power consumption:
  * Operation at much lower cathode pressure (regulated)
  * A well-insulated surrounding oven
  * Heat exchange 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 sensors
  * A capable processor with dynamically tunable control algorithms
  * Materials improvements to enhance resistance to carbon deposition

Shameless advertisement

* Extensive laboratory capabilities will be discussed on Thursday (Steen)
* MOXIE funding is exhausted at end of year, we are seeking new uses for the lab (with potential funding sources!)



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.

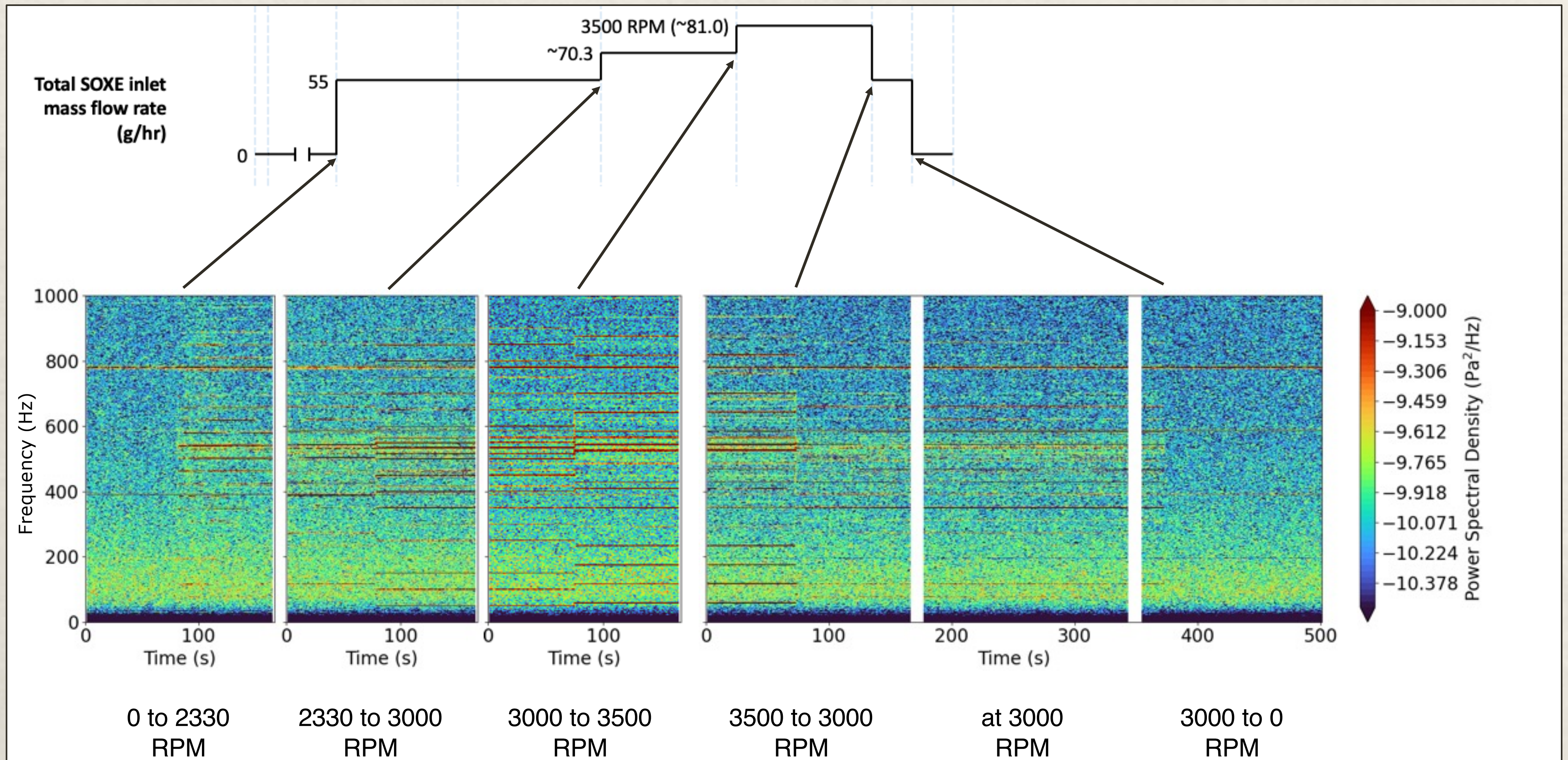
Backup

To be updated

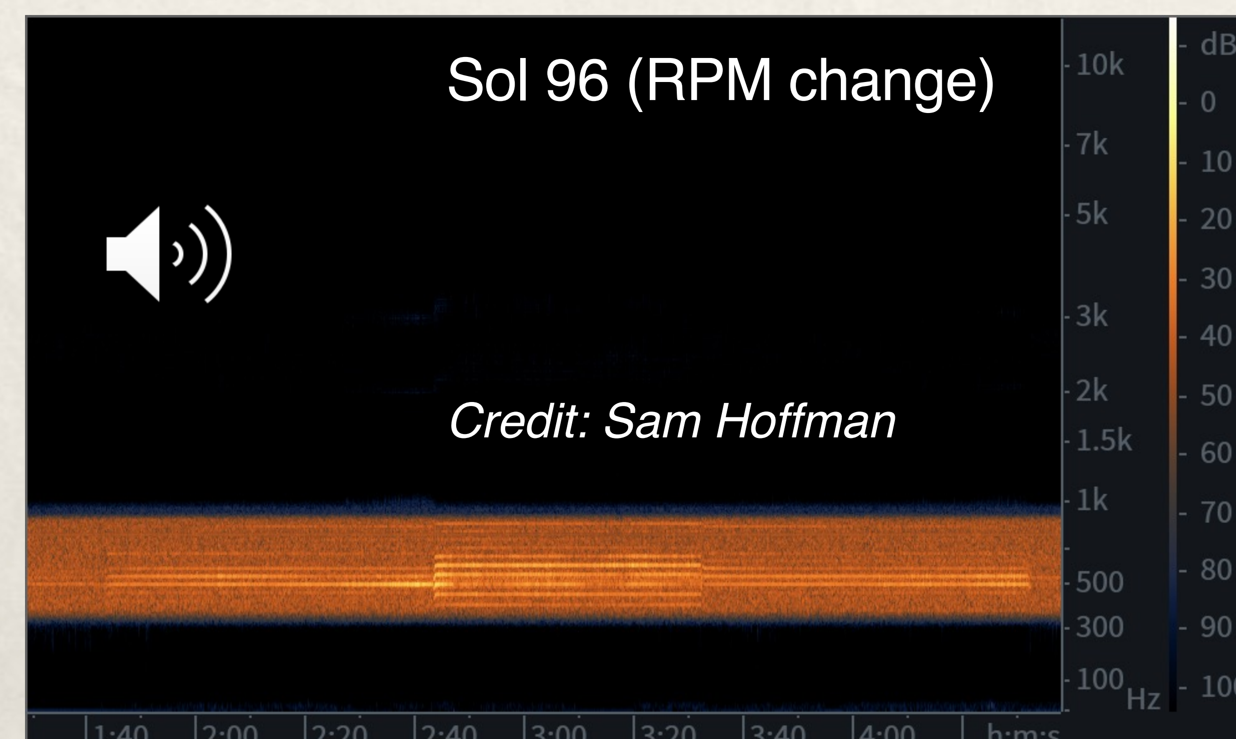
MOXIE compressor recorded by SCAM mic

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

Sol 276 (turn-on)



Supercam microphone spectrograms (courtesy Chide et al.)

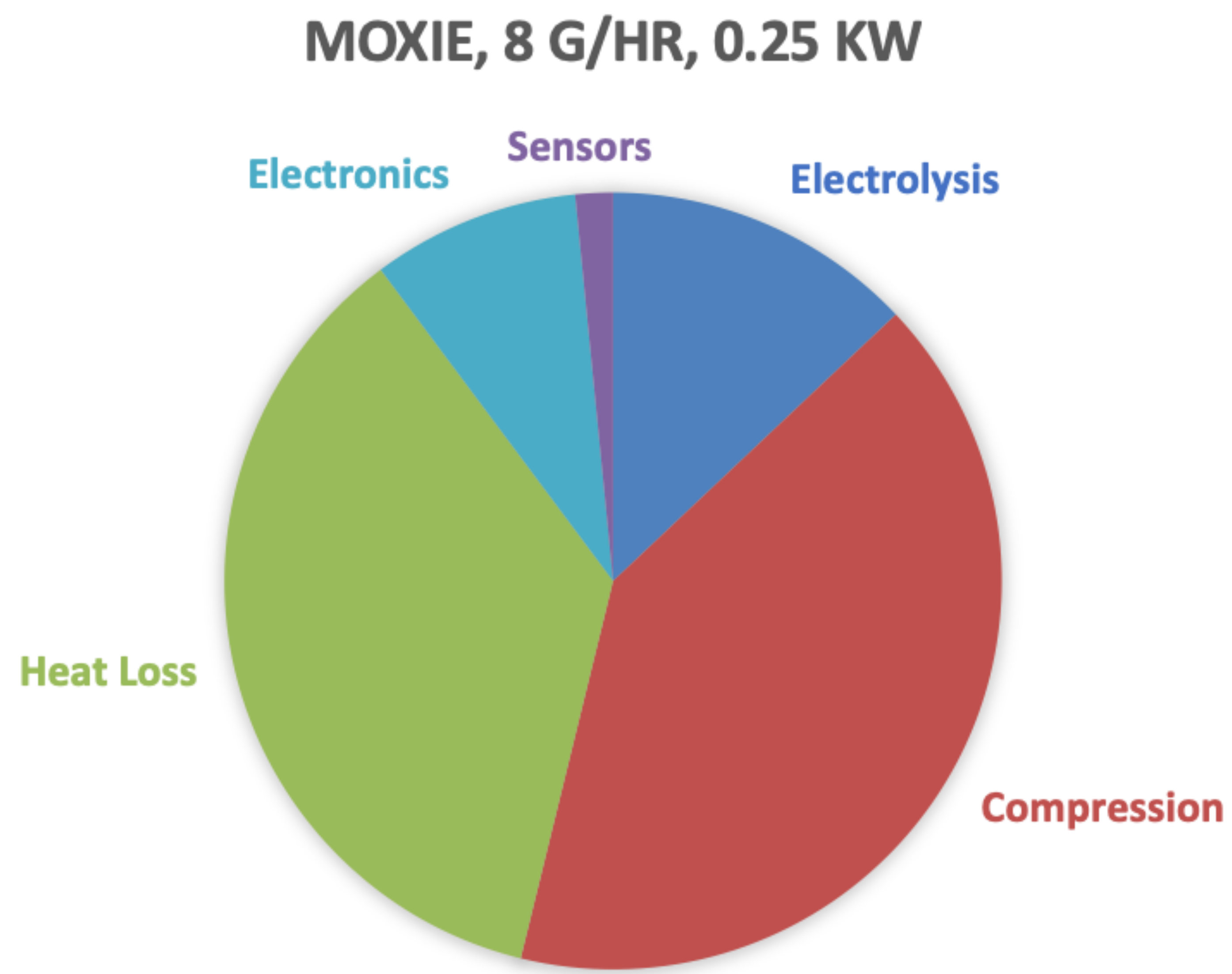


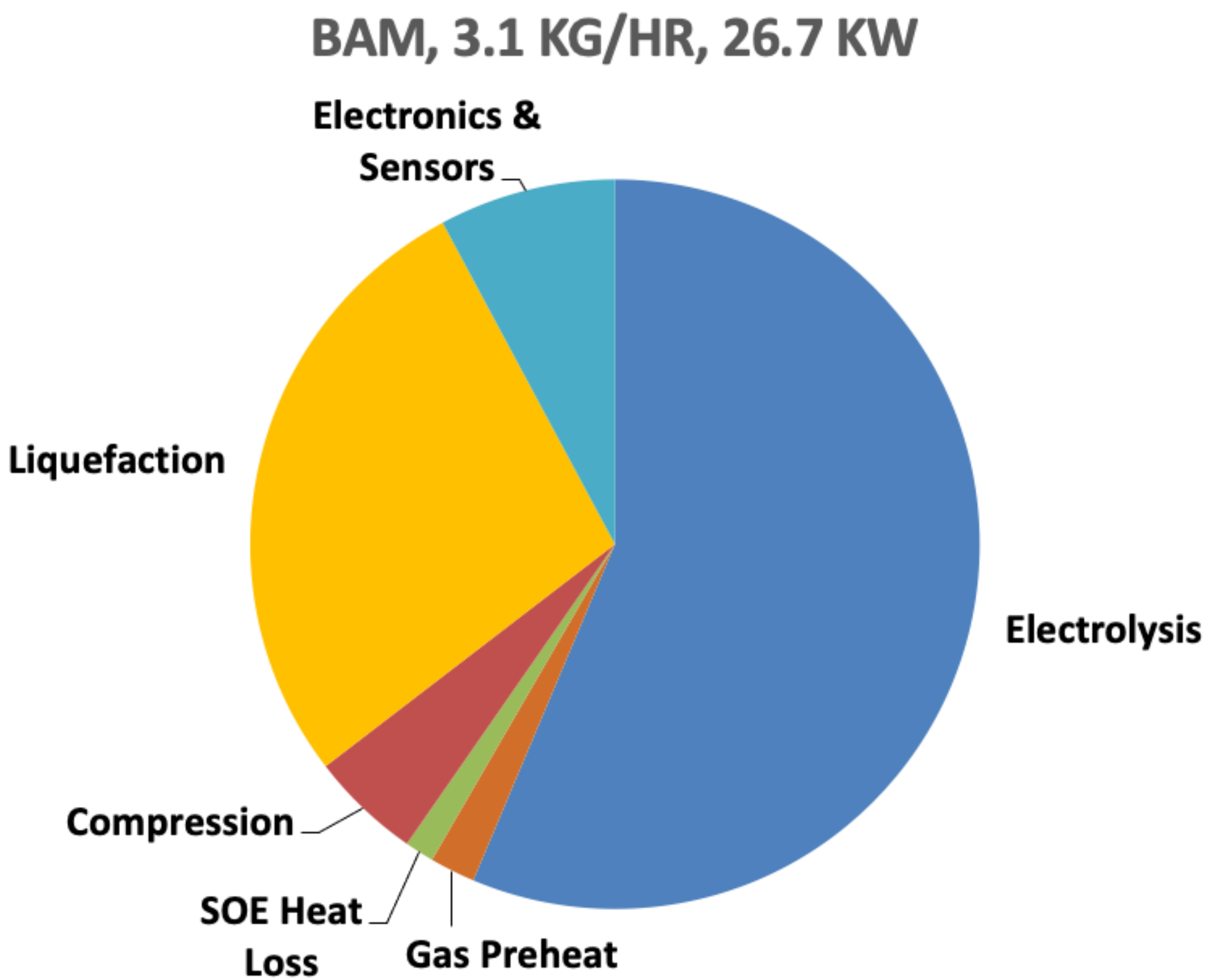
The path to full-scale

MOXIE Mars Oxygen ISRU Experiment

- A full-scale system will need to:
  - Produce >200x more oxygen
  - Operate continuously for over a year
  - Be smarter and more adaptive
- Power efficiency will be improved:
  - Low density operation will dramatically reduce compressor power
  - A proper oven will dramatically reduce heat loss
- Components scale-up is in progress

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





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

How we expect MOXIE will be used

* For early missions, a scaled-up version will save up to 30 tons of cargo by providing O_2 for propellant (~27 tons) and breathing (~2 tons).
* Later, adapted to co-generation, as part of a system to combine H_2O and CO_2 to make methane and oxygen.
* As part of an environmental control unit for habitat modules and rovers to heat, cool, scrub CO_2, and replenish O_2.

Runs to date

2021

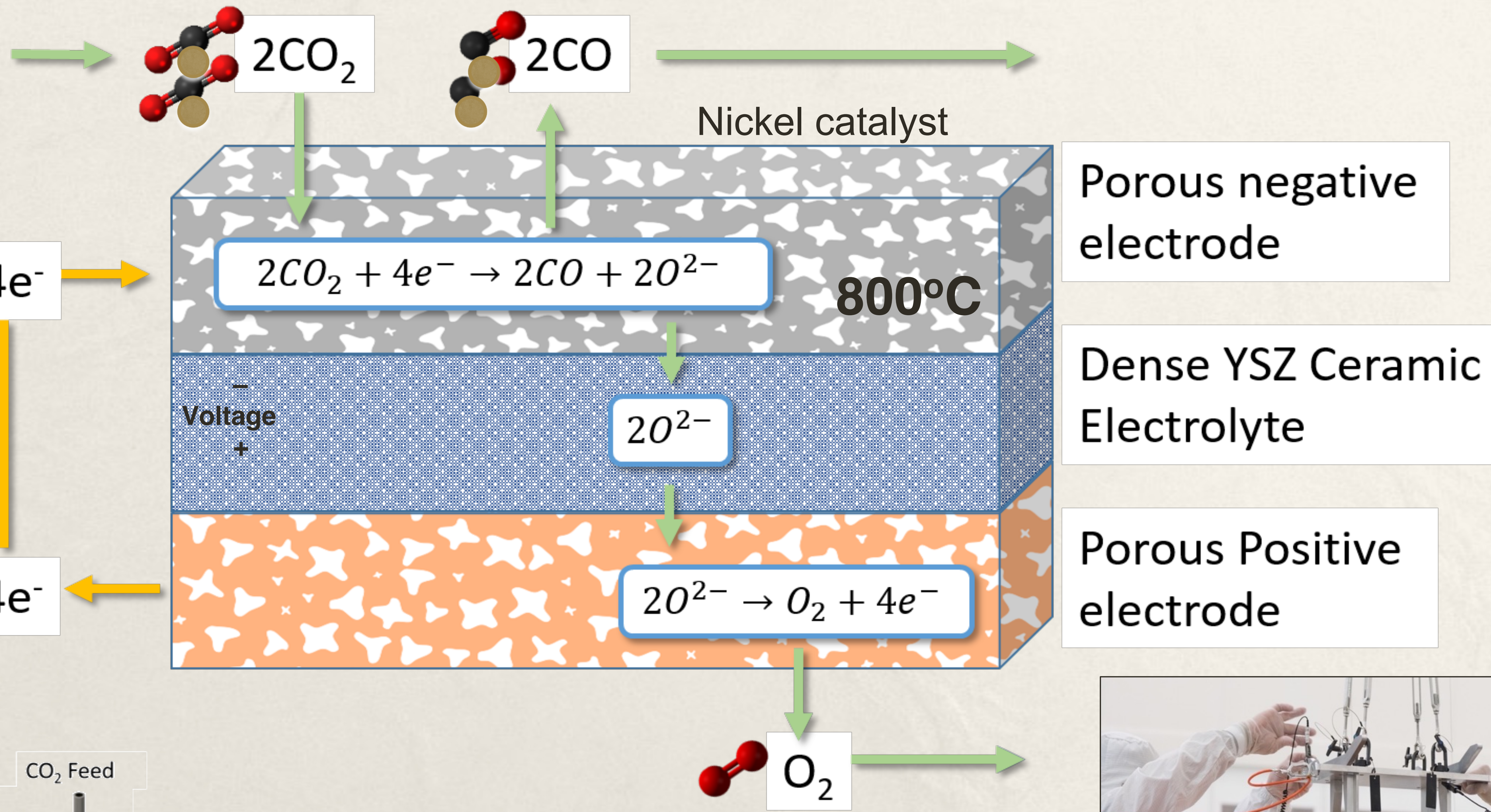
OC #	FM-OC9	FM-OC10	FM-OC11	FM-OC12	FM-OC13	FM-OC14	FM-OC15
Comment	1st oxygen!	1st microphone	1st daytime run	1st Temperature sweep (to determine series resistance)	1st flow sweep (to determine oxygen purity)	Generic nighttime run (intermediate density)	Generic daytime run (low density)
Date	20-Apr-21	12-May-21	1-Jun-21	27-Jul-21	16-Aug-21	24-Oct-21	27-Nov-21
Sol	60	81	100	155	176	241	276
Total O2 (g)	5.40	6.92	6.92	8.92	8.12	6.86	6.77
Peak rate (g/hr)	6.00	8.00	8.00	6.00	6.90	7.61	7.22
Duration (min)	59	74	71	96	82	74	74
Average rate (g/hr)	5.49	5.61	5.85	5.58	5.94	5.56	5.49
Time of day	Night	Night	Day	Night	Night	Night	Day
Microphone	No	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

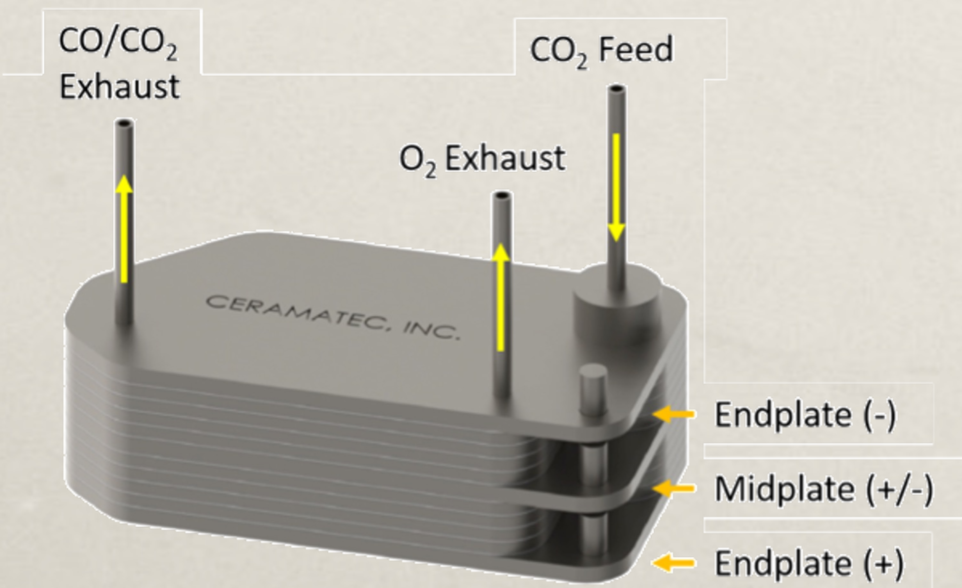
2022-3

OC #	FM-OC16	FM-OC17	FM-OC18	FM-OC19	FM-OC20	FM-OC21	FM-OC22
Comment	Generic daytime run (lowest density, just after dust event)	Unbalanced stack current to determine middle lead resistance	Voltage Mode (summer night)	Voltage Mode (Max oxygen)	Voltage Mode (Sustained max O2)	Repeat of flow sweep (higher cathode overpressure)	P4-feedback and low flow tests
Date	10-Jan-22	21-May-22	11-Jun-22	21-Aug-22	28-Nov-22	18-Feb-23	21-Apr-23
Sol	317	444	467	514	631	710	771
Total O2 (g)	6.73	8.91	8.03	9.11	9.17	7.53	6.60
Peak rate (g/hr)	7.01	7.60	7.56	10.44	10.56	5.95	8.95
Duration (min)	74	97	86	70	70	82	75
Average rate (g/hr)	5.46	5.54	5.63	7.80	7.86	5.51	5.28
Time of day	Day	Night	Night	Night	Night	Night	Night
Microphone	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Predecessors	None	None	None	None	None	None	None

TOTALS
13 runs
106.054 grams O2
1083.15 total minutes
5.90 g/hr (average)

The Solid OXide Electrolysis (SOXE) cell

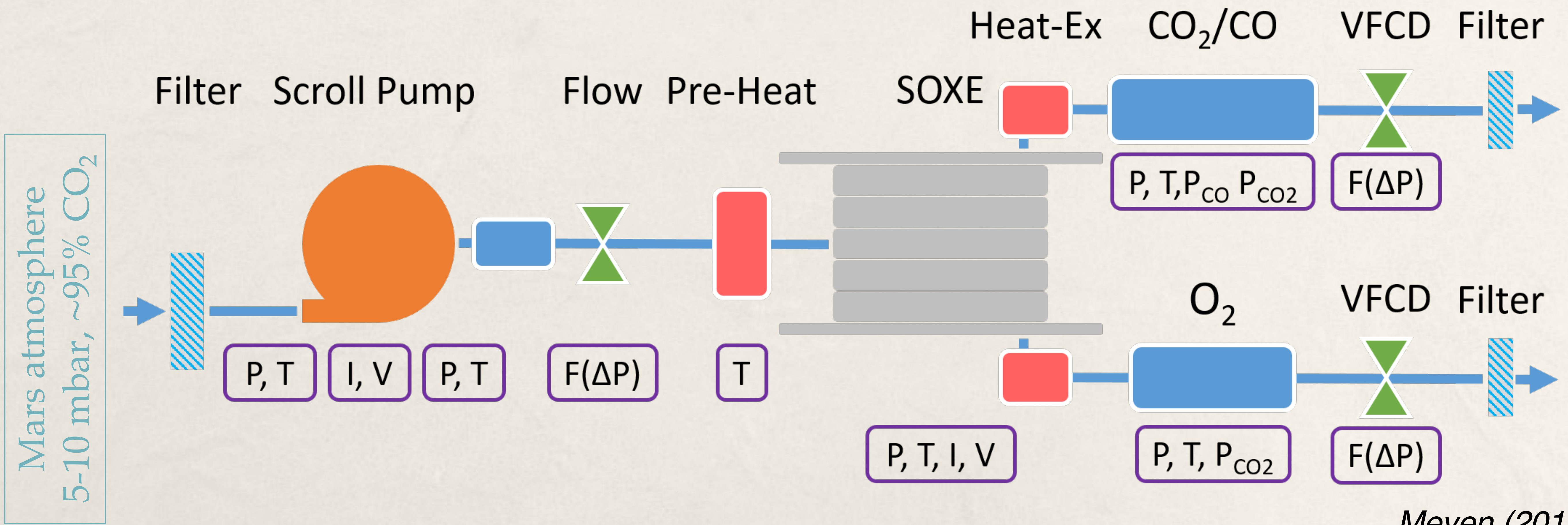




SOE: $CO_2 \rightarrow CO + O$
SOFC: $CO + O \rightarrow CO_2$

How MOXIE works

MOXIE
Mars Oxygen
ISRU Experiment



Meyen (2015)