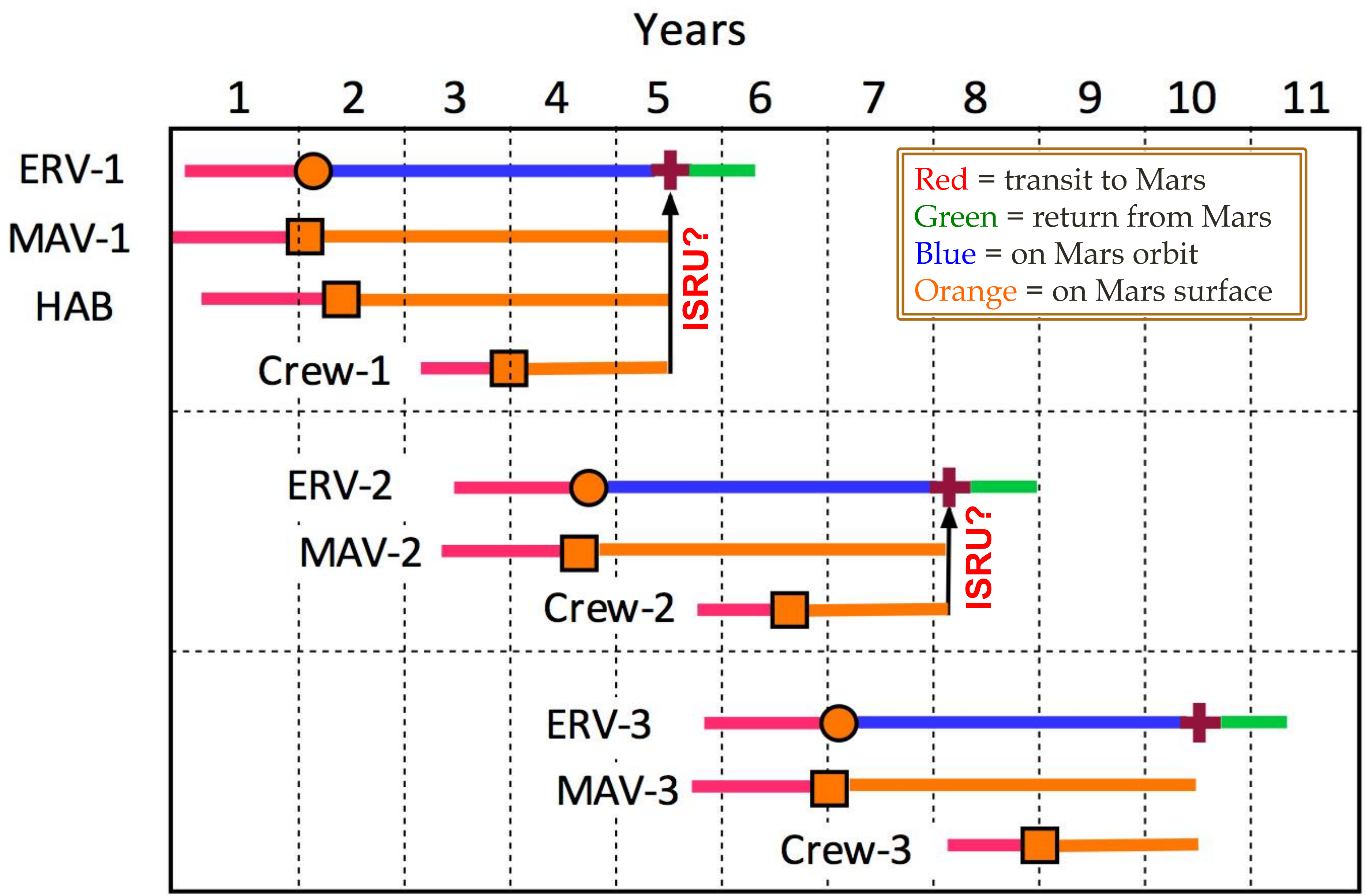
Reference technology

(Mostly MOXIE)

Long Term Mission Sequence



Benefits of ISRU propellant

ELEMENT	DRM-1 (mT)	DRM-3 (mT)	COMMENT
Ascent capsule	4	6	Includes crew of 6
Ascent propulsion stage	3	5	Typically 15% of propellant requirement
Propellant (CH_4 + O_2)	26	39	
Mass saved in LEO if ISRU produces CH_4 + O_2	300 -500	440-800	Depends on assumptions re: aerocapture/propulsion
Mass saved in LEO if ISRU produces only O_2	230-380	330-620	Depends on assumptions re: aerocapture/propulsion

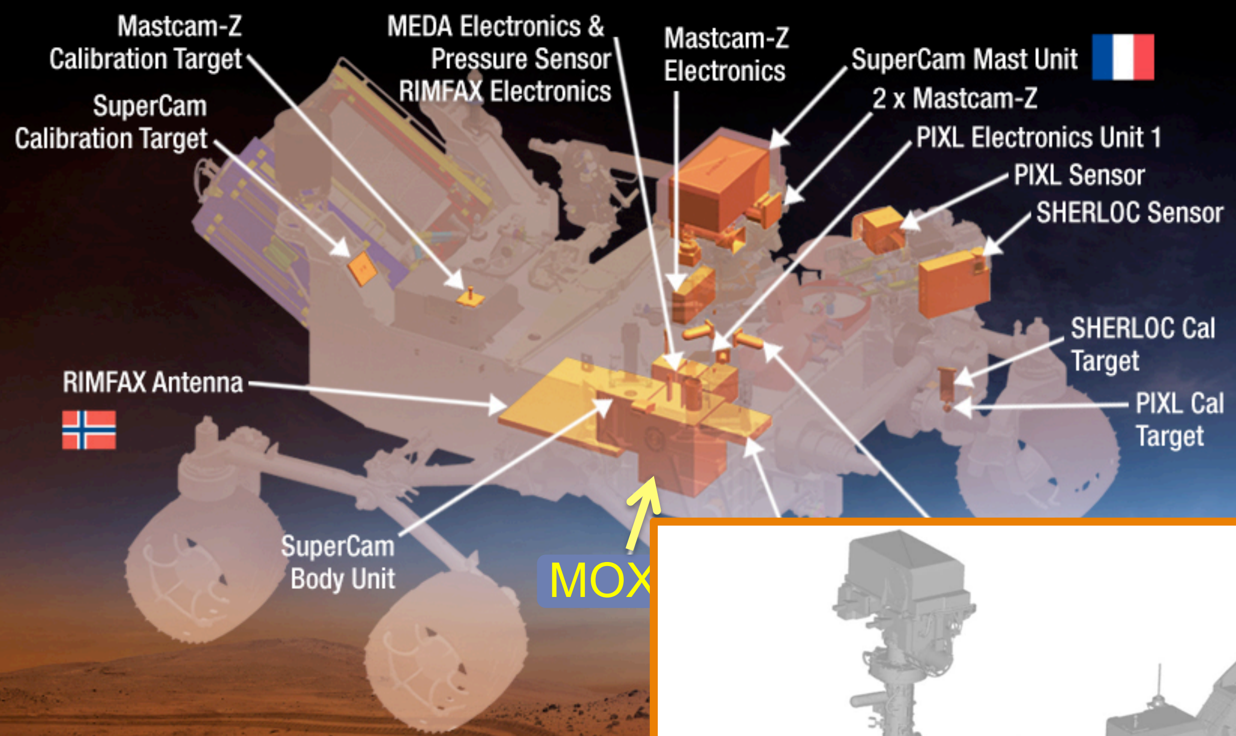
Robotic ISRU: Make vs "buy"

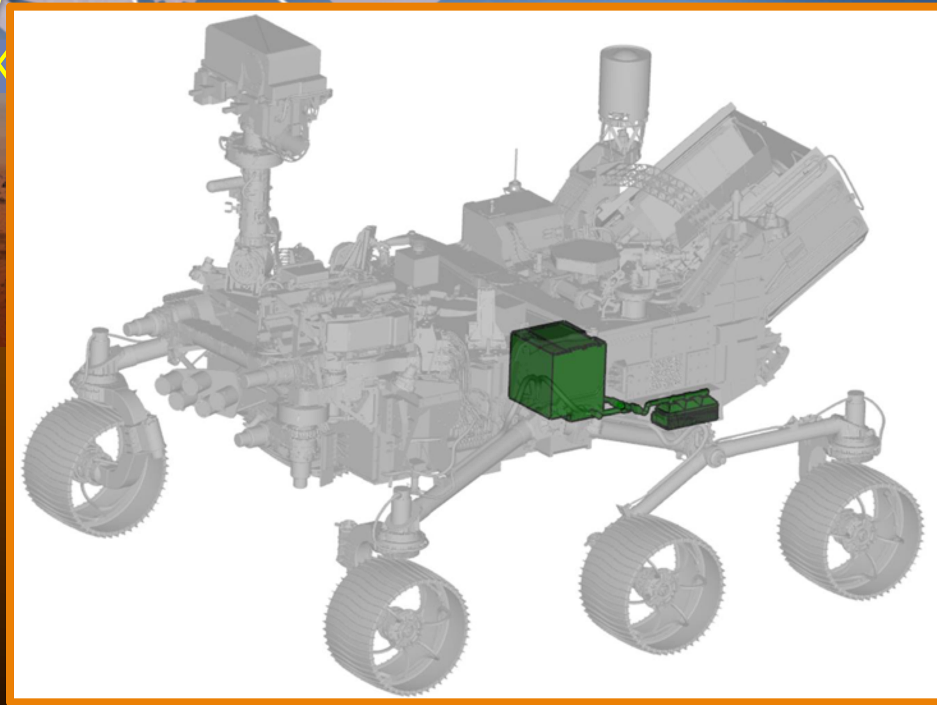
- Assumptions:
  - >25 kW power source
  - >12 months to produce propellant
- $CO_2 \rightarrow O_2$
  - Mass: ~1 mT for system saves ~25 mT transported
  - Constraints imposed on mission: None
- $H_2O + CO_2 \rightarrow CH_4$ (additional)
  - Mass: ~0.7 mT for system saves ~7 mT transported
  - Constraints imposed on mission:
    - Landing where water is available
    - Robotic prospecting, excavation, testing

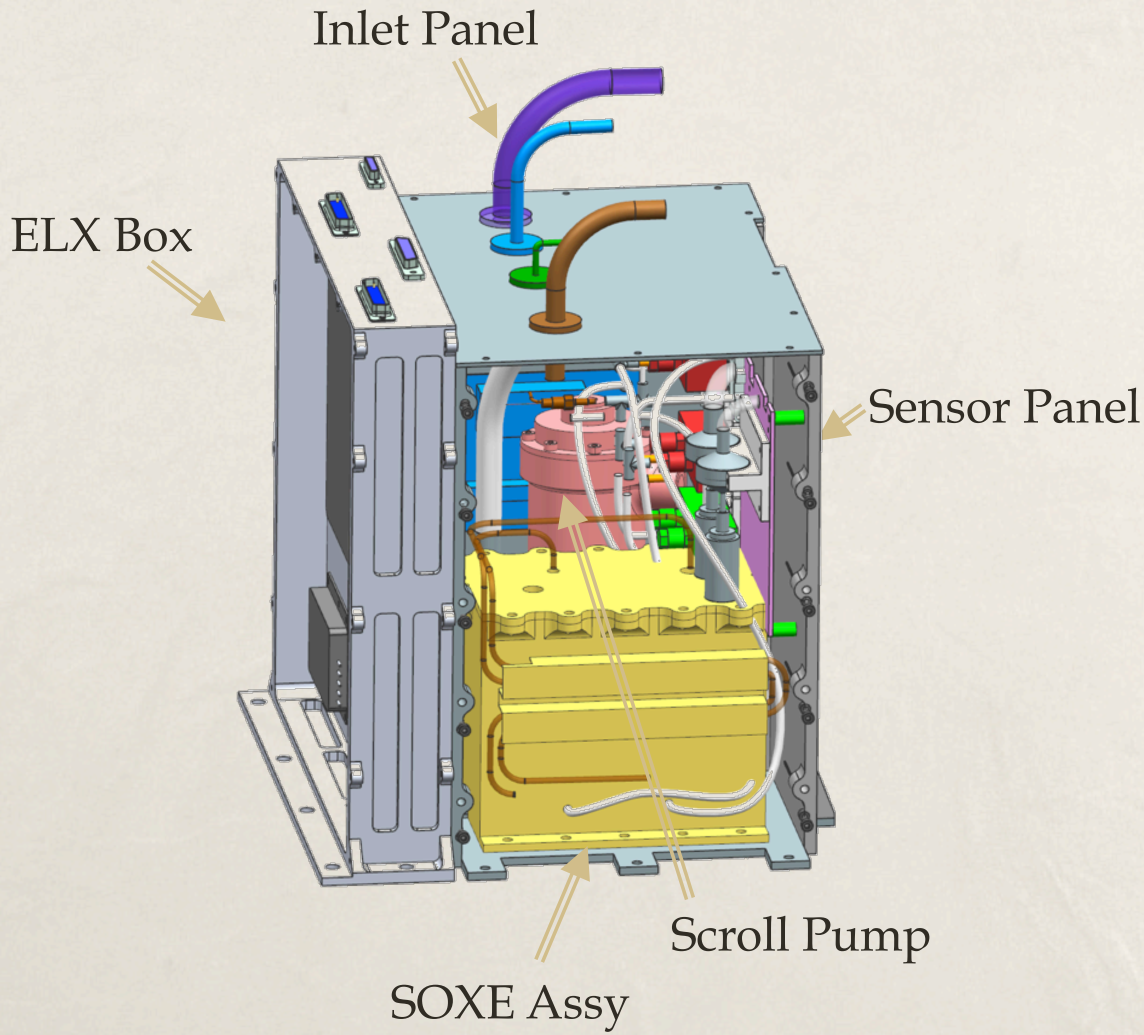
	Propellant-related S/C Mass (mT)						Figures of merit (n:1)			Other considerations		
Scenario	**ISRU h/w**	**O2**	**CH4**	**Total**	**Mass Savings**	**Propellant Produced (mT)**	**Mass savings: ISRU h/w mass**	**Production: ISRU-related s/c mass**		**Requires excavation?**	**Constrains landing site?**	**Flight-like prototype?**
No ISRU	0	24.6	7	31.6		0						
LOx only	1	0	7	8	**24**	24.6	**24**	**3**		No	No	Yes
LOx + CH4	1.7	0	0	1.7	**30**	31.6	**18**	**19**		Yes	Yes	No

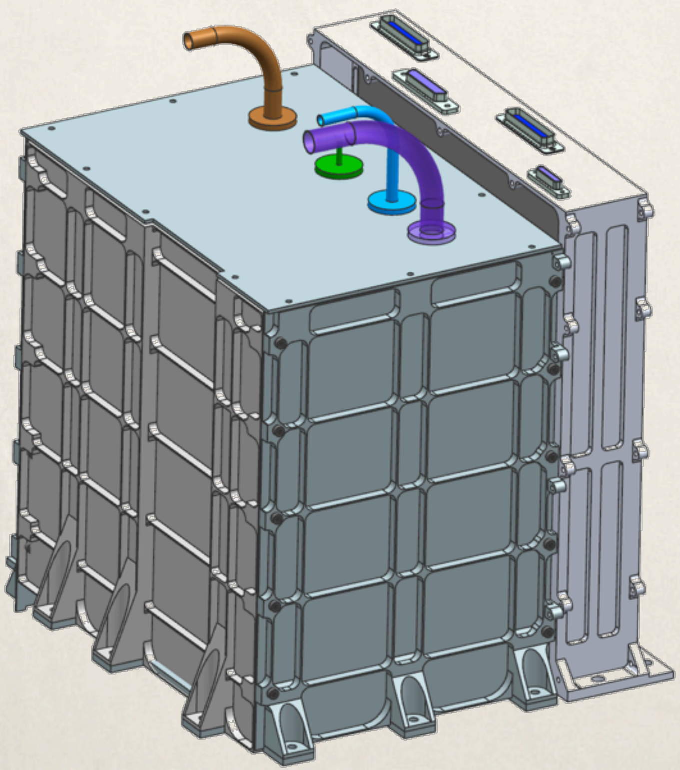
Source: M-WIP study

Mars 2020 Rover

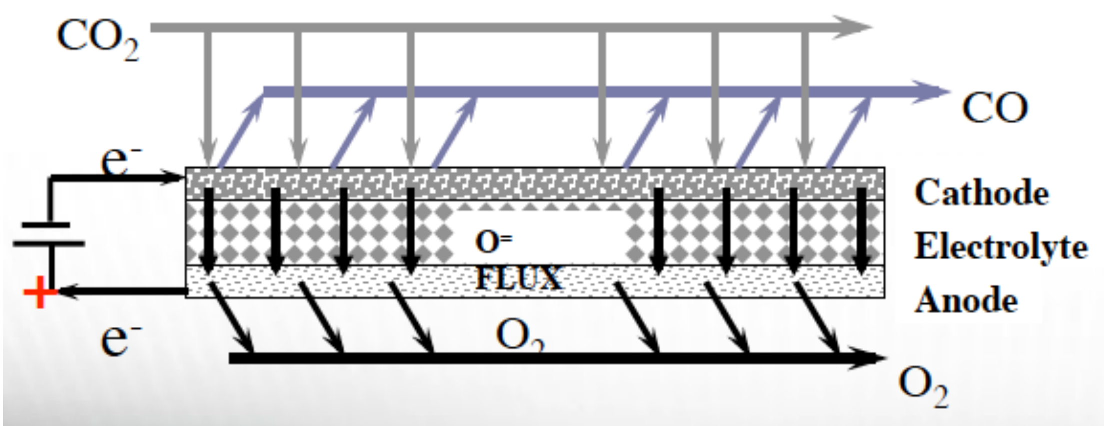




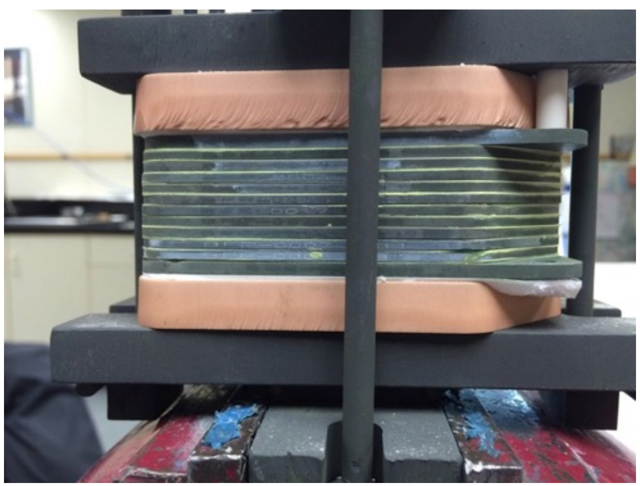




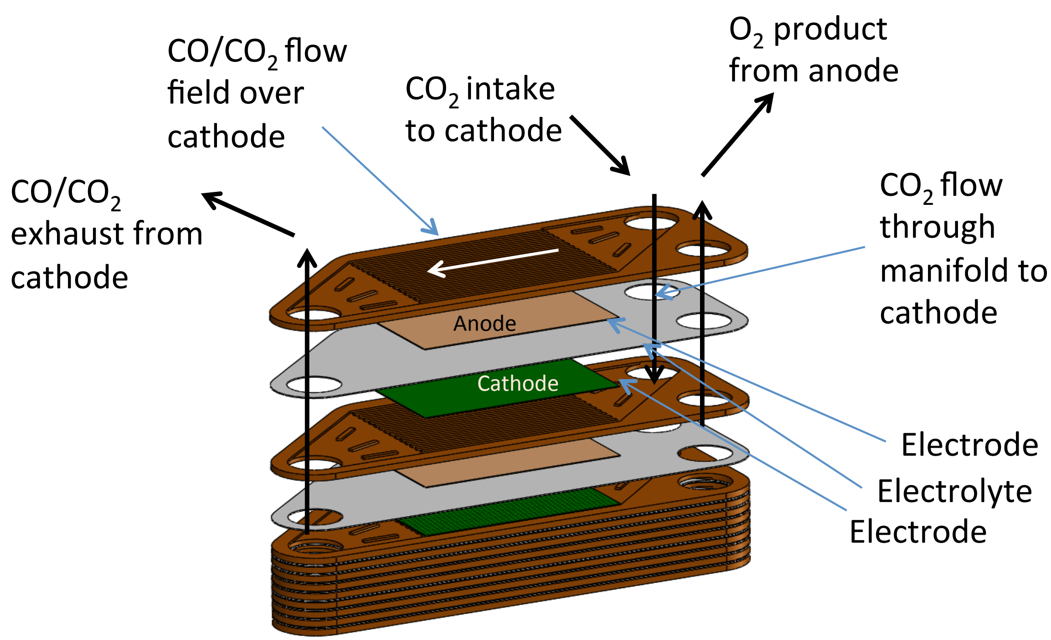
- ~1:200 scale production
- ~1:400 scale operating time
- No product storage
- No fuel production



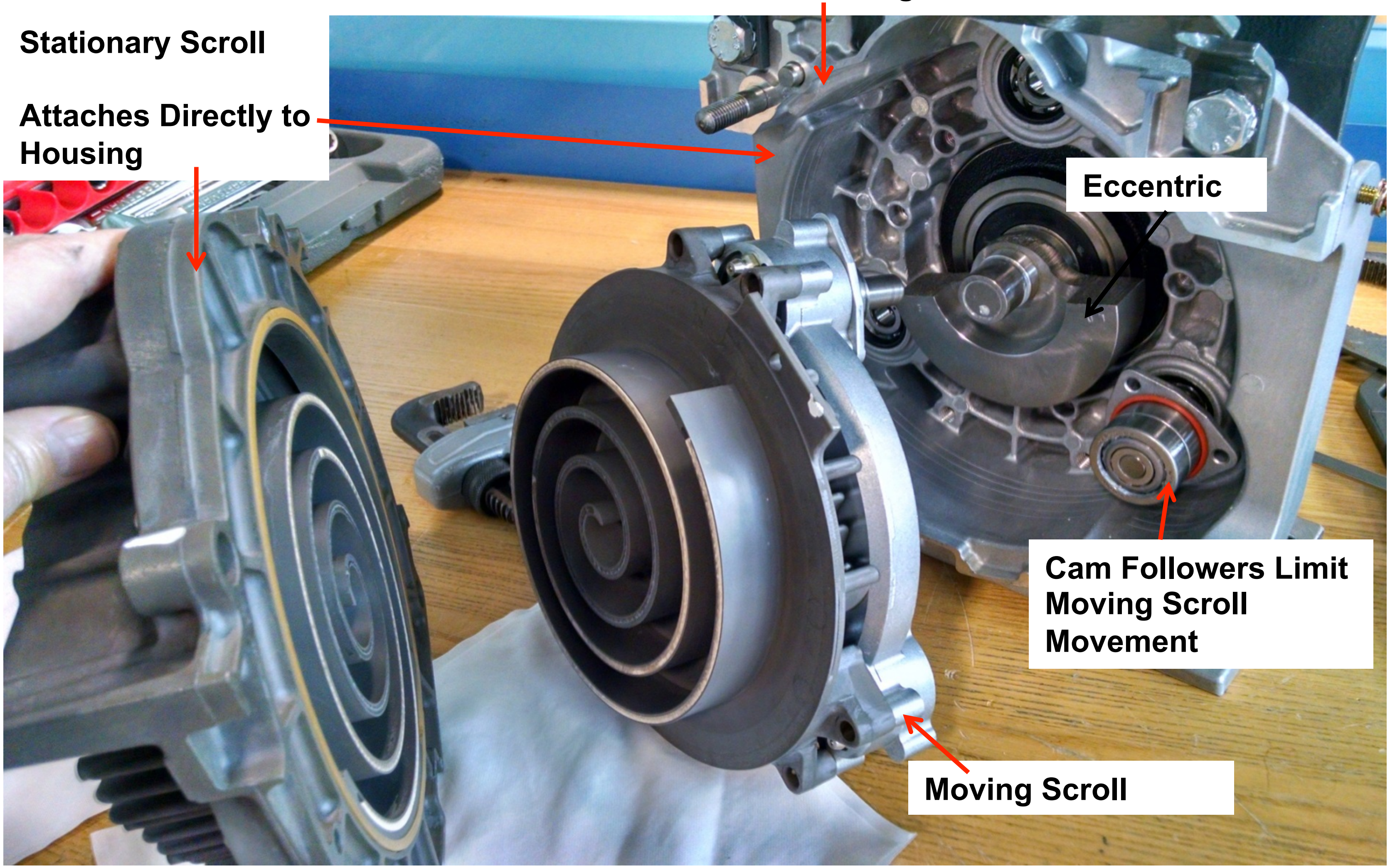
SOXE



SOXE 11 cell stack fabricated by Ceramatec

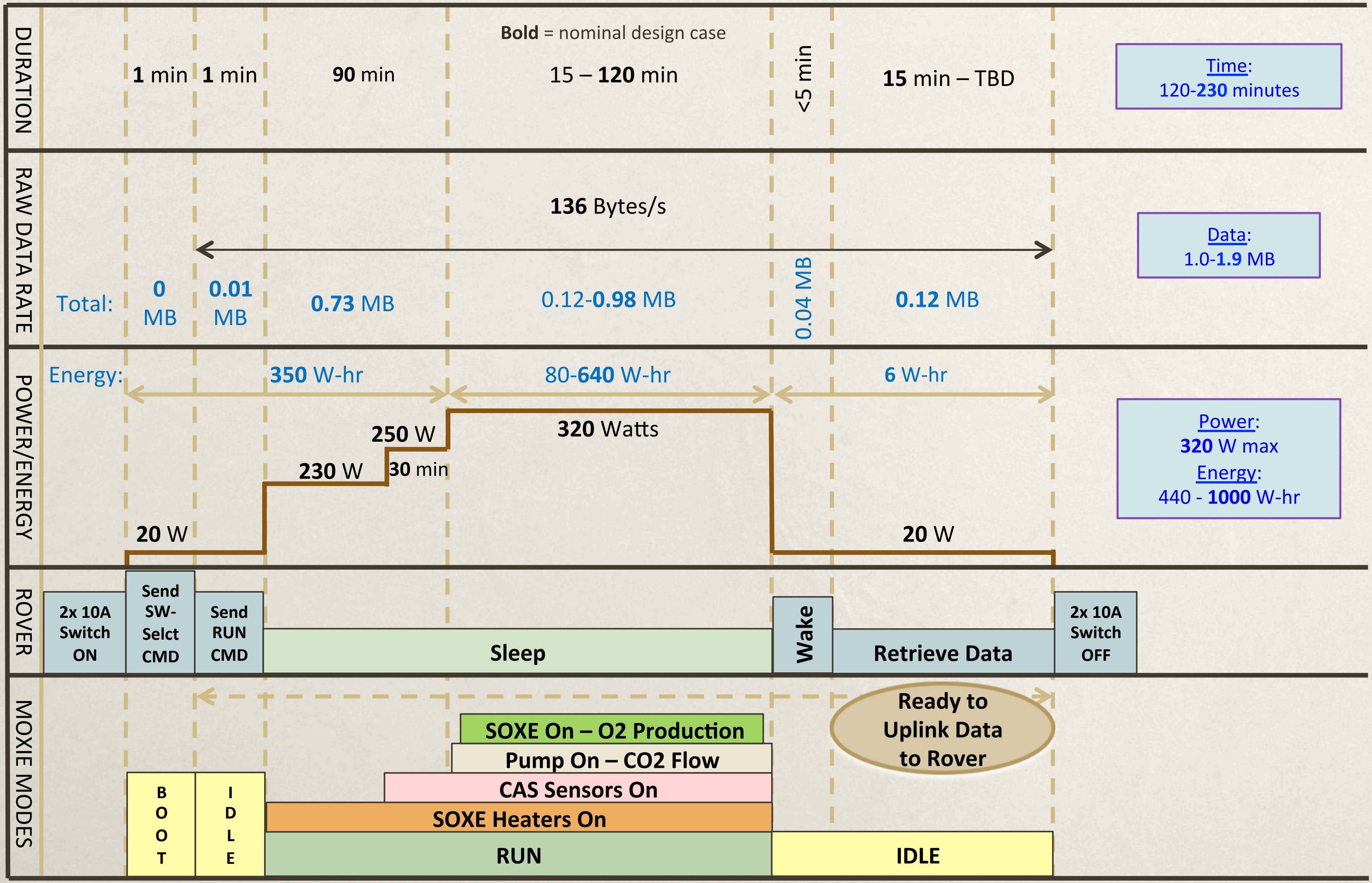


Scroll pump



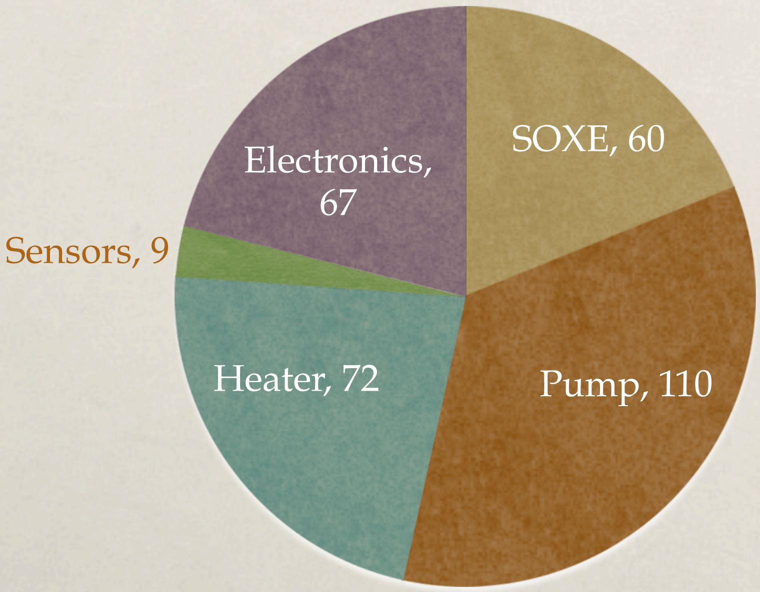
- Alternatives: Cryogenic, sorption bed

Day in the Life



Where does the power go?

* SOXE current:	60W
* Pump:	110W
* Stack heaters (mostly make-up heat):	72W
* Sensors, incl. panel heating:	9W
* Electronics, mostly DC/DC conversion:	67W
Total	**320W**



2024 ISRU Validation w/ MSR option

Concept:

Leveraging MOXIE, a 2024 validation mission to:

- Demonstrate end-to-end resource utilization and validation
- Launch a 6U CubeSat MAV payload with sample receptacle from Mars to elliptical orbit
- Offer option for delivery of Mars 2020 sample

Technologies to be demonstrated:

- Precision Landing of >> 1 mT, possibly SRP
- 1 kW power system (nuclear or solar)
- ISRU O_2 generation (>5x break-even)
- Mars Ascent Vehicle (MAV)
- Cryogenic O_2 storage and transfer to MAV
- Sample transfer to MAV
- MAV ascent to (elliptical) orbit
- Cubesat w/ station-keeping in Mars orbit
- Possible MAV propulsion (solar or SEP) to raise MAV orbit or return to Earth

Rough numbers:

- ISRU System mass — 21 kg
- ISRU Power — 1067 W
- O_2 production rate — 50 g/hr
- Time to generate O_2 — 89 sols

- MAV dry mass — 24 kg
- MAV payload mass — 12 kg
- CH_4 mass — 31 kg
- ISRU O_2 mass — 109 kg (5.2x system mass)

Notional Mission Timeline:

March, 2021:
- Mars 2020 arrives at Mars

July 2024:
- End Mars 2020 primary mission
- ISRU Mission Launches

March 2025:
- ISRU Mission Lands

June 2025:
- Complete ISRU MAV Fueling
- [Optional] Mars 2020 sample transfer
- MAV Launch

December 2026:
- End ISRU Primary Mission

What limits O_2 production?

1. **Inlet flow**
   * Together with CO_2 utilization fraction, determines O_2 production
   * Limited by overall pump capability
   * Limited by inlet gas density, which is determined by:
     * **Ambient pressure & temperature**
     * **Pressure drop across filter, including dust**

2. **Available power**
   * **Safe current limit of 4A**
   * Power limit of 35W per supply (not normally a constraint)
   * Circuit limit of 10A (not normally a constraint)
   * Thermal constraints at high power (depends on many factors)

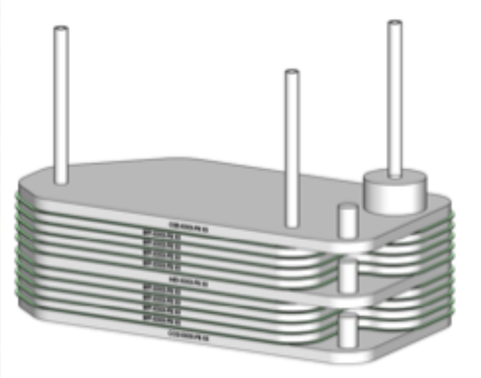
3. **SOXE capability**
   * All the electrochemistry is captured in one empirical number, ASR, and a more-or-less constant number, OCV
   * Scale by area (22.7 cm^2 and number of cells (5x2=10)
   * Limited by safe operating voltage and % CO_2 utilization, largely TBD

How do these factors rank in importance?

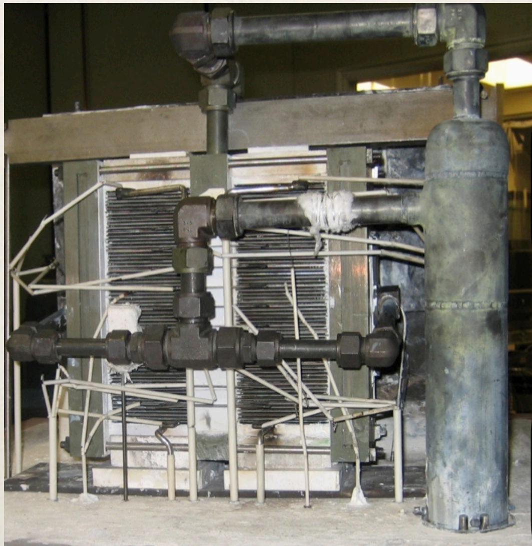
SOXE Challenges

CERAMATEC
TOMORROW'S CERAMIC SYSTEMS

Mars 2020 Project

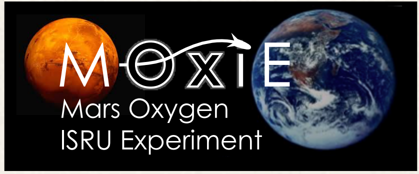


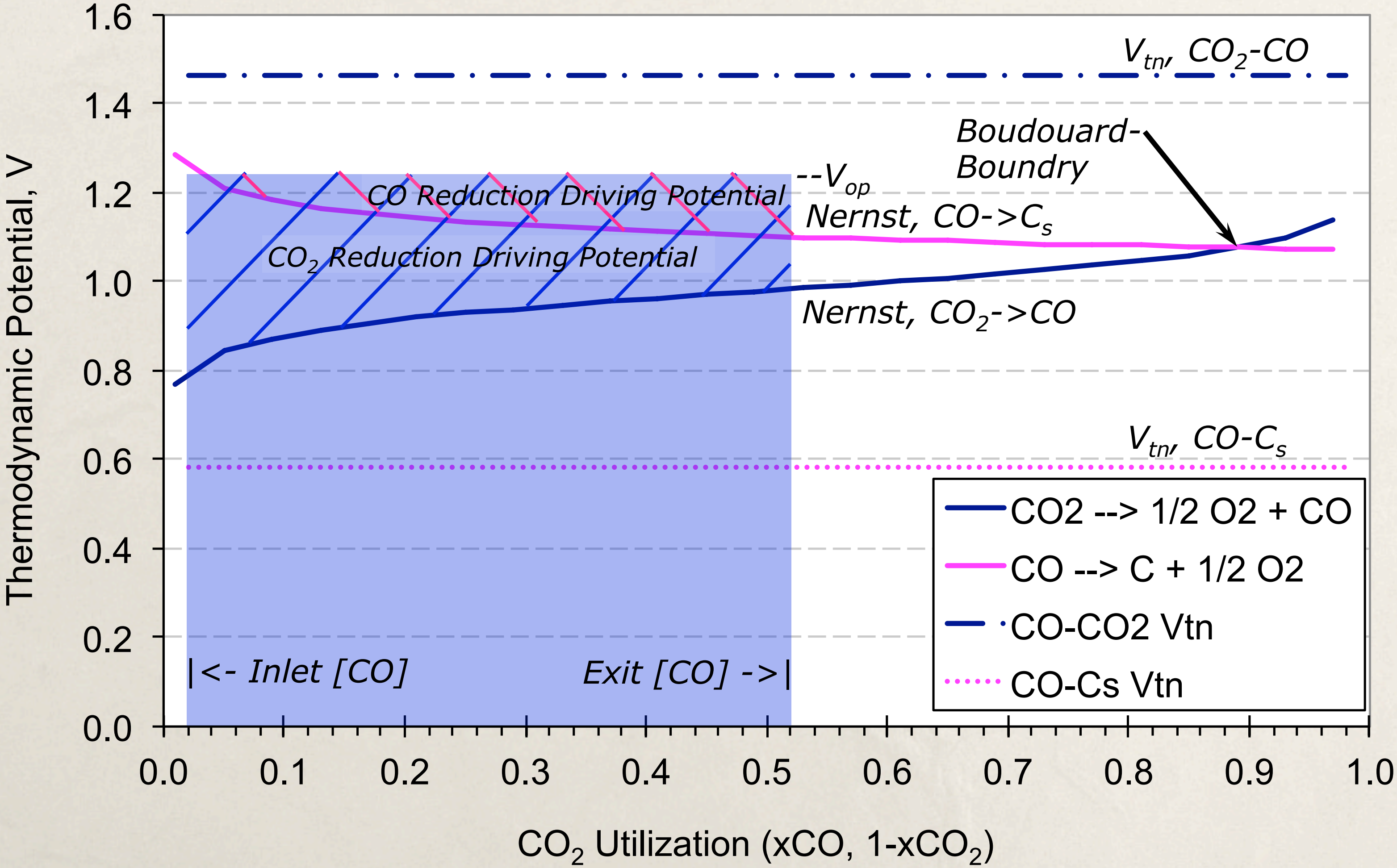
- Challenges & approaches
  - Dry CO_2 electrolysis
    - Custom materials
  - Heat/cool cycling
    - Controlled startup/shutdown; CTE matching
    - Cold-side compression to minimize pre-heat energy
  - Oxidation
    - CO recirculation
  - Coking
    - Limit on operating voltage
  - Low pressure environment
    - Hermetic (glass) sealing to formed interconnect
    - Compression fixture
  - Shock & vibration
    - Isolation mounting if needed



- Under development by Ceramatec, Inc. (a division of CoorsTek)

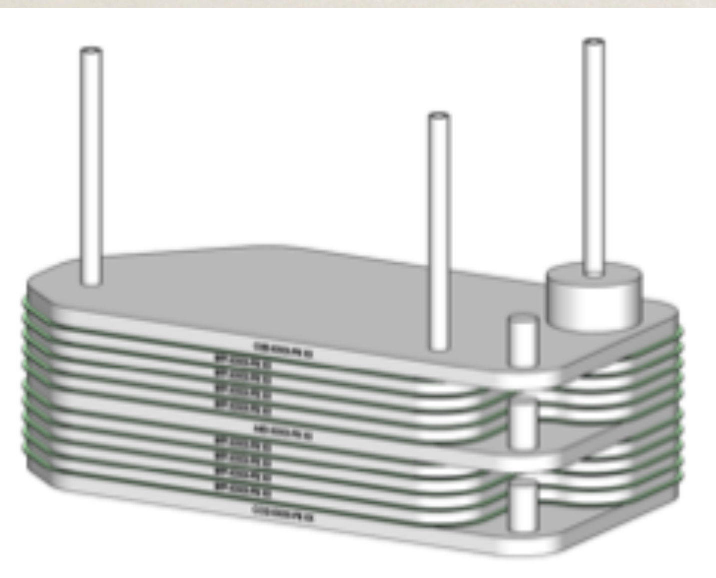
V_{op} Limited by CO Reduction Potential

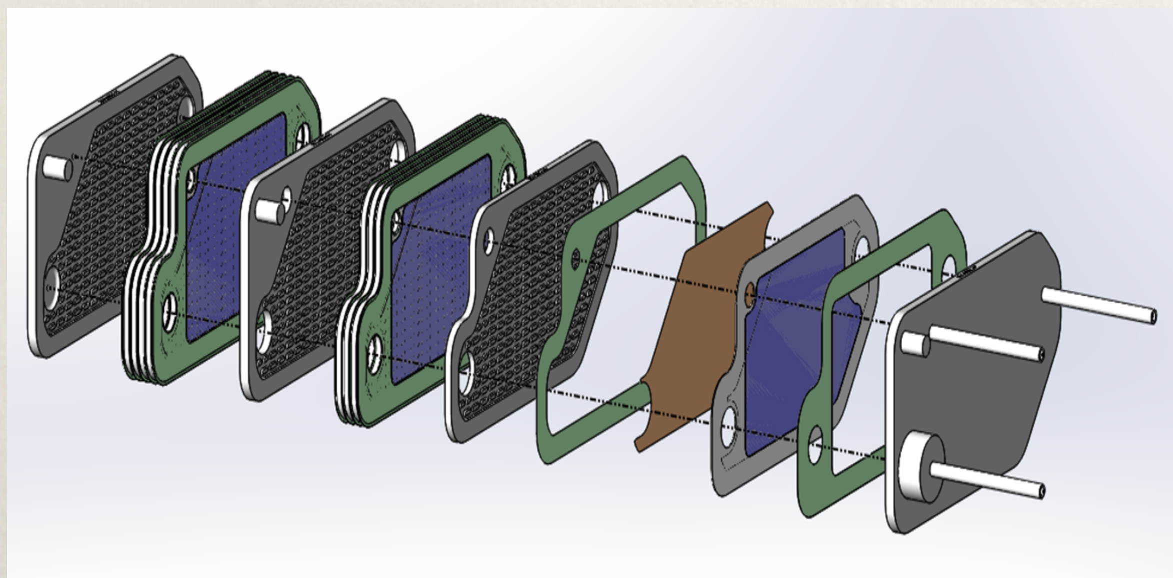




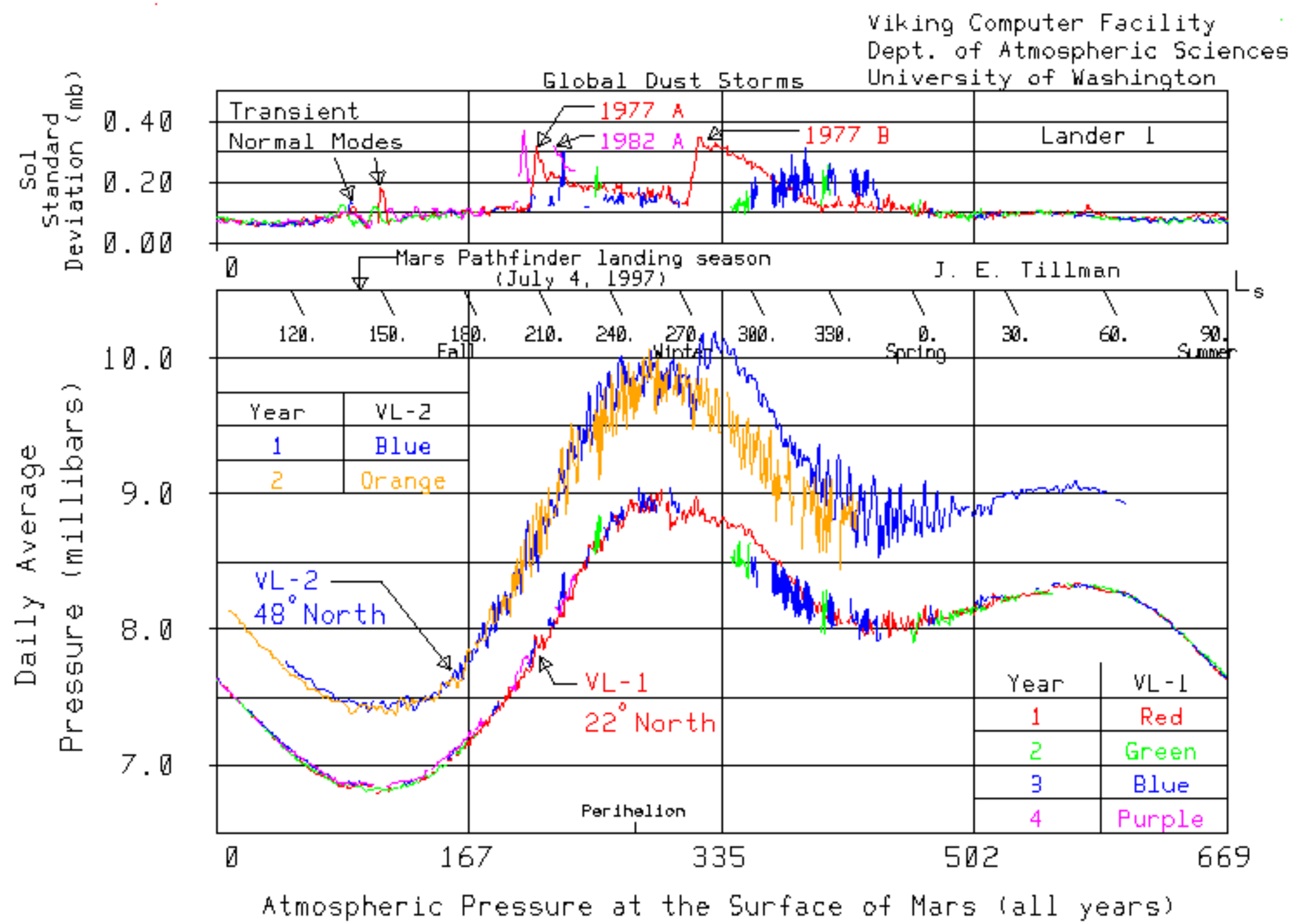
SOXE Summary

- Results & Findings:
  - Low ASRs (2-2.5)
  - Stable to heat/cool cycling
  - Oxidation is a bigger challenge than coking
  - SOXE capability exceeds MOXIE resources on Mars
- Still to be studied:
  - Limits on CO2 utilization, voltage, temperature
  - Long-term performance (>1000 hrs)

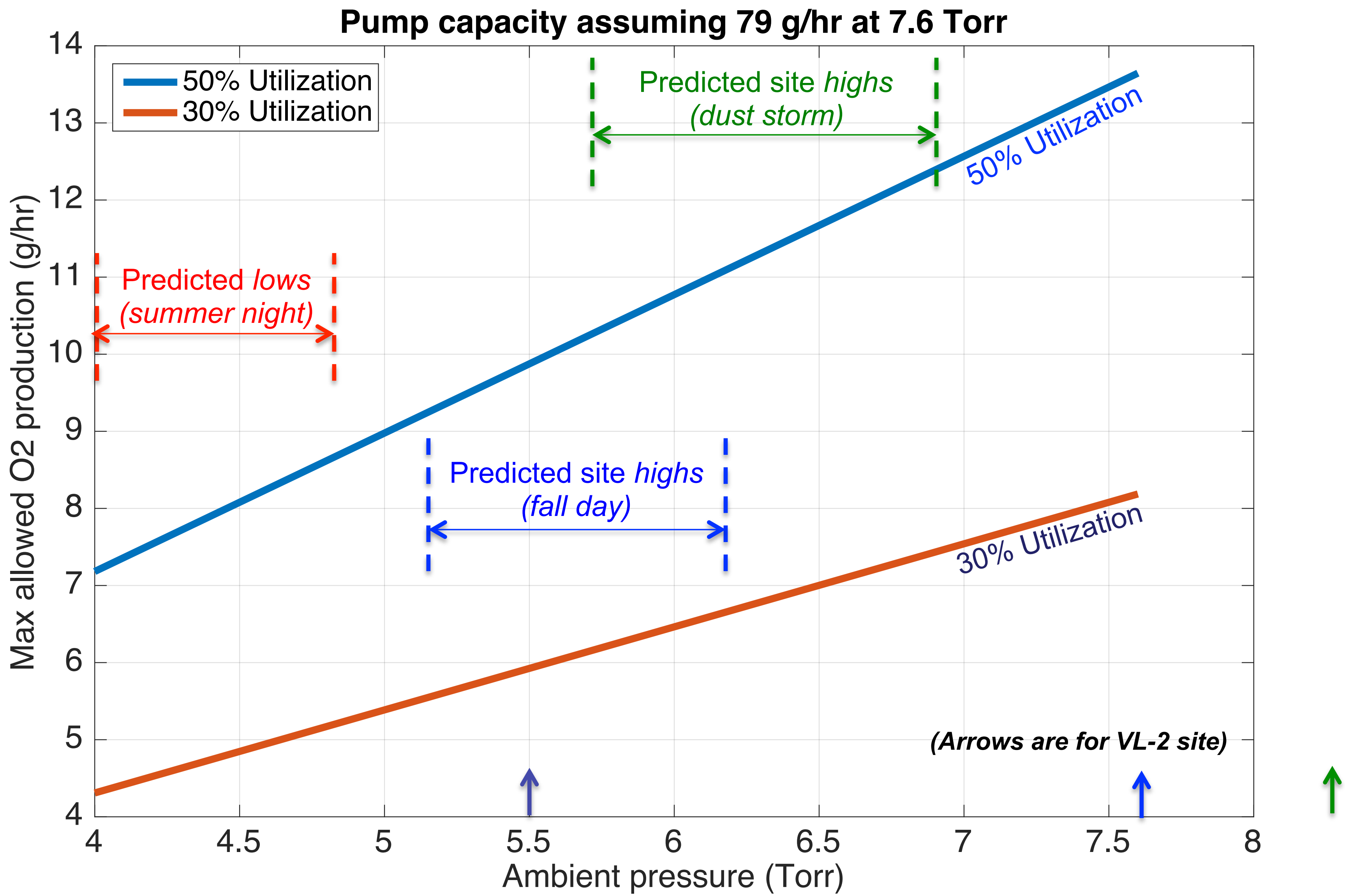




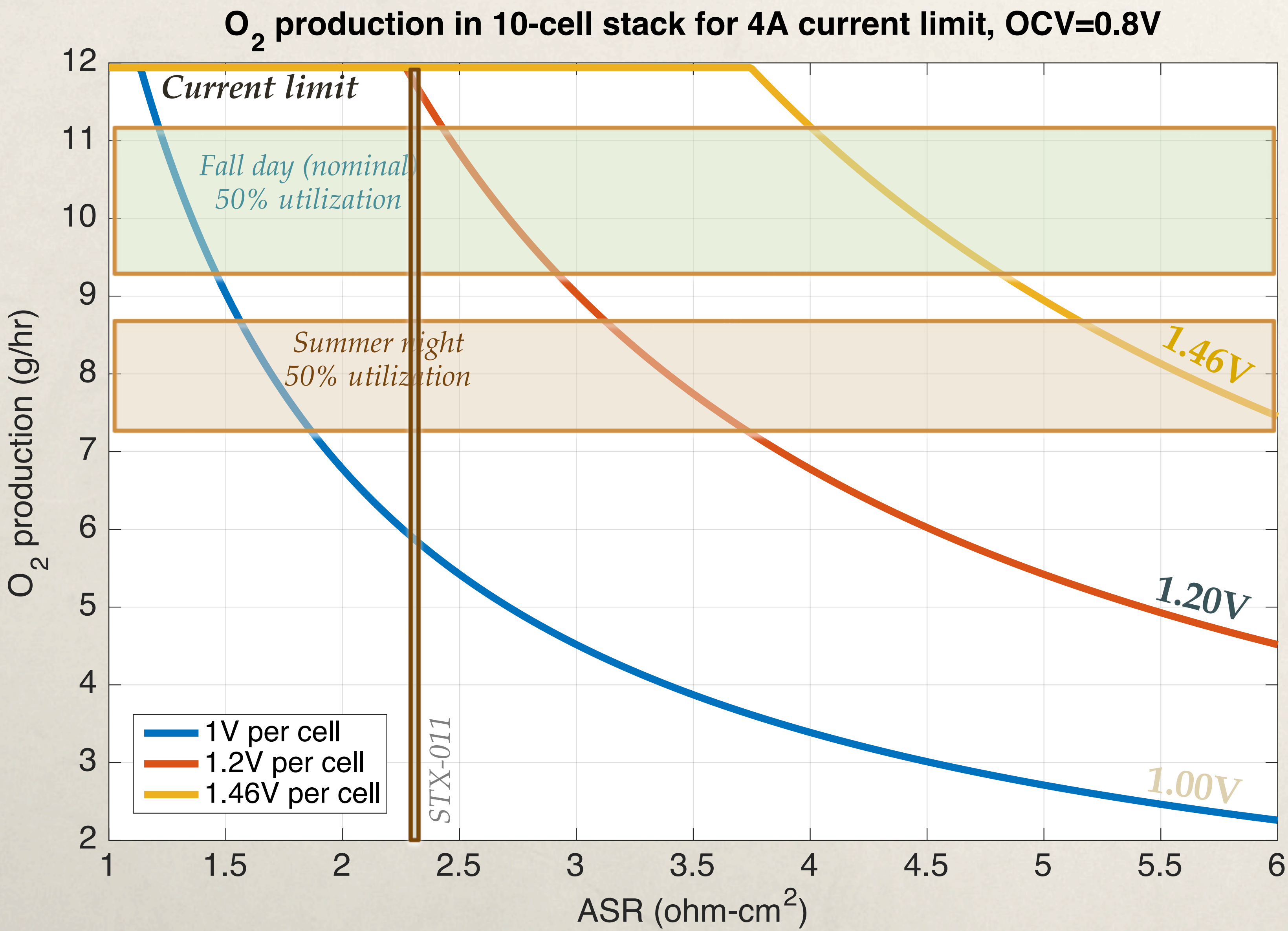
Viking Pressure Data



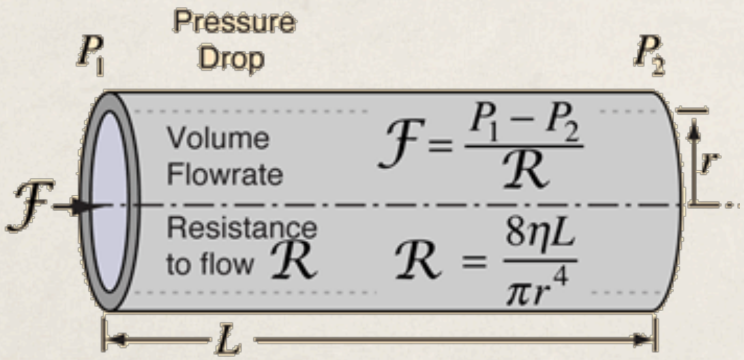
Pump capacity (at 20°C inlet)



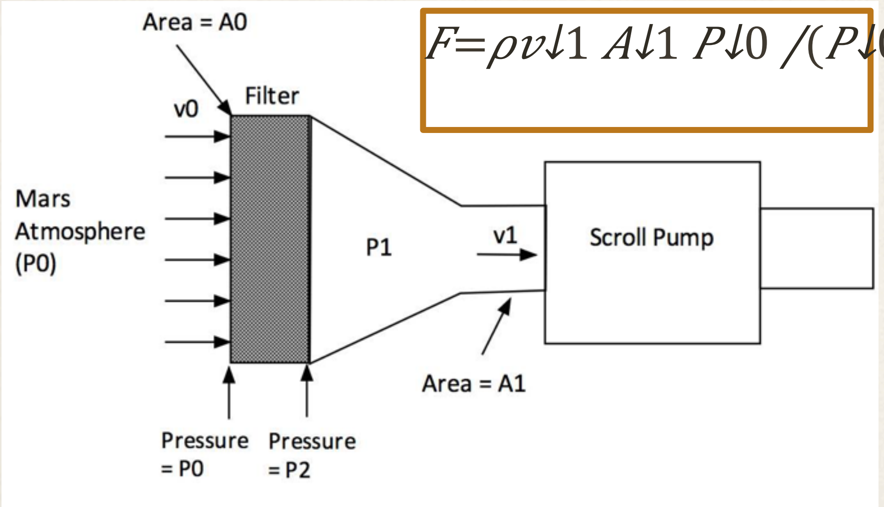
SOXE Performance v. ASR

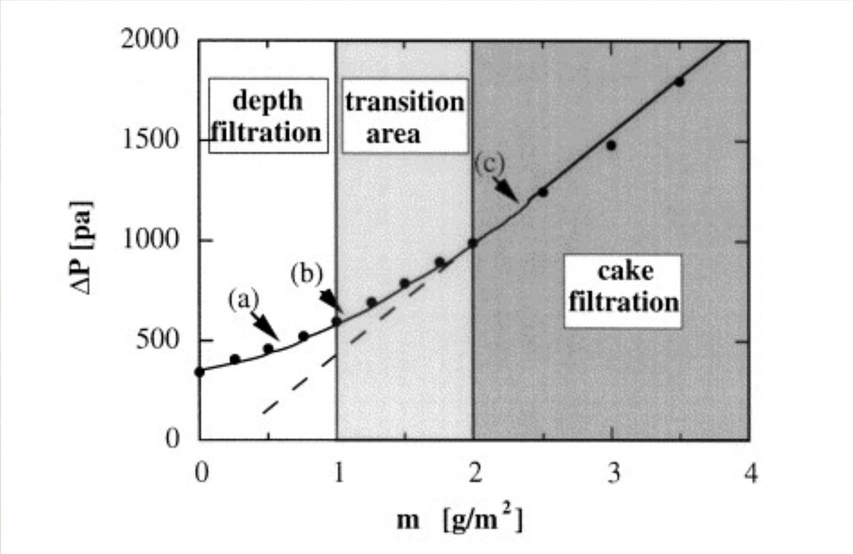


Filter sensitivity to dust



* MOXIE will ingest ~50 mg dust through a 264 cm^2 *pleated* filter, or ~2 g/m^2.
* Incident velocity v_0 typically ~5 cm/s, comparable to Thomas study (right), but particles are typically larger.
* Begin to get in trouble between 1-10 g/m^2
* Full-scale MOXIE will ingest ~5 kg dust over 1 year
* Dust storms result in up to x10 deposition.

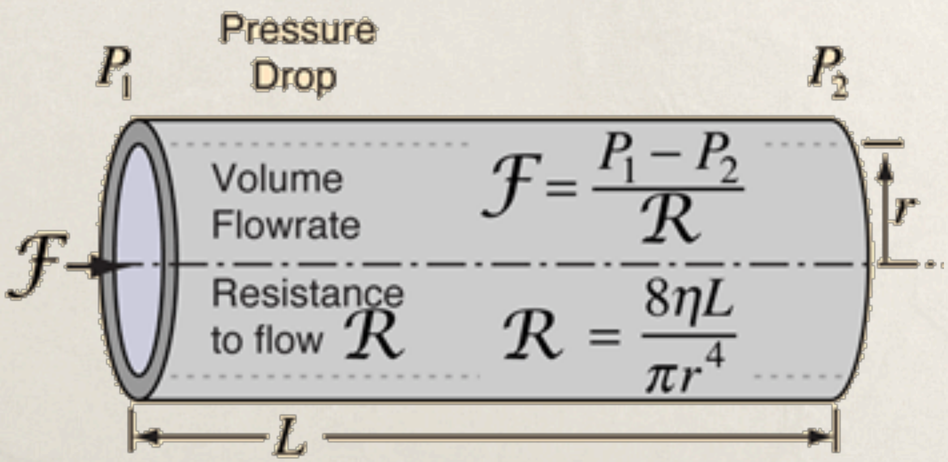




v_0-=5 cm/s, d_p=0.15 μm. From D. Thomas et al. (1999) *J. Aero. Sci.*, 30 (2), 235-246.

Dust conclusions

* → Filters need to have huge surface area if they are not to obstruct flow, and are degraded by a few microns of dust
* The way forward?
  * Filter-less first-stage pumping?
  * Cyclone or electrostatic mitigation?

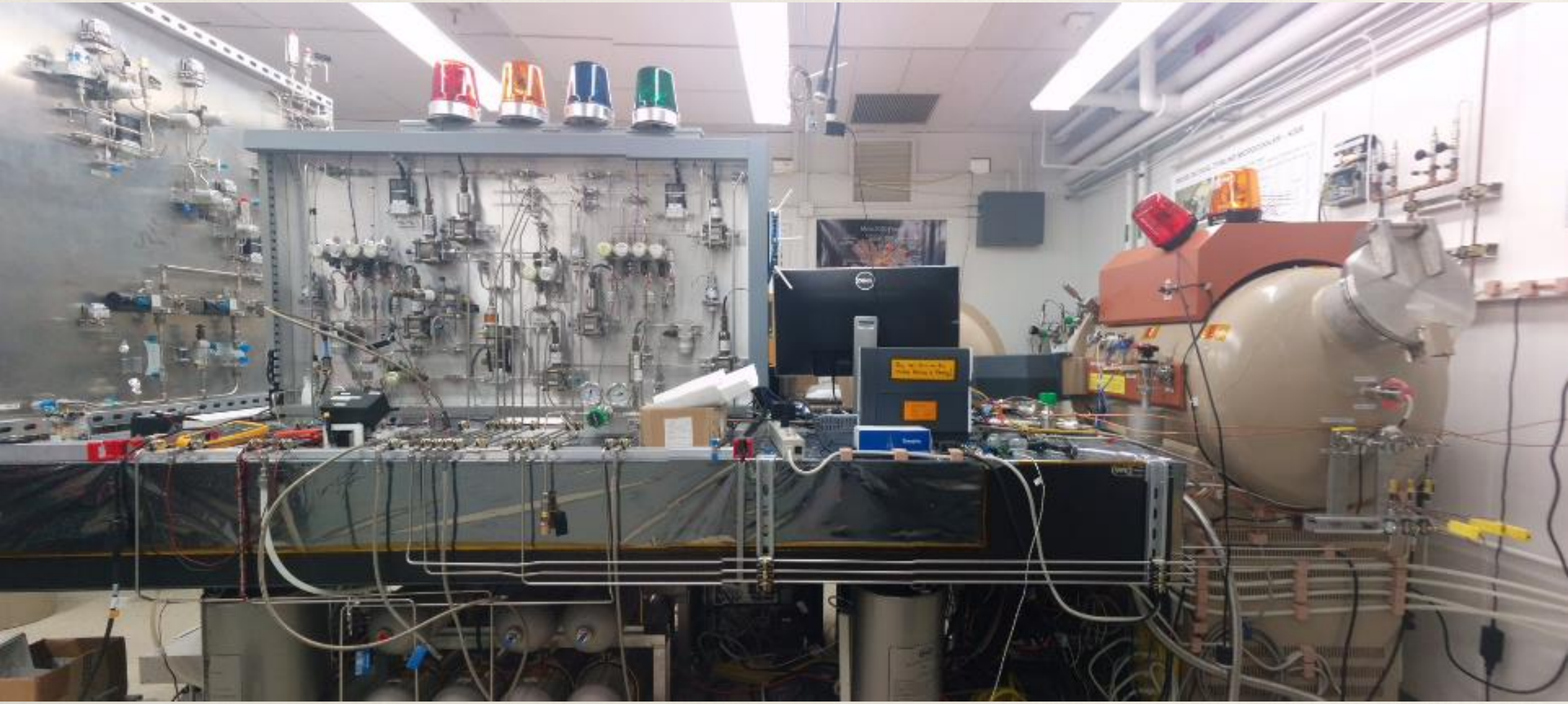


Take-aways

* MOXIE production rate is determined by a number of factors, including:
    * SOXE capability
    * Pump capability
    * Power supply capability
    * Safe operating conditions (TBD)
    * Landing site & weather
    * Filtering and dust
* It is not currently expected that overall O_2 production will be limited by SOXE performance. This is probably typical of reference systems.

MOXIE
Mars Oxygen
ISRU Experiment

Special thanks to the amazing JPL Project Team!



MOXIE Testbed

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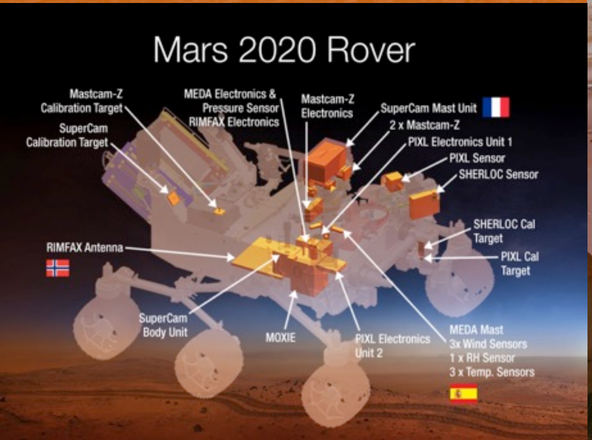
J. Hoffman, *MIT (DPI)*
G. Sanders, *JSC*
D. Rapp, *Consultant*
B. Yildiz, *MIT*
G. Voecks, *JPL*
K. Lackner, *ASU*
J. Hartvigsen, *Ceramatec*
P. Smith, *Space Expl. Instr.*
W. T. Pike, *Imperial Coll.*
M. Madsen, *U. Copen.*
C. Graves, *DTU (Coll.)*
M. de la Torre Juarez, *JPL (Coll.)*



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

HAYSTACK OBSERVATORY

MOXIE

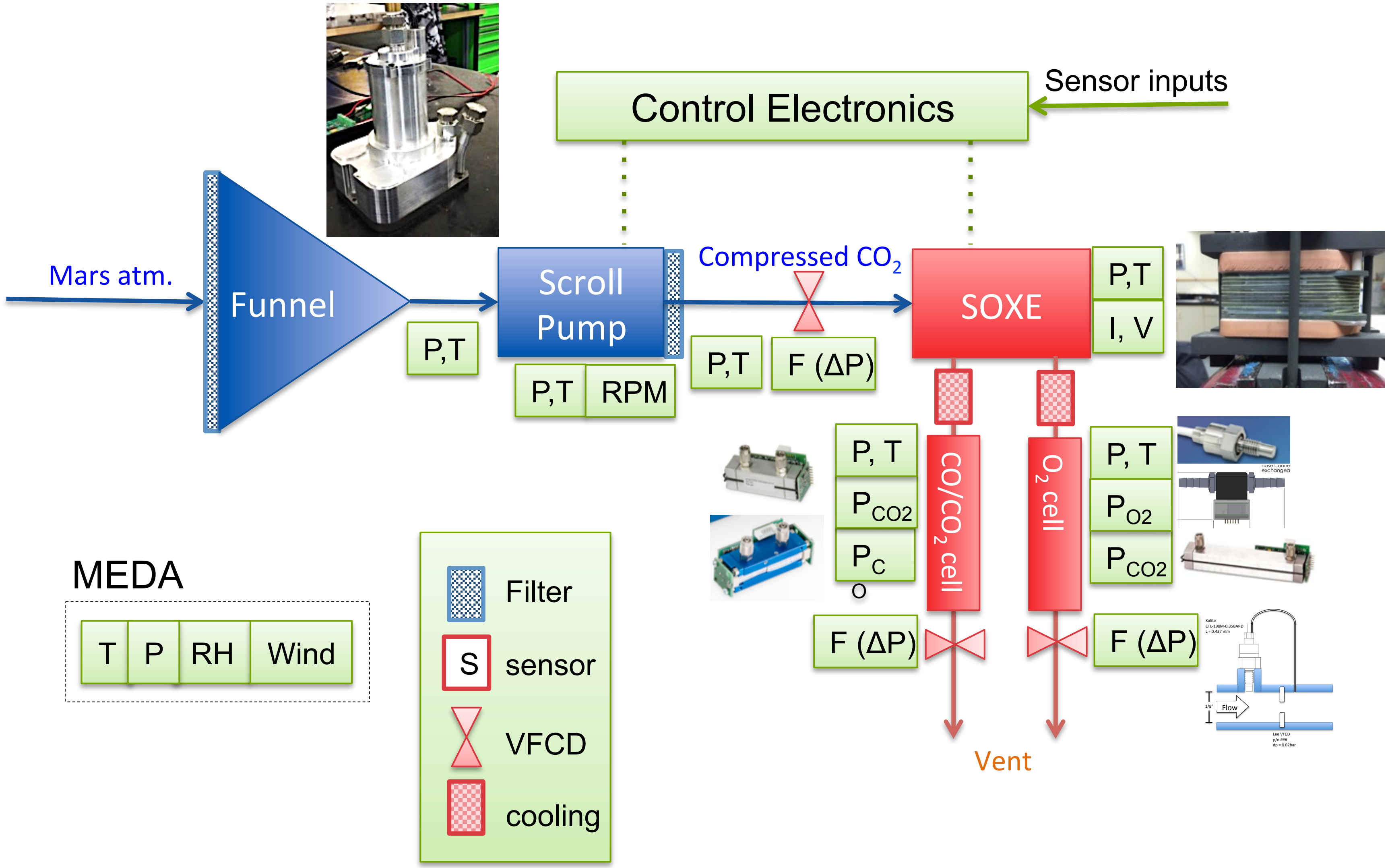
The Mars Oxygen ISRU Experiment On NASA's Mars 2020 Rover

A joint project of NASA's:
- HEOMD
- STMD
- SMD

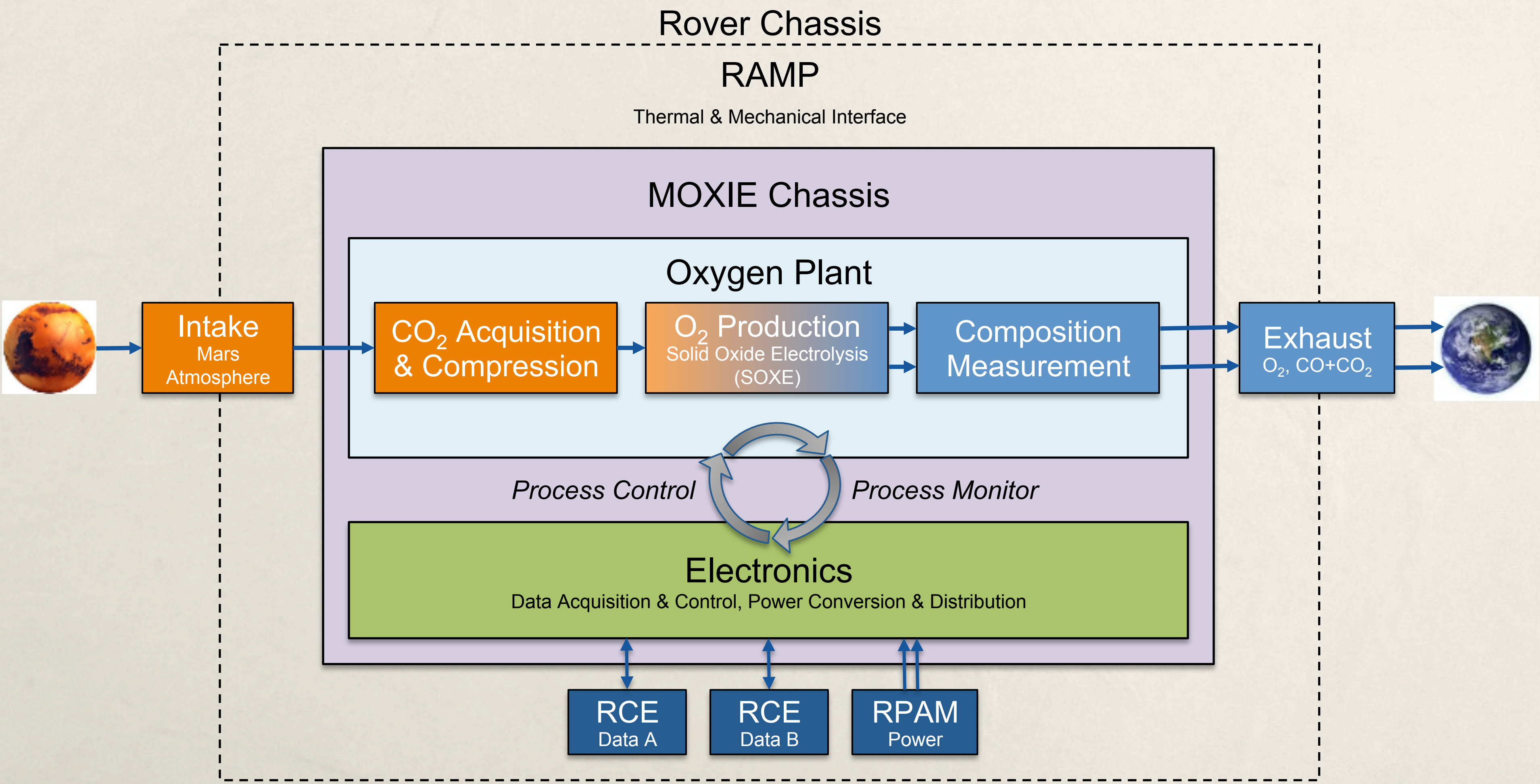
More MOXIE

Backup slides

Anatomy of MOXIE



MOXIE Functional Block Diagram



Uncertainties in production rate

- MOXIE production rate is a balance of:
  - SOXE capability
  - Pump capability
  - Power supply capability
  - Safe operating conditions (TBD)
  - Landing site (TBD)
  - Season and time of day

Landing site characteristics

Mars Oxygen ISRU Experiment

- Potential landing site elevations and pressure
  - **Planet average:** ~4.6 Torr, but not really relevant (see below)
  - **Elevation:** Varies over *many* kilometers, dominated by hemispheric dichotomy. *Corresponding surface pressure varies by more than x2.*
- Likely landing sites
  - **Prior to M2020:** Lowlands favored for EDL. MSL, Viking < -3.6 km.
  - **M2020:** Sites considered between -2.6 and -0.6 km
  - **Human landing:** For EDL reasons, almost certain to be < -3.5 km.
- Types of pressure variation the rover will experience:
  - **Seasonal:** Up to 30% due to polar deposition of CO_2 (predictable)
  - **Diurnal:** 5-12% depending on topography (predictable)
  - **Weather:** A few % typically, up to 12% increase in global dust storms
  - **Local topography:** Several %, but below resolution of GCM

Global Climate Model predicts

	A	B	C	D	E	K	L	M	N	O	R	S
1					MOLA	GCM (Forget et al) [2]					VL1-based [3]	
2			Lat	Long	Elevation	Ls 150		Ls 260		Max*	Low	High
3	#		(deg N)	deg (E)	(m)	Low (T)	High (T)	Low (T)	High (T)	(Torr)	(Torr)	(Torr)
4	7	**Nili Fossae**	21.097	74.3494	-655	3.89	4.12	4.84	5.18	5.72	3.76	5.63
5		E. Margaritifer [b]	-5.596	353.835	-1249	3.98	4.27	4.87	5.33	5.78		
6	2	**Eberswalde [a]**	-23.7749	-33.5147	-1400	4.19	4.57	4.85	5.32	5.74	4.04	6.06
7		Nili Carbonate [b]	21.7	78.9	-1458	4.19	4.29	5.32	5.51	6.14		
8	8	**SW Melas**	-9.8132	-76.4679	-1886	4.19	4.61	5.02	5.57	6.17	4.23	6.34
9	1	**Columbia Hills [a]**	-14.5478	175.6255	-1900	4.22	4.62	5.17	5.79	6.22	4.23	6.34
10	6	**NE Syrtis**	17.8889	77.1599	-2035	4.36	4.52	5.57	5.82	6.53	4.27	6.40
11	3	**Holden Crater**	-26.62	-34.8713	-2129	4.42	4.89	5.03	5.57	5.99	4.30	6.46
12	5	**Mawrth Valles**	23.9685	-19.0609	-2247	4.45	4.58	5.67	5.93	6.50	4.38	6.58
13	9	Hypanis Valles [a,c]	11.8	314.6	-2600	4.59	4.81	5.84	6.22	6.92		
14	4	**Jezero Crater**	18.4386	77.5031	-2620	4.57	4.76	5.85	6.14	6.90	4.50	6.76
15		VL-1 [1]	22.48	-49.79	-3627	4.82	4.98	6.17	6.54	7.30		
16		MSL (Landing)**	-4.59	137.44	-4400	5.22	5.70	6.50	7.28	8.00		
17		VL-2 [1]	47.97	-225.47	-4505	5.49	5.58	7.41	7.61	8.28		
18	10	McLaughlin Crater [c]	21.818	337.749	-5028	5.60	5.86	7.32	7.76	8.45		
19												
20	Notes											
21	*	"Dust Storm Max Solar" mode.										
22	**	Now at -4292										
23	[a]	Added at 2nd workshop										
24	[b]	Eliminated after 2nd workshop										
25	[c]	Under consideration for science assessment only.										
26												
27	[1]	Smith, D.E. et al, J. Geophys. Res. 106, 23689 (2001)										
28	[2]	http://www-mars.lmd.jussieu.fr/mcd_python/. "Climatology Ave"mode										
29	[3]	From Mike Mischna										

Considerations in eventual design

- Where do we land? Weigh *perceived* science value against:
  - Ready availability of water ice (i.e. high latitude)
  - Safety/ease of landing (low elevation, maybe low latitude)
  - Surface traverse capability

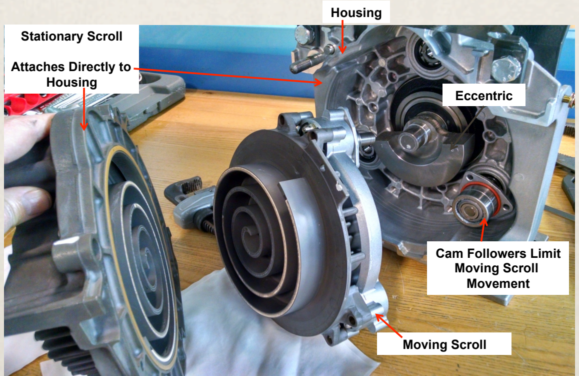
- Assuming low latitude (no ice)… what limits performance? What infrastructure is available?
  - Human base will likely need nuclear reactor → plentiful power during ISRU stage
  - Oxygen storage will likely need cryogenics → may as well use it for other systems, e.g.
    - Parallel, out-of-phase cryogenic CO_2 acquisition instead of pump.
    - Separation of Ar, N_2 for buffer gases in habitat.
    - Further purification of breathable O_2.

- Assuming high latitude, ready ice availability…
  - Do we want to do CO_2 ISRU at all?

Pump constraints

* **Things we can estimate:**
  * *Reference performance:* 79 g/hr for inlet gas P=7.6 Torr, T= 20°C.
  * *Ambient pressure and temperature modulation:* Varies predictably with season, time of day, and to a small extent, weather.
  * *Pressure drop from ambient to pump inlet:* <10% (ignoring dust)
* **Things we don't yet know**
  * Where we will land
  * Safe CO_2 utilization factor (tested 30%, probably ok at 50%)
  * Heating of gas from outside to pump inlet (so we'll assume 20C).

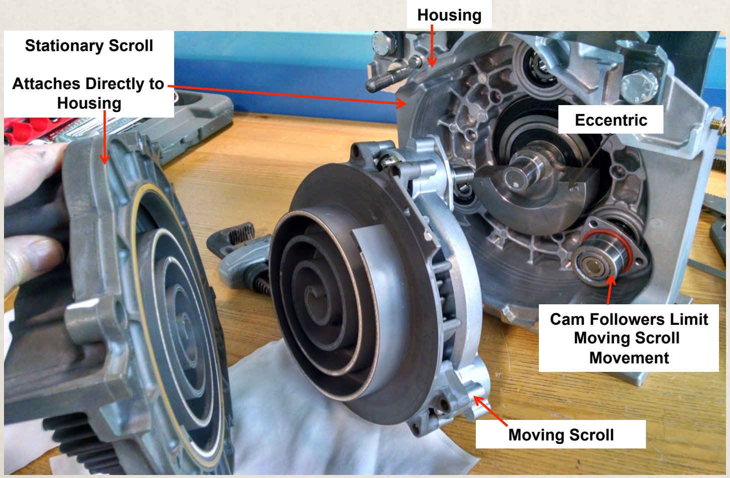
The MOXIE scroll compressor is under development by Air Squared, Inc., Broomfield, CO



Pump Trades and extensibility

* Trade for MOXIE
  * Scroll pump was found to be the only feasible approach on a small scale that can do real time compression without intermediate storage.

* Trade for full-scale mission
  * Scroll pump can be scaled at least 10-fold, is energy-efficient, and lifetime should be adequate.
  * Cryogenic options may be more favorable if cryogenic subsystem is used for O_2 storage. Energy may not be a factor.

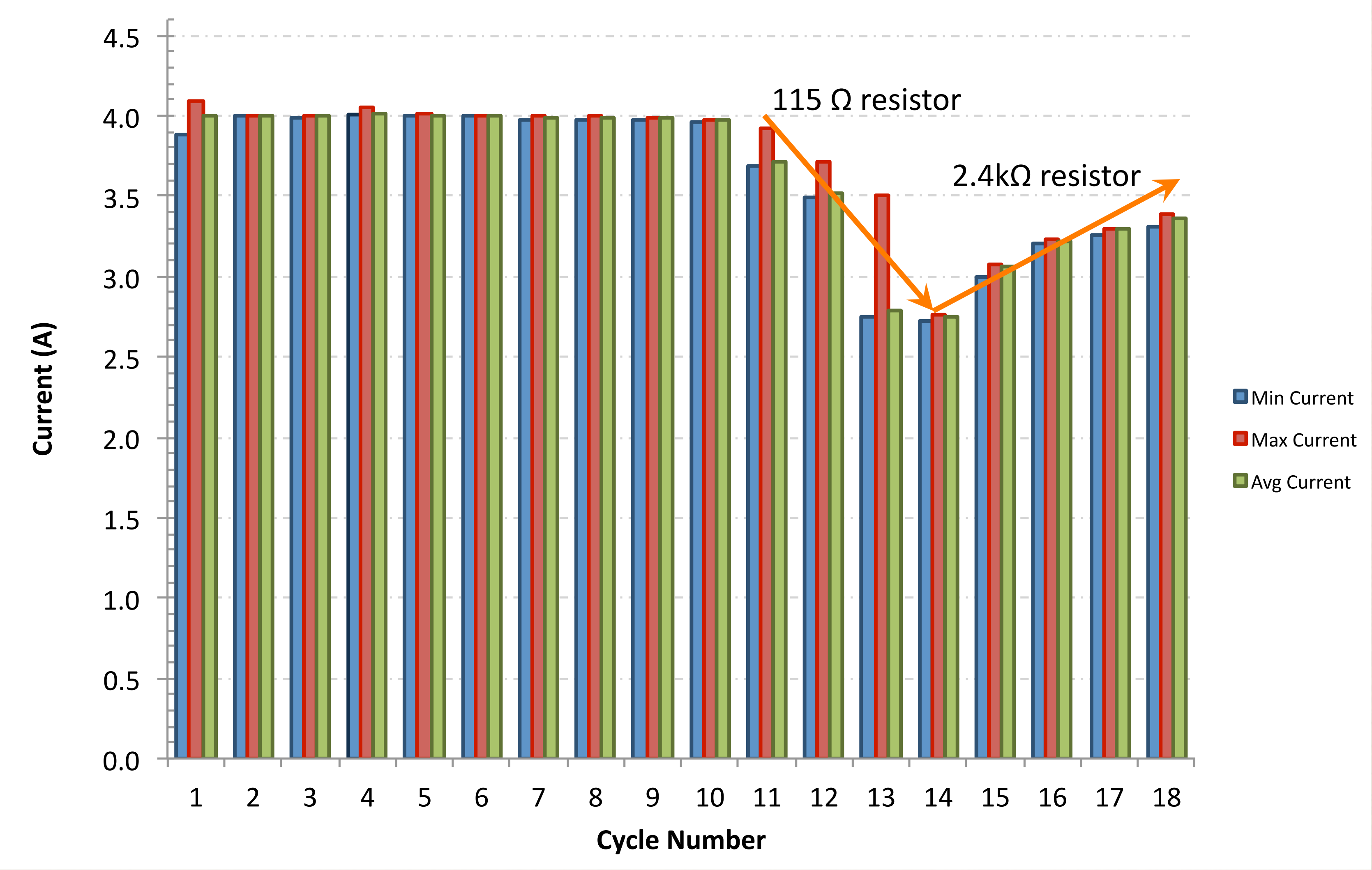


SOXE Constraints

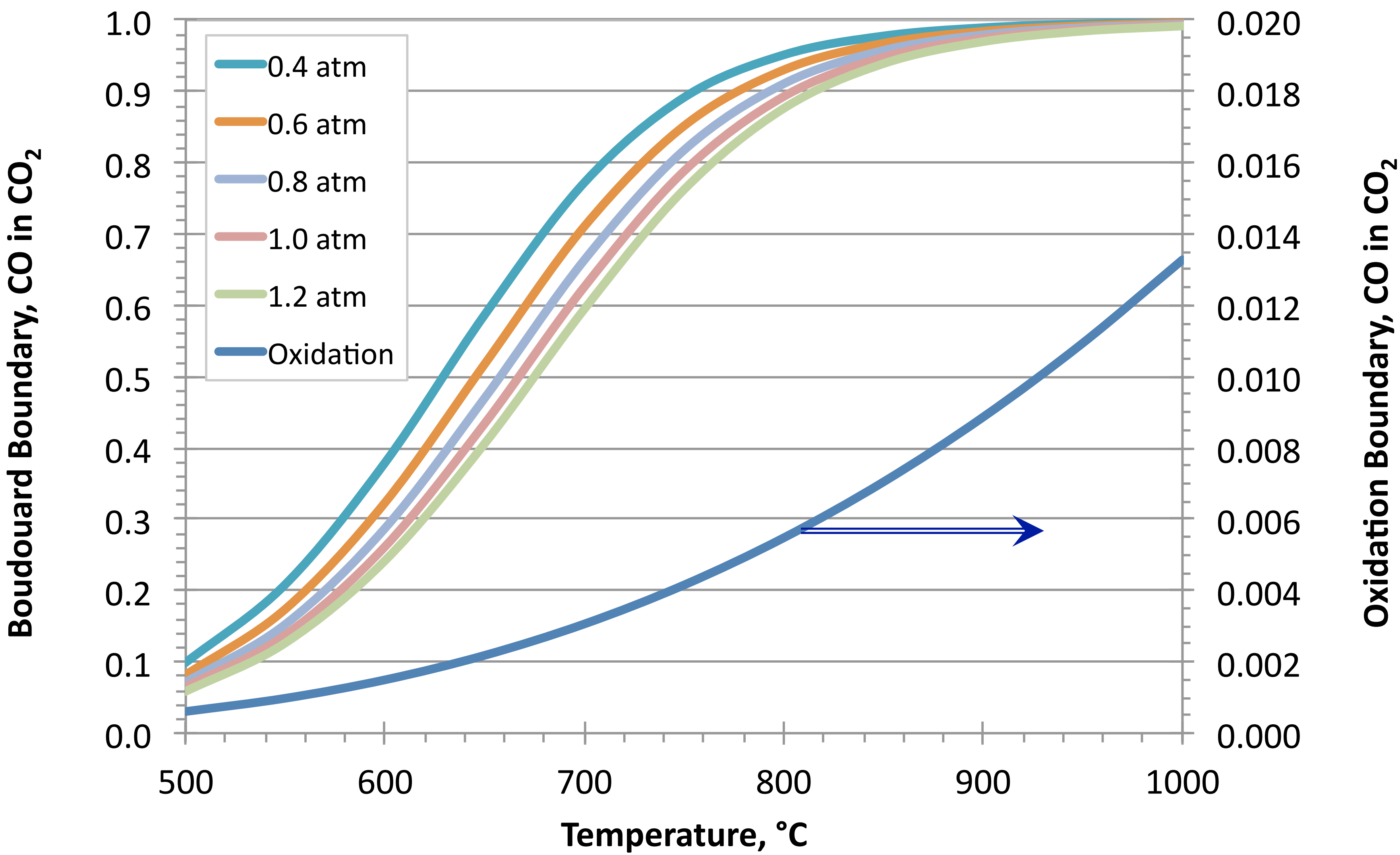
MOXIE
Mars Oxygen
ISRU Experiment

- **Things we know**
  - Area (22.7 cm^2) and number of cells (10)
  - Power supply limit: 4A, 35W.
- **Things we can estimate**
  - *Starting ASR:* ~2.5 Ω-cm^2 after a few test cycles
  - OCV: ~0.8V
  - *Observed degradation:* ~0.1 Ω-cm^2 per cycle.
- **Things we don't know yet**
  - *Safe operating voltage.* Presumed somewhere between 1.2V (test condition) and 1.46V (thermal neutral).
  - *Safe CO_2 utilization fraction:* We have run up to 60%. Currently running at 30%. General sense is that 50% is probably ok.

Stability with heat/cool cycling & test of intentional oxidation from power supply leakage



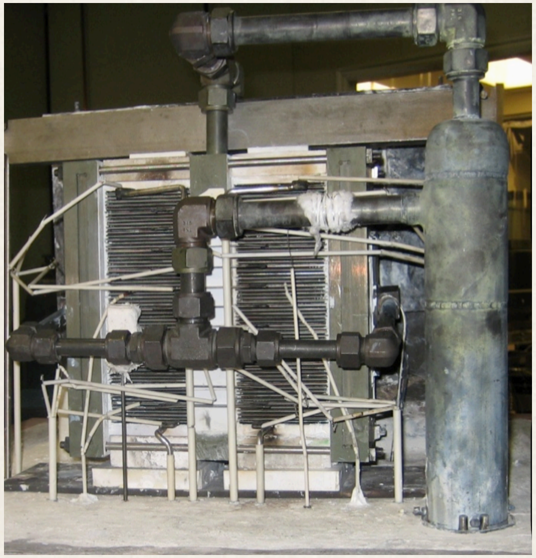
Boudouard and Ni Oxidation Limits



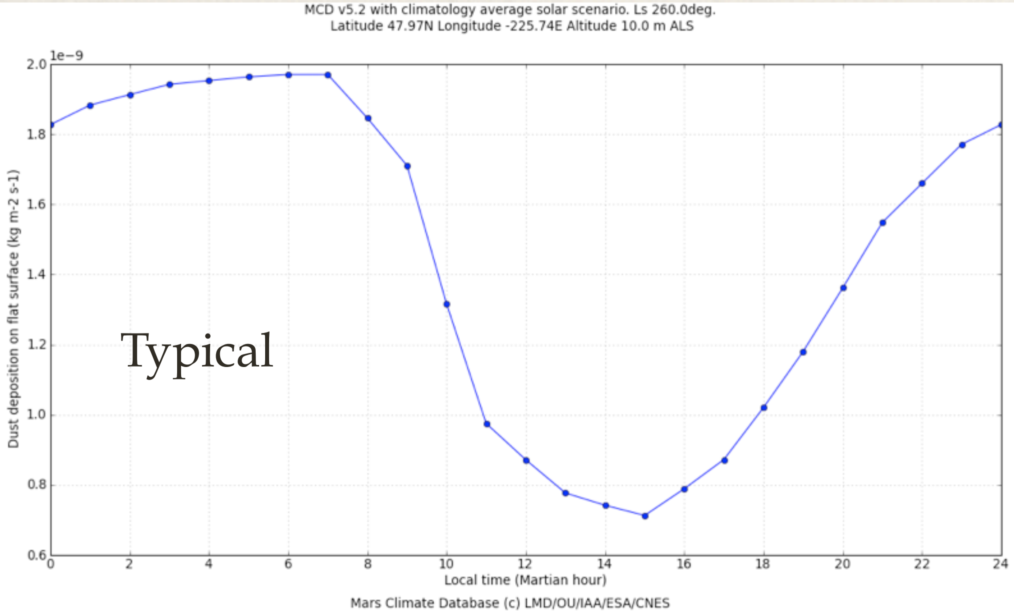
SOXE extensibility

Mars Oxygen ISRU Experiment

* MOXIE is intended to be ~1% scale model of eventual human-scale system
* SOXE is readily scalable by increasing # of stacks.
* Indications are that lifetime is acceptable but more tests needed.
* May want to cascade stacks to utilize "waste" CO_2



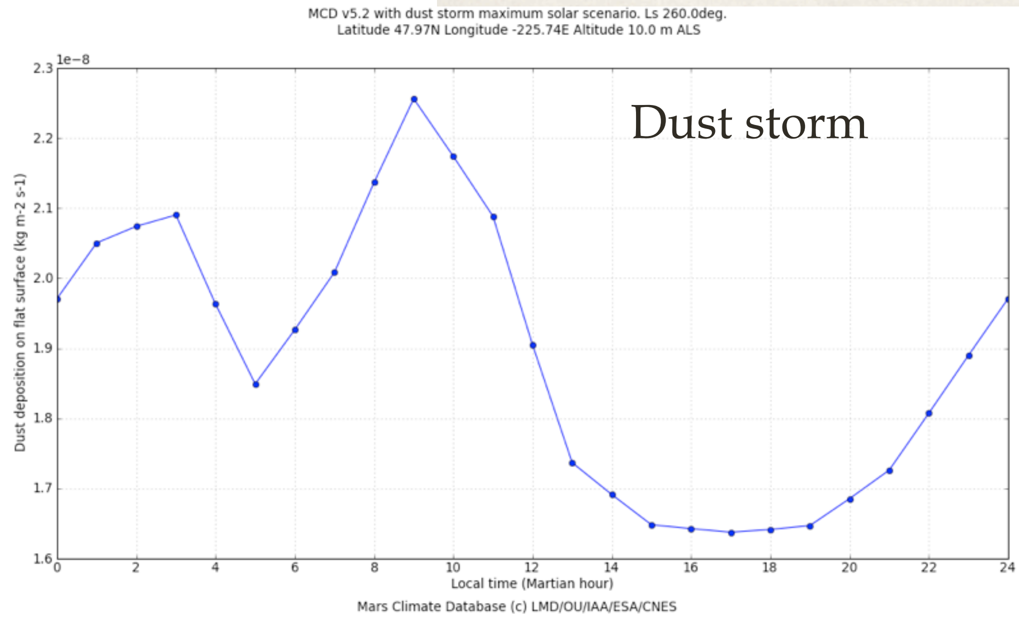
Dust deposition rates



Peak 2×10^{-9}

Deposition (kg/m^2-s) over the course of a day at Ls=260, VL-2 site

Peak 2.3×10^{-8}



Questions?