



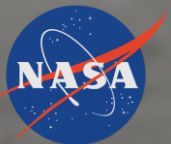
Carbothermal Reduction Demonstration (CaRD) Gas Analysis Subsystem Development

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Background

- Oxygen comprises ~44% of lunar regolith



Substance	Wt%
SiO ₂	44.77
Al ₂ O ₃	18.25
CaO	12.53
FeO	11.72
MgO	9.22
TiO ₂	2.45
Na ₂ O	0.44
Cr ₂ O ₃	0.33
MnO	0.21
K ₂ O	0.18
P ₂ O ₃	0.16
S	0.08
Total	100.33

Element	Wt%
O	43.62
Si	20.93
Al	9.66
Fe	9.11
Ca	8.95
Mg	5.56
Ti	1.47
Na	0.32
Cr	0.22
Mn	0.16
K	0.15
P	0.09
S	0.08

(Taken from Lunar Sourcebook; values averaged over samples collected from the following landing sites: Apollo 15, Apollo 16, Apollo 17, Luna 20 and Luna 24.)

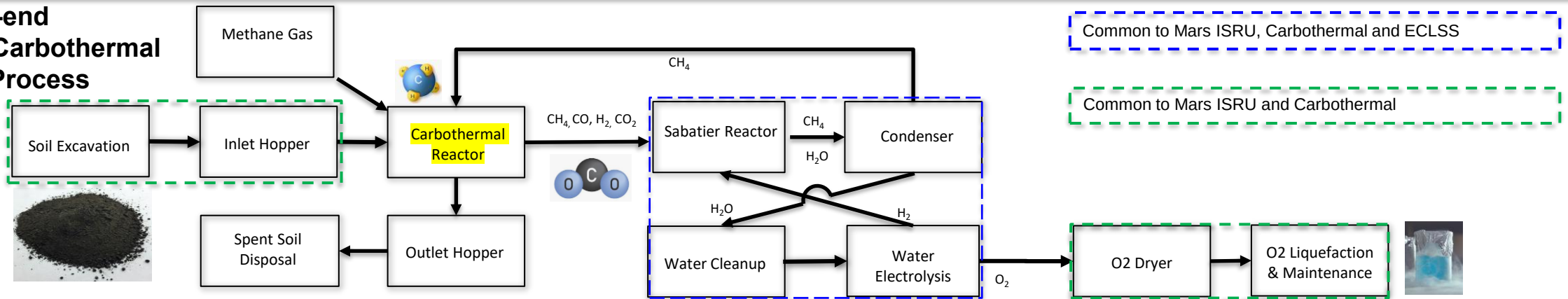
Background

- Carbothermal Reduction Demonstration (CaRD)
 - Oxygen From Regolith (O2FR) Technology Development
 - One of several, including Molten Regolith Extraction (MRE) and Hydrogen Plasma Reduction
- Utilizes the carbothermal reduction process
 - Idealized reaction: $\text{SiO}_2(l) + 2\text{C}(s) + \Delta \longrightarrow \text{Si}(l) + 2\text{CO}(g)$
 - Can reduce other metals as well.
 - Main products include silicon/metal, CO, and CO₂.
- CaRD is a competing O2FR method due to:
 - Demonstrated automated regolith handling in and out of reaction zone.
 - Demonstrated at relevant scale (currently used industrially for Si production).
 - Commonality with Mars ISRU and ECLSS technologies.

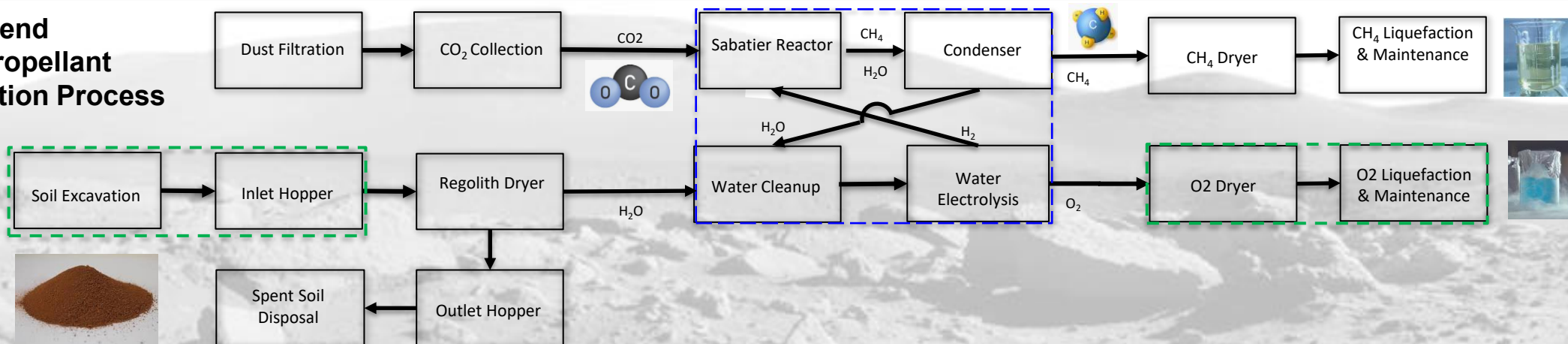
Background

- Oxygen can be recovered from CO and CO₂.

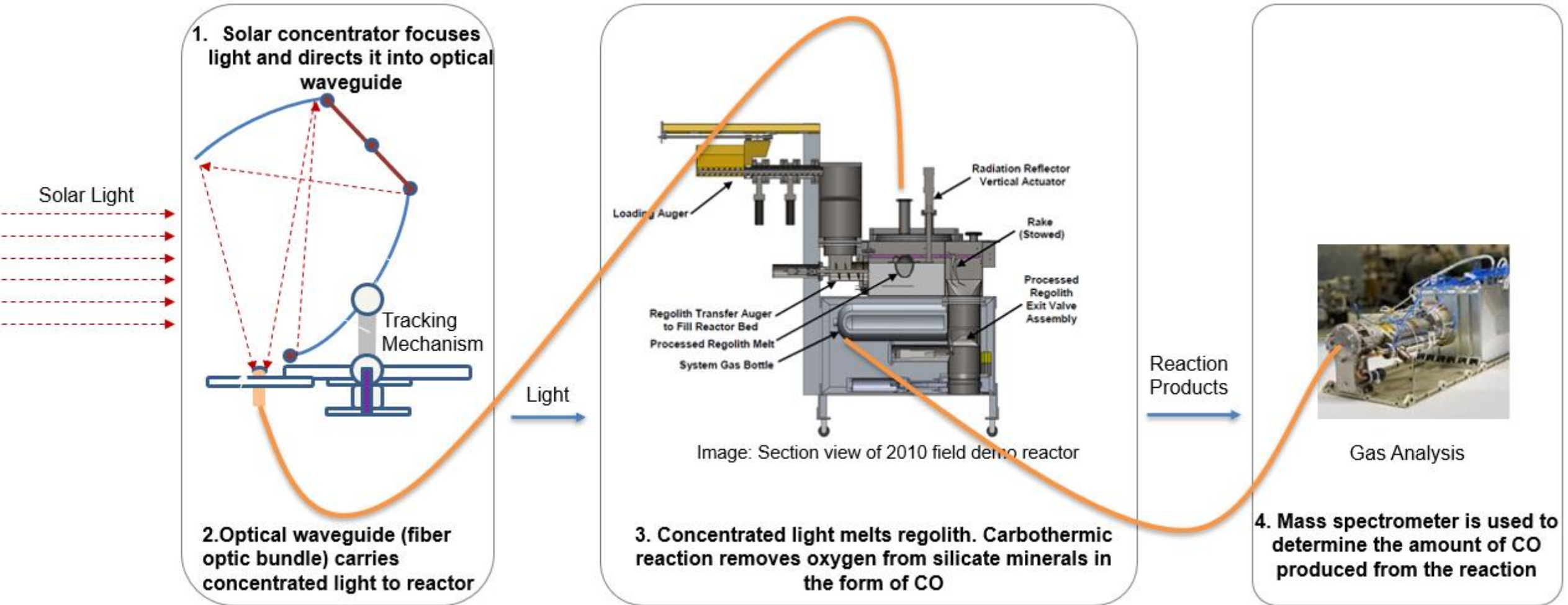
End-to-end Lunar Carbothermal O₂FR Process



End-to-end Mars Propellant Production Process

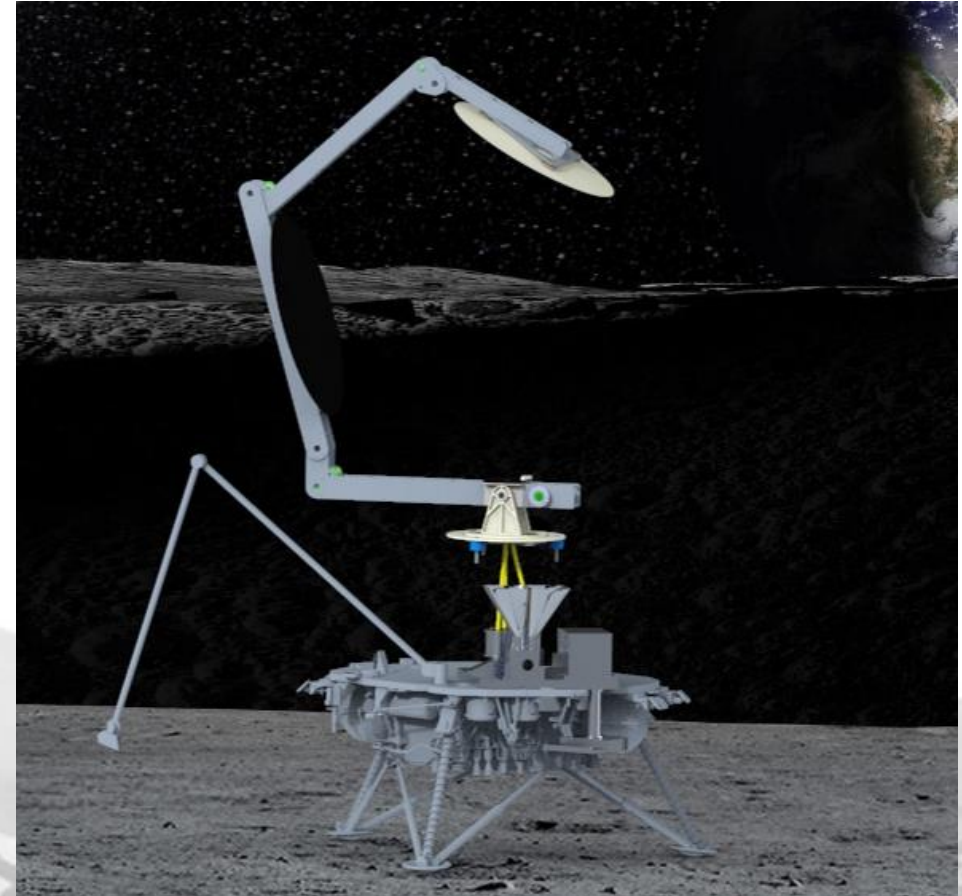


CaRD Concept of Operations



CaRD Project Goal

- Raise TRL of an integrated CaRD system to propose a flight demonstration at the lunar poles
 - Integrated demonstration of solar concentrator, carbothermal reactor, and gas analysis system in a relevant environment
 - Can then transition to mid-size CLPS payload upon project completion



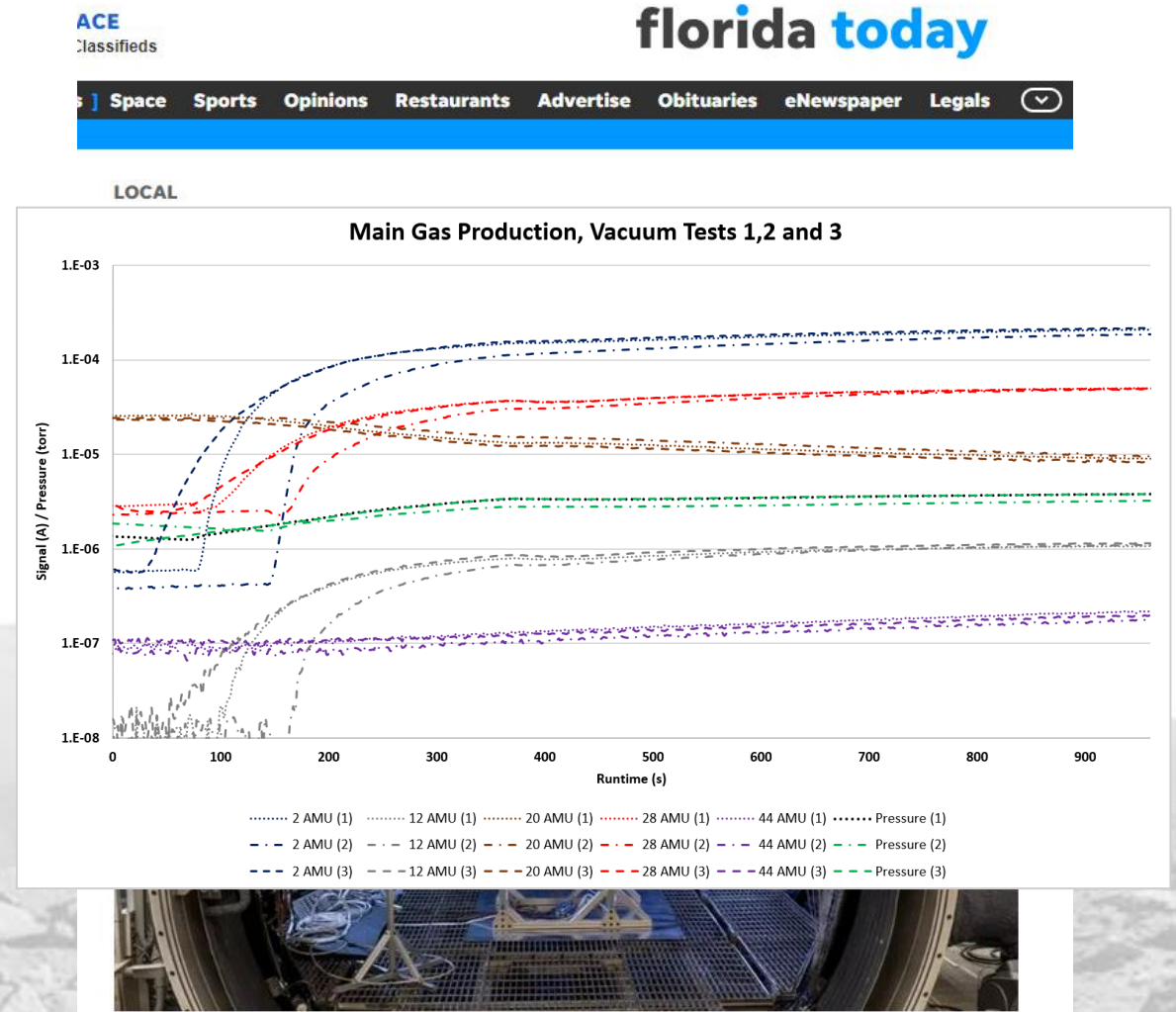
Mockup Image of Potential CaRD Lander

KSC Gas Analysis

- The CaRD project is led by JSC, with the CaRD reactor manufactured via SBIR by Sierra Space
- Researchers at NASA's Kennedy Space Center lead the gas analysis portion of the project
- Test campaign in late 2022 and early 2023 to analyze gases for a CaRD system in thermal vacuum testing at JSC
- Test campaign in late 2023 and early 2024 to analyze gases for an automated CaRD reactor at Sierra Space in Madison, WI

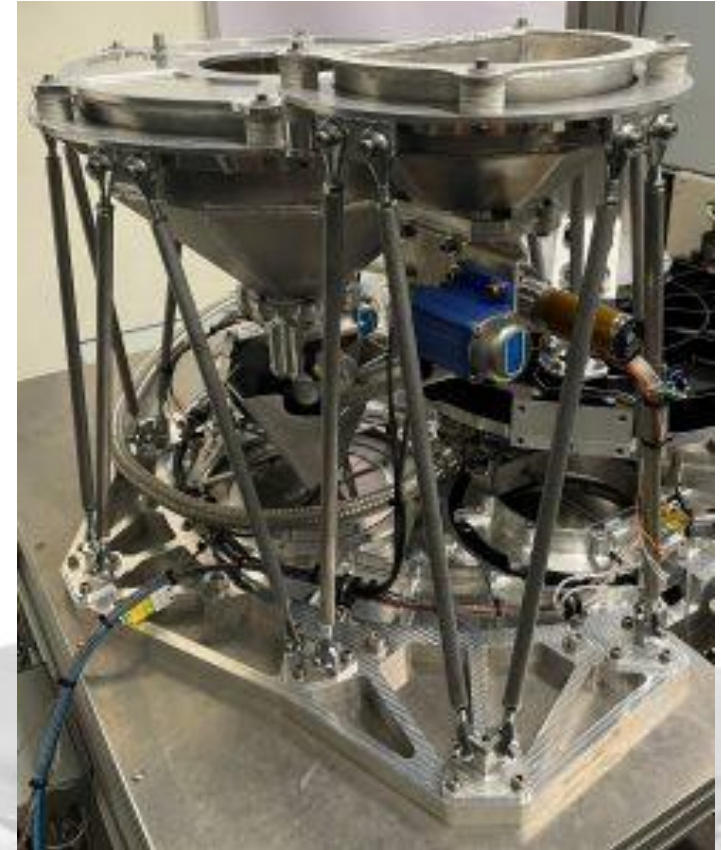
Brassboard Testing

- March 2023, JSC Energy Systems Test Area (ESTA)
- Demonstrated 'proof of concept' in a thermal vacuum with a manual CaRD reactor
- Observed production of CO via gas chromatography and residual gas analysis
- Used argon as background gas.
- Compared residual gas analyzer (RGA) to gas chromatograph (GC) and found them to report comparable results
- Observed oxygen production of 15.79 g/kWh; an order of magnitude greater than the target key performance parameter of 1.25 g/kWh
- Negligible CO₂ was observed



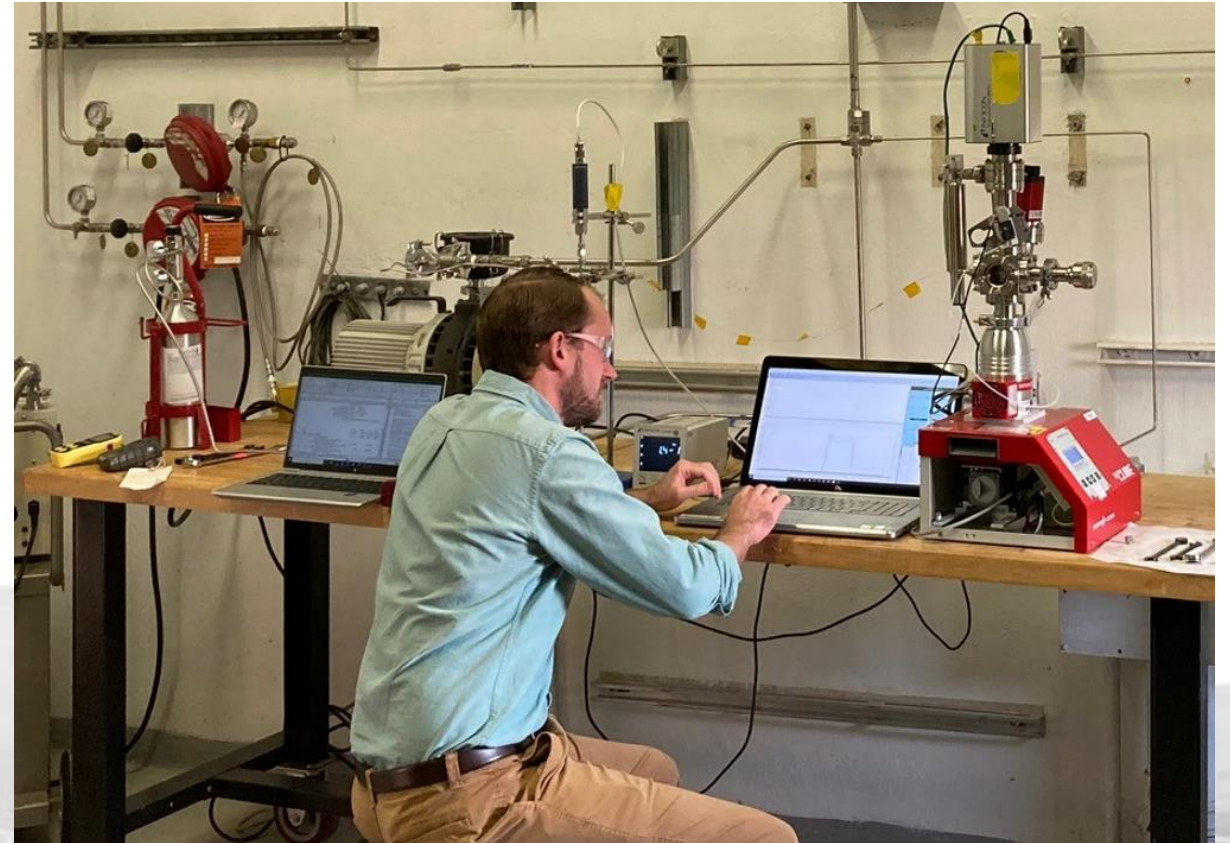
Flight-Forward CaRD

- Use H₂ as the balance gas (will be available via ISRU on the Moon and recycled from Sabatier/electrolysis)
- Automated CaRD reactor: Sierra Space Carbothermal Oxygen Production Reactor (COPR; see ICES-2023-313)
 - Provides automated handling of regolith
 - Thermal energy provided by laser
- KSC gas analysis test campaign
 - Sept 2023 RGA with CO/H₂ at JSC/ESTA
 - Jan 2024 RGA with COPR at SS



Experimental - RGA

- Inficon Transpector™ quadrupole mass spectrometer (similar to MSolo)
- Cross-beam electron ionization source
- Electron multiplier detector
- Fused-silica Restek™ GC capillary (85 cm) for pressure reduction
- External manifold pressure of 3-4 psia
- Internal pressure $<1 \times 10^{-6}$ hPa



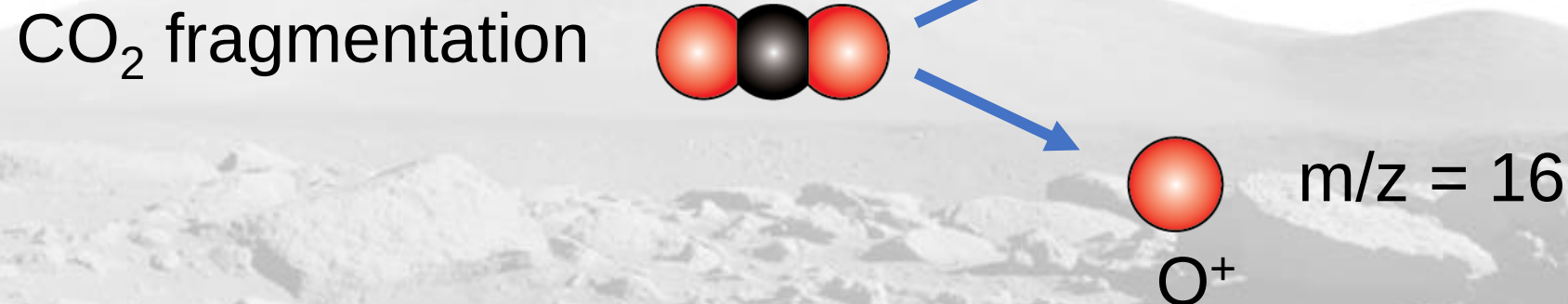
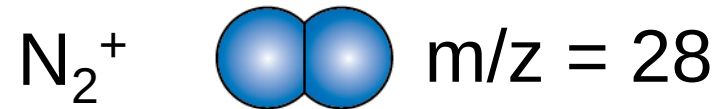
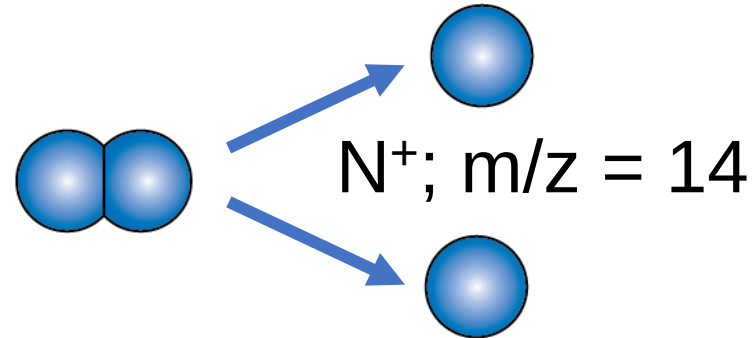
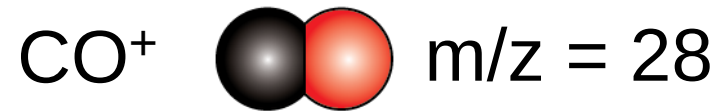
Experimental - Calibration

- Used CO standard gases in H₂ at 1, 2, 5, and 10% CO
- Purged system with pure H₂
- Collected background signal for 5 min
- Pressurized manifold to 1, 2, 4, and 8 psia
- Measured RGA current at $m/z = 2, 14, 28, \text{ and } 44$



Experimental - Corrections

Primary difficulty: $m/z = 28$



N_2 fragmentation factors

Ion	m/z	FF
N_2^+	28	0.88
N^+	14	0.12

CO_2 fragmentation factors

Ion	m/z	FF
CO_2^+	44	0.70
CO^+	28	0.11
O^+	16	0.06
C^+	12	0.01

Experimental - Corrections

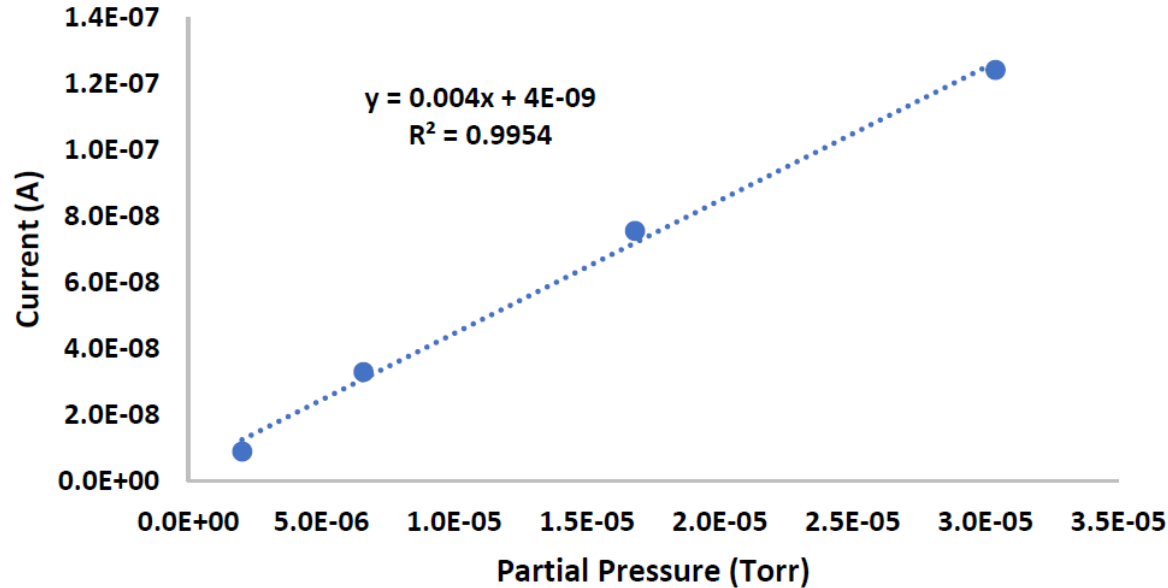
$$I_{CO} = I_{28} - \frac{0.11}{0.70} \times (I_{44} - I_{44BG}) - \frac{0.88}{0.12} \times I_{14} - I_{28BG}$$

- I_{CO} = current at 28 from CO gas
- I_{28} = total ion current at 28 (from CO^+ and N_2^+)
- I_{44} = total ion current at 44 (from CO_2^+)
- I_{14} = total ion current at 14 (from N^+)
- I_{XXBG} = background current for $m/z = XX$
- Other values are fragmentation factors

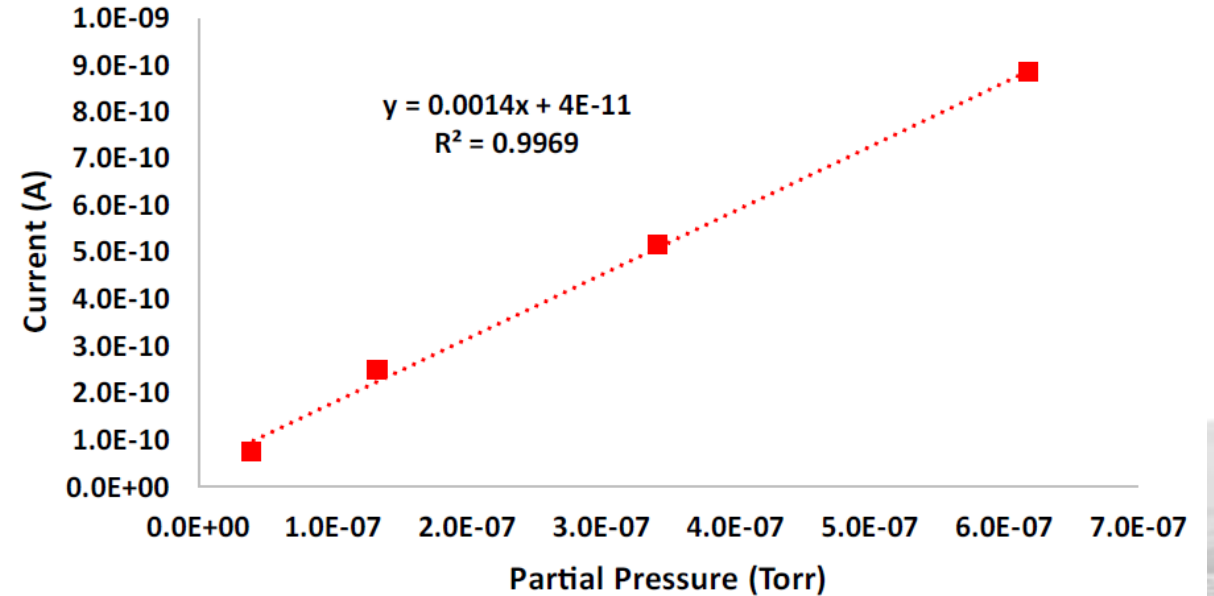
Experimental - Cal Curves

Corrected ion currents were linear with partial pressure.

Hydrogen



Carbon Monoxide



Experimental - Calculations

If we consider only H₂ and CO, we can use the H₂ balance gas as an internal reference for the CO response according to their calibration curve sensitivities (m_{CO} and m_{H_2}).

$$m_{CO} = \frac{I_{28}(CO)}{P_{TPP} \cdot f_{CO}}$$

$$m_{H_2} = \frac{I_2(H_2)}{P_{TPP} \cdot (1 - f_{CO})}$$

P_{TPP} = total pressure from the RGA's total pressure plate

f_{CO} = mole fraction of carbon monoxide

$I_{28}(CO)$ = ion current at $m/z = 28$ resulting only from CO

$I_2(H_2)$ = ion current at $m/z = 2$ resulting from H₂ (background subtracted)

Experimental - Calculations

If we consider the ratio of the slopes (determined experimentally from the above calibration curves), $R = m_{CO} / m_{H_2}$ then:

$$f_{CO} = \frac{I_{28}(CO)}{P_{TPP} \cdot R \cdot m_{H_2}} = \frac{I_{28}(CO) \cdot P_{TPP} \cdot (1 - f_{CO})}{P_{TPP} \cdot R \cdot I_2(H_2)} = \frac{I_{28}(CO) \cdot (1 - f_{CO})}{R \cdot I_2(H_2)}$$

and

$$f_{CO} = \frac{Q}{Q + 1} \quad \text{where} \quad Q = \frac{I_{28}(CO)}{I_2(H_2) \cdot R}$$

Calibration – Challenge Tests

Challenge Test	Actual %CO	Measured %CO	Rel %error
1	2.0	2.1	6.4
2	5.0	5.1	1.2
3	5.0	5.3	6.2
4	2.0	1.9	2.6
5	5.0	5.0	0.6
6	2.0	2.0	2.2
		average	3.2

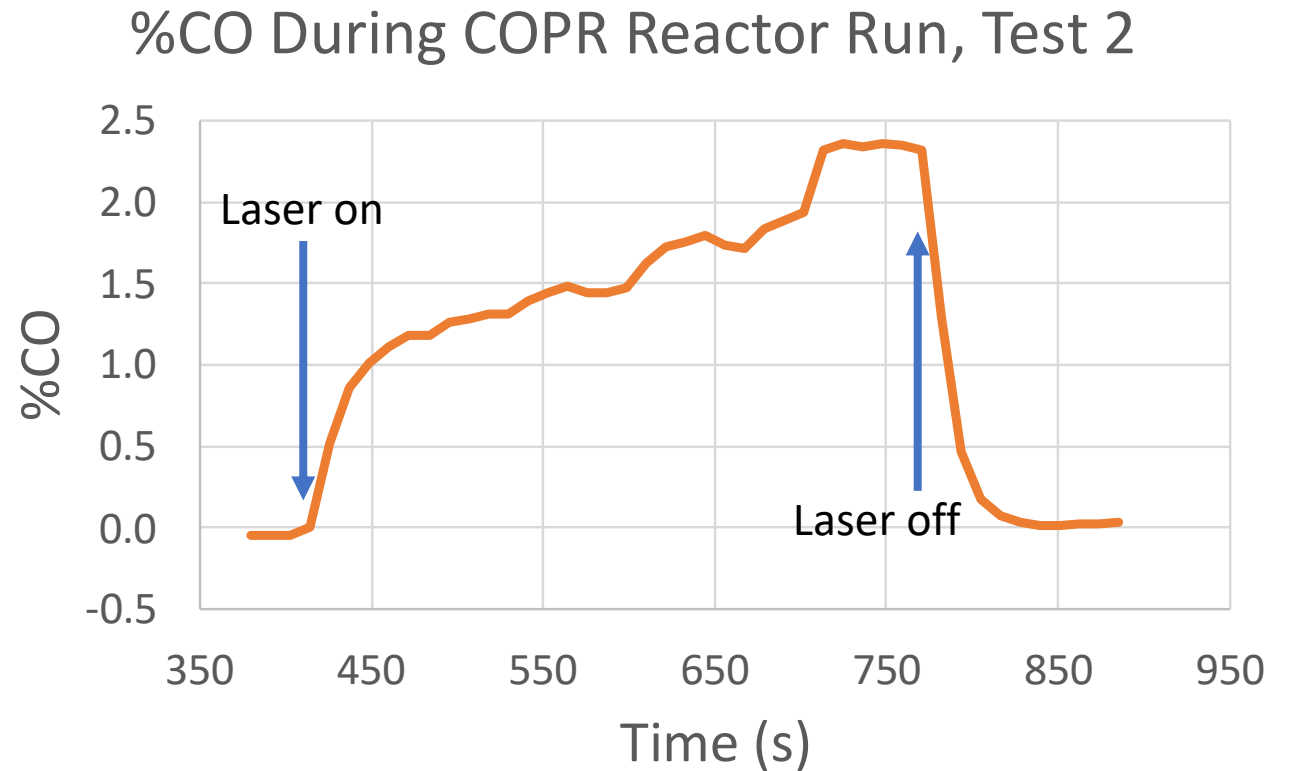
COPR Testing

- During COPR runs, the RGA capillary was attached to the reactor effluent
- Provided a measurement of each m/z value every ~7 sec
- Were able to observe %CO in real-time during each reactor run
- Compared to GC measurements by Sierra Space



COPR Testing

- Obvious where laser is turned on and off (360 s run time)
- Heat from laser produced CO



Comparison to GC Results

Table 2. Measured CO extraction comparing RGA and GC measurements.

Test name	SS Test name	mCO(g) RGA Integration	mCO(g) SS	Variance (%)
Test 1	COPR - 7	5.112	4.840	5.5
Test 2	COPR - 8	4.030	3.642	10.1
Test 3	COPR - 9	3.827	3.965	3.5
Test 4	COPR - 10	2.062	3.120	40.8
Test 5	COPR - 11	3.393	3.846	12.5
AVG		4.09	4.07	7.9
STD		0.73	0.53	4.1

Conclusions

- Brassboard test demonstrated quantification of CO in Ar background
- Calibration testing at JSC-ESTA demonstrated quantification of CO in H₂ (3.2% relative error)
- COPR testing at Sierra Space demonstrated quantification of CO in H₂ carbothermal reactor effluent (7.9% relative error)
- Next: Measure effluent CO of the COPR in a thermal vacuum (happening as we speak)

Acknowledgements

- Entire CaRD Team
- KSC Applied Chemistry Laboratory
- JSC Energy Systems Test Area
- Funding



Thank You! Questions?

Thank you for your time!

Any questions?

