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Real-Time Gas Analysis for the Carbothermal Demonstration Project's Integrated Prototype Testing

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Agenda

Oxygen: An Abundant Lunar Resource

Substance	Wt%
SiO_2	44.77
Al_2O_3	18.25
CaO	12.53
FeO	11.72
MgO	9.22
TiO_2	2.45
Na_2O	0.44
Cr_2O_3	0.33
MnO	0.21
K_2O	0.18
P_2O_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

Oxygen is the most abundant element found in lunar regolith.

NASA photo AS11-40-5877

(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.)

Carbothermal Reduction

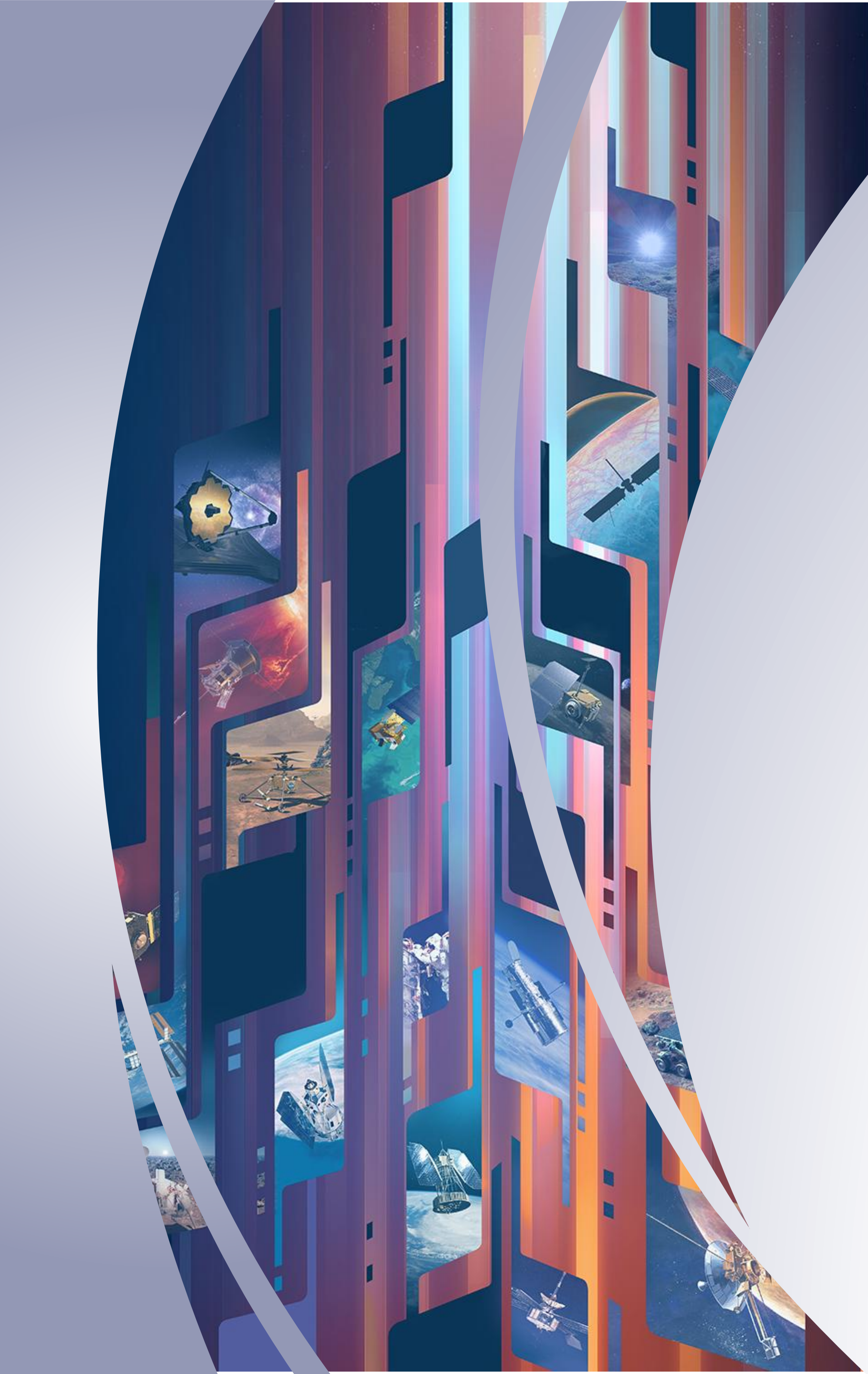
Utilizes heat and a carbon source to extract oxygen in the form of CO

$$SiO_2(l) + 2\,C(s) \rightarrow 2\,CO(g) + Si(l)$$

- Used for the industrial production of pure silicon
  - Reliable
  - Well understood
- Undergone an extensive test campaign (since .

https://www.sierraspace.com/press-releases/sierra-space-unveils-breakthrough-technology-designed-to-extract-oxygen-from-lunar-soil/

Sierra Space carbothermal reactor in the large thermal vacuum chamber at JSC Energy Systems Test Area.

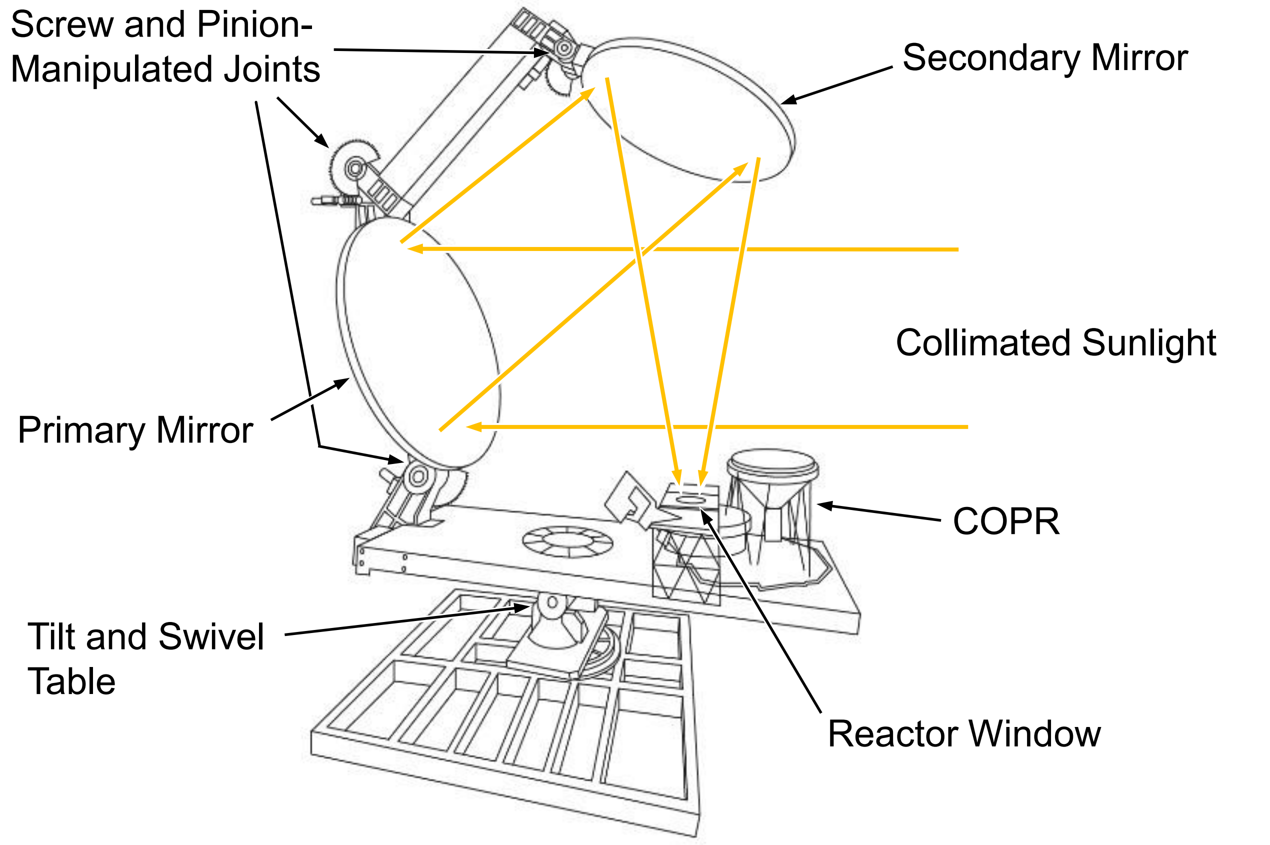


Carbothermal Reduction (CaRD) and Molten Regolith Electrolysis (MRE) NASA Test Campaigns

CaRD:

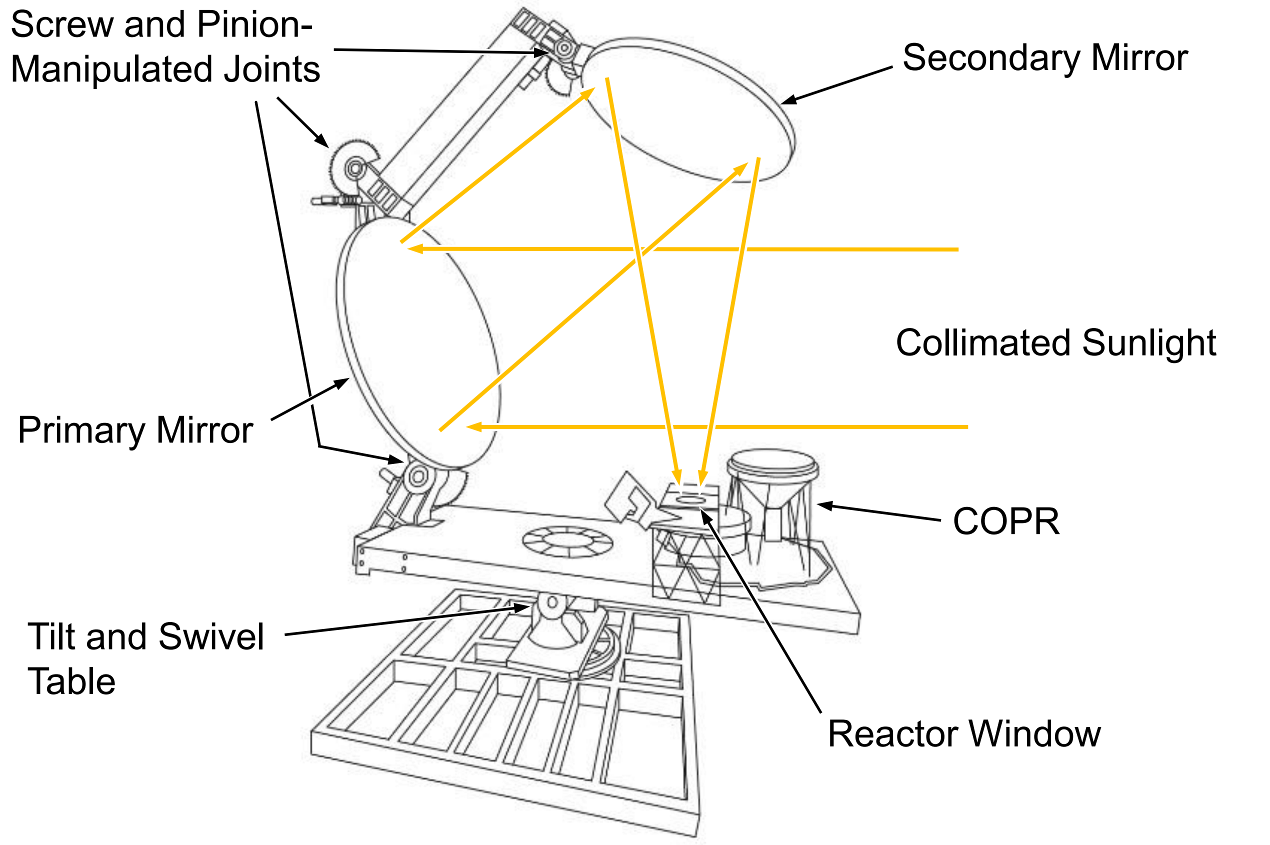
Test Date	Test Location	Test Environment	Illumination Source	Gas Analysis Method
Feb. 2023	ESTA/JSC, Houston, TX	Thermal Vacuum	Laser	RGA + GC
Jan. 2024	Sierra Space, Madison, WI	Laboratory	Laser	RGA + GC
Jul. 2024	ESTA/JSC, Houston, TX	Thermal Vacuum	Laser	RGA
Aug. 2025	ESTA/JSC, Houston, TX	Laboratory	Solar Concentrator	RGA

Carbothermal Reduction Integrated Test



NASA. “Sunlight Extracts Oxygen from Regolith Using Solar Chemistry.” NASA Johnson Space Center, Feb. 13, 2026.
https://www.nasa.gov/centers-and-facilities/johnson/sunlight-extracts-oxygen-from-regolith-using-solar-chemistry/

Carbothermal Reduction Integrated Test



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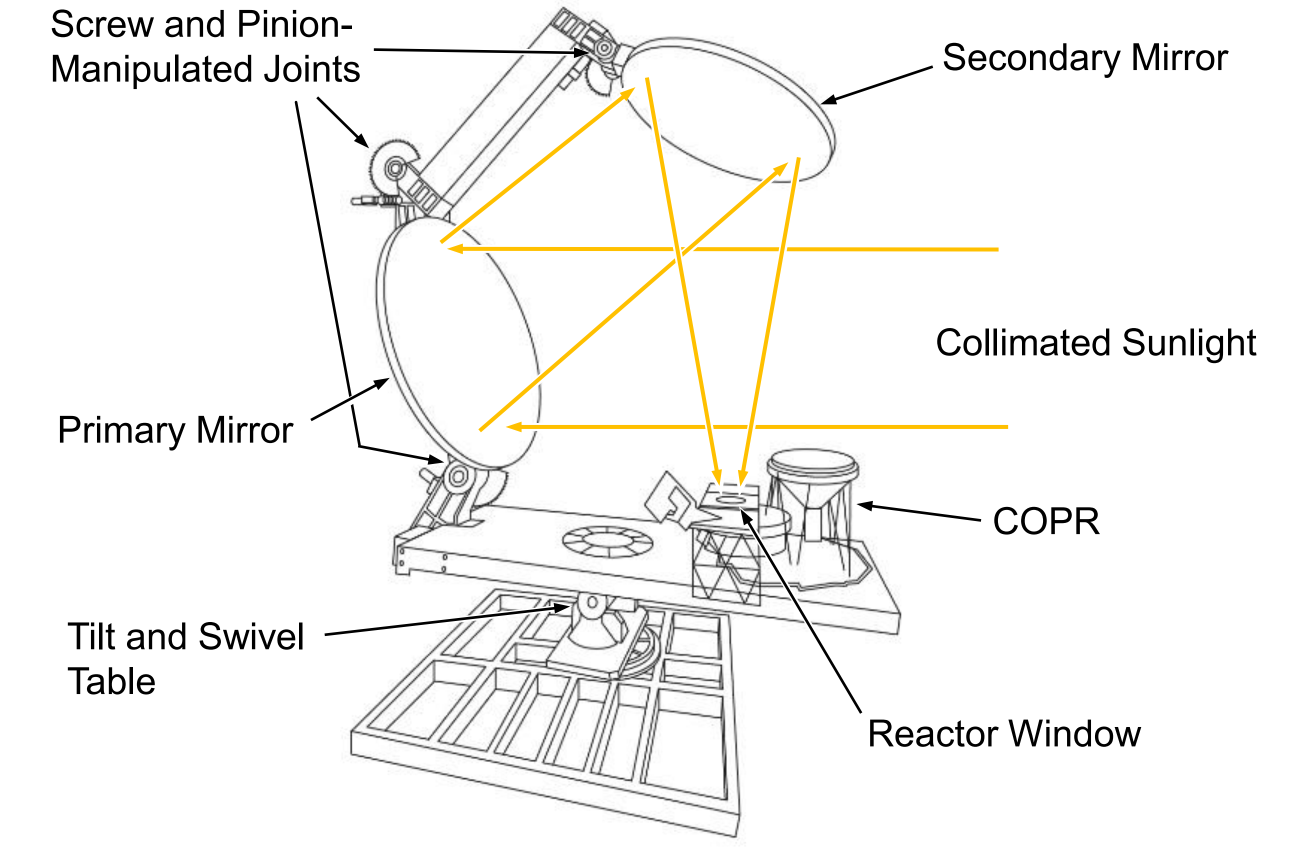
Carbothermal Reduction Integrated Test



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Carbothermal Reduction Integrated Test

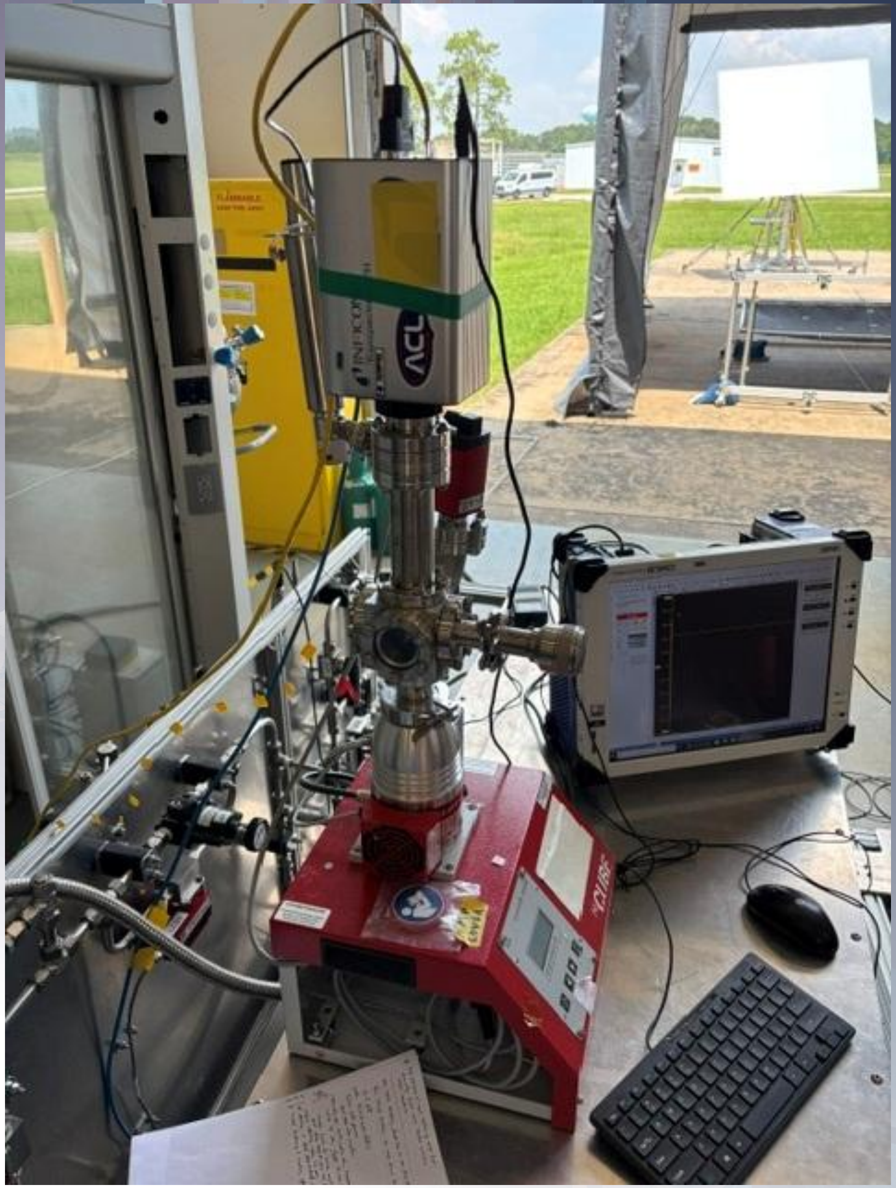
CaRD Integrated Prototype Testing

- Reactor was the Carbothermal Oxygen Production Reactor (COPR) developed by Sierra Space (Madison, WI).
- 2-mirror solar concentrator developed by NASA's Glenn Research Center and Composite Mirror Applications, LLC.
- Avionics and control systems + product gas analysis system (MSolo/RGA) developed by NASA's Kennedy Space Center.
- Project led by NASA's Johnson Space Center, and testing at JSC's Energy Systems Test Area (ESTA).
- Successfully demonstrated direct solar powered carbothermal reduction.

NASA. "Sunlight Extracts Oxygen from Regolith Using Solar Chemistry." NASA Johnson Space Center, Feb. 13, 2026.
https://www.nasa.gov/centers-and-facilities/johnson/sunlight-extracts-oxygen-from-regolith-using-solar-chemistry/

Residual Gas Analyzer (RGA)

- Based on the Mass Spectrometer for Observing Lunar Operations (MSolo) RGA.
- Utilized an Inficon cross-beam ion source with a quadrupole mass analyzer.
- Vacuum provided by a Pfiefer Hi-Cube turbo pump vacuum system.
- In this testing did not require ballast purges (no hydrogen carrier gas).
- Was connected to the Sierra Space gas panel via 85 cm 0.5 mm dia capillary.
- Measured CO concentration in real-time.



Calibration Method

- Utilized the sweep gas as an internal standard against which the concentration of the CO was determined.
- Performed a single-point calibration before each CaRD run with either 1% or 2% CO in sweep gas.
- Evaluated calibration with a challenge test with either 1% or 2% CO in sweep gas (the one not used for the calibration).

Calibration Method

Corrected ion current for carbon monoxide ($I_{28}(CO)$)

$$I_{28}(CO) = I_{28}(TOT) - I_{28}(BG) - \left(I_{44}(TOT) - I_{44}(BG)\right) \bullet \frac{0.11}{0.70} - I_{14}(TOT) \bullet \frac{0.93}{0.06}$$

$I_{28}(TOT)$: total measured ion current for m/z = 28

$I_{28}(BG)$: background current for m/z = 28

$I_{44}(TOT)$: total measured ion current for m/z = 44

$I_{44}(BG)$: background current for m/z = 44

$I_{14}(TOT)$: total measured ion current for m/z = 14.

*Corrected current for the sweep gas (I_{SW}) was similarly calculated.

Calibration Method

Mole fraction of CO (f_{CO}) can then be found from:

$$f_{CO} = \frac{I_{28}(CO) \bullet (1 - f_{CO})}{R \bullet I_{SW}}$$

which simplifies to

$$f_{CO} = \frac{Q}{Q+1} \qquad \textit{where} \qquad Q = \frac{I_{28}(CO)}{R \bullet I_{SW}}$$

R: ratio of the single point calibration slopes for I_X vs partial pressure X (determined from single-point calibration).

Results

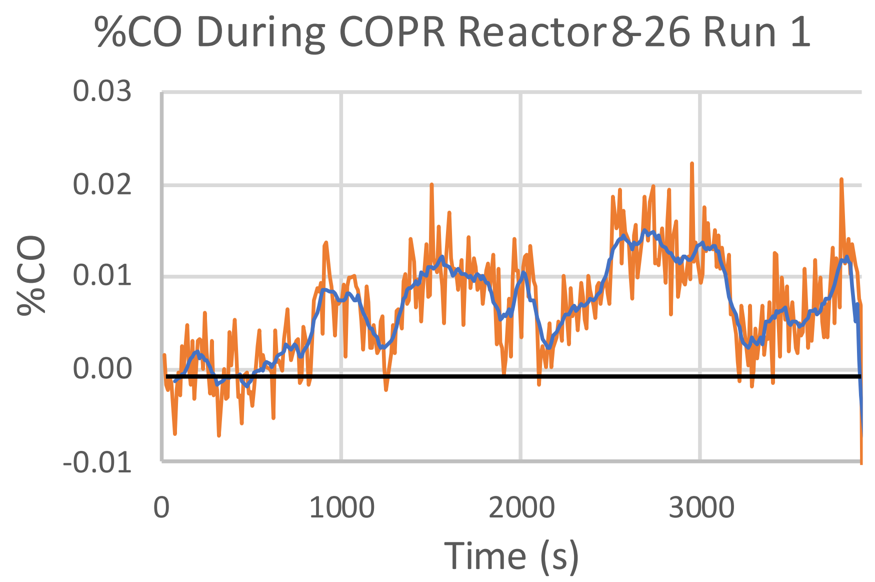
%CO = 100*f_{CO}

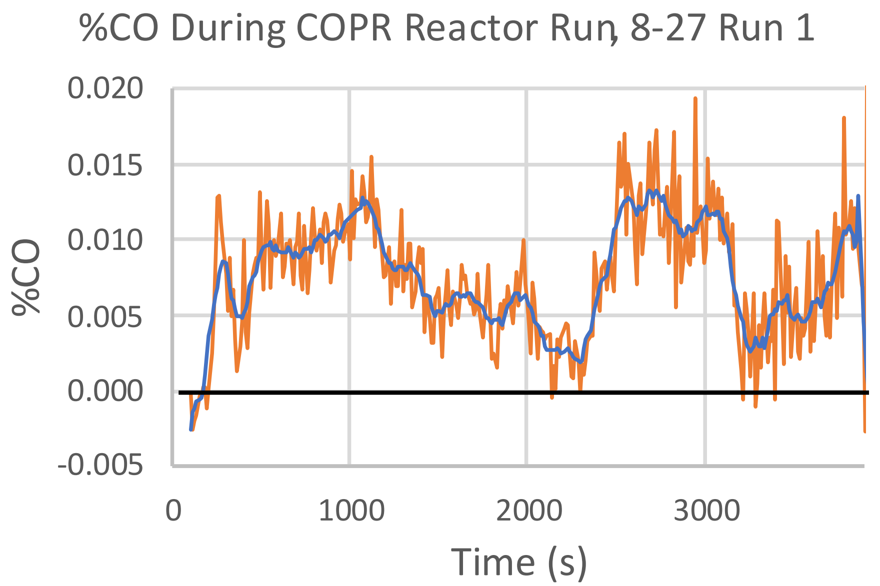
Orange = full data (1 datum/12 s)

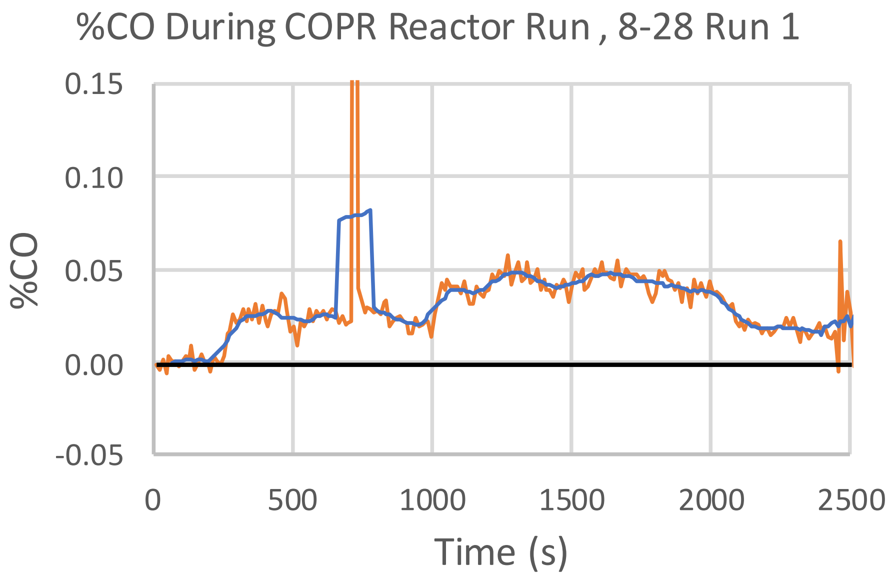
Blue = 11 pt moving average

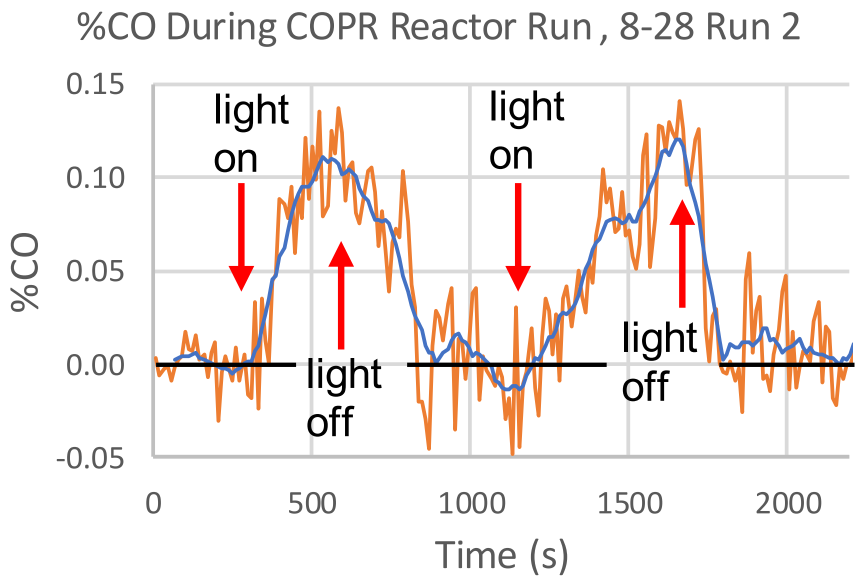
Black = zero

Integrated to yield total CO produced.









Results (Figures of Merit)

Test Date	Run	Number of Blank/Baseline Measurements (n)	Standard Deviation of Blank/Baseline Measurements (%CO)	Limit of Detection (%CO)	Limit of Quantitation (%CO)
08-26-2025	Run 1	48	0.00101	0.00301	0.01006
08-27-2025	Run 1	10	0.00260	0.00780	0.02598
08-28-2025	Run 1	13	0.00044	0.00131	0.00438
08-28-2025	Run 2	11	0.00170	0.00510	0.01701

Results (Production)

Test Date	Run	Test Duration (min)	Total CO produced (g)	CO Production Rate (g/min)	Equivalent O_2 Produced* (g)
08-26-2025	Run 1	51	0.130±0.003	0.0025	0.074±0.002
08-27-2025	Run 1	71	0.327±0.011	0.0046	0.187±0.006
08-28-2025	Run 1	36	0.341±0.003	0.0095	0.195±0.002
08-28-2025	Run 2	32	0.098±0.001	0.0031	0.056±0.001

Conclusions

- Real-time quantification method is applicable over a wide range of test conditions.
- Here concentrations were much lower and test durations much longer than previous tests (~30 min vs 6 min).
- CO production corresponded to solar illumination.
- Likely that RGA could be an applicable method for lunar in-situ monitoring (especially since MSolo is flight-rated), though this must be considered speculative at this time.

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QUESTIONS?

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