

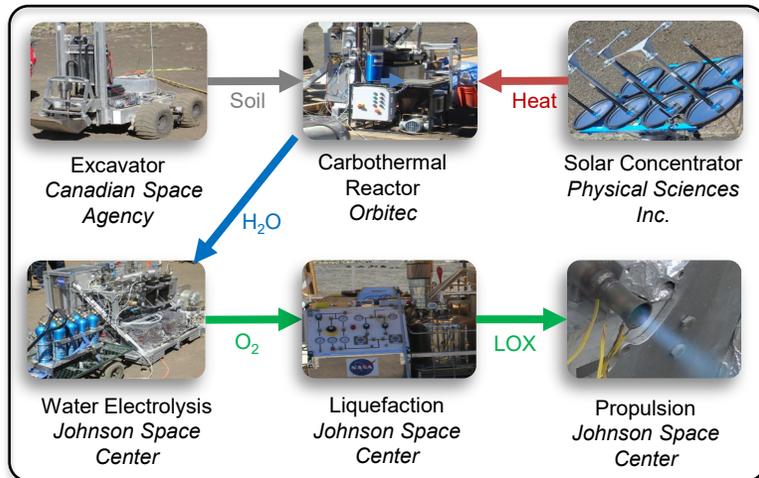


Carbothermal Reduction Demonstration (CaRD) Project Status 2023



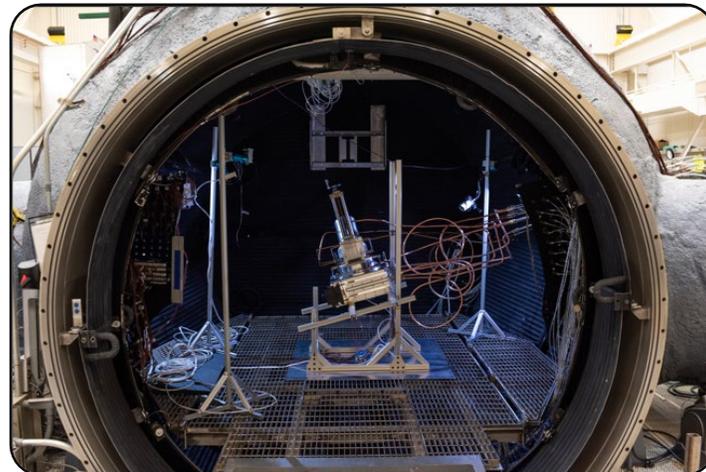
CaRD project scope includes all of the subsystems necessary to determine the performance of the carbothermal reduction process ($\text{SiO}_2 + 2\text{C} \rightarrow \text{Si} + 2\text{CO}$) on the lunar surface. Downstream components that convert CO into oxygen gas can be implemented at a larger scale once the yield is known.

Past



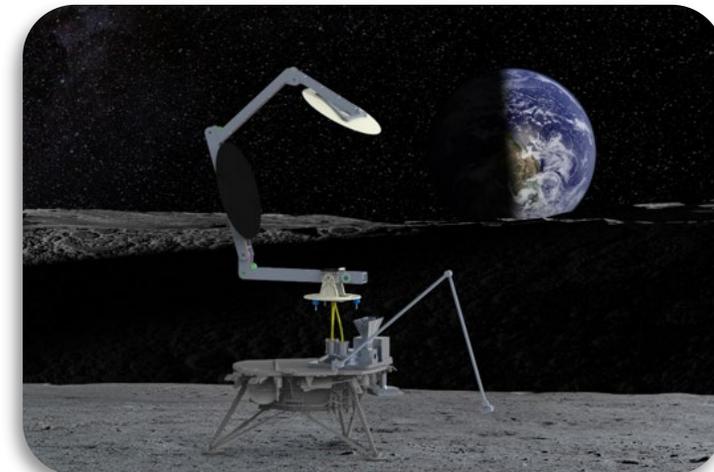
“Dust to Thrust” Demonstration 2010

Present

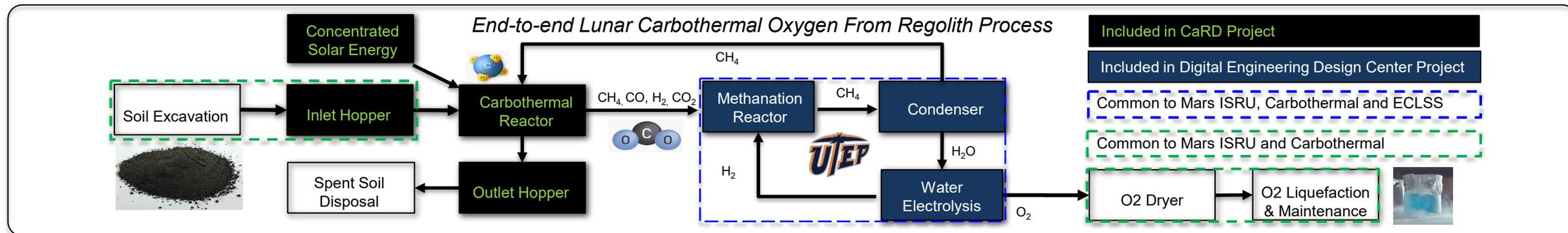


Carbothermal Reactor Developed by Sierra Space Inside 15ft Dirty Thermal Vacuum Chamber at JSC

Future



CaRD Prototype Test in FY24. Targeting Payload on the Lunar Surface in 2027



The current cost to land 1kg on the lunar surface is \$1.2M. At that rate, landing 10 tonnes of LOX would cost \$12B



"Dust to Thrust" 2010



Excavator
Canadian Space Agency

Tephra



Carbothermal Reactor
Orbitec (Now Sierra Space)

Heat



Solar Concentrator
Physical Sciences Inc.

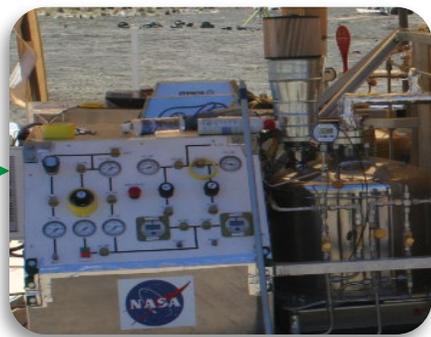


Heat



Water Electrolysis
Johnson Space Center

H₂O



Liquefaction
Johnson Space Center

LOX



Propulsion
Johnson Space Center

Plume



Sintered Pad
Physical Sciences Inc.
NORCAT



Example of TRL 4 to 6 for the Moon



Component TVAC

Component Vibration

Component Dust

Subsystem Vibration

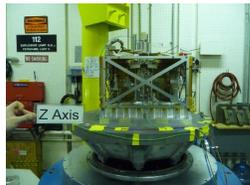
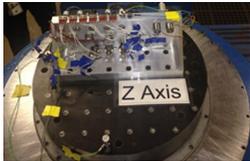
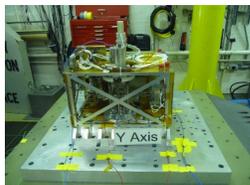
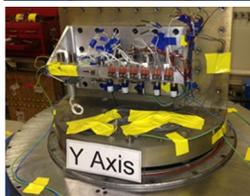
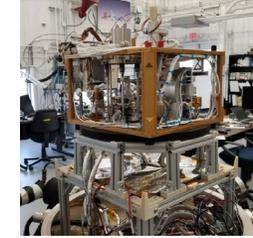
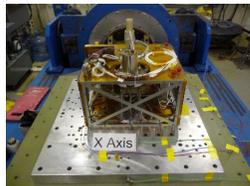
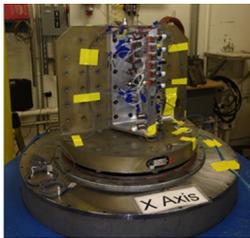
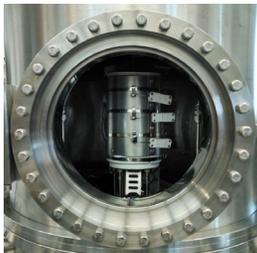
Integrated Vibration

Thermal Cycles

Component Thermal Vacuum

Integrated Thermal Vacuum

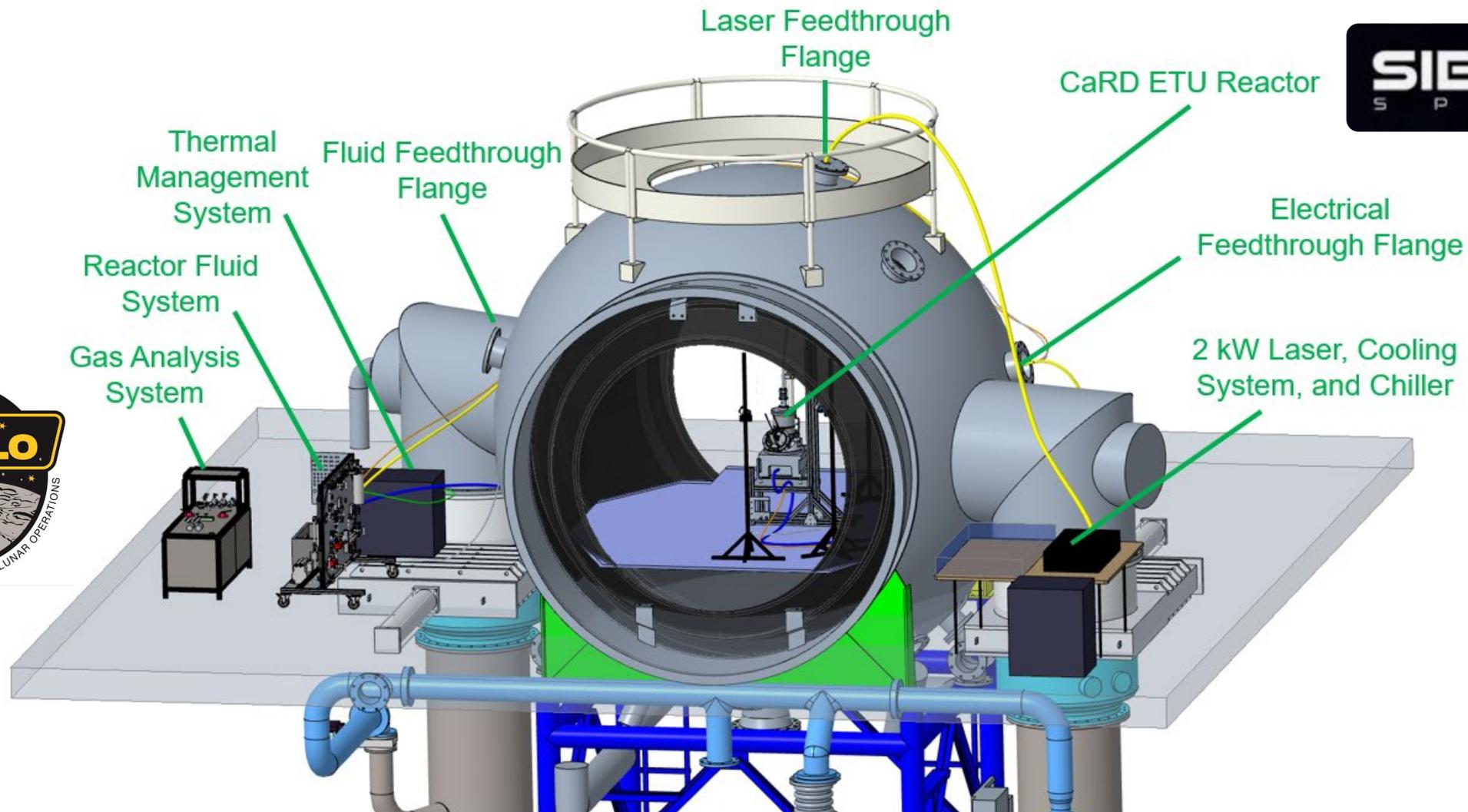
Torque Margin/Dust



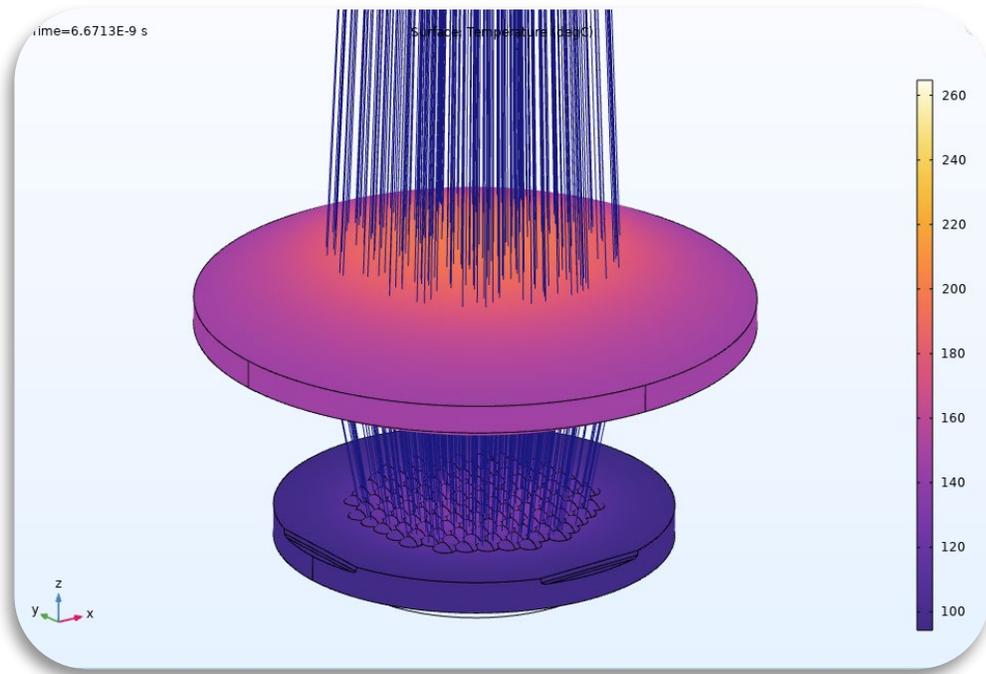
[Environmental Testing of the OVEN](#)



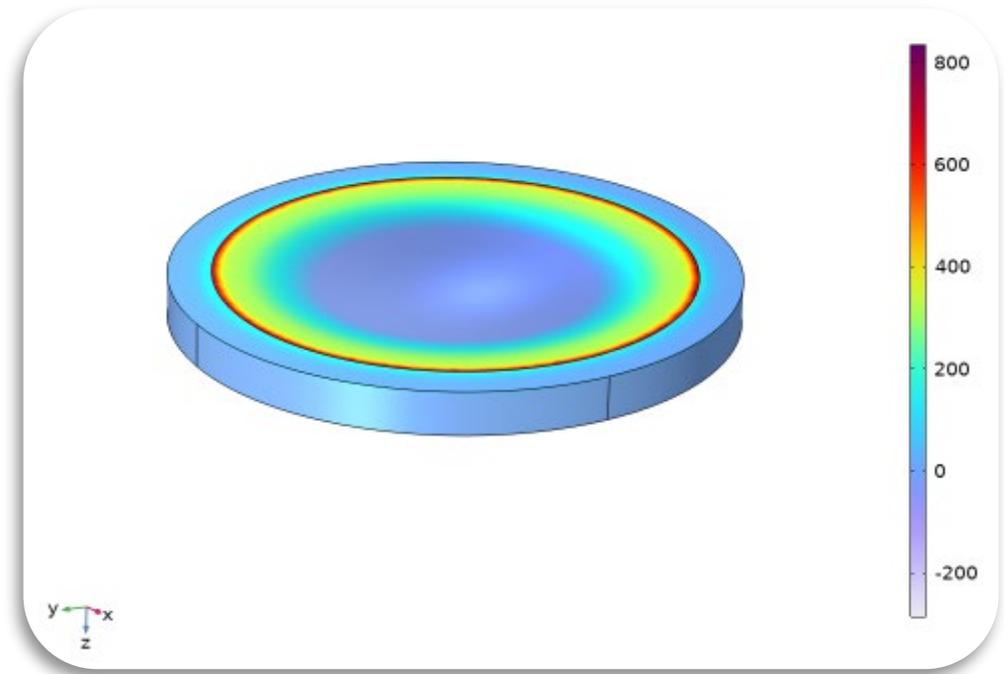
CaRD Environmental Test Unit (Brassboard)



COMSOL Multiphysics Analysis



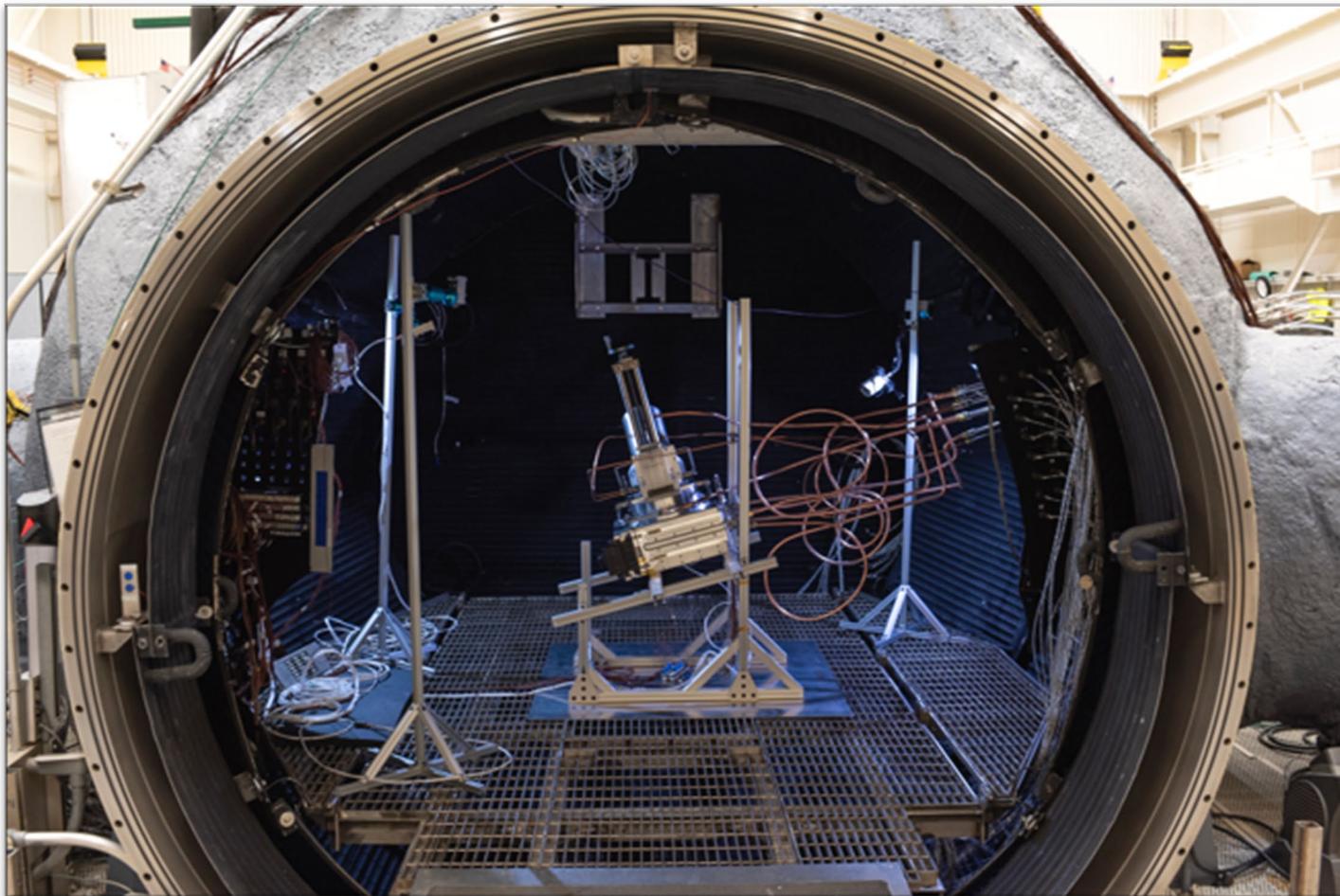
Lens Heating Analysis



Lens Stress Analysis



CaRD Brassboard Test Results



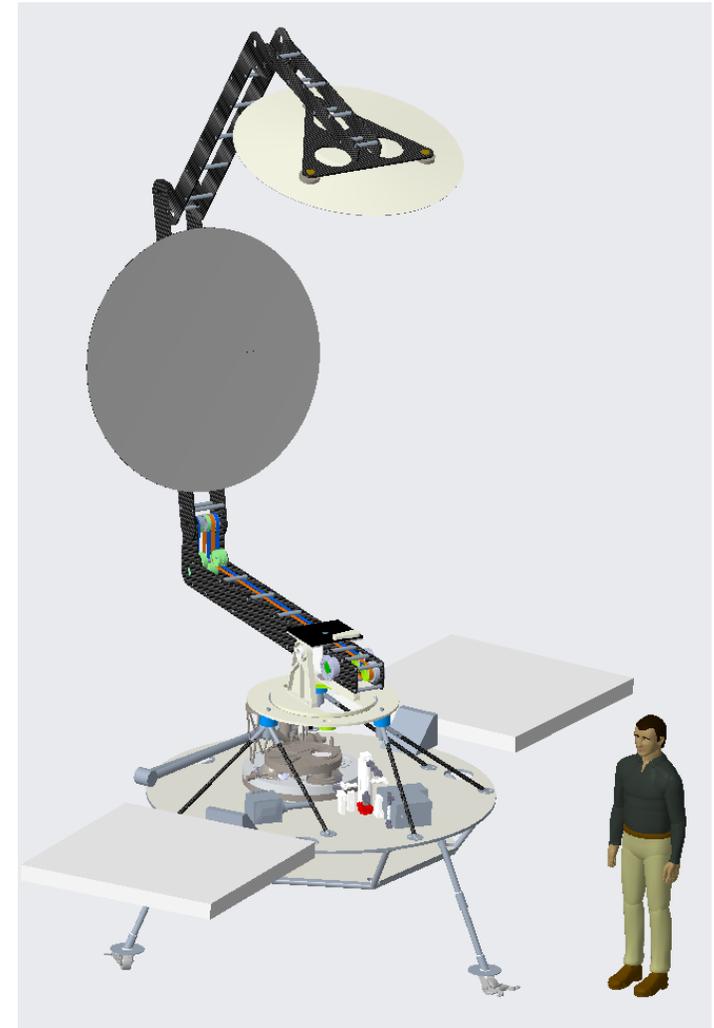
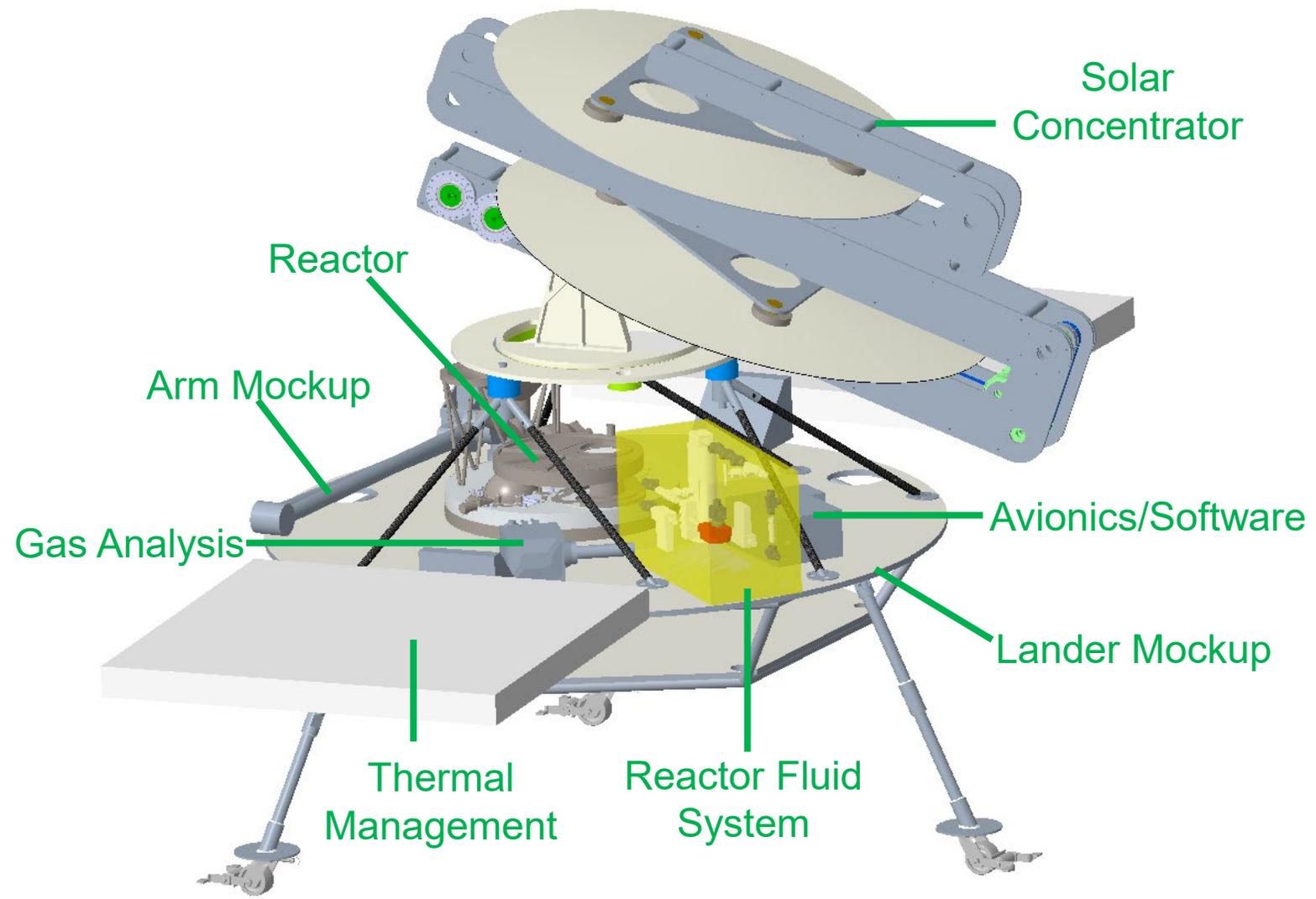
Test Number	grams oxygen extracted/ kWh thermal
CaRD Ambient	13.42
CaRD Vacuum 1	11.53
CaRD Vacuum 2	15.79
CaRD Vacuum 3	10.77

This test will be repeated in 2024 with an automated reactor being developed by Sierra Space through the Carbothermal Oxygen Production Reactor (COPR) Tipping Point project



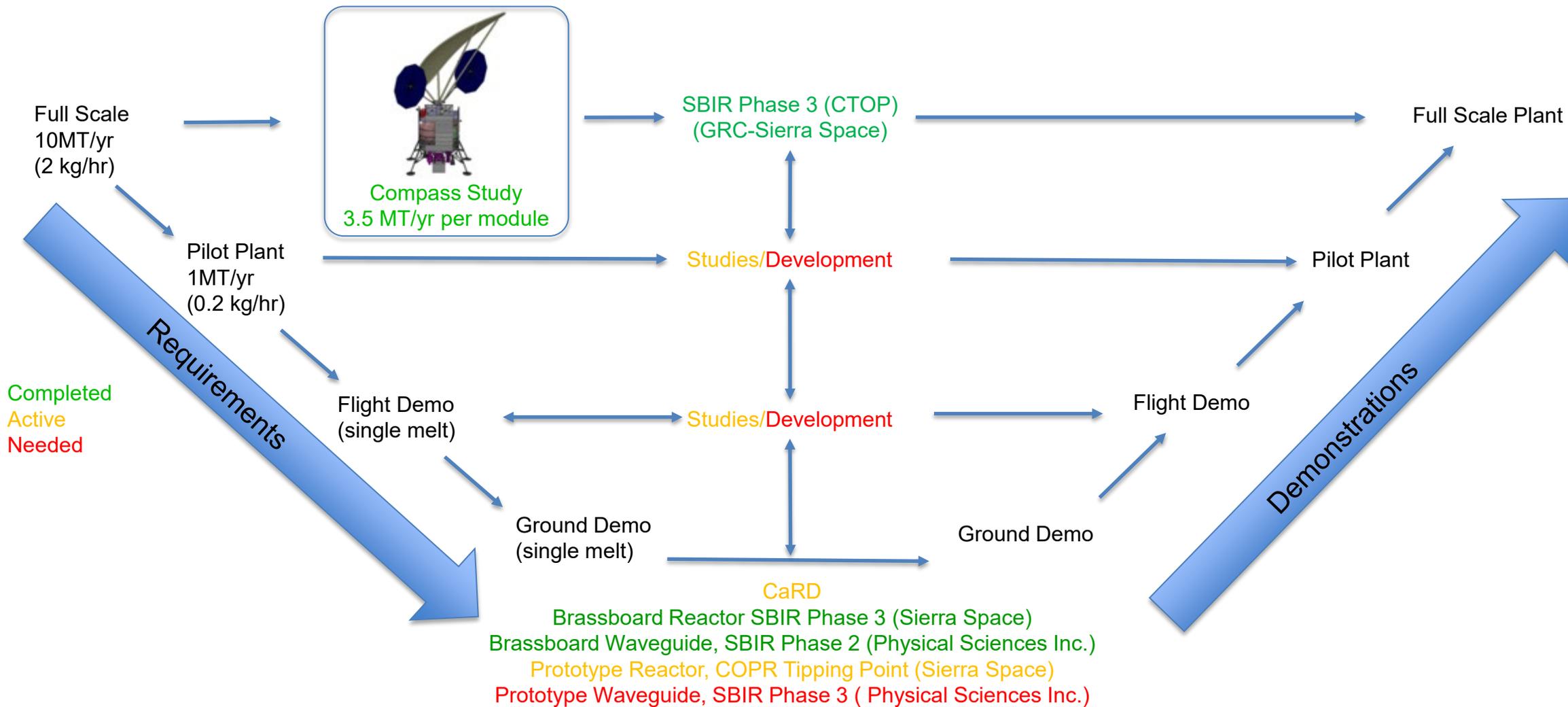


CaRD Prototype



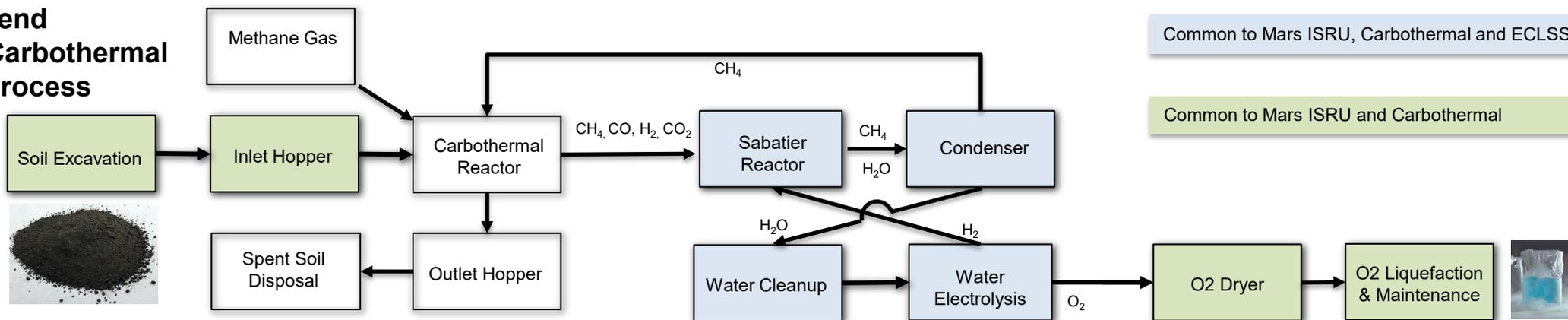


Long Term Overview

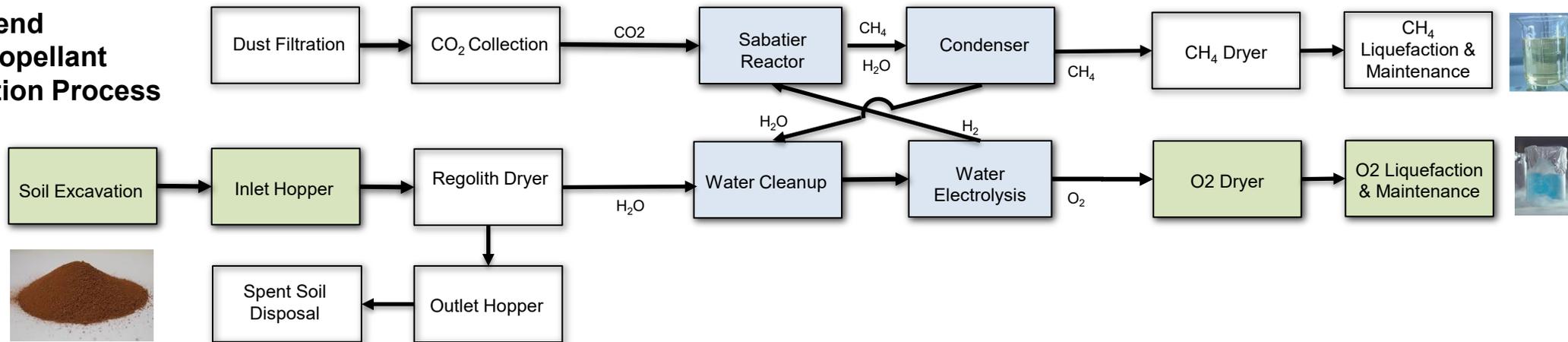


Mars and ECLSS Commonality

End-to-end Lunar Carbothermal O₂FR Process



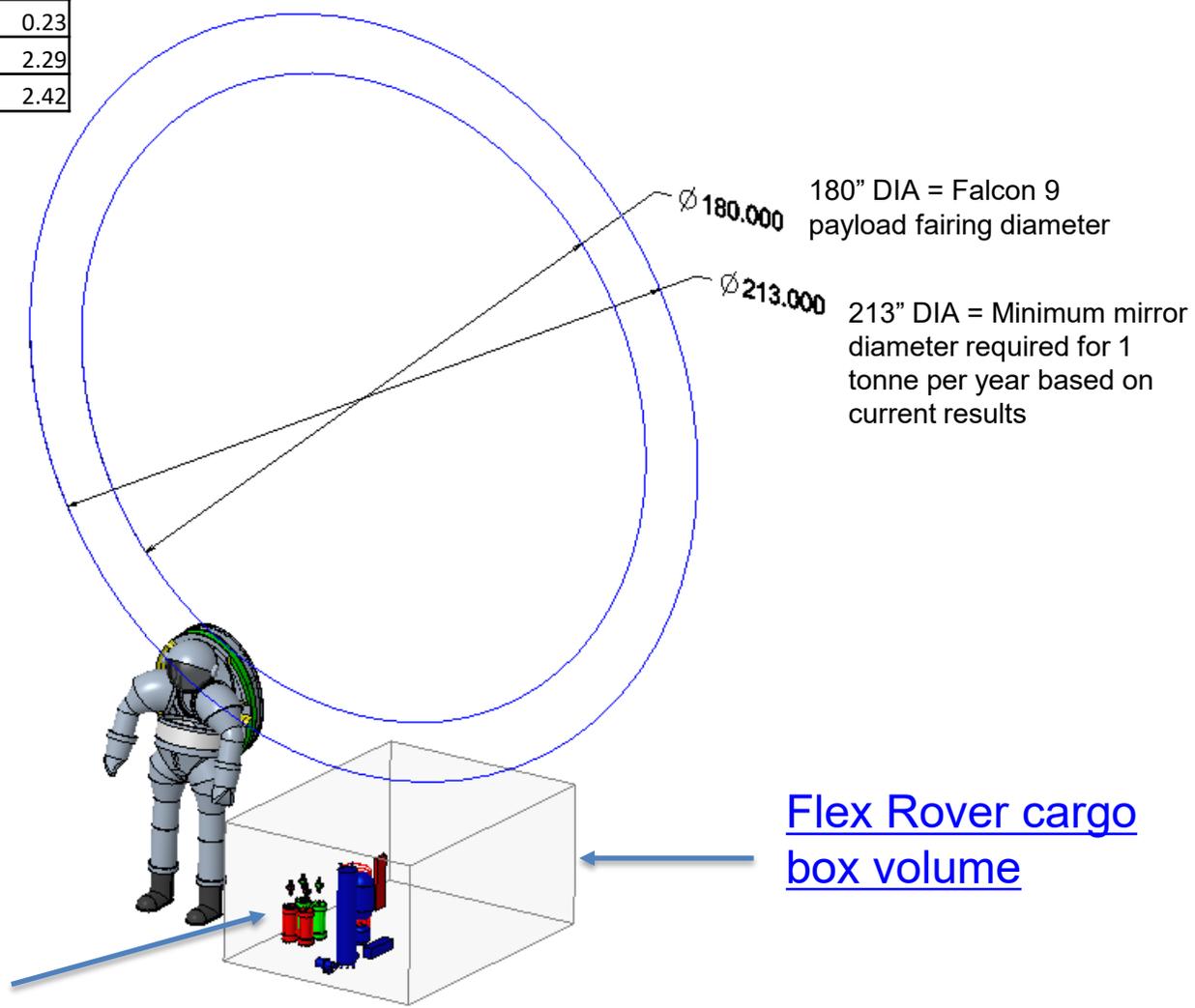
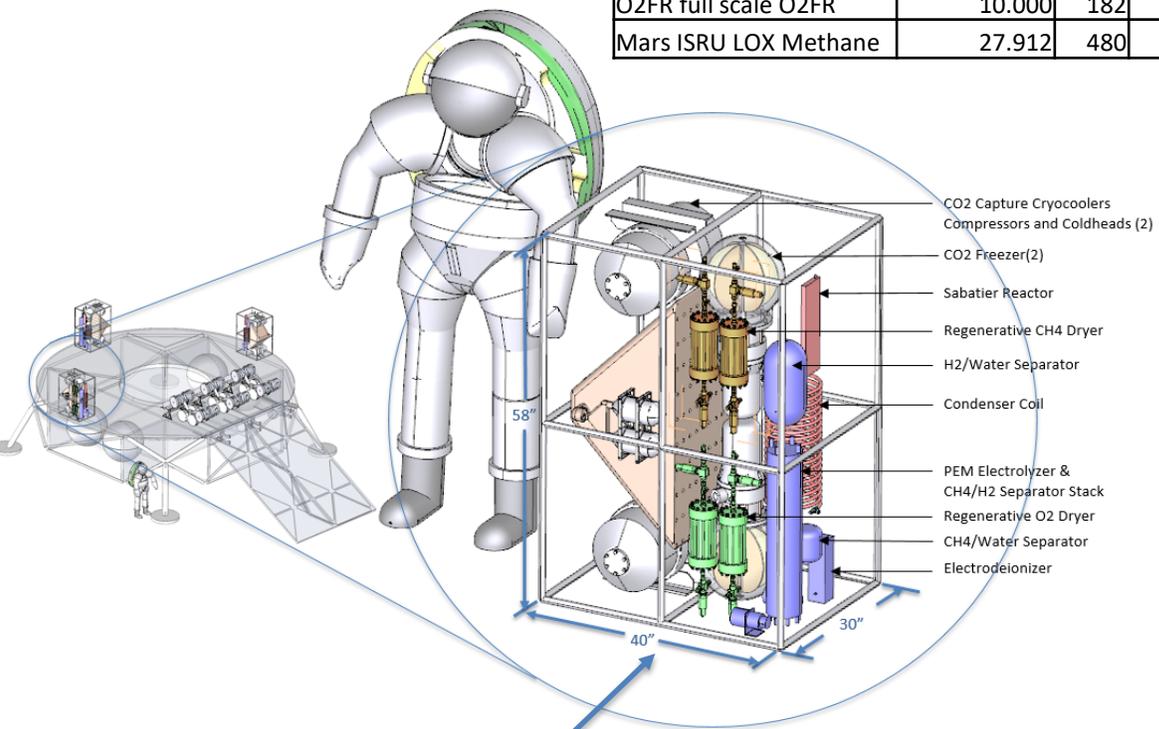
End-to-end Mars Propellant Production Process





Scalability & Modularity

	Tonnes of O ₂	days	kg/day	kg/hr
O2FR pilot plant	1.000	182	5.49	0.23
O2FR full scale O2FR	10.000	182	54.95	2.29
Mars ISRU LOX Methane	27.912	480	58.15	2.42



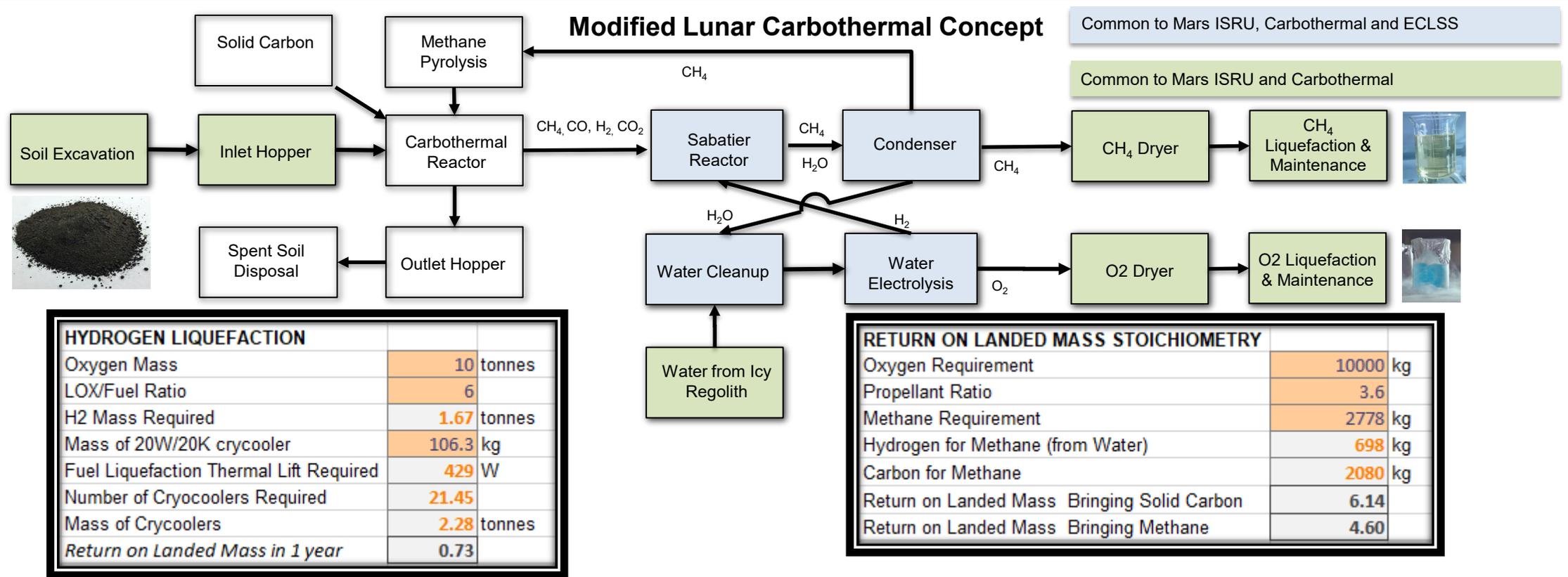
Notional packaging of Mars ISRU module sized for 40% of Mars LOX/Methane. 3 modules x 40% = 120% of full scale

Reference: [Kleinhenz, J. E., & Paz, A. \(2017\). An ISRU propellant production system for a fully fueled Mars Ascent Vehicle. In 10th Symposium on Space Resource Utilization \(p. 0423\).](#)

Components common to Mars ISRU module would easily fit inside of a flex rover cargo box



Mars Commonality – Expanded to Lunar LOX/Methane



- Producing both LOX and LCH4 on the moon would be the best “Moon to Mars” architecture for propellant production and can be accomplished if solid carbon is combined with hydrogen sourced from lunar water
- Current hydrogen liquefaction cryocooler technology will have to operate for over a year in order to see a return on landed mass (assuming 183 days of sunlight per year)¹
- The use of solid carbon to drive a carbothermal reduction reaction has been demonstrated for terrestrial silicon production²
- Methane pyrolysis technology is being developed for terrestrial hydrogen and carbon production³

References:

1) Nugent, B. T., Grotenrath, R. J., & Johnson, W. L. (2022). 20 Watt 20 Kelvin Reverse Turbo-Brayton Cycle Cryocooler Testing and Applications.

2) Maeng, S. H., Lee, H., Park, M. S., Park, S., Jeong, J., & Kim, S. (2020). Ultrafast carbothermal reduction of silica to silicon using a CO2 laser beam. *Scientific reports*, 10(1), 21730.

3) Methane Pyrolysis for Hydrogen-Opportunities and Challenges