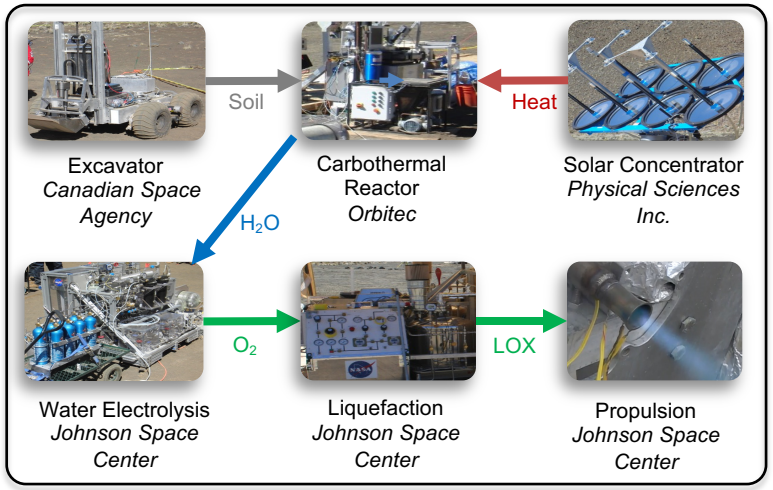
Carbothermal Reduction Demonstration (CaRD) Project Status 2023

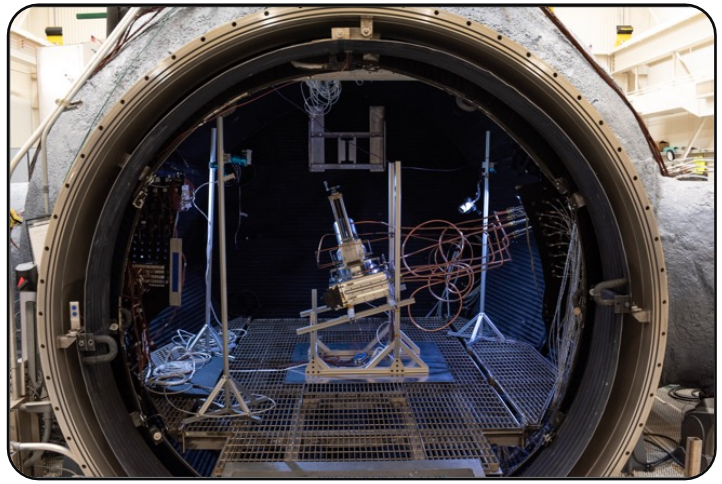
CaRD project scope includes all of the subsystems necessary to determine the performance of the carbothermal reduction process ($SiO_2 + 2C \rightarrow Si + 2CO$) on the lunar surface. Downstream components that convert CO into oxygen gas can be implemented at a larger scale once the yield is known.

Past



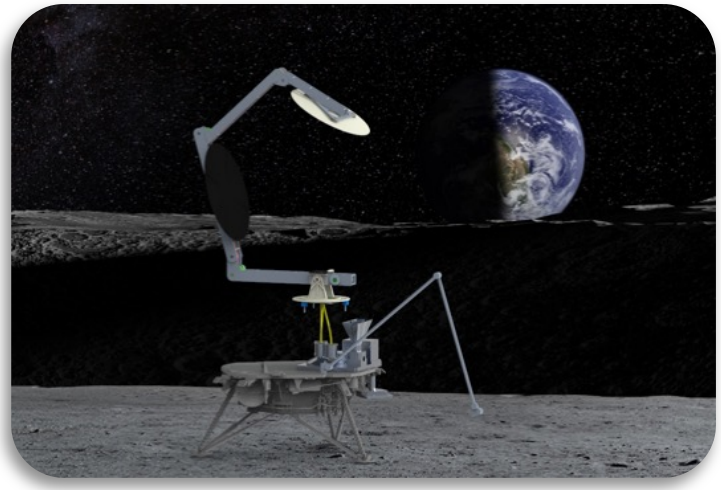
"Dust to Thrust" Demonstration 2010

Present

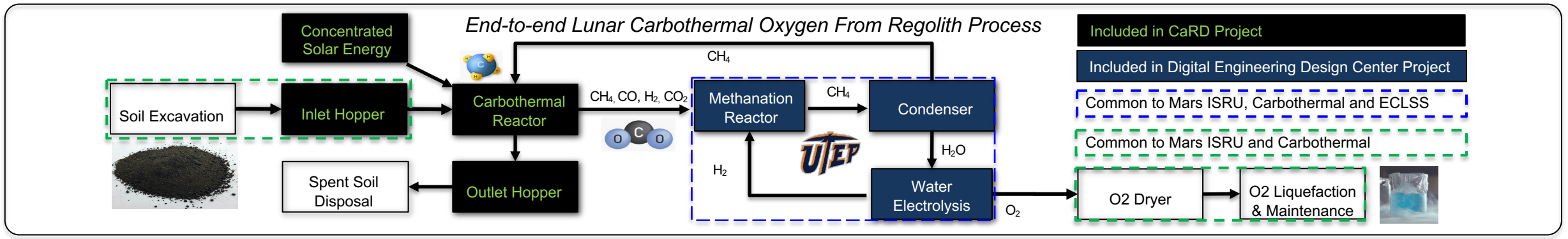


Carbothermal Reactor Developed by Sierra Space Inside 15ft Dirty Thermal Vacuum Chamber at JSC

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

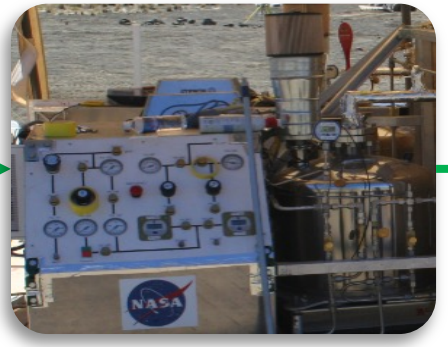
Solar Concentrator
Physical Sciences Inc.

H_2O

Heat

Water Electrolysis
Johnson Space Center

O_2

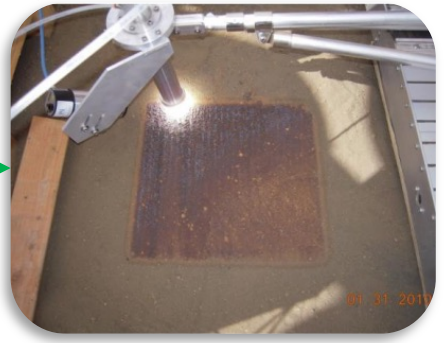


Liquefaction
Johnson Space Center

LOX

Propulsion
Johnson Space Center

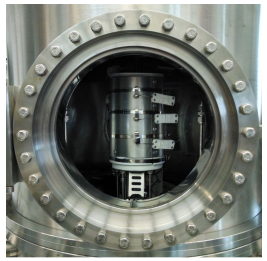
Plume

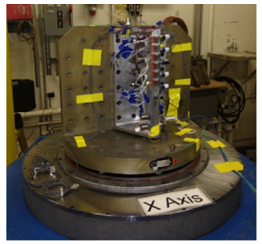


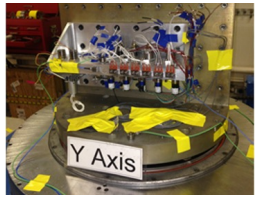
Sintered Pad
Physical Sciences Inc.
NORCAT

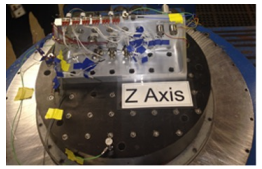
Example of TRL 4 to 6 for the Moon

Component TVAC | Component Vibration | Component Dust | Subsystem Vibration | Integrated Vibration | Thermal Cycles | Component Thermal Vacuum | Integrated Thermal Vacuum | Torque Margin/Dust

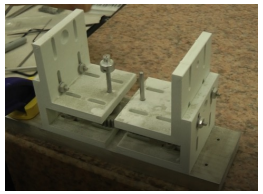
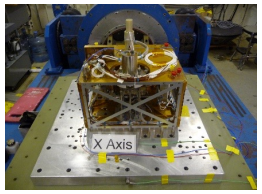


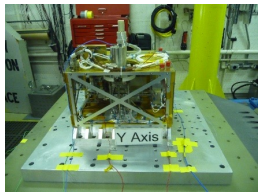


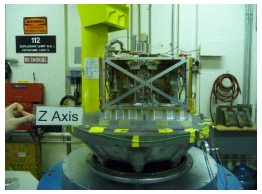


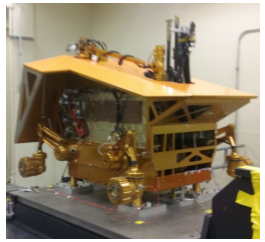
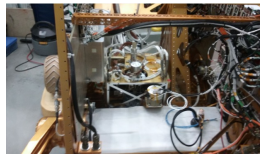


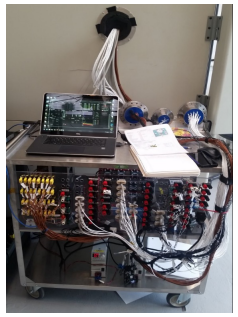
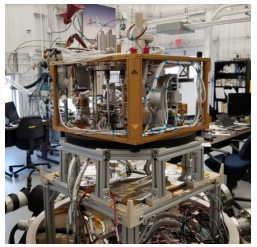


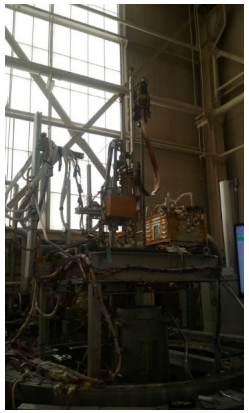







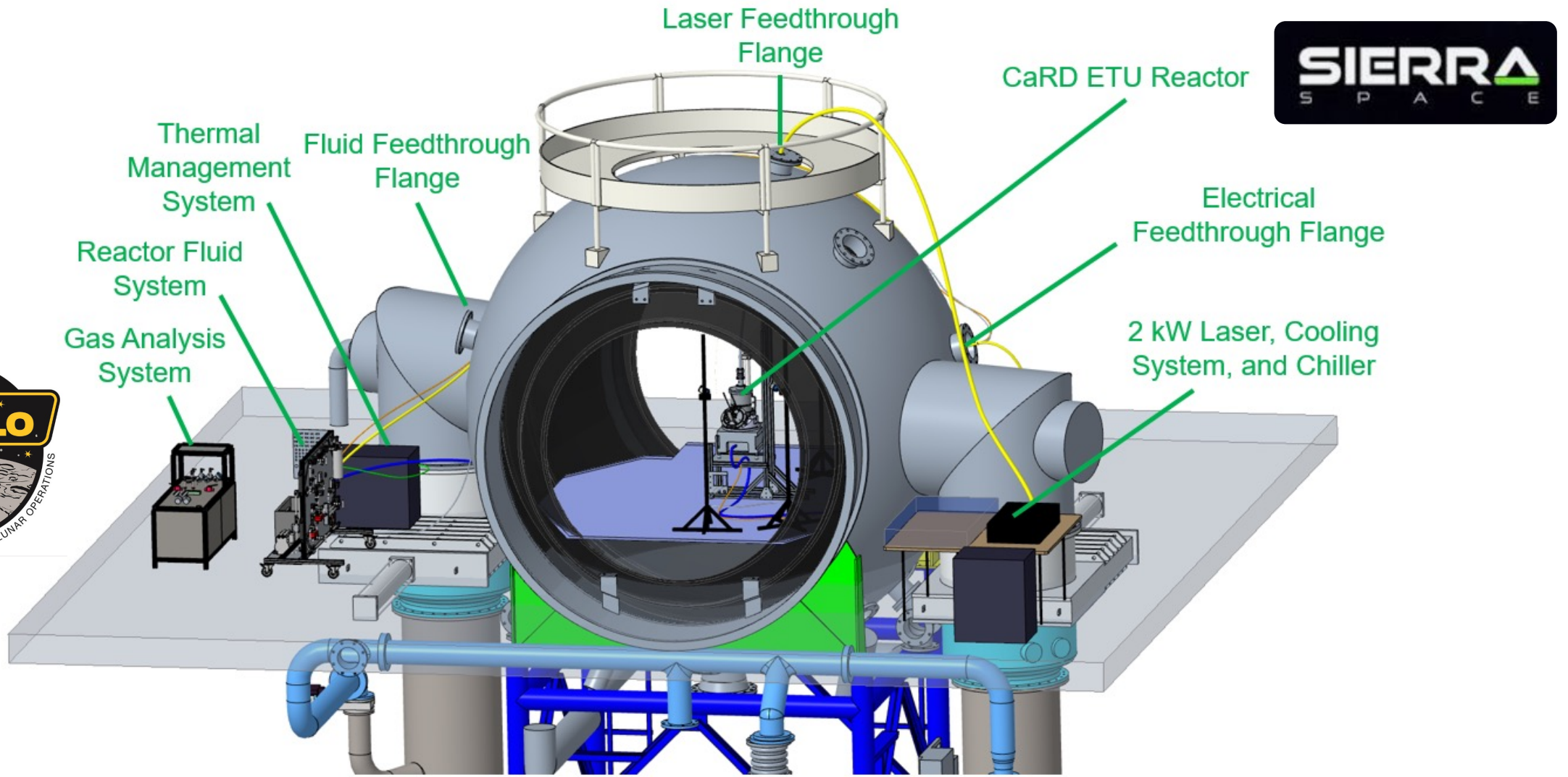



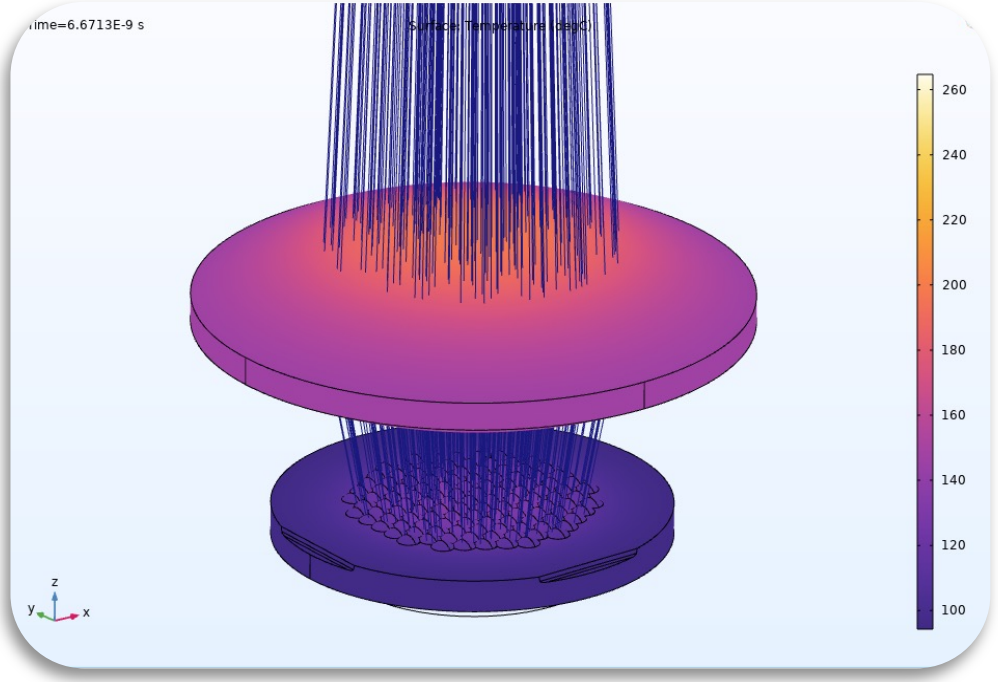



[Environmental Testing of the OVEN]

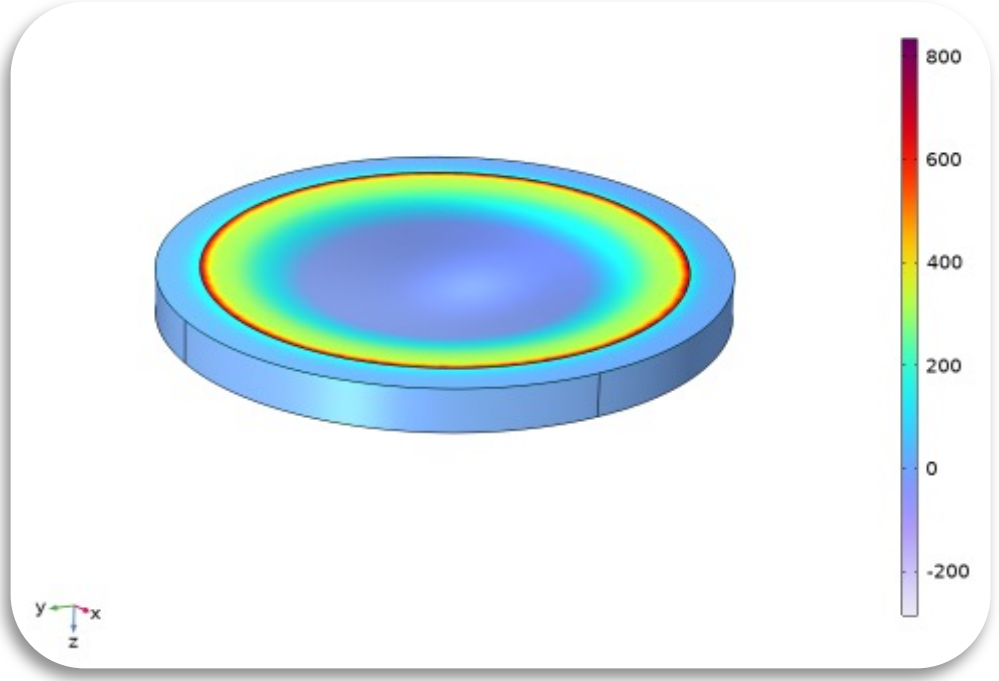
CaRD Environmental Test Unit (Brassboard)



COMSOL Multiphysics Analysis

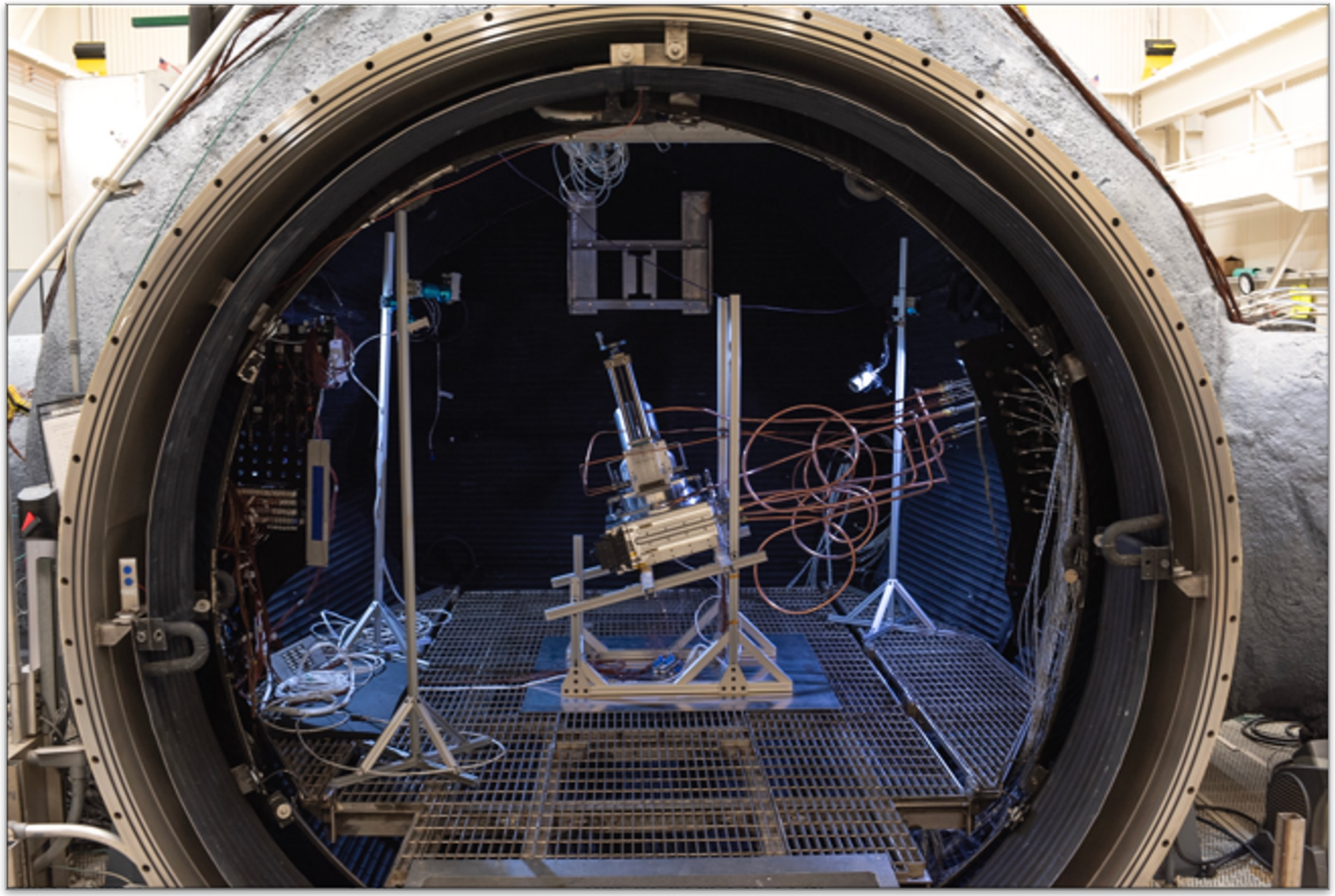


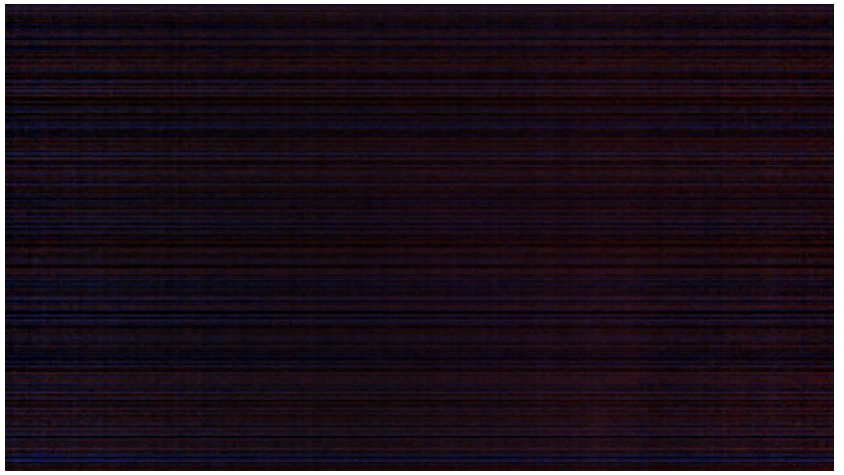
Lens Heating Analysis



Lens Stress Analysis

CaRD Brassboard Test Results

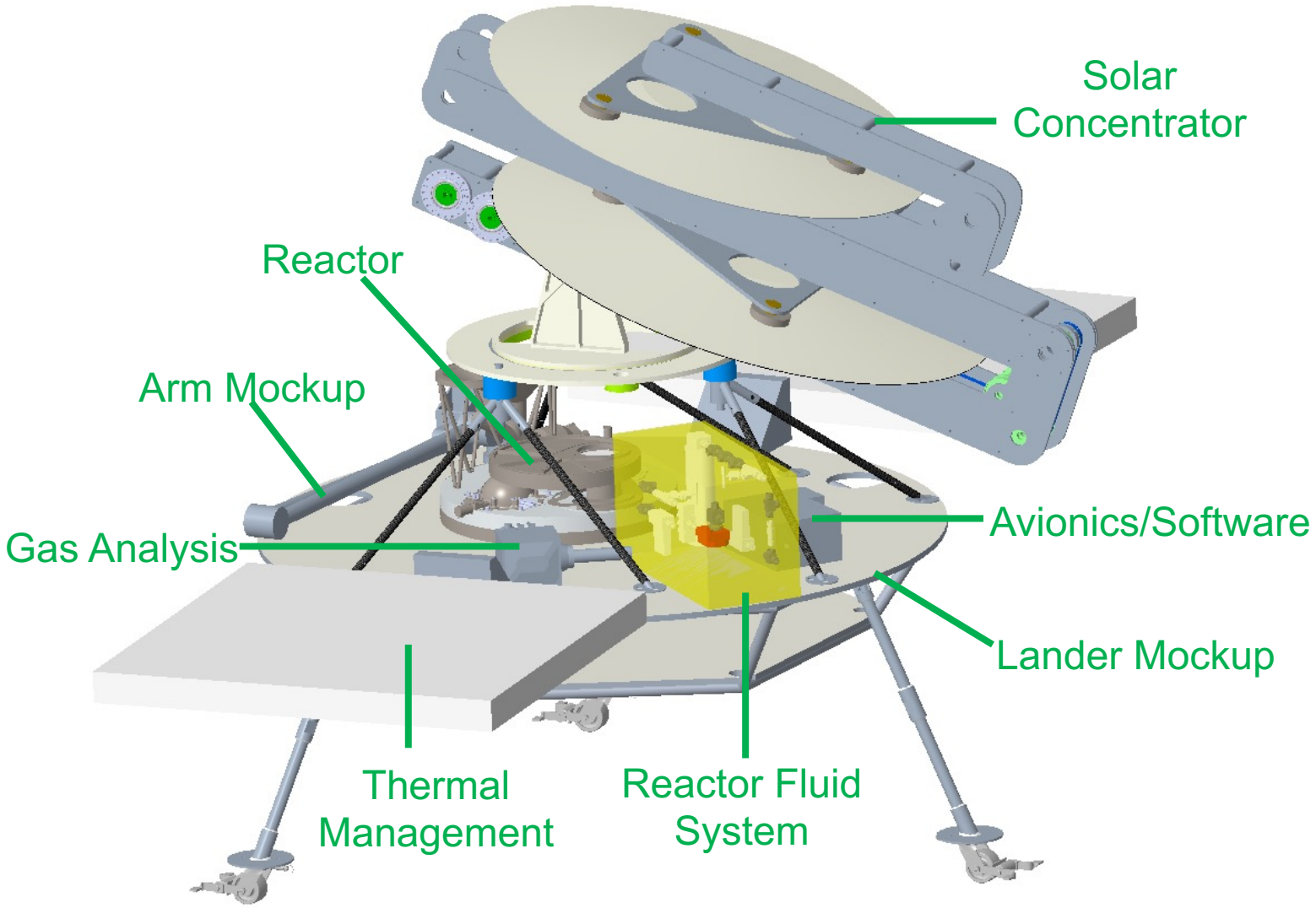


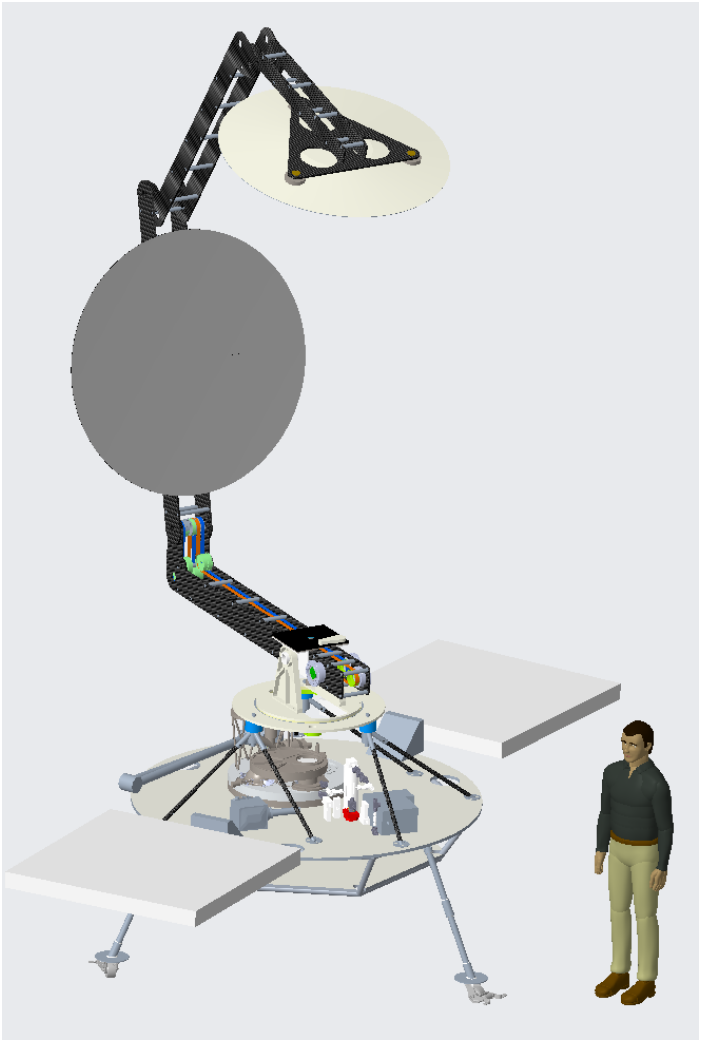


Test Number	grams oxygen extracted/ kWh thermal
CaRD Ambient	13.42
CaRD Vacuum 1	11.53
CaRD Vacuum 2	15.79
CaRD Vacuum 3	10.77

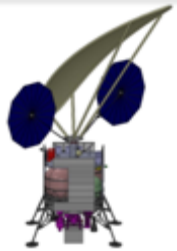
This test will be repeated in 2024 with an automated reactor being developed by Sierra Space through the Carbothermal Oxygen Production Reactor (COPR) Tipping Point project

CaRD Prototype





Long Term Overview



Compass Study
3.5 MT/yr per module

Full Scale
10MT/yr
(2 kg/hr)

Pilot Plant
1MT/yr
(0.2 kg/hr)

Flight Demo
(single melt)

Ground Demo
(single melt)

SBIR Phase 3 (CTOP)
(GRC-Sierra Space)

Studies/Development

Studies/Development

Full Scale Plant

Pilot Plant

Flight Demo

Ground Demo

Requirements

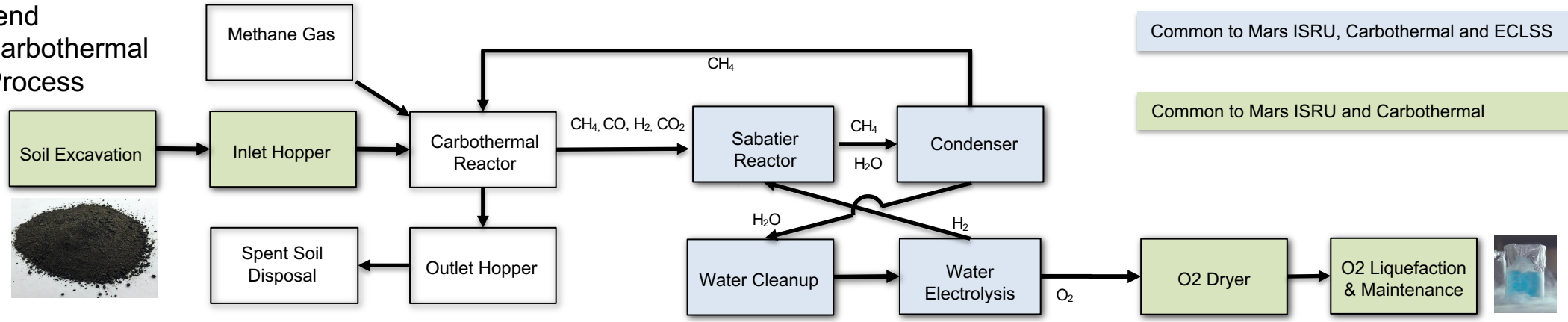
Demonstrations

Completed
Active
Needed

CaRD
Brassboard Reactor SBIR Phase 3 (Sierra Space)
Brassboard Waveguide, SBIR Phase 2 (Physical Sciences Inc.)
Prototype Reactor, COPR Tipping Point (Sierra Space)
Prototype Waveguide, SBIR Phase 3 (Physical Sciences Inc.)

Mars and ECLSS Commonality

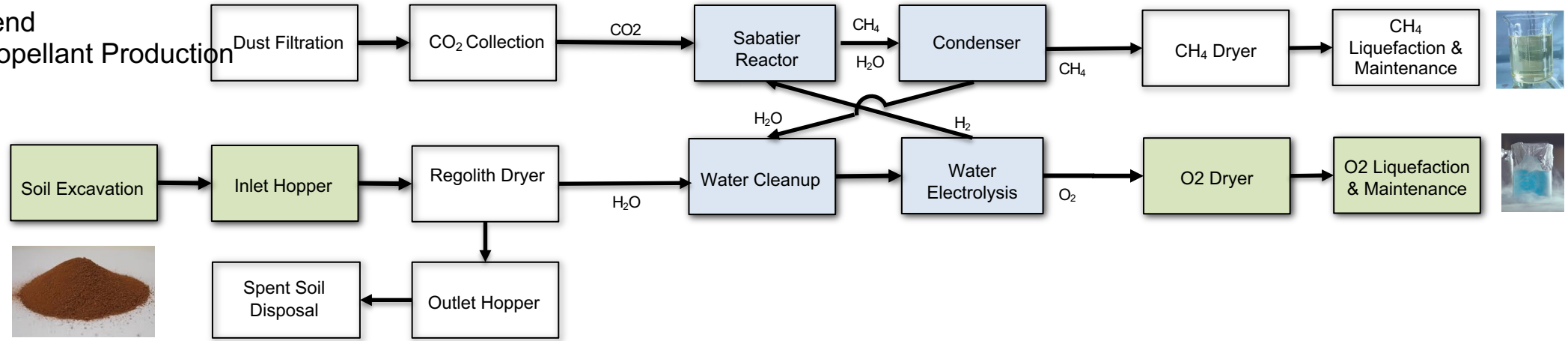
End-to-end Lunar Carbothermal O2FR Process



Common to Mars ISRU, Carbothermal and ECLSS

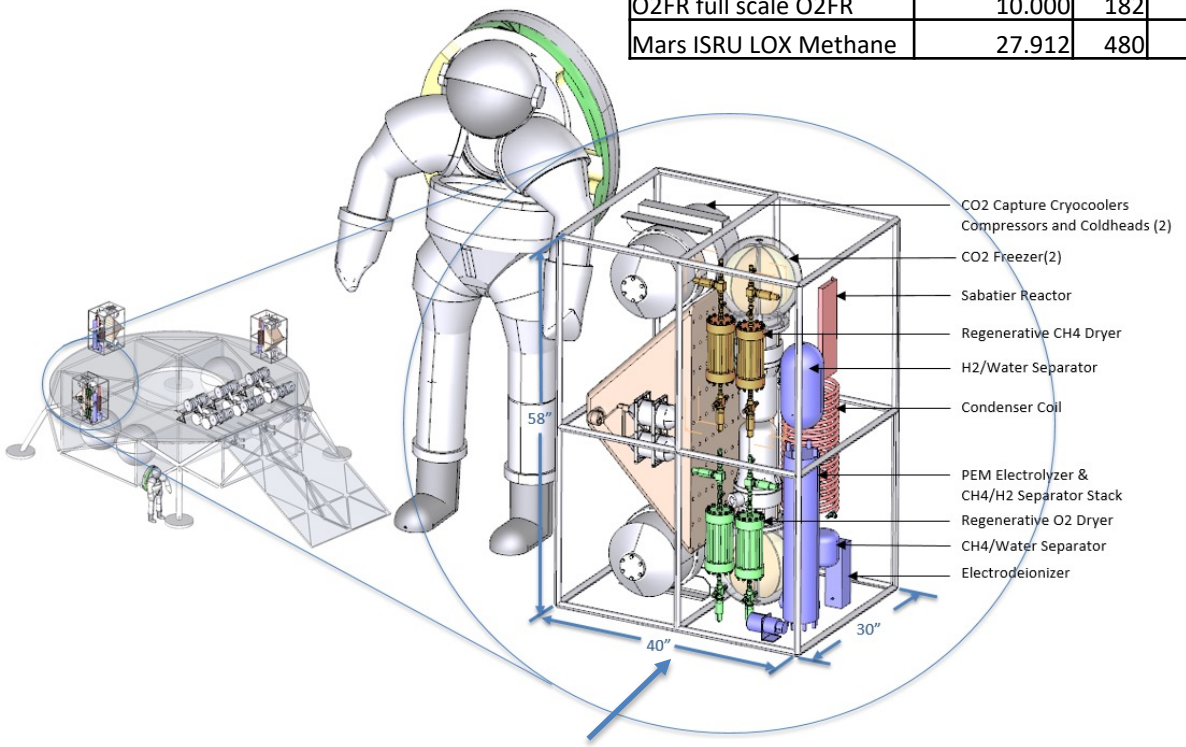
Common to Mars ISRU and Carbothermal

End-to-end Mars Propellant Production Process



Scalability & Modularity

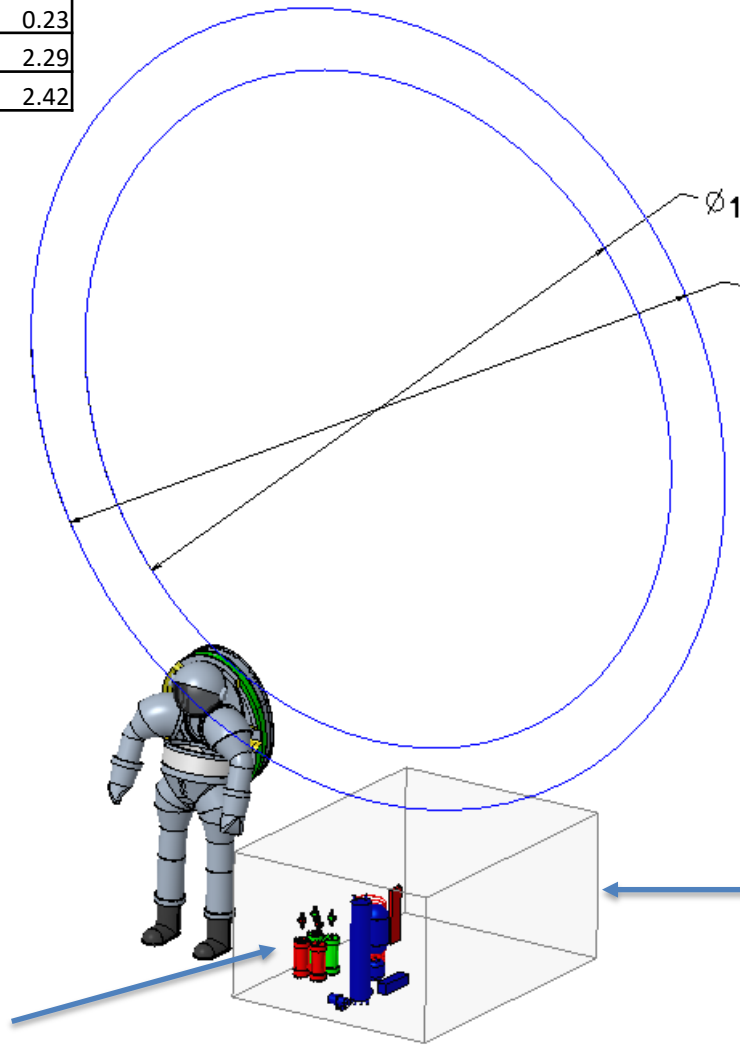
	Tonnes of O_2	days	kg/day	kg/hr
O2FR pilot plant	1.000	182	5.49	0.23
O2FR full scale O2FR	10.000	182	54.95	2.29
Mars ISRU LOX Methane	27.912	480	58.15	2.42



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

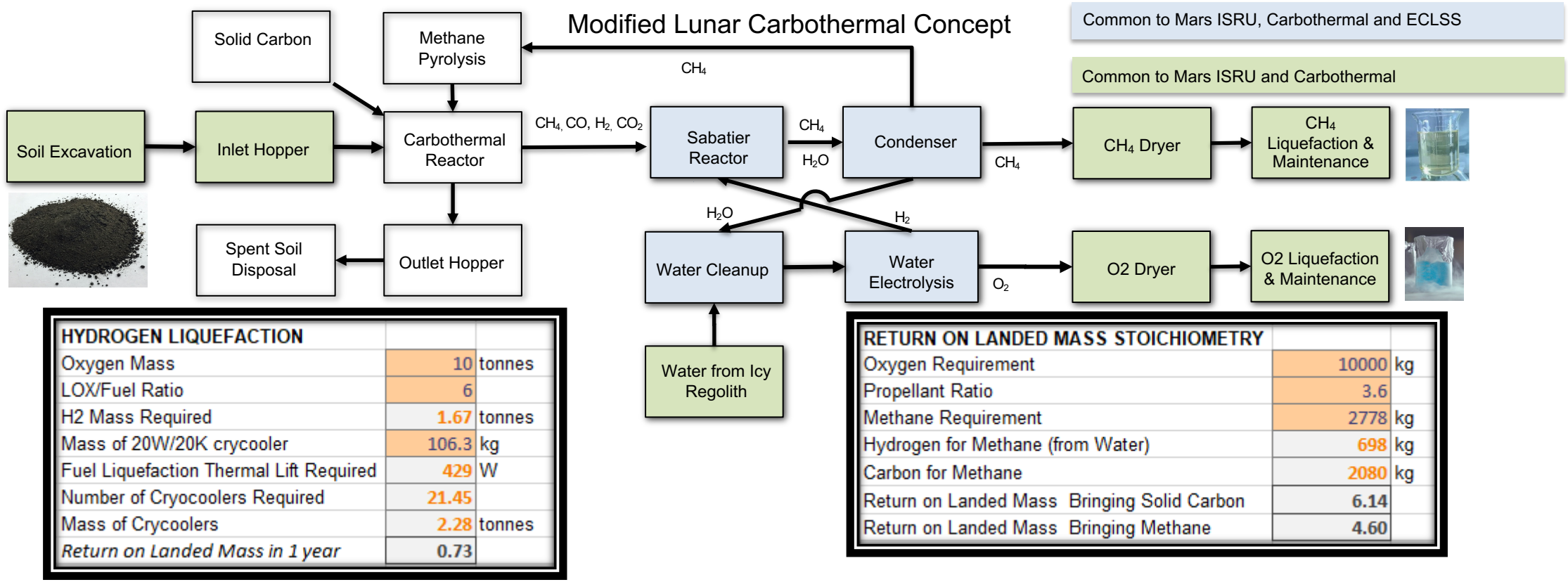


180" DIA = Falcon 9 payload fairing diameter

213" DIA = Minimum mirror diameter required for 1 tonne per year based on current results

Flex Rover cargo box volume

Mars Commonality – Expanded to Lunar LOX/Methane



HYDROGEN LIQUEFACTION		
Oxygen Mass	10	tonnes
LOX/Fuel Ratio	6	
H2 Mass Required	1.67	tonnes
Mass of 20W/20K crycooler	106.3	kg
Fuel Liquefaction Thermal Lift Required	429	W
Number of Cryocoolers Required	21.45	
Mass of Crycoolers	2.28	tonnes
Return on Landed Mass in 1 year	0.73	

RETURN ON LANDED MASS STOICHIOMETRY		
Oxygen Requirement	10000	kg
Propellant Ratio	3.6	
Methane Requirement	2778	kg
Hydrogen for Methane (from Water)	698	kg
Carbon for Methane	2080	kg
Return on Landed Mass Bringing Solid Carbon	6.14	
Return on Landed Mass Bringing Methane	4.60	

- 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 crycooler 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 production[2]
- Methane pyrolysis technology is being developed for terrestrial hydrogen and carbon production[3]

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