National Aeronautics and
Space Administration

Technology Assessment for Producing Propellant from Lunar Water

2023 NASA Exploration Science Forum

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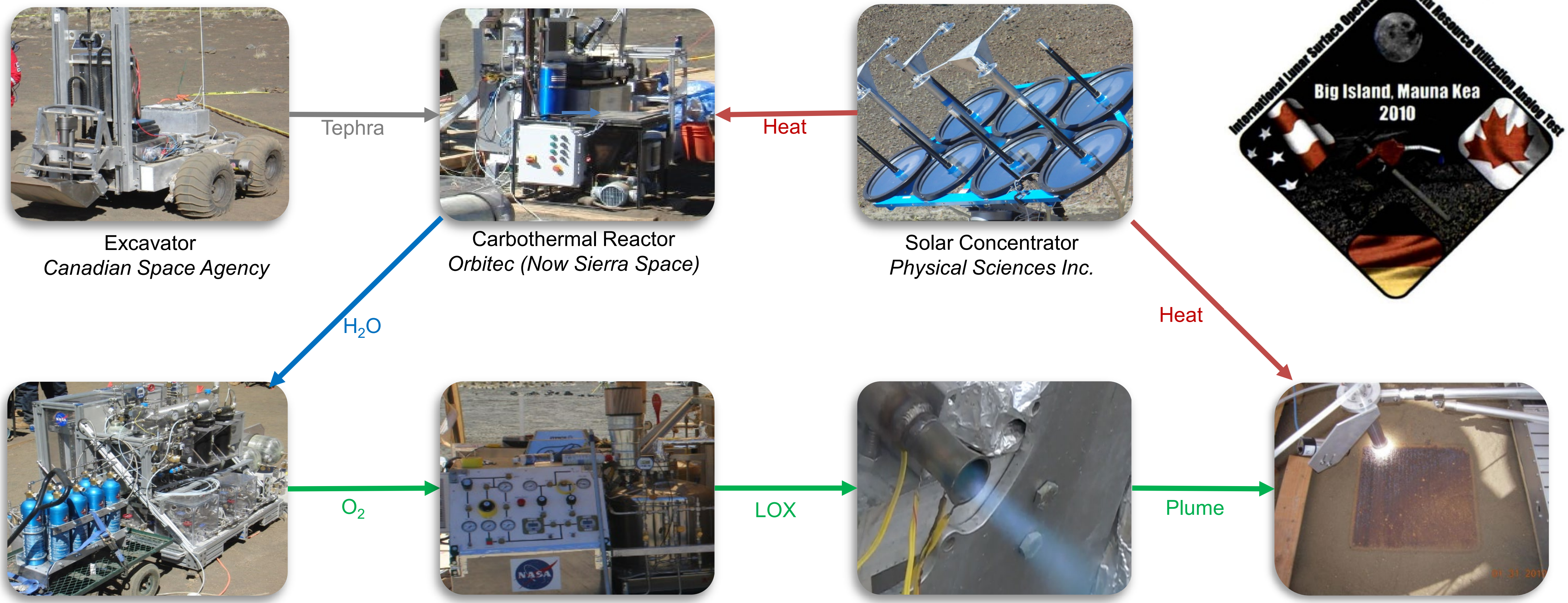
“Dust to Thrust” 2010



Excavator
Canadian Space Agency

Tephra

Carbothermal Reactor
Orbitec (Now Sierra Space)

Heat

Solar Concentrator
Physical Sciences Inc.

International Lunar Surface Operations • In-Situ Resource Utilization Analog Test
Big Island, Mauna Kea
2010

H_2O

Heat

Water Electrolysis
Johnson Space Center

O_2

Liquefaction
Johnson Space Center

LOX

Propulsion
Johnson Space Center

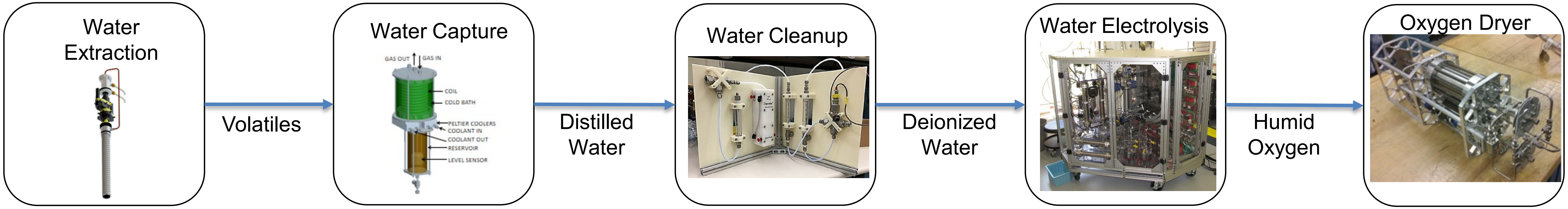
Plume

Sintered Pad
Physical Sciences Inc.
NORCAT

Water purification and gas drying steps used consumables in this demonstration

RESOURCE and Parallel Projects

RESOURCE is a SSERVI CAN 3 project lead by Dr. Jennifer Heldmann of NASA Ames Research Center. Proposed RESOURCE scope included a task lead by JSC to combine existing subsystems into an integrated system to demonstrate the end-to-end production of pure dry oxygen from an icy regolith mixture without using consumables.

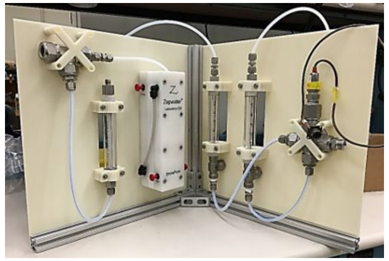


Water Extraction → Volatiles → Water Capture → Distilled Water → Water Cleanup → Deionized Water → Water Electrolysis → Humid Oxygen → Oxygen Dryer

Project Name	Technology					Rate	Lead	Program	FY19				FY20				FY21				FY22				FY23				FY24			
	Water Extraction	Water Capture	Water Cleanup	Water Electrolysis	Oxygen Drying	kg O2/hr																										
Resource Exploration and Science of OUR Cosmic Environment (RESOURCE)	🟦	🟦	🟦	🟦	🟦		NASA	SSERVI					🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Adv Thermal Mining Approach for Extraction, Transportation, and Condensation of Lunar Ice	🟦	🟦				0.002	UTEP	LuSTR											🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩						
Fundamental Regolith Properties, Handling and water Capture (FLEET)	🟦	🟦				0.44	NASA	GCD									🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Thermal Management System for Lunar Ice Miners – Advanced Cooling Technologies SBIR	🟦	🟦				0.36	Advanced Cooling Technologies	SBIR													🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩				
ISRU Collector of Ice in a Cold Lunar Environment (ICICLE)		🟦				0.1	Paragon Space Development Corp	SBIR													🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩				
ISRU water purification and Hydrogen/Oxygen Production (IHOP)			🟦	🟦		1.19	Paragon Space Development Corp	BAA					🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩					
OxEON TP (Water Only)			🟦	🟦	🟦	0.875	OxEON	Tipping Point						🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩							
OxEON BAA (Mars Co-electrolysis & Methanation)			🟦	🟦	🟦	0.788	OxEON	BAA		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩							

Multiple new efforts with related technologies and parallel schedules include the development of hardware that will become available to the RESOURCE team at JSC.

Water Purification and Deionization



EDI test stand at JSC

Typical PEM electrolyzer feedwater requirements (deionized water)

EDI performance
(0.84 at inlet, 13.25 at outlet)

Distilled water

Water mixed with LHT simulant, distilled and filtered to <0.5 microns

Tap water

Conductivity (microsiemens/cm^2)	Resistivity (Mega Ohm/cm^2)
0.056	18
0.063	16
0.071	14
0.083	12
0.100	10
0.133	7.5
0.200	5
0.500	2
1.000	1
1.333	0.75
2.000	0.5
4.000	0.25
10.000	0.1
20.000	0.05
40.000	0.25
100.000	0.01
200.000	0.005
500.000	0.002
1000.000	0.001
2000.000	0.0005
5000.000	0.0002
10000.000	0.0001

Anticipated water from IHOP (WIPE 2.0)

Water from IHOP (WIPE 1.0) [2]

Mixed volatile stream (CO, H_2, H_2S, NH_3, SO_2, CH_3OH, CH_4, CO_2) after freeze distillation (ICICLE) [1]

Water/LHS mixture

Acronyms:
EDI: Electrodeionization
IHOP: ISRU water purification and Hydrogen/Oxygen Production
ICICLE: ISRU Collector of Ice in a Cold Environment
LHS: Lunar Highlands Simulant
PEM: Proton Exchange Membrane
WIPE: Water, ISRU-derived, Purification Equipment

Electrolysis Comparison

Proton Exchange Membrane

Pros

- Flight heritage (ISS)
- Efficient gas compression
- High operating pressures
- Relatively low operating temperature (~30 ^{o} C)

Cons

- Liquid water must be kept above 0^{o} C during lunar night
- Feedwater must be deionized
- Radiator is required to reject waste heat
- Oxygen dryer is required

Solid Oxide Electrolyzer

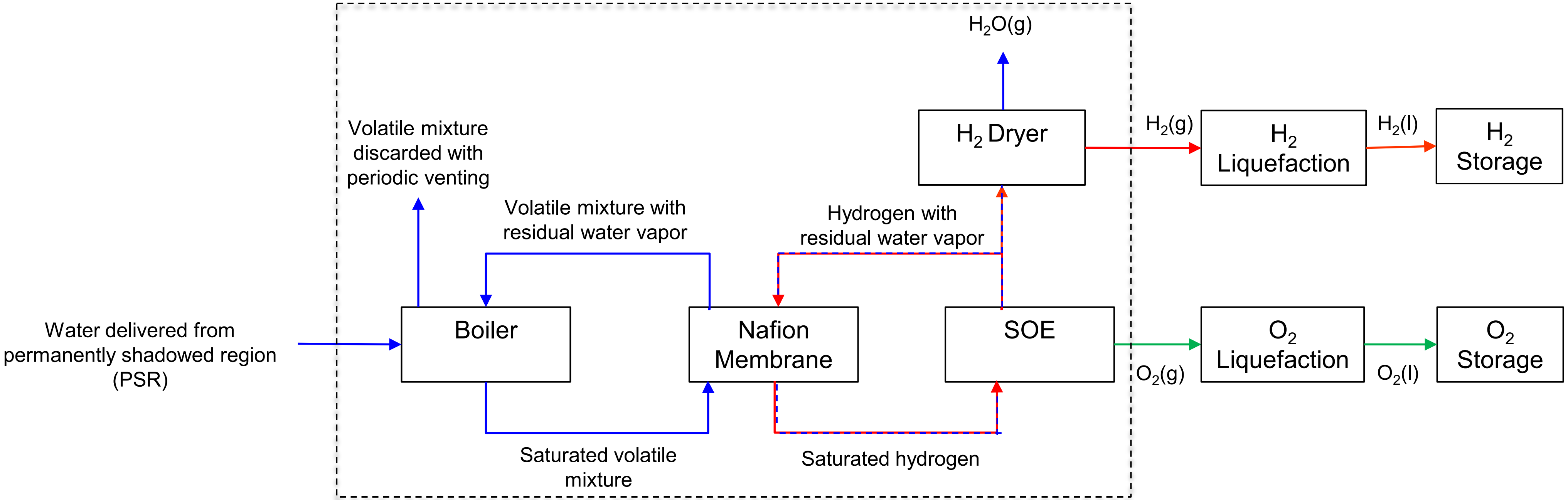
Pros

- Does not require deionized feedwater
- Oxygen is dry and pure
- Flight heritage (MOXIE)
- Should be able to survive lunar night with minimal power
- Waste heat can be used to keep stack at operating temperature

Cons

- Low operating pressure (< 30 psia)
- High operating temperature (~800 ^{o} C)
- Output gases are hot and may require more liquefaction power and/or more radiator mass depending on heat recuperation efficiency
- Water will need to be vaporized twice, once for extraction and again for electrolysis

Propellant from Lunar Water Concept



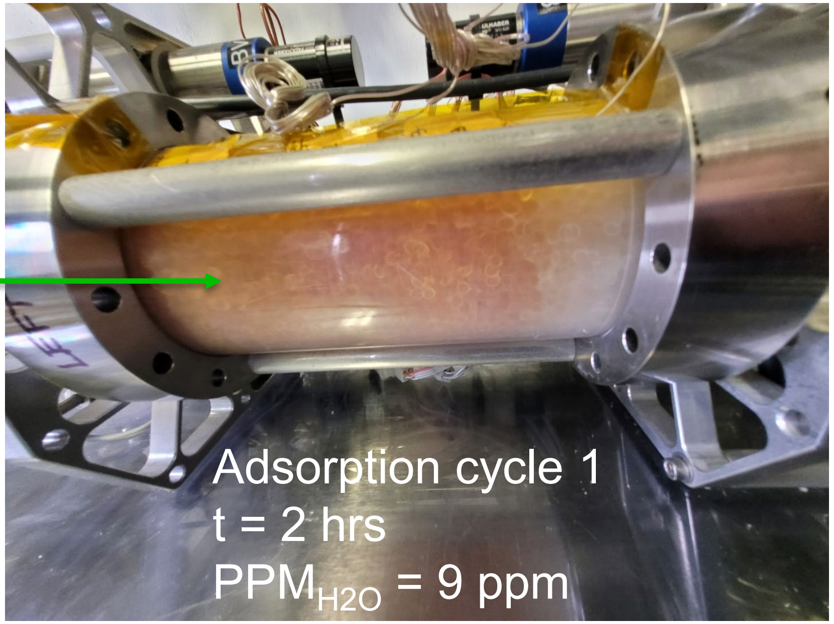
Subsystems identified for RESOURCE demonstration pending hardware acquisition

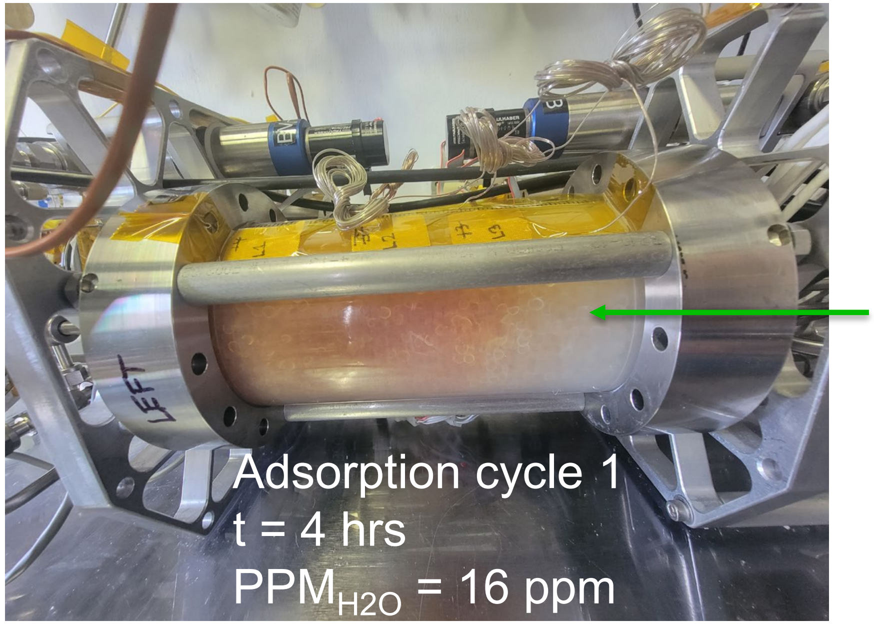
Simplified flow diagram for a lunar propellant production plant that uses no consumables

Gas Drying

Propellant	Water, ppmV, max	Source
Oxygen	26.3	MIL-PRF-25508H, Grade B
Hydrogen	9	MIL-PRF-27201E
Methane	1	MIL-PRF-32207, Grade A

Indicating desiccant is orange when it contains < 6% water


Adsorption cycle 1
t = 2 hrs
PPM_{H2O} = 9 ppm


Adsorption cycle 1
t = 4 hrs
PPM_{H2O} = 16 ppm

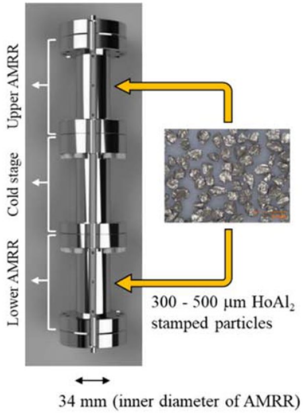
Indicating desiccant is white when it contains > 6% water but will continue to adsorb until saturated

1st test with regenerative gas drying system developed at Johnson Space Center

Hydrogen Liquefaction

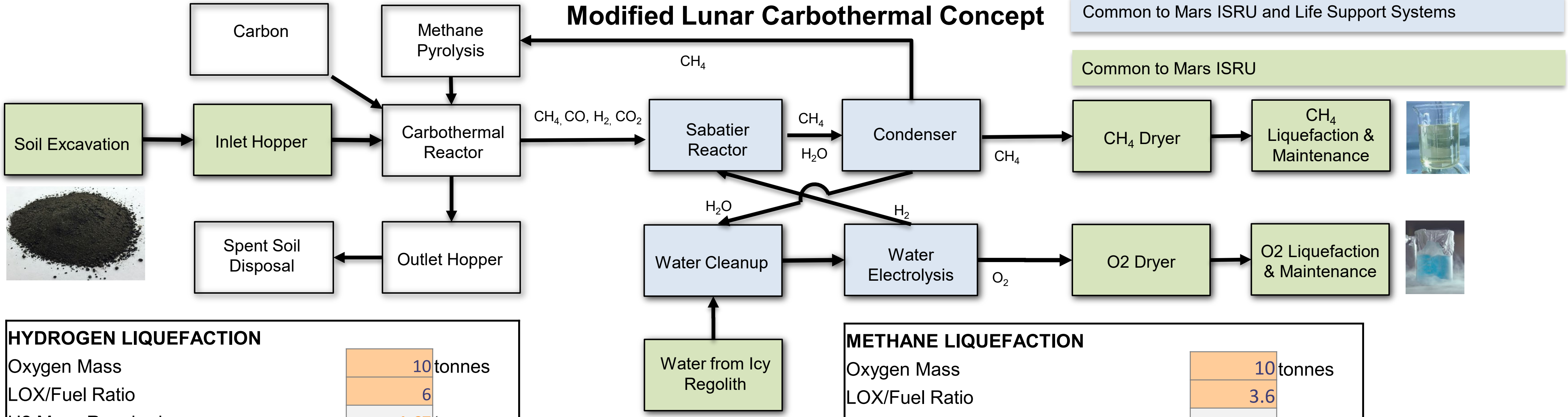
- Magnetocaloric and elastocaloric refrigeration systems exhibit potential for lunar cryogenic fluid management
- Active Magnetic Regenerative Refrigeration (AMRR) systems leverage magnetocaloric materials, and their subsequent temperature changes when exposed to magnetic fields, to transport thermal energy
  - Rare earth element dependence, high magnetic field requirements, and poor heat transfer limit current refrigerants
  - Superparamagnetic high entropy alloys show promise in improving structural and functional performance of the materials
- Elastocaloric Cooling (eC) systems leverage shape memory alloys, and their subsequent temperature changes when exposed to stresses, to transport thermal energy
  - Fatigue and temperature dependence limit current alloys
  - Cryogenic superelastic alloys demonstrate increased capability at low temperature, and longer service life
- Adoption of caloric refrigeration systems is largely limited by the existence and/or availability of capable refrigerants, cost, mass, and technological readiness
- Advancements in ferroic materials research (e.g. novel high entropy alloy compositions) stand to increase the viability of these systems by improving refrigerant performance and reducing both mass and cost

	Vapor Compression [3]	Magnetocaloric[4-5]	Elastocaloric[6-8]
Mass Including Radiator (kg)	2340	TBD	TBD
Power (kW)	20.81	1.36	7.5
Operating Temperature (K)	12-298	0.007-298	4.2-298
Heat Lift @ 20K (W)	20	3	0.5
Cycle Type	Turbo-Brayton	AMRR (Sterling)	eC (Brayton)
2nd Law Efficiency (%)	~25	50+	50+



Lunar LOX/Methane Concept

Modified Lunar Carbothermal Concept


Common to Mars ISRU and Life Support Systems

Common to Mars ISRU

Soil Excavation

Inlet Hopper

Carbon

Methane Pyrolysis

Carbothermal Reactor

Outlet Hopper

Spent Soil Disposal

CH_4, CO, H_2, CO_2

Sabatier Reactor

CH_4

H_2O

Condenser

CH_4

CH_4

CH_4 Dryer

CH_4 Liquefaction & Maintenance

H_2O

H_2

Water Cleanup

Water Electrolysis

O_2

O2 Dryer

O2 Liquefaction & Maintenance

Water from Icy Regolith

HYDROGEN LIQUEFACTION		
Oxygen Mass	10	tonnes
LOX/Fuel Ratio	6	
H2 Mass Required	**1.67**	tonnes
Carbon Mass Required (tonnes)	0	tonnes
Mass of 20W/20K crycooler	106.3	kg
Fuel Liquefaction Thermal Lift Required	**429**	W
Number of Cryocoolers Required	**22**	
Mass of Cryocoolers & Radiators	**2.34**	tonnes
Return on Landed Mass in 1 year	**0.71**	

METHANE LIQUEFACTION		
Oxygen Mass	10	tonnes
LOX/Fuel Ratio	3.6	
CH4 Mass Required	**2.78**	tonnes
Carbon Mass Required (tonnes)	2.08	tonnes
Mass of Cryotel GT	3.1	kg
Fuel Liquefaction Thermal Lift Required	**169**	W
Number of Cryocoolers Required	**8**	
Mass of Cryocoolers & Radiators	**0.065**	tonnes
Return on Landed Mass in 1 year	**1.30**	

- Producing both LOX and LCH4 on the moon would be a good “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)[9]
- The use of solid carbon to drive a carbothermal reduction reaction has been demonstrated for terrestrial silicon production[10]
- Methane pyrolysis technology is being developed for terrestrial hydrogen and carbon production[11]

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