2024

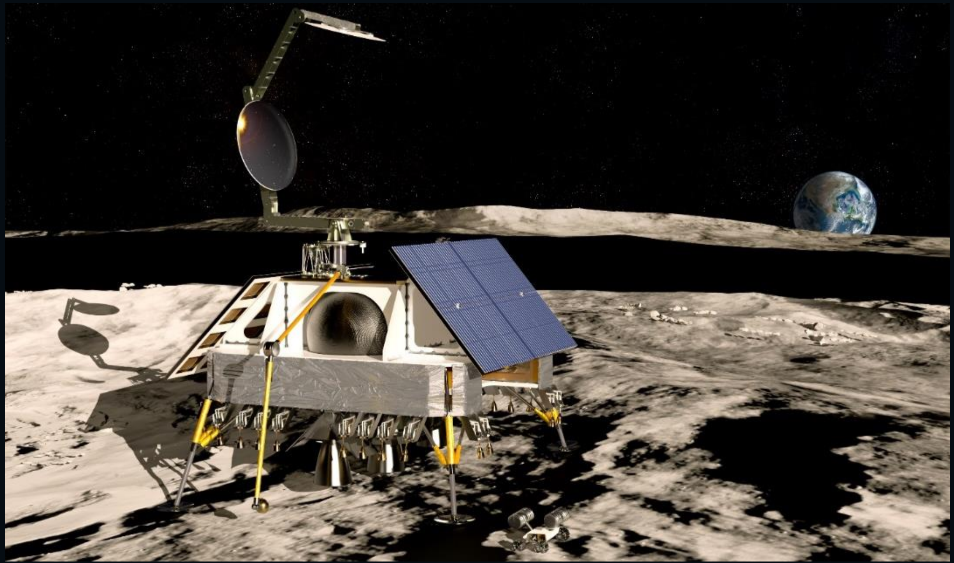
SIERRA SPACE

Lunar Oxygen Production and Energy Storage Node

This work was conducted under the DARPA 10-Year Lunar Architecture Capability Study (LunA-10) under contract HR0011-24-3-0310

Lunar Oxygen Production and Energy Storage Node

- Three Main Functions
  - Oxygen Extraction from Regolith
    - Direct Solar Power Input
  - Fuel Cell Energy Storage
    - Lunar Night Survival
  - Chemical Conversion
    - Waste Stream Recycling
    - Energy Efficient Long-Term Propellant Storage



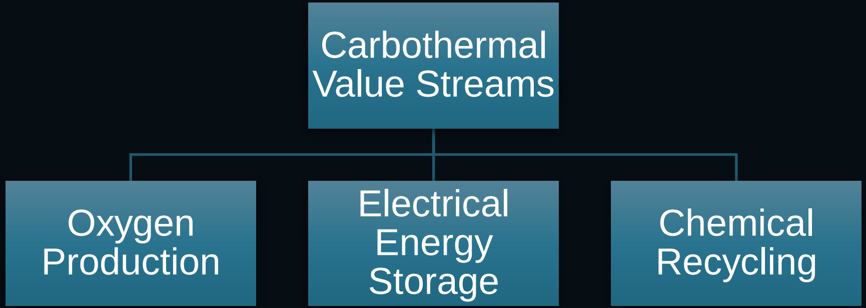
Source: Sierra Space

Artist concept of a carbothermal oxygen production plant

Carbothermal Oxygen Production Process

$MO_x(l) + xCH_4(g) \rightarrow M(l) + xCO(g) + 2xH_2(g)$	Carbothermal & Pyrolysis
$xCO(g) + 3xH_2(g) \rightarrow xH_2O(g) + xCH_4(g)$	Methanation
$xH_2O(l) \rightarrow xH_2(g) + 0.5xO_2(g)$	Water Electrolysis
$\boldsymbol{MO_x(l) \rightarrow M(l) + 0.5xO_2(g)}$	**Net Reaction**

- Carbothermal reduction uses methane and heat to extract oxygen from the metallic oxides within lunar regolith to produce CO/CO_2
- The oxygen is stored, the hydrogen is recycled back into the system



Source: Sierra Space

Lunar Oxygen Production

- Sierra Space's carbothermal oxygen production process (TRL 6) extracts oxygen from lunar regolith.
    - Could operate anywhere on the moon

- Produces reduced metallic slag which could be refined into pure metals or used as construction material

- Uses direct solar heating to significantly reduce electricity usage
    - Could substitute electrical energy

Source: Sierra Space (*Artist concept)*

Regolith is delivered to the ISRU plant

Regolith

Source: Sierra Space

Regolith simulant actively undergoing carbothermal reduction

Recycled Carbon

Slag

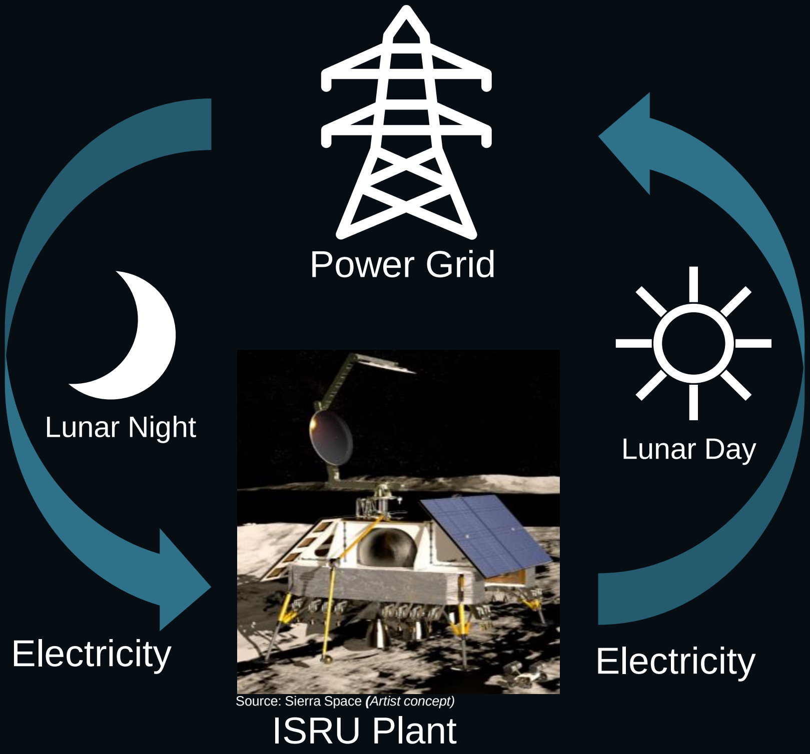
Source: Sierra Space

Oxygen

Source: Sierra Space

Fuel Cell Energy Storage

- Electrolysis is used to store energy during the lunar day and a fuel cell provides electricity during lunar night
- Uses electricity to split water into hydrogen and oxygen during the day
  - Oxygen is extracted from lunar regolith to reduce launch mass
- The fuel cell reacts the hydrogen and oxygen to produce electricity during lunar night



Source: Sierra Space *(Artist concept)*

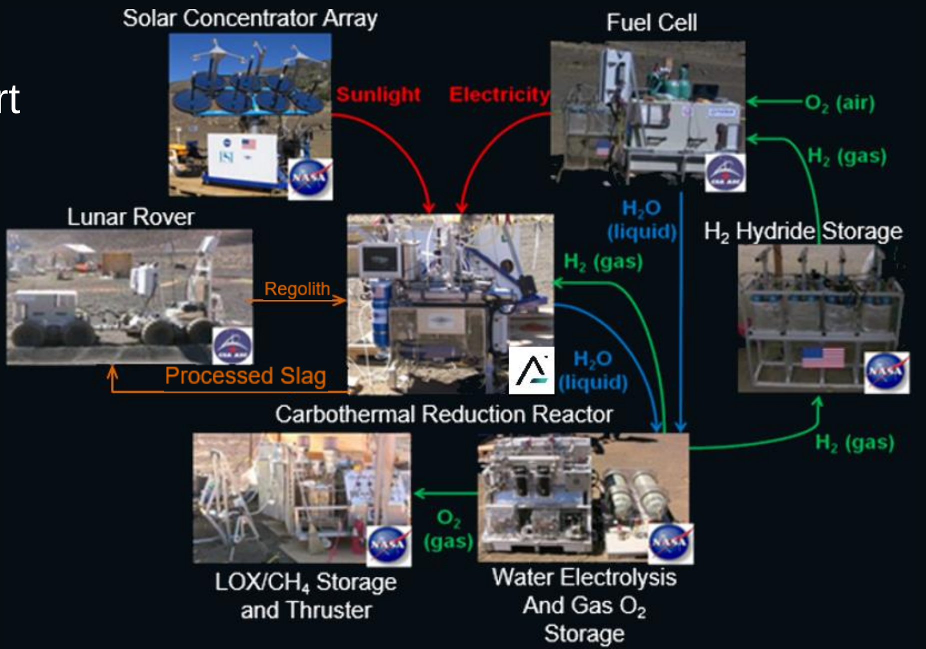
Chemical Conversion

- Could recycle and reuse chemicals
  - Convert chemicals for storage or transport
  - Reduce resupply requirements
- Examples:
  - Propellant waste (ullage, boil-off)
  - Fuel cell waste (water)
  - ECLSS waste (carbon dioxide, biological)

$$Methane \Leftrightarrow Carbon + Hydrogen$$

$$Water \Leftrightarrow Hydrogen + Oxygen$$

$$Carbon\ Dioxide \Leftrightarrow Carbon + Oxygen$$



Brass board architecture test has demonstrated functionality

Source: https://ttu-ir.tdl.org/server/api/core/bitstreams/11c6ddf9-b539-47b8-8b36-0bd618320ea9/content

Value Stream Inputs and Outputs

Oxygen Production

Inputs

- Lunar Regolith
- Electricity (day)
- Communications
- Carbon
  - Propulsion ullage
  - ECLSS Waste
- Hydrogen
  - Propulsion ullage

Outputs

- Oxygen
  - Propulsion
  - ECLSS
- Slag
  - Construction feedstock
  - Metals refinement

Energy Storge

Inputs

- Electricity (day)
- Communications

Outputs

- Electricity (Night)
  - Night survival
  - Night ops

Chemical Recycling

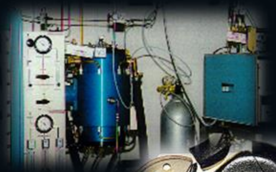
Inputs

- Water
  - Fuel cell rovers
- Hydrogen
  - Propulsion ullage
- Oxygen
  - Propulsion ullage
- Methane
  - Propulsion ullage
  - ECLSS waste
- Carbon Dioxide
  - ECLSS waste

Outputs

- Water
  - ECLSS
  - Fell cell rovers
  - Cold Gas propellant
  - Long term storage
- Hydrogen
  - Fuel cell rovers
  - Propellant
- Oxygen
  - Propellant
  - ECLSS
- Methane
  - Propellant
- Carbon
  - ISRU Steel
- Carbon Dioxide
  - Coolant (Scaling phase only)

Carbothermal Development

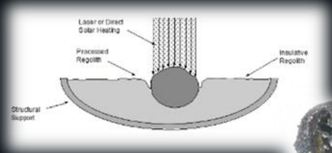


Source: Sierra Space

Source: Sierra Space

1993

Hot-wall furnace experiments



Source: Sierra Space

Source: Sierra Space

1998

Direct energy processing approach developed to allow long duration reactor operation

Source: Sierra Space

2022

Large scale fully automated reactor demonstration

Source: Sierra Space

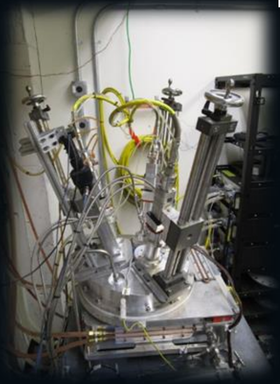
2021-2024

Flight forward, automated reactor demonstrator development

Source: Sierra Space

2010

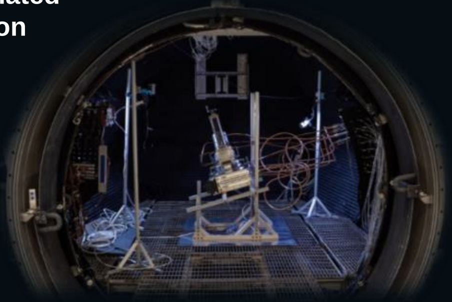
End-to-end carbothermal field test with solar energy, Sabatier reactor, electrolysis & thruster



Source: Sierra Space

2020

Scaling Design & Testing



Source: https://www.fox13seattle.com/news/nasa-extracts-oxygen-from-lunar-soil-simulant-for-the-first-time

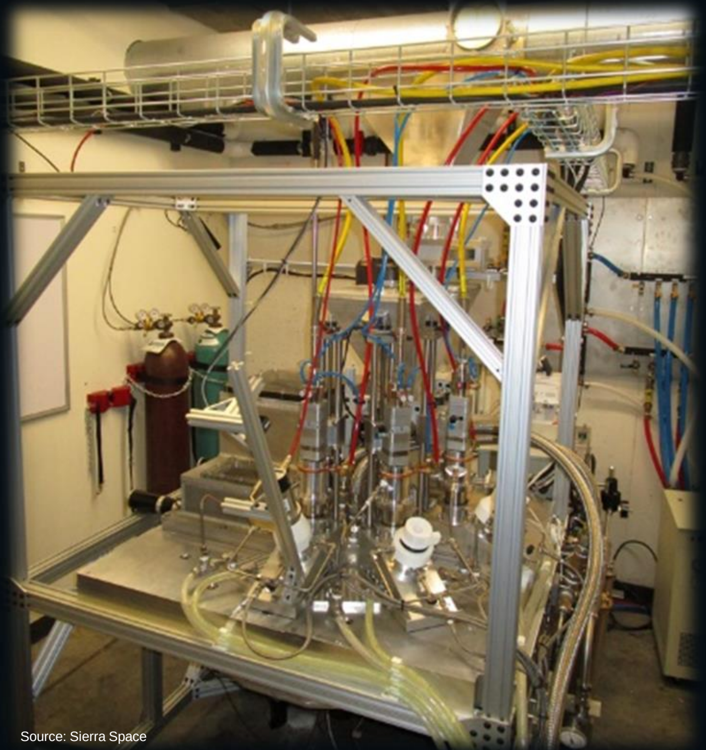
2023

Thermal vacuum test to TRL 6

Carbothermal Reactor Strategy

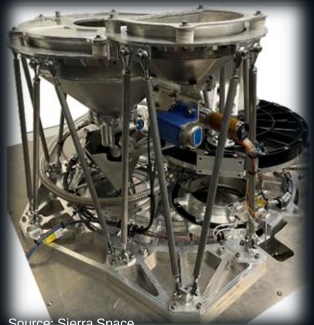
Source: Sierra Space

Optimize performance (Complete)



Source: Sierra Space

Show how process scales (Complete)



Source: Sierra Space

Flight forward demonstrator (Current effort)

Demand to and from ISRU plant

X denotes the demand exists but has not been quantified or is proprietary

* Denotes rough number of the correct order of magnitude

All values are estimated and noncommittal

Demand to ISRU Plant

	Electricity, Day, (Surge, watts)	Electricity, Night Survival (W)	Electricity (Night Operations, Kw)	Oxygen (MT/launch)	Hydrogen (kg/year)	Slag (kg/Day)	Carbon (kg/year)	Heat (watts)	Water (kg/year)	Liquification Services (kg/year)	Water	CO2
Blue Origin	X	1000	10*	X	X					X	X	
Cislunar Industries		150*	10*			50*	X					
Crescent Space Services		30	.13*									
Fibertek		200	5*									
Firefly Aerospace		10	.04*	0.6					X		X	
GITAI		10*										
Helios Project Ltd												
Honeybee Robotics												
ICON Technology, Inc.		10*	5*			720						
Nokia		100										
Northrop Grumman		X	X									
Redwire Space												
SpaceX				200								X

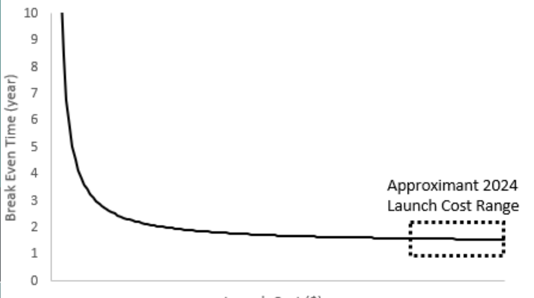
Source: Sierra Space & companies indicated

Demand From ISRU Plant

	Communication to Earth (Mbps)	Communication to Moon (Kbps)	Electricity, Day (watts)	Electricity, Night (Watts)	Methane (MT/Landing)	Hydrogen (Mt/Launch)	Lunar Regolith (kg/day)	Water (kg/year)	Oxygen (Only in specific scenarios)	Empty Tankage Rental	Transport to Lunar Surface
Blue Origin	2-5	30	X			X			X	X	X
Cislunar Industries											
Crescent Space Services	2-5	30									
Fibertek	2-5	30									
Firefly Aerospace											
GITAI USA							50*				
Helios Project Ltd									X		
Honeybee Robotics			X								
ICON Technology, Inc.											
Nokia	2-5	30									
Northrop Grumman											
Redwire Space			X								
SpaceX	2-5	30			10					X	X

Source: Sierra Space & companies indicated

Commercialization



Source: Sierra Space

	Estimated Price	Rationale
Sell Oxygen	~500-750 $k/kg	Based off a ~25% discount of landing cost
Sell Slag	~15-50 $K/kg	Estimate based on how much it costs to purchase regolith, robotic costs to remove, and added value of reduced metals
Sell Nighttime Electrical	~20-30X Day time cost	Covers fuel cell use, electrolysis, re-liquification of oxygen and storage of hydrogen
Rent Oxygen/Hydrogen Rental	~300 $k/kg	Based off a ~25% discount of landing cost. Quantities limited based on methane/hydrogen supply
Sell Water	~500-750 $k/kg	Rent hydrogen/oxygen for fuel cell use and accept it back in the form of water. Fee if not returned. Assumes 1% of rental is lost.
Buy Daytime Electrical	Market Rate	Electricity needs to be sold cheaper than it costs to develop and ship panels from earth
Buy communications	Market Rate	Priced by supply and demand of communication suppliers

Source: Sierra Space

- ISRU Commodities expected to track with launch and landing cost
  - Materials sold at a discount to launch and landing costs
  - Currently at ~$1M/kg