Developments of Bosch Process Architectures for ISRU and Terrestrial Applications

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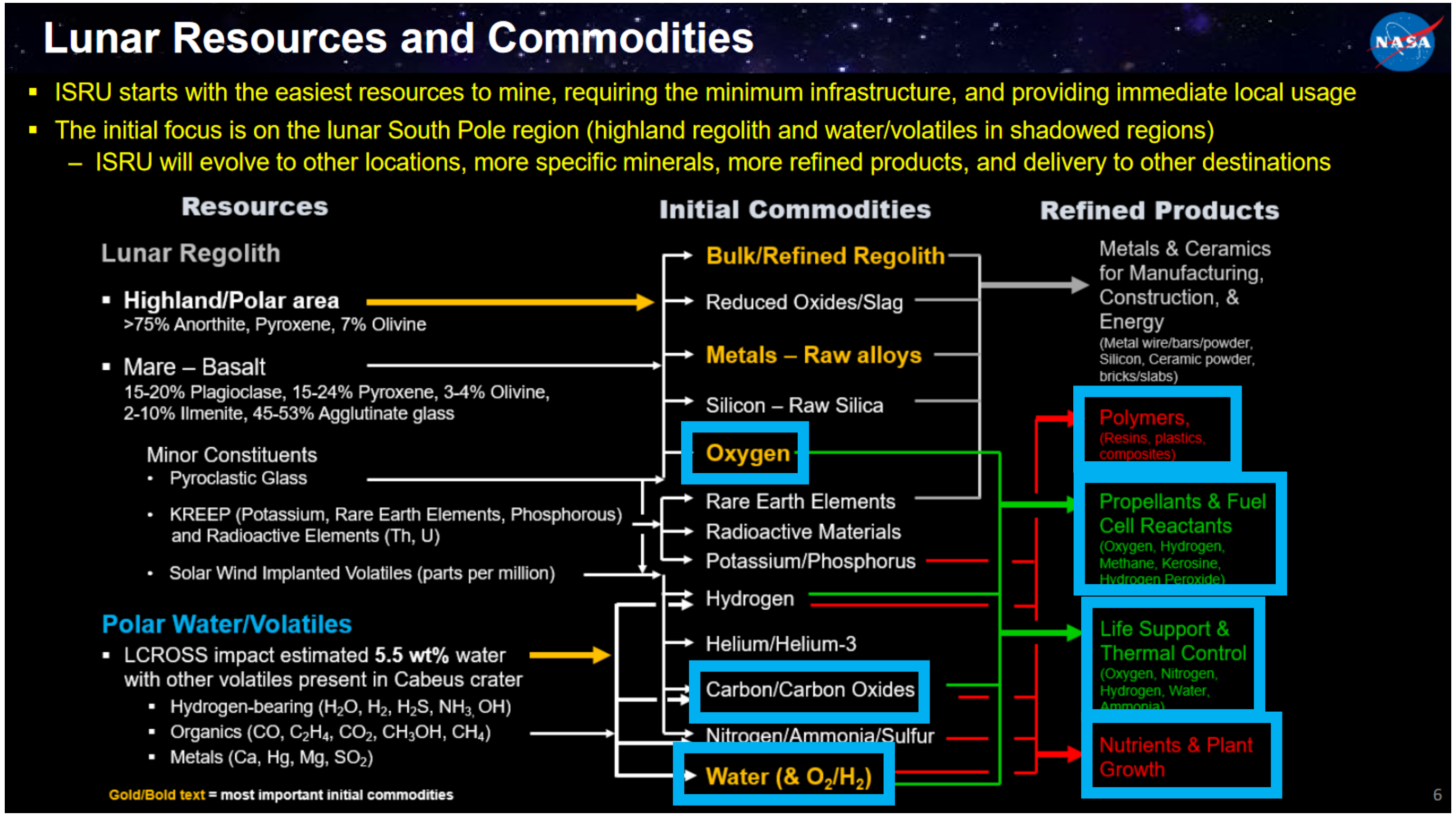
Beau Compton/NASA GRC
Jackson Stewart/ NASA GRC
Cleveland, OH

Bosch Project Overview

- In-situ Resource Utilization (ISRU) enables sustainable operations on the Moon, Mars, and beyond
- The general Bosch process:
  - $CO_2 + 2H_2 \rightarrow 2H_2O + C_{(s)}$
  - Produces valuable resources (O_2 and $C_{(s)}$) in ISRU environments
  - Captures and utilizes CO_2 from Earth's atmosphere
- A system has not been designed, integrated, scaled, or tested for ISRU or terrestrial applications



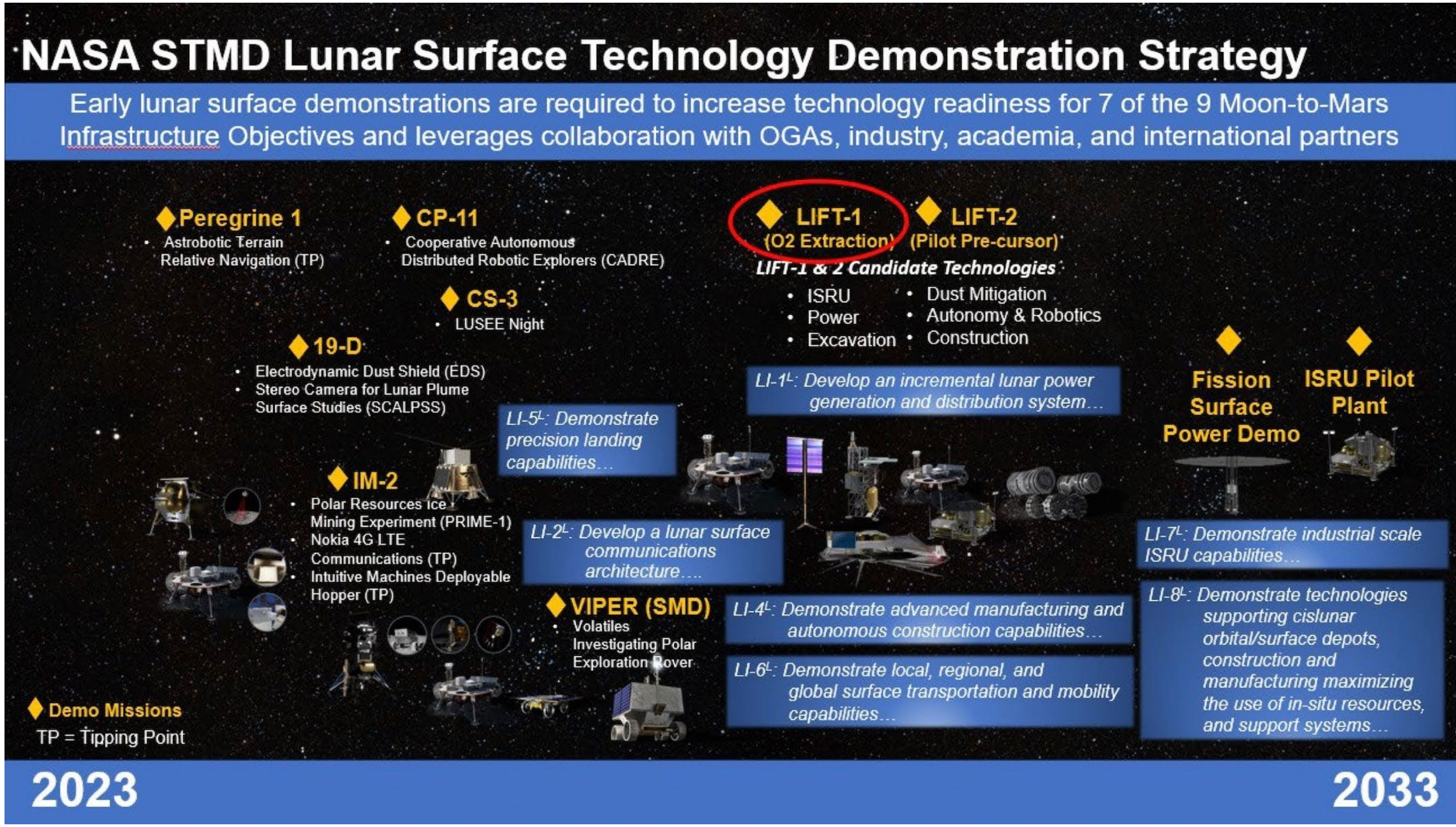
Sanders, G. & Kleinhenz, J., "*In Situ Resource Utilization (ISRU) Envisioned Future Priorities*", Luxembourg Space Week, 2022.

Background: Bosch for ISRU

- NASA's Space Technology Mission Directorate (STMD) is planning to demonstrate ISRU technologies:

<u>Lunar</u> – near term
- LIFT-1 will focus on O_2 extraction from the Lunar regolith
- Bosch process produces required carbon feedstock for O_2 extraction technology such as Carbothermal reduction

<u>Martian</u> – longer term
- Bosch process uses Mars's high CO_2 atmosphere to produce O_2 and $C_{(s)}$

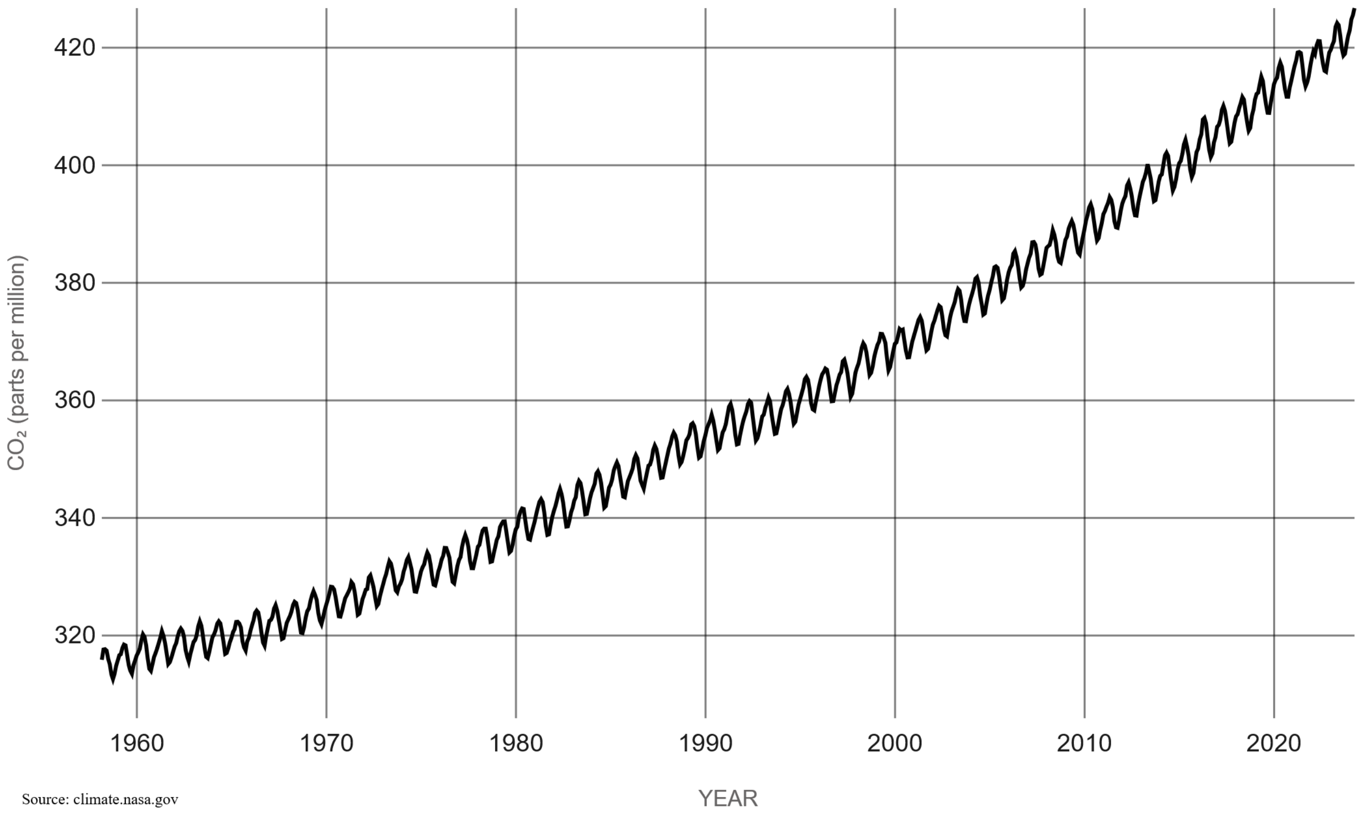


NASA Space Technology Mission Directorate (STMD) Lunar Infrastructure Foundational Technologies-1 (LIFT-1) Request for Information (RFI)

Bosch for Earth

- Bosch process can be used for terrestrial carbon capture
- Flue gas applications are most promising

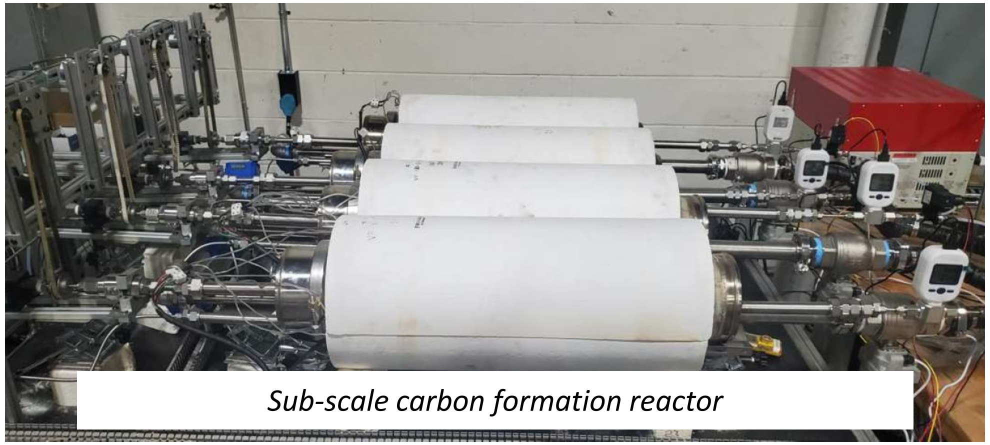
Terrestrial CO_2 concentrations



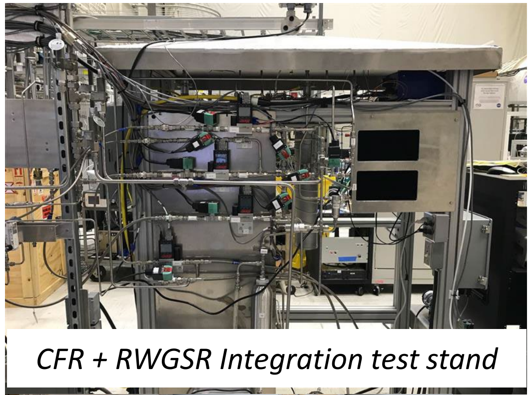
Source: climate.nasa.gov

Introduction to CUTLAS

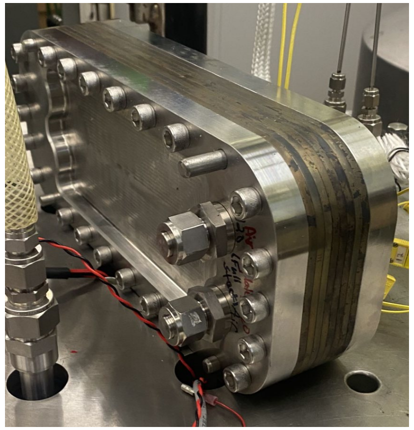
- STMD's CUTLAS project will advance components, subsystems, and models of Bosch process system:
- Components
  - Carbon + water production and removal (Carbon formation reactor (CFR))
  - CO_2 acquisition (sorption pump)
  - Solar thermal receiver subsystem
- Sub-system integration
  - Water & heat recovery devices + CFR
  - Solar thermal receiver + CFR
  - CFR + Reverse Water Gas Shift Reactor (RWGSR)
- System models
  - ISRU environments
  - Terrestrial environment



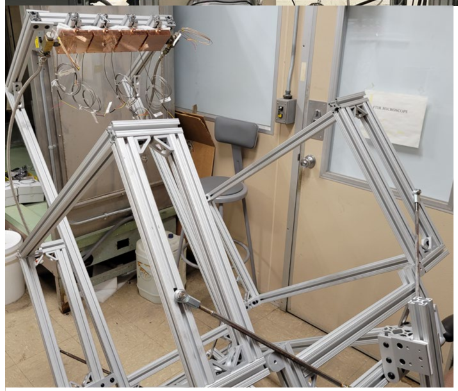
Sub-scale carbon formation reactor



CFR + RWGSR Integration test stand

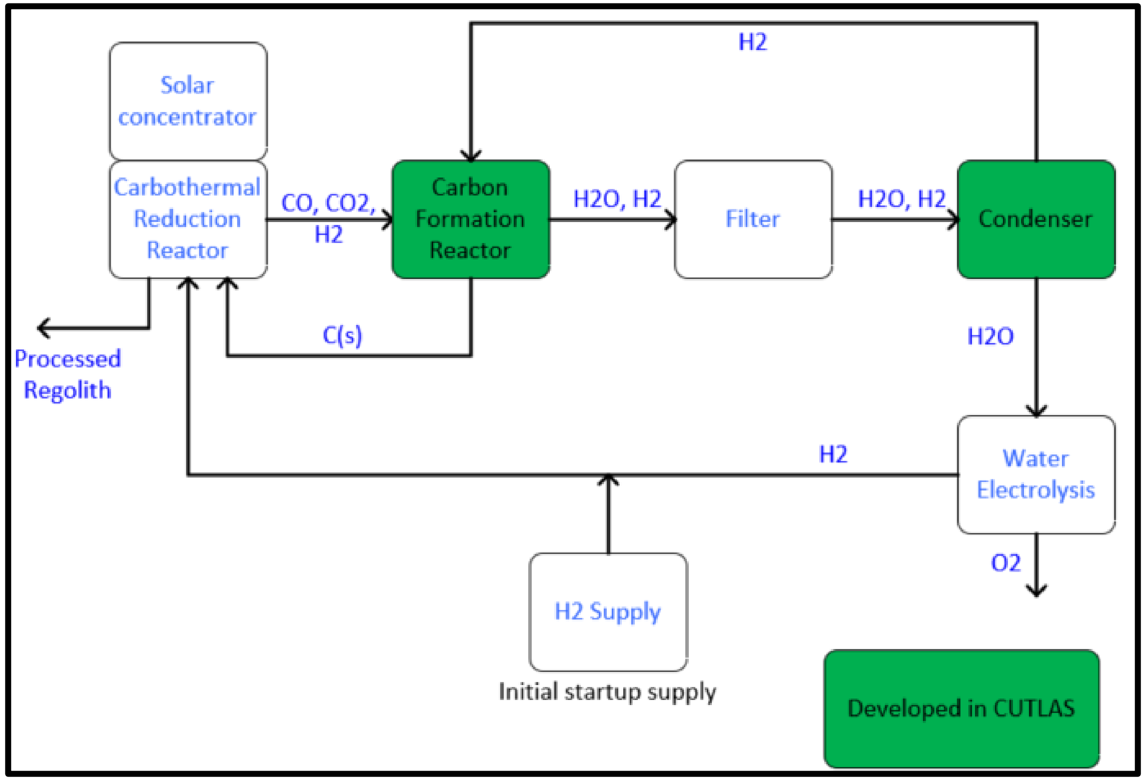


Sorption pump



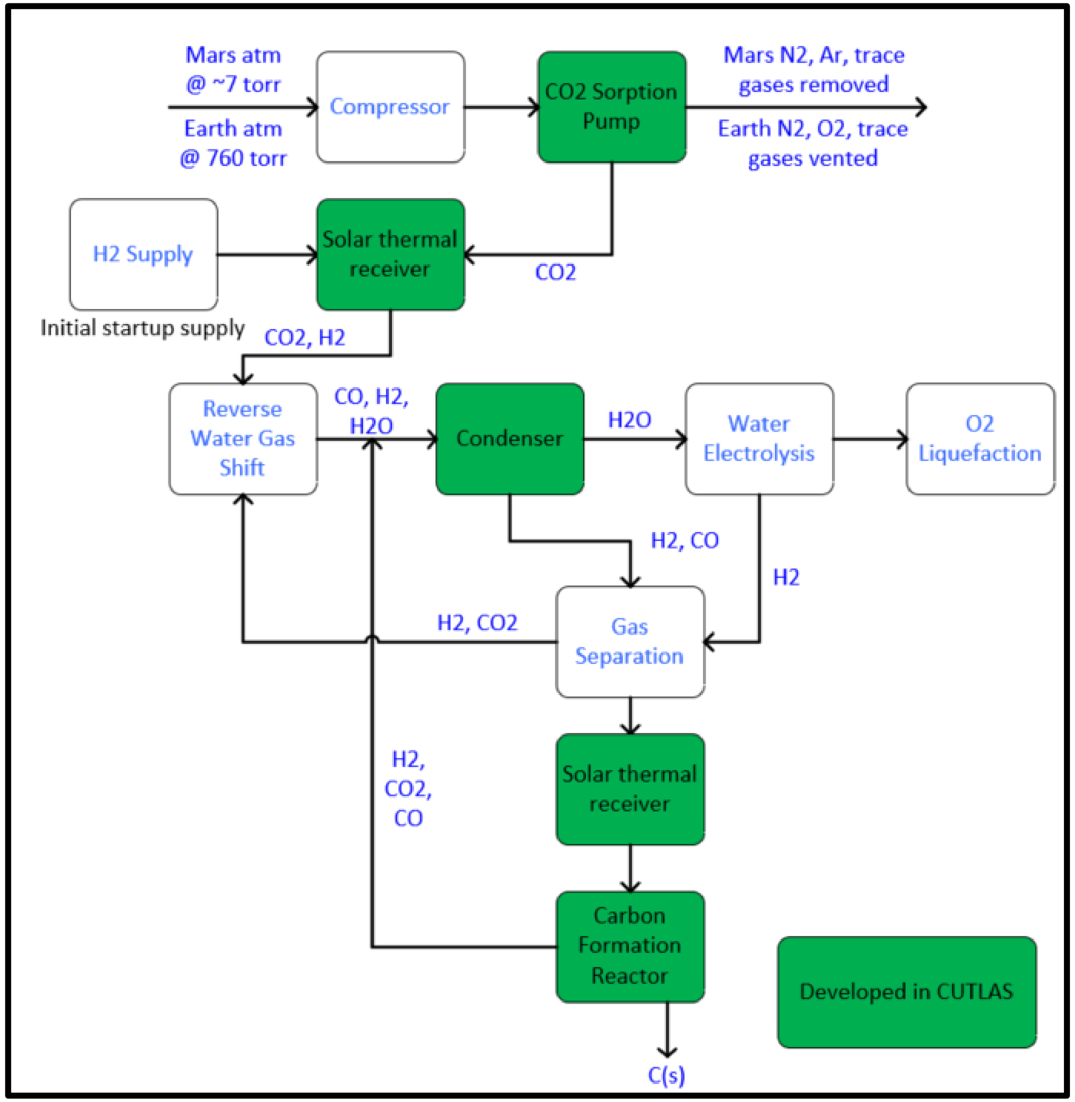
Subscale solar thermal receiver

Applicable System Architectures



Flow Diagram of Lunar Bosch Reactor

- Technologies advanced in project CUTLAS are highlighted in green



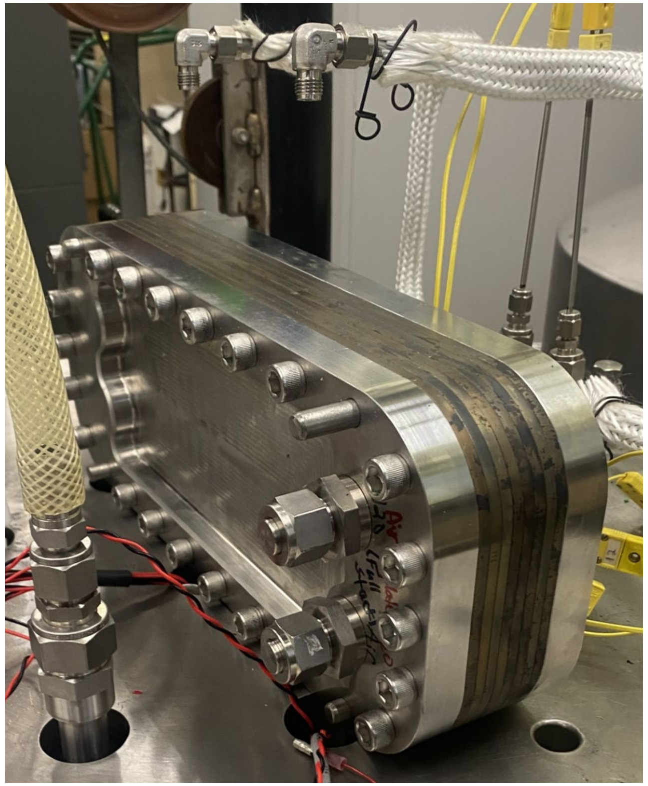
Flow Diagram of Atmospheric Bosch System (terrestrial/Martian applications)

CUTLAS for Atmospheres: Sorption Pump

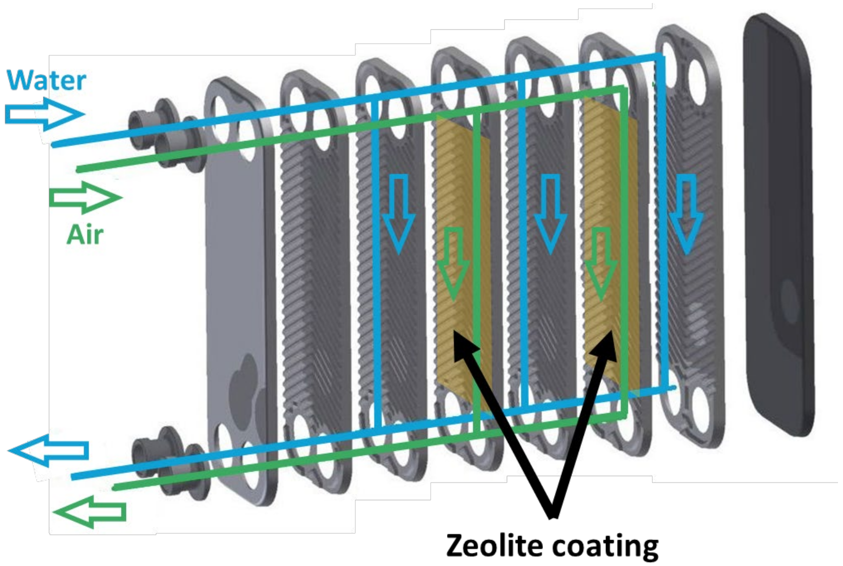
- The Rapid Cycle Temperature Swing Adsorption pump (RC-TSA) uses a stacked plate geometry to rapidly cycle thin zeolite coated layers
    - CO_2 is scrubbed and pressurized in the process

Current work:

- Laboratory testing using a simulated terrestrial flue gas environment (up to 20% CO_2)
- Modeling predictions*†
    - 86 seconds breakthrough time
    - 4.7 kg/day of CO2 throughput
- Scaled-up, the RC-TSA design is expected to demonstrate a 12 kg/day throughput
    - This demonstration will be of similar scale to ISS sorption technology
    - A trade with required power draw and mass is future work



RC-TSA unit in GRC test setup



Flow diagram of heat exchange fluid and CO_2-rich air

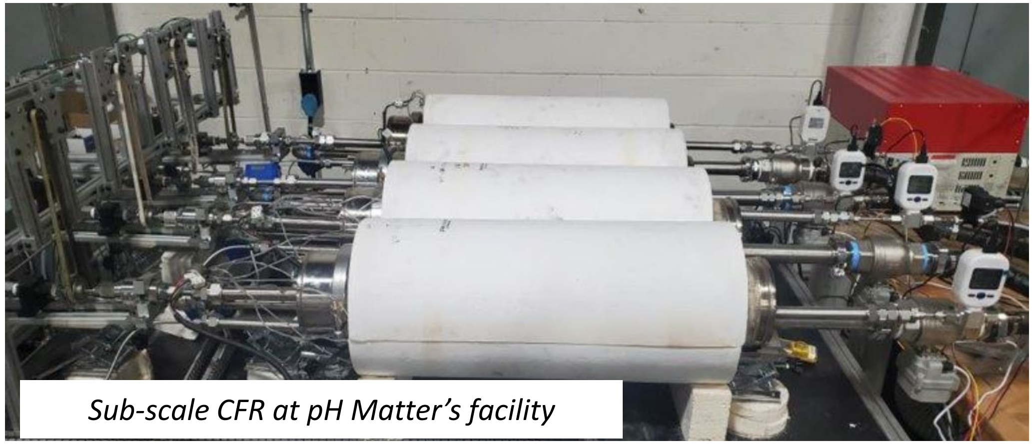
Photo of zeolite coating on stainless steel plates

*Assuming 20% CO2 and 253 kPa inlet pressure

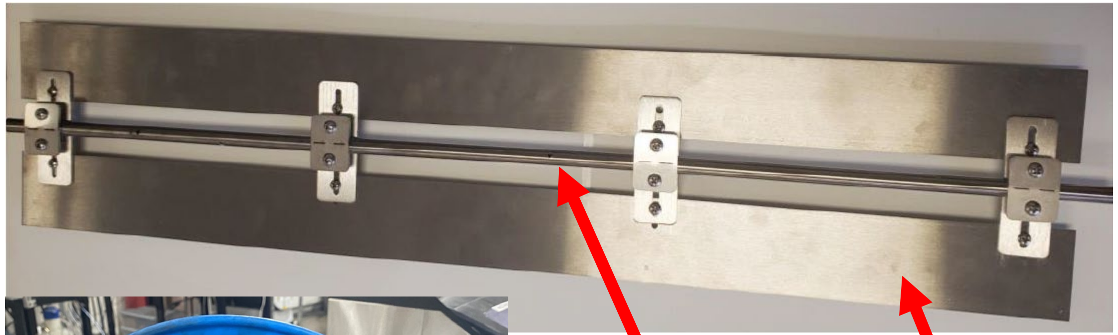
†Wilson, T., Zatania Lojo, A., Compton, B., and Cooper, M., "Conservation Law Model of a Rapidly Cycled Temperature Swing Adsorption Pump in a Terrestrial Environment," *53rd International Conference on Environmental Systems*, 2024 (not yet published)

CUTLAS: Carbon Formation Reactor

- The Carbon Formation Reactor (CFR) leverages the Boudouard reaction:
  - $2CO \rightarrow CO_2 + C_{(s)}$
  - Also produces H_2O along with RWGSR
- In development at external commercial partner, pH Matter in Columbus, OH
  - Rotating attritor arms are used to apply catalyst and remove solid carbon
  - Based on design proposed for ISS with improved automation and reliability for ISRU
- Current work:
  - Baseline performance testing of sub-scale CFR
  - Subsystem integration with the solar thermal receiver and water/heat recovery hardware
  - Scaled up (10x) design completed CDR in May 2024
    - Objective of reducing mass, power, and volume while further improving automation and performance



Sub-scale CFR at pH Matter's facility



Holes for catalyst spray

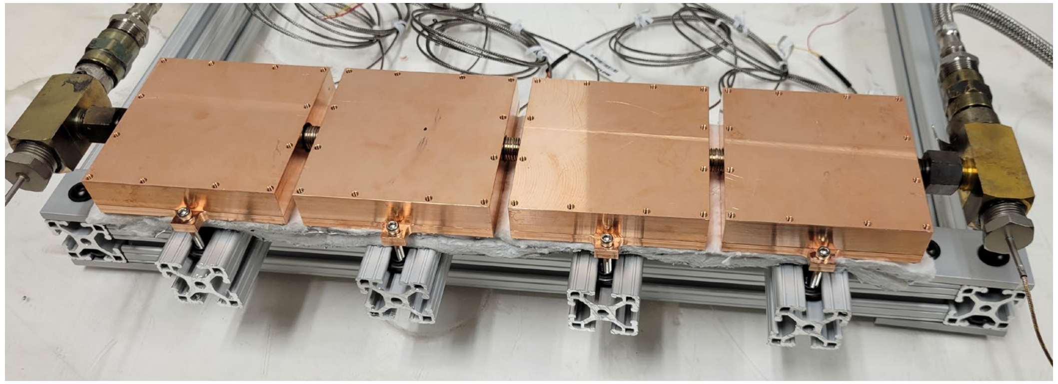
Attritor arms for catalyst distribution and carbon removal

Carbon produced from reactor

CUTLAS: Solar Thermal Receiver

- CFR requires reactants 475-550°C
- Solar Thermal Receiver (STR) designed for CUTLAS
  - Efficiently transfers thermal energy to the reactants using a solar concentrator
  - Reduces interdependence of the solar heating designs from the CFR

- Current work:
  - Development of a shape memory alloy (SMA) device to passively regulate thermal energy to the receiver
  - Benchtop testing to anchor the current model and baseline performance
  - Design of a scaled-up STR
    - To be integrated with the sub-scale CFR for demonstration testing



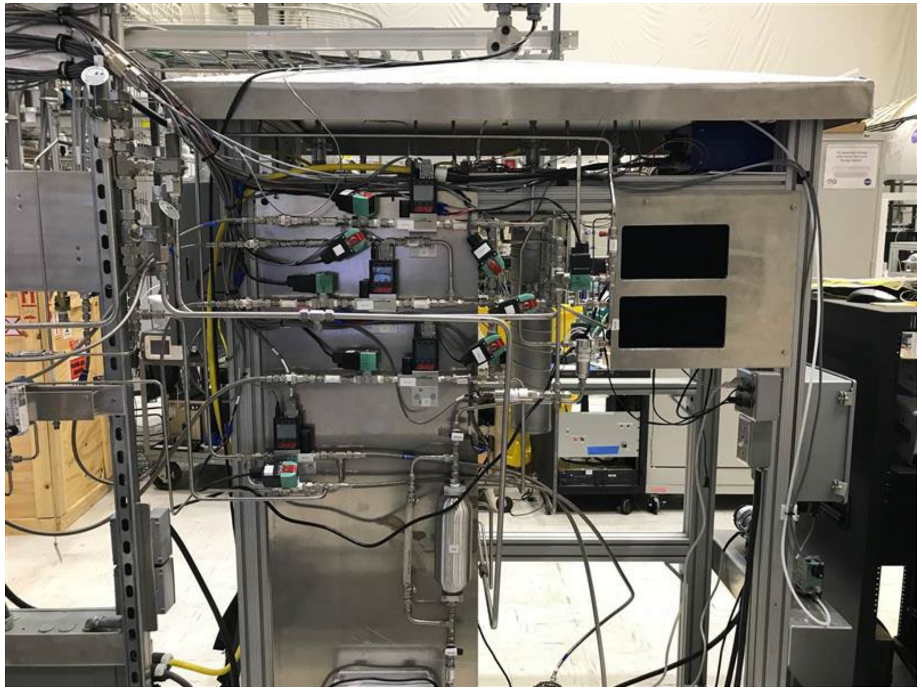
Solar thermal receiver prototype

Benchtop solar thermal receiver integrated with solar concentrator (reflectors not shown)

CUTLAS: Bosch Reactor Integration Testing

- To produce H_2O and $C_{(s)}$ in Martian/terrestrial environments, Bosch requires two reactors
  - CFR (downstream)
  - Reverse Water Gas Shift Reactor (RWGSR)

- RWGSR developed for an ISS project is being integrated with the CFR
- Objective of the tests:
  - Demonstrate integration of the core Bosch reactors in sequence
  - Baseline performance in expected ISRU conditions
- Testing is expected to complete in September 2024

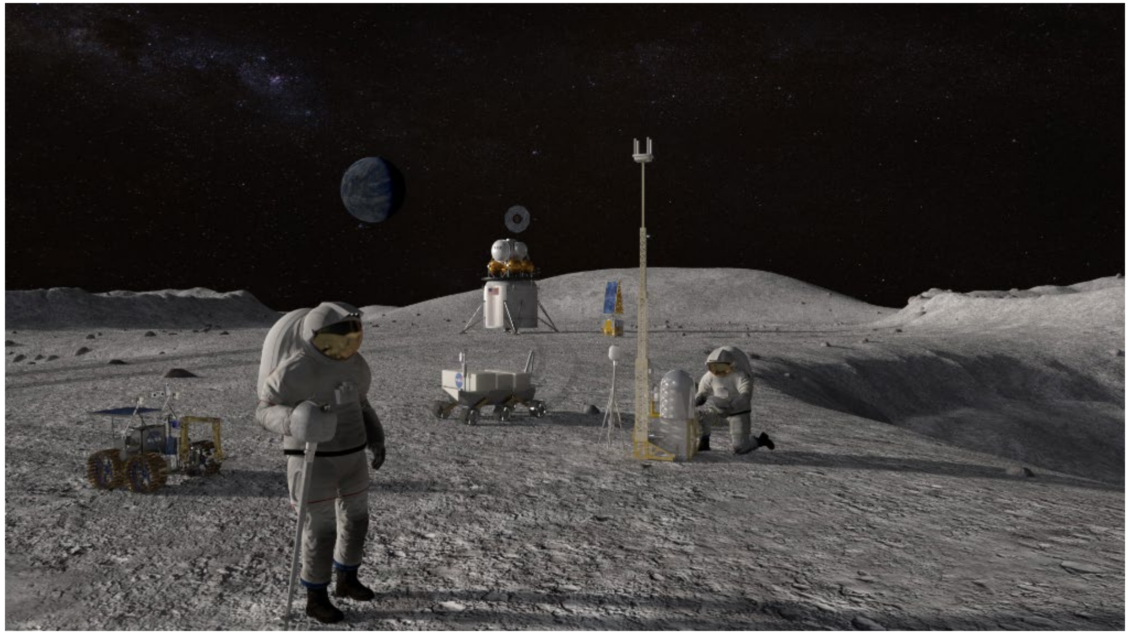


RWSGR-CFR Integration test stand at MSFC

Looking Towards the Future

- CUTLAS will complete currently scoped testing and modeling efforts in FY2025

- Next steps to further develop the Bosch process system:
- Design of scaled-up components
  - Terrestrial sorption pump
  - Solar thermal receiver
  - Carbon formation reactor
- Sub-system integration
  - Solar thermal receiver and solar concentrator
  - Solar thermal receiver, water/heat recovery hardware, and carbon formation reactor



Artistic concept of astronauts with Lunar habitation technology

- System models
  - Incorporate results of Lunar, Martian, and terrestrial Bosch process component testing
- Investigate uses of carbon produced by Bosch for ISRU applications:
  - Sodium ion battery manufacturing
  - Filtration/adsorption
  - Additive manufacturing

- The Bosch process needs further development to be ready for future flight opportunities such as LIFT-1, eventually supporting lunar surface Artemis missions and crewed missions to Mars

Meet the team

1. Beau Compton/PI
2. Jack Stewart/Co-I/PM
3. Tim Giesy/Integration Lead
4. Travis Wilson/Modeling
5. Arland Zatania Lojo/Modeling
6. Nathan Wilson/Intern
7. Michael Cooper/Modeling
8. pH Matter/CFR Development
9. Margaret Proctor/COR
10. Will Huddleston/Battery Development
11. Rehan Rashid/Intern
12. Don Dornbusch/Battery Development
13. Leah Struchen-Deans/Mentor
14. Erica Montbach/Mentor

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- Thomas Halstead
- Cory Thomas
- James Knox
- Richard Schunk
- Frank Lam
- Julie Kleinhenz
- Leslie Gertsch
- Marc Abadie

System Scalability

- System scalability critical to success
  - Table below demonstrates the required reaction flow rates scale by about a factor of 10 each for ISRU and terrestrial needs

	Previously built scale	ISRU scale		Terrestrial scale	
	ISS (4 CM) Sub-scale	**Moon**[1,2]	**Mars**[2]	**Earth**	
CO2 Sorption Pump				ECI Scale	Goal
CO2 (kg/hr)	0.18	N/A	1.5	15	150 - 1500
Reverse Water Gas Shift					
CO2 (kg/hr)	0.18	N/A	1.5	15	150 - 1500
Carbon Formation Reactor					
CO (kg/hr)	0.1	1.1	1.0	10	100 - 1000
C (kg/hr)	0.045	0.5	0.45	4.5	45 - 450

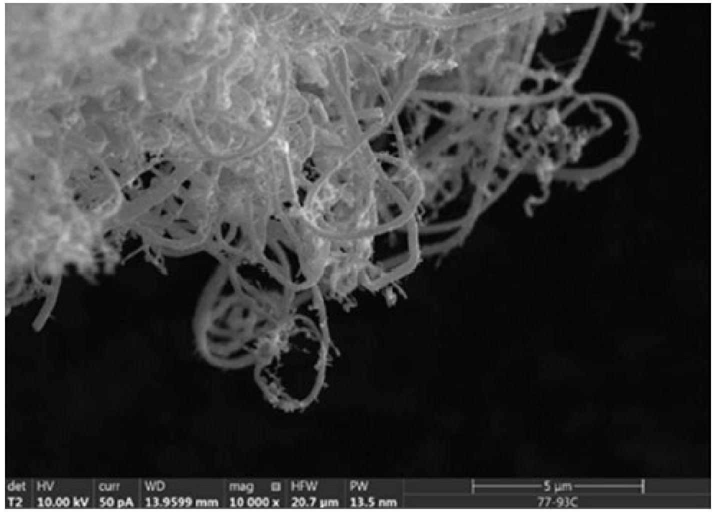
1. Next Space Technologies for Exploration Partnerships-2 (NextSTEP-2), Appendix D: In-Situ Resource Utilization (ISRU) Technologies. Posted December 2017. (https://www.nasa.gov/nextstep/isru).
2. Linne, D.L., et. al., "Lunar Production System for Extracting Oxygen from Regolith," J. Aerosp. Eng., 2021, 34(4): 04021043. (DOI: 10.1061/(ASCE)AS.1943-5535.0001269)

CUTLAS: Carbon Studies

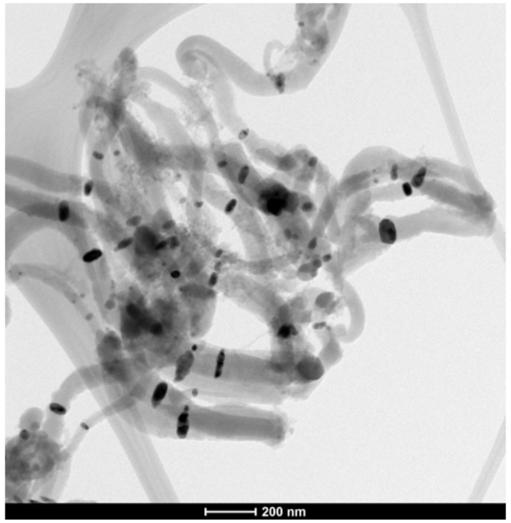
- The carbon produced from the Bosch process shows promise for several ISRU applications:
  - Sodium ion battery manufacturing
  - Filtration/adsorption
  - Additive manufacturing

- CUTLAS is investigating the plausibility of these uses by testing
  - The electrochemical performance of this Bosch carbon in a coin cell configuration
  - Filtration/adsorption performance for VOCs, ammonia, and CO_2 by activating the Bosch carbon

- CFR catalyst entrainment in the carbon may detrimentally impact performance



Scanning electron microscopy of Bosch carbon



Transmission electron microscopy of Bosch carbon showing entrained catalyst

Coin cell battery manufactured with Bosch carbon