National Aeronautics and Space Administration

# Current Activities in the Advanced Exploration Systems ISRU Project

Presented at the

Joint Space Resources Roundtable/Planetary & Terrestrial Mining and Sciences Symposium

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# ISRU Project Objectives

- Scope: Develop and demonstrate, in ground demonstrations, the component, subsystem, and system technology to enable production of mission consumables from regolith and atmospheric resources at a variety of destinations
  - Initial focus
    - Critical technology gap closure
    - Component development in relevant environment (TRL 5)
  - Interim goals
    - ISRU subsystems tests in relevant environment (Subsystem TRL 6)
  - End goals
    - End-to-end ISRU system tests in relevant environment (System TRL 6)
    - Integrated ISRU-Exploration elements demonstration in relevant environment

***Overall Project Goals***

***System-level TRL 6 to support future flight demonstration missions***

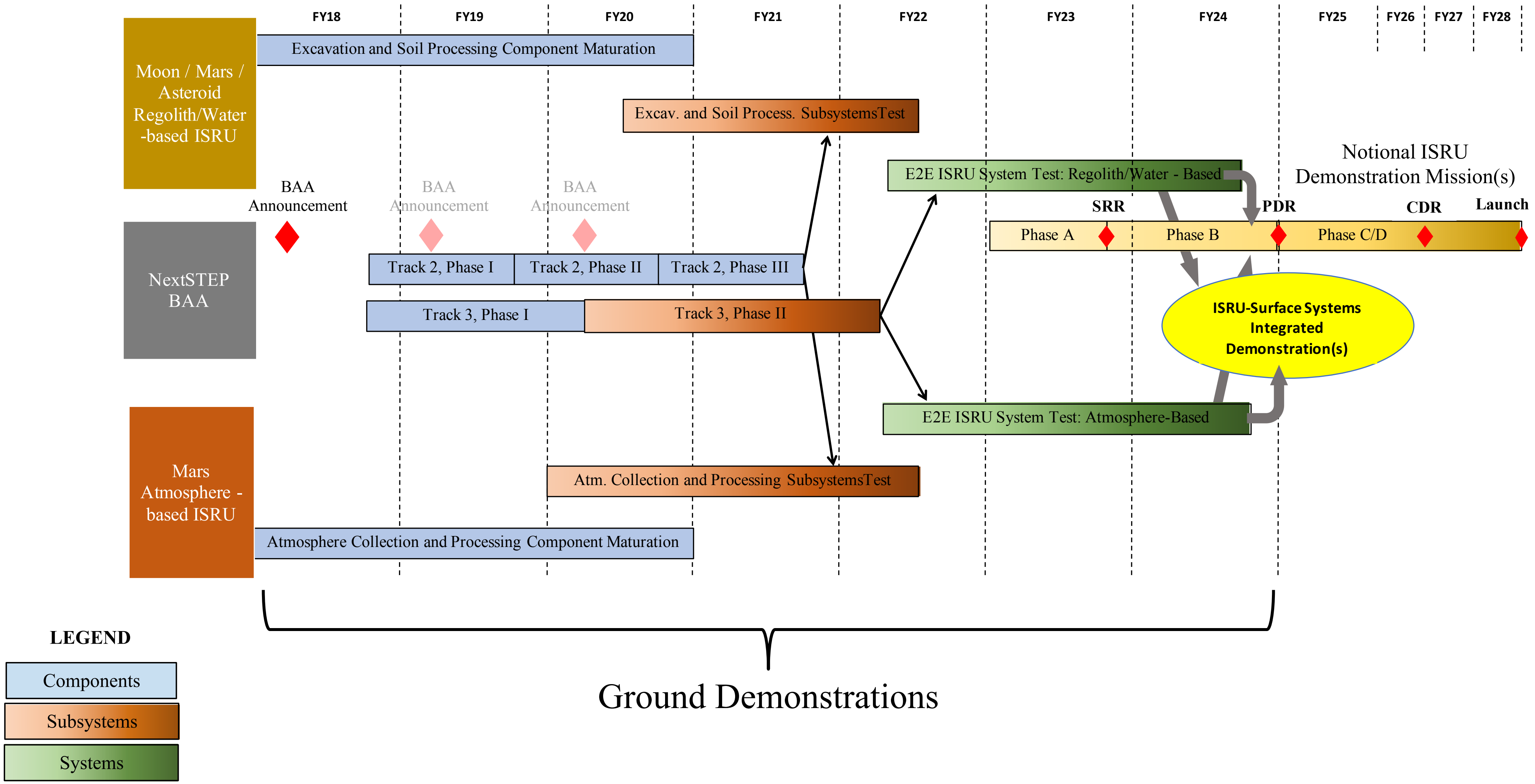
***Provide Exploration Architecture Teams with validated, high-fidelity answers for mass, power, and volume of ISRU Systems***

- **HEOMD Advanced Exploration Systems** — ISRU Program Exec – N. Suzuki
  - **In-Situ Resource Utilization Project** — Project Manager – D. Linne
    - 2.0 Systems Engineering & Integration
      - 2.1 Requirements / Arch Definition
      - 2.2 System Modeling & Analysis
      - 2.3 System Level Integration
      - 2.4 ISRU-Surface Systems Integration
    - 4.0 Component & Subsystem Technology Development
      - 4.1 Atm Carbon Dioxide Collection Subsystem
      - 4.2 Oxygen Production Subsystem
      - 4.3 Methane Production Subsystem
      - 4.4 Water Electrolysis Subsystem
      - 4.5 Mobility Subsystem
      - 4.6 Prospecting Subsystem
      - 4.7 Excavation Subsystem
      - 4.8 Soil Processing Subsystem
      - 4.9 Product Storage and Distribution Subsystem
    - 5.0 System Validation & Test
      - 5.1 Environmental Test Infrastructure
      - 5.2 Simulants Development
      - 5.3 Regolith/Water-Based System
      - 5.4 Mars Atm-Based System
      - 5.5 ISRU-Surface Systems Integrated Demonstrations

- **STMD**
  - Game Changing Development
  - Center Innovation Fund
  - Small Business Innovation Research
  - Space Technology Research Grants

# ISRU Project Schedule

**All dates are subject to evolving agency policy and funding priorities**



# FY18 In-House Activities

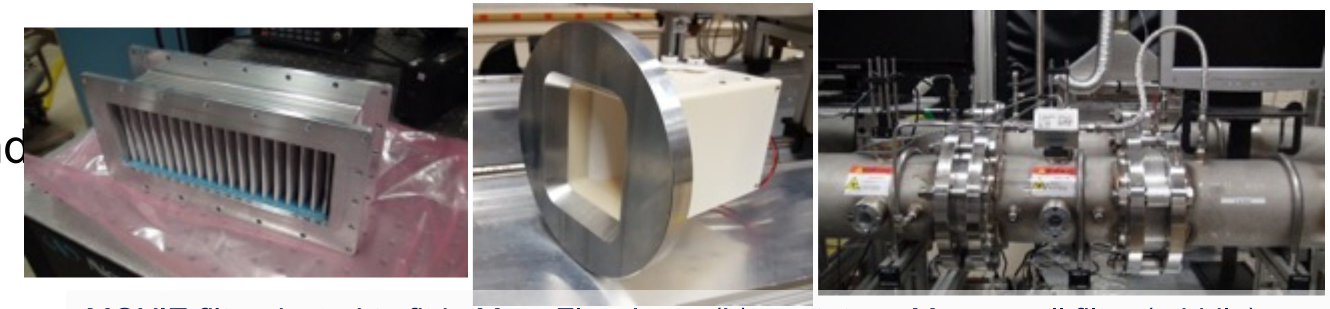
# Dust Filtration and Mitigation (WBS 4.1)

## Media Filter

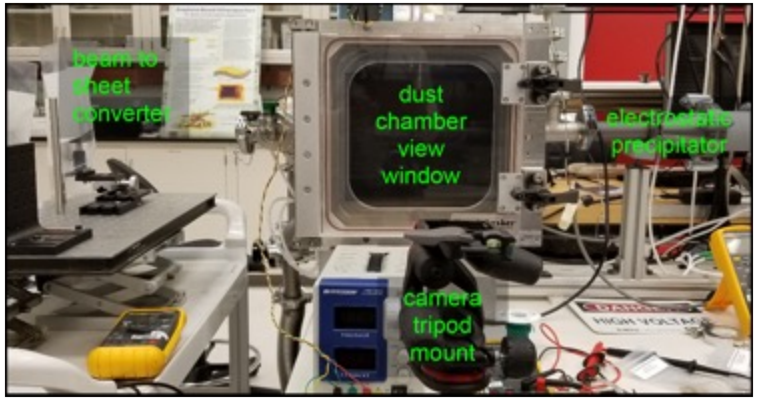
- MOXIE support: completed flow performance tests and initial dust loading tests of the MOXIE HEPA filter in the Mars Flow Loop
- Designed and fabricated prototype full-scale scroll filter for testing of renewable filter performance
- Mars Flow Loop upgrades: installed more sensitive instrumentation, improved imaging, and increased run duration capability

## Electrostatic Precipitator (ESP)

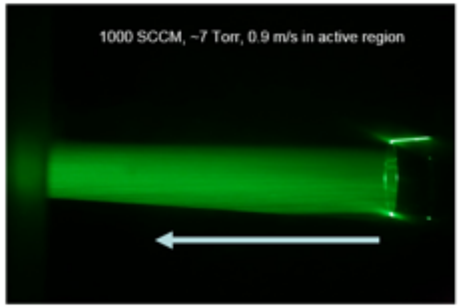
- Plasma-physics based model predicts particle charge and trajectory
- Characterizing dust environment from fluidized-bed injection dust environment using laser sheet visualization and Fine Particle Analyzer



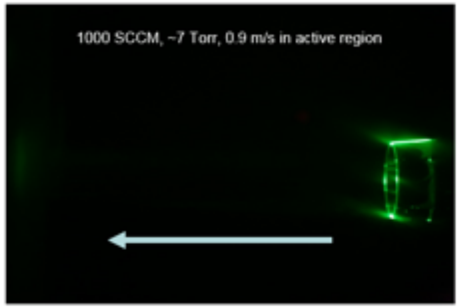
MOXIE filter ducted to fit in Mars Flow Loop (L); prototype Mars scroll filter (middle); Mars Flow Loop test section (R)




Camera and laser imaging configuration (left); Demonstration of ESP effectiveness using laser sheet visualization (bottom)

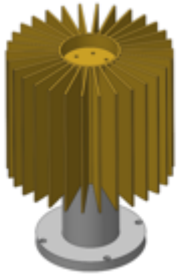
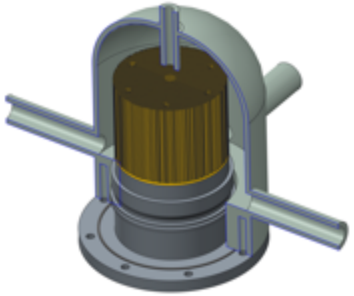
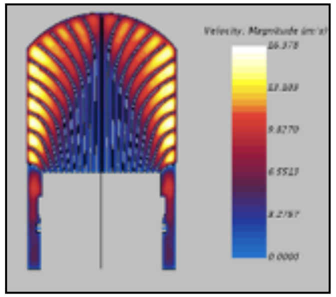
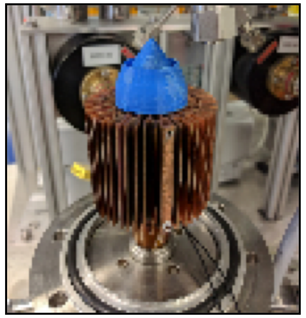
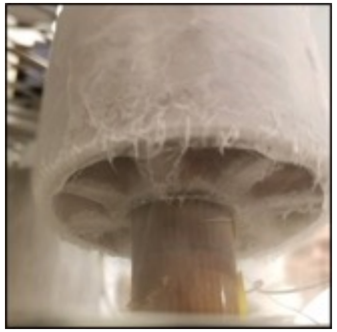



Precipitator off




Precipitator on (~1400 volts, 500μA)

# $CO_2$ Acquisition (WBS 4.1.3)

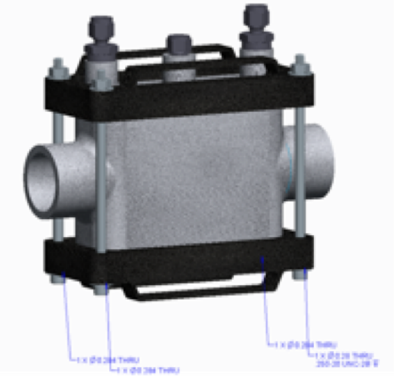
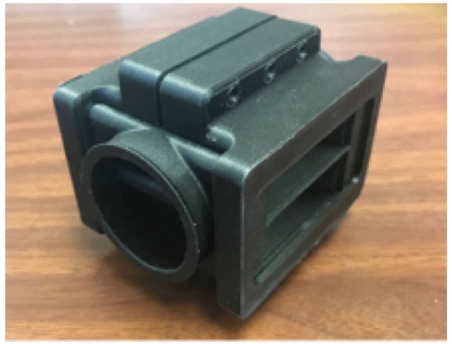
Cryofreezer cold-head concepts and modeling (top); cold-head installed on test stand (bottom left); CO2 ice accretion

## Full Scale $CO_2$ Freezer Design, Component Testing, and Modeling

- Designed, modeled, fabricated, and tested multiple sub-scale cold-head designs to optimize freezing efficiency
- Design and fabrication of full scale cryofreezer

## Rapid Cycle Adsorption Pump (RCAP) Design, Testing, and Modeling

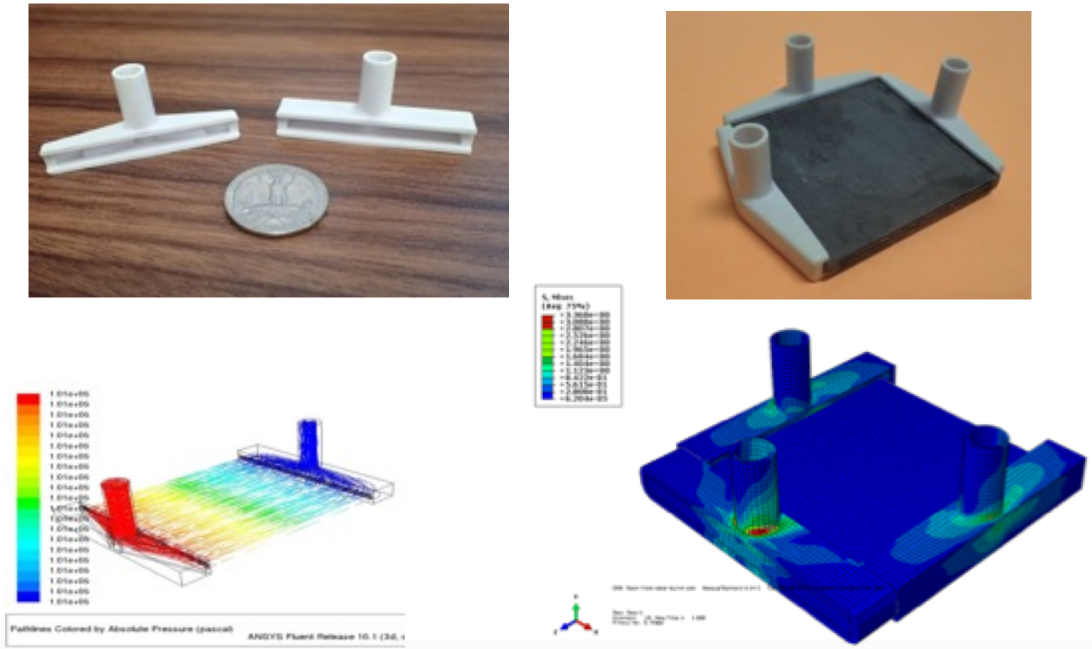
- Full 240 second adsorption and desorption pressurization cycle simulated
- Heat transfer to sorbent pellet bed is limited by pellet to pellet thermal conductivity
  - Possibly add metal fins, pins, foam, or metal shot pellets to enhance heat transfer from wall
- Additive manufacturing (3D Printing) in aluminum
  - Modular: can swap out different cold plates, adsorbent plates
  - Minimized microchannel dimensions (1 mm hydraulic diameter) for maximum convective heat transfer

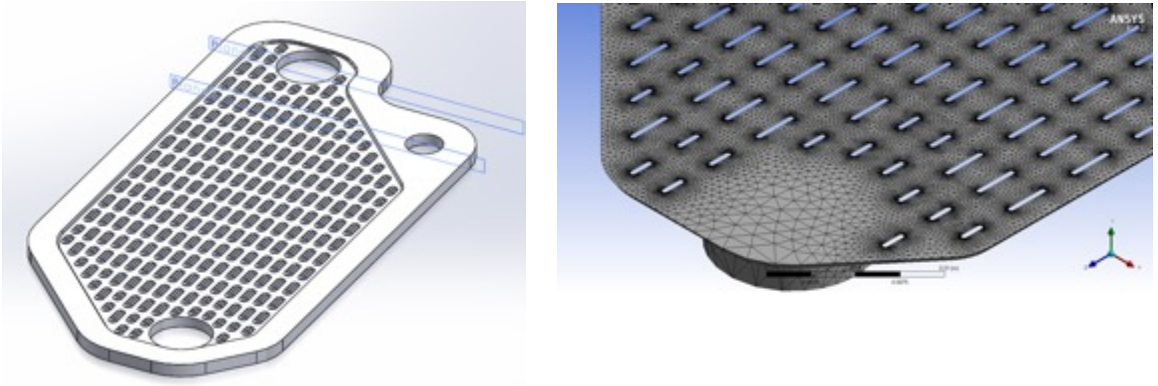

Rapid cycle adsorption pump 'one-plate' assembly design (L); RCAP 'one-plate' test-printed in plastic

# Solid Oxide Electrolysis (SOE) (WBS 4.2.2)

- Manifolds for GRC bi-supported cell (BSC) SOE design
  - Improve gas flow distribution to stack
  - Reduce number of sealing joints and joint stresses
- SOE Modeling (Thermal, Fluid, Mechanical)
  - Modeled gas flow and stresses in the GRC BSC manifolds and stack
  - Modeling MOXIE SOE stack; have created geometries within SolidWorks for $CO_2$ plate, $O_2$ plate, Mid-plate, and individual element plates
- SOE General Test Stand
  - Completing general test stand at JSC to enable testing and diagnostics of various vendors' stacks
- SOE Materials-Technology Comparison
  - Reviewing cathode & anode electrode materials used in industry to understand challenges and limitations
  - Testing electrode materials on single cells to compare performance, degradation



Bi-supported SOE Stack: (top left) 3D printed baffled manifold (L) next to original open manifold (R); (top right) 3D printed manifolds loose-fit to 3-cell stack; (bottom left) fluid pathlines through manifolds and stack; (bottom right) effective stress (Mises) under 6.8 g load in x-direction



MOXIE SOE Stack: SolidWorks geometry of element plate (L) and preliminary Co2 fluid volume mesh (r)

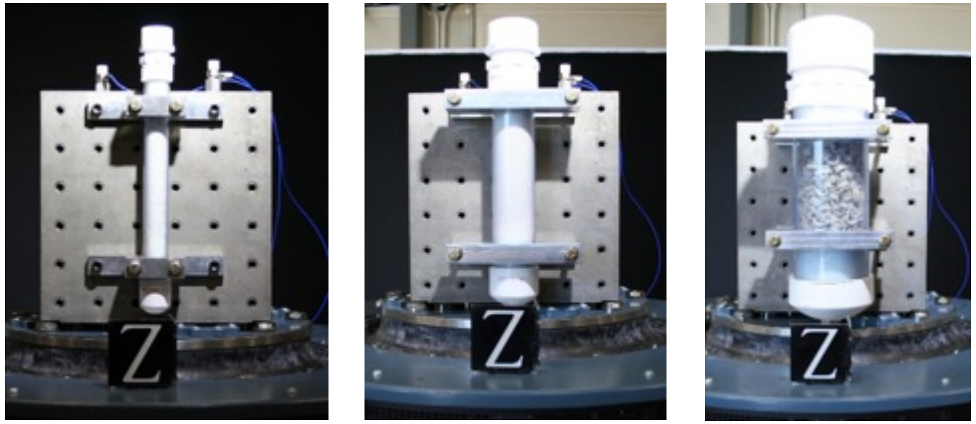
# Sabatier (WBS 4.3.1)

## Sabatier Design Study

- Defined the Sabatier design space, including reactor type, thermal management, gas recycling/separation
- Modeled Sabatier systems with one or two reactors with different types of thermal management
- Adding thermal management schemes and recycling and gas separation to model

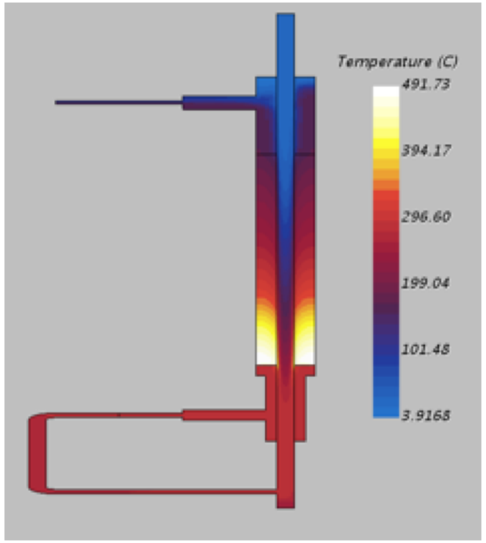
## Catalyst Screening

- Performing compression testing on new and used catalyst pellets
- Performing vibration testing on different catalyst pellet types under different load conditions
- Preparing to test catalysts for performance and degradation



Vibration testing on packed bed reactors

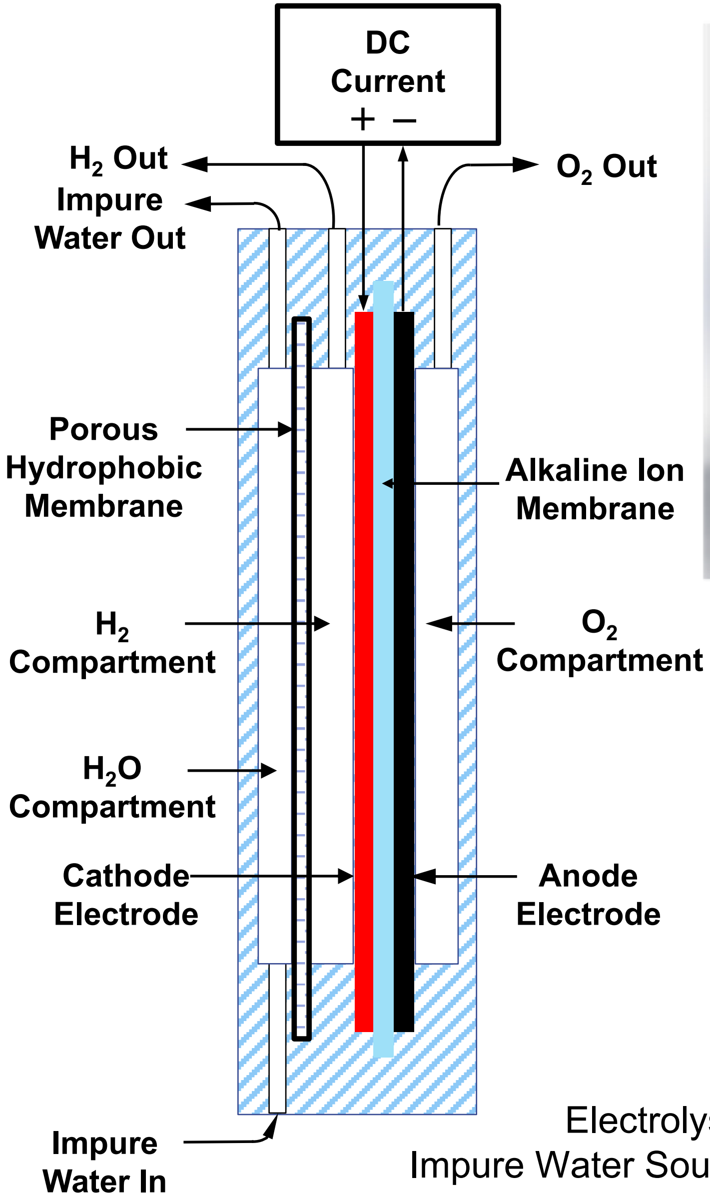
Post-vibration testing showing catalyst dust migration



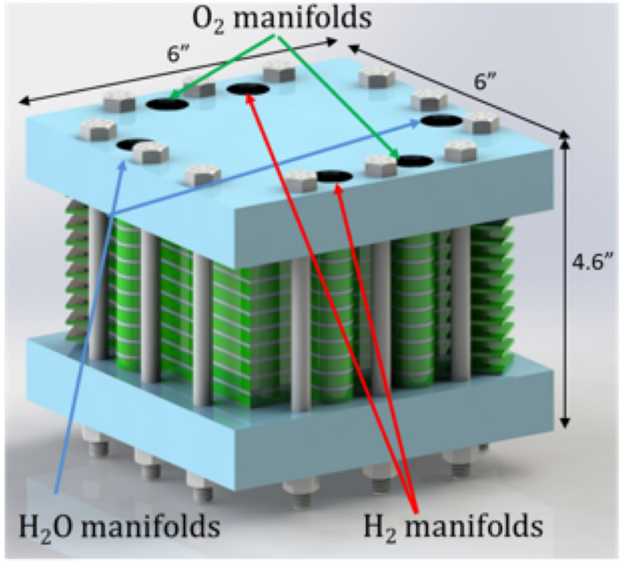

Preliminary thermal modeling

# Water Electrolysis (WBS 4.4)

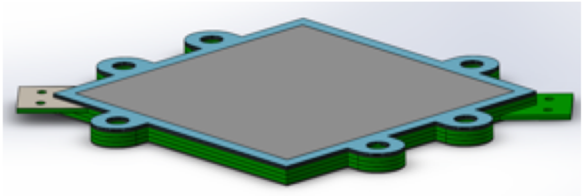
- Adapt alkaline water electrolysis membranes and electrodes to be used in a unique cell impure water source configuration
- Each cell has three compartments
  - Evolved oxygen
  - Evolved hydrogen
  - Water with contaminants
- Porous hydrophobic membrane permits water vapor to permeate the membrane, preventing transport of bulk liquid water and contaminants into hydrogen compartment
- Liquid water stream also acts as cooling stream
- Cells will be connected electrically in parallel because of high electrical conductivity expected of the contaminated water




Electrolysis Cell
Impure Water Source Configuration




Electrolysis Cell Stack Design



Unit Cell

# Excavation / Resource Acquisition (WBS 4.7) and Soil Processing (WBS 4.8.2)

- Resource Acquisition – Excavation Subsystem
  - Regolith geotechnical properties
  - Terramechanics of digging tools – how does size, shape, angle, vibration, etc. affect mass, power, and efficiency of excavation
  - Soil transport and transfer – what is proper size of the digging tool and carrying capacity, how to transfer soil, what is the transfer energy
  - Autonomous operation – what sensors are needed for surface navigation, health management, repair and maintenance, how to go over or around obstacles, how to communicate with multiple excavators

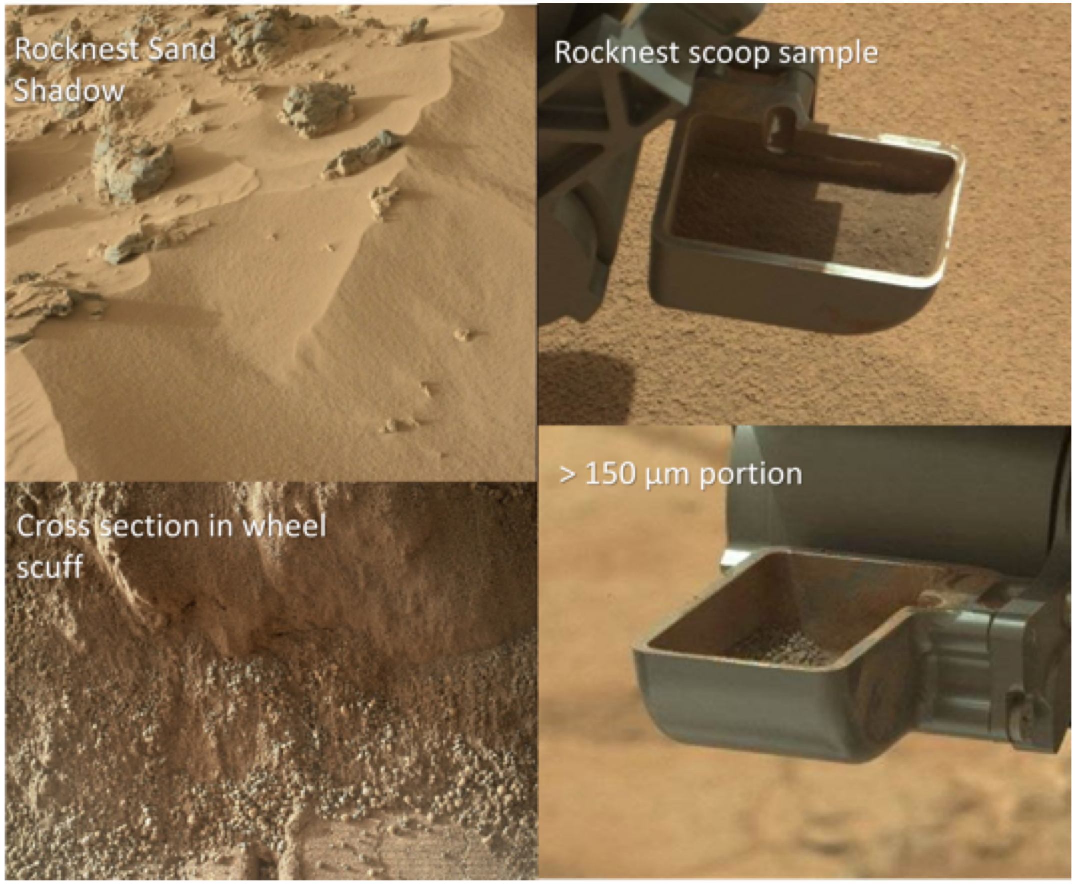
- Soil Processing – Soil Water Extraction
  - Batch and/or Continuous Open and/or Closed processors
    - How to feed the soil into / out of the reactor
    - Most efficient way to heat the soil
    - How much pre-processing of the soil is needed
  - Buried icy soils and deep ice deposits
    - What is the overburden material likely to be and should we strip or drill through

Initial excavator test hardware for compacted / frozen granular

Hard material test “ripper”

# Simulants Development- Mars Hydrated Soil (WBS 5.2.2)

- Define and document the expected resources possible at human mission landing sites and define physical, mineral/chemical, and water/volatile characteristics
- Working to define the overburden material and possible ice characteristics for Mars deep ice deposits
- Definition, production, and distribution of new Mars physical and chemical granular soil simulant
  - Matches Rocknest water release profile and grain size properties
  - Uses Mars Mojave Simulant (MMS) as base with additive to match desired characteristics
  - Recent tests show it cannot be rejuvenated after extracting water
  - Interagency agreement with CRREL to produce 1000 kg
- Beginning to define additional new Mars simulants of more consolidated hydrated material that might be found at Jezero Crater or NE Syrtis



# Next Space Technologies for Exploration Partnerships-2 (NextSTEP) Broad Agency Announcement

## Appendix D – ISRU Technology

## Enhancing Lunar Exploration with ISRU Strategies

BAA Track 1

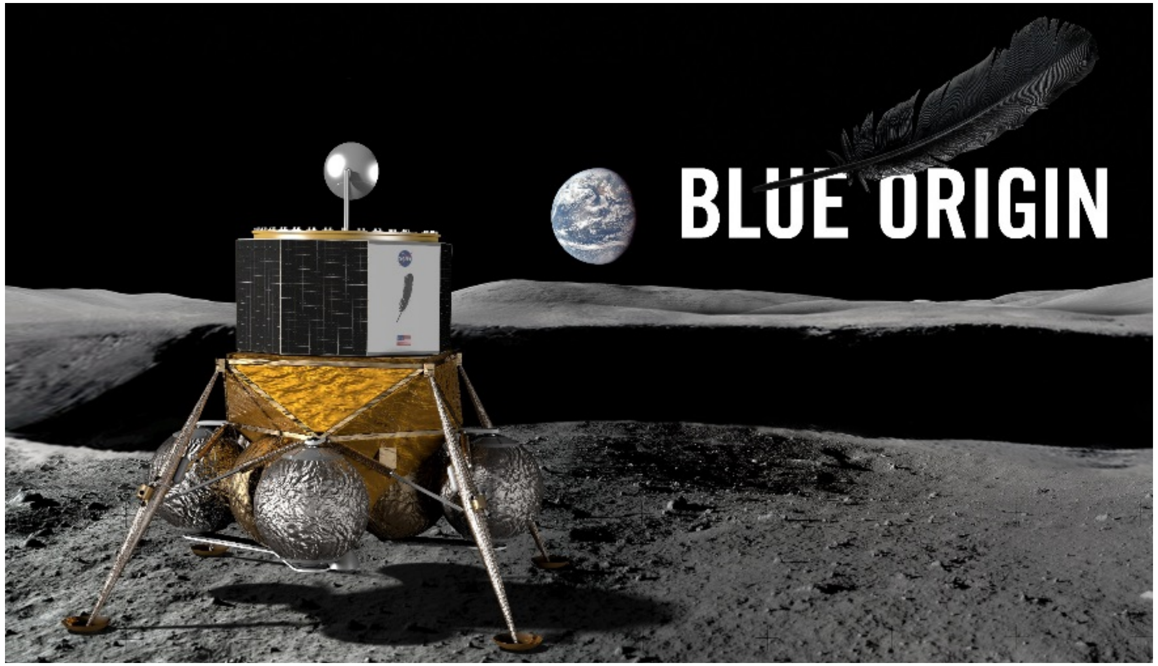
Team
- Dr. Christie Iacomini (Blue Origin Principal Investigator)
- Kent Joosten (Subcontractor)

## Technology Transfer and Commercialization

- Spin-in: Existing liquid propulsion and space system technologies
- Spin-out: *Blue Moon* commercial lunar lander

## Objectives & Approach

**Lunar ISRU Study**
- Model volatile lunar resources needed for various missions
- Sensitivities based upon concentrations
- How commercial architectures can utilize and/or transfer ISRU derived commodities



# ISRU Affordability Thresholds
BAA Track 1

Team

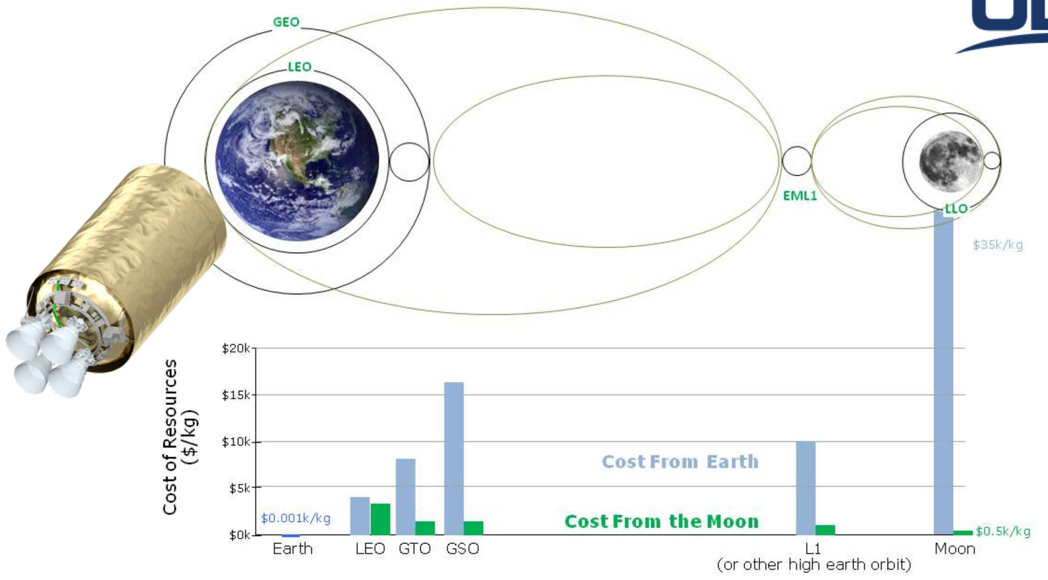
- United Launch Alliance

## Objectives & Approach

- Identify production rate requirements, and maximum price for ISRU propellants at the lunar surface in order to be less expensive than earth-based propellants in support of a range of potential missions & propellants utilizing ISRU $LH_2$, $LO_2$, or $H_2O$
- Requirements assessment and economic analysis grounded by experience with stage designs to derive transportation usage and cost

## Technology Transfer and Commercialization

- ULA has keen interest in emergence of commercial cislunar activity, and in potential for less expensive propellants to fuel ULA in-space transportation
- ULA upper stages Integrated Vehicle Fluids have capability well matched to emergence of lunar ISRU propellant transportation



# Integrated Architecture Trade Studies on ISRU Technologies for Human Space Exploration

BAA Track 1

## Team


- Koki Ho, University of Illinois, PI


## Technology Transfer and Commercialization

- <u>'Spin-in':</u> leveraging organization/PI's expertise and capabilities in multi-disciplinary design optimization, space logistics modeling, and ISRU modeling.
- <u>'Spin-out':</u> enhancing organization/PI's capabilities in ISRU trade study modeling and general network optimization methods; promoting collaboration with industry and government in space and terrestrial applications; education of next generation of engineers.

## Objectives & Approach

<u>Major project objectives:</u> perform trade studies to evaluate the benefits of ISRU, analyze the tradeoff on ISRU options, and optimize the design of infrastructure and architecture elements.

<u>Technical Approach</u>

- Perform optimization and trade studies on ISRU surface infrastructure.
- Perform space logistics optimization and trade studies with both ISRU infrastructure and in-space architecture elements integrated.
- Upgrade the NASA's past/existing studies.

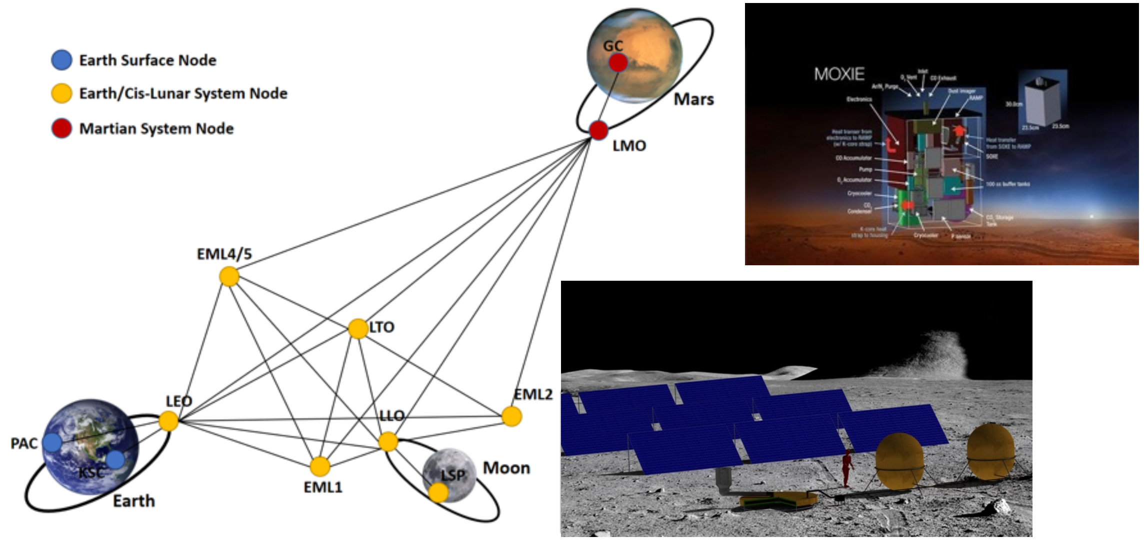



*Fig. Network modeling of space logistics enables architecture optimization and evaluation of the value of ISRU (Credit: UIUC, MIT, NASA)*

## NextSTEP-2 ISRU Technology – Water Electrolysis

BAA Track 1

- Program – Darren Samplatsky will act as the team lead. He has proven repeated success in efficiently meeting challenging ECLSS objectives
- Advanced Technology – Phillip Baker will provide the technical leadership for the trade study effort with expertise in water electrolysis cell design and system architecture.
- Safety – Scott Schneider will provide safety and hazards assessment during the trade study effort, with relevant experience in ISS systems employing hazardous fluids.

## Technology Transfer and Commercialization

Relevant system design and operational experience from both the ISS Oxygen Generation Assembly (below left) and the U.S. Navy Oxygen Generator (below right) will prove valuable in assessing technical approaches for the Mars ISRU water electrolysis system for propellant production.

## Objectives & Approach

- Conduct a trade study of available water electrolysis cell and system designs to identify an optimal solution for generating oxygen and hydrogen as key reactants in a propellant manufacturing process for a Mars ascent vehicle.
- Identify and assess trade study factors to appropriately weigh key requirements for a water electrolysis system – factors to be considered include launch mass and volume, operational efficiency, safety and reliability and simplicity.
- Select a baseline system design and create a development pathway to burn down technical risks.

ISS OGA

U.S Navy OG

UTC Aerospace Systems

# Compact High Efficiency Self-Cleaning Dust Filter for Martian Air

BAA Track 2

## Team

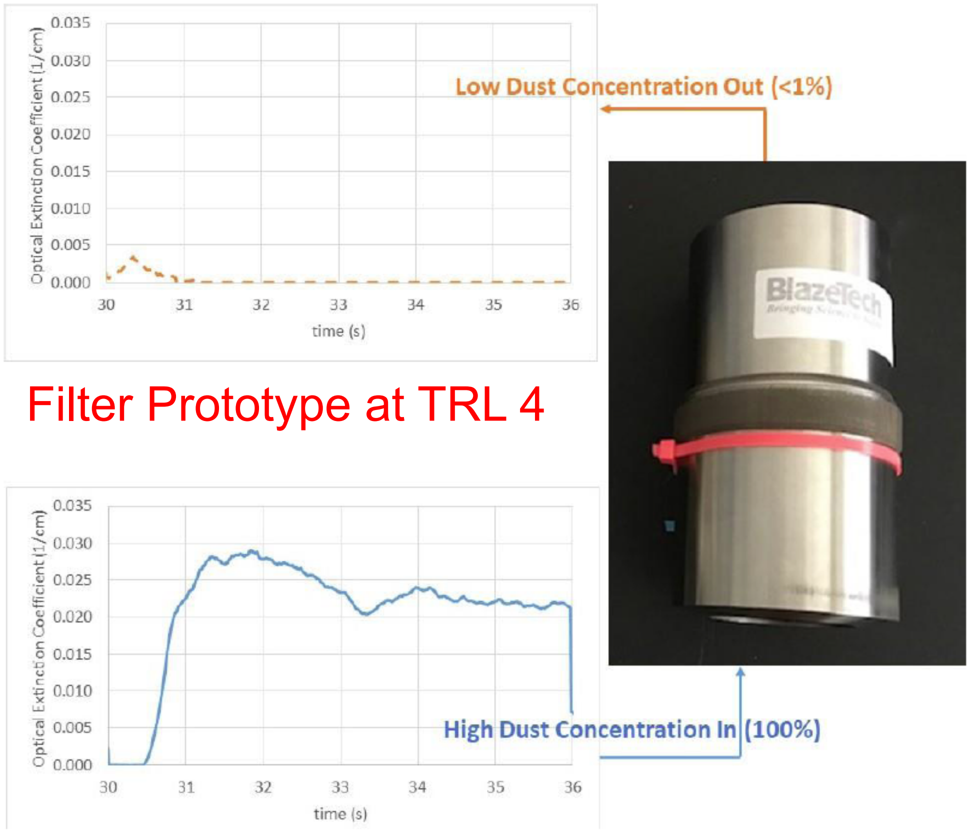
- Dr. **Vijay V. Devarakonda**, BlazeTech Corp., PI
- Dr. N. Albert Moussa, BlazeTech Corp., Analysis
- Dr. Raheem Bello, Afthon, Testing
- Mr. Kevin Goold, AGS, Fabrication

## Technology Transfer and Commercialization

- Spin-in: BlazeTech's Martian dust filter technology developed through a recent NASA SBIR project is the starting point for the proposed project
- Spin-out: successful completion of proposed technology advancement will benefit BlazeTech's technologies for controlled dust aerosolization and fine particle characterization

## Objectives & Approach

- Objective: Develop and demonstrate a compact high efficiency self-cleaning dust filter to remove > 99% of 0.05 to 10 µm sized particles from Martian gas
- Mature filter technology from current level (TRL 4) to TRL 5 in the proposed effort through:
    1. Controlled parametric testing under Martian environment simulated in a 75 $ft^3$ vacuum chamber to fine-tune filter operation for > 99% filtration efficiency
    2. Design and analysis to lower filter size, mass, and power requirement
    3. Characterization, documentation, and delivery of β-prototype




Filter Prototype at TRL 4

# Hydrogen and Methane Separator for Martian ISRU Processing
BAA Track 2

## Team

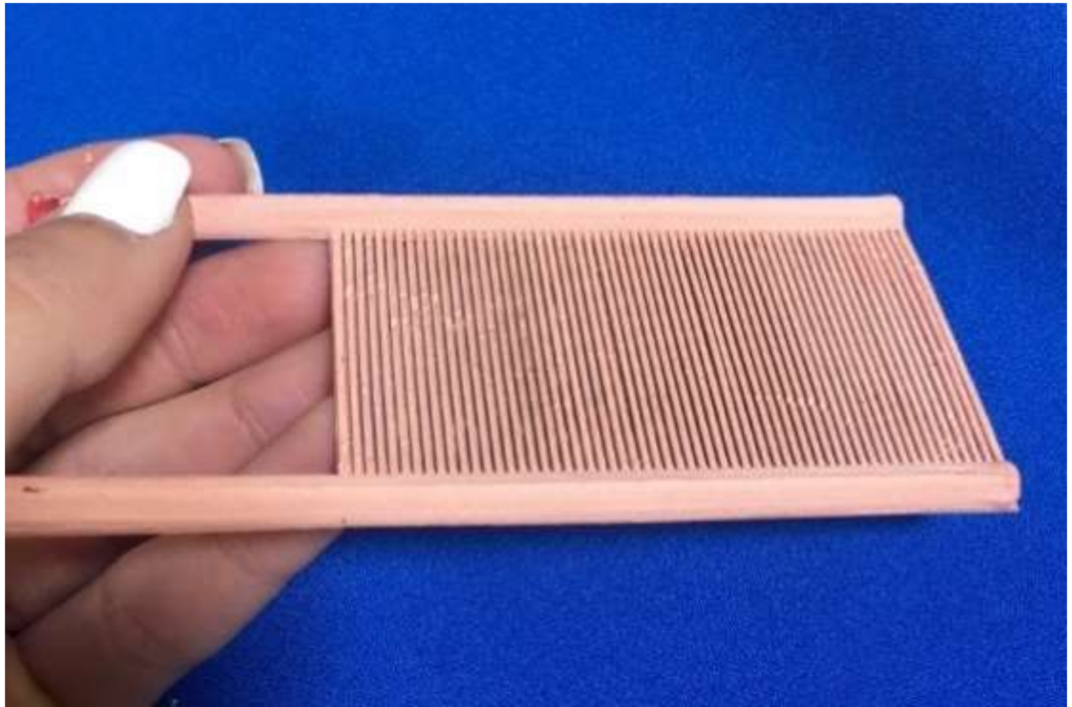
- Skyhaven Systems, LLC

## Technology Transfer and Commercialization

- The separator is applicable for NASA's rocket engine testing and launch support operations that need to separate hydrogen and helium gas mixtures
- Commercial separations for MRI and nuclear energy processes

## Objectives & Approach

- Develop and demonstrate a $H_2/CH_4$ separator for NASA's Martian ISRU processing at a TRL 5.



# **ISRU-derived Water Purification and Hydrogen Oxygen Production (IHOP) Component Development**

BAA Track 2


## **Paragon Space Development Corporation**

- Laura Kelsey, Principal Investigator & Program Manager
- Barry W. Finger, Chief Engineer
- Patrick Pasadilla, Deputy Program Manager
- Chad Bower, Thermal Systems Technical Lead

## **Giner, Inc.**

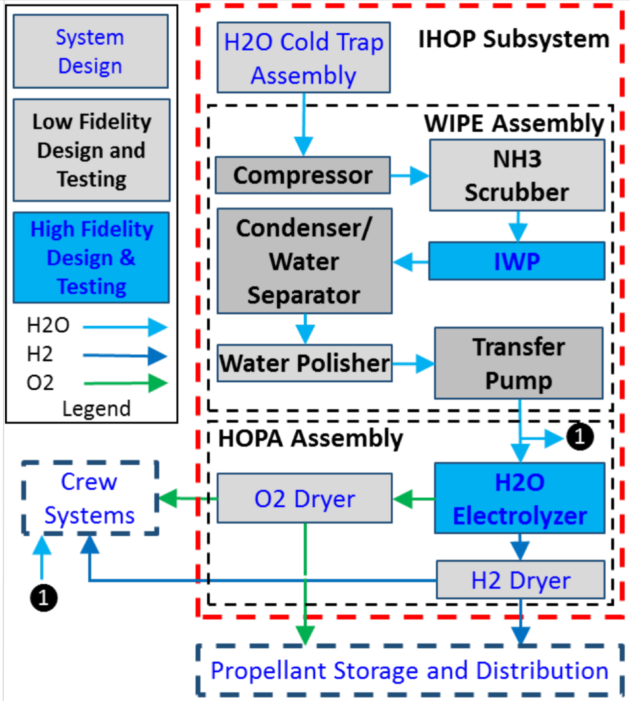
- Jason Willey, Senior Project Engineer
- Winfield Greene, Mechanical Engineer
- Simon Stone, Director – Applied Electrochemistry

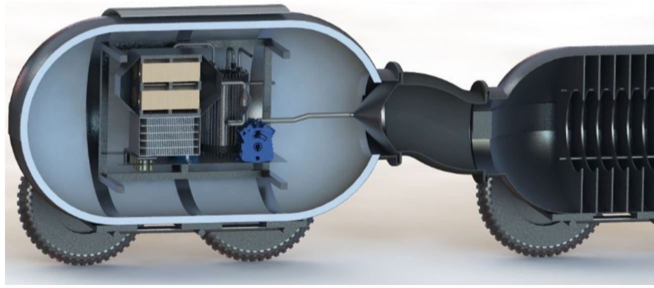

## **Technology Transfer and Commercialization**

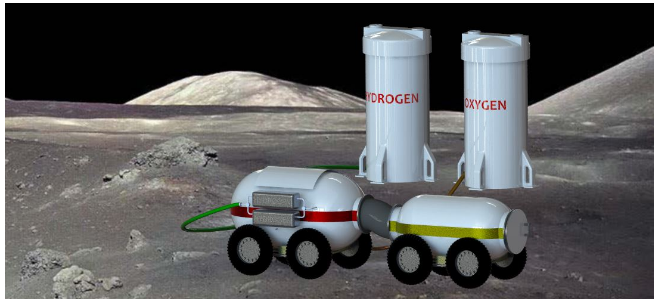
- Paragon draws on our Ionomer-membrane Water Processing (IWP) technology applications including Contaminant Robust In situ Water Extractor, Brine Processor Assembly for ISS, and Humidity Control Subsystem for Boeing CST-100 to develop the **Water ISRU-derived Purification Equipment** (**WIPE**) and **Hydrogen Oxygen Production Assembly** (**HOPA**) components
- Giner's lightweight electrolyzer technology is the direct descendant of Giner's first stack built in 2004 under NASA contract
- Lifetime testing feeds directly into NASA future utilization of this technology
- IHOP advancement will be applied to Paragon's ISRU and water processing applications for NASA and commercial deep space exploration and planetary uses

## **Objectives & Approach**

- Rapidly advance the maturity of IHOP water purification and electrolyzer components through completion of design work and component-level testing
- Optimize the integration of the WIPE and HOPA Assemblies and develop the IHOP high fidelity prototype components through preliminary design.
- Demonstrate integrated performance of the WIPE and HOPA assemblies at full scale under relevant operating conditions and advance key component technologies from TRL 4 to 5





# Advanced Alkaline Electrolyzer to Support NASA ISRU Application

BAA Track 2

Team: Teledyne Energy Systems

- Dr. Thomas I. Valdez – PM
- Michael Miller – PI
- Stuart Pass – System design
- Ying Song – MEA design

## Technology Transfer and Commercialization

- Provide high pressure water electrolysis stack for life support and/or fuel cell reactant in space
- Offer high pressure electrolysis within the commercial hydrogen market where TESI is presently an active participant.

## Objectives & Approach

- Develop and test a high pressure, alkaline based water electrolysis stack. The chemistry and cell configuration being proposed will require less feed water processing then present commercial high pressure electrolyzers require. The goal is to develop an electrolysis process that can support the level of contaminants expected in ISRU water.
- The approach is to build and test a single cell stack followed by a 10-cell breadboard based on the full size stack design.

# RedWater: Extraction of Water from Mars' Ice Deposits
BAA Track 3

## Water Team (Engineering team):
•Kris Zacny, Honeybee Robotics, PI
•Gale Paulsen, Honeybee Robotics, Systems Engineer
•Phil Morrison, Honeybee Robotics, Water extraction/engineering lead
•Bolek Mellerowicz, Honeybee Robotics, Lead Electrical/Controls
•Kristian Mueller, Honeybee Robotics, Project Manager

## Red Team (Review team)
•Michael Hecht, Massachusetts Institute of Tech., Mars melt probes, ISRU (Phoenix, MOXI, Chronos)
•Nathaniel Putzig, Planetary Science Institute, Mars ice deposits (SHARAD, TES, THEMIS)
•Fredrik Rehnmark, Honeybee, drilling/engineering
•Dara Sabahi, NASA Jet Propulsion Lab (retired), Systems Eng. and Mars Ops. (MSL, MER, Phoenix)
•Paul van Susante, Michigan Technological University, Mars excavation and ISRU

## Objectives
RedWater is a water extraction system from Mars ice deposits (e.g. Arcadia Planitia; 10s of meters ice deposits underneath <20m regolith). It combines two terrestrial technologies into one: Coiled Tubing for making a hole and RodWell for melting/pumping water.

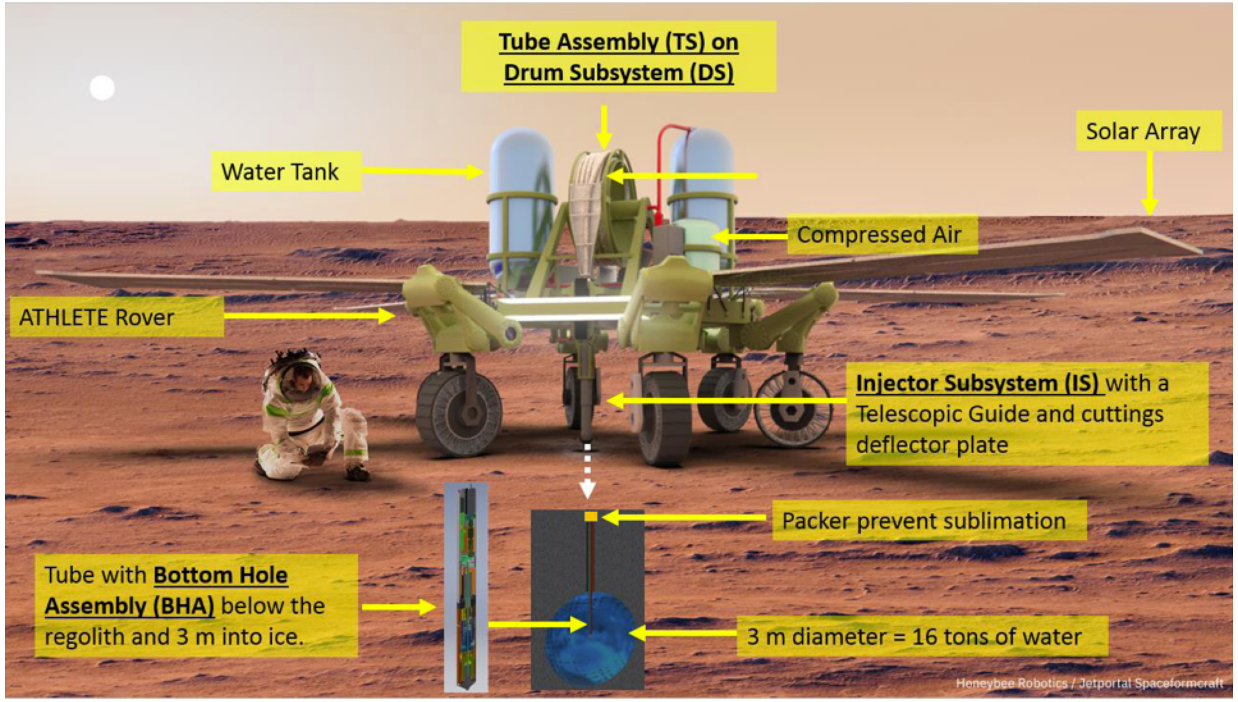
**The goals are:**
•Develop TRL6 water extraction system,
•Demonstrate feasibility of mining water in Mars chamber
•Provide engineering and performance data for extracting 16 tons of water.

## Technical approach
•Demonstrate critical components of the RedWater for Mars
  •Making a hole (drilling, pneumatic chips transport, tube assembly and injector, drum)
  •Extracting water (melting, water-jetting, pumping)
•Test components in Mars chamber and freezer to reach TRL5
•Develop and validate thermal model for hardware and melting
•Design and hold Primary Design Review (PDR)
•Fabricate RedWater TRL6 subsystem (drilling/water extraction)
•Test RedWater in 5 m freezer and 3.5 m Mars chamber to reach TRL6

# Technology Transfer and Commercialization

## Terrestrial and space technology relevant to project
•Coiled Tubing (mining, oil and gas) – commercial technology
•Rodriquez Well (water extraction in Antarctica and Greenland) – commercial technology
•Melt Probes (Europa, Mars) – Honeybee and NASA JPL (Chronos) technology
•Heat Flow Probe (Europa, Mars, Moon) – Honeybee technology
•Deep Drilling (Europa, Mars) – Honeybee technology

## Terrestrial and space technology that will benefit from project
•Coiled Tubing (mining, oil and gas) – spinoff into terrestrial market
•Rodriquez Well (water extraction in Antarctica, Greenland) – spinoff to terrestrial market
•Melt Probes (Europa, Mars) – spinoff into space market
•Heat Flow Probe (Europa, Mars, Moon) – spinoff into space market
•Deep Drilling (Europa, Mars) – spinoff into space market



# Production of $O_2$ & Fuels from In-Situ Resources on Mars

BAA Track 3

Key Members: Joseph Hartvigsen, Principal Investigator
S. Elangovan, Scientist
Organization: OxEon Energy, LLC
Role: Electrolysis Stack
Fuel Synthesis Reactor
Component integration
JPL Facility: Mars Environmental Chamber

## Technology Transfer and Commercialization

- OxEon personnel designed high temperature electrolysis modules working with DOE, NASA, Phillips 66
- Delivered SOXE stacks for MOXIE on 2020 Mars Rover launch
- Conducted fuels synthesis work for Department of Energy, Naval Research Laboratory, Hunt Oil, State of Wyoming
- Current contracts with State of Utah on high temperature electrolysis / co-electrolysis; commercial entity
- Current contracts on fuels synthesis with American Refining Group, Naval Research Laboratory, Calvert Energy, Verdis
- Proprietary design for modular, transportable fuel synthesis reactor
- NASA specific development of rugged, hermetic $CO_2$-steam co-electrolysis stack with fuel synthesis reactor integration will enable commercial application of renewable energy storage as synthetic hydrocarbon fuels

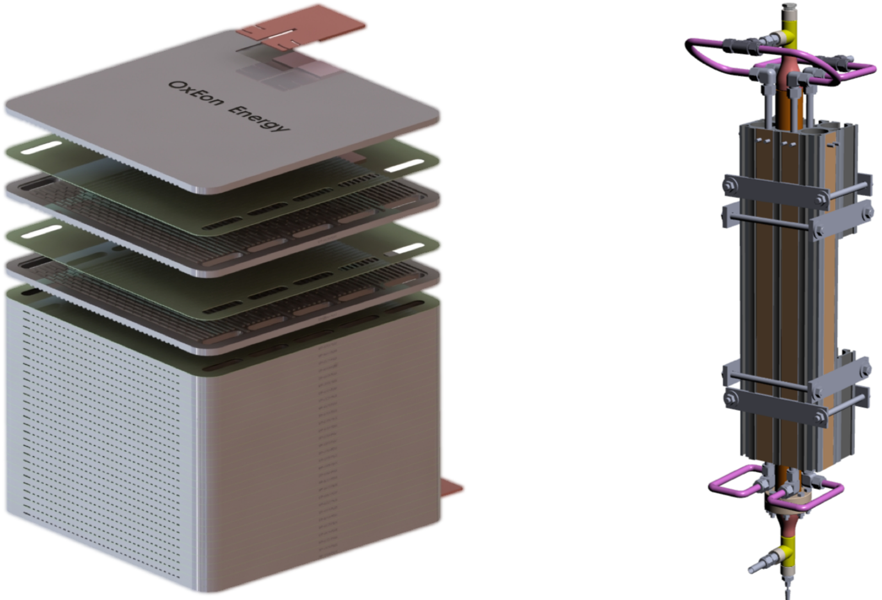
## Objectives & Approach

Objectives:

- Produce a large format electrolysis stack that produces high purity oxygen, $H_2$, & CO
- Produce a methanation reactor
- Use the $H_2$, CO from electrolysis to produce $CH_4$ at desired volumes

Approach:

- Phase 1: Individual component fabrication and testing; component integration design; test components in relevant environment
- Phase 2: Finalize integrated design; build an integrated system; test system in relevant environment



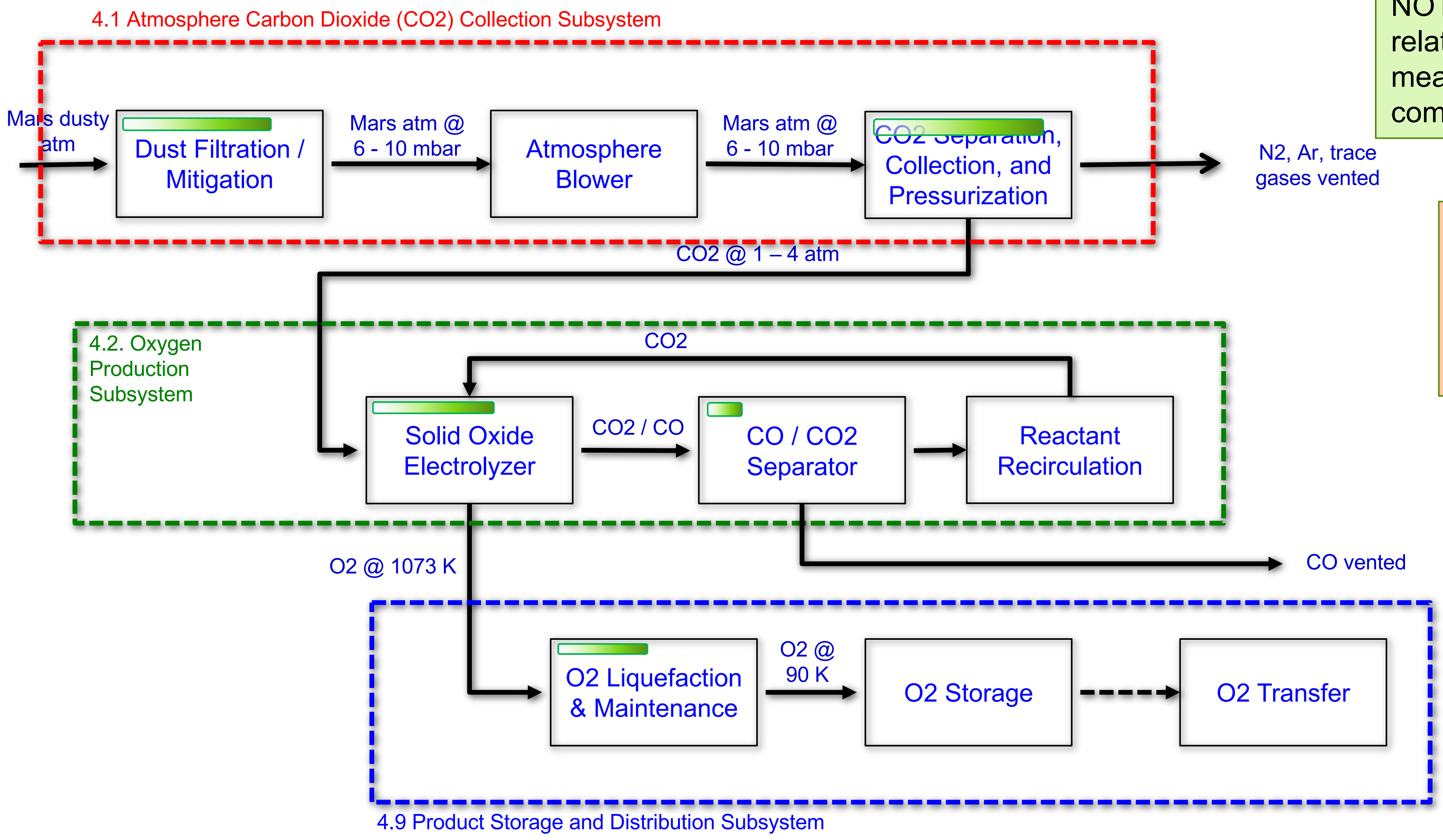

OxEon $CO_2$ Electrolysis Stack and Methanation Reactor Renderings

# Appendix: Current Status of ISRU Systems

# ISRU Subsystem and System Flow Charts

- Flow charts represent scope of ISRU project and define components, subsystems, and systems
  - Systems shown are examples and do not represent all possible options for ISRU systems at the Moon and Mars
  - Two options shown for $O_2$ production from atmosphere
    - Solid oxide electrolysis of $CO_2$ (SOE)
    - Reverse Water Gas Shift (RWGS)
  - Two options shown for $O_2$ and fuel production from atmosphere and water
    - Sabatier with ‘traditional’ water electrolysis
    - Solid oxide co-electrolysis of water and $CO_2$ with separate or integrated Sabatier reaction
  - Systems show current activity and gaps – what we are doing today and the challenges that we face
    - Some systems have unique gaps/challenges and some challenges/gaps are common to multiple systems
  - Legend:
    - Green bars inside boxes represent relative amounts of in-house activity as measured by progress towards TRL, $$ invested, or both
    - Orange bars show how recently awarded BAA contracts will help fill gaps

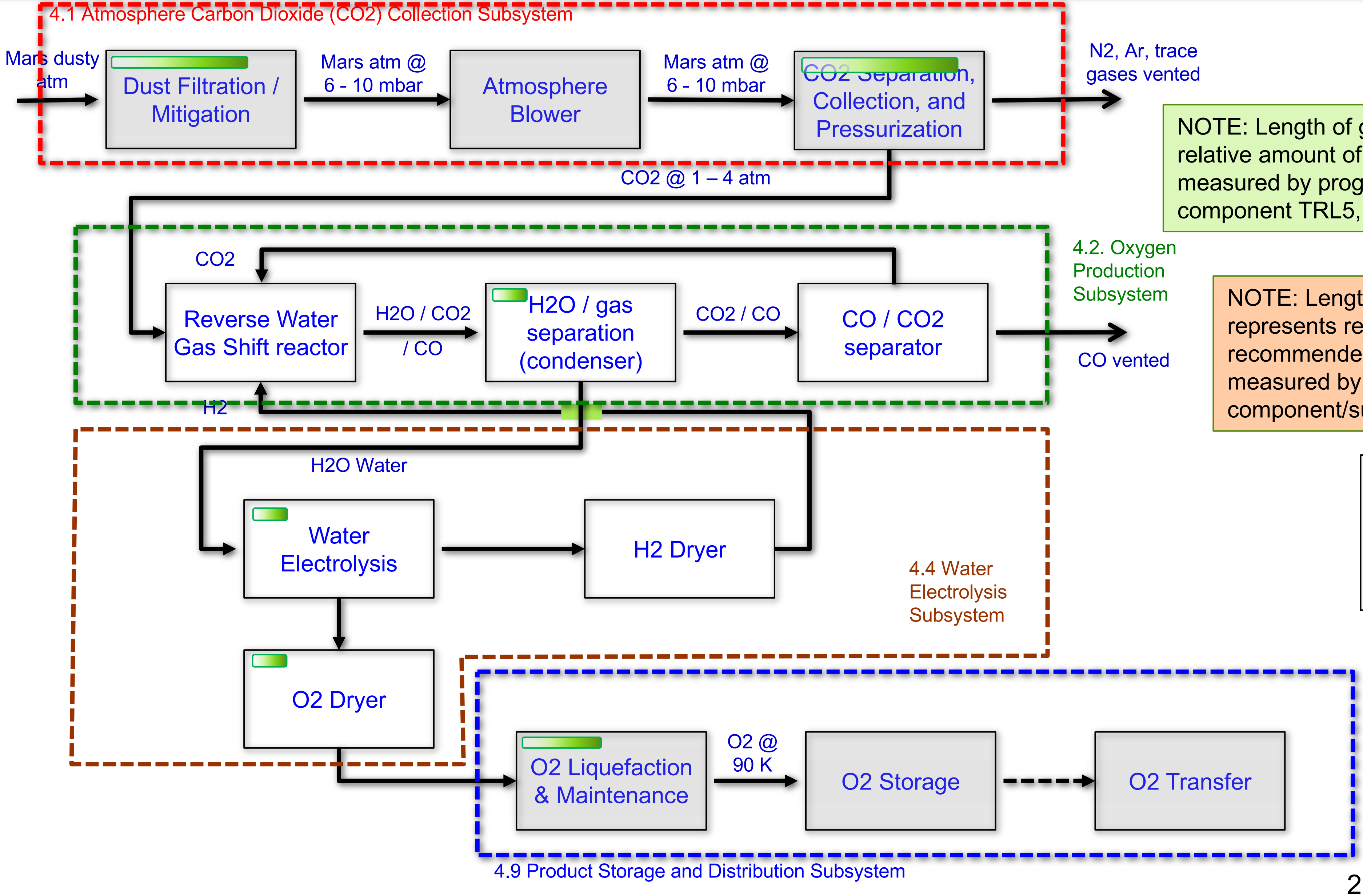
# Oxygen Production from Atmosphere Integrated System (SOE Option)




NOTE: Length of green bar represents relative amount of in-house activity as measured by progress towards component TRL5, $ investment, or both

NOTE: Length of orange bar represents relative gap filled by recommended BAA award as measured by progress towards component/subsystem TRL5/6

# Oxygen Production from Atmosphere Integrated System (RWGS Option)

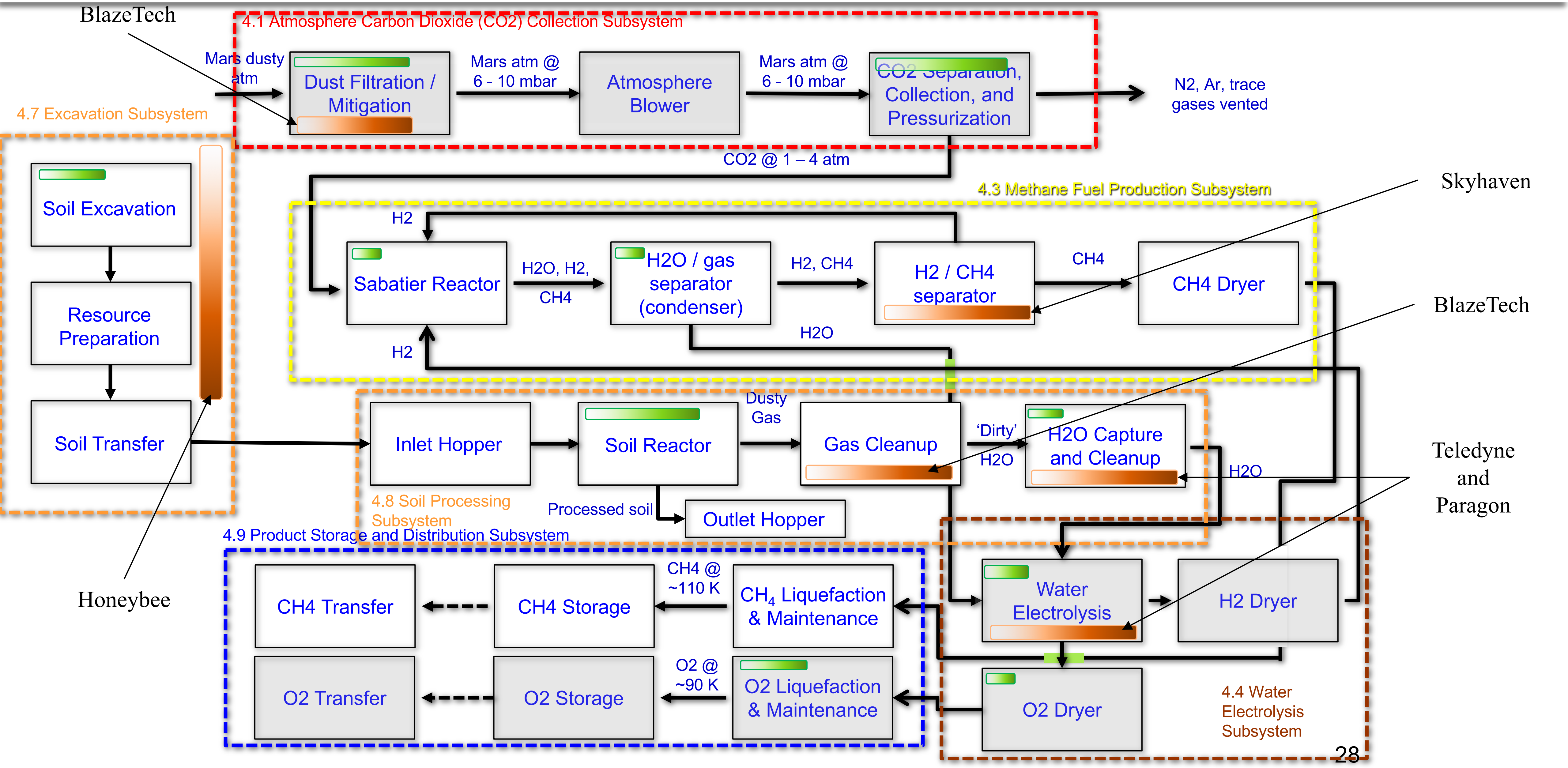



NOTE: Length of green bar represents relative amount of in-house activity as measured by progress towards component TRL5, $ investment, or both

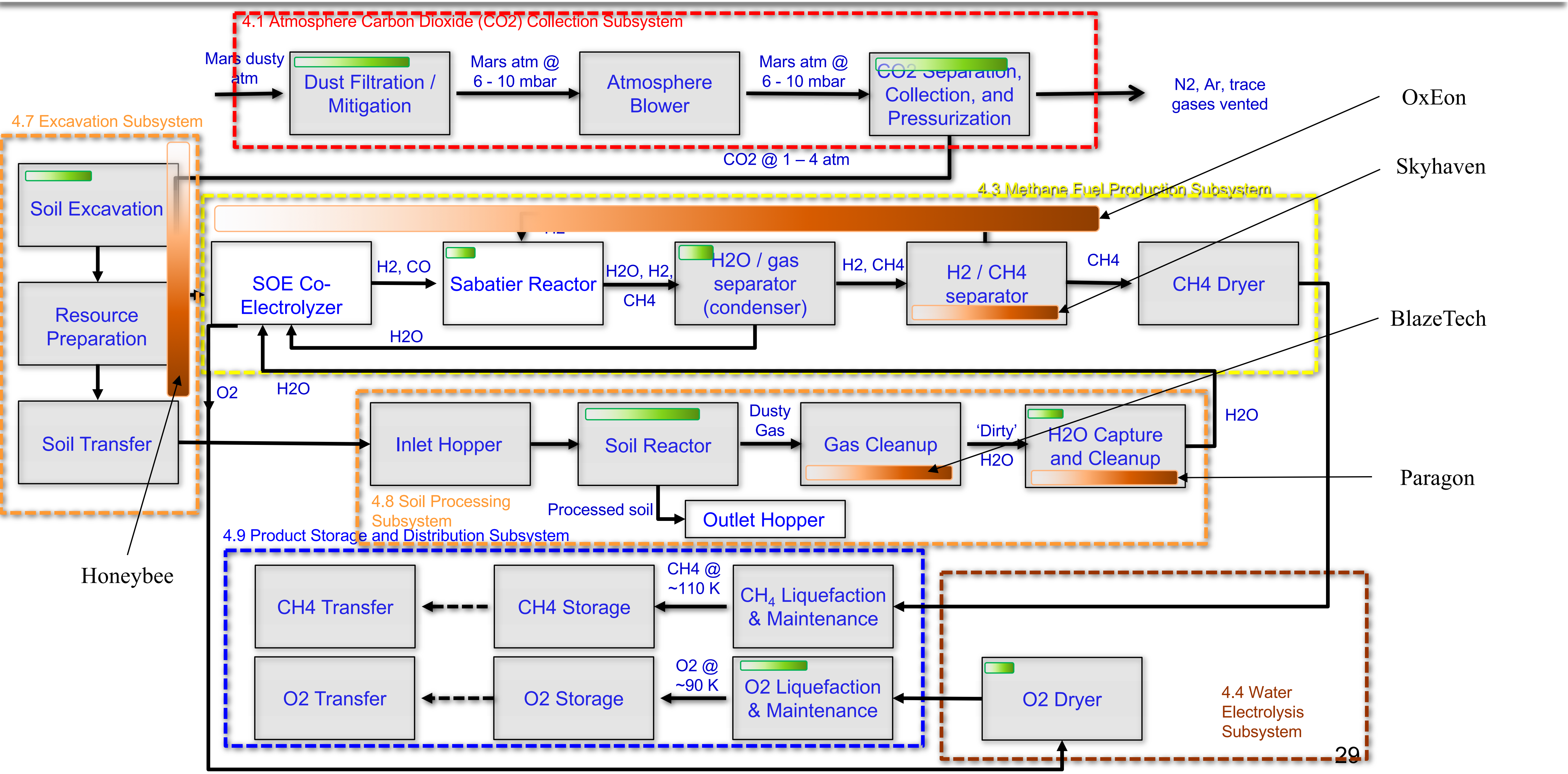
NOTE: Length of orange bar represents relative gap filled by recommended BAA award as measured by progress towards component/subsystem TRL 5/6

Gray boxes are same components as previous systems

# ISRU Fuel and Oxygen Production End-to-End Integrated System – Mars Traditional Water Electrolysis Option



# ISRU Fuel and Oxygen Production End-to-End Integrated System – Mars Co-Electrolysis Option



# ISRU Fuel and Oxygen Production End-to-End Integrated System – Moon Polar Water Option