National Aeronautics and Space Administration

ISRU

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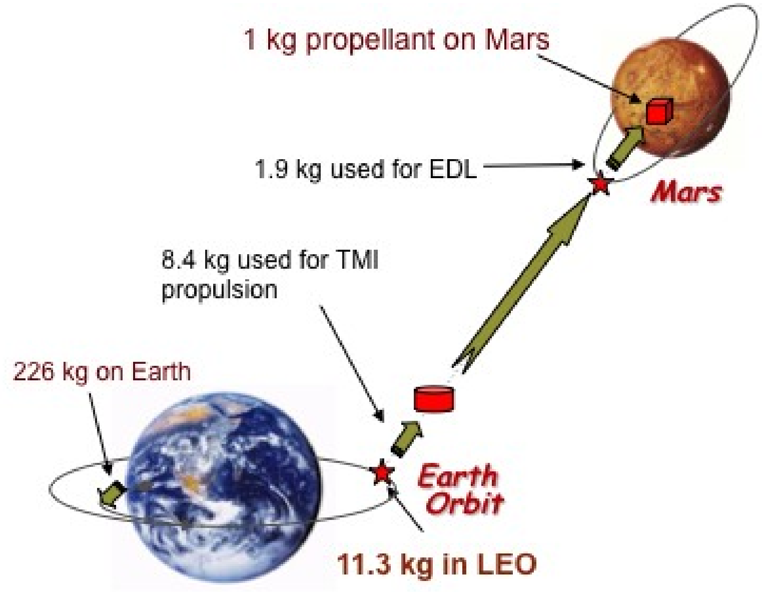
Diane Linne, Project Manager, NASA GRC

ISRU

Project Overview

Why is this project important?

- Production of large consumables (propellants, life support) on the surface of the Moon or Mars significantly reduces launch costs and enables sustained exploration
  - Every 1 kg produced on the surface saves 7 to 11 kg launched to LEO
- Reliance on in-situ produced propellants and life support consumables has never been done before and represents a new paradigm for space exploration – we must prove the capability at the system level before it will be incorporated



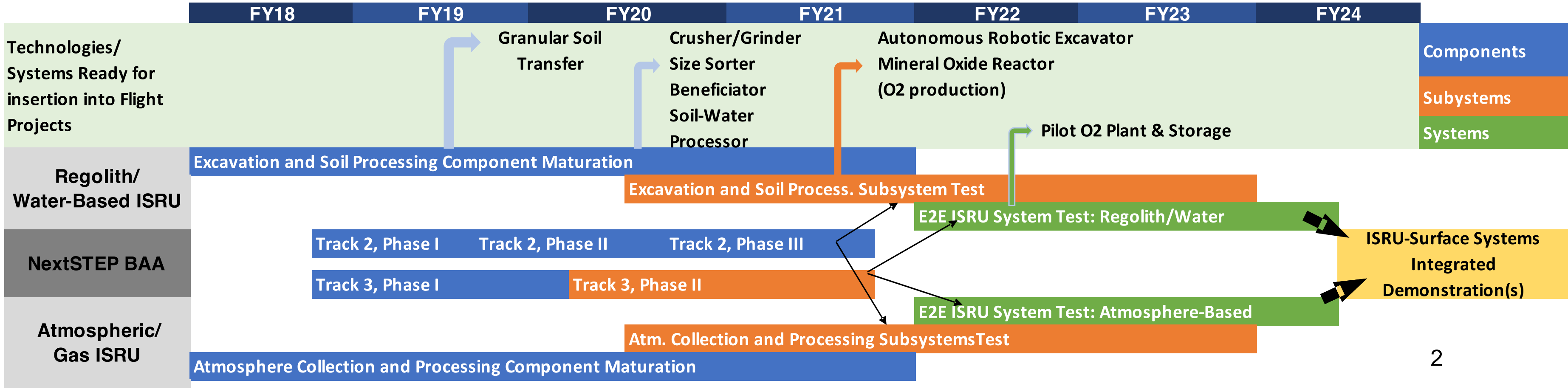
Estimates based on Aerocapture at Mars

Objectives

- 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

Current activities

- NASA in-house technology development at GRC, JSC, KSC, and JPL
- 10 NextSTEP BAA awards



FY18 FY19 FY20 FY21 FY22 FY23 FY24

Technologies/ Systems Ready for insertion into Flight Projects

Granular Soil Transfer

Crusher/Grinder
Size Sorter
Beneficiator
Soil-Water Processor

Autonomous Robotic Excavator
Mineral Oxide Reactor (O2 production)

Pilot O2 Plant & Storage

Components

Subsystems

Systems

Regolith/ Water-Based ISRU

Excavation and Soil Processing Component Maturation

Excavation and Soil Process. Subsystem Test

E2E ISRU System Test: Regolith/Water

NextSTEP BAA

Track 2, Phase I

Track 2, Phase II

Track 2, Phase III

Track 3, Phase I

Track 3, Phase II

ISRU-Surface Systems Integrated Demonstration(s)

Atmospheric/ Gas ISRU

E2E ISRU System Test: Atmosphere-Based

Atm. Collection and Processing SubsystemsTest

Atmosphere Collection and Processing Component Maturation

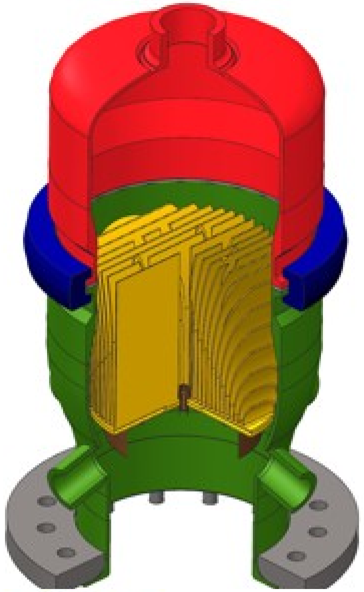
ISRU

Major Accomplishments – NextSTEP BAA Awards

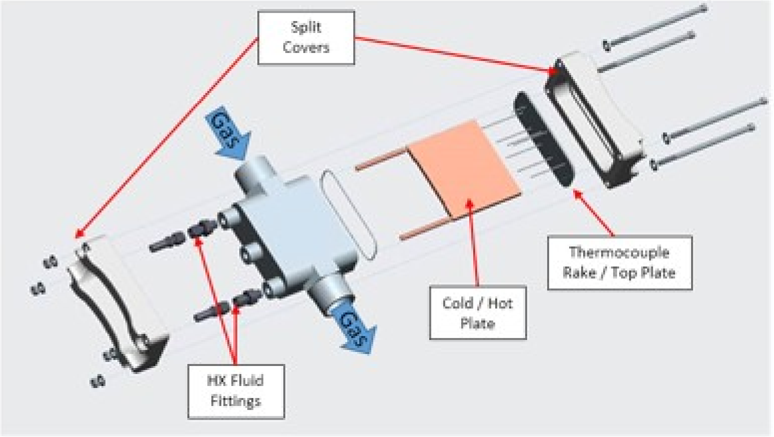
- **Track 1: Trade Studies (< 1 year): 4 Awards**
  - 3 architecture trade studies: Blue Origin, ULA, University of Illinois
  - 1 technology trade study on water electrolysis subsystem: UTC Aerospace
- **Track 2: Component Development (3 years): 4 Awards**
  - BlazeTech (dust filtration); Skyhaven (H_2 separation); Paragon (water clean-up and electrolysis); Teledyne (dirty water electrolysis)
- **Track 3: Subsystem Development (3.5 years): 2 Awards**
  - Honeybee Robotics (excavation, acquisition, and storage of Mars subsurface ice/water)
  - OxEon (oxygen and fuel production from Mars CO_2 and water)
- **Awards announced May 31st**
- **Total Value ~$10M**
- **Track 1 contracts are underway**
- **Track 2 and 3 are at various stages of the procurement process**

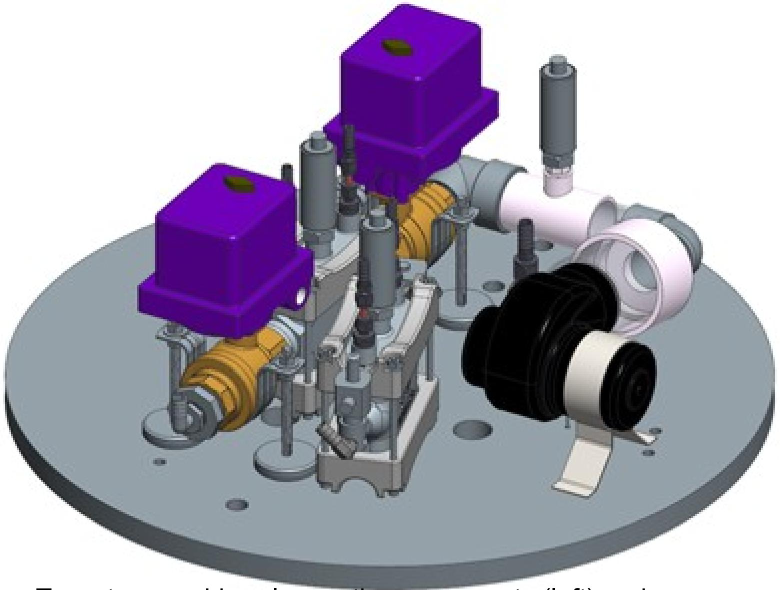
WBS 4.1 Atmosphere Carbon Dioxide Collection Subsystem
Major Accomplishments

- **Completed flow performance tests of the ISRU Scroll Filter in the Mars Flow Loop**
- **Electrostatic precipitator geometry optimization**
  - Stack of 137 cylindrical precipitators with a 71 mm diameter and 100 cm length can collect 3 μm-diameter particles flowing at 6 kg/hr at 99% efficiency
- **Completed design and initiated fabrication of full-scale CO2 cryofreezer**
  - Cold head design based on lessons learned from sub-scale testing and analysis of multiple cold-heads
- **Rapid cycle adsorption pump single-stage fabrication and test preparations completed**
  - Two-stage design 95% complete and procurement ~30% complete


Cryofreezer chamber cut-away view of cold head

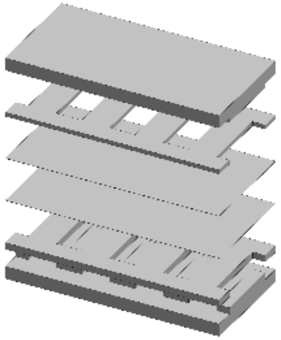

Cryofreezer two-part cold head

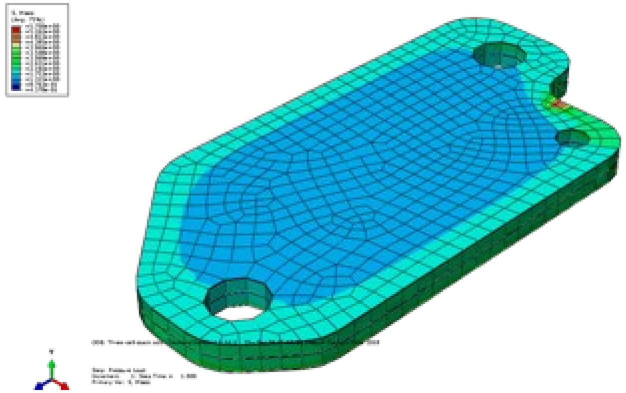



Two-stage rapid cycle sorption pump parts (left) and layout(above) in Mars chamber

WBS 4.2 Oxygen Production, 4.3 Fuel Production, and 4.4 Water Electrolysis Subsystems
Major Accomplishments

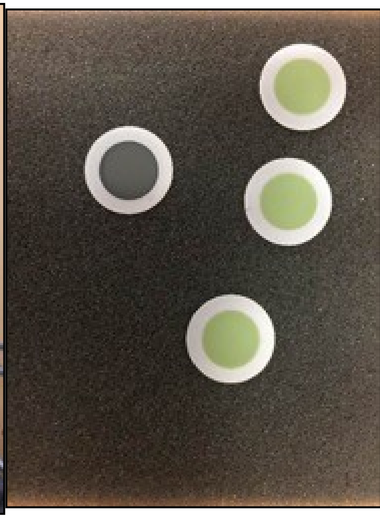
- **SOE Modeling**
  - Completed MOXIE stack structural / thermal response at operating conditions
  - Created single plate model with reaction kinetics
- **SOE Materials Selection – Electrode Development**
  - Completed build-up of 4-gas test facility for button cell testing
  - Procured single button cells for evaluation
- **Completed physical tests of Sabatier catalysts and measured performance post-test**
- **Completed fabrication of dirty-water electrolyzer stack**
  - Completed test rig fabrication and assembly

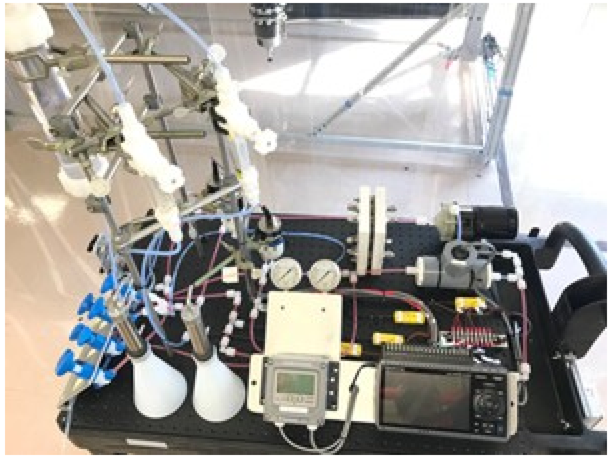

Exploded view of MOXIE layering


3-cell MOXIE stack stress distribution


Gas flow panel and furnace in fume hood

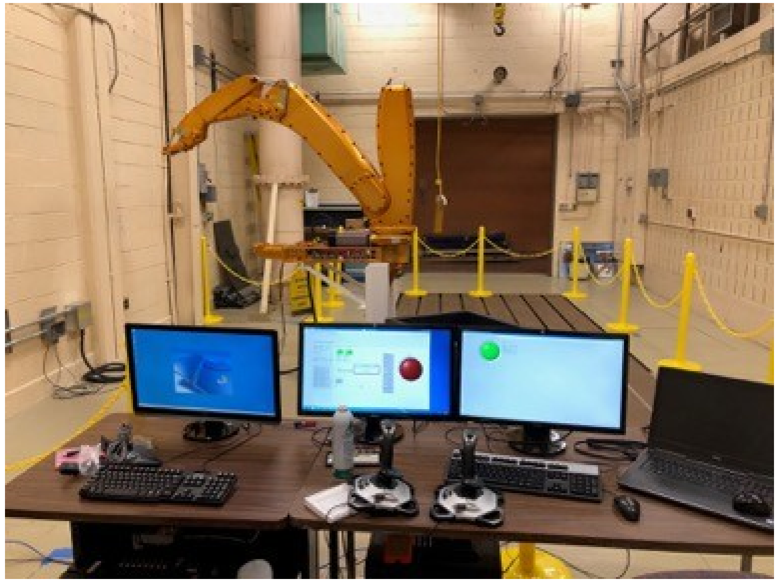

Single cell test fixture with button cell installed


Vendor supplied button cells


Electrolysis test rig

WBS 4.7 Excavation Subsystem
Major Accomplishments

- **Surface granular material lab space reconditioned and hardware installed**
  - Multiple pre-programmed bucket trajectory profiles test calibration runs with empty bucket and in pea-gravel (analog mass)
- **Consolidated / hard excavation testing of single tooth ripper**
  - Tested in gypsum rock as Mars mineral and lunar icy deposits analog
  - Initial testing captured 3-axis forces, cuttings mass and size distributions, excavate volume, and high speed video
- **Autonomous excavation task initiated and developing concepts for excavation tasks and maintenance and repair design**



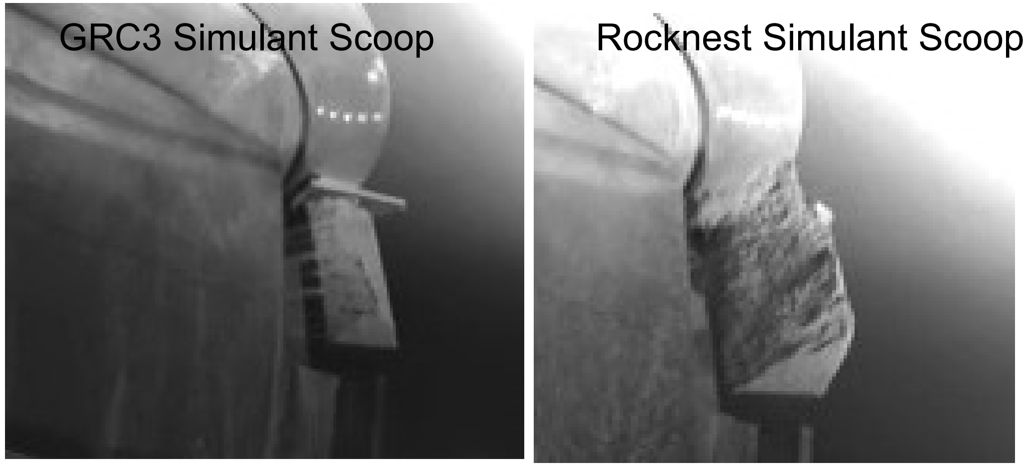
Initial granular excavator test hardware installed

Hard material ‘ripper’ single tooth test

WBS 4.8 Soil Processing Subsystem
Major Accomplishments

- **Microwave processing tests successfully extracted water in porous tube reactor**
  - Water release and heat efficiency with new Mars Rocknest simulant performed up to 100 °C
- **Open air processor tested with Mars Rocknest simulant**
  - Design modifications to improve soil flow and heating
  - significantly different material flow behavior
- **Auger-dryer soil flow testing completed with acrylic casing**
  - SS casing with heaters installed and completing test preparations
- **Partnership agreement (MOU) with the Army Cold Region Research and Engineering Laboratory (CRREL) signed for modification of CRREL Rodwell models to account for Mars environment**
  - Preliminary experiment design for test apparatus

Auger-dryer with acrylic casing



GRC3 Simulant Scoop

Rocknest Simulant Scoop

Open air bucket wheel scoop of GRC3 simulant compared to Rocknest simulant in Mars chamber

ISRU
Project Performance

🟩 = project is meeting its commitments
🟨 = project is not meeting its commitments, but has mitigation plans
🟥 = project is not meeting its commitments, and needs external assistance

Performance (Project Manager's overall assessment)

Project	Tech	Cost	Sch	Prg	Status
ISRU	🟩	🟩	🟨	🟩	First year of funding resulted in slow start while team was built and individual task plans finalized. Many hardware fabrication & test tasks are just entering testing phase now with completion in 1st quarter of FY19.

Milestone Status

FY18 AES Milestones	Planned Completion Date	Actual Completion Date	Comments
Issue NextSTEP BAA for ISRU trade studies and component technologies	12/4/17	12/4/17	Posted: 12/4/17 Proposals Received: 3/12/18 Awards Announced: 5/31/18
Complete testing of Auger Dryer for soil flow and heating efficiency	8/1/18	Soil Flow: 9/18 Heating: 1/19	Took NSSC 3 months to place a $25K PR with quotes supplied by requester.

ISRU
Challenges, Issues, & Risks

Challenges

- Being most popular kid on the block results in a lot of outside (the project) activity requiring time from ISRU leadership to keep up with studies, workshops, calls for proposals, etc. from both within and outside NASA
  - Would be easier to manage if we had the budget and FTE commensurate with this popularity
- Direction to refocus on the Moon makes it difficult to maintain any Mars work
  - Will experience start-up delays on lunar work as we resurrect the tasks and SME's from the '00 ISRU work
  - Will likely result in stopping most of Mars ISRU work due to insufficient budget to do both properly
- Reduction in FTE allotment at GRC and JSC resulting in loss of key team members
  - Challenge in FY18 getting people assigned to ISRU, now in FY19 will only be asking for partial people which will be difficult

Budget Issues

- Budget of \$10M is half of requested \$20M in FY19 as minimum required to maintain schedule of components – subsystem – systems development to meet flight opportunities
- Will be unable to post 2nd BAA solicitation to maintain public-private partnership approach

#	Risk	Mitigation
1	Lack of sufficient quantities of real lunar regolith (or perfect simulant) for hardware development	- Working with SCLT to forming a simulant advisory committee to create simulant strategy and then find the money for it - Look for opportunities to fly soil handling/processing component hardware demos

ISRU

Plans

- **Plans for FY19**
  - Complete testing of filters, cryofreezer, sorption pump (single stage and two-stage), SOE electrode materials, dirty water electrolyzer, granular excavation, microwave processor, auger-dryer, and subsurface ice properties
  - Evaluate status of previous lunar ISRU activities and restart key component development in hydrogen reduction, carbothermal reduction(?), size sorting, mineral beneficiation, and soil delivery
  - Evaluate, and test, existing soil processors at lunar conditions
  - Complete planning of autonomous excavation development path and initiate tasks
  - Develop lunar ISRU requirements, evaluate status of existing lunar component models, create new models where needed, perform lunar ISRU system-level trade studies in coordination with power, cryo, lander, and autonomy SMEs

ISRU

Partnerships

- AES Autonomous Systems and Operations (ASO) and NASA Platform for Autonomous Systems (NPAS)
  - 'Tiger Team' formed to develop plans for autonomous excavation and delivery technology development
  - Developing plans for joint ISRU, ASO, NPAS, and robotics activity to develop and demonstrate autonomous excavation
- AES Life Support Systems
  - Sorption pumps: sorbent isotherm data, collaboration on COMSOL models
  - Scroll filters: design collaboration
  - Process sensors: collaboration with Environmental Monitoring element team to identify ISRU sensor needs, existing SOA, gaps to be filled
  - Cryofreezers to separate CO_2 out of cabin air / out of Mars atmosphere
- AES Lander Technology
  - Funding ISRU liquefaction and storage technology development needed by ISRU
- MOXIE
  - ISRU project testing MOXIE HEPA filter in Mars Flow Loop
  - Modeling MOXIE SOE stack and using MOXIE test data to validate our models
- STMD: Low Cost Upper Stage: 3D printing of GR-Cop84 cold heads for ISRU cryofreezer testing
- SMD: Supporting landing site characterization (resources and physical), development of Mars simulants

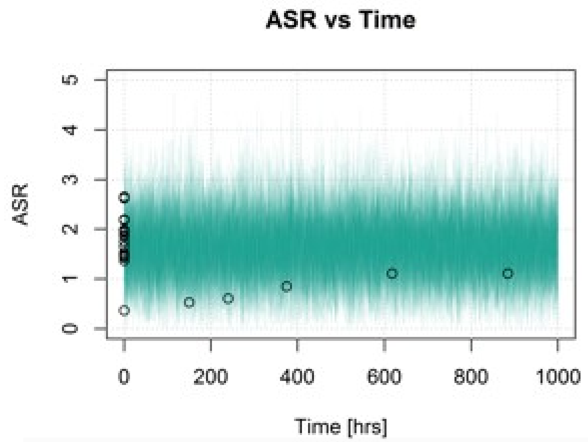
Backup

ISRU FY18 Highlights since mid-year review

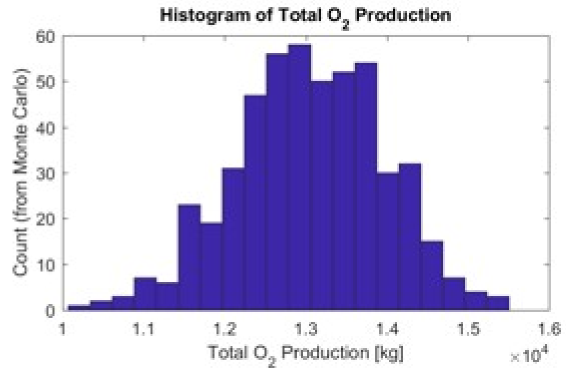
WBS 2.2 System Modeling and Analysis
Summary of Accomplishments

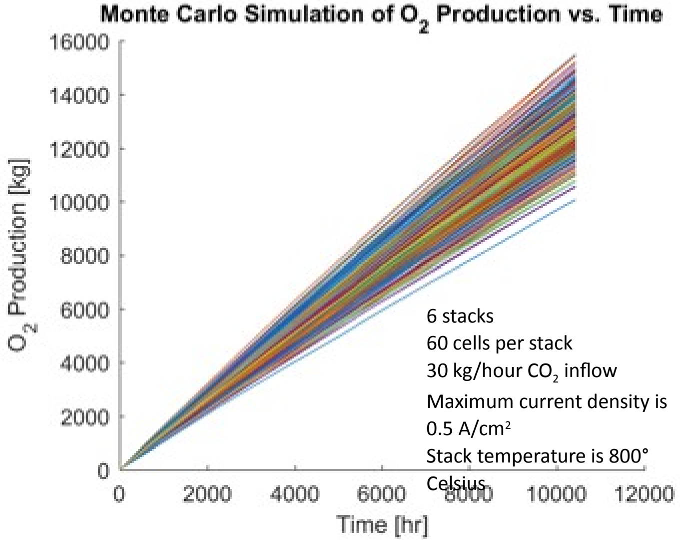
System Modeling & Analysis

- Completed reliability model and analysis for ISRU O_2 only system.
  - Due to lack of component reliability data, model and analysis was reduced to assessing the solid oxide electrolyzer (SOE) only.
  - An empirically-based SOE performance model was developed based on the Area Specific Resistance (ASR) parameter and focused on a single failure mechanism, performance degradation.
  - A Bayesian distribution methodology was applied using simple linear degradation model and Monte Carlo simulations were used to compute the SOE reliability, i.e. the probability that total O_2 production requirement is met.
  - Analysis results elucidate the sensitivity and need to properly account for degradation in component and system sizing.
  - Model and analysis provided a proof-of-concept demonstration, with the aim of extending to a full ISRU system.

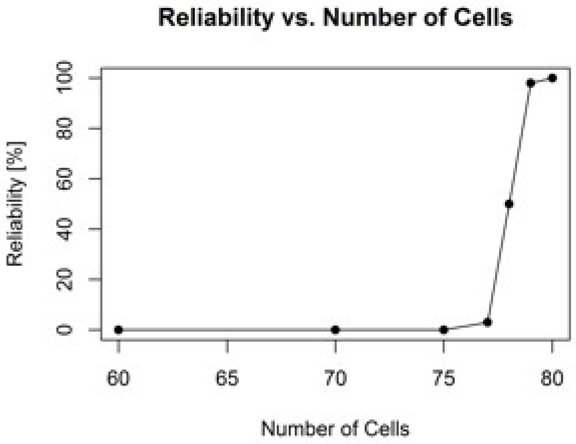


SOE degradation model. Degradation parameter is Area Specific Resistance (ASR).





6 stacks
60 cells per stack
30 kg/hour CO_2 inflow
Maximum current density is 0.5 A/cm^2
Stack temperature is 800° Celsius



Reliability as a function of # cells/stack where number of SOE stacks = 6.

Sample inputs and results from reliability model analysis.

WBS 4.1.1 Electrostatic Filtering

Summary of Accomplishments

ESP-1. Geometry Optimization

- Developed a physics-based model in COMSOL Multiphysics ® along with the DC plasma, electrostatics, laminar flow, and particle kinemat modules
- Obtained electron density distributions as well as density distribution for negative and positive ions—Analysis showed that CO_2^+ ions dominate dust particle charging
- Produced current-voltage (I-V) curves and ion density data with COMSOL plasma module.
- *I-V* curves match experimental curves in region of interest.
- Model shows that a stack of 137 cylindrical precipitators with a 71 mm diameter and 100 cm in length can collect 3 μm-diameter particles flowing at 6 kg/h with an efficiency of 99%

SOL model shows
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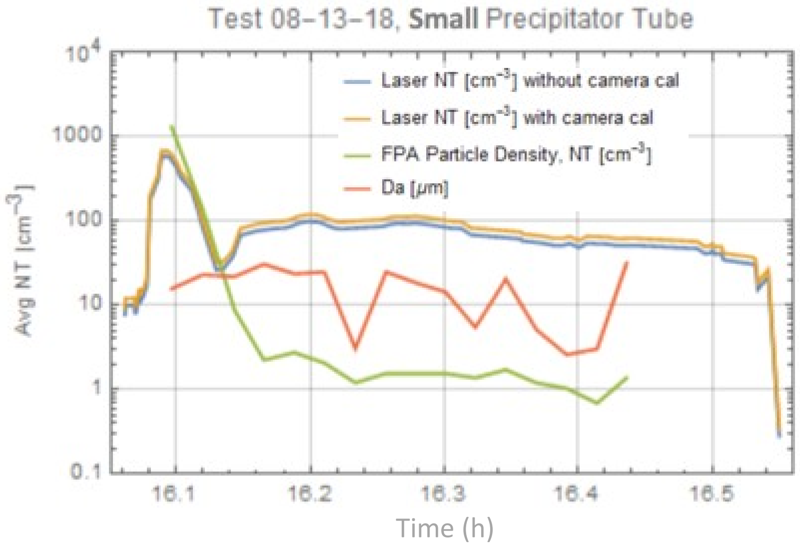
ESP-2. Dust Aerosolization

- Modified existing Fine Particle Analyzer to measure particle size and density
- Obtained preliminary values of particle sizes and dust particle densities for particles flowing at ~300 cm/s in precipitator at 5 Torr combining Fine Particle Analyzer and laser extension method
- Currently using SEM analysis to measure sizes of sampled particles to determine causes of discrepancies in the results of the two methods

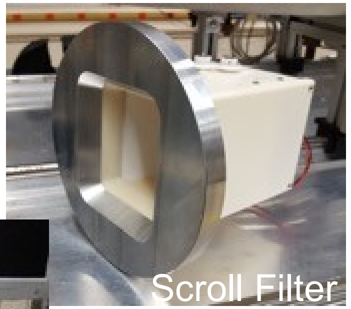


Particle density in cm^{-3} and particle diameter in μm using Fine Particle Analyzer and Laser Extinction method. There is a discrepancy in the results of the two methods.

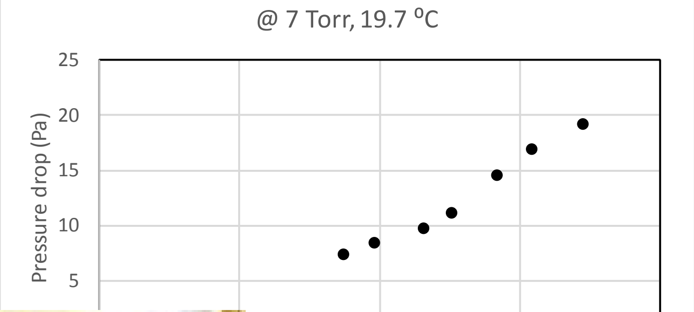
WBS 4.1.1 Media Filters
Summary of Accomplishments

List Significant Accomplishments this FY18:

- MOXIE support
  - Completed flow performance tests of the MOXIE HEPA filter in the Mars Flow Loop.
  - Completed a set of dust loading tests on the MOXIE HEPA filter.
  - Provided guidance on the MOXIE filter Aarhus test plan.
- Filter requirements
  - Held first round of discussion with ISRU element team leads to discuss their filtration needs and requirements. Followed up requirement discussions at the KSC ISRU F2F.
- Mars Flow Loop upgrades and improvements
  - Installed new more sensitive orifice, improved imaging (reduced stray light), and minimized leak rate through improved pipe component alignment and replacement of fittings. Procured updated instrumentation for the Particle Dynamics Analysis system.
- ISRU Scroll Filter
  - Completed flow performance tests of the ISRU Scroll Filter in the Mars Flow Loop.
- Mars Desert Research Station, MDRS (Crew 188)
  - Configured ISRU Scroll filter for use in a two week MDRS simulated Mars mission with Crew 188 commanded by Ryan Kobrick (Embry-Riddle Aeronautical University) in January 2018. The filter was tested for its performance inside the Habitat and its



Mars Atmospheric Flow Loop



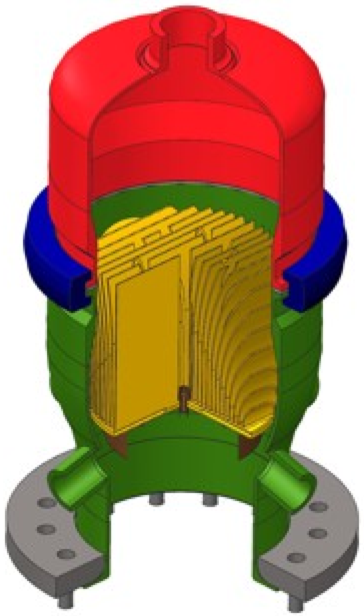
MDRS Crew 188 in airlock

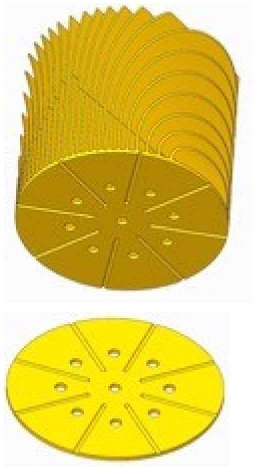
WBS 4.1.3 CO$_2$ Acquisition - Cryofreezer

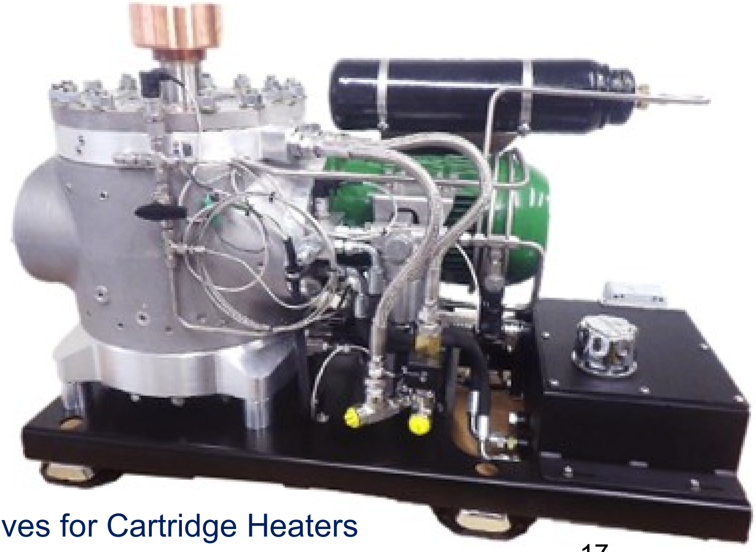
Summary of Accomplishments

Full-Scale CO$_2$ Freezer Design, Component Testing, and Modeling

- Wrapped up all testing on the small scale Atmospheric Processing Module (APM).
  - Total of five cold head designs were tested, the deposition and sublimation performance of each was assessed, and optimization of entire cycle was analyzed.
- Presented two papers at AIAA Space 2018 on CO$_2$ Freezer work:
  - CO2 Freezer Cold Head Design Study
  - Full-Scale CO2 Freezer Project Developments for Mars Atmospheric Acquisition.
- Preparations for Full-Scale CO2 Freezer testing:
  - Completed Preliminary Design Review (7/26/18)
  - Completed Software Assurance Classification Assessment (SACA)
  - Procured 300 W (min) cryocooler that will be delivered in Q1 FY19
  - Finalized design of freezer chamber and the supporting fluid systems
  - Finalized design of cold head based on APM test results and modeling of flow field
  - Procured all necessary materials, equipment and hardware
  - Initiated fabrication of freezer chamber and cold head
  - Initiated assembly of the supporting fluid and control/data systems.
- Began investigating CFD tools to enable phase change and transient model simulations.
- Initiated FY19 planning at the ISRU Workshop held at Kennedy in September of 2018.







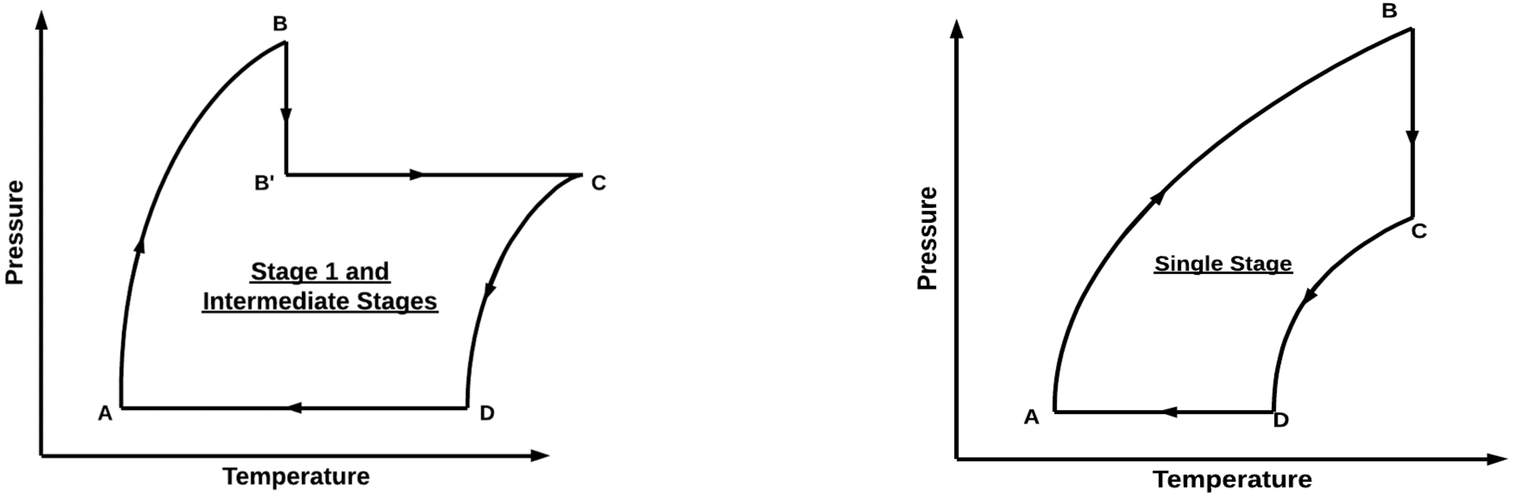
Top Left: Freezer Chamber Cut-Away
Top Right: 2-Piece Cold Head with Grooves for Cartridge Heaters
Bottom: AF-Cryo Evercold STC90 Cryocooler

WBS 4.1.3 Rapid Cycle Adsorption Pump
Summary of Accomplishments 1

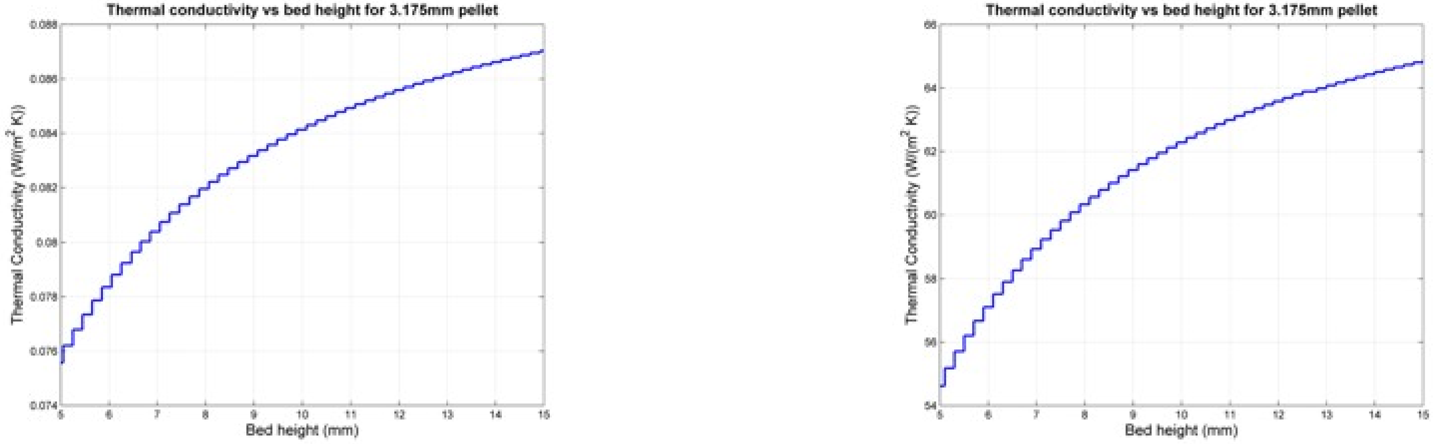
RCAP Modeling

- **Cycle Analysis Modeling**
  - Created version 2 in Matlab
  - Better description of multi-stage RCAP analysis
  - Optimizes mass collection versus output pressure (top left figure)
  - Recuperation and post mechanical compression implemented
- **Thermal Desktop (Sinda / Fluint) Modeling**
  - “4BMX” (MSFC) Porous bed conduction heat transfer model implemented
  - Modeled both heritage PNNL design and single stage, one-plate configuration
  - Results indicate that the “4BMX” constants should be anchored to upcoming single stage, one-plate test
  - Conduction paths, especially Aluminum shot, should be considered because of a 750 X increase in thermal conductivity (bottom figures)

Thermodynamic Cycles used
for RCAP Cycle Code



Comparison of Porous Bed Thermal Conductivity
Zeolite only (left) Compared against
50 % Aluminum Shot (right), 50 % Zeolite 13 X Adsorbent (By Volume)
~750X Improvement in Thermal Conductivity



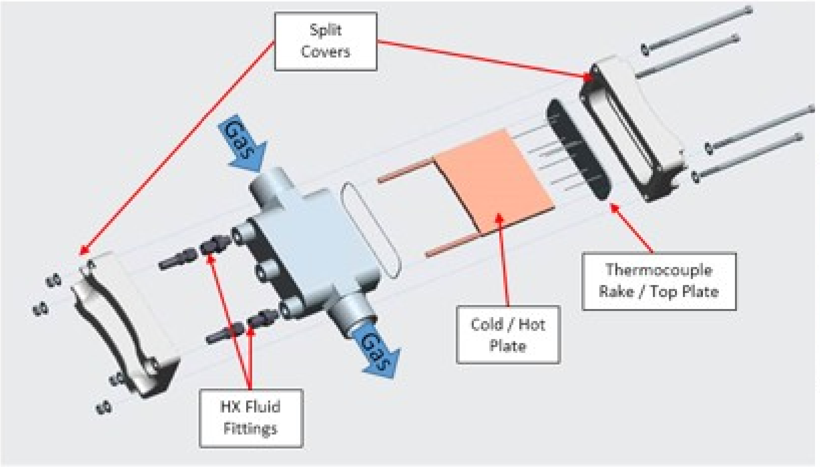
WBS 4.1.3 Rapid Cycle Adsorption Pump
Summary of Accomplishments 2

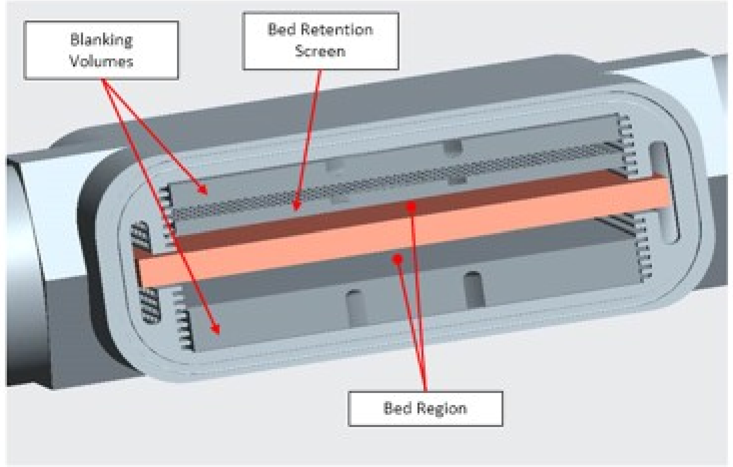
Single Stage, One-Plate Configuration

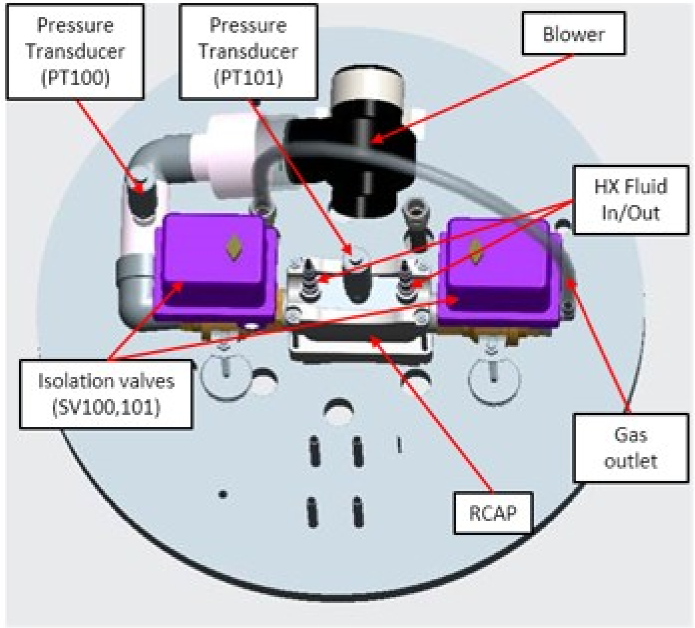
- **Testing starts soon**
  - Design, procurement complete
  - TRR complete
    - Evaluating different bed depths and sorbent particles sizes to determine effects on performance and to correlate model
- **Hardware**
  - 3D printed aluminum alloy housing
  - Quickly reconfigurable
  - Instrumented for temperature and pressure
  - Automated conops for evaluation of short / long period performance transients

Two Stage, Single-Plate Configuration

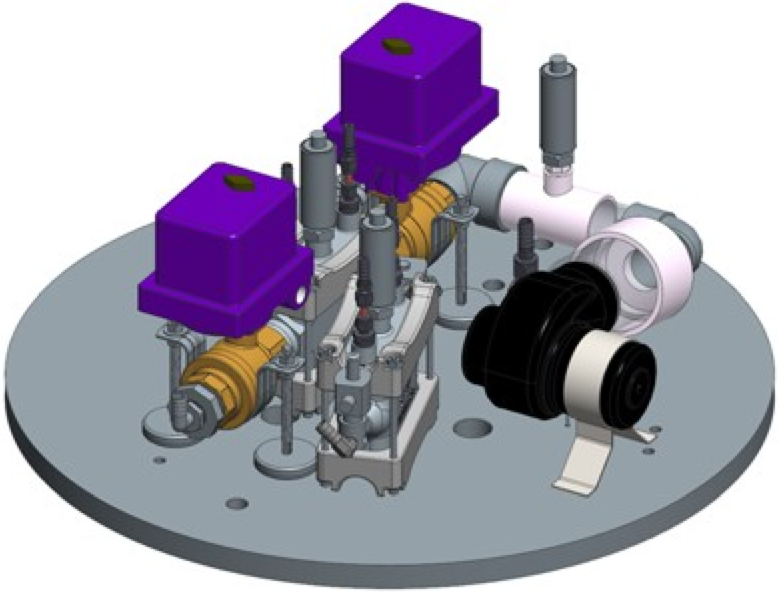
- **Design ~95%, procurement ~ 30%**
  - Design commonality and flexibility to accommodate single stage insights







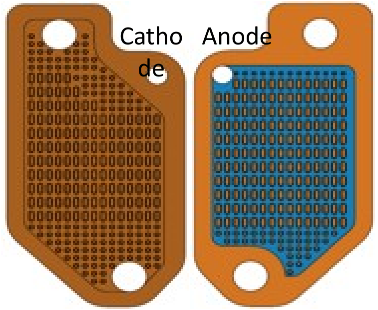
Single Stage Layout



Two Stage Layout

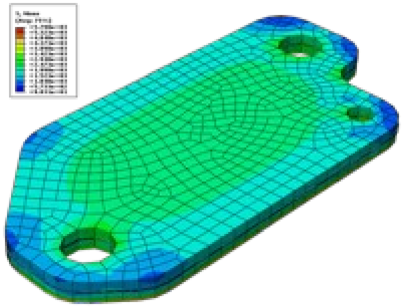
WBS 4.2 Solid Oxide Electrolysis (SOE) Technology
Summary of Accomplishments

- **SOE Modeling (Thermal, Fluid & Mechanical)**
  - Created geometry/mesh of a MOXIE stack
  - Created geometries within SolidWorks for:
    - CO_2 plate
    - O_2 plate
    - Mid-plate
    - Individual element plates
  - Created single SOXE plate fluid modeling
  - Completed MOXIE stack structural / thermal response at operating conditions
  - Created Single plate with reaction kinetics
  - Completed parametric analyses on structural / thermal response of stack
  - Final report in work

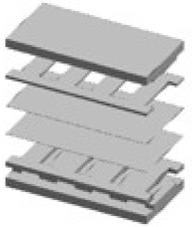


MOXIE/SOXE interconnect plate used for molding

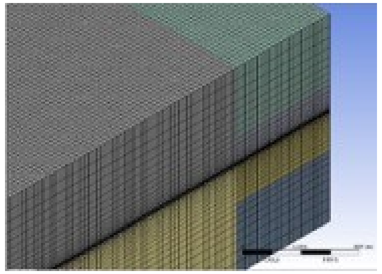
SolidWorks geometry of element plate



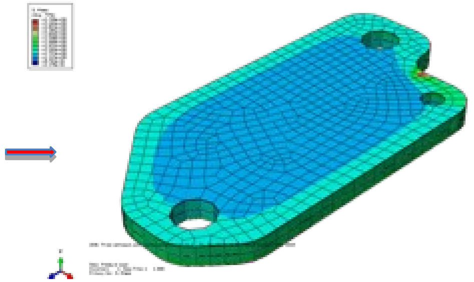
Single cell with electrode stress distribution



Exploded view of layering model

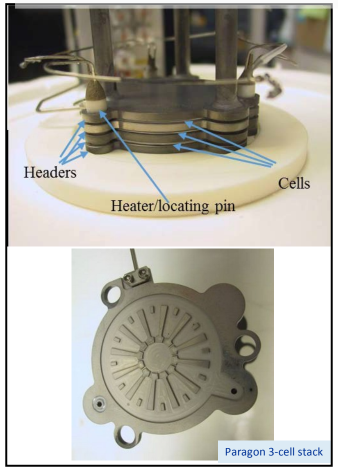


Mesh density of layering model

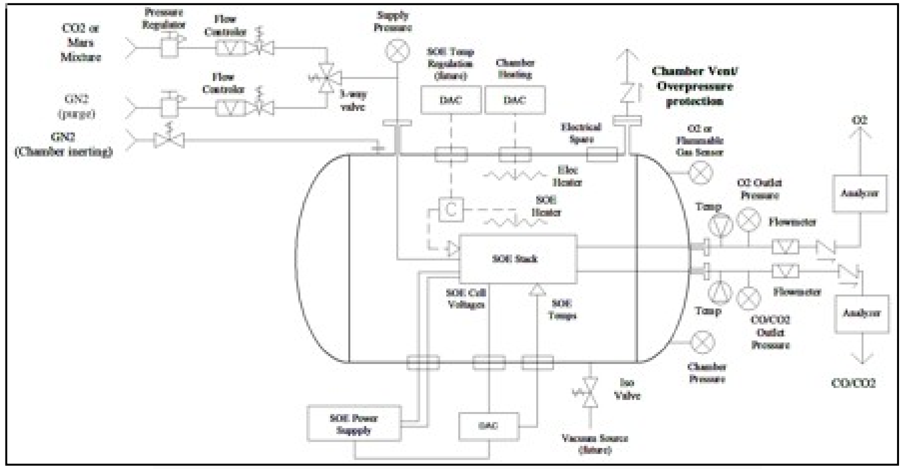


Three cell stack stress distribution

- **SOE General Test Stand**
  - Complete a detail SOE Materials Technology Comparison data file
  - Completed requirements and design reviews
  - Selected Paragon for developing a 3-cells SOE stack
  - Completed SOE stack PR: 4200663729
  - Test Stand fabricate, installation, instrumentation, controls & TRR completion scheduled for 1/9/2019
  - Additional procurements are in progress
  - Paragon Stack arrival 1/18/2019
  - Testing of Paragon stack scheduled for 1/20/2019



Paragon 3-cell SOE stack



SOE General Test Stand layout
(in assembly phase)

WBS 4.2 Solid Oxide Electrolysis (SOE) Technology
Summary of Accomplishments

- **SOE Materials Selection-Electrode Development**
  - Completed initial research and literature review for cathode electrode materials. Will be documented and revised to include cathode development work under OxEon Phase I SBIR work.
  - Completed build-up of test facility including gas flow panel to allow 4 gas mixing, and completed safety permit and pressure exclusion reviews.
  - Completed installation of gas flow panel, gas cylinder piping, furnace, etc. in fume hood.
  - Procured single button cells for evaluation, and cells with anode only to allow advanced cathode comparison with baseline.
    - Complete Test Readiness Review (TRR): 10/19/2018
    - Complete testing for baseline cells: 02/27/2019
    - Complete In-house electrode fabrication: 05/24/2019
    - Post-evaluation report: 09/27/2019

Gas flow panel and furnace in fume hood

Single cell test fixture with button cell installed

Vendor supplied button cells

WBS 4.3.1 Sabatier

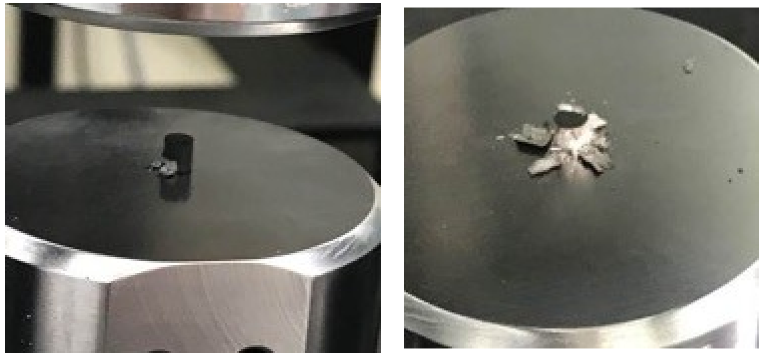
Summary of Accomplishments

SAB-1 Design Study

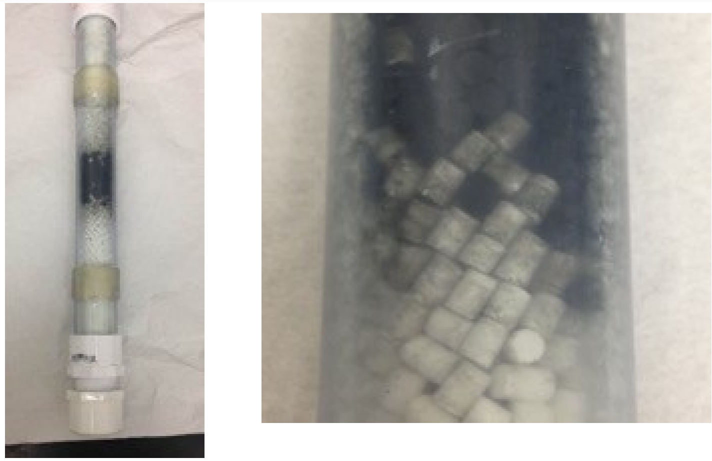
- Finished modeling Sabatier systems with one or two reactors with different types of thermal management.
- Presented this work at 48th International Conference on Environmental Systems:
  - P.E. Hintze, A.J. Meier, and M.G. Shah, “Sabatier System Design Study for a Mars ISRU Propellant Production Plant”, ICES-2018-155.
- Began trade of different thermal management systems for Sabatier reactor and condenser.

SAB-2 Catalyst Screening

- Identified catalyst types (pellets, microlith, microchannel) and potential contaminants (from soil, atmosphere, and liquid water).
- Performed physical testing of catalysts showing the changes that occurred after usage.
- Performed vibration tests to evaluate different packing materials and methods.
- Began performance testing to evaluate catalyst response to vibrations and Mars relevant contaminants.



New pellets, left, generated less dust than used pellets, right, upon crushing



0.5% Ruthenium on aluminum oxide catalyst after vibration test. Dust generated during vibration can be seen in the right image, coating the white aluminum oxide pellets.

(Multiple WBS) Separators

Summary of Accomplishments

Generic Separation Test Stand

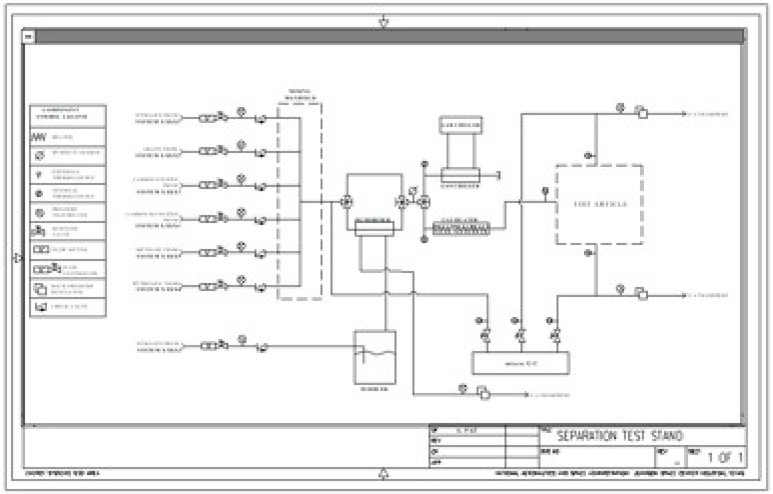
- Developed preliminary requirements
- Developed schematic

WBS 4.1.3.3.1 CO_2, N_2 and Ar Separation

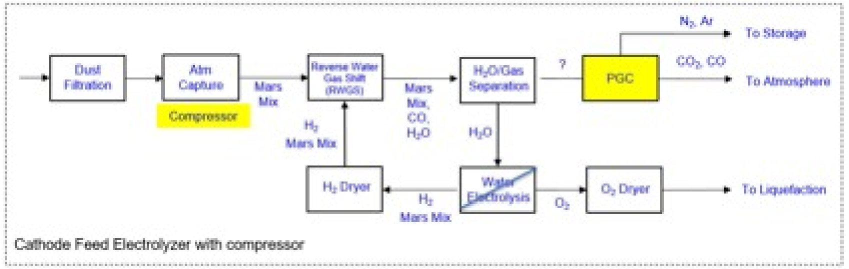
- Collected several papers relevant to separating N_2 and Ar from CO_2
- Evaluated multiple conops to determine the impact of not removing N_2 and Ar from the CO_2.
  - In all LOX-only ISRU conops, there is no need to separate Ar and N_2 from the CO_2
  - In all LOX/CH_4 conops, Ar and N_2 would need to be separated.
- Investigated Preparative Gas Chromatography as a candidate for separating these gases without a large pressure/temperature swing

WBS 4.2.3 CO, CO_2 Separation

- Collected papers relevant to CO, CO_2 Separation
- Phase 1 SBIR awarded to TDA research for high temperature (>650°C) CO_2 sorbent.



Schematic of Generic Separation Test Stand



Example of CO_2, N_2 and Ar Separator Placement

(Multiple WBS) Separators
Summary of Accomplishments

WBS 4.3.2 H_2O, Gas Separation (Condensers)

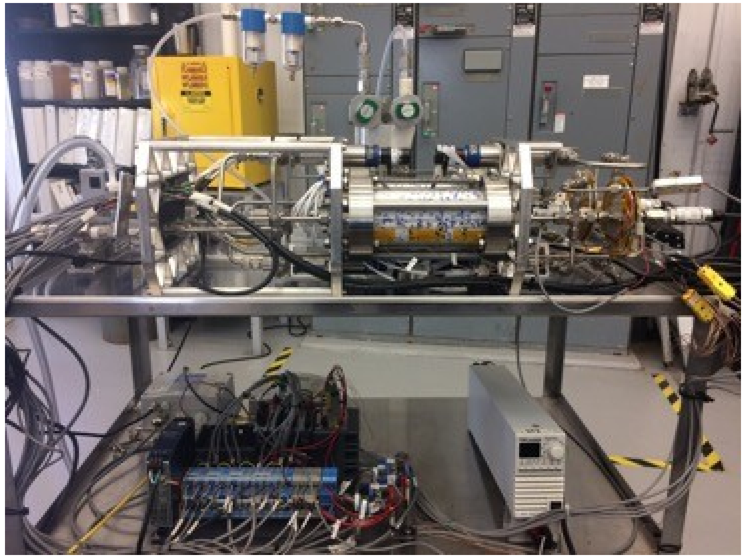
- Investigated COMSOL and SINDA/FLUINT as potential software tools for high fidelity modeling of sophisticated condenser designs

WBS 4.3.3 H_2, CH_4 Separation

- Collected several papers relevant to separating H_2 from CH_4
- Engaged liquefaction and propulsion community about the impact of not separating H_2 from CH_4

WBS 4.4.3 Regenerative Gas Dryers

- Identified necessary test stand modifications and procured components
- Recalibrated sensors on the test stand
- Identified and procured multiple desiccants
- Engaged ECLSS community about their experience with water sorption and regeneration of desiccants
- Identified humidity sensors that can work in pure oxygen and pure methane environments



Regenerative Gas Dryer Test Stand

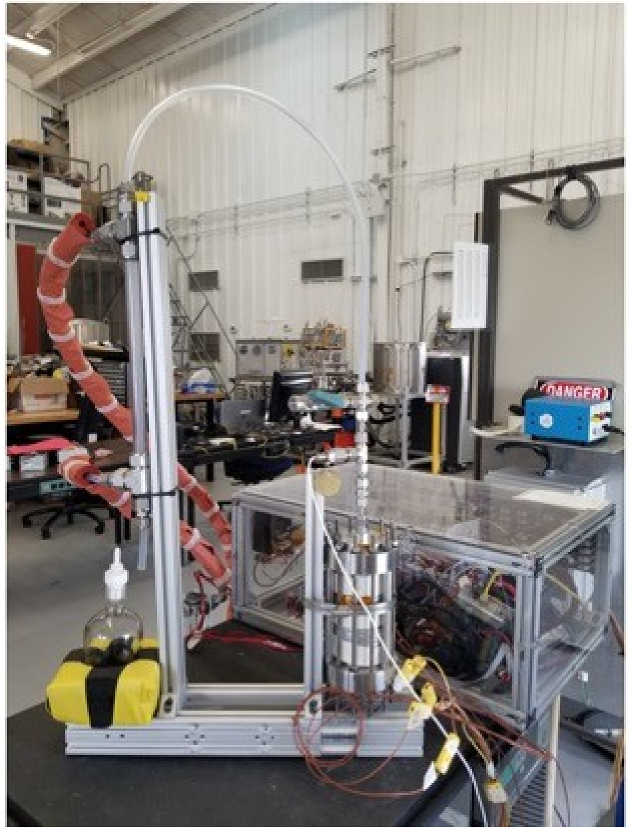
Tunable Laser Diode Humidity Sensor Developed by JPL for Previous ECLSS Application

(Multiple WBS) Separators

Summary of Accomplishments

WBS 4.8.5 Water Cleanup

- Analyzed water samples extracted from JSC Mars-1A simulant from previous test program
- Manufactured custom pressure vessel lid with no filter (to compare against existing pressure vessel lid with embedded filter)
- Developed test stand to extract and condense water from Mars soil simulant.
- Pressure Systems Design Review of Test Stand



Water Extraction Test Stand

Water Samples Analyzed from Previous Test Program

WBS 4.4 Water Electrolysis
Summary of Accomplishments

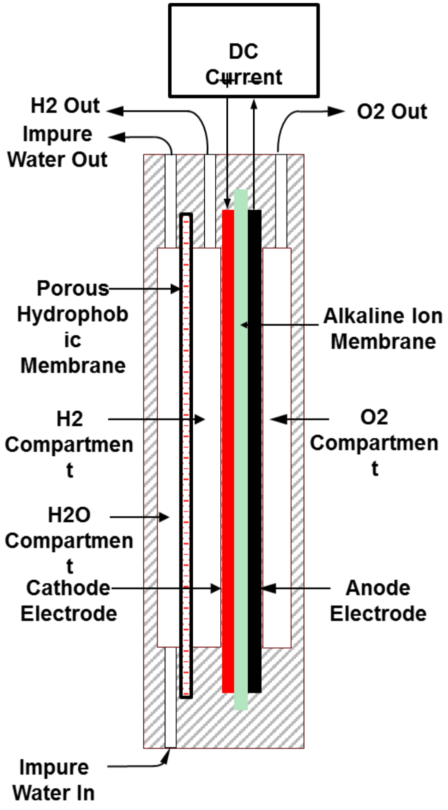
Accomplishments since Mid Term

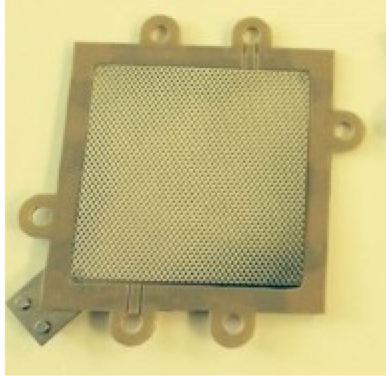
- **03/18 Design Test Rig**
- **08/18 Electrolysis Cell/Stack Assembly Completed**
- **09/18 Test Rig completed.**

The cell stack will operate using highly salt/mineral laden water that provides the water source and cell stack cooling.

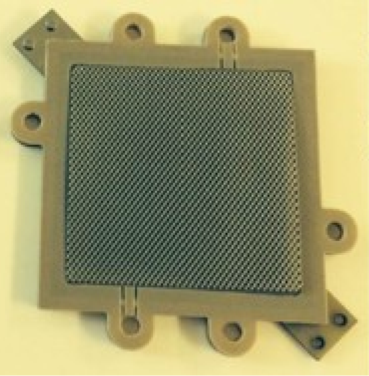
Electrolyze Projected Performance

Number of Cells : 10 Cells
Cell Area : 100 cm2/cell
Power Usage : 340 Watts
H_2O Conversion : 67 gm H2O/hr
O_2 Production : 59.6 g O2/hr, (0.69 slpm)
H_2 Production : 7.4 g H2/hr, (1.38 slpm)



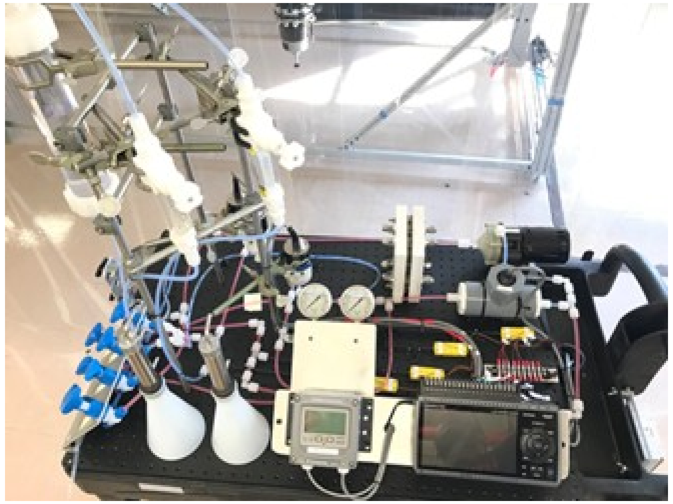


Anode Cell Separator Assy (O2 Side of Cell)

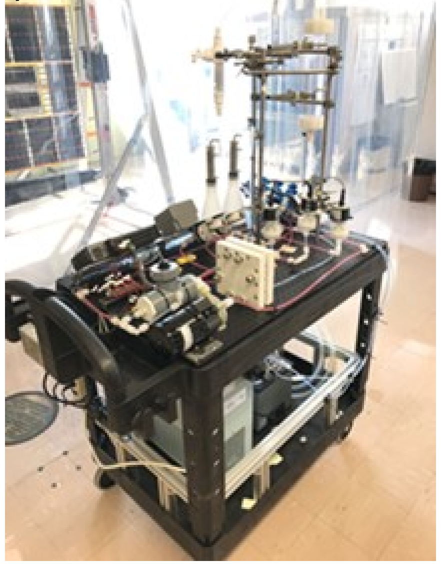


Cathode Cell Separator Assy (H2 Side of Cell)

Cathode Cell Separator w Porous PTFE Membrane



Electrolysis Test Rig Top View



Electrolysis Test Rig

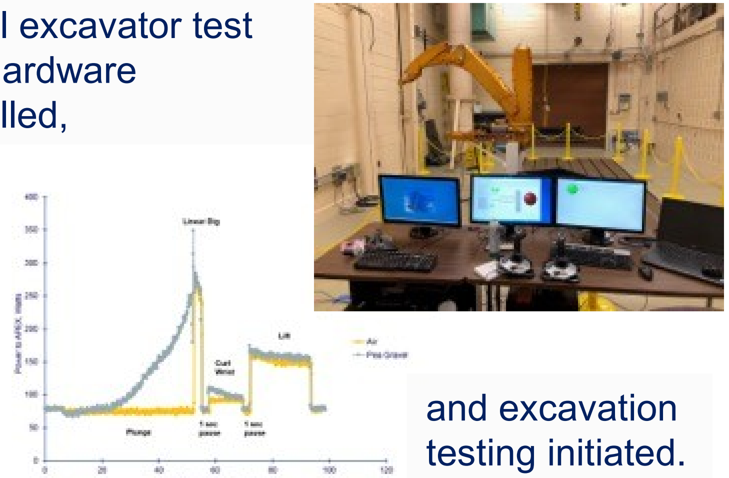
WBS 4.7 Excavation / Resource Acquisition
Summary of Accomplishments

Excavation / Resource Acquisition - Grouped for Comparisons:

○ Questions identified to be addressed
✓ Accomplished to date

- Surface Granular Material (4.7.1)
  - ○ Fundamental excavation terramechanics (vs. location)
  - ○ Actuation / automation / life limiting mechanisms (common)
  - ○ Transport / surface mobility / storage (common to WBS 4.7)
  - ✓ New ISRU laboratory space at GRC reconditioned / in use
  - ✓ Excavation test hardware installed, calibrated, and reviewed
  - ✓ Pre-programmed bucket trajectory profiles run multiple times, comparison between bucket empty and with pea-gravel (analog mass)
- Surface Consolidated / Hard Material (4.7.2)
  - ○ Fundamental forces / energy to fracture (vs. material type)
  - ○ Water content / variability (vs. location)
  - ○ Method / mechanism (e.g. variable spacing ripper)
  - ✓ Redirected ripper assessment, to measure single tooth forces in KSC lab
  - ✓ Acquired bulk gypsum rock, as Mars target and lunar icy deposits analog
  - ✓ Re-tasked, instrumented shop equipment for quantitative pick testing
  - ✓ Initial testing captured 3-axis forces, cuttings mass and size distributions, excavated volume, and high speed video

Initial excavator test lab hardware installed,



and excavation testing initiated. (4.7.1)

Hard material "ripper" pick test
(4.7.2)

WBS 4.7 Excavation / Resource Acquisition
Summary of Accomplishments

Excavation / Resource Acquisition - Grouped for Comparisons:

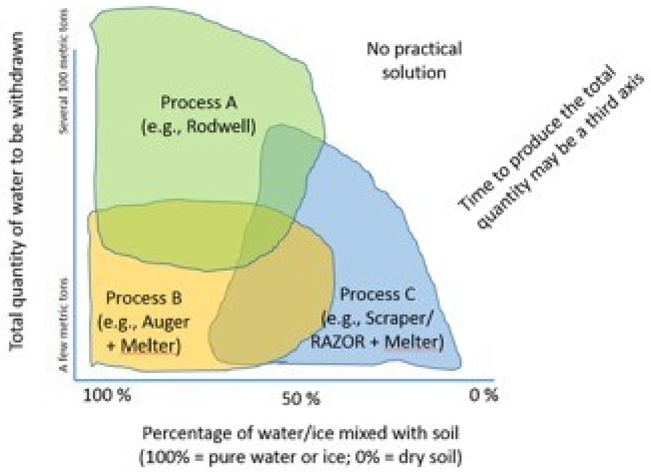
- ○ Questions identified to be addressed
- ✓ Accomplished to date

- Subsurface Resource Access / Acquisition (4.7.3)
  - ○ Locating / characterizing subsurface water-rich resources
  - ○ Drill / melt vs. mine vs. expose / mine (“strip-mine”)
  - ○ Rate for efficient extraction of water (vs. loss, heat loss)
  - ✓ JPL initial assessment, then personnel redirected to autonomy

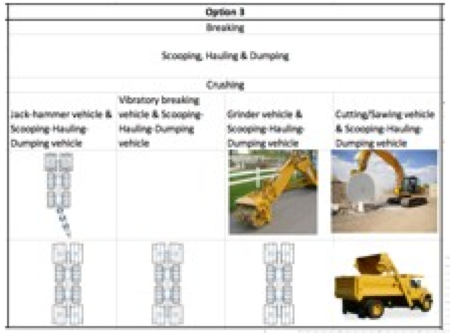
- Surface Granular & Surface Consolidated / Hard Material (4.7.1 & 4.7.2)
  - ○ What sensors are required for **autonomy**? (e.g. for navigation, health management)
  - ○ How many autonomous excavators of what size?
  - ○ How to autonomously decide where/how to navigate?
  - ○ What communication is needed for autonomy? Between excavators, and w/processing?
  - ✓ Decomposed autonomous resource acquisition into representative tasks
  - ✓ Developed concepts for tasks: breaking, scooping, hauling, dumping and crushing
  - ✓ Developed maintenance and repair design concepts for autonomous operations
  - ✓ Gathered equipment data from terrestrial mining operations, analyzed for rules-of-thumb on sizing, energy and mass, to estimate comparable systems requirements for ISRU excavation and material delivery

Subsurface Resource Access / Acquisition

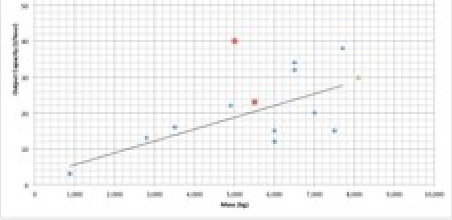
(4.7.3)



Example functional decomposition



Autonomy

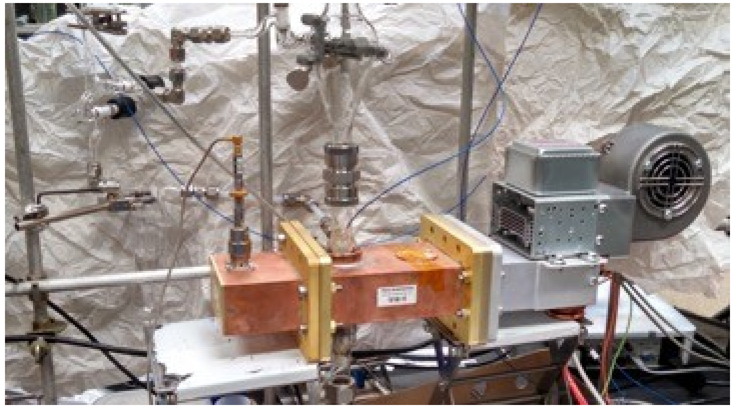


Commercial crushers output vs mass

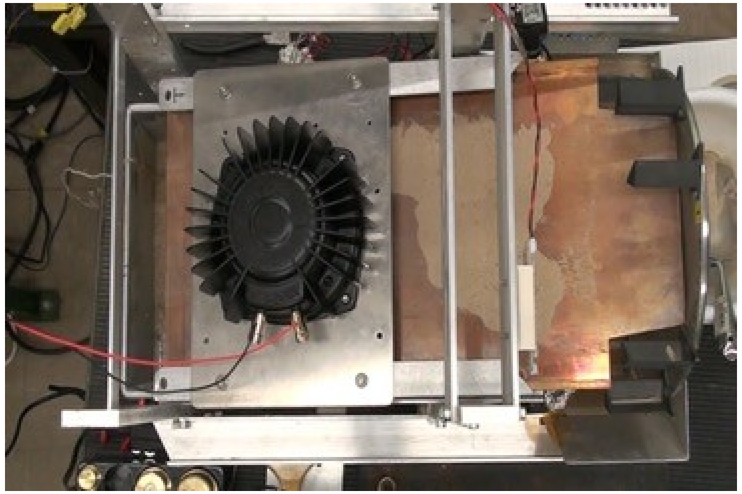
WBS 4.8.2 Soil Processing

Summary of Accomplishments

- **Microwave Processor (JPL): Granular hydrated regolith**
  - Laboratory tests have validated water extraction from porous tube reactor:
    - Initial heating runs performed up to 100C
    - Water release and heat efficiency with new Mars Rocknest simulant
  - Two microwave systems tested for efficiency: Solid state amplifier and magnetron.
    - Control system implemented for active frequency tracking
  - Initial power efficiency numbers show good agreement with model predictions
  - Agreement in place with Honeybee Robotics to develop soil feed system and condenser
    - Testing of current breadboard system will take place in Honeybee Robotics thermal vacuum chamber in Nov. 2018
- **Open 'Air' Processor (GRC): Granular hydrated regolith**
  - Paper on initial breadboard tests (2017) presented at the Earth and Space conference in April 2018
  - Design modification to improve repeatability and data accuracy
  - System tested with new Mars Rocknest Simulant; significantly different material flow behaviour
  - Initial data analysis of flow parameters incorporated into model for scaling



Microwave Processor, JPL: Soil feeds into porous tube which is inside waveguide cavity. A pump used to extract water moving through porous Pyrex tube.

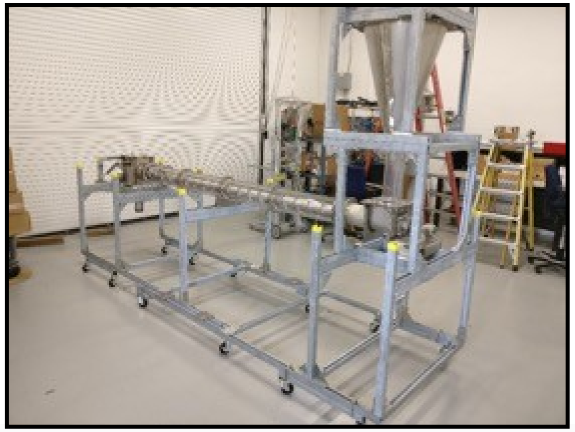


Open 'Air' Processor, GRC: Soil is deposited on a vibrating heated tray using a bucket wheel. A sweep gas of Mars 'air' conveys water vapor to the condenser.

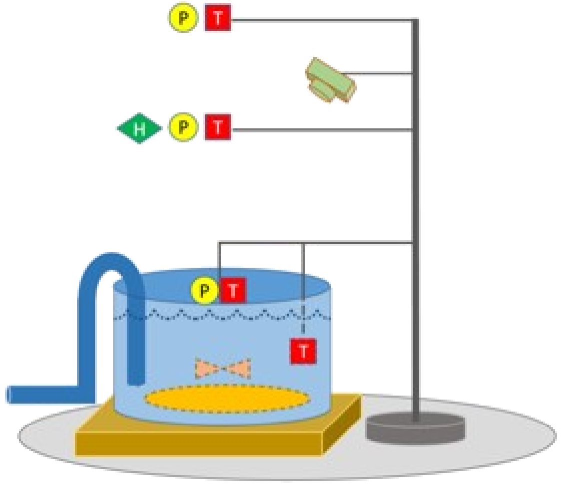
WBS 4.8.2 Soil Processing
Summary of Accomplishments

- **Auger Dryer (JSC): Granular hydrated regolith**
  - Phase 1 system: Testing complete
    - Clear Acrylic casing to characterize flow behavior
    - Tested with new Mars Rocknest Simulant
  - Phase 2 system is in hand
    - Stainless Steel casing with heaters for water release tests
    - Heaters installed and control system is in place
- **Rodwell Ice mining (JSC): Subsurface Ice**
  - Partnership agreement (MOU) with the Army Cold Region Research and Engineering Laboratory (CRREL) signed
    - CRREL developed the Rodwell model that is currently being used and is helping to modify/validate for Mars environment
  - Technical Interchange Meeting (TIM) held at JSC with CRREL
    - Test parameters identified and preliminary test matrix developed
  - Preliminary experiment design for test apparatus
    - Facility identified at JSC for initial sublimation testing at Mars conditions.

  - Paper published and presented at AIAA Space 2018



Auger Dryer, JSC: An auger is used to convey material through a heated tube. Vapor pressure drives water out of system. Auger pitch and soil column are used to seal.



Rodwell Ice mining (JSC): A preliminary test apparatus design to measure key parameters under Martian environmental conditions

WBS 5.2.2 Simulants

Summary of Accomplishments

Rocknest Soil Simulant

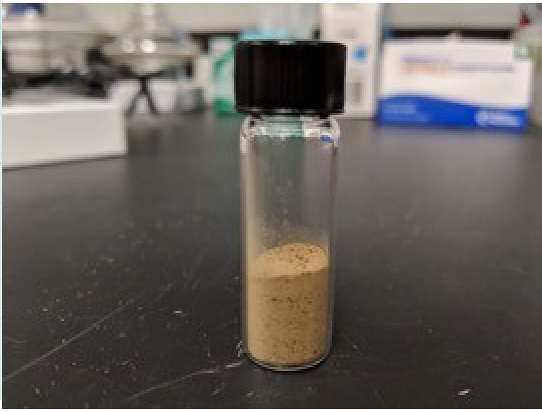
- Production of ~780 kg of Mars soil simulant
  - Developed recipe based on hundreds of analyses of commercially available material
  - Matched volatile content found by MSL Rover
  - Utilized the Mojave Mars Simulant (MMS) from JPL as the core component
  - Mixed at USGS – shipped at end of Sept 2018
    - 100 kg to GRC
    - 100 kg to JPL
    - 580 kg to JSC

Opportunities w/ New Simulants

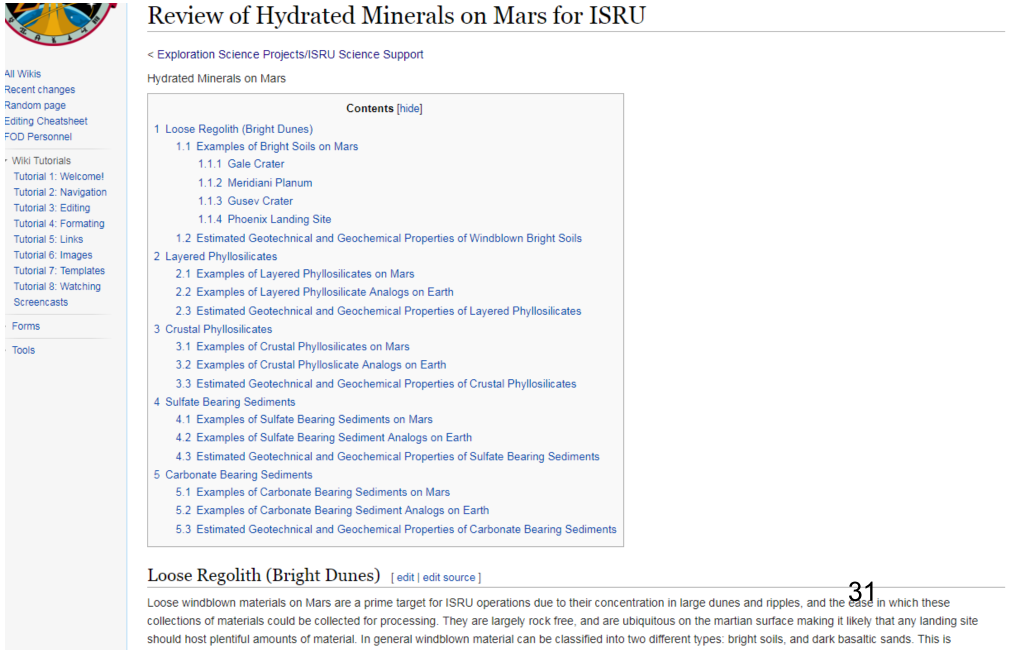
- **Mars**
  - Highest H_2O content material on Mars: Polyhydrated Sulfate (identified a potential commercially available ingredient – Ferric Sulfate – for a new martian simulant)
  - Constructed wiki-page reviewing information about a wide range of different ISRU targets on Mars & Earth analogs
- **Moon**
  - Collaboration with USGS – new batch of Lunar Highlands Simulant (NU-LHT) available for purchase

Rocknest Mars Simulant

Mixture N	WT %
$NaClO_4$	1
Goethite PIGMENT (dark)	1.5
pyrite (natural)	1
Ferric Sulfate	1
High Capacity GFO (Bayoxide)	5
Reg capacity GFO	2.5
Foresterite	10
MMS	78



Mars Hydrated Minerals Wiki Page



Review of Hydrated Minerals on Mars for ISRU

< Exploration Science Projects/ISRU Science Support

Hydrated Minerals on Mars

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    1.1.2 Meridiani Planum
    1.1.3 Gusev Crater
    1.1.4 Phoenix Landing Site
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2 Layered Phyllosilicates
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Loose Regolith (Bright Dunes) [edit | edit source]

Loose windblown materials on Mars are a prime target for ISRU operations due to their concentration in large dunes and ripples, and the ease in which these collections of materials could be collected for processing. They are largely rock free, and are ubiquitous on the martian surface making it likely that any landing site should host plentiful amounts of material. In general windblown material can be classified into two different types: bright soils, and dark basaltic sands. This is

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

Appendix D – ISRU Technology

Team

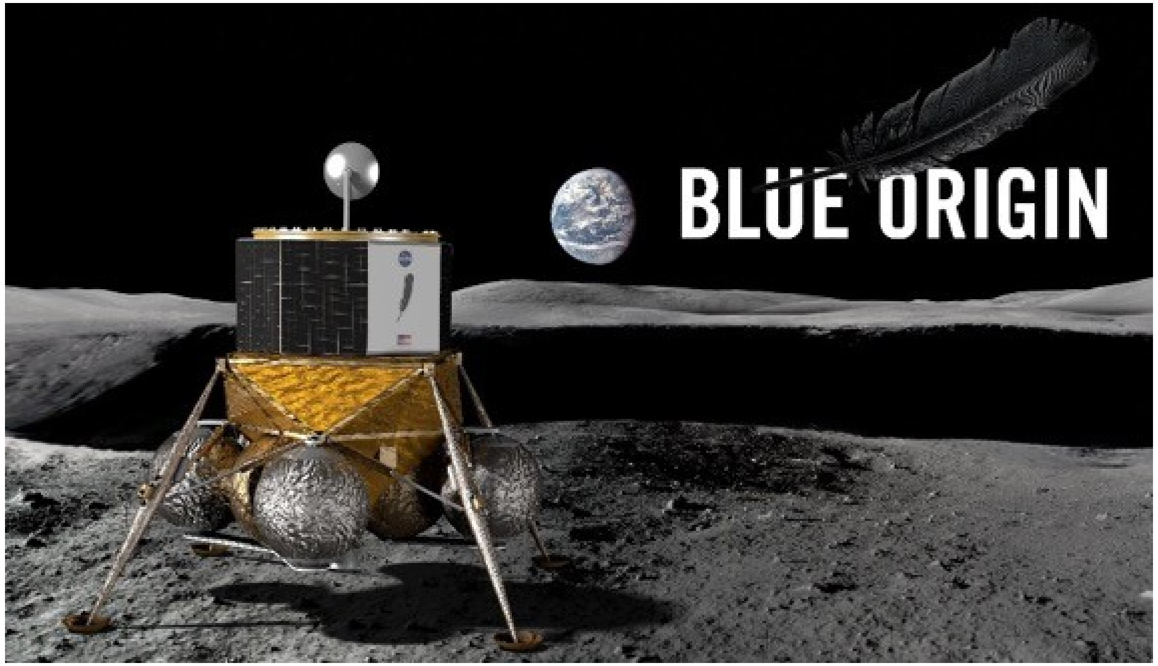
- Dr. Christie Iacomini (Blue Origin Principal Investigator)
- Kent Joosten (Subcontractor)

- 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



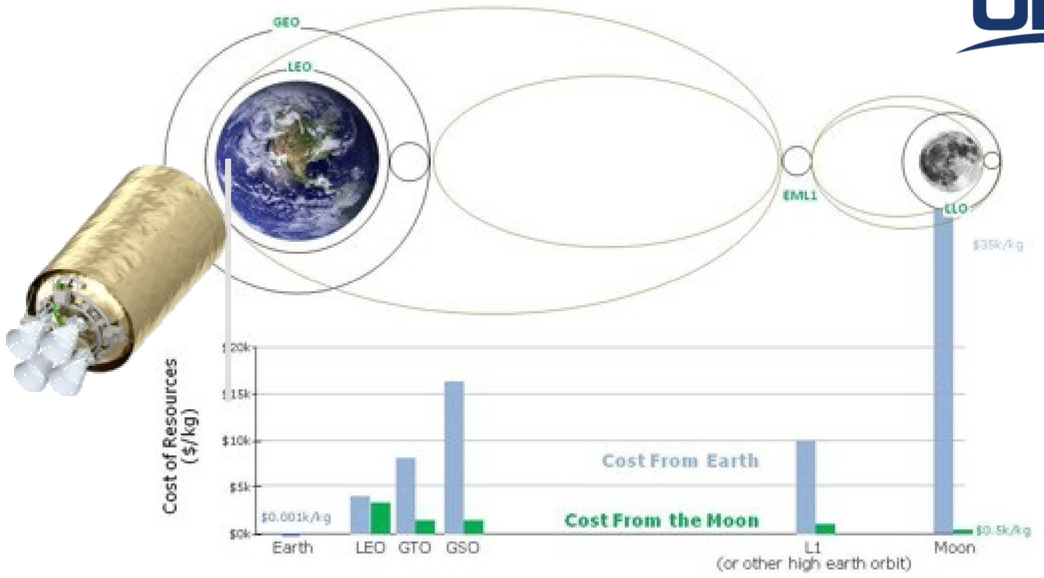
Team

- United Launch Alliance

- 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

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



BAA Track 1

Team

- Koki Ho, University of Illinois, PI

- <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.

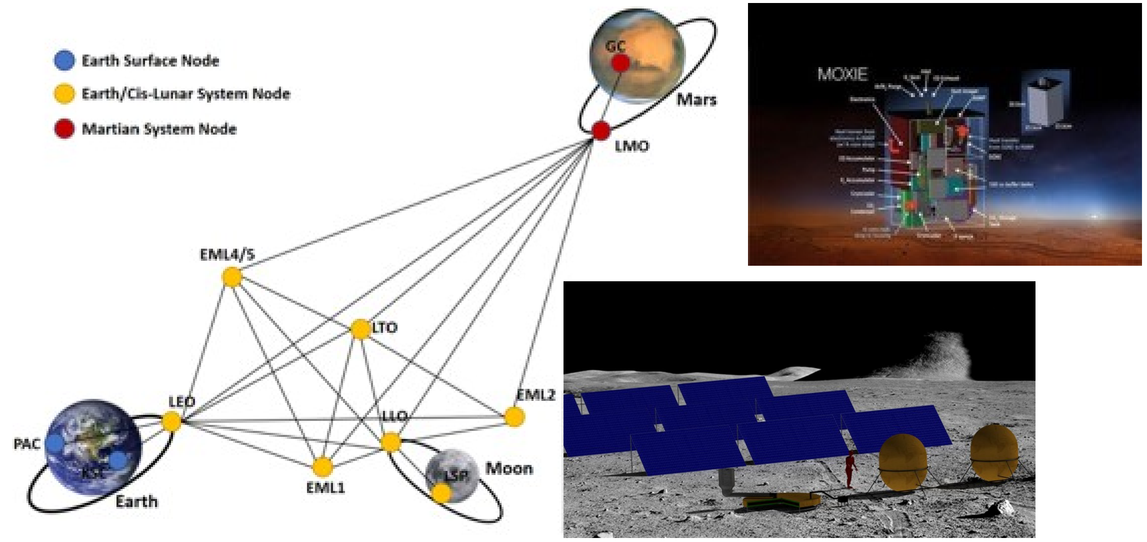


Fig. Network modeling of space logistics enables architecture optimization and evaluation of the value of ISRU (Credit: UIUC, MIT, NASA)

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- 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.

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

BAA Track 2

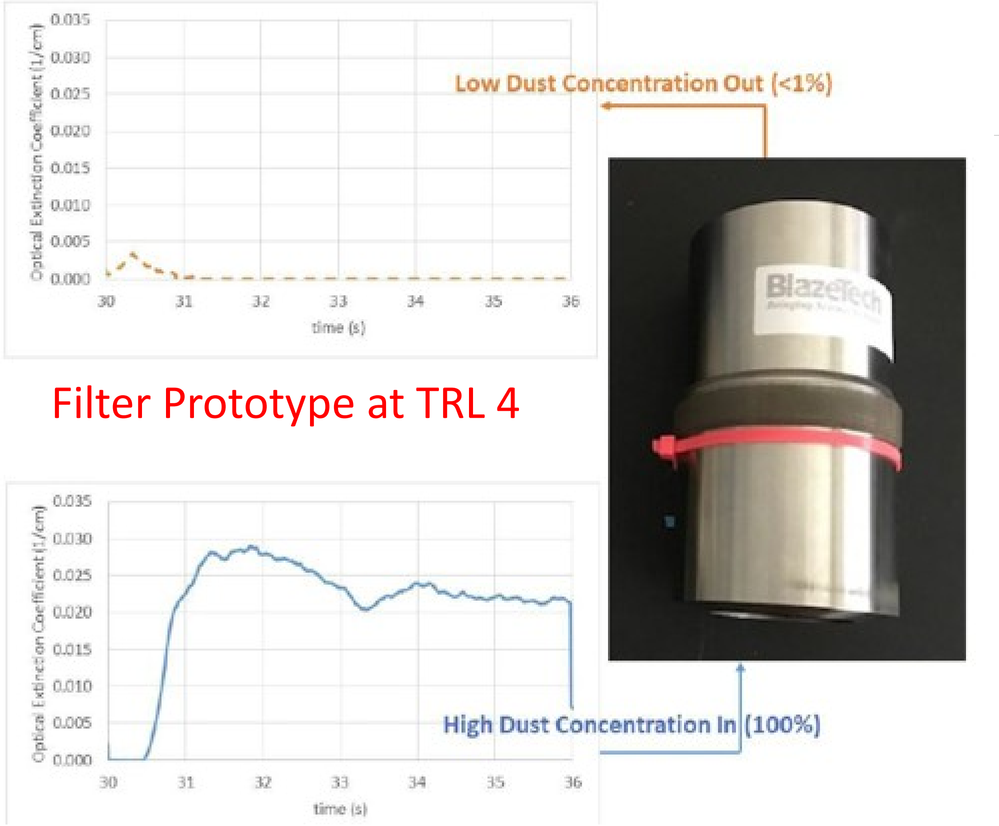
Team

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

- 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

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BAA Track 2

Team

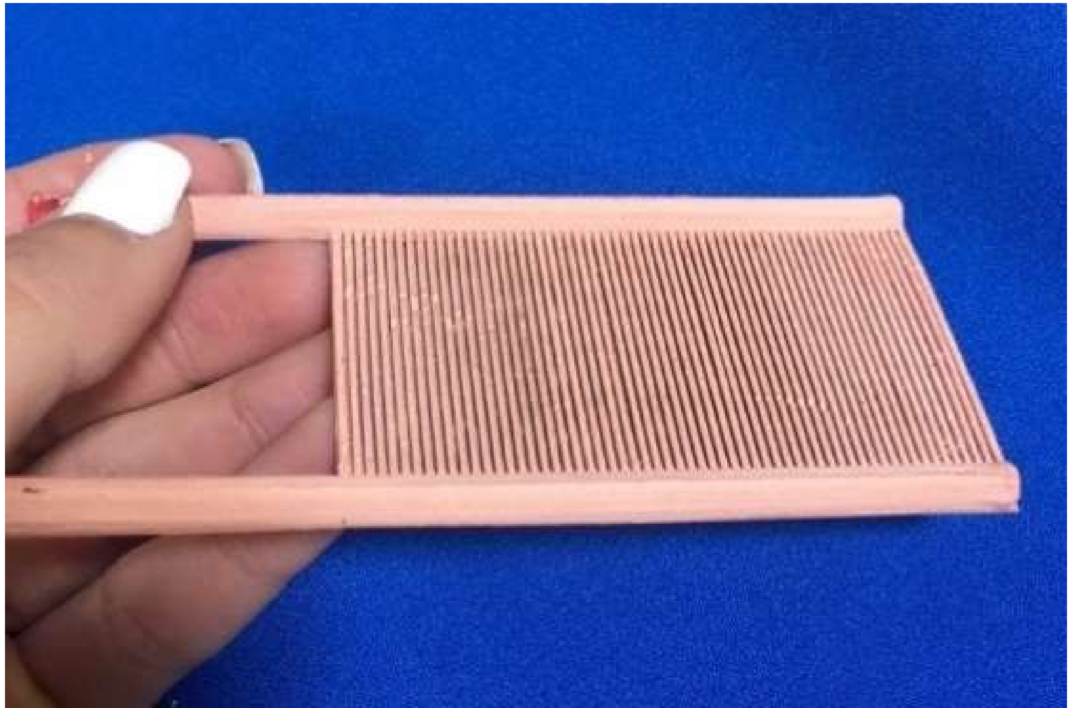
- Skyhaven Systems, LLC

[redacted]

- 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.



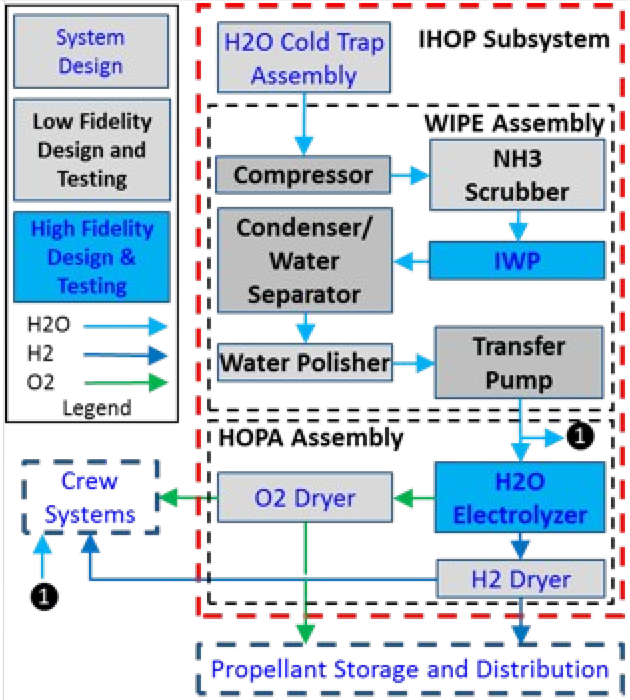
Paragon Space Development Corporation
- Laura Kelsey, Principal Investigator & Program Manager
- Barry W. Finger, Chief Engineer
- Patrick Pasadilla, Deputy Program Manager
- Chad Bower, Thermal Systems Technical Lead

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

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



System Design

Low Fidelity Design and Testing

High Fidelity Design & Testing

H2O

H2

O2

Legend

IHOP Subsystem

H2O Cold Trap Assembly

WIPE Assembly

Compressor

NH3 Scrubber

Condenser/ Water Separator

IWP

Water Polisher

Transfer Pump

HOPA Assembly

❶

Crew Systems

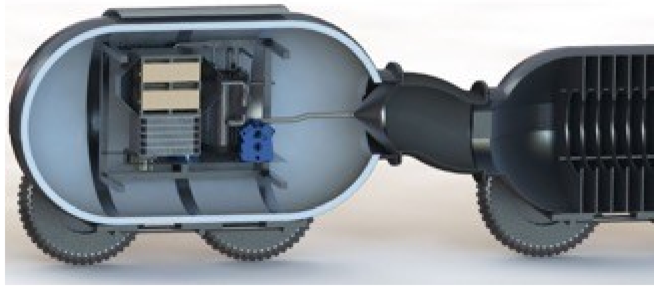
O2 Dryer

H2O Electrolyzer

H2 Dryer

❶

Propellant Storage and Distribution



BAA Track 2

Team: Teledyne Energy Systems

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

- 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

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

- 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

Objectives

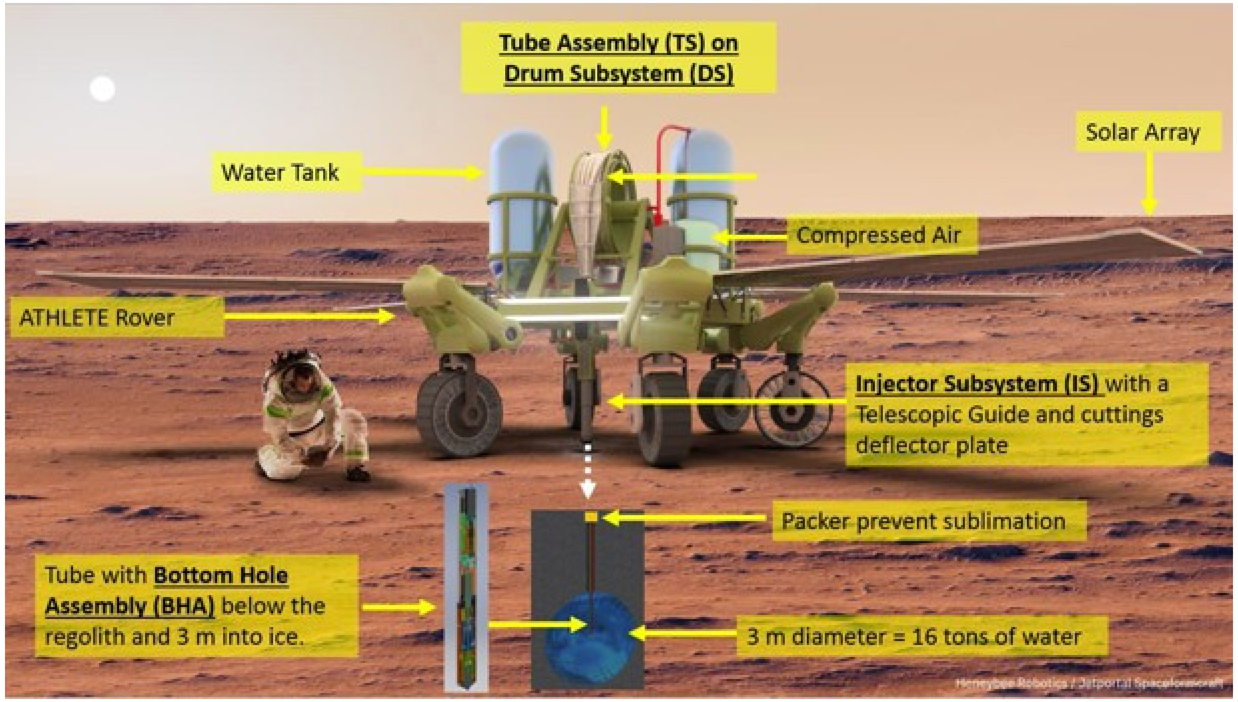
RedWater is a water extraction system from Mars ice deposits (e.g. Arcadia Planitia; 10s of meters ice deposits underneath <20m regolith). It combines two terrestrial technologies into one: Coiled Tubing for making a hole and RodWell for melting/pumping water.

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



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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

[redacted]

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