National Aeronautics and Space Administration

Overview of NASA ISRU Technology Development

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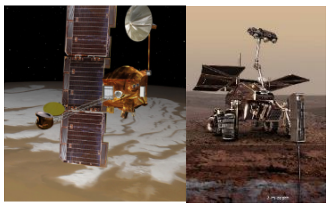
Introduction

- **NASA's Advanced Exploration Systems (AES) in the Human Exploration and Operations Mission Directorate (HEOMD) has initiated a new project for ISRU Technology focused on component, subsystem, and system maturation in the areas of**
  - Water/volatiles resource acquisition
  - Water/volatiles and atmospheric processing into propellants and other consumable products
- **NASA's Game Changing Development (GCD) program in the Space Technology Mission Directorate (STMD) has an ISRU project focused on component technology development in the areas of**
  - Mars atmosphere acquisition including dust management
  - Oxygen production from Mars atmosphere for propellant and life support consumables
- **Together, these two coordinated projects are working towards a common goal of demonstrating ISRU Systems in preparation for future flight**
  - Intent to engage the external community when funding becomes available

What is *In Situ* Resource Utilization (ISRU)?

ISRU involves any hardware or operation that harnesses and utilizes 'in-situ' resources to create products and services for robotic and human exploration

Resource Assessment (Prospecting)

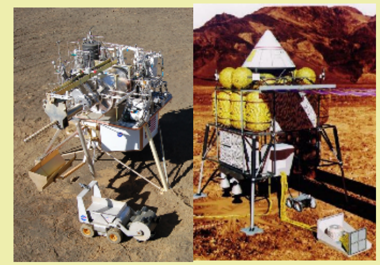


Assessment and mapping of physical, mineral, chemical, and water resources, terrain, geology, and environment

Resource Acquisition

Excavation, drilling, atmosphere collection, and preparation/ beneficiation before processing

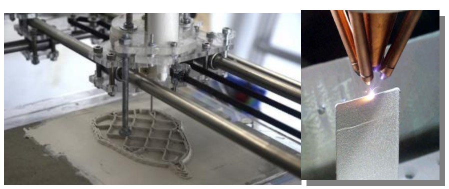
Resource Processing/ Consumable Production



Extraction and processing of resources into products with immediate use or as feedstock for construction & manufacturing

- **Propellants, life support gases, fuel cell reactants, etc.**

In Situ Manufacturing



Production of replacement parts, complex products, machines, and integrated systems from feedstock derived from one or more processed resources

In Situ Construction

Civil engineering, infrastructure emplacement and structure construction using materials produced from *in situ* resources

- **Radiation shields, landing pads, roads, berms, habitats, etc.**

In Situ Energy

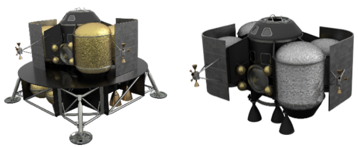
Generation and storage of electrical, thermal, and chemical energy with *in situ* derived materials

- **Solar arrays, thermal storage and energy, chemical batteries, etc.**

- **'ISRU' is a capability involving multiple elements to achieve final products** (mobility, product storage and delivery, power, crew and/or robotic maintenance, etc.)
- **'ISRU' does not exist on its own.** By definition it must connect and tie to users/customers of ISRU products and services

Decisions To Be Made Can Have Long Term Implications

Exploration Element | **Options** | **Studies That Can Impact Development Decisions**



Landers/Ascent

LO_2/CH_4 vs NTO/MMH

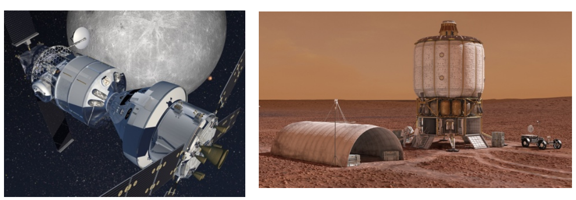
- Lower performing propellants (e.g., NTO/MMH) would affect all transportation assets due to different rendezvous orbit
- ISRU vs bring ascent propellant: Extra landers with tankers to transfer propellant on the surface

In-Space Transportation

ISRU Compatible vs Earth Storable

Chemical, Nuclear-Thermal, or SEP

- "Off-the-Shelf" storables vs ISRU-compatible for
  - Orion Service Module
  - Mars SEP/Hybrid stage
  - Phobos Crewed Vehicle
- Chemical (O_2/H_2 or O_2/CH_4) vs SEP for cis-lunar and Mars human transit vehicles



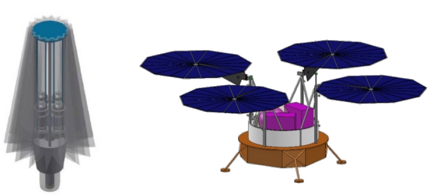
In-Space & Surface Habitats

Degree of ECLSS Closure

Trash Management

Radiation Shielding

- Water removal from brine
- CO_2 reduction to carbon or ethylene
- Compaction/Jettison vs trash-to-gas or propellant
- Earth supplied or in-situ radiation shielding
  - ISRU water, plastic, or regolith



Lander & Surface Power

Nuclear vs Solar

Battery vs Regenerative Fuel Cell

- Solar Power for Mars Human Surface: ISRU is 1 of 2 main users; day/night power strongly affects operations
- Pressurized rover baselined with batteries and nuclear reactor vs regenerative fuel cell

ISRU Technology Development Needed Now

- ISRU is a *disruptive* capability
  - Enables more affordable exploration than today's paradigm
  - Requires integrated system design approach
  - Allows more sustainable architectures to be developed
- Understand the ripple effect in the other Exploration Elements
  - MAV, EDL, Habitats, Life Support, Power
- Every Exploration Element *except* ISRU has some flight heritage (power, propulsion, habitats, landers, life support, etc.)
  - ISRU *will require* a flight demonstration mission on Mars before it will be included in the critical path
    - Mission needs to be concluded at least 10 years before first human landed mission to ensure lessons learned can be incorporated into final design
  - ISRU Formulation team has generated a (still incomplete) list of over 75 technical questions on more than 40 components and subsystems that need to be answered before the 'right' ISRU system will be ready for flight

ISRU State-of-the-Art: Resource Acquisition, Processing, Consumables Production

- Significant work has been performed to demonstrate feasibility of ISRU concepts and develop components and technologies (TRL 1-3)
  - **Moon/Mars**
    - Mars atmosphere collection, separation, and processing into O_2 or O_2/CH_4
    - Lunar regolith excavation, beneficiation, and processing to extract O_2
    - Civil engineering/soil stabilization
  - **Asteroid**
    - Acquisition concept work is just starting through STMD-ESI, BAAs, and SBIR/STTRs

- Some development & testing has been performed at the system level (TRL 4-6)
  - **Moon** (Lab, Analog sites)
    - RESOLVE, PILOT, ROxygen
  - **Mars** (Lab, Environment)
    - Portable Mars Production Plant (early '90s), Mars Sabatier/Water Electrolysis System (Mars env. chamber '00), MIP (flight experiment for cancelled Mars '01)
    - MOXIE scheduled to fly on Mars 2020 mission

- However, **significant work is needed to mature these technologies**
  - Development & testing much closer to full-scale for human mission needs
  - Much longer operational durations
  - Much more testing to validate performance under relevant environmental conditions
  - Integrate many components and subsystems into system prototypes
  - Realize synergy between ISRU and other system technologies, such as life support/fuel cell, power, surface mobility

ISRU Critical Challenges That Need to Be Addressed

- What is the 'right' set of components and subsystems to enable production of mission consumables from either regolith or atmospheric resources at a variety of destinations?
- What is the performance and life that can be expected from the ISRU system in the actual environment?
- How does the ISRU system integrate and interact with other systems (e.g., power, lander, life support, etc.)?
  - ConOps
  - Power sharing
  - Total surface thermal management
  - Maintenance and refurbishment

Overall Goal: System-level TRL 6 to support future Pathfinder missions

ISRU Technology Project

- Scope: Develop the component, subsystem, and system technology to enable production of mission consumables from either regolith or atmospheric resources at a variety of destinations
- Objective: Advance ISRU System-level technology readiness to prepare for flight demonstrations
  - 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

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

Example of ISRU Components and Subsystem Definition

4.1 Atmosphere Carbon Dioxide (CO_2) Collection Subsystem

Subsystem

Dust Filtration / Mitigation

Atmosphere Blower

CO2 Separation, Collection, and Pressurization

4.2 02 Production Subsystem

4.3 Methane Production Subsystem

- Media filter
- Mechanism(s) to renew and/or clean filter media
- Electrostatic filter device
- Mechanism(s) to clean out electrostatic filter components
- Electronics for electrostatic filter
- Inlet duct and filter housing

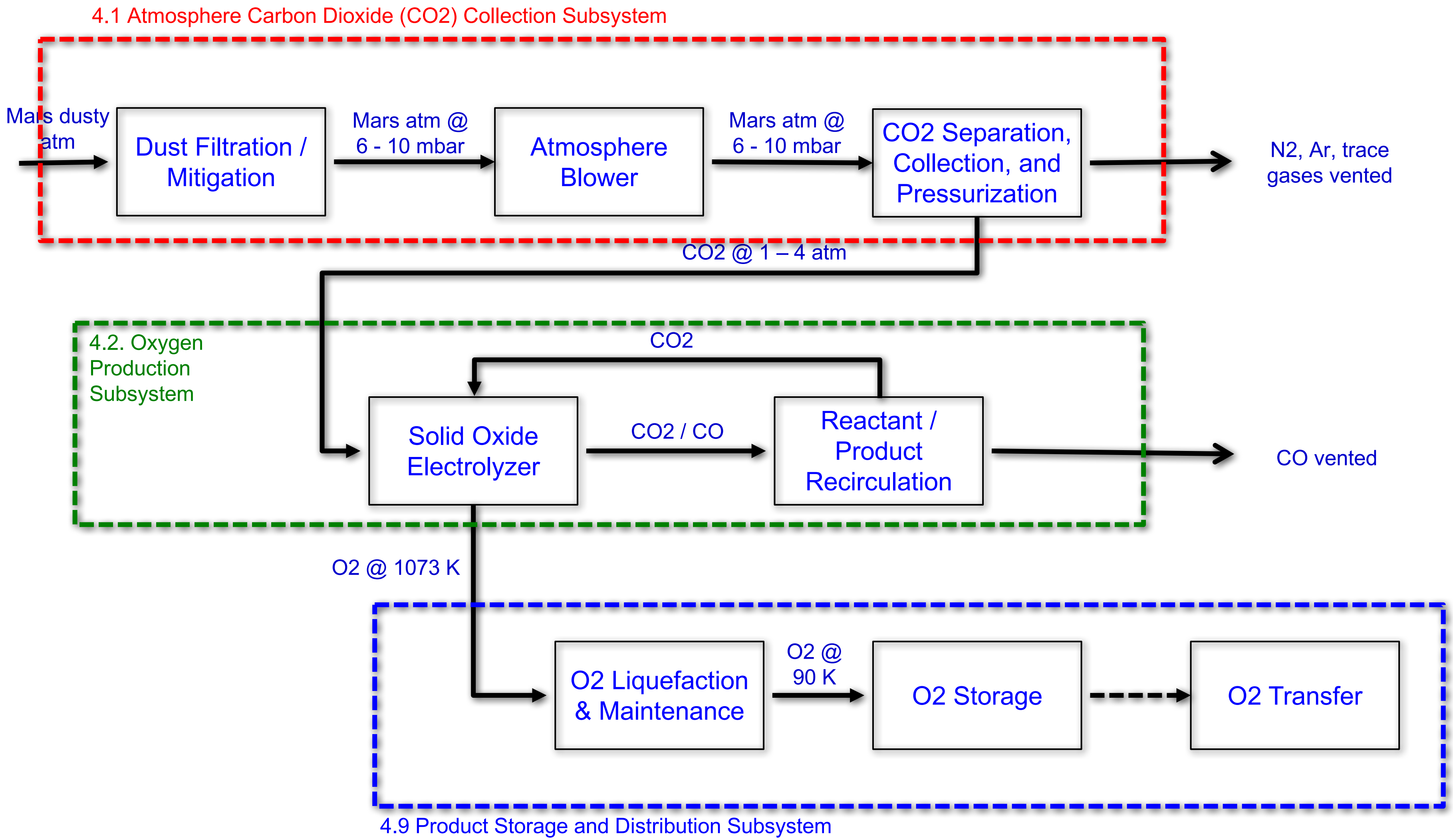
- Low pressure/density gas blower with small (~2:1) compression ratio

- High efficiency cryocooler (150 K cold-finger)
- CO2 collection chamber and cold head
- CO2 mass/pressure control for CO2 freezer
- Microchannel sorption pump(s) (multiple stages)
- Hot/cold thermal management system for sorption pumps
- Mechanical compressor (>100:1 pressure ratio)
- CO2 / atmospheric gas separation
- CO2 collection / buffer tank for sorption pumps and/or mechanical compressor

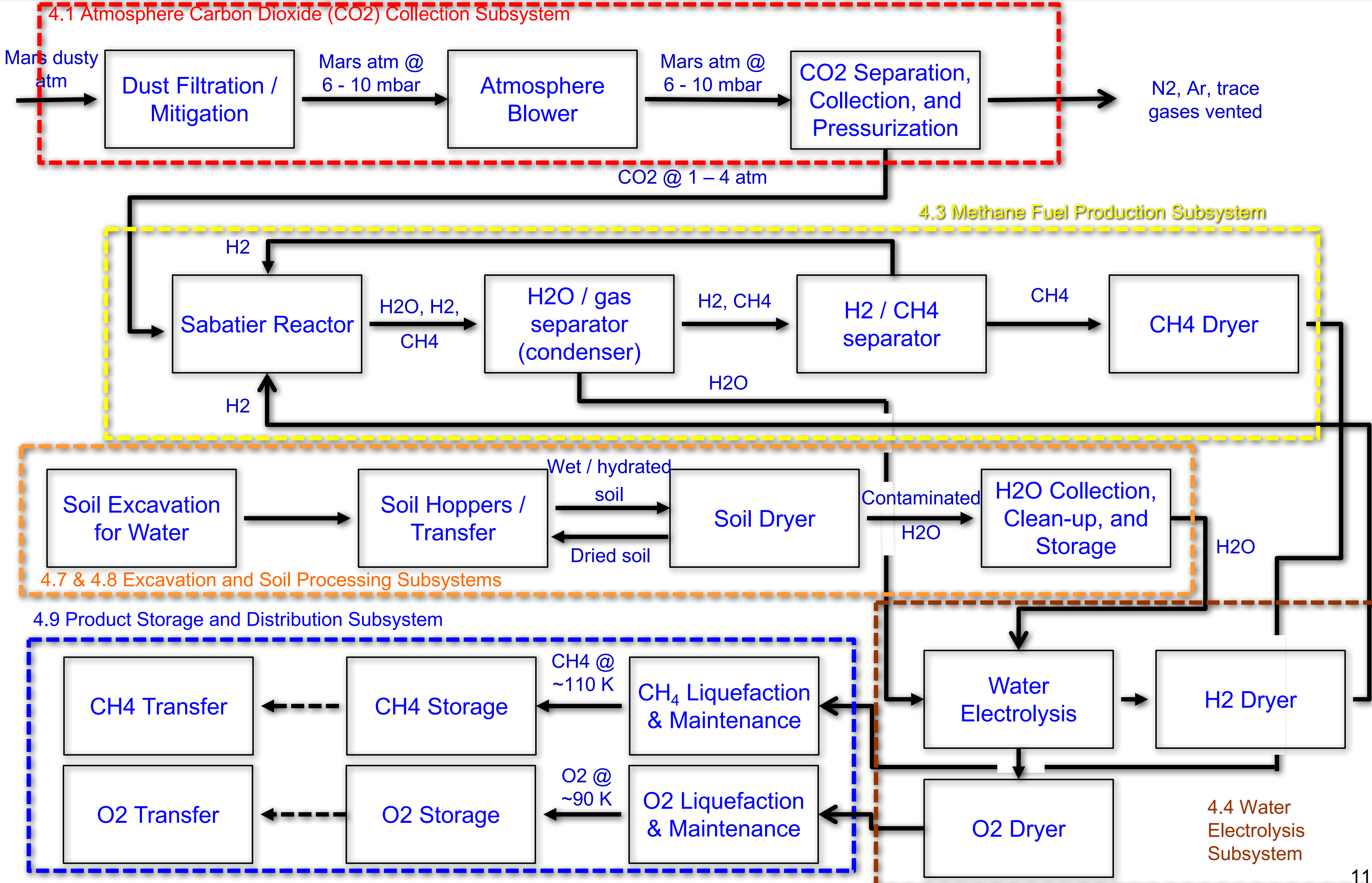
Components

Example of ISRU System Definition

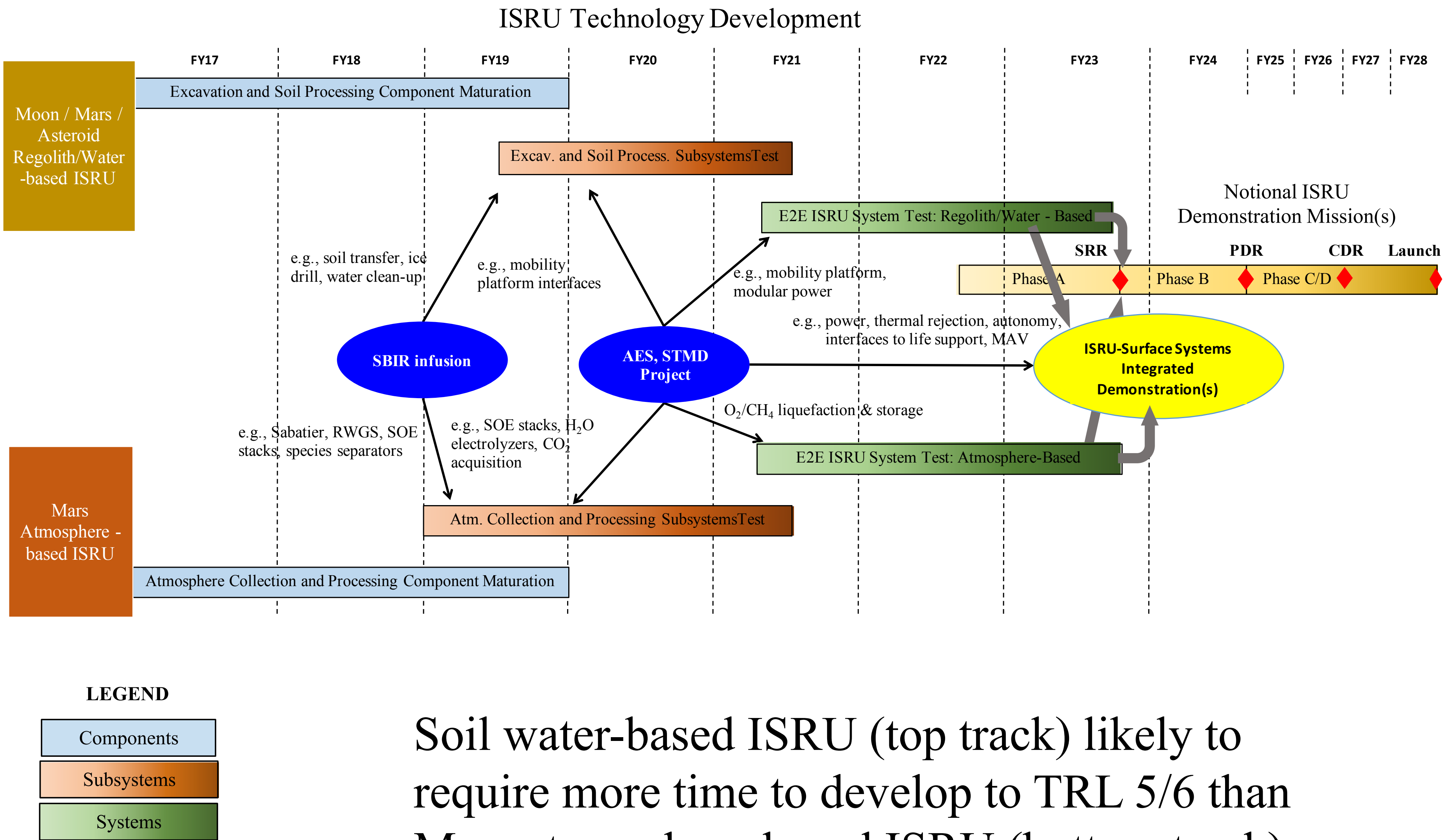
Oxygen Production from Atmosphere Integrated System (SOE Option)



ISRU Fuel and Oxygen Production End-to-End Integrated System

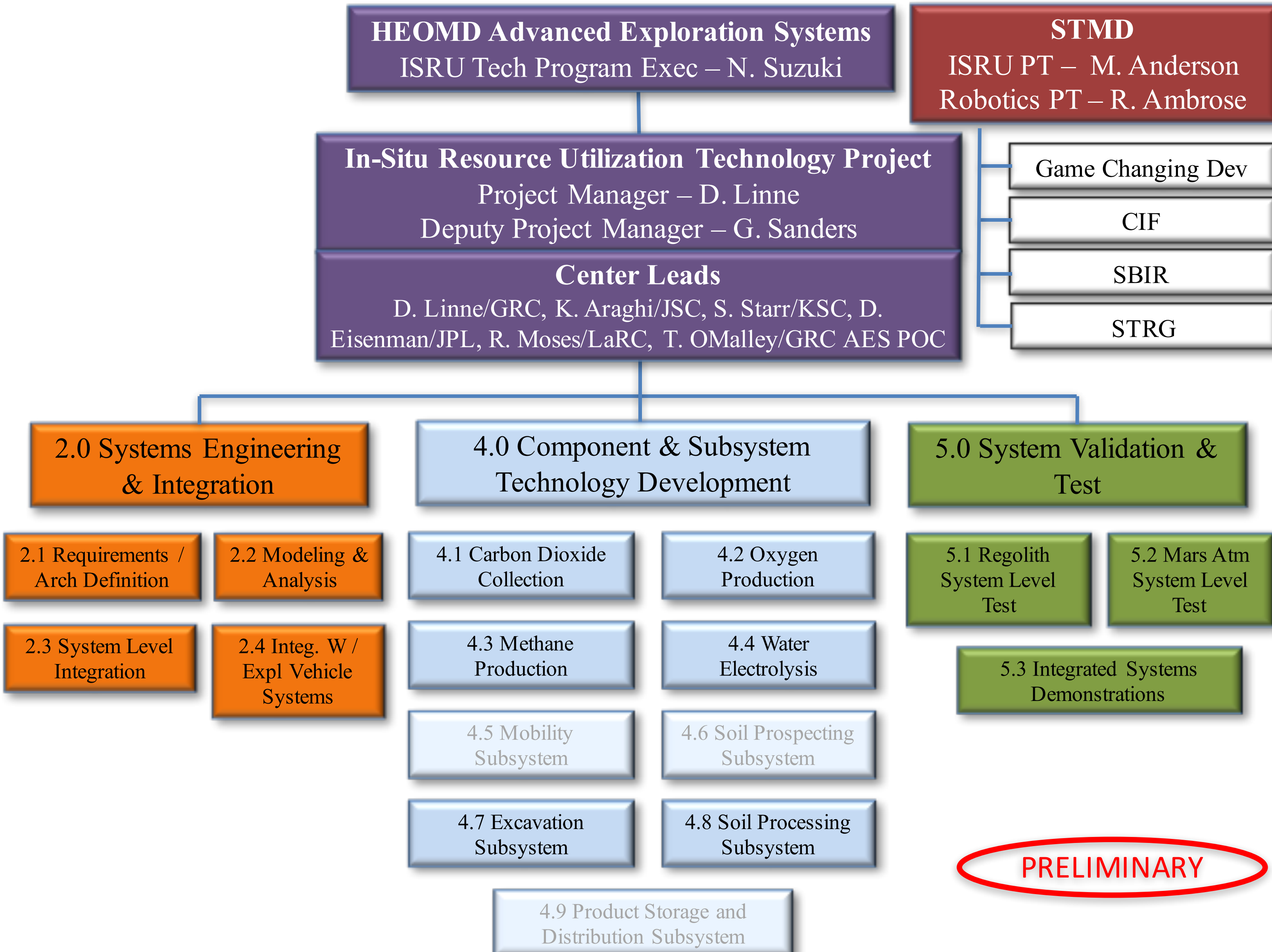


ISRU Technology Project Schedule (Notional)



Soil water-based ISRU (top track) likely to require more time to develop to TRL 5/6 than Mars atmosphere-based ISRU (bottom track)

ISRU Project Structure



FY17 Overview

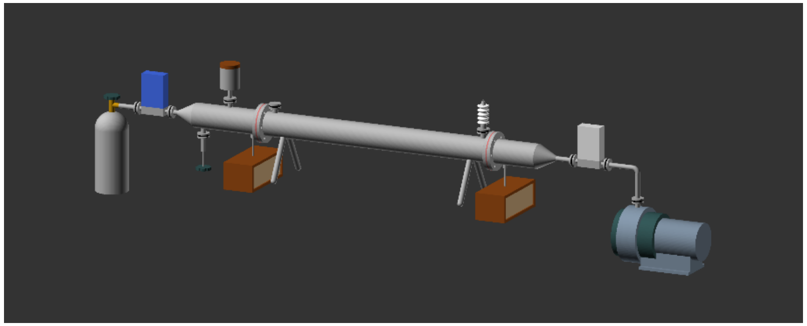
2.0 Systems Engineering and Integration

- Exploration Mission Architecture teams
  - Provide ISRU systems mass, power, volume, and concept of operations input to mission architecture teams
  - Work with other projects to identify common technology needs (e.g., water electrolysis) and dependent technology needs (e.g., mobility platform)
- System Modeling
  - Develop system model framework to link physics-based component models into integrated system model
  - Perform trade study on effects of mass, power, volume of Mars oxygen/fuel production system as a function of water resource type (hydrated minerals, icy soils, deep ice)
- System Level Integration - Thermal Management
  - Evaluate system-level thermal integration challenges and identify and analyze potential solutions
    - Hot and cold components within the system
    - Synergistic use of waste heat from external to ISRU system
- Autonomy and Control
  - Evaluate challenges and potential solutions for long-duration untended operation, with focus on autonomous navigation and operation of excavation and delivery subsystem

4.1.1 Dust Filtration and Mitigation

- Scroll Media Filters
  - Create physics-based model and validate
    - Existing data from testing in Mars flow loop
    - Possible test data from MOXIE (Mars Oxygen In-Situ Resource Utilization Experiment)
  - Design full-scale media filter component for fabrication and testing in FY18
- Electrostatic Precipitators
  - Develop and test electrostatic precipitator to remove dust from Mars atmosphere at the intake to the ISRU plant
  - Create physics-based model and validate with test data
  - Use model to optimize geometry
- Cyclone Separators
  - Evaluate past lunar ISRU work and on-going SBIR for applicability to Mars atmosphere dust filtration

Scroll filter designed for Space Station

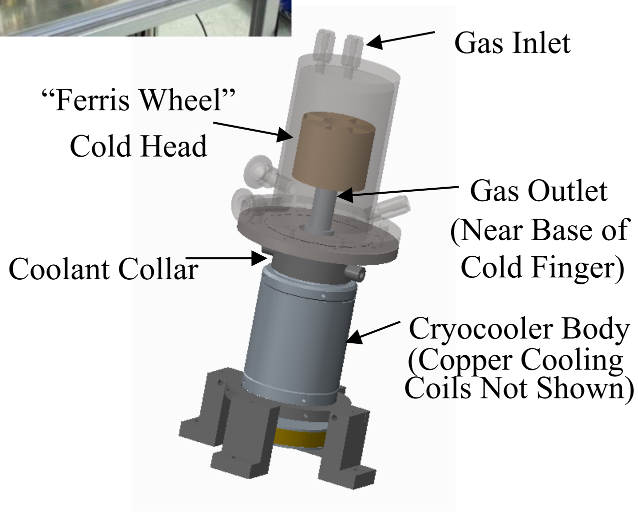


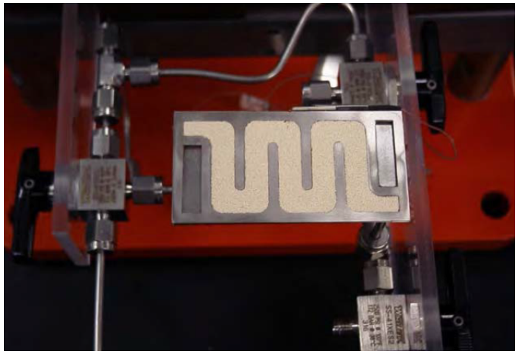
Electrostatic Precipitator Design

4.1.3 CO_2 Separation, Collection, and Pressurization

- Cryofreezer
  - Create physics-based model and validate
    - Existing data from testing in Mars flow loop
    - Possible test data from MOXIE project
  - Design and evaluate multiple cold-head concepts to maximize collection efficiency
- Rapid Cycle Sorption Pump
  - Modeling and detailed design using finite element structural, fluid, and thermal modeling tools
    - Predict performance for different CO_2 sorbent materials
  - Develop thermal design to enable rapid thermal cycling
  - Develop and test new sorbent materials
- Mechanical Compressors
  - Modeling and design of radial (centrifugal, axial) and positive displacement (e.g., scroll) to determine performance, power, and volume
  - Identify critical scaling limitations of different compressor types

CO_2 freezers and chiller (left) and 3D model (below)

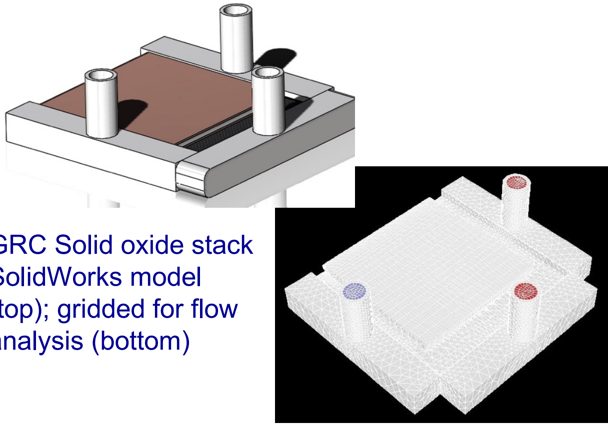




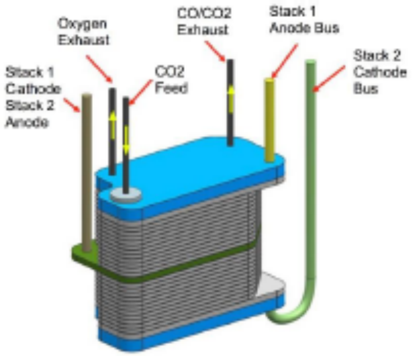
Opened view of a single adsorber unit

4.2.2 Solid Oxide Electrolysis

- Assess state-of-the-art
  - Identify key enablers and critical technology gaps to achieve scale-up, stable performance, and long life
  - Evaluate differences in fabrication methods, reliability, scalability, thermal cycling, thermal ramp rates, operating pressures, sealing, and longevity
- Structural and thermal modeling
  - Create finite element fluid, mechanical, and thermal models of solid oxide stacks
  - Use models to evaluate and improve manifolds, identify stress points during thermal cycling, aid in scale-up
- Advanced fabrication methods
  - 3D print zirconia oxide manifold for GRC bi-supported cell design
  - Test 3D-printed manifolds on small stacks
- Technology investment and development roadmap

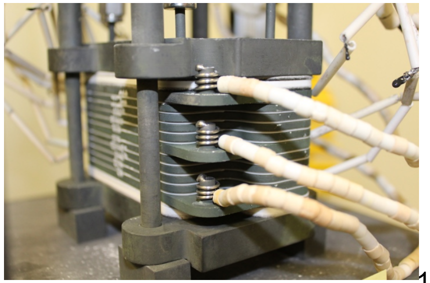


GRC Solid oxide stack SolidWorks model (top); gridded for flow analysis (bottom)



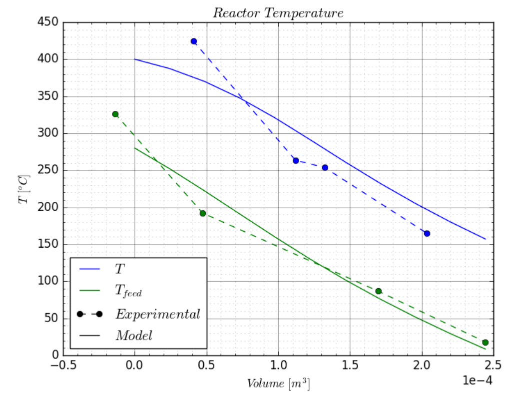
MOXIE Solid Oxide Electrolyzer (Ceramatec) model (above) and in test stand (below)

Paragon Solid Oxide Electrolyzer

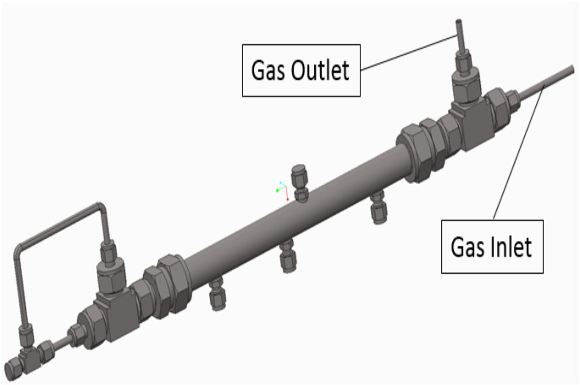


4.3.1 Sabatier Reactor

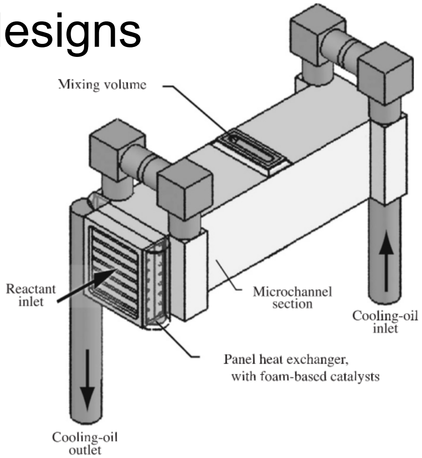
- Modeling
  - Create a physics-based model of existing subscale Sabatier reactor
  - Validate model with data from existing reactor
  - Generate data with large-scale reactor and use to validate model
- Testing
  - Test subscale reactor at different conditions (H_2:CO_2 ratio, flow rates, etc.)
  - Build full-scale reactor and measure performance
  - Test reactors to optimize operations, especially on start-up and shut-down
- Review state of the art reactor designs
- Technology investment and development roadmap



Example of modelled reactor temperatures compared to experimental



Packed bed Sabatier reactor 3D model (above)



Microchannel Sabatier reactor designed by PNNL.

K. P. Brooks, J. Hu, H. Zhu, R. J. Kee, Methanation of carbon dioxide by hydrogen reduction using the Sabatier process in microchannel reactors. *Chem. Eng. Sci.* **62**, 1161–1170 (2007).

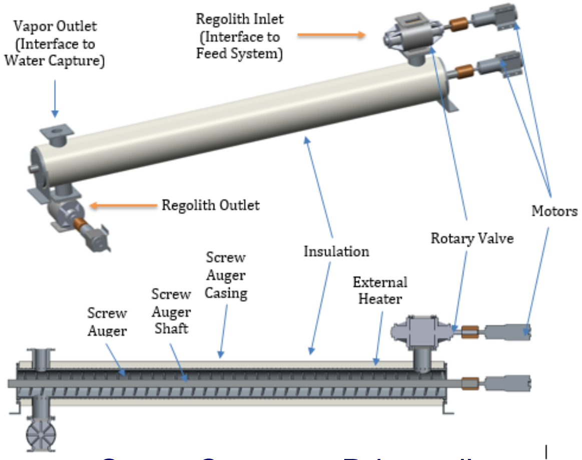
4.7.1 Soil Excavation for Water

- Excavation modeling
  - Update lunar excavation models to include excavation of different resource types
    - Mars hydrated minerals
    - Icy soils at moon and Mars
    - Deep ice deposits on Mars
  - Validate with existing data and new data when available
- Excavator design
  - Use models to evaluate proposed excavation concepts and generate new concepts
  - Develop test plans for new excavator concepts and gather data for further model validation

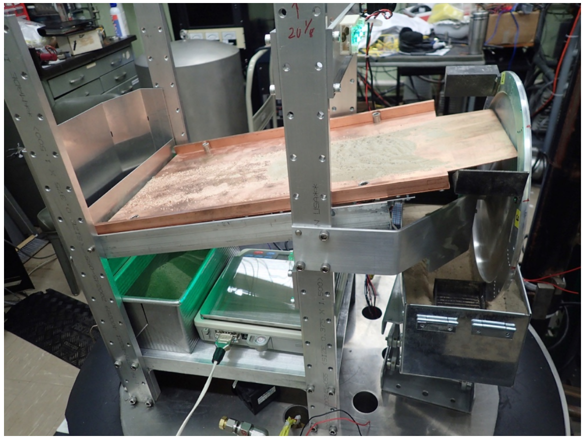
KSC RASSOR (Regolith Advanced Surface Systems Operations Robot) excavator delivering loose soils

4.8.2 Soil Dryers

- Closed processors
  - Closed or partially closed reactor
  - Receives delivered regolith, extracts and separates water, deposits spent regolith for disposal
- Open processors
  - Process and extract the water at the site
  - Includes in-situ extraction of deep ice deposits in liquid or gas phase
  - Complete testing of GRC in-situ processor concept
- Soil processing designs
  - Create models to evaluate proposed concepts and generate new concepts
  - Develop designs for one batch and one in-situ concept
  - Develop test plans for soil processing concepts



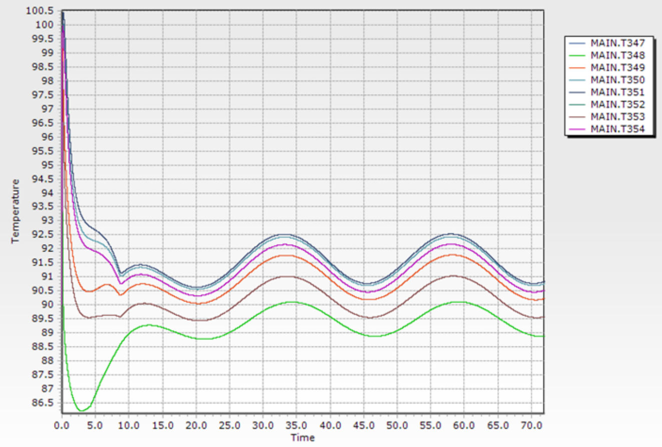
Screw Conveyor Drive soil processor concept



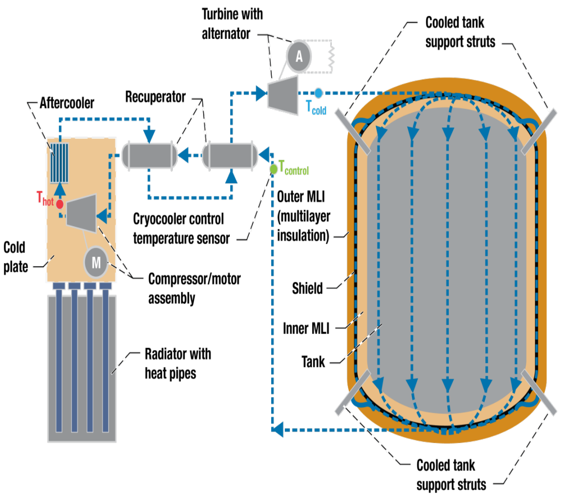
Concept for open water extraction soil processor

4.9.1 O_2/CH_4 Liquefaction & 4.9.2 O_2/CH_4 Storage

- Develop integrated thermal fluid models
  - Thermal Desktop model of oxygen liquefaction and zero-boil-off storage in Mars Ascent Vehicle tank
  - Model transients including cryocooler operation over daily and seasonal external temperature variations
- Validate models with existing and new (when available) test data
  - Liquid Oxygen Zero-Boil-Off Experiment
  - Liquefaction brassboard testing
- Trade study comparing mass and thermal performance of insulation systems for Mars applications
  - Aerogel based soft vacuum (5 Torr) optimized insulation systems
  - MLI based hard vacuum optimized (with 5 Torr vacuum shell) insulation systems
  - Lightweight vacuum systems such as Quest Products
- O_2 liquefaction brassboard test (funding dependent)
  - Fill level heat transfer issues with using tank wall
  - Transient fluid dynamics responses to periodic cooling (for example if cryocooler was only on at "night")
  - Data for model validation



Tank based cryocooler system transient response to daily Mars temperature swings



Notional Broad Area Cooling System Schematic (Reverse Turbo-Brayton cryocooler shown)

Note: ISRU Liquefaction currently managed under AES/Lander Tech

Summary

- NASA ISRU Technology projects in HEOMD and STMD are developing ISRU technology for the Moon, asteroids, and Mars
  - Focus on acquisition and consumables production and storage
  - Component -> subsystem -> system progression
- Emphasis on testing in relevant environment early and often
- Raise System-level TRL in preparation for potential demonstration missions
- Provide Exploration Architecture Teams with validated, high-fidelity answers for mass, power, volume, and concept of operations