Mars ISRU & Civil Engineering Current Thinking and Approaches

Presentation to the International Mars Exploration Working Group (IMEWG)

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Outline

- Mars water resources mining and processing
  - Lunar ISRU feed forward/risk reduction to Mars
- Mars in-situ construction
  - Lunar ISRU feed forward/risk reduction to Mars
- What does ISRU still need from Mars science missions?

Mars Atmosphere & Water Resource Attributes

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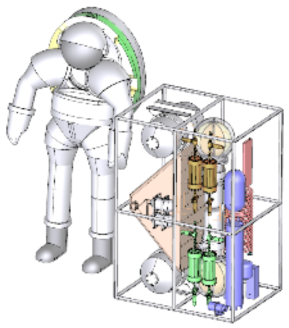
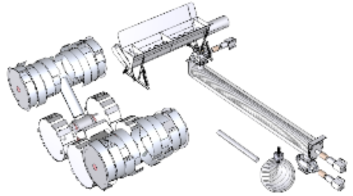
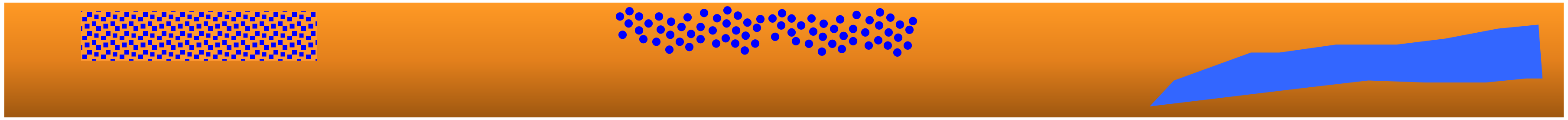
Atmosphere Processing



Atmosphere
- Pressure: 6 to 10 torr (~0.08 to 0.1 psi);
- >95% Carbon Dioxide
- Atm. temperature: +35 C to -125 C
- **Everywhere on Mars;** Lower altitude the better
- Chemical processing similar to life support and regenerative power

Granular Regolith Processing for Water



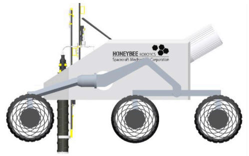


Mars Garden Variety Soil
- **Low water concentration 1-3%**
- **At surface**
- **Granular;** Easy to excavate
- **300 to 400 C heating for water removal**
- Excavate and transfer to centralized soil processing plant
- **Most places on Mars**; 0 to +50 Deg. latitude

Gypsum/Sulfate Processing for Water

Gypsum or Sulfates
- Hydrated minerals 5-10%
- **At Surface**
- **Harder material:** rock excavation and crushing may be required
- **150 to 250 C heating for water removal**
- **Localized concentration in equatorial and mid latitudes**

Icy Regolith Processing for Water



Subsurface Ice
- **90%+ concentration**
- **Subsurface glacier or crater**: 1 to 3 m from surface possible
- **Hard material**
- **100 to 150 C heating for water removal**
- Downhole or on-rover processing for water removal
- **Highly selective landing site for near surface ice or exposed crater;** >40 to +55 Deg. latitude

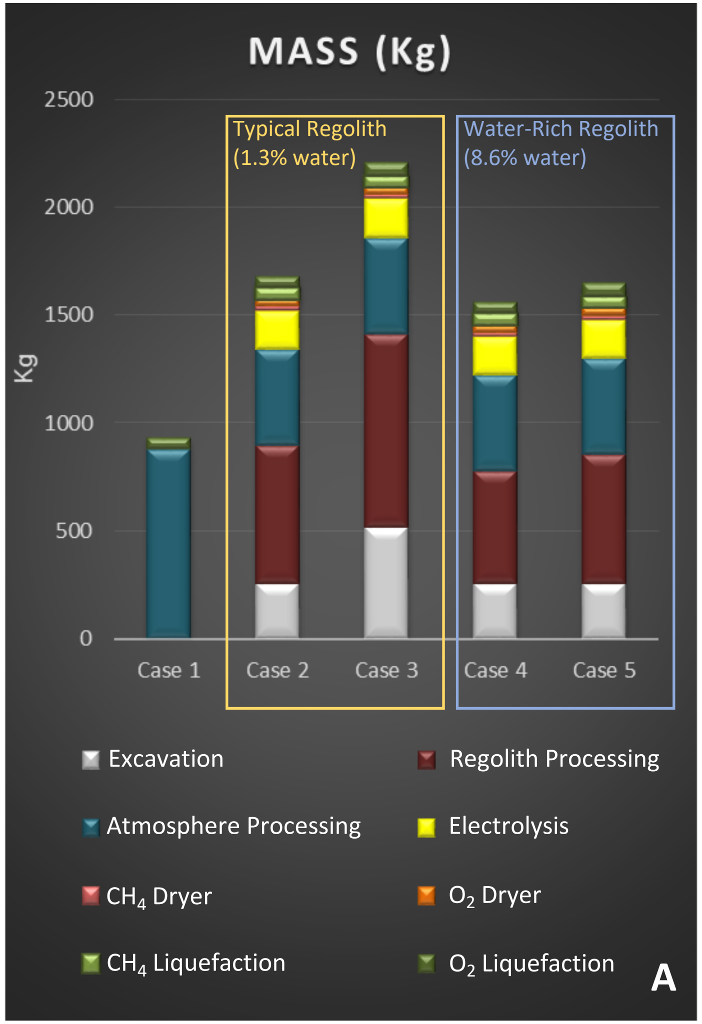
Increasing Complexity, Difficulty, and Site Specificity

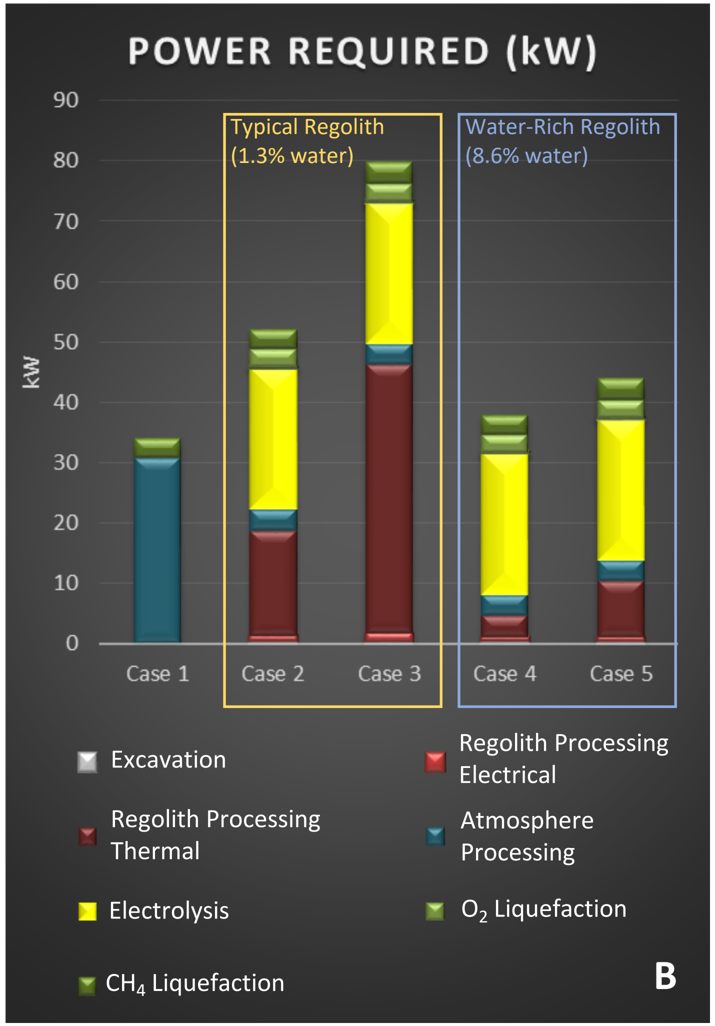
Mars Soil-Water Mining and Processing

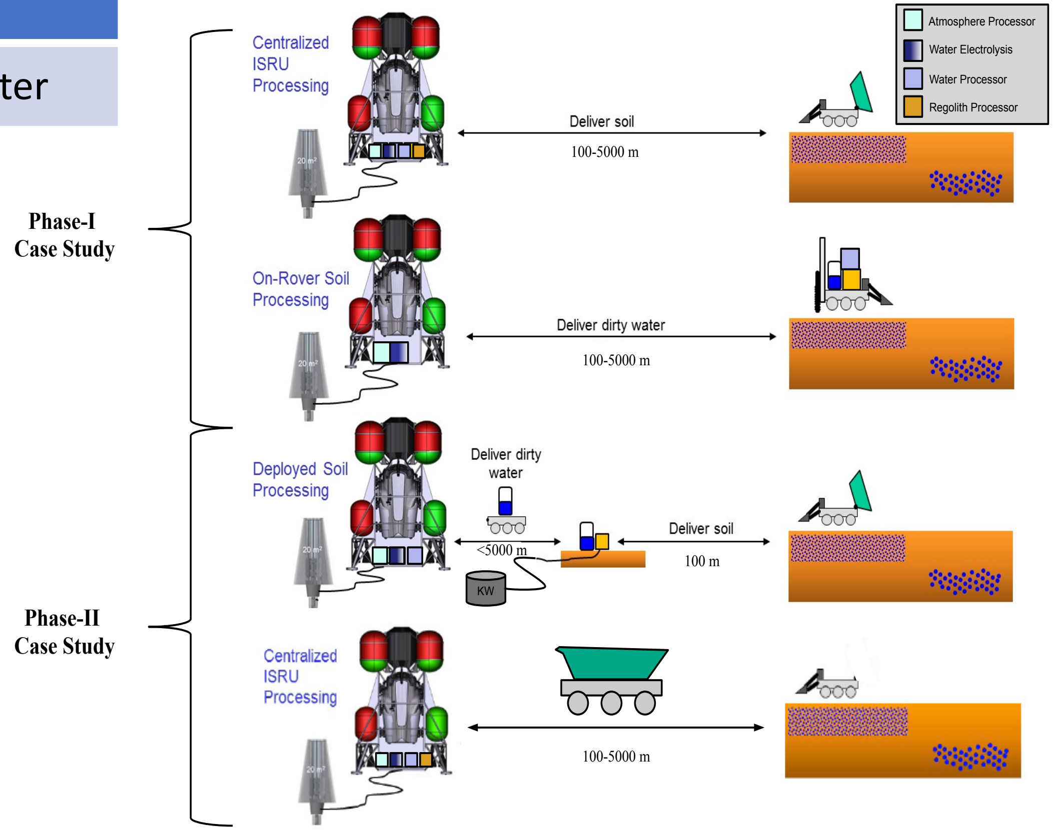
Mars Soil-Water Mining – *Trade Study*

2017 Mars ISRU Study Results

Case 1	Case 2 + 4	Case 3 + 5
Oxygen propellant	Ascent Propellants	Ascent Propellants + Life Support water





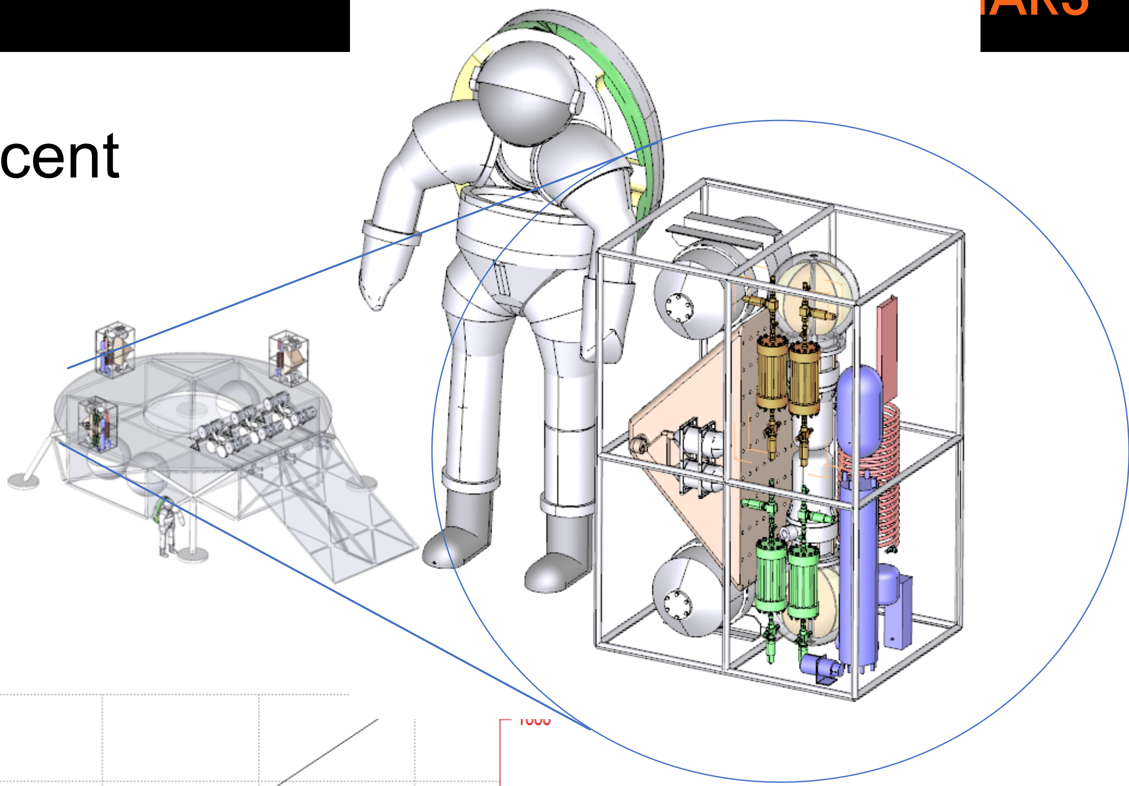


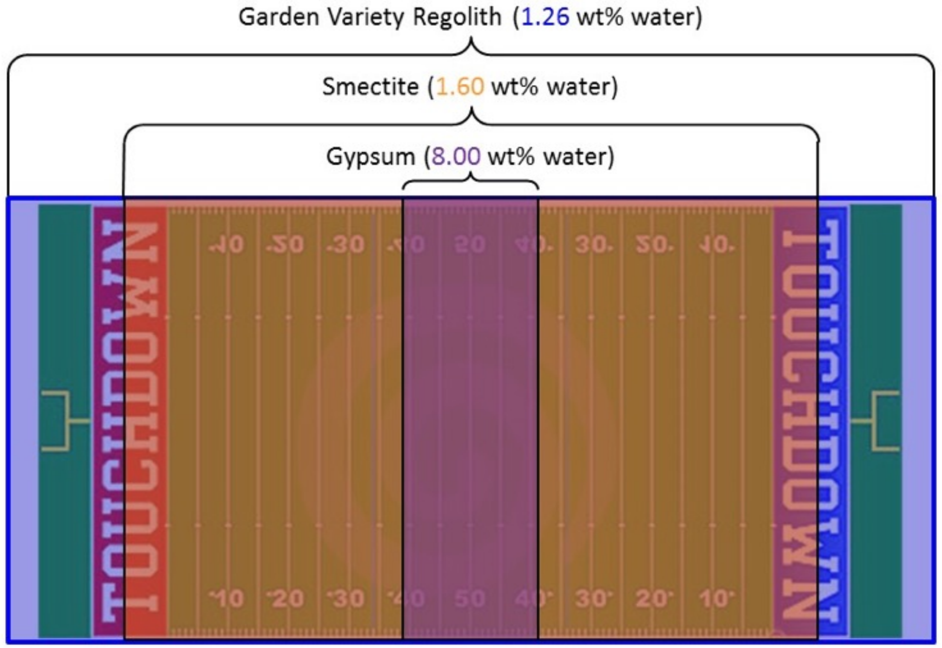
Higher Yield regolith

- The addition of life support consumables has only marginal impact on mass and power
- Due to decrease in processing temperature, power levels are comparable to Oxygen-only case
- Larger mass reduction (25%) due to fewer excavators

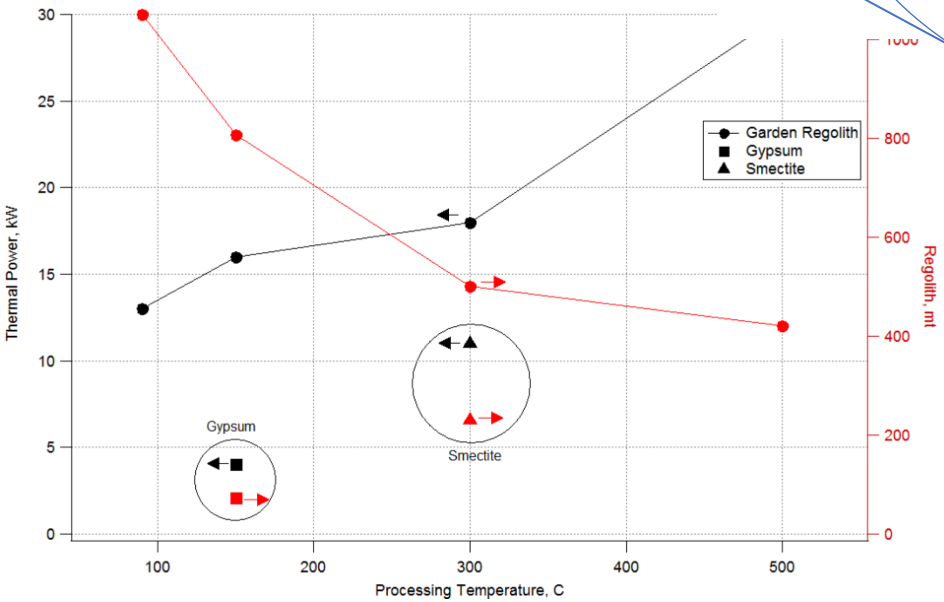
Impact of Water Content in Regolith on Results

- The real benefit of targeting higher weight percent water regolith is the power saving
  - Less regolith to excavate and transport
  - Less regolith to heat
  - Heating at a lower temperature





Surface area required per mobile excavator with the following assumptions:
- 3 excavators used; Each excavator provides 40% of required water; Excavation depth = ~5cm (2.0 in)



Mars Soil-Water Mining and Processing – *Technology Development*

Excavation

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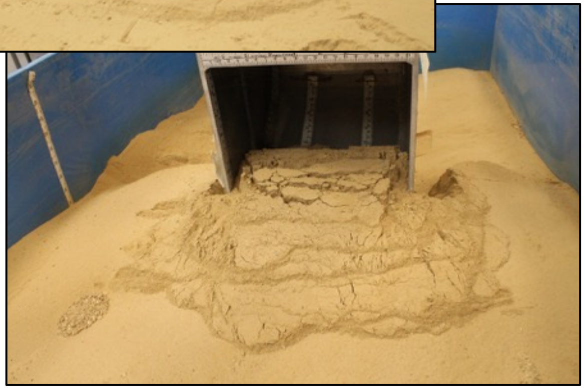
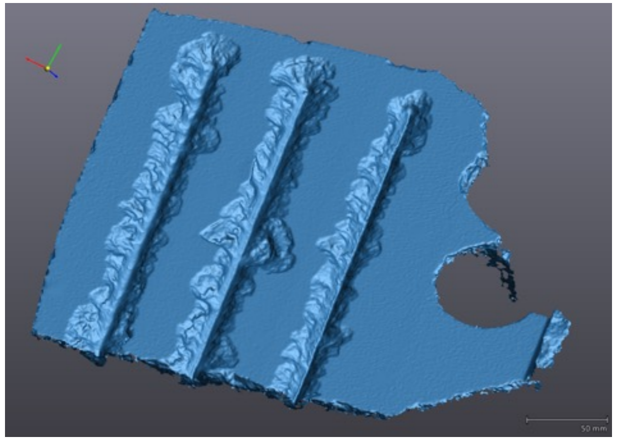
- Fundamental forces in compacted granular regolith
- Excavation force model validated with test data
- Fundamental forces / energy to fracture hard material with single pick test



Top Left: Excavation lab at NASA GRC; Top Right: Bow wake in lightly compacted-simulant; Right: Bow wake in highly-compacted simulant



Left to Right: Single-pick test stand with gypsum block; single-pick test; two excavated lines; 3D scan of excavated lines to measure excavated volume

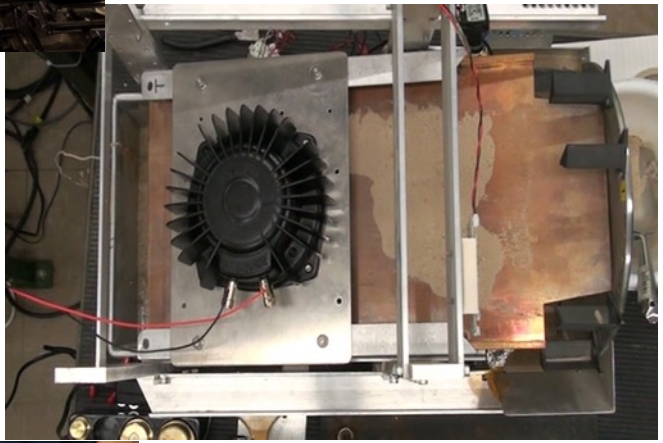
Water Extraction – Hydrated Minerals and Granular

- Auger dryer flow visualization tests
- Soil plug / column concept for sealing tested
- Open ‘air’ processor tested with multiple simulants
- Microwave water extraction from porous tube reactor
- Microwave extraction in Mars chamber tests initiated

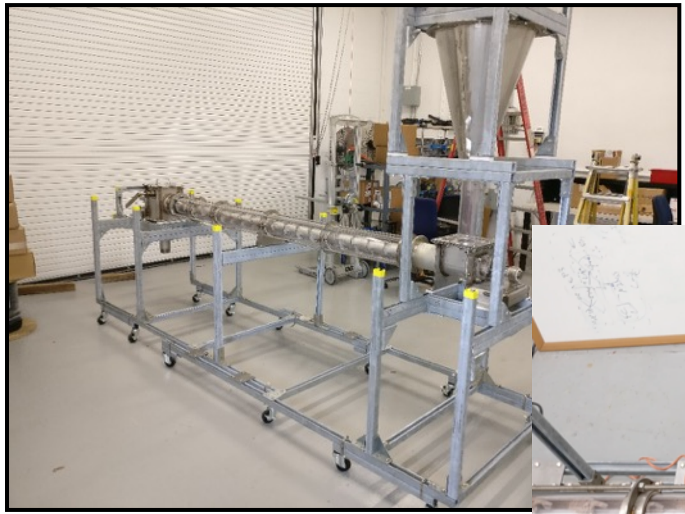
Microwave Processor

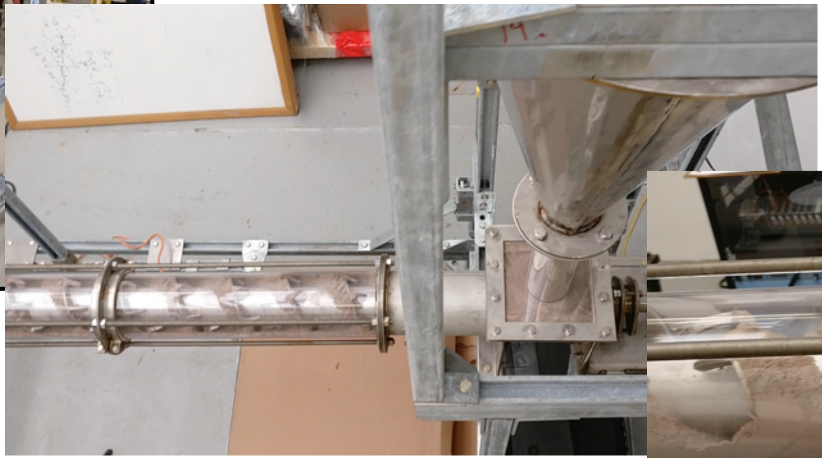
LN2 Traps to capture water

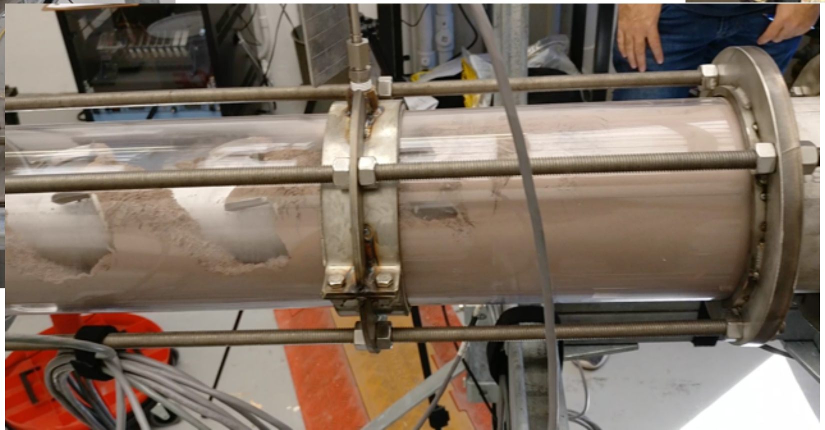
Microwave processor testing at -20C



Open ‘air’ processor showing bucket wheel delivering regolith onto heated plate





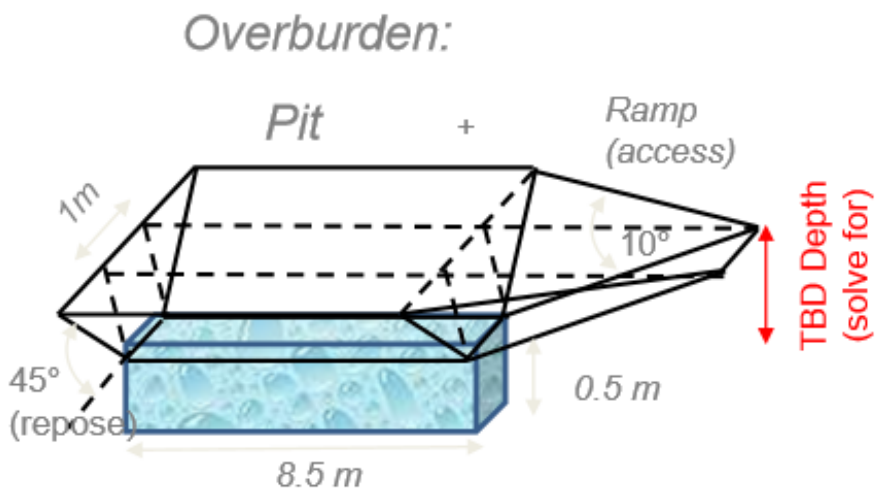


Auger dryer flow visualization (left), inlet hopper (middle), plug flow developing at exit (right)

Subsurface Ice ISRU Mining Options

Pit Mining

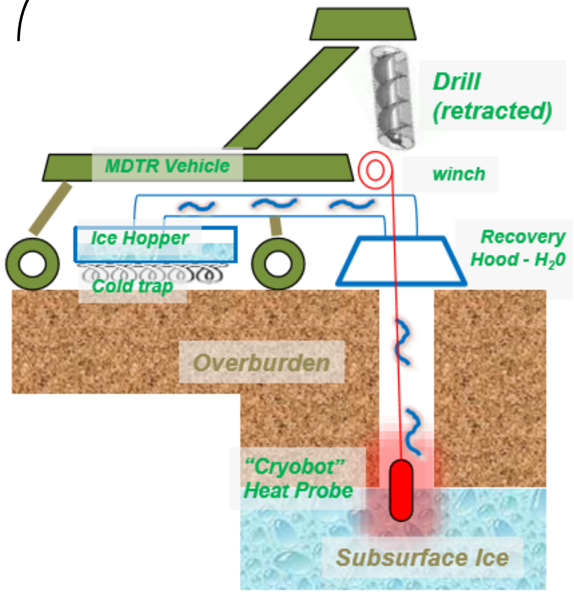
Remove Overburden

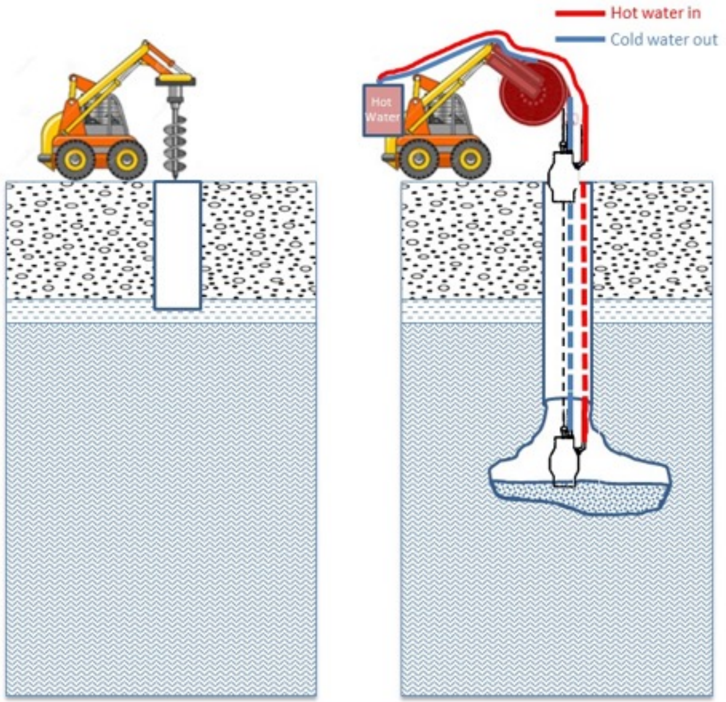


Subsurface Volatilization

Subsurface Melting (Rodwell)

Drill Through Overburden





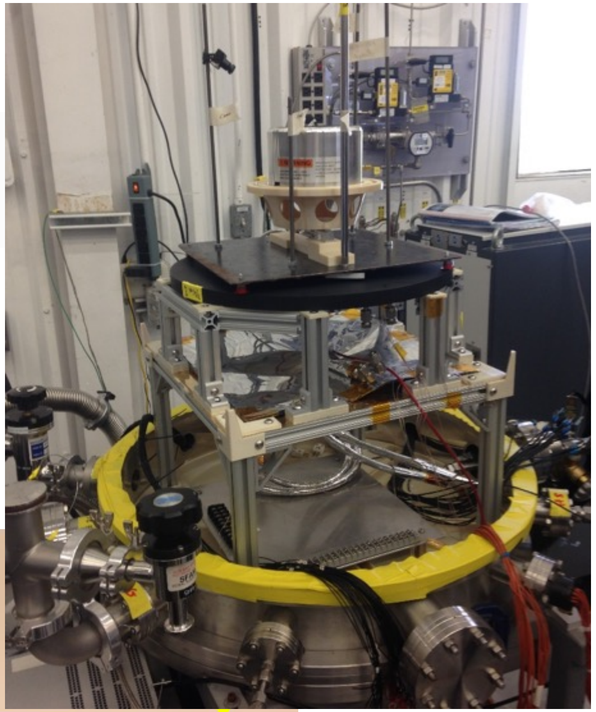
Phase 1: Drill through overburden into top of ice.

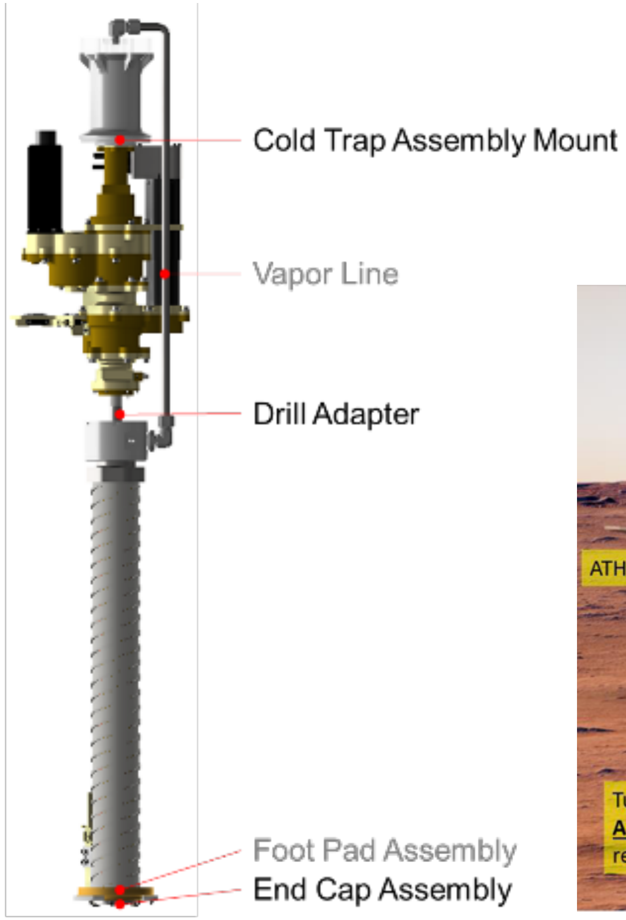
Phase 2: Melt into ice. Begin forming water pool.

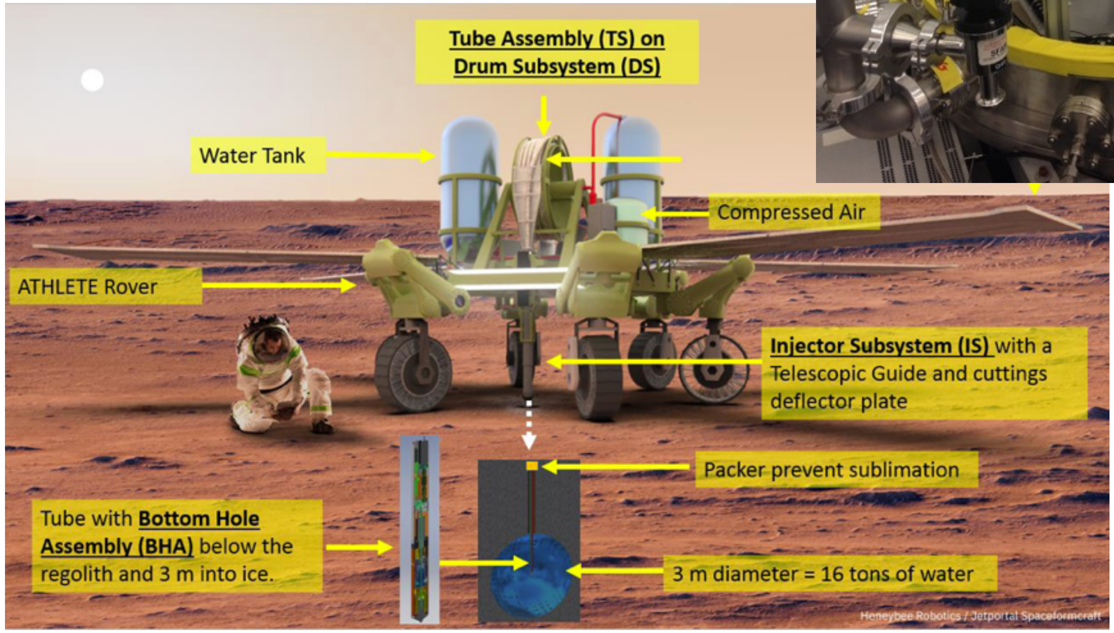
Water Extraction – Subsurface Ice

- Rodwell ice mining modeling and fundamental data
- SBIRs and NextSTEP BAA with Honeybee Robotics for Rodwell subsystem demonstration

Test hardware to measure fundamental sublimation properties at Mars pressure and temperature





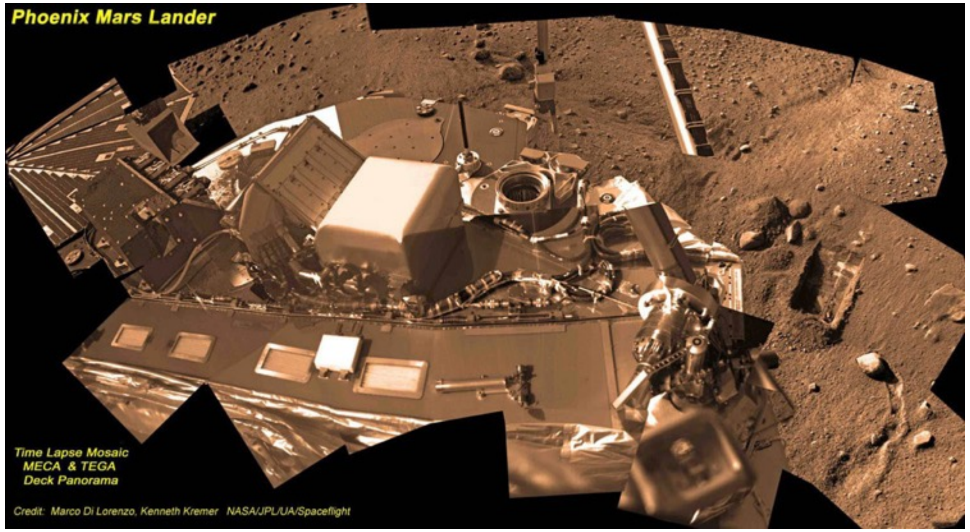


Honeybee Robotics Planetary Volatile Extractor (PVEx) Drill (left) and concept for Extraction of Water from Mars' Ice Deposits (right)

Simulant Development

- New prototype Mars simulant to replicate the 1-3 wt% water release from the Rocknest aeolian sand shadow in Gale crater
- ‘Dirty’ water recipe developed for Mars water

JSC Rocknest (left to right): prototype simulant, 5-gallon buckets of USGS-produced simulant, JSC Rocknest



Mars ‘dirty’ water recipe (right) based on: Microscopy, Electrochemistry, and Conductivity Analyzer (MECA) instrument (above) on the Phoenix lander on Mars

Mars ISRU Water Simulant Mixture					
Reagent Name	**Chemical Formula**	**Amount**	**Unit**	**Amount**	**Unit**
Water	H2O	25	ml	2000	ml
Calcium Carbonate	CaCO3	40	mg	3200	mg
Magnesium Carbonate	MgCO3	20	mg	1600	mg
Magnesium Sulfate Heptahydrate	MgSO4* 7H2O	30	mg	2400	mg
Potassium Chloride	KCl	0.8	mg	64	mg
Sodium Bicarbonate	NaHCO3	3	mg	240	mg
Calcium Chlorate Tetrahydrate	Ca(ClO4)2*4H2O	11.5	mg	920	mg
Magnesium Chlorate Hexahydrate	Mg(ClO4)2*6H2O	8.3	mg	664	mg

(Dirty) Water Electrolysis

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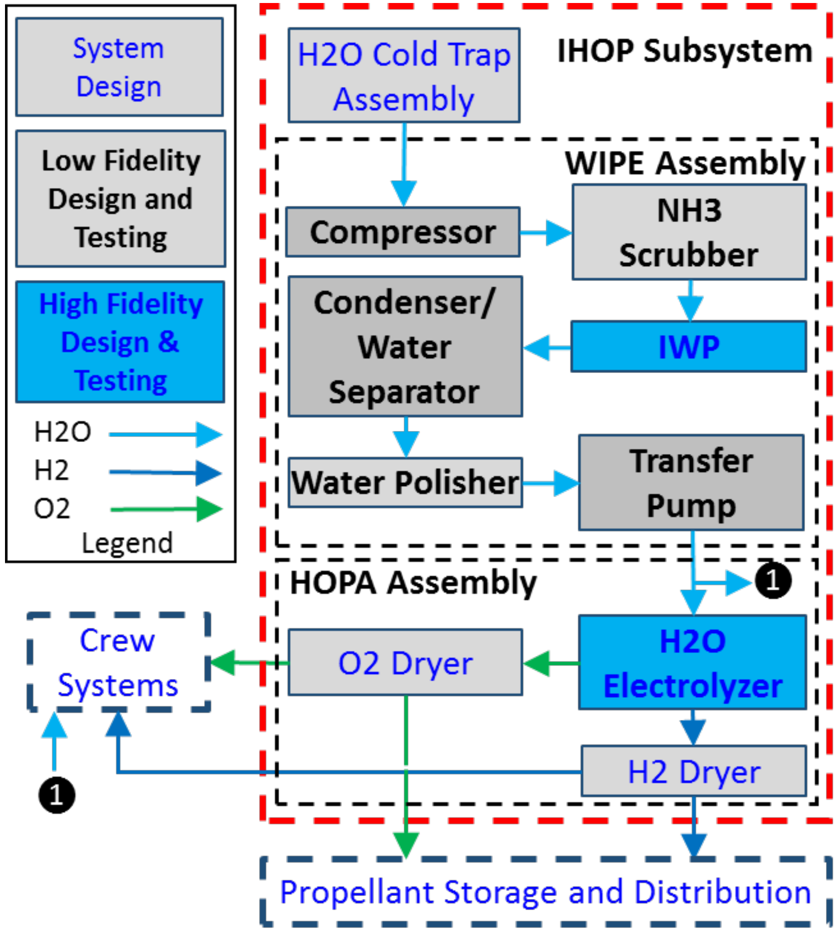
- Alkaline water electrolysis membranes/electrodes combined with porous hydrophobic membrane to operate on salt mixture anticipated from Mars ISRU water recovery
- NextSTEP BAA with Paragon / Giner featuring Ionomer-membrane water processing technology to purify water before electrolyzer
- NextSTEP BAA with Teledyne featuring high-pressure, alkaline-based water electrolysis stack tolerant to contaminants

Example Teledyne off-the-shelf alkaline water electrolyzer



Paragon ISRU-derived Water Purification and Hydrogen Oxygen Production concept

Moon to Mars

NASA Lunar ISRU Purpose

EXPLORE MOON to MARS

Lunar ISRU To Sustain and Grow Human Lunar Surface Exploration

- Lunar Resource Characterization for Science and Prospecting
  - Provide ground-truth on physical, mineral, and volatile characteristics – provide geological context;
  - Test technologies to reduce risk for future extraction/mining
- **Mission Consumable Production (O_2, H_2O, Fuel):**
- Learn to Use Lunar Resources and ISRU for Sustained Operations
  - *In situ* manufacturing and construction feedstock and applications

Lunar ISRU To Reduce the Risk and Prepare for Human Mars Exploration

- Develop and demonstrate technologies and systems applicable to Mars
- Use Moon for operational experience and mission validation for Mars; Mission critical application
  - Regolith/soil excavation, transport, and processing to extract, collect, and clean water
  - Pre-deploy, remote activation and operation, autonomy, propellant transfer, landing with empty tanks
- Enable New Mission Capabilities with ISRU
  - Refuelable hoppers, enhanced shielding, common mission fluids and depots

Lunar ISRU To Enable Economic Expansion into Space

- Lunar Polar Water/Volatiles is Game Changing/Enabling
- Promote Commercial Operations/Business Opportunities
- Support/promote establishment of reusable/commercial transportation

Core ISRU Technologies Are Applicable To Both Moon and Mars

EXPLORE MOON to MARS

Lunar & Mars ISRU Share Many Common Technologies & Modules

Lunar Production Target

10 t O_2 / yr
or
15 t H_2O / yr

Lunar ISRU

- Resource acquisition and site preparation (**225 – 1360 kg / day**)
- Water & volatile extraction
- Oxygen production from regolith (**2.0 kg O_2 / hr**)
- Water electrolysis (**2.8 kg H_2O / hr**)
- All processing systems
- All oxygen storage and transfer systems

Core Technologies

- Soil excavation and transfer
- Water extraction from soil/solid material
- Water distillation

- CO_2 & N_2 Acquisition & Separation

- Methanation Reactor
- H_2 / H_2O / CH_4 Separation
- H_2O Condensers

- H_2O Cleanup
- H_2O Electrolysis
- H_2O Storage

- Heat Exchangers

- Liquid Vaporizers
- O_2 & Fuel Storage (0-g & reduced-g)
- O_2 Feed & Transfer Lines
- O_2/Fuel Couplings

Mars ISRU

- Resource acquisition (**720 – 2660 kg / day**)
- Water extraction from soil
- Mars atmosphere resource collection and conditioning
- Fuel production
- Oxygen production (**2.2 – 2.7 kg O_2 / hr**)
- Water electrolysis (**3.0 kg H_2O / hr**)
- All processing systems
- All oxygen storage and transfer systems (Note: Mars atmosphere does not allow for MLI usage)

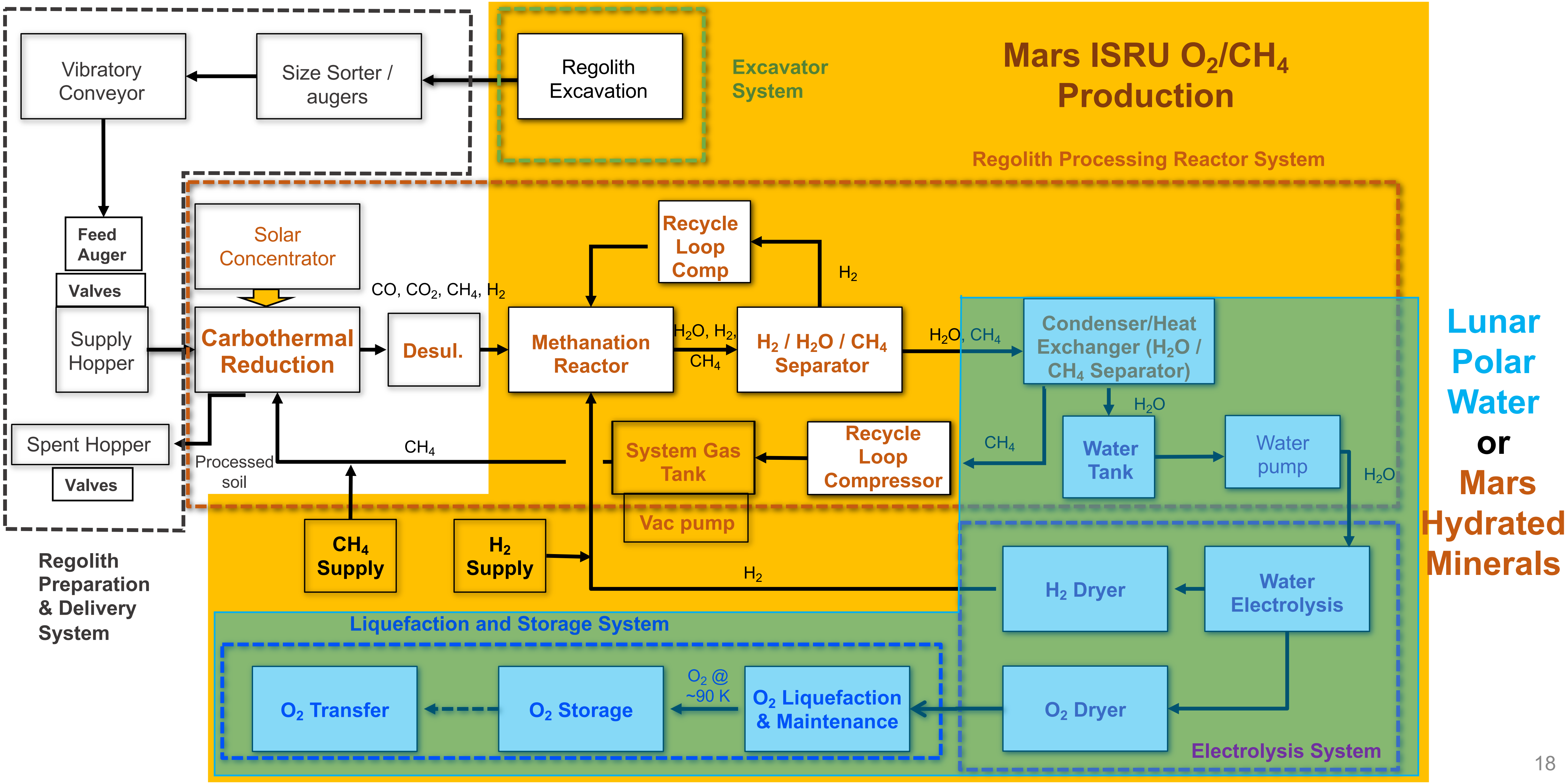
Mars Production Target

23 t O_2 only
or
28 t O_2 & 7 t CH_4

per mission
(~26 months)

Oxygen Extraction from Regolith - EXAMPLE

Carbothermal Reduction End-to-End Integrated System Flow Chart



Construction

Robert Moses / LaRC

In-Situ Construction vs Manufacturing Defined?

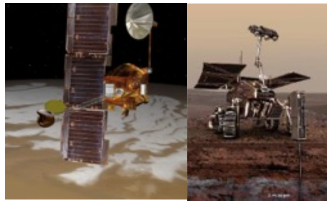
- We offer the following definitions:
- In Situ "Construction" =
  - "large elements, low dimensional tolerances, not necessarily 3D printed, possibly sintered in place"
  - i.e., bulky, clunky, mostly regolith-based production

- In Situ "Manufacturing" =
  - "high tolerance, small components, typically 3D printed"
  - i.e., spare parts out of plastics and metals

Within the Scope of ISRU

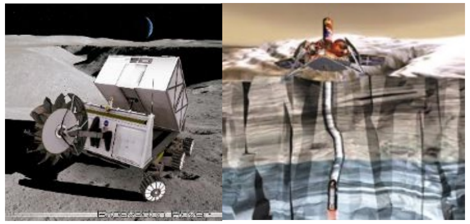
ISRU involves any hardware or operation that harnesses and utilizes ‘in-situ’ resources to create products and services for robotic and human exploration

Resource Assessment (Prospecting)



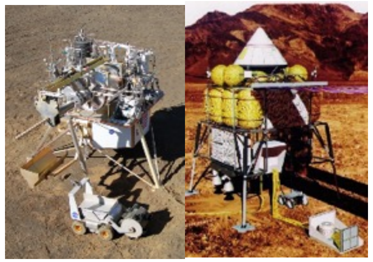
Assessment and mapping of physical, mineral, chemical, and water resources, terrain, geology, and environment

Resource Acquisition



Atmosphere constituent collection, and material/volatile collection via drilling, excavation, transfer, and/or manipulation before Processing

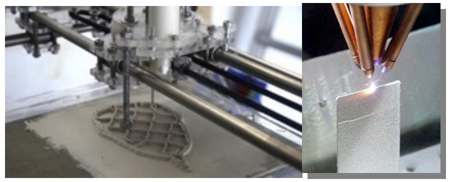
Resource Processing/ Consumable Production



Conversion of acquired 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.

Lunar ISRU Capabilities are the Same/Similar Needed for Mars Exploration

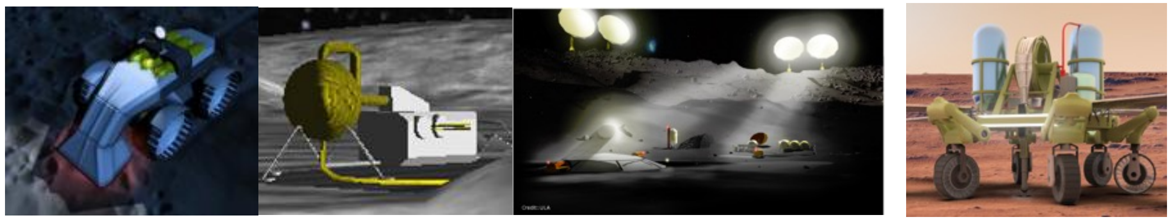
EXPLORE MOON to MARS

Resource Prospecting – Looking for Water

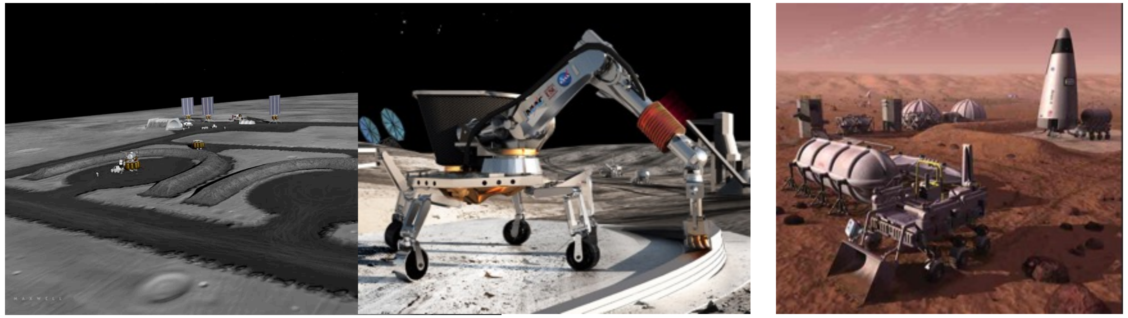
Hydrated minerals & subsurface ice on Mars

Mining Polar Water & Volatiles

Mining near surface ice on Mars

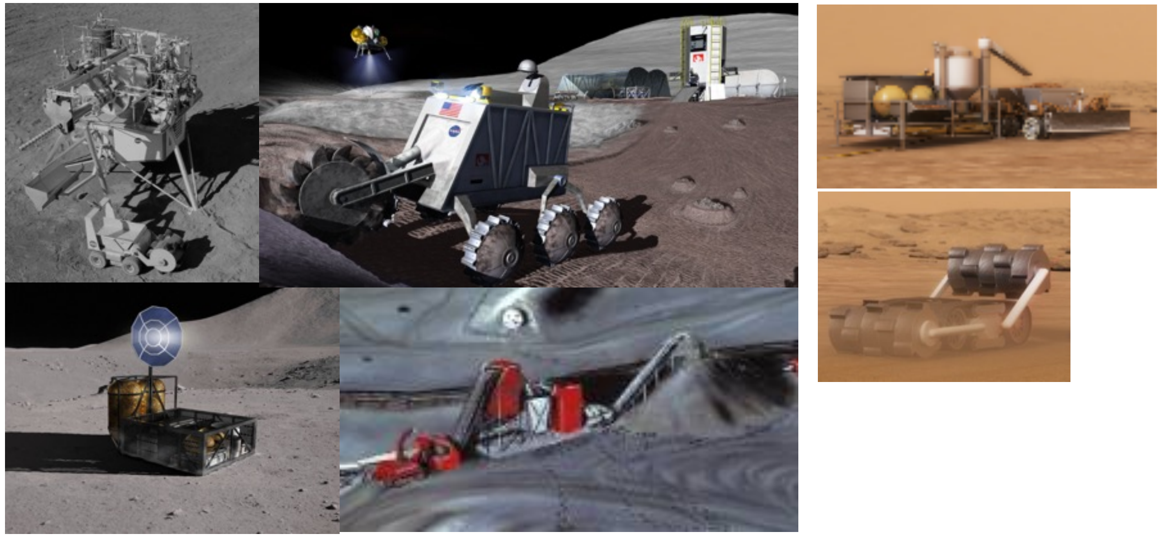


Landing Pads, Berms, Roads, and Structure Construction

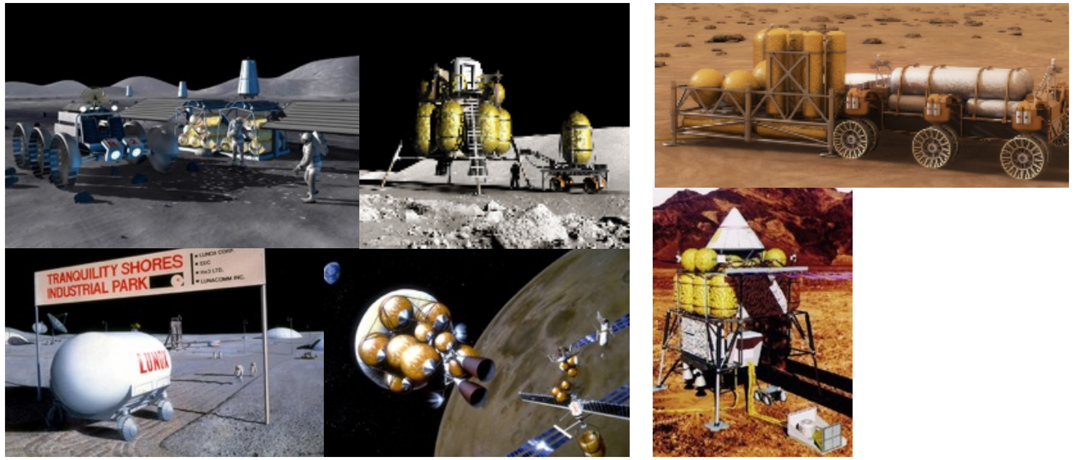


Excavation & Regolith Processing for O_2 Production

Excavation & Processing for H_2O Extraction



Refueling and Reusing Landers & Rovers



Construction Philosophy

EXPLORE MOONtoMARS

WHAT'S NEEDED?

(DEFINED BY ARCHITECTURE)

- Pressurized Structures
- Landing & Launch Pads
- Fission / Blast Berms
- Radiation Shielding for crew and equipment
- Road and route ways
- Other infrastructure such as trenches and compacted foundations
- Non-pressurized structures such as garages, hangars, and refueling depots
- Dust-free zones for parking and operations
- Access to Energy / Power

CIVIL ENGINEERING IN NATURE

WHAT'S THERE?

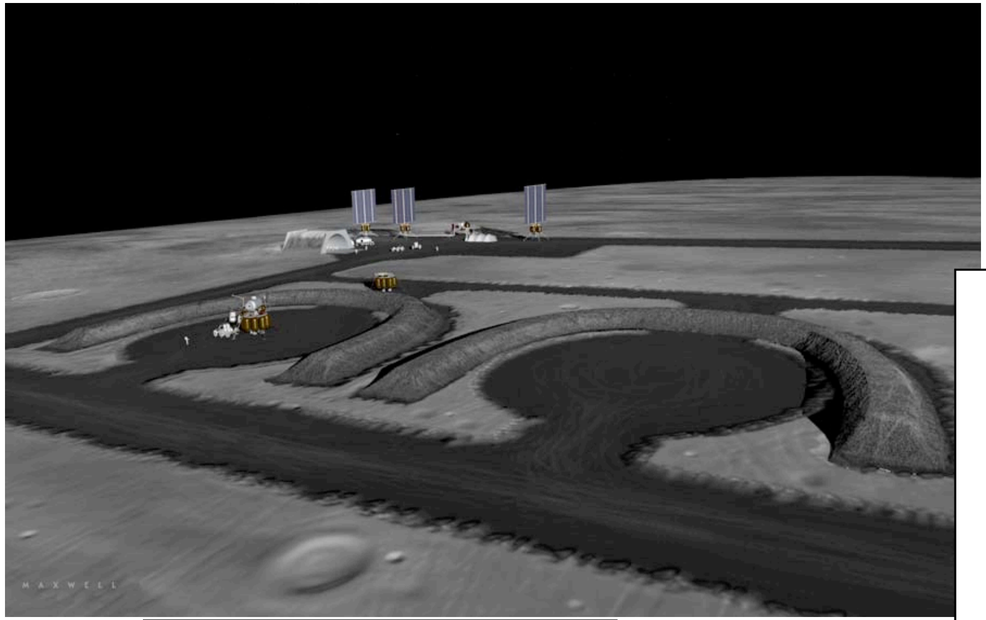
(GEOLOGICAL & GEOTECHNICAL)

- **Natural Resources**
  - Abundant Solar Energy
  - Water & other volatiles
  - Regolith
    - Bulk material for construction
    - Extracted metals from minerals
    - Basalt glass fiber for composites
  - Mars Atmosphere
- **Tools & Processes**
  - Seismic
  - Ground Penetrating Radar
  - Borings
  - Sample Assays
  - Mining & Refining
  - Production & Storage
  - Others

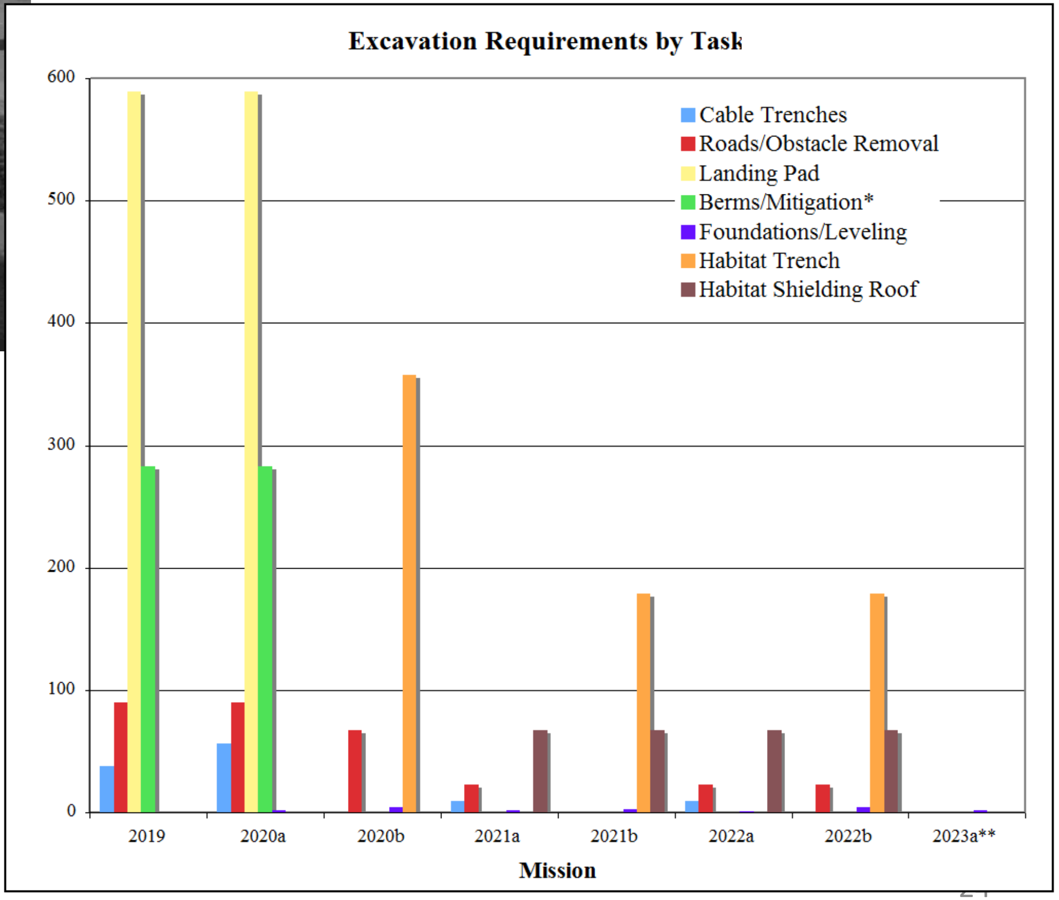
ISRU IN NATURE

Lunar Surface Construction Tasks: Moving Regolith

EXPLORE MOON to MARS



Criteria for Lunar Outpost Excavation
R. P. Mueller and R. H. King
Space Resources Roundtable –SRR IX
October 26, 2007
Golden, Colorado



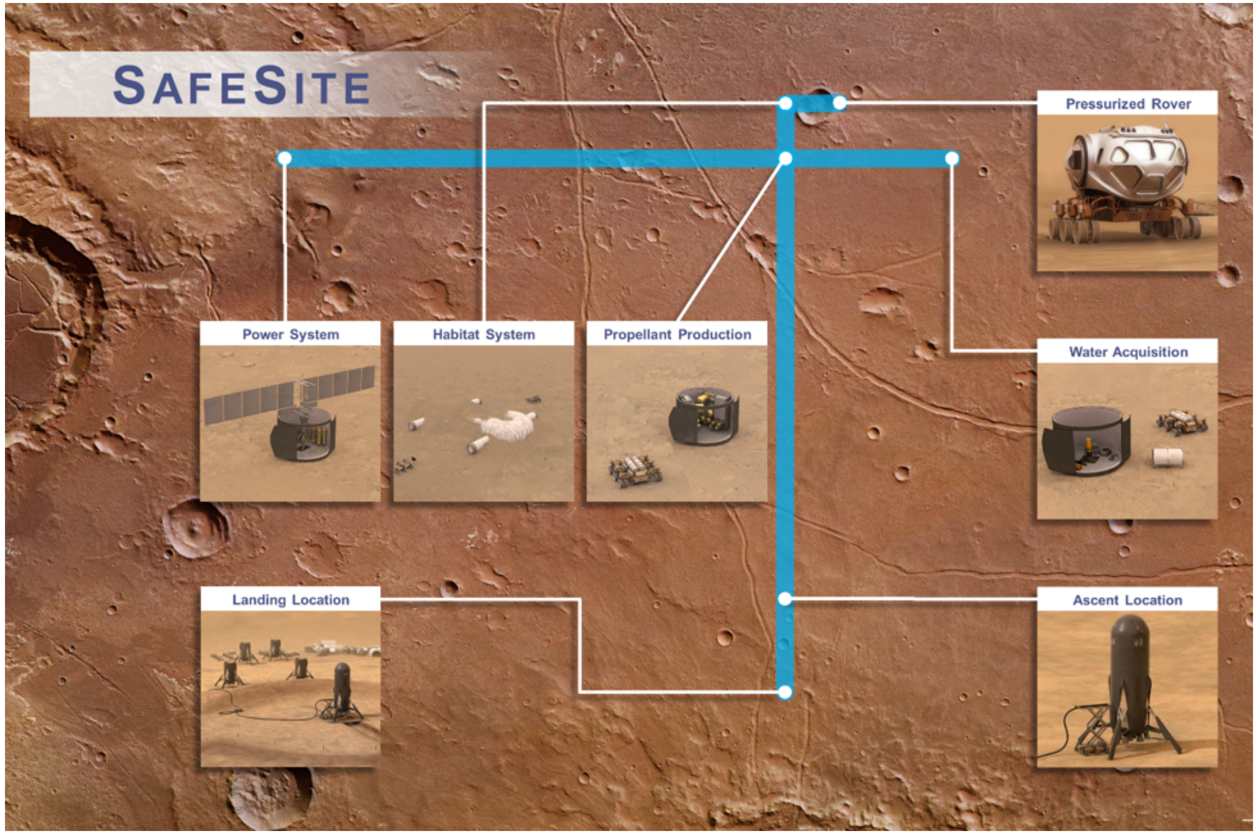
SUMMARY	
Task	%
Trenching	4
Clearing and Compacting	48
Building Berms	18
Habitat Shielding	31
	100
Ice Mining	17
Regolith Mining	83
Construction	84
Mining	16

Safe Site Architecture Overview

EXPLORE MOON to MARS

Key Features

- Focus on safety
- Operate on Mars long before crew arrival to determine unknown failure modes
- Repurposable and reusable ascent/descent stage with abort capabilities
- Expansive water-based ISRU initially
- Redundant habitation and logistics
- Robotic surface site preparation
- Includes some construction similar to Lunar base concepts

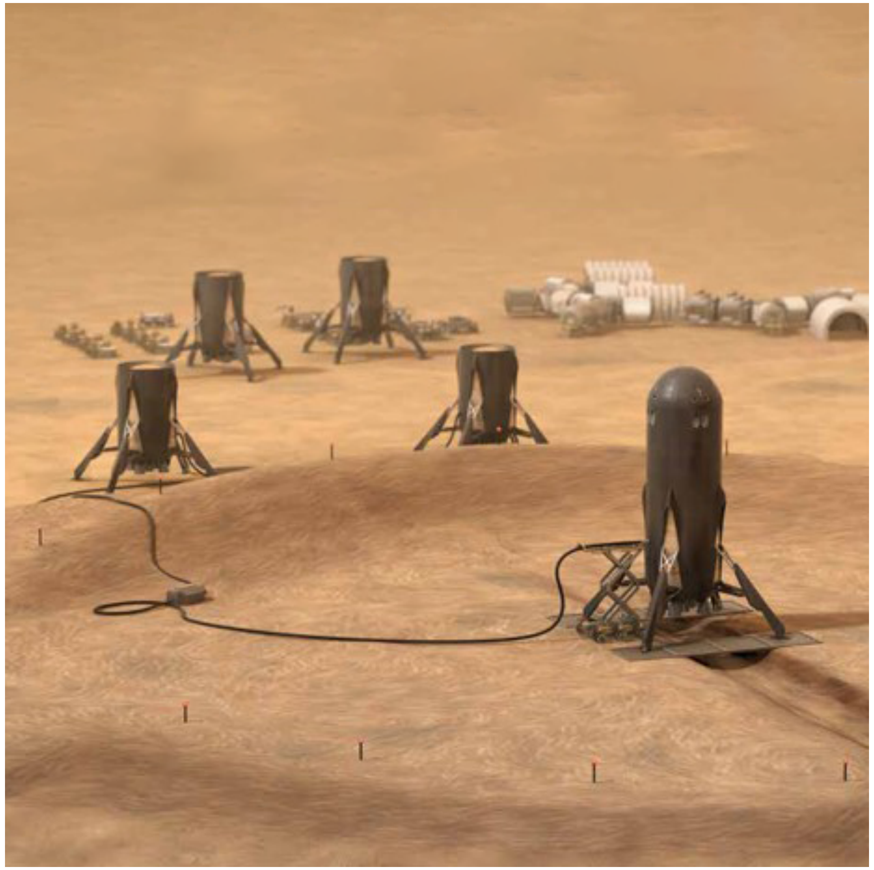


Safe Site architecture trades additional cost and schedule for addressing identified risks and expanding capability.

Comparison to DRA 5 and Evolvable Mars Campaign

EXPLORE MOON to MARS

DRA 5.0	EMC	Safe Site
Focused on minimizing time and cost to complete campaign		Longer build-up time, higher costs; significant safety-focus
Minimal ISRU		Large-scale in-situ water acquisition and processing
Disposable Transportation	Reusable In-space Transportation	Reusable ascent/descent Transportation
Assumes crew will be able to perform critical duties upon arrival		Minimal requirements on crew upon arrival

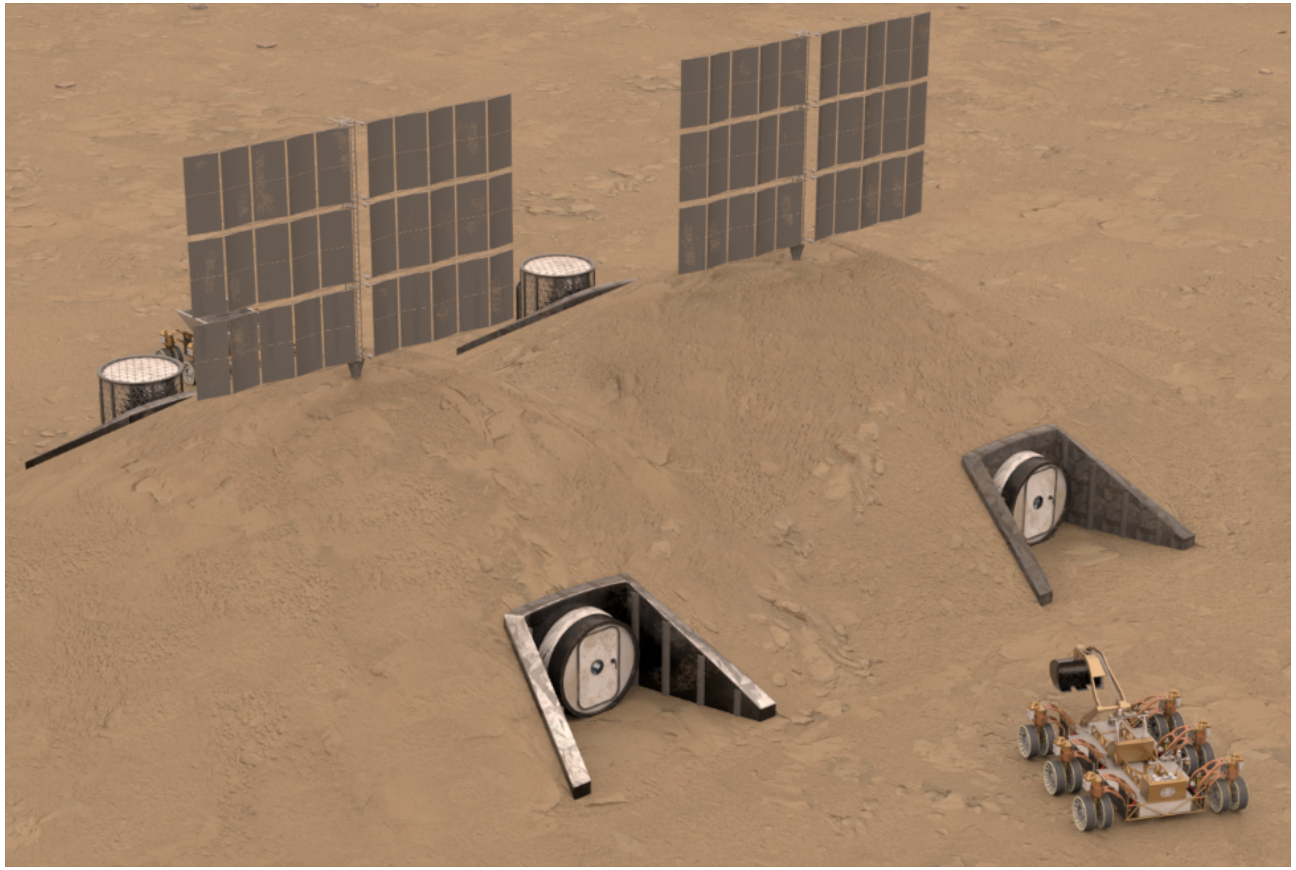


Safe Site trades greater schedule and cost for increased safety and capability, enabling an expandable surface infrastructure.

Beyond Safe Site

EXPLORE MOON to MARS

- Study addressed capabilities to realize a safe site for an initial crew of 4 for 500 days
- Concept can expand to support longer-term and larger outpost
  - Possible through additional logistics, habitation modules, civil engineering equipment, power generation, etc.
  - Provide additional experience, heritage in order to reduce uncertainties
- Going forward (The Roles of the Moon)
  - Extending the Study to include the Lunar Surface as a Mars Analog
  - Human in the Loop allows quicker resolution during development of capabilities and failure modes identification for needed technologies



Safe Site provides a point for evaluating an architecture that emphasizes crew safety and capability, allowing for exploration of the trade space relative to traditional architectures.

Importance of Surface Construction

EXPLORE MOON to MARS

- Mission challenges that In Situ Construction can help solve
  - Ejecta damage to lander & surrounding assets during Landing & Launch
  - Ejecta in orbit
  - Cratering under the lander
  - Reusability
    - Rocket plume Interactions study is underway
  - GCR shielding
    - Analysis is well underway at LaRC
  - Habitation systems
- Construction requires lots of energy!!
  - Fixed power systems based on fission technology constrain mobility
  - Recharging stations in a dusty environment pose huge risks and maintenance issues
  - Mobile power systems integrated with equipment provide better risk and maintenance postures

Lunar Surface ISRU Capabilities

Current State of the Art and Gaps – *In Situ* Construction

= Past/Recent
= Selected/Planned
= Needed to Close Gap

EXPLORE MOON to MARS

Capability Breakdown – Mining Architectures

- Area Clearing and Leveling
- Berm Building
- Trenching and Burial
- Landing Pad/Road Construction
- Unpressurized Structures/Shielding
- Pressurized Structures

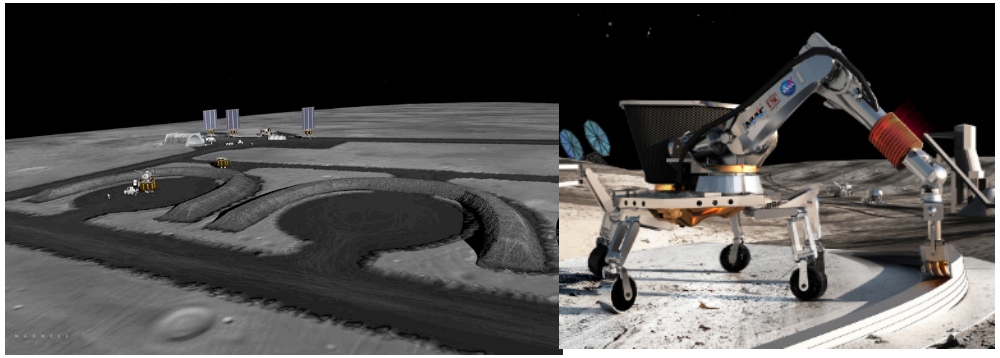
Capability Today – Proof of Concept & Engineering Breadboards

- **Areas Clearing and Leveling/Berm Building (TRL 4)**
  - Built and tested area clearing, leveling, and grading under terrestrial conditions on mobile platforms (Note: CSA demonstrated autonomous landing pad/road construction at analog site)
- **Trenching and Burial (TRL 4)**
  - Built and tested backhoes and RASSOR and tested under terrestrial conditions on mobile platforms
- **Landing Pad/Road Construction (TRL 3)**
  - Built and tested regolith sintering under terrestrial conditions
  - Built and tested sintered bricks/pads with laboratory equipment
- **Unpressurized and Pressurized Structures (TRL 3/4)**
  - Built and tested regolith/plastic binder additive manufacturing techniques
  - Built and tested regolith/cement additive manufacturing techniques; Collaboration with US Army Corps of Engineers
  - Florida League of Cities/KSC partnership on recycled plastic binder construction
  - **NASA 3D Printed Habitat Centennial Challenge**

Capability Near-Term

- STRG - Material Response Model of Biopolymer-Stabilized Regolith
- STRG - Concentrated Solar Regolith Additive Manufacturing
- STRG - Collaborative Manipulation for Space Exploration and Construction
- CIF proposals: Landing pad construction, Repurpose composite structure materials, Lattice reinforced regolith concrete
- Bio produced polymers for regolith binding

Landing Pads, Berms, Roads, and Structure Construction

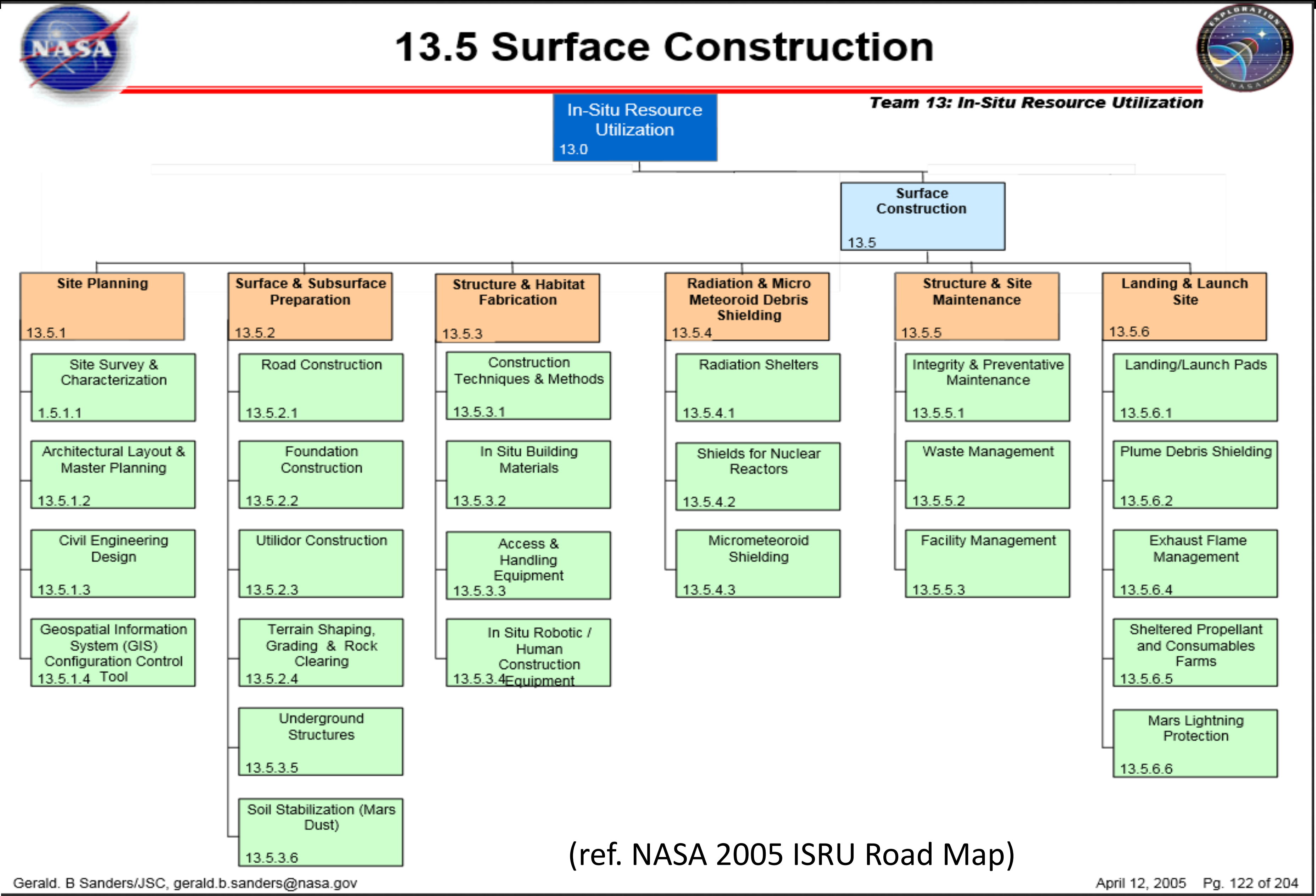


Capability Gap

- Construction application requirements
- Evaluation and selection of binders and binder/regolith mixtures
- Design, build, and test flight-like hardware for performance and operation evaluation under terrestrial and space environments
- Increase autonomy of operations
- Increase testing to 100’s of days under lunar environmental conditions

Construction per the 2005 Roadmap

EXPLORE MOON to MARS

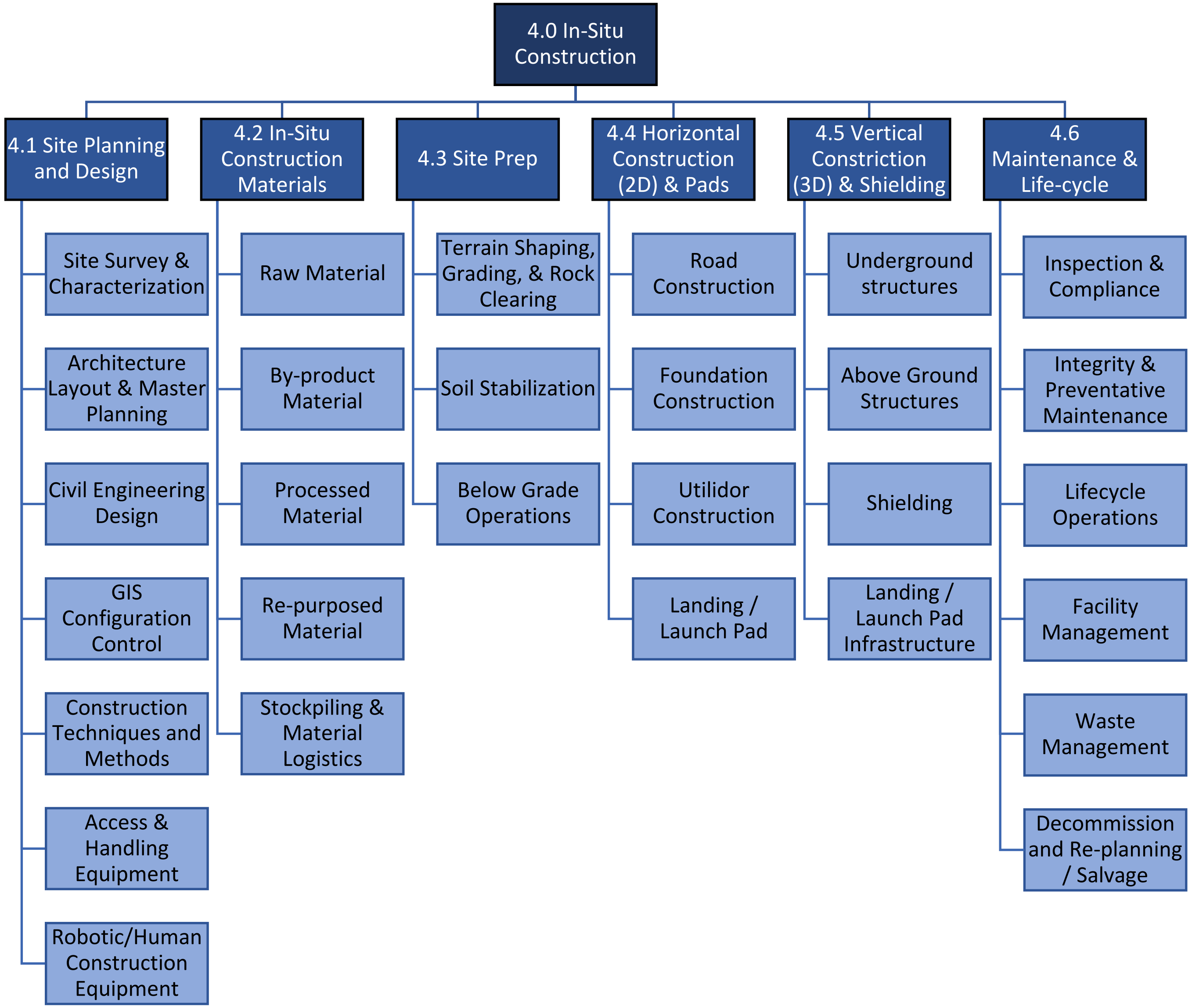


(ref. NASA 2005 ISRU Road Map)

Proposed New Mapping for Requirements Development

EXPLORE MOON to MARS

Uses Construction industry terminology



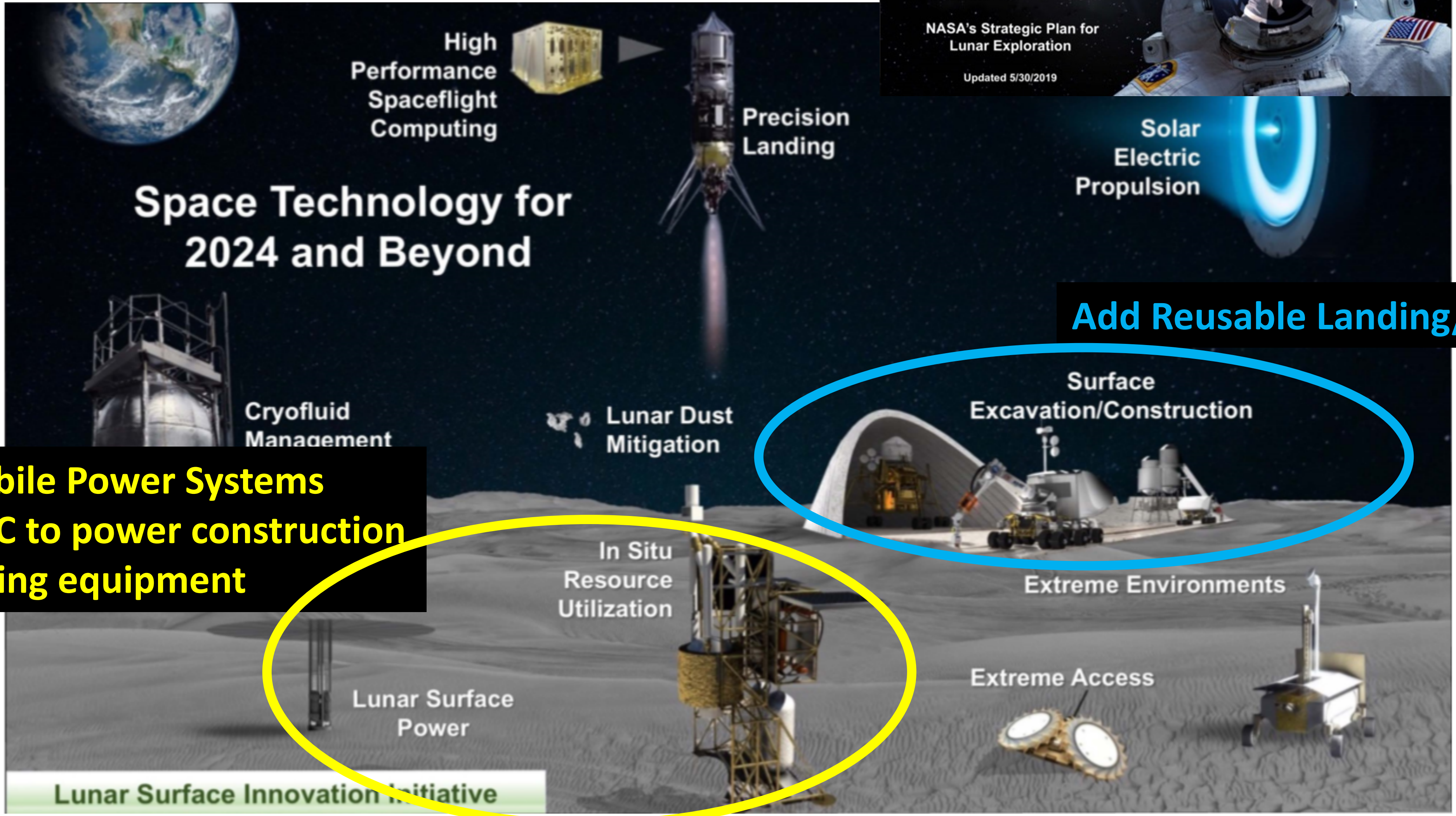
Data Sources for Deriving Requirements

- Surface Architecture & Mission
  - Yields mining concepts of operations & infrastructure designs
- Launch and Landing Pads
  - Plume interactions study (EDL and Aerosciences)
  - Design analysis cycles for ascent and descent modules
- Berms
  - Fission Reactors: NASA's Kilopower Fission Reactor Design
  - Blast Berms: see Pads
- GCR Overcoats
  - Analysis at LaRC by Singleterry & Moses
  - Results update and report coming soon
- Surface Habitats
  - Gravity loads due to overburden
- Drive aisles
  - Mobility driven
- Trenches
  - Utilities driven

Moon Offers Mars Process Rehearsals Near-Term

EXPLORE MOON to MARS

Notional Additions to Artemis…



Add Reusable Landing/Launch Pads

Add Mobile Power Systems like NTAC to power construction and mining equipment

https://www.nasa.gov/sites/default/files/atoms/files/america_to_the_moon_2024_artemis_20190523.pdf

ISRU Needs from Mars Science

Julie Kleinhenz / GRC

Example of Mars measurement needs

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Targeted measurement	Context/rationale	Accuracy (initial estimate)
Overburden particle size distribution and mineralogy	Rock/boulder size and number to define surface preparation needs. Identify presence of material that can serve as aggregates for construction. Understand thickness & particle size of dust layer for material handling concerns.	0.5 m boulder size
Overburden Density / Compaction / bearing strength	Understand stability and strength of surface material for hardware emplacement. This information also drives the selection of tools needed for material handling and soil manipulation (excavation, transport, etc)	Density: ±0.5 g/cm^3
Overburden topography (slope)	Slope angles, depth of depressions, presence of rock outcrops	± 10%
Layered structure of ice and regolith in shallow subsurface	If in a location where subsurface water is present, this information helps inform stability of surface particularly if mining of water is considered in the vicinity of construction hardware emplacement.	± 0.5 m vertical
Diurnal and Seasonal accumulation/disappearance of ice/ice-soil mixtures at surface and subsurface	Understand stability and strength of surface material for hardware emplacement. Dirunal variation may impact surface properties but also the use of material for binders, etc.	± 10%
Volumetric fraction of ice in subsurface regolith	Understand stability and strength of surface material for hardware emplacement. These subsurface layers may impact properties of material under mechanical action (e.g., compaction, excavation, drilling) and when thermal conditions change (e.g., environment, energy input from machinery).	Volumetric fraction: ± 10% With a spatial resolution as follows: Vertical: ± 0.5 m Horizontal: ± 1 m

Minerals of interest for water ISRU

EXPLORE MOONtoMARS

- The hydrated minerals shown are of interest to ISRU as a water source
- After water is extracted the dehydrated material would be available for construction
  - While the composition and properties of the waste material will need evaluation, that the material is already excavated and available for transport is of value.

	Deposit Type			
Essential Attribute	A. Ice	B. Poly-hydrated Sulfate	C. Clay	D. Typical Regolith (Gale)
Depth to top of deposit (stripping ratio)	3 m	0 m	0 m	0 m
geometry, size	bulk	bulk	bulk	bulk
Mechanical character of overburdern	sand	NA	NA	NA
Concentration and state of water-bearing phase within the minable volume				
–Phase 1	90% ice	40% gypsum[1]	40% smectite[2]	23.5% basaltic glass[3]
–Phase 2	--	3.0% allophane[4]	3.0% allophane[4]	3.0% allophane[4]
–Phase 3	--	3.0% akaganeite[5]	3.0% akaganeite[5]	3.0% akaganeite[5]
–Phase 4	--	3.0% smectite[2]	3.0% akaganeite[5]	3.0% bassanite[6]
–Phase 5	--	--	--	3.0% smectite[2]
Geotechnical properties				
–large-scale properties (“minability”), e.g. competence, hardness	competent--hard	sand--easy	sand--easy	sand--easy
–fine-scale properties (“processability”) , e.g. competence, mineralogy	no crushing needed	no crushing needed	no crushing needed	no crushing needed
The nature and scale of heterogeneity	variation in impurities	±30% in concentration	±30% in concentration	±30% in concentration
Distance to power source	1 km	1 km	1 km	100 m
Distance to processing plant	1 km	1 km	1 km	100 m
Amenability of the terrain for transportation	flat terrain	flat terrain	flat terrain	flat terrain
Presence/absence of deleterious impurities	dissolved salts	none	none	perchlorate?
First order power requirements	TBD	TBD	TBD	TBD

The M-WIP (Mars Water ISRU Planning) study was lead by SMD/Mars Program office and involved academy and industry members to identify impacts of Mars resources and their location, and the data still needed to best define them.

- The MWIP team report is posted: http://mepag.nasa.gov/reports/Mars_Water_ISRU_Study.pptx

International Mars Sample Return Objectives and Samples Team (iMOST): ISRU objectives

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- The iMOST study was chartered in November, 2017 by the International Mars Exploration Working Group (IMEWG) to assess the **expected value of the samples** to be collected by the M-2020 rover. Included is a request to:
  - **Update the proposed scientific objectives** of Mars Sample Return (MSR)
  - Map out the **kinds of samples** that would be desired/required to achieve each of the objectives, and the implied **measurements** on the returned samples

ISRU	Evaluate the type and distribution of in-situ resources to support potential future Mars Exploration
Invest. 7A	Determine the **concentration, mineralogic basis, and variation of water** in martian surface materials and identify associated chemical constituents that may negatively impact potential end-use processes of this water.
Invest. 7B	Characterize the **physical and thermophysical properties of martian surface materials** to influence the design of potential future ISRU surface systems and to develop **high-fidelity simulant material** for use in ISRU engineering test beds.
Invest. 7C	Identify components in martian granular material that may be beneficial or detrimental to its use for **in-situ agriculture**.
Invest. 7D	Contingent on discovering significant concentrations of **natural metallic resources**, characterize the source materials to enable predictions of where and how such deposits may be concentrated on Mars.

International MSR Objectives and Samples Team (iMOST),*The potential science and engineering value of samples delivered to Earth by Mars sample return*, Meteoritics & Planetary Science vol. 54, p. 667-671, (executive summary only), https://doi.org/10.1111/maps.13232; open access web link to full report (*Meteoritics & Planetary Science*, vol. 54, S3-S152): https://doi.org/10.1111/maps.13242.

Summary

EXPLORE MOON to MARS

- Many concepts being examined for acquisition of water-containing resources and extraction of water
  - Combination of NASA in-house, small business, and public-private partnerships
- Converting water or rock into usable products on Mars takes significant amounts of energy and power
  - Construction systems are mobile in nature, much like on a terrestrial mining and construction site
    - Cannot rely on diesel fuel to power mobile equipment
- Need more data on overburden, vertical/spatial location, geotechnical properties
- Moon to Mars Commonalities
  - Many common technologies and subsystems
  - Many common consumables and surface operations of interest
- Moon to Mars Differences
  - Lunar vacuum and thermal environment is more severe than Mars surface environment; especially permanently shadowed craters
  - Lunar regolith is much more abrasive than Mars dust

The Moon offers Mars Mission Planners an analog test ground to practice and perfect ISRU systems in the presence of astronauts before depending on them for safe operations on Mars