Johnson Space Center Engineering Directorate

L-8: In-Situ Resource Utilization Capabilities

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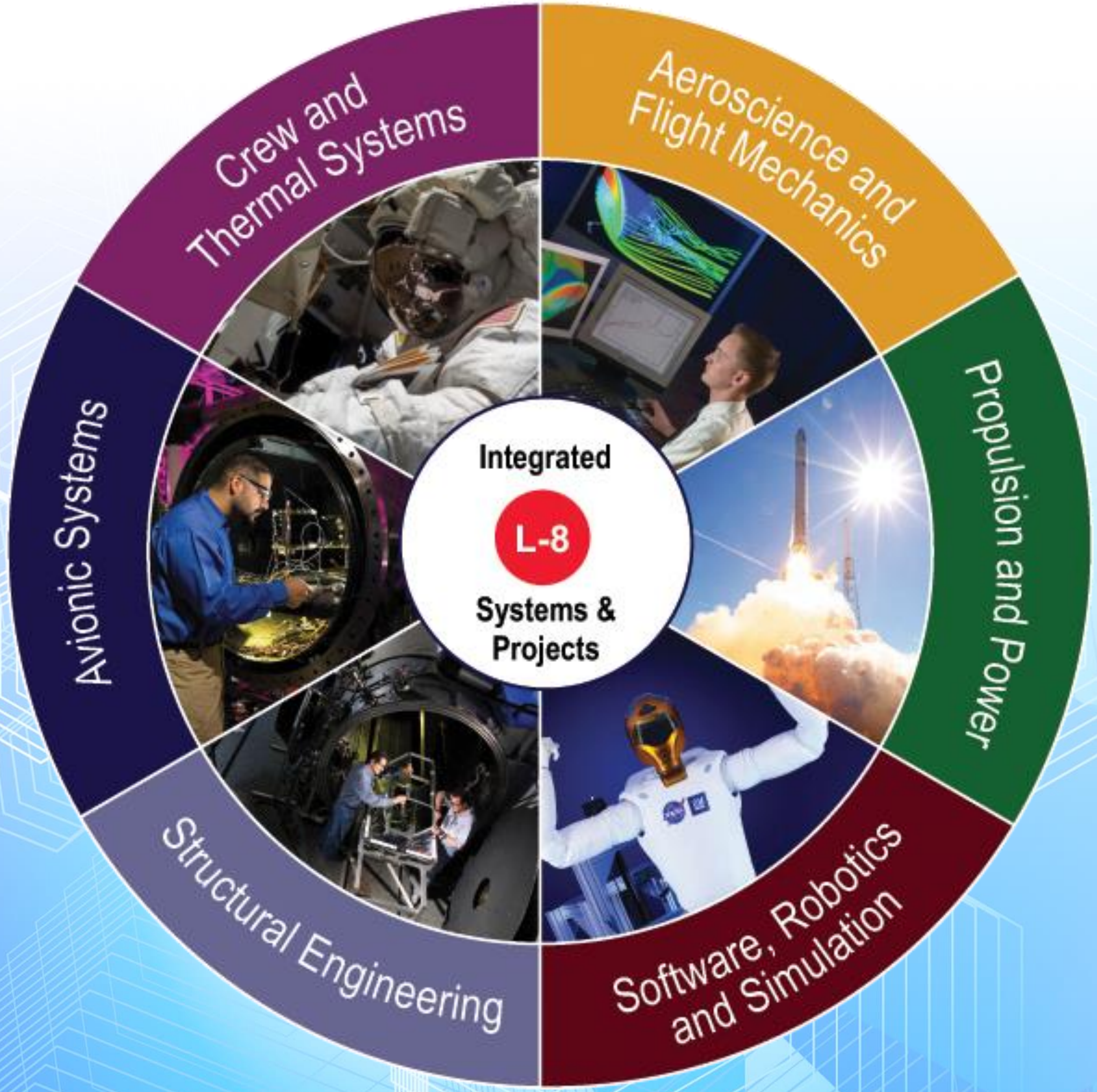
JSC Engineering: HSF Exploration Systems Development



- We are sharpening our focus on Human Space Flight (HSF) Exploration Beyond Low Earth Orbit
- We want to ensure that HSF technologies are ready to take Humans to Mars in the 2030s.
  - Various Roadmaps define the needed technologies
  - We are attempting to define <u>our</u> activities and dependencies
- Our Goal: Get within 8 years of launching humans to Mars (L-8) by 2025
  - Develop and Mature the technologies and systems needed
  - Develop and Mature the personnel needed
- We need collaborators to make it happen, and we think they can benefit by working with us.

EA Domain Implementation Plan Overview

JSC Engineering: HSF Exploration Systems Development

- Life Support
- Active Thermal Control
- EVA
- Habitation Systems

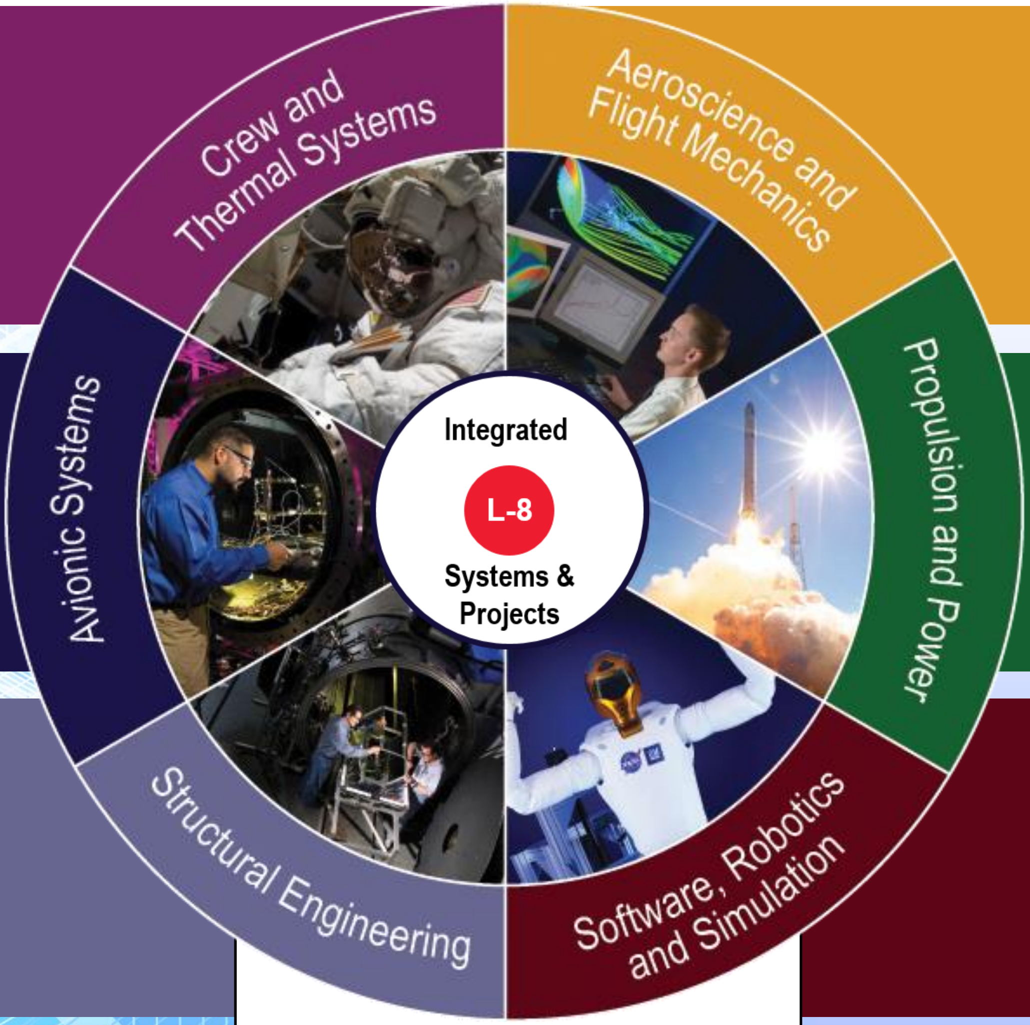
Entry, Descent, & Landing -
Autonomous Rendezvous & Docking -
Deep Space GN&C -

- Human System Interfaces
- Wireless & Communication Systems
- Command & Data Handling
- Radiation & EEE Parts

Reliable Pyrotechnics -
Integrated Propulsion, Power, & ISRU -
Energy Storage & Distribution -
Breakthrough Power & Propulsion -

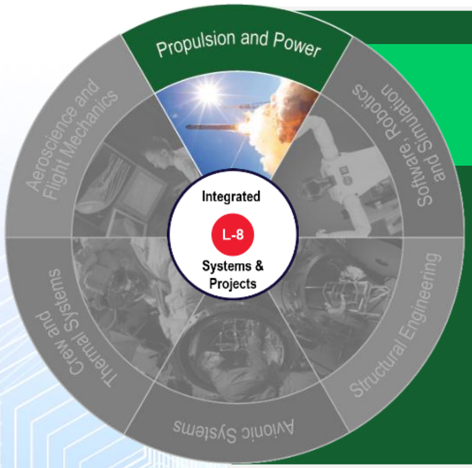
- Lightweight Habitable Spacecraft
- Entry, Descent, & Landing
- Autonomous Rendezvous & Docking
- Vehicle Environments

Crew Exercise -
Simulation -
Autonomy -
Software -
Robotics -



AA-2 | iPAS | HESTIA | Morpheus

Propulsion and Power:
In Situ Resource Utilization (ISRU)



- Integrated Propulsion, Power, & ISRU
- Reliable Pyrotechnics
- Energy Storage & Distribution
- Breakthrough Power & Propulsion

The Problem

- **For every 1 kg landed on Mars, 7.5 to 11 kg has to be launched into orbit from Earth.**
- 23 mT of oxygen and 6.5 mT of methane propellants are needed for the Mars crewed ascent vehicle. This equates to the payload mass of 3 to 5 SLS launches
- Propulsion, power, and life support systems need to be designed from the start to use ISRU products
- Current ISRU technologies and systems are subscale engineering breadboards with limited space/Mars environmental testing

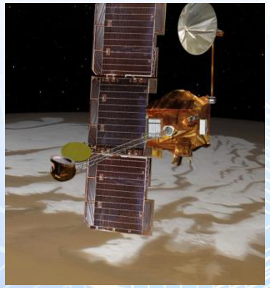
In-Situ Resource Utilization Capabilities

- **NASA is developing technologies, systems, & operations to:**
  - **Find, extract, and process *in situ* resources**
  - **Store, transfer, and distribute products**
- To maximize the benefits and minimize the mass and development costs, NASA is developing propulsion and power systems, which can be integrated with life support and thermal management systems, that use common ISRU-derived reactants and storage
- Developing and incorporating ISRU into human missions faces many of the same technology, infrastructure, environment, and deployment needs and challenges as the terrestrial mining, chemical processing, construction, and energy industries
- NASA hopes to partner by spinning-in and off technologies, operations, and best practices with industry through BAAs, CANs, SAAs, and SBIRs.

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

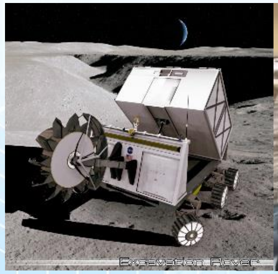
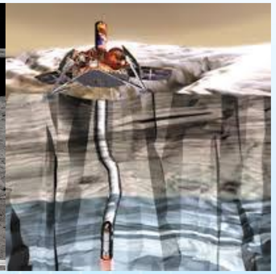
ISRU involves any hardware or operation that harnesses and utilizes 'in-situ' resources to create products and services for robotic and human exploration

Resource Assessment (Prospecting)



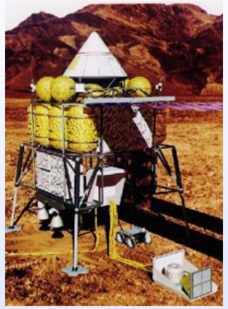

Assessment and mapping of physical, mineral, chemical, and volatile/water resources, terrain, geology, and environment

Resource Acquisition

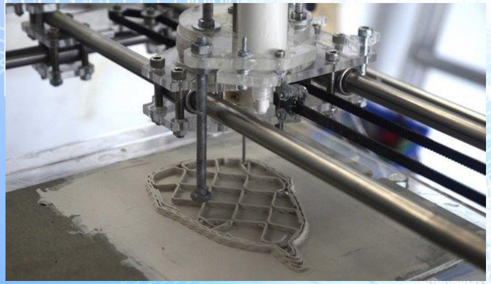
Extraction, excavation, transfer, and preparation/ beneficiation before Processing

Resource Processing/ Consumable Production

Processing resources into products with immediate use or as feedstock for construction and/or manufacturing
- Propellants, life support gases, fuel cell reactants, etc.

In Situ Manufacturing

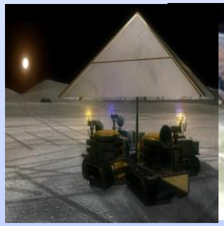
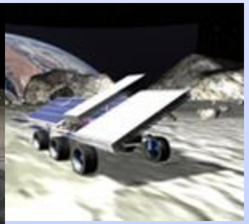


Production of replacement parts, complex products, machines, and integrated systems from feedstock derived from one or more processed resources

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

Space Resources and Products of Main Interest

Moon: Three major resources

- **Regolith**: oxides and metals
  - Ilmenite 15%
  - Pyroxene 50%
  - Olivine 15%
  - Anorthite 20%
- Solar wind volatiles in regolith
  - Hydrogen 50 – 150 ppm
  - Helium 3 – 50 ppm
  - Carbon 100 – 150 ppm
- **Water/ice** and other volatiles in polar shadowed craters
  - 1-10% (LCROSS)
  - Thick ice (SAR)

Mars: Three major resources

- **Atmosphere**:
  - 95.5% Carbon dioxide,
  - 2.7% Nitrogen,
  - 1.6% Argon
- **Water in soil**: concentration dependant on location
  - 2% to dirty ice at poles
- Oxides and metals in the soil

Resources of Main Interest

- Oxygen
- Water
- Hydrogen
- Carbon/CO_2
- Nitrogen
- Metals
- Silicon

Near Earth Asteroids: ~85% of Meteorites are Chondrites

Ordinary Chondrites 87%

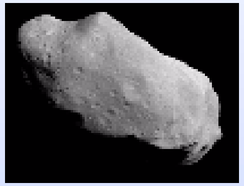
FeO:Si = 0.1 to 0.5
Fe:Si = 0.5 to 0.8

Pyroxene
Olivine
Plagioclase
Diopside
Metallic Fe-Ni alloy
Trioilite - FeS

Source of metals (Carbonyl)

Carbonaceous Chondrites 8%

Highly oxidized w/ little or no free metal
Abundant volatiles: up to 20% bound water and 6% organic material



Source of water/volatiles

Enstatite Chondrites 5%

Highly reduced; silicates contain almost no FeO
60 to 80% silicates; Enstatite & Na-rich plagioclase
20 to 25% Fe-Ni
Cr, Mn, and Ti are found as minor constituents

Easy source of oxygen (Carbothermal)

ISRU Integrated with Exploration Elements

Mission Consumables

ISRU Functions & Elements

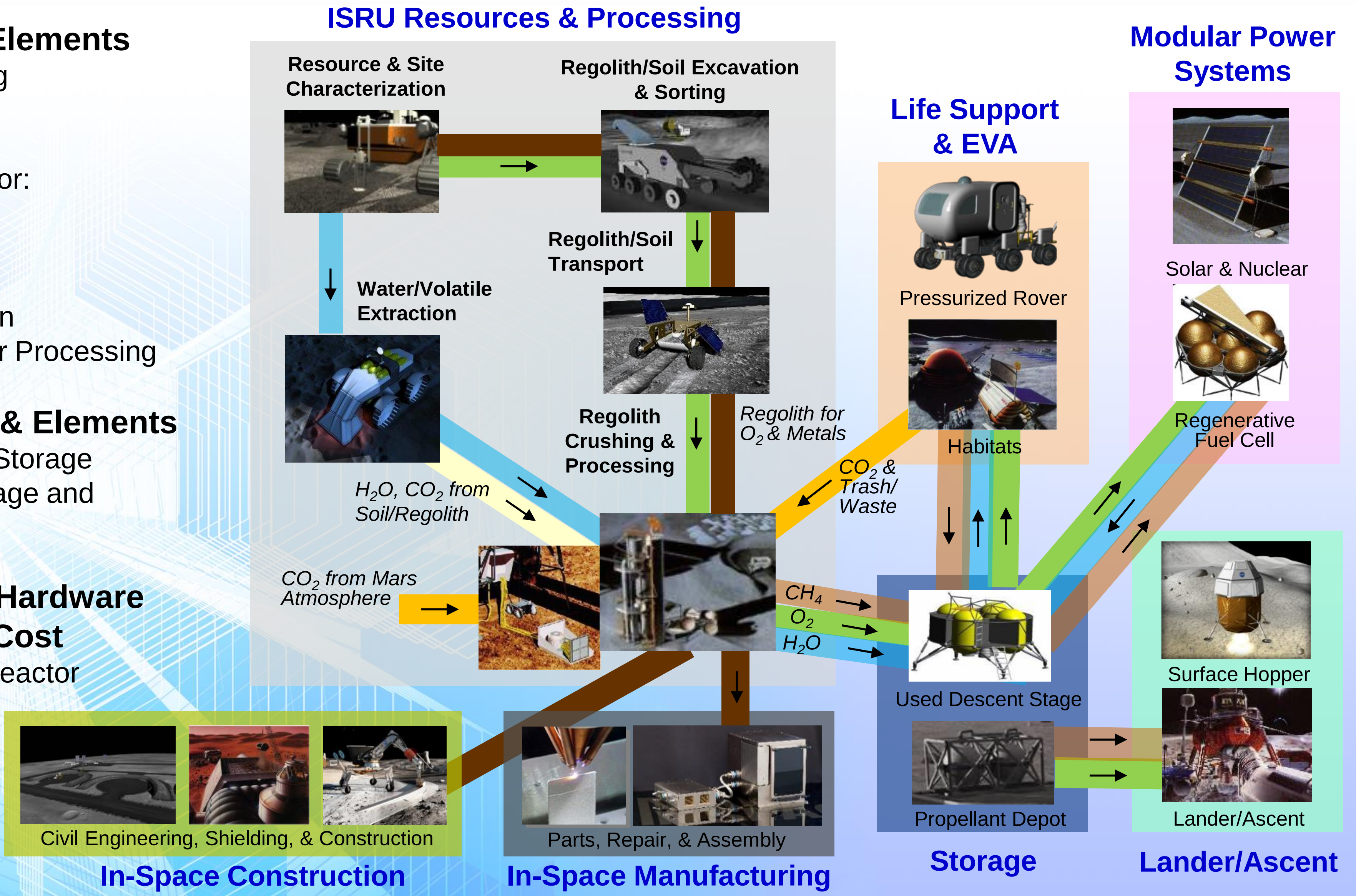
- Resource Prospecting
- Excavation
- Regolith Transport
- Regolith Processing for:
  - Water/Volatiles
  - Oxygen
  - Metals
- Atmosphere Collection
- Carbon Dioxide/Water Processing

Support Functions & Elements

- Power Generation & Storage
- O_2, H_2, and CH_4 Storage and Transfer

Potentially Shared Hardware to Reduce Mass & Cost

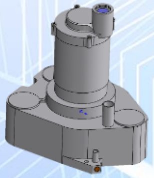
- Solar arrays/nuclear reactor
- Water Electrolysis
- Cryogenic Storage
- Mobility

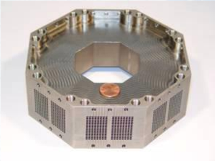


ISRU Processes and Products

Mission Consumables - *Lab and Pilot Scale for Industry*

Atmosphere Processing
- Dust Filtration
- Gas Separation (CO_2,N_2, Ar)
- Gas Pressurization (0.1 to >15 psia)
  - Pumps/Compressors
  - Cryogenic Separation
  - Adsorption





Chemical Processing
- CO_2 Reduction
  - Solid Oxide Electrolysis
  - Reverse Water Gas Shift
  - Bosch
- Fuel Production
  - Sabatier (CH_4)
  - Fischer Tropsch
  - Alcohols
  - Ethylene → Plastics
- Water Processing
  - Water Electrolysis (PEM vs SOE)
  - Water Cleanup/Deionization

Solid Processing
- Regolith Excavation/Extraction
  - Drills/Augers (1 to 3 m)
  - Load/Haul/Dump
  - Bucketwheels/Drums
- Regolith/Soil Transfer
  - Augers
  - Pneumatic
  - Bucket ladders
- Water/Volatile Extraction
  - Hydrated soils
  - Icy soils
- Trash/Waste Processing
  - Steam Reforming/Oxidation
  - Pyrolysis
- Oxygen Extraction from Minerals
  - Hydrogen Reduction of Iron Oxides
  - Methane Reduction of Silicates
  - Molten Oxide Reduction
- Metal Extraction from Minerals
  - Molten Oxide Reduction
  - Ionic Liquid Acids
  - Biological Extraction

- **Potential Lunar Resource Product Needs**
  - 1,000 kg oxygen (O_2) per year for life support backup (crew of 4)
  - 3,000 kg of O_2 per lunar ascent module launch from surface to L1/L2*
  - 16,000 kg of O_2 per reusable lunar lander ascent/descent vehicle to L1/L2 (fuel from Earth)*
  - 30,000 kg of O_2/Hydrogen (H_2) per reusable lunar lander to L1/L2 (no Earth fuel needed)*
- **Potential Mars Resource Product Needs**
  - 20,000 kg to 25,000 kg of oxygen (O_2) per ascent mission (2 kg/hr)
  - 5700 kg to 7150 kg of methane (CH_4) per ascent mission
  - 14,200 kg of water (H_2O) per ascent mission

***Note: ISRU production numbers are only 1st order estimates for 4000 kg payload to/from lunar surface**

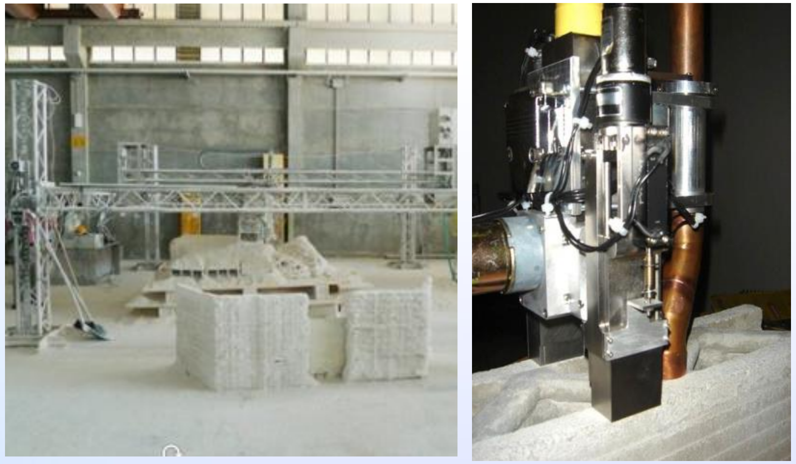
ISRU Processes and Products

Construction: Roads, Landing Pads, Structures, Plume Protection

Area Leveling/Grading/Berms

Autonomous & Tele-operation

Additive Construction

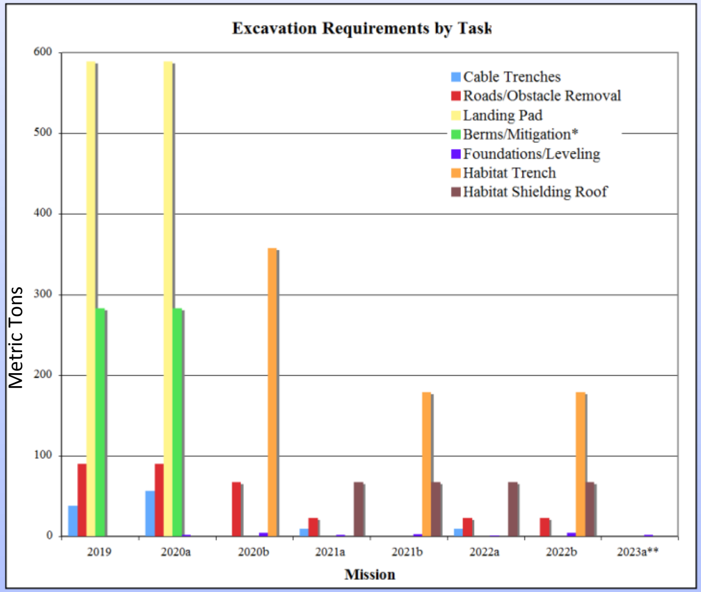


Sintered/Fabricated Pavers

Surface & Subsurface Evaluation

Combustion Synthesis

Waterless Concrete



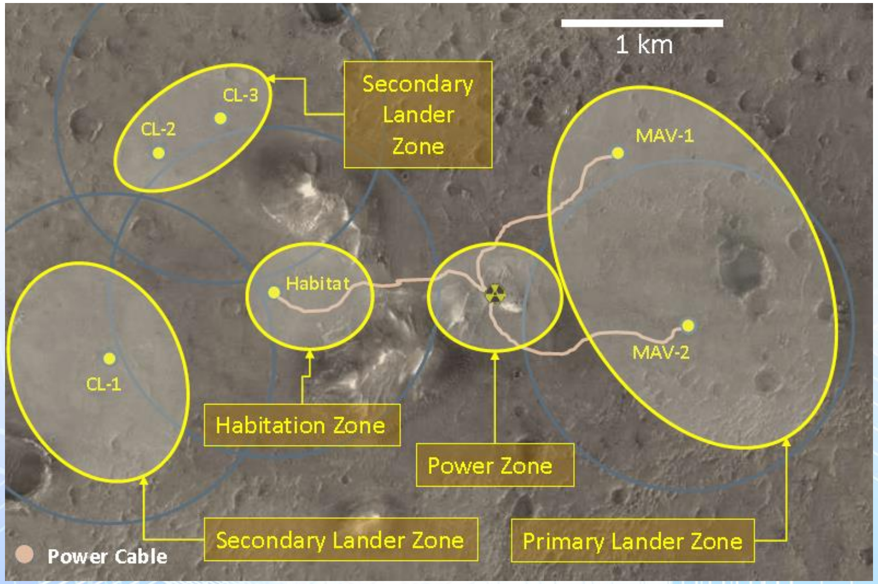
The Economics of ISRU

Whether a resource is 'Useful' is a function of its *Location* and how *Economical* it is to extract and use

- **Location**
  - Resource must be assessable: slopes, rock distributions, surface characteristics, etc.
  - Resource must be within reasonable distance of mining infrastructure: power, logistics, maintenance, processing, storage, etc.
  - Resource must be within reasonable distance of transportation and delivery of product to 'market': habitats, landers, depots, etc.

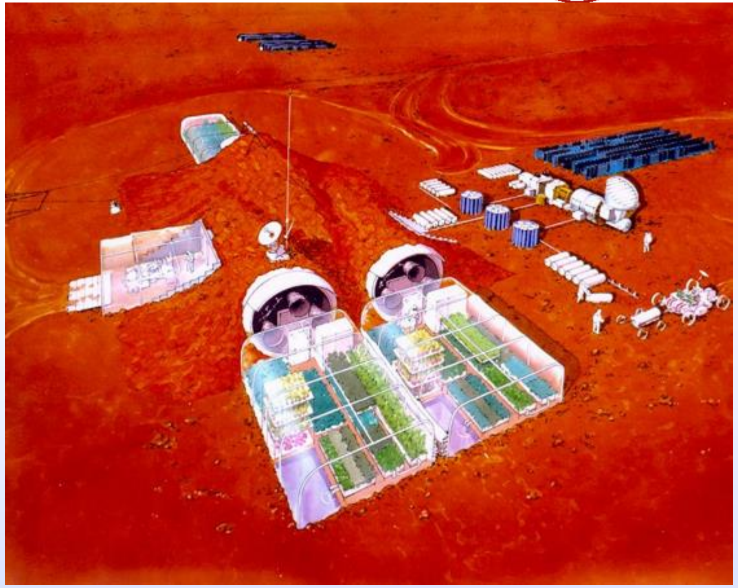
- **Resource extraction must be 'Economical'**
  - **Concentration and distribution of resource and infrastructure needed to extract and process the resource allows for Return on Investment (ROI)** for:
    - **Mass ROI** - Mass of equipment and unique infrastructure compared to brining product and support equipment from Earth
    - **Cost ROI** - Cost of equipment and unique infrastructure compared to elimination of launch costs or reuse of assets (ex. reusable vs single use landers)
    - **Mission ROI** - Extra exploration or science hardware, extended operations, newly enabled capabilities
    - **Crew Safety ROI** - Increased safety compared to limitations of delivering product from Earth: life support, radiation shielding, delivery delay, etc.
    - **Time ROI** - Time required to achieve 1 or more ROIs.
  - **Amount of product needed justifies investment in extraction and processing**
    - Requires near and long-term view of exploration and commercialization strategy to maximize benefits (phasing)
  - **Transportation of product to 'Market' (location of use) must be considered**
    - Use of product at extraction location most economical
    - Resource used may be a function of mission phase and amount needed

ISRU Products, Operations, and Resources Will Grow As Mission Needs and Infrastructure Grow



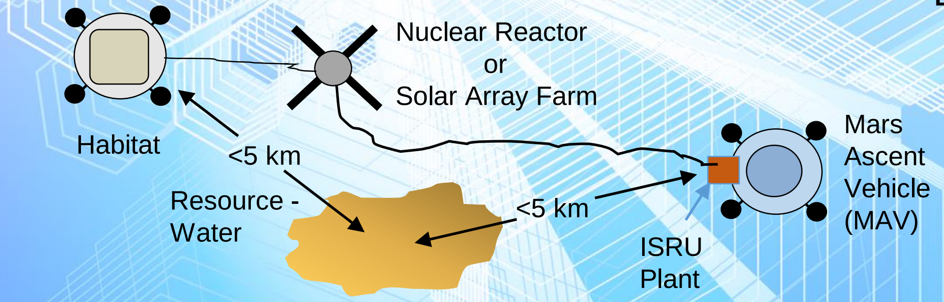
Initial Conditions:

- Hardware delivered by multiple landers before crew arrives; Multiple landing zones
- Elements offloaded, moved, deployed, and connected together remotely
- 12-18 month stay for crew of 4 to 6; Gaps of time between missions where crew is not present
- Each mission delivers extra hardware & logistics

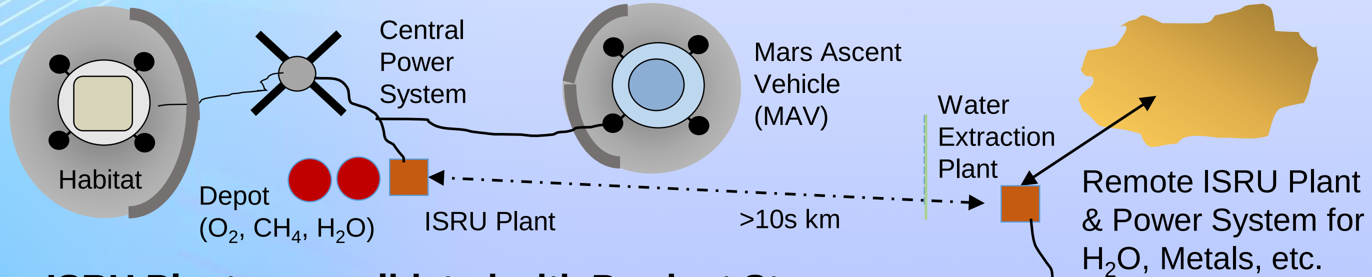


Ultimate Goal

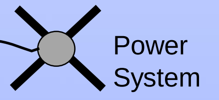
- Consolidated and integrated infrastructure
- Indefinite stay with larger crews
- Roam (and mine) anywhere within 200 km diameter Exploration Zone
- Earth independent; *In situ* ability to grow infrastructure: power, habitation, food, parts, etc.



- **ISRU hardware integrated with Landers**
- **Resource very close to landing site/Ascent vehicle**

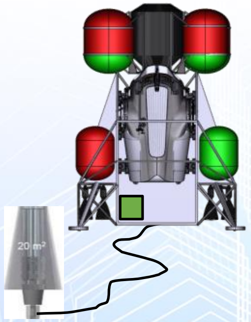


- **ISRU Plants consolidated with Product Storage**
- **Civil Engineering and In Situ Construction operations**
- **Resources can be farther from Habitat and Ascent Vehicle**

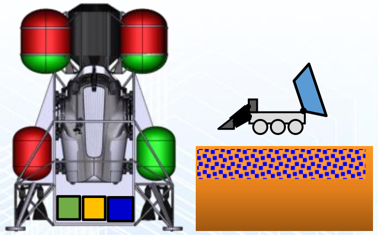


ISRU "Rich" Architecture

Ascent O_2 Production

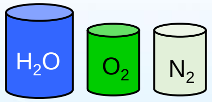


Ascent O_2 & CH_4 Production



Life Support Backup (DRM 3)

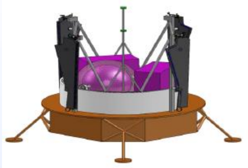
- 4500 kg of O_2
- 3900 kg of N_2
- 23,200 kg of water (H_2O)



Consumable Depot

Preposition Consumables To Extend Traverses in Exploration Zone

- Reuse Surface Pathfinder lander design with ISRU to preposition crew consumables at sites of exploration interest away from Habitat



Increasing Usage and Architecture Impact

ISRU Processes

- Atm. CO_2 to O_2

ISRU Products

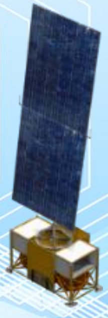
- 20 to 24 mT O_2

ISRU Processes

- Atm. Processing
- H_2O Processing
- Soil Processing for H_2O

ISRU Products

- 20 to 24 mT O_2
- 6 to 7 mT CH_4
- 14 mT H_2O (used)



PUP

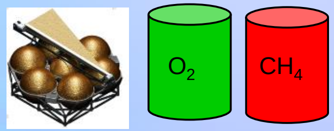
Mobile Power

- Fuel cell and reactant storage instead of batteries & carrying nuclear reactor
- Amount: 1000 kg O_2 & 350 kg CH_4 per 14 day traverse

Crewed Rover

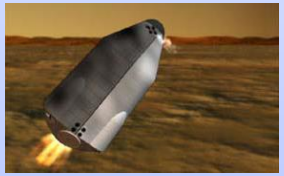
Habitat Backup Power

- Fuel Cell reactants for Dust Storms
- 14.8 KW at up to 120 days
- Amount: 21 mT O_2 & 9 mT CH_4



Hoppers & Reusable Landers

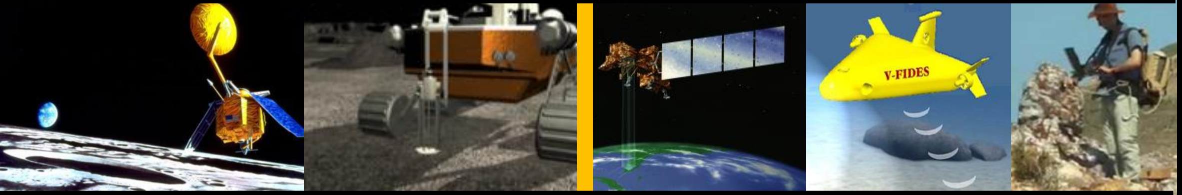
- Reuse previous landers to deliver cargo/crew to other destinations
- Amount: TBD based on distance and payload



Landing Pad and Road Construction | **Radiation Shielding & Habitat Burial** | **Habitat Construction**

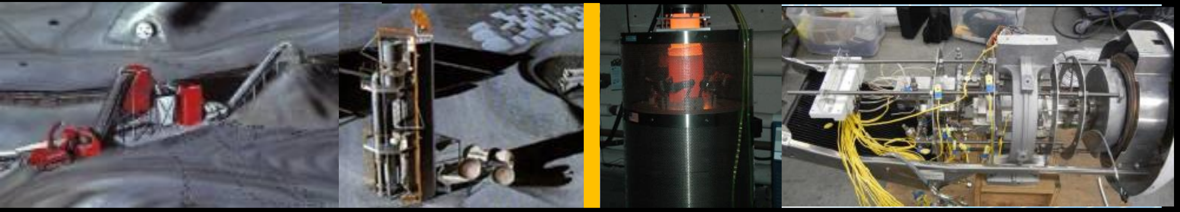
There are A lot of Similarities between ISRU and Terrestrial Applications

Prospecting for Resources



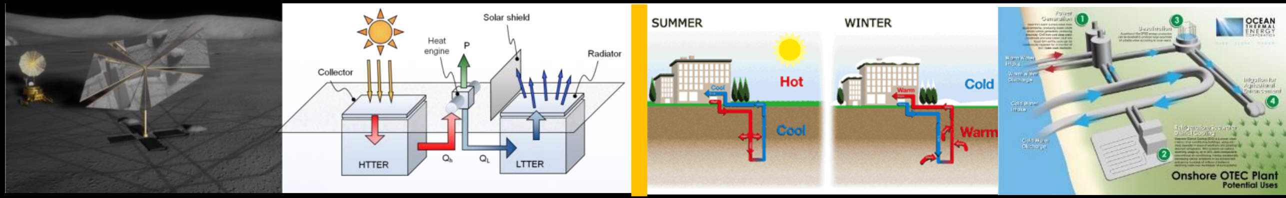
Mining for Resources

Resource Processing (Gas, Liquids, Solids)



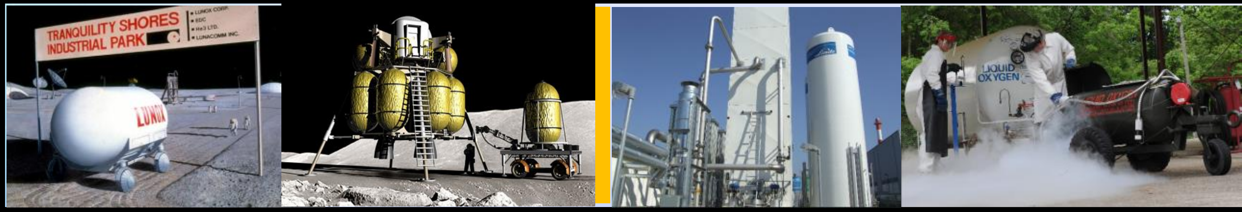
Civil Engineering & Construction

Thermal Energy



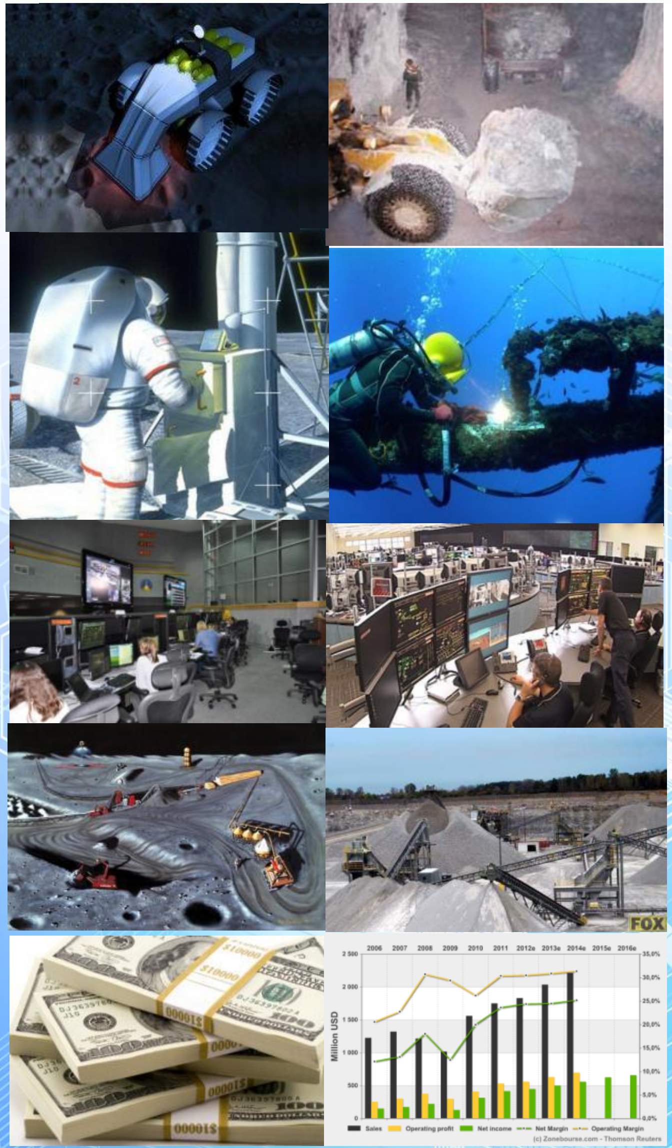
Alternative Energy (Fuel Cells & Trash to HC)

Liquefaction, Storage, and Transfer



Remote Operations & Maintenance

ISRU Has Common Challenges with Terrestrial Industry



Severe Environments

- Extreme temperatures
- Large changes in temperature
- Dust and abrasion
- No pressure vs Extreme pressure
- Environmental testing

Maintenance

- Minimal maintenance desired for long operations
- Performing maintenance is difficult in environments
- Minimize logistics inventory and supply train

Operations/Communication

- Autonomous and tele-operation;
- Delayed and potentially non-continuous communication coverage
- Local navigation and position information

Integration and Infrastructure

- Hardware from multiple countries must be compatible with each other
- Common standards; Common interface
- Optimize at the architecture/operation level vs the individual element
- Establish and grow production and infrastructure over time to achieve immediate and long-term Returns on Investment

Return on Investment

- Need to have a return on investment to justify expense and infrastructure buildup
- Multi-use: space and terrestrial applications

ISRU: Where We Are Today

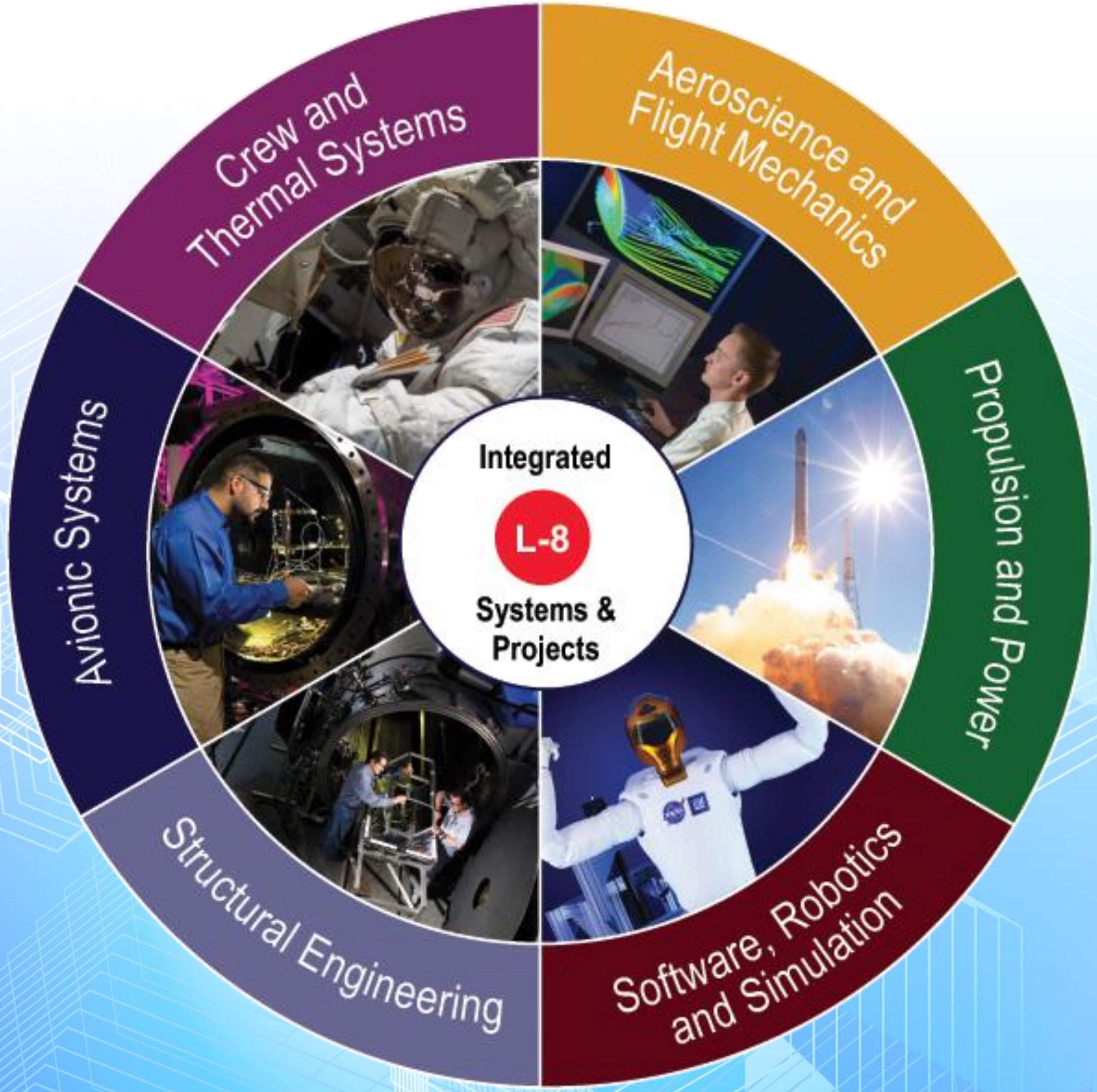
- **Most Prospecting, Excavation, and Consumable Production technologies, systems, and technologies have been shown to be feasible at subscale and for limited test durations**

- **Drivers**
  - **Hardware simplicity and life are as important as minimizing mass and power**
  - **Hardware commonality with other systems (propulsion, power, life support, thermal) can significantly reduce costs and logistics**

- **Work still required to:**
  - **Scale up production and processing rates to human mission needs (*lab and pilot scale for terrestrial industry*)**
  - **Operate hardware and systems under relevant mission environments; Understand how to take advantage of the environment and day/night cycle**
  - **Perform long-duration testing to understand hardware life, maintenance, and logistics needs**
  - **Add autonomy to operations, especially for mining operations**

- **Partnering with Terrestrial Industry and co-leveraging hardware is important to NASA**
  - **Address common needs and challenges**
  - **Reduce costs and increase return on investments**

JSC Engineering: HSF Exploration Systems Development



- We want to ensure that HSF technologies are ready to take Humans to Mars in the 2030s.
- Our Goal: Get within 8 years of launching humans to Mars (L-8) by 2025
- We need collaborators to make it happen, and we think they can benefit by working with us.
  - Upcoming NextSTEP Broad Area Announcement (BAA)
  - Small Business Innovation Research (SBIR)

Backup

ISRU Is Synergistic with Terrestrial Needs

JSC Engineering: HSF Exploration Systems Development

Food/Water

- *Improve water cleanup techniques*
- *Advance food/plant growth techniques and nutrient production*

Construction

- *Reduce or eliminate cement and asphalt – renewable materials*
- *Alternative construction techniques – 3-D printing*
- *Remote operation and automation*

Mining

- *Increase safety*
- *Reduce maintenance*
- *Increase prospecting mining, and processing efficiency*
- *Improve environmental compatibility*

Energy

- *More efficient power generation, storage and distribution*
- *Increase renewable energy: Use sun, thermal, trash, and alternative fuel production*

Promote *Reduce, Reuse, Recycle, Repair, Reclamation*

…for benefit of Earth, and living in Space.

Challenges for ISRU Development and Implementation

Many common with Terrestrial Industry

Space Resource Challenges

- What resources exist at the site of exploration that can be used?
  - Are there enough of the right resources; Return on Investment
- What are the uncertainties associated with these resources?
  - Form, amount, distribution, impurities/contaminants
- How to address planetary protection requirements?
  - Environmental protection, remediation

ISRU Technical Challenges

- Is it technically feasible to collect, extract, and process the resource?
- How to maximize performance/minimize mass
- How to achieve high reliability and minimal maintenance requirements?
- How to minimize power through thermal management integration and taking advantage of environmental conditions?

ISRU Operation Challenges

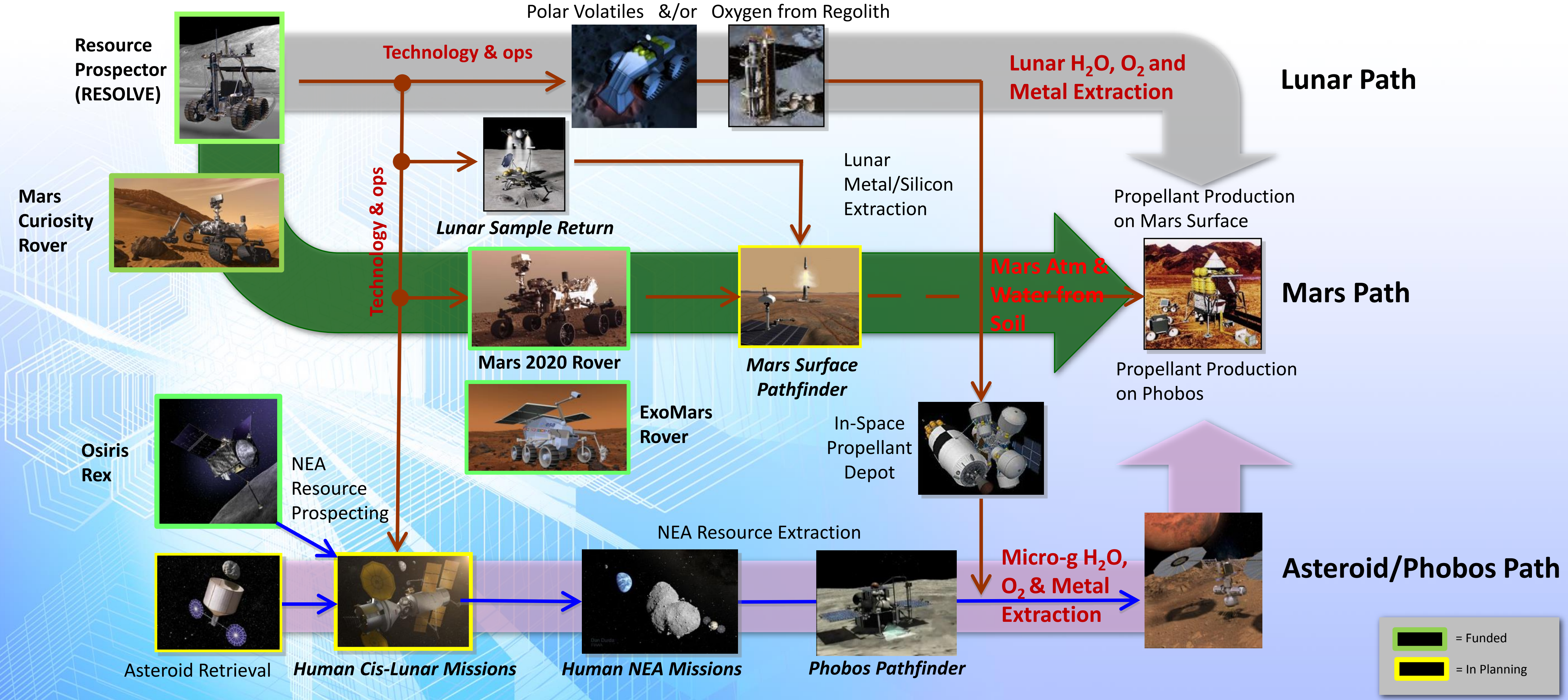
- How to operate in extreme environments, including temperature, pressure, dust, and radiation?
- How to achieve long duration, autonomous operation and failure recovery?
- How to operate in low gravity or micro-gravity environments?
  - Anchoring/weight-on-bit
  - Friction, cohesion, and electrostatic forces may dominate in micro-g

ISRU Integration Challenges

- How to optimize at the architectural level rather than the system level?
- How are other systems designed to incorporate ISRU products?
- How to manage the physical interfaces and interactions between ISRU and other systems?
- How to establish and grow production and infrastructure over time to achieve immediate and long-term Returns on Investment

Overcoming these challenges requires a multi-discipline and integrated approach

Possible ISRU Pathways to Mars



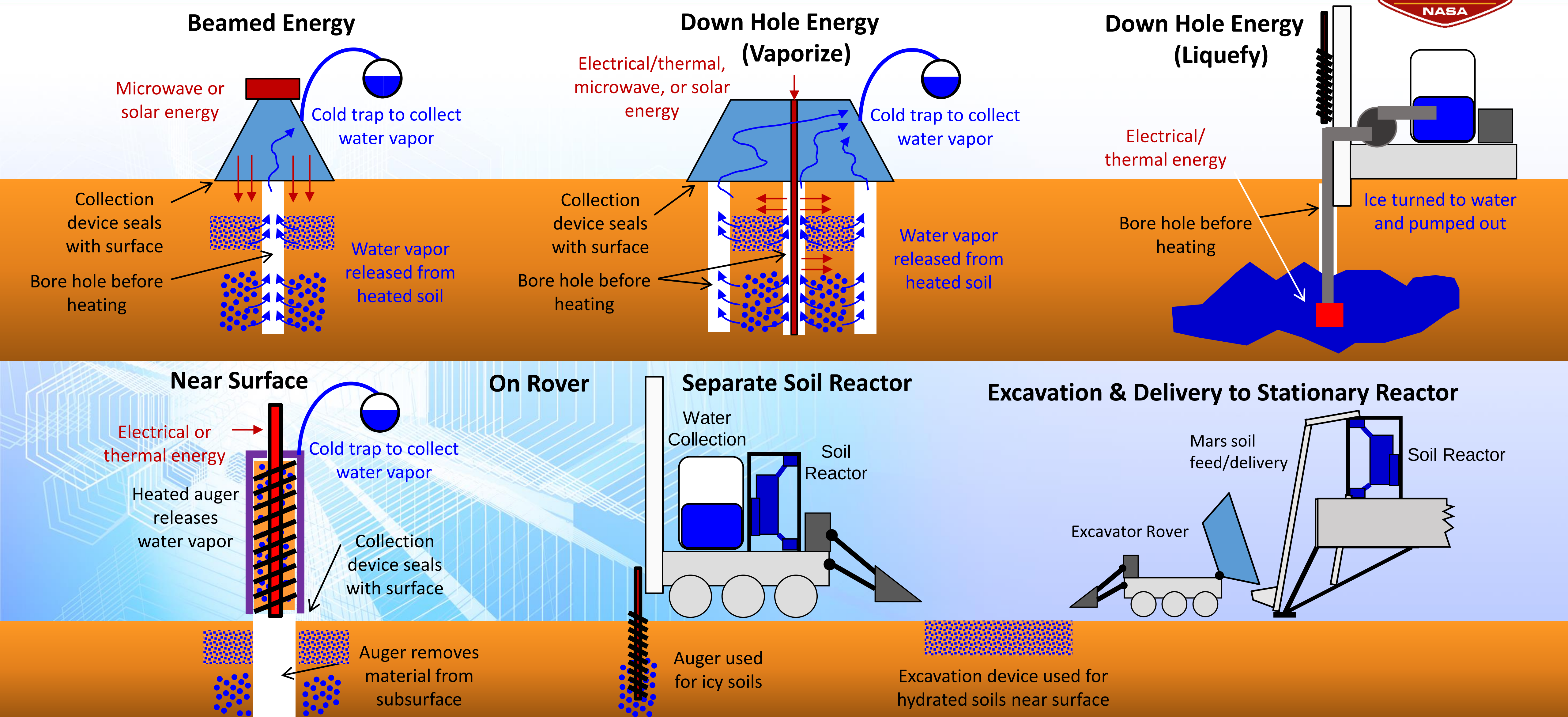
Mars mineral resources of interest for ISRU / CE

Resource	Potential Mineral Source	Reference
Water, Hydration/ Hydroxyl	Gypsum – ($CaSO_4.2H_2O$) Jarosite – ($KFe^{3+}_3(OH)_6(SO4)_2$) Opal & hydrated silica – ($SiO_2.nH_2O$) Phyllosilicates Other hydrated minerals (TBR)	Horgan, et al.(2009), Distribution of hydrated minerals in the north polar region of Mars, J. Geophys. Res., 114, E01005 Mustard et al.(2008), Hydrated silicate minerals on Mars observed by the Mars Reconnaissance Orbiter CRISM instrument, Nature 454, 305-309
Water, Ice	Icy soils Glacial deposits	Mellon & Feldman (2006) Dickson et al. (2012)
Iron*	Hematite, Magnetite, Laterites Jarosite, Triolite, Ilmenite	Ming et al. (2006), Geochemical and mineralogical indicators for Aqueous processes in Columbia Hills of Gusev Crater, Mars" JGR 111, E02S12 Poulet et al. (2007), Martian surface mineralogy from OMEGA/Mex: Global mineral maps" JGR 112, E08S02
Aluminum*	Laterites, Aluminosilicates Plagioclase, Scapolite	
Magnesium*	Mg-sulfates, Mg-rich olivines, Forsterite	
Silicon	Pure amorphous silica Hydrated silica Phyllosilicates	Rice et al. (2010), "Silica-rich deposits and hydrated minerals at Gusev Crater, Mars: Vis-NIR spectral characterization and regional mapping" Icarus 205 (2010) 375–395
Titanium*	Ilmenite, Titanomagnetite	Ming et al. (2006), JGR 111, E02512

	Oxides (Wt%)													Elements (ppm)			
	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Cr_2O_3	Cl	SO_3	Ni	Zn	Br	Ge
MER Spirit – Laguna Soils, Panda Subclass	46.8	0.79	10.5	16.1	0.33	9.6	6.2	3	0.38	0.75	0.35	0.6	4.6	684	190	42	6
Rocknest Soil (Portage)	43.0	1.2	9.4	19.2	0.42	8.7	7.3	2.7	0.49	0.95	0.49	0.69	5.5	456	326	34	
Mojave Mars Simulant	49.4	1.09	17.1		0.17	6.1	10.5	3.3	0.48	0.17	0.05		0.1	118	71		0.07

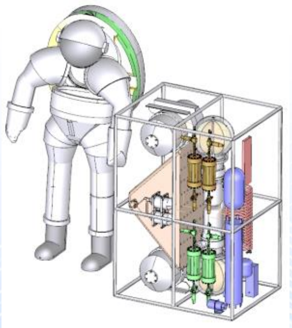
* Mineable metals may be found in geologic features such as: dikes, grabens, impact craters

In Situ Water Extraction vs Excavation and Processing

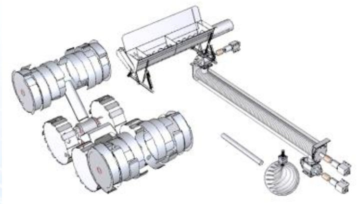


Mars ISRU: Atmosphere & Water Resources and Difficulty

Atmosphere Processing

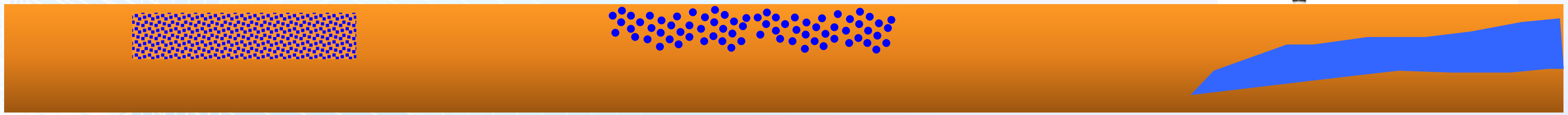


Granular Regolith Processing for Water



Gypsum/Sulfate Processing for Water

Icy Regolith Processing for Water



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

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

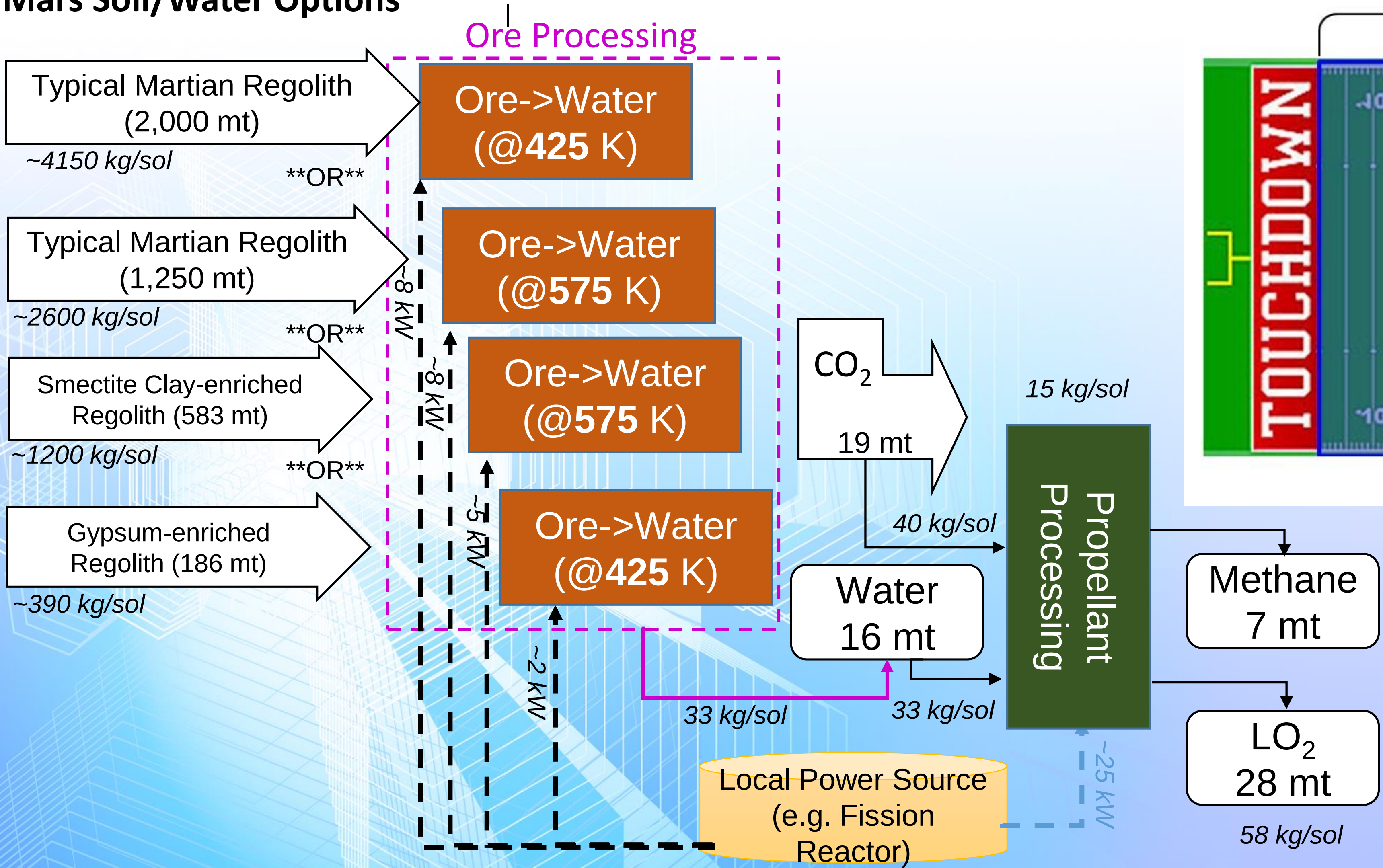
Gypsum or Sulfates
- Hydrated minerals 5-10%
- **At Surface**
- **Harder material:** rock excavation and crushing may be required
- **150 to 250 C heating for water removal**
- **Localized concentration in equatorial and mid latitudes**

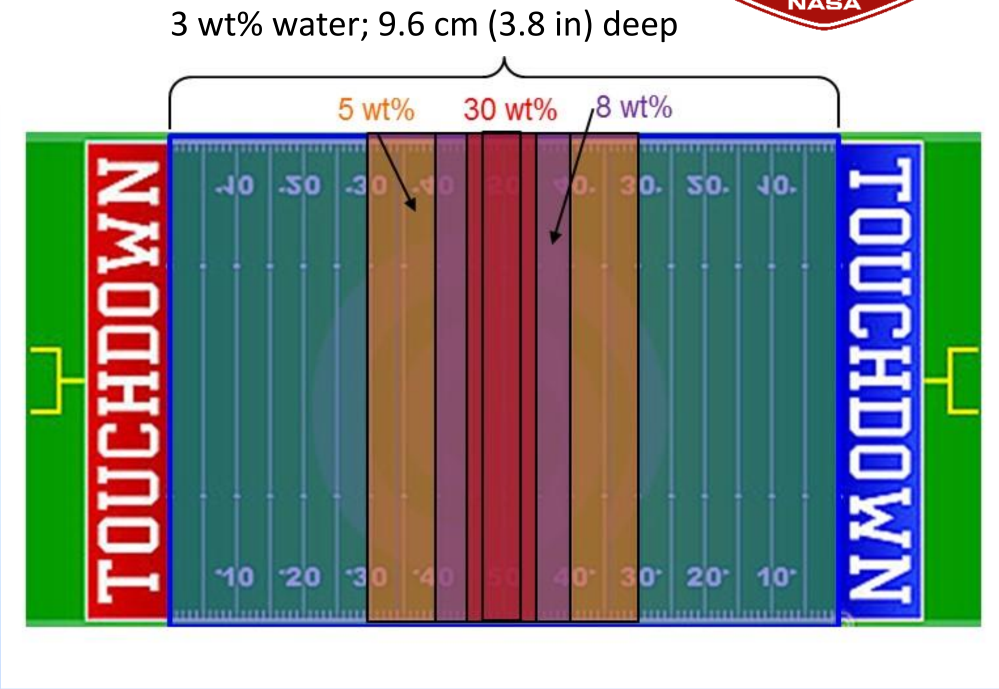
Subsurface Ice
- **90%+ concentration**
- **Subsurface glacier or crater**: 1 to 3 m from surface possible
- Hard material
- **100 to 150 C heating for water removal**
- Downhole or on-rover processing for water removal
- **Highly selective landing site for near surface ice or exposed crater; >**40 to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

Increasing complexity, Difficulty, and Site Specificity

Mars ISRU Processing Rates for Ascent Vehicle Propulsion

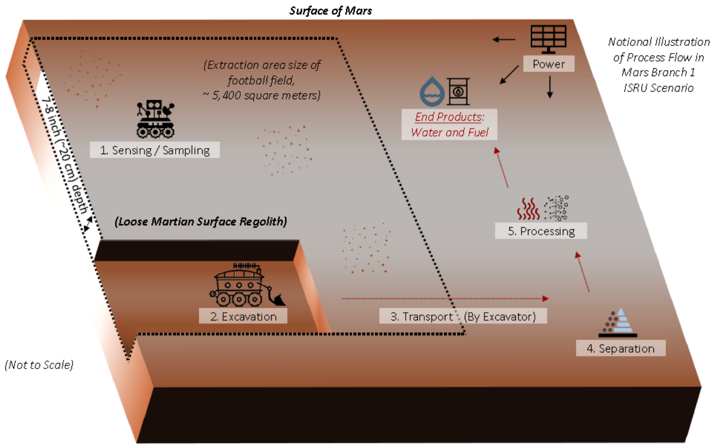
Mars Soil/Water Options



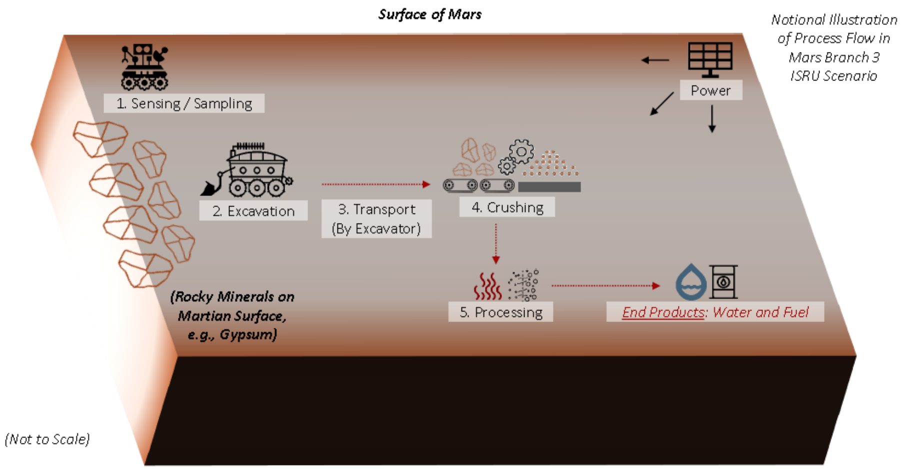


Extra-Terrestrial Mining Operations

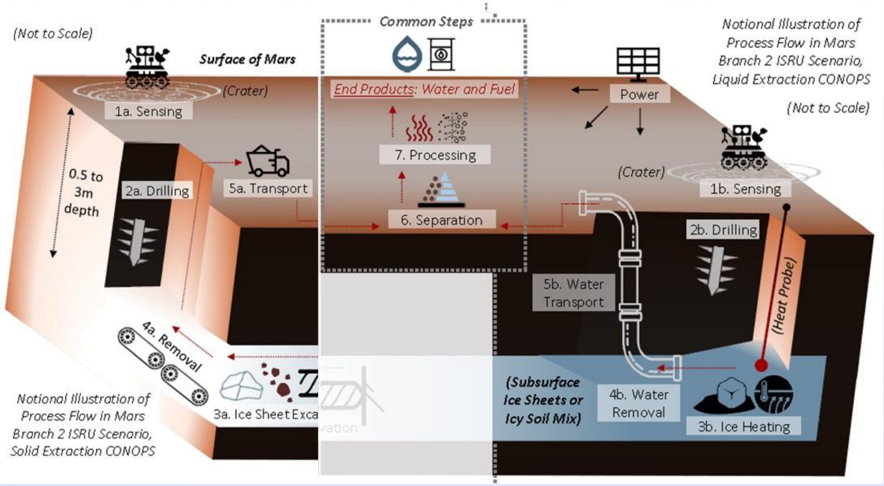
Granular Soil Resource



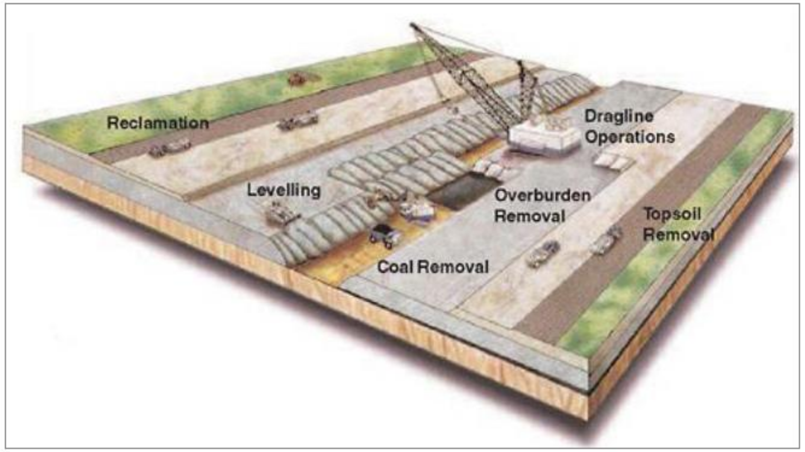
Hard Mineral Resource



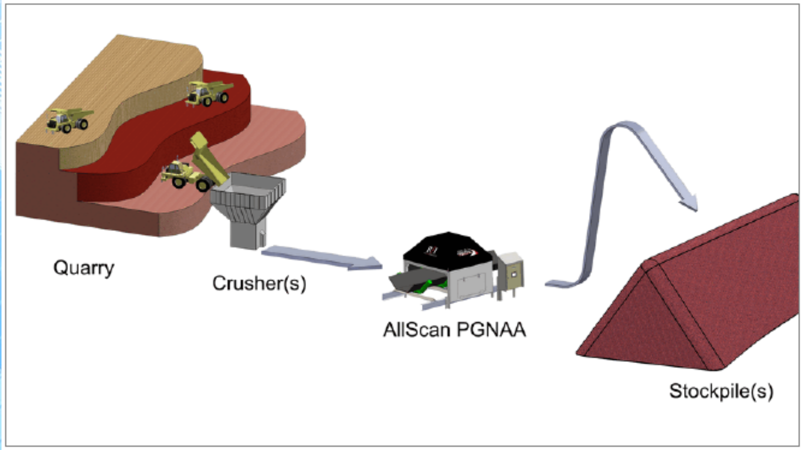
Icy Resource



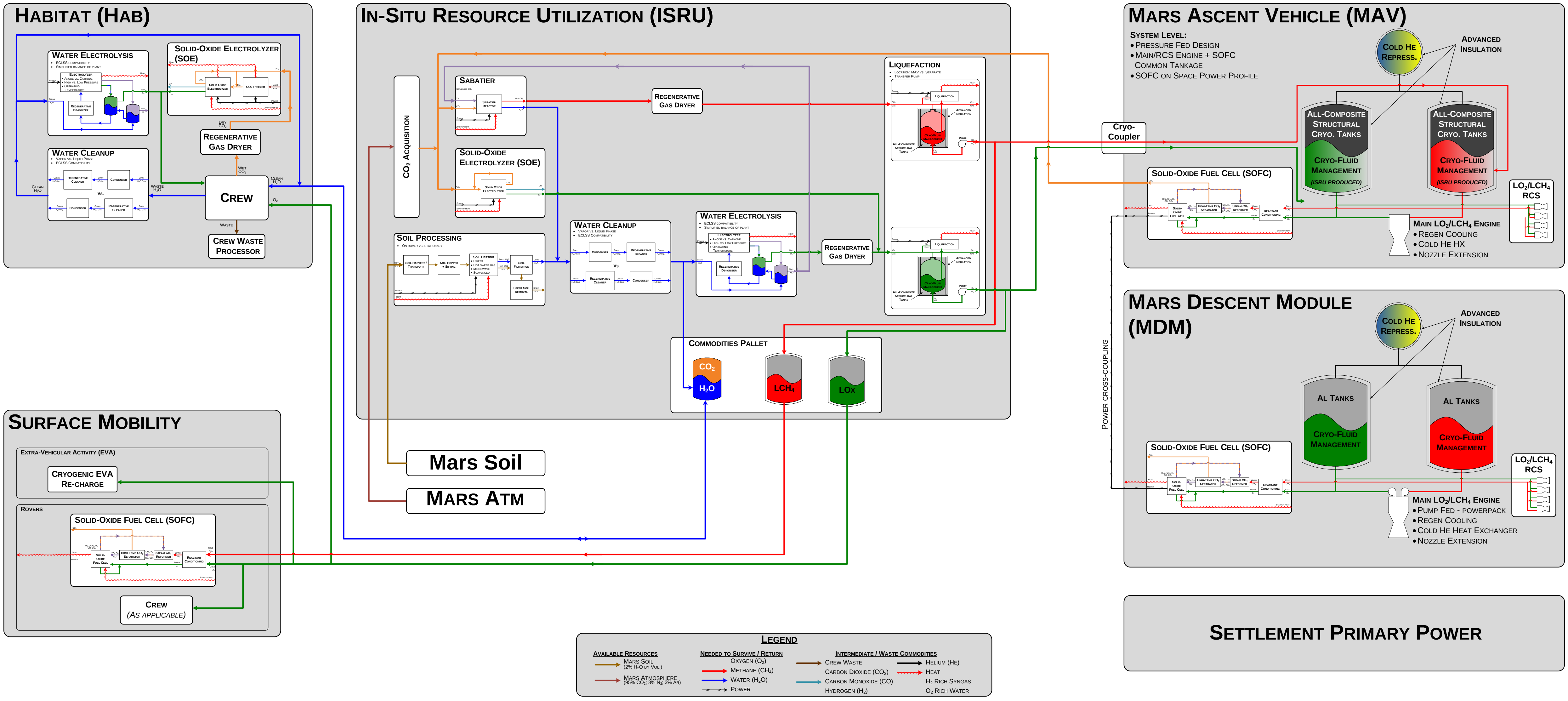
Surface Mining



Quarry Mining



Integrated Mars LO_2/LCH_4 – ISRU Technology Architecture



Integrated Lunar LO_2/LCH_4 – ISRU Technology Architecture