Reduced Gravity and Environmental Issues in the Design and Operation of In-Situ Resource Utilization (ISRU) Systems for Human Missions

Presentation to
The Committee on
Biological and Physical
Sciences in Space (CBSS)
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Vision for Using Space Resources

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

Resources

- Traditional**:** **Water**, atmospheric gases, volatiles, solar wind volatiles, metals, alloys, sunlight, etc.
- Non-traditional: Trash and wastes from crew, spent landers and residuals, etc.

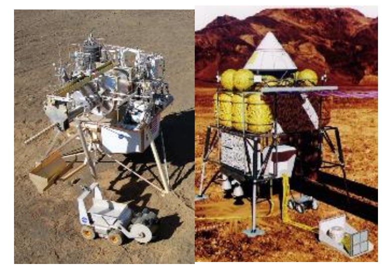
Resource Assessment (Prospecting)

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

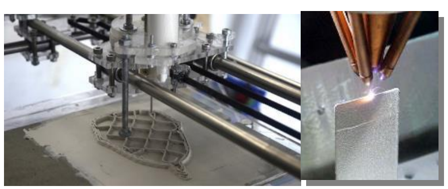
Resource Processing/ Consumable Production



Conversion of acquired resources into products with immediate use or as feedstock for construction & manufacturing

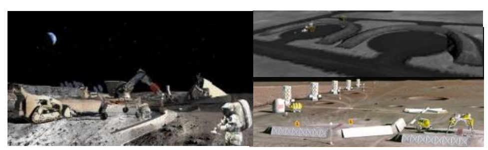
- ➢ Propellants, life support gases, fuel cell reactants, etc.

In Situ Manufacturing



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

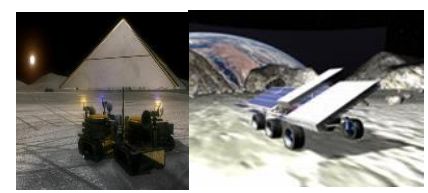
In Situ Construction



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

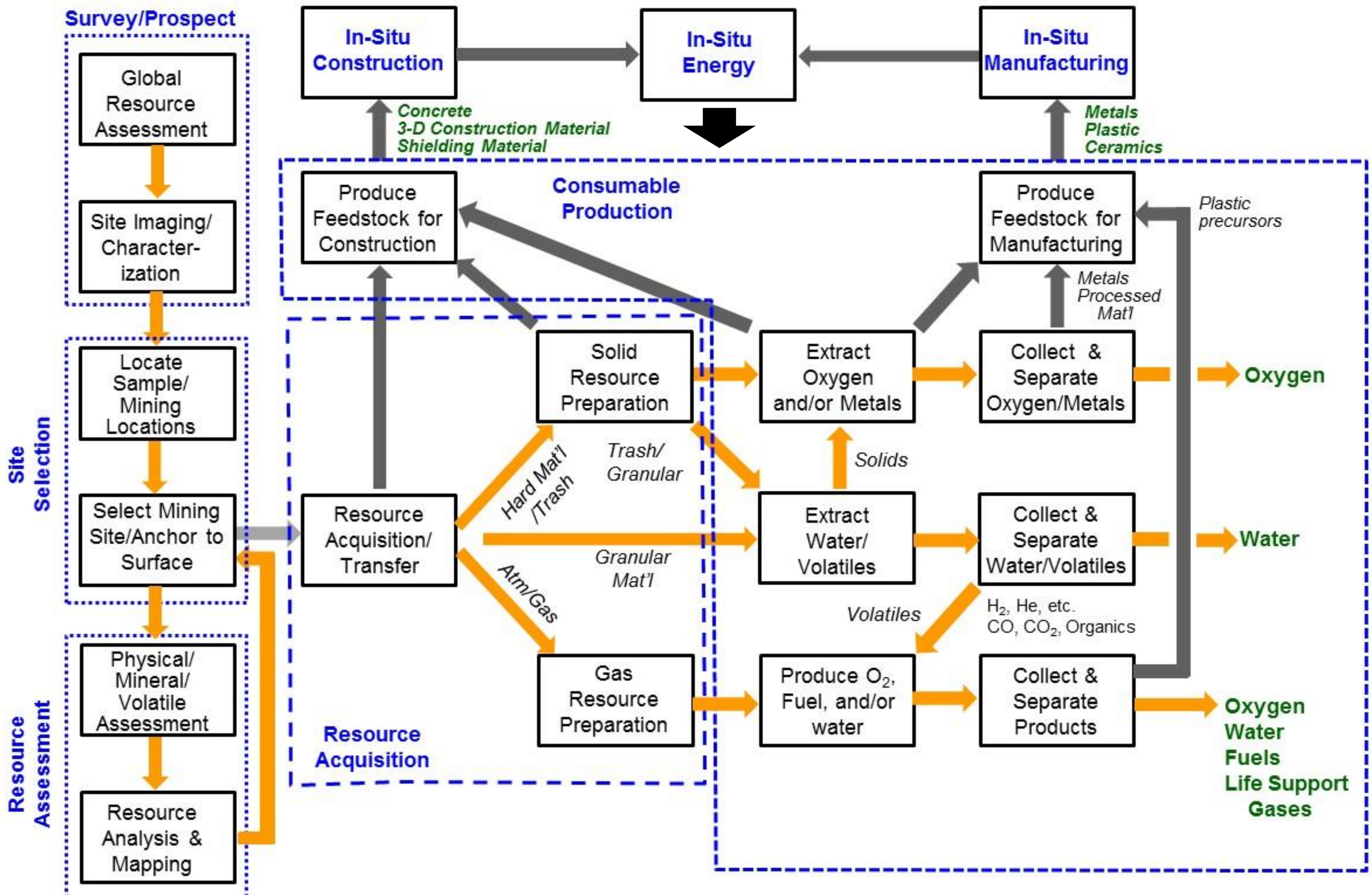


Generation and storage of electrical, thermal, and chemical energy with *in situ* derived materials

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

- ➢ **'ISRU' is a capability involving multiple elements to achieve final products**
- ➢ **'ISRU' does not exist on its own.** Must connect and tie to users/customers of ISRU products

ISRU Capability-Function Flow Chart



Both Physical/Chemical and Biological Processes are Under Consideration

Why ISRU and Why Now?

Why ISRU?

- **ISRU Provides Solutions to Human mission mass, risk, and long-term affordability**
  - ISRU propellant is **ENABLING** for first human missions to Mars.
- **Supports NASA's Goals of Becoming Earth Independent and Commercializing Space**

Why 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
- **ISRU can significantly impact other Exploration Elements**
  - Ascent vehicle, Entry, descent, and landing, Habitats, Life Support, Power
- **Decisions are being made now that have long term implications**
  - Technology and process selections for Power, Propulsion, and Life Support can limit or eliminate benefits of ISRU
- **Every Exploration Element *except* for ISRU has some flight heritage (power, propulsion, habitats, landers, life support, etc.)**
  - ISRU *will require* an end-to-end flight demonstration mission before it will be included in the critical path
  - Flight demonstration mission needs to be concluded well in advance of human Mars surface missions to ensure lessons learned can be incorporated into the final design

Potential 'Solutions' Provided by ISRU

Increase Sustainability/Decreases Life Cycle Costs

- **Reduce launch mass and/or number of launchers required**
- **Reuse landers and transportation elements can provide significant cost savings**
- Growth in capabilities in life support, habitats, powers, etc.
- Enables path for commercial involvement and investment

Increase Mission Performance and Capabilities

- Longer stays, increased EVA, or increased crew over baseline with ISRU consumables
- Increased payload-to-orbit or delta-V for faster rendezvous with fueling of ascent vehicle
- Increased/more efficient stationary and mobile fuel cell power architecture with ISRU
- Decreased logistics and spares brought from Earth

Reduce Mission and Crew Risks

- Minimizes/eliminates life support consumable delivery from Earth
- Increases crew radiation protection over Earth delivered options
- Can relax critical requirements in other system performance
- Minimizes/eliminates ascent propellant boiloff leakage issues
- Minimizes/eliminates landing plume debris damage – Civil engineering and construction

Increases Science

- Greater surface and science sample collection access thru in-situ fueled hoppers
- Greater access to subsurface samples thru ISRU excavation and trenching capabilities
- Increased science payload per mission by eliminating consumable delivery

Mission Variables for Implementation of ISRU

Location	Moon, Mars, Mars Moons, Near-Earth Asteroids
Resource Location Factors	Slopes, craters, rock size/distribution, geographic location (poles, equator)
Environmental Factors	Climate (temperature, wind, season), pressure/vacuum, sunlight, gravity
Resource Demand and Availability	Atmosphere/Gases (carbon dioxide), Water/Ice, Volatiles (hydrogen, helium), Metals (iron, nickel, titanium), Non-Metals (silicon, oxygen)
Resource Extraction Method	Gas separation/compression, surface regolith/granular material mining, rock/quarry mining, subsurface mining/drilling extraction
Resource Pre-Processing and Transportation	Sorting, crushing/sizing, beneficiation; buckets, augers, conveyors, pneumatic
Resource Processing	Electrical, chemical, thermal
Products Needed	Human consumables, propellants, stored energy, construction & manufacturing feedstock
Time	Time available for product production; Time available for setup; Day/night cycle

Mission Variables for Implementation of ISRU

Variables of Greatest Interest to Biological and Physical Sciences

Variable	Examples	Interest
Location	Moon, Mars, Mars Moons, Near-Earth Asteroids	
Resource Location Factors	Slopes, craters, rock size/distribution, geographic location (poles, equator)	
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Main *Natural* Space Resources of Interest

	Moon	Mars	Asteroids	Uses
Water	Icy Regolith in Permanently Shadowed Regions (PSR) Solar wind hydrogen with Oxygen	Hydrated Soils/Minerals: Gypsum, Jarosite, Phylosilicates, Polyhdrated Sulfates Subsurface Icy Soils in Mid-latitudes to Poles	Subsurface Regolith on C-type Carbonaceous Chondrites	▪ Drinking, radiation shielding, plant growth, cleaning & washing ▪ Making Oxygen and Hydrogen
Oxygen	Minerals in Lunar Regolith: Ilmenite, Pyroxene, Olivine, Anorthite	Carbon Dioxide in the atmosphere (~96%)	Minerals in Regolith on S-type Ordinary and Enstatite Chondrites	▪ Breathing ▪ Oxidizer for Propulsion and Power
Carbon	▪ CO, CO_2, and HC's in PSR ▪ Solar Wind from Sun (~50 ppm)	Carbon Dioxide in the atmosphere (~96%)	Hydrocarbons and Tars (PAHs) in Regolith on C-type Carbonaceous Chondrites	▪ Fuel Production for Propulsion and Power ▪ Plastic and Petrochemical Production
Metals	Minerals in Lunar Regolith ▪ Iron/Ti: Ilmenite ▪ Silicon: Pyroxene, Olivine, Anorthite ▪ Magnesium: Mg-rich Silicates ▪ Al:: Anorthitic Plagioclase	Minerals in Mars Soils/Rocks ▪ Iron: Ilmenite, Hematite, Magnetite, Jarosite, Smectite ▪ Silicon: Silica, Phyllosilicates ▪ Aluminum: Laterites, Aluminosilicates, Plagioclase ▪ Magnesium: Mg-sulfates, Carbonates, & Smectites, Mg-rich Olivine	Minerals in Regolith/Rocks on S-type Stony Iron and M-type Metal Asteroids	▪ *In situ* fabrication of parts ▪ Electical power transmission

Similar Resources and Needs Exist at Multiple Locations

Moon, Mars, & Near Earth Objects (NEOs)

	Moon	Mars	NEOs
Gravity	1/6 g	3/8 g	Micro-g
Temperature (Max) (Min.) (Min. Shade)	110 °C/230 °F -170 °C/-274 °F -233 °C/-387.4 °F	20 °C/68 °F -140 °C/-220 °F	110 °C/230 °F -170 °C/-274 °F -233 °C/-387.4 °F
Solar Flux	1352 W/m^2	590 W/m^2	Varied based on distance from Sun
Day/Night Cycle	28+ Days - Equator Near Continuous Light or Dark - Poles	24.66 hrs	Varied - hrs
Surface Pressure	1x10^{-12} torr	7.5 torr	1x10^{-12} torr
Atmosphere	No	Yes CO_2, N_2, Ar, O_2	No
Soil	Granular	Granular & clay; low hydration to ice	Varied based on NEO type
Resources	Regolith (metals, O_2) H_2O/Volatile Icy Soils	Atmosphere (CO_2) Hydrated Soils	Regolith (metals, O_2) Hydrated Soils H_2O/Volatile Icy Soils

- **The Moon has aspects in common with NEOs/Phobos**
- **The Moon has a gravity field in common with Mars**

- **NEO micro-gravity environment is the largest difference between destinations**

Economics of ISRU for Space Applications (1)

A 'Useful' Resource Depends on the Location, What is needed, How much is needed, How often it is needed, and How difficult is it to extract the resource

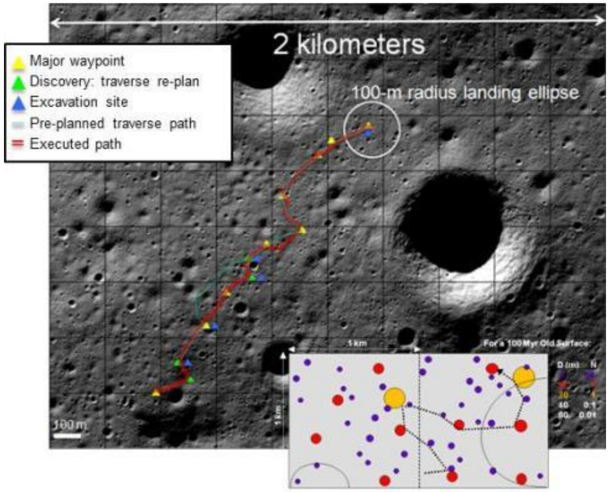
- **Location**
  - Resource must be assessable: slopes, rock distributions, surface characteristics, etc.
  - Resource must be within reasonable distance of mining infrastructure: power, logistics, maintenance, processing, storage, etc.

- **Resource extraction must be 'Economical'**
  - **Concentration and distribution of resource and infrastructure needed to extract and process the resource must allow for Return on Investment (ROI)** for:
    - Mass ROI - mass of equipment and unique infrastructure compared to bringing product and support equipment from Earth. Impacts number and size of launch vehicles from Earth
      - 1 kg delivered to the Moon or Mars surface = 7.5 to 11 kg launched into Low Earth Orbit
    - Cost ROI - cost of development and certification of equipment and unique infrastructure compared to elimination of launch costs or reuse of assets (ex. reusable vs single use landers)
    - Time ROI - time required to notice impact of using resource: extra exploration or science hardware, extended operations, newly enabled capabilities, etc.
    - Mission/Crew Safety ROI - increased safety of product compared to limitations of delivering product from Earth: launch mass limits, time gap between need and delivery, etc.
  - **Amount of product needed must justify investment in extraction and processing**
    - Requires long-term view of exploration and commercialization strategy to maximize benefits
    - Metric: mass/year product vs mass of Infrastructure
  - **Transportation of product to 'Market' (location of use) must be considered**
    - Use of product at extraction location most economical

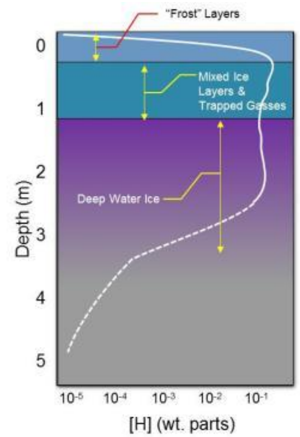
Economics of ISRU for Space Applications (2)

Need to understand the Concentration and Distribution of Resource

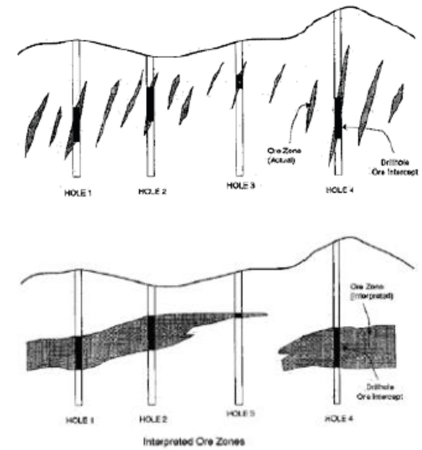
Need to Evaluate Local Region (1 to 5 km)



Need to Determine Vertical Profile



Need to Determine Distribution



Need to assess What is needed, How much is needed, How often it is needed

- **Resource Product Needs**

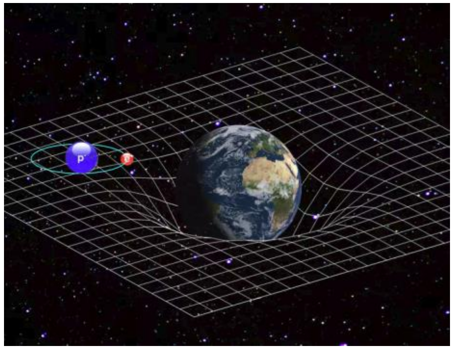
Location	Product	Amount (kg)	Need/Time	Use
Moon	O_2	1000	Per Year	Crew Breathing - Life Support Consumable Makeup
	O_2	3000 - 3500	2x Per Year	Non-Reusable Crew Ascent Vehicle Propulsion - Surface to Low Lunar Orbit: Earth fuel
	O_2	~16000	2x Per Year	Reusable Ascent/Descent Propulsion - Surface to L_1/L_2: Earth Fuel (4000 kg payload)
	O_2/H_2	~30,000	2x Per Year	Reusable Ascent/Descent Propulsion - Surface to L_1/L_2 (4000 kg payload)
	H_2O	150,000	2x Per Year	Lunar Human Outpost & Reusable Transportation
	O_2/H_2	150,000	Per Year	Anount needed for Propellant Delivery to LDRO for Human Mars Mission
Mars	O_2/CH_4	22,728/6978	Per Use/1x 480 Days	Non-Reusable Crew Ascent Vehicle Propulsion - Surface to High Mars Orbit
	O_2/CH_4	59,000/17,100	Per Use/1 or2x Per Yr	Reusable Ascent/Descent Propulsion - Surface to Mars Orbit
	H_2O	3,075	Surface/500 Days	Life Support System Closure
	H_2O	15,700	Per Use/1x 480 Days	Extracted H_2O to Make Non-Reusable Ascent Vehicle Propellant
	H_2O	38,300	Per Use/1 or2x Per Yr	Extracted H_2O to Make Reusable Ascent/Descent Vehicle Propellant

= Initial Requirement   = Horizon Goal

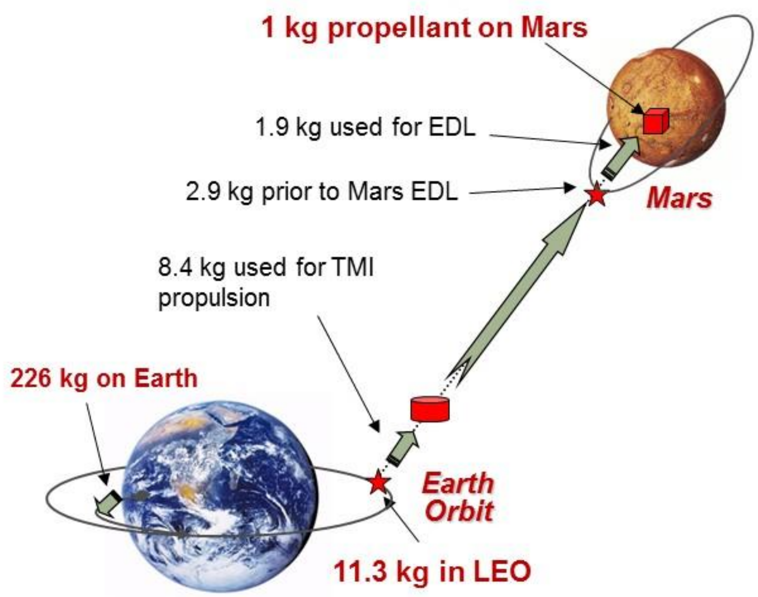
Leverage (Gear) Ratios using ISRU

Every 1 kg of propellant made on the Moon or Mars saves 7.4 to 11.3 kg in LEO

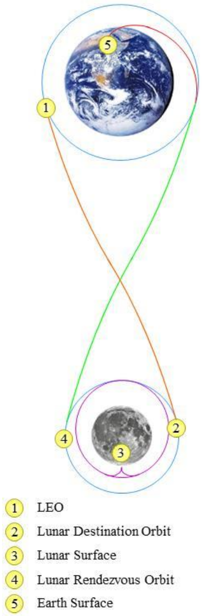
Potential 334.5 mT launch mass saved in LEO
= 3 to 5 SLS launches avoided per Mars Ascent



- **Mars mission**
  - Oxygen (O_2) only — 75% of ascent propellant mass: 20 to 23 mT
  - O_2/Methane (CH_4) — 100% of ascent propellant mass: 25.7 to 29.6 mT
    Regeneration of rover fuel cell reactant mass
- **Phobos mission**
  - Trash to O_2/CH_4 — 1000+ kg of propellant



Estimates based on Aerocapture at Mars



A Kilogram of Mass Delivered Here…	…Adds This Much Initial Architecture Mass in LEO	…Adds This Much To the Launch Pad Mass
Ground to LEO	-	20.4 kg
LEO to Lunar Orbit (#1→#2)	4.3 kg	87.7 kg
LEO to Lunar Surface (#1→#3; e.g., Descent Stage)	7.5 kg	153 kg
LEO to Lunar Orbit to Earth Surface (#1→#4→#5; e.g., Orion Crew Module)	9.0 kg	183.6 kg
Lunar Surface to Earth Surface (#3→#5; e.g., Lunar Sample)	12.0 kg	244.8 kg
LEO to Lunar Surface to Lunar Orbit (#1→#3→#4; e.g., Ascent Stage)	14.7 kg	300 kg
LEO to Lunar Surface to Earth Surface (#1→#3→#5; e.g., Crew)	19.4 kg	395.8 kg

ISRU Development and Implementation Challenges/Risks

Space Resource Challenges

R1 What resources exist at the site of exploration that can be used?

R2 What are the uncertainties associated with these resources?
Form, amount, distribution, contaminants, terrain

R3 How to address planetary protection requirements?
Forward contamination/sterilization, operating in a special region, creating a special region

ISRU Technical Challenges

T1 Is it technically feasible to collect, extract, and process the resource?
Energy, Life, Performance

T2 How to achieve long duration, autonomous operation and failure recovery?
No crew, non-continuous monitoring, time delay

T3 How to achieve high efficiency, reliability, and minimal maintenance requirements?
Thermal cycles, mechanisms/pumps, sensors/ calibration, wear

ISRU Operation Challenges

O1 How to operate in extreme environments?
Temperature, pressure/vacuum, dust, radiation

O2 How to operate in low gravity or micro-gravity environments?
- Drill/excavation force vs mass, soil/liquid motion, thermal convection/radiation
- Friction, cohesion, and electrostatic forces may dominate in micro-g

ISRU Integration Challenges

I1 How are other systems designed to incorporate ISRU products?

I2 How to optimize at the architectural level rather than the system level?

I3 How to manage the physical interfaces and interactions between ISRU and other systems?

Overcoming these challenges requires a multi-discipline and integrated approach

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ISRU Operation Challenges

- **Operation in severe environments**
  - Efficient excavation of resources in dusty/abrasive environments
  - Methods to mitigate dust & dust filtration for Mars atmospheric processing
    - Filter effectiveness, pressure drop, sealing & rotating mechanism degradation, etc.
  - Extreme temperature changes and/or extremely low temperatures
    - Material selection, embrittlement, thermal management, etc.
  - Radiation and vacuum exposure
  - Wide variation in potential resource hardness, density/porosity, etc.

- **Operation in low/micro-gravity**
  - Low-gravity on Moon/Mars
    - Low reaction force excavation in reduced and micro-gravity
    - Granular material flow different in low-g; increase in electrostatic/friction effects
    - Liquid slosh is amplified
    - Kicking up dust is amplified; dust settling is different
    - Rotational inertia is not reduced, but gravity to resist tipping is reduced!
    - Fluidized & molten reactors impacted by gravity and thermal convection differences
    - Unknown impact on biological processing
  - Micro-g environment for asteroids and Phobos/Deimos
    - Anchoring/weight-on-bit for resource extraction
    - Material handling and transport completely different than Moon/Mars techniques
    - Feedstock, product, and reactant separation
      - Gas/liquid, gas/solid, and liquid/solid reactors and separation
    - Friction, cohesion, and electrostatic forces may dominate in micro-g
    - Unknown impact on biological processing

ISRU Product/Resource Processing Options Under Consideration

Oxygen/Fuel Production from Mars Atmosphere

Atmosphere Collection
- 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
  - Ionic Liquid/PEM Electrolysis
- Fuel Production
  - Sabatier (CH_4)
  - Fischer Tropsch
  - Alcohols
  - Ethylene → Plastics
- Water Processing
  - Water Electrolysis (PEM vs SOE)
  - Water Cleanup/ Deionization

Products from Crew Waste/Trash

Solid Transport
- Material Transport & Preparation
  - Augers
  - Crushing &
  - Shredding
  - Sorting

Chemical Processing
- Trash Reduction
  - Steam reforming
  - Oxidation/combustion
  - Pyrolysis
  - Ionic liquids
- Syngas Processing
  - Sabatier (CH_4)
  - Fischer Tropsch
  - Alcohols
  - Ethylene → Plastics
- Water Processing
  - Water Electrolysis (PEM vs SOE)
  - Water Cleanup/ Deionization

Water/Volatile Extraction From Soils

Solid Extraction and Transport
- Granular Soil Excavation/Extraction →
  - Drills/Augers (1 to 3 m)
  - Load/Haul/Dump (LHD)
  - Bucket Wheels/Drums
  - Pneumatic Transport
- Consolidated Material Extraction & Preparation →
  - Drills/Augers
  - Percussive Blades
  - Ripper & LHD
  - Crushing & Sorting
- Material Transfer →
  - Augers
  - Pneumatic
  - Bucket ladders

Water/Volatile Extraction
- Hydrated soils
  - Open Reactor/Heating
  - Closed Fluidized Reactor
  - Auger Dryer
- Icy soils
  - Transport to Reactor
  - Downhole Enclosure
  - Downhole Heating & Removal

Oxygen & Metal Extraction from Minerals

Oxygen Extraction from Minerals
- Hydrogen Reduction of Iron Oxides
- Methane Reduction of Silicates
- Ionic liquids/Acids
- Molten Oxide Reduction

Metal Extraction from Minerals
- Molten Oxide Reduction
- Molten Salt Reduction
- Ionic Liquids/Acids
- Biological Extraction

Location to Reduce/Eliminate ISRU Challenges/Risks

	Earth	Orbital	Surface
What resources exist at the site that can be used?	S	S	**P**
What are the uncertainties associated with these resources?	S	S	**P**
How to address planetary protection requirements?	P		V
Is it technically feasible to collect, extract, & process resources?	P		V
How to achieve long duration, autonomous operation?	P		V
How to achieve high reliability/minimal maintenace?	P		V
How to operate in extreme environments?	S/V	**P** NEA	**P**
How to operate in low/micro gravity?	S	**P** NEA	**P**
How other systems designed to incorporate ISRU products?	P		V/**P**
How to optimize at the architectural level with ISRU?	P		V
How to manage the interfaces/interactions with other systems?	P		V

P = Primary; V = Validation, S = Support

- Most challenges and risks to ISRU development and incorporation can be eliminated through design and testing under Earth analog or environmental chamber testing at the component, subsystem, and system level
  - **Adequate simulants are critical for valid Earth based testing**
- Critical challenges/risks associated with fully understanding the extraterrestrial resource (form, concentrations, contaminants, etc.) and ISRU system operation under actual environmental conditions for extended periods of time can only be performed on the extraterrestrial surface
- Product quality based on actual in situ resource used should be validated at the destination
- ISRU precursors/demonstrations are extremely beneficial for validation of Earth-based testing and analysis

Low/Micro-g & Space Environment Testing and Operations Relevant to ISRU

Testing Relevant to Micro-g/Space Environment on ISS or Gateway

- Fundamental research on ISRU processes effected by gravity or radiation for Mars moon/asteroid ISRU
  - Gas/liquid, solid/gas, solid/liquid, solid/solid, and molten processors and reactors
- Long-duration micro-g/space radiation testing of biological-based ISRU processes
- Crew waste/trash processing into
  - Propellant or vent gases
  - Radiation shielding
  - Plastics for manufacturing
- Manufacturing with *in situ* produced plastics
- Cryogenic storage and transfer of fluids for possible reusable landers
- Lunar sample evaluation before sending highest priority samples back to Earth

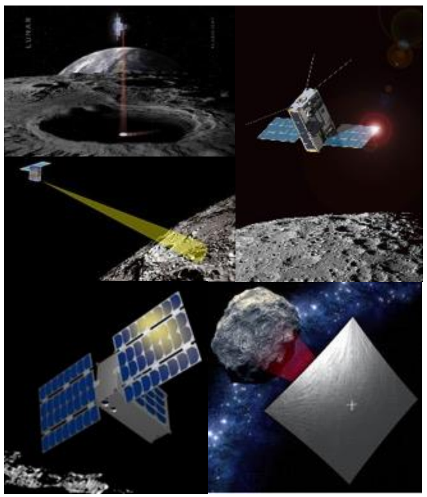
Partial-g Testing

- Testing of ISRU processes effected by gravity or radiation for Moon/Mars ISRU
  - Gas/liquid, solid/gas, solid/liquid, solid/solid, and molten processors and reactors
- Long-duration micro-g/space radiation testing of biological-based ISRU processes

Current NASA ISRU-Related Missions Under Development

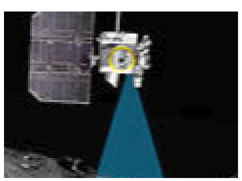
Resource Prospector – RESOLVE Payload

- Examine minerals: Near IR
- Measure water (H_2O): Neutron spec, Near IR spec., GC/MS
- Measure volatiles – H_2, CO, CO_2, NH_3, CH_4, H_2S: GC/MS



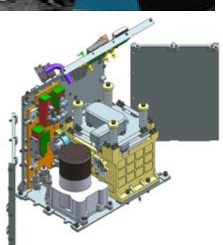
Cubesats (SLS EM-1 2018)

- Lunar Flashlight: Uses a Near IR laser and spectrometer to look into shadowed craters for volatiles
- Lunar IceCube: Carries the Broadband InfraRed Compact High Resolution Explorer Spectrometer (BIRCHES)
- LunaH-MAP: Carries two neutron spectrometers to produce maps of near-surface hydrogen (H)
- Skyfire/LunIR: Uses spectroscopy and thermography for surface characterization
- NEA Scout: Uses a science-grade multispectral camera to learn about NEA rotation, regional morphology, regolith properties, spectral class



Korea Pathfinder Lunar Orbiter (KPLO)

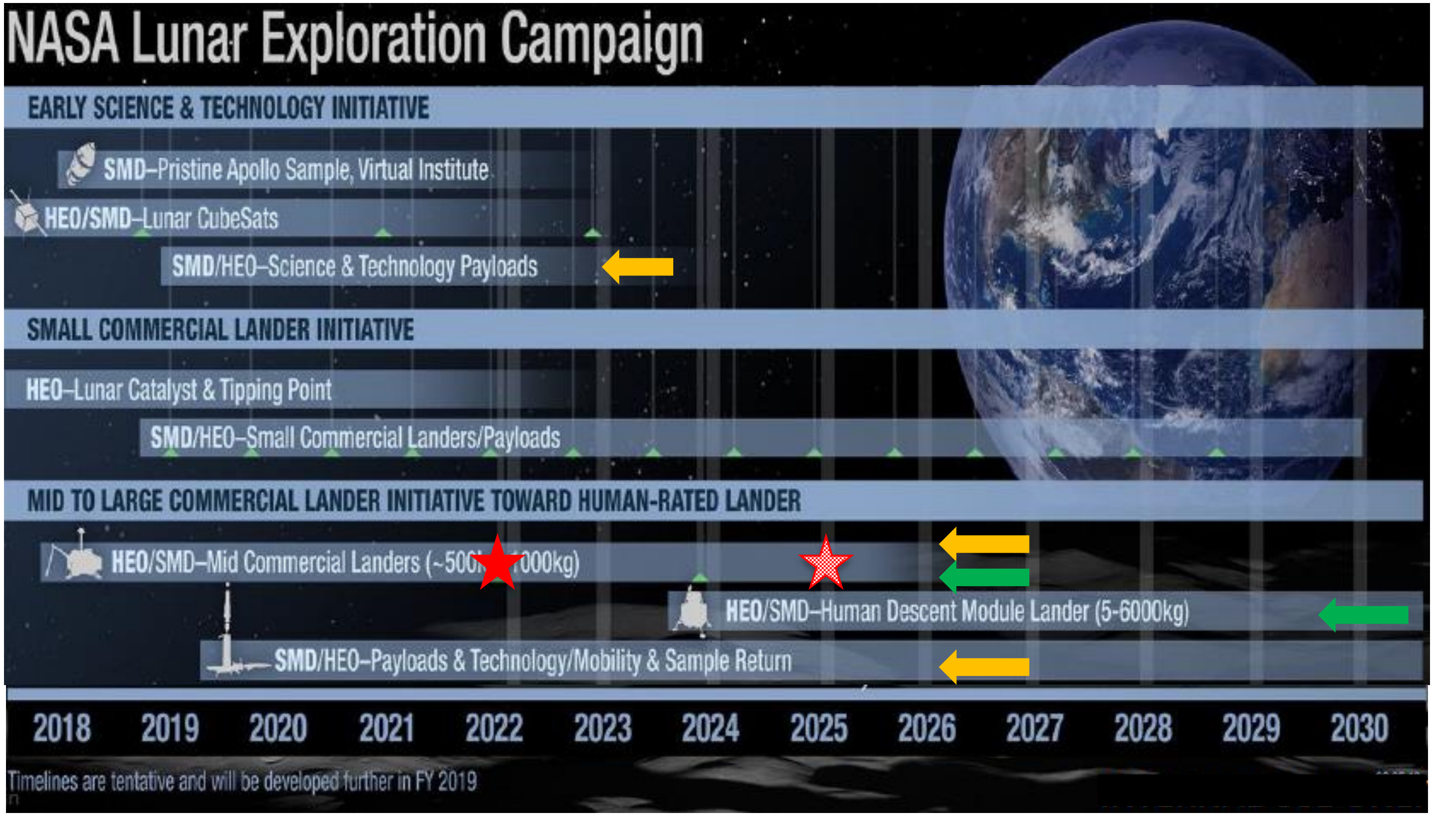
- ShadowCam: Map reflectance within permanently shadowed craters



Mars 2020 ISRU Demo

- Make O_2 from Atm. CO_2: ~0.01 kg/hr O_2; 600 to 1000 W-hrs; 15 sols of operation
- Scroll Compressor and Solid Oxide Electrolysis technologies
- Payload on Mars 2020 rover

New Lunar Exploration Campaign



= *Potential* Resource Prospecting and ISRU Technical and Commercial Demonstrations

= *Potential* Date for Resource Prospector (RP) mission

= *Notional* RP Follow-on/Polar Volatile mining mission

= *Potential* ISRU Capability or Pilot Scale Demos

Assessment Required for How ISRU will Support And Advance Human Lunar Exploration and Commercial Development

Strategic Knowledge Gaps (SKGs) for Moon & Mars

Utilize SKGs and Commercial interests as drivers for Demos and Pilot Plants

Lunar Strategic Knowledge Gaps

I. Understand the lunar resource potential.		
	A. Solar Resources	
	B. Regolith Resources 1 (Earth testing)	
	C. Regolith Resources 2: Volatiles in mare and highland regolith	
	D. Polar Resources	
		Geotechnical charactgeristics of cold traps
		Physiography and accessibility of cold traps
		Charging and plasma environment characterization
		Water/volatile characterization 1 to 2 meters deep
		Water/volatile characterization over 10's of meters
		Mineralogical, elemental, molecular, and isotopic make up of volatiles
		Physical nature of volatiles
		Spatial and temporal distribution of surface OH/H2O
		Measure exospheric water and monitor movement towards PSRs
	E. Pyroclastic Deposit Resources	
	F. Lunar ISRU production efficiency 1 (Earth testing)	
	G. Lunar ISRU production efficiency 2	
II. Understand the lunar environment and its effects on human life.		
	A. Solar Activity (Earth based)	
	B. Radiation at the lunar surface	
		Radiation environment on the surface 2
		Radiation shielding effect of lunar materials 2
	C. Biological impact of dust	
	D. Maintaining peak human health	
III. Understand how to work and live on the lunar surface.		
	A. Resource Production	
		Technology for excavation of lunar resources
		Technologies for transporting lunar resources
		Technologies for comminution of lunar resources
		Technologies for beneficiating lunar resources
	B. Geodetic Grid and Navigation	
		Lunar topography data
		Autonomous surface navigation
	C. Surface Trafficability	
	D. Dust and Blast Ejecta	
		Lunar dust remediation
		Regolith adhesion and associated mechanical degradation
		Descent/ascent engine blast ejecta
	E. Plasma environment and charging	
	F. Energy production and storage	
		Energy production and storage - non polar missions
		Energy production and storage - polar missions
		Propellant scavenging
	G. Radiation shielding	
	H. Micrometeroite shielding	
	I. Lunar mass contribution/distribution	
	J. Habitat, life support and mobility	

Mars Strategic Knowledge Gaps

Atmospheric SKGs	
	A1-1 Global Temperature Field
	A1-2 Global Aerosol Profiles and Properties
	A1-3 Global Winds and Wind Profiles
	A2-1 Atmospheric Modeling
	A4-3 Aerocapture Demo
	B1-1 Dust Climatology
	B1-2 Global Surface Pressure: Local Weather
	B1-3 Surface Winds
	B1-4 EDL Profiles
	B1-5 Atmospheric Electricity Conditions
	B1-6 EDL Technology Demo
	B1-7 Ascent Technology Demo
Mars Surface and ISRU	
	B6-1 Dust Physical, Chemical and Electrical Properties
	B6-2 Dust Column Abundances
	B6-3 Trace Gas Abundances
	B7-1 Regolith Physical Properties and Structure
	B7-4 Auto Rover Tech Demo
	B7-6 Sample Handling Tech Demo
	B8-1 Fission Power Tech Demo
	D1-1 Cryo Storage Demo
	D1-2 Water ISRU Demo
	D1-3 Hydrated Mineral Compositions
	D1-4 Hydrated Mineral Occurrences
	D1.5 Shallow Water Ice Composition and Properties
	D1-6 Shallow Water Ice Occurrences
Mars Surface Hazards	
	B4-1 Electricity
	B4-2 Dust Physical, Chemical, and Electrical Properties
	B4-3 Regolith Physical Properties and Structure
	B7-2 Landing Site Selection
	B7-3 Trafficability
	B7-5 Environmental Exposure Tech Demo
Phobos/Deimos	
	A3-1 Orbital Particulate Environment
	A4-1 Autonomous Redezvous and Docking
	C1-1 Surface Composition
	C2-1 Electrostatic and Plasma Environments
	C2-2 Gravitational Field
	C2-3 Regolith Properties
	C2-4 Thermal Environment
	C3-1 Anchoring and Surface Mobility Systems - Tech Demo
Planetary Protection	
	B2-1 Biohazards
	B5-1 Identify and Map Special Regions
	B5-2 Model Induced Special Regions
	B5-3 Microbial Survival, Mars Conditions
	B5-4 Develop Contanminant Dispersal Model
	B5-5 Forward Contamination Tech Demo
	C2-4 Thermal Environment

Planetary Protection Concerns for ISRU and Search for Life on Mars

- Forward contamination: Biological traces introduced to Mars
- Creation of special region: liquid water at 'comfortable' temperatures for long periods of time
  - COSPAR defines Special Regions as "a region within which terrestrial organisms are likely to replicate"

Further Concerns for ISRU and Crewed Operations

- Release of solids (dust grains) generated by excavation or drilling or reactor feeding spillover etc… after contact with machinery may be transported by winds and deposited somewhere else.
- Subsurface material attaches to spacesuit and goes into habitat through maintenance activities
- Release of gases/liquids through leakage, venting operations, or failure that could confuse search for life

➢ Note: ISRU processes considered so far do not include biological or synthetic biology approaches

Backup

What are Space Resources?

- **'Resources'**
  - Traditional**:** **Water**, atmospheric gases, volatiles, solar wind volatiles, metals, alloys, etc.
  - Non-traditional: Trash and wastes from crew, spent landers and residuals, etc.
- **Energy**
  - Thermal Energy Storage Using Modified Regolith
    - Thermal conductivity of unmodified lunar regolith is very low (~1 mW/m-K); good insulator.
  - Permanent/Near-Permanent Sunlight
    - Stable thermal control & power/energy generation and storage
  - Permanent/Near-Permanent Darkness
    - Thermal cold sink for cryo fluid storage & scientific instruments
- **Environment**
  - Vacuum
  - Micro/Reduced Gravity
  - Large Thermal Gradients
  - Atmosphere Drag
- **Location**
  - Stable Locations/'Real Estate':
    - Earth viewing, sun viewing, space viewing, staging locations
  - Isolation from Earth
    - Electromagnetic noise, hazardous testing & development activities (nuclear, biological, etc.), extraterrestrial sample curation & analysis, storage of vital information, etc.

ISRU Related Development within NASA

ISRU

Resource Assessment/ Prospecting
- 1.1 Site Imaging/ Characterization
- 1.2 Physical Property Evaluation
- 1.3 Atmosphere/Gas Resource Evaluation
- 1.4 Mineral/Chemical Resource Evaluation
- 1.5 Volatile Resource Evaluation
- 1.6 Data Fusion, Analysis, Mapping & Monitoring

TRL 1-3 | TRL 4-6 | Flight Dev

Moon | Mars | NEAs

Resource Acquisition
- 2.1 In Situ Atmosphere/Gas Resources
- 2.2 Planetary Material Resources
- 2.3 Discarded Material/Trash Resources

TRL 1-3 | TRL 4-6 | Flight Dev

Mars | NEAs

Resource Processing/ Consumables
- 3.1 Extract/Produce Oxygen
- 3.2 Extract/Produce Fuel
- 3.3 Extract/Produce Water
- 3.4 Extract/Separate Gases for Life support/Science
- 3.5 Extract/Produce Manufacturing Feedstock
- 3.6 Extract/Produce Construction Feedstock
- 3.7 Extract/Produce Food Production Feedstock

TRL 1-3 | TRL 4-6 | Flight Dev

Moon | Mars

In Situ Construction
- 4.1 Area Clearing, Landing Pads, Roads
- 4.2 Excavation - Berms, Trenches, Burial
- 4.3 Structure/ Habitat Construction
- 4.4 Shielding Construction

TRL 1-3

Moon | Mars

Manufacturing with ISRU Feedstock
- 5.1 Manufacturing with *In Situ* Regolith/ Metal/Silicon
- 5.2 Manufacturing with *In Situ* derived Plastics
- 5.3 Manufacturing with *In Situ* Produced Ceramics
- 5.4 Manufacturing with Recovered/Recycled /Repurposed Materials

TRL 1-3 | TRL 4-6 | Flight Dev

Moon | Mars | ISS

In Situ Energy
- 6.1 Use of *In Situ* Material for Thermal Energy Storage
- 6.2 Use of *In Situ* Material for Electrical Energy Storage
- 6.3 *In Situ* Solar Array Production

The Chemistry of Mars ISRU

2nd Step

Oxygen (O_2) Production Only

Zirconia Solid Oxide CO_2 Electrolysis (SOE)

$2\,CO_2 \xrightarrow{900-1000\,C} 2\,CO + O_2$ [Pt catalyst] → O_2

Reverse Water Gas Shift (RWGS)

$CO_2 + H_2 \underset{}{\overset{400-650\,C}{\rightleftharpoons}} CO + H_2O$ [catalyst] → H_2O → WE to O_2

Bosch

$CO_2 + 2\,H_2 \xrightarrow{450-600\,C} C + 2\,H_2O$ [Ni, Ru, Fe, or Co catalyst] → H_2O → WE to O_2

Oxygen (O_2) & Methane (CH_4) Production

Sabatier Catalytic Reactor (SR)

$CO_2 + 4\,H_2 \overset{200-300\,C}{\rightleftharpoons} CH_4 + 2\,H_2O$ [Ru catalyst] → H_2O, CH_4 → WE to O_2

Methane Reformer

$CO + 3\,H_2 \xrightarrow{250\,C} CH_4 + H_2O$ [Ni catalyst] → H_2O, CH_4 → WE to O_2

Electrochemical Reduction

$CO_2 + 2\,H_2O \longrightarrow CH_4 + 2\,O_2$ [Anode/Cathode] → O_2, CH_4

Other Hydrocarbon Fuel Production

Fischer-Tropsch (FT)

$n\,CO + (2n+1)\,H_2 \xrightarrow{>150\,C} C_nH_{2n+2} + n\,H_2O$ [catalyst] → H_2O, C_nH_{2n+2} → WE to O_2

Methanol

$CO + 2\,H_2 \xrightarrow[50-100\,atm]{250\,C} CH_3OH$ [ZnO catalyst] → CH_3OH

$CO_2 + 3\,H_2 \longrightarrow CH_3OH + H_2O$ → H_2O, CH_3OH → WE to O_2

Oxygen (O_2) &/or Hydrogen (H_2) Production

Water Electrolysis (WE)

$2\,H_2O \longrightarrow 2\,H_2 + O_2$ → O_2, $2\,H_2$

Steam Reforming

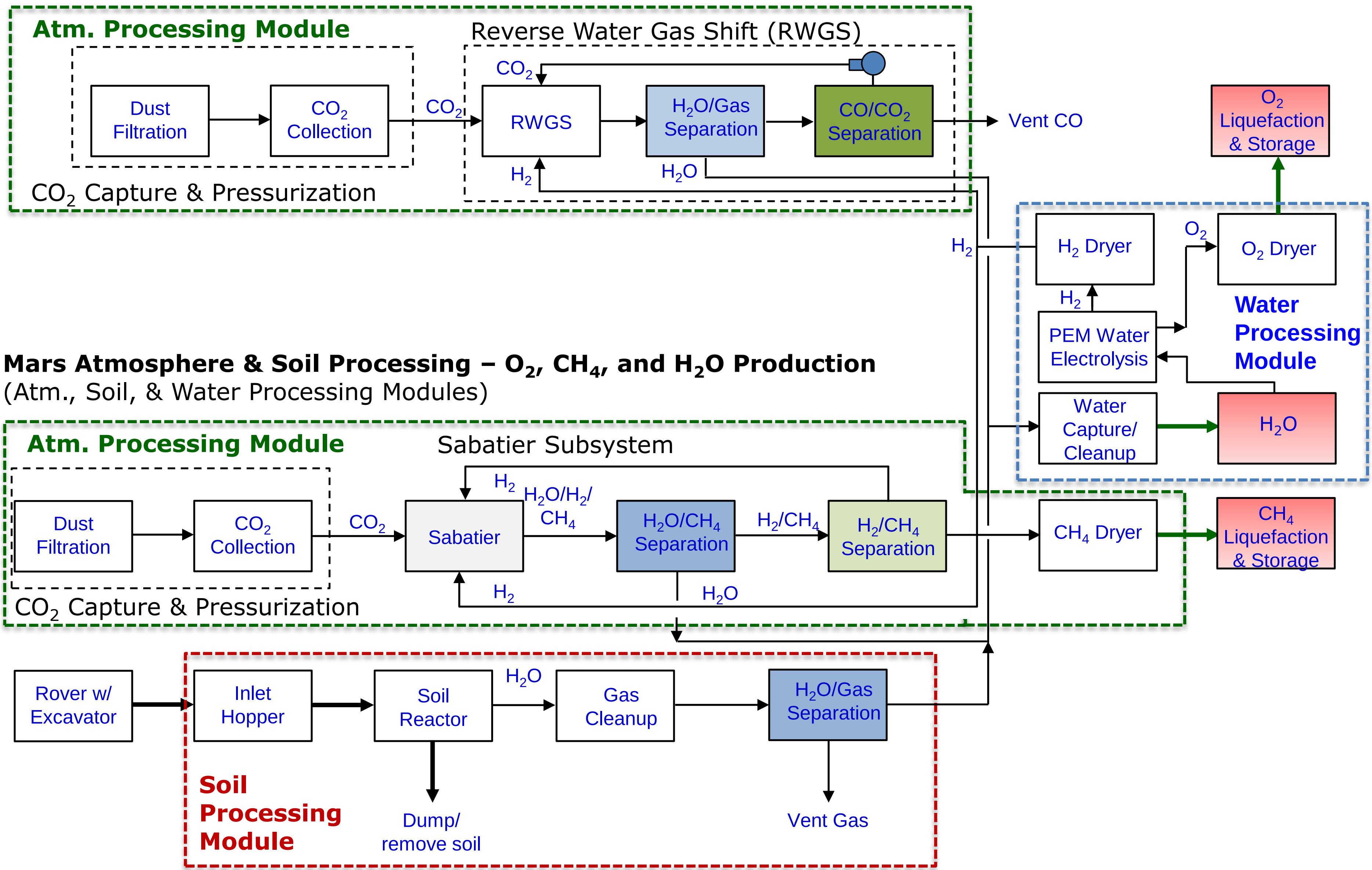
$H_2O + CH_4 \longrightarrow 3\,H_2 + CO$ → $3\,H_2$

Dry Reforming

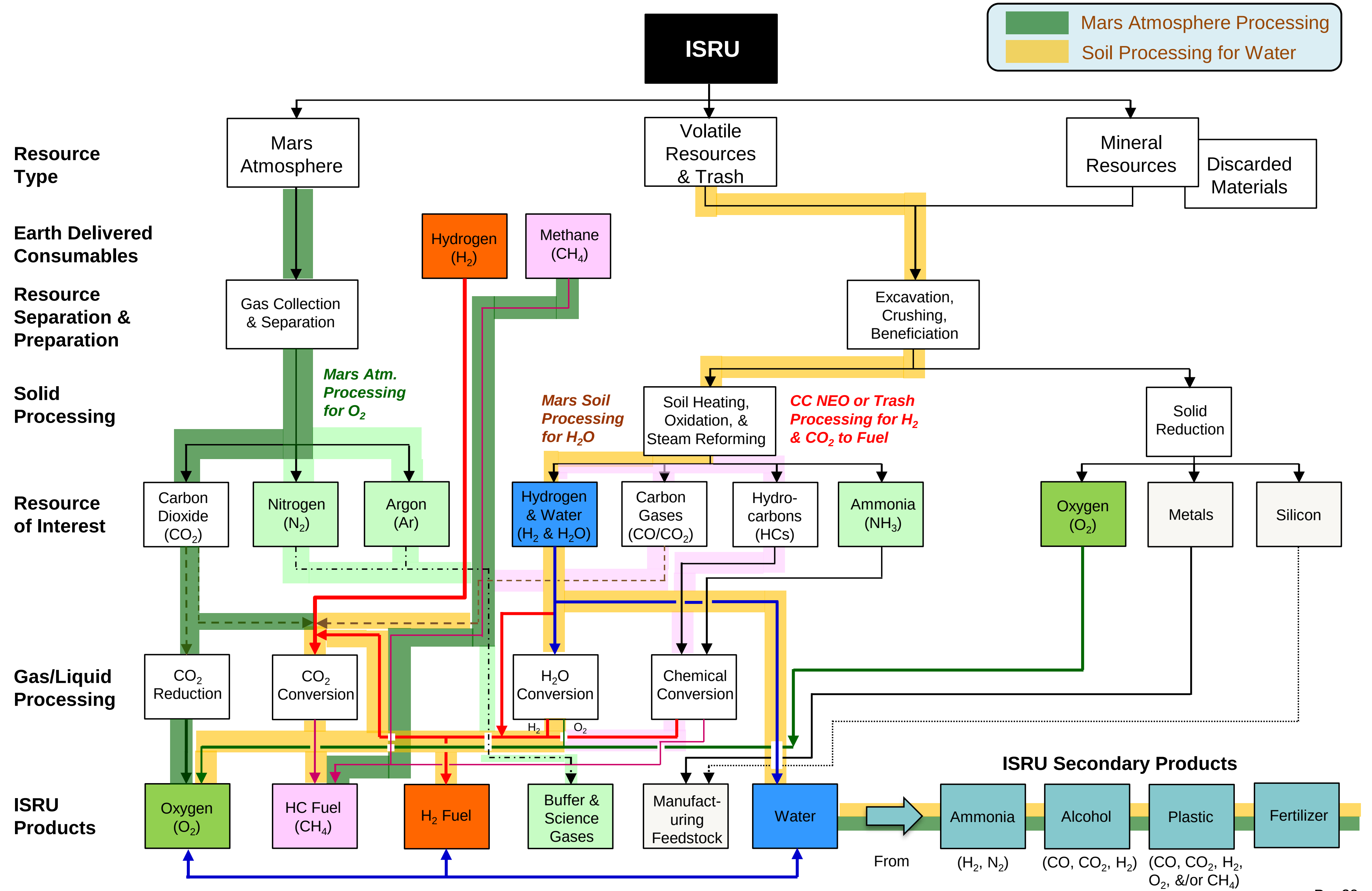
$CO_2 + CH_4 \longrightarrow 2\,H_2 + 2\,CO$ → $2\,H_2$

Mars Consumable ISRU: PEM-Based Electrolysis

Mars Atmosphere Processing – O_2 Only Production (Atm. & Water Processing Modules)

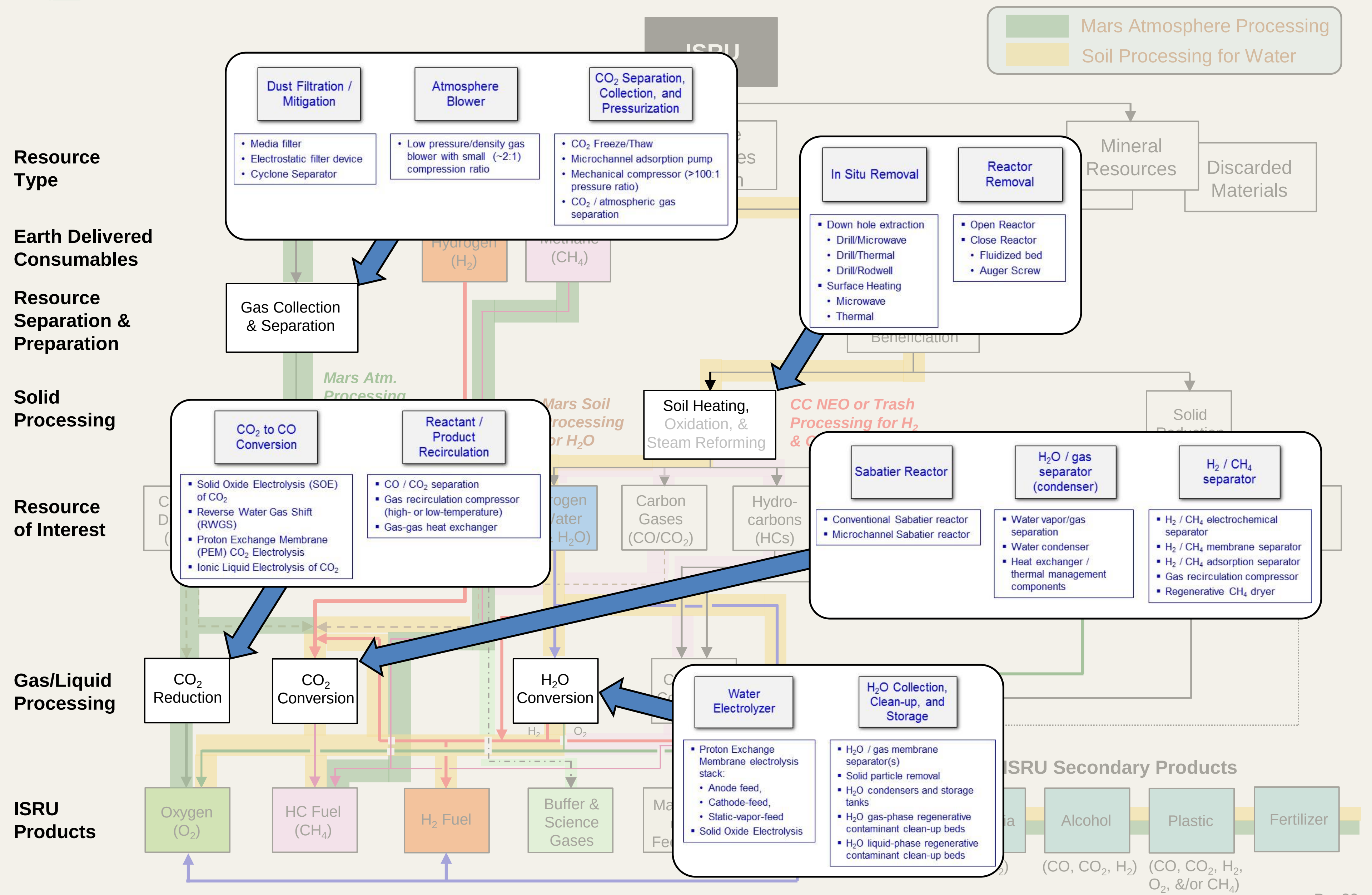


ISRU Consumables Production Decision Tree



ISRU Consumables Production Decision Tree

Each Decision Has Technical Solution Options



Space Resources Challenges

- **What resources exist at the site of exploration that can be used?**
  - Oxygen and metals from regolith/soils
  - Water/Ice
  - Atmospheres & volatiles
  - Thermal environments
  - Sunlight
  - Shielding: Lava tubes, regolith, water, hills/craters
- **What are the Uncertainties associated with the Resources?**
  - Polar volatiles:
    - **Where is it**, What is there, how is it distributed, terrain and environment, contaminants?
  - Mars water/ice in soil
    - What form is the water (ice, mineral-bound), how is it distributed, terrain and environment, contaminants?
  - Near Earth Objects/Asteroids/Mars Moons
    - What is there, how is it distributed, environment, contaminants
    - Ability to revisit NEO of interest (time between missions)
    - What techniques are required for micro-g mining and material processing?
- **Planetary Protection - Mars**
  - Forward contamination prevention
  - Avoid Special Regions and preventing creation of Special Regions during extraction and processing to extract water
  - Use of biological ISRU processes

❖ Good simulants are needed for development

ISRU Technical Challenges

- **Is it Technically feasible to collect, extract, and process the Resource?**
  - Energy: Amount and type (especially for polar resources in shadowed regions); ISRU processing thermal energy recovery and reuse
  - Life: High temperatures, process thermal cycling, reactive/caustic reagents, reactive/caustic contaminants in resources, abrasive regolith/cutting edge wear,
  - Performance: Catalyst/biological process degradation, reactant/product losses, separation losses
  - Amount of new technology required

- **Long-duration, autonomous operation and failure recovery**
  - Significant time delays in communication can prevent real-time operation:
  - Non-continuous communication/monitoring from Earth

- **High reliability and minimum (zero) maintenance**
  - No (or minimal) maintenance capability for pre-deployed and robotic mission applications
  - Networking/processing strategies (idle redundancy vs over-production/degraded performance)
  - Develop highly reliable thermal/mechanical cycle units (valves, pumps, heat exchangers, etc.)
  - Develop highly reliable, autonomous calibration control hardware (sensors, flowmeters, etc.)

ISRU Integration Challenges

- **Integration Challenges with other Exploration Systems**
  - Exploration systems must be designed to utilize ISRU provided products from the start;
    - Self-reliance vs reliance on ISRU (external to normal system boundaries)
    - Eliminate need to redesign and requalify hardware and mission elements (ex. landers with different propulsion systems or reusable vs throw-away)
  - Optimize at spacecraft/architecture level vs individual system level
    - May cause selection of different technologies/approaches than for original individual system (ex. water electrolysis for ISRU, power, and life support)
  - Physical integration/incorporation of multiple systems
    - Interfaces and standards
    - Connections for different applications (ex. trash processing providing propellants for propulsion requires connection into existing propulsion system or separate propulsion system)

Key Programmatic Questions for Space Resources

- **How do Space Resources support the Goals/Objectives of human exploration?**
  - Science & Technology, Extending Human Frontiers, Economic Expansion, Global Partnerships, Inspiration and Education
  - Affordability and Sustainability
  - Strategic, Industrial (spin-in/spin-off), Environmental
- **What are the early Priorities for Space Resource Development & Implementation for human exploration beyond Earth orbit?**
  - Crew: life support, radiation protection, habitats
  - Transportation: propellants, depots, landing pads/berms
  - Energy: solar array fabrication, thermal storage and use
- **What is needed to insert Space Resources into human exploration plans?**
  - Quantify return on investment in mass, cost, and risk compared to missions without use of space resources
  - Tie other system development and implementation to ISRU products
  - Define architectures enabled or significantly enhanced with space resources
  - Demonstrate, Demonstrate, Demonstrate in analogs and especially planetary surface missions
  - ➢ Space Resources need to be critical for human exploration mission success

Key Commercial Questions for Space Resources

- **Are there commercial markets besides government space exploration?**
  - Cis-lunar space transportation system
  - Satellite refueling/delivery
  - Space tourism and settlement
  - Mining for space and Earth applications
  - Space-based solar power
  - ???
- **How can Governments promote commercial space resource utilization development and implementation?**
  - Government sharing /partnering on data and technology development
  - Plan for on-ramps or transition to commercial activities in government funded space exploration
  - Buy services/products (don't worry about how it is accomplished)
  - Space treaty; favorable legislation and regulations
  - Prizes
- **What is the best balance between government and commercial development of space resource utilization?**
  - Government to provide data and technology that can be used by commercial enterprises as well as by researchers
- **What is the best balance between space agency partnerships/bartering and commercial development of space resource utilization?**
  - Minimize bartering when product/service can be provided by a commercial entity

Key Considerations in Pursuing Terrestrial or Space Mining

Consideration	Description	Current Similarities/Differences
Equipment Requirements	Mass, complexity, and scale required for resource extraction, transfer, and processing	▪ Mass in not as important for terrestrial mining. ▪ Scale of space mining currently significantly smaller ▪ Minimizing complexity is important for both
Infrastructure Requirements	Support capabilities necessary for comm., nav., power, maintenance, personnel, and operations	▪ Minimizing infrastructure needs and time to establish infrastructure capabilities are critical for both ▪ Similar power, communication, and personnel needs
Energy Required	Type and amount of energy necessary for extraction & processing	▪ Energy efficiency more important for space mining ▪ Solar/renewable energy/power systems are more important for space mining
Transportation	Type, capability, frequency, and cost of transportation required to support operations and to ship products	▪ Minimizing transportation is important to both ▪ Shipment of cryogenic products more difficult than water or minerals
Location & Environment Adaptability	Adaptability of existing equipment and infrastructure to extreme temperatures and remote locations	▪ Adapting and operating in extreme temperature and abrasive environments is important to both ▪ Space mining has more extreme environments
Level of Autonomy Needed	Ability of equipment to function/operate with minimal or no oversight	▪ Tele-operation capabilities important to both ▪ Autonomy more important for space mining due to limited crew availability & communication time delays
Maintenance & Logistics Requirements	Level of equipment degradation/failure expected; Spares and personnel availability	▪ Minimizing logistics/spares is important to both for remote locations ▪ Minimizing maintenance more important for space mining due to limited crew availability
Environmental Impact & Regulations	Immediate and long-term impact on local environment; Regulations and restrictions on processing & operations	▪ Environmental impact, regulations, and restrictions are more important to terrestrial mining ▪ Planetary Protection rules unique to Space Mining

Similar Needs for Terrestrial & Space Mining

Resource Prospecting

- Physical & Mineral Characterization Instrument Types
  - LIBS
  - GPR
  - Raman/IR
  - XRD/XRF
  - Hyperspectral
  - Shear Vane/Cone Penetrometer
- Miniaturization and Ruggedness of Instruments
- Data Integration, Display, and Analysis of Resources

Mining

- Mine Operation Planning Tools
- Mining Technologies
  - Excavation
  - Drilling
  - Consolidated Material Cutting/ Fracturing
  - Crushing/Sorting
  - Mineral Beneficiation
  - Transport
- Environmental Compatibility
  - Design for Thermal Extremes
  - Material Selection
  - Lubricants
  - Wear Resistant Coatings
- Equipment Testing Under Realistic Conditions
  - Soil Bins/Controlled Testing
  - Analog Test Sites/In-Mine Testing
  - Environmental Simulation Facilities
  - Actual or Simulated Materials (Simulants)

Processing

- Atmosphere Collection
  - Gas Compression
  - Atmosphere Filtration
- Chemical Processing
  - Hydrogen Production
  - Syngas Production and Conversion
  - CO/CO_2 Conversion to Fuel and Plastics
- Solids Processing
  - Granular Material Drying
  - Wear-Resistant Valves
- Metal Extraction (Oxygen Release)
  - Mineral Electrolysis
  - Acid Extraction
  - Biological Extraction

Remote Operations

- Mining Tele-operations
  - Approaches and Human Interfaces
  - Same as Mining Autonomy
- Mining Autonomy
  - Approaches
  - Avionics, Software, Instruments, Sensors, & Cameras Needed
  - Communications Infrastructure: Wireless, Bandwidth, Delays

Product Storage and Transfer

- Liquefaction for Oxygen and Hydrogen

Space Mining Needs

- Low Mass
- High Levels of Autonomy
- Low Maintenance/Long Life
- Modular, Multi-Mission Infrastructure
  - Plug-and-Play
- High Density/Regenerable Energy - All Electric
  - Electro-Mechanical Actuators vs Hydraulics
  - Fuel Cells/Batteries vs Combustion Engines