Space Resources Utilization:
Technologies and Potential Synergy with Terrestrial Mining & Construction

Presentation for the
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Gerald (Jerry) Sanders
ISRU Chief Engineer
NASA/Johnson Space Center, Houston, TX, 77058 USA
gerald.b.sanders@nasa.gov

What are Space Resources?

- **'Resources'**
  - Traditional**:** **Water**, atmospheric gases, volatiles, solar wind volatiles, metals, etc.
  - Non-traditional: Trash and wastes from crew, spent landers and residuals, etc.
- **Energy**
  - 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
  - High Thermal Gradients
- **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.

Natural Space Resources

Four major resources on the Moon:

- **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)
- Discarded materials: **Lander and crew trash and residuals**

Three major resources on Mars:

- **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 Interest

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

~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 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)

Vision for Using Space Resources

Vision for Using Space Resources

Resource Prospecting
- Lunar Ice/Volatiles
- Mars Water
- Minerals/Metals
- Near Earth Asteroids

Resource Acquisition
- Extraction, Excavation, Transfer
- Beneficiation/Size Sorting
- Gases and Liquids

Consumable Production
- Propellants
- Life Support
- Fuel Cell Reactants
- Metal Feedstock
- Plastic Feedstock

Civil Engineering & Construction
- Civil Engineering:
- Landing Pads, Roads, Berms
- Habitats

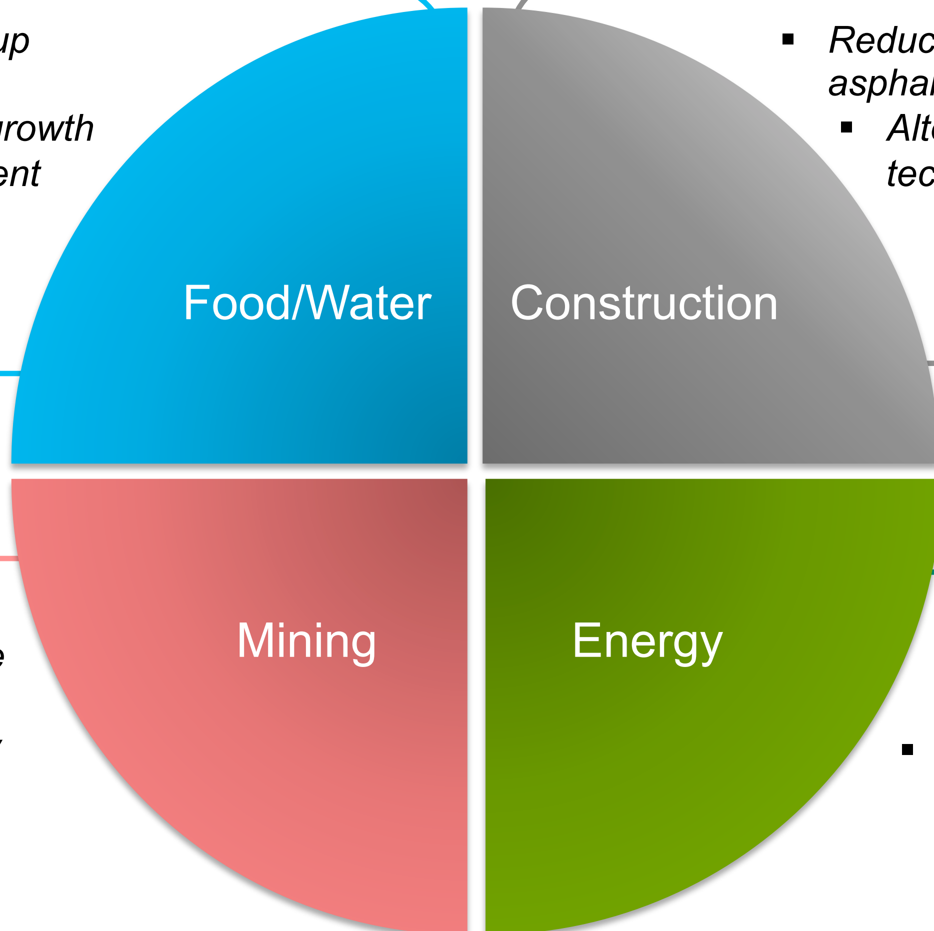
Manufacturing
- Parts
- Trusses & Structural Components
- Electronics
- Assemblies

Energy
- Thermal Storage
- Solar Array Production
- Space-based Solar Power Beaming
- Helium-3 Mining

Space Resource Utilization Is Synergistic with Terrestrial Needs

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

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

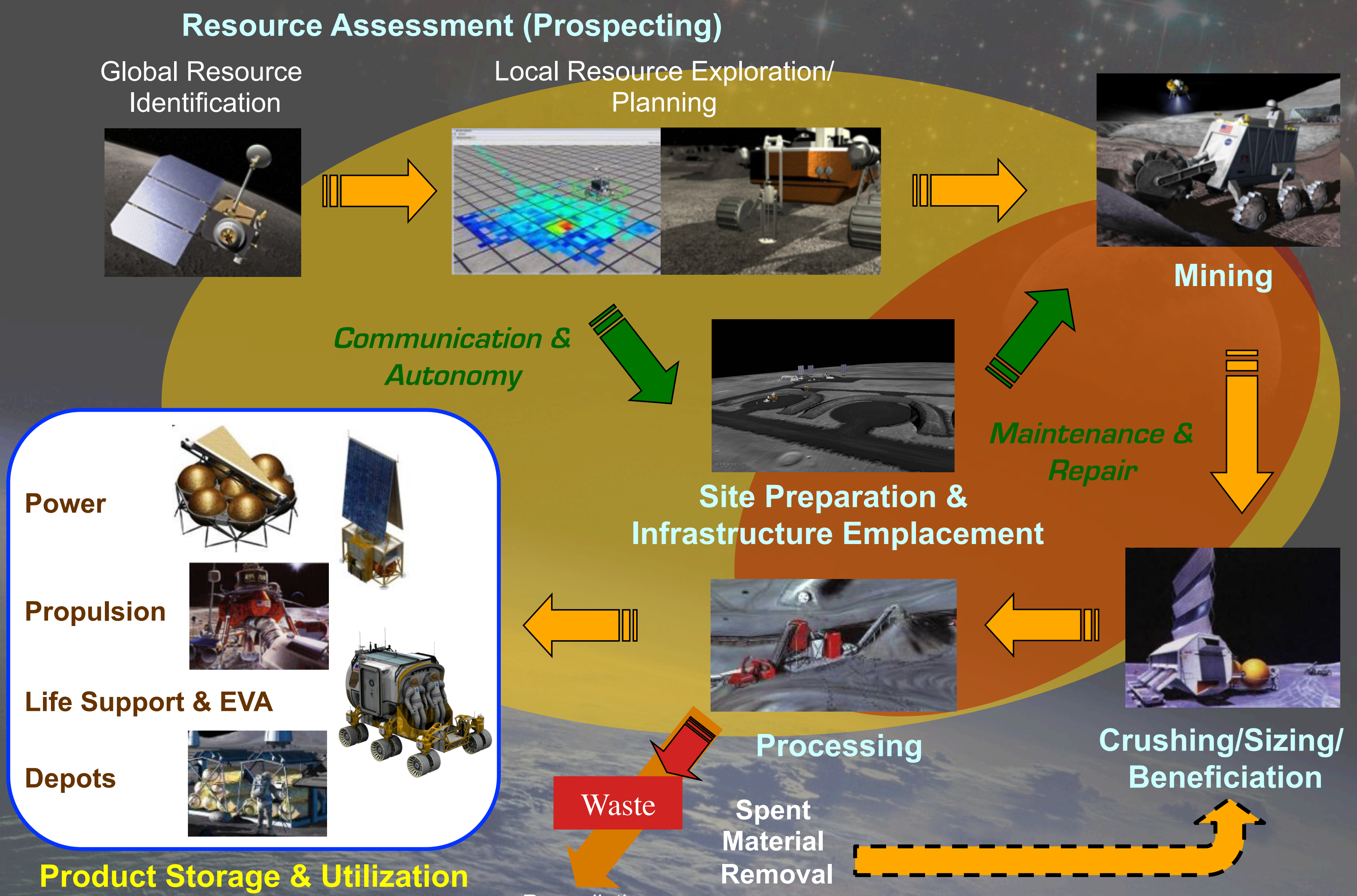


- *Increase safety*
- *Reduce maintenance*
- *Increase prospecting and mining efficiency*

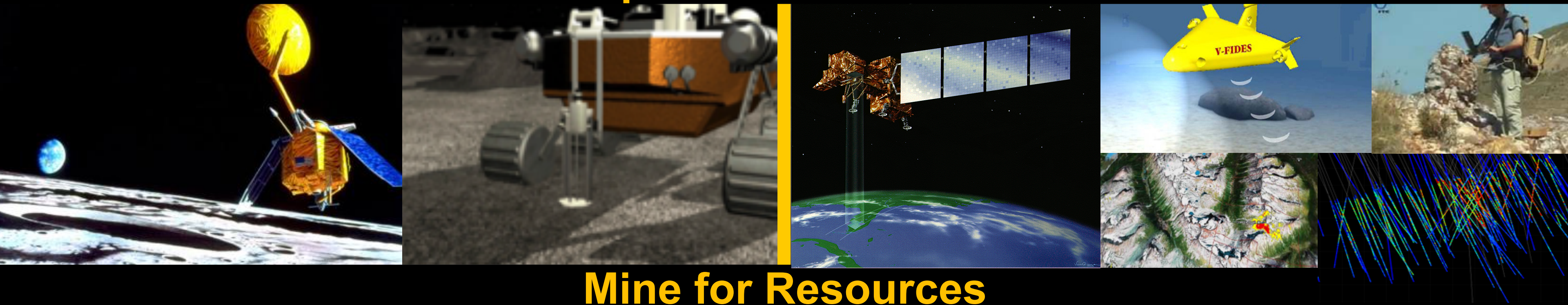
- *More efficient power generation, storage and distribution*
- *Reduce or eliminate petroleum/gas usage – Use sun, thermal, trash, and alternative fuel production*

Promote *Reduce, Reuse, Recycle, Repair, Reclamation*
***…*for benefit of Earth, and living in Space.**

Space 'Mining' Cycle: *Prospect to Product*



Prospect for Resources

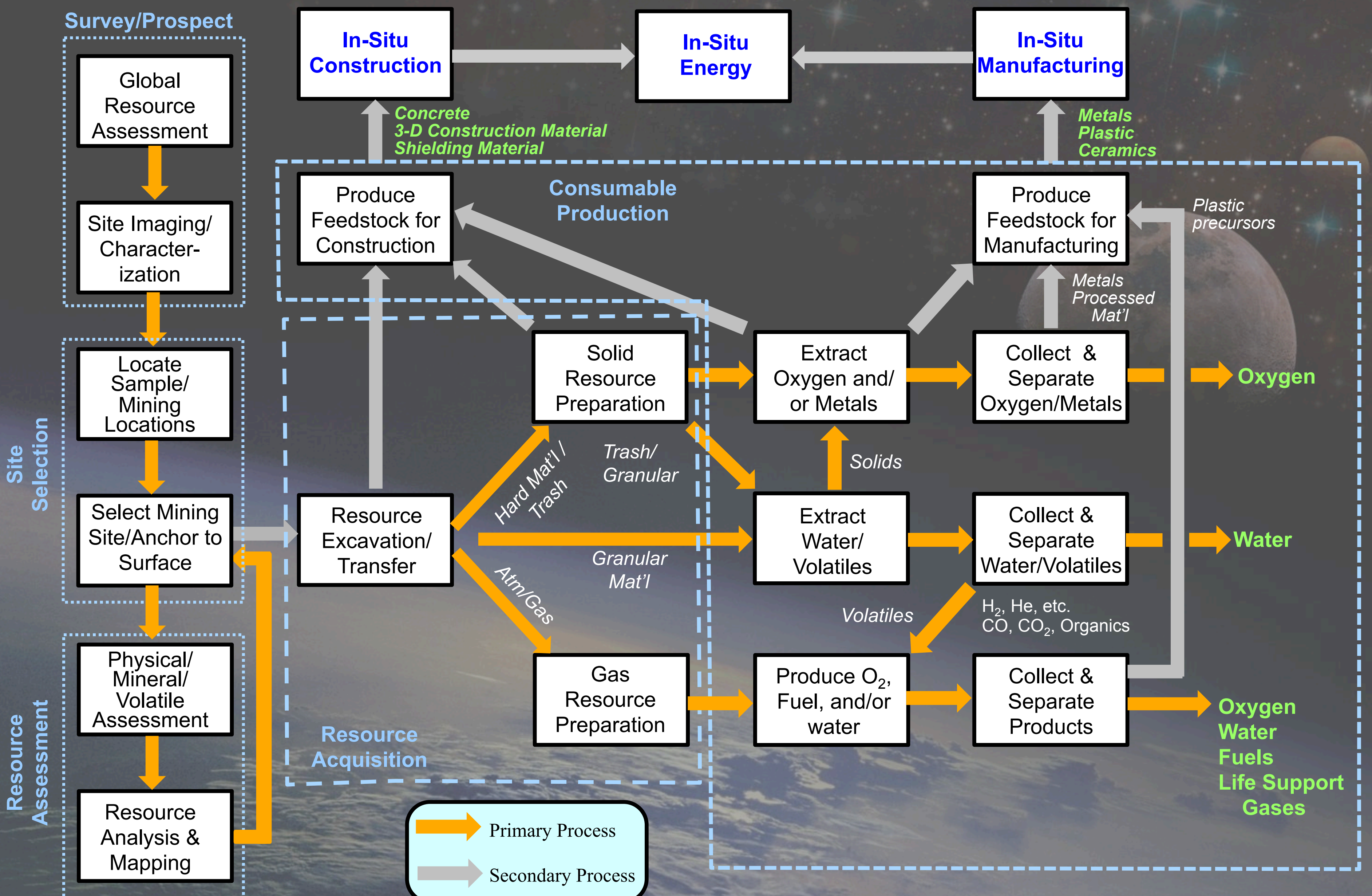


Mine for Resources

Resource Processing

Remote Operation & Maintenance

ISRU Capability-Function Flow Chart



Space Resource Challenges

- **What resources exist 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
  - Preventing creation of 'Special Regions' during extraction and processing to extract water

❖ 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)
  - Life, maintenance, performance
  - Amount of new technology required
- **Long-duration, autonomous operation**
  - Autonomous control & failure recovery
  - No crew for maintenance; Non-continuous 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 Operation & Integration Challenges (1)

- **Operation in severe environments**
  - Radiation
  - Efficient excavation of resources in dusty/abrasive environments
  - Methods to mitigate dust/filtration for sustained operations
- **Operation in low/micro-gravity**
  - Low-gravity on Moon/Mars
    - Low reaction force excavation in reduced and micro-gravity
    - Liquid slosh is amplified
    - Kicking up dust is amplified
    - Dynamics like walking are in slow motion (fall time to ground between steps is longer)
    - Rotational inertia is not reduced, but gravity to resist tipping is reduced!
  - Micro-g environment for asteroids and Phobos/Deimos
    - Anchoring/weight-on-bit
    - Material handling and transport
    - Material separation
    - Friction, cohesion, and electrostatic forces may dominate in micro-g

ISRU Operation & Integration Challenges (2)

- **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

Common Challenges with Terrestrial Mining









Severe Environments

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

Maintenance

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

Operation

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

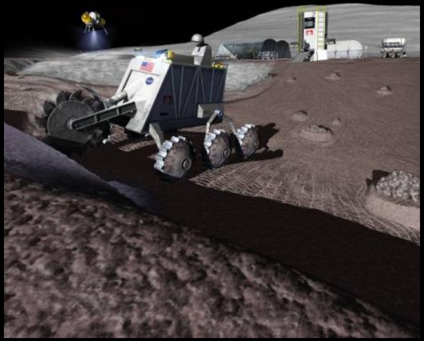
Integration

- Hardware from multiple countries must be compatible with each other
- Common standards; Common interface

Return on Investment

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

Space Mining & Construction . . .



Excavation & Material Processing

Surface & Subsurface Evaluation

Landing Pads & Roads

Autonomous & Tele-operation

3-D Printing

Combustion Synthesis

Waterless Concrete

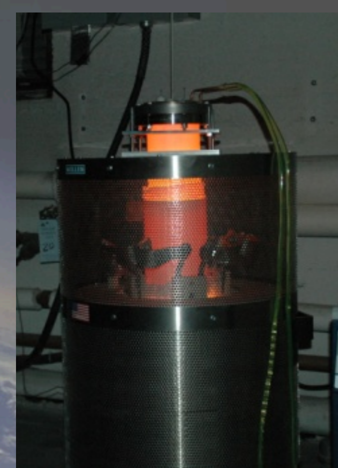
Gerald. B Sanders/JSC, gerald.b.sanders@nasa.gov

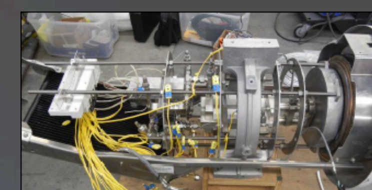
. . . Can Benefit Terrestrial Mining and Construction

Innovative Building Construction

Autonomous & Tele-operation

Innovative Construction Materials





Longer Life, More Efficient Chemical & Mineral Processing

Robotic Mining Challenges

Competitions

- Three Centennial Excavation Challenge Competitions (2007, 2008 and 2009) open to all; $500,000 award
- Five Lunabotics/Robotic Mining Competitions (2010 - 2014) – open to universities
- Rules aimed at addressing challenges for extraterrestrial mining: autonomy, low mass, low power

Challenges addressed by competition:

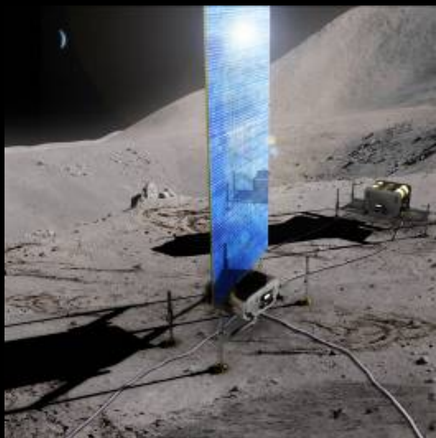
- Object Recognition and Pose Estimation
- Fusing vision, tactile and force control for manipulation
- Achieving human-like performance for piloting vehicles
- Full immersion, telepresence with haptic and multi modal sensor feedback
- Understanding and expressing intent between humans and robots
- Verification of Autonomous Systems
- Supervised autonomy of force/contact tasks across time delay
- Rendezvous, proximity operations and docking
- Mobile manipulation that is safe for working with and near humans

Benefit to NASA

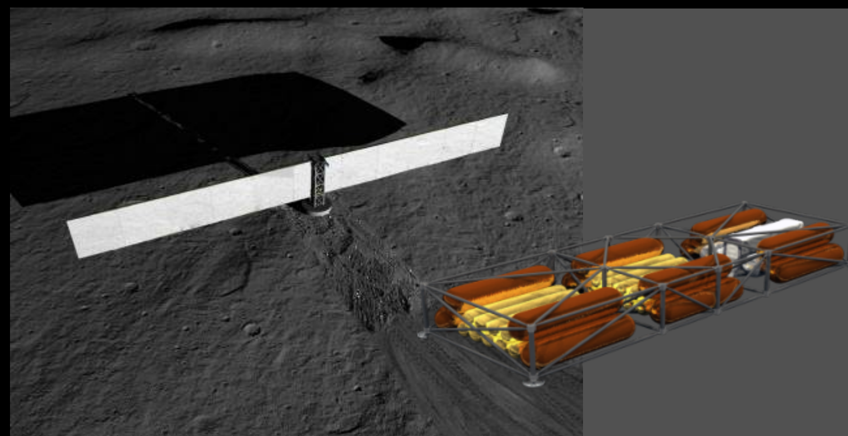
- Examination of large number of mobility/traction and excavation devices
- Out of the box thinking

Space Power Systems and Energy Management . . .

Space Resource Utilization Needs Lots of Energy . . .



Solar

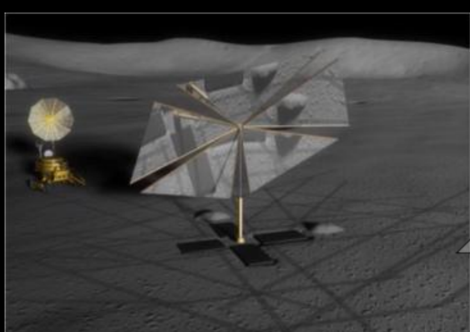


Nuclear

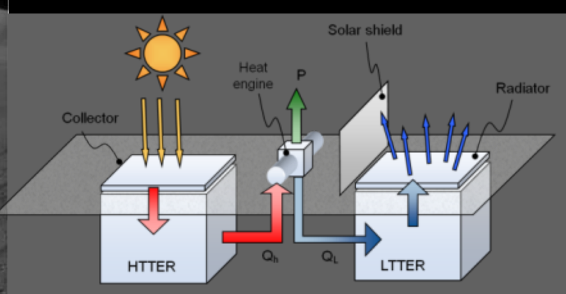
Fuel Cell & Battery

Power Beaming

Using Space Resources Can Help Produce Energy. . .

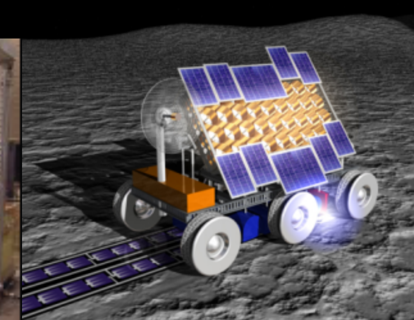


Thermal Storage



Thermal Difference

Resource/Trash to Fuel

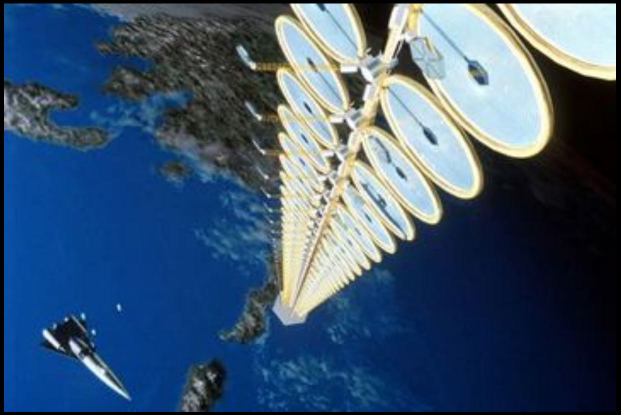


In-Situ Solar Production

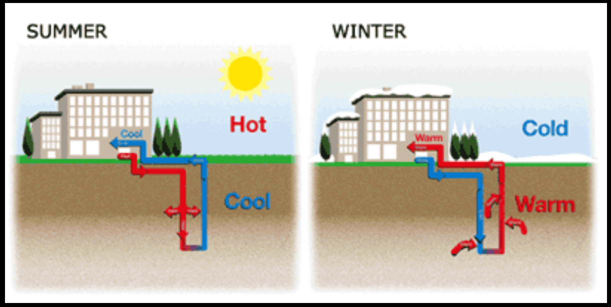
. . . Can Benefit Terrestrial Power Systems & Energy Management

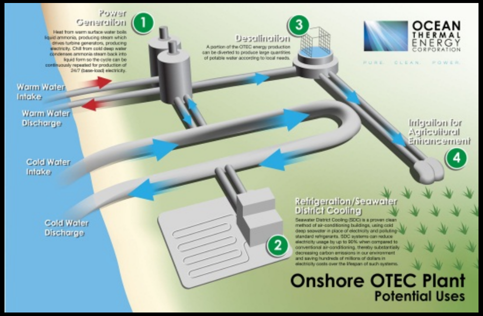
Solar

Fuel Cell & Battery



Power Beaming





Thermal Storage & Thermal Difference

Resource/Trash to Fuel

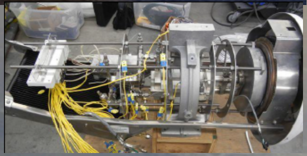
Common Needs Can Lead To Shared Solutions

Energy

Fuel Cell Technology and Applications to Reduce Emissions

Mine Safety

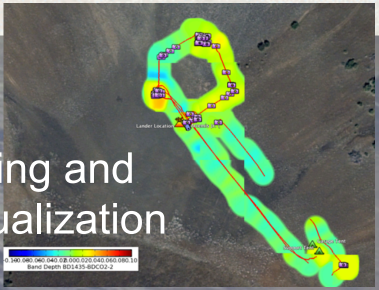
Safe Haven and Rescue Suits based on NASA Life Support and EVA Technology



Microchannel Processing for On-Location Gas-to-Liquid Conversion

Mining & Processing

Tele-Operation and Autonomous Operations



Prospecting and Data Visualization

Non-Eroding Electrodes

Dry Drilling

Economics of ISRU

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

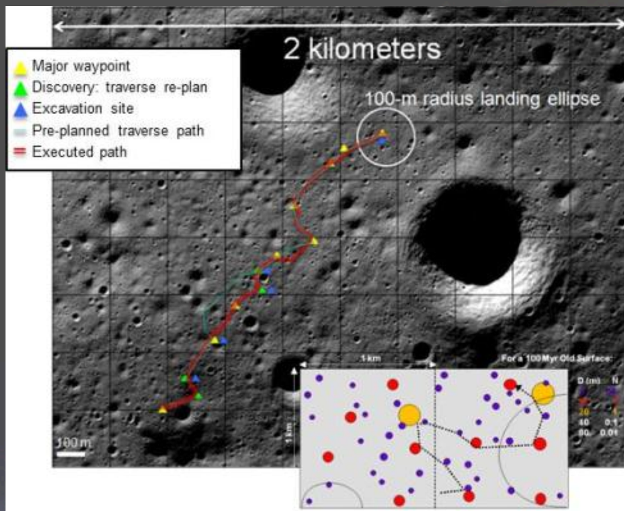
- **Location**
  - Resource must be assessable: slopes, rock distributions, surface characteristics, etc.
  - Resource must be within reasonable distance of mining infrastructure: power, logistics, maintenance, processing, storage, etc.
  - Resource must be within reasonable distance of transportation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

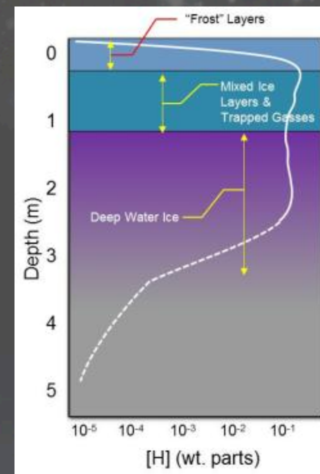
Economic Assessment

Need to assess the extent of the resource 'ore body'

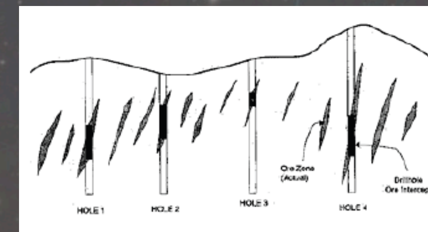
Need to Evaluate Local Region (1 to 3 km)



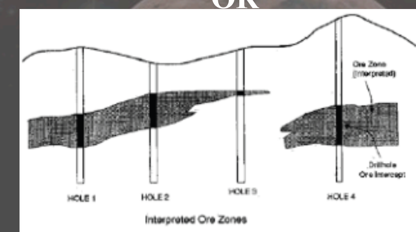
Need to Determine Vertical Profile



Need to Determine Distribution



OR



An 'Useful' Resource Depends on What is needed, How much is needed, How often it is needed, and What is required to extract the resource

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

Potential Lunar Resource Product Needs

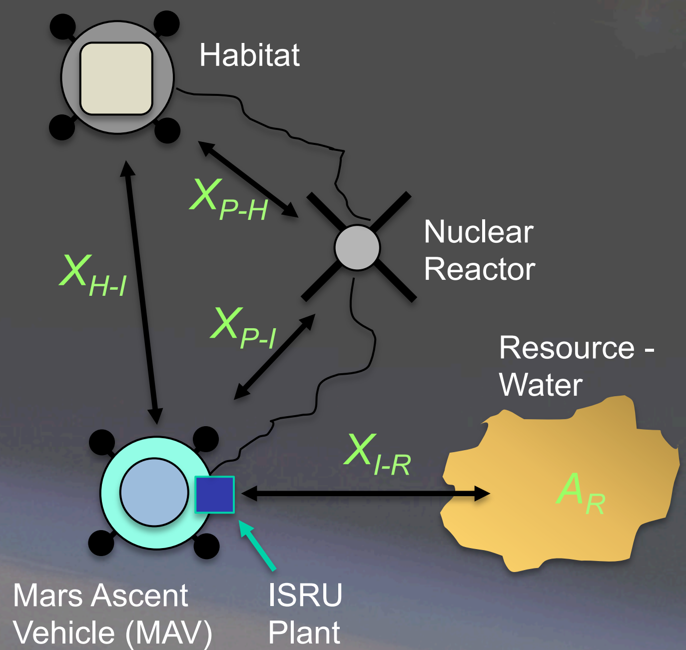
- 1,000 kg oxygen (O_2) per year for life support backup (crew of 4)
- 3,000 kg of O_2 per lunar ascent module launch from surface to L_1/L_2*
- 16,000 kg of O_2 per reusable lunar lander ascent/descent vehicle to L_1/L_2 (fuel from Earth)*
- 30,000 kg of O_2/Hydrogen (H_2) per reusable lunar lander to L_1/L_2 (no Earth fuel needed)*

Potential Mars Resource Product Needs

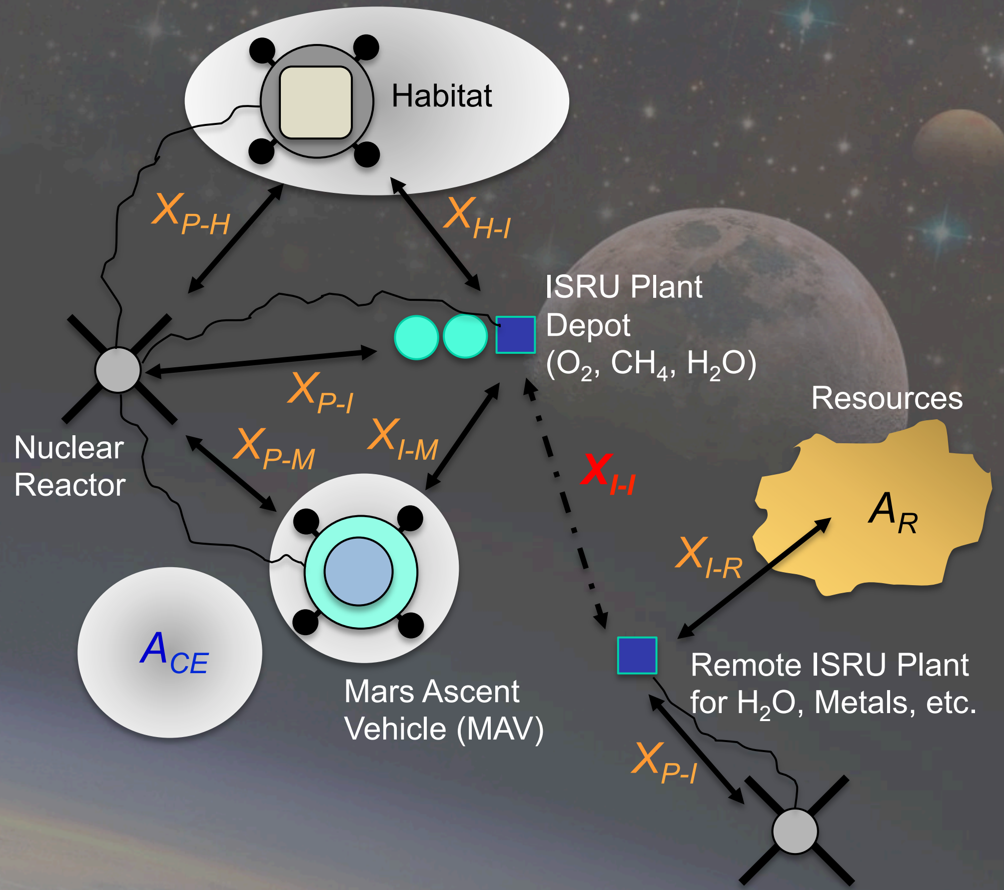
- 20,000 to 25,000 kg of oxygen (O_2) per ascent mission
- 5700 to 7150 kg of methane (CH_4) per ascent mission
- 14,200 kg of water (H_2O) per ascent mission

Emplacement and Mine Development Phasing

Emplacement Phase



Consolidation or Utilization Phase



X_{H-I} = distance between Habitat and ISRU Plant

X_{P-I} = distance between Power and ISRU Plant

X_{P-H} = distance between Power and Habitat

X_{I-R} = distance between ISRU Plant and Resource

A_R = Area of Resource

X_{I-M} = distance between ISRU Plant and MAV

X_{I-I} = distance between ISRU Plants

A_R = Area of Civil Engineering

Questions?

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

Common Space Resources Can Lead to Core Capabilities for All Destinations

Common Resources & Processes Support Multiple Mission Destinations

Possible Destinations

Habitats

Moon

Mars & Phobos

Near Earth Asteroids & Extinct Comets

Europa

Titan

Common Resources

Water
- Moon
- Mars
- Comets
- Asteroids
- Europa
- Titan
- Triton
- **Human Habitats**

Carbon
- Mars (atm)
- Asteroids
- Comets
- Titan
- **Human Habitats**

Metals & Oxides
- Moon
- Mars
- Asteroids

Helium-3
- Moon
- Jupiter
- Saturn
- Uranus
- Neptune

Core Building Blocks

- Atmosphere & Volatile Collection & Separation
- Regolith Processing to Extract O_2, Si, Metals
- Water & Carbon Dioxide Processing
- Fine-grained Regolith Excavation & Refining
- Drilling
- Volatile Extraction Ovens
- 0-g & Surface Cryogenic Liquefaction, Storage, & Transfer
- In-Situ Manufacturing

Core Technologies

- Microchannel Adsorption
- Constituent Freezing
- Molecular Sieves

- Carbothermal Reduction
- Ionic liquids
- Oxide Electrolysis

- Water Electrolysis
- CO_2 Electrolysis
- Sabatier Reactor
- RWGS Reactor
- Methane Reformer
- Microchannel Chem/ thermal units

- Scoopers/buckets
- Conveyors/augers
- Pneumatic transport
- Dry Drilling

- Thermal/Microwave Heaters
- Heat Exchangers
- Liquid Vaporizers

- O_2 & Fuel Low Heatleak Tanks (0-g & reduced-g)
- O_2 Feed & Transfer Lines
- O_2/Fuel Couplings

ISRU Technology Development Options

	Resource Prospecting (Moon, Mars, NEO)	Oxygen/Fuel from Mars Atmosphere	Water from Extraterrestrial Soils (Moon, Mars, NEO)	Oxygen/Metal from Soils (Moon, Mars, NEO)	Trash Processing for Fuel
Regolith-Soil Extraction					
Regolith (granular) Excavation & Transfer	X		X	X	
Hard Material Excavation & Transfer	P			P	P
Hydrated Soil /Material Excavation & Transfer	P		X	X	X
Icy-Soil Excavation & Transfer	X		X	X	
Resource Characterization					
Physical Property Evaluation	X				
Mineral/Chemical Evaluation	X			X	
Volatile-Product Analysis	X	X			X
Regolith-Soil Processing					
Crushing			P	X	P
Size Sorting				P	
Beneficiation/Mineral Seperation				P	
Solid/Gas Processing Reactor	X		X	X	X
Solid/Liquid Processing Reactor				P	
Volatile Cleanup			X	X	X
Extended Operation Power Systems			P	P	
Extended Operation Thermal Systems			P	P	
Gas Processing					
Dust/Particle Filtration		X	X	X	X
CO_2 Capture - Separation		X		P	X
CO_2 Conversion into CO-O_2		P			
CO_2 Conversion into H_2O-CH_4		P		P	X
H_2-CH_4 Separation		P		P	X
Water Processing					
Water Capture	X		X	X	X
Water Cleaup - Purity Measurment			X	X	X
Water Electrolysis		P	X	P	X
Regenerative Dryers		P	X	P	X

X = Needed; P = Possible Need

Technology Options

- Auger
- Pneumatic Transport
- Bucketwheel/Bucketdrum
- Scoop/Clamshell
- Percussive Scoop

- Auger
- Percussive Scoop

- Gas Chromatograph
- Mass Spec
- Laser Diode
- IR Spectrometer

- Fluidized Bed (with or w/o assisted mixing)
- Cyclone Reactor
- Rotating/Centrifugal Reactor
- Auger Reactor
- Ionic Liquid Reactor
- Carbothermal Reactor
- Molten/Molten-Salt Reactor
- Supercritical Water Reactor

Heating Method
- Resistive Heater
- Microwave
- Inductive Heating
- Solar

- Membrane Separator
- CO_2 Freezer Pump
- Rapid Cycle Adsorption Pump

- Solid Oxide Electrolysis
- Reverse Water Gas Shift

- Sabatier
- Ionic Liquid Reactor
- Electrochemical Reactor

- PEM-based Non-Flow Through
- Solid Oxide Electrolysis

- Freezing
- Adsorption

ISRU Development Areas vs Mission Applications

ISRU Development Areas	Resource Prospector (Moon, Mars, NEO)	Atmosphere Processing (Mars)	Regolith/Soil Processing for Water (Moon, Mars, NEO)	Material Processing for Oxygen/Metals (Moon, NEO)	Trash Processing to Fuel
Regolith-Soil Extraction					
Regolith (granular) Excavation & Transfer	X		X	X	
Hard Material Excavation & Transfer	P			P	P
Hydrated Soil /Material Excavation & Transfer	P		X	X	X
Icy-Soil Excavation & Transfer	X		X	X	
Resource Characterization					
Physical Property Evaluation	X				
Mineral/Chemical Evaluation	X			X	
Volatile-Product Analysis	X	X			X
Regolith-Soil Processing (Volatiles, O_2, Metal)					
Crushing			P	X	P
Size Sorting				P	
Beneficiation/Mineral Seperation				P	
Solid/Gas Processing Reactor	X		X	X	X
Solid/Liquid Processing Reactor				P	
Contaminant Removal			X	X	X

ISRU Development Areas	Resource Prospector (Moon, Mars, NEO)	Atmosphere Processing (Mars)	Regolith/Soil Processing for Water (Moon, Mars, NEO)	Material Processing for Oxygen/Metals (Moon, NEO)	Trash Processing to Fuel
Gas Processing					
Dust/Particle Filtration		X	X	X	X
CO_2 Capture - Separation		X		P	X
CO_2 Conversion into CO-O_2		P			
CO/CO_2 Conversion into H_2O-CH_4		P		P	X
H_2-CH_4 Separation		P		P	X
Water Processing					
Water Capture	X		X	X	X
Water Cleaup - Purity Measurment			X	X	X
Water Electrolysis		P	X	P	X
Regenerative Dryers		P	X	P	X
Support Systems					
Extended Operation Power Systems			P	P	
Extended Operation Thermal Systems			P	P	
Cryogenic Liquefaction, Storage, and Transfer					

P = Possible need

Main Discriminators: material (physical, mineral) water content/form (ice, hydration, surface tension), gravity (micro, low), pressure, (vacuum, atm.), and weathering

Gerald. B Sanders/JSC, gerald.b.sanders@nasa.gov