SPACE RESOURCE UTILIZATION: TECHNOLOGIES AND POTENTIAL SYNERGISM WITH TERRESTRIAL MINING, Gerald B. Sanders, NASA Johnson Space Center, Mail Code EP3, Houston, TX. 77058, gerald.b.sanders@nasa.gov

Space Resources and Their Uses: The idea of using resources in space to support human exploration and settlement or for economic development and profit beyond the surface of Earth has been proposed and discussed for decades. Work on developing a method to extract oxygen from lunar regolith started even before humans set foot on the Moon for the first time. The use of space resources, commonly referred to as *In Situ* Resource Utilization (ISRU), involves the processes and operations to harness and utilize resources in space (both natural and discarded) to create products for subsequent use. Potential space resources include water, solar wind implanted volatiles (hydrogen, helium, carbon, nitrogen, etc.), vast quantities of metals and minerals in extraterrestrial soils, atmospheric constituents, unlimited solar energy, regions of permanent light and darkness, the vacuum and zero-gravity of space itself, trash and waste from human crew activities, and discarded hardware that has completed its primary purpose. ISRU covers a wide variety of concepts, technical disciplines, technologies, and processes. When considering all aspects of ISRU, there are 5 main areas that are relevant to human space exploration and the commercialization of space: 1. Resource Characterization and Mapping, 2. *In Situ* Consumables Production, 3. Civil Engineering and Construction, 4. *In Situ* Energy Production and Storage, and 5. *In Situ* Manufacturing.

ISRU & Terrestrial Mining: There are four areas where development and utilization of space resources is highly synergistic with terrestrial needs: Food/Water Production, Mining, Construction, and Energy. When considering space resources, especially the areas of mining and processing of resources into usable commodities, ISRU developers have adopted and modified terrestrial approaches to come up with the Space Mining Cycle, or ‘Prospect to Product’. For both space and terrestrial mining, the first step is prospecting; first globally and then locally to find and characterize (physical, mineral, and volatile) the resources that exist, as well as the terrain and the geological context in which the resource is found. Once the resource has been sufficiently characterized and mapped, mining and resource processing can be begin. As with terrestrial mining, subscale feasibility and pilot operations are performed to verify that the resource can be extracted, that performance and maintenance goals can be achieved, and that the product meets quality expectations.

In the last two years, NASA has focused on developing and implementing a sustainable human space exploration program with the ultimate goal of exploring the surface of Mars with humans. The plan involves developing technology and capability building blocks critical for sustained exploration, such as ISRU. The evolvable plan develops and expands human exploration in phases starting with missions that are reliant on Earth, to performing ever more challenging and longer duration missions in cis-lunar space and beyond, to eventually being independent from Earth. As these missions progress, human presence will also evolve from a few days, to weeks and months, to semi and permanent presence in space. Because the crew may not be present during space mining operations, or because ISRU products may need to be produced before the crew arrives to reduce mission risk, reliable communication for remote operations, autonomy, and high reliability are extremely important for ISRU to be successful incorporated into human mission plans.

ISRU & Terrestrial Mining Challenges: When considering the implementation of space resource utilization into plans for the human exploration of space, there are three primary challenges: space resource challenges, ISRU technical challenges, and operation and integration challenges. Even though NASA has sent robotic probes to the Moon, Mars, and asteroids, and astronauts have returned samples from the Moon, there are still significant challenges associated with using space resources. What resources exist at the destination of interest, what are the uncertainties associated with the known resources that could cause problems, and what are the variations in resources that might be encountered? As in terrestrial mining, robotic and human prospecting will be required. Since the extraction and processing of resources in space has never been demonstrated, technical challenges exist that must be overcome. Is it technically feasible to collect, extract, and process the resource present? Is it possible to operate continuously for long periods of time with limited involvement from the crew or Earth for control and maintenance? Finally, to achieve the full benefits of extracting and using space resources, ISRU operations must be performed in severe environments (radiation, abrasive dust, and low or micro-gravity conditions), and other systems must be designed to accept products from ISRU operations. This is particularly challenging for space applications since NASA will be working with space agencies around the world. Therefore, product quality, common standards, and common interfaces will need to be defined and implemented. As with terrestrial mining, ISRU must provide a return on investment with respect to mass, cost, and risk reductions compared to missions that do not include ISRU. The return on investment will be significantly affected by how much and how often space resource products are used, and by what missions or exploration activities are enabled with these products that could not otherwise be achieved.

ISRU & Terrestrial Mining Common Areas of Interest: While space and terrestrial mining might seem worlds apart, the fact that both have common challenges means that both can have common interests and solutions. The list below is not meant to be all inclusive but to highlight some of the most obvious areas of common interest between space and terrestrial mining so that further discussions can delve deeper and expand the list.

Remote/Autonomous Operations. As easily assessable resources become harder and harder to find, terrestrial mining has had to venture into more remote and hostile environments (artic, underwater, deeper). As this occurs, the cost and safety of personnel involvement increases to the extent that remote and autonomous operations become economical. Because astronaut time is valuable and limited, remote and autonomous operation of ISRU is required.

Regenerative 'Green' Power. All space operations are limited due to two things: propulsion (transportation) and power availability. As the high cost and particulate concerns associated with diesel fuel, terrestrial mining will need to incorporate more environmentally friendly and renewable energy solutions. Both regenerative/hydrocarbon fuel cells and collection and conversion of carbon dioxide are critical to both the space and mining industries

Dust Mitigation/Severe Environment Operation. As stated under Remote/Autonomous Operations, terrestrial mining is venturing into more remote and hostile environments. Mining in space requires the ability to potentially encounter and handle extreme temperatures as well as temperature swings, the vacuum of space, and severe radiation. Even worse, since space soils, or regolith, are not exposed to wind and rain weathering conditions on Earth, the dust is extremely fine, sharp, hard, and abrasive. Lubricants are difficult to incorporate into space hardware that must operate continuously for long periods of time, so dust mitigation for mining, power systems, and crew operations is critical.

High Reliability/High Performance. To provide a return on investment for space mining, the infrastructure required for prospecting, excavation, extraction/processing, product storage, and power needs to be compared to just brining the product in the first place. Therefore, the more efficient the end-to-end process, the faster/greater return on investment.

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

Presentation for the Planetary & Terrestrial Mining Sciences Symposium (PTMSS)

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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.

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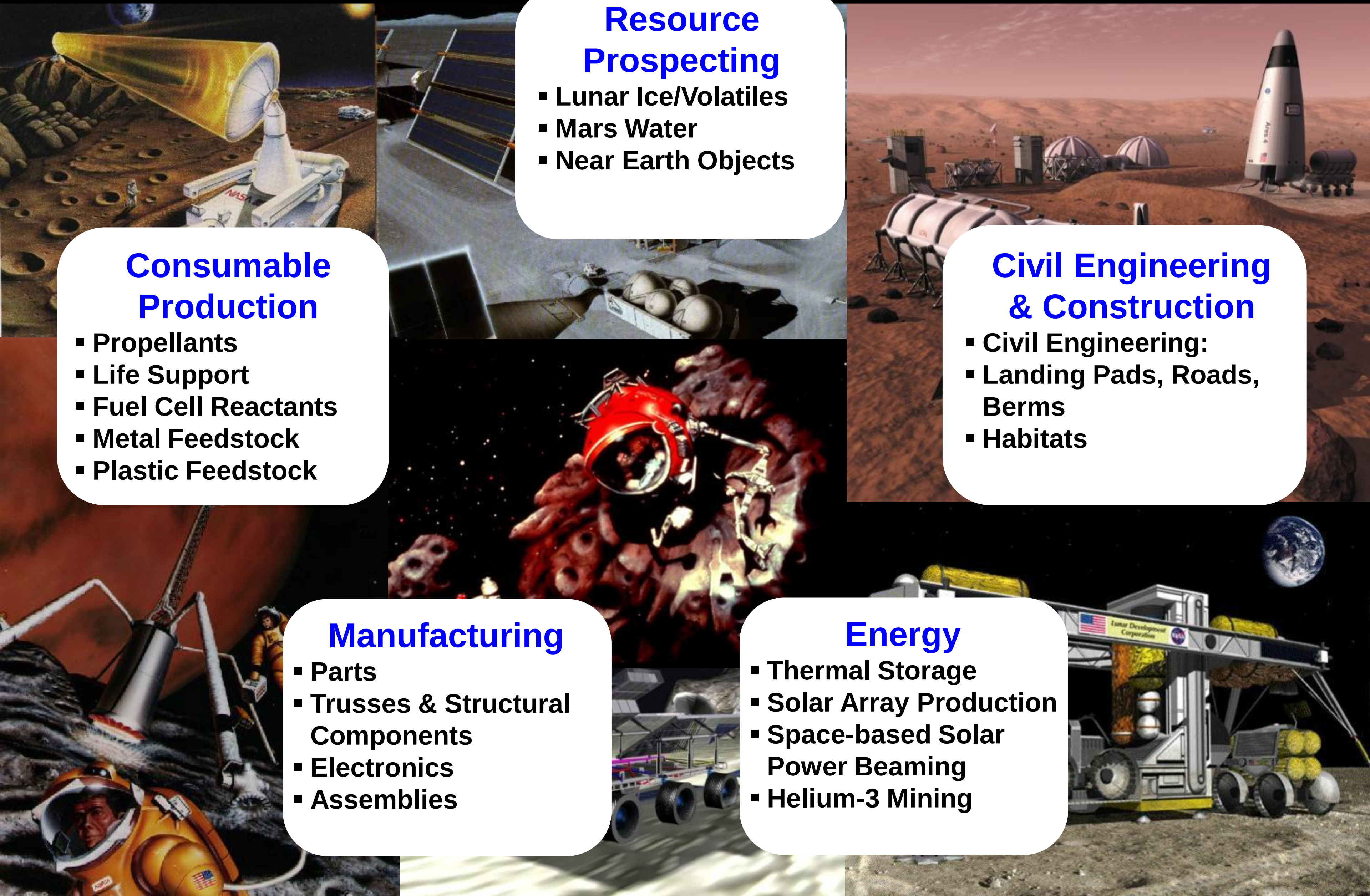
Vision for Using Space Resources

Vision for Using Space Resources



Resource Prospecting
- Lunar Ice/Volatiles
- Mars Water
- Near Earth Objects

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

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

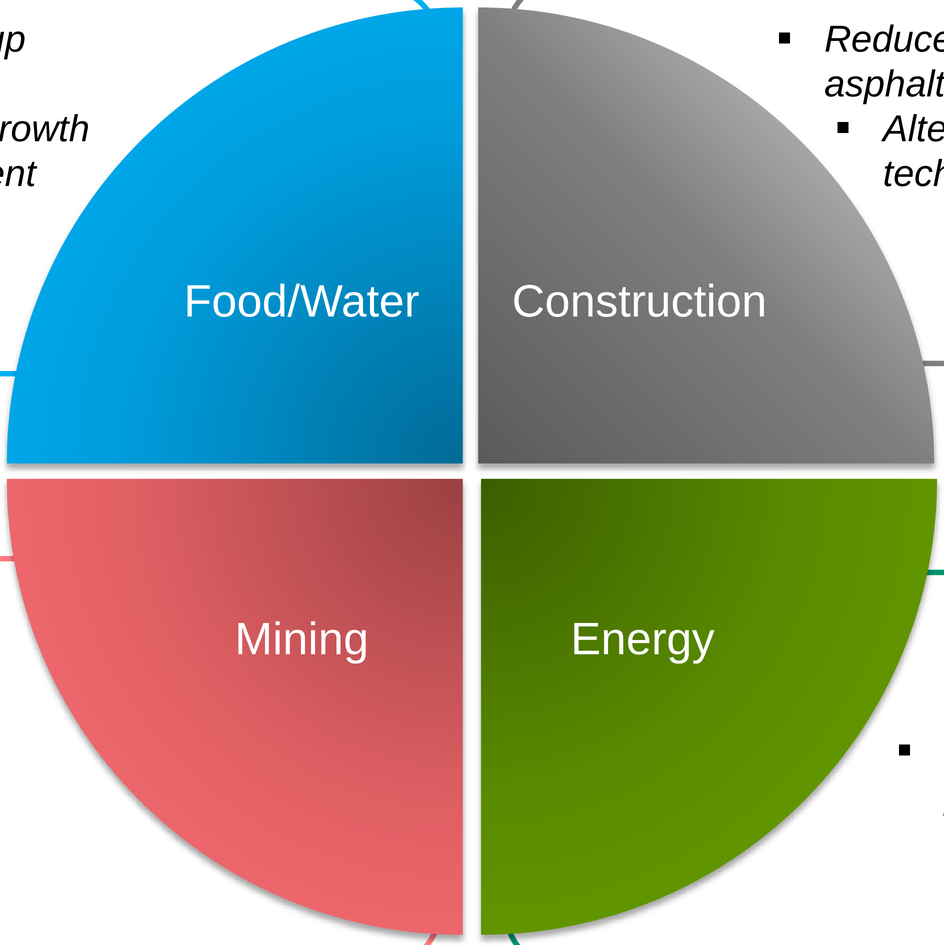
Manufacturing
- Parts
- Trusses & Structural Components
- Electronics
- Assemblies

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*

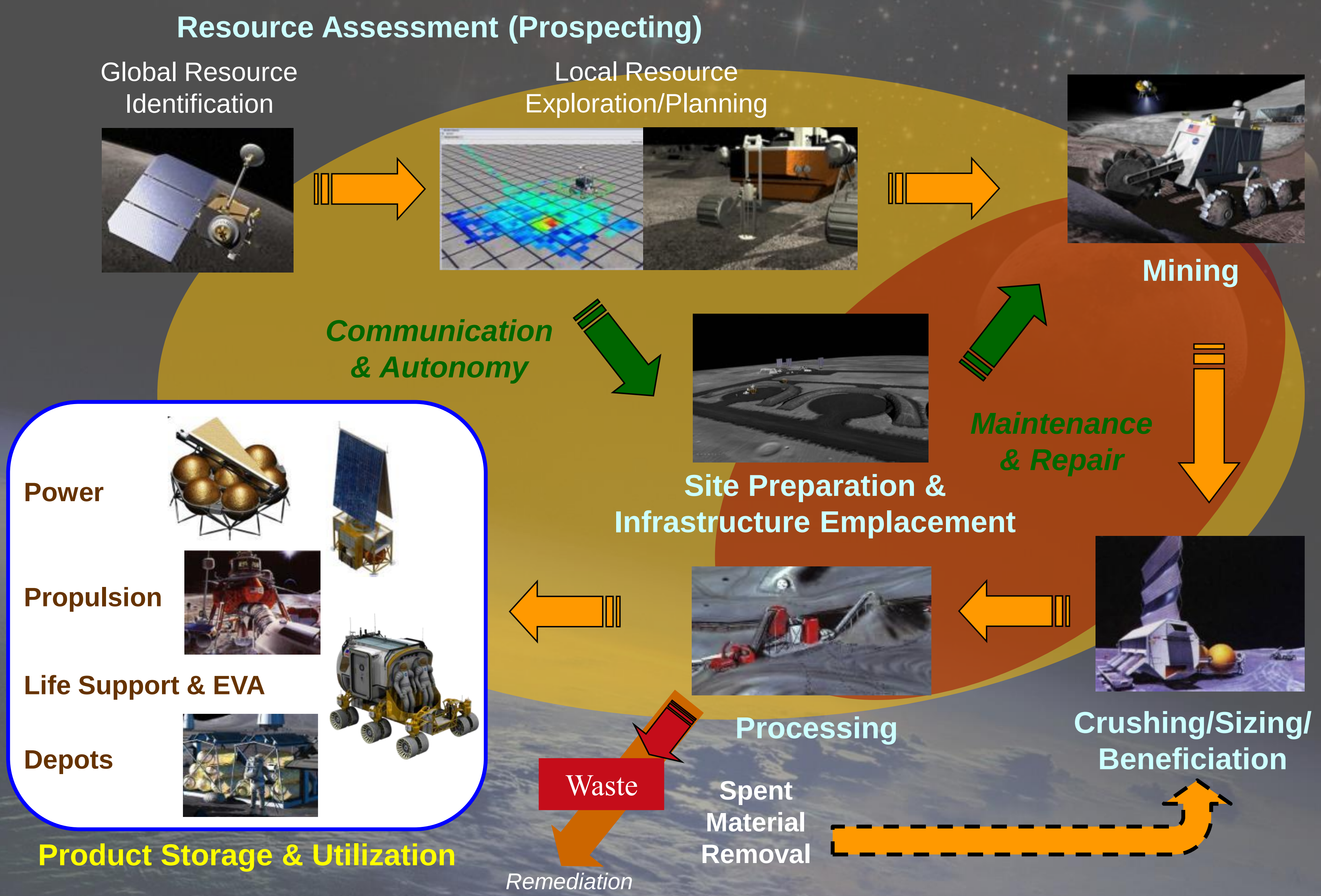


- *Increase safety*
- *Reduce maintenance*
- *Increase prospecting and mining efficiency*

- *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*



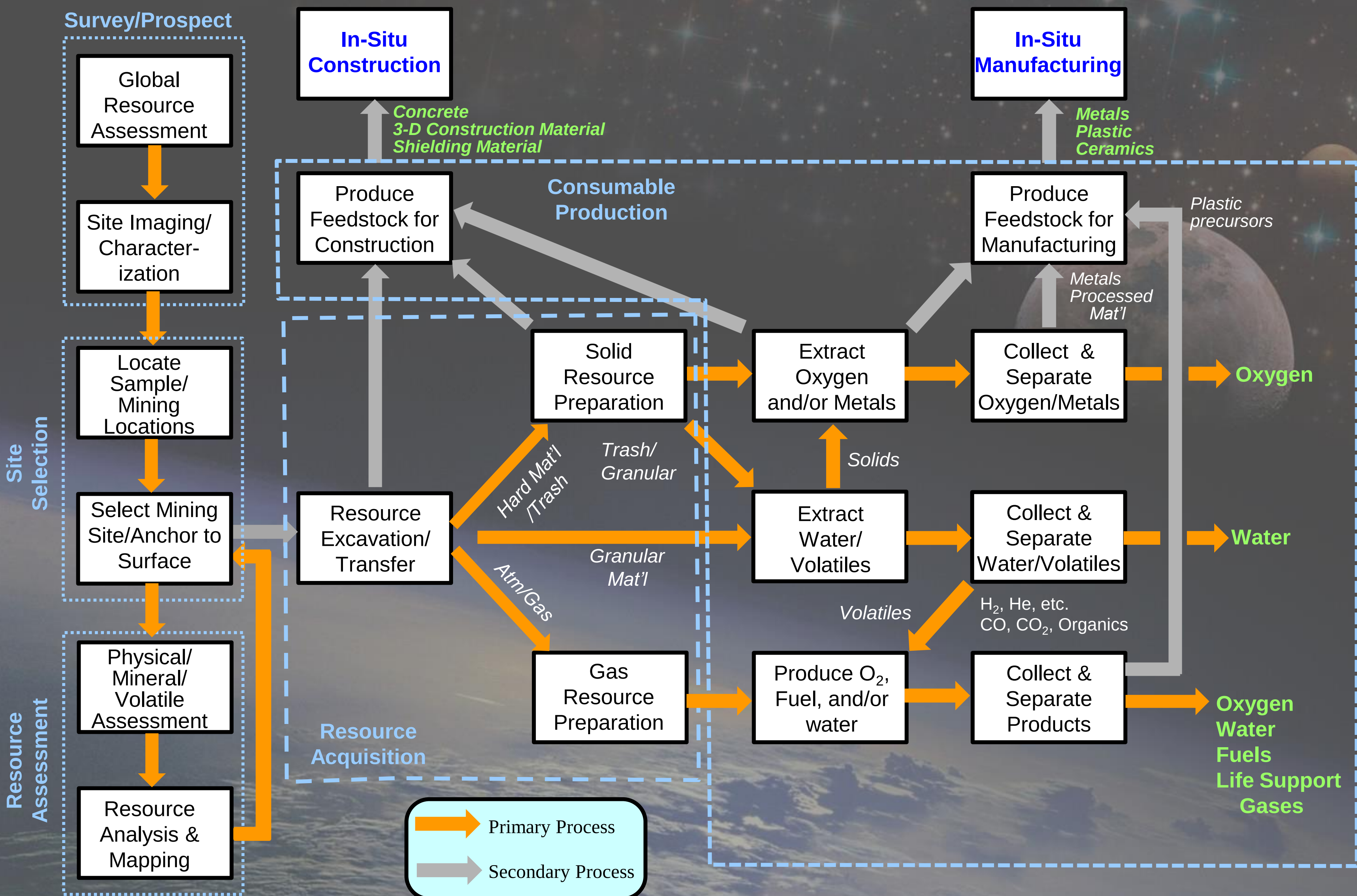
Prospect for Resources

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?
- **What are the variation in resources from place to place?**
  - Local diversity (heterogeneity)
  - Global diversity (equatorial, highland, polar)
  - Destination diversity (Moon, Mars, asteroids)

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

- **Operation in severe environments**
  - Radiation
  - Efficient excavation of resources in dusty/abrasive environments
  - Methods to mitigate dust/filtration for sustained operations
  - 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

- **Integration and Operation with other Exploration Systems**
  - Exploration systems must be designed to utilize ISRU provided products; may cause selection of different technologies/approaches than previously planned or used

- **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









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

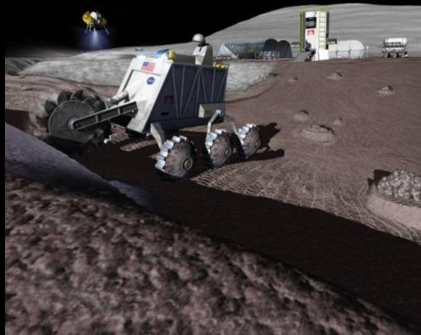
Integration

- 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 . . .

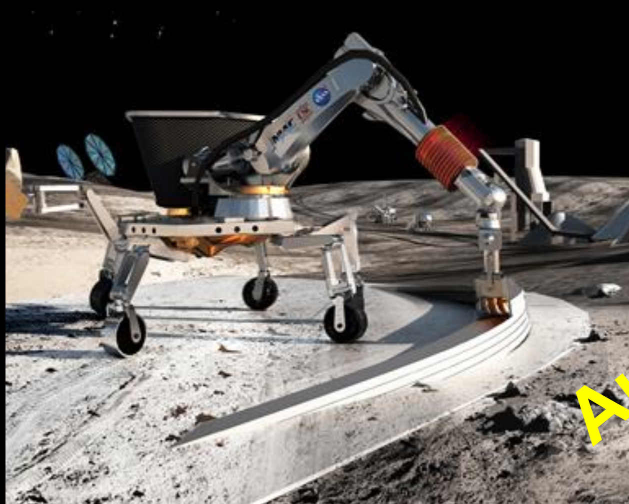


Excavation & Material Processing

Surface & Subsurface Evaluation

Landing Pads & Roads

Autonomous & Tele-operation



3-D Printing

Combustion Synthesis

Waterless Concrete

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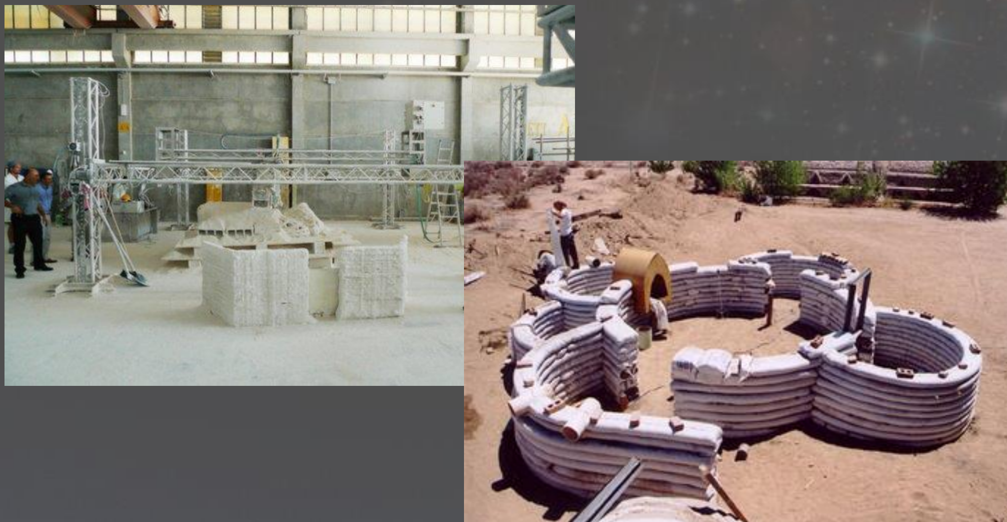
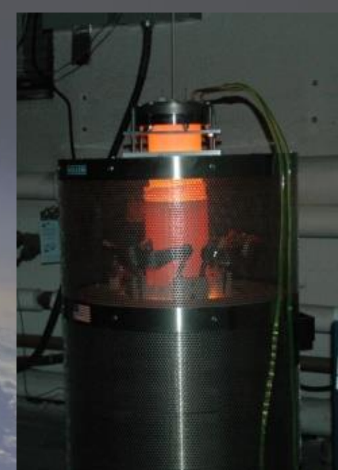
. . . Can Benefit Terrestrial Mining and Construction



Innovative Building Construction

Autonomous & Tele-operation

Innovative Construction Materials



Longer Life, More Efficient Chemical & Mineral Processing

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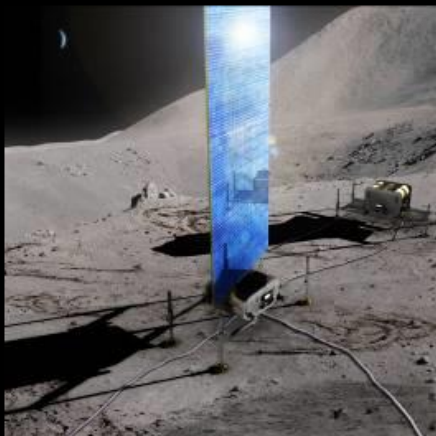
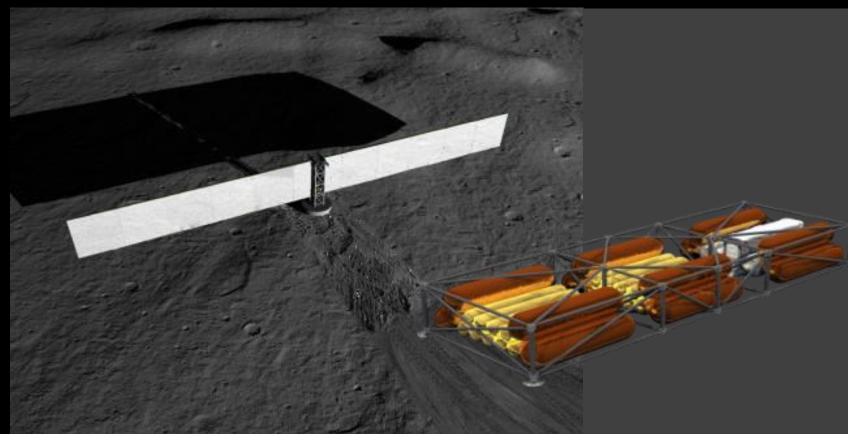
Space Power Systems and Energy Management . . .

Space Resource Utilization Needs Lots of Energy . . .

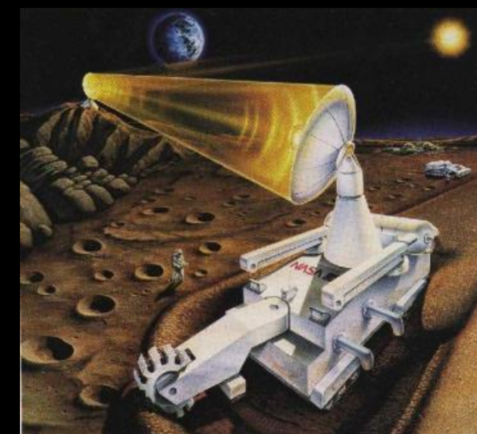


Solar



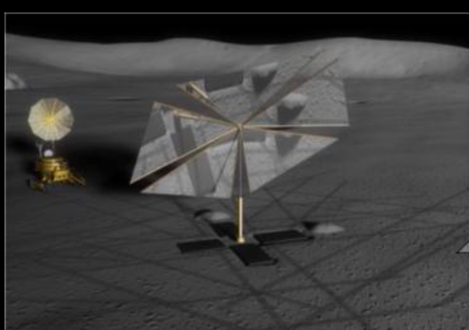
Nuclear

Fuel Cell & Battery

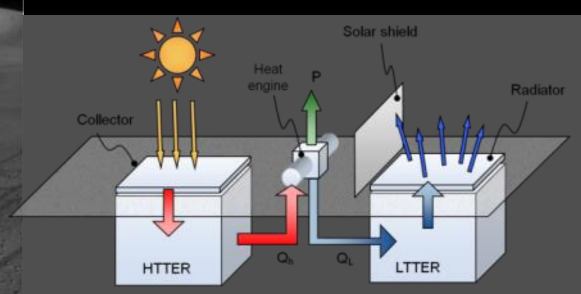


Power Beaming

Using Space Resources Can Help Produce Energy. . .

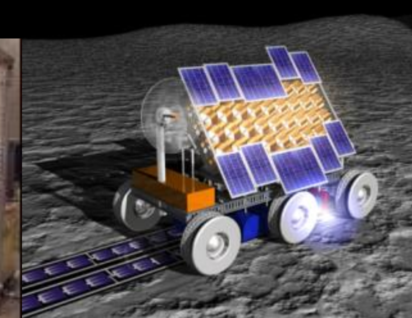


Thermal Storage



Thermal Difference

Resource/Trash to Fuel

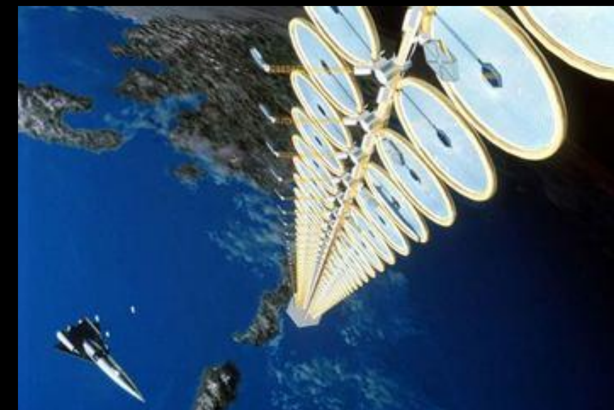


In-Situ Solar Production

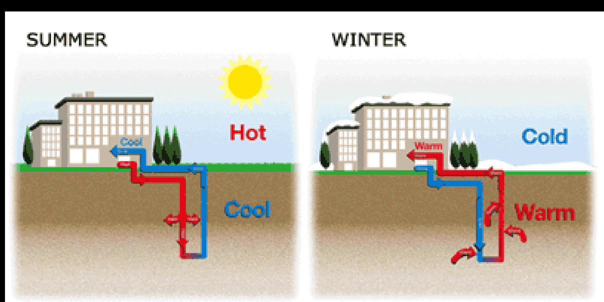
. . . Can Benefit Terrestrial Power Systems & Energy Management

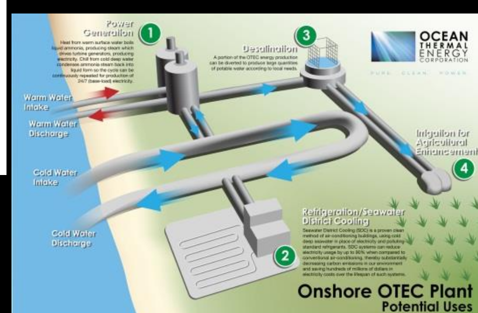
Solar

Fuel Cell & Battery



Power Beaming





Thermal Storage & Thermal Difference

Resource/Trash to Fuel

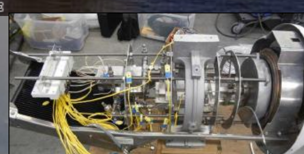
Common Needs Can Lead To Shared Solutions

Energy

Fuel Cell Technology and Applications to Reduce Emissions

Mine Safety

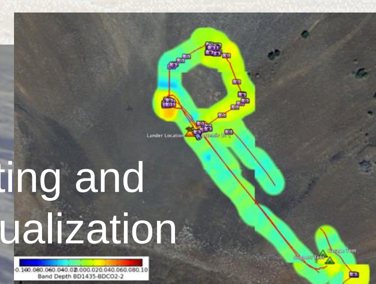
Safe Haven and Rescue Suits based on NASA Life Support and EVA Technology



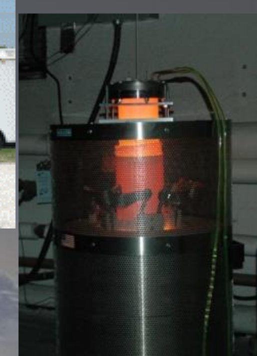
Microchannel Processing for On-Location Gas-to-Liquid Conversion

Mining & Processing

Tele-Operation and Autonomous Operations



Prospecting and Data Visualization



Non-Eroding Electrodes

Dry Drilling

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Questions?

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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