

SPACE RESOURCE UTILIZATION: NEAR-TERM MISSIONS AND LONG-TERM PLANS FOR HUMAN EXPLORATION, Gerald. B. Sanders, NASA Johnson Space Center, Mail Code EP3, Houston, TX. 77058, gerald.b.sanders@nasa.gov.

NASA's Human Exploration Plans: A primary goal of all major space faring nations is to explore space: from the Earth with telescopes, with robotic probes and space telescopes, and with humans. For the US National Aeronautics and Space Administration (NASA), this pursuit is captured in three important strategic goals: 1. Ascertain the content, origin, and evolution of the solar system and the potential for life elsewhere, 2. Extend and sustain human activities across the solar system (especially the surface of Mars), and 3. Create innovative new space technologies for exploration, science, and economic future. While specific missions and destinations are still being discussed as to what comes first, it is imperative for NASA that it foster the development and implementation of new technologies and approaches that make space exploration affordable and sustainable. Critical to achieving affordable and sustainable human exploration beyond low Earth orbit (LEO) is the development of technologies and systems to identify, extract, and use resources in space instead of bringing everything from Earth. To reduce the development and implementation costs for space resource utilization, often called *In Situ* Resource Utilization (ISRU), it is imperative to work with terrestrial mining companies to spin-in/spin-off technologies and capabilities, and space mining companies to expand our economy beyond Earth orbit.

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 starting with the Space Launch System (SLS) and Orion crew spacecraft and utilizing the International Space Station as a springboard into the solar system. 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. The goal is no longer just to reach a destination, but to enable people to work, learn, operate, and live safely beyond the Earth for extended periods of time, ultimately in ways that are more sustainable and even indefinite.

***In Situ* Resource Utilization and Importance of Space Resources:** *In Situ* Resource Utilization 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. Since much of what ISRU encompasses can be considered 'space mining', ISRU developers have used the terrestrial mining philosophy as a starting point to developed a Space ISRU Mining Cycle, or "Prospect to Product", to identify and focus technology, process, and integrated testing activities.

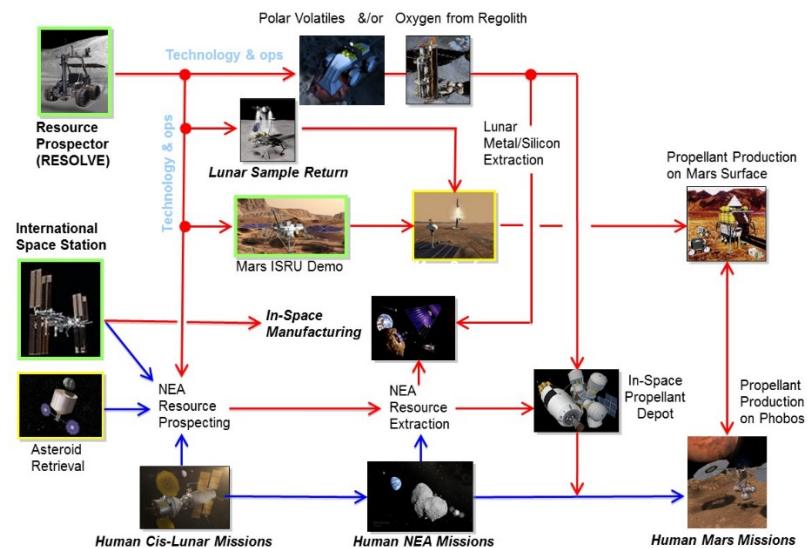
There are five major benefits for incorporating the use of space resources into human space exploration missions; mass reduction, cost reduction, risk reduction and increased mission

flexibility, enhancing/enabling human expansion into space, and terrestrial/space commercialization. For every kilogram landed on the Moon or Mars, 7.5 to 11 kg must be launched into LEO from Earth. Since propellants make up between 70 and 90% of the mass of chemical propulsion stages and landers, making propellants in-space and on the surface of the Moon and Mars can significantly reduce what needs to be launched from Earth; thereby reducing cost and mass. ISRU can also further reduce costs by enabling reusability of equipment and transportation vehicles that were previously discarded once their consumables had been used. Extraction and production of metals, plastics, and building materials also reduces risks due to failures, reduces logistics from Earth, and enhances or enables the expansion of human exploration and the commercialization of space.

Implementation of Space Resources into Human Space Exploration: Since the extraction of resources in space has never been demonstrated, and because there are uncertainties in the resources that may exist at destinations of human exploration interest, ISRU and mission planners have adopted a phased approach for incorporating ISRU into human missions: Phase 1 - Scout and demonstrate, Phase 2 – Pilot-scale demonstration in non-mission critical roles, Phase 3 – Utilization. This stepwise approach starts with site selection, leading to exploratory prospecting and focused resource assessment, to performing mining and processing feasibility before full production begins. To understand what technologies and capabilities are needed for each phase of ISRU incorporation as well as how these technologies and capabilities need to evolve in terms of scale and operation, NASA utilized the space mining cycle as a starting point to define a detailed capability/function flow diagram. For each capability in the diagram, NASA has further defined what technology and process options exist, what is the state-of-the-art for each option, and what needs to be done to fully develop the capability.

Because NASA is interested in exploring and potentially using the resources on the Moon, Mars and it's moons, and even near-Earth asteroids (NEAs), further evaluations were performed to understand the similarities and differences in the resources at each of these destinations as well as the technologies and processes required to find, extract, and process their resources into usable products.

By doing so, NASA can focus its attention and funding on technologies and processes that could potentially be used in multiple locations and applications, as well as develop building block capabilities that can be evolved and expended as human exploration proceeds farther from Earth and for longer durations. With the ultimate goal of long-term human exploration of the surface of Mars, ISRU



planners have also proposed a flexible and evolutionary progression of robotic and human assisted missions associated with finding, extracting, and eventually utilizing the resources of space. As denoted in green (actual mission) and yellow (in planning), the development and incorporation of space resources into human exploration has already started, and details will be provided.

Space Resource Utilization and Human Exploration of Space

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

May x, 2015
Montreal, Canada

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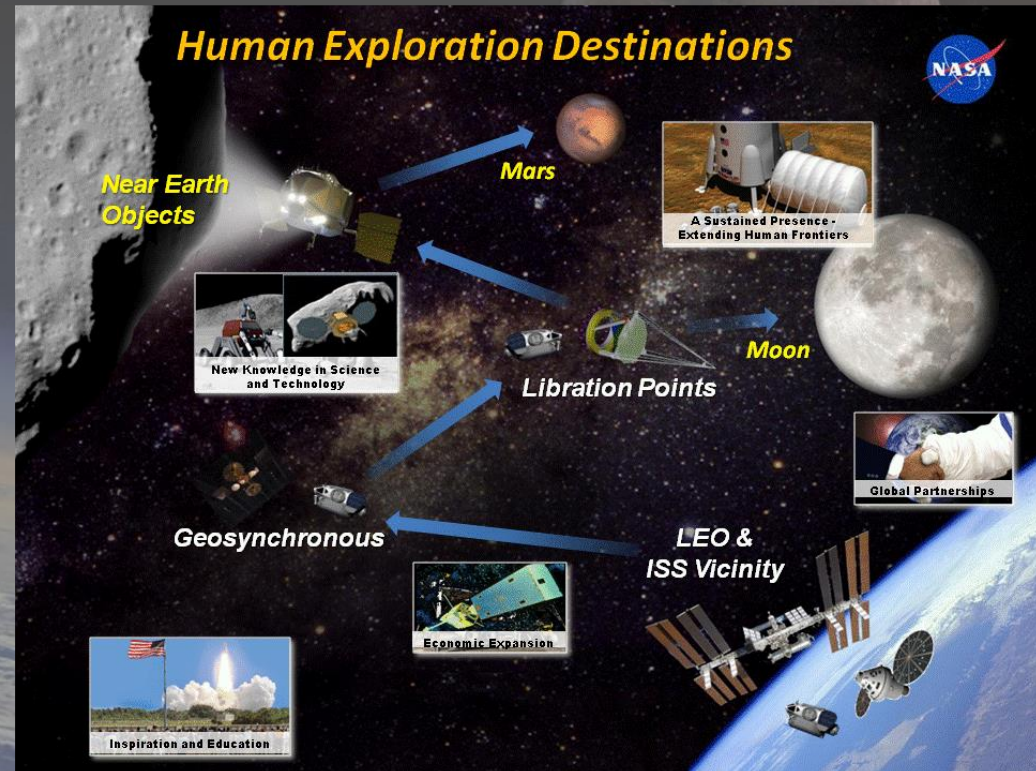
NASA Strategic Goals:

- Extend and sustain human activities across the solar system
- Ascertain the content, origin, and evolution of the solar system and the potential for life elsewhere.
- Create the innovative new space technologies for our exploration, science, and economic future

Affordable and Sustainable

Critical for exploration beyond low Earth orbit

- Robotics & Automation
- Power Systems
- Propulsion
- Habitation & Life Support
- **Space Resource Utilization**



Pioneering Space - Goals

“Fifty years after the creation of NASA, our goal is no longer just a destination to reach. Our goal is the capacity for people to work and learn and operate and live safely beyond the Earth for extended periods of time, ultimately in ways that are more sustainable and even indefinite. And in fulfilling this task, we will not only extend humanity’s reach in space -- we will strengthen America’s leadership here on Earth.”

- President Obama, April 2010



Sustainable Human Space Exploration

NASA's Building Blocks to Mars

U.S. companies provide affordable access to low Earth orbit

Mastering the fundamentals aboard the International Space Station

Pushing the boundaries in cis-lunar space

Developing planetary independence by exploring Mars, its moons, and other deep space destinations

The next step: traveling beyond low-Earth orbit with the Space Launch System rocket and Orion crew capsule

*Missions: 6 to 12 months
Return: hours*

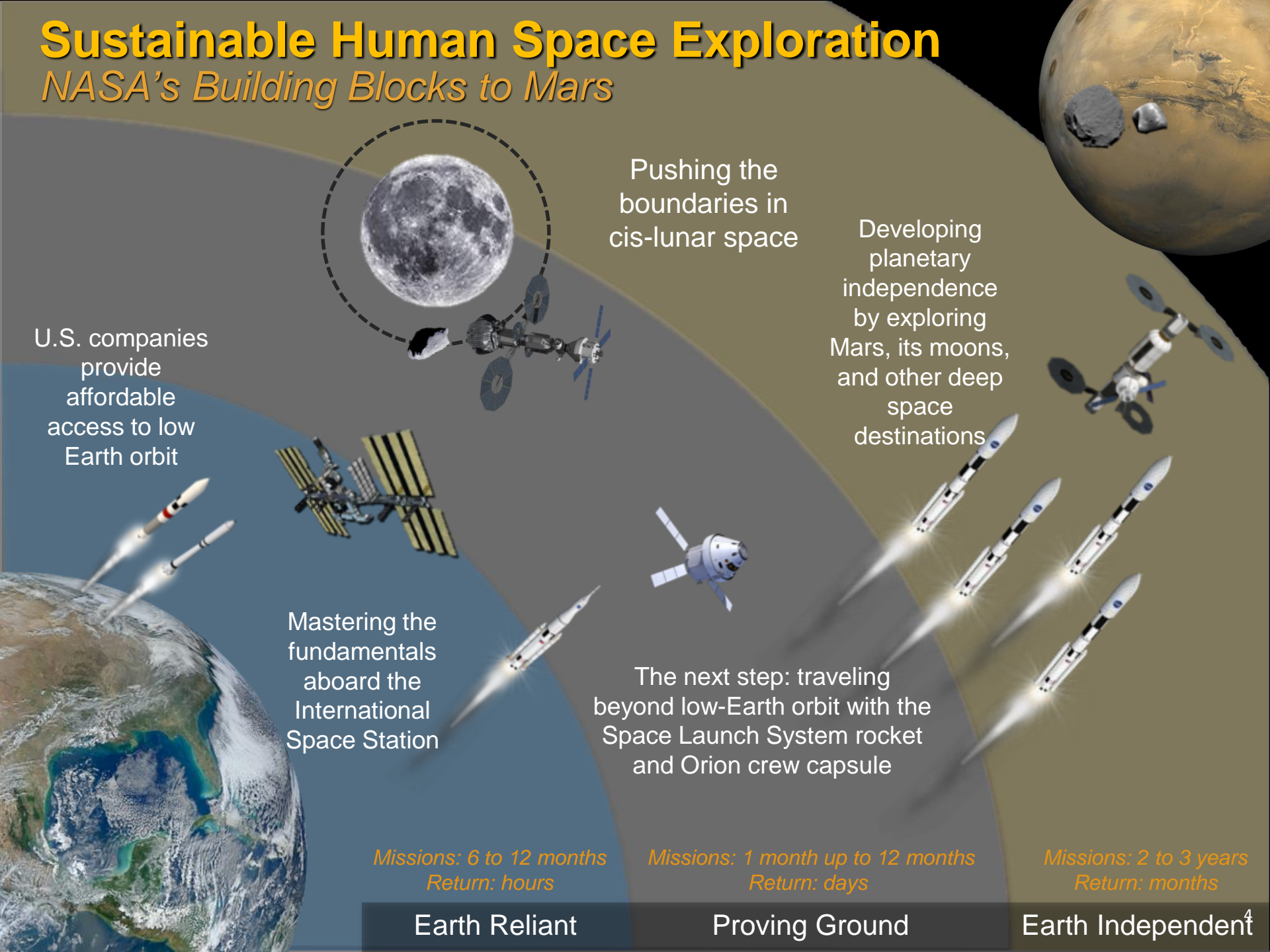
*Missions: 1 month up to 12 months
Return: days*

*Missions: 2 to 3 years
Return: months*

Earth Reliant

Proving Ground

Earth Independent⁴



Evolvable Mars Campaign: Enabling Technologies

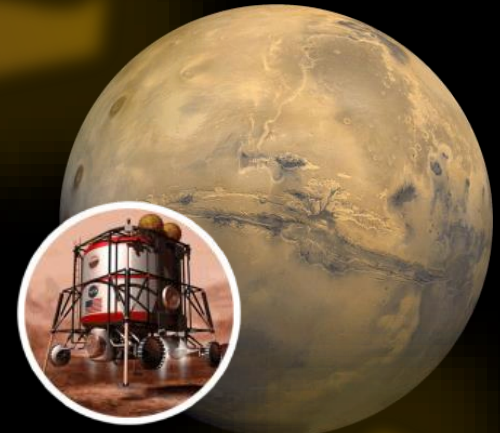
Preliminary

Transportation

- Oxygen-Rich Staged Combustion (ORSC) Engine Technology
- Chem Prop (In-Space): LOX/Methane Cryo (Propulsion & RCS)
- Solar Electric Propulsion & Power Processing
- 10-100 kW Class Solar Arrays
- Cryo Propellant Acquisition & ZBO Storage
- AR&D, Prox Ops & Target Relative Navigation
- EDL, Precision Landing, Heat Shield
- Autonomous Vehicle Systems Management
- Mission Control Automation beyond LEO

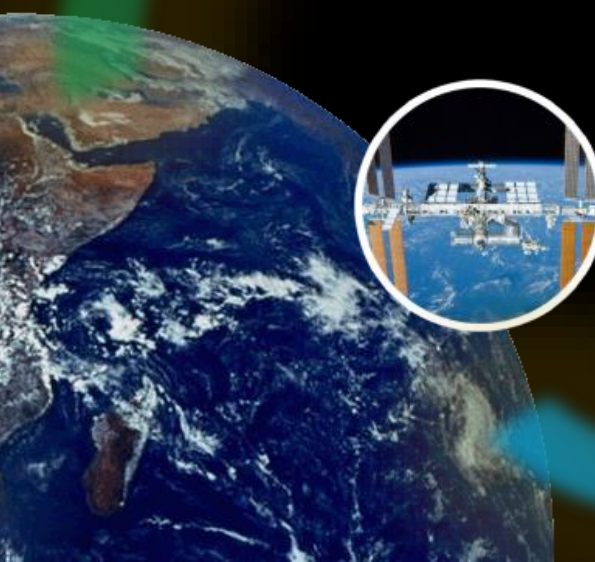
Staying Healthy

- Advanced, High-Reliability ECLSS
- Long-Duration Spaceflight Medical Care
- Long-Duration Spaceflight Behavioral Health & Performance
- μ -G Biomedical Counter-Measures for Long-Duration Spaceflight
- Deep Space Mission Human Factors & Habitability
- In-Flight Environmental Monitoring
- Human SPE & GCR Radiation Exposure Prevention & Protection
- Fire Prevention, Detection, Suppression (Reduced Pressure)



Working in Space

- Autonomy beyond LEO
- High Data Rate Forward Link Communications
- High-Rate, Adaptive, Internetworked Proximity Communications
- In-Space Timing & Navigation for Autonomy
- Fission Surface Power (FSP)
- ISRU (Atmospheric & Regolith)
- Mechanisms (low-temp), Dust Mitigation
- Tele-robotic Control of Robotic Systems with Time Delay
- Robots Working Side-By-Side with Suited Crew
- Robotics & Mobility **EVA Exploration Suit and PLSS**
- **Electro-Chemical Power Systems**
- **Advanced Fire Protection Systems**
- Deep Space Suit & Mars Surface Suit (EVA)
- Surface Mobility
- Suit Port, u-G tools & anchoring
- Advance Software Development/Tools



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.

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**

Resources of Interest

- **Oxygen**
- **Water**
 - Hydrogen
 - Carbon/CO₂
 - Nitrogen
 - Metals
 - Silicon

~85% of Meteorites are Chondrites

Ordinary Chondrites

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

87%

Pyroxene
Olivine
Plagioclase
Diopside
Metallic Fe-Ni alloy
Troilite - 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

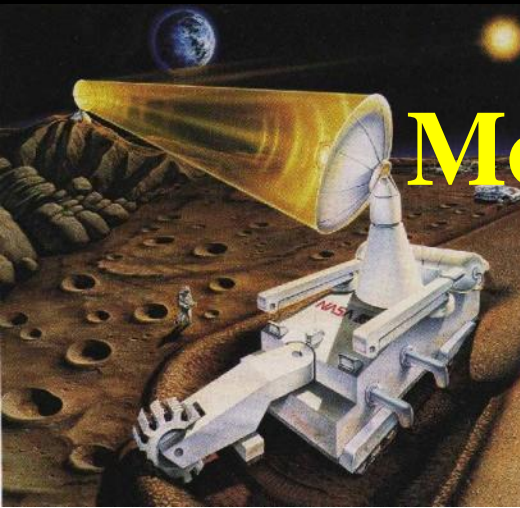
Easy source of oxygen (Carbothermal)

Three major resources on Mars:

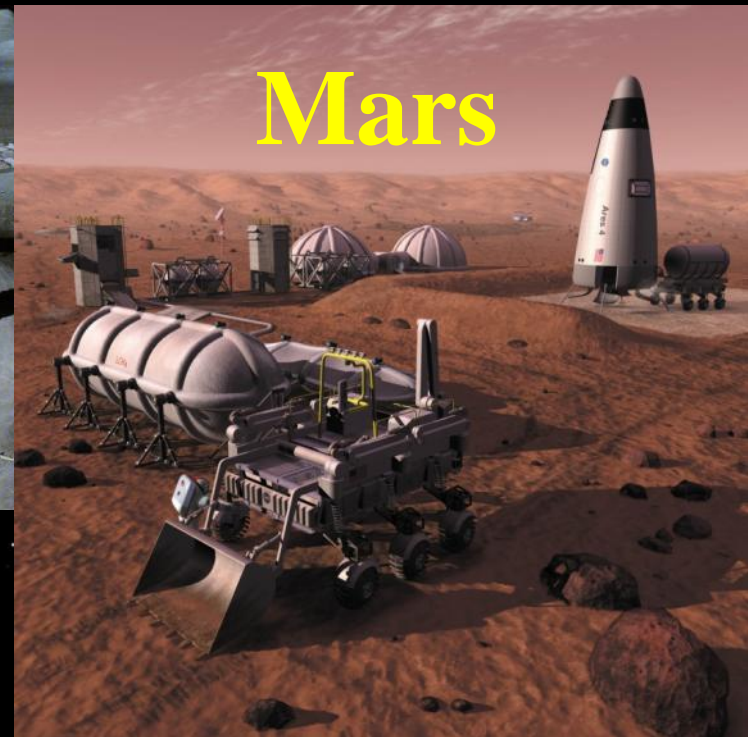
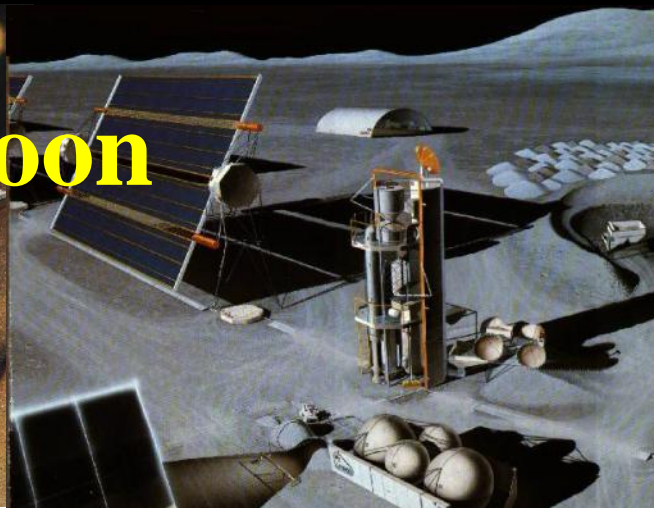
- **Atmosphere:**
 - 95.5% Carbon dioxide,
 - 2.7% Nitrogen,
 - 1.6% Argon
- **Water in soil:** concentration dependant on location
 - 2% to dirty ice at poles
- Oxides and metals in the soil



Vision for Using Space Resources



Moon



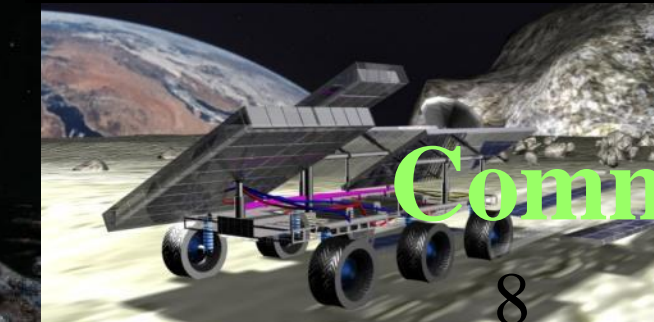
Mars



Phobos



NEAs



Commercial



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

Five Major Areas of ISRU

➤ Resource Characterization and Mapping

Physical, mineral/chemical, and volatile/water

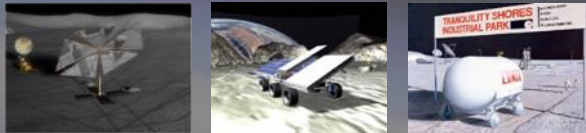
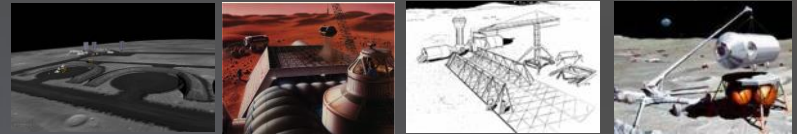


➤ Mission Consumable Production

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

➤ Civil Engineering & Surface Construction

Radiation shields, landing pads, roads, habitats, etc.



▪ In-Situ Energy Generation, Storage & Transfer

Solar, electrical, thermal, chemical

▪ In-Situ Manufacturing & Repair

Spare parts, wires, trusses, integrated structures, etc.

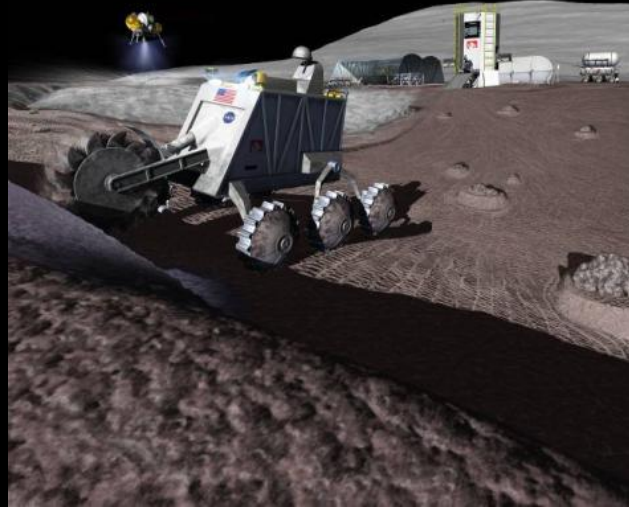


➤ **'ISRU' is a capability involving multiple technical discipline elements** (mobility, regolith manipulation, regolith processing, reagent processing, product storage & delivery, power, manufacturing, etc.)

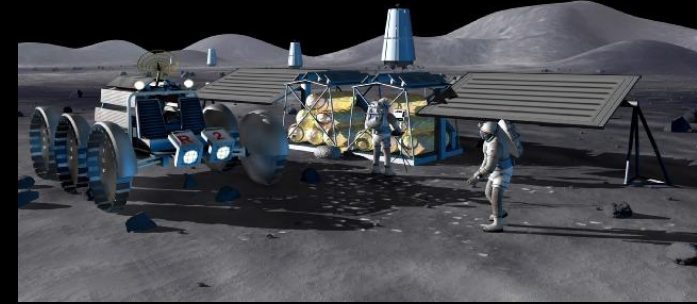
➤ **'ISRU' does not exist on its own.** By definition it must connect and tie to multiple uses and systems to produce the desired capabilities and products.

Potential Lunar ISRU Mission Capabilities

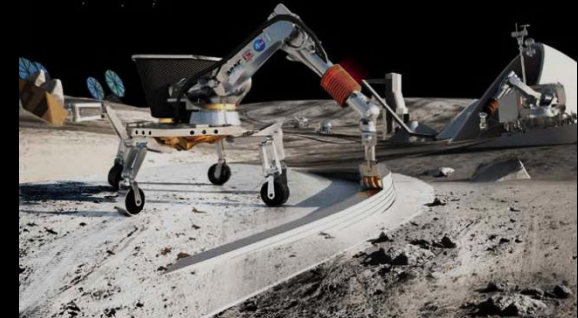
Excavation & Regolith Processing for O₂ and Metal Production



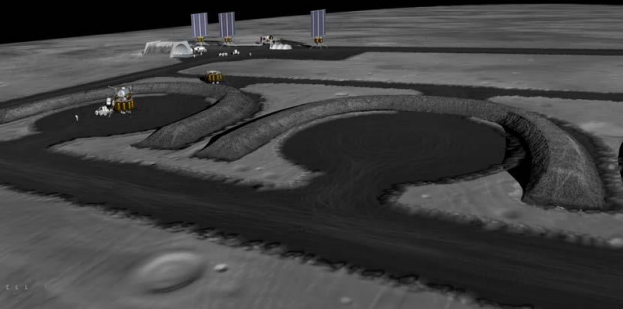
Consumable Depots and Waypoints for Crew & Power



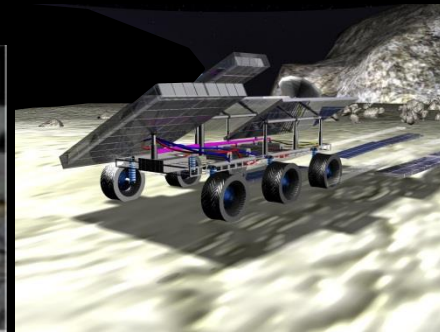
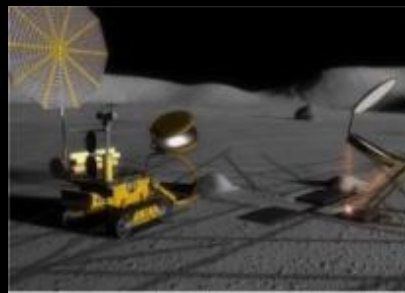
Structure and Habitat Construction



Polar Ice/Volatile Prospecting & Mining



Solar and Thermal Energy Storage Construction

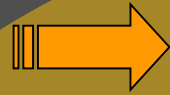


Landing Pads, Berm, and Road Construction

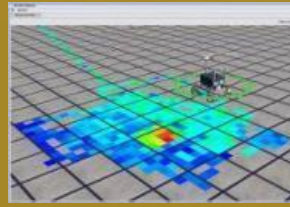
Space 'Mining' Cycle: *Prospect to Product*

Resource Assessment (Prospecting)

Global Resource Identification

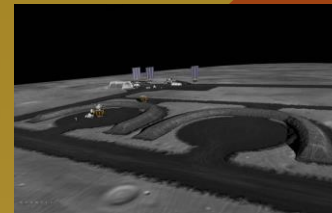


Local Resource Exploration/Planning



Mining

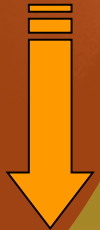
Communication & Autonomy



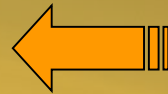
Site Preparation & Infrastructure Emplacement



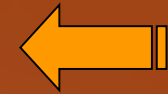
Maintenance & Repair



Crushing/Sizing/
Beneficiation



Processing



Spent
Material
Removal

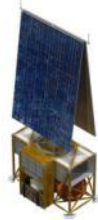


Waste

Remediation



Power



Propulsion



Life Support & EVA



Depots

Product Storage & Utilization

Space Resources Utilization Changes How We Can Explore Space

Mass Reduction

- >7.5 kg mass savings in Low Earth Orbit for every 1 kg produced on the Moon or Mars
- Chemical propellant is the largest fraction of spacecraft mass

Cost Reduction

- Allows reuse of transportation systems
- Reduces number and size of Earth launch vehicles

Risk Reduction & Flexibility

- Number of launches & mission operations reduced
- Use of common hardware & mission consumables enables increased flexibility
- In-situ fabrication of spare parts enables sustainability and self-sufficiency
- Radiation & landing/ascent plume shielding
- Reduces dependence on Earth

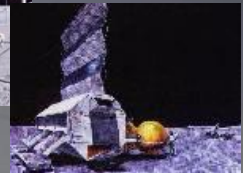
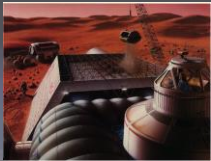
Space Resource Utilization

Solves Terrestrial Challenges & Enables Space Commercialization

- Develops alternative & renewable energy technologies
- New renewable construction
- CO₂ remediation
- Green metal production
- Provides infrastructure to support space commercialization
- Propellant/consumable depots at Earth-Moon L1 & Surface for Human exploration & commercial activities

Expands Human Presence

- Increase Surface Mobility & extends missions
- Habitat & infrastructure construction
- Substitutes sustainable infrastructure cargo for propellant & consumable mass



Make It vs Bring It – A New Approach to Exploration

Reduces Risk

- Minimizes/eliminates life support consumable delivery from Earth – Eliminates cargo delivery failure issues & functional backup to life support system
- Increases crew radiation protection over Earth delivered options – In-situ water and/or regolith
- Can minimize impact of shortfalls in other system performance – Launch vehicles, landers, & life support
- Minimizes/eliminates ascent propellant boiloff leakage issues – In-situ refueling
- Minimizes/eliminates landing plume debris damage – Civil engineering and construction

Increases Performance

- 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 and more efficient surface nighttime and mobile fuel cell power architecture with ISRU
- Decreased logistics and spares brought from Earth

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

Increases Sustainability/Decreases Life Cycle Costs

- Potential reuse of landers with in-situ propellants can provide significant cost savings
- Enables in-situ growth capabilities in life support, habitats, powers, etc.
- Enables path for commercial involvement and investment

Supports Multiple Destinations

- Surface soil processing operations associated with ISRU applicable to Moon and Mars
- ISRU subsystems and technologies are applicable to multiple destinations and other applications
- Resource assessment for water/ice and minerals common to Moon, Mars, and NEOs



How ISRU Enables Future Moon & Mars Missions



Every 1 kg of product made on the Moon or Mars saves 7.5 to 11.3 kg in Low Earth Orbit

➤ 25,000 kg mass savings from propellant production on Mars for ascent = 187,500 to 282,500 kg launched into LEO

1 kg propellant on Mars

1.9 kg used for EDL

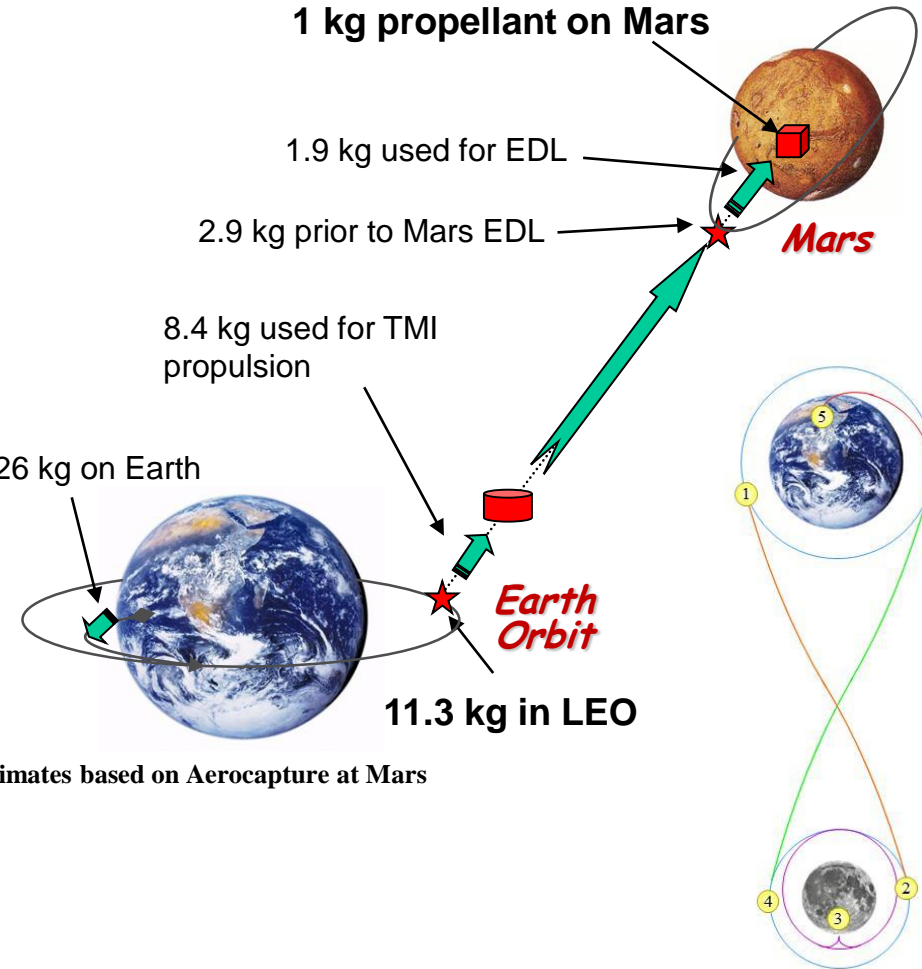
2.9 kg prior to Mars EDL

8.4 kg used for TMI propulsion

226 kg on Earth

11.3 kg in LEO

Estimates based on Aerocapture at Mars



- 1 LEO
- 2 Lunar Destination Orbit
- 3 Lunar Surface
- 4 Lunar Rendezvous Orbit
- 5 Earth Surface

A Kilogram of Mass Delivered Here...

...Adds This Much Initial Architecture Mass in LEO

...Adds This Much To the Launch Pad Mass

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

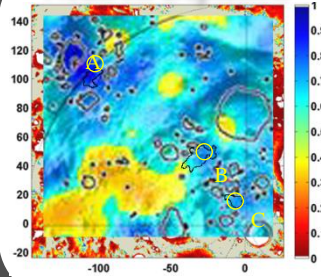
Implementation Strategy for Space Resource Utilization

- **Three phases of ISRU implementation to minimize risk to human exploration plans**
 - **Phase 1: Scout and Demonstrate** – *Mission Feasibility*
 - Evaluate potential exploration sites: terrain, **geology/resources**, lighting, etc.
 - Demonstrate critical technologies, functions, and operations
 - Evaluate environmental impacts and long-term operation on hardware: dusty/abrasive/electrostatic regolith, radiation/solar wind, day/night cycles, polar shadowing, etc.
 - **Phase 2: Pilot Scale Demonstration** – *Mission Enhancement*
 - Perform critical demonstrations at scale and duration to minimize risk of utilization
 - Obtain design and flight experience before finalizing human mission element design
 - Pre-deploy and produce product before crewed missions arrive to enhance mission capability
 - **Phase 3: Utilization Operations** – *Mission Enabling*
 - Produce at scale to enable ISRU-fueled reusable landers and support extended duration human surface operations
 - Commercial involvement or products bought commercially based on Phase 2
- **Identify technologies and systems for multiple applications (ISRU, life support, power) and multiple mission (Moon, Mars, NEOs)**
- **Multinational (government, industry, and academia) involvement for development and implementation leading to space commercialization**

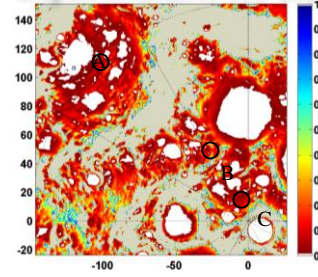
Stepwise Approach to Utilizing Space Resources

Or mineral maps for oxygen/metals

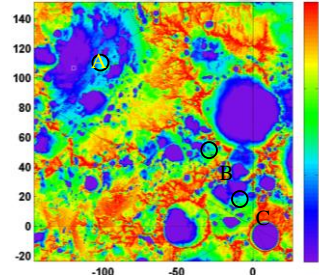
Neutron Depletion



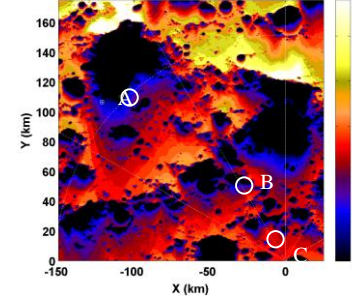
Depth to Stable Ice (m)



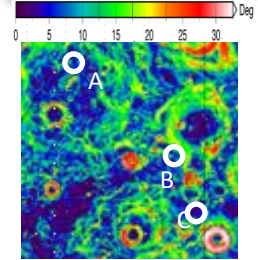
Days of Sunlight



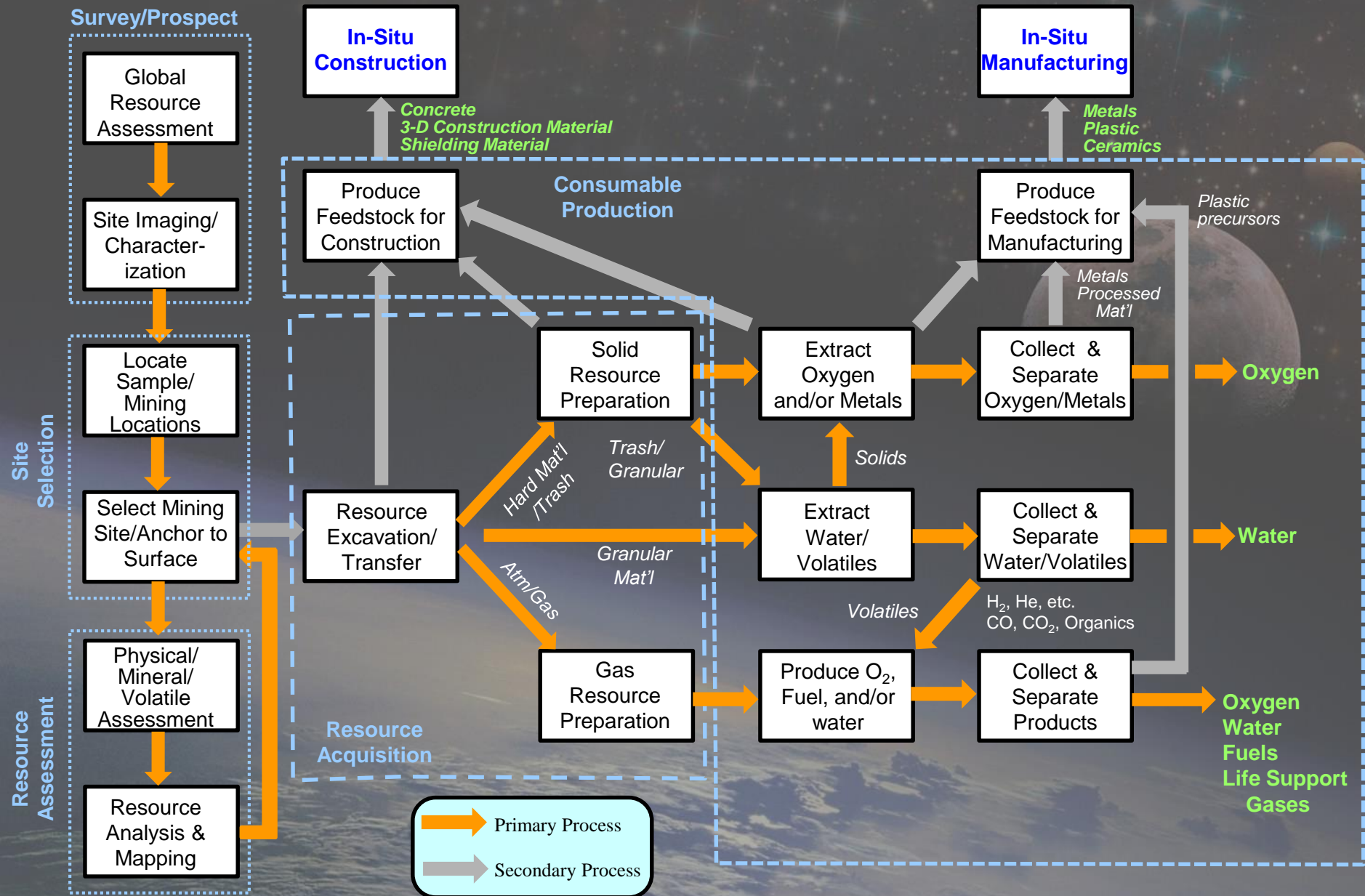
Comm Visibility (Days)



Slopes at 25 m Scale (deg)

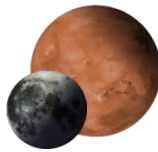


ISRU Capability-Function Flow Chart





Moon, Mars, & Near Earth Objects (NEOs)



	Moon	Mars	NEOs
Gravity	1/6 g	3/8 g	Micro-g
Temperature (Max)	110 °C/230 °F	20 °C/68 °F	110 °C/230 °F
(Min.)	-170 °C/-274 °F	-140 °C/-220 °F	-170 °C/-274 °F
(Min. Shade)	-233 °C/-387.4 °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)	Atmosphere (CO ₂)	Regolith (metals, O ₂)
		Hydrated Soils	Hydrated Soils
	H ₂ O/Volatile Icy Soils		H ₂ O/Volatile Icy Soils

- **The Moon has aspects in common with Mars and NEOs/Phobos**
- **All destinations share common technologies, processes, and operations**
- **NEO micro-gravity environment is the largest difference between destinations**

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	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						Gas Processing					
Regolith (granular) Excavation & Transfer	X		X	X		Dust/Particle Filtration		X	X	X	X
Hard Material Excavation & Transfer	P			P	P	CO ₂ Capture - Separation		X		P	X
Hydrated Soil /Material Excavation & Transfer	P		X	X	X	CO ₂ Conversion into CO-O ₂		P			
Icy-Soil Excavation & Transfer	X		X	X		CO/CO ₂ Conversion into H ₂ O-CH ₄		P		P	X
Resource Characterization						H ₂ -CH ₄ Separation		P		P	X
Physical Property Evaluation	X					Water Processing					
Mineral/Chemical Evaluation	X			X		Water Capture	X		X	X	X
Volatile-Product Analysis	X	X			X	Water Cleanup - Purity Measurement			X	X	X
Regolith-Soil Processing (Volatiles, O₂, Metal)						Water Electrolysis		P	X	P	X
Crushing			P	X	P	Regenerative Dryers		P	X	P	X
Size Sorting				P		Support Systems					
Beneficiation/Mineral Separation				P		Extended Operation Power Systems			P	P	
Solid/Gas Processing Reactor	X		X	X	X	Extended Operation Thermal Systems			P	P	
Solid/Liquid Processing Reactor				P		Cryogenic Liquefaction, Storage, and Transfer					
Contaminant Removal			X	X	X						

P = Possible need

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

Lunar and Space Exploration Vision for Space Resource Utilization

- **Affordable and Sustainable Human Exploration** requires the development and utilization of space resources
- **The search for potential resources (Prospecting) and the production of mission critical consumables (propellants, power reactants, and life support gases) is the primary focus of NASA technology and system development since they provide the greatest initial reduction in mission mass, cost, and risk.**
- **Two approaches to implement space resources into human space missions**
 - Scout/Demonstrate, Pilot-operations in non-mission critical role, Utilize in mission
 - Exploratory assessment, focused assessment, and Mining Feasibility
- **Selection of common technologies and processes for multiple destinations is recommended**
- **Plans for developing ISRU through an evolution of missions starting with the lunar Resource Prospector Mission and Asteroid Retrieval Mission has been proposed to minimize risk**
 - Several missions in this evolutionary plan have been initiated or are in the planning stage

Questions?

