Space Resource Utilization and Human Exploration of Space

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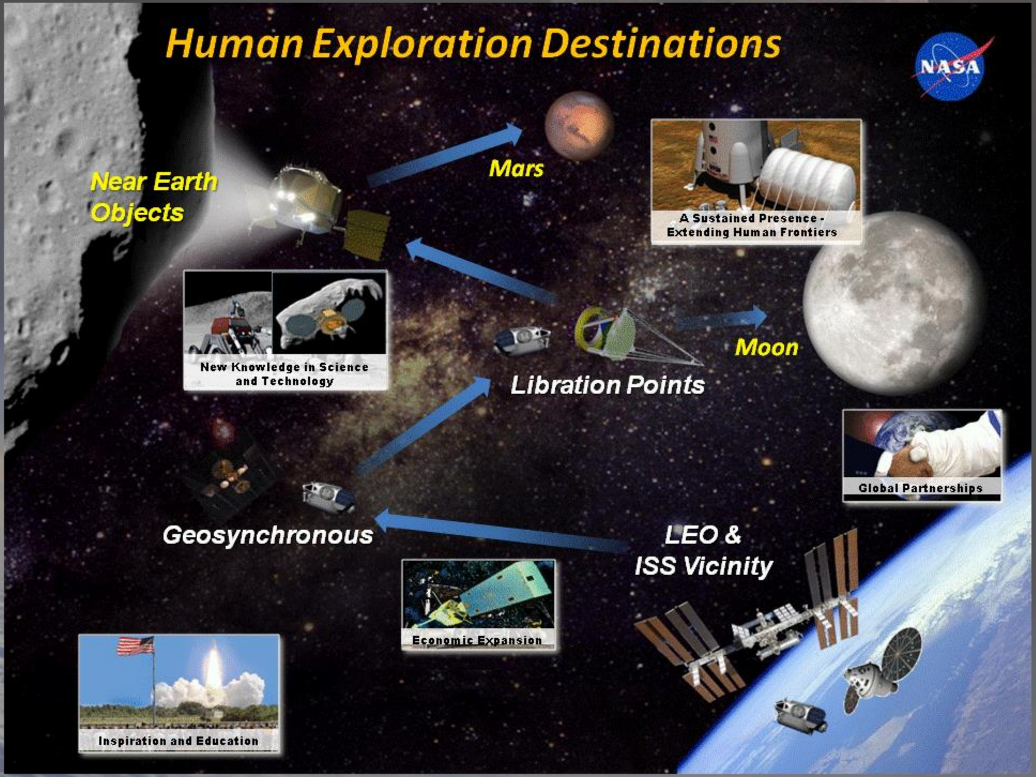
NASA Strategic Goals:

- 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**



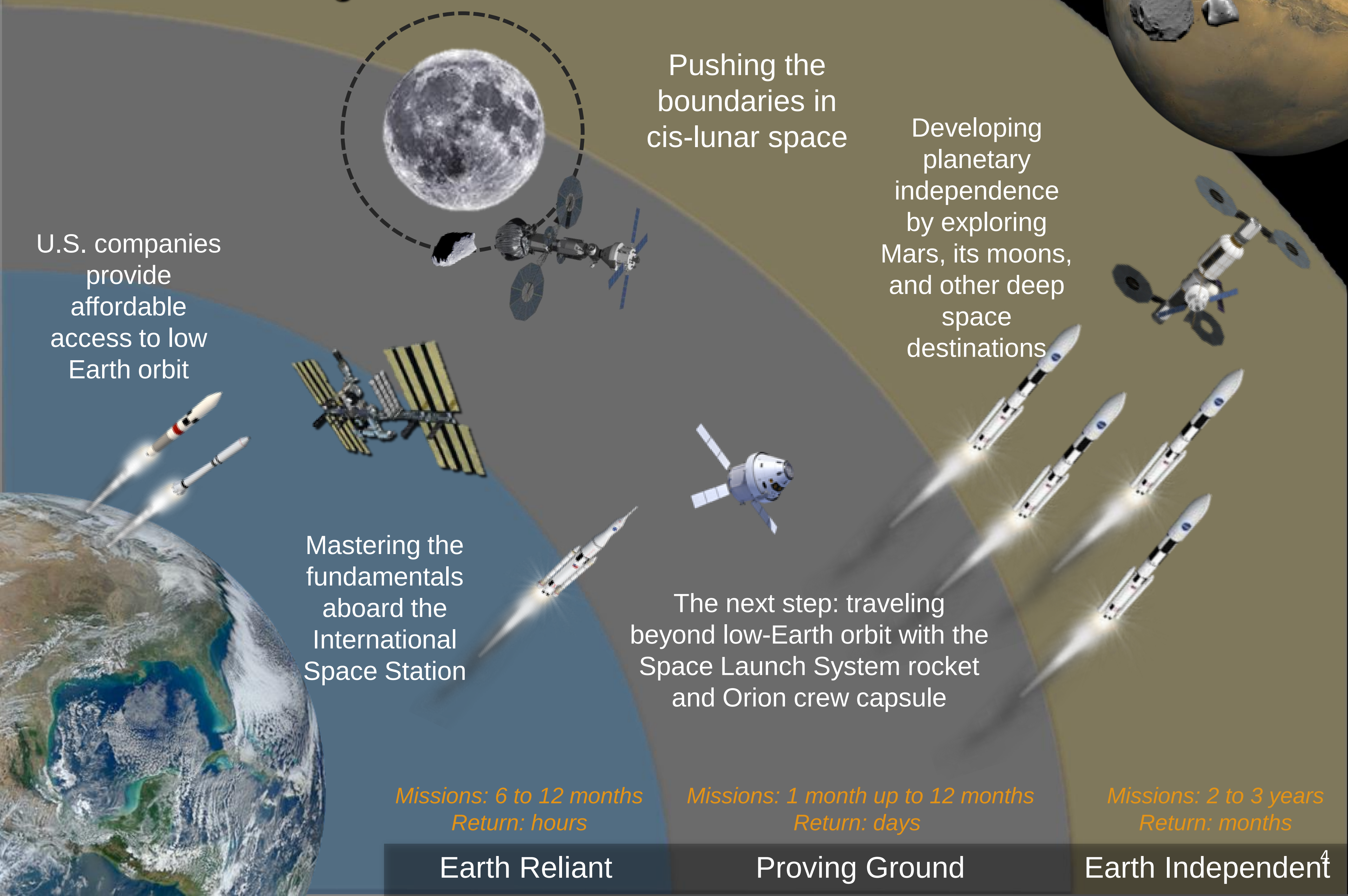
Pioneering Space - Goals

"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

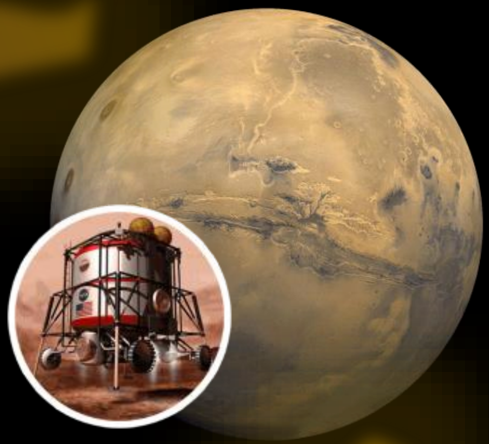
Sustainable Human Space Exploration

NASA's Building Blocks to Mars



Evolvable Mars Campaign: Enabling Technologies

Preliminary

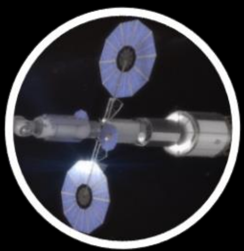


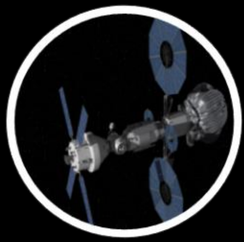
Transportation

- 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.

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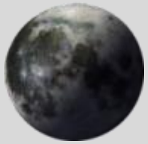
Space Resources



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

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

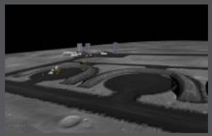
Five Major Areas of ISRU

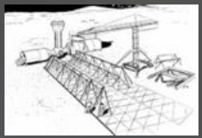
- **Resource Characterization and Mapping**
  Physical, mineral/chemical, and volatile/water

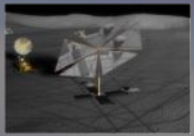
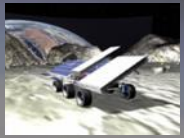



- **Mission Consumable Production**
  Propellants, life support gases, fuel cell reactants, etc.

- **Civil Engineering & Surface Construction**
  Radiation shields, landing pads, roads, habitats, etc.





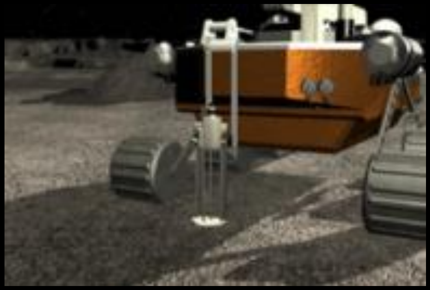

- **In-Situ Energy Generation, Storage & Transfer**
  Solar, electrical, thermal, chemical

- **In-Situ Manufacturing & Repair**
  Spare parts, wires, trusses, integrated structures, etc.

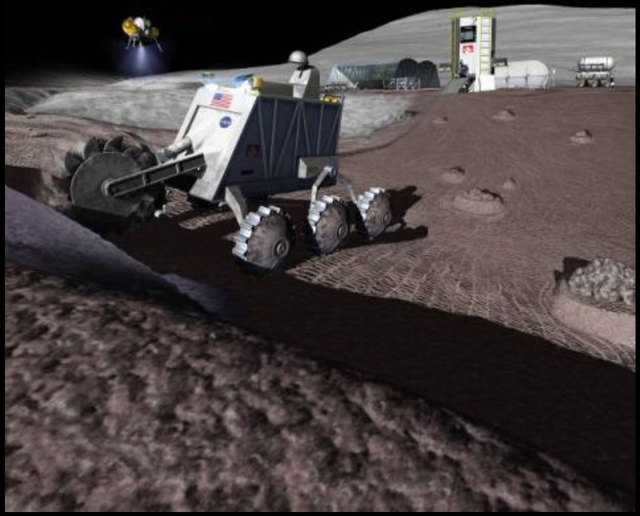


- **‘ISRU’ is a capability involving multiple technical discipline elements** (mobility, regolith manipulation, regolith processing, reagent processing, product storage & delivery, power, manufacturing, etc.)
- **‘ISRU’ does not exist on its own.** By definition it must connect and tie to multiple uses and systems to produce the desired capabilities and products.

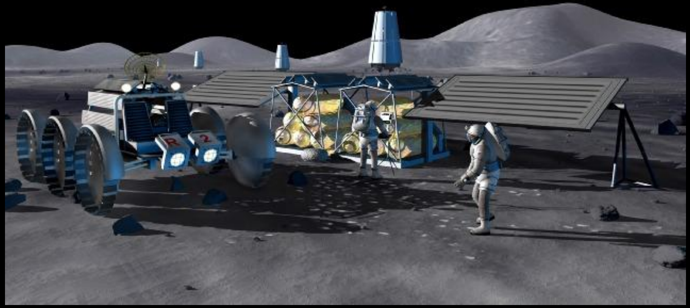
Potential Lunar ISRU Mission Capabilities



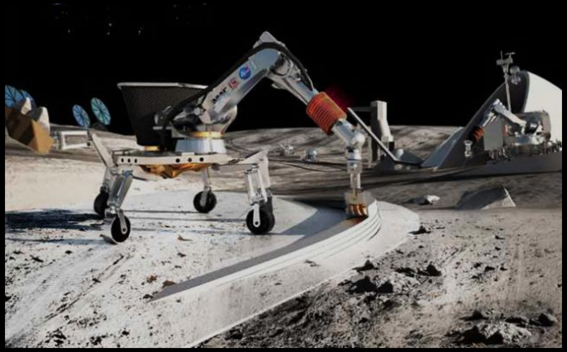
Excavation & Regolith Processing for O_2 and Metal Production



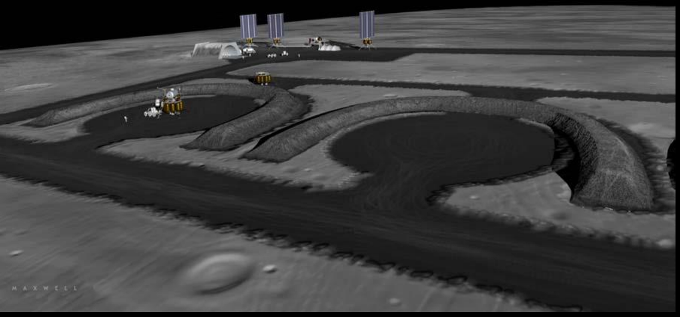
Consumable Depots and Waypoints for Crew & Power



Structure and Habitat Construction

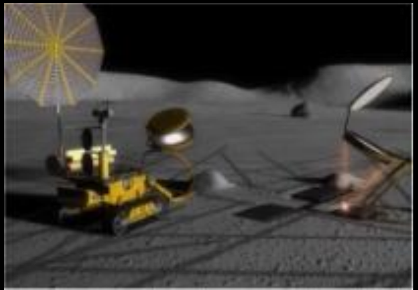


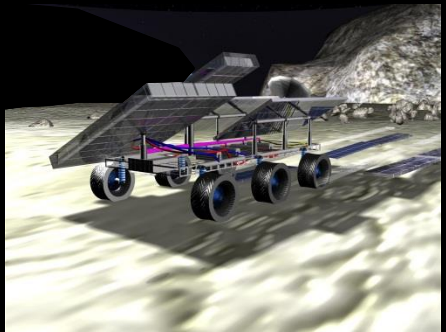
Polar Ice/Volatile Prospecting & Mining



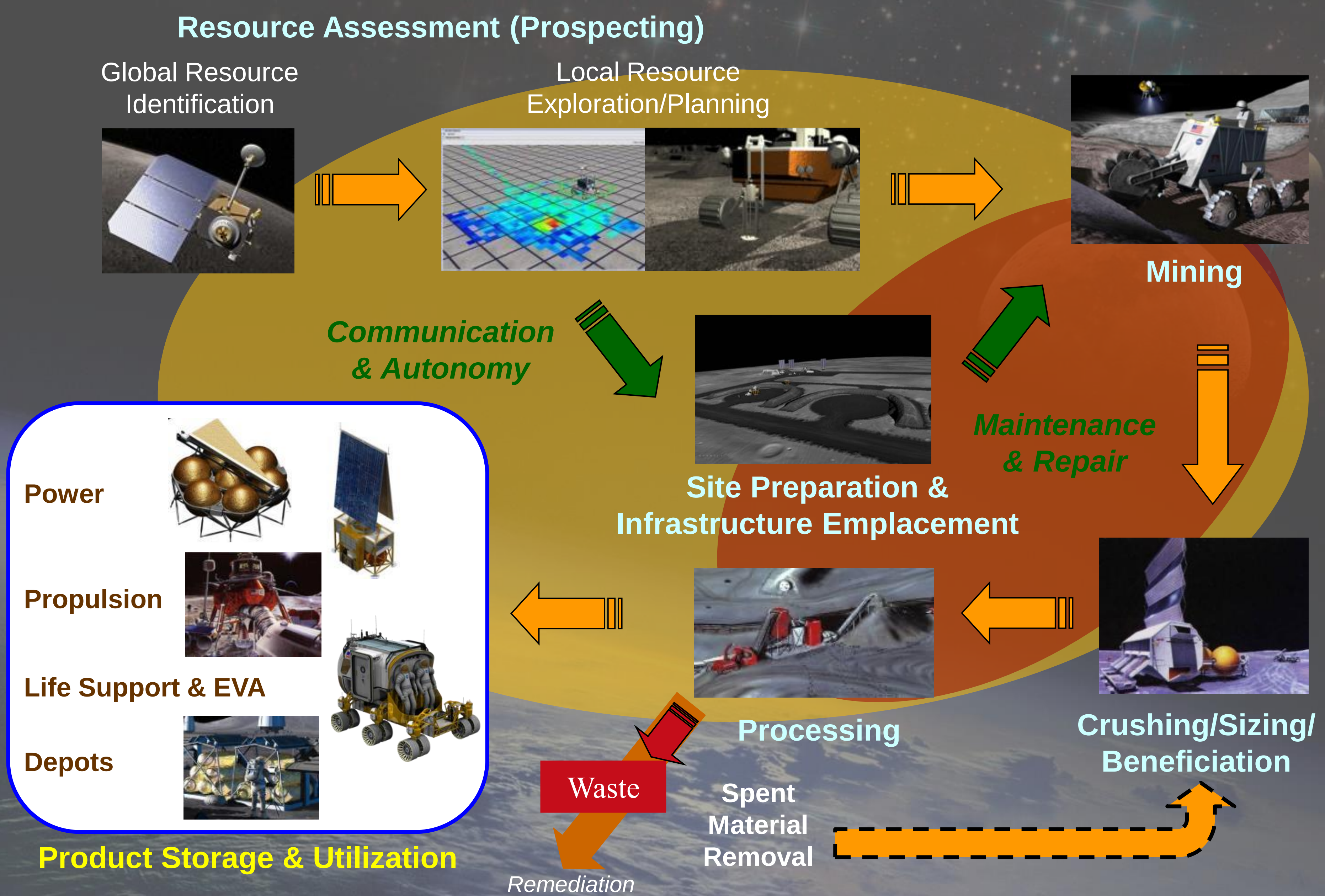
Landing Pads, Berm, and Road Construction

Solar and Thermal Energy Storage Construction





Space ‘Mining’ Cycle: *Prospect to Product*



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

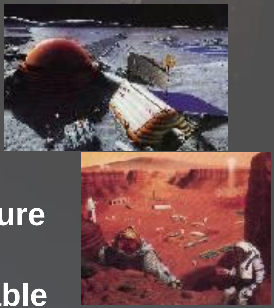
- Allows reuse of transportation systems
- Reduces number and size of Earth launch vehicles

Space Resource Utilization

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

Expands Human Presence



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

Solves Terrestrial Challenges & Enables Space Commercialization

- Develops alternative & renewable energy technologies
- New renewable construction
- CO_2 remediation
- Green metal production

- Provides infrastructure to support space commercialization
- Propellant/consumable depots at Earth-Moon L1 & Surface for Human exploration & commercial activities

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

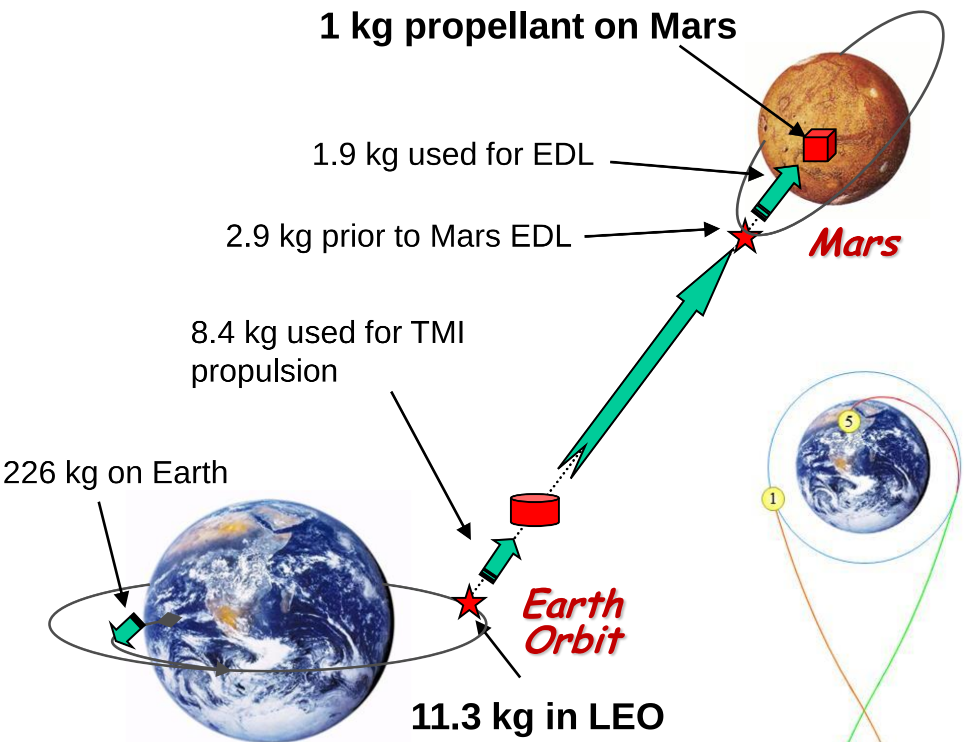
Supports Multiple Destinations

- 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

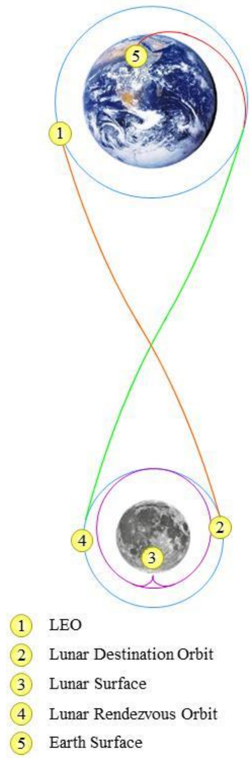
How ISRU Enables Future Moon & Mars Missions

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



Estimates based on Aerocapture at Mars



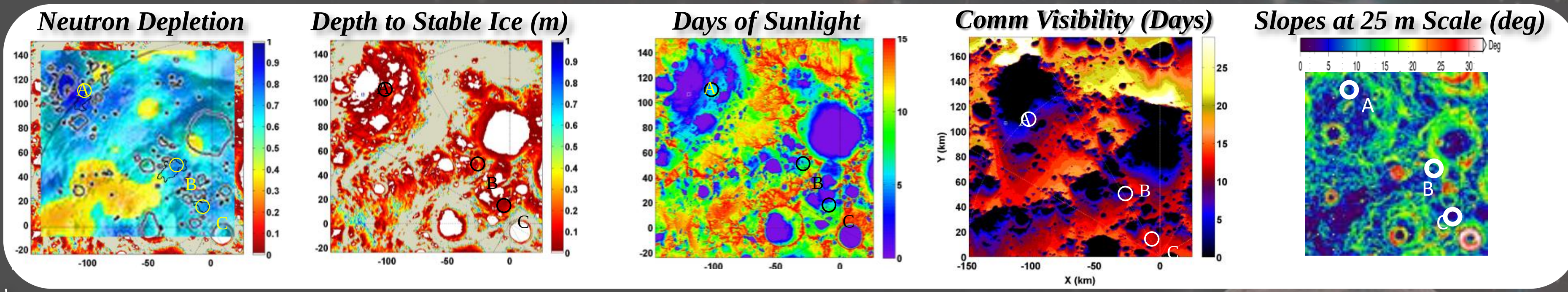
A Kilogram of Mass Delivered Here…	…Adds This Much Initial Architecture Mass in LEO	…Adds This Much To the Launch Pad Mass
Ground to LEO	-	20.4 kg
LEO to Lunar Orbit (#1→#2)	4.3 kg	87.7 kg
LEO to Lunar Surface (#1→#3; e.g., Descent Stage)	7.5 kg	153 kg
LEO to Lunar Orbit to Earth Surface (#1→#4→#5; e.g., 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

Implementation Strategy for Space Resource Utilization

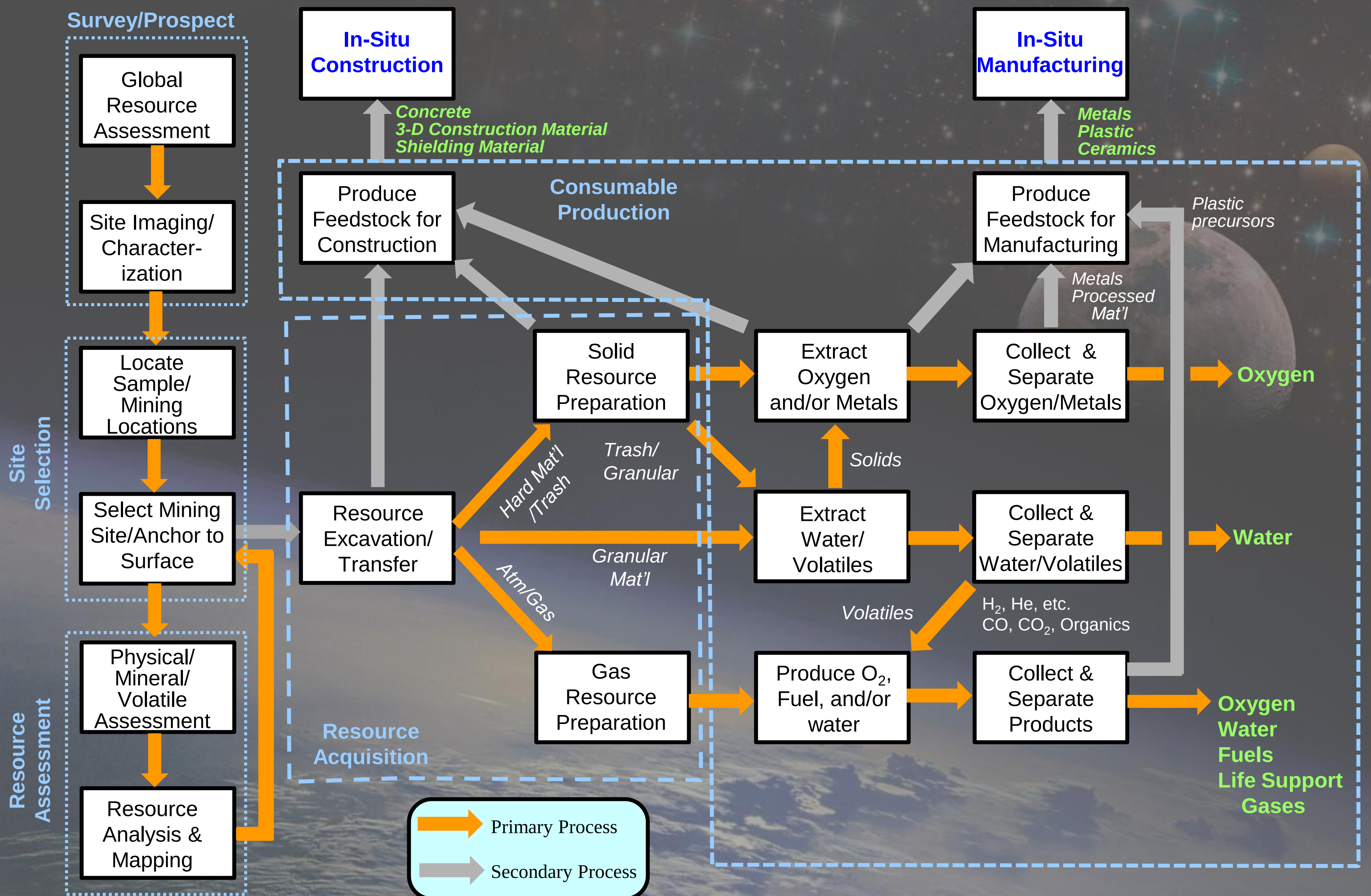
- **Three phases of ISRU implementation to minimize risk to human exploration plans**
  - **Phase 1: Scout and Demonstrate** – *Mission Feasibility*
    - Evaluate potential exploration sites: terrain, **geology/resources**, lighting, etc.
    - Demonstrate critical technologies, functions, and operations
    - 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



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) (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 Mars and NEOs/Phobos**
- **All destinations share common technologies, processes, and operations**

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

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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

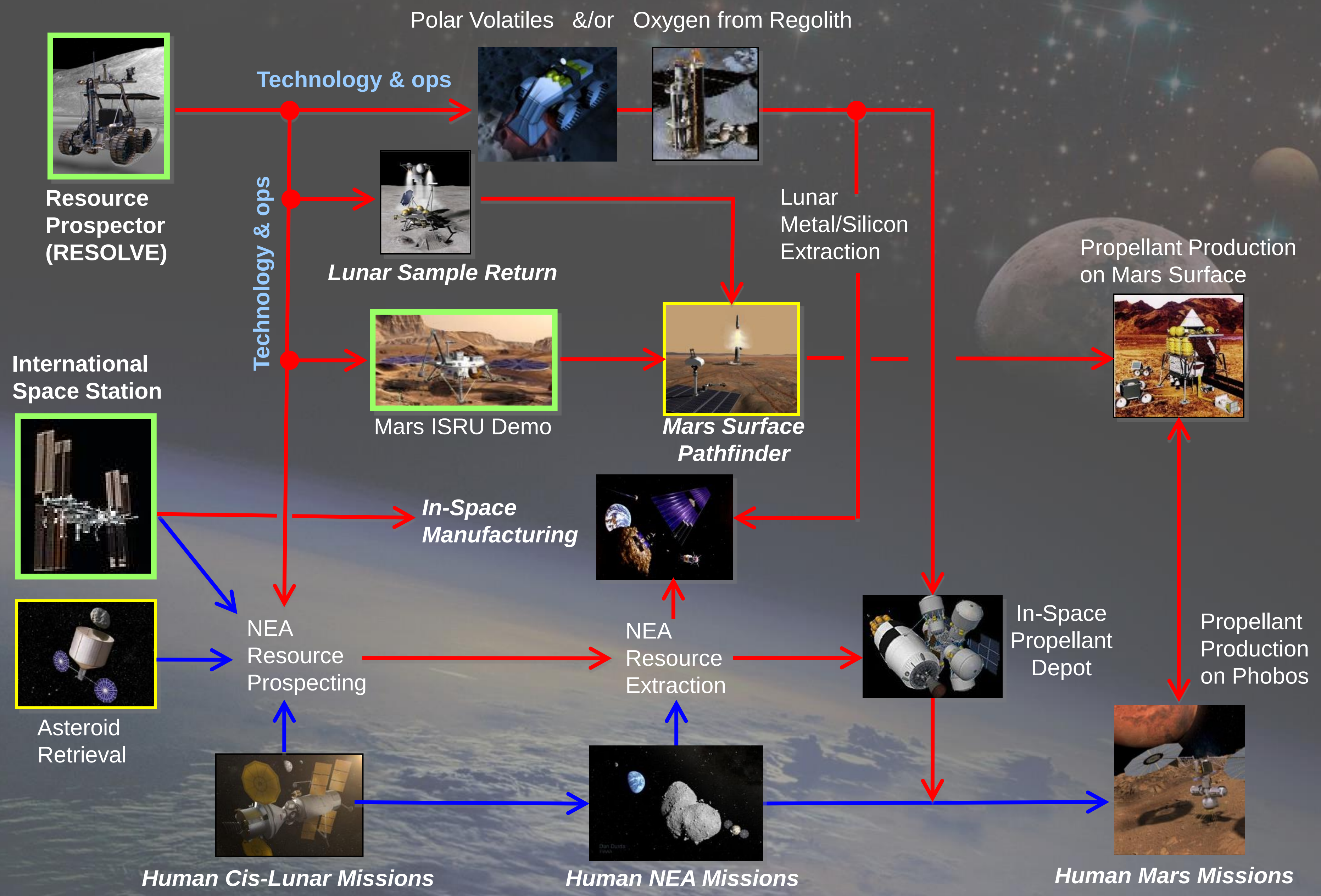
ISRU Development Areas	Resource Prospector (Moon, Mars, NEO)	Atmosphere Processing (Mars)	Regolith/Soil Processing for Water (Moon, Mars, NEO)	Material Processing for Oxygen/Metals (Moon, NEO)	Trash Processing to Fuel
Gas Processing					
Dust/Particle Filtration		X	X	X	X
CO_2 Capture - Separation		X		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

Notional Mission Evolution with ISRU

(for planning)



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?