LUNAR POLAR IN SITU RESOURCE UTILIZATION (ISRU) AS A STEPPING STONE FOR HUMAN EXPLORATION. Gerald B. Sanders, NASA-Johnson Space Center, 2101 NASA Parkway, Houston, TX,

Introduction: A major emphasis of NASA is to extend and expand human exploration across the solar system. While specific destinations are still being discussed as to what comes first, it is imperative that NASA create new technologies and approaches that make space exploration affordable and sustainable. Critical to achieving affordable and sustainable exploration beyond low Earth orbit (LEO) are the development of technologies and approaches for advanced robotics, power, propulsion, habitats, life support, and especially, space resource utilization systems. Space resources and how to use them, often called In-Situ Resource Utilization (ISRU), can have a tremendous beneficial impact on robotic and human exploration of the Moon, Mars, Phobos, and Near Earth Objects (NEOs), while at the same time helping to solve terrestrial challenges and enabling commercial space activities. The search for lunar resources, demonstration of extraterrestrial mining, and the utilization of resource-derived products, especially from polar volatiles, can be a stepping stone for subsequent human exploration missions to other destinations of interest due to the proximity of the Moon, complimentary environments and resources, and the demonstration of critical technologies, processes, and operations.

ISRU and the Moon: There are four main areas of development interest with respect to finding, obtaining, extracting, and using space resources: Prospecting for resources, Production of mission critical consumables like propellants and life support gases, Civil engineering and construction, and Energy production, storage, and transfer. The search for potential resources and the production of mission critical consumables are the primary focus of current NASA technology and system development activities since they provide the greatest initial reduction in mission mass, cost, and risk. Because of the proximity of the Moon, understanding lunar resources and developing, demonstrating, and implementing lunar ISRU provides a near and early opportunity to perform the following that are applicable to other human exploration mission destinations:

- Identify and characterize resources, how they are distributed, and the material, location and environment in which they are found;
- Demonstrate concepts, technologies, and hardware that can reduce the cost and risk of human exploration beyond Earth orbit;
- Use the Moon for operation experience and mission validation for much longer missions that are farther from Earth
- Develop and evolve ISRU to support sustained, economical human presence beyond Earth's orbit, including promoting space commercialization

As Table 1 depicts, the Moon provides environments and resources applicable to Mars and NEOs. Two lunar ISRU resource and product pathways that have notable synergism with NEO, Phobos/Demos, and Mars ISRU are oxygen/metal extraction from regolith, and water/volatile extraction from lunar polar materials. To minimize the risk of developing and incorporating ISRU into human missions, a phased implementation plan is recommended that starts with prospecting and demonstrating critical technologies on robotic and human missions, then performing pilot scale operations (in non-mission critical roles) to enhance exploration mission capabilities, leading to full utilization of space resources in mission critical roles. Which lunar ISRU pathway is followed will depend on the results of early resource prospecting/proof-of-concept mission(s), and long-term human exploration plans.

Table 1. Human Destination Characteristics

	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

Why the Lunar Poles and Resources?: The poles of the Moon provides an optimal location for sustained surface operations with areas of near permanent sunlight for power and habitats, and permanent shadow for power, science instruments, and resources. The shadowed areas at the lunar poles may contain large quantities of hydrogen and water as well as other volatiles that may be extremely helpful such as carbon monoxide, ammonia, and light hydrocarbons. With these resources, a wide range of consumables can be produced for propulsion, life support, and power. As with other locations on the Moon, oxygen and metals can also be extracted from the lunar regolith. From these resources, sustained and reusable transportation is possible for lunar surface-to-surface exploration, surface-to-orbit, and even cis-lunar space, as well as increased crew safety for life support and radiation shielding. Ultimately, ISRU propellants, consumables, and metals can enable the commercialization of cis-lunar space.

Determining Whether Operationally Useful Resources Exist at the Poles: While the Lunar Crater Observation and Sensing Satellite showed that hydrogen, water, and other volatiles exist in at least one shadowed crater at the lunar poles, and the Lunar Reconnaissance Orbiter and other scientific spacecraft show that these volatile resources may exist elsewhere, it is still necessary to determine whether the volatile resources at the poles are 'operationally useful', i.e. the usefulness of a resource is likely a function of its location and how economical it is to extract and use.

With respect to the location, the resource must be accessible , it must be within a reasonable distance of the mining infrastructure (including power, logistics, processing, etc.), and it must be within reasonable distance of transportation capabilities to ensure the product can reach the necessary 'markets'. For lunar polar volatiles, there are five main site selection criteria: 1) presence of surface/subsurface volatiles (neutron spectrometer, radar, optical), 2) traversable terrain, 3) limited solar illumination/subsurface temperature <100 K, traversable terrain, 4) direct to Earth communication, and 5) hospitable environment nearby for outposts and infrastructure.

For the resource extraction and processing to be economical, the concentration and distribution of the resource and associated processing technique must allow for a return on investment (ROI) for mass, cost, time, and/or mission and crew safety. This is highly dependent on what product is needed, how much is needed, how often it is needed, and what is required to extract the resource. During NASA's Constellation Program, a production need of 1000 kg of oxygen per year was desired to eliminate life support consumable delivery needs from Earth for a crew of 4 to 6. Performing first-order rocket equation propellant needs for a reusable lunar lander from the lunar surface to an Earth-Moon L_1/L_2 Lagrange point, somewhere between 3000 kg of oxygen to 30,000 kg of oxygen and hydrogen are required per mission depending on whether a depot at L_1/L_2 containing propellants from Earth are used for some of the mission phases. Laboratory tests to date have shown that infrastructure for oxygen extraction from regolith can provide mass and cost ROI for these production needs in less than 3 years.

To determine whether polar volatile resources are operationally useful, a three-phase approach of Exploratory Assessment, Focused Assessment, and Mining Feasibility is recommended. The Exploratory Assessment is potentially a short duration mission to evaluate the physical and mineral characteristics of polar regolith, determine the distribution of polar volatiles down to 1 to 2 meters and spatial distribution to 1 to 3 km, validate site selection methods, and validate the design and operation of the hardware. NASA's Resource Prospector Mission (RPM) and Russia's Luna 27 mission which are both tentatively scheduled for 2017/2018 will perform this type of resource assessment. If the site looks promising, a focused Assessment, possibly nuclear powered to allow for sustained operations in the shadowed region, should be pursued to fully assess the distribution of polar resources as well as determine the economics of extracting them. Finally, a mining feasibility mission (either demonstration or pilot scale) should be flown to validate mining and resource extraction and collection techniques for a sustained period of time.

Lunar Polar ISRU as a Stepping Stone for Human Exploration: Using NASA's Resource Prospector and Asteroid Retrieval concept missions as potential starting points, a notional evolutionary mission sequence can be constructed to guide in the selection and development of common technologies and systems that will minimize the cost and risk for development and utilization of space resources for multiple human exploration destinations. The International Space Station can also be utilized to begin the examination of micro-gravity effects on regolith collection, transport, and processing. Should NASA and other space agencies proceed from the initial lunar polar volatile Exploratory Assessment phase with RPM and Luna 27 to more Focused Assessments and Mining Feasibility, the ISRU and mission capabilities evolved and developed for these missions can serve as the basis for enabling other missions to NEA's, Phobos, and Mars.

Acknowledgement: Understanding of terrestrial prospecting and mining approaches were obtained from several presentations by Dale Boucher (NORCAT) and John Chapman (Chapman Mining Services). Definition of operationally useful resources has benefitted from discussions at the Keck Institute of Space Studies (KISS) study on New Approaches to Lunar Ice Detection and Mapping.

National Aeronautics and Space Administration

Lunar Polar ISRU as a Stepping Stone for Human Exploration

Presentation to
Lunar Exploration Analysis Group (LEAG) Workshop

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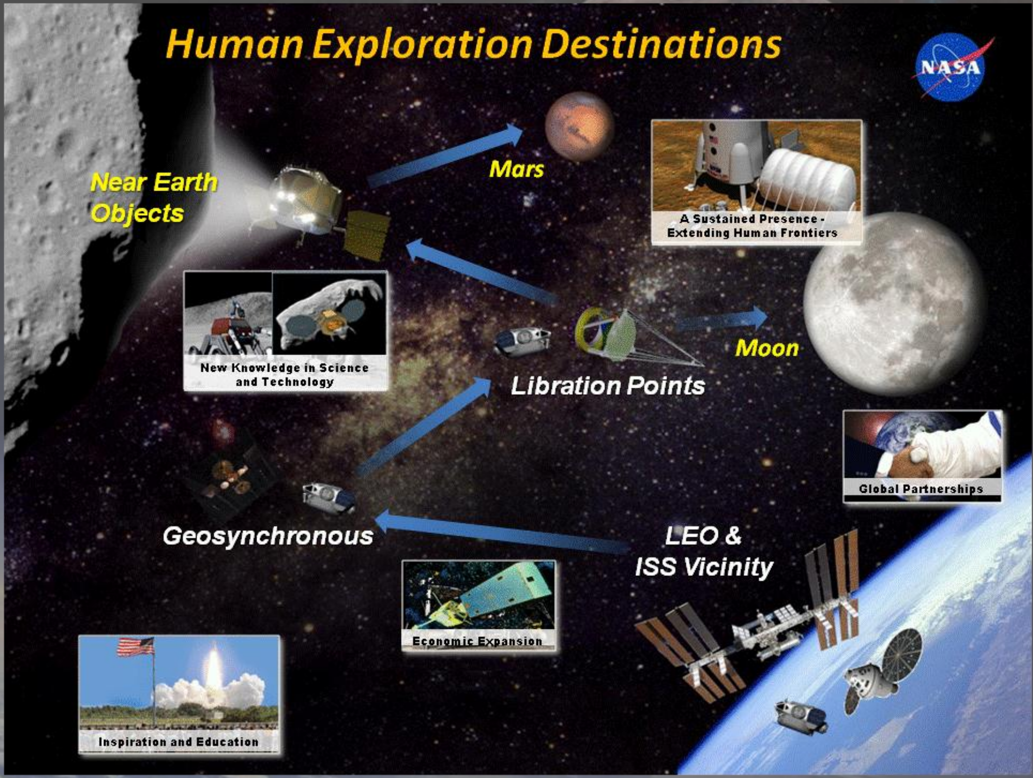
NASA Strategic Goals:

- Extend and sustain human activities across the solar system
- Create the innovative new space technologies for our exploration, science, and economic future

Affordable and Sustainable

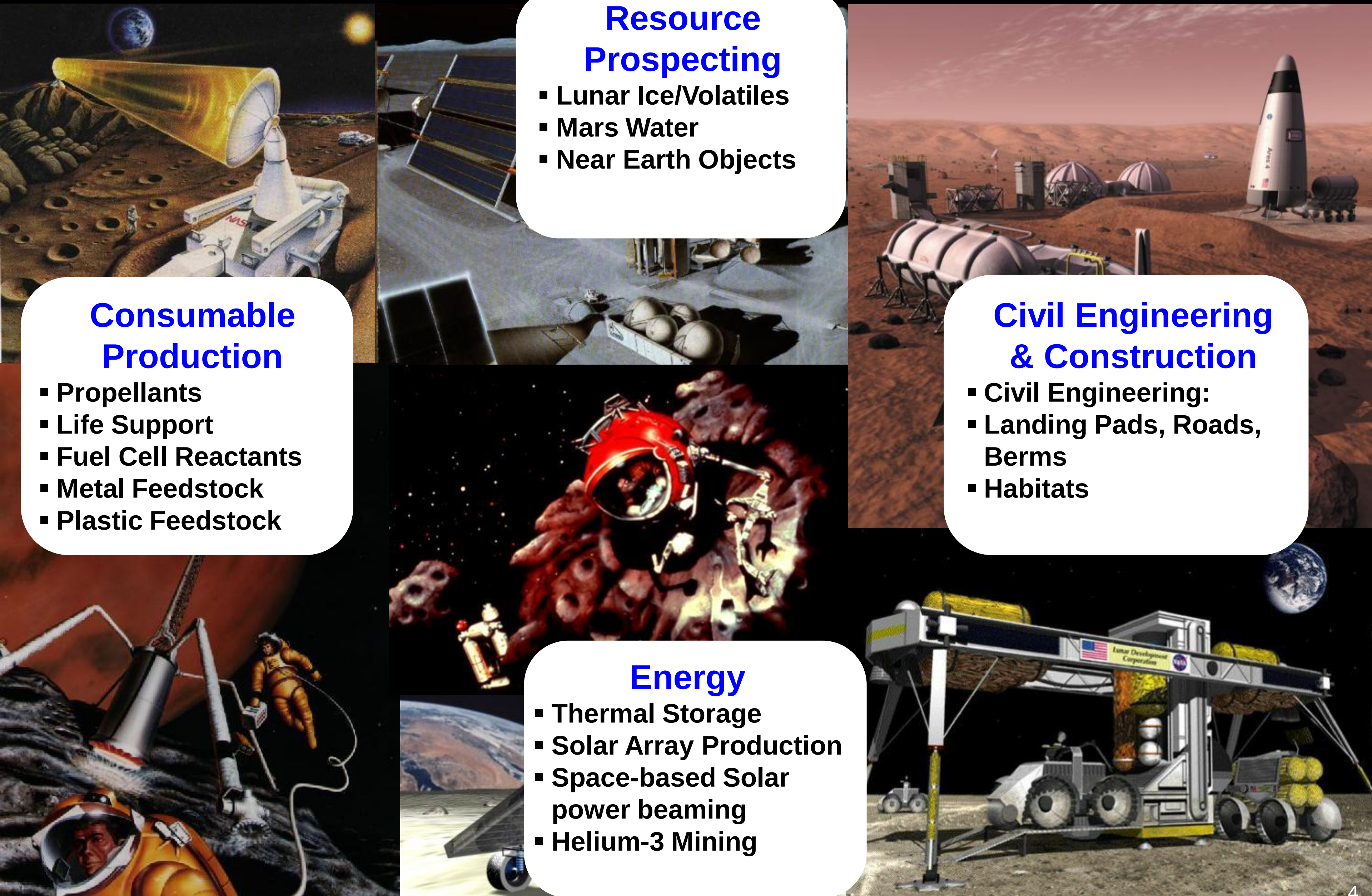
Critical for exploration beyond low Earth orbit

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



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

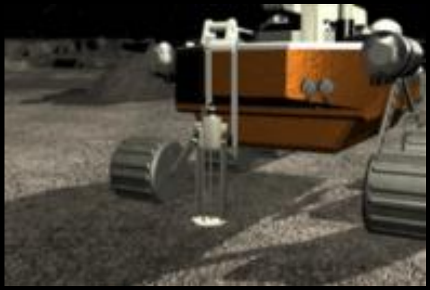
Civil Engineering & Construction

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

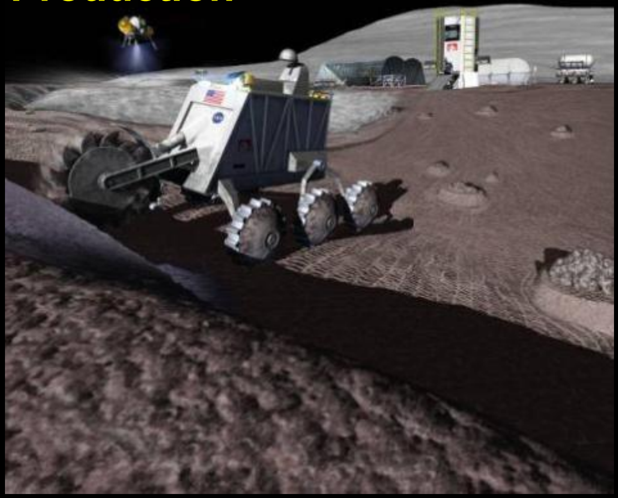
Energy

- Thermal Storage
- Solar Array Production
- Space-based Solar power beaming
- Helium-3 Mining

Potential Lunar ISRU Mission Capabilities

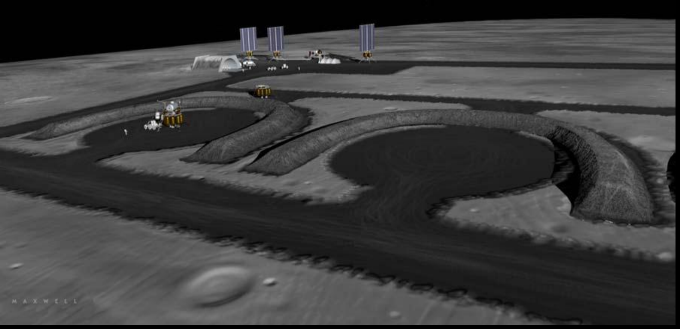


Excavation & Regolith Processing for O_2 Production



Consumable Depots for Crew, Power, & Propulsion

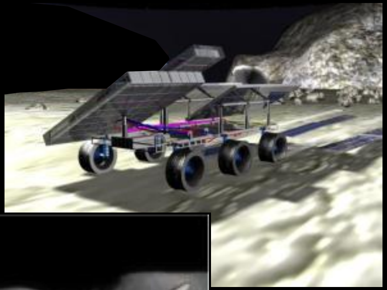
Polar Ice/Volatile Prospecting & Mining

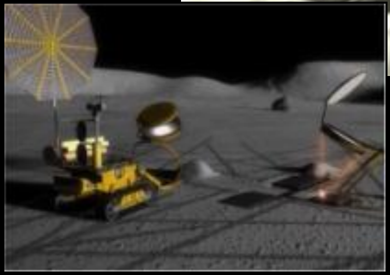


Landing Pads, Berm, and Road Construction

Structure and Habitat Construction

Solar and Thermal Energy Storage Construction





Lunar In Situ Resource Utilization (ISRU) Development & Incorporation Objectives

- Identify and characterize resources on Moon, especially polar region
- Demonstrate concepts, technologies, & hardware that reduce the cost & risk of human exploration beyond Earth orbit
  - Demonstrate capabilities and technologies applicable to multiple destinations; Asteroids, Phobos, and Mars
- Use Moon for operational experience and mission validation for Mars
  - Pre-deployment & activation of ISRU assets
  - Long-duration autonomous operations with restricted communications and maintenance
  - Making and transferring mission consumables
  - Landing crew with pre-positioned return vehicle or ‘empty’ tanks
- Develop and evolve ISRU to support sustained, economical human presence on the Moon and beyond
  - Surface operations
  - Lunar and space transportation
  - Crew safety
  - ➢ Commercialization of space

Moon, Mars, & Near Earth Objects (NEOs)

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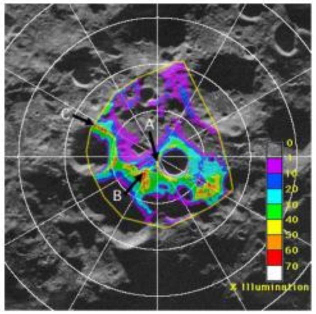
- **The Moon has aspects in common with Mars and NEOs/Phobos**
- **All destinations share common technologies, processes, and operations**

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

Why Lunar Polar Resources? – Game Changing for Human Exploration Architectures



Surface Location – *Optimal location for sustained surface operations*

- Areas of near permanent sunlight (>70% sunlight per year)
  - Lower thermal extremes and greater use of solar power
  - Regolith based resources for oxygen and metals
- Areas of permanent shadow
  - Cold locations for cryogenic storage, instruments, and thermal energy generation
  - Polar volatiles may include hydrogen, water, ammonia, carbon monoxide, and organics
- ISRU
  - Lunar polar ISRU may be good analog for C-type asteroid and Mars icy soil ISRU

Transportation – *Enables coordinated and sustained transportation*

- Enhances and/or Enables Reusable Space Transportation
  - Lunar Surface to Orbit (LLO or L_1/L_2) or direct return to Earth
  - Cis-lunar transportation (L_1/L_2 to GEO/LEO)
  - Surface-to-surface hopping
- L_1/L_2 propellant depots and staging enhances exploration beyond Cis-Lunar space

Crew Safety – *Increase Safety over Earth Supplied Capabilities*

- Backup to life support; reduces risk/need for full closure
- Increased radiation production with water/regolith over Earth supplied shielding

Commercialization of Space – *Reduce cost for sustained exploration*

- Lunar, cis-lunar, and LEO-to-GEO transportation services
- Propellant depots
- Energy for:
  - Lunar surface and cis-lunar space operations
  - Earth
- Resources for space and Earth industries/manufacturing
- Space tourism

Benefit of ISRU Derived Propellants is a Function of Lander Design, Use, & Rendezvous/Depot Orbit

Benefit

ISRU for Lunar Ascent/Descent & Other Destination Use

Deliver O_2/Fuel or Water to Depots for usage elsewhere
- Return to Earth (cis-lunar)
- Delivery to LEO
- NEO's and Mars

Requires reusable single stage lunar lander w/ substantial payload capability
- **Cryos vs Water**

ISRU for Lunar Ascent/Descent & Global Surface Exploration

Produce O_2 & Fuel

- **Requires reusable single stage lunar lander**
- **<u>Does not require orbital depot</u> for ascent/descent if both O_2 & fuel can be produced on the surface**

ISRU For Lunar Ascent Only

Propellant for Ascent Only; Descent Propellant from Earth or Orbital Depot

Approach considered for Constellation & most Lunar architecture studies since it supports two stage non-reusable lander concepts from start

The greater the Delta-V of maneuvers performed by ISRU-derived propellants, the greater the benefit

ISRU Implementation Strategy

- ISRU implementation is phased to minimize risk to human exploration plans
  - **Prospect 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.
  - **Pilot Scale Operation** – *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
  - **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 previous mission results
- Identify technologies and systems for multiple applications (ISRU, life support, power) and multiple mission (Moon, Mars, NEOs)
- Multinational involvement based on expertise and long-term objectives

Possible Lunar ISRU Pathways - Regolith O_2 and/or Polar Volatiles

Polar Resource/ISRU Proof-of-Concept Demo(s)

Oxygen Extraction from Regolith/Solar Wind Volatiles

Critical Function Demo

Pilot-Scale Operations

Polar Ice/Volatile Extraction

Purpose: ***Prospect***

- Understand and characterize the resources and environment at the lunar poles for science and ISRU
- Determine the 'economic' feasibility of lunar polar ice/volatile mining for subsequent use

Purpose: ***Demo***

- Verify critical processes & steps
- Verify critical engineering design factors for scale-up
- Address unknowns and Earth based testing limitations
- Identify life issues

Purpose: ***Begin to Utilize***

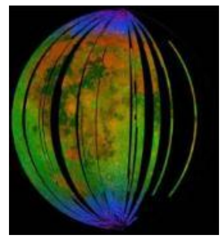
- Enhance or extend capabilities/reduce mission risk
- Verify production rate, reliability, and long-term operations
- Verify integration with other surface assets
- Verity use of ISRU products for full implementation

Which path depends on results of proof-of-concept mission(s)

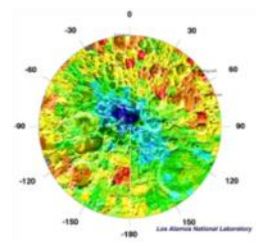
Global Assessment of Lunar Volatiles

Apollo Samples

Moon Mineralogical Mapper (M^3)

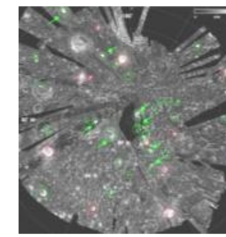


Lunar Prospector
Lunar Recon Orbiter (LRO)



Lunar Crater Observation & Sensing Sat. (LCROSS)

Clementine
Chandrayaan
LRO
Mini SAR/RF

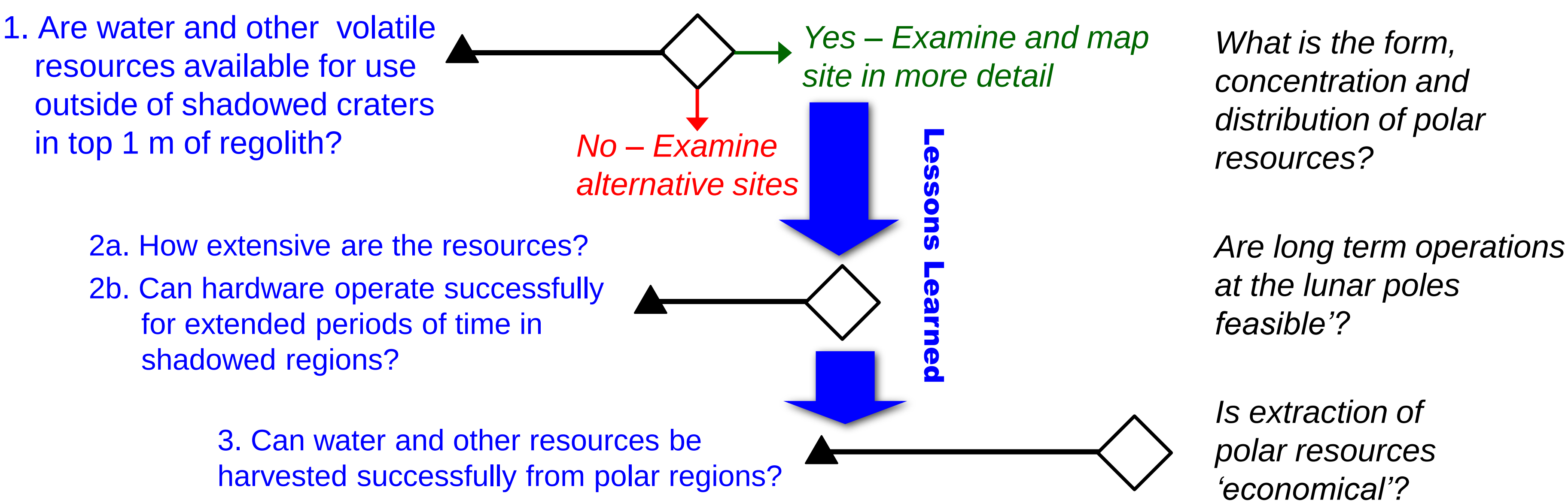


	Solar Wind	Core Derived Water	Water/Hydroxyl	Polar Volatiles	Polar Ice
Instrument	Apollo samples Neutron Spectrometer	Apollo samples	M3/LRO	LCROSS	Mini SAR/RF
Concentration	Hydrogen (50 to 150 ppm) Carbon (100 to 150 ppm) Helium (3 to 50 ppm)	0.1 to 0.3 wt % water in Apatite 0 to 50 ppm water in volcanic glass	0.1 to 1% water; 1-2% frost on surface in shadowed craters	**3 to 10% Water** equivalent Solar wind & cometary volatiles **(CO, H2, NH3, organics)**	Ice layers
Location	Regolith everywhere	Regolith; Apatite	Upper latitudes	Poles	Poles; Permanent shadowed craters
Environment	Sunlit	Sunlit	Low sun angle Permanent shadow <100 K	Low or no sunlight; Temperatures sustained at <100 K	<100 K, no sunlight
Depth	Top several meters; Gardened	Top 10's of meters	Top mm's of regolith	Below 10 to 20 cm of desiccated layer	Top 2 meters

What is Required to Utilize Lunar Volatile Resources?

- **Understand the resources**
  - What resources are there (minerals, volatiles, water/ice)?
  - How abundant is each resource?
  - What are the areal and vertical distributions and hetero/homogeneity?
  - How much energy is required to locate, acquire and evolve/separate the resources?
- **Understand environment impact on extraction and processing hardware**
  - What is the local temperature, illumination, radiation environment?
  - What are the physical/mineralogical properties of the local regolith?
  - Are there extant volatiles that are detrimental to processing hardware or humans?
  - What is the impact of the regolith and environment on sustained mechanical and processing activities?

A Stepwise Approach to Understanding Resources and Retiring Risk is Required



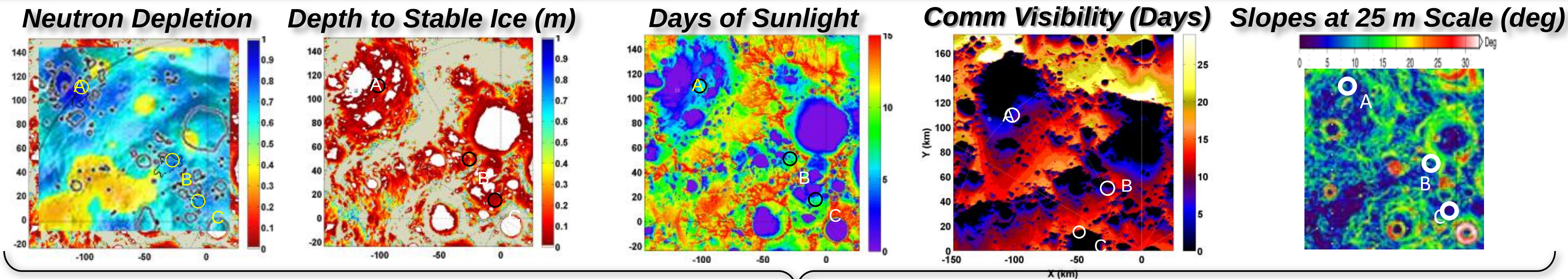
Determining 'Operationally Useful' Resource Deposits

Whether a resource is 'Operationally 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.

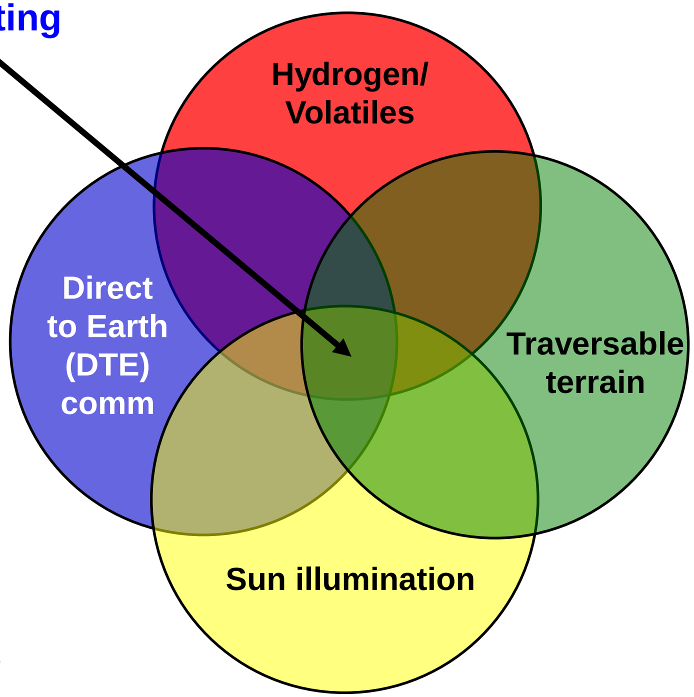
- **Resource extraction must be 'Economical'**
  - Concentration and distribution of resource and processing technique allows for Return on Investment (ROI) for:
    - Mass ROI - mass of equipment and unique infrastructure compared to brining product and support equipment from Earth
    - Cost ROI - 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 for radiation shielding, 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

Site Selection Criteria for *Initial Assessment* of Polar Volatiles for ISRU



Polar landing site based on meeting the following four Main criteria

1. Surface/Subsurface Volatiles
   - High hydrogen content (LRO LEND instrument)
   - Constant <100 K temperatures 10 cm below surface (LRO Diviner instrument)
   - Surface OH/H_2O (M^3, LRO LAMP)
2. Reasonable terrain for traverse
3. Direct view to Earth for communication
4. Sunlight for duration of mission for power generation (non-nuclear)



Criteria for Science missions can be different

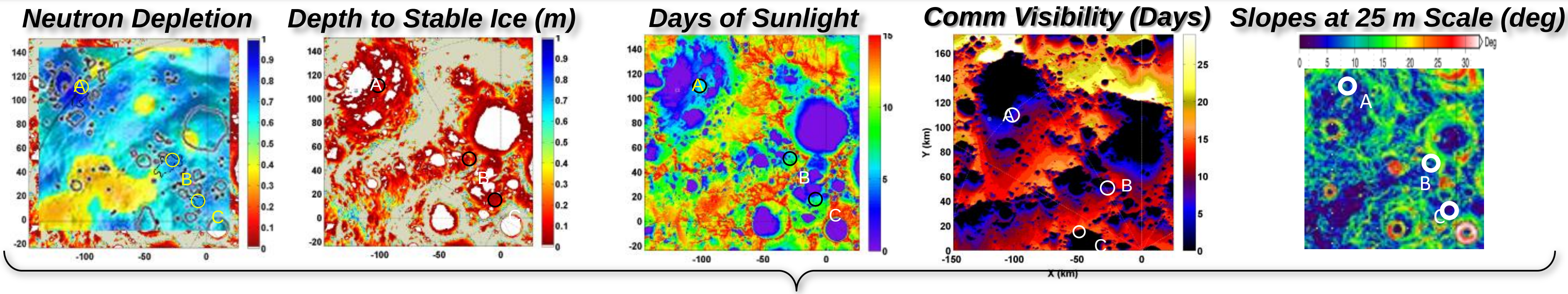
- Solar illumination not a criteria for battery (short duration) or nuclear (long-duration) powered mission concepts
- DTE excludes some polar craters and lunar farside locations unless a comm orbiter is available
- Traversable terrain not required for stationary landers, impacters, or penetrators

Competing Mission Drivers

Sunlit → Science Value → **Permanent Shadow**

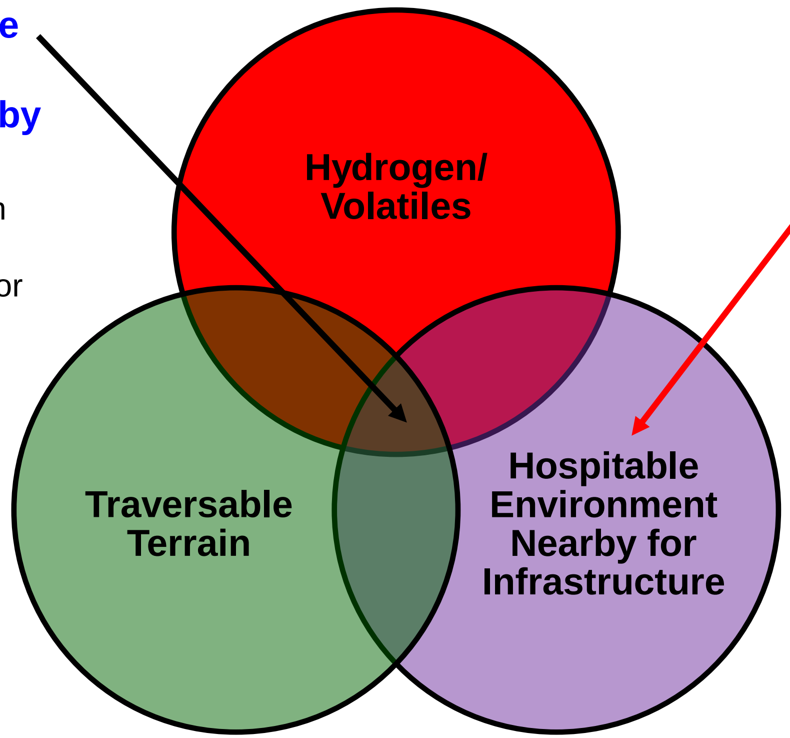
Months/Years ← Mission Duration ← **Hours/Days** (without Nuclear)

Site Selection Criteria for *Mining* of Polar Volatile for ISRU



Criteria for ISRU Mining can be different based on mining Infrastructure/Outpost at nearby Hospitable Environment

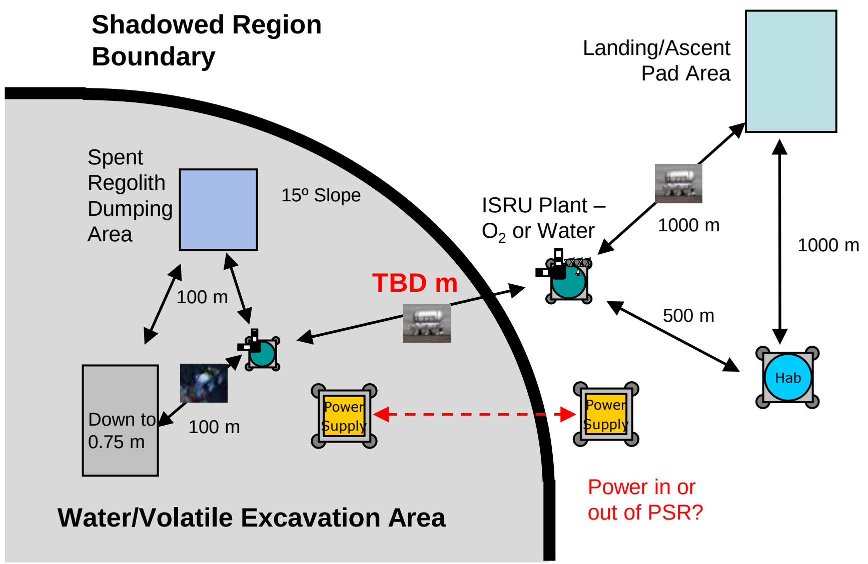
- Solar illumination at mining location not a criteria with power beaming from outpost/infrastructure nearby or for nuclear powered mission concepts
- DTE communication to mining location not required with relay from mining infrastructure



Understanding the geological context of polar volatiles across lunar polar regions is critical for selecting the mining and infrastructure location

Determining ‘Operationally Useful’ Resource Deposits - *Location*

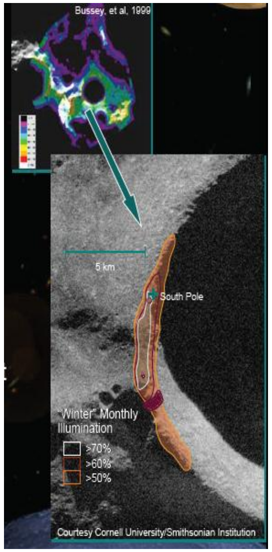
Need to assess the location of the ‘ore body’



Polar region
- Solar >70% per year with 100 hr max. eclipse periods
- Highland regolith (iron poor)

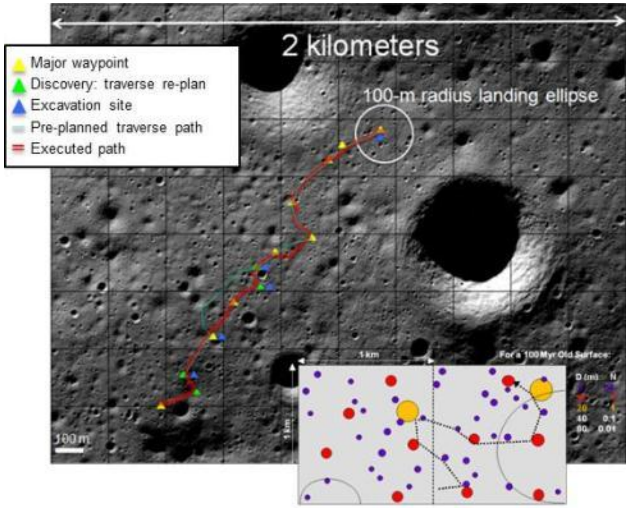
Permanently Shadowed Crater
- Nuclear power, power cable, or power beamed for elements that stay in the crater.

Equatorial region
- Solar 50% per year with 28+ day/night cycle
- High titanium/iron oxide

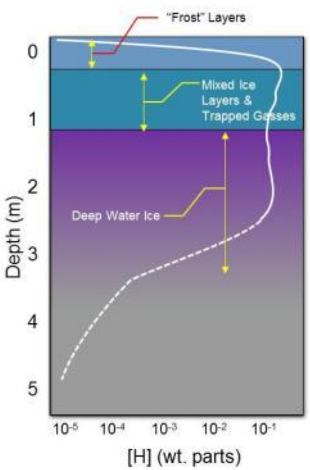


Need to assess the extent of the resource ‘ore body’

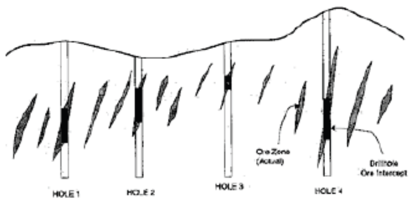
Need to Evaluate Local Region (1 to 3 km)



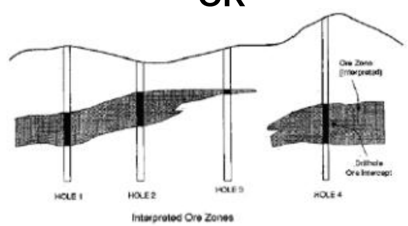
Need to Determine Vertical Profile



Need to Determine Distribution



OR



Determining 'Operationally Useful' Resource Deposits - *Economics*

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

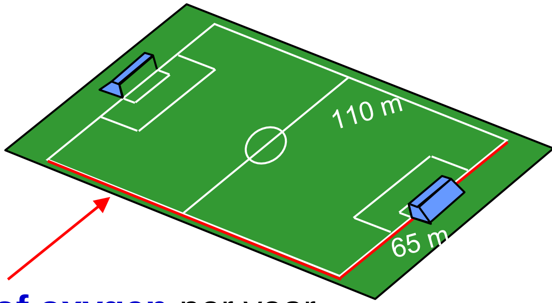
Potential Lunar Resource Needs

- 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)*

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

Mining Equipment – Oxygen Extraction

- Excavation rates required for 10 MT O_2/yr production range based on Oxygen extraction efficiency of process selected and location
  - Hydrogen reduction at poles (~1% extraction efficiency): 150 kg/hr
  - Carbothermal reduction (~14% extraction efficiency): 12 kg/hr
  - Electrowinning (up to 40%): 4 kg/hr

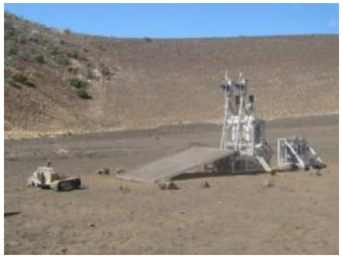


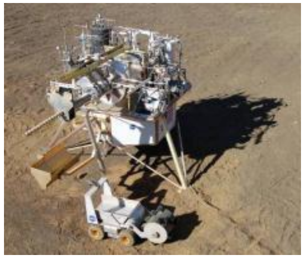
10 MT of oxygen per year requires excavation of a soccer field to a depth of 0.6 to 8 cm**!** **(1% & 14% efficiencies)**

- Laboratory tests showed high excavation rates of 150 to 250 kg/hr for **SMALL** excavation vehicle (<150 kg)

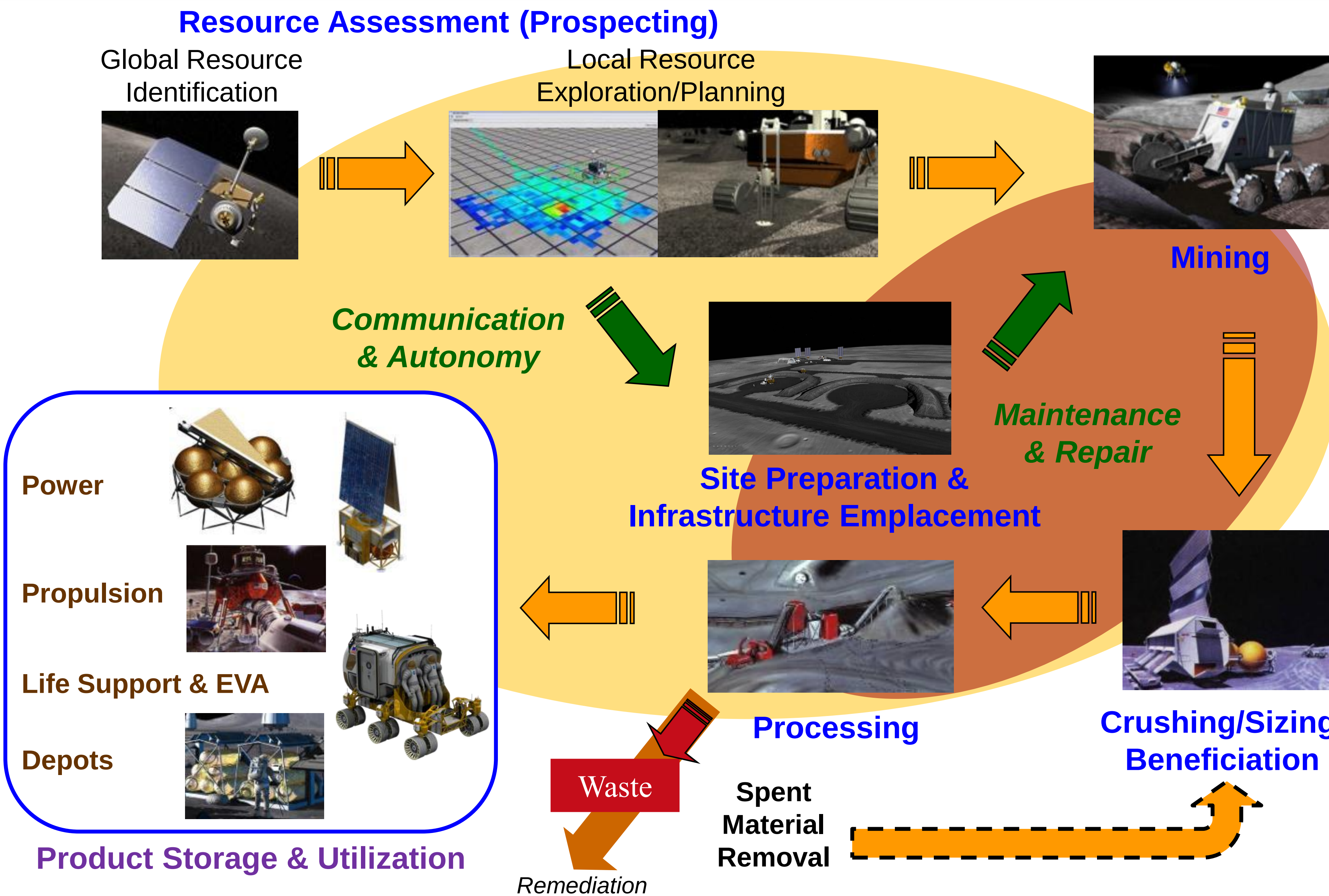
Cratos Excavator

- Analog field test show oxygen extraction from regolith doesn't required excessive processing equipment/infrastructure





Space 'Mining' Cycle: *Prospect to Product*

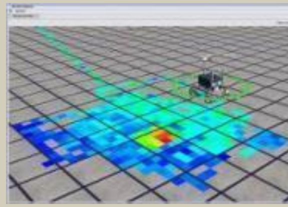


Space 'Mining' Cycle: *Prospect*

Resource Assessment (Prospecting)

Global Resource Identification

Local Resource Exploration/Planning



Mining

Type and Scale of Prospecting Needed to Utilize Lunar Volatiles

Exploratory Assessment

- Short duration mission:
  - 5 to 9 days
  - Hours in shadowed area
- Evaluate physical and mineral properties of polar regolith
- Evaluate distribution of polar volatiles in 1 to 3 km area
  - Neutron & Near IR spectrometer
  - 3 to 5 cores; 1 to 2 meters deep
  - GC, MS & IR volatile measurements
- Validate site selection approach for locating volatiles at lunar poles
  - Missions to different destinations?
  - Data sharing or competitors?
- Validate design and operation of hardware

Resource Prospector (RESOLVE)

Luna 25/27

Focused Assessment

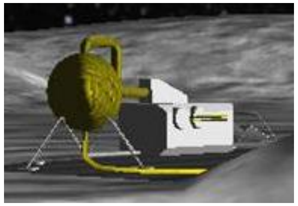
- Long duration mission:
  - 6+ months
- Perform more extensive evaluation of volatile distribution in polar region: larger area and more samples
- Demonstrate extended operations in polar shadowed region
- Examine contaminants in water
- Validate site selected for long-term mining operations
- *Map the location & concentration of the lunar volatile resources*

Economic Feasibility Assessment

RLEP-2 Type Mission

Mining Feasibility

- Demonstrate ISRU hardware for sustained excavation, processing, collection and storage of polar water and other volatiles of interest present
- Demonstrate water cleaning, and processing
- Demonstrate fuel production (from carbon-bearing volatiles)
- Demonstrate long-term storage of products (O_2, CH_4)
- Demonstrate power system for extended duration operations in polar shadowed region
- *Determine mining, transportation, infrastructure and logistics needs to sustain mining operations*



Number of missions required depends on hardware, mission concepts, and amount of information obtained

Resource Prospector Mission

Regolith & Environmental Science and Oxygen & Lunar Volatile Extraction (RESOLVE)

RPM is an internationally developed (NASA and CSA) mission/payload that that can perform two important missions for Science and Human Exploration of the Moon

Prospecting Mission: (Polar site)

- ✓ **Verify the existence of and characterize the constituents and distribution of water and other volatiles in lunar polar surface materials**
  - **Map the surface distribution of hydrogen rich materials**
  - **Determine the mineral/chemical properties of polar regolith**
  - **Measure bulk properties & extract core sample from selected sites**
    - To a depth of 1m with minimal loss of volatiles
  - **Heat multiple samples from each core to drive off volatiles for analysis**
    - From <100K to 423 K (150° C)
    - From 0 up to 100 psia (reliably seal in aggressively abrasive lunar environment)
  - **Determine the constituents and quantities of the volatiles extracted**
    - Quantify important volatiles: H_2, He, CO, CO_2, CH_4, H_2O, N_2, NH_3, H_2S, SO_2
    - Survive limited exposure to HF, HCl, and Hg

ISRU Processing Demonstration Mission: (Equatorial and/or Polar Site)

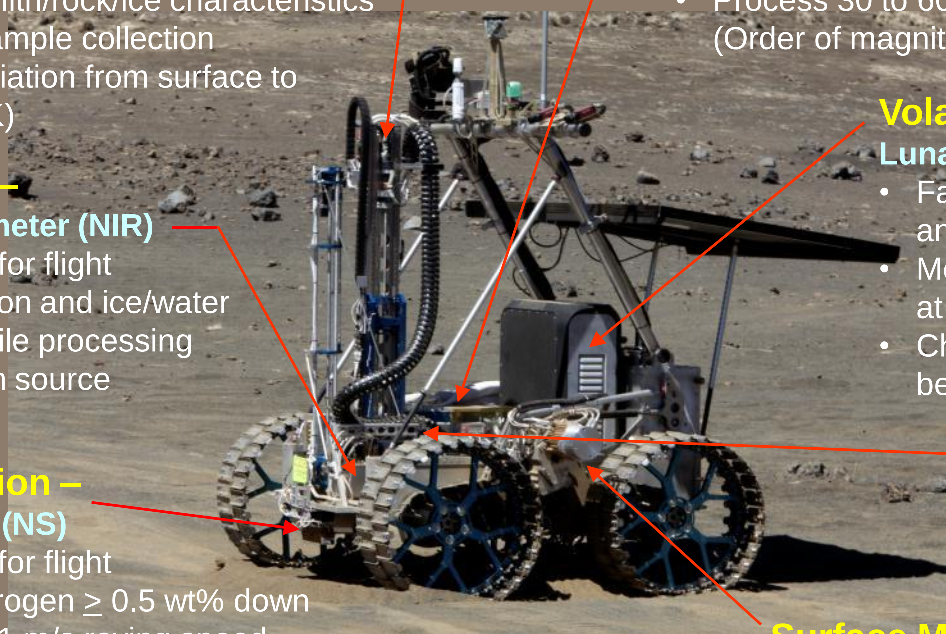
- ✓ **Demonstrate the Hydrogen Reduction process to extract oxygen from lunar regolith**
  - **Heat sample to reaction temperature**
    - From 150° C to 900° C
  - **Flow H_2 through regolith to extract oxygen in the form of water**
  - **Capture, quantify, and display the water generated**

Resource Prospector Mission (RPM)

Sample Acquisition –
Auger/Core Drill [CSA provided]
- Complete core down to 1 m; Auger to 0.5 m
- Minimal/no volatile loss
- Low mass/power (<25 kg)
- Wide variation in regolith/rock/ice characteristics for penetration and sample collection
- Wide temperature variation from surface to depth (300K to <100K)

Sample Evaluation –
Near Infrared Spectrometer (NIR)
- Low mass/low power for flight
- Mineral characterization and ice/water detection before volatile processing
- Controlled illumination source

Resource Localization –
Neutron Spectrometer (NS)
- Low mass/low power for flight
- Water-equivalent hydrogen ≥ 0.5 wt% down to 1 meter depth at 0.1 m/s roving speed



Volatile Content/Oxygen Extraction –
Oxygen & Volatile Extraction Node (OVEN)
- Temperature range of <100K to 900K
- 50 operations nominal
- Fast operations for short duration missions
- Process 30 to 60 gm of sample per operation (Order of magnitude greater than TEGA & SAM)

Volatile Content Evaluation –
Lunar Advanced Volatile Analysis (LAVA)
- Fast analysis, complete GC-MS analysis in under 2 minutes
- Measure water content of regolith at 0.5% (weight) or greater
- Characterize volatiles of interest below 70 AMU

Operation Control –
Flight Avionics [CSA/NASA]
- Space-rated microprocessor

Surface Mobility/Operation
[CSA mobility platform]
- Low mass/large payload capability
- Driving and situation awareness, stereo-cameras
- Autonomous navigation using stereo-cameras and sensors
- NASA contributions likely for communications and thermal management

RESOLVE Instrument Suite Specifications
- Nom. Mission Life = 4+ cores, 5-7 days
- Mass = 80-100 kg
- Dimensions = w/o rover: 68.5 x 112 x 1200 cm
- Ave. Power; 200 W

Lunar Resource Prospecting Instruments

	Resource Instruments Recommended for RLEP-2 Mission	RESOLVE	Luna 27	Optimal Prospector
Lander Instruments				
Site Characterization & Operation Support	Stereo Imaging System Beacon (navigation/data reference)	360° camera capability	TV imaging X	360° camera capability X Comm & Power
Dust Properties	Langmuir probe (levitated dust) Particle counter (levitated dust) Electron Paramagnetic Resonance Spectrometer (determine reactivity of dust for biologic implications)		Dust measurements Measuremetns of plasma/neutrals	
Physical/Geotechnical Properties	Arm Magnets (for magnetic susceptibility) Shear vane/Cone penetrometer		Possible arm/scoop Drill (2 m) Direct thermal measurement	
Subsurface Properties			Sesimic activity measurement Radio measurements of temperature	
Mineral Characterization	Sample Processing System (TBD)		IR, UV, gamma ray spec. Optical imaging	
Volatile Characterization	Sample Processing System (TBD)		Sample Processing System GC/MS and Laser MS	
Mobile Instruments				
Site & Terrain Properties	Stereo Imaging System	Navigation and drill site imaging		Navigation anddrill site imaging
Dust Properties	Magnets (for magnetic susceptibility)			Magnets Microscope
Physical/Geotechnical Properties	Drill (2 m) Arm/Scoop Shear vane/Cone penetrometer	X (1 m) - Measure while drilling	TBD	X - Cone Penetrometer/Shear Vane Regolith thermal measurement
Subsurface Properties	Neutron Spectrometer Subsurface: Ground Penetrating Radar	X -		Neutron & Gamma Spec GPR and/or Microwave Sounder
Mineral Characterization				Mossbauer/XRF Raman and LIBS
Volatile Characterization	Sample Processing System GC/MS Tuneable Diode Laser	X X Near IR: H_2O/OH Eval		X X TDL or Raman

Finding to Utilizing Polar Water/Volatiles -
Possible Evolution of Surface Systems

RPM Mission 1
Exploratory Assessment

RESOLVE 1.0 | Polar Rover 1.0

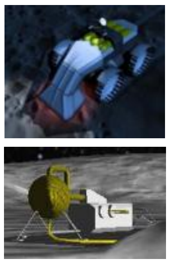
- Short Duration Mission
  - Short duration in shadowed area (hrs)
- Validate design and operation of hardware
- Evaluate distribution of polar volatiles in 1 to 3 km area
- Validate site selection approach for locating volatiles at lunar poles

RPM Mission 2
Focused Assessment

RESOLVE 1.1 | Polar Rover 1.1 | Polar Power 1.0

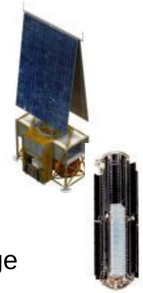
- Upgrade rover for longer term operation on the Moon and in shadowed areas
- Perform more extensive evaluation of volatile distribution in polar region: larger area/more samples
- Upgrade physical/mineral instruments
- Examine purity of water collected & possibly test cleaning technique
- Demonstrate power system for extended duration operations in polar shadowed region (*Note: mass estimate is based on remainder of lander payload capability*)

IceMiner Mission
Mining Feasibility



Rover 2.0 w/ Excavation & Processing

Water Plant & Product Storage



Polar Power 1.1

- Finalize polar rover design (tandem rover possible)
- Demonstrate ISRU hardware for sustained excavation, processing, and collection of polar water/volatiles
- Demonstrate water cleaning, processing, and storage
- Demonstrate fuel production (from carbon-bearing volatiles)
- Upgrade power system for polar operations
- ➢ *Note: Size of stationary processing unit will be a function of lander payload and desired processing scale*

Approach to Minimize Cost for ISRU

- Utilize evolutionary and modular approach to hardware design to allow for flexibility in mission payloads and growth in system capabilities
- Reutilize or slightly modify lander, rover, and payload from *RPM* to maximum extent possible for subsequent missions
  - Reuse/modify rover for prospecting, excavation, and mobile mining operations
  - Modify RESOLVE reactor/GCMS for *OxMiner* demonstration
- Identify technology and hardware shared with other applications (*Most hardware is not ISRU mission specific*)
  - Water electrolysis and storage hardware with life support and regenerative power
  - Fuel cells and power beaming hardware with space and terrestrial power
  - Oxygen liquefaction and storage hardware with propulsion/lander
  - Rovers with Exploration and Science
- Utilize extra lander payload capability for secondary goal demonstrations
- International partnerships:
  - Direct involvement: ex. CSA RESOLVE drill and rover, international lander, etc.
  - Indirect involvement: data from other lunar missions (ex. *Luna 25/27*)
- Commercial partnerships:
  - Google X Prize landers and rovers
  - Potential cost share with propellant production service provider for *IceMiner* and *IceStation* missions

Exploration Forward: Technologies, Systems, and Operations are Extensible to Mars Exploration and Possibly NEAs*

- *Resource Prospector* Mission 1
  - Subsurface sample acquisition and handling
  - Technologies for Mars soil/water characterization
  - Planetary lander & Precision landing
  - Limited rover/payload autonomy
- *Resource Prospector* Mission 2. Potential upgrades
  - Greater precision landing
  - Greater rover/payload autonomy
  - Water capture and purity evaluation
  - Possible sample caching demonstration
  - Advanced power systems
- *IceMiner* mission.
  - More capable planetary lander
  - Mars polar icy soil/permafrost excavation
  - Icy soil processing to extract water
  - Water cleaning and processing
  - Fuel production from carbon-bearing volatiles
  - Oxygen liquefaction and storage
  - Power beaming and/or nuclear power
  - Increased rover and payload operation autonomy
  - Long duration soil excavation and processing operation in dusty/thermal environment

❖ *Impact of gravity on technologies and processes requires further examination for NEA mission applicability*

Stepping Stone Approach for Demonstration & Utilization of Space Resources

Microgravity Processing & Mining

ISS & Space Habitats

ISRU Focus
- Trash Processing into propellants
- Micro-g processing evaluation
- In-situ fabrication

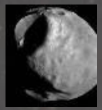
Purpose: Support subsequent robotic and human missions beyond Cis-Lunar Space

Near Earth Asteroids & Extinct Comets

ISRU Focus
- Micro-g excavation & transfer
- Water/ice prospecting & extraction
- Oxygen and metal extraction
- In-situ fabrication & repair
- Trash Processing

Purpose: Prepare for Phobos & future Space Mining of Resources for Earth

Phobos



ISRU Focus
- Micro-g excavation & transfer
- Water/ice and volatile prospecting & extraction

Purpose: Prepare for orbital depot around Mars

Planetary Surface Processing & Mining

Moon

ISRU Focus
- Regolith excavation & transfer
- Water/ice prospecting & extraction
- Oxygen and metal extraction
- Civil engineering and site construction

Purpose: Prepare for Mars and support Space Commercialization of Cis-Lunar Space

Mars

ISRU Focus
- Mars soil excavation & transfer
- Water prospecting & extraction
- Oxygen and fuel production for propulsion, fuel cell power, and life support backup
- Manufacturing & Repair

Purpose: Prepare for human Mars missions

ISRU Development Areas vs Mission Applications & Destinations

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

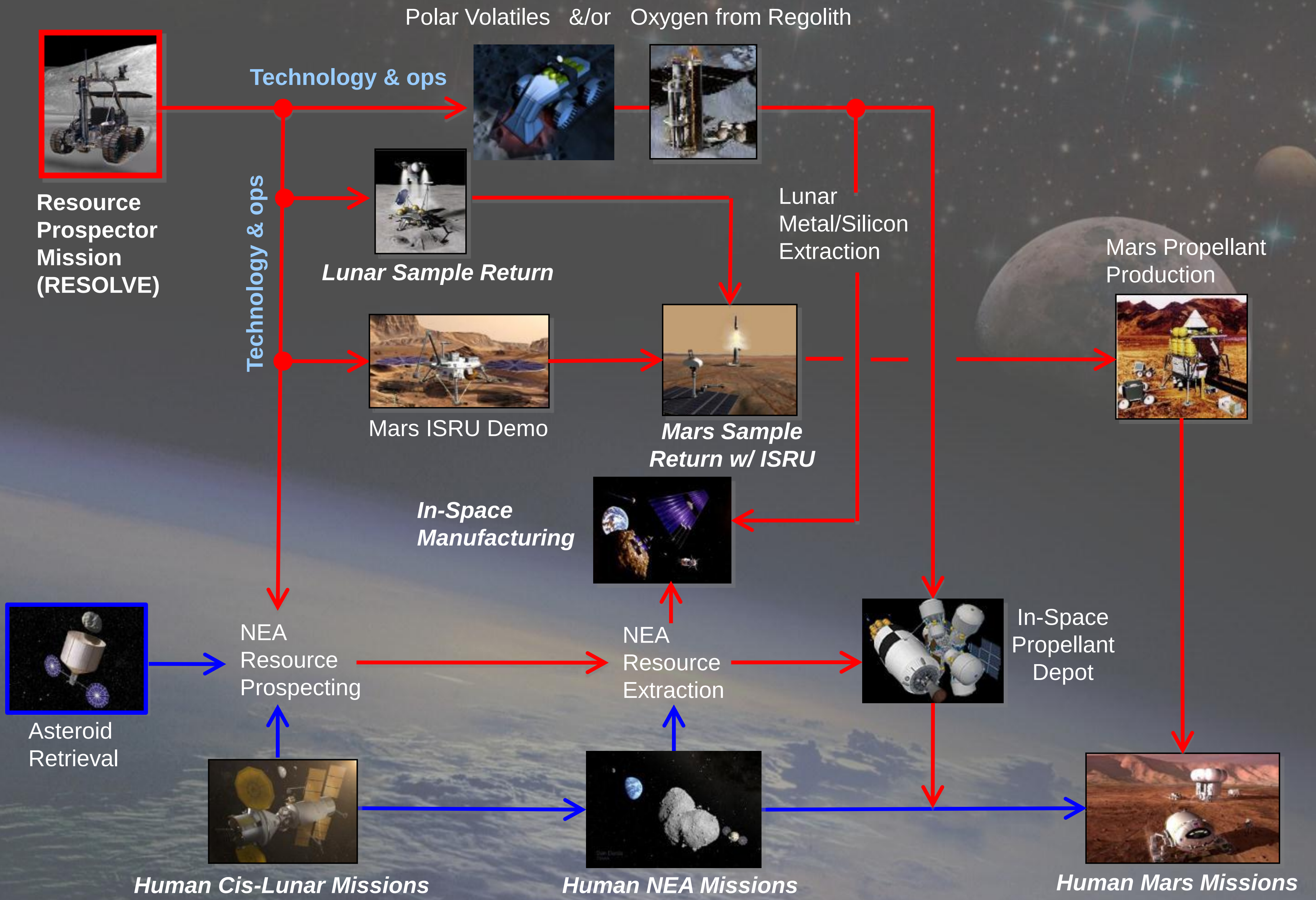
ISRU Development Areas	Resource Prospector (Moon, Mars, NEO)	Atmosphere Processing for Oxygen and Fuel (Mars)	Regolith/Soil Processing for Water (Moon, Mars, NEO)	Material Processing for Oxygen Extraction (Moon, NEO)	Material Processing for Metal Extraction (Moon, NEO)	Trash Processing to Water & Fuel
Atmosphere/Gas Collection						
Dust/Particle Filtration		X	X	X	X	X
CO_2 Capture - Separation		X		P		X
N_2 & Ar Capture - Separation						
Gas Processing						
CO_2 Conversion into CO-O_2		X				
CO/CO_2 Conversion into H_2O-CH_4		P		P	P	X
Gas-Gas Separation & Recycling		X	P	P	P	X
Water Processing						
Water Capture	X		X	X		X
Water Cleaup - Purity Measurement			X	X		X
Water Electrolysis		P	X	P		X
Regenerative Dryers		P	X	P		X
Support Systems						
Extended Polar Operation Power Systems	P		P	P	P	
Extended Polar Operation Thermal Systems	P		P	P	P	
Mobility	X		X	X	X	
Cryogenic Liquefaction, Storage, and Transfer		X		X		P
Autonomous Operation	X	X	X	X	X	

X = Needed; P = Possible need

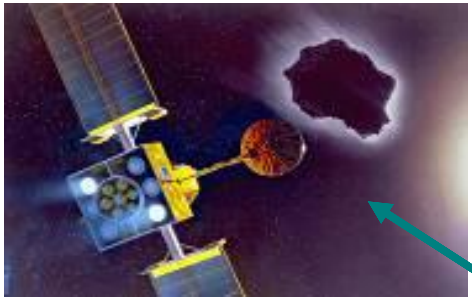
Main Discriminators: material (physical, mineral) water content/form (ice, hydration, surface tension), gravity (micro, low), pressure, (vacuum, atm.), and weathering

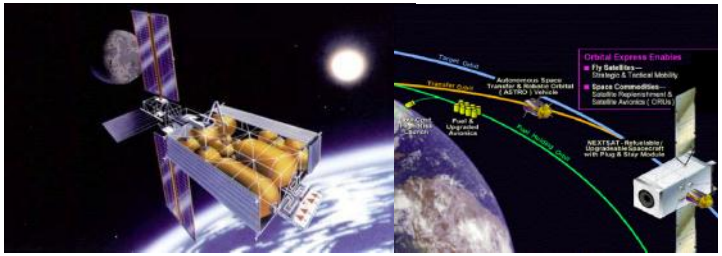
Notional Mission Evolution with ISRU

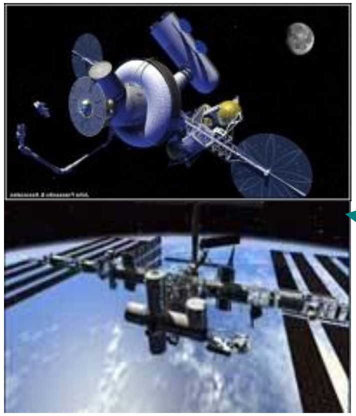
(for planning)

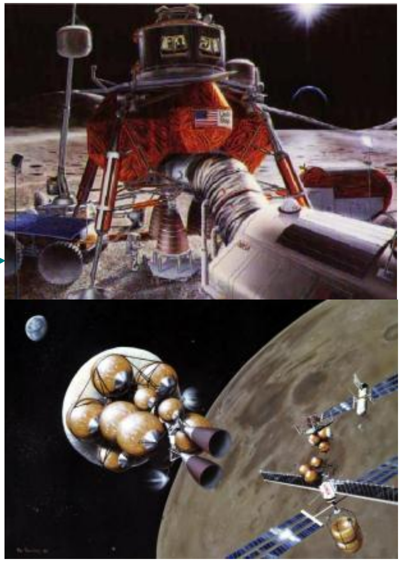


Commercial Markets for Lunar/NEA ISRU Derived Propellants & Materials









NASA-Science

Debris Management

Satellite Servicing & Refueling

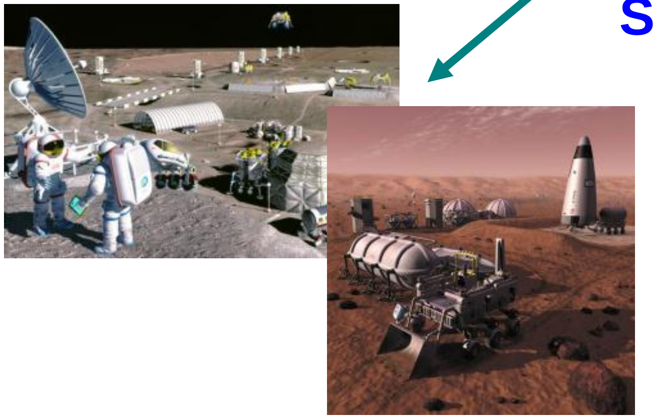
Lunar & Space Transportation

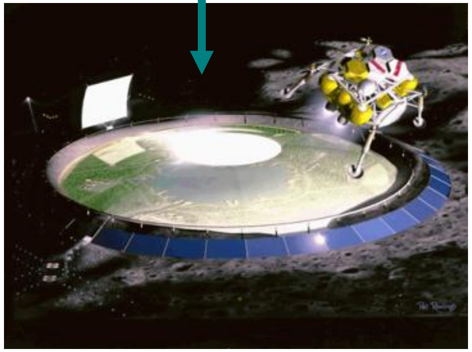
Space Habitats

Human Exploration

Space Solar Power

Space Tourism-Colonies





Lunar ISRU as A Stepping Stone for Human Exploration Beyond Earth Orbit

- The Moon is relatively close to Earth and provides comparable environments and resources for other destinations
- ISRU Technologies and Capabilities developed for the Moon can be utilized at other destinations of interest
- ISRU Operations demonstrated on the Moon can be utilized at destinations must further from Earth minimizing mission and crew risk
- Lunar Polar Volatiles are game changing for sustained human exploration and the commercialization of space

Questions?

Backup

ISRU and Science Are Synergistic

- **Lunar and Mars Science and ISRU resource assessment share common objectives**
  - Physical and geologic composition, structure, origin, and evolution of the lunar crust and subsurface (mGEO-2, mGEO-5, and mGEO-10)
  - Location, distribution, and movement of solar, bombardment, and endogenous lunar volatiles (mGEO-9, mGEO-12, mGEO-13, and mGEO-14).
  - Mars "Follow the Water"

- **Lunar and Mars science and ISRU resource assessment can share common instruments, hardware, field tests, and remote operations**
  - XRD/XRF – Mineral composition
  - Mossbauer Spectrometer – Iron-bearing minerals before & after processing
  - Raman Spectrometer/LIBS – Remote evaluation of minerals & water content
  - Gas Chromatograph (GC) – Molecular composition
  - Mass Spectrometer – Isotope composition
  - Neutron Spectrometer – water content/distribution
  - Ground Penetrating Radar – Subsurface features for excavation; ice layer
  - Sample acquisition, transfer, crushing, and measuring

- **Lunar Volatile/Water Prospecting (RESOLVE drill and instrument package) could be good follow up mission to LCROSS**

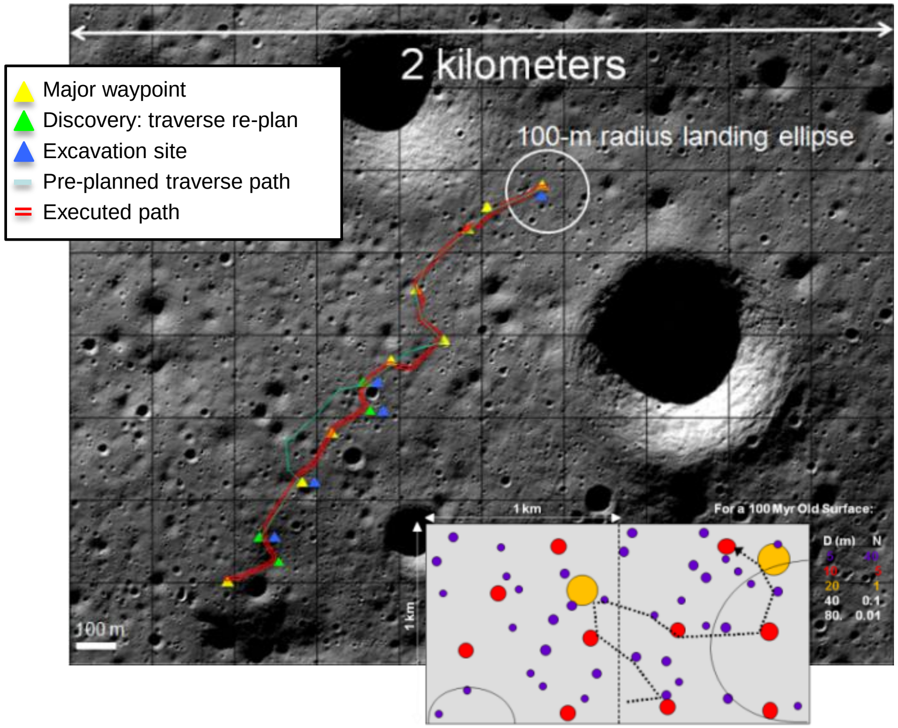
- **Lunar and Mars ISRU capabilities can enhance science mission return**
  - Hoppers & larger sample returns
  - Infrastructure, consumable gases, etc. to support science instrument deployment and ops

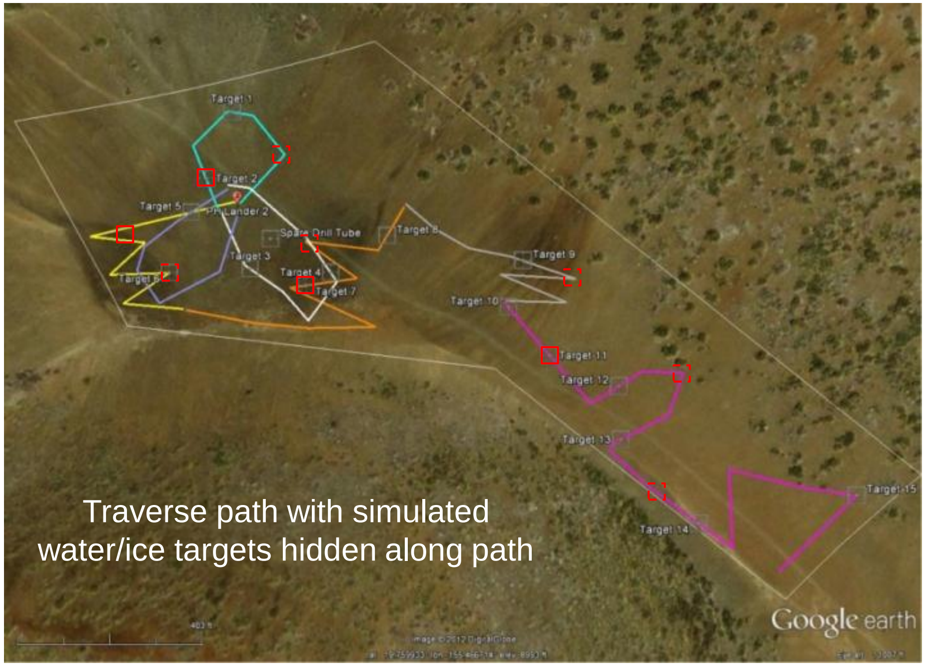
Observed Volatiles at the LCROSS Site

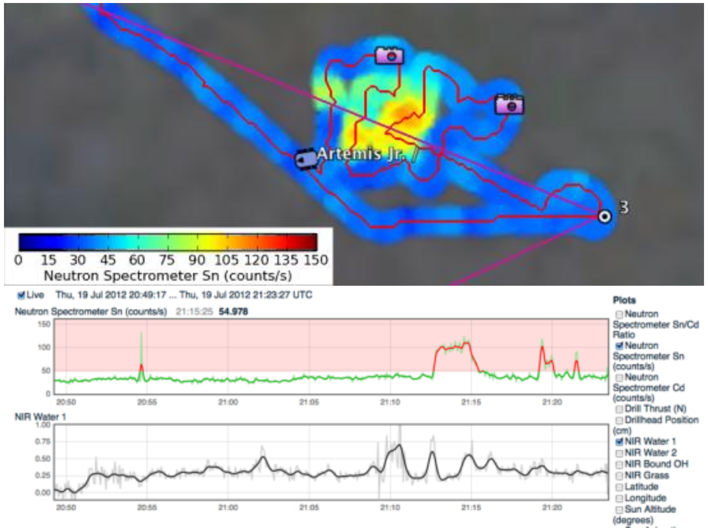
					Instrument			
	Column Density (# m^{-2})	Relative to H2O(g) (NIR spec only)	Concentration (%)	Long-term Vacuum Stability Temp (K)	UV/Vis	NIR	LAMP	M3
CO	1.7e13±1.5e11		5.7	15			x	
$H_2O(g)$	5.1(1.4)E19	1	5.50	106		x		
H_2	5.8e13±1.0e11		1.39	10			x	
H_2S	8.5(0.9)E18	0.1675	0.92	47	x	x		
Ca	3.3e12±1.3e10		0.79				x	
Hg	5.0e11±2.9e8		0.48	135			x	
NH_3	3.1(1.5)E18	0.0603	0.33	63		x		
Mg	1.3e12±5.3e9		0.19				x	
SO_2	1.6(0.4)E18	0.0319	0.18	58		x		
C_2H_4	1.6(1.7)E18	0.0312	0.17	~50		x		
CO_2	1.1(1.0)E18	0.0217	0.12	50	x	x		
CH_3OH	7.8(42)E17	0.0155	0.09	86		x		
CH_4	3.3(3.0)E17	0.0065	0.04	19		x		
OH	1.7(0.4)E16	0.0003	0.002	>300 K if adsorbed	x	x		x
H_2O (adsorb)			0.001-0.002					x
Na		1-2 kg		197	x			
CS					x			
CN					x			
NHCN					x			
NH					x			
NH_2					x			

Volatiles comprise possibly 15% (or more) of LCROSS impact site regolith

Exploratory Prospecting for Lunar Volatiles

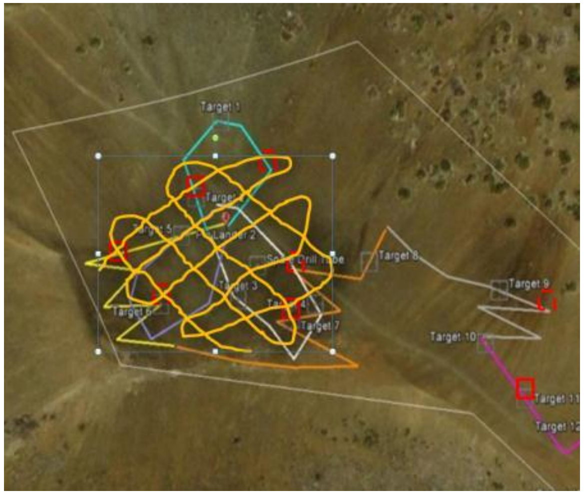






- Hypothesize location of volatiles based global data, terrain, and geological context
- Plan traverse before landing based on location estimates and rover capabilities
- Utilize non-invasive surface and subsurface instruments to guide selection of sample sites; Instrument suite may be limited
- Perform coring and volatile analysis at selected locations
- Re-plan traverse based on accumulations of results and new hypotheses

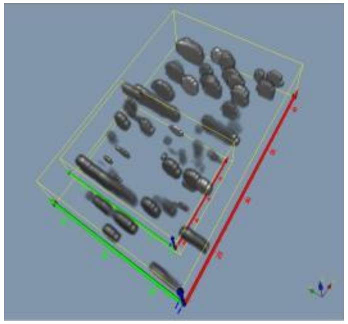
Focused Resource Assessment of Polar Volatiles

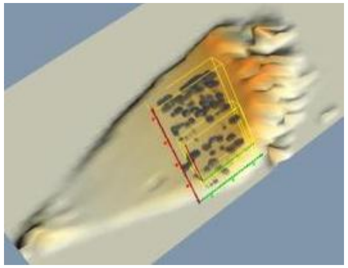


Traverse paths to fill in missing data

Rover-Data localization equipment

Rovers performing coordinated area assessment





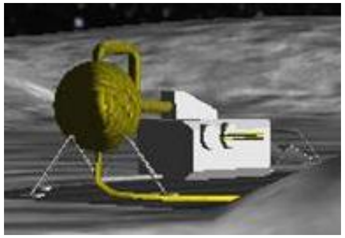
Data fusion with terrain information

- Plan a more extensive and thorough traverse based on filling in holes in data gathered from the Exploratory Assessment; Utilize multiple rovers if possible for redundancy and greater coverage (multinational?)
- Utilize more extensive instrument suite if possible to gather greater data on both volatile location and characteristics
  - Besides NS and Near IR, potentially include GPR and more mineral/physical instruments
- Utilize more instruments to assess volatiles and potential contaminants released and condensed with water
- Build 3-D interpretation of data as it is collected; utilize to redirect traverse and data sampling activities
- Utilize extended operations to provide lessons learned for
  - Designing mining feasibility hardware
  - Establishing operation protocols and procedures for remote mining
  - Verifying communications, localization, and situational awareness

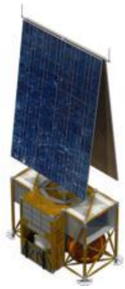
Mining Feasibility for Polar Volatiles

- Demonstrate critical mining and processing hardware
  - Finalize polar rover/mobility design for subsequent mining operations
  - Demonstrate ISRU hardware for sustained excavation, processing, and collection of polar water/volatiles
  - Demonstrate water cleaning, processing, and storage that can be scaled up to mining rates
  - Demonstrate fuel production from carbon-bearing volatiles if present
  - Demonstrate power system for sustained operations
- Finalize operation protocols and procedures for remote mining
- Establish mine infrastructure and operation area layout
- Establish benchmarks for logistics, mean-time between failures, etc.

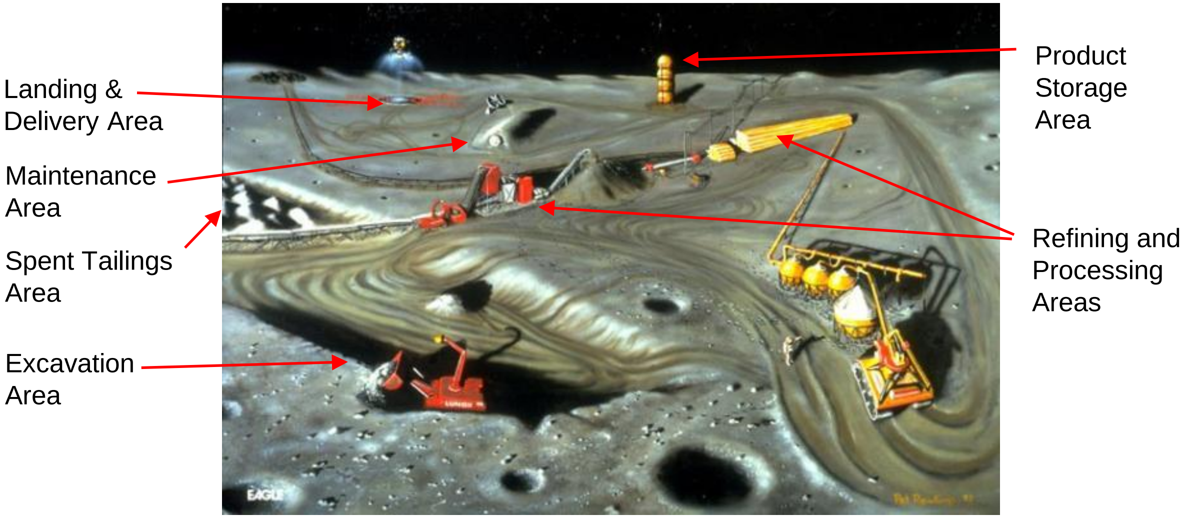
Polar Mobility, Excavation & Processing



Water Plant & Product Storage

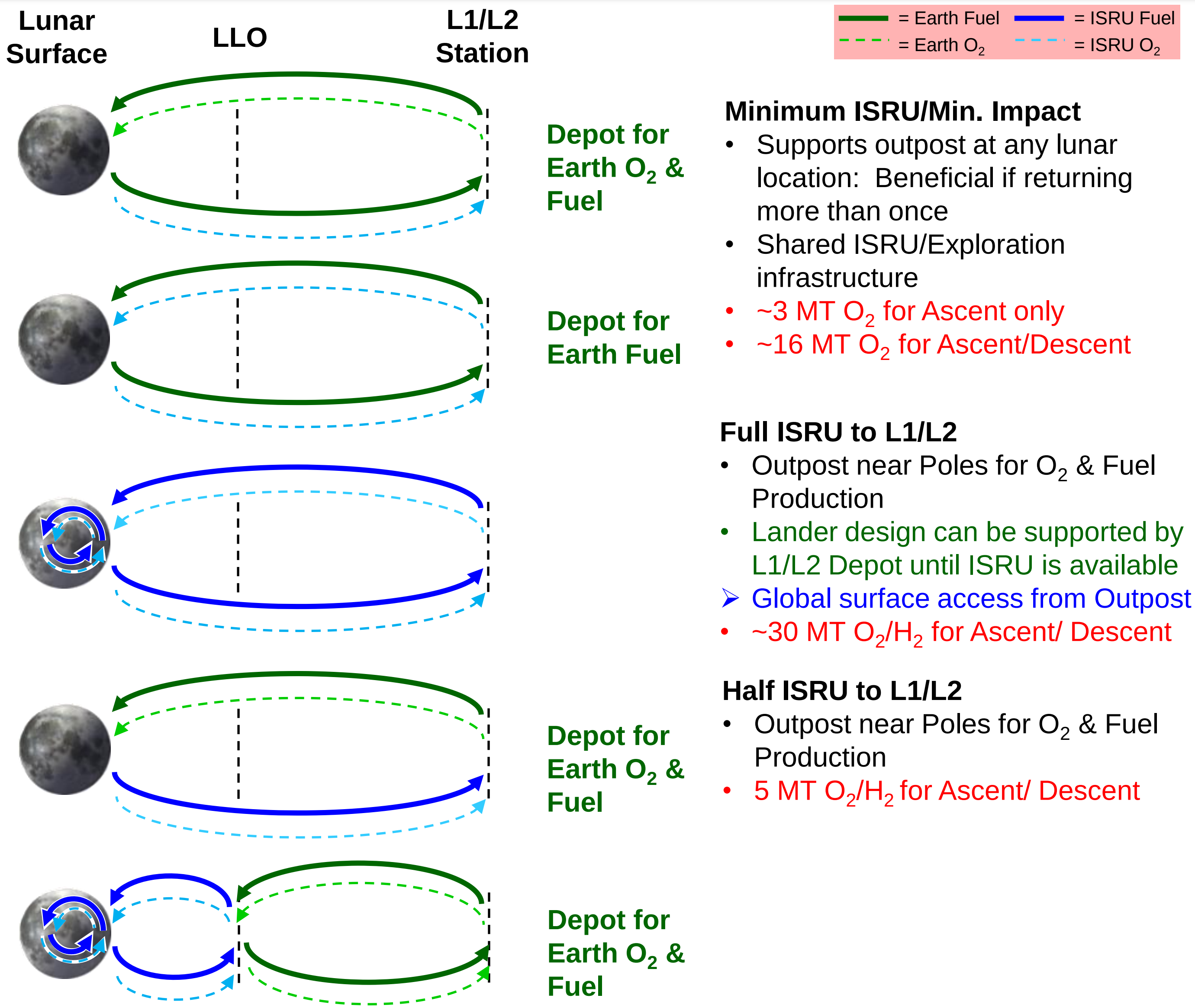


Polar Power System



Plan for Mine/Infrastructure Layout & Operation

ISRU and Lunar Transportation Architectures



Option 1A
Non-Reusable Lander
ISRU O_2 for Ascent
with Earth Fuel

Depot for Earth O_2 & Fuel

Option 1B
Reusable Lander
ISRU O_2 for Ascent/Descent
with Earth Fuel

Depot for Earth Fuel

Minimum ISRU/Min. Impact
- Supports outpost at any lunar location: Beneficial if returning more than once
- Shared ISRU/Exploration infrastructure
- ~3 MT O_2 for Ascent only
- ~16 MT O_2 for Ascent/Descent

Option 2: Surface Depot
Reusable Lander
ISRU O_2/Fuel for Ascent/Descent

Full ISRU to L1/L2
- Outpost near Poles for O_2 & Fuel Production
- Lander design can be supported by L1/L2 Depot until ISRU is available
- ➢ Global surface access from Outpost
- ~30 MT O_2/H_2 for Ascent/ Descent

Option 3: Dual Depot
Reusable Lander
ISRU O_2/Fuel for Ascent
with Earth O_2/Fuel for Descent

Depot for Earth O_2 & Fuel

Half ISRU to L1/L2
- Outpost near Poles for O_2 & Fuel Production
- 5 MT O_2/H_2 for Ascent/ Descent

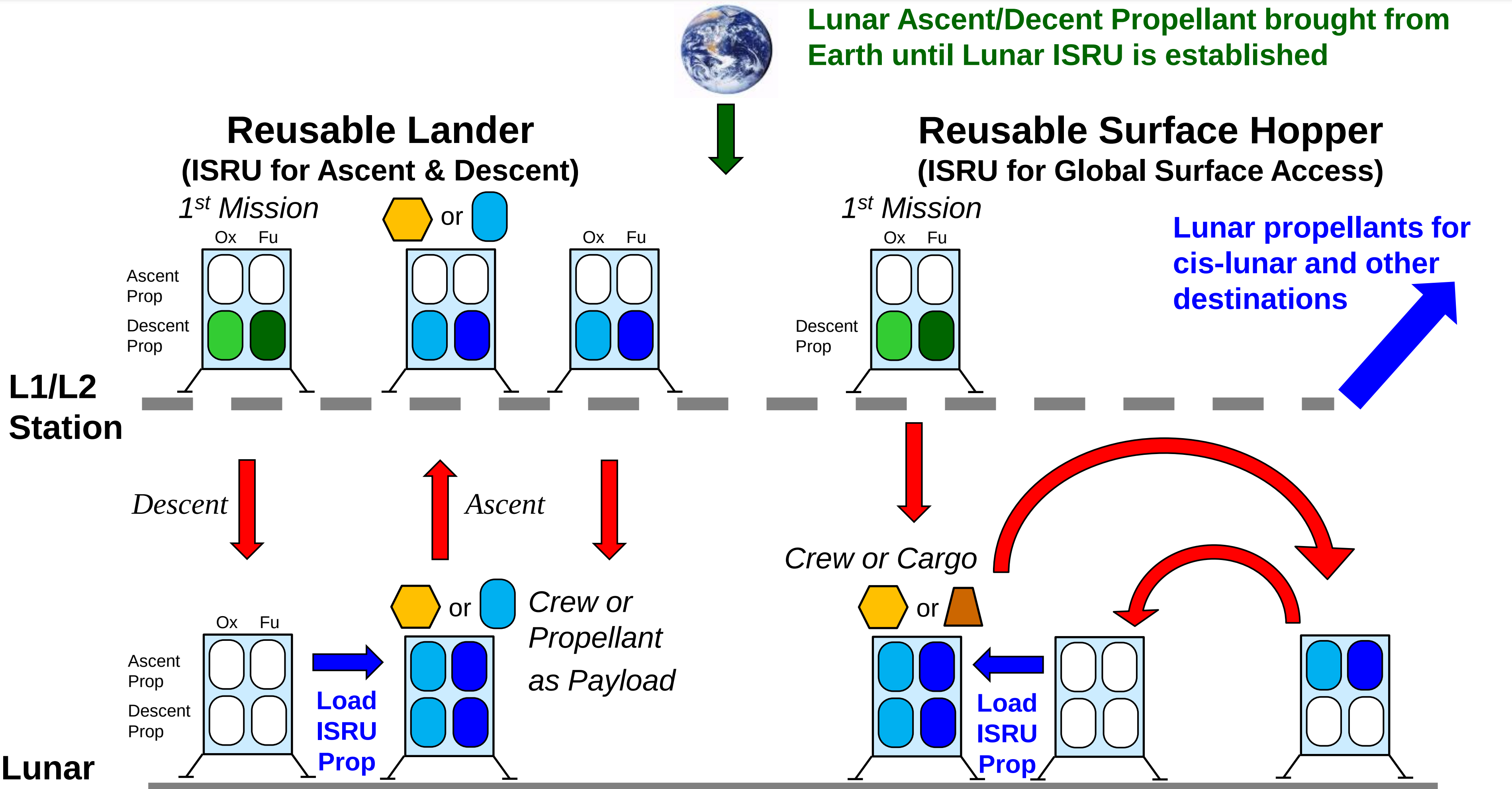
Option 4: Taxi/Lander Combo to LLO
ISRU O_2/Fuel for Ascent/Descent
with Earth O_2/Fuel for Descent/Ascent

Depot for Earth O_2 & Fuel

Note: ISRU production numbers are only 1st order estimates for 4000 kg payload

Option 2: Lunar Exploration Strategy with ISRU

ISRU O_2 & Fuel Production – Surface Depot Only



- Surface Outpost facility
- Near Poles for O_2 & Fuel Production
- Requires ~ 30,000 kg O_2/H_2 per mission

- *Unknown hopping distance possible with same ascent/descent vehicle design*