POTENTIAL LUNAR IN-SITU RESOURCE UTILIZATION EXPERIMENTS AND MISSION SCENARIOS

G. Sanders[1]

Lunar Surface System Office, NASA Johnson Space Center, Houston, TX., USA[1]

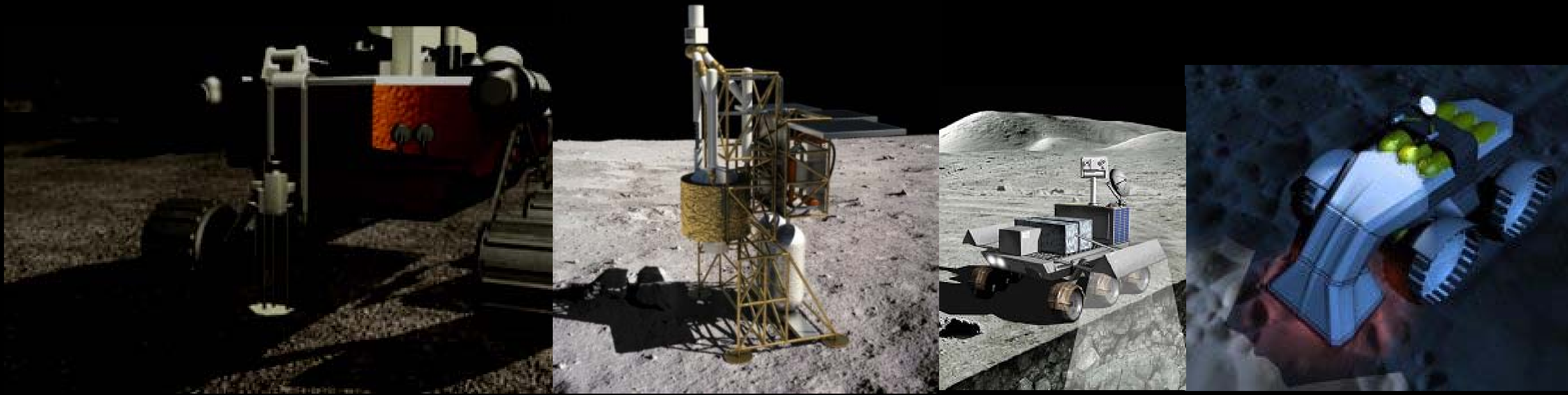
ABSTRACT. The extraction and use of resources on the Moon, known as In-Situ Resource Utilization (ISRU), can potentially reduce the cost and risk of human lunar exploration while also increasing science achieved. By not having to bring all of the shielding and mission consumables from Earth and being able to make products on the Moon, missions may require less mass to accomplish the same objectives, carry more science equipment, go to more sites of exploration, and/or provide options to recover from failures not possible with delivery of spares and consumables from Earth alone. The concept of lunar ISRU has been considered and studied for decades, and scientists and engineers were theorizing and even testing concepts for how to extract oxygen from lunar soil even before the Apollo 11 mission to the Moon.

There are four main areas where ISRU can significantly impact how human missions to the Moon will be performed: mission consumable production, civil engineering and construction, energy production, storage, and transfer, and manufacturing and repair. The area that has the greatest impact on mission mass, hardware design and selection, and mission architecture is mission consumable production, in particular, the ability to make propellants, life support consumables, and fuel cell reagents. Mission consumable production allows for refueling and reuse of spacecraft, increasing power production and storage, and increased capabilities and failure tolerance for crew life support. The other three areas allow for decreased mission risk due to radiation and plume damage, alternative power systems, and failure recover capabilities while also enabling infrastructure growth over Earth delivered assets.

However, while lunar ISRU has significant potential for mass, cost, and risk reduction for human lunar missions, it has never been demonstrated before in space. To demonstrate that ISRU can meet mission needs and to increase confidence in incorporating ISRU capabilities into mission architectures, terrestrial laboratory and analog field testing along with robotic precursor missions are required. A stepwise approach with international collaboration is recommended. The first step is to understand the resources available through orbital and surface exploration missions. Resources of particular interest are hydrogen, hydroxyl, water, and other polar volatile resources recently measured by Chandrayaan, Lunar Reconnaissance Orbiter (LRO), and the Lunar Crater Observation and Sensing Satellite (LCROSS). The second step is to demonstrate critical aspects of ISRU systems to prove ISRU is feasible under lunar environmental and resource conditions (ex. subscale oxygen extraction from regolith). The third step is to perform integrated missions with ISRU and other connected systems, such as power, consumable storage, surface mobility, and life support at a relevant mission scale to demonstrate ISRU capabilities as well as the critical interfaces with other exploration systems. If possible, the mission should demonstrate the use of ISRU products (ex. in a rocket engine or fuel cell). This 'dress rehearsal' mission would be the final step before full implementation of ISRU into human missions, and may be performed during human lunar exploration activities. This stepwise approach is the most conservative approach, and may only be possible with international cooperation due to the limited number of robotic missions each nation/space agency can perform within their budget.

[1]Phone: +281 483-9066, E-mail: gerald.b.sanders@nasa.gov

Potential Lunar In-Situ Research Utilization (ISRU) Experiments and Mission Scenarios



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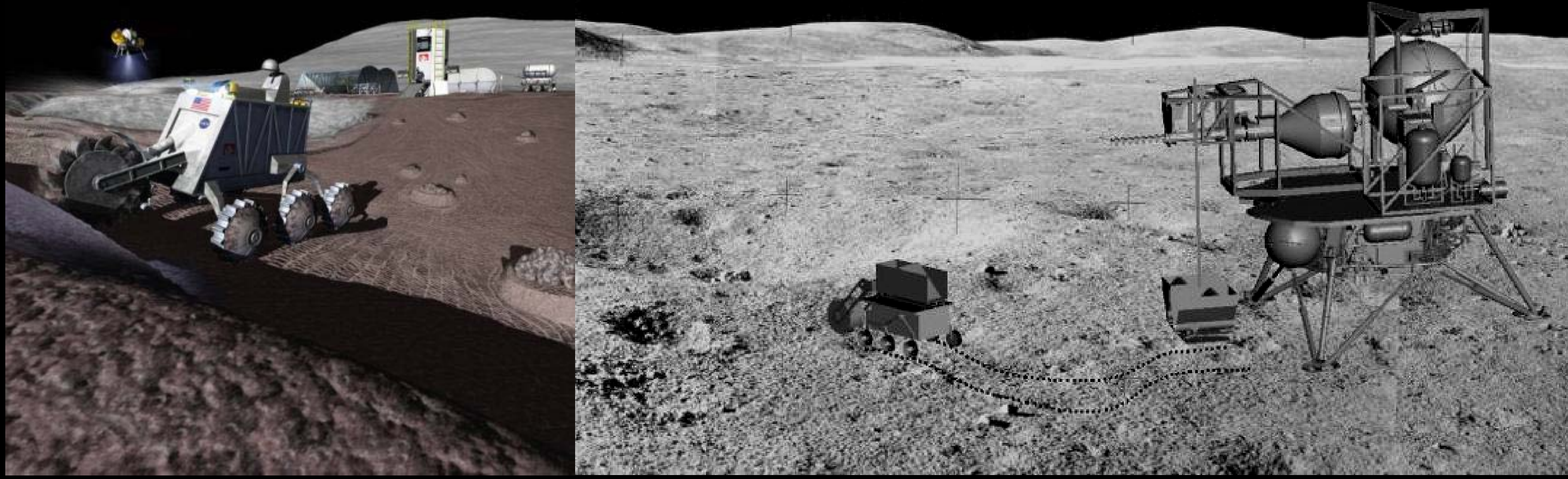


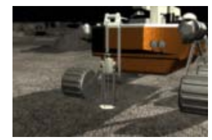
Gerald Sanders, NASA Johnson Space Center. gerald.b.sanders@nasa.gov

What is In-Situ Resource Utilization (ISRU)?

ISRU involves any hardware or operation that harnesses and utilizes 'in-situ' resources (natural & discarded) to create products and services for robotic and human exploration

Five Major Areas of ISRU

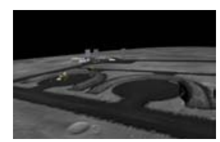
- **Resource Characterization and Mapping**
  Physical, mineral/chemical, and volatile/water

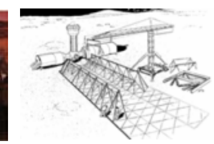





- **Mission Consumable Production**
  Propellants, life support gases, fuel cell reactants, etc.

- **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.

ISRU Can Strongly Influence Design of Human Exploration Systems

Incorporation of ISRU can strongly effect requirements and hardware/technology options selected

Requirements Connectivity	
Propulsion Systems	Propellant/Pressurant Quantity Propellant/Pressurant Type Residual Amount (scavenging) Storage Type & Capability
Life Support/EVA Systems	Consumable Quantity Consumable Type Waste Products/Trash Quantity Waste Products/Trash Type Storage Type & Capability
Surface Mobility	Vehicle Size Terrain Mobility Capabilities Power Requirements Fuel Cell Reagent Quantity Fuel Cell Reagent Type
Surface Power	Daylight Power Amount Nighttime Power Amount Fuel Cell Storage Capability Nuclear Reactor Placement/Shielding
Habitat	Placement Shielding/Protection Assembly/Inflation Capability

Hardware Connectivity	
Propulsion Systems	Propellant/Pressurant Storage & Valving Solar Collectors/Solar Thermal Propulsion
Life Support/EVA Systems	Consumable Storage & Valving Water Processing/Electrolysis Carbon Dioxide Processing Liquid/Gas Separation Solar Collectors/Trash Processing
Surface Mobility	Mobility Platforms Actuators, Motors, & Control Software
Surface Power	Consumable Storage & Valving Water Processing/Electrolysis Liquid/Gas Separation Solar Collectors/Solar Thermal Storage
Science Instruments	Geotechnical Properties Mineral Characterization Volatile Characterization Subsurface access Inert Gas Storage & Valving
Testing & Certification	Surface Analogs Environment Simulation Chambers Lunar and Mars simulants

Problem with Incorporation of ISRU into Missions

- **ISRU incorporated into human exploration missions is a conundrum**
  - Learning to use the resources at the site of exploration (ISRU) to reduce cost and risk is considered an important part of why we are exploring space
  - However, since ISRU has never been flown/demonstrated, mission planners do not want to rely on ISRU for mission success
  - Architectures and elements that do not rely on ISRU are designed differently and benefits downstream are greatly reduced (ex. ELS and Lander Propulsion)
  - Therefore, ISRU is not ‘Critical’ for the architecture and implementation is delayed, **BUT** . . .

Early ISRU Validation Thru Precursors = **Earlier ISRU Incorporation and Use in Missions** = **Greater cost & risk reduction; Earlier Sustainability**

- **Two possible approaches to break the “Catch 22” cycle**
  - Perform integrated ground tests of ISRU with linked surface and transportation systems to validate interfaces and product availability and quality
  - **Fly ISRU demonstrations on robotic precursor missions to validate environmental compatibility, performance, and interfaces with other Exploration systems**

Why Perform Analog Field Tests & Fly Lunar ISRU Demonstrations?

Why Analog Field Tests?

- **Technical Rationale for Performing Analog Field Testing**
  - Mature Technology
  - Evaluate Mission Architecture Concepts Under Applicable Conditions
  - Evaluate Operations & Procedures
  - Integrate and Test Hardware from Multiple Organizations
  - Develop engineers and project managers
- **Intrinsic Benefits of Analog Field Testing**
  - Develop International Partnerships
  - Develop Teams and Trust Early
  - Develop Data Exchange & Interactions with International Partners (ITAR)
  - **Outreach and Public Education**

Why Robotic Precursor Missions?

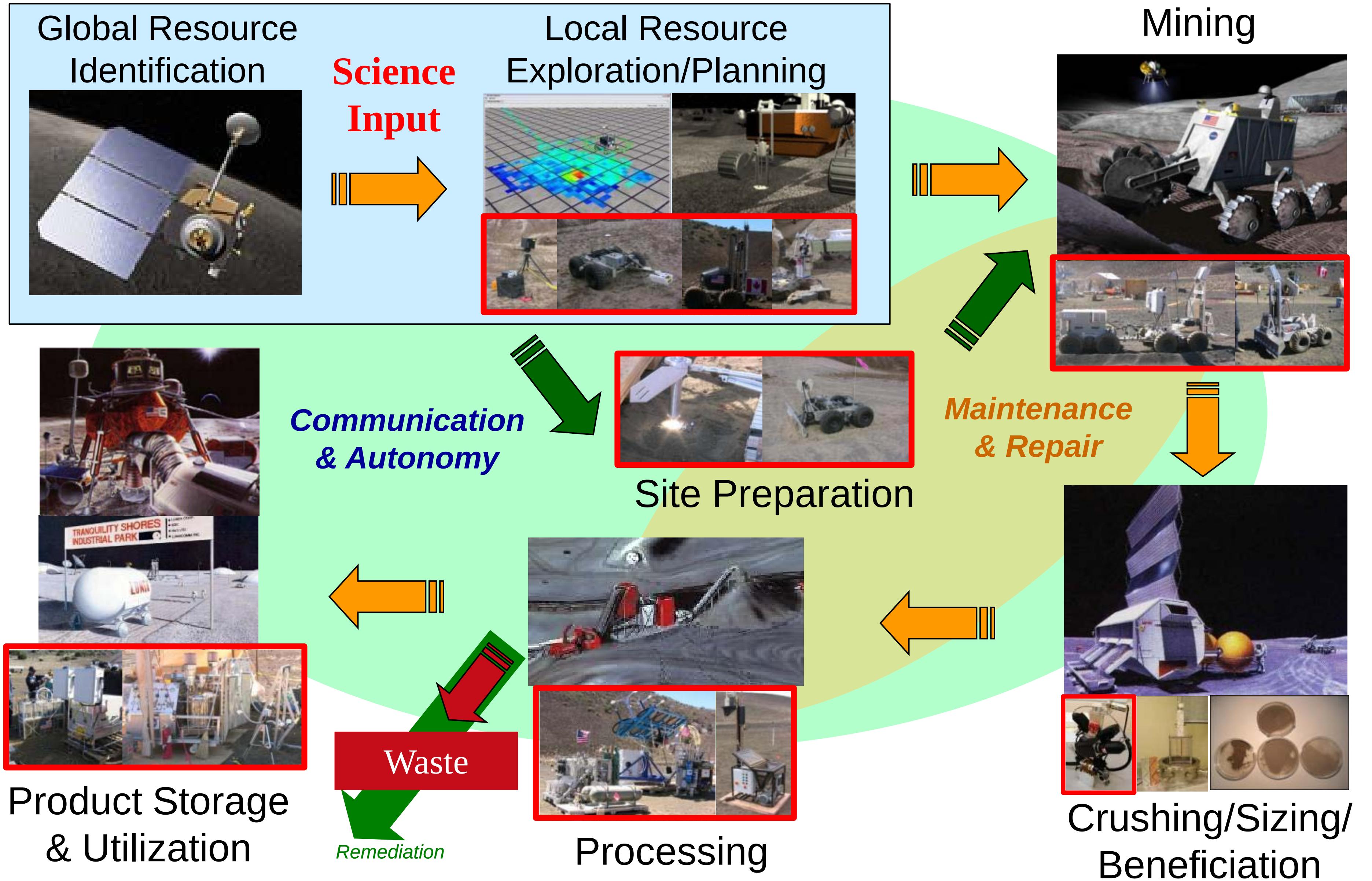
- **Validate Earth-based development & testing and overcome Earth-based limitations**
  - Long duration lunar environment simulation testing is difficult and expensive
  - Lunar simulants will not cover all contaminants and variations of actual lunar material
  - Compare ISRU system Earth and lunar performance and operation
- **Increase confidence in ISRU**
  - Show it can be done on the Moon!
  - Demonstrate critical functions and obtain design for full scale system development
  - Utilize ISRU products (fuel cell, propulsion, etc.) to minimize risk for ISRU incorporation
- **Early ISRU demonstrations can influence design of other exploration systems**
  - Propulsion, life support, power, habitats, and mobility systems
- **Engage & Excite Public**

Environment Chamber (C), Analog (A) and Flight Demonstrations (D) should address the following risks

		Risk	Potential Impact
A D	1	Potential resource is not available at site of exploration	Mission failure if resource processing and product is critical to mission success
	2	Resource is present BUT	
	a	Form is different than expected (concentration, state, composition, etc)	Processing failure or reduced production rate
D	b	Location is different than expected (depth, distribution, terrain)	Resource not obtainable or reduced production rate
	c	Unexpected impurities	Processing failure, degraded performance, and/or product contamination
C D	3	ISRU system does not operate properly in lunar environment (vacuum, temperature, temperature swings, 1/6 g)	Processing failure or degraded performance/increased energy required
C D	4	ISRU system does not operate properly after sustained exposure to lunar regolith	Processing failure, degraded performance, and/or loss of product
A	5	ISRU systems and products not are compatible with end-user (interfaces, contaminants)	Mission failure if resource processing and product is critical to mission success

G. Sanders/JSC, gerald.b.sanders@nasa.gov

Space ISRU ‘Mining’ Cycle



ISRU Analog Field Testing Overview & Results

- **Early Surface Preparation**
  - **Mosses Lake, June 2008**: LANCE Blade mounted to "Chariot" mobile platform
  - **Flagstaff, Sept. 2009**: LANCE Blade mounted to "Chariot" & LER platforms

- **1st Validation of Lunar Prospecting & ISRU System Performance**
  - **Mauna Kea, Nov. 2008:** RESOLVE mounted on "Scarab" mobile platform; PILOT and ROxygen hydrogen reduction from regolith Outpost-scale systems
  - CSA international involvement and support; DLR co-testing; PISCES & Hawaii

- **1st Integrated ISRU and Surface System Operations**
  - **Mauna Kea, Feb. 2010:** "Dust to Thrust", ISRU Carbothermal reduction with excavation, fuel cell power, reactant storage, and LO_2/CH_4 thruster firing on prepared surfaces
  - CSA lead and highly integrated testing ; PISCES & Hawaii

Major Results

☑ Area clearing performed by large and moderate sized rovers

☑ Lunar polar ice/resource prospecting hardware and operations demonstrated

☑ Oxygen extraction from regolith demonstrated at mission scales and efficiencies

- Hydrogen Reduction & Carbothermal Reduction

☑ ISRU systems integrated with excavation/mobility, fuel cell power, and gaseous/cryogenic fluid storage and transfer

☑ Semi-autonomous and Remote operations through satellite demonstrated

☑ International partnerships and small businesses in critical roles and operations

International Involvement in NASA ISRU Activities

ISRU analog field testing promote joint development & integration

Canadian Space Agency

- Surface mobility and navigation for ISRU – *Carried NASA experiments and instruments*
- Drilling technology for Moon/Mars - *Joint work and integrated into RESOLVE experiment*
- Resource prospecting – *Integration of RESOLVE and Mossbauer on CSA Rover; science instruments*
- Site characterization, planning, & preparation – *Blade modeling & surface sintering; landing pad construction*
- Regolith excavation and delivery/removal – Bucketwheel development, *Deliver regolith to NASA ISRU plants*








German Space Agency (DLR)

- Instrumented "Mole" & Sample Capture Mole
- Mossbauer & Mossbauer/X-Ray Fluorescence (XRF) Instrument – Integrated onto CSA rover
- Surface mobility for science



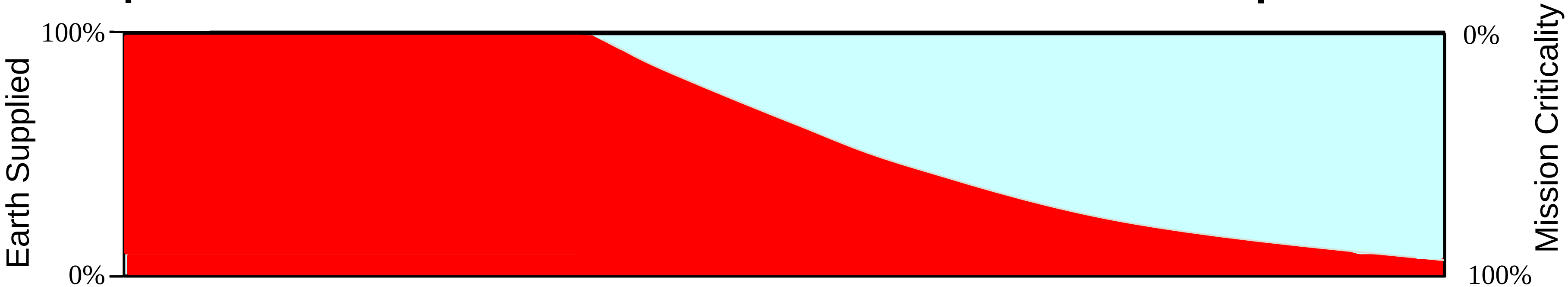
JPL Partnership with Michelin on 'Tweels' testing

– *Integrated onto CMU rover (HRS funded)*



Stepwise Approach to ISRU Incorporation into Lunar Missions

Prospect | **Demonstrate** | **Pilot** | **Full Implementation**



Prospect

Purpose
- Verify resource type, amount, and distribution
- Verify energy required to excavate and extract volatile resources

- Lunar Orbit
- Robotic Precursors

Demonstrate

Purpose
- Verify critical processes & steps
- Verify Critical engineering design factors (forces, energy required, etc.)
- Address unknowns or Earth based testing limitations (simulants, 1/6 g, contaminants, etc.)

- Robotic Precursors
- Sorties

Pilot

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

- Robotic Precursors
- 14 to 28 day missions
- Repeat visit sites
- Sites of extreme access difficulty

Full Implementation

Purpose
- *Enhance or enable new mission capabilities*
- *Reduce mission risk*
- *Increase payload & science capabilities*

- Long-duration Stays (>60 days)
- Commercial space operations

Possible ISRU Experiments & Mission Concepts

Payloads listed below are a subset of missions of potential interest. As payload size increases, the benefits and amount of risk reduced is substantially greater, but less flight opportunities may be available

- Risk Reduction Payloads
  - Concept/Subsystem Evaluation: ~15 kg Class
    1. Size Sorting & Mineral Beneficiation Demo (Concept validation & Environmental compatibility)
    2. Physical/Mineral Characterization Instrument Suite (Mineral resource availability)
  - Proof-of-Concept Demos: ~50 kg Class
    3. Lunar Polar Volatile/Ice Characterization Payload (Resource availability & Environmental compatibility)
    4. Subscale Oxygen Extraction from Regolith (Concept validation & Environmental compatibility)
  - Pilot Demonstration: ~300 kg Class
    5. Integrated ISRU Pilot-scale O_2 Production and Surface System Demonstration
- Game Changing or Infrastructure Growth ISRU Payloads
  - Concept/Subsystem Evaluation: ~15 kg Class
    6. Surface Sintering Demonstration (Concept validation)
  - Proof-of-Concept Demos: ~50 kg Class
    7. Thermal "Wadi" Nighttime Survival Demo (Concept validation & Environmental compatibility)
  - Pilot Demonstration: ~300 kg Class
    8. Solar array production
- Pre-deployment of ISRU for Human Lunar Exploration

3. Lunar Polar Resource Characterization Precursor Mission Concept

Purpose

- ✓ **Understand the resources, esp. water/ice** (minerals, volatiles, water/ice)
  - – What resources are there, how abundant, and what is the areal and vertical distribution?
- ✓ **Understand environment impact on extraction and processing hardware**
  - – What is the local temperature, pressure, radiation environment?
  - – What are the physical/mineralogical properties of the local regolith?
  - – Are there extant volatiles that are detrimental to processing hardware or humans?
- ✓ **Gain knowledge to guide future mission architecture decisions**

Approach and Objectives

- **Utilize hardware that has applicability to follow-on ISRU missions**
  - – Can we effectively separate and capture volatiles of interest?
  - – Can we execute repeated processing cycles (reusable chamber seals, tolerance to thermal cycles)?
- **Link ISRU, Exploration, and Science lunar robotic mission objectives**
- **Develop partnerships with industry and International Partners**

Resource Characterization	1	**Determine form and conc. of H_2/H_2O in permanently shadowed regions**	Science - Resource Focused
	2	Determine other volatiles available (CO, NH_3, CH_4, HCN, ?)	
	3	Determine grain size distribution and morphology of regolith	
	4	Determine quantity of which volatile(s) are evolved by crushing	
	5	Determine chemical/mineralogical properties	
	6	Determine difference between sunlit and shadowed regions	
	7	Determine spatial distribution of resources	
In-Situ Resource Utilization Demo	8	Determine bulk excavation related physical properties of regolith	Engineering - Processing Focused
	9	Demonstrate capture and separation of water	
	10	Demonstrate scalable oxygen production technique	
	11	Engage & Excite Public/Education Outreach	

Why is a Polar Hydrogen/Ice Resource Precursor Mission Important?

- **Long-term sustainability/"Game Changing"**
  - Availability of water for propellants can strongly influence propulsion system design (propellant selection and reusability) and transportation architecture (depots, hoppers, lander reuse, etc.)
  - Reuse of cargo and human landers and transportation elements can reduce long-term mission costs and enable new mission concepts over current GPoD
  - Availability of water may influence long-term operations dealing with science, radiation protection, food production, etc.) over what is available from scavenging water from landers
- **Risk Reduction**
  - Availability of water provides dissimilar capability to life support and scavenging water from lander propulsion systems in case of failure or reduced performance
  - Similar hardware and operations could be used for assessing water as a resource on Mars for human exploration mission plans
- **Science**
  - Cargo and human lander missions may begin to contaminate polar sites
  - Provide "Ground Truth" to LRO/LCROSS and other lunar orbiter missions
  - Provide scientific data that supports understanding of the Solar System and Earth-Moon formation and history

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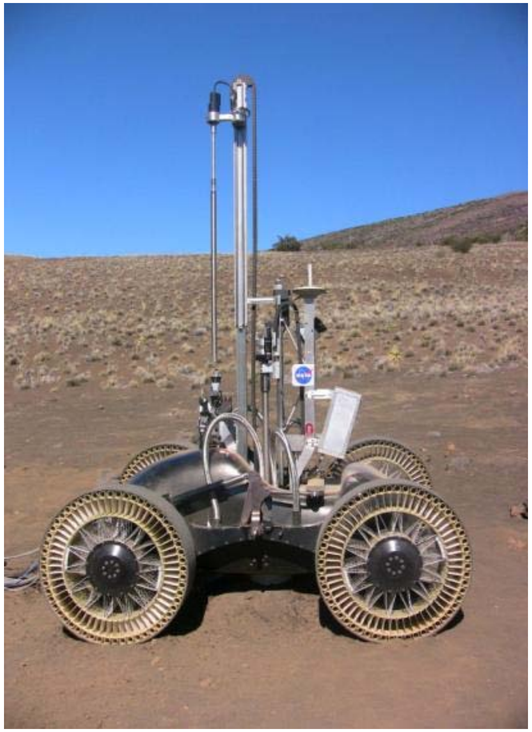
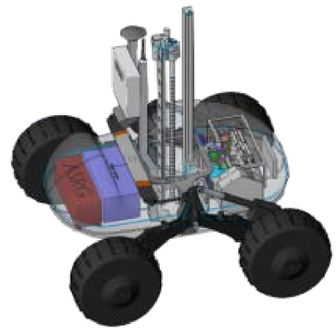
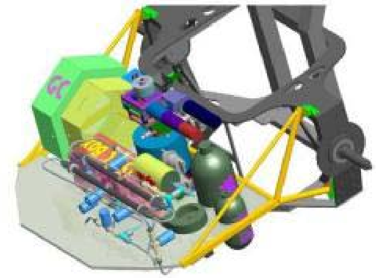
Regolith and Environment Science & Oxygen and Lunar Volatile Extraction (RESOLVE)

Field Tested twice at Analog site in Hawaii



Integration onto Scarab

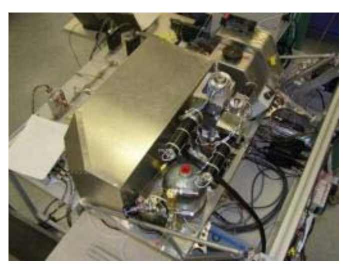




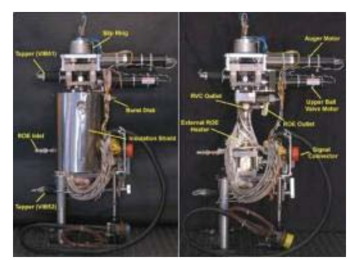
Combined Sample Metering & Crusher Unit

Integration onto Scarab

Drill, Sample Transfer & Crusher (NORCAT)



RESOLVE Integrated System #2



Combined Volatile Reactor & O_2 Production Demo

Gas Chromatograph

4. Lunar ISRU Proof-of-Concept Precursor Payload Concept

Purpose

- ✓ **Demonstrate critical operations and functions using scalable design to demonstrate O_2 production from regolith is possible** so lunar architecture can take full advantage of the capability from the start
- ✓ **Address uncertainties associated with actual lunar regolith and environment** with respect to critical attributes and functions of ISRU O_2 Production system
- ✓ Operate for as long as possible or until it break to **provide life and performance degradation over time for Outpost design**

Approach

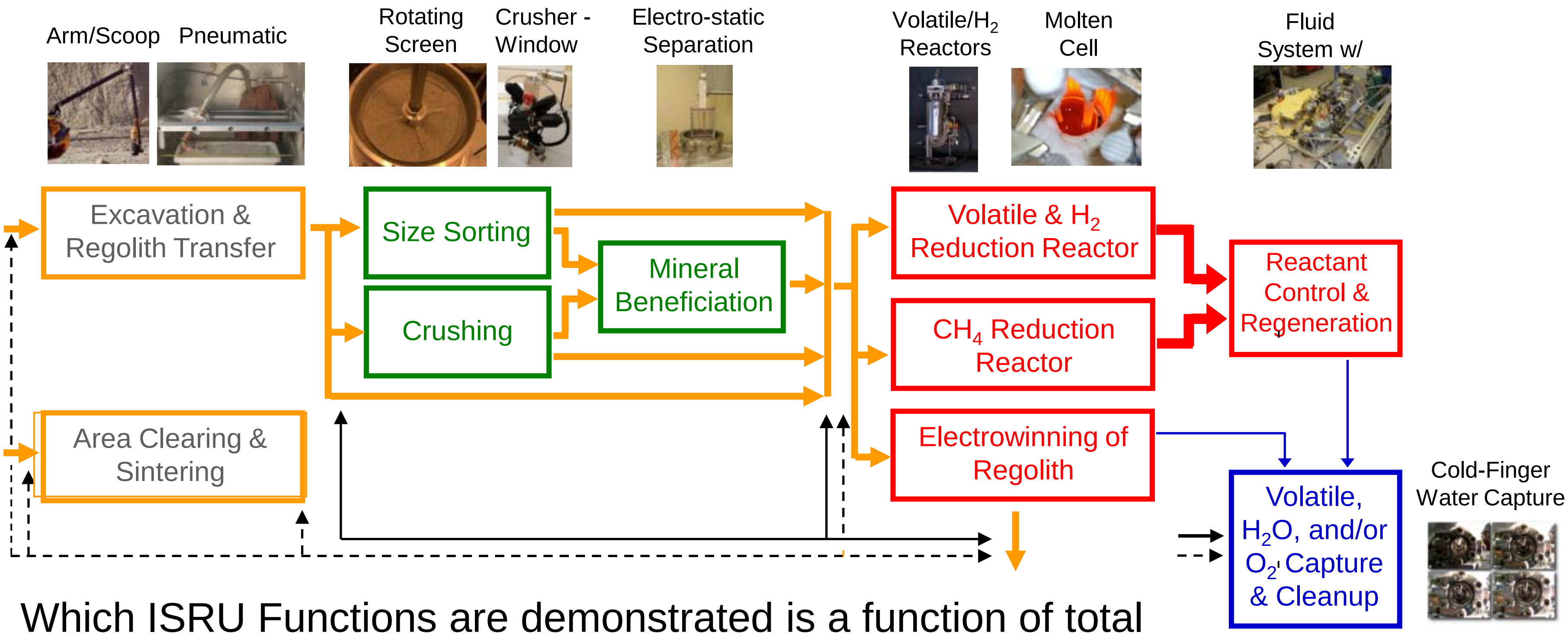
- **Design to be lightweight** (<60kg) and **low power** (<200 W ave.) to fit on any lunar robotic precursor missions of opportunity
- **Utilize existing** breadboard and flight **hardware** designs **to minimize risk and cost**

Precursor Concept – Subscale O_2 production from regolith demo with lunar Science

- ➢ **Lunar ISRU oxygen (O_2) production demo**
  - **Incorporate mineral, gas, and solar wind volatile characterization instruments** to support Lunar Science and verify ISRU H_2 reduction process performance
- ➢ **Include Science Instruments** for lunar science and ISRU process performance evaluation
  - Mass Spectrometer (MS) and/or Gas Chromatograph (GC) for solar wind volatile and ISRU production contaminant measurements
  - Combined XRD-XRF/Mossbauer for mineral characterization and iron-reduction evaluation
  - Camera/microscope on arm/scoop or on metering device window for visual inspection
  - Other mineral characterization instrument?

Lunar ISRU Precursor Payload Concept:
Subscale Oxygen Extraction from Regolith Demonstration

Critical ISRU Functions



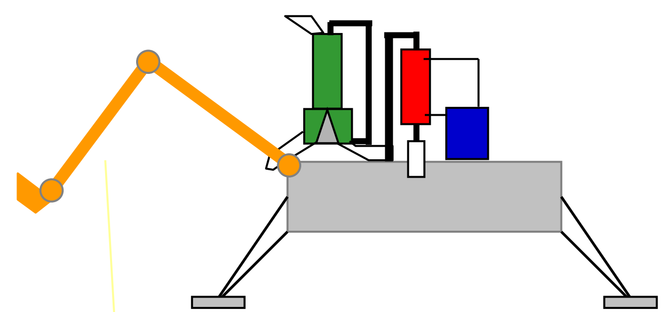
Which ISRU Functions are demonstrated is a function of total payload mass and power available & Partnership Interest

Lunar Science & ISRU Characterization Functions

- - -► Optical inspection (Camera & microscope)

⟶ Mineral Assessment (XRD/XRF, Moessbauer, Raman)

⟶ Volatile/Gas Assessment (Mass spectrometer - Gas chromatograph)



5. Integrated ISRU-Surface System Demonstration (1 of 2)

Mission is 'Dress rehearsal' for critical Human Mission Systems

Purpose

- ✓ **Demonstrate surface mobility - Excavator:**
  - Relevant mobile platform scale and design
  - Relevant regolith excavation and transport techniques for oxygen production
  - Relevant navigation (hardware & software), operation, and life experience
- ✓ **Demonstrate oxygen extraction from regolith (ISRU):**
  - Oxygen production at near early Outpost scale rate (0.2 to 0.5 MT O_2/yr rate)
- ✓ **Demonstrate surface solar/fuel cell power system at polar region (Power)**
  - Relevant scale power module unit for Outpost including solar array/rotary joint and fuel cell system
  - Common water electrolysis and reactant storage for ISRU oxygen production and fuel cells
- ✓ **Demonstrate long-term storage of cryogenic oxygen (Surface Systems/Crew Lander)**
  - Liquefaction and storage oxygen
  - 6 months of lunar day/night storage heat leak/boil-off prevention experience in dusty lunar environment for Altair LO_2/CH_4 ascent vehicle, surface and mobile power module, and EVA/ECLSS
- ✓ **Demonstrate heat rejection and thermal management at polar region (Thermal)**
  - 6 months of radiator performance data in dusty lunar environment
- ✓ **Evaluate dust on performance & demonstrate dust mitigation technique(s)**
  - Evaluate dust buildup, performance impact, and mitigation techniques for arrays, radiators, & tanks
- ✓ **Option: Demonstrate integration/ties to propulsion system**
  - If LO_2/CH_4 lander propulsion system, tie into propulsion system tankage
  - Transfer LO_2 from cryo tank into lander LO_2 tank.
  - Increase methane storage above needed for mission and perform thruster firing

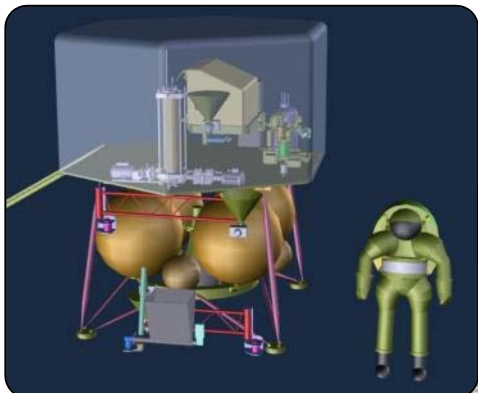
Approach

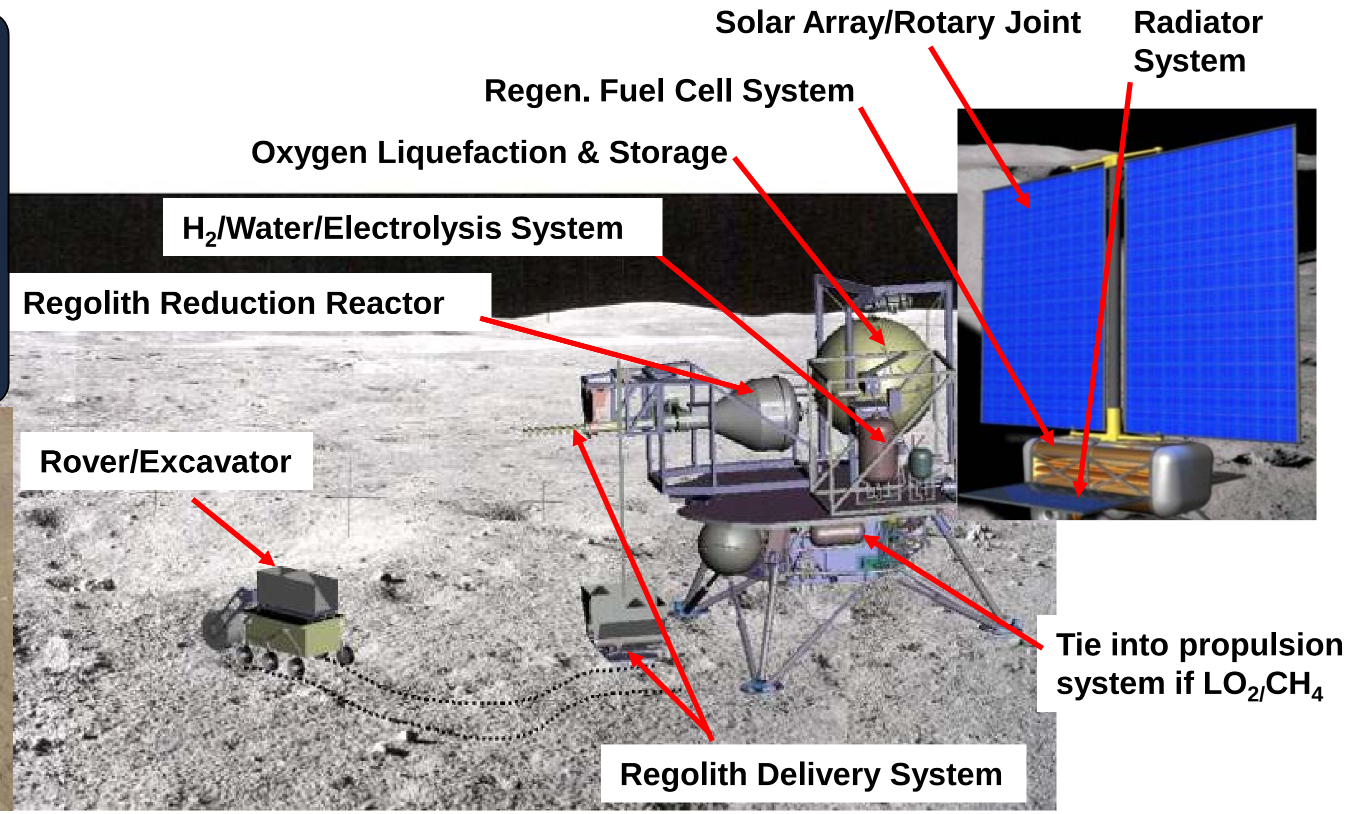
- **Six month min. surface operations for performance, life, and operation experience**
- **Integrated Surface Design and Operation**
  - Demonstrate coordinated, semi-autonomous excavation and oxygen production for minimum of 6 mo.
  - Demonstrated communications and Earth ground support operation and control

G. Sanders/JSC, gerald.b.sanders@nasa.gov

Integrated ISRU-Surface System Demonstration (2 of 2)

- ✓ Utilize Human mission scale hardware design – Either scale down (>1/5th) or minimize redundancy (1 vs 3 of same hardware)
- ✓ Design to maximum payload available to achieve highest scale
- ✓ Operate for 6 months to 1 year to provide polar year operating and hardware life

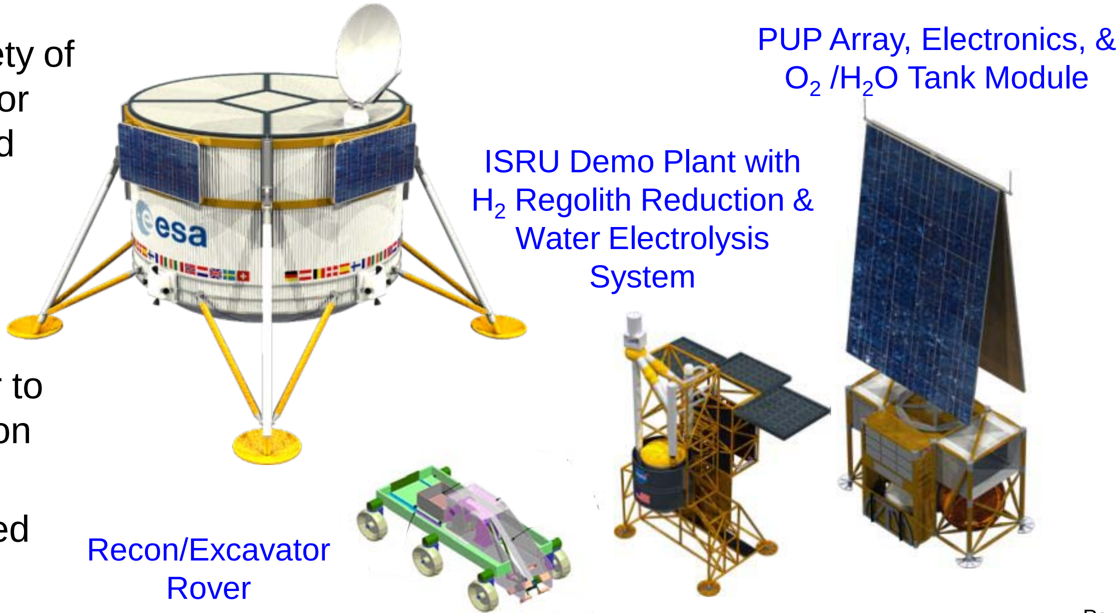




Graphics are not meant to illustrate actual hardware/system proposed but only to depict major elements

Pre-deployment of ISRU for Human Lunar Exploration: Provide Early Consumables & Enhanced Power

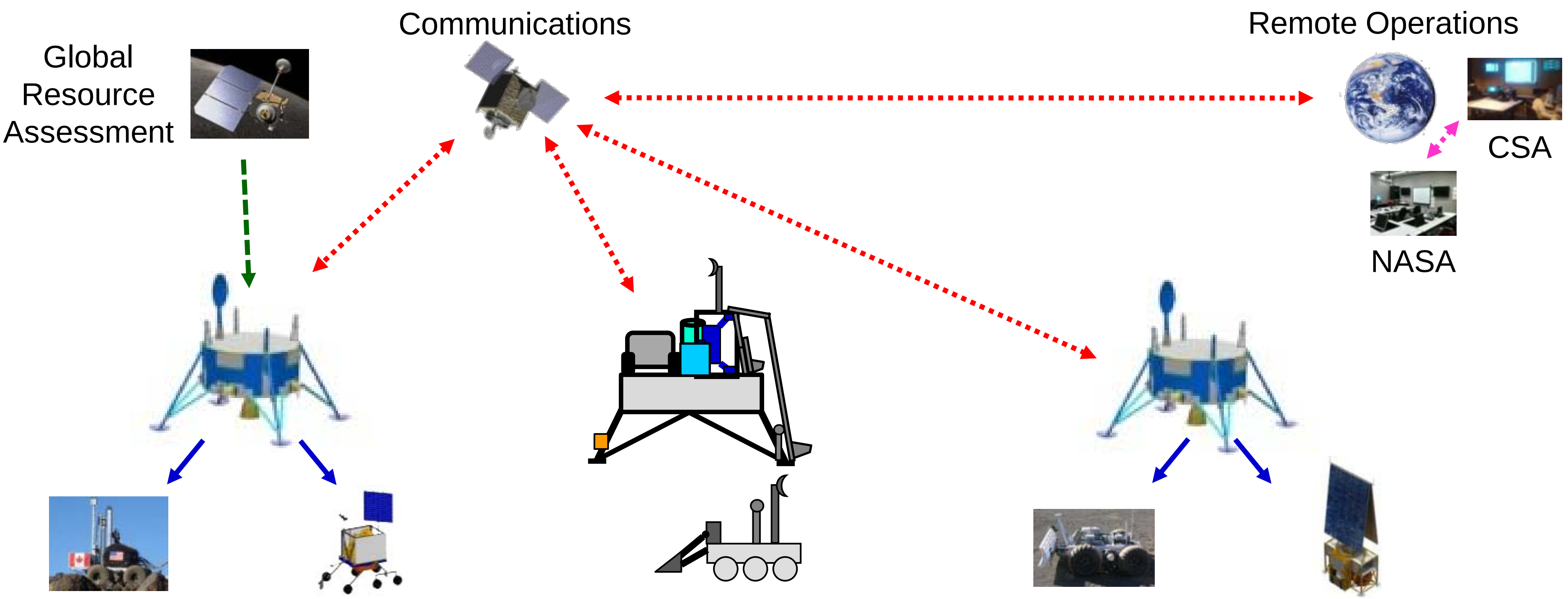
- **Concept**:
  - Launch resource prospecting/excavation rover, ISRU Demo Plant, and elements of Portable Utility Pallet (PUP) on ESA Cargo lander
  - Produce oxygen and water in-situ to fill PUP before crew arrives
  - Utilize elements of power and consumable storage PUP when crew arrives
  - Options:
    - Convert PUP battery power storage to fuel cell storage. Utilize tanks for oxygen and water
    - Add life support system elements to ISRU Demo Plant for gray water processing
    - Make oxygen and water tanks modular for swapout replacement
- **Benefits**
  - Early generation of life support and radiation shielding consumables (O_2 and H_2O) and extra power for contingency and eclipse periods
  - Allows extend stay or range and safety of pressurized-rover science missions for repeat visit sites by having power and life support consumables present
  - Recycle dirty water thru distillation/ water processor (ECLSS)
  - Combine science and site/resource prospecting instruments to excavator to allow for reconnaissance at waystation remote sites and pre-cache samples
  - If successful, process can be repeated at other exploration sites



Potential Areas of Interest for Future Analog Test

Scout & Prepare for Human Mission

Scout Terrain & Resource → **Cache Consumables with ISRU** → **Prepare Site & Power System** → **Crew Arrives**



1a. Characterize & Map Polar Volatiles/Ice Resources
or Mars H_2O

1b. Characterize & Map Terrain and Resources for Oxygen Extraction from Regolith and Site Preparation

2. Lunar O_2 Production Lander Demo
(Create cache of O_2 for crew and power)
or Mars H_2O

3. Prepare Site for Crewed Lander to Minimize Risk

4. Establish Power & Consumable Infrastructure before Crew Arrives

Use Stepping Stone Approach to ISRU Demos & Utilization for Multiple Destinations

Microgravity Mining

ISS & Habitats

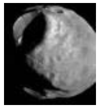
ISRU Focus
- Trash Processing into propellants
- Micro-g processing evaluation
- In-situ fabrication

Purpose: Support subsequent robotic and human missions beyond Cis-Lunar Space
- Reduce long-term costs
- Confidence in process feasibility
- Confidence in ISRU to investors

Near Earth Asteroids & Extinct Comets

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

Purpose: Prepare for Phobos & future Space Mining of Resources for Earth
- Confidence in resources present
- Confidence in process repeatability
- Confidence in ISRU to investors



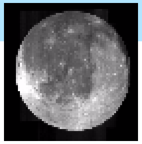
Phobos

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

Purpose: Prepare for orbital depot around Mars
- Confidence in resources present
- Confidence in process repeatability

Planetary Surface Mining

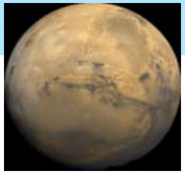
Moon



ISRU Focus
- Regolith excavation & transfer
- Water/ice prospecting & extraction
- Oxygen and metal extraction

Purpose: Prepare for Mars and support Space Commercialization of Cis-Lunar Space
- Test in harsh environment
- Remote operations with short time delay
- Confidence in process repeatability
- Confidence in ISRU to investors

Mars



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

Purpose: Prepare for human Mars missions
- Test in harsh environment
- Remote operations with long time delay
- Confidence in resources present
- Confidence in process repeatability and product quality