ISRU Robotic Precursor Mission Opportunities

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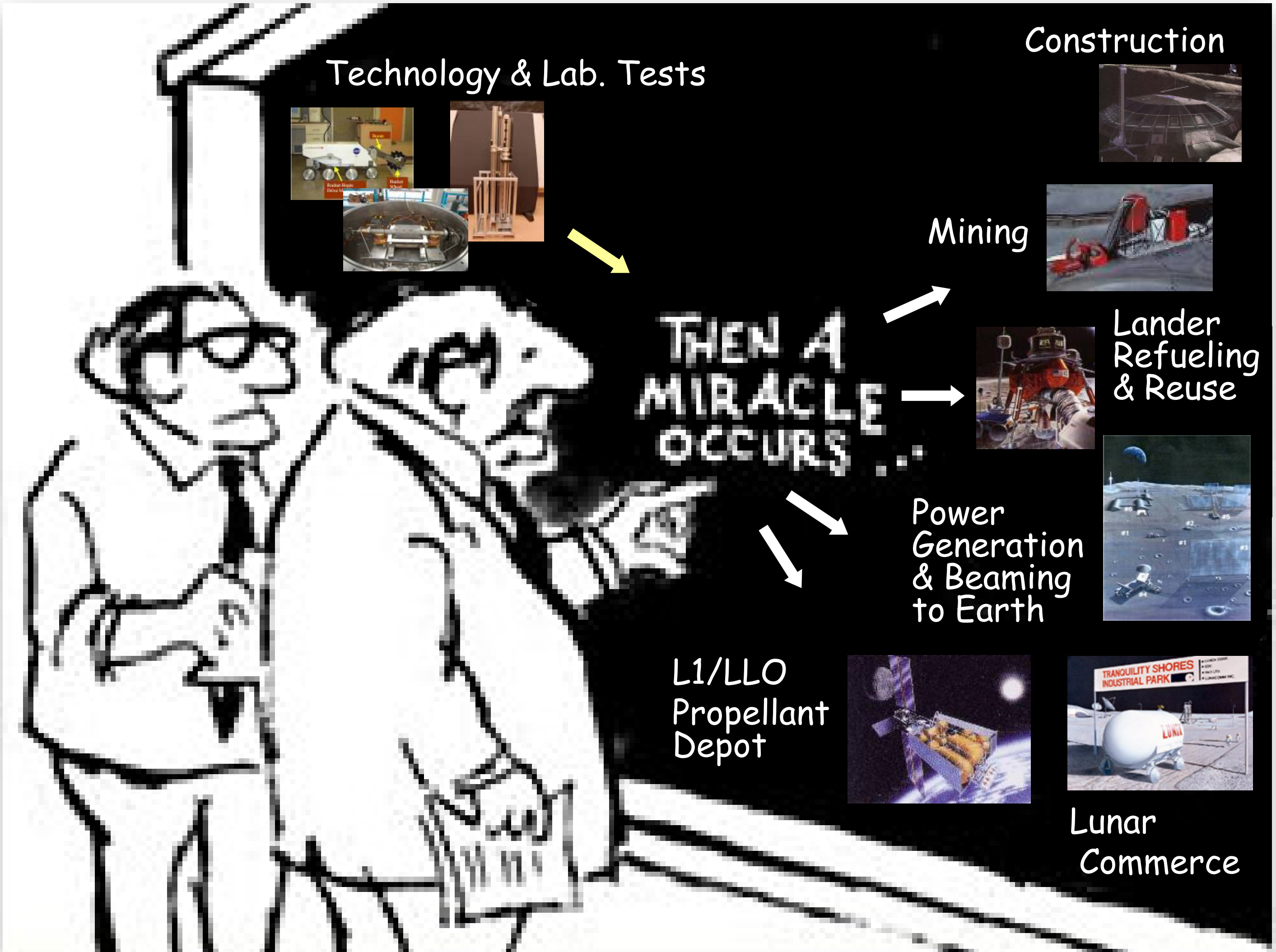
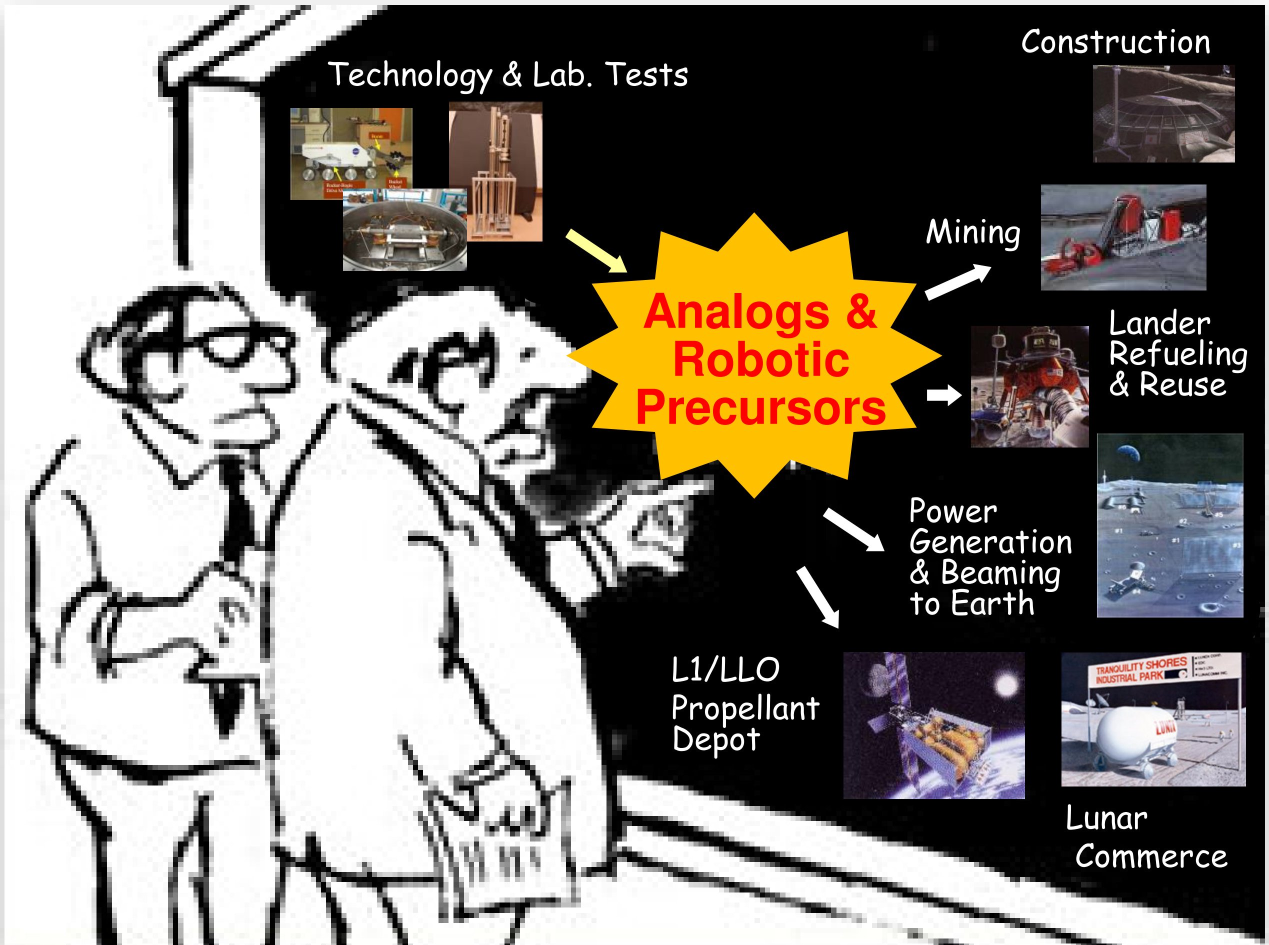
The Story of ISRU



"I think more work is needed in this step."

Where We Are Today



"I think we found the solution"

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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 and performance capability

Why Perform Analog Field Tests?

Concrete Benefits of Field/Analog 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 Field/Analog Testing

- Develop International Partnerships
- Develop Teams and Trust Early
- Develop Data Exchange & Interactions with International Partners (ITAR)
- *Outreach and Public Education*

Why Fly Lunar ISRU Demonstrations?

- **Validate Earth-based development & testing and overcome 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; validate or modify Earth-based testing for next flight system

- **Increase confidence in ISRU**
  - Show it can be done on the Moon!
  - Demonstrate critical functions and obtain design and operational data to minimize design and mission risk for full scale system
  - Utilize ISRU products in expected role (fuel cell, propulsion, etc.) to minimize risk for ISRU incorporation into human exploration missions

- **Early ISRU demonstrations can reduce human exploration cost & risk**
  - Increase payload capability to lunar surface by reducing consumables and propellants
  - Reduce risk to crew through radiation and landing plume protection and increased mission flexibility
  - Demonstrate capabilities applicable to NEO and human Mars exploration

- **Prepare engineers and managers for full scale hardware development**

- **Engage & Excite Public**
  - ISRU encompasses the pioneer spirit of exploration by “living off the land”
  - It shows the public that NASA is serious about long-term human exploration; ISRU is not about just ‘planting flags’

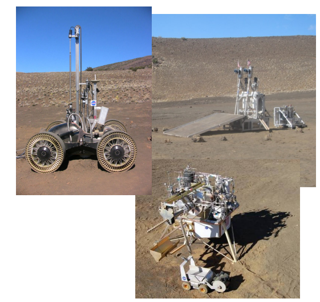
ISRU Risks and Mission Implications

ISRU 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

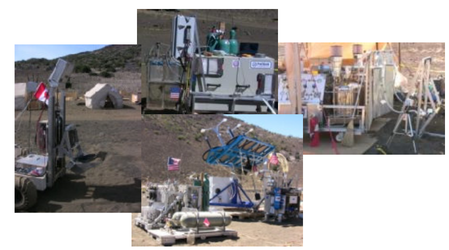
ISRU Analog Field Testing Overview & Results

- **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



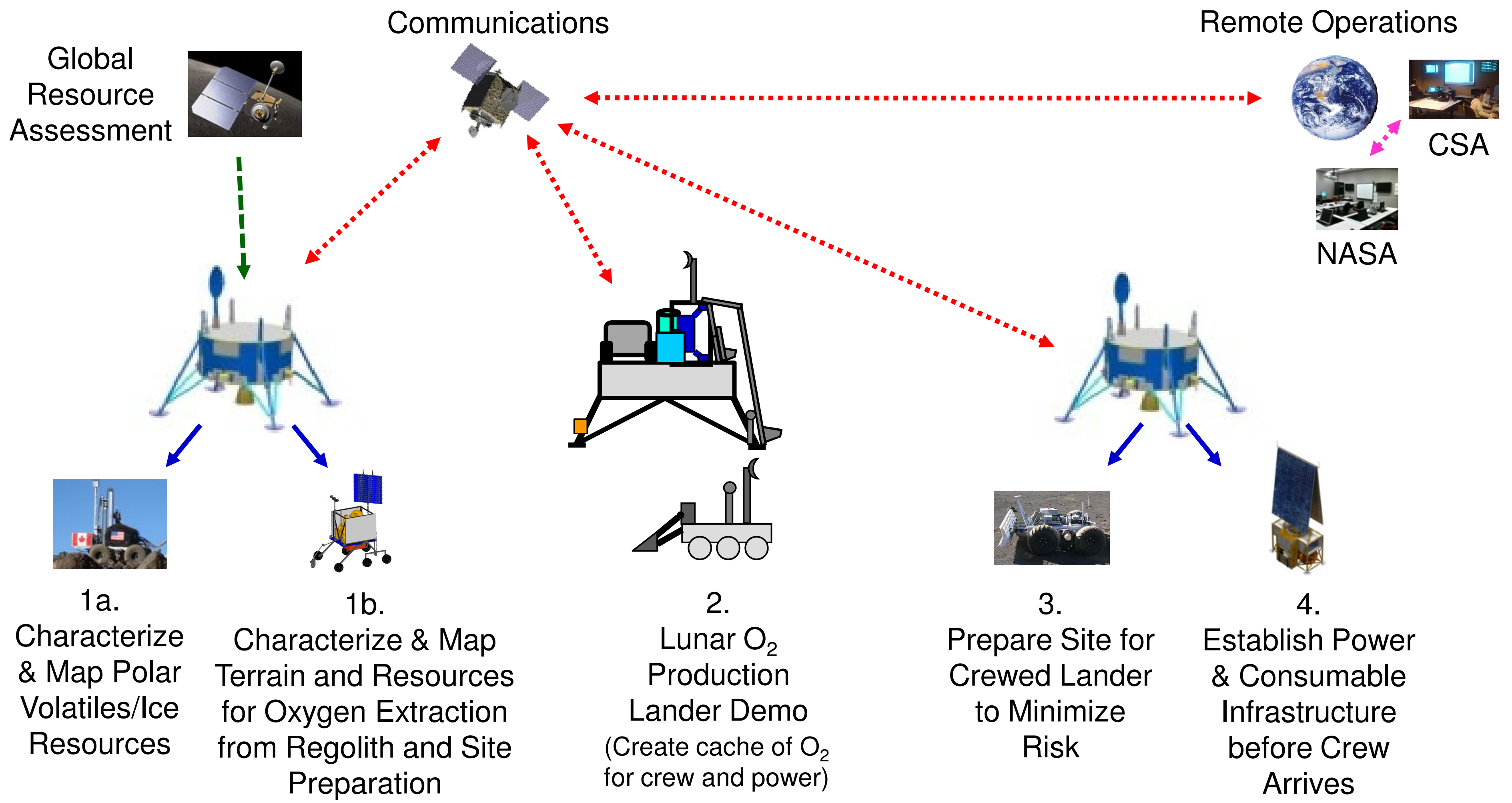
Major Results

- ☑ 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
- ☑ ISRU systems integrated with excavation/mobility, fuel cell power, and gaseous/cryogenic fluid storage and transfer
- ☑ Semi-autonomous and Remote operations through satellite
- ☑ International partnerships and small businesses in critical roles and operations

Potential Areas of Interest for Future Analog Tests

Scout & Prepare for Human Mission

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



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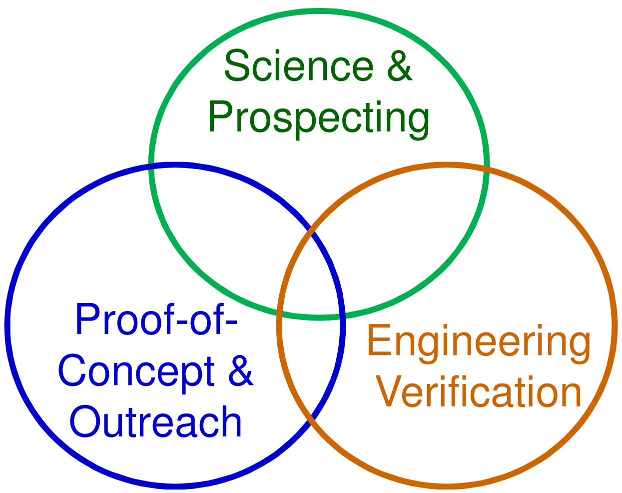
Types of Precursor ISRU Missions

- Need to select "What" the mission objective is. This will drive mass and power required and collaborators.

What is the form, concentration, and distribution of potential resources?
(physical, mineral, and volatile characterization)



Is the fundamental process possible on the Moon?
(scale and design is not applicable to full scale system)

Can a full scale system meet mission objectives?
(scale, design, and mission duration are applicable to full scale system)

Precursor ISRU Mission Type Pros/Cons

Mission Type	Pros	Cons
Science/Resource Data	Ground truth of hydrogen/water volatiles	Minimal engineering data for follow-on designs - Limited commercial business case other than availability of resource
	Better understanding of lunar mineral form & distribution	Limited commercial interest other than availability of resource
	Some extraction energy data possible	Minimal public outreach for ISRU; Mostly science
	Science is not 'opportunistic'; Possible large Science interest	
Proof-of-Concept Experiment	ISRU operations performed; Demonstrates feasibility	Science aspect may be minimal
	Can be small mass and volume	Minimal data for commercial business case - Design and operation most likely not scalable
	Perform public engagement - ex. drop of water	May only involve subsystems and not end-to-end processes
Engineering Validation of ISRU	Engineering Data obtained for key aspects of ISRU O_2 production and volatile extraction	Science aspect may be reduced; less instruments or fidelity of measurement
	Can demonstrate end-to-end process	Largest mass and cost to perform
	Greatest commercial interest to develop business case	
	Public engagement - 1st step in 'Living off the land'	

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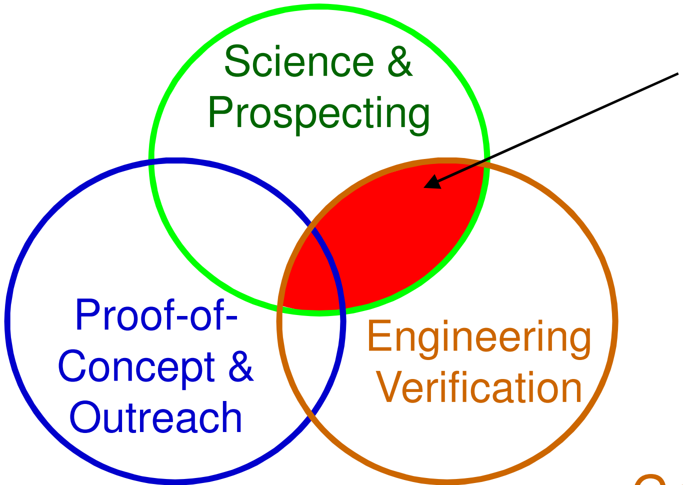

Good balance between Science & Engineering for ISRU in small payload missions if possible

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Lunar ISRU Demonstrations of Potential Interest

ISRU-Related Process	Potential Options	Criticality
Resource Characterization	Geotechnical Data Size/Shape Mineral (esp. Polar) Volatile/Ice	Med to High
Excavation & Material Handling	Scoop Blade Pneumatic	High
Size Sorting	Vibration screen Cyclone	Med
Mineral Beneficiation	Electrostatic Magnetic	High
Regolith Crushing	Regolith/Rock Regolith/Ice	Low Med
Surface Sintering/Hardening	Solar Microwave Binder	Med
Oxygen Extraction from Regolith	H_2 Reduction CH_4 Reduction Molten Salt Electrolysis Molten Oxide Electrolysis	High
Regolith Heating	Electrical Solar Microwave	Med
Product Cleanup and Capture	Adsorption Thermal/Cryogenic Distillation Deionization	High

New Opportunities for ISRU Precursor Demonstrations

Notional

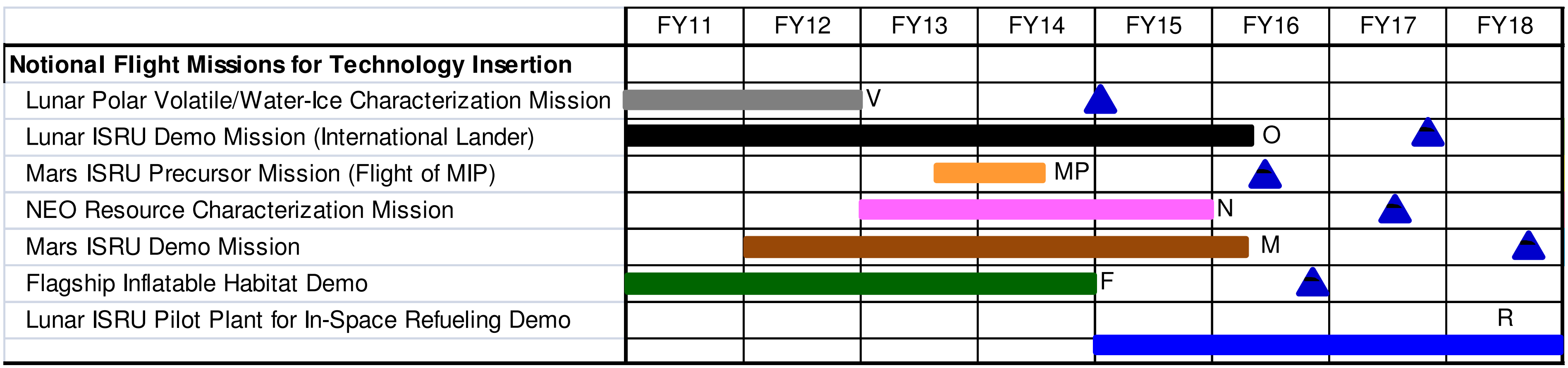
Opportunities	Date	ETDD Technologies	ISRU Interest
Flagship Technology Demonstrations	-		
• In-Space Propellant Storage & Transfer	2015	Cryogenic Propellant Storage & Transfer	CFM for space & surface Depots
• Solar Electric Propulsion	2016	High-Power Electric Thrusters	
• Inflatable Habitat	2016	Inflatable Structures; Closed-Loop Life Support	Trash-to-fuel processing for propulsion; In-Situ Fabrication
• Aerocapture	2016	Entry, Descent, & Landing Technology	
Robotic Precursor Missions	-		
• Mars Science Laboratory	2011	Mars EDL Instrumentation (MEDLI); Radiation Assessment Detector (RAD)	
• Google Lunar X-Prize	2013	Autonomous Precision Landing; Teleoperation of rovers; **ISRU**	Small (5 to 15 kg) single aspect validation; Demo-scale processing (50 to 100 kg)
• Lunar Lander / Rover	2015	ISRU; Autonomous Precision Landing; Lunar Rover	Volatile/Ice characterization; Oxygen from Regolith
• Mars Orbiter	2016	Aerocapture	
• NEO Rendezvous	2017	Electric propulsion; autonomous ops; automated rendezvous; **ISRU**	Micro-g material transfer; mineral and volatile prospecting
• Mars Orbiter / Lander	2018	Aerocapture; Entry, Descent, & Landing; **ISRU**	Mars atmosphere to O_2; Mars soil/water processing; nuclear power
ISS Utilization	-		Micro-g material transfer; processing proof of concept for planetary and NEO missions
			In-situ fabrication and repair
International	-		
• JAXA SELENE-2	2015	**ISRU**; Autonomous Precision Landing	Volatiles and O_2 from Regolith
• ATV/HTV	2016	Fire detection & suppression	

Schedule is Tight!

Primary Objectives of ISRU Roadmap

- Develop technologies and systems to support flight demonstrations
- Demonstrate ISRU capabilities at relevant mission scale to support Architecture Planning

Notional Schedule of ISRU Demonstrations



Bars denote technology and system development activities under ETDD

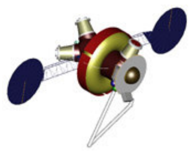
Schedule and development activities require:

- Parallel development activities for multiple destinations
- Significant coordination with other ETDD areas: Robotics, Cryogenic Fluids, Life Support, High Efficiency Power, and Advanced Chemical Propulsion
- Industry, academia, other government agency, and International Space Agency participation

Use Stepping Stone Approach to ISRU Demonstration & Utilization

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

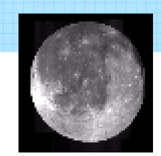
Phobos

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

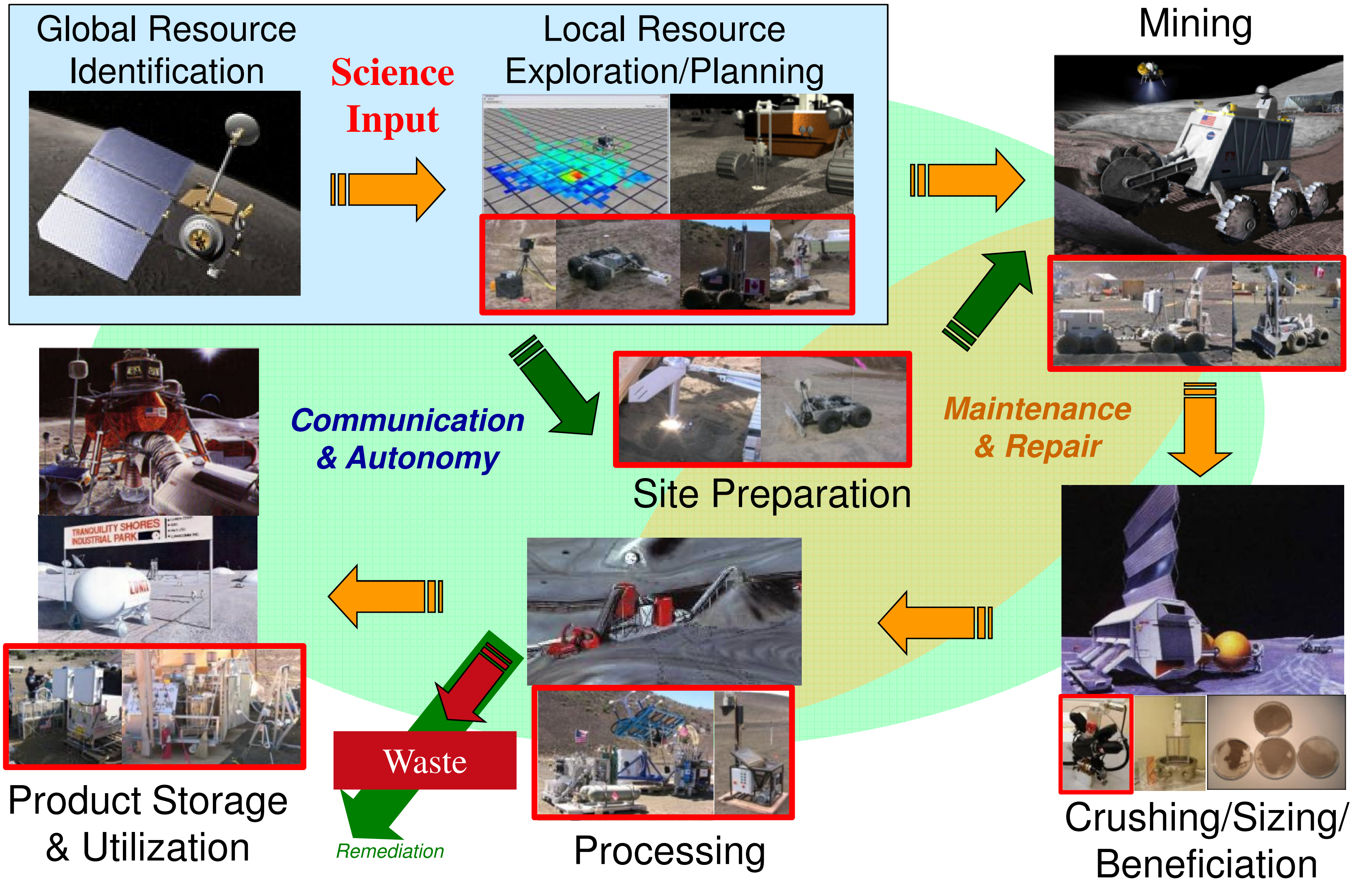
ISRU Focus
- Mars soil excavation & transfer
- Water prospecting & extraction
- Oxygen and fuel production for propulsion, fuel cell power, and life support backup

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

Backup

Analog Field Test Theme

Space Resource Utilization Operation Cycle



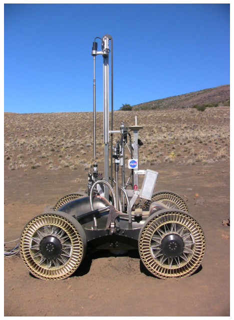
Early Surface Preparation Field Evaluation

- **Mosses Lake, June 2008**: LANCE Blade mounted to “Chariot” mobile platform
  - 1st integrated field test of ISRU hardware on mobility platform for surface construction
  - No articulation capability on blade required mobile platform to perform all x-y-z actuations
  - Large area cleared and berm built via on-site, visual tele-operation
  - Blade interference with ground on rough terrain due to extension from front end

- **Flagstaff, Sept. 2009**: LANCE Blade mounted to “Chariot” & LER platforms
  - Z-axis articulation capability on blade allowed better ground clearance on rough terrain
  - Quick disconnect mechanism allowed for blade integration and removal for dedicated tests
  - Similar overall surface preparation performance

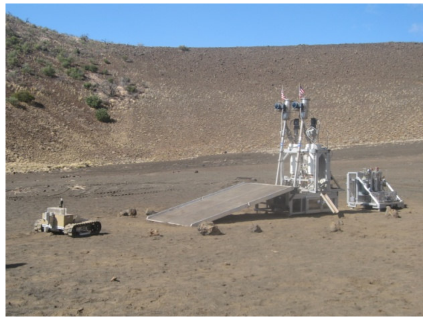
ISRU Hardware Tested at Analog Site (Nov 2008)

Lunar Prospecting

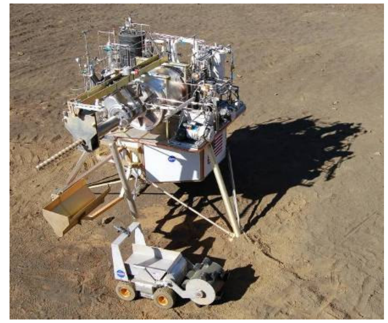


- Scarab Rover
- RESOLVE
- TriDAR Vision System
- Tweels

Outpost-Scale O_2 from Regolith

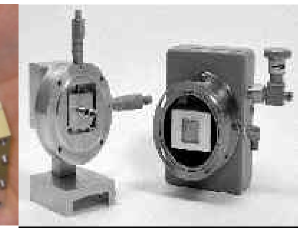


- ROxygen H_2 Reduction
- Water Electrolysis
- Cratos Excavator



- PILOT H_2 Reduction
- Water Electrolysis
- Bucketdrum Excavator

Process Control & Science



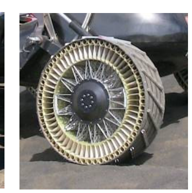
- Moessbauer
- Mini Chemin XRD/XRF

- **Canadian Space Agency**
  - TriDAR imager, Satellite communications, remote operation of Drill and TriDAR navigation, and on-site personnel and payload mobility
  - NORCAT, Xiphos, Argo, Virgin Technologies, EVC, Ontario Drive Gear, **University of Toronto**

- **German Space Agency (DLR)**
  - Instrumented “Mole” & Sample Capture Mole

- **Carnegie Mellon University**
  - SCARAB Rover

- **JPL Partnership with Michelin on ‘Tweels’ testing**



Analog Field Test Hardware & Operation Integration (Feb. 2010)