NASA’s In-Situ Resource Utilization Project
Presentation to the Synthetic Biology Workshop

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October 30, 2010

What are Space Resources?

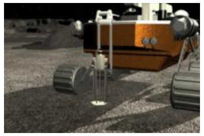
- **'Resources'**
  - Traditional**:** **Water**, atmospheric gases, volatiles, solar wind volatiles, metals, etc.
  - Non-traditional: Trash and wastes from crew, spent landers and residuals, etc.
- **Energy**
  - Permanent/Near-Permanent Sunlight
    - Stable thermal control & power/energy generation and storage
  - Permanent/Near-Permanent Darkness
    - Thermal cold sink for cryo fluid storage & scientific instruments
- **Environment**
  - Vacuum
  - Micro/Reduced Gravity
  - High Thermal Gradients
- **Location**
  - Stable Locations/'Real Estate':
    - Earth viewing, sun viewing, space viewing, staging locations
  - Isolation from Earth
    - Electromagnetic noise, hazardous testing & development activities (nuclear, biological, etc.), extraterrestrial sample curation & analysis, storage of vital information, etc.

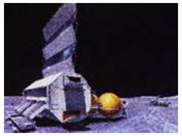
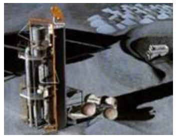
What is In-Situ Resource Utilization (ISRU)?

ISRU involves any hardware or operation that harnesses and utilizes ‘in-situ’ resources to create products and services for robotic and human exploration

Five Major Areas of ISRU

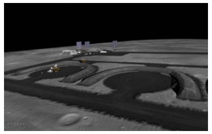
- **Resource Characterization and Mapping**
  Physical, mineral/chemical, and volatile/water

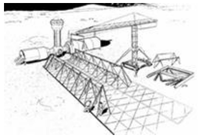


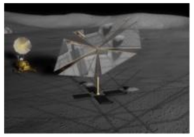
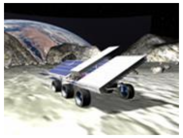




- **Mission Consumable Production**
  Propellants, life support gases, fuel cell reactants, etc.

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

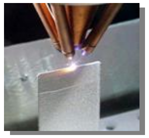





- **In-Situ Energy Generation, Storage & Transfer**
  Solar, electrical, thermal, chemical

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



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

Why ISRU?

It Enables Affordable, Flexible, & Sustainable Exploration

Space Resource Utilization

Mass Reduction

Propellant Production

- Reduces Earth to orbit mass by 20 to 45% for Mars missions
- 3.5:1 to 5:1 mass savings leverage from Moon/Mars surface back to Low Earth Orbit

Cost Reduction

- Reduces number and size of Earth launch vehicles
- Allows reuse of transportation assets
- Minimizes development costs

Risk Reduction & Flexibility

- Number of launches & mission operations reduced
- Use of common hardware & mission consumables enables increased flexibility
- In-situ fabrication of spare parts enables sustainability and self-sufficiency
- ISRU can provide dissimilar redundancy
- Radiation & Plume Shielding
- Reduces dependence on Earth

Expands Human Presence

- Increase Surface Mobility & extends missions
- Habitat & infrastructure construction
- Propellants, life support, power, etc.
- Substitutes sustainable infrastructure cargo for propellant & consumable mass

Solves Terrestrial Challenges & Enables Space Commercialization

- Develops alternative & renewable energy technologies
- CO_2 remediation
- Green metal production
- Provides infrastructure to support space commercialization
- Propellant/consumable depots at Earth-Moon L1 & Surface for Human exploration & commercial activities

Camping vs Staying
(Apollo vs Lunar Outpost)

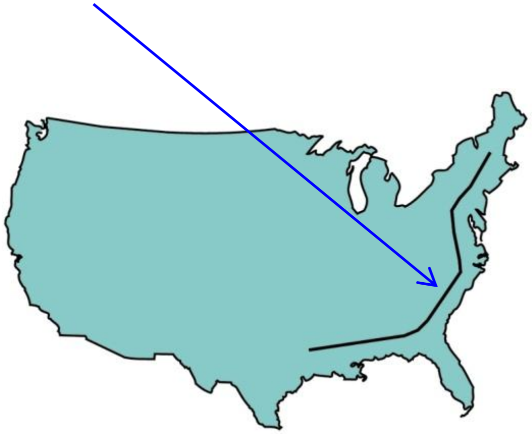
	Camping	Staying
Water/Food	Brought: Freeze-dried, canned, and canteen Local: stream	Brought: Low mass speciality items (salt, sugar, spices, yeast) Local: Well and rain capture bucket for water; garden, berries/fruit trees, and animals for food
Shelter	Lightweight tent	Cave, Cabin, or some form of environmental protection
Energy	Brought: Non rechargable batteries and Kerosine Local: sticks/branches on the ground	Local: Cut trees/charcoal, water wheel, wind, still/distillation
Local Transportation	Walking	Horse or animal; steam or combustion engine

Take almost everything with you

Take items to help you "Live off the Land"

You do not need ISRU for camping trips, but you do need it if you are going to stay and be productive

We wouldn't have gotten far if we couldn't use the local resources

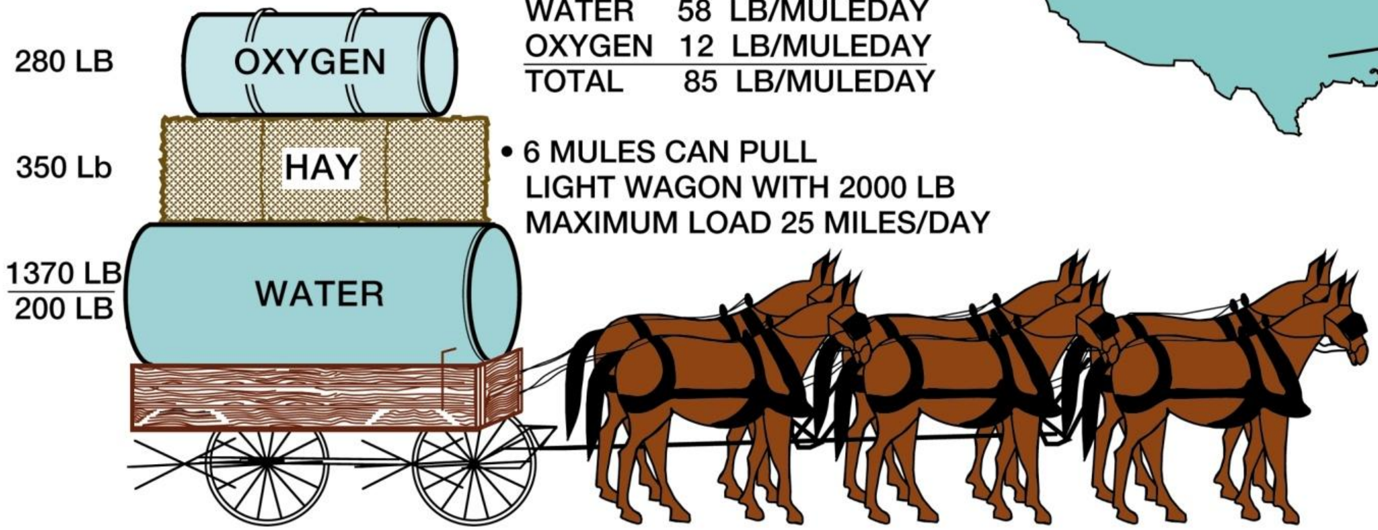


HAYBURNER ANALOGY

- MULE CONSUMABLES

HAY	15 LB/MULEDAY
WATER	58 LB/MULEDAY
OXYGEN	12 LB/MULEDAY
TOTAL	85 LB/MULEDAY

- 6 MULES CAN PULL LIGHT WAGON WITH 2000 LB MAXIMUM LOAD 25 MILES/DAY



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- $\frac{(2000\ \text{LB}) \times (25\ \text{MILES/DAY})}{(6\ \text{MULES}) \times (85\ \text{LB/MULEDAY})} = \text{RANGE}$

- MAXIMUM RANGE = 100 MILES

ISRU vs Non-ISRU Architectures

For ISRU to be viable it must have following:

- Mass payback
  - Product vs infrastructure, replacement parts, power systems, etc.
- Cost payback; Return on Investment
  - DDT&E costs & launch costs vs launch costs for product alone
  - Cost credit due to reuse of exploration assets (ex. landers)
- Mission and crew risk reduction must outweigh increased risk of ISRU system

When Evaluating ISRU Concepts, you need to evaluate the following:

- 'Launch mass saved' or 'Launch mass avoided'
- Process and operation complexity
- Process scalability
- Ability to operate without human presense
- Mean-time between failure; reliability
- System power, mass & volume
- Mass of product/service vs Mass of ISRU "system"
- Amount of infrastructure and ease of delivery/deployment required before products are delivered for use
- Amount of reagents and hardware consumables brought from Earth

It's not about being able to do ISRU.

It's not about having the most efficient ISRU system.

It is about achieving the benefits of ISRU for a reasonable cost, mass, and risk.

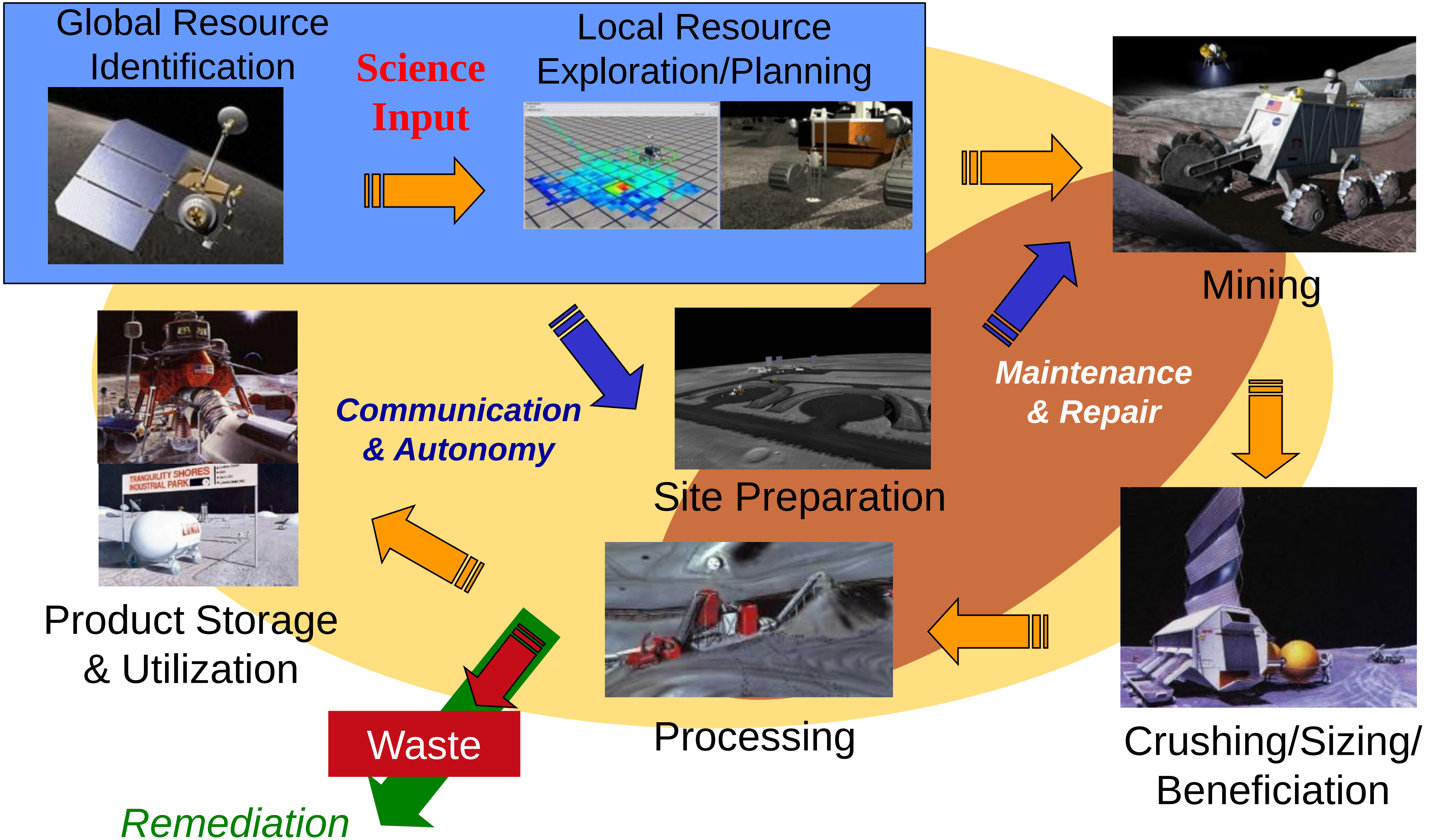
Top-Level ISRU Development & Integration Strategy

- **Not Everything Can Be Funded Immediately**
- Need *Early, Achievable, & Visible* milestones & successes
  - Must ensure constant delivery of products; with incremental growth in both number of products & quantity of products
  - Early missions must require minimum infrastructure and provide the biggest mass/cost leverage
  - Surface construction and manufacturing will start with simple/high leverage products and expand to greater self-sufficiency capability
- Need to take evolutionary approach in development & missions
  - Early hardware needs to be achievable, not optimized
  - Early hardware needs to be scalable to future missions
  - Each design/demonstration activity needs to build on lessons learned from previous work and show clear benefit metrics
  - Research activities and technology development must be continuously performed and focused to enable sustained momentum and growth
  - Capabilities need to be able to grow with growth in:
    - Resource & process understanding
    - Human surface activities
- No single process or technology is best
  - Develop two or more approaches if possible to ensure success

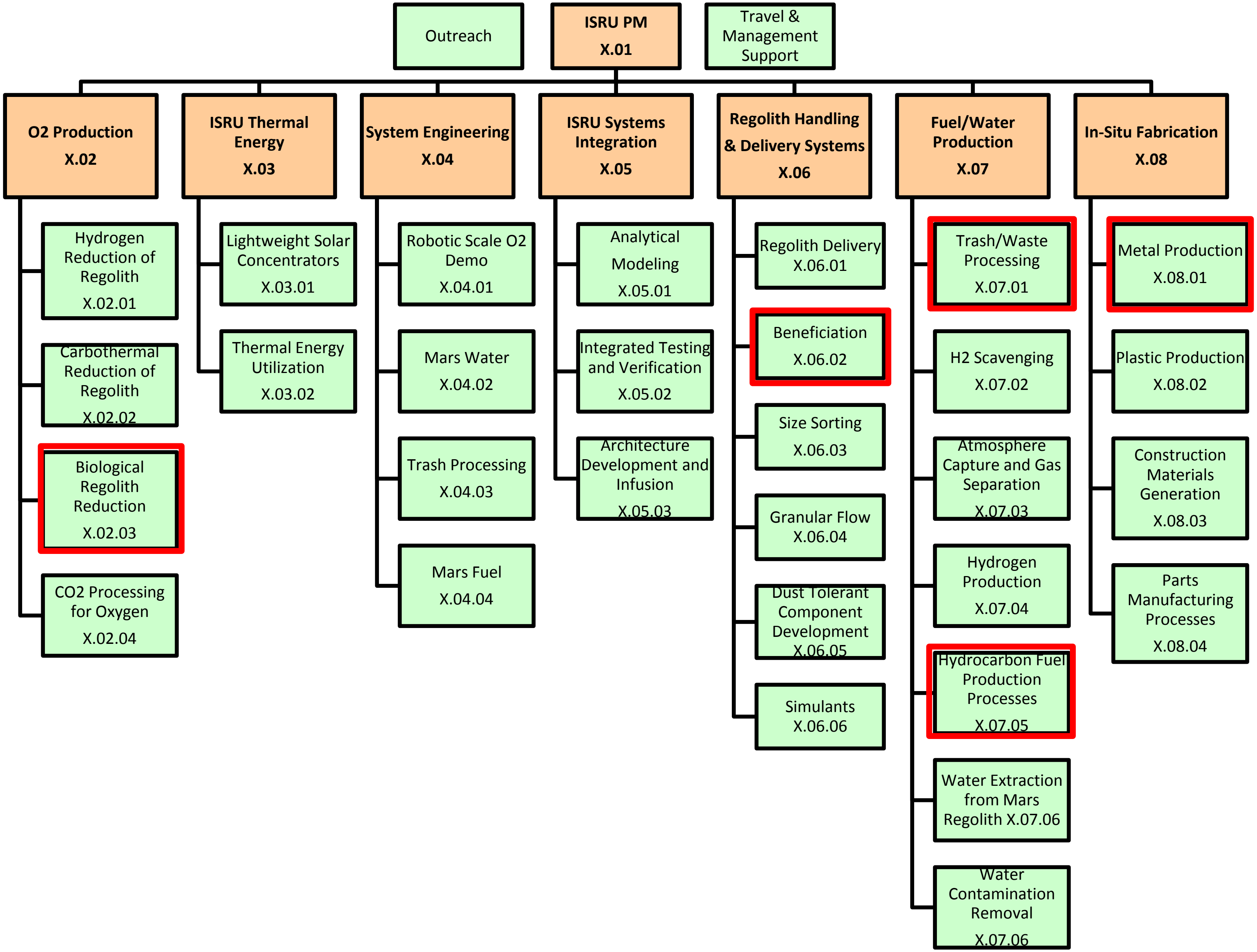
ISRU must achieve mass and cost payback

Space ISRU 'Mining' Cycle

All steps need to be considered when evaluating ISRU concepts

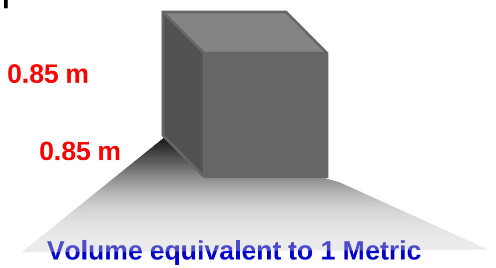


ISRU Work Breakdown Structure (FY11+)



Analogies to Understand ISRU Systems

- 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

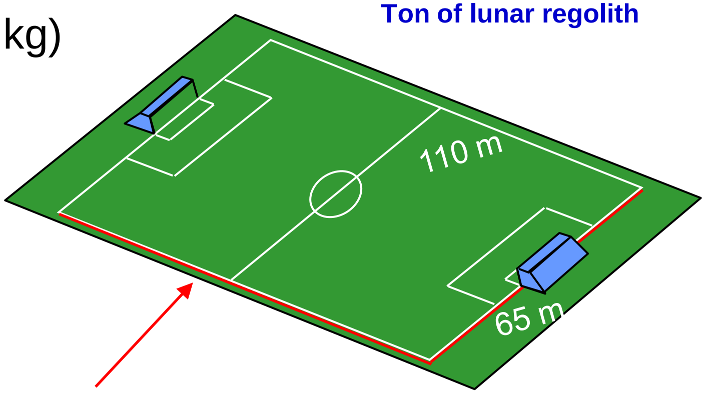


Volume equivalent to 1 Metric Ton of lunar regolith

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


Cratos Excavator

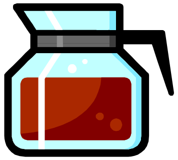

IR&D rovers at LMA



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

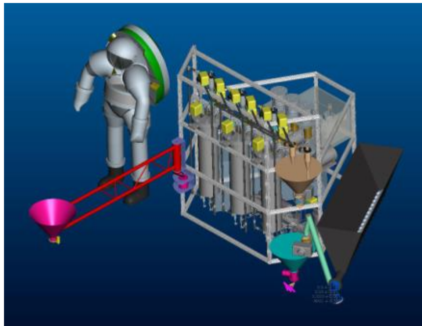
- Oxygen Processing Reactors are not large, even for 1% efficient systems & With No Beneficiation

1 MT of oxygen per year requires an excavation rate of **<1/2 cups per minute!**
(1% efficiency - 70% light) (worst case)



300 MT of oxygen per year requires a regolith excavation rate of ~**10 cups per minute**!
(14% efficiency - 70% time-polar region)

Lowest Efficiency Concept Sized for 1 MT of oxygen/year



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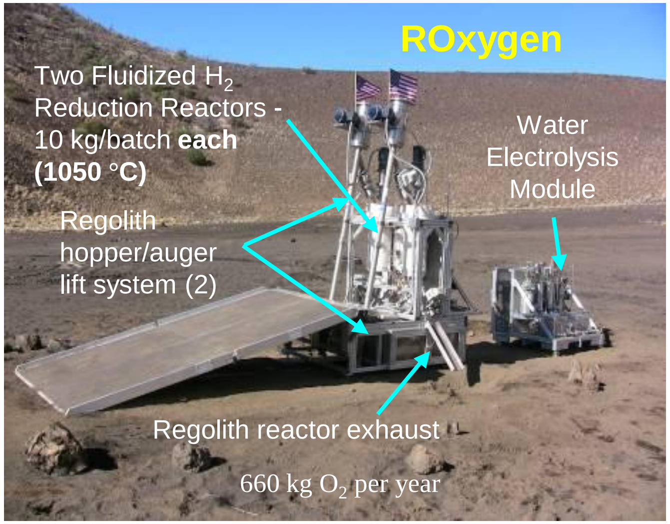
Lunar Processing – Oxygen & Metal Extraction

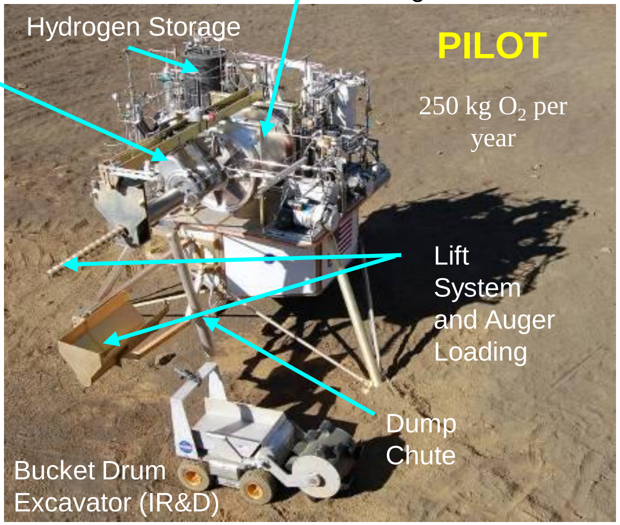
Hydrogen Reduction of Regolith



1. Heat Regolith to >900 C

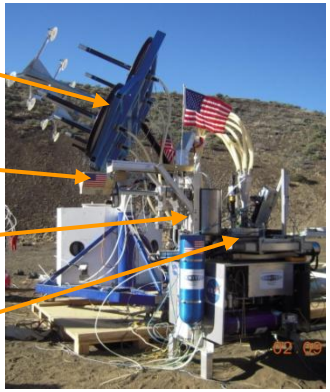
2. React with Hydrogen to Make Water

3. Crack Water to Make O_2



$$FeO + H_2 \rightarrow Fe + H_2O; \qquad 2H_2O \rightarrow 2H_2 + O_2$$

Carbothermal Reduction of Regolith



1. Melt Regolith to >1600 C

2. React with Methane to CO

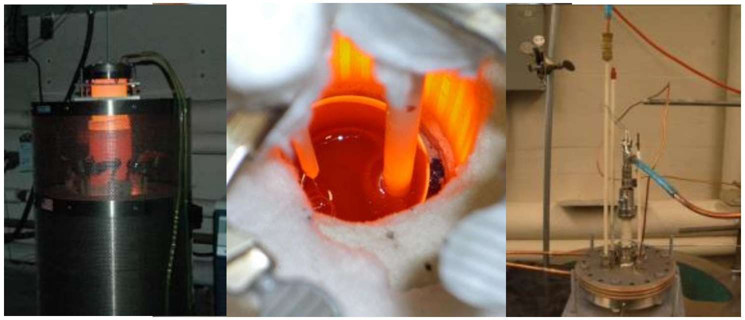
3. Convert CO to Methane & Water

4. Crack Water to Make O_2

$$SiO_4 + CH_4 \rightarrow CO + 2H_2 + Si; \dashrightarrow CO + 3H_2 \rightarrow CH_4 + H_2O;$$

$$2H_2O \rightarrow 2H_2 + O_2$$

Molten Electrolysis of Regolith



1. Melt Regolith to >1600 C

2. Apply Voltage to Electrodes To Release Oxygen

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

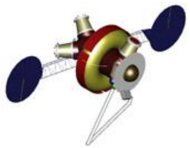
Major Results

- ☑ 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

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

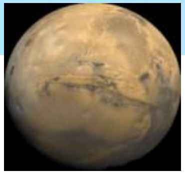
Planetary Surface Mining

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

Benefits of Incorporating ISRU into Lunar Architecture

Reduces Risk

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

Increases Performance

- Longer stays, increased EVA, or increased crew over baseline with ISRU consumables
- Increased payload-to-orbit or delta-V for faster rendezvous with ‘topping off” or complete fueling of ascent vehicle
- Increased and more efficient surface nighttime and mobile fuel cell power architecture with ISRU

Increases Science

- Greater surface and science sample collection access thru in-situ fueled hoppers
- Greater access to subsurface samples thru ISRU excavation and trenching capabilities
- Increased science payload per mission by eliminating consumable delivery

Increases Sustainability/Decreases Life Cycle Costs

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

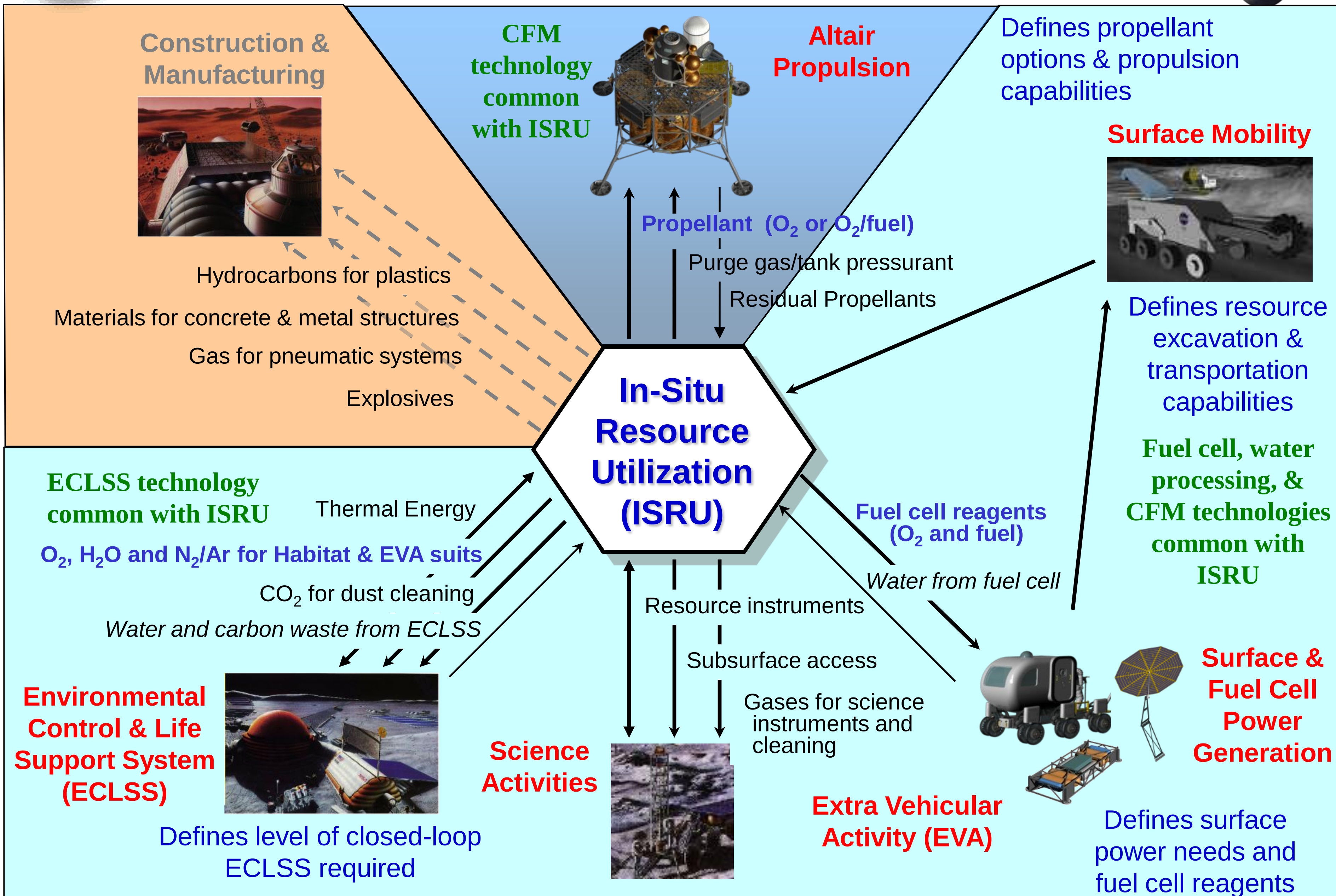
Mars Forward

- Demonstrates surface operations associated with ISRU and oxygen/propellant storage and transfer
- Critical lunar ISRU subsystems and technologies are similar to Mars atmospheric processing
- Lunar excavation and regolith processing systems are similar with Mars soil processing to extract water
- Lunar water/ice and mineral characterization subsystems are similar Mars water/soil characterization

Earth-based Benefits (Spin-in/Spin-off)

- Alternative fuels and energy
- Construction and powder industries
- Metal production and CO_2 Reduction

Surface Systems Element Connectivity with In-Situ Resource Utilization (ISRU)



ISRU Connectivity With Other Surface Elements

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

Requirement Connectivity	
Propulsion Systems	Propellant Quanity Propellant Type Residual Amount Storage Capability
Life Support/EVA Systems	Consumable Quantity Consumable Type Waste Products/Trash Consumable Storage Capability
Surface Mobility/HRS	Vehicle Size Terrain Mobility Capabilities Tele-operation Requirements Autonomy Requirements Power Requirements Fuel Cell Reagent Quantities 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 Storage & Valving Solar Collectors/Solar Thermal Propulsion Consumable Storage & Valving Water Processing/Electrolysis Carbon Dioxide Seperation and Processing Liquid/Gas Separation Solar Collectors/Trash Processing
Surface Mobility/HRS	Mobility Platforms Actuators, Motors, & Control Software
Surface Power	Consumable Storage & Valving Water Processing/Electrolysis Liquid/Gas Separation Solar Collectors/Solar Thermal Power & Storage
Science Instruments	Geotechnical Properties Mineral Properties Volatile Characterization Mobility Platforms
Testing & Certification	Surface Analogs Environment Simulation Chambers Lunar Regolith Simulants Simulant Bed Preparation

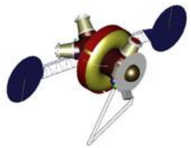
Design & Implementation Impacts of ISRU on Surface Exploration Elements

- **Life Support**
  - Degree of closed-loop air/water cycle and technologies/capabilities required depends on availability of ISRU water and oxygen. (ex. trade ISRU supplied water for 'dirty' water for propellant production)
  - Possible common water and air processing technologies and hardware
  - Amount of logistics required from Earth per year, size/mass of logistics carrier, and delivery rate
  - ➢ Disposal of trash and plastic waste – possible ISRU water, fuel production, and fabrication/repair feedstock by processing with ISRU oxygen
- **Extra Vehicular Activity (EVA)**
  - Liquid oxygen (LO_2) vs high pressure oxygen for Portable Life Support System (PLSS). LO_2 considered for PLSS only if available from ISRU
  - Water cooling/venting vs alternative cooling for PLSS. Availability of ISRU water or LO_2 could impact logistics and design
  - Amount of logistics required from Earth per year, size/mass of logistics carrier, and delivery rate
- **Surface Habitat & Mobile Power**
  - Consumable amount and storage concept for fuel cell reactants for night time power system (high pressure oxygen vs LO_2) different if ISRU is available (12% mass savings for LO2)
  - System capability to regenerate fuel cell reactants for surface mobility units (increase size of ISRU water electrolysis and storage system vs separate dedicated system)
- **Lunar Lander Propulsion**
  - ISRU O_2 (and possibly CH_4) enables resupply ascent vehicles
  - Use of LSAM descent tanks for ISRU storage minimizes downmass
  - Reuse of LSAM descent stage for hopping to other location or return to orbit provides growth capabilities to Outpost and human exploration at fraction of the cost of dedicated mission from Earth
- **Outpost Layout, Deployment, and Surface Operations**
  - Mobile regolith transport systems for propellant/consumables production plant can double as road graders, landing site groomers, regolith shielding/insulating structure builders, etc

ISRU is not Destination Specific

Common Resources & Processes Support Multiple Robotic/Human Mission Destinations

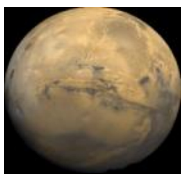
Possible Destinations



Habitats

Moon

Mars & Phobos



Near Earth Asteroids & Extinct Comets

Europa

Titan

Common Resources

Water
- Moon
- Mars
- Comets
- Asteroids
- Europa
- Titan
- Triton
- **Human Habitats**

Carbon
- Mars (atm)
- Asteroids
- Comets
- Titan
- **Human Habitats**

Metals & Oxides
- Moon
- Mars
- Asteroids

Helium-3
- Moon
- Jupiter
- Saturn
- Uranus
- Neptune

Core Building Blocks

- Atmosphere & Volatile Collection & Separation
- Regolith Processing to Extract O_2, Si, Metals
- Water & Carbon Dioxide Processing
- Fine-grained Regolith Excavation & Refining
- Drilling
- Volatile Furnaces & Fluidized Beds
- 0-g & Surface Cryogenic Liquefaction, Storage, & Transfer
- In-Situ Manufacture of Parts & Solar Cells

Core Technologies

- Microchannel Adsorption
- Constituent Freezing
- Molecular Sieves

- Hydrogen Reduction
- Carbothermal Reduction
- Molten Oxide Electrolysis

- Water Electrolysis
- CO_2 Electrolysis
- Sabatier Reactor
- RWGS Reactor
- Methane Reformer
- Microchannel Chem/thermal units

- Scoopers/buckets
- Conveyors/augers
- No fluid drilling

- Thermal/Microwave Heaters
- Heat Exchangers
- Liquid Vaporizers

- O_2 & Fuel Low Heatleak Tanks (0-g & reduced-g)
- O_2 Feed & Transfer Lines
- O_2/Fuel Couplings

ISRU Risks

- **Resource Risks** (due to incomplete prospecting)
  - Potential resource is not available
  - Resource not available at landing site
  - Resource is present, *BUT*
    - Form is different than expected (concentration, state, composition)
    - Location is different than expected (depth, distribution)
    - Unexpected impurities
- **Technical Risks**
  - Level of maintenance & repair unknown
  - Uncertainty in performance and amount regolith excavation required
  - Sealing for regolith processing systems .
  - System reliability.
    - More complex systems are more likely to fail and more difficult to fix.
    - Robustness and flexibility often conflict, though both are needed in new environments.
    - Scaling issues are non-linear and non-trivial.
    - Difficult to test with simulations; field experience required (more=better).
  - Effects of lunar and Mars environmental conditions.

General ISRU Development & Operation Challenges & Risks

- Obtaining/providing adequate physical and chemical/mineral lunar simulants to validate ISRU processes and equipment on Earth before launch
- Identifying (or upgrading) test facilities that can adequately simulate lunar environments: vacuum, solar/temperature, regolith/dust, implanted resources (solar wind volatiles & water/hydrogen)
- Addressing the different requirements between development projects and LPRP/Sortie mission needs (ex. RLEP2 polar mission vs RESOLVE project)
- Developing a better knowledge of the level of maintenance required for long-duration operations (years)
- Developing autonomous control & failure recovery capabilities (Minimal/no crew for maintenance; Non-continuous monitoring), especially for coordinating operations for multiple assets
- Characterization of form and spatial distribution of resources to the degree necessary to plan use of ISRU processes at possible sites of exploration

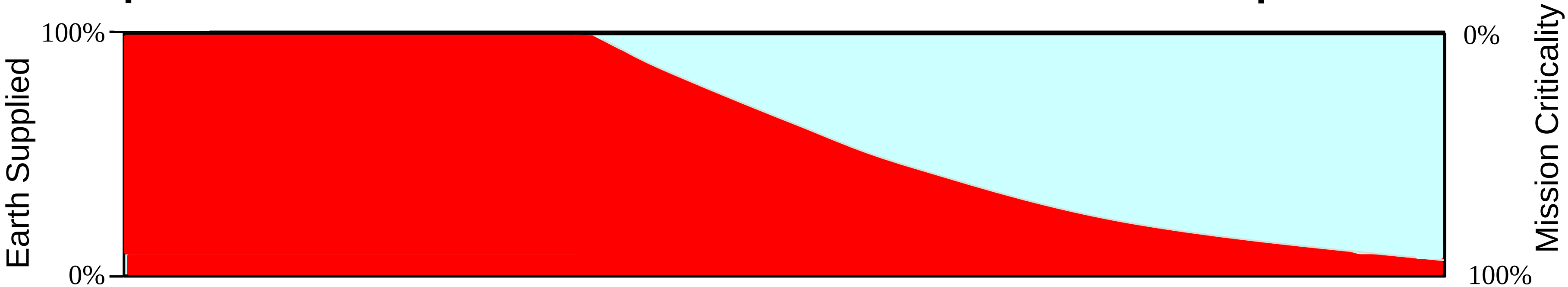
Risks and Mission Implications of ISRU Incorporation in Human Exploration

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

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*

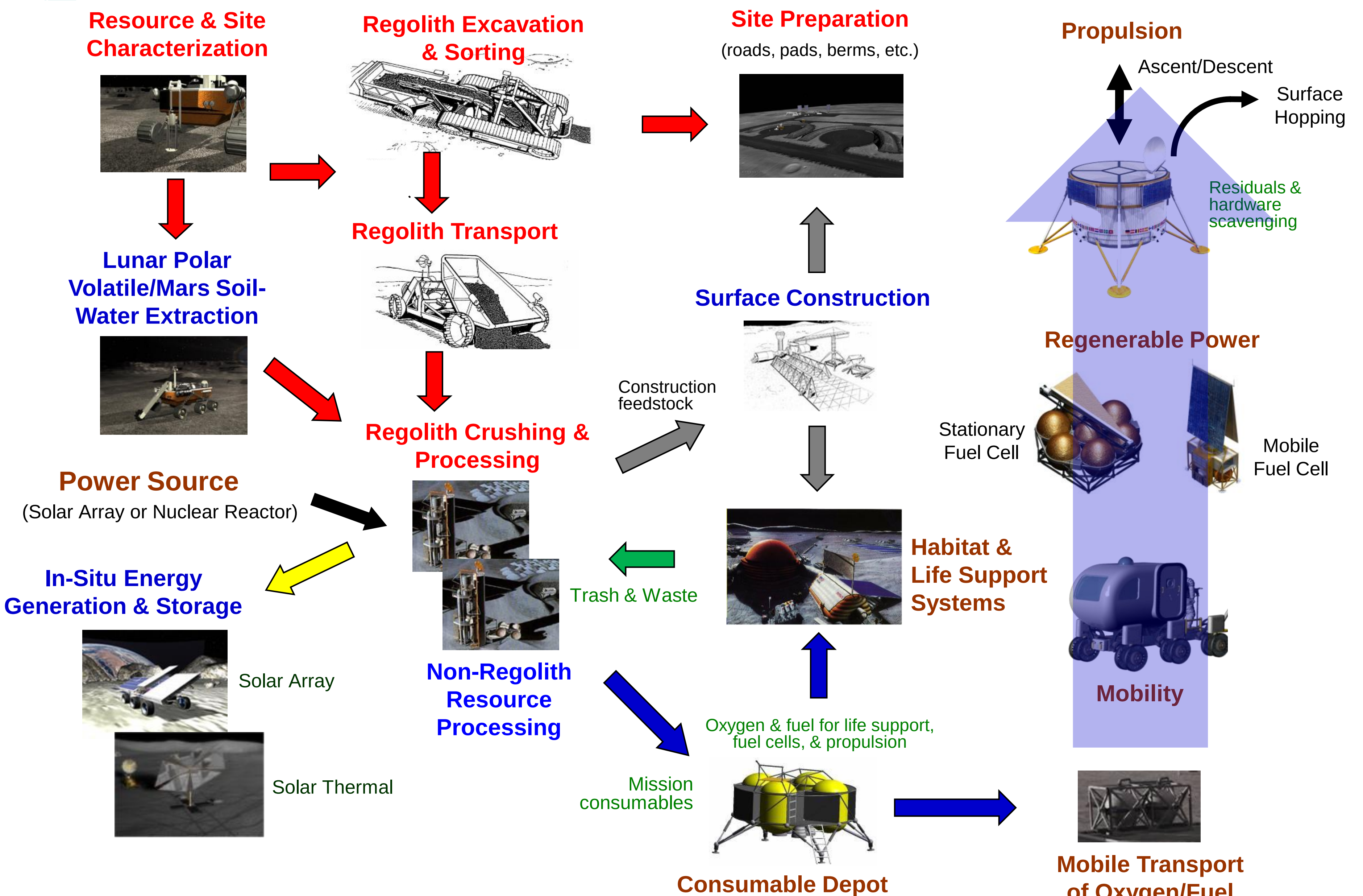
- **Robotic Precursors**
- **14 to 28 day missions**
- **Repeat visit sites**
- **Sites of extreme access difficulty**

Full Implementation

Purpose

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

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



Resource & Site Characterization
Regolith Excavation & Sorting
Site Preparation
(roads, pads, berms, etc.)
Propulsion
Ascent/Descent
Surface Hopping
Residuals & hardware scavenging
Regolith Transport
Lunar Polar Volatile/Mars Soil-Water Extraction
Surface Construction
Regenerable Power
Construction feedstock
Stationary Fuel Cell
Mobile Fuel Cell
Regolith Crushing & Processing
Power Source
(Solar Array or Nuclear Reactor)
Habitat & Life Support Systems
Trash & Waste
In-Situ Energy Generation & Storage
Solar Array
Non-Regolith Resource Processing
Mobility
Oxygen & fuel for life support, fuel cells, & propulsion
Solar Thermal
Mission consumables
Consumable Depot
Mobile Transport of Oxygen/Fuel

Lunar & Mars Resources

Moon Resources

Ilmenite - 15%
- $FeO \cdot TiO_2$ (98.5%)

Pyroxene - 50%
- $CaO \cdot SiO_2$ (36.7%)
- $MgO \cdot SiO_2$ (29.2%)
- $FeO \cdot SiO_2$ (17.6%)
- $Al_2O_3 \cdot SiO_2$ (9.6%)
- $TiO_2 \cdot SiO_2$ (6.9%)

Olivine - 15%
- $2MgO \cdot SiO_2$ (56.6%)
- $2FeO \cdot SiO_2$ (42.7%)

Anorthite - 20%
- $CaO \cdot Al_2O_3 \cdot SiO_2$ (97.7%)

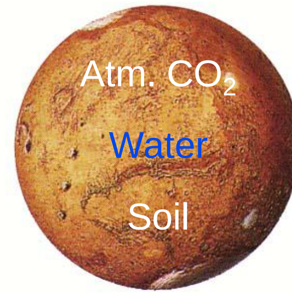
Water (?, >1000 ppm)

Solar Wind
- Hydrogen (50 - 100 ppm)
- Carbon (100 - 150 ppm)
- Nitrogen (50 - 100 ppm)
- Helium (3 - 50 ppm)
- ^3He (4 - 20 ppb)

Mars Resources

Soil*
- Silicon Dioxide (43.5%)
- Iron Oxide (18.2%)
- Sulfur Trioxide (7.3%)
- Aluminum Oxide (7.3%)
- Magnesium Oxide (6.0%)
- Calcium Oxide (5.8%)
- Other (11.9%)
- Water (2 to >50%)[XX]

*Based on Viking Data
[XX]Mars Odyssey Data



Atmosphere
- Carbon Dioxide (95..5%)
- Nitrogen (2.7%)
- Argon (1.6%)
- Oxygen (0.1%)
- Water (210 ppm)

Lunar Resources

- Oxygen is the most abundant element on the Moon
- Solar wind deposited volatile elements are available at low concentrations
- Metals and silicon are abundant
- Water may be available at poles
- Lunar mineral resources are understood at a global level with Apollo samples for calibration

Mars Resources

- Atmospheric gases, and in particular carbon dioxide, are available everywhere at 6 to 10 torr (0.1 psi)
- Viking and Mars Odyssey data shows that water is wide spread but spatial *distribution and form of water/ice is not well understood* (hydrated clays and salts, permafrost, liquid aquifers, and/or dirty ice)

Lunar ISRU vs. Non-ISRU Mission Study Results

First Lunar Outpost

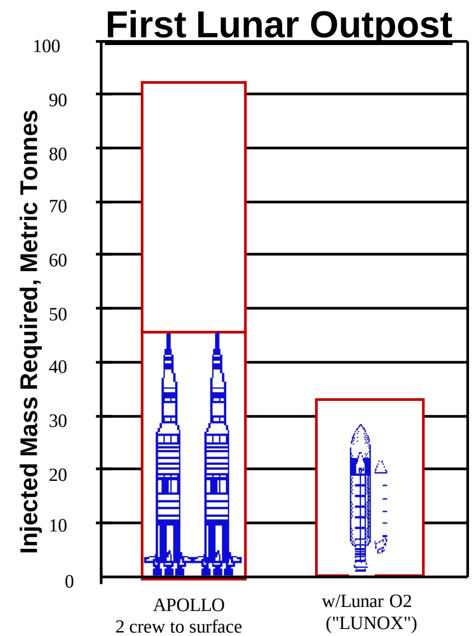
- Examined cost and mass impact on lunar base with lunar produced oxygen for both propulsion and life support (no closed life support system)
- **50% reduction** in development **cost** of and **50% reduction** in launch **mass** with Lunar oxygen production

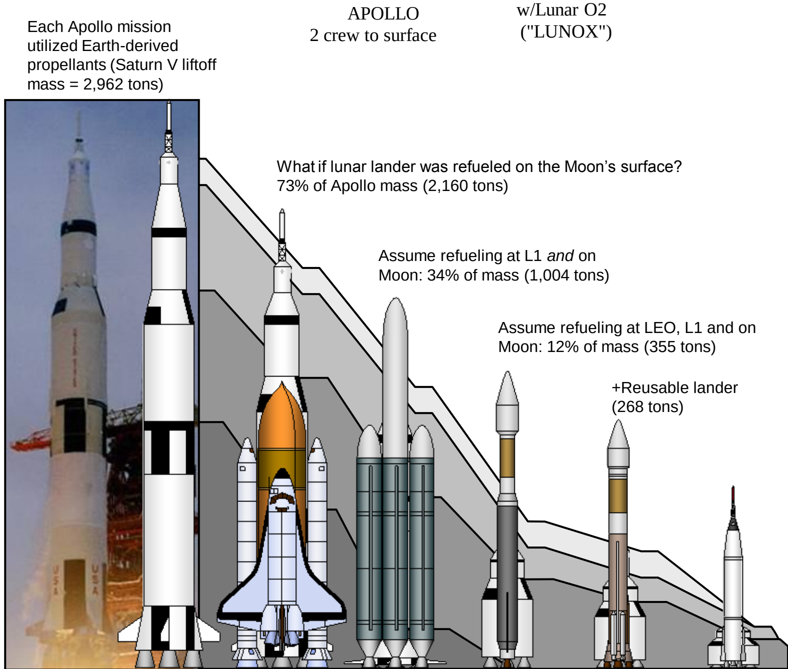
Colorado School of Mines Study

- Examined mass impact on sequential increase in ISRU capabilities with initial lift-off mass of Apollo
- **27% liftoff mass reduction** with refueling lunar Lander with Lunar propellants
- **66% liftoff mass reduction** with refueling on surface & L1 with Lunar propellants
- **88% liftoff mass reduction** with refueling at LEO, L1, and moon surface with Lunar propellants

Boeing ISRU Impact Study on VSE

- ISRU enables reusability
- Reusability of landing elements can significantly reduce system mass
  - **87% mass reduction** for landers/ascent vehicles with 10 reuses
  - **50% mass reduction** for delivery hardware (LVs, TLI stages, etc.) with 10 reuses





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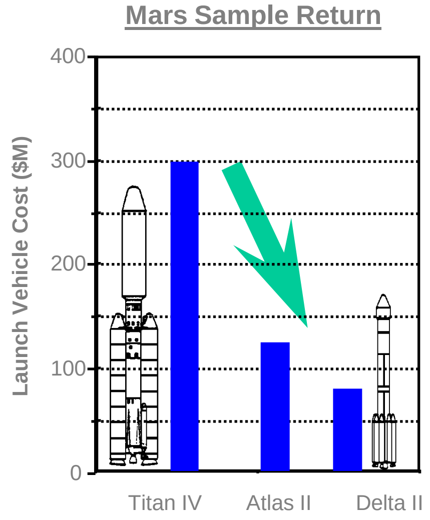
Mars ISRU vs. Non-ISRU Mission Study Results

Mars Sample Return with & without ISRU (Multiple Studies)

- **20% to 35% reduction** in launch **mass** for Mars Sample Return
- Possible use of Delta II or Atlas II versus Titan IV or Proton **reduces launch cost** by a **factor of 2 to 3** (1996)
- ISRU ***enables*** Direct Earth return sample return mission with large sample (5+ kg)
- Propellant production unit for Mars sample return mission is:
  - Same scale of production unit to supply EVA oxygen or EVA fuel cell powered rover
  - Scalable to human mission propellant production package



Human Mars Missions

- **21 to 25% mass reduction** for Human Mars Design Reference Mission
  - Smaller lander = smaller Mars trans stage and Mars orbit capture vehicles
  - Greater mass savings with increasing Delta-V (i.e. higher Mars rendezvous orbit)
- **3.6:1 mass savings leverage** from Mars surface back to Low Earth Orbit (Mars Ref Mission), i.e. 30 MT of in-situ propellant production equals >100 MT in Low Earth Orbit
- **5:1 mass savings leverage** from Mars surface (recent JPL study)