Overview of Past Lunar *In Situ* Resource Utilization (ISRU) Development by NASA

Presentation to
ESA Workshop:
Towards the Use of
Lunar Resources
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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

Resources

– Traditional**:** **Water**, atmospheric gases, volatiles, solar wind volatiles, metals, alloys, sunlight, etc.

– Non-traditional: Trash and wastes from crew, spent landers and residuals, etc.

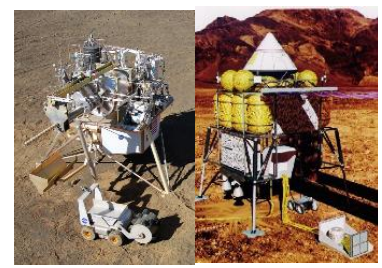
Resource Assessment (Prospecting)

Assessment and mapping of physical, mineral, chemical, and water resources, terrain, geology, and environment

Resource Acquisition

Atmosphere constituent collection, and material/volatile collection via drilling, excavation, transfer, and/or manipulation before Processing

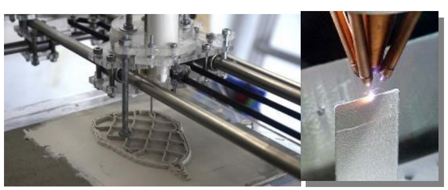
Resource Processing/ Consumable Production



Conversion of acquired resources into products with immediate use or as feedstock for construction & manufacturing

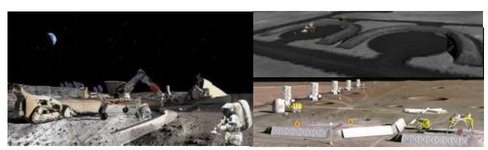
➢ Propellants, life support gases, fuel cell reactants, etc.

In Situ Manufacturing



Production of replacement parts, machines, and integrated systems from feedstock derived from one or more processed resources

In Situ Construction



Civil engineering, infrastructure emplacement and structure construction using materials produced from *in situ* resources

➢ Radiation shields, landing pads, roads, berms, habitats, etc.

In Situ Energy

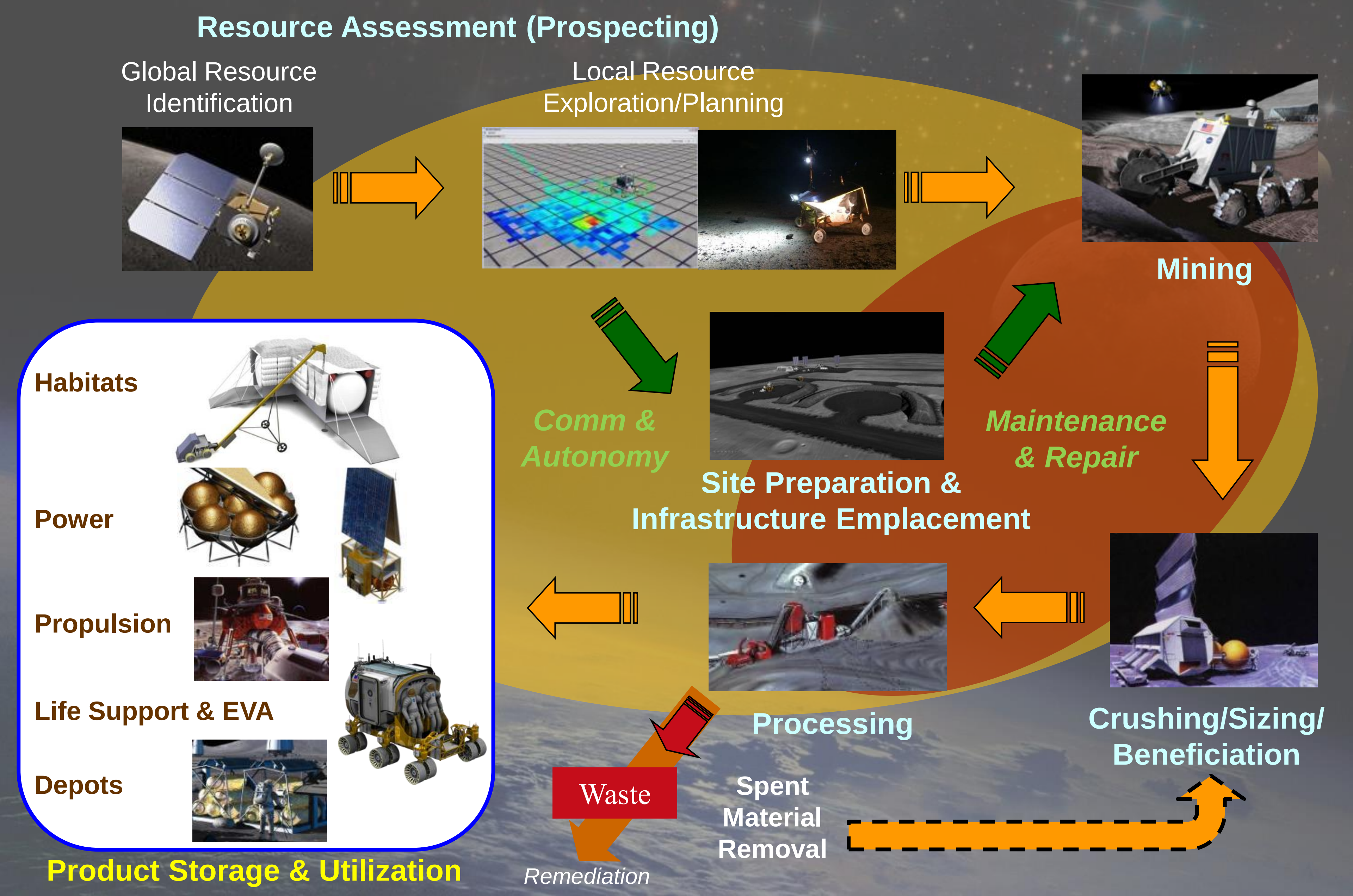
Generation and storage of electrical, thermal, and chemical energy with *in situ* derived materials

➢ Solar arrays, thermal storage and energy, chemical batteries, etc.

➢ **‘ISRU’ is a capability involving multiple elements to achieve final products**

➢ **‘ISRU’ does not exist on its own.** Must connect and tie to users/customers of ISRU products

Space 'Mining' Cycle: *Prospect to Product*



ISRU Changes How We Can Explore Space

Mass Reduction

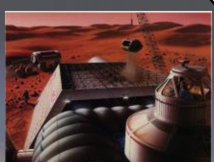
- >7.5 kg mass savings in Low Earth Orbit for every 1 kg produced on the Moon or Mars
- Chemical propellant is the largest fraction of spacecraft mass

Cost Reduction

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

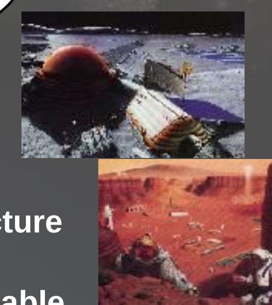
Space Resource Utilization

Risk Reduction & Flexibility



- Number of launches & mission operations reduced
- Use of common hardware & mission consumables enables increased flexibility
- In-situ fabrication of spare parts enables sustainability and self-sufficiency
- Radiation & landing/ascent plume shielding
- Reduces dependence on Earth

Expands Human Presence



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

Solves Terrestrial Challenges & Enables Space Commercialization

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

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

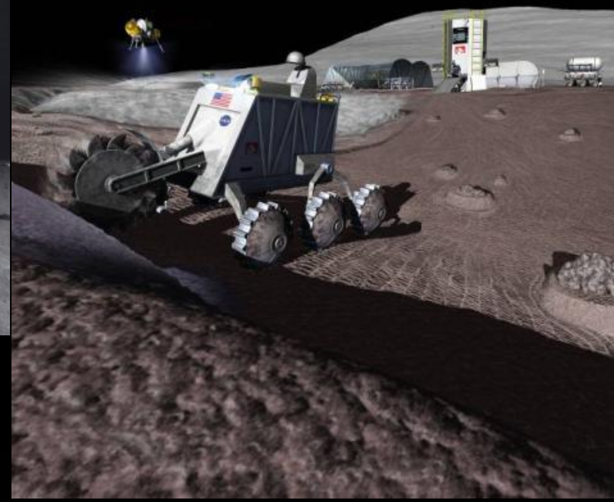
ISRU for Lunar Missions

- **Lunar Resource Prospecting & Mine Planning**
  - Terrain and surface feature mapping
  - Surface/subsurface mineral and glass concentration & distribution mapping
  - Solar wind & polar volatile concentration & distribution mapping
- **Mission Consumable Production**
  - Complete Life Support/Extra Vehicular Activity closure for Oxygen (O_2) and water (H_2O)
  - Produce/regenerate Fuel Cell Reactants (in conjunction with Power)
  - Gases for science and cleaning
  - **Propellant production**; O_2 and fuel (H_2 and/or CH_4) for robotic and human vehicles
- **Site Preparation and Outpost Deployment/Emplacement**
  - Site surveying and terrain mapping
  - Crew radiation protection (In-situ water production or bulk regolith)
  - Landing area clearing, surface hardening, and berm building for Lunar Lander landing risk and plume mitigation
  - Area and road clearing to minimize risk of payload delivery and emplacement
- **Outpost Growth and Self-Sufficiency**
  - Fabrication of structures that utilize in-situ materials (with Habitats)
  - Production of feedstock for fabrication and repair (with Sustainability)
  - Solar array, concentrator, and/or rectenna fabrication (with Power)
  - Thermal energy storage & use from processed regolith (with Power)

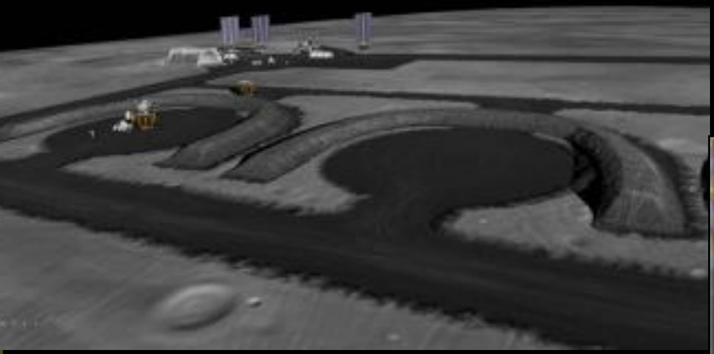
Lunar ISRU Mission Capability Concepts

Resource Prospecting – Looking for Polar Ice

Excavation & Regolith Processing for O_2 Production

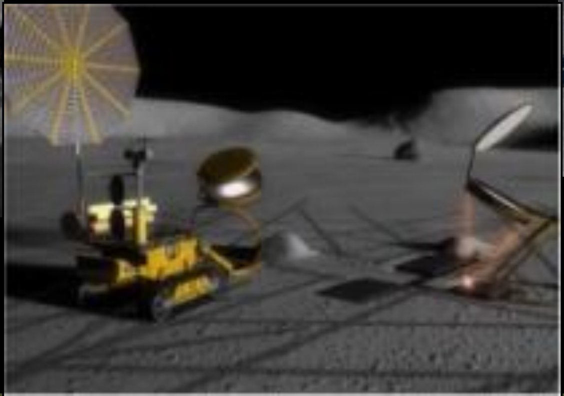


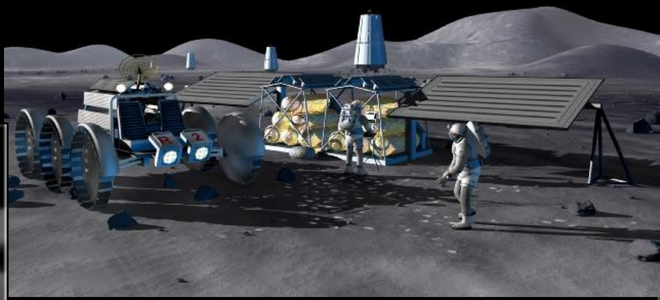
Carbothermal Processing with Altair Lander Assets



Landing Pads, Berm, and Road Construction

Thermal Energy Storage Construction





Consumable Depots for Crew & Power

Use the Moon as a Precursor to Mars

- **Identify and characterize available resources (especially polar region) that:**
  - Strongly influence mission phases, locations, and designs to achieve maximum benefit of ISRU
  - Is synergistic with Science and space commercialization objectives
  - Is synergistic with surface water characterization on Mars

- **Demonstrate ISRU concepts, technologies, & hardware that reduce the mass, cost, & risk of human Mars missions**
  - Excavation and material handling & transport
  - Volatile/hydrogen/water extraction
  - Thermal/chemical processing subsystems for oxygen and fuel production
  - Cryogenic fluid storage & transfer
  - Trash/Waste Processing in conjunction with Life Support
  - Metal extraction and fabrication of spare parts

- **Use Moon for operational experience and mission validation for Mars**
  - Pre-deployment & remote activation and operation of ISRU assets without crew
  - Making and transferring mission consumables (propellants, life support, power, etc.)
  - Landing crew with pre-positioned return vehicle or ‘empty’ tanks
  - ‘Short’ (<90 days) and ‘Long’ (300 to 500 days) Mars surface stay dress rehearsals

- **Develop and evolve surface exploration assets linked to ISRU capabilities that enable new exploration capabilities**
  - Human and robotic hoppers for long-range surface mobility and global science access; power-rich distributed systems; enhanced radiation shielding, etc.
  - Repair, fabrication, and assembly techniques to mitigate mission risk and logistics mass.

Lunar Resources & Products of Interest

LUNAR RESOURCES

MARE REGOLITH

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%

VOLATILES (Solar Wind & Polar Ice/H_2)

Hydrogen (H_2)	50 - 150 ppm
Helium (He)	3 - 50 ppm
Helium-3 (^3He)	10^{-2} ppm
Carbon (C)	100 - 150 ppm
Polar Water (H_2O)/H_2	1 - 10%

→ Thermal Volatile Extraction

Hydrogen Reduction of Ilmenite/glass Process

Fluidized Bed Reactor

$2FeTiO_3 + 2H_2 \xrightarrow{900°C} 2H_2O + 2Fe + 2TiO_2$ → 2Fe

Water electrolysis

$O_2 + 2H_2 \xleftarrow{25°C} 2H_2O$ → O_2

Sulfuric Acid Reduction Process

Desolve/Digest Reactor

$2FeTiO_3 + 2H_2SO_4 \rightarrow 2H_2O + 2FeSO_4 + 2TiO_2$

Electrolysis bed

$O_2 + 2Fe + 2H_2SO_4 \leftarrow 2H_2O + 2FeSO_4$ → O_2, 2Fe

Methane Reduction (Carbothermal) Process

Methane Reduction Furnace

$2FeTiO_3$, Fe_2SiO_4, $FeSiO_3$, Mg_2SiO_4, $MgSiO$, $CaSiO_3$ $+ 2CH_4 \xrightarrow{1625°C}$ $2CO + 4H_2 +$

- $2TiO_2 + 2Fe$ → 2Fe
- $2FeO + Si$
- $FeO + Si$
- $2MgO + Si$
- $MgO + Si$
- $CaO + Si$

→ Si

Methane Reformer

$2H_2O + 2CH_4 \xleftarrow{250°C} 2CO + 6H_2$

Water electrolysis

$2H_2O \xrightarrow{25°C} 2H_2 + O_2$ → O_2

Molten Electrolysis

Molten Electrolysis Reactor

- $2SiO_2 \rightarrow 2SiO + O_2$ → O_2
- $2FeTiO_3 \rightarrow 2Fe + 2TiO_2 + O_2$
- $2FeO \rightarrow 2Fe + O_2$

→ O_2, 2Fe

Vapor Pyrolysis Process

Pyrolysis Reactor/Condenser

- $2SiO_2 \xrightarrow{>2000°C} 2SiO + O_2$ → O_2
- $2FeTiO_3 \xrightarrow{2500°C} 2Fe + 2TiO_2 + O_2$
- $2FeO \xrightarrow{>2000°C} 2Fe + O_2$

→ O_2, 2Fe

- $2Al_2O_3 \xrightarrow{>2000°C} 4AlO + O_2$ → O_2
- $2Al_2O_3 \xrightarrow{>2000°C} 2AlO + 2Al + O_2$ → O_2, 2Al
- $2MgO \xrightarrow{>2000°C} 2Mg + O_2$
- $2CaO \xrightarrow{>2000°C} 2Ca + O_2$

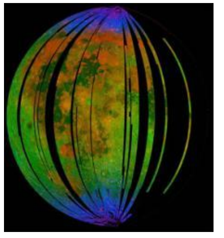
→ O_2

- $2CaAl_2Si_2O_8 \xrightarrow{2500°C} 2Ca + 4AlO + 4SiO + 4O_2$ → $4O_2$, 2Ca
- $2CaAl_2Si_2O_8 \xrightarrow{2500°C} 2Ca + 2AlO + 2Al + 4SiO + 5O_2$ → $5O_2$, 2Al, 2Ca

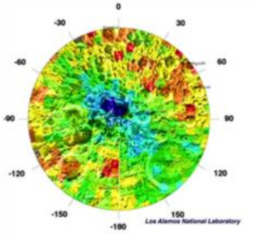
Global Assessment of Lunar Volatiles

Apollo Samples

Moon Mineralogical Mapper (M^3)

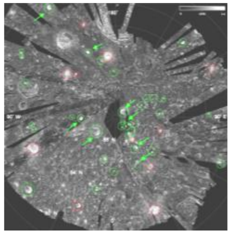


Lunar Prospector Lunar Recon Orbiter (LRO)



Lunar Crater Observation & Sensing Sat. (LCROSS)

Clementine Chandrayaan LRO Mini SAR/RF



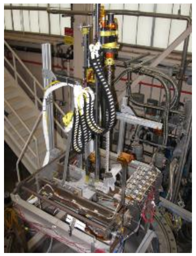
	Solar Wind	Core Derived Water	Water/Hydroxyl	Polar Volatiles	Polar Ice
Instrument	Apollo samples Neutron Spectrometer	Apollo samples	M3/DIVINER	LCROSS	Mini SAR/RF
Concentration	Hydrogen (50 to 150 ppm) Carbon (100 to 150 ppm) Helium (3 to 50 ppm)	0.1 to 0.3 wt % water in Apatite 0 to 50 ppm water in volcanic glass	0.1 to 1% water; 1-2% frost 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

Development of Lunar ISRU Technologies & Systems

- **Resource Characterization & Mapping**
  - Lunar polar ice/volatile characterization
    - RESOLVE/Resource Prospector
- **Mission Consumable Production**
  - Oxygen Extraction from Regolith
    - Hydrogen Reduction
    - Carbothermal Reduction
    - Molten Oxide Electrolysis
    - Ionic Liquids
  - Oxygen and Fuel from Mars Atmosphere
    - Carbon Dioxide Capture
    - Mars Soil Drying
  - Water and Fuel from Trash
    - Steam Reforming
    - Combustion/Pyrolysis
  - Water Processing
    - Water Electrolysis
    - Water Cleanup
- **In-Situ Energy Generation, Storage & Transfer**
  - Solar Concentrators
  - Heat Pipes
- **Civil Engineering & Surface Construction**
  - Lunar Regolith Excavation
  - Lunar Regolith and Mars Soil Transfer
  - Lunar Regolith Size Sorting & Beneficiation
  - Lunar Regolith Simulant Production
  - Surface Preparation

NASA ISRU Soil/Water Extraction and Trash Processing Technology Development



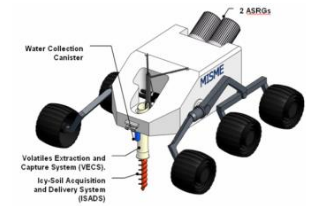


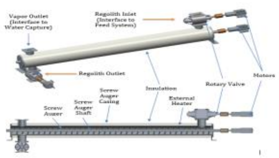
Soil Acquisition and Excavation

- Sample drills and augers (JPL, ARC, SBIRs)
- Scoops and buckets (GRC, KSC, JPL, Univ., SBIRs)
- Auger and pneumatic transfer (KSC, GRC, SBIRs)



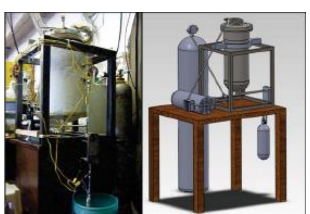





Water Extraction from Soils

- Closed soil reactors: fluidized & auger (JSC, SBIRs)
- Microwave soil processing (MSFC, JPL, SBIR)
- Open soil processing reactors (GRC)
- Downhole soil processing (MSFC, SBIRs)
- Capture for lunar/Mars soil processing (NASA, SBIRs)
- Water cleanup for lunar/Mars soil processing (KSC, JSC, SBIRs)

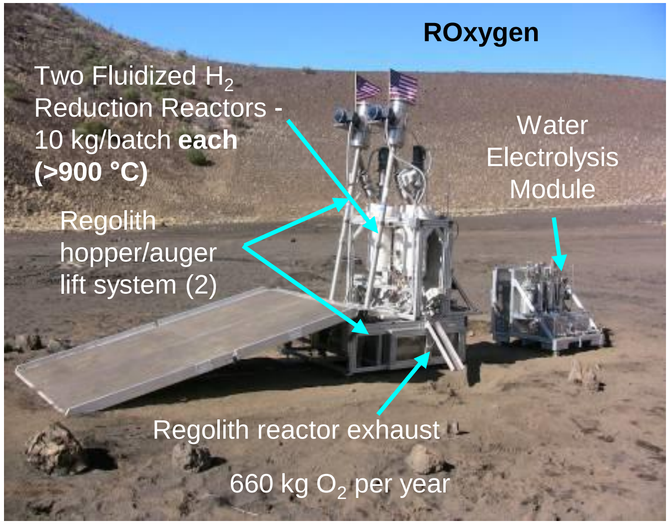


Trash/Waste Processing into Gases/Water

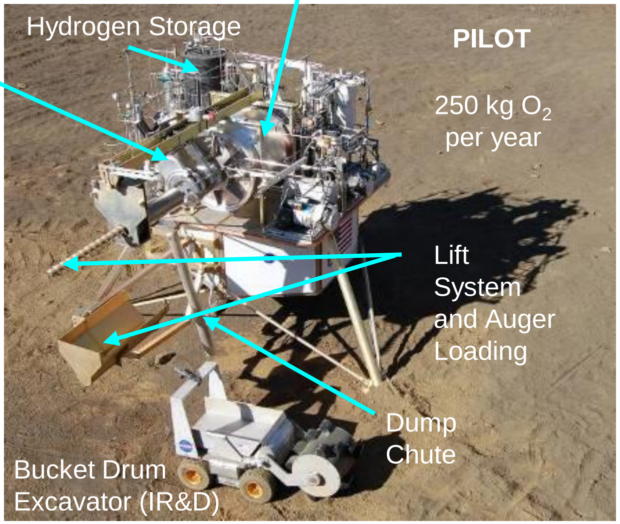
- Combustion, Pyrolysis, Oxidation/Steam Reforming (GRC, KSC, SBIRs)

Lunar Processing – Oxygen & Metal Extraction

Hydrogen Reduction of Regolith



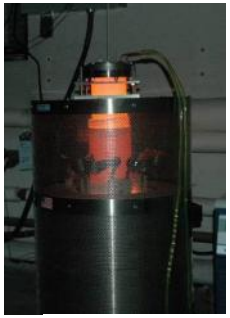
1. **Heat Regolith to >900 C**
2. **React with Hydrogen to Make Water**
3. **Crack Water to Make O_2**

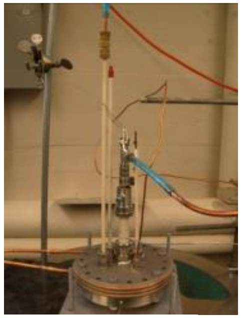


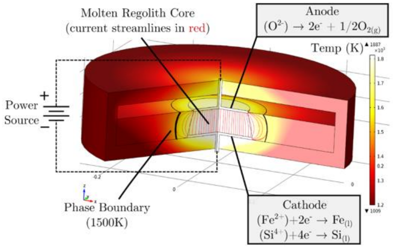
Carbothermal Reduction of Regolith

1. **Melt Regolith to >1600 C**
2. **React with Methane to produce CO and H_2**
3. **Convert CO and H_2 to Methane & Water**
4. **Crack Water to Make O_2**

Molten Electrolysis of Regolith



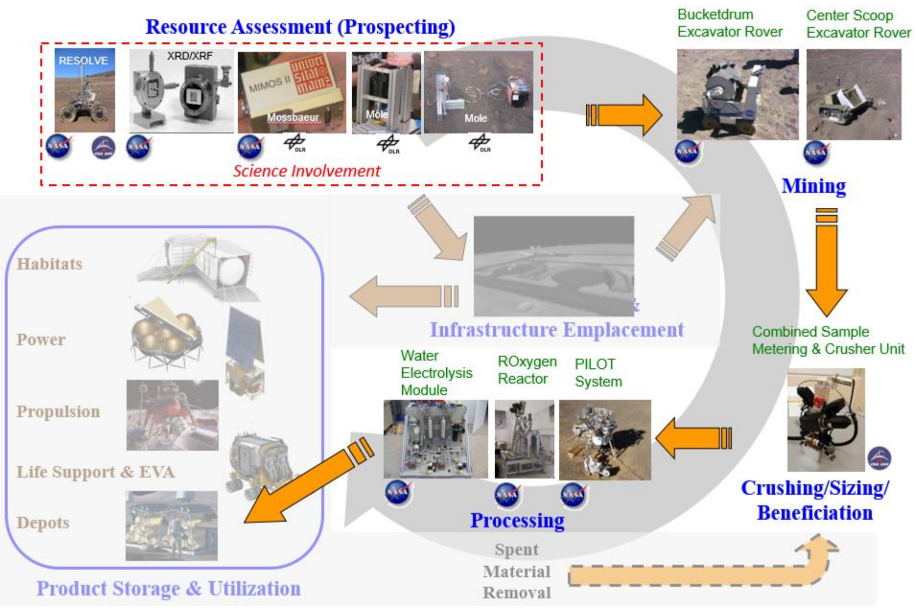




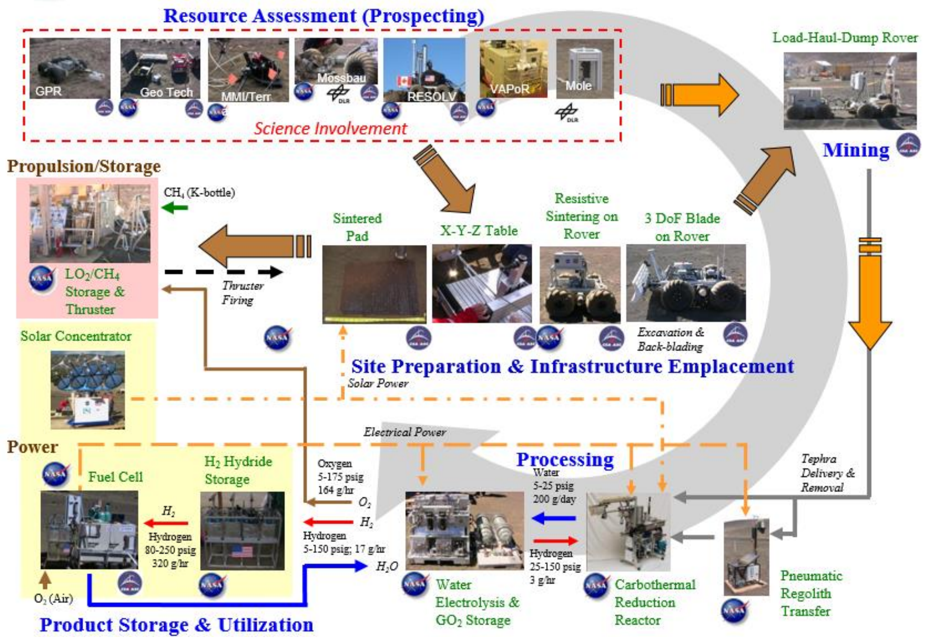
1. **Melt Regolith to >1600 C**
2. **Apply Voltage to Electrodes To Release Oxygen**

ISRU Development: System Testing and Integration Through Analog Field Tests

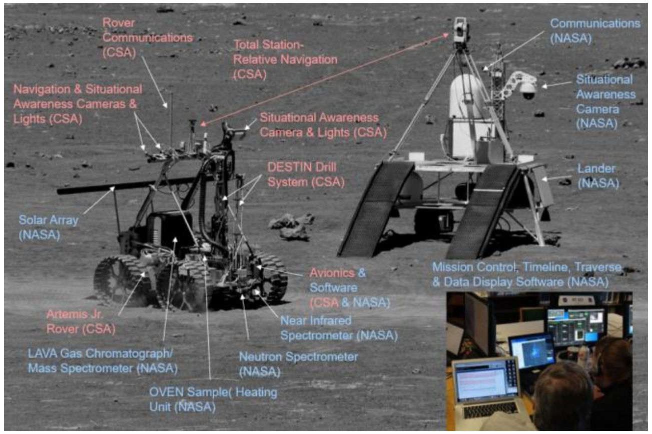
Hardware & Operation Integration at 2008 Analog Field Test

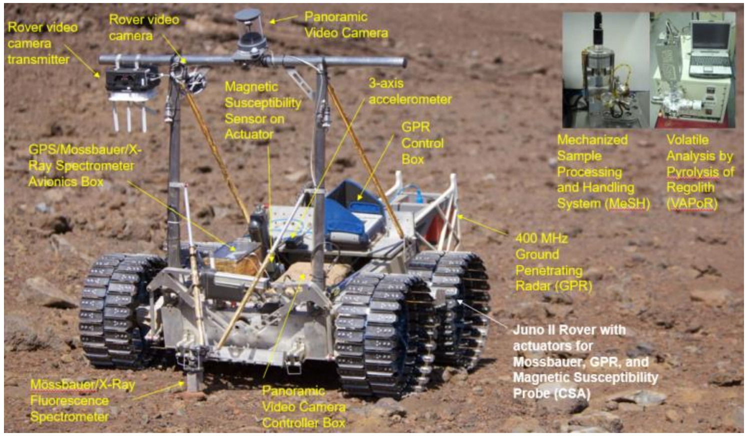


Hardware & Operation Integration at 2010 Analog Field Test



Lunar Polar Volatile & Mineral Prospecting at 2012 Analog Field Test



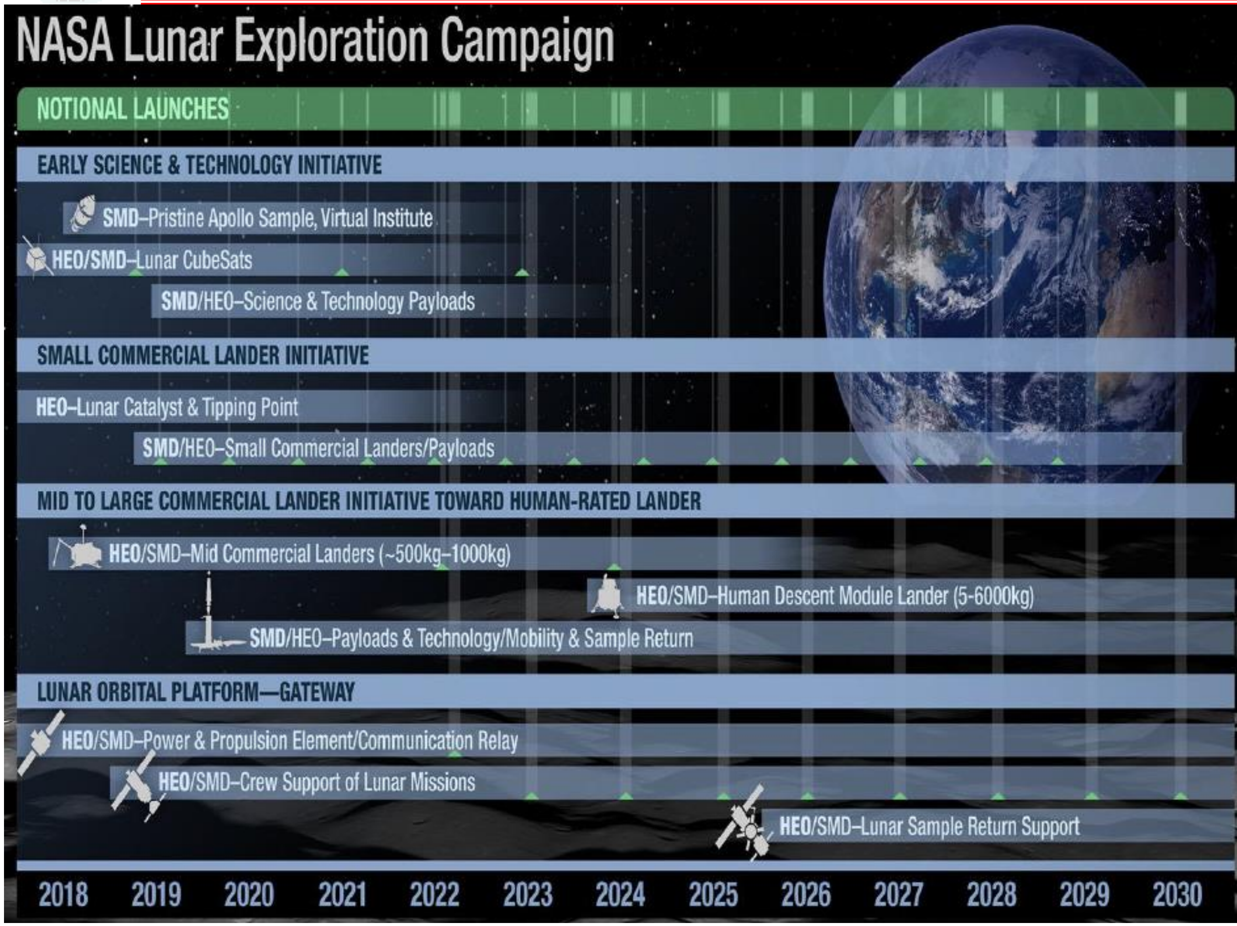


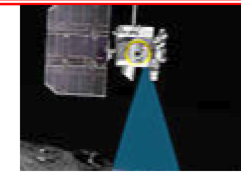
Lunar ISRU TRL Advancement

Significant advancement from 2006 to 2010

TRL increase in ETDP	At Start	At End	Delta	
System Level				
Lunar Volatile Characterization (RESOLVE)	1	5	4	Advanced since 2010
H_2 Reduction of Regolith	2-3	5	2-3	
CH_4 Reduction of Regolith	2-3	5	2-3	
Molten Oxide Reduction of Regolith	2	3	1	
Trash Processing for Water/Methane Production	2	2-3	0-1	Advanced since 2010
Subsystem Level				
Regolith Transfer & Handling				
Regolith Transport Into/Out of Reactor	2	5	3	
Beneficiation of Lunar Regolith	2-3	2-3	0-1	
Size Sorting of Lunar Regolith	2-3	2-3	0-1	
Oxygen Extraction From Regolith				
H_2 Reduction of Regolith Reactor	3	5	2	
Gas/Water Separation & Cleanup	2	4-5	2-3	Advanced since 2010
CH_4 Reduction of Regolith Reactor	3	5	2	
CH_4 Reduction Methanation Reactor	3-4	4-5	1-2	
MOE of Regolith Anode/Cathode	1-2	3-4	2-3	
MOE of Regolith Molten Mat'l Removal	1-2	3	1-2	
MOE Cell and Valving	2-3	3	0-1	
Water/Fuel from Trash Processing				
Trash Processing Reactor	2	2-3	0-1	Advanced since 2010
In-Situ Energy Generation, Storage, and Transfer				
Solar Thermal Energy for Regolith Reduction	2	5	3	

Lunar ISRU-Related Missions





Korea Pathfinder Lunar Orbiter (KPLO) - 2020

- ShadowCam Map reflectance within permanently shadowed craters

Commercial Lunar Payload Services (CLPS)

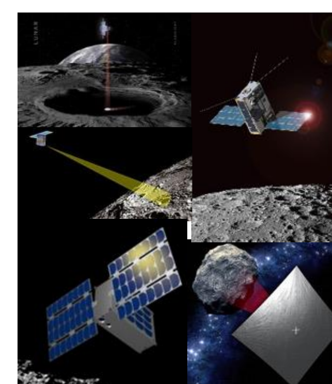
- Request for Proposals for 50, 200, and 500 kg class payload missions

Dev. & Advancement of Lunar Instrumentation (DALI)

- Request for Proposals for science instruments & ISRU experiments

Science/Prospecting Cubesats (SLS EM-1 2018)

- Lunar Flashlight: Near IR laser and spectrometer to look into shadowed craters for volatiles
- Lunar IceCube: Broadband InfraRed Compact High Resolution Explorer Spectrometer
- LunaH-MAP: Two neutron spectrometers to produce maps of near-surface hydrogen (H)
- Skyfire/LunIR: Spectroscopy and thermography for surface characterization
- NEA Scout: Multispectral camera for NEA morphology, regolith properties, spectral class

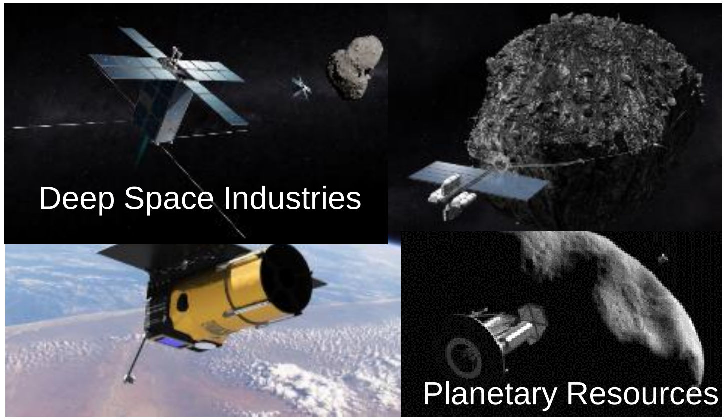


Space Commercialization & Mining

Promote Terrestrial Involvement in Space & ISRU: Spin In-Spin Out

Private Industry

Resource Prospecting



Commercial Cargo & Crew

SNC *Dream Chaser*

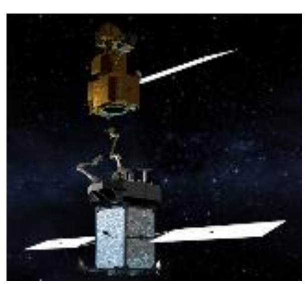
SpaceX
Dragon2

Boeing
CST-100

ULA Cislunar 1000 Vision

Use lunar derived propellants

Satellite Servicing



Government Interest & Legislation

US Space Law & Directives

H. R. 2262—18

"CHAPTER 513—SPACE RESOURCE COMMERCIAL EXPLORATION AND UTILIZATION

"§ 51303. Asteroid resource and space resource rights

"A United States citizen engaged in commercial recovery of an asteroid resource or a space resource under this chapter shall be entitled to any asteroid resource or space resource obtained, including to possess, own, transport, use, and sell the asteroid

US Space Resource Act

Public Law 114–90
114th Congress

An Act

Nov. 25, 2015
[H.R. 2262]

To facilitate a pro-growth environment for the developing commercial space industry by encouraging private sector investment and creating more stable and predictable regulatory conditions, and for other purposes.

US Commercial Space Launch Competitiveness Act

59501

Presidential Documents

Space Policy Directive–1 of December 11, 2017

Reinvigorating America's Human Space Exploration Program

Space Directive 1

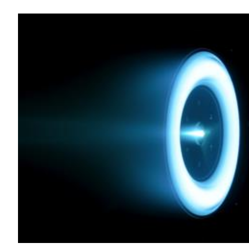
Luxembourg Space Law

NASA NextSTEP Broad Agency Announcements

Crew habitats

FabLab

Power & Propulsion Studies



ISRU

Final Comment

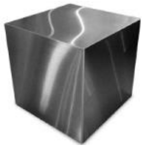
It's not about being able to do ISRU.
It's not about having the most efficient ISRU system.

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

Thank You

Questions?

Main *Natural* Space Resources of Interest for Human Exploration

	Moon	Mars	Asteroids	Uses
Water (Hydrogen) 	Icy Regolith in Permanently Shadowed Regions (PSR) Solar wind hydrogen with Oxygen	Hydrated Soils/Minerals: Gypsum, Jarosite, Phylosilicates, Polyhdrated Sulfates Subsurface Icy Soils in Mid-latitudes to Poles	Subsurface Regolith on C-type Carbonaceous Chondrites	▪ Drinking, radiation shielding, plant growth, cleaning & washing ▪ Making Oxygen and Hydrogen
Oxygen 	Minerals in Lunar Regolith: Ilmenite, Pyroxene, Olivine, Anorthite	Carbon Dioxide in the atmosphere (~96%)	Minerals in Regolith on S-type Ordinary and Enstatite Chondrites	▪ Breathing ▪ Oxidizer for Propulsion and Power
Carbon (Gases) 	▪ CO, CO_2, and HC's in PSR ▪ Solar Wind from Sun (~50 ppm)	Carbon Dioxide in the atmosphere (~96%)	Hydrocarbons and Tars (PAHs) in Regolith on C-type Carbonaceous Chondrites	▪ Fuel Production for Propulsion and Power ▪ Plastic and Petrochemical Production
Metals 	Minerals in Lunar Regolith ▪ Iron/Ti: Ilmenite ▪ Silicon: Pyroxene, Olivine, Anorthite ▪ Magnesium: Mg-rich Silicates ▪ Al: Anorthitic Plagioclase	Minerals in Mars Soils/Rocks ▪ Iron: Ilmenite, Hematite, Magnetite, Jarosite, Smectite ▪ Silicon: Silica, Phyllosilicates ▪ Aluminum: Laterites, Aluminosilicates, Plagioclase ▪ Magnesium: Mg-sulfates, Carbonates, & Smectites, Mg-rich Olivine	Minerals in Regolith/Rocks on S-type Stony Iron and M-type Metal Asteroids	▪ *In situ* fabrication of parts ▪ Electical power generation and transmission

Note: Rare Earth Elements (REE) and Platinum Group Metals (PGM) are not driving Resources of interest for Human Exploration

ISRU Implementation Life Cycle

Identify Resource & Products

Resource Definition
- Determine Resource Utilization End Goals
- Initial Feasibility Study
- Multi-Site Evaluation
- Initial Cost Analysis
- Weigh Alternatives
- **Go/No-Go Decision**
- Plan Program and Approach

Prospecting
- Global Resource Evaluation
- Site Selection
- Site Imaging/ Characteriza-tion
- Resource Identification and Verification

Resource Analysis
- Estimate Reserve Size
- Test/Sample Resource Quality
- Understand Geotechnical Properties of Minerals
- Resource Analysis for Other Potential Uses/Users
- Assess Return On Investment

Establish Site & Operations

Mining Technology Readiness
- Demonstrate 'Scalable' Hardware
- Demonstrate Operations for All Processes from Extraction to Product Storage
- Evaluate Processing Options

Site-Mine Planning
- Select Mining Site
- Environmental Analysis
- Electronic Modeling & Simulation
- Develop Power Sources
- Infrastructure Analysis
- Design Transportation and Comm.
- Contingency Planning

Site-Mine Development
- Infrastructure Development/ Set up
- Site Preparation, Landing, and Roads
- Construct Infrastructure and Processing Facilities

Perform Mining Ops

Site-Mine Operations & Maintenance
- Excavation
- Resource Extraction
- Manage Operations
- Remediate Site as Needed

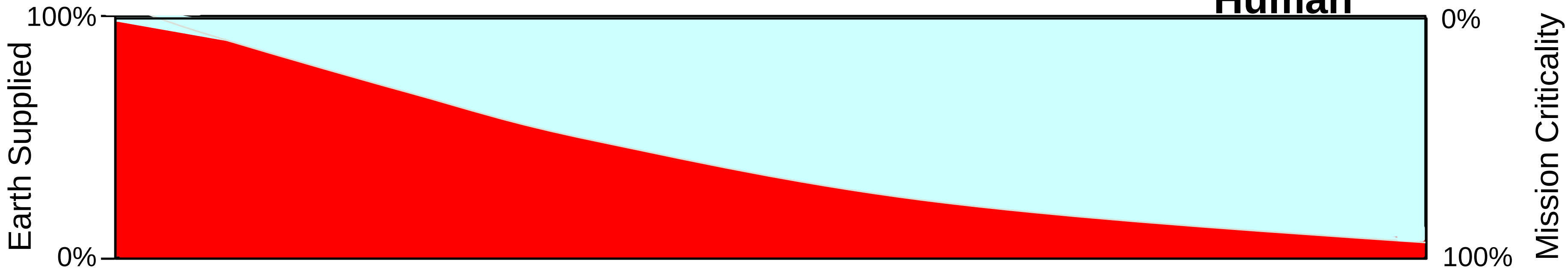
Processing
- Sort and Refine Resources
- Process Resources Into Feedstocks
- Resource Transfer
- Recycle or Repurpose Wastes or Byproducts for Useful Purposes

Product and Application
- Export Resources from Site
- Convert Resource to Finished Product
- Deliver to End Users

Phased Approach to ISRU Architecture Incorporation

Current approach is to utilize phased approach to incorporate ISRU with minimum risk to mission success

Resource Prospecting/ Proof-of-Concept Demos	Engineering Validation & Pilot Operations	Utilize/Full Implementation Human



Resource Prospecting/ Proof-of-Concept Demos

Purpose

- Characterize local material/resources; evaluate terrain, geology, lighting, etc.
- Demonstrate critical technologies, functions, and operations
- Verify critical engineering design factors & environmental impacts
- Address unknowns or Earth based testing limitations (simulants, micro/low-g, contaminants, etc.)

- **ExoMars**
- **Resource Prospector**
- **Mars 2020**
- **Lunar Cubesats**

Engineering Validation & Pilot Operations

Purpose

- 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

- **Mars Surface Pathfinder**
- **Lunar short stay**

Utilize/Full Implementation Human

Purpose

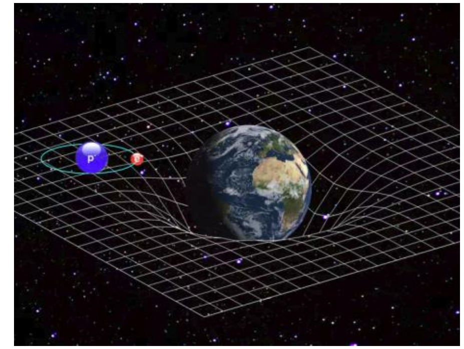
- Enhance or enable new mission capabilities
- Reduce mission risk
- Increase payload & science capabilities

- **Mars DRA 5.0**
- **Evolvable Mars Campaign**
- **Lunar Outpost**

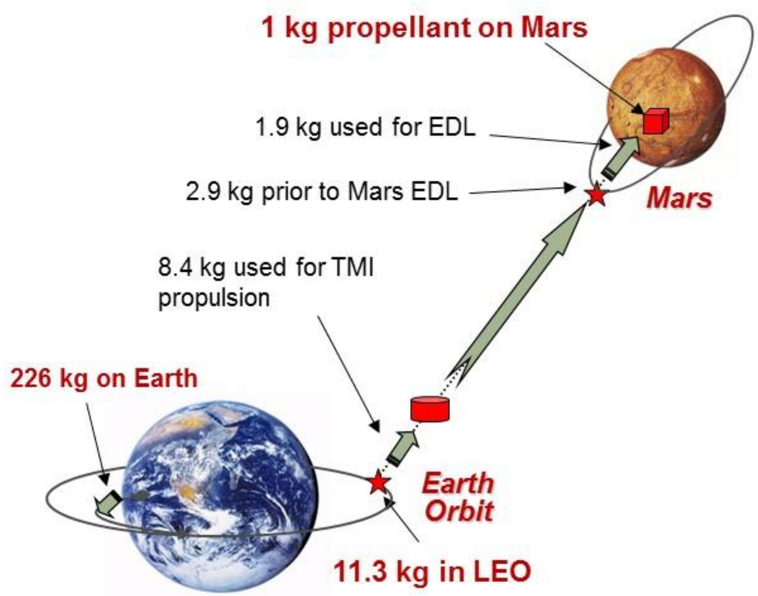
Leverage (Gear) Ratios using ISRU

Every 1 kg of propellant made on the Moon or Mars saves 7.4 to 11.3 kg in LEO

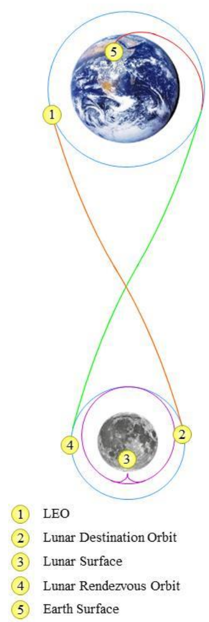
Potential 334.5 mT launch mass saved in LEO
= 3 to 5 SLS launches avoided per Mars Ascent



- **Mars mission**
  - Oxygen (O_2) only — 75% of ascent propellant mass: 20 to 23 mT
  - O_2/Methane (CH_4) — 100% of ascent propellant mass: 25.7 to 29.6 mT; Regeneration of rover fuel cell reactant mass
- **Phobos mission**
  - Trash to O_2/CH_4 — 1000+ kg of propellant



Estimates based on Aerocapture at Mars



A Kilogram of Mass Delivered Here…	…Adds This Much Initial Architecture Mass in LEO	…Adds This Much To the Launch Pad Mass
Ground to LEO	-	20.4 kg
LEO to Lunar Orbit (#1→#2)	4.3 kg	87.7 kg
LEO to Lunar Surface (#1→#3; e.g., Descent Stage)	7.5 kg	153 kg
LEO to Lunar Orbit to Earth Surface (#1→#4→#5; e.g., Orion Crew Module)	9.0 kg	183.6 kg
Lunar Surface to Earth Surface (#3→#5; e.g., Lunar Sample)	12.0 kg	244.8 kg
LEO to Lunar Surface to Lunar Orbit (#1→#3→#4; e.g., Ascent Stage)	14.7 kg	300 kg
LEO to Lunar Surface to Earth Surface (#1→#3→#5; e.g., Crew)	19.4 kg	395.8 kg

ISRU Influence on Mission Architectures

ISRU has greatest influence at the site of the resource/production

- **Transportation (propellant is the largest 'payload' mass from Earth)**
  - Crew ascent from Moon/Mars surface
    - O_2 only provides up to 80% of propellant mass
    - O_2/fuel – full asset reuse and surface hopping
  - Crew/Cargo ascent and descent from Moon/Mars surface – reusable
  - Supply orbital depots for in-space transportation
    - Cis-lunar (L1 to GEO or LEO)
    - Trans-Mars

- **Power (mission capabilities are defined by available power)**
  - Nighttime power storage/generation
    - Fuel cell reactants – increase amount and regeneration
    - Thermal storage
  - Mobile power – fuel cell reactants
  - Power generation: in situ solar arrays, 'geo'thermal energy

- **Infrastructure and Growth**
  - Landing pads and roads to minimize wear and damage
  - Structures and habitats

- **Crew Safety**
  - Radiation protection
  - Logistics shortfalls (life support consumables, spare parts)

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 Impact on Exploration System Requirements

	Without ISRU	With ISRU
Propulsion	Propellant selection based on development cost and performance	Propellant selection based on ISRU products from available resources
	Propulsion cycle (pressure vs pump) based on development cost and performance	Production cycle based on influence of ISRU on Delta-V and reusability
	Non-reusable or limited reusability with Earth supplied propellants and depots	Reusability with single stage landers possible
Life Support	Air and Water recycling technologies and systems based on maximizing closure of oxygen and water loops	ISRU products can reduce the level of closure required, thereby reducing development cost and system complexity
	Trash/waste processing aimed at maximizing water extraction and minimizing oxygen usage	Trash/waste transferred to ISRU to maximize fuel production and minimize residuals. Trash processing hardware can be minimized to some level of drying
Habitat	Radiation and micrometeoroid shields based on Earth supplied materials. Storm closets to minimize mass impact	Regolith (piling or habitat burial) or in-situ water for greater radiation protection possible. This can change habitat layout and eliminate need for storm closets
	Fully constructed on Earth. Hard shell or inflatable	In-situ shelters construction possible. Consumables for inflation
	Self-contained thermal management	Use of thermal energy sharing with ISRU or creation of in-situ thermal storage for heat removal or usage
Mobility	Mobility primarily based on science and human activities	Mobility based on high torque/low speed excavation and civil engineering needs
	Full situational awareness and flexible navigation system	Simplified situational awareness and navigation required for ISRU applications
Power	Self-contained units. Solar array and batteries	Distributed power generation and storage, esp. fuel cell reactant storage and regeneration
	Fuel cell reactant based on regeneration technique alone	Fuel cell reactant based on in-situ resources available
	Increase in power generation is a function of delivery from Earth	In-situ growth of power thru fuel cell consumable, in-situ thermal, and in-situ manufacturing

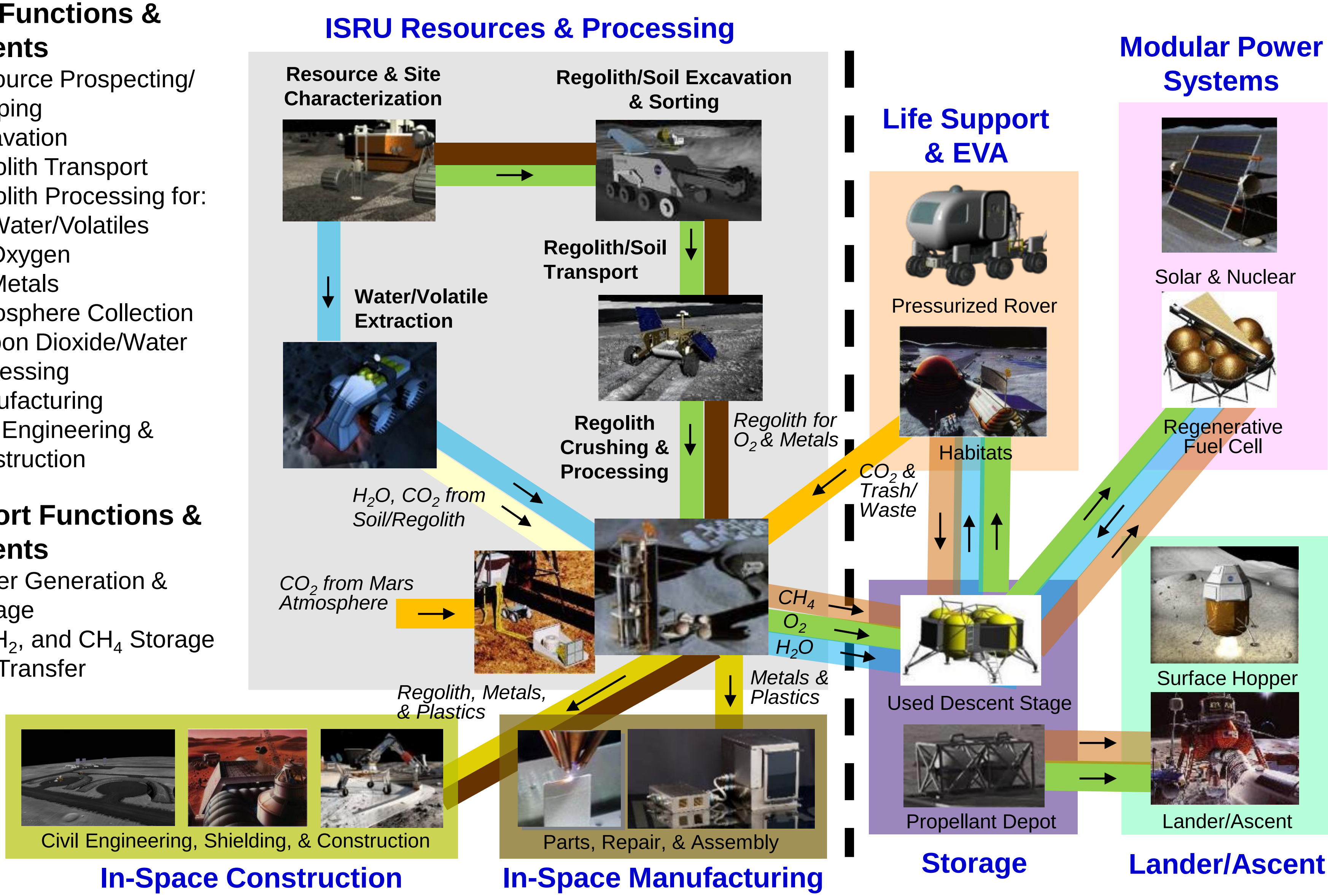
ISRU Integrated with Exploration Elements
(Mission Consumables)

ISRU Functions & Elements

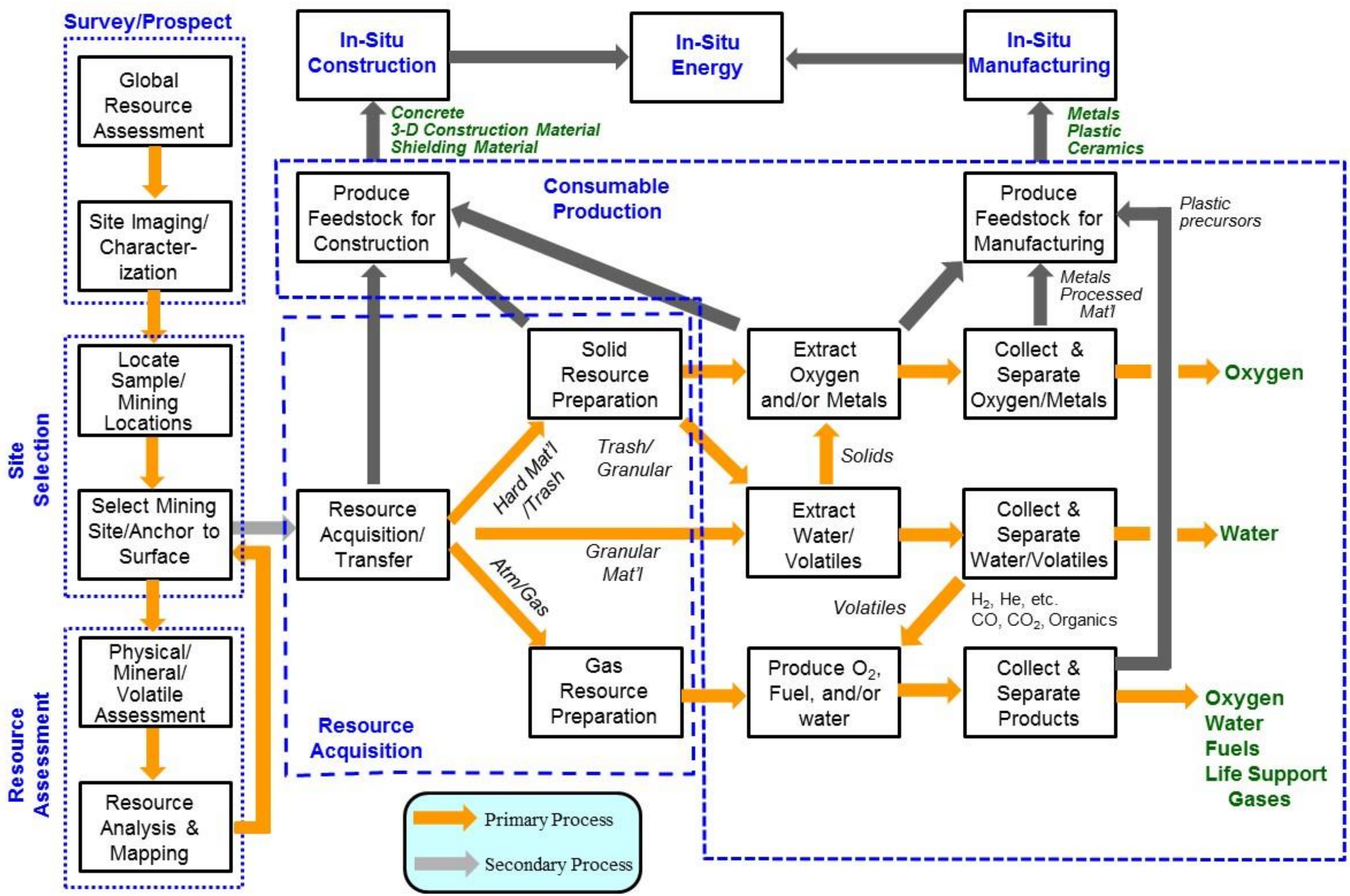
- Resource Prospecting/ Mapping
- Excavation
- Regolith Transport
- Regolith Processing for:
  - Water/Volatiles
  - Oxygen
  - Metals
- Atmosphere Collection
- Carbon Dioxide/Water Processing
- Manufacturing
- Civil Engineering & Construction

Support Functions & Elements

- Power Generation & Storage
- O_2, H_2, and CH_4 Storage and Transfer



ISRU Capability-Function Flow Chart



Mission Consumables: Regolith vs Polar Water/Volatiles

- **Oxygen from Regolith**
  - **Can be incorporated into the architecture from the start with low-moderate risk**
    - Resource characteristics and parameters are reasonably well known
    - Multiple approaches for extraction possible; 2 demonstrated to TRL 4-5 for short periods of time
  - **Provides 75 to 80% of chemical propulsion propellant mass (fuel from Earth)**
  - Experience from regolith excavation, beneficiation, and transfer applicable to In Situ Manufacturing and Construction and Mars hydrated soil extraction

- **Water and Volatiles from Polar Regolith**
  - **Cannot be incorporated into the architecture from the start with low-moderate risk**
    - Resource characteristics and parameters are not well known
  - **Polar Water/Volatiles is "Game Changing" and Enables Long-term sustainability**
    - Availability of water for propellants can strongly influence propulsion system design (propellant selection and reusability) and transportation architecture (depots, hoppers, lander reuse, etc.)
    - Provides 100% of chemical propulsion propellant mass
    - Reuse of cargo and human landers and transportation elements can reduce long-term mission costs and enable new mission concepts
    - Provides significantly more options for radiation protection, food production, etc. over what is available from lunar regolith

NASA should pursue both Development and Insertion of Oxygen from Regolith with Prospecting and Evaluation of Polar Ice/Volatiles for Long Term Sustainability

Why Perform Analog Field Testing for Science, Exploration & ISRU?

Key Programmatic Analogue Field Test Purpose

- **Expand NASA and CSA partnership; Include other International Partners in analogues**
- **Expand integration of Science & Engineering for exploration, particularly with ISRU**
- **Link separate technology and system development activities**
- Develop and enhance remote operations and mission concepts; introduce new technologies
- Evaluate parallel paths and competing concepts
- Be synergistic with other analogue test activities (past and future)
- **Public Outreach, Education, and "Participatory Exploration"**

Key Technical Analogue Field Test Purpose

- **Stress hardware under realistic environmental and mission operation conditions to improve path to flight**
- Improve remote operations & control of hardware for surface exploration and science
- Promote the testing of multiple surface and transportation systems to better understand integration and operation benefits and issues
- Promote use of common software, interfaces, & standards for control and operation (ISECG)
- Focus on interfaces, standards, and requirements (ISECG)
- Focus on modularity and 'plug n play' integration (ISECG)

Intrinsic Benefits of Field/Analog Testing

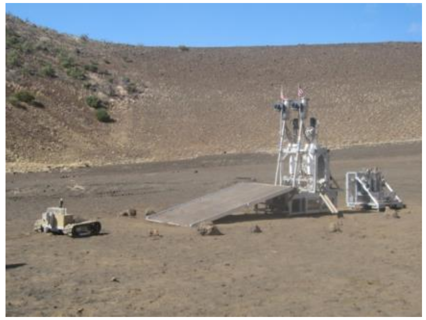
- Develop Scientists, Engineers, and Project Managers for future flight activities
- Develop International Partnerships
- Develop Teams and Trust Early
- Develop Data Exchange & Interactions with International Partners (ITAR)

1st ISRU Analog Field Test: 2008 (1 of 2)

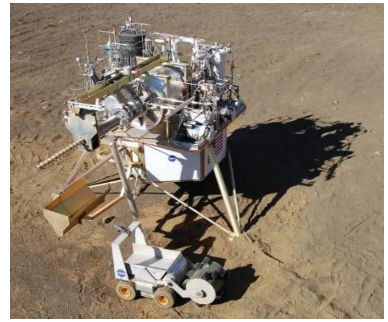
Lunar Prospecting

- Scarab Rover
- RESOLVE
- TriDAR Vision System
- Tweels

Outpost-Scale O_2 from Regolith

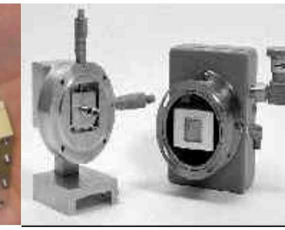


- ROxygen H_2 Reduction
- Water Electrolysis
- Cratos Excavator



- PILOT H_2 Reduction
- Water Electrolysis
- Bucketdrum Excavator

Process Control & Science



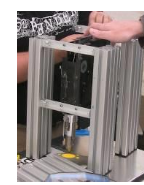
- Moessbauer
- Mini Chemin XRD/XRF

▪ 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

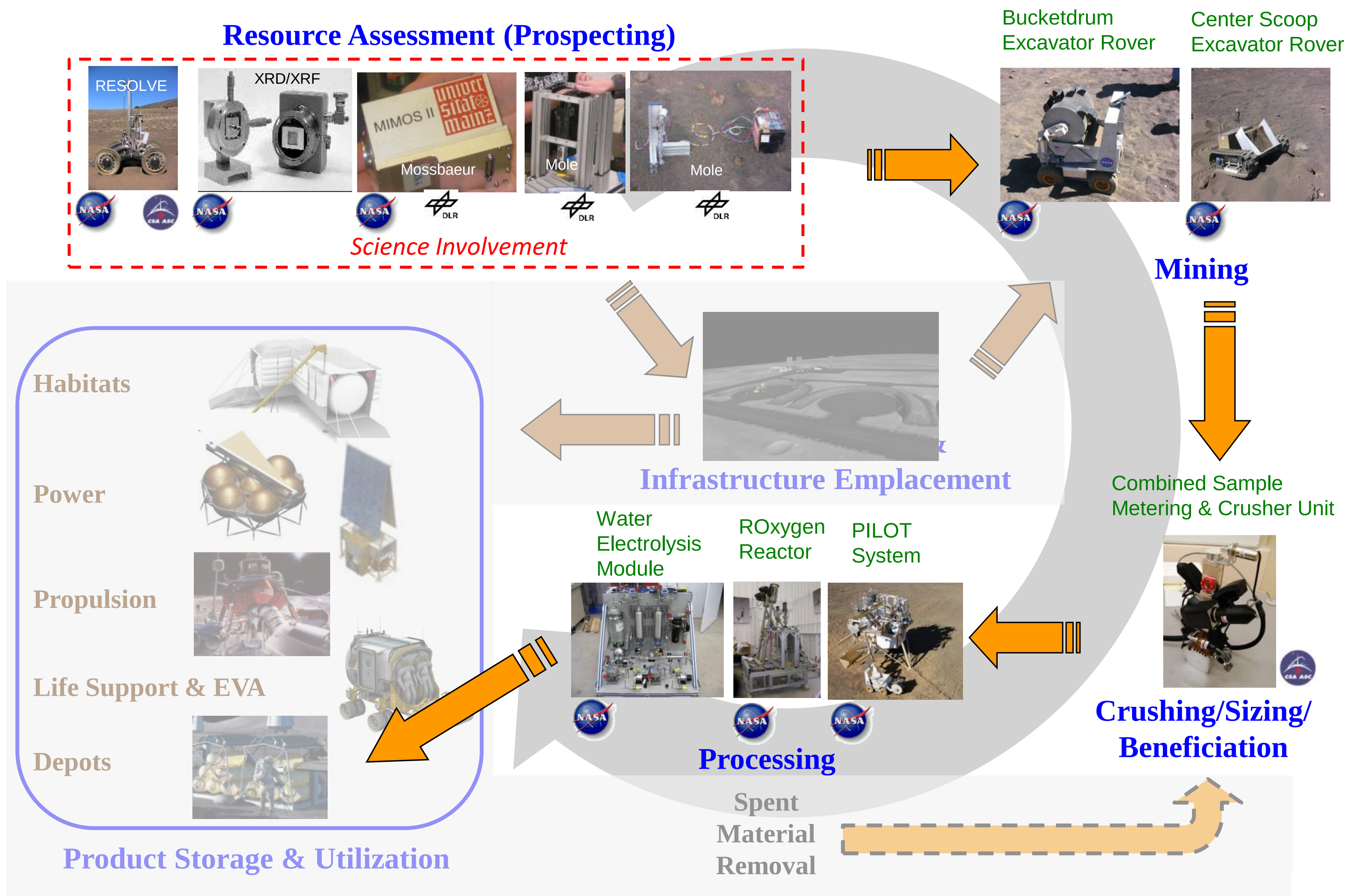


▪ Carnegie Mellon University

- SCARAB Rover

▪ JPL Partnership with Michelin on 'Tweels' testing

1st ISRU Analog Field Test: 2008 (2 of 2)



NASA Hardware List & Team Members

	Participant/Hardware Supplier
Site & Resource Exploration	
▪ RESOLVE Drill	NASA/NORCAT
▪ Combined Moessbauer/XRF	JSC KA/University of Mainz (Germany) & DLR
▪ MMAMA/FSAT Instruments	
– Cone Penetrometers (Dynamic, Percussive, & Manual)	Honeybee Robotics
– Heat Flow Probe	Honeybee Robotics
– Multispectral Microscopic Imager (MMI)	Arizona State Univ.
– X-Ray Diffraction	Arizona State Univ.
– Borehole XRF	LaRC, APL/Univ of Wash.
– VAPoR Mass Spectrometer	GSFC
– RESOLVE Chemical Plant –Gas Chromatograph	KSC, JSC, GRC, ASRC
– Data Integration	ARC, UC Davis, & McMaster Univ
Site Preparation & Excavation	
▪ Solar Concentrator & fiber optics with sun tracking system	PSI (SBIR Phase III)
▪ Resistive heater surface sintering	KSC
Oxygen Extraction from Regolith	
▪ Carbothermal reduction module with regolith feed system	Orbitec
▪ ROxygen Gen 1 water electrolysis module	JSC
▪ Pneumatic regolith lift device	KSC/ASRC & Honeybee
Energy	
▪ Solar Concentrator & fiber optics with sun tracking system	PSI (SBIR Phase III)
▪ Sunlight flux/intensity measurement instrument	PSI
▪ Power conditioning for fuel cell power system	NORCAT & JSC
Product Storage and Utilization	
▪ Liquid oxygen/methane tank and cryocooler cart	JSC
▪ Hydrogen hydride tanks	JSC and CSA
▪ O_2/CH_4 thruster hot-fire into tephra	JSC and WASK

8 System Modules – 7 Instruments

6 NASA Centers, 6 Small Businesses, 5 Universities

(42 people plus visitors)

2nd ISRU Analog Field Test: 2010 (2 of 3)

CSA Hardware/Software List

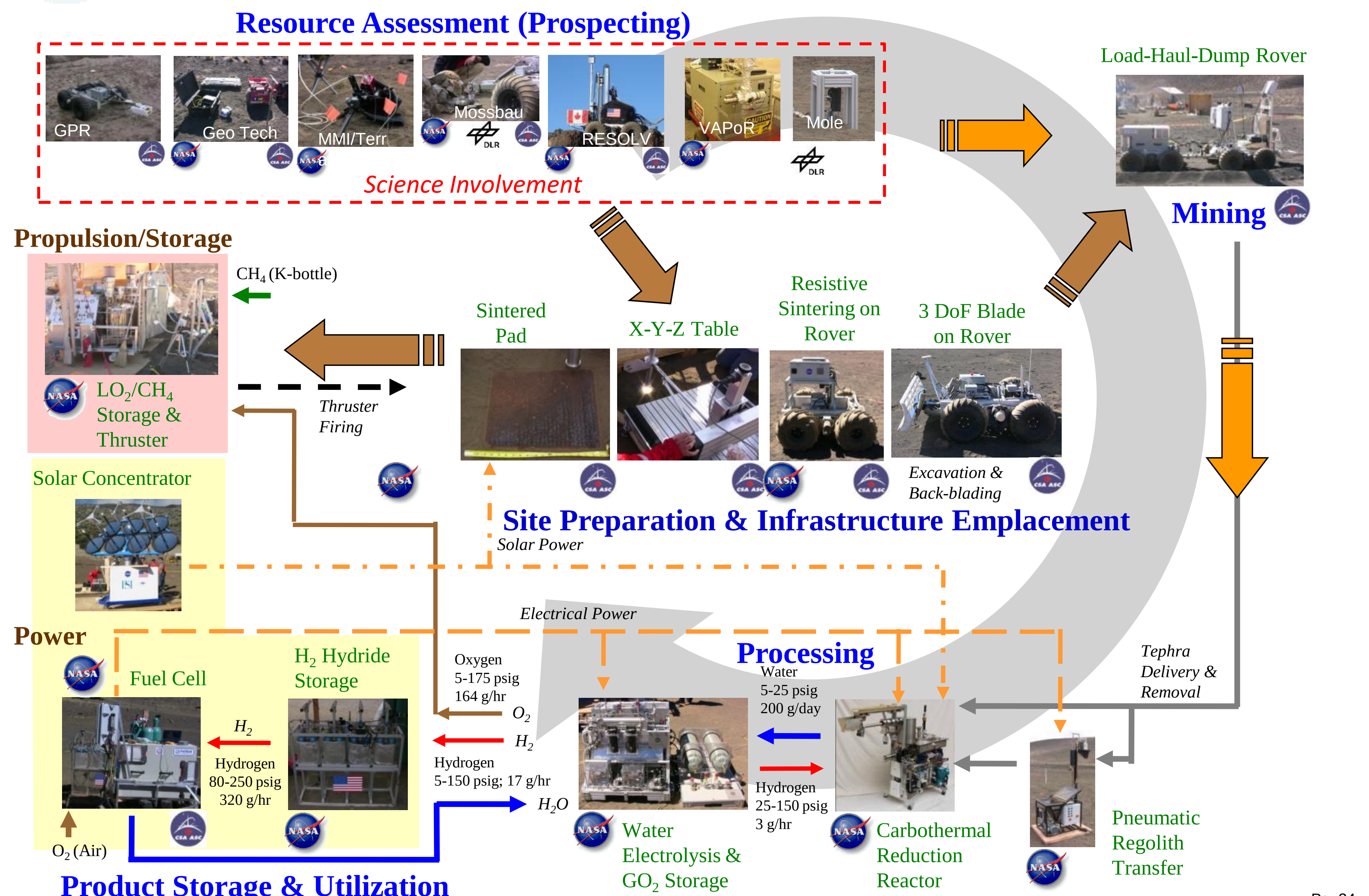
Item	Participant/Hardware Supplier
Site & Resource Exploration	
• TriDAR vision system (Triangulating LIDAR)	Neptec
• ERT (Extended Range TriDAR, also called DTO)	Neptec
• HPC (data compression software) (Hybrid Processing Card)	Xiphos
• Ground Penetrating Radar(3)	Noggin
• 3D Data Fusion (3 D subsurface visualization software)	Xiphos
• EXPLORE (ISRU site selection filter and algorithm software)	NORCAT
• Geotechnical Measurement Equipment (Cone Penetrometer/Shear Vane)	NORCAT
Site Preparation & Excavation	
• ISRU MAT/ANT Rovers (6) (Multi Agent Teaming/Artificial Neural Tissue)	NORCAT/ODG/Univ of Toronto
• Articulated joint (coupling of 2 rovers to accommodate heavy payloads)	NORCAT/ODG
• Plow Attachments (3)	NORCAT/EVC
• Excavation Attachments: Long (1) & Short (1)	NORCAT/EVC
• Autonomous Regolith Delivery system (1)	NORCAT/Neptec
• Solar Sintering XYZ Table Rastering Device (1)	NORCAT
Product and Utilization	
• Mining vehicle Fuel Cell/H_2 Hydride Tank (1 at 10 KW)	NRCan (Natural Resources Canada)
Infrastructure	
• Satellite Communications to CSA HQ (Mainland) VoIP service	CSA/CRC (Communications Research Center)
• Secure telemetry links to other agencies from CSA	CSA/CRC
• On-Site Wireless Communications	Virgin Tech
• Multi media studio	CSA/CRC
• ExDOC Control Center at CSA HQ (Exploration Development Ops Centre)	CSA
• Large Rover (Argo Avenger)	CSA/Ontario Drive (ODG)
• Lunar Link Emulator (LLE)	Xiphos
• Base Camp (mining camp structures), personnel tracking system	CSA/NRCan
• Food Preparation	YUM Culinary/Cambrian College

12 System Modules & Attachments; Infrastructure

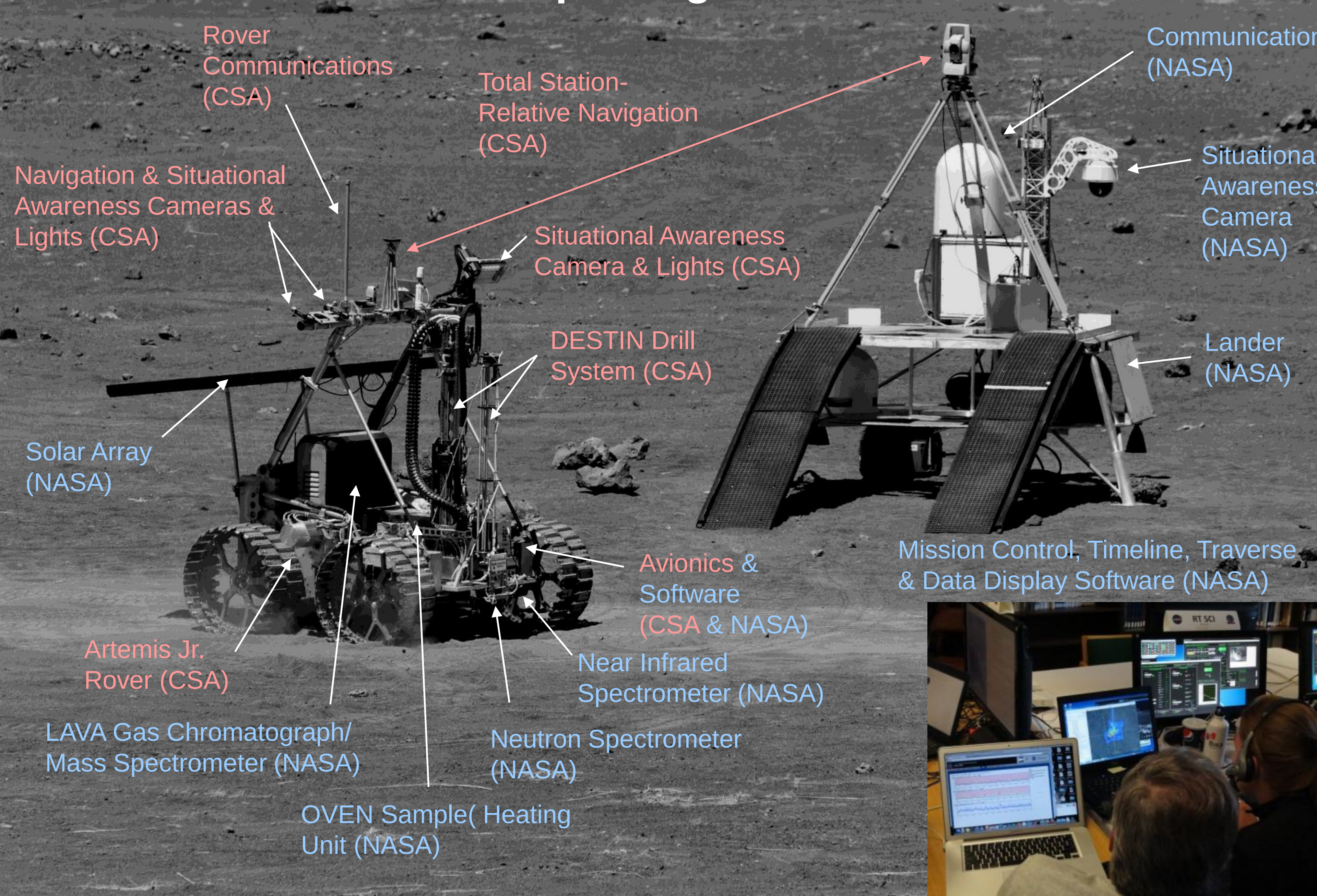
3 Government Agencies, 8 Small Businesses, 2 Universities

(46 people plus visitors)

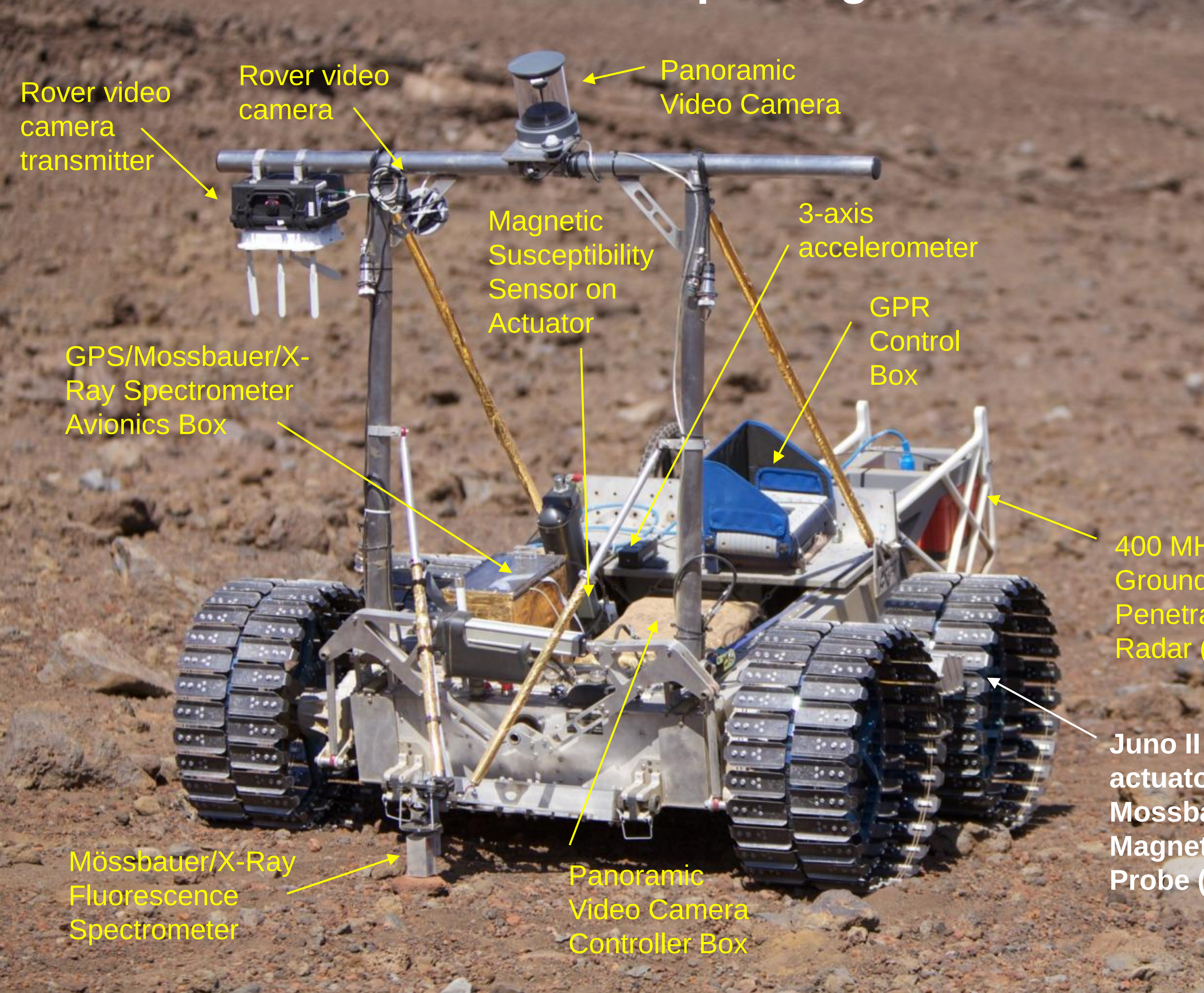
2nd ISRU Analog Field Test: 2010 (3 of 3)



3rd ISRU Analog Field Test: Lunar Polar Prospecting Mission Simulation



3rd ISRU Analog Field Test: Lunar Polar Prospecting Mission Simulation



Mechanized Sample Processing and Handling System (MeSH)