Title: NASA In-Situ Resource Utilization (ISRU) Technology and Development Project Overview

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ABSTRACT

Since the Vision for Space Exploration (VSE) was released in 2004, NASA, in conjunction with international space agencies, industry, and academia, has continued to define and refine plans for sustained and affordable robotic and human exploration of the Moon and beyond. With the goal of establishing a lunar Outpost on the Moon to extend human presence, pursue scientific activities, use the Moon to prepare for future human missions to Mars, and expand Earth’s economic sphere, a change in how space exploration is performed is required. One area that opens up the possibility for the first time of breaking our reliance on Earth supplied consumables and learn to “live off the land” is In-Situ Resource Utilization (ISRU). ISRU, which involves the extraction and processing of space resources into useful products, can have a substantial impact on mission and architecture concepts. In particular, the ability to make propellants, life support consumables, and fuel cell reagents can significantly reduce the cost, mass, and risk of sustained human activities beyond Earth. However, ISRU is an unproven capability for human lunar exploration and can not be put in the critical path of lunar Outpost success until it has been proven. Therefore, ISRU development and deployment needs to take incremental steps toward the desired end state. To ensure ISRU capabilities are available for pre-Outpost and Outpost deployment by 2020, and mission and architecture planners are confident that ISRU can meet initial and long term mission requirements, the ISRU Project is developing technologies and systems in three critical areas: (1) Regolith Excavation, Handling and Material Transportation; (2) Oxygen Extraction from Regolith; and (3) Volatile Extraction and Resource Prospecting, and in four development stages: (I) Demonstrate feasibility; (II) Evolve system w/ improved technologies; (III) Develop one or more systems to TRL 6 before start of flight development; and (IV) Flight development for Outpost. To minimize cost and ensure that ISRU technologies, systems, and functions are integrated properly into the Outpost, technology development efforts are being coordinated with other development areas such as Surface Mobility, Surface Power, Life Support, EVA, and Propulsion. Lastly, laboratory and field system-level tests and demonstrations will be performed as often as possible to demonstrate improvements in: Capabilities (ex. digging deeper); Performance (ex. lower power); and Duration (ex. more autonomy or more robustness). This presentation will provide the status of work performed to date within the NASA ISRU project with respect to technology and system development and field demonstration activities, as well as the current strategy to implement ISRU in future robotic and human lunar exploration missions.
NASA
In-Situ Resource Utilization (ISRU)
Technology and Development Project Overview

Presentation to the
Space Technology Applications International Forum
Feb. 11, 2008

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- ISRU is a critical capability and key implementation of the VSE and sustained human exploration.

- At the same time, ISRU on the Moon is an unproven capability for human lunar exploration and can not be put in the critical path of architecture until proven.

- Therefore, ISRU (as an end in and of itself) is manifested to take incremental steps toward the desired endstate.

- Architecture is designed to be open enough to take advantage of ISRU from whatever source when available.
Three Pronged Approach to ISRU Development & Incorporation

- **Identify how ISRU fits into Architecture for Sustained human presence on the Moon**
  - Non-critical path initially with fall back strategy
  - Evolutionary with growth in:
    - Capability
    - Criticality
    - Ties to Mars
    - Ties to Space Commercialization

- **Build confidence in ISRU early and often**
  - Multiple generations of hardware and systems developed
  - Extensive ground and analog site testing for operations, maintenance, and interconnectivity
  - Robotic precursors if possible to reduce risk AND
    - Tie to common science objectives for regolith, mineral, and volatile characterization
    - Tie to long-term operations associated with Outpost deployment and operation

- **Early NASA involvement in all aspects of ISRU with transition to industry**
  - Ensures NASA is ‘smart’ buyer
  - Ensures lessons learned from ground and flight demonstrations are transferred to all of industry (unless pre-agreement established for commercialization aspect)
  - Ensures long-term industry involvement
What is Lunar 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.

In-Situ Lunar Resources
- ‘Natural’ Lunar Resources:
  - Regolith, minerals, metals, volatiles, and water/ice
  - Sunlight, vacuum, thermal gradients/cold sinks
- Discarded Materials
  - LSAM descent stage fuel residual scavenging, tanks, etc. after landing (with Power)
  - Crew trash and waste (after Life Support processing is complete)

Lunar ISRU Products and Services (Lunar Architecture Team findings)
- Site Preparation and Outpost Deployment/Emplacement
  - Site surveying and resource 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
- Mission Consumable Production
  - Complete Life Support/Extra Vehicular Activity closure for Oxygen (O2) and water
  - Propellant production for robotic and human vehicles
  - Regenerate and storage life support and fuel cell power consumables (in conjunction with Life Support and Power)
- Outpost Growth and Self-Sufficiency
  - Fabrication of structures that utilize in-situ materials (in conjunction with Habitats)
  - Solar array, concentrator, and/or rectenna fabrication (in conjunction with Power)
  - Thermal energy storage & use from processed regolith (in conjunction with Power)
  - Production of feedstock for fabrication and repair (in conjunction with Sustainability)
ISRU Consumable Production for Lunar Architecture

- **O₂ Production from Regolith**
  - 2 MT/yr production rate for surface mission consumables – 1 MT/yr for ECLSS/EVA and 1 MT/yr to make water
  - Capability manifested on 6th landed mission (before start of permanent presence)
  - Increased production to 10 MT/yr during Outpost operation could also support refueling 2 ascent vehicles per year to further increase payload delivery capability

- **In-Situ Water Production**
  - Scavenge minimum of 55 kg of hydrogen (max. ~252 kg) from each LSAM descent stage after landing and add to in-situ oxygen to make 1 MT/yr of water
  - Polar water extraction not evaluated in Lunar Architecture Phase II effort. Not needed unless large scale in-situ propellant (O₂ & H₂) production is required

- **In-Situ Methane Production**
  - Pyrolysis processing of plastic trash and crew waste with in-situ oxygen can make methane
  - Capability supports LSAM Ascent ‘top-off’ in case of leakage, power loss, or increased payload to orbit

<table>
<thead>
<tr>
<th>ISRU Processing Requirements</th>
<th>kg/yr (min.)</th>
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<tbody>
<tr>
<td>Oxygen Production</td>
<td></td>
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<tr>
<td>For ECLSS &amp; EVA</td>
<td>1000</td>
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<tr>
<td>For Water Production</td>
<td>800</td>
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<tr>
<td>For LSAM Ascent Propulsion</td>
<td>7600</td>
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<tr>
<td>Water Production</td>
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<tr>
<td>For ECLSS &amp; EVA (from in-situ O₂ + Scavenged H₂)</td>
<td>900</td>
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<tr>
<td>Required H₂ Scavenged from LSAM Descent Stage</td>
<td>100</td>
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<tr>
<td>For radiation shielding (*one time production need)</td>
<td>1000 to 2000*</td>
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<tr>
<td>Water Electrolysis</td>
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<tr>
<td>For ISRU</td>
<td>1125</td>
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<tr>
<td>For Night time Power</td>
<td>7335</td>
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<tr>
<td>For Pressurized Rover Power (45 kg/mission)**</td>
<td>1260</td>
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<tr>
<td>Methane Production</td>
<td></td>
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<tr>
<td>For LSAM Ascent Propulsion (max)</td>
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</table>

** 28 excursions per year with at least 1 MPU
ISRU - Related Surface Elements & Activities

Red Header = Within scope of current ISRU Project
Blue Header = Out of scope of current ISRU Project
Brown Header = Funded by other ETDP Project

Resource & Site Characterization
- Regolith Excavation
- Regolith Transport
- Regolith Processing
- Site Preparation (roads, pads, berms, etc.)

Polar Volatile Extraction

Power Source
(Solar Array or Nuclear Reactor)

In-Situ Energy Generation & Storage
- Manufacturing feedstock

 Manufacturing & Repair
- Crew trash & waste

Life Support Systems
- Life Support Systems

Non-Regolith Resource Processing
- Construction feedstock

Product Storage
- Mission consumables
- Residuals & hardware scavenging

Mobile Transport of Oxygen
- Hoppers & Ascent Vehicles

Surface Construction
- Oxygen & fuel for life support, fuel cells, & propulsion
- Oxygen & fuel for life support, fuel cells, & propulsion

Habitats & Shelters
- Surface Mobility Asset
Near-term Critical Connectivity

Near-term Secondary Connectivity

Robert Ambrose
NASA Participants in Lunar ISRU Development

- **JSC – Project & ISRU Integration Lead**
  - ISRU management and system modeling
  - ROxygen and ROE hydrogen reduction oxygen extraction from regolith design and laboratory testing
  - Lunar material science & handling (KA)
  - Lunar simulant development support (KA)
  - ISRU integrated and field demonstration lead
  - ISRU Small Business Innovative Research (SBIR) topic and subtopic leads

- **KSC – Oxygen Production Lead**
  - Regolith & Environmental Science and Oxygen & Lunar Volatile Extraction (RESOLVE); Lead and Sample collection, volatile chamber, and water/hydrogen collection and processing
  - Regolith electrolysis oxygen production modeling and laboratory testing
  - Lunar regolith excavation modeling and development support; lead for large-rover based
  - ISRU SBIR subtopic support

- **GRC – Excavation & Transport Lead**
  - Lunar-g particle and material behavior modeling and testing
  - Regolith excavation and material transport modeling, development and laboratory testing; lead for small-rover based
  - Oxygen extraction from regolith modeling & research
  - RESOLVE volatile oven
  - Solar concentrator for oxygen production
  - ISRU SBIR subtopic support

- **JPL – Instrument & Resource Prospecting Lead**
  - System and architecture modeling
  - RESOLVE – regolith chemical and physical characterization; regolith thermal probe
  - In-situ instruments and sensors for resource and site assessment

- **MSFC – Simulant Development Lead**
  - Lunar simulant development
  - Regolith electrolysis oxygen production modeling and laboratory testing
  - Solar concentrator for oxygen production
  - ISRU SBIR subtopic support

- **ARC – Site Characterization & SMD Involvement**
  - Mars science drilling and subsurface exploration expertise
  - Site characterization & resource prospecting instrumentation and mapping hardware and software
  - Rover/arm integration and operations with ISRU
Possible Excavation Needs & Requirements for the Outpost

- **Excavation for Oxygen Production**
  - Evaluated a number of excavation options
  - Parametrics presented are based on a front-end/overshot loader that scoops and dumps into bin on back of chassis
  - If operate continuously, primary difference between small and large chasses is rate of drain on battery
    - Very inefficient to dig slowly/small amounts per scoop - lifting arm and dumping into bin is primary energy drain

- **Excavation for Outpost: Landing pads and berms**
  - Largest outpost emplacement excavation requirement over life of Outpost
  - If landers are not moved, a new pad needs to be prepared *every 6 months*
  - Capability Manifested on 1st landed mission

- **Excavation for Outpost: Habitat protection**
  - Multiple options if regolith shielding for radiation or thermal is desired
  - Trenching and inflatable covers evaluated for excavation impact

- **Excavation for Outpost Emplacement**
  - Excavate ramp or hole for nuclear reactor emplacement/shielding
  - Prepare pathways for transferring cargo from lander
  - Prepare trenches for cables

- **Excavation for Science**
  - Prepare trenches for subsurface geologic/stratigraphy access for Science
  - Core extraction drilling for subsurface sample acquisition (resource characterization)
  - Site preparation for antenna deployment
Integrated Approach to Lunar Excavation & Material Handling Development

**Develop Ability to Simulate Lunar Conditions**
- Lunar Regolith Simulant Test Bins for different locations and depths
- Thermal/Vacuum Chambers
- Partial-Gravity Parabolic Aircraft
- Radiation/Dust Exposure

**Develop and Test Hardware Under Controlled Conditions**
- Ground support equipment to measure, forces and torques, and power
- Implements to understand regolith/hardware interaction for modeling
- Implements to examine excavation and material transport concepts

**Known Lunar Environment & Hardware Operation Data**
- Surveyor Telemetry
- Apollo Crew Measurements
- Returned Lunar Samples
- Clementine/Lunar Prospector/Lunar Reconnaissance Orbiter

**Model Regolith Properties & Hardware/Regolith Interactions**
- Lunar Regolith Simulant Particles
- Soil Properties (interacting particles)
- Hardware Concepts (movement/forces)
- Machine/Soil Interactions (force/power)
- Estimate Hardware Performance on the Moon
- End to End ISRU System Models

**Develop and Test Hardware & Operations For Mission Needs**
- Integrate and test implements on rovers
- Interaction of regolith handling and transport with other subsystems
- Automation and logistics
- Operation planning, coordination, and execution
Lunar Regolith Excavation Development

Soil Preparation and Controlled Testing

Surveyor Arm/Scoop Re-fabrication and Controlled Laboratory Testing at GRC

Excavation Hardware – Small Rover-based

Cratos Small Excavator at GRC
Cratos w/ Hard Regolith Cutter Concept
Buckwheel Testing At NORCAT
Bucketwheel Excavator at CSM
Bucketdrum Excavator at LMA (IR&D)

Excavation Hardware – Large Rover-based

Chariot (Chassis C) Vehicle
Area Clearing Blade on Chariot
Multi-purpose End-effector on Chariot
Mobility Platforms for ISRU

Three main ISRU capabilities require different mobility platform attributes

- Site and resource characterization
- Oxygen extraction from regolith
- Site preparation and Outpost emplacement

Small Platforms (<50 kg payload)

Pros
- Lightweight, easy to package multiple units
- Supports Robotic Precursor oxygen extraction systems

Cons
- May not have mass or force to allow deep digging or area clearing
- May not have life required for long term operations
- Rocks may be problem

Medium Platforms (+100 kg payload)

Pros
- Higher mass and force than Small platforms will allow area clearing and berm building
- Easier to package multiple units than Large platforms
- Supports site characterization & Science objectives

Cons
- May be oversized for just oxygen extraction and undersized for extensive site construction

Large Platforms (+1mT kg payload)

Pros
- Good for area clearing, berm building, and hole/trench digging
- Easily meets all early ISRU needs with only fraction of operational time needed

Cons
- Extremely oversized for Outpost O₂ production
- Multiple units represent significant payload mass investment

All ISRU-Mobility Platform options need to be evaluated in laboratory and field tests before Final Architecture decisions are made.
Regolith Beneficiation

**Regolith Iron-Oxide Beneficiation (KSC)**
- Feldspar: \( \text{(Na,K)}\text{AlSi}_3\text{O}_8\text{SiO}_2 \) 40% 
- Spodumene: \( \text{LiAlSi}_2\text{O}_6 \) 40% 
- Olivine: \( \text{(Mg,Fe)}_2\text{SiO}_4 \) 10% 
- Ilmenite: \( \text{FeTiO}_3 \) 10%

- Reade Advanced Materials ~ 300 mesh sieved 
- Further sieved to 50-75 \( \mu \text{m} \) size range

**Beneficiated Regolith after 1st Pass (PTFE Charger)**
- As mixed 
- +ve plate 
- -ve plate 
- Bottom tray

**Important for \( \text{H}_2 \) Reduction to increase efficiency**

Lunar Simulant Development

- **OB1 Highland Simulant (NORCAT/UNB)**
- **Lunar Highland (LHT) Simulant (MSFC-USGS)**
- **JSC1a (ORBITEC)**

Regolith Mitigation

- **Transparent electrodes on glass with lunar simulant; Raman spectrum not attenuated negatively**
- **Integration of electrode/window into Metering Device/Crusher for RESOLVE EBU#2 now in work**


**O₂ Production From Regolith Overview & Plans**

- **Develop and evaluate the performance of production technologies.**
  - O₂ production in early Outpost can eliminate logistics resupply from Earth, by up to 2 to 4 MT/yr (EVA and life support makeup).
  - Technologies under development range from low yield/low technical difficulty to high yield/high technical difficulty.
  - High yield technologies may reduce the amount of regolith required to make oxygen and ultimately produce usable metals and silicon for in-situ fabrication.

- **Oxygen Extraction from Regolith Systems (includes Excavation)**
  - Hydrogen Reduction (~1% extraction efficiency at poles; 5% at equator):
  - Carbothermal Reduction (14 to 28% extraction efficiency)
  - Molten Electrolysis (up to 40%)

- **Develop Prototype Systems for Hydrogen Reduction and Carbothermal Reactors for end-to-end field demonstrations (with excavation) by end of FY08**
  - Scaled for 1 MT/yr O₂ Production Rate
  - Share Common Hardware When Possible (e.g. Water Electrolysis)
  - Prototype will be integrated with Excavation Hardware for a field demonstration at an analog site.
  - Prototypes will operate for a minimum of four hours per day for up to 7 straight days (allows us to study startup and shutdown issues)

- **Investigate Molten Oxide Electrolysis (MOE) for feasibility**
  - MOE has highest yield of all O₂ production technologies
  - MOE can also theoretically produce pure metals
  - Investigations will focus on key technical challenges to insure feasibility (Inert Anode, Cell Design, Materials Feed and Metals Removal)
### Oxygen Production from Regolith Results (Polar Region)

**Conclusions**

- All size systems show mass payback in first year of operation, even for low-yield $H_2$ reduction option

- Carbothermal achieves much higher yield which results in lower mass at lower production rates, but higher thermal energy requirement
  - Higher technology risk than hydrogen reduction

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

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### Polar Outpost - Based on 70% Sunlight/ISRU Operation per year

<table>
<thead>
<tr>
<th>ISRU System Option</th>
<th>O$_2$ per year (MT)</th>
<th>Mass* (kg)</th>
<th>Subsystem Mass (kg)</th>
<th>Volume* (m$^3$)</th>
<th>Power** (kW)</th>
</tr>
</thead>
</table>
| Hydrogen reduction  | 1                   | 590        | 231 - Excavation tools  
  359 - O$_2$ production & storage | 4.6     | 1.5     |
|                     | 2                   | 791        | 231 - Excavation tools  
  560 - O$_2$ production & storage | 7.7     | 2.8     |
|                     | 5                   | 1366       | 231 - Excavation tools  
  1135 - O$_2$ production & storage | 17.9    | 7.0     |
|                     | 10                  | 2194       | 231 - Excavation tools  
  1963 - O$_2$ production & storage | 38.5    | 15.3    |
| Carbothermal (w/Chassis C) | 1           | 416        | 75 - Excavation tools  
  341 - O$_2$ production & storage | 3.2     | 2.2     |
|                     | 2                   | 703        | 75 - Excavation tools  
  628 - O$_2$ production & storage | 7.2     | 4.5     |
|                     | 5                   | 1545       | 75 - Excavation tools  
  1470 - O$_2$ production & storage | 18.5    | 11.8    |
|                     | 10                  | 2878       | 75 - Excavation tools  
  2803 - O$_2$ production & storage | 33.9    | 25.2    |
| Carbothermal (w/2 mini-excavators) | 2          | 747        | 150 - Excavators (2)  
  597 - O$_2$ production & storage |           |           |

* Mass and volume include 20% margin
** Power is electrical power only and includes 10% margin

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Excavation rates required for 10 MT O$_2$/yr production

- 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
ISRU O₂ Extraction from Regolith Development

H₂ Reduction Rotating Reactor System (PILOT-LMA)

PILOT Hydrogen Reduction Kinetic Reactor

Reactor-Regolith Handling/Transport Testbed

CH₄ Carbothermal Reduction Reactor System (PILOT-ORBITEC)

Regolith Handling/Transport Testbed

PILOT Carbothermal Reactor Testbed

Methane Regeneration Reactor

H₂ Reduction Fluidized-Bed Reactor System (ROE & ROxygen - NASA)

Hydrogen Reduction Fluidized Subscale Reactor Testbed

Water Electrolysis Breadboard
ISRU O₂ Extraction from Regolith Development (Cont.)

Regolith Salt & Molten Electrolysis

Ilmenox (FFC Process) Cell at FIT

Molten Electrolysis Cell at MIT

Low-Temperature Electrolysis Cell at KSC

Early Electrolysis Cell Test at MSFC

Outpost O₂ Extraction Plant Concept with Solar Concentrator & O₂ Storage

Fully raised position

Robotic Precursor O₂ Extraction Plant Concept with Micro Excavator (LMA)

Fully lowered position

Robotic Precursor O₂ Extraction Subscale Demo
RESOLVE will incorporate five experiment modules from three NASA institutions; JSC, KSC, JPL
- Support from GRC & MSFC
- Drill and excavation expertise from Northern Centre for Advanced Technology (NORCAT)
- Significant university and Lunar science expertise

The five RESOLVE modules are:

- **EBRC - Excavation and Bulk Regolith Characterization (KSC/NORCAT/CSM)**
  Provide capability of extracting samples of regolith down to 1 meter and determine geo-technical characteristics of the regolith.

- **ERPC - Environment and Regolith Physical Characterization (JPL)**
  Determine the particle size, shape, color, and chemical characteristics of regolith samples and the regolith temperature in the permanently shadowed crater.

- **RVC - Regolith Volatile Characterization (KSC/GRC)**
  Provide capability of evolving and measuring volatiles from regolith samples to determine the form and concentration of hydrogen-bearing molecules in shadowed regions near the lunar poles. Also, determine other volatiles of interest.

- **ROE - Regolith Oxygen Extraction (JSC/GRC)**
  Demonstrate the ability to chemically extract oxygen from the regolith samples.

- **LWRD – Lunar Water Resource Demonstration (KSC)**
  Demonstrate the ability to capture and quantify water and hydrogen produced/evolved by the ROE and/or RVC from the regolith samples. In addition the LWRD shall split the water that is captured into hydrogen and oxygen using electrolysis.
Drill, Metering Device, & Crusher (EBRC) Accomplishments

- Demonstrated the acquisition of 1 meter deep samples in unconsolidated and cryogenic regolith/water mixture
- Demonstrated transfer of core to metering device
- Demonstrated metering length of sample and cutting sample
- Demonstrated crushing samples to 1 millimeter particle sizes

Drill & Sample Transfer

Metering Device

Crusher

Simulant Chamber for Extraction

NORCAT: Northern Centre for Advanced Technology
Raman/CHAMP Instrument EBU1 Layout

- CHAMP optical design complete for far-field, 30 μ/pixel hand lens, and 3 μ/pixel microscope (with color & UV light)
- Raman Spectroscopy capability designed to yield chemical/mineral content measurements to within 1 wt% per compound including the identification of any hydrogen compounds that are present
- Hardware built and in assembly

This is a 3D representation that illustrates the current details of the mounting interfaces of Lens Cells #1 and #2.

CHAMP Illuminator

MIDP CHAMP Imager

Integrated CHAMP/MMRS breadboard

Eschelle Raman Spectrometer for EBU1

Instrument Layout for Raman/CHAMP EBU1

Working Distance

Infinity Imager/Camera Images

Translation Stage for Raman/CHAMP EBU1

Handlens Images

High Resolution Microscope with 3D Topographic Images

Far-field to Microscope Optics Design

Working Distance

UV LEDs illuminated

Red LEDs illuminated

White LEDs illuminated

CHAMP Illuminator

Integrated CHAMP/MMRS breadboard

Eschelle Raman Spectrometer for EBU1

Instrument Layout for Raman/CHAMP EBU1
✓ Heating chamber built and tested to investigate vibro-fluidization amplitude/frequency, vacuum and microwave heating

✓ Successfully met the objective of heating simulant (150 C) to release and capture ~1 gram of hydrogen and water

✓ Successfully measured volatile gas species and quantity characteristics:
  - Detection limits: 0-20% water (0.05 wt% in regolith), 10 PPM Hydrogen & Helium; Modified to also separate and detect CO, CO₂, CH₄, O₂ and H₂S
Lunar Water Resource Demonstration (LWRD) Accomplishments

- Both Water Capture and Hydrogen Capture beds successfully tested.
- Quantification via temperature and pressure measurement currently only accurate to within 30%; Desire 10%
- Successfully performed water droplet freeze/thaw visualization (Public Outreach)
- Water droplet successfully electrolyzed

Water Droplet Demonstration

BaCl₂ in air 25 hrs at RT  BaCl₂ after heating in 400°C  Hydrated Salt Holder
Regolith Oxygen Extraction (ROE) Accomplishments

Oxygen Extraction From Regolith Demonstration System

✓ Successfully met the objective of 1 gram of oxygen extracted per 100 grams of regolith.

✓ Successfully proved dust filtration, and regolith fluidization and heating.

✓ Successfully proved system design and approximate volume and power goals.

➢ Future plans include realistic sealing for regolith inlet/outlet and reduced system & reactor mass.

Inlet & outlet doors with realistic gas feed & exit methods that allow dirt to fall in & out of the chamber

Realistic reactor chamber, heating method, & fluidization of the regolith for thermal mixing & product removal

Commercial off-the-shelf water capture bed, pump, instrumentation, and hydrogen storage tank

Bottle of water not included but can be produced 😊

H₂ Kinetic Reaction Characterization Testbed
RESOLVE – Rover Integration

- **Objectives:**
  - Demonstrate a mobility system for polar and dark operations
  - Demonstrate rover-based RESOLVE operations for drilling and characterizing lunar resources/ice and demonstrating oxygen extraction from regolith

- **Description:**
  - The RESOLVE engineering breadboard (EBU1) drill is mounted on the Carnegie Mellon Univ. (CMU) Scarab rover. The rover autonomously drives in the dark to a sampling location in FY07. The RESOLVE drill is used to acquire a core sample of ‘lunar regolith’.
  - In FY08 a complete 2nd generation RESOLVE EBU#2 is attached to the CMU Scarab rover. The drill extracts a core and transfers it to the RESOLVE crusher and oven. The rover drives to a new sampling location. All RESOLVE operations are demonstrated.

- **FY07 - Field tests**
  - Local field demo September 07:
    - Operate drill with CMU Scarab rover
  - Local field demo December 07:
    - Operate drill with CMU Scarab rover
    - Operate Scarab with Dark Operations software

- **FY08**
  - Upgrade both rover and RESOLVE system (EBU2) and test at remote site

- **FY09**
  - Upgrade system with additional science and mobility/navigation assets
ISRU Development & Integration Strategy

- Develop ISRU through phased ground development without requiring LPRP missions
  - LPRP missions would reduce risk of resource, process, and environment uncertainties that ground facilities could not adequately replicate
  - Technology and System development tasks be directed at Outpost applications but will also anticipate (not preclude) possible LPRP scale applications

- **ISRU Technology and Systems developed in 4 Phases** (2-3 years each phase)
  - Phase I: Demonstrate Feasibility
  - Phase II: Evolve System w/ Improved Technologies
  - Phase III: Develop 1 or more systems to TRL 6 Before Start of Flight development
  - Phase IV: Flight Development for Outpost

- Be prepared to participate in robotic precursor missions should opportunity arise
  - Site characterization, resource mapping, and/or ISRU precursor
  - Outpost ‘dress rehearsal’ mission

Regolith Excavation & Oxygen Extraction from Regolith

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<td>LPRP (Notional)</td>
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- Feasibility TRL 2-4
- Adv. Dev. TRL 4-5
- Fit. Protype TRL 5-6
- Flt. Dev. TRL 7-9
- Element Need Date (PDR)
- Fit. Date

ISRU Precursor Demonstration (O₂ Production and Resource/Site Characterization)

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<tbody>
<tr>
<td>Engineering Unit</td>
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<td>Prototype Unit</td>
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<td>LPRP (Notional)</td>
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- Feasibility TRL 2-4
- Fit. Protype TRL 5-6
- Flt. Dev. TRL 7-9
- Element Need Date (PDR)
- Fit. Date
Integrated Capability and Analog Site Demonstrations

Utilize laboratory and analog site demonstrations to:

- Demonstrate needed capabilities and operations for Lunar Outpost and technology/system ‘customers’
- Demonstrate evolution and incremental growth in technologies and systems for Capabilities (ex. digging deeper); Performance (ex. lower power); and Duration (ex. more autonomy or more robustness).
- Unite separate technology development efforts within NASA
- Develop partnerships and relationships across NASA and other US government agencies, and with International Partners, Industry, and Academia

<table>
<thead>
<tr>
<th>Site Preparation &amp; Outpost Construction</th>
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<tbody>
<tr>
<td>COTS blade on Chariot rover @ JSC</td>
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<td>Area clearing/berm building field demo</td>
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<tr>
<td>- Includes: excavator &amp; O₂ liquefaction &amp; storage</td>
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<td>Integrated Carbothermal reduction reactor &amp; Solar Concentrator</td>
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<tr>
<td>RESOLVE H₂ reduction field test</td>
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<td>Upgraded ROxygen reactor with Solar Concentrator</td>
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<tr>
<td>Full-scale Carbothermal reduction reactor &amp; Solar Concentrator</td>
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<th>Site Characterization &amp; Resource Prospecting</th>
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<tr>
<td>K10s with GPR and 3D lidar at Haughton</td>
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<tr>
<td>RESOLVE drill integration onto CMU rover at CMU</td>
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<tr>
<td>K10s with GPR and Neutron Spectrometer at ARC</td>
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<tr>
<td>RESOLVE drill/CMU rover field test at CMU</td>
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<tr>
<td>Combined K10 and RESOLVE/CMU field test</td>
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<table>
<thead>
<tr>
<th>Year</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
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▲ = In-Situ Resource Utilization (ISRU)-led Demo  ◇ = Human-Robotic Systems (HRS)-led Demo  ◈ = Structures & Mechanics-led Demo
**ISRU System & Surface Operations Ground Demo Plan**

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<th>2009</th>
<th>In Planning</th>
<th>2010</th>
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<td><strong>Site Preparation &amp; Outpost Deployment</strong></td>
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<tr>
<td>Cover inflatable shelter with material using Caterpillar and micro-excavator before inflation</td>
<td>Perform area clearing and with Chariot &amp; ISRU Blade</td>
<td>Add increased capabilities (ex. build berm and dig hole for reactor)</td>
<td>Examine other ISRU end-effectors on Chariot/Athlete</td>
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<td>Examine ISRU end-effectors on other platform</td>
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<td>Add Autonomy &amp; increased capabilities and durations to ISRU hardware. Add new dedicated ISRU platform</td>
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**Oxygen Extraction from Regolith**

Excavation and oxygen production from regolith with H₂ Reduction at 250 kg to 1000 kg per year rate for 1 to 5 days

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<td>Add to Chariot</td>
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<td>Add to Scarab</td>
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<td>Integrate other science instruments for prospecting on single platform (ex. GPR, Neutron Spec. etc.)</td>
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(At Hawaii)