Lunar Simulants, Analogues, and Standards: Needs and Realities for Mission Technologies Development

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Why does NASA need requirements on dirt?

- The needs of multiple disciplines and projects
  - Exploration surface vehicles
  - Resource characterization equipment
  - Regolith processing equipment

- The needs of the exploration program
  - Need to validate approaches and make comparisons
  - Need to recommend test standards
In-Situ Resource Utilization Can Provide Significant Benefits to Mission Architectures

- More than 7.5:1 mass savings by leveraging mass from Moon/Mars surface back to Low Earth Orbit
- Reduces Lunar mission launch mass by 27 to 88% depending on reusability and propellant depot options

Space Resource Utilization

Mass Reduction

- Allows reuse of transportation assets
- Reduces number and size of Earth launch vehicles
- Minimizes DDT&E & operation costs through use of common technologies

Cost Reduction

- Reduces dependence on Earth

Risk Reduction & Flexibility

- Provides ‘safe haven’ capabilities for aborts and delayed cargo resupply
- Can reduce number of launches and mission operations
- Radiation and landing/ascent plume shielding
- Increases flexibility and options for contingency and failure recovery operations
- Reduces dependence on Earth

Expands Human Presence

- Increases Surface Mobility & extends missions
- Habitat & infrastructure construction
- Propellants, life support, power, etc.
- Substitutes propellant & consumable mass for new science or infrastructure cargo

Enables Space Commercialization

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

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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.

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.

Resource Characterization & Mapping
- Lunar polar ice/volatile characterization
  - RESOLVE

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

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
  - Microchannel Reactors
- Water and Fuel from Trash
  - Steam Reforming
  - Combustion/Pyrolysis
- Water Processing
  - Water Electrolysis
  - Water Cleanup

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## Main Areas of ISRU and Applicability to Surface Systems

<table>
<thead>
<tr>
<th>Resource Characterization &amp; Mapping</th>
<th>EVA</th>
<th>Life Support</th>
<th>Power</th>
<th>Propulsion</th>
<th>Manufacturing</th>
<th>Habitats</th>
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ISRU Strongly Influences Element Designs and Architecture Choices

- **Construction & Manufacturing**
  - Cryogenic Fluid Mgmt: Lander/AscentPropulsion
  - Propellant (O₂ or O₂/fuel)
  - Purge gas/tank pressurant
  - Residual Propellants

- **Cryogenic Fluid Mgmt**
  - Hydrocarbons for plastics
  - Materials for concrete & metal structures
  - Gas for pneumatic systems
  - Explosives

- **ECLSS technology**
  - Common with ISRU
  - O₂, H₂O and N₂/Ar for Habitat & EVA suits
  - CO₂ for dust cleaning
  - Water and trash/waste from ECLSS

- **Surface Mobility**
  - Defines resource excavation & transportation capabilities
  - Fuel cell, water processing & Cryo Fluid Mgmt technologies common with ISRU

- **Environmental Control & Life Support System (ECLSS)**
  - Defines level of closed-loop ECLSS required

- **Science Activities**
  - Subsurface sample access
  - Gases for science instruments and cleaning

- **Extra Vehicular Activity (EVA)**
  - Thermal Energy
  - Fuel cell reagents (O₂ and fuel)
  - Water from fuel cell

- **In-Situ Resource Utilization (ISRU)**
  - Thermal Energy
  - Resource instruments

- **Surface & Fuel Cell Power Generation**
  - Defines surface power needs and fuel cell reagents
Space 'Mining' Cycle & Integration with Surface/Transportation Elements

**Science Involvement**

- Global Resource Identification
- Local Resource Exploration/Planning
- Product Storage & Utilization
  - Power
  - Propulsion
  - Life Support & EVA
  - Depots
- Communication & Autonomy
  - Site Preparation
  - Processing
  - Maintenance & Repair
  - Crushing/Sizing/Beneficiation

**Other Elements**
- Waste
- Remediation

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ISRU & Surface System Development & Integration Challenges

Life:
- Hardware and systems must operate for months and years and not just days in the harsh lunar vacuum, radiation, thermal, and dust environment

Schedule:
- Nations/space agencies must be allowed freedom to pursue areas of interest with delivery dates that are consistent with their budgets

Interoperability:
- Hardware and systems from multiple countries must be compatible with each other to achieve desired capabilities and operations

System/Element Integration:
- Critical systems, such as power, propulsion, thermal, and life support for each major lunar surface element are often designed and optimized based on their own requirements instead of from a more integrated element/vehicle perspective or surface architecture perspective.

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Importance of Analog Field Testing to Prepare for Human Exploration Beyond Low Earth Orbit

Partner Infusion
International, Commercial, Other Government Agencies

Analog Field Tests Validate Key Integrated Architecture Requirements and Concepts

Technology Development
(Energy Storage, Robotics, Human Factors, etc.)

Architecture Element Concept
(Rover, Habitat, Robotics, Power, ISRU, etc.)

Surface Operation/Integration Concepts
(Outpost Maintenance, Exploration, etc.)

Science Concepts
(Site Survey’s, Geological Sampling/Curation, etc.)

Crew Training
(Outpost Maintenance, Science, Exploration, etc.)

Outreach & Participatory Exploration
(Web 2.0, Virtual Reality, Simulations, etc.)

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Exploration Mission Analog Types

Mission Focused Analog
- Focus on performing relevant mission scenarios
  - Mission relevant hardware not as important
- Stress timeline and operations
- Examine remote operations and procedures
- Examine system/capability influence on mission

Hardware Focused Analog
- Focus on mission relevant hardware and scale
- Stress hardware (get out of laboratory)
- Examine how environment impacts hardware design and operation
- Examine integration and interaction of hardware and systems

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Desert RATS
NEEMO
Pavilion Lake

3rd Hawaii ISRU
  - Surface Ops

1st & 2nd Hawaii ISRU
  - Surface Ops

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ISRU-Surface Operations Analog Test Focus

Hardware Focus

Space Mining Cycle Module & Operation Objectives

Demonstrate mobile resource characterization (physical, mineral, and volatile) capabilities for lunar polar missions

- Link science operations and instrumentation with site characterization & resource prospecting/mapping needs

Demonstrate technologies and end-to-end system operations for mission critical consumable production on Moon, Mars, & NEO’s (oxygen, water, fuel)

Demonstrate civil engineering and site preparation capabilities that might be required for future human missions (landing pads, roads, protection, etc.)

Surface Element /Transportation Module & Operations Objectives

Link Power, Propulsion, Life Support, ISRU, and Cryogenic Fluid Management technology, system, and module development efforts within NASA (ETDD, OCT, SBIR, IR&D) and with industry and external partners

Develop interfaces and standards for fluids/electrical/data

Demonstrate performance and operations of modules for all surface and transportation system elements.

Demonstrate evolutionary growth of capabilities through technology and module upgrades when available

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What are the needs of the technology projects?

- Needs of the surface vehicles
  - Physical and geotechnical

- Needs of the regolith handling hardware
  - Physical and mineralogical

- Needs of the regolith processing hardware
  - Mineralogical and chemical
  - But also...physical as well (example of RESOLVE devpt – fluidization, interfaces with the crusher)
Designing requirements for ‘special dirt’ ... what approach to choose?

Start with our knowledge of the Moon

- Apollo and Luna samples data
- Apollo surface observations and measurements

Identify what features are mineralogical in nature and those that are due to formation processes specific to the Moon

- Mineralogical features can be reproduced with some exceptions
- Formation processes are more challenging or even impossible to reproduce
Approach to requirements

The needs of the various technology development areas overlap

- Physical features like grain size, shape and bulk density are important to all
- Modal composition is critical to guarantee that simulants can be used by many users

Some needs are overriding

- Chemical compositions can be controlled by proper choice of terrestrial minerals but source locations are very important
- Choosing the mineralogy of the simulant becomes a top priority to simulate the right geotechnical properties and control the chemical composition for chemical processing
Lunar Highlands Regolith Simulants

A focus on lunar highlands is a good place to start:

• The highlands represent 75% of the lunar surface
• The regolith possesses a remarkable physical uniformity throughout the lunar surface
• What mineralogy to choose?
  • Fewer returned samples represent the Highlands
  • Norite is a dominant component
• Ranking of needs is important to identify the economics of simulants materials and their level of fidelity (FoM)
Lunar Highlands Regolith Simulants

The mineralogical variety of the Highlands is not tightly bound

- Choices must be made to avoid trying to duplicate every sample known

- Representation of several critical minerals and lithic components is needed to control both the physical properties and the chemical composition

- Current approach by NASA is to identify simulant materials from different sources and provide an evaluation tool based on figures of merit (FoM)
Lunar Highlands Regolith Simulants

Major requirements
- Modal composition
- Grain size and distribution
- Grain shape and distribution
- Bulk density

Environmental requirements
- Mixing procedures
- Compaction procedures
- Storage protocols
Integration of In-Situ Resource Utilization (ISRU) capabilities into missions presents both challenges as well as benefits for future missions to the Moon and Mars.

- However, since ISRU systems and capabilities have not flown, mission planners have been hesitant to include ISRU capabilities in mission critical roles, thereby significantly reducing the benefits that ISRU can provide in mission mass and cost reductions.

For ISRU systems to provide products and services to ‘customers’ such as life support, propulsion, and power systems, close development of requirements, hardware, and operations between ISRU and these systems are required.

To address these development and incorporation challenges, NASA and CSA initiated a series of analog field test demonstrations at sites in Hawaii.

- Two tests completed in November of 2008 and February of 2010 have demonstrate all the critical steps in operating ISRU systems on the lunar surface at relevant mission scales as well as integration with power and propulsion systems.

- The third field test planned for July 2012 will demonstrate that a mission to the lunar poles to locate and characterize ice and other volatiles is possible in a highly integrated mission with multiple space agencies.

- These analog field tests have shown that not only are ISRU systems feasible at relevant mission scales, that they can be successfully integrated into mission architectures.
Conclusions

Requirements on a few main properties of the regolith can be defined to drive simulant development.

Production of the resulting simulants will be economically feasible while maintaining quality control.

We must adopt a concept that enables quick response to changing knowledge and implementation of that knowledge between simulant batches.
Taxonomy of Lunar Simulant Materials
## Current lunar simulant materials (U.S.)

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<tr>
<th>Simulant</th>
<th>Info</th>
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<tr>
<td><strong>United States:</strong></td>
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<tr>
<td>ALS</td>
<td>Arizona Lunar Simulant</td>
<td>Low-Ti Mare (geotechnical)</td>
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<td></td>
<td><em>Desai et al., 1993</em></td>
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<tr>
<td>BP-1</td>
<td>KSC / Arizona Black Point quarry waste (Basalt); using for large excavation exercises with BLADE</td>
<td>Low-Ti mare (geotechnical)</td>
<td>Rob Mueller/KSC</td>
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<td></td>
<td><em>Rahmatian &amp; Metzger, in press</em></td>
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<td>CSM-CL</td>
<td>Colorado School of Mines – Colorado Lava Unpublished</td>
<td>geotechnical</td>
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<td>GCA-1</td>
<td>Goddard Space Center</td>
<td>Low-Ti mare (geotechnical)</td>
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<td><em>Taylor et al., 2008</em></td>
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<td>GRC-1 &amp; -3</td>
<td>Glenn Research Center (Sand, clay mixture used in SLOPE Facility for mobility/excavation)</td>
<td>Geotechnical: standard vehicle mobility lunar simulant</td>
<td>Allen Wilkinson/GRC</td>
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<td></td>
<td><em>Oravec et al., in press</em></td>
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<tr>
<td>GSC-1</td>
<td>Goddard &quot;Simulant&quot;; material from local site that is being used for drilling tests</td>
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<td>Peter Chen/GSFC</td>
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<td>JSC-1*</td>
<td>Johnson Space Center</td>
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<td><em>McKay et al., 1994</em></td>
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<td>JSC-1A, -1AF, -1AC</td>
<td>Orbitec created under a NASA contract</td>
<td>Low-Ti mare (general use)</td>
<td><a href="http://orbitec.com/store/simulant.html">http://orbitec.com/store/simulant.html</a></td>
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<td><em>(JSC-1A was produced from the same source material after a gap of some years when JSC-1 ran out)</em></td>
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<td>MLS-1*</td>
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**Current lunar simulant materials (International)**

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<td>China (Chinese Academy of Sciences) a basaltic simulant made to represent Apollo 14 Zheng et al., 2008</td>
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<td>CLRS-1</td>
<td>Chinese Lunar Regolith Simulant Chinese Academy of Sciences, 2009</td>
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<td>CLRS-2</td>
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<td>CUG-1</td>
<td>China He et al., 2010</td>
<td>Low-Ti mare (geotechnical)</td>
<td>presentation at LPSC 2010 conference</td>
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<td>NAO-1</td>
<td>NAO-1, National Astronomical Observatories, Chinese Academy of Sciences Li et al., 2009</td>
<td>Highlands (general use)</td>
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<td>TJ-1, TJ-2</td>
<td>China (Tongji University) ; a basaltic ash feedstock with olivine and glass Jiang et al., in press</td>
<td>Low-Ti mare (geotechnical)</td>
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<td>CHENOBI</td>
<td>Canada (Physical &amp; Chemical properties simulat)</td>
<td>Highlands (geotechnical)</td>
<td><a href="http://www.evcltd.com/index_005.htm">http://www.evcltd.com/index_005.htm</a></td>
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<td>OB-1</td>
<td>Canada Olivine-Bytownite Battler &amp; Spray, 2009</td>
<td>Highlands (general use geotechnical)</td>
<td><a href="mailto:jrichard@norcat.org">Jim Richard</a> PH: 705-521-8324 x205 / <a href="mailto:jrichard@norcat.org">jrichard@norcat.org</a> <a href="http://www.norcat.org/innovation-regolith.aspx">http://www.norcat.org/innovation-regolith.aspx</a></td>
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<td>FJS-1 (type 1)</td>
<td>Fuji Japanese Simulant Kanamori et al., 1998</td>
<td>Low-Ti mare (geotechnical)</td>
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<td>FJS-1 (type 2)</td>
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<td>Oshima base simulant</td>
<td>Sueyoshi et al., 2008</td>
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<td>Kohyama base simulant</td>
<td>Sueyoshi et al., 2008</td>
<td>Intermediate between highlands and mare (general use)</td>
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<td>KohLS-1</td>
<td>Korea Koh Lunar Simulant Jiang et al. 2010</td>
<td>Low-Ti mare (geotechnical)</td>
<td>presentation at Earth &amp; Space 2010: Experimental Study of Waterless Concrete for Lunar Construction by Sung Won Koh, Jaemin Yoo, Leonhard Bernold, and Tai Sik Lee, Hanyang University, Korea.</td>
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</table>

Others - This may not be a complete listing.
Classification of lunar simulants

Simulant materials can be classified by the type of regolith they simulate

- Mare materials
- Highland materials
- Special glass materials (e.g., pyroclastic)

Another classification arise by type of technology development

- Excavation, drilling and transport (BP-1, OB-1, Chenobi)
  - Simulants developed to reproduce physical properties mainly: shape, density, hardness, glass fraction, particle size distributions
  - These simulants are not necessarily high fidelity in mineralogy and chemistry
- Chemical processing (JSC1-A, NU-LHT-N1)
  - Simulants developed to reproduce mineralogical and chemical compositions as well as some physical properties: major and minor components, inclusion of nanophase iron.
  - These simulants tend to reflect higher fidelity
Technology Needs for lunar simulants

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- Special glass materials (e.g., pyroclastic)

Another classification arises by type of technology development

- Excavation, drilling and transport (BP-1, OB-1, Chenobi)
  - Simulants developed to reproduce physical properties mainly: shape, density, hardness, glass fraction, particle size distributions
  - These simulants are not necessarily high fidelity in mineralogy and chemistry
- Chemical processing (JSC1-A, NU-LHT-N1)
  - Simulants developed to reproduce mineralogical and chemical compositions as well as some physical properties: major and minor components, inclusion of nanophase iron.
  - These simulants tend to reflect higher fidelity
Importance of Analog Field Testing to Prepare for Human Exploration Beyond Low Earth Orbit

Partner Infusion
International, Commercial, Other Government Agencies

Analog Field Tests Validate Key Integrated Architecture Requirements and Concepts

Technology Development
(Energy Storage, Robotics, Human Factors, etc.)

Architecture Element Concept
(Rover, Habitat, Robotics, Power, ISRU, etc.)

Surface Operation/Integration Concepts
(Outpost Maintenance, Exploration, etc.)

Science Concepts
(Site Survey's, Geological Sampling, Curation, etc.)

Crew Training
(Outpost Maintenance, Science, Exploration, etc.)

Outreach & Participatory Exploration
(Web 2.0, Virtual Reality, Simulations, etc.)

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Exploration Mission Analog Types

**Mission Focused Analog**
- Focus on performing relevant mission scenarios
  - Mission relevant hardware not as important
- Stress timeline and operations
- Examine remote operations and procedures
- Examine system/capability influence on mission
- Use of low fidelity simulant materials relevant to interfaces

**Hardware Focused Analog**
- Focus on mission relevant hardware and scale
- Stress hardware (get out of laboratory)
- Examine how environment impacts hardware design and operation
- Examine integration and interaction of hardware and systems
- Use of high fidelity simulant materials relevant to hardware functions

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