Lunar In Situ Resource Utilization

Summary of Sessions

- The primary advantage of lunar resource utilization is the potential to make space exploration beyond LEO more affordable
- Uncertainties associated with potential economic advantages of lunar resources have been reduced over the last year through international activities including
  - ISRU and robotic technology demonstrations at analog sites
  - Remote sensing of the lunar surface via orbiters
  - Preliminary analysis of results from the LCROSS impactors
- Over the next year, additional (economic) risks associated with the use of lunar resources are expected to be retired through ISRU and robotic technology demonstrations and continued analysis of data from remote sensing spacecraft (e.g., LRO)
- Future steps, which can be accomplished over the next five to ten years, include landed assets:
  - Stationary and rover platforms (prospectors) to determine the best sites for resource extraction
  - Technology demonstrators and pilot plants to prove the economics of lunar resource utilization
- Implications include very near-term opportunities to begin to transition to a more affordable, sustainable space-resource-based architecture for human spaceflight

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Session Contents

- R Wegeng, *Introduction: Bringing the Moon into Earth's Economic Sphere*
  - Defined the basic premise of ISRU; that lunar resources – and other resources of near-Earth space – can be used to:
    - Make space exploration beyond LEO more affordable
    - Bring direct benefits back to the Earth
  - Identified the following challenges for the next decade:
    - Confirm the presence, form, quantities and locations of lunar resources
    - Reduce ISRU technology risks
    - Determine the economics of lunar ISRU
  - Suggested "Affordability" and "Productivity" (the ratio of value to cost) as attributes of sustainable space architectures and systems
  - Illustrated notional approaches for lunar resource processing and the buildup of lunar assets leading to a mining settlement on the Moon

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Session Contents

- G Sanders, *Exploration Sustainability: Benefits and Hurdles of Incorporating In-Situ Resource Utilization*
  - Defined In-Situ Resource Utilization
  - Identified the attributes of programmatic sustainability
    - Continually improve performance and capability
    - Continually reduce risk to mission and crew
    - Continually reduce cost for performing missions and operations; increase “Value”
    - Continually reduce dependence on Earth-supplied logistics and infrastructure
    - Establish common “Vision” and long-term plan that public supports
    - Continually engaging and exciting the public (thereby support for government activities)
    - Increase benefits to Countries supporting exploration and the Earth
    - Robust & Flexible: Allow for new ideas and flexibility in priority schedules
  - Discussed the pros and cons of Lunar ISRU
  - Discussed the current approach to incorporating ISRU in the lunar architecture plus ISRU insertion opportunities
  - Concluded that, for maximum effectiveness, ISRU needs to be planned/ incorporated within the exploration architecture “from the start”

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Session Contents

- M Bualat, *2009 Human Robotic Systems (HRS) Overview*
  - Described NASA's Human Robotic Systems project
    - A multi-center team engaging the challenges of humans working with, commanding and supervising lunar exploration robots
  - Contrasted lunar exploration with Mars exploration and compared robotics for un-crewed missions, short-stay missions and outpost missions
  - Described HRS project goals
    - Surface mobility: Expand range of operations for the surface crew
    - Surface Handling: Transport, position and connect surface equipment
    - Human-Systems Interaction: Enhance operability
  - Discussed 2009 Accomplishments
    - Robotic Recon Experiment
    - Desert RATS Field Tests
  - Discussed Plans for FY2010

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Session Contents

- W Larson, *In Situ Resource Utilization Field Demonstrations*
  - Provided an overview of ISRU activities/development strategy
    - Oxygen extraction from regolith
    - In-situ water/fuel production
    - ISRU precursor activities
    - Integrate hardware & demonstrate capabilities
  - Discussed FY2009 analog field tests as vehicles to increase TRLs
    - PISCES Field Test Infrastructure
    - International & University Involvement
    - ROxygen, PILOT and RESOLVE Field Tests
  - Described planned analog field tests for FY2010
    - Carbothermal reduction with solar thermal heating
    - Electrolysis of water
    - Oxygen liquefaction and storage
    - RESOLVE on a CSA provided mobility platform
    - Integrated science instruments for resource prospecting
    - Utilization of oxygen produced (rocket thruster firing)
    - Soil sintering for rocket plume mitigation
  - Concluded that, by the end of February 2010, ISRU field tests will have demonstrated “dust to thrust”

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Session Contents

- Kurt Sacksteder, *Thermal Wadis: Using Regolith for Thermal Management*
  - Provided an update on Thermal Wadi feasibility studies
    - Modeling indicates that Thermal Wadis can provide a reasonably moderate thermal environment for rovers and other assets
    - Laboratory work on regolith simulants confirms the expectation of improved thermal properties by melting and/or sintering lunar regolith
  - Narrated an animation showing the manufacturing of a thermal mass and the assembly of a Thermal Wadi by a compact lunar rover
  - Identified concepts that make use of “natural thermal wadis” if they can be identified at suitable locations on the lunar surface
  - Future work includes
    - Extending the modeling to include rover concepts
    - Demonstrating various methods of making thermal wadis that could be deployed using simple lander/rover systems

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Session Contents

- Panel (LA Taylor, B Joliffe and GJ Taylor): *Lunar Prospecting "Desirements"*
  - Discussed regolith particle size distribution
  - Identified immature regolith as better for mineral beneficiation than mature regolith
  - Identified impact craters as opportunities to probe into the lunar interior
  - Discussed solar wind volatile species in Apollo samples
  - Identified questions for resource utilization (e.g., where are ilmenite concentrations in the regolith the highest? And is the lower crust or upper mantle a source of rare metals?)
  - Discussed how LRO data can be used to better identify lunar resources
  - Discussed applications of lunar volatiles

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Session Contents

- Panel (LA Taylor, B Joliffe and GJ Taylor): *Lunar Prospecting "Desirements" (continued)*
  - Discussed prospecting of volatile resource deposits in polar regions
    - Orbital sensing
    - Targeted (LCROSS)
    - Landed (In-Situ)
  - Discussed characteristics of volatiles in polar regions
    - Chemical/molecular forms
    - Distribution
    - Relationship to polar ice traps, geology
    - Physical properties
  - Discussed "desirements" for polar volatiles
    - Thermal and illumination conditions
    - Relationship of volatile deposits to permanent shadow/thermal environment
    - Geochemical survey: regional, in-situ, local
    - Concentrations and molecular forms
    - Lateral and vertical extent and variability of deposits
    - Topography for planning access to deposits

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Session Contents

- Panel (LA Taylor, B Joliffe and GJ Taylor): *Lunar Prospecting "Desirements" (continued)*
  - Discussed prospecting of volcanic pyroclastic deposits
    - Can be processed to produce metallic iron and oxygen
    - Enriched in Zn, Cd, Hg, Pb, Cu, F & Cl
    - Prospecting "desirements" for include:
      - Bulk chemical composition
      - Concentrations of volatiles
      - Physical properties
      - Relative amounts of crystals and glass
      - In-situ H2O extraction experiments
      - Lateral and vertical variations
      - Characterization of volcanic systems
  - Discussed prospecting of evolved igneous rocks
    - Produced/differentiated as the "Lunar Magma Ocean" cooled and solidified
    - Potential sources of non-metals (Zr, P, Li, K) which are enriched in selected minerals
    - Extraction processes may be complex
    - Prospecting begins with orbital measurements of places with highest concentrations, followed by detailed surface studies of concentrations and distributions
    - Required long traverses, mapping, and determining vertical variations (crater ejecta, drilling)

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Session Contents

- Panel: (D Boucher, M Bualat & W Whitaker) *Robotic Lunar Rover Prospectors*
  - Discussed lunar prospecting ("prospecting 101")
    - Surface exploration
    - Drilling
      - Exploratory drill holes
      - Development drilling
      - Reserve drilling
    - Value of ore body ("tonage" and "grade" [concentration])
    - Development
      - What is the energy cost of recovery?
    - Feasibility Stage
  - Noted that the waste from a lunar ISRU plant may be the product for another process
  - Discussed robotic site surveys
    - Civil engineering, geophysical, resource prospecting
    - Ground truthing for remote sensing
    - Haughton Crater Field Test (Devon Island, Canada)
      - Analog for lunar craters such as Shackleton Crater
      - K-10 rover (3rd generation)
      - Optech ILRIS-3D (topograpic mapping)
      - JPL CRUX GPR (subsurface mapping)
    - Haugton Crater Lessons Learned
      - Dense coverage requires long distance driving
      - Continuous navigation is a key enabler
      - Instrument constraints have huge impact
      - Visualization tools essential for rapid contingency handling & high duty cycle; provide awareness of robot status & perception; facilitates situational awareness

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Session Contents

- Panel: (D Boucher, M Bualat & W Whitaker) *Robotic Lunar Rover Prospectors (continued)*
  - Discussed robotic site surveys (continued)
    - HYDRA Field Test
      - K-10 rover with integrated HYDRA tested at ARC
      - Demonstrate utility of HYDRA Neutron Spectrometer (NS) for near-surface hydrogenous deposits (e.g., hydrogen prospecting)
    - Hydra Phase I: Site Characterization Traverse
      - Identify 'hot' or 'cold' spots via epithermal and thermal neutrons
    - HYDRA Phase II: Interesting Locations
      - Return to 'hot' or 'cold' spots, characterize extent of deposit
    - Observation: Systematic surveys should be performed by robots (unproductive for humans)
  - Discussed experiences from other rovers/robots
    - Russian Lunohkod rovers
      - Pressurized shell, bimodal operation
    - Three-Mile Island cleanup
    - Meteorite hunting
    - CMU rover 200 km field test
    - Scarab (mobility traversing)
  - Current state of the art:
    - Significant attention has been paid to rover propulsion
    - Little attention to thermal management
    - Power
      - Lunar rovers likely to be about 2 watts/kg
      - Mars rovers are about 1 watt/kg due to reduced sunlight

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Session Contents

- Panel: (D Boucher, M Bualat & W Whitaker) *Robotic Lunar Rover Prospectors (continued)*
  - Discussed concept for lightweight rover prospectors
    - 60 kg mass
    - 120 kw solar, 273 watt-hours batteries
    - 50 km traverses per lunar light period
    - Thermal management challenges
      - Must dump heat that is internally generated and received
      - Must remain warm through periods of darkness
      - Lava tubes may provide overnight sites
      - Interesting innovation: Batteries that tolerate deep freeze
  - Fulfillment of robotic lunar prospectors
    - Must provide thermal management
    - Longevity essential
      - Critical due to cost
    - High performance
    - High payload ratio
    - Generality essential for diverse prospecting capability
    - Polar machines: Likely to be distinct from equatorial machines

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- P Clark, *Geothermal Concepts for Lunar Surface Science Packages*
  - Discussed geothermal concept designs for thermal support and/or power as alternatives to the use of radioisotopes for supporting science packages on the lunar surface
    - Combined solar thermal/stirling geothermal power
    - Heat pipe based thermal protection system
    - Geothermalized regolith: Innovative drilling, thermalizing materials, fluid injection technology
  - Described the use/injection of a high thermal conductivity/thermal capacity fluid to improve regolith thermal properties and create a thermalized regolith energy storage medium
    - Two candidate fluids with very low vapor pressures identified: AOS Thermal Grease 52030 (a perfluorinated non-silicone zinc oxide) and ionic liquids (organic salts)
  - Power concept includes stirling cycle heat engine integrated with geothermalized regolith, heat pipe and radiator
  - Drill concept, for deploying heat pipe and injecting thermalizing fluids uses a piezoelectric flywheel-driven, high-torque drill assembly

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- E Faierson, *Lunar Construction Material Production Using Regolith Simulant in a Geothermal Reaction*
  - Described geothermite reactions
    - Minerals plus reducing agent
    - Self-propagating High Temperature Synthesis (SHS)
    - Exothermic reaction requires initial heat input
    - Near-net shape product with high compressive strength
  - Discussed experiments with lunar regolith simulants (JSC-1A and JSC-1AF) plus aluminum powder
    - Sample prep and reaction initiation
    - Product characterization (X-ray diffraction, Scanning Electron Microscope, Compressive Strength)
  - Described potential lunar applications
    - Auxiliary lunar physical asset/habitat construction material
      - Structural
      - Radiation shielding
      - Micrometeorite protection
    - Lunar dust mitigation
      - Lunar landing sites
      - Roads
      - Blast berms
    - Mineral processing
    - Thermal energy storage (e.g., thermal wadis)
  - Similar applications for Mars

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- M Marone, *Lunar Oxygen Production and Metals Extraction using Ionic Liquids*
  - Described ionic liquids (ILs)
    - New class of materials that can be engineered at the molecular level for a particular task
    - Molten salts with melting points near room temperature
    - Low vapor pressure, low flammabiliy
    - “Green”
    - Chemically and thermally stable
  - Discussed approach
    - Solubilization of regolith in IL medium to convert metal oxides to water and metallic ions
    - Electrolysis of water (to produce oxygen and hydrogen)
    - Regeneration of IL medium
  - Discussed and provided videos of solubilization of JSC-1 using IL
  - Next steps include work to demonstrate IL regeneration
    - It is expected that successful regeneration can be accomplished through electrochemical methods