PS Lunar Energy and Mineral Resources: New Insights from the Lunar Reconnaissance Orbiter*

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Abstract

The Lunar Reconnaissance Orbiter (LRO), launched in June 2009, is armed with an array of instruments—LAMP, LOLA, LEND, Mini-SAR, DIVINER, LCROSS—that collectively are detecting, mapping, and measuring a variety of lunar-energy and mineral resources. LRO applies similar remote-sensing techniques used in Earth-orbiting satellites to environmental monitoring, mapping, and mineral exploration. However, LRO is also detecting hydrogen, water ice, helium-3, radionuclides, and rare-earth elements (REEs). These in situ resources can support extended scientific missions to the Moon, as well as provide permanent bases with local sources of rocket propellants, nuclear and solar energy, construction materials, and food and water. For example, water ice is disseminated within the shallow (<40-cm) regolith in permanently shadowed craters near the poles. Recent findings from DIVINER and LCROSS have confirmed >5 wt% hydrogen in some permanently shadowed craters near the South Pole. In addition, regolith-bound hydrogen in nonpolar areas occurs in sufficient abundance to contribute significantly to the overall accessible resource base. LRO is also refining our understanding of the distribution and concentration of metals in lunar basalts, as well as thorium and uranium associated with silicic volcanic domes. Broad areas of the regolith having high concentrations of KREEP (potassium, REEs, and phosphorus) are associated with late-stage magmatic outflows concentrated in Oceanus Procellarum. However, recent LRO data also indicate up to 55 ppm thorium in farside feldspathic terrains that were formerly thought to have low thorium content. Further, the availability of REEs and energy minerals, such as thorium and uranium, indicates that with existing technology, we could support an active program on the moon, and with reasonable advances in technology, the Moon could export high-valued materials to Earth such as helium-3. Viable and potentially self-supporting lunar bases on the Moon can provide a support facility as well for missions to Mars or mining activities on Near-Earth and Main-Belt asteroids.

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Lunar Energy and Mineral Resources:
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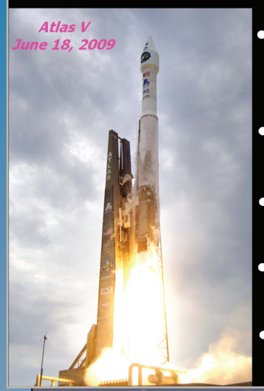
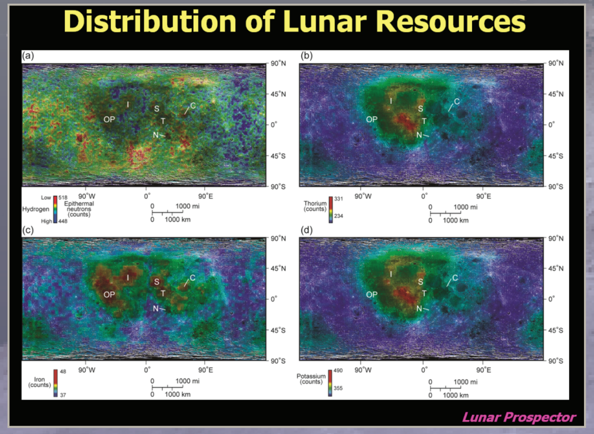
LRO Mission and Resource Base

LRO Mission Profile



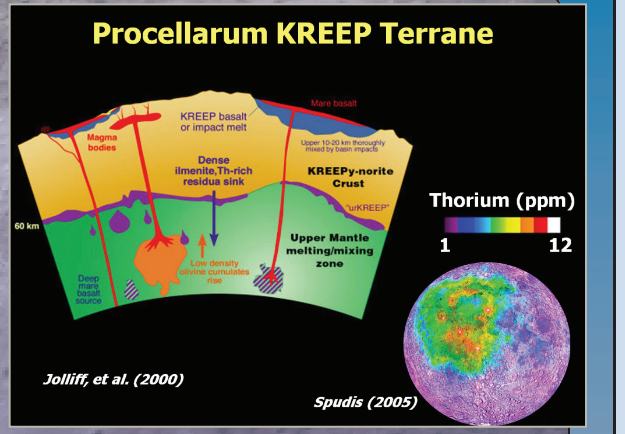
- Create comprehensive Lunar atlas and map resources for human settlement
- Map lunar surface features
- Detect and map polar ice
- Study lunar radiation environment
- Map and select landing sites

Fig. 1. Launch and mission profile of the Lunar Reconnaissance Orbiter (LRO).


Distribution of Lunar Resources

Lunar Prospector

Fig. 3. Surface distribution of (a) hydrogen, (b) thorium, (c) iron, and (d) potassium from Lunar Prospector data.


Procellarum KREEP Terrane

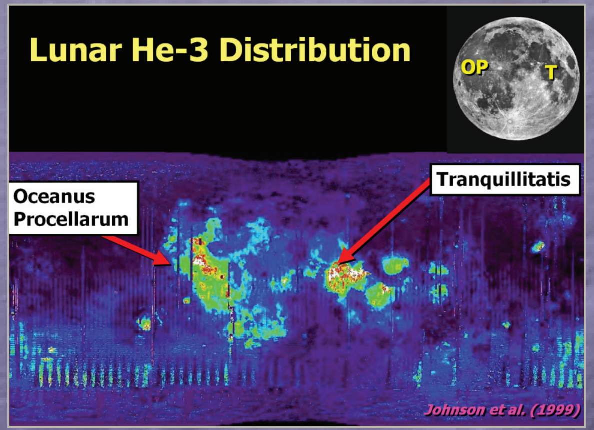
Jolliff, et al. (2000)
Spudis (2005)

Fig. 5. Late-stage magmatic melts in Procellarum KREEP (potassium—rare earth elements—phosphorus) terraine are rich in thorium and other radio nuclides.

Lunar Resources

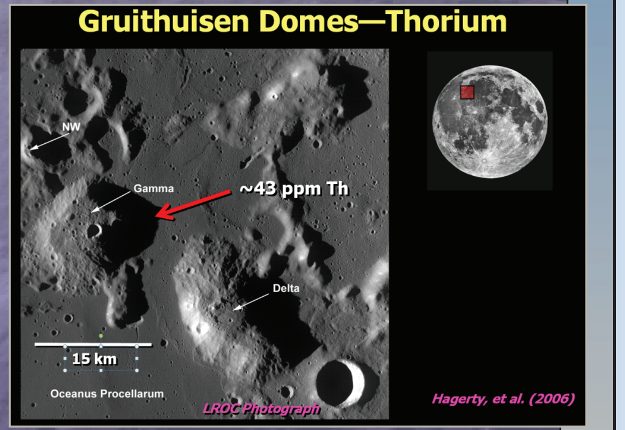
Resource	Use	Occurrence
Helium-3	Energy	Mature regolith
Hydrogen	Propellant, water	Mature regolith, poles
Oxygen	Propellant, air/water	Global
Nitrogen, carbon	Food and plastics	Breccias/regolith
Metals/bulk regolith Iron Titanium Aluminum	Construction Moon base Shielding Roads Solar power facility	Regolith, mare

Fig. 2. Lunar resources. The Moon contains abundant hydrogen and water for rocket propellants and a variety of other materials that could support human settlement.


Lunar He-3 Distribution

Johnson et al. (1999)

Fig. 4. Distribution of helium-3. Greatest concentrations (>10 ppb) are associated with iron- and titanium-rich regolith.


Gruithuisen Domes—Thorium

LROC Photograph
Hagerty, et al. (2006)

Fig. 6. Silicic domes such as Mons Gruithuisen in Procellarum KREEP terrane have locally high concentrations of thorium (>40 ppm).

Resource Summary

Although water on the Moon was only recently verified by the LCROSS (Lunar Crater Observation and Sensing Satellite) mission in 2009, it was hypothesized to occur in cold traps in polar regions >50 years ago (Watson and others, 1961). Indications of high levels of hydrogen at the lunar poles originally came from the Clementine mission in 1994 that were based on polarized radar signatures from deeply shadowed craters near the Moon's South Pole. Moreover, neutron spectroscopy data from the 1999 Lunar Prospector mission revealed elevated levels of polar hydrogen (Lucey, 2009). A leading explanation for these hydrogen anomalies is that water-ice deposits and other volatiles accumulated as ejecta from lunar impacts from water- and volatile-rich comets and asteroids that have settled in areas of permanent shadow at or near the Moon's poles in the last 3 billion years (Ga). Arnold (1979) estimated that the amount of water delivered to the Moon from cometary impacts over the past 2 Ga could be as much as 10^{10} metric tons (10^{13} kg). Although volatiles deposited on the lunar surface rapidly sublimate in sunlit areas where the temperature reaches 212°F (100°C) during the day (Bussey and others, 2005), these materials would be stable in areas of permanent shadow, where the temperature is slightly above absolute zero. The Moon's low obliquity (~1.5°) results in significant shadowed and weakly illuminated areas near the North and South Poles.

The primary objective of the recent LCROSS mission was to measure the concentration of water ice (ice:dust ratio) in permanently shadowed regolith in lunar polar areas. As a means of detecting water ice in these areas, the upper stage of the Centaur rocket for LRO was impacted at >5,600 mi hr^{-1} (>9,000 km hr^{-1}) into a permanently shadowed area in the Cabeus A crater near the South Pole in October 2009. The objective of this human-made impact was to create an ejecta plume and to detect water ice (OH [hydroxyl] molecules) from the LEND (Lunar Exploration Neutron Detector) instrument package on the LRO satellite. The impact event was recorded to assess the nonuniform distribution of water ice and other volatiles in the ejecta plume. The impact created a small crater 70 to 100 feet (21.3 to 30.5 m) in diameter. The ejecta plume in the LCROSS field of view is estimated to have contained 220 lb (~100 kg) of water vapor (Hayne and others, 2010; NASA, 2010a). Moreover, other volatiles such as carbon dioxide (CO_2), carbon monoxide (CO), and organic molecules like methane (CH_4), methanol (CH_3OH), and ethanol (C_2H_5OH) may also have been present in the plume, given the spectral signatures. Finally, DIVINER (Lunar Radiometer Experiment) data indicate extremely low temperatures in permanently shadowed areas in the lunar south polar area, including Cabeus A, where temperatures are <-388°F (<40°K) (NASA, 2010b).

Water-Ice Resources and Areas for Human Settlement

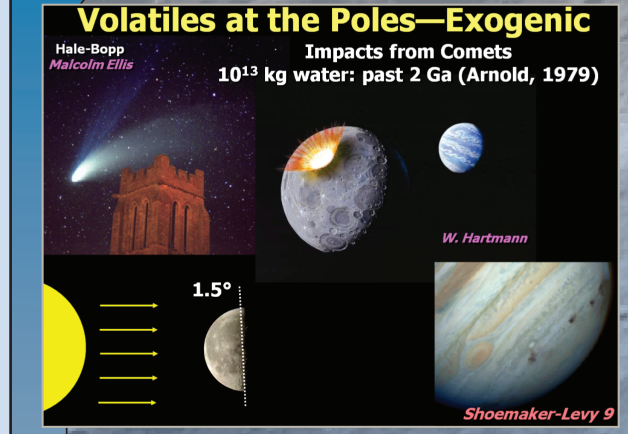

Volatiles at the Poles—Exogenic

Fig. 7. ~10^{13} kg of water ice and other volatiles may have accumulated in permanently shadowed areas at the lunar poles in the past two billion years owing to impacts from comets and volatile-rich asteroids.

LCROSS
(Lunar CRater Observation and Sensing Satellite)

- measure the concentration of water ice (ice to dust ratio) in PSRs
- Oct. 8, 2009: Upper stage impact >9,000 km hr^{-1}

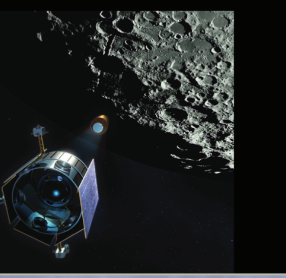


Fig. 9. The upper stage of the Centaur rocket for the LRO mission impacted Cabeus A crater near the South Pole so that a dust- and volatile-rich plume could be analyzed to detect water directly .

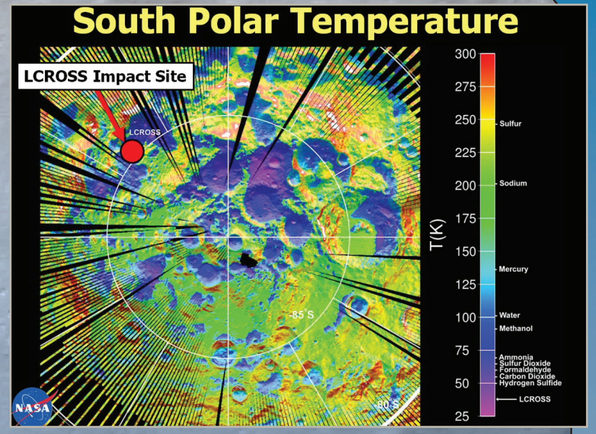
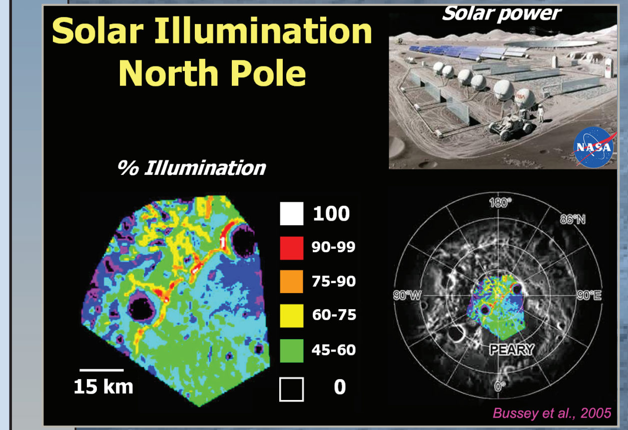
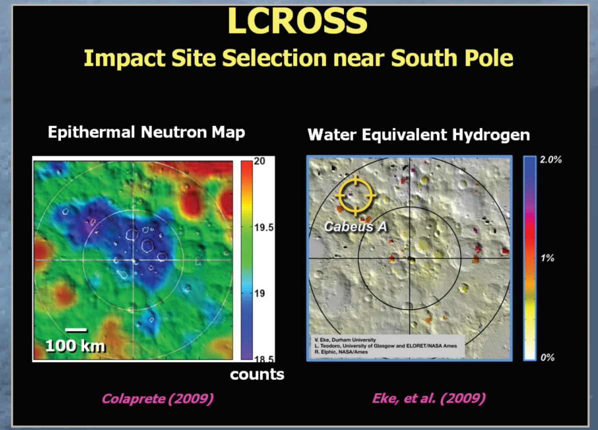

South Polar Temperature

Fig. 11. South polar temperatures measured from DIVINER, with temperature levels for stable accumulation for a variety of volatiles.


Solar Illumination North Pole

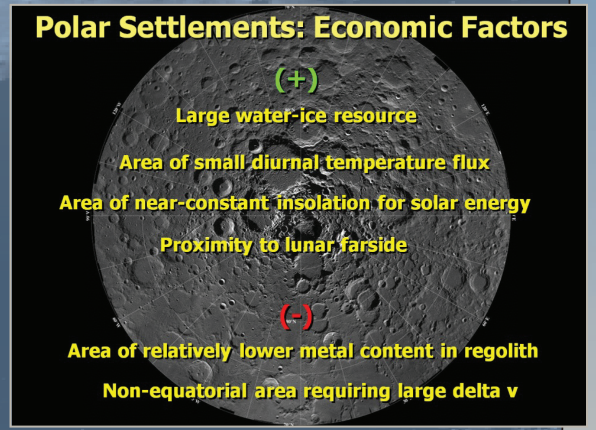
Bussey et al., 2005

Fig. 8. Areas of constant and near-constant solar illumination in polar areas are ideal for solar-power facilities to process water-ice resources in adjacent cold traps in permanently shadowed craters.


LCROSS
Impact Site Selection near South Pole

Colaprete (2009)
Eke, et al. (2009)

Fig. 10. Epithermal neutron map and water-equivalent hydrogen levels in the South Pole region.


Polar Settlements: Economic Factors

(+)
Large water-ice resource
Area of small diurnal temperature flux
Area of near-constant insolation for solar energy
Proximity to lunar farside

(-)
Area of relatively lower metal content in regolith
Non-equatorial area requiring large delta v

Fig. 12. Positive and negative economic factors in polar areas for human settlement.

Areas for Human Settlement

The lunar poles are commonly cited as optimal sites for human settlement, owing to their abundant water-ice resources, although hydrogen-rich volatiles are also present in nonpolar areas (Clark, 2009; Pieters and others, 2009; Sunshine and others, 2009). In addition, topographically high crater rims near the poles experience near-constant insolation and are ideal for solar-power generation that could supply the energy to process water-ice resources occurring in permanently shadowed areas within adjacent craters (Bussey and others, 2005; Lucey, 2009; Spudis, 2009). Minor variations in diurnal temperature that would have a lesser impact on personnel and equipment owing to less thermal stress have also been cited as a favorable factor for polar settlements (Bussey and others, 1999). For example, the temperature at the lunar equator ranges from -292°F to 212°F (-180°C to 100°C), but the surface temperature for weakly illuminated areas near the poles is commonly -58°F (-50°C), with little variation (Heiken and others, 1991).

Nearside equatorial areas have traditionally been considered as sites for lunar settlements and landing because most Apollo Missions visited these areas and they are readily accessible from nonpolar, low lunar orbits (LLO) (Yazdi and Messerschmid, 2008). Some equatorial areas are relatively enriched in titanium-bearing basalts high in ilmenite content and helium-3 deposits in Mare Tranquillitatis, Mare Marginis, and isolated areas in the south part of Oceanus Procellarum (Schmitt, 2006). These areas could be mined by unmanned, solar-powered robots where helium-3 concentrations exceed 10 ppb. However, lunar equatorial areas have several negative attributes that may limit their attractiveness for settlement or for launching facilities for shipment of lunar resources to Earth. For example, equatorial areas contain no sites with near-constant insolation for maximizing solar power generation. Another economic factor to consider in deciding on the equatorial area as one of the principal bases of operations would be the requirement for sufficient power generation during the long (~14-day) lunar night, as well as the expense in transporting water from the poles, although such transport could be avoided by the manufacture of water directly in the equatorial area from hydrogen entrained in the regolith.

Acknowledgments

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