

PS Optimal Locations for Lunar Settlements and Industrial Facilities*

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Abstract

The Moon has a variety of regions for potential human settlement. Lunar facilities should be strategically located to maximize access to resources and to efficiently transfer material from mining sites to the primary Moon base, involving minimal delta-v costs. Resources include water-ice, volatiles (hydrogen and nitrogen), nuclear materials (helium-3, thorium, and uranium), rare earth elements (REEs), and metals including titanium and iron. An important factor is the duration of insolation (sunlight), where solar-power facilities could be constructed in polar areas with near-constant illumination. Polar areas are cited as optimal sites for lunar settlement, owing to the presence of elevated areas (crater rims) that experience near-constant insolation, ideal for solar power. Polar areas also contain water-ice deposits in permanently shadowed cold traps within crater floors. Nearside equatorial areas are possible sites for lunar settlements, as they are readily accessible from non-polar, low lunar orbits (LLO). Many of these areas contain titanium-bearing basalts, REEs, thorium in silicic domes, as well as regolith-bound hydrogen and helium-3. Nearside limb regions could take advantage of line-of-sight communications with Earth and could be near a farside radio telescope away from Earth-radio interference. However, regolith hydrogen in limb areas is limited to restricted mare basalts. The lunar farside contains even fewer mare areas than nearside limb areas. The lunar farside also has no line-of-sight communication potential with Earth, although a relay satellite in the L2 Lagrangian point could overcome this disadvantage. The optimal location, therefore, is not a single area, but is defined by the needs of the location. If constant communication is required and power generation from non-solar sources is possible, the nearside equatorial regions can be considered optimal. Conversely, if proximity to water-ice deposits and constant solar exposure is necessary, then only a polar location meets these criteria. Ideally, advances in efficient orbital communications satellites would remove communication as a limiting criterion. Expected advances in lightweight fission or fusion power plants, or in beamed power systems could remove remaining limiting criteria, and allow scientific goals to be the primary consideration, with the entire lunar surface being considered in choosing a location for a permanent settlement.



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The Moon has a variety of regions for potential human settlement. Lunar facilities should be located strategically to maximize access to resources and to transfer material efficiently from mining sites to the primary Moon base, involving minimal delta-v costs. Resources include water-ice, volatiles (hydrogen and nitrogen), nuclear materials (helium-3, thorium, and uranium), rare earth elements (REEs), and metals such as titanium and iron. Crucial is the duration of insolation (sunlight), in which solar-power facilities could be constructed in polar areas with near-constant illumination. Polar areas are cited as optimal sites for lunar settlement, owing to the presence of elevated areas (crater rims) that experience near-constant insolation, ideal for solar power. Polar areas also contain water-ice deposits in permanently shadowed cold traps within crater floors. Nearside equatorial areas are possible sites for lunar settlements because they are readily accessible from nonpolar, low lunar orbits (LLO). Many of these areas contain titanium-bearing basalts, REEs, and thorium in silicic domes, as well as regolith-bound hydrogen and helium-3. Nearside limb regions could take advantage of line-of-sight communications with Earth and could also be near a farside radio telescope away from Earth-radio interference. However, regolith hydrogen in limb areas is limited to restricted mare basalts. The lunar farside contains even fewer mare areas than nearside limb areas. The lunar farside also has no line-of-sight communication potential with Earth, although a relay satellite in the L2 Lagrangian point could overcome this disadvantage. The optimal location, therefore, is not a single area, but areas defined by the needs of the location. If constant communication is required and power generation from non-solar sources is possible, nearside equatorial regions can be considered optimal. Conversely, if proximity to water-ice deposits and constant solar exposure are necessary, then only a polar location would meet these criteria. Ideally, advances in efficient orbital communications satellites would remove communication as a limiting criterion. Expected advances in lightweight fission or fusion power plants or beamed-power systems could remove remaining limiting criteria and allow scientific goals to be the primary consideration, with the entire lunar surface being considered in choosing a location for a permanent settlement.

Return to the Moon

Why Return to the Moon?

- **Earth's closest neighbor**
 - Three-day trip
 - Technology already exists to return to the Moon
 - Less than 0.1% surface area visited by humans
- **Abundant resources**
 - Water and volatiles for human settlement and rocket fuel
 - Metals for Moon base and solar-power facilities
- **Technology development**
 - Settlements: Learning experiences for Mars
 - Mining
 - Space-power systems

Fig. 1. Justifications for returning to the Moon.

Return to the Moon



Fig. 3. Original timetable and rocket technology for the Constellation program.

Earth-Moon Transportation Systems

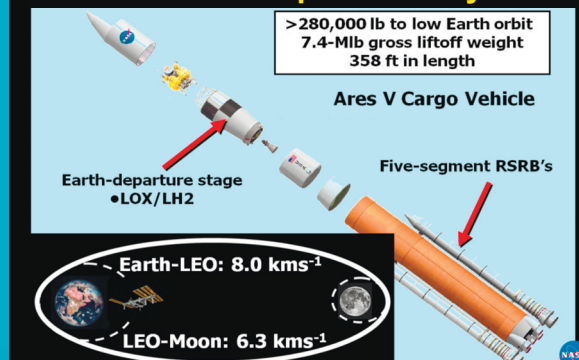


Fig. 5. Constellation program with Aries cargo vehicle and Earth-Moon orbital configuration.

Moon—Much Left to Explore



Fig. 2. A tiny fraction of the lunar surface has been explored by Apollo missions.

LEO Missions

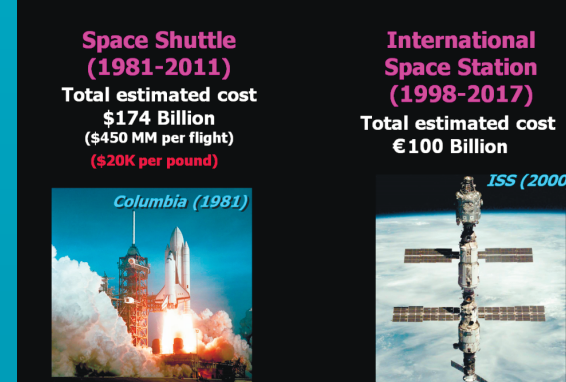


Fig. 4. Costs and achievements for two LEO (low-Earth-orbit) programs.



Fig. 6. Benefits from mining the Moon.

Rocket Propellants

Lunar Hydrogen and Water

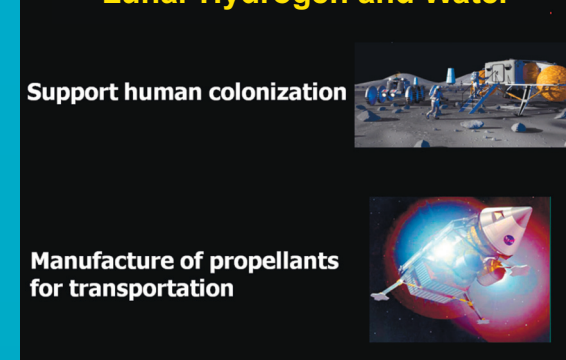


Fig. 7. Significance of lunar hydrogen and water.

Rocket Propellants: Fuels

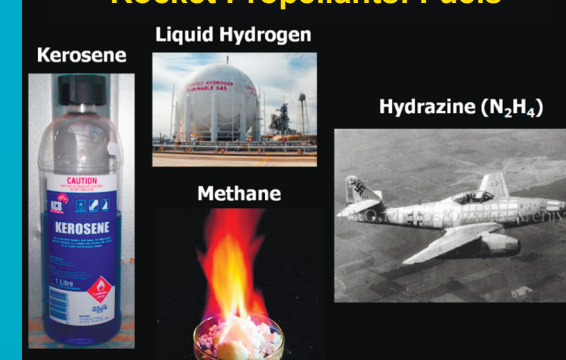


Fig. 9. Examples of common rocket fuels.

Altair Moon Lander



Fig. 11. Diagram of Altair Moon lander from the Constellation program.

Rocket Propellants

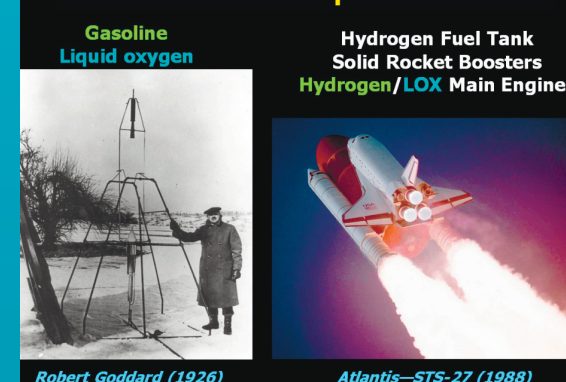


Fig. 8. Historical examples of rocket propellants.

Rocket Propellants: Oxidizers



Fig. 10. Examples of common rocket oxidizers.

Oxygen-Producing Station

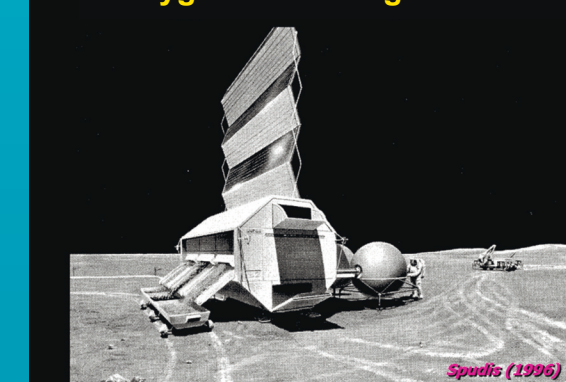


Fig. 12. Hypothetical oxygen-producing station on the Moon.

Lunar Resources

The Moon contains a wide variety of materials that can potentially be used for power generation, manufacture of rocket propellants, and construction of settlements and facilities. Successful and economic development of these lunar resources will involve several factors that include energy costs in constructing mining infrastructure, extraction of ores, and refining and concentration of resources, as, for example, heating of the regolith to 700°C to obtain hydrogen and helium-3. In addition, time and effort will need to be expended in characterizing, mapping, and selectively targeting areas where resources are concentrated. For example, optimizing the production of ilmenite will involve identifying areas of relatively high concentrations of titanium-rich regolith, such as those in Mare Tranquillitatis that were sampled during the Apollo 11 mission. Detailed mapping of areally restricted pyroclastic volcanic-vent deposits will be required to characterize potential resources of a suite of volcanogenic elements that include iron, zinc, cadmium, mercury, lead, copper, and fluorine. Rare metals and platinum-group elements may also reside in low concentrations in regolith breccias, highland impact breccias, and segregated impact melt sheets, as well as possible layered mafic intrusives.

Hydrogen occurs over most of the Moon in the regolith in low abundance (typically <100 parts per million [ppm]) owing to implantation from the solar wind and is a source of water for human consumption and rocket propellants. Recent results from spectroscopic studies also suggest the widespread occurrence of hydrated lunar materials. Thorium, helium-3, and uranium are sources of power generation and rocket propulsion. Thorium is relatively abundant in the south part of Oceanus Procellarum, where it is associated with late-stage melts rich in KREEP (Potassium/Rare-Earth-Elements/Phosphorus) constituents. Although thorium and uranium are present only as trace elements in most lunar rocks, even in those with abundant KREEP constituents, they may be most concentrated in regolith developed on the slopes and at the base of rhyolitic domes such as Mons Gruithuisen in northwest Mare Imbrium. Oxygen, a volumetrically important constituent of silicate minerals, is ~45% of the lunar soil by mass. The Moon also contains volatiles such as nitrogen and carbon, the building blocks of plastics and foodstuffs that will be vital to sustaining life on the Moon. These occur in very low levels of concentration (commonly <2 and <10 ppm, respectively) bound in breccias, the regolith, and possibly in recent volatile deposits. Volatiles, including water, also occur in lunar pyroclastic glasses.

Lunar Terrains, Metals, and Radionuclides

| 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 | Construction | Regolith, mare |
| Iron | Moon base | |
| Titanium | Shielding | |
| Aluminum | Roads | |
| | Solar-power facility | |

Fig. 13. Lunar resources. The Moon contains abundant hydrogen and water for rocket propellants and a variety of other materials that could support human settlement.

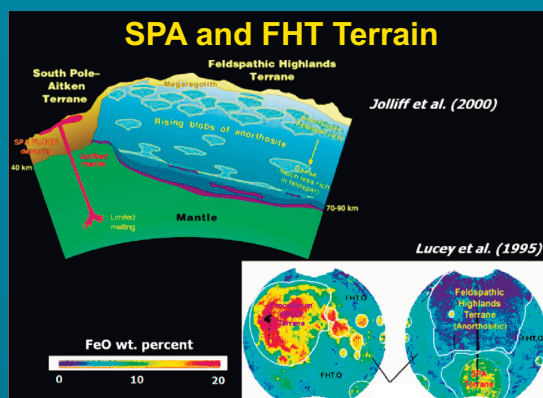


Fig. 14. SPA (south pole-Aitken) and FHT (feldspathic highlands) terrains, with wt. percent FeO.

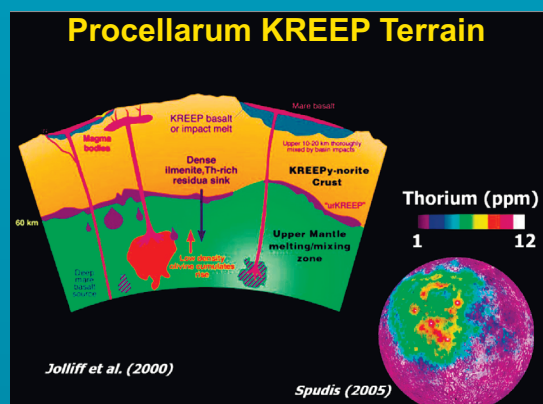


Fig. 15. Late-stage magmatic melts in Procenarum KREEP (potassium—rare earth elements—phosphorus) terrain are rich in thorium and other radionuclides.

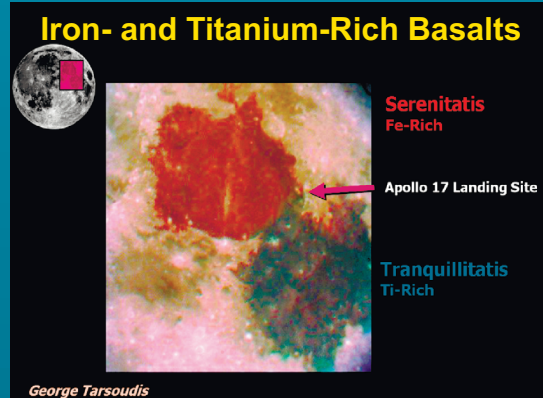


Fig. 16. Example of variability in lunar basalts in terms of appearance and metal content.

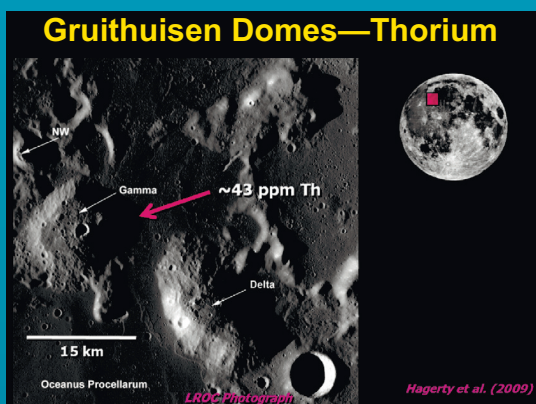


Fig. 17. Thorium-bearing silicic domes in the Mons Gruithuisen region.

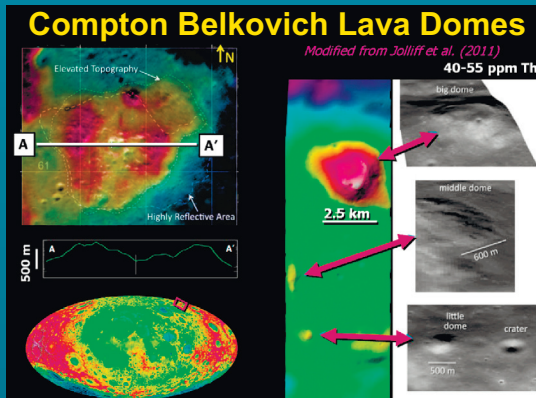


Fig. 18. Compton Belkovich Dome complex on the lunar farside.

Volatiles

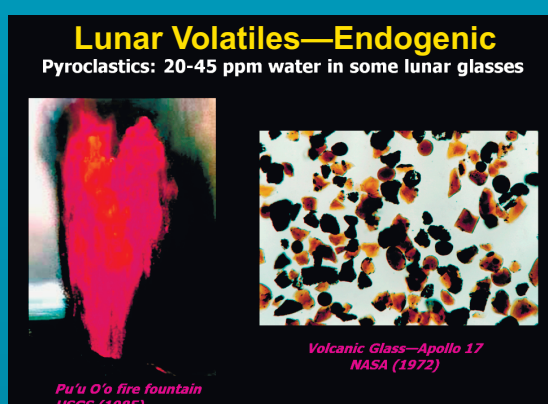


Fig. 19. Water content in some lunar glasses of pyroclastic origin.

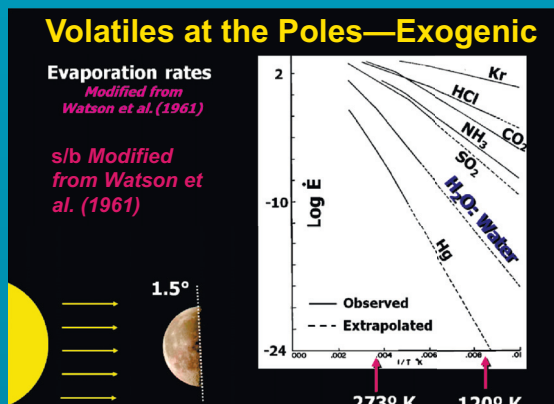


Fig. 21. Variety of volatiles hypothesized to exist at the lunar poles.

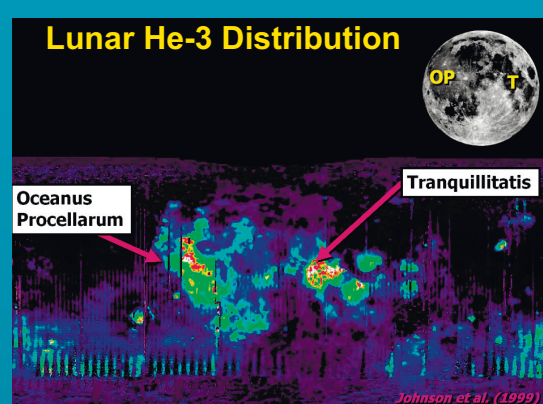


Fig. 23. Distribution of lunar helium-3 based on Lunar Prospector data.

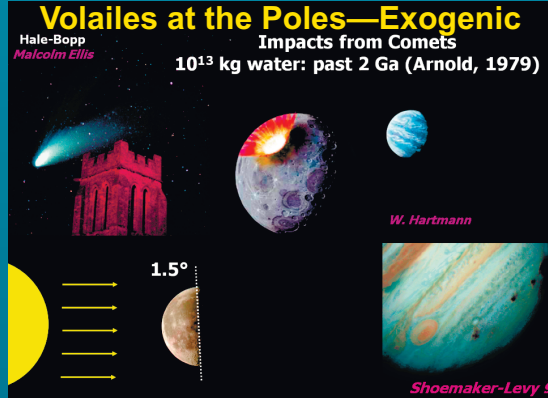


Fig. 20. ~10¹³ kg of water-ice and other volatiles may have accumulated in permanently shadowed areas at the lunar poles in the past 2 billion years owing to impacts from comets and volatile-rich asteroids.

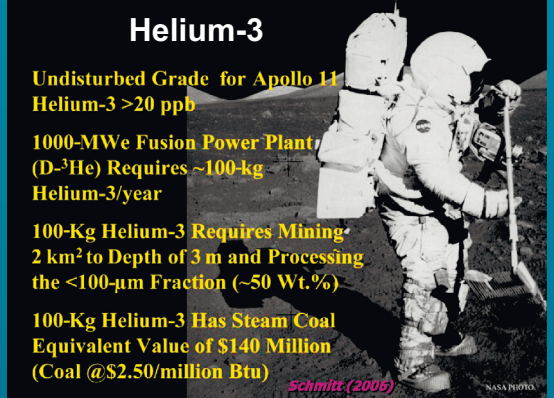


Fig. 22. Economic aspects of lunar helium-3.

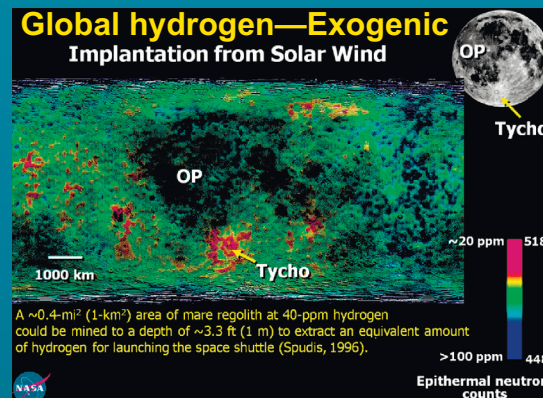


Fig. 24. Global hydrogen abundance in the lunar regolith.

Polar Investigations



Fig. 25. Kaguya photograph of permanently shadowed areas near the Moon's south pole.

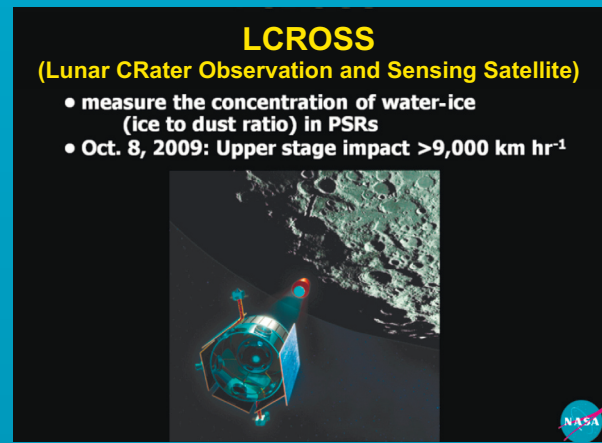


Fig. 27. Artist sketch of LCROSS (Lunar CRater Observation and Sensing Satellite).

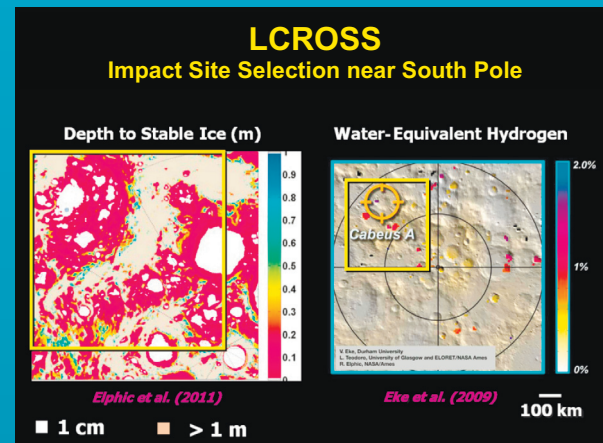


Fig. 29. Depth to stable ice in the lunar regolith and distribution of water-equivalent hydrogen in the south polar region.

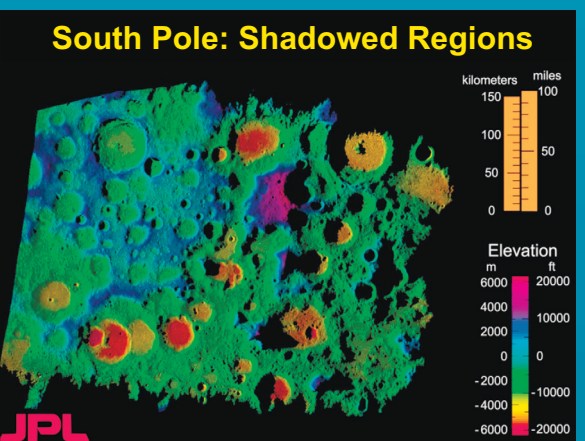


Fig. 26. Elevation map of heavily cratered region near the lunar south pole.

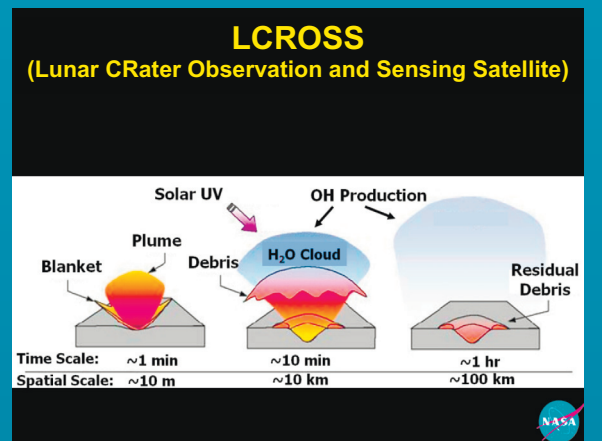


Fig. 28. LCROSS plume-impact model.

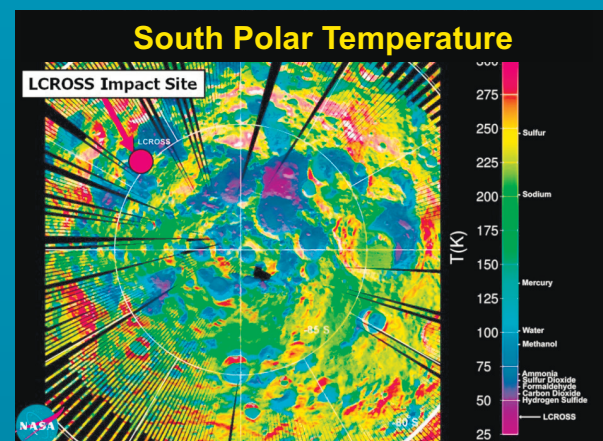


Fig. 30. Temperature map of the lunar south pole from DIVINER data.

Polar Settlements and Mission Architectures

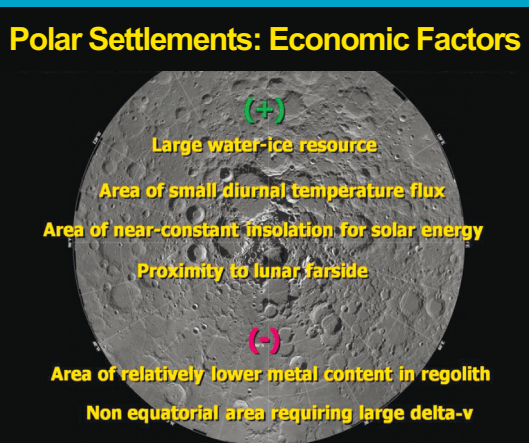


Fig. 31. Economic factors associated with lunar polar settlements.

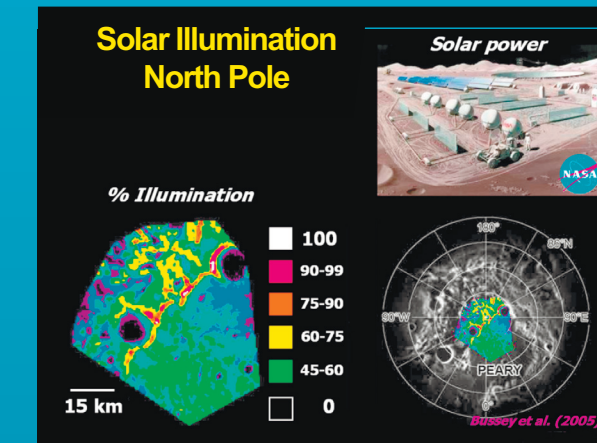


Fig. 33. Areas of constant and near-constant solar illumination in polar areas are ideal for solar-power installations on the Moon.

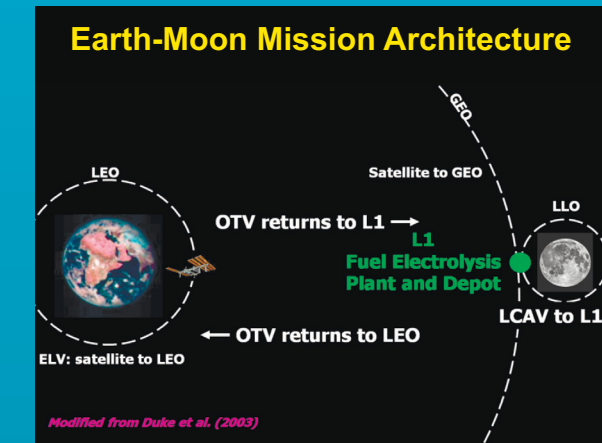


Fig. 35. Earth-Moon mission architecture involving the L1 Lagrangian point.

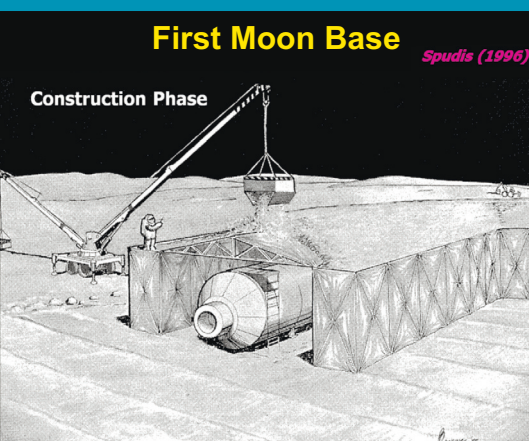


Fig. 32. The first Moon base will likely be modest in scale.

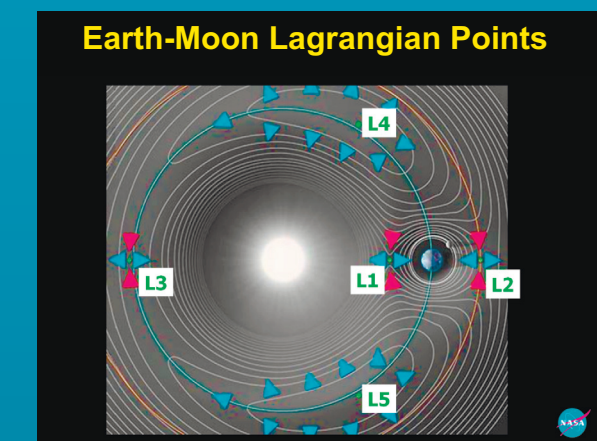


Fig. 34. Earth-Moon Lagrangian points. L1 and L2 could serve as fueling depots for human missions to the Moon.

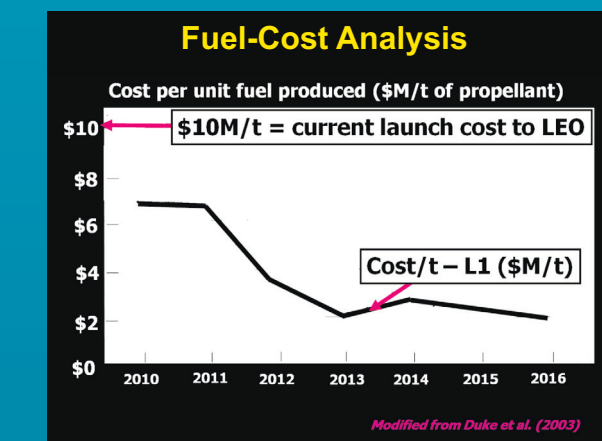


Fig. 36. Fuel-cost analysis associated with Earth-Moon architecture portrayed in Fig. 35.

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