Lunar Surface Science Virtual Workshop: Lunar Volatiles

1. Overview

This document summarizes two breakout discussions on the themes of **'Characterizing and Sampling Polar Volatiles'** (~44 participants) and **'Understanding and Operating in the Polar Environment'** (~25 participants), organized as part of the Lunar Surface Science Workshop Virtual Session on Lunar Volatiles on July 29, 2020. The summary below also incorporates points raised during a subsequent community discussion (~12 participants) at the Annual Meeting of the Lunar Exploration Analysis Group (LEAG) on September 15, 2020. Since this is a working draft, a comprehensive list of references is not included in this version of the document. Key points are highlighted in **bold text.**

2. Characterizing and Sampling Polar Volatiles

2.1. GUIDING QUESTIONS

2.1.1. What are sample priorities from the science community that can help guide Artemis sample collection?
2.1.2. What volatiles are present and how would we sample them at the south pole? How do we transport and curate these samples?
2.1.3. What environment would be encountered? What components of the sampling process impact human operations and safety?
2.1.4. What measurements are necessary to make in situ to close knowledge gaps?

2.2. SUMMARY OF DISCUSSION

2.2.1. What are sample priorities from the science community that can help guide Artemis sample collection? It is challenging to define sample requirements without more detailed knowledge of the sample. However, a step-wise strategy could be: (i) validate orbital measurements with in situ ground truth; (ii) scratch/dig below the surface with in situ techniques to see what is there, since most orbital techniques are blind at depth; (iii) decide what needs to be cryogenically preserved based on in situ compositional measurements, taking into account volatility and chemistry that might occur at different temperatures; (iv) note that it may be acceptable for some compounds to be returned in gaseous rather than solid phase.

2.2.2. What volatiles are present and how would we sample them at the south pole? How do we transport and curate these samples? Five operational activities and concerns emerged:

- **MEASURE MULTIPLE SPECIES:** Water is important, but other volatiles (e.g. the amount and type of S-bearing species) are important as well in determining their origin.

- **PRESERVE STRATIGRAPHY:** It is important to know the geological stratigraphy – whether there are ice pebbles, solid slabs of ice, polar frost, etc. that might be melted, but should be recorded if possible. In order to preserve stratigraphy, it is ideal to collect a core sample (to cm- or mm-resolution?). Many ISRU applications are concerned with ice in the top meter, but constructing a complete scientific picture may require a search for deep ice at > 5 m (e.g., with ground penetrating radar, passive microwave or active/passive microwave sensors).

- **PRESERVE VOLATILE SPECIES:** It is important that we do not lose the "contaminants" in volatile sample collection and it is equally important to not let samples contaminate/react with the storage container. The potential impact of contaminants such as H_2S or HCN is quite important with respect to reactivity and toxicity. Issues listed below need to be addressed:
  - At what levels do these become dangerous for astronauts? (e.g., 30 ppt of H_2S is highly toxic and life threatening.)
  - How do trace materials affect electrolysis? ISRU?
  - Is there a temperature to stay below so that contaminants do not outgas, or should they be removed?
  - Carbon-containing contaminants may yield information on the role of the solar wind and comets in volatile delivery.

- **MAINTAIN THE LOWEST TEMPERATURES POSSIBLE:** The sample temperature should be kept cold enough so that there is no loss of volatiles in the sample. More information is preserved at lower temperatures.
  - Maybe –80 C is sufficient, but technologies can progress to allow for colder and colder storage/transport in the future.
  - Keeping more volatiles (e.g., S) would require temperatures below 50 K.
  - Another architecture and approach could be heating everything up and analyzing in situ, and then returning 'remnants' for analysis to cut down on sample handling, storage and transportation challenges. Bringing everything back to its original state may be more Flagship-scope than Discovery.
  - Allowing toxic volatiles to escape may require chemical separation or trapping.

- **COLLECT COMPOSITIONAL MEASUREMENTS:** The general consensus was that mass spectrometric analyses should always be run on any collected samples. It is important to look at isotopic ratios, which can help understand lunar volatiles with respect to volatiles of terrestrial, cometary, and other origins.

2.2.3. What environment would be encountered? What components of the sampling process impact human operations and safety? Based on known transport and temperature profiles, there may be a sub-surface permafrost zone. This would imply that ISRU could be possible in regions other than the 'polar caps' or PSRs. **However, the science driving the delivery, formation, transport and sequestration of volatiles is not well-understood.**

- **LOCATIONS:** There are merits in sampling not only deep in PSRs, but also in more illuminated regions.

  Volcanism may have supplied a significant inventory of volatiles to PSRs; therefore, volatiles at/near a volcanic vent (e.g., Schrodinger) should be measured. This would allow comparison to volatiles measured in Apollo volcanic samples. Explosive (pyroclastic) eruptions are much more volatile-rich than effusive (mare) eruptions. These could lead to transportation of water to polar PSRs. For example, it has been suggested that a peak in mare basalt activity may have produced a transient atmosphere that could have aided in the migration of volatiles to the poles. It is useful to model pyroclastic eruptions and their contributions to the polar inventory. Though the current focus is on (South) polar areas, there may be additional opportunity with the CLPS program to visit a young volcanic feature.

There is also merit in sampling a turned-over rock for pristine material vs. nearby exposed material, and in examining volatiles near magnetic swirls to study space weathering effects.

Examining non-polar volatiles is important since some may have pre-biotic chemistry relevance.

- **PLANETARY AND ASTRONAUT PROTECTION:** The potential effects of outgassing from human suits or spacecraft on volatile composition/contamination is a major concern. It is important to know what species are being admitted and at what concentrations.

  Potential effects of microbes being released; at what rates is this a concern? Overall the safety of humans in the long-term in scientific sample collection/curation must be a priority.

2.2.4. What measurements are necessary to make in situ to close knowledge gaps? In addition to other measurements identified above, sampling should also be carried out in irradiated vs. shielded regions, as well as at craters of different ages. A time chronology of volatile migration/delivery may be correlated with impacts.

There is a need for an integrated, strategic campaign to characterize the composition, abundance and distribution of lunar polar volatiles. Both science and ISRU would benefit from this.

3. Understanding and Operating in the Polar Environment

3.1. GUIDING QUESTIONS

3.1.1. How is the polar environment different from the non-polar environment?
3.1.2 How does this environment shape operational and safety considerations for human and robotic exploration?
3.1.3. What are the critical outstanding questions related to operations in the polar environment, and how do we address them?

3.2. SUMMARY OF DISCUSSION

The sections below outline some of the key considerations when planning for crewed mission operations in the lunar polar environment, particularly permanently shadowed regions (PSRs), where volatiles may be present. This discussion was guided by the questions above.

3.2.1. TEMPERATURE

The extreme cold of PSRs is perhaps the defining characteristic of the lunar polar environment. However, **the polar thermal environment is highly variable**, over a range of spatial (down to the centimeter-scale) and temporal (from diurnal to seasonal) scales. Individual PSRs have average temperatures that range from extreme (< 40 K) to temperate by comparison (~100 K). While the thermal environments of larger PSRs have been well-characterized from orbit, the temperatures of smaller PSRs (including centimeter-scale 'micro cold traps') are less well understood. Illuminated regions may have day-time temperatures of 200–300 K. Operationally, the spatial variability of polar temperatures raises the possibility of **dynamic sublimation and condensation** of volatiles on suits and equipment as crew-members move between regions, and the potential for transport of outgassed volatiles. The need to **survive, operate and thermally equilibrate to low temperatures** (particularly when sampling volatiles) also poses challenges for suit and tool materials and design, as well as operations planning. Despite these challenges, the variability of the polar thermal environment also offers unique scientific opportunities, such as the ability to observe how volatiles respond to changes in surface temperature over time.

3.2.2. ILLUMINATION CONDITIONS

Illumination conditions are related to surface temperature, but also present operational challenges of their own. **Low angle lighting conditions** may pose a challenge for navigation by making it difficult to discern features of the terrain. Polar illumination conditions have been modeled in detail based on remote sensing data, and continue to be investigated at the smaller, rover- and human-scale in testbeds, virtual reality, and field studies. Illumination conditions are also a key consideration in decisions regarding **power systems**, such as whether solar power is sufficient, or whether batteries or nuclear generators are required. Systems that enable crew-members to work in the dark by providing **'night vision' at infrared and other wavelengths** may be instrumental to polar operations.

3.2.3. TERRAIN

High resolution topographical data reveal the lunar poles to be rugged, with steep slopes in many regions of interest. However, the availability of these datasets also allows for sophisticated traverse planning. The **potential influence of surface or sub-surface volatiles (particularly ices) on terrain trafficability** by wheels and boots (and on **geotechnical properties** more generally) has not yet been examined in detail. Polar terrain also factors into the design of **communications systems**, since Earth may not always be visible. Communications infrastructure should be designed to be adaptable to operations at both north and south polar regions.

3.2.4. ELECTRICAL ENVIRONMENT

The plasma and electrical environments at the lunar poles are of both fundamental scientific as well as operational interest, but have not yet been characterized in situ. Recent studies have modeled the expansion of solar wind plasma into polar craters as the solar wind flows over crater rims, with implications for **surface charging** and **electrical grounding** of exploration systems. Characterizing the electrical environment, and the broader space environment, at the lunar poles remains an outstanding question of considerable interest.

3.2.5. VOLATILES

Despite remarkable advances over the past decade, our understanding of the lunar volatile system – its composition and the processes that shape it – is fundamentally incomplete, with implications for scientific operations and operational safety at the lunar poles. **Contamination is a two-way concern**: mission planning should take into consideration both the impact of non-indigenous volatiles released from spacecraft and spacesuits, and the potential impact of indigenous volatiles (such as some of those detected by the LCROSS mission) that may be hazardous to the safety of crew-members and equipment.

3.2.6. MISSION PLANNING

Planning for both **precursor missions** and **long-term sustainability** is important to furthering lunar science and exploration. Several currently planned missions, both orbital and landed, will lead to advances in understanding that should inform plans for exploration of the lunar poles. Targeted precursor missions could play an important role in surveying future landing sites in preparation for subsequent exploration. Communications systems and other infrastructure should be designed with a view to long-term sustainability and enabling access to the lunar surface beyond the poles. There are multiple stakeholders in lunar polar exploration – from the international science and commercial communities to the wider public – and the interests of all of these stakeholders deserve careful consideration.