Volatile Sample Return by Artemis III

White Paper submitted to the Artemis Science Definition Team

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Introduction: While the study of lunar volatiles is listed as an Artemis goal, *the return of lunar volatile samples to Earth is key to meeting this goal and developing a thorough understanding of the evolution and chemical evolution of the Moon.* Sample return has several advantages over *in-situ* analyses, and here we focus on the scientific motivations for volatile sample return from Artemis III, which we recommend as an immediate need to prepare for future Artemis missions that have this objective. The science motivations for such samples include understanding isotope fractionation, noble gas composition, organics, and prebiotic species. We also identify associated challenges with the environment, transit/storage, and curation, which could affect the overall science return, including changes to samples between (and including) collection and analyses, and meeting planetary protection and human safety requirements. Some of the advantages and challenges of volatile sample return from various planetary environments have been outlined previously by us in a white paper submitted to the Planetary Science and Astrobiology Decadal Survey 2023-2032 [1].

The science value of an Artemis volatile sample return over *in-situ* analyses: Volatiles–defined here as elements or compounds that are gases or liquids at standard pressure and temperature–play critical roles in much of planetary science. For lunar science, volatiles are important to understanding the history and evolution of the Earth-Moon system, and may either be sequestered by cold traps in shadowed regions or trapped within the mineral structure of the regolith [e.g., 2]. Ices in lunar regolith can inform the local geological and geochemical processes and provide information about interactions with the space environment or other bodies. They are also a potentially valuable resource for In Situ Resource Utilization (ISRU, see e.g. [3]). The types of volatiles delivered to the terrestrial planets early in the history of the Solar System by comet and asteroidal impacts can also be investigated.

Although some information on volatiles can be obtained from in-situ analyses, sample return missions offer significant improvements in sample handling and processing, analytical sensitivity, contextual understanding, and contamination knowledge. Analyses of the returned samples can be iterative and fully adaptive — results are not limited by the selection of the initial mission design. Returning samples allows for the use of state-of-the-art analyses, providing for the ultimate in modern-day precision, sensitivity, resolution, and reproducibility, thus avoiding limitations associated with cost, power, mass, and reliability that would have affected or precluded making similar measurements in situ. Through volatile sample return, the mission's payload effectively includes all the world's current and future analytical instrumentation. Returned samples can be placed into geologic context and provide crucial complementary information for other studies. Once returned to Earth, they are maintained in controlled curatorial environments that minimize sample alteration. The value of lunar sample return missions has been clearly demonstrated by previous programs, including Apollo and Luna, all of which profoundly increased our understanding of key scientific questions in planetary science. However, these missions returned only rocky material, containing at best a tiny fraction of volatile compounds. By collecting a volatile sample from the lunar south pole, we will obtain a record of the volatile history of the Earth-Moon system while facilitating future lunar exploration via ISRU.

Challenges for preserving the science of volatile sample return: Returning volatiles from key locations on the Moon poses unique and potentially severe technical challenges depending on the temperature and pressure requirements of the analytes. The capacity for volatile preservation and curation must be incorporated into the mission architecture in order to preserve the science. Lunar sample return specifications are being defined elsewhere.

Astronaut safety and sample contamination considerations. The presence of a volatile sample in the crew cabin poses several risks, both to the sample and to the crew. First, the sample may contain volatiles that are toxic at low (likely extremely low) concentrations. The sample should be vacuum sealed to prevent release, and the container constructed of materials that will not degrade the sample or be degraded by it. In addition, safety measures should be taken to ensure crew survival in the event of volatile release. These considerations will protect both the crew and the sample, maximizing mission success and science return.

Curation and long-term storage. The curation of volatiles focuses on preserving the sample after Earth return and facilitating sample science to the greatest extent possible. Some volatiles may be immediately analyzed upon return. For longer-term preservation, special conditions and operations are required. Preservation of the physical state of the sample will need to be defined based on the mission science requirements: e.g., solid and gas sample storage have different temperature and handling conditions [e.g., 4]. Colder storage temperatures will be needed to slow or prevent chemical reactions. Sample temperature requirements and species of interest also dictate the storage and purge conditions to be met. In all cases, the sample must be isolated from the atmosphere to minimize contamination from terrestrial gases. Storage materials must be compatible to avoid reactions with typical curatorial materials (e.g. steel). Preliminary examination (PE) to document the sample for cataloguing typically includes weighing, photographing, and nondestructive classification of the sample. PE will need to allow for rapid analysis of samples without contamination or alteration while consuming the lowest amount of sample possible. After PE, the sample would be placed in cold storage and monitored to ensure sample integrity for the long term.

Limit volatile-volatile or volatile-solid chemical reactions during return. Materials compatibility, toxic chemical monitoring, sample containment & handling; and sample handling procedures may be more complicated. Chemical changes to the sample must be avoided during long-term storage. Mitigation approaches such as sealing and leak-rate monitoring can address both contamination and losses. Keeping the returned samples cold mitigates volatile loss, but could enhance trapping of contaminants. PE procedures used in the past for rocky and refractory materials must be revised for gas or ice samples.

Avoiding volatile loss and fractionation of volatile samples. Heat sterilization post collection, though effective, would drive reactions and destroy ices. Other methods of sterilization from categorized sites that may have an acceptable level of alteration of the sample (e.g. ionizing radiation (x-ray, ɣ, ^{0}n or β particles)) can be employed. Since the sample must be returned hermetically sealed to prevent air contamination, the ability to chemically sterilize the container exterior via strong oxidizing and/or reducing agents is possible. Leveraging off of propellant (e.g. N_2H_4 and N_2O_4) plumbing technologies could be effective. Current forward planetary protection cleaning and sterilization technologies, such as DHMR should largely be sufficient, though more heat-tolerant materials are desirable.

Summary: A thorough understanding of the lunar environment and of the Earth-Moon system requires careful analyses of lunar volatiles, and the most advantageous way to extract the best science from lunar volatile samples is to return them to state-of-the-art Earth laboratories for current and future studies. We advocate for volatile sample return from Artemis III.

References: [1] Milam, S. N., et al. (2020), Volatile Sample Return (Planetary Decadal White Paper), https://arxiv.org/abs/2007.14899; [2] Gerasimov, M. V. 40th COSPAR Scientific Assembly. Held 2-10 August 2014, in Moscow, Russia, Abstract id. B0.1-27-14; [3] McAdam et al., Artemis SDT White Paper; [4] Glavin DP et al. (2018) International Workshop on Instrumentation for Planetary Missions.