# Science from an Active Volatile Release Experiment

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## INTRODUCTION

It has been recognized since the Apollo era that ***almost any landed lunar mission will be an active volatile release experiment, due to the release of exhaust gases during descent and ascent***. Artemis III presents a remarkable scientific opportunity to investigate, in situ, the interaction of volatiles with the lunar surface, with far-reaching implications for understanding active volatile processes on airless silicate bodies. This paper outlines key science objectives that could be accomplished by systematic observations of the lunar surface and exosphere after landing.

The three human landing systems currently under development are anticipated to burn between $10^3$ to $10^6$ kg of liquid oxygen with liquid hydrogen or liquid methane (Wired, TechCrunch), releasing $H_2O$ or $CO_2$ and other oxidation products into the lunar exosphere. Based on recent numerical simulations of a smaller-scale landing (Prem et al., 2020), as well as surface-based measurements after the Apollo 12 landing (Freeman et al., 1972), some fraction of these exhaust gases will remain in the lunar exosphere and surface for several lunar days.

In addition to being primary exhaust gases, carbon dioxide and water are also species of particular scientific interest. Both $H_2O$ and $CO_2$ have been detected at the lunar poles (Colaprete et al., 2010), and are associated (to different degrees) with all of the major suggested source mechanisms for lunar volatiles – volcanic outgassing, hydrated impactors, and the solar wind. Understanding how volatiles are transported and interact with the lunar surface is critical to reading the record of inner solar system history written at the lunar poles, and to understanding the behavior of surface boundary exospheres across the solar system. These are Decadal-level science questions, clearly traceable to the SCEM and ASM-SAT reports, as well as the Artemis Science Plan themes of 'Study of Planetary Processes' and 'Understanding Volatile Cycles'.

## SCIENCE OBJECTIVES

The presence of a well-characterized source (spacecraft exhaust) and the remarkably variable thermal environment at the poles make a polar landing a particularly compelling volatile release experiment. The science objectives below address the questions of how volatiles (particularly exhaust gases) are transported, how they interact with the regolith, and how they are sequestered.

**1. Determine the nature of volatile adsorption in polar regolith.** The question of what happens when a $H_2O$ (or other volatile) molecule strikes the lunar surface is the critical parameter that determines the rate of past and present transport of volatiles to polar cold traps. Upon contact with the surface, a molecule may be scattered, held by van der Waals forces (physisorbed), chemically bound (chemisorbed) or break apart (dissociatively adsorbed). The activation energies for these processes have been studied in the lab (e.g., Poston et al., 2015), but remain to be definitively determined in situ, and are sensitive to surface temperature, surface composition, passivation state, and amount of adsorbate present (ranging from small fractional coverage to more than a monolayer). In situ studies also enable measurements that can probe the three-dimensional structure of the upper regolith to understand the diffusion or deposition of volatiles at some depth.

**2. Constrain the rate of sublimation of cold-trapped volatiles.** Our current understanding of the thermal stability of volatile ices is based on available data for vapor pressure as a function of temperature. Predictions of sublimation rates at the low temperatures and near-vacuum pressures of the lunar poles vary (Andreas, 2007), and have not yet been directly measured. The Artemis III landing is likely to deposit more than a monolayer of exhaust in cold, shadowed terrain (including, perhaps, in small-scale and/or temporary cold traps), enabling direct measurements of sublimation or condensation rates of bulk ices for a range of temperatures at very low pressures. The two most likely exhaust gases, $H_2O$ and $CO_2$, are thought to have volatility temperatures (over geological time-scales) of ~110 K and ~54 K, respectively (Zhang and Paige, 2009), but may be stable to higher temperatures at the several monolayer-level, enabling meaningful measurements even at polar locations outside large-scale cold traps.

**3. Measure the spatial and temporal variability of exospheric and surface adsorbed volatiles.** Volatile transport on nominally airless bodies is a richly detailed process that occurs across the solar system, and remains a subject of active scientific study. Systematic measurements of the propagation of exhaust volatiles would test and advance scientific understanding of the processes at play. Simulations and Apollo-era measurements indicate that many exhaust gases persist in the lunar exosphere for several lunar days, but volatile transport can occur over a range of timescales, driven by hourly, diurnal, and seasonal changes in surface temperature. Some fraction of exhaust volatiles may be cold-trapped within minutes to hours. Measurements of spatial and temporal variability may also elucidate non-thermal surface processes such as photon-stimulated desorption (DeSimone and Orlando, 2014). The mechanisms that may govern the transport of exhaust volatiles are also key drivers of the Moon's contemporary and past volatile cycles.

## IMPLEMENTATION AND IMPACT

The measurements required to address the questions above essentially involve measuring surficial and exospheric volatiles at different locations and over time, and are well within the reach of current instrumentation. Crew members could measure exhaust volatiles after landing and/or deploy instruments to characterize ascent plume dispersal after their departure. Long-lived instrumentation is an advantage, but not a requirement. These measurements are also likely to serve multiple purposes – not only addressing the objectives above, but also providing ground-truth for remote sensing observations and crucial context for sample collection. The first crewed landing also presents an important opportunity to study volatile interactions with terrain that is relatively uncontaminated prior to more intensive activity.

The polar environment is highly variable at scales smaller than can be characterized from orbit, and Artemis III crew members may play a critical role in determining appropriate locations to deploy instrumentation and acquire data, and in recording geological context in detail. Crew members may also have the capability to deploy multiple sensors to acquire concurrent, in situ measurements of volatiles at different locations, or to conduct additional active experiments (e.g. the controlled release of a small amount of water) to clarify physical mechanisms of interest.

The science objectives outlined here address critical gaps that remain in our understanding after decades of data analysis, laboratory experiments, and theoretical modeling. Closing these gaps would lead to fundamental advances in our understanding of the lunar volatile system and of processes that operate on many other solar system worlds.

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