LUNAR VOLATILES AS A RESOURCE FOR SCIENCE AND EXPLORATION. D. M. Hurley[1], the LEAG Executive Committee[a]; [1]Applied Physics Laboratory, Johns Hopkins University, Laurel, MD (dana.hurley@jhuapl.edu).

Introduction: Our knowledge of volatiles on the Moon has made significant progress in that last decade. However, many unanswered questions remain that will guide the work on Lunar Volatiles for years to come. In the general path of planetary exploration that proceeds from flyby to orbit, to land, to rove, to return samples, Lunar Volatiles research is in the "orbit" stage. Interestingly, general research on the Moon has been through all of those stages in the 1960s and 1970s, even including human exploration, without addressing lunar volatiles. The progress made postdates those efforts, enabled by orbiters, varying instrumentation, and technology advances for analyzing returned samples.

Volatiles on the Moon have both scientific and exploration significance. For exploration, water represents a valuable resource that can be mined for production of propellant and life support. Most visions of sustained operations in space beyond low Earth orbit include exploiting resources on the Moon to reduce the cost of planetary exploration. The in situ resource utilization (ISRU) of lunar water will require a combination of science, engineering, policy, and business development.

For science, lunar volatiles offer a window into the past inventory of volatiles in the Inner Solar System, including volatiles retained by the Moon during its formation, fluxes of exogenous volatiles over billions of years as well as the present day [1-3]. The Moon's environment is representative of many other airless bodies in the Solar System where the surfaces are highly activated. Weathering by ion bombardment, photons, and meteoroid impacts distorts the mineralogical and electronic structure of the surface [4]. Interactions between gases and the surface play an important role in volatile distribution and retention [5]. The Moon's relative ease of accessibility enables investigation of these processes in situ more readily than its more distant cousins. In addition, the extremely cold, persistently shadowed regions (PSR) at the lunar poles are an interesting laboratory for prebiotic chemistry. Many of the building blocks for life are potentially retained in the PSRs where they are exposed to cosmic rays, meteoroid impacts, and potentially electric discharges [6]. These stimuli can slowly synthesize complex molecules over the long lifetime of volatiles in the PSRs [7].

Vision: In 2050, the proposed Moon Village [8] will be at some stage of implementation. Therefore, the Moon will host a combination of activities from a diverse set of nations and commercial groups. Lunar volatiles will be in regular use for exploration efforts. Commercial entities will be harvesting the volatiles and improving production strategy. The Moon will be a testing ground for ISRU efforts on asteroids and Mars.

Scientifically, much work will have been done to understand the sources, sinks, age, and redistribution of volatiles on the Moon. Ongoing work will use the Moon as a baseline for comparison of volatiles on other airless bodies such as Mercury, asteroids, and the Martian moons. Scientific work will focus on interactions between volatiles and external drivers especially in PSRs, where the cold temperatures retain the more volatile compounds.

Pathway and Vision: Multiple documents already exist containing suggestions for the roadmap for lunar research including the Scientific Context for the Exploration of the Moon (SCEM) report [9], the Lunar Exploration Roadmap (LER) [10], including the implementation strategy that explores and utilizes lunar volatile resources [11], the Volatiles Strategic Action Team (VSAT) report [12], and the ISECG Global Exploration Roadmap [13]. Here we highlight some aspects that will enable scientific progress and exploration goals, and also reflect the LEAG LER implementation plan [11].

2020s: Lunar remote sensing can still provide a wealth of information on lunar volatiles: monitoring sources, sinks; mapping distributions; determining composition and physical form; and quantifying abundances. Cubesat and Smallsat opportunities provide a low-cost method to perform targeted investigations of single pieces of the system. A dedicated long-lived volatiles orbiter mission could make significant progress at understanding the hydrological cycle on the Moon.

Many questions are, however, better answered by an in situ investigation. Landed missions to the surface of the Moon both inside and outside of the PSRs are required to provide ground truth to the remote sensing investigations and provide in situ subsurface data. Landed packages can inform on the composition of volatiles, the physical form, the abundance and the distribution. They can monitor ongoing processes. With commercial entities planning lunar landers, these investigations can be included as rideshares. Multiple dedicated missions offer efficient means to assess lunar volatiles in situ. These should address scientific and exploration objectives, which largely overlap in the early stages. Inclusion of ISRU demonstration packages is a necessary step toward regular production of resources from lunar volatiles.

2030s: The landed exploration with mobility will lead to understanding the magnitude, accessibility, form, and extractability of volatile deposits. This in turn will lead to sample return, where the most sophisticated instrumentation is available to conduct the analysis. Cryogenic sample return of lunar volatiles from inside and outside of the PSRs will validate and extend the results from remote sensing and in situ analysis (see also [14]).

As humans become part of activities near and on the Moon, they can assist in furthering both science and exploration objectives. Their contributions may include tele-operation of landed craft, instrument deployment, production plant set-up and maintenance, and sample acquisition. ISRU will begin. Operations will develop on the Moon of increasing magnitude. The methods will be ported for potential demonstration on Mars and asteroids.

Investigations of comparable bodies including Mercury and asteroids will progress. A mission impacting into PSRs at Mercury will provide important constraints on the volatiles there. In situ analysis on asteroids will provide detailed analogous data for relating processes on the Moon and asteroids.

2040s: Asteroid and Martian ISRU operations expand and enable further exploration. Landed missions on Mercury investigate sources, composition, and distribution of volatiles on Mercury. The overall understanding of volatile inventories of the Inner Solar System becomes more detailed in terms of relative importance of sources through space and time, roles of external drivers to alter the composition and distribution, radiation-induced and surface-catalyzed molecular synthesis.

Critical Issues: While science and exploration have many aligned objectives, consideration must be made that they do not inhibit one another. For example, large-scale operations on the lunar surface will introduce volatiles into the lunar environment that can migrate to the PSRs. Scientific analysis should precede major utilization efforts to maintain the scientific integrity of the region. Fortunately, the scientific analysis enables the eventual utilization by providing the necessary prospecting and characterization to design the extraction technique.

The PSRs, however, are an extremely challenging environment. From an operational perspective, the low temperature and lack of solar power complicate the engineering and design of systems, particularly with respect to power. Some lunar PSR not only lack sunlight, but Earth visibility as well, requiring communications via an orbiter. The lack of high-resolution images increases the uncertainty in surface operations.

Multiple nations are presently planning and conducting lunar programs. Coordination of those activities through ISECG or a similar organization can maximize the return for each participating nation, reduce reproduction of effort, and provide an array of resources for all involved. Policy for international cooperation and for private/public coordination is a critical component to development of lunar volatiles.

Conclusion: Lunar volatiles are important to both exploration and science. They retain a record of the volatile history of the Moon and the inner solar systems and can provide insight into the evolution of the Sun. From an exploration perspective they can significantly reduce the cost of spaceflight by providing water for both life support and fuel (as well as other volatiles) by reducing the amount of mass launched from the Earth. Lunar volatiles will not be understood by orbital data alone, in situ surface and subsurface samples and data will be required for scientific and exploration objectives.

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