LUNAR EXPLORATION ANALYSIS GROUP

Rapid Response Specific Action Team in response to

COSPAR Planetary Protection Inquiry

8 May 2020

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Purpose and Scope

On 21 April 2020, the NASA Lunar Exploration Analysis Group (LEAG) received a request from Dr. Lori Glaze, Director, Planetary Science Division, NASA Headquarters, to coordinate a community response to questions generated by the Committee on Space Research (COSPAR) Panel on Planetary Protection with a response date of 8 May 2020. As part of this request, the LEAG Executive Committee adopted a two tiered approach to respond to this request and established the COSPAR Rapid Response Special Action Team (hereafter, COSPARRRSAT).

Tier One of the response was that 25 members of the LEAG and CAPTEM communities with relevant technical experience were contacted and asked for input as part of a Rapid Response Specific Action Team (RRSAT). In light of the ongoing public health emergency and associated time constraints on members of our community due to COVID-19, only 8 of the contacted members of the lunar exploration community had sufficient time to meaningfully participate.

COSPARRRSAT Membership

- Dr. Samuel Lawrence, LEAG Chair (Co-facilitator), Lead Lunar Exploration Scientist, NASA Johnson Space Center
- Dr. Barbara Cohen, LEAG Vice-Chair (Co-facilitator), NASA Goddard Space Flight Center
- Dr. Brett Denevi, LEAG Vice-Chair, (Co-facilitator), Johns Hopkins University Applied Physics Lab
- Dr. Juliane Gross, Rutgers University, Deputy Lunar Sample Curator and Chair of the CAPTEM Lunar Sample Subcommittee
- Dr. Charles Shearer, University of New Mexico
- Dr. Clive Neal, University of Notre Dame
- Dr. Amy Fagan, Western Carolina University
- Dr. Jamie Cook, NASA Goddard Space Flight Center
- Dr. Jose Aponte, NASA Goddard Space Flight Center
- Dr. Daniel Glavin, NASA Goddard Space Flight Center
- Dr. Jason Dworkin, NASA Goddard Space Flight Center

Each of the members listed above provided considered responses to the questions generated by COSPAR. Due to the short timescale of this activity, no attempt to arrive at a consensus opinion was possible. The facilitators helped format the report.

Tier Two of the LEAG Response involved distributing a questionnaire to the community via the “Lunar-L” listserv, which has over 700 registered recipients, to obtain a snapshot of community sentiment, which garnered 31 responses. LEAG has summarized those responses, and they are included in this report. In light of the short timescale of this action, there was insufficient time to have a virtual meeting to integrate these responses. Thus, “raw” responses are included here, with some commentary by the LEAG Executive Committee.

All responders, both the SAT members and the community sentiment snapshot, were encouraged to view their responses in the context of the current Artemis program, which involves clear direction to return to the Moon for long-term exploration and utilization.

Caveats

Considering that this is a rapid response SAT conducted amidst a global pandemic, the LEAG Executive Committee wishes to emphasize that these are not definitive answers and should only be considered a “snapshot” of community sentiment. **Establishing an agreed-upon community consensus that balances both the narrowly scientific perspective reflected in the questions provided by COSPAR and the equally legitimate commercial and resource utilization perspectives which are also a focus of the Artemis program will require a significantly longer time period to establish rapport and consensus amongst a diverse set of stakeholder communities.** As will be evident from the nature of the responses garnered, there is considerable spectrum of opinion, as might reasonably be expected in a large and diverse community.

Preface by the LEAG Executive Committee

Presidential Space Policy Directive - 1, clarified by the Findings of the 5th Meeting of the National Space Council, directs the United States to land American astronauts at the South Pole of the Moon by 2024, by any means necessary, and to establish a permanent lunar outpost at the South Pole by 2028, a project later named Project Artemis. Thus, the stated policy objective of American lunar exploration is to enable significant off-world resource extraction by commercial entities and sustained human presence on the surface of the Moon. Such activities are also called out explicitly in the LEAG Lunar Exploration Roadmap (US-LER) as community objectives. **In that light, human activities on the lunar surface are unavoidable, and solutions that outright preclude surface exploration and resource extraction are both infeasible and undesirable.** A clear theme of the SAT responses is the inarguable need for pragmatic balance between exploration objectives, economic development, and narrow scientific goals.

The scientific and exploration importance of the lunar polar regions are explicitly called out in the 2018 LEAG Advancing Science of the Moon (ASM-SAT) report, which can be found here and which the reader is strongly advised to read in its entirety.

https://www.lpi.usra.edu/leag/reports/ASM-SAT-Report-final.pdf.

ASM-SAT highlighted the following science objectives for lunar polar volatiles:

> "Information is still needed regarding the: 1) detailed elemental, mineralogical, and isotopic compositions of lunar volatiles, 2) volatile source(s), 3) transport, retention, alteration, and loss processes for volatiles in PSRs, 4) geotechnical properties of the polar regolith, and 5) ancient solar environment. Recommendations for implementation from the 2007 NRC report remain relevant. Further information about the distribution and abundance of polar volatiles can still be gained from high-spatial resolution orbital measurements. Landed missions can provide information about the physical properties of the regolith; vertical and lateral distribution of volatiles; in situ measurements of chemical, isotopic, and mineralogic characteristics of polar deposits; and cryogenic sample return could provide a wealth of details on the origin and complexity of lunar volatiles."

Clearly, all of these science objectives remain relevant as the surface exploration and resource utilization priorities of Project Artemis are implemented.

Although there is potential impact to volatiles-science from human and robotic activities in the lunar polar regions, science objectives relating to volatiles are just one important component of a broad continuum of fundamental scientific advances enabled by a sustained human lunar presence; understanding and utilizing volatiles are not the only important scientific objective of current lunar efforts, which also include objectives of advancing astrophysics, heliophysics, fundamental physics, geophysics, geology, and economic geology. This broad continuum of advances enabled by lunar exploration is also emphasized by the US-LER, the ASM-SAT, the LEAG Back to the Moon report, and the LEAG Next Steps on the Moon report (see Appendix). Irrespective of any perceived or real impact on understanding volatiles at the poles, the sustained human and robotic activity enabled by the sustained human presence at the Artemis Base Camp will undeniably result in tremendous paradigm-shifting advances across a variety of science disciplines as well as the necessary workforce development and engineering expertise to enable ambitious voyages to other destinations, such as Ceres.

Below is a compiled list of responses to the questions from COSPAR from the COSPARRRSAT members and viewpoints from other members of the lunar exploration community. Responses have only been lightly edited for clarity, typographical errors, and an effort for conciseness. Some questions generated responses that were all in agreement in the affirmative or dissent, whereas other questions divided the community and the responses were separated into groups of “Responses for Yes” and “Responses for No.”

COSPARRRSAT Responses

Question 1. Are the volatiles in the Permanently Shadowed Regions (PSR) on the Moon of significant interest in the study of chemical evolution (i.e. primordial chemistry as precursor to the origin of life on Earth and potentially other planets, moons and planetary bodies)?

In keeping with previous LEAG reports, the overwhelming assessment to this question was "Yes, the volatiles in the PSRs are of significant interest."

- Yes. However, we still do not know the nature of the chemicals in the PSR. The LCROSS mission gave tantalizing indications of organic compounds but we do not know how the impact may have altered these materials, nor if any contribution to these deposits was made by the Surveyor, Luna, Apollo, or Chang'E missions. However, such lander contributions will be surficial because even micrometeoroid impacts will only garden the top 1-2 cm.
- Yes, in situ analysis and/or return of volatile materials from the PSR are of high scientific interest, especially now that comet sample return is not in the cards for the near future. PSRs may preserve these compounds and their history in a way that isn't accessible by other means.
- Yes, they are! The composition and type of volatiles found in the PSR will be of fundamental importance for the study of organics as a precursor to the origin of life on Earth (and other planetary bodies). The lunar surface represents an archive that has stored the information about the materials present during the Earth-Moon formation and later evolution, including life on Earth. It will give us insights into the material that was available during that time span when life evolved on Earth and thus, potential precursor materials.
- Yes. There seem to be several different sources (endogenous and exogenous) for the volatiles on the lunar surface, and therefore we need more information to better constrain how much is due to each source. Such work may have implications for the source of water on Earth and therefore early habitability on our host planet. Some lunar volatiles are endogenous, coming from the Moon itself through degassing processes at a local scale or a regional to global scale such as through mare volcanism that could have emplaced a transient atmosphere, some of which may have settled into the PSRs . Other lunar volatiles likely have an exogenous origin such as solar wind interactions with the lunar regolith, cometary and asteroidal impacts, interplanetary dust, and interstellar molecular clouds. In addition, it has been proposed that there may be organics within the ices of the PSRs that could have been delivered to the Moon through impact events; the Moon lacks Earth's destructive plate tectonics and weathering processes, and was once much closer to Earth (~21 Earth radii 3.9 Ga compared to the current ~60) therefore to learn about the potential delivery of organics to Earth early in its history, we must be able to access the pristine PSRs. Volatiles need to be studied from the PSRs in their pristine

form to determine their source, evolution, and implications for the origin of the Moon and potentially sources of water and life on Earth.
- There are different sources of lunar volatiles and organics. We do not understand their contribution to lunar volatile reservoirs, interactions, and cycles. These are all important for our understanding of the Earth-Moon system.

Question 2. Are you concerned that contamination carried by a spacecraft to the Moon (e.g., organic materials, volatile products of propellant, biological payloads) could compromise future investigations to study chemical evolution?

There was a divergence of professional assessment inherent in the answers to this question. Some specific scientific investigations could be impacted. The conclusive Apollo evidence demonstrates most geoscience investigations will not be meaningfully impacted. Characterizing propellant is a straightforward mitigation step, as is sampling sufficient distance from a lander to ensure lack of contamination.

Furthermore, it is worth emphasizing that exploring the Moon and regions of scientific interest absolutely and unequivocally requires propulsive landings on the lunar surface, and all scientific advances will be outright prevented if attempts are made to restrict landings.

Responses for Yes:

- Yes, we are mostly concerned about hypergolic (e.g. hydrazine) thruster products that could migrate and condense in near-surface materials. Such condensed products could then present a challenge for in situ analyses that do not have compound specific isotopic analysis capability (e.g., D/H ratios of NH_3 and H_2, $^{15}N/^{14}N$ of NH_3, N_2, etc) needed to differentiate between Earth contamination and volatiles of exogenous or endogenous origins. This would probably be less of a concern for sample return, where we can make these types of measurements and determine origins of the detected compounds, although this presumes that the isotopic composition of likely condensation products were understood through control experiments/measurements and the sample collection and return system was sufficiently clean.
- Yes, very much. Not only the space craft, propellant, etc. but also the sample container and tools that will be used to pick up, collect, and store the PSR samples in will/could have an effect on contamination and thus future chemical evolution. However, if we have rigorous witness plates/witness materials available of all materials that came in contact with the samples during the collection, transition, and storage process, we might be able to mitigate some of these concerns that way (similar to the process of how the ANGSA 73002 core sample for organic material is handled today). It may be important to conduct

in situ measurements to understand the degree of modification of the sample once it is collected, stored, curated for.

Responses for No:

- No. Most geologic studies do not need to be overly concerned with contamination by spacecraft unless they are studying volatiles. Even some of the Apollo samples are "contaminated," such as several from Apollo 17 whose bag was found in the return capsule surrounded by ocean water; these samples are clearly not ideal for studying lunar volatiles, but are still perfect for petrologic and most mineralogic studies that could examine the thermal history of lunar volcanism.
- No. Any contamination by landers to ice deposits in the PSRs will be on the surface or at least within the top 1-2 cm (see answer to 1.). Given the Category II documentation for missions to the Moon, we know the types of contamination that could occur with landed lunar missions since 2008. Given the documentation surrounding the Surveyor and Apollo programs, any contamination from those lander engines can be estimated.

Question 3: Are you concerned about the long-term degradation of organic materials (e.g., structural material with resin like CFRP, polymeric seals, wire-sleeves, etc.)?

Some members of COSPARRRSAT expressed concerns, others expressed strongly negative opinions in this regard. In general, this was a difficult question to address without a clear definition of "long-term". Regardless, this question can be addressed through careful siting of permanent surface infrastructure in the polar regions. Laboratory experiments as well as studies of space-exposed hardware at the Artemis Base Camp will be important towards assessing how much of concern this really is in the context of actual space missions.

Responses for Yes:

- Yes, understanding long term materials degradation is a concern. Laboratory experiments (or at a minimum, archiving of some of the relevant material for future studies) would be needed to fully understand the potential contribution of these materials.
- Yes. Many volatiles are unstable and might interact with other material, such as resin, polymeric seals etc. If these materials are being used, there needs to be a thorough study first as to the composition of these types of materials, and their effect on volatile components. Again, we need witness plates/materials for all materials that would be used for sample collection, transport, and storage. It would also be necessary to assess how various storage containers/boxes will allow preservation of volatiles, ices, organics,

and gases to mitigate concerns about degradation and maybe fractionation of organic materials.

Responses for No:

- No. These are miniscule compared to the sizes of the PSRs and I amazed that this is being asked. Given that the nylon flags planned by Apollo astronauts are still intact (as seen by LRO imagery), I don't think this is an issue.
- No. It depends on what is meant by long-term. How quickly do these materials degrade and in what manner? If it takes millions of years for the materials to degrade, then it likely is of no concern, but if the materials degrade within a few years and that material is placed right at the edge of a PSR, then that could potentially become an issue.

Question 4: Are you concerned about organic volatiles released by certain types of propellants?

A majority of COSPARRRSAT members did not view this as a concern, although propellants containing organics may impact certain investigations.

Responses for Yes:

- Yes, although the exact concern depends on the propellant used and its by-products. We are concerned about any volatile propellant by-products (not just organic) that are also known to be present in comets.

Responses for No:

- No. Only in the volatile-rich areas where volatile and organic studies are most likely to be conducted.
- No – because these will be documented. However, using liquid oxygen – liquid hydrogen engines will mitigate this issue. If COSPAR thinks this is a problem, I would suggest a COSPAR finding could be that recommend that liquid O-H engines be used on all landed missions to the Moon. I DO NOT support putting stricter planetary protection constraints on the Moon.
- Potentially yes, depends on the propellant and where the samples would be collected in respect to its distance.
- No. Propellants were identified in lunar regolith from under the Apollo landers. Preliminary organic measurements being made on previously unopened station 3 samples collected during Apollo 17 (further from the lander) do not show propellant contamination. Further work on these previously sealed samples will provide answers tied to degree of surface contamination and contamination penetration into the regolith. These samples should have a much lower organics background than PSRs. The ability to sample from depth and to limit contamination (and decomposition) of organics during

collection, storage, and curation should be more important. Also, the collection of samples from depth in PSR may provide insights into the degree of contamination during previous missions.

Question 5: Would an organic material list describing the kinds and amounts of organic materials on a spacecraft mitigate your concerns?

COSPARRRSAT members supported, in general, the concept of some form of an organic material list, with one very strong and well-formed dissenting opinion.

Responses for Yes:

- Yes, this would be a good idea, especially as a potential source of knowledge if there is a failure and the spacecraft impacts the surface, spreading materials. Assuming a nominal landing, the primary contamination concern is thruster exhaust byproducts and any mechanisms employed to collect or analyze samples.
- Yes. We cannot know what studies may arise in the next 50 years, and therefore should document this. The sample curation at JSC has the composition of the tools that the astronauts used in case researchers need that information to examine a potential source of contamination during sample collection. The same should hold true for materials that may be released onto the surface such as propellants.
- Yes. A list of organic materials associated spacesuits, spacecraft, tools, and sampling containers would be useful for not only mitigation, but to identify potential sources of contamination in returned samples. Apollo tools, curation environment and perhaps even spacecraft parts have been previously monitored. A more rigorous documentation during Artemis is appropriate.

Responses for No:

- Only partially. A list of all materials that the samples are coming in contact with would be needed and a set would need to be available as witness plates. It would also need to be assessed how extraction of regolith using different techniques will cause science loss (for example, ice sublimation fractionate d/H, organic species breakdown etc.), and how solid samples would react with the volatiles that are lost. There is so much we don't know.
- The Category II designation for the Moon is sufficient. No change needed.

Question 6: Would establishment of lunar PSR protected areas with controlled access and avoidance of unnecessary contamination (e.g., obsolete parts of spacecraft like used propulsion stages) mitigate your concerns?

SAT members displayed a diverse range of assessments on this topic with a majority not in favor. The phrasing of the question resulted in some confusion about what, exactly, was being asked.

Responses for Yes:

- Yes, as long as there will still be witness plates/materials available and as long as there would be in situ measurements carried out to understand the degree of modification of the sample once it is collected, stored, curated for and how extraction of regolith from PSR using different techniques will cause science loss. I think it is also necessary to think about/assess tools-to-sample cross contamination and cross contamination among PSR samples including organic contamination.

Responses for No:

- Perhaps, but it may be important to look into possibility of using propellants less likely to emit compounds of interest (e.g. cold gas, H_2/O_2, inertia (e.g. MASCOT), wheels, etc.) that could be used for any landers/hoppers/rovers that enter permanently shadowed regions. For contamination, “green propellant” plumes are also a contamination concern. Note that there may be no gas plume that is acceptable to all volatile science since C_xH_y, NO_x, NH_3, H_2O, Xe, or possibly N_2 may be of importance to some research.
- No. There may be contaminants derived from more distant sources. These still need to be documented. It would be best to be able to identify sources of contamination rather than to go to extremes to remove it. I think the best solution would be to restrict access to a select number of PSR and open-up other PSRs. The “open” PSR will allow observations to address contamination issues. The “restricted” PSRs could be “saved” for future generations once we have a clearer understanding of these contamination issues.
- No. Attempting to assert pre-emptive designation of protected areas on the Moon is not a good idea since there would be so many different actors on the scene with different agendas. A requirement for a “no trace left behind model” is infeasible as it could severely restrict some of the potential science experiments that could be left on the lunar surface indefinitely such as the lunar retroreflectors; these are an unlikely source of contamination, but just an example of a long-acting experiment, and we do not want to preclude future lunar payloads that have not yet been conceived.

- DO NOT DO THIS! It is not needed. My concern is that COSPAR will view lunar PSRs as they do Mars Special Regions. I am completely against that, and no protected areas are needed.

Question 7: Given the possibility of biological payloads landed on lunar surface for life-science experiments and for long-term archiving of biological samples, are you concerned about the either controlled or uncontrolled introduction and release of biological materials (living and dead) into the lunar system?

A majority of SAT members did not view this as a significant concern.

Responses for Yes:

- I think if there are rigorous protocols in place to avoid cross contamination on all levels (collection, transit, and storage (in the space craft, during transport to Earth, and once back on Earth), and if there is material available as witness materials, so we can compare organic material to each other, the concern can be mitigated. However, it is a concern.

Responses for No:

- No. The lunar environment is hostile to biological life as we know it.
- No. Most biological samples would not survive long on the lunar surface, such as the cotton plants grown on Chang'e 4, which survived for only about a week.

Community Views

LEAG received 31 responses to the questionnaire distributed widely to the community, which are summarized below.

Question 1. Are the volatiles in the Permanently Shadowed Regions (PSR) on the Moon of significant interest in the study of chemical evolution (i.e. primordial chemistry as precursor to the origin of life on Earth and potentially other planets, moons and planetary bodies)?

Responses were overwhelmingly yes, noting that they represent maybe the most accessible reservoir of solar system volatiles and could potentially answer fundamental questions about volatile transport to the Earth-Moon system. However, many also point out that we don't know the extent or composition of these reservoirs, or whether they are pristine records of volatiles in the solar system.

Responses for Yes:

- The geological context, isotope analyses and ages of water and organic deposits will shed new light on volatile migrations in the early solar system, in a period that life just emerged on Earth.
- These samples are critical for understanding the history of volatile delivery to the Earth-Moon system. They are also relevant to understanding the origin and evolution of volatiles throughout the solar system.
- Knowledge of the volatiles in the permanently shadowed region would yield valuable information about the origin of said molecules, e.g. delivery, solar wind, or radiolytic. As the moon is an airless body, this knowledge would be logically extended to other airless bodies such as mercury and comets/asteroids and meteorites.
- The LCROSS mission detected an intriguing mixture of compounds in one PSR, the origins and relative abundances of which remain to be understood. It is worth noting that we do not yet have an inventory of what compounds are present in lunar PSRs; they may turn out to be of more, or less, interest to this question accordingly. Lunar PSRs may also be analog environments for more distant regions of the solar system.
- Their origin would be "primordial" relative to the Moon only if they related to lower mantle volatiles released during post or near post mare pyroclastic eruptions. It is conceivable that recycled solar system primordial volatiles originally as part of comets carbonaceous chondrites have been deposited in PSRs.
- Although since the origin of the reservoir is unknown, it is unclear which period of time the volatiles originate. We note that LCROSS detected possible organic material which they concluded could be of cometary/asteroid origins or possibly from in situ cold grain

chemistry. So the jury is still out on the significance of this material in an astrobiological sense.
- It's possible that solar wind and impact gardening has churned up the volatiles to the point that the record has been lost but we don't know that and won't until we perform the experiment.

Responses for Maybe:

- No way to know until we sample them and understand their composition far better than we do with existing remote sensing data.
- Possibly. We need to go and inventory what is there.
- With extensive impact activity on the surface of the Moon, water deposits are not early nor "primordial".
- I would say they are of some, not significant interest in chemical evolution.
- In the absence of a genetic model for their origin this question can not be unequivocally answered.

Question 2. Are you concerned that contamination carried by a spacecraft to the Moon (e.g., organic materials, volatile products of propellant, biological payloads) could compromise future investigations to study chemical evolution?

Responses mostly expressed concern for contamination effects, but most went on to suggest that there are multiple ways to consider the effect and cope with it. Few responses clearly described an experiment or scientific concern that would be irrevocably altered.

Responses for Yes:

- The very act of making the measurement of the volatile content and composition, will alter the pristine state of said volatile content and composition.
- I am particularly concerned about contamination by volatiles, which may be hard to contain, and have an affinity for the polar environment. In addition to complicating studies of surface chemistry, volatiles may also complicate measurements of the extant volatile inventory.
- This is why a pre-planned landing site, contaminant mitigation, and modeling of contamination migration are important on the surface of the Moon.
- But if done properly, the effect will be insignificant or can be compensated for.
- However, a mitigation could be to drill/sample a few mm beneath the surface, which has been demonstrated on other planetary surfaces and is not super challenging. And is probably desired anyway for the science

- I would like to see propellant with an isotope or molecular tracer be used so that we can assay levels of contamination.

Responses for No:

- There will be contamination of volatiles through spacecraft outgassing that can quickly re-condense on the top surface of the regolith. I am not worried about the listed examples. There are mitigation methods such as documenting contamination knowledge (CK) of the spacecraft and subsurface sampling.
- I believe that we need to carefully study the contamination introduced by spacecraft activity so that we can subtract it as we would a background signal.
- Not especially, properly acquired core samples should be protected from volatile products
- I do not think that a hard line of "no landings" should be taken in this area. Rather, I can see that landings in permanently shaded regions provide a good possibility of experiments of opportunity (e.g., how to propellant effects land and distribute around a PSR?)
- Contamination by spacecraft has already happened many times in the past. We have to account for it anyway.
- The Moon has already had a lot of organic and inorganic material of terrestrial origin delivered to it by Apollo and robotic missions. It is likely that uncontaminated material can still be found in the subsurface.
- Mass balance suggests this is not a realistic concern.
- In some respect, this may serve as a marker, much as large nuclear tests or volcanic eruptions do in Earth ice cores. If possible, propellants should be tagged with some kind of isotopic marker that can be differentiated from insitu lunar volatiles.
- Not if good, but not extreme, protocols are followed. Accessing lunar resources for use in space, on the Moon, and on Earth is a more important objective than preserving pristine organics

Question 3. Are you concerned about the long-term degradation of organic materials (e.g., structural material with resin like CFRP, polymeric seals, wire-sleeves, etc.)?

Responses are divided approximately equally; however, the responses themselves have similar concerns whether they self-identify as “yes” or “no.” Respondents accept that materials will degrade and suggest that they will be recognizable or negligible.

Responses for Yes:

- naturally these things will decay and leave their mark. There is no way of landing without contaminating the surface.
- all materials delivered to the surface of the Moon should be carefully evaluated to determine their impact of organic materials originating on the Moon.
- but good engineering should solve those problems.

Responses for No:

- these should be undetectable far enough away from the site.
- not for PSR mission lifetimes
- I would not worry about degradation of such materials noticeably affecting the environment around the spacecraft on the timescales of exploration.
- I am not concerned about the solid organic materials such as resin, polymer, or sleeves. These are recognizable contamination that we can usually recognize easily with a microscope.

Question 4. Are you concerned about organic volatiles released by certain types of propellants?

Responses are overwhelmingly yes, because volatilized propellant can move much farther from the landing site. Knowledge of the potential contaminants is important.

Responses for Yes:

- although the question is insufficiently specific. Contamination is a function of type and quantity, and we don't know either.
- Though not every organic volatile is equally concerning
- Hurley found that propellants break apart chemically and these molecules lying on a cold crater floor might not quickly desorb from the cold trap, but could be released by micrometeoroid impact vaporization and particulate ejection to other parts of the crater floor.
- If organic volatiles from some propellants are recognizable, for example, very distinct organic compounds with enriched In or Ir and with unique isotope signatures, then we can recognize the contamination and distinguish from the indigenous lunar water and organics in the PSR. The contamination knowledge of all space hardware is important.
- If possible, propellants should be tagged with some kind of isotopic marker that can be differentiated from in situ lunar volatiles.

Responses for No:

- These can be well-understood if documented and characterized. Can even be thought as point sources to study the dynamics of volatiles in and around cold traps.

Question 5. Would an organic material list describing the kinds and amounts of organic materials on a spacecraft mitigate your concerns?

Responses agree that a materials list should be part of good protocols so that scientists can at the very least understand potential contaminants. More research into the mechanisms of material transport on the Moon is also a necessary component of understanding potential contamination.

Responses for Yes:

- A list of all organic materials used on a spacecraft is necessarily part of the contamination knowledge. In addition, research will need to characterize their stability under the lunar surface environment and the products of decomposition and sublimation.
- If the source of organic and volatile materials was carefully monitored, and if possible isotopically "tagged" it could actually serves as a way for us to measure diffusion of volatiles into the regolith, etc with a controlled source.
- spacecraft engineers should strive to use low outgassing materials in general.
- scientists should be allowed to have input on the materials chosen if any materials are found to have a detrimental impact on science.

Responses for No:

- contamination of any kind is still contamination.
- Not mitigate, but would help identify potential confounding constituents.
- Only if coupled with a model of how these materials could be transferred to the sample site. If there is no transfer mechanism, this does not matter.

Question 6. Would establishment of lunar PSR protected areas with controlled access and avoidance of unnecessary contamination (e.g., obsolete parts of spacecraft like used propulsion stages) mitigate your concerns?

Responses overwhelmingly express support for balancing the scientific benefit of pristinity with a pragmatic approach to exploration. There were few clear expressions that fully supported a controlled-access approach.

Responses:

- I would like to see protected areas formed and managed in a way that provides balance between deriving science results from this non-renewable legacy resource and establishing a long-term/permanent human presence on the surface of the Moon. I am concerned about science loss but also fully support human exploration of the Moon.
- I have no concerns. Protected areas on the Moon are not necessary. With the contemplated extensive presence on the lunar surface, components brought in by spacecraft and humans can be adequately characterized and not result in anyone reaching the wrong conclusions about materials intrinsic to the Moon and those brought in by impactors.
- If such areas were "roped" off, I think they should be of very limited value. I would also be concerned that the costs/efforts to comply with such a requirement might be significant, and not worth the benefit.
- Would more than address them, and is probably overkill.
- No. It would replace one concern with another. I advocate use of guidelines.
- Controlled access will help but won't entirely avoid contamination. Any spacecraft landed or crashed anywhere on the Moon will outgas, portions of the outgassed vapor will eventually end up in the PSRs. But, diverting spent hardware away from impact on the Moon is a big help
- Partially. I strongly recommend an international agreement be sought and supported to restrict lunar polar investigations to only ONE pole until the character, form, and abundance of any volatiles present are well known and documented (i.e. at the South Pole, since activities have already been focused there).
- Yes, for scientific reasons, but completely invalid for resource acquisition purposes.
- Yes, to a large extent. However, it is likely volatiles from elsewhere on the lunar surface will migrate to PSR, so other mitigations will also be needed
- Perhaps. I think the goals, feasibility and effectiveness of this idea are worth investigating.
- Yes, as we never know what future scientists will want to study.
- Yes, so long as it is balanced appropriately with the development of PSR volatiles as resources.

- Yes, to a large extent. But the protected area can't be just at the ground level. It has to be a no fly over zone to protect from volatile contamination and accidental crashes.
- Maybe, but these may need to be quite large (whole quadrant?) given uncertainties in the mobility and dynamics of volatiles. Also would this have precluded LCROSS, from which a lot was learned.

Outcomes

The scientific interest in studies of the lunar polar regions, specifically pertaining to volatiles, is clear from this “snapshot” of community sentiment. As will be evident from the nature of the responses garnered, there is considerable variation of opinion, as might reasonably be expected in a large and diverse community. This report highlights areas where consensus can be reached and where further research could potentially be helpful in some respects. Equally clear, is that no scientific advances in these fields will be possible without vigorous surface exploration efforts in the polar regions, especially in and around the permanently shadowed craters.

As the Cornerstone of the Solar System, lunar exploration is immensely important for planetary science. The Moon’s potentially vast polar resource deposits are uniquely enabling for the creation of the thriving cislunar economy needed to develop the firm foundation - in terms of capabilities, workforce, and resource production - required for more ambitious voyages to other destinations in the Solar System.

As previously discussed, establishing an agreed-upon community consensus that pragmatically balances both the narrowly scientific perspective reflected in the questions and the equally legitimate commercial and resource utilization perspectives not considered here, particularly in the context of an active exploration program that is making steady progress, will require a significantly longer time period to establish rapport and functioning working relationships amongst the relevant stakeholder communities.

Appendix: Relevant LEAG Reports

United States Lunar Exploration Roadmap (US-LER):

http://www.lpi.usra.edu/leag/roadmap

LEAG Advancing Science of the Moon Report

https://www.lpi.usra.edu/leag/reports/ASM-SAT-Report-final.pdf

LEAG Next Steps on the Moon Report

https://www.lpi.usra.edu/leag/reports/NEXT_SAT_REPORT%20(1).pdf

LEAG International Polar Volatiles Coordination SAT

https://www.lpi.usra.edu/leag/reports/V-SAT-2-Final-Report.pdf

LEAG Back to the Moon Workshop Outcomes

https://www.hou.usra.edu/meetings/leag2017/B2M_Report_Final.pdf

Report from the 2007 NASA Advisory Council Workshop on the Lunar Exploration Architecture

https://www.lpi.usra.edu/meetings/LEA/finalReport.pdf

LEAG/CAPTEM Analysis Document

https://www.lpi.usra.edu/leag/reports/LEAG_CAPTEMCurationReview.pdf

LEAG Themes, Objectives, and Phasing Special Action Team

https://www.lpi.usra.edu/leag/reports/top_sat_report.pdf

About the Lunar Exploration Analysis Group

The Lunar Exploration Analysis Group (LEAG) was established in 2004 to support NASA in providing analysis of scientific, commercial, technical, and operational issues to further lunar exploration objectives. LEAG was jointly established by the Science Mission Directorate (SMD) and the Human Exploration and Operations Mission Directorate (HEOMD) and blends members of both communities, building bridges between science, exploration, and commerce whenever and however possible. LEAG is led by a Chair and a Vice-Chairs who lead an Executive Committee that serves as the principal representatives of the United States lunar exploration community to stakeholders, including NASA and the international community. LEAG has a standing Commercial Advisory Board (CAB) to offer programmatic insights into the capabilities provided by industry. LEAG is a community-based, volunteer-driven, interdisciplinary forum. Membership is open to all members of the lunar exploration community and consists of lunar and planetary scientists, life scientists, engineers, technologists, human system specialists, mission designers, managers, policymakers, and other aerospace professionals from government, academia, and the commercial sector.

About the LEAG Lunar Exploration Roadmap

The LEAG United States Lunar Exploration Roadmap (LER) is the cohesive strategic plan for using the Moon and its resources to enable the exploration of all other destinations within the Solar System by leveraging affordable investments in lunar infrastructure. The US-LER is a living document developed over four years through a comprehensive community-based process and was released in 2012. The roadmap lays out a sustainable plan for Solar System exploration that allows NASA to use its lunar surface infrastructure to explore small bodies, Mars, and beyond. Following the US-LER will enable commercial development, through early identification of commercial opportunities that will create wealth and jobs to offset the initial investment of the taxpayer. The roadmap will also, with careful planning, enable international cooperation to expand our scientific and economic spheres of influence while enabling an expansion of human and robotic space exploration. The Roadmap is located at: https://www.lpi.usra.edu/leag/roadmap/ and the implementation plan is located at: https://www.lpi.usra.edu/leag/reports/RoboticAnalysisLetter.pdf