Addressing the Myths: Human Health Risk Assessment Context for Lunar Dust

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Lunar dust poses legitimate challenges for NASA's return to the moon under Artemis, with human health concerns being among the technical gaps that must be overcome if we are to achieve mission success. Part of that challenge includes accurate risk communication, which is key to informed spaceflight operations. This is complicated by a number of myths that surround lunar dust health risks; false assumptions, half-truths, and generalizations that affect risk perceptions by the stakeholder community. Are silicosis and lung cancer legitimate concerns with future Artemis exposures? Is NASA basing its lunar dust exposure standard on very limited findings from Apollo? The NASA Human Health & Performance (HHP) Directorate has the responsibility for addressing these sorts of questions in accurately representing crew health risks associated with lunar dust exposure under Artemis. As part of that mission, this paper evaluates several of these myths, while sharing supporting risk assessment insights and technical findings that will hopefully provide a more balanced perspective on the lunar dust challenges we collectively face.

Acronyms and Nomenclature

ATSDR = *Agency for Toxic Substances and Disease Registry*
ECLSS = *Environmental Control and Life Support System*
EVA = *Extravehicular Activity*
HEPA = *High-efficiency Particulate Air Filtration*
HHP = *Human Health and Performance*
LADTAG = *Lunar Airborne Dust Toxicity Assessment Group*
NASA = *National Aeronautics and Space Administration*
PEL = *Permissible Exposure Limit*

I. Introduction

Myth may be a word that seems out of place in the context of a scientific examination of the human health aspects of lunar dust, but its definition as “a widely held but false belief or idea” makes it relevant to the risk communication challenge inherent to this subject area. To be clear, in our information age, we all can have difficulty in maintaining a fully-informed and balanced perspective on topics in which we have an interest, and it is natural and healthy to revisit our understanding from time-to-time to ensure its integrity. Information that circulates through our ubiquitous and diverse media can sometimes be sensationalized, and even the implications of valid scientific information can be difficult to interpret without broader context.

Lunar dust (the finest size portion of loose surficial material called lunar regolith) is a topic that logically has drawn significant public and scientific interest, even before the days of Apollo. For example, it was conjectured by some that visiting spacecraft wouldn’t be able to find stability on the moon due to the regolith structure and depth, or that unknown biologicals in the dust would pose hazards to humans, plants, etc. While some of these practical concerns may have been largely put to rest during our Apollo missions, others were reinforced and at least partially validated by our Apollo experience. For example, lunar dust did pose notable operational challenges during the mission, and there were examples of adverse health effects experienced by some crew. Adding complexity to this history, the new ambitious Artemis mission has key differences from Apollo, and draws legitimate questions and speculation about the key findings from the volumes of scientific research that have been conducted on lunar dust over the ensuing decades. What do we really know or what gaps remain in regard to lunar dust crew health risks, and how extensively can this information be leveraged as NASA pursues exploration of the south lunar pole under Artemis? While it is not possible to address all questions on lunar dust health risk in the scope of this paper, the goal is to more closely evaluate a few of the more high-profile beliefs that surround lunar dust and to provide more complete context. Most myths are at least partially built upon elements of truth, and we will find this to be the case in our examination of crew health risks of lunar dust, as well.

II. Myth #1: Lunar Dust was a Consistent and Substantive Crew Health Issue during Apollo

There may be a prevailing perception that Apollo crew consistently experienced adverse health effects associated with lunar dust during their missions, and that these health expressions were notable and significant in nature. While it is important to not understate the degree of health concern with a ubiquitous substance like lunar dust, a more balanced view is to say that Apollo crew had mixed experiences and health consequences in regard to lunar dust exposures.

Perhaps the best holistic reference in regard to this topic came from the Apollo Medical Operations Project: Recommendations to Improve Crew Health and Performance for Future Exploration Missions and Lunar Surface Operations[1]. This forum included first-hand perceptions on lunar dust (among other topics) from attending Apollo crewmembers. First, it was clear that while dust burdens varied by mission, crew generally were all exposed to lunar dust and had personal perspectives on the topic. On one end of the spectrum were a minority of crew who had notable adverse physiological responses, including symptoms that were characterized as "hay fever" or "allergic reactions" that included watery eyes, nasal/eye irritation, and similar effects (Note: many of these reported physiological symptoms are also associated with inflammatory responses that are not immune-mediated, and a recent NASA-funded study has shown that lunar dust does not appear to have true allergenic properties). Crew with this mindset logically stressed the importance of individual crew susceptibility in preparing for future missions. Conversely, there were some crew who noted that lunar dust was present in the cabin atmosphere, but was relatively well-tolerated, especially after some minimal adaptation time. Exemplifying this viewpoint, at least one responder suggested that fiberglass particles posed a bigger health concern than lunar dust. Many crewmembers occupied the middle ground, noting that lunar dust seemed to be a manageable nuisance from a health perspective during these missions, but that more study and preparation was needed, especially if longer missions were desired. This group noted that there were important aspects of chronic exposures and risks that needed to be addressed, stressing inherent uncertainties and the difficulty in simulating lunar dust properties in ground-based studies. Crew almost universally stressed that lunar dust mitigation was key, and that the human system would benefit from preventative approaches that protected other key vehicles systems (e.g., hatch operation and seal integrity).

Does this wide spectrum of individual perceptions of lunar dust during Apollo mean that there are discrepancies that require resolution? Actually, the answer is quite the opposite; this outcome is exactly what you would expect when approaching a candid cohort of individuals recalling exposures to an environmental stressor. First, to a degree, crew were exposed to differing dust levels and intensities. While this may explain a range of responses to a minor degree, this is unlikely to be a main variable. Perhaps more importantly, there is always a range of individual physiological response that must be kept in mind when addressing environmental exposures. Even with a relatively homogeneous group like Apollo crew, there will be some individuals who have minimal susceptibility to a specific health impairment, while others exposed similarly will exhibit more pronounced responses. As an example, one crew may be more prone to nasal congestion, but may be less susceptible to an irritant response compared to their colleagues. Finally, it should be noted that most of this reporting largely addresses "in-mission" health observations, and this must be combined with the negative findings from post-flight medical analysis to provide a comprehensive crew health risk picture. Thus, it should be stressed that returned Apollo crews did not have to be treated for dust-related medical conditions (e.g., pulmonary therapy, treatment for ocular damage). In conclusion, Apollo crews experienced a spectrum of in-mission individual health responses (including the absence of effect) in association with lunar dust exposure, but no significant dust-related conditions that required management post-flight. It is important to maintain a balanced risk perspective when describing the Apollo experience.

III. Myth #2: NASA is Reliant Upon the Limited Apollo Experience in Protecting Artemis Crew

Preparing for future Artemis missions logically includes the development of technical standards for lunar dust (e.g., permissible exposure limit or PEL) and development of corresponding control technologies and mitigations. As described above, much of the scientific community is familiar with the Apollo experience, and has some conceptions about the crew health challenges by lunar dust. In contemplation about preparations for future Artemis missions, it might be assumed that NASA's evidence base on lunar dust health risk is primarily informed by that prior Apollo experience. The reality is that NASA logically does leverage this unique flight history, and given the limited available analogues, it is wise to extrapolate as many lessons learned as possible in informing Artemis planning. However, there are important limitations in the Apollo mission design and experience that must be accounted for in extrapolating lunar dust findings to Artemis missions. Similarly, there are uncertainties and research gaps that were logical unaddressed scientific concerns in preparing for more extensive lunar exploration. Fortunately, Apollo is by no means the only source of toxicological evidence on lunar dust that is available, and there has been over fifty years of research that has significantly advanced our understanding of the health ramifications of lunar dust exposure. While full treatment of these topics is well beyond the scope of this paper, a few limitations from Apollo and a summary of the primary research is highlighted in the following sections.

Image 1. Surface operations and lunar dust during Apollo

A. Application of Apollo Findings

There are a number of caveats that should be observed in assessing the transportability of lunar dust observations from Apollo. At a fundamental level, it should be noted that significant amounts of lunar dust were introduced to the Apollo vehicles (especially the Lunar Module) during these surface missions. As missions preceded the development of modern high-efficiency particulate air filtration (HEPA) technology, the crew indirectly relied on lithium hydroxide systems and cleaning with wet towels, which were likely only marginally effective. The lithium hydroxide system was intended for carbon dioxide removal, although this technology has a hygroscopic effect and can scrub particles with the cabin humidity (although less effective with smaller particles below 10 microns which have the higher health significance)[1]. In contrast, Artemis missions have the potential to be much more successful in dust mitigation thanks to newer technologies and more informed preparation/mitigations.

As described previously, with respect to crew exposure and risk estimation, individual variability to toxic effect must be considered, and Apollo only involved twelve crew exposed over six surface missions. These missions didn't have the benefit of lunar dust monitoring data (either during mission or with post-flight archives), so it is difficult to predict the levels of lunar dust exposure experienced during these missions (an obvious key limitation in correlating health observations). Further, the frequency of dust-introducing extravehicular activity (EVA) and the length of the surface mission (3 days or less) were both relatively limited in comparison with Artemis plans. This is especially true when recognizing that early planned Artemis mission durations (6.5 day surface stays), are intended to be extended to 30 days and beyond. Future missions may experience lunar dust conditions or health outcomes that were not realized in the limited Apollo evidence base. Thus, health observations for lunar dust (including the absence of effects) relevant to short-term Apollo missions may be difficult to relate to much longer exposure durations. In summary, to a significant extent, Apollo lunar dust experiences likely represent a "reasonable worst-case" for our early Artemis missions, and can be used to inform safety assessments for off-nominal performance scenarios,etc. However, health observations over limited missions must be interpreted with some caution, and by their nature these data can't solely inform a lunar dust PEL.

B. Research

Fortunately, the interest in lunar dust and its toxicity has spurred a sizable amount of research over the decades since Apollo. This includes specialized research involving (1) actual lunar dust samples returned from Apollo, and (2) simulants that were selected to mimic key properties of lunar dust, along with advancements in understanding of mechanisms and principles in the general field of particulate toxicity. There are several recent scientific reviews that have done a credible job of summarizing the most relevant literature on lunar dust[2,3,4]. Rather than trying to rehash much of the evidence base, this section will focus on summarizing the foundational NASA work that led to the establishment of a lunar dust PEL.

Thanks to the contributions of the toxicologists, chemists, and geologists (both internal and external to NASA) that comprised the Lunar Airborne Dust Toxicity Assessment Group (LADTAG), NASA had a fairly robust body of direct scientific evidence that was leveraged to inform a PEL for lunar dust. As described in Figure 1., beginning in 2005, LADTAG was organized by NASA in an effort to better understand lunar dust exposure considerations for crew health with respect to future lunar surface missions. Experts shared their initial perspectives on an appropriate lunar dust PEL, and those individual estimates spanned a 300 fold range. To better resolve this uncertainty, the team decided that animal testing with returned Apollo dust samples was warranted. Geologists contributed by characterizing the spectrum of returned dust samples from Apollo to determine the most representative dust for the purposes of risk assessment[5]. Based on several criteria, Apollo 14 dust was selected as being most representative and appropriate for the purposes of the toxicological testing and risk-based development of a PEL. The team also expended significant effort in simulating (through grinding and other treatments) surface reactivity properties of lunar dust that were suspected to be absent in returned Apollo dust samples.

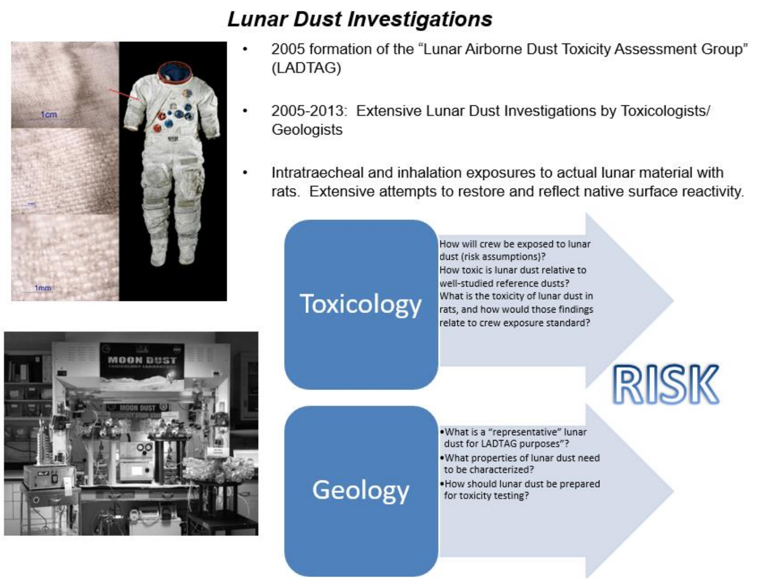

Figure 1. Lunar dust investigation strategy under LADTAG (2005-2013)

Toxicologists considered relevant exposure routes for lunar dust, and ultimately developed animal testing methodologies to assess crew health risks (rodents for inhalation exposures and rabbits for assessing ocular effects). Where appropriate, testing methodologies also included well-studied reference dusts (quartz/titanium dioxide) for toxicological context. Rodent inhalation exposures to the Apollo 14 and reference dusts were conducted over a 4 week period (6 hrs/day), with comprehensive histopathological evaluation. A complete summary of the LADTAG findings was presented in the "Lunar Dust Toxicity: Final Report"[6]. The key takeaways were as follows:

- Lung inflammation, septal thickening, and other signs of respiratory system toxic challenge were seen in rats exposed to lunar dust, with negative outcomes increasing with exposed dose. This consistent relationship provided a sound basis for establishment of a lunar dust PEL. Lunar dust was found to be moderately toxic relative to the other studied reference mineral dusts[7].

- Efforts to activate the lunar dust were successful in recreating surface reactivity, but this surface activation was not found to influence the toxicity of the dust particles[8]. Pulmonary toxicity of the dust is believed to be mediated through mechanisms not primarily dependent on surface reactivity[9].

- Risk of eye abrasion was an additional consideration with lunar dust[10]. Lunar dust testing in test animals was associated with relatively mild levels of irritation. With a maximum possible score (Draize criteria) of 110 points, lunar dust only produced a score of 4 points (slight redness and swelling of the conjunctiva after 1 hr, which resolved within 24 hours). While not as sensitive as lung inhalation, ocular impacts can still have health and operational impacts, consistent with the crew experience during Apollo.

Combining these toxicology findings with relevant adjustments and exposure assumptions, NASA derived an inhalation-protection PEL for lunar dust in 2014, which was later adopted in NASA Standard 3001 Volume 2. Lunar dust exposures are believed to credibly follow "Haber's Rule", which is a principle that allows risk to be expressed as a function of the product of Concentration x Exposure Duration (i.e., higher concentrations are allowable if compensated by shorter exposure durations). This relationship allows for flexibility in setting differing mission-specific PELs while maintaining risk consistency. Thus, a 30 day PEL of 0.4 mg/m^3 for lunar dust is also equated to a 1.6 mg/m^3 PEL that would apply over a shorter 7 day mission duration[7].

In summary, lunar dust exposures for our future Artemis missions are informed by both our Apollo experience and by a scientific evidence base that has been formed by years of gap identification and corresponding strategic research. As this includes a multi-year NASA collaborative research effort that utilized actual lunar dust and representative animal test models[6], there is less uncertainty in establishing exposure guideline than might be expected with a unique material like lunar dust. Of course, knowledge gaps will always exist in some form and NASA will need to be open to continued learning about lunar dust and its potential effects as we prepare for the challenges of Artemis.

IV. Myth #3: Lunar Dust Exposure Poses Credible Crew Health Risk of Silicosis and/or Cancer

One of the challenges in trying to summarize credible health concerns with lunar dust is the inherent complexity of risk awareness in our modern information age. There is no shortage of studies, opinions, or news feeds, and many of these may gain visibility through a biased focus on extreme aspects of the subject area. Even if balanced presentation is desired, lunar dust is a complex subject area and there are technical nuances and key details that must be taken into account if health risks are to be accurately understood. An example of this confusion can be observed in the public perception by some that lunar dust has potential to cause several high-profile diseases, silicosis and cancer. Fortunately, this is a situation of perception not corresponding to reality, but having an inaccurate view on these serious health consequences can negatively affect perspective on the adequacy of NASA's balanced lunar dust risk posture (e.g., "Given my perception of the silicosis risk, why is NASA allowing for any crew exposure to lunar dust?").

A. Review of Lunar Silica Content

It is true that silica minerals (e.g., silicon dioxide) comprise a substantial component of lunar dust (47% for Apollo 14 regolith[5]). As typical beach sand might have 70-80% silica, it is not surprising that lunar dust can be abrasive to skin and eyes. However, the overall silica mineral portion of lunar dust is not what explains its toxicity (if this were true, a casual trip to the beach would require hazmat precautions). Instead, toxicity is largely dictated by the presence of a specific structural form of silica called crystalline silica. This form of silica has a highly structured molecular arrangement, and is much more fibrogenic than other less toxic forms of silica collectively referred to as amorphous silica[11]. Primary forms of crystalline silica are quartz and cristobalite, whereas familiar forms of amorphous silica include diatomaceous earth and olivine[5].

Since not all silica is created equal, it is important to understand what form of silica will likely be encountered during lunar surface missions if we are to properly contextualize health risks. As described in NASA's 1991 Lunar Sourcebook; "Silica minerals (crystalline silica) include several structurally different minerals, all of which have the simple formula SiO_2. These minerals are generally rare on the Moon. This rarity is one of the major mineralogic differences between the Moon and the Earth, where silica minerals are abundant in such common rocks as granite, sandstone, and chert"[12]. This doesn't mean that crystalline silica is completely absent from the lunar regolith (the mineral cristobalite is the primary form on the mood when crystalline silica is present), but its presence is much more limited relative to what is observed on Earth. From data in the Lunar Sourcebook[12], crystalline silica would be expected to be present at no more than 1-2% in lunar regolith, which is substantially less than what is found in other silica sources on Earth (for example, granites can commonly contain 50% or more crystalline silica).

B. Silicosis and Cancer

Now that we understand that crystalline silica is the main source of toxicity concern among silica minerals, and that lunar dust will have minimal crystalline content, it is worthwhile to revisit the assertion that lunar dust poses a risk of silicosis and/or cancer. As described by the Agency for Toxic Substances and Disease Registry (ATSDR), "Silicosis is a progressive, irreversible, fibrotic lung disease resulting from inhalation and pulmonary deposition of respirable dust containing crystalline silica. The causal relationship between inhalation of crystalline silica and development of this severe, debilitating lung disease is well-established and not under dispute. No other substances, including amorphous silica, are known to produce the unique pathological changes observed in silicosis"[13]. While there are several different forms of silicosis (e.g., acute silicosis, simple silicosis), in most instances, disease expression requires either decades of exposure or intensive shorter-term exposures to freshly-fractured materials with significant crystalline silica content. Neither of these situations is relevant to our lunar missions.

In regard to cancer, it is true that crystalline silica is considered a Group 1 carcinogen (known to be carcinogenic to humans), but similar associations are not made with amorphous silica[13]. Further, while associated cancer risk can't be "proven" to be non-existent, significant and prolonged occupational-type exposures are generally necessary for cancer to be a legitimate environmental concern, and these are not consistent with Artemis lunar dust exposure scenarios. This potential is even further reduced by the recognition that sustained injury of the respiratory system is understood to often be a required precipitating factor in pulmonary cancer initiation and progression[13]. Combined with the recognition that NASA is already implementing efforts to protect the crew respiratory system during future missions (e.g., PEL establishment, dust mitigations, HEPA filtration, monitoring), cancer is simply not a credible health outcome with lunar dust exposure in Artemis.

V. Myth #4: Existing Lunar Dust Findings Aren't Applicable to South Polar Exploration

NASA is targeting the lunar south pole with its ambitious Artemis surface landing missions. There are many environmental challenges (e.g., lighting conditions, cold temperatures) inherent to a south pole landing objective that were less of a concern with Apollo and its equatorial focus. With respect to lunar dust, it is logical to also question whether the health conclusions based on equatorial lunar dust are translatable to Artemis conditions. Some may even assert that the same resource expenditure described for LADTAG would need to be duplicated to address new Artemis dust challenges. The good news is that, for several reasons, the lunar dust findings and PEL derived from the LADTAG results are expected to similarly apply to protecting Artemis crews. This conclusion is based on the specific manner in which the LADTAG risk assessment was conducted, as well as knowledge of limited practical variability between equatorial and south polar sites with respect to key regolith characteristics. These are discussed further in the following sections.

A. Review of General Lunar Regolith Mineralogy

First, it is worth clarifying that there are two broad classifications of lunar regolith: highlands and mare. With the exception of one highlands site (Apollo 16), the Apollo missions typically encountered lunar mare. Lunar mare is generally characterized by the presence of basaltic minerology as compared to the anorthositic nature common to the lunar highlands. Both of these types can be largely characterized by the relative presence of three predominant mineral types: pyroxene, plagioclase feldspar, and olivine, in addition to the presence of ubiquitous lunar glass[14]. Thus, while there are certainly differences between highlands and mare regolith, there is also a high degree of similarity and predictability in terms of what general types of minerals will be encountered by crew during a lunar mission (much more than would be seen in terms of terrestrial mineralogy variation). Logically following, from an engineering perspective there is an informed expectation that the basic regolith properties (e.g., density, structure, particle size) at the lunar south pole will be "in family" with our equatorial experiences[14]. The same can be said of the similarities from a toxicological perspective. As discussed earlier, the crystalline silica content of the regolith is an important factor in health risk assessment for mineral dusts. While neither type has significant crystalline silica content, highlands regolith appears to have lower relative crystalline silica composition compared to lunar mare. As a direct comparison, Apollo 14 regolith mixture had a reported crystalline silica content of 0.7%, while the crystalline content of the highlands-typical Apollo 16 regolith mixture was $<0.1\%$[15]. Recognizing that these are both small datasets, it is reasonable to simply conclude that there is not likely to be greater crystalline silica content at a highlands-dominated lunar south pole (thus validating the health-protectiveness of a PEL based on Artemis 14 testing and data).

B. LADTAG Risk Assessment Strategy

Additionally, it is worth noting that the LADTAG team strategically selected the Apollo 14 samples for in-depth animal testing and use in lunar dust risk assessment. As demonstrated in Figure 2, one of the reasons Apollo 14 dust was selected for study is that it represented intermediate geological characteristics (neither exclusively highland nor mare characteristics). For risk assessment purposes, this approach affords a broader applicability in reasonably applying the PEL. As stated in the LADTAG Final Report, "Samples from Apollo 14 regolith are generally considered to be a combination of mare and highland soils. This means that our test material was well representative of the dust that covers much of the visible surface of the moon"[6]. Thus, given the nature of the risk assessment approach and the limited differences among expected minerology, it is unlikely that a costly repeat of LADTAG-scale evaluations (using a slightly different Apollo dust) would result in a drastically different lunar dust PEL.

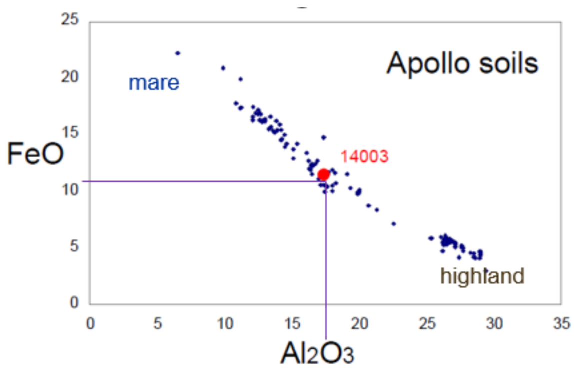

Figure 2. Depiction of intermediate characteristics of Apollo 14 regolith sample (14003) used in LADTAG in relation to other Apollo samples[16]

VI. Conclusion

Given the amount of visibility and interest in lunar dust, it is inevitable that there is a need for regular reaffirmation of fact and fiction when it comes to the state of knowledge regarding crew health considerations. There are undoubtedly other valid questions surrounding lunar dust that deserve attention, and the intent of this paper was simply to address some of the more common misconceptions. The overall takeaway message is that there is a solid body of evidence that can be leveraged in making informed risk decisions on lunar dust as part of Artemis. At the same time, there needs to be an openness toward new findings and progress in closure of remaining research gaps. Proper balance is important to ensure health protection, but not unnecessarily overdesign lunar dust controls or complicate mission operations. In summary, despite inherent uncertainties, NASA is well-positioned to approach Artemis missions with confidence with respect to lunar dust human health risk management.

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