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Defining an abrasion index for lunar surface systems as a function of dust interaction modes and variable concentration zones

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ABSTRACT

Unexpected issues were encountered during the Apollo era of lunar exploration due to detrimental abrasion of materials upon exposure to the fine-grained, irregular shaped dust on the surface of the Moon. For critical design features involving contact with the lunar surface and for astronaut safety concerns, operational concepts and dust tolerance must be considered in the early phases of mission planning. To systematically define material selection criteria, dust interaction can be characterized by two-body or three-body abrasion testing, and sub-categorically by physical interactions of compression, rolling, sliding, and bending representing specific applications within the system. Two-body abrasion occurs when a single particle or asperity slides across a given surface removing or displacing material. Three-body abrasion occurs when multiple particles interact with a solid surface, or in between two surfaces, allowing the abrasives to freely rotate and interact with the material(s), leading to removal or displacement of mass. Different modes of interaction are described in this paper along with corresponding types of tests that can be utilized to evaluate each configuration. In addition to differential modes of abrasion, variable concentrations of dust in different zones can also be considered for a given system design and operational protocol. These zones include (1) outside the habitat where extensive dust exposure occurs, (2) in a transitional zone such as an airlock or suitport, and (3) inside the habitat or spacesuit with a low particle count. These zones can be used to help define dust interaction frequencies, and corresponding risks to the systems and/or crew can be addressed by appropriate mitigation strategies. An abrasion index is introduced that includes the level of risk, *R*, the hardness of the mineralogy, *H*, the severity of the abrasion mode, *S*, and the frequency of particle interactions, *F*.

1. Introduction

Unexpected issues were encountered during the Apollo era of lunar exploration due to detrimental abrasion of materials upon exposure to the fine-grained, irregular shaped dust on the surface of the Moon, as cataloged by Gaier at the National Aeronautics and Space Administration (NASA) Glenn Research Center (GRC) (Gaier, 2007). With an aim of mitigating these problems on future exploration missions, the investigation of lunar abrasion issues falls under the Dust Management Project (DMP) initiative at NASA. One goal of the research being conducted within the DMP is to develop recommendations and standardized testing protocols for evaluating the impact of lunar dust abrasion on proposed surface system materials and operations. This paper describes the formation of lunar dust and historical abrasion issues; the lunar regions that define the mineralogy expected during exploration; the abrasion modes and interaction forces that cause wear in terms of two- and three-body abrasion severity; and the relative spacecraft exposure zones that determine the probability of dust interactions. The four major contributors to wear – hardness of the mineralogy, *H*; level of risk, *R*; the severity of the abrasion mode, *S*; and the frequency of particle interactions, *F* – can be synthesized into a non-dimensional abrasion index, introduced here, which is suggested as an aid for hardware designers and mission planners.

2. Lunar abrasion history

Micrometeorite flux can be estimated for the surface of the Moon and is dependent on the Earth–Moon alignment. The backside or far side of the Moon experiences a higher rate of impacts,

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Abbreviations: ASTM, ASTM International, formerly American Society for Testing and Materials; DMP, Dust Management Project; EVA, Extravehicular Activity; EVAS, Extravehicular Activity Systems; GRC, Glenn Research Center; NASA, National Aeronautics and Space Administration; Ra, surface roughness; UCB, University of Colorado at Boulder; USGS, United States Geological Survey; ZL, Zeroline; ZOI, Zone of Interaction

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which may result in different characteristic lunar regolith composition. A power law can approximate the average number of micrometeoroid impacts and size distribution. Micrometeoroid average sizes range from 30 to 150 μm in radius with masses of 10^{-10}–10^{-8} kg impact the Moon at speeds averaging 7–20 km/s (Colwell et al., 2007; Belk et al., 1997). Lunar soil formation is primarily due to innumerable micrometeorite impacts forming everything from spheres to highly angular and irregular shape silicate glass particles (Taylor et al., 2005). Pulverization of the lunar materials creates small particles that either remain as independent dust particles or rapid melting and solidification can cause agglutinate formation or large conglomerate particles (impact breccias). Pulverization can also completely melt the materials forming glass (Rickman and Street, 2008a). This process causes some mixing from region to region on the Moon, but in the absence of an atmosphere or any form of fluid motion, the particles are not sorted by size and they maintain their sharp edges and points resulting in their abrasive properties. A lack of sorting also allows higher concentrations of abrasive minerals, such as spinel (Sunshine et al., 2010), to build up in one region versus being evenly distributed. More than a quarter of the soil is made up of agglutinates (fused soil), and only small fractions are impact-generated glasses and breccias (Colwell et al., 2007).

Various definitions are used by different groups to describe what size particles constitute "dust". Lunar regolith occupies the upper several meters (in some cases up to 15–20 m) of the Moon and consists of unconsolidated rocks, pebbles, and dust over lunar bedrock (Colwell et al., 2007). Colwell et al. (2007) categorized regolith smaller than 1 cm as "soil", less than 1 mm as "fines", and smaller than 100 μm (effective particle radius of 50 μm) as "dust". Over 95% of the regolith particles are under 1.37 mm, 50% are under 60 μm (the thickness of a human hair strand), 10–20% are finer than 20 μm, and 5% are less than 3.3 μm (Plescia, 2008; Taylor and Hill, 2005). Dust accounts for 10–20% of the regolith's bulk mass (Taylor and Hill, 2005). NASA's Constellation program uses a definition of less than 10 μm for dust (Plescia, 2008), while the DMP in NASA's Exploration Technology Development Program has heretofore been using 20 μm. The health exposure programs refer to dust as less than 5 μm, which is the respiratory cut-off. The properties and composition of dust particles of less than 20 μm are not well known, as this portion of lunar samples was not well preserved partially because the dust grains in that range adhered to the sample bags and were not removed or analyzed.

Determining an accurate material lifetime estimate for operations is critical, as it influences launch mass and failure modes. Specific effects of lunar dust on Extravehicular Activity Systems (EVAS) during the Apollo era were cataloged by Gaier (2007) who additionally pointed out that the severity of dust problems was consistently underestimated by ground tests. Specific concerns for astronauts on lunar Extravehicular Activities (EVA) included issues such as vision obscuration, false instrument readings, dust coating and contamination, loss of traction, clogging of mechanisms, abrasion, thermal control problems, seal failures, inhalation and irritation, excessive crew time being used to clean EVA suits and equipment, and electrical conductivity. Problems spanned the entire mission from before touchdown, when jet-blasted dust obscured vision leading to a landing that straddled a crater, to continuous eye irritation all the way back to earth. In one case, the Lunar Module landed straddling a small crater and was tilted 10° off normal; 11° off normal is where a 'no lift off' capability is determined.

Specific to the focus of this paper, abrasion problems recorded from the Apollo missions by Gaier (2007) included:

- Conrad and Bean's suits worn though above the boot, including micrometeoroid protection layer and several layers of breached Kapton® multi-layer thermal insulation;
- Wear on outer layer of Mylar® multi-layer insulation on boots;
- Pressure failures;
- Gauge dials scratched (Lunar Roving Vehicle unreadable on Apollo 16), and pitting. Schmitt's visor sunshade so scratched he could not see in certain directions (Apollo 17); and
- Apollo 17 astronaut glove covers were worn through after drilling cores on two (of three) EVA excursions.

3. Lunar regions

Traditionally, the Moon has been categorized into two distinct regions: the basaltic-rich mare (plural: maria) and the anorthositic highlands as seen in Fig. 1. The regolith is deeper in the older highlands than the maria. The maria contains dark basalts, while the lunar highlands have lighter-colored feldspar-rich rocks (Colwell et al., 2007). Lunar topography can be further categorized into zones by geomorphological features such as impact craters and their respective sub-features, including crater basins, crater rims, slopes, and central peak/rings. The significance of understanding lunar geology is that it is a predictor of the mineralogy to be expected during exploration in different regions, which therefore can be used to define localized effects that lunar dust may have on systems (Kobrick et al., 2008; Kobrick and Klaus, 2008). Regolith properties will also change with exploration frequency from a pristine native state to a perturbed surface changing the mineralogy and particle size and shape exposure. Most of the Apollo era samples were taken on the near side of the Moon (facing Earth) and therefore are primarily mare-based. The mare only covers 16% of the lunar surface area (Dunbar, 2007) leaving a wide gap in exploration knowledge of the fundamental lunar regions.

Table 1 lists the significant lunar minerals, their reported Mohs hardness values, their approximated abundance, and chemical composition. Ideally as we collect data from the Moon in future missions, abundance and concentrating processes can be quantitatively addressed. An example of a concentrating process is the proposed use of beneficiation, a process used in mining for separating key minerals from the feedstock, prior to extracting oxygen from ilmenite. Fundamental material properties indicate that a harder material will abrade a softer material. Experience has shown that the mineral friability and the material toughness (of the material being abraded) contribute to the wear interactions. The abundance of a given mineral directly relates to the frequency of interaction expected during a lunar mission.

Data from the Moon Mineralogy Mapper, an imaging spectrometer on-board India's Chandrayaan-1 spacecraft, indicated spinel-rich deposits in the near side dark mantle. The strongest spinel signatures occurred as small concentrations on the scale of

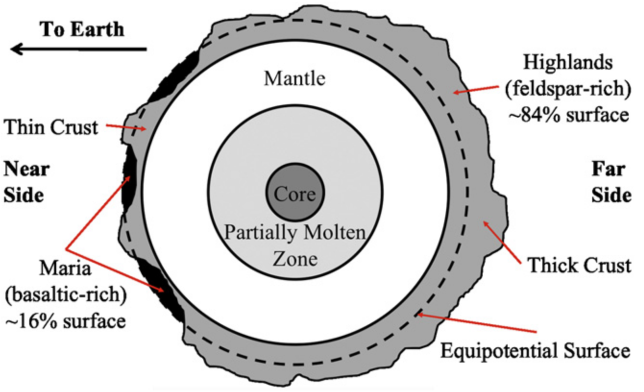

Fig. 1. The fundamental lunar regions include the basaltic-rich maria and feldspar-rich highlands (adapted from Lang, 2003).