NASA/TM—2010-216792

Defining an Abrasion Index for Lunar Surface Systems as a Function of Dust Interaction Modes and Variable Concentration Zones

Ryan L. Kobrick and David M. Klaus
University of Colorado at Boulder, Boulder, Colorado

Kenneth W. Street, Jr.
Glenn Research Center, Cleveland, Ohio

October 2010

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*

- E-mail your question via the Internet to *help@sti.nasa.gov*

- Fax your question to the NASA STI Help Desk at 443–757–5803

- Telephone the NASA STI Help Desk at 443–757–5802

- Write to:
  NASA Center for AeroSpace Information (CASI)
  7115 Standard Drive
  Hanover, MD 21076–1320

NASA/TM—2010-216792

Defining an Abrasion Index for Lunar Surface Systems as a Function of Dust Interaction Modes and Variable Concentration Zones

Ryan L. Kobrick and David M. Klaus
University of Colorado at Boulder, Boulder, Colorado

Kenneth W. Street, Jr.
Glenn Research Center, Cleveland, Ohio

Prepared for the
Lunar Dust, Plasma and Atmosphere: The Next Steps
sponsored by the University of Colorado
Boulder, Colorado, January 27–29, 2010

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

October 2010

Acknowledgments

This research was supported by a NASA Graduate Student Researchers Program (GSRP) grant (NNX07AR55H) provided by the Dust Management Project, under the Exploration Technology Development Program. Test equipment and support were provided by the NASA Glenn Research Center. Additional support was provided by BioServe Space Technologies at the University of Colorado at Boulder (UCB) and the Achievement Rewards for College Scientists (ARCS) Foundation, Inc. The concepts within the paper were presented at the first workshop on “Lunar dust, plasma and atmosphere: The next steps” held January 27–29, 2010 at the Laboratory for Atmospheric and Space Physics, UCB. Anorthosite was provided by NASA GRC from the USGS. Prof. Joe Smyth (UCB) provided the ruby spinel and olivine samples.

Available from

NASA Center for Aerospace Information
7115 Standard Drive
Hanover, MD 21076–1320

National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312

Available electronically at http://gltrs.grc.nasa.gov

Defining an Abrasion Index for Lunar Surface Systems as a Function of Dust Interaction Modes and Variable Concentration Zones

Ryan L. Kobrick and David M. Klaus
University of Colorado at Boulder
Boulder, Colorado 80309

Kenneth W. Street, Jr.
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

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.

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 catalogued 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. These 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.

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, which may result in different characteristic lunar regolith composition. A power law can approximate the average number of micrometeoroid impacts and size distribution. Micrometeoroid sizes range from 30 to 150 μm in radius with masses of 10^{-10} to 10^{-8} kg impact the Moon at speeds averaging 7 km/s (Colwell et al., 2007). 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 or causes agglutinate formation to occur which forms large conglomerate particles (or impact breccias). Pulverization can also completely melt the materials forming glass (Rickman and Street, Jr., 2008a). This process causes some mixing from region to region on the Moon, but in the absence of an atmosphere or any form of erosion or fluid motion, the particles are not sorted by size and they maintain their abrasive properties. More than a quarter of the soil is made up of agglutinates (fused soil), and only a small fraction 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 to 20 m) of the Moon and consists of unconsolidated rocks, pebbles, and dust over lunar bedrock (Colwell et al., 2007).

Table 1 gives several definitions of lunar regolith types, and Table 2 shows the distribution of particle sizes in the lunar regolith.

TABLE 1.—LUNAR REGOLITH DEFINITIONS

Regolith type	Maximum particle size	Reference
Soil	<1 cm	Colwell et al., 2007
Fines	<1 mm	Colwell et al., 2007
Dust[a]	<100 μm[b]	Colwell et al., 2007
	<20 μm	Dust Management Project of NASA’s Exploration Technology Development Program (up to Aug. 2010)
	<10 μm	NASA’s Constellation Program (Plescia, 2008)
	<5 μm	Health-exposure programs (respiratory cutoff)

[a]Dust forms 10 to 20 percent of the bulk mass of lunar regolith (Taylor and Hill, 2005).
[b]Effective particle radius of 50 μm.

TABLE 2.—LUNAR REGOLITH PARTICLE SIZES[a]

Maximum particle size	Distribution of regolith particle sizes, percentage of total particles
<1.37 mm	95
<60 μm (thickness of human hair)	50
<20 μm	10 to 20
<3.3 μm	5

[a]Plescia (2008) and Taylor and Hill (2005).

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 for analysis.

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 10º off normal; 11º 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 (DuPont) multi-layer thermal insulation;
- Wear on outer layer of Mylar (DuPont) 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.

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 Figure 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 percent of the lunar surface area (Dunbar, 2007) leaving a wide gap in exploration knowledge of the fundamental lunar regions.

Table 3 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. 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.

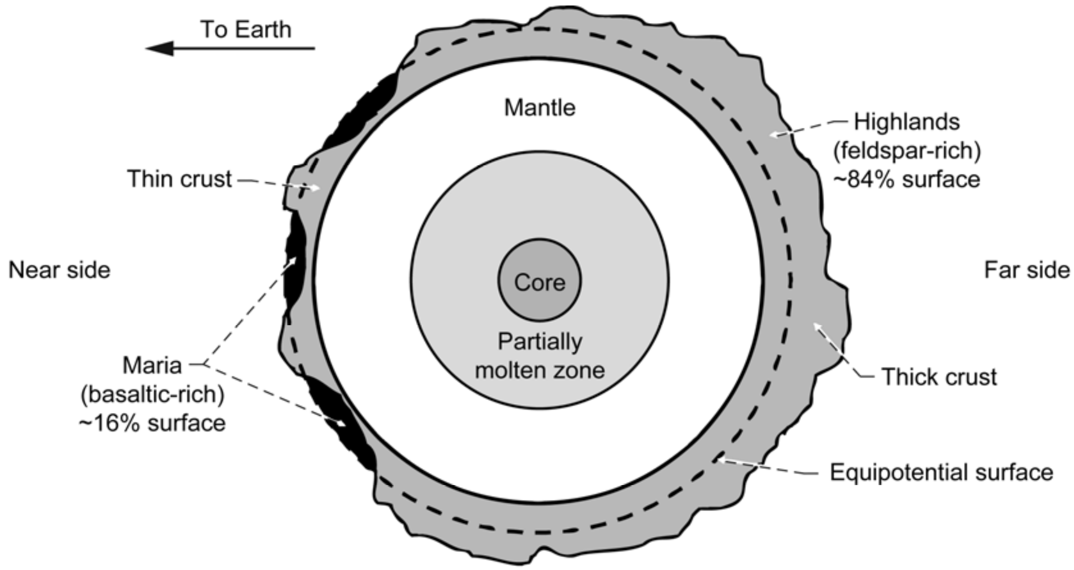

Figure 1.—The fundamental lunar regions include the basaltic-rich maria and feldspar-rich highlands (adapted from Lang, 2003).

TABLE 3.—SIGNIFICANT LUNAR MINERALS
[Rickman and Street, Jr., 2008A.]

Mineral	Mohs	Percent	Chemical composition
Anorthite	6	A[a]	$CaAl_2Si_2O_8$
Bytownite	6.0 to 6.5	M[b]	$(Ca,Na)(Si,Al)_4O_8$
Labradorite	7	M	$(Ca,Na)(Si,Al)_4O_8$
Olivine	6.5 to 7.0	M	$(Mg,Fe)_2SiO_4$
Fayalite	6.5 to 7.0	---	Fe_2SiO_4
Forsterite	6.5 to 7.0	---	Mg_2SiO_4
Clinoenstatite	5.0 to 6.0	M	$Mg_2 [Si_2O_6]$
Pigeonite	6	M	$(Mg,Fe^{+2},Ca)_2[Si_2O_6]$
Hedenbergite	6	M	$CaFe^{+2}[Si_2O_6]$
Augite	5.5 to 6.0	M	$(Ca,Na)(Mg,Fe,Al,Ti)[(Si,Al)_2O_6]$
Enstatite	5.0 to 6.0	A	$Mg_2[Si_2O_6]$
Spinel	7.5 to 8.0	m[c]	$MgAl_2O_4$
Hercynite	7.5 to 8	m	$Fe^{+2}Al_2O_4$
Ulvospinel	5.5 to 6.0	m	$TiFe^{+2}{}_2O_4$
Chromite	5.5	m	$Fe^{+2}Cr_2O_4$
Troilite	4	t[d]	FeS
Whitlockite	5	t	$Ca_9(Mg,Fe^{+2})(PO_4)_6(PO_3OH)$
Apatite	5	t	$Ca_5(PO_4)_3(OH,F,Cl)$
Ilmenite	5.5	m	$Fe^{+2}TiO_3$
Native Iron	4.5	t	Fe

[a]abundant
[b]major
[c]minor
[d]trace

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 <1 km and were observed to be associated with small fresh craters and crater walls (Sunshine et al., 2010). Since spinels are the hardest minerals previously encountered on the Moon, deposits could be associated with a higher frequency of abrasive wear and higher exploration risk for material lifetime.

When the abrasive hardness is similar to or larger than the substrate, the interactions approach polishing, and wear resistance improves by an order-of-magnitude. When the abrasive exceeds the substrate hardness, polishing will continue. Hardness is the resistance to localized plastic deformation (typically in the form of an indentation scratch). The traditional and earliest quantifiable method of measuring hardness is by a scratch test, which compares the ability of the substance to scratch or be scratched by a series of standard minerals, the Mohs Scale. With several standard test methods available, lunar dust hardness can be approximated (see Fig. 2 for scale comparison including commonly used or proposed space construction materials). In passing, it should be noted that hardness ranges occur for minerals due to compositional variation (e.g., Diamond), crystal orientation (e.g., Apatite) and environmental humidity. Hardness values may be significant for multiple investigations, specifically abrasion wear, as they can indicate how a material may react in a given environment.

Another observation made during this research was that two minerals with similar hardness values, but different toughness values (ability to absorb mechanical or kinetic energy up to failure), produced significantly different wear levels. Toughness is the resistance of a material to fracture when stressed and can be quantified by the area under a stress-strain curve. Brittle materials include ceramics and minerals, whereas tough or ductile materials include metals and alloys like carbon steel. Materials like silica have a high hardness value but are brittle, resulting in less abrasivity than minerals with high hardness and toughness (Rickman and Street, 2008b). On the other hand, ceramic construction materials and coated materials also tend to be brittle resulting in failures that do not occur in metals. Further, manufacturing processes can lead to different surface hardening and surface finishes for metals. Work hardening also occurs for some metals altering the surface hardness, which also affects the toughness making it difficult to have a direct correlation between hardness and abrasive wear.

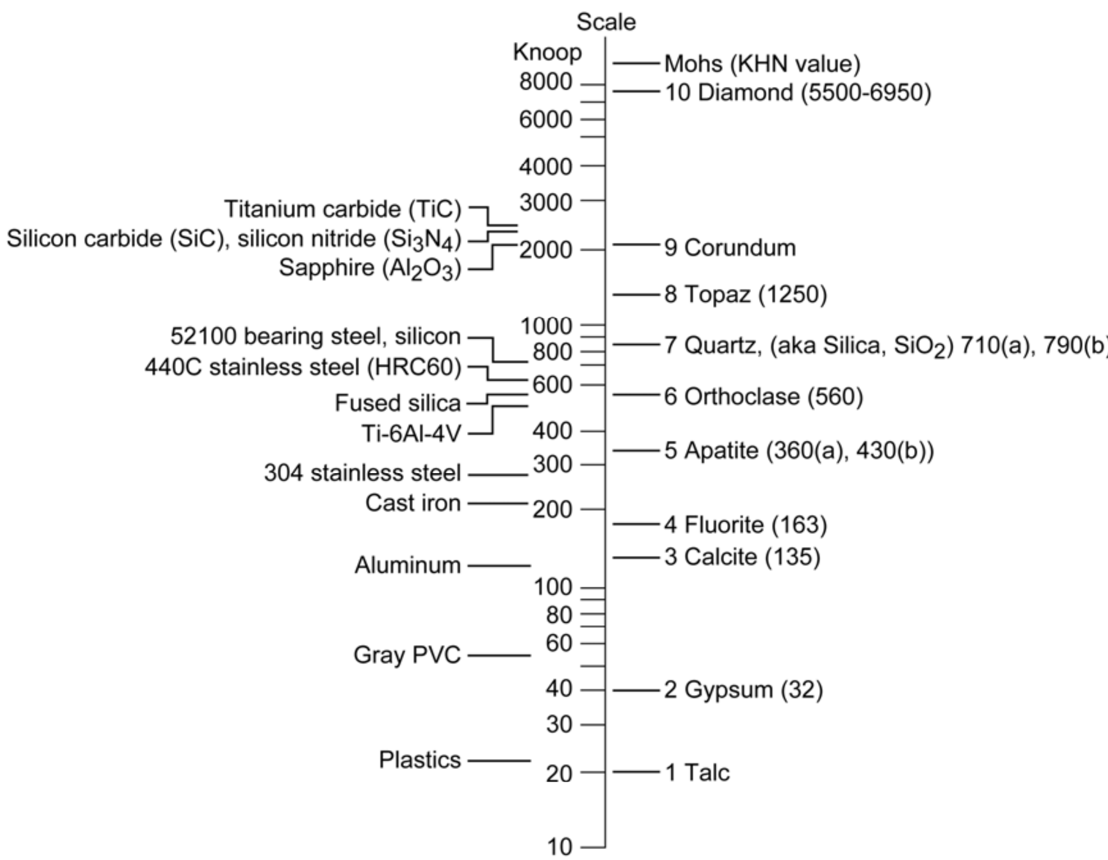

Figure 2.—Comparison of Mohs to Knoop hardness (Rickman and Street, Jr., 2008a) with typical spacecraft materials. (a = parallel and b = perpendicular to axis).

Density of regolith is also important for exploration activities in the different lunar regions. Relative density increases with regolith depth, suggesting that the regolith becomes more compacted (Colwell et al., 2007). Because of the properties of density, void ratio, cohesion, and friction angles, crater rims are expected to be less dense (less than 50 percent) than their surrounding lunar terrain (Colwell et al., 2007). This is important for exploration activity operations as it may result in more dust leaving the surface as well as greater penetration into the soil. The density from actual missions was found to be higher than predicted, and the increase with depth was suggested to be primarily due to self-weight. Density estimations and calculations suggest that the soil on slopes is considerably weaker (Mitchell et al., 1972) or less dense due to the observed lower mechanical soil (or regolith) stability.

Recent conference discussions regarding the results from NASA's Lunar Crater Observation and Sensing Satellite (LCROSS) have indicated that the crater slope regolith where the LCROSS impacted had a lower density than expected. The term 'fluffy regolith' has been used to describe the density phenomenon. Density mapping analysis and mission architecture planning will need to consider that lunar regolith layering is not fully understood and may not be predictable with current data (Colaprete et al., 2010).

Abrasion Modes

The lunar science community identified the abrasive nature of lunar dust as one of the top five physical properties of interest. Abrasion's importance was ranked as 'high' because it affects any material that moves or has a sealing surface. In the field of Tribology, abrasion is one of the four basic types of wear or physical mechanisms for material removal or displacement (see Fig. 3) (ASTM, 1997) and is the most severe and most costly form of wear (Budinski and Ives, 2005). Wear resistance is not a basic material property, but a system response of the material as a function of its use (ASTM, 1997). Abrasive wear occurs when a hard protuberance (asperity) on the surface of a material, or a hard, loose particle trapped between surfaces, plastically deforms, gouges or cuts the counter surface as a result of motion. The result is a series of grooves in soft material or surface fractures in brittle material. Additionally, with hard material this is often accompanied by the resulting formation of wear particles. Abrasion can be sub-categorized by degree of freedom into two tribosystems; two-body and three-body wear. Two-Body abrasive wear occurs when hard particles or protuberances, which produce the wear of one body, are fixed on the surface of the opposing body (ASTM, 2005). A simplified example would be sandpaper against a surface. Three-Body abrasive wear occurs when loose particles are introduced or generated between the contacting surfaces (ASTM, 2005). For example, this occurs when sand is continually poured between two plates rubbing against each other. Two-body fixed abrasives are typically used for testing plastics, metals, ceramics, and composites, while three-body testing is used for all materials (Budinski and Ives, 2005).

Degree of freedom influences the abrasiveness of a test, and generically two-body abrasion will produce significantly higher wear than three-body, because three-body particles have the ability to roll (two-body abrasive particles are fixed in orientation during wear). This may make two-body

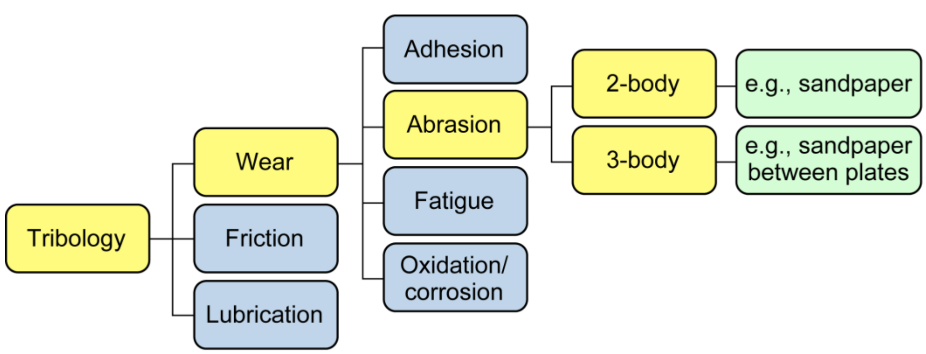

Figure 3.—Overview of tribology and types of wear.

measurement easier to obtain since the wear would be more sizeable. The wear on a material is fairly constant when the abrasive is much harder than the material. For this reason, the material property of hardness can be used as an estimate of how much abrasion is expected between a pair of materials as previously stated. Each industry has developed custom tests that are specific to their environment and interaction type of wear. Some of these tests have become standards with ASTM International and relevant examples are listed in Table 4.

Determining the appropriate test for various abrasive scenarios is an ongoing process. For space surface applications, additional methods are being developed to examine the fundamental modes of wear. The known spacesuit/spacecraft lunar dust contamination points combined with the Apollo era issues help define the modes of wear that need to be investigated. The two main modes of dust interactions occur when spacecraft, spacesuit, or robotic materials either come into direct contact with lunar dust (a two-body problem), or when dust is trapped between two surfaces in relative motion (a three-body problem). In the examples presented in Figures 4 and 5, it should be noted that wear could be occurring on all materials involved. Under categorization of wear, sliding and rolling are considered non-abrasive wear (Budinski, 2007), but for the purposes of defining interactions, rolling also coincides with rotation.

TABLE 4.—SUMMARY OF RELEVANT ASTM STANDARDS FOR ABRASION TESTING

Test name (abbreviated)	ASTM standard	Degree
Loop abrasion test	G 174 (replace G 65)	Two-body
Drum abrasion test	G 132	Two-body
Scratch test	G 171	Two-body
Plastic abrasion test (withdrawn)	D 1242	Two-body
Taber abraser	D 4060	Two-body
Abrasion by particle movement	Nonstandard Tests	Two-body
Printer ribbon test	G 56	Two-body
Yarn test	D 3108	Two-body
Magnetic tape abrasivity test	-----------	Two-body
Rock abrasiveness by CERCHAR Method	D 7625	Two-body
Gouging abrasion with jaw crusher	G 81	Three-body
Dry-sand, rubber, wheel abrasion	G 65	Three-body
Wet-sand abrasion	G 105	Three-body
Taber with ancillary grit feeder	F 510	Three-body
Disk versus disk	-----------	Three-body
High abrasion test	-----------	Three-body
Wet high-stress abrasion test	B 611	Three-body
Chemo-mechanical planarizing	-----------	Three-body
Ball cratering test	VAMAS	Three-body
Gas jet erosion test	G 76	Three-body
Abrasion resistance of textile fabrics	D 3884	Three-body

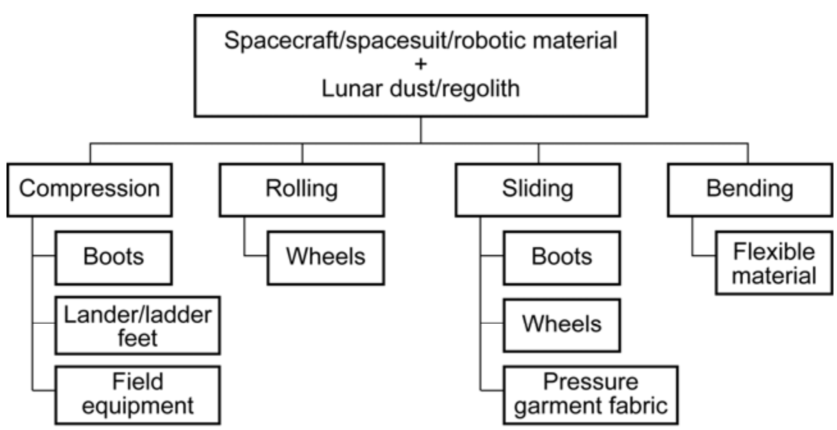

Figure 4.—Materials interacting directly with lunar dust (Kobrick et al., 2008).

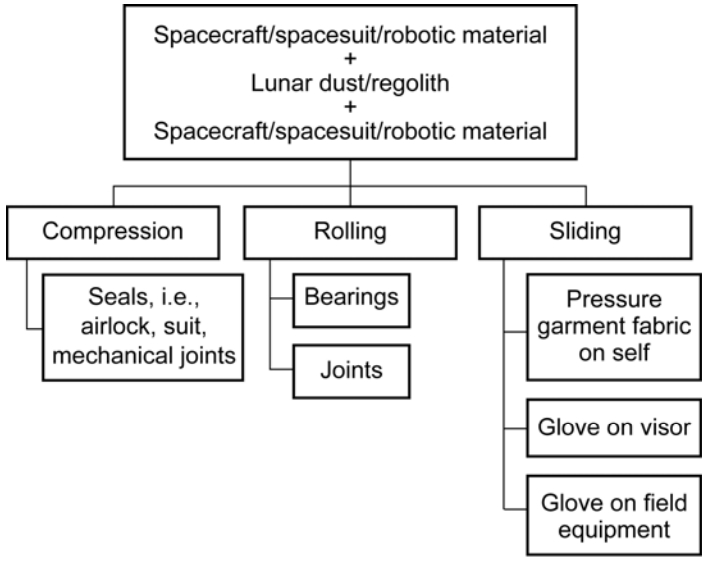

Figure 5.—Materials interacting with lunar dust between them (Kobrick et al., 2008).

Although Figure 5 addresses interactions with two similar or different space construction materials interacting with dust, fundamentally it can be viewed as dust interacting independently on each surface with the same applied force. With this reasoning it would not be necessary to test multiple materials in the same abrasion test, but the independent results can be extended towards applications or scenarios that include two or more materials interfacing with dust.

With the different abrasion-modes, relevant tests can be developed that utilize either a two-body or three-body apparatus relevant to the specific interaction and loaded accordingly with the appropriate normal force. The type of measurements will depend primarily on the test configuration, but will also take into account common practices of employing mass changes, volume loss measurements, and surface deformation evaluation, as applicable.

The ASTM 171 Standard for scratch testing was determined to be the best practice for investigating the fundamental interactions of a single particle on a given material with a two-body test. The methodology, along with results, is extensively explained in previous papers by the authors (Kobrick et al., 2008, 2009, 2010a, 2010b, 2010c; Kobrick and Klaus, 2008). Figure 6 is a photograph of the standard diamond tip with 200 μm radius and 120º apex angle scratching aluminum (Al) 6061–T6. ASTM 171 prescribes running three scratch tests, with one width measurement each. With current technology, a complete 3–D profile of the surface can be generated and mathematically analyzed. The authors' proposed new method generates three surface profiles per scratch that includes approximately 480 cross sections each, totaling 4,320 cross sections per tip to specimen combination.

A key finding during the investigation was that the ASTM G 171 Standard utilized scratch width the key measured variable, but this methodology neglected the volumetric differences within the scratch and surrounding area. The authors' main suggested improvement to the current standard was to include an entire 'Zone of Interaction' (ZOI) to more fully characterize the abraded material. Figure 7 shows a cross section or a representative scratch indicating the ZOI boundary conditions, which were suggested to be three times the surface roughness (Ra).

The standard scratch test normally uses a diamond stylus with an applied constant normal load as it translates over the specimen surface. Since lunar exploration activities will encounter a variety of mineralogy, but not including diamonds, custom tips were also investigated. Figure 8 shows a ruby spinel ($MgOAl_2O_3$, CU–Boulder #2348, from Kandy, Ceylon, Dana No. 7211) tip mounted in a custom holder for testing, chosen for its high hardness value. Other minerals tested included anorthosite (from U.S. Geological Survey, USGS, base materials of the NU–LHT highland simulant, source Stillwater

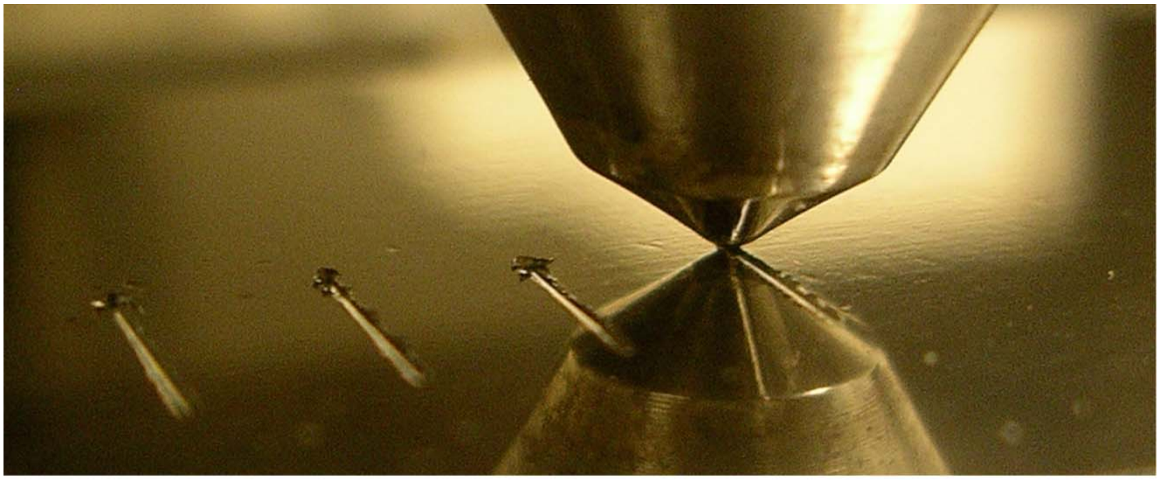

Figure 6.—Diamond 200-µm radius tip mounted on Revetest automatic scratch tester abrading Al 6061–T6 as specified by ASTM G 171 (Kobrick et al., 2010a, 2010b).

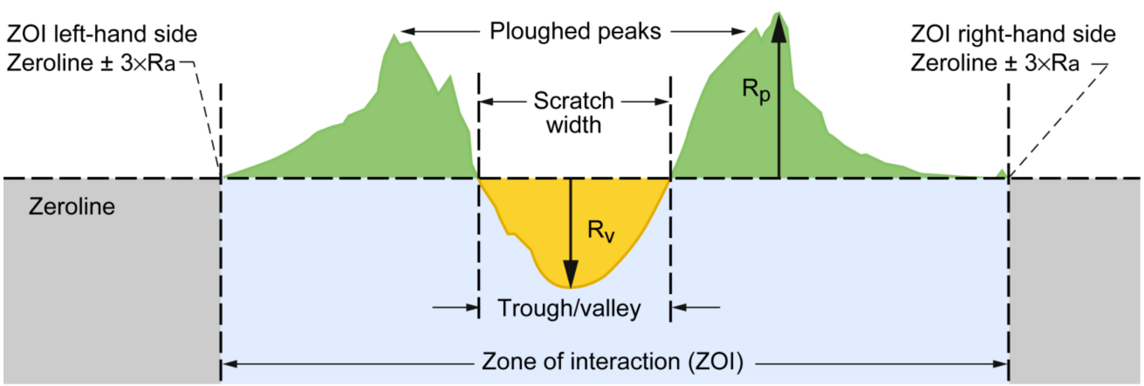

Figure 7.—Example of boundary conditions for zone of interaction at ± 3×Ra showing negative and positive displacements (Kobrick et al., 2010a, 2010b).

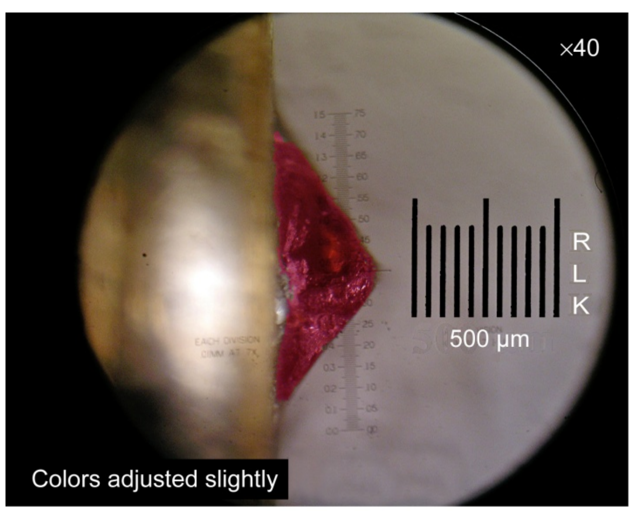

Figure 8.—Custom ruby spinel tip developed for two-body abrasion investigation.

TABLE 5.—THREE-BODY ABRASION TEST SUMMARY
[Kobrick et al., 2010c]

	Number of abrasive tests				
Material	JSC–1AF	JSC–1AF <25um	Alumina	Silica	NU–LHT–2M
6061 Aluminum	3	3	4	4	3
1018 Steel	3	3	4	4	3
1045 Steel	3	3	4	4	3
PMMA	3	3	4	4	3

Mine, MT), enstatite (from NASA GRC, source Mogok, Sagaing District, Mandalay Division, Burma–Myanmar) and olivine (from CU–Boulder lab, source AZ) because of their higher abundance on the Moon and higher Mohs hardness values. Due to the friability of these minerals, they shattered under low normal loads creating secondary and tertiary scratches. These interactions were also indications that a simple scratch width did not suffice for describing abrasion interactions. Custom tips also add the complication of having different geometries and crystal orientations, so comparing results is currently only qualitative.

A secondary study was conducted to investigate three-body abrasion with a modified tribotester and dry abrasives, based on ASTM Standard B 611 (Kobrick et al., 2010c). Standard abrasives of alumina and silica were compared to lunar simulants of JSC–1AF (mare region simulant) and NU–LHT–2M (highland region simulant) and are summarized in Table 5. The tests showed that each material tested (aluminum 6061, steel 1010, 1018, and 1045, and PMMA) reacted similarly to the silica abrasive for softer materials and that the alumina abrasive showed more wear on all materials than the counterparts (Kobrick et al., 2010c). Since alumina was demonstrated to be more abrasive than the simulants, systems could be tested using this common abrasive instead of a lunar simulant to yield a higher safety factor, but at the potential cost of unnecessarily overdesigning the system. Ongoing testing is investigating this approach with varying sizes of alumina particle sizes on the same material set.

Spacecraft Dust Concentration Zones

In addition to the specific mode of dust interaction, the spacecraft and surrounding environment can be subdivided into three fundamental dust concentration zones as depicted in Figure 9 ranging from (1) outside the habitat where extensive dust exposure occurs, (2) in a transitional area such as an airlock or suitport, and (3) inside the habitat or spacesuit with a low particle count. These zones can also be mapped to robotic systems as well, where the transitional zone boundaries could be at mechanical interfaces and the internal zones would be the circuit boards. These lunar zones can be used to help define dust interaction frequencies, characterize environmental risks to the systems and/or crew, influence material selection (based on location of part and exposure), or affect the operational protocols used during the mission architecture.

Defining the entry probability that a grain of dust will come in contact with an astronaut on an EVA and then comparing that data to actual field tests can be used as a means of validating a measure of effectiveness for various dust mitigation technologies and strategies. For example, the probability of dust grain entering the lander post EVA can be defined as Equation (1) (Hyatt et al., 2007).

$$P = P_a\,(1 - P_L^{Ext})\;T\;P_L^{Int} \tag{1}$$

where P_a is the probability of a grain in the near-vicinity of an astronaut adhering to a spacesuit, P_L^{Ext} is the loss probability of a dust grain external to the habitat in regular EVA activity or mitigation process, P_L^{Int} is the probability of grain release from the suit internal to the habitat. The variable T is defined as the transmission coefficient of the internally released dust grain from the airlock to the habitable volume of the habitat (i.e., no airlock $T = 1$) (Hyatt et al., 2007).

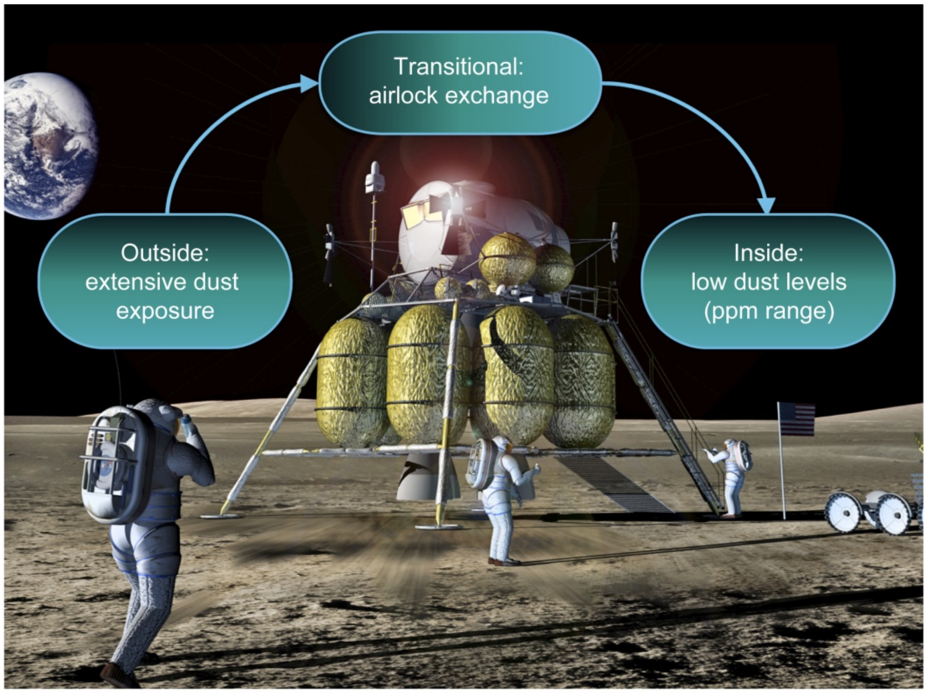

Figure 9.—The three fundamental dust zones of the spacecraft environment (adapted from NASA photo).

Probability approximations can be used in trade studies for selection of critical exploration systems such as solar panels, mechanical interfaces, and lunar lander airlock concepts. Other trade studies could include dust characteristics, material performance, material properties (such as flexibility), power requirements and mass allocation.

The following list summarizes potential technologies/solutions that could help address dust contact prevention and/or removal (Belden et al., 1991; Calle et al., 2006; Harrington et al., 1990; Taylor et al., 2005; Taylor and Hill, 2005; Walton, 2007). Some of these techniques were employed during the Apollo era, such as brushing, with mixed success. The purpose of this list is to demonstrate various dust mitigation options that have previously been investigated or proposed. The primary shortcoming with most of these approaches is that they jump directly to a solution without properly characterizing the interaction between the dust and the system that caused the problem in the first place. Some of the demonstrations have only been conducted with simulants while others that have used real lunar samples, which represent only specific lunar locations (e.g., most are mare samples) and not the bulk composition of the Moon. It should be pointed out that none of these studies have used dust in the same state of surface activation that will be experienced under actual lunar conditions. Selection of future landing sites will dictate the average particle size distribution and mineral composition that need to be investigated.

1. Brushing—bristle, suction Styrofoam (Dow Chemical Company), cheese cloth
2. Electrostatic—curtain, surface, passive suction, passive brush
3. Jet —with shield, with surface
4. Spinning—shield, surface
5. Dust monitoring
6. Chemical—suction
7. Vibrating—surface, suction, blower
8. Materials—Chromel-R woven into boots/gloves, abrasion-resistant silicone RTV–630 soles/finger tips.
9. Avoidance of PVC products

10. Teflon (DuPont) over Gore fabric twill or composite Ortho fabric
11. Cleaning—Nylon bristle brush (coarse grains), wet wipes, and zippers and seals cleaned and re-lubricated with Krytox (Miller-Stephenson Chemical Company, Inc.) oil and grease.
12. Fluid—foams, gels, liquid and gas solutions
13. Helmet visor "peel-offs"
14. Lightweight coveralls
15. Magnetic manipulation
16. CO_2 "snow" cleaning

Abrasion Index Development

For designing space exploration systems that will encounter dusty regolith, various known input parameters described above can be characterized and mathematically combined to create a non-dimensional abrasion index (illustrated by the basic flow chart displayed in Fig. 10). The creation of an abrasion index can be used to improve the performance and reliability of exploration systems in the areas of: abrasive risk identification; specific mitigation strategies; mission design, such as landing location or field operations; hardware design; testing protocols in the laboratory; and material selection for surface systems.

The next steps in defining a non-dimensional abrasion index would be to quantify the input variables as identified with appropriate scales and then assign weighted criteria to normalize each category so that they can be combined into a final, unitless value. The following discussion includes suggestions for input variables under each category covered in this paper for abrasion on materials, parts, or full systems. An abrasion index showing key variables is functionally described in Equation (2):

$$\text{Abrasion Index} = f\,(R, H, S, F) \tag{2}$$

where

Abrasion index	non-dimensional value quantifying the overall abrasion level
R	material, part or system risk to mission success
H	weighted average hardness value of localized mineralogy
S	severity of abrasion in terms of two- or three-body
F	the frequency of dust particle interactions

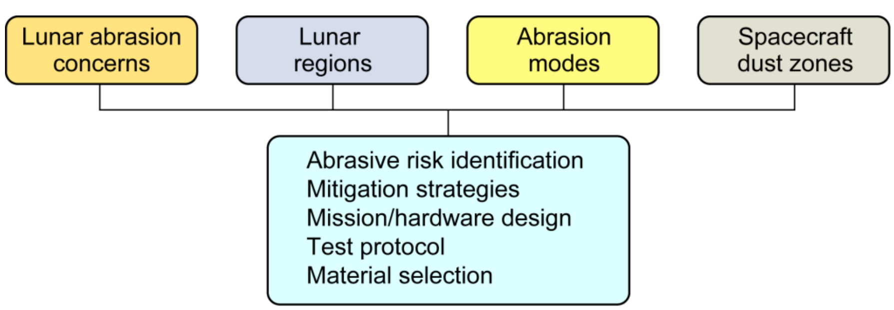

Figure 10.—Flow chart of all necessary inputs required to define an abrasion index.

The lessons learned from lunar abrasion and spaceflight history are that systems will each have unique component-level risks associated with functionality and operations. For example, a spacesuit glove seal would be considered to be a higher risk part than the portable life support system (PLSS) outer fabric layer. An abraded seal can lead to a pressure leak presenting direct astronaut safety concerns, but abrasion to the PLSS fabric may only reduce the amount of padding or potentially change the radiative properties of the material if dust becomes embedded. For an abrasion index, risk to mission success, *R*, is an important variable that must be systematically characterized. A high value would mean that the item is critical to the mission based on historical experience, ongoing data collection or testing. In our example, the glove seal would have a higher value than the PLSS cover. Other potential variables relating to lunar abrasion history could be measured by proximity to the outermost exposed surface or number of cycles expected. Material selection also relates to the system risk, as a soft aluminum with a low hardness value is prone to abrasion.

Lunar regions determine the specific mineralogy that will be encountered by a surface system. The Moon-Sun-Earth alignment influences the degree of micrometeorite bombardment and radiation flux, which can be estimated with current data. The stability of the terrain (crater rims, slopes, and other geological features) will also influence the minerals expected to be displaced by exploration and interacted with each system. The key abrasive variable from lunar regions is the mineralogy hardness value, *H*, which can be measured using various hardness scales. The *H*-value expected in the location of exploration would be determined by a weighted average of hardness values and particle distribution (size and quantity). A high value means that the expected terrain encountered would have more abrasive particles. An example of a high *H*-value region is the spinel deposit regions mentioned previously in the paper.

Modes of two- and three-body abrasion determine the severity, *S*, of expected particle interactions with materials and systems. A high value means that the interaction is expected to cause more wear under anticipated normal loads. This variable could also be binary, if a relationship can be established comparing two- to three-body abrasion. For example, *S* would be a multiplier in the abrasion index of the ratio of two- to three-body wear for a given system.

A final variable category is dependent on the spacecraft dust zones and relates to the frequency, *F*, of particle interactions. A higher value implies more particles are expected to interact with the system. Additional variables could include the probability of interaction in each type of dust zone (based on Hyatt et al., work for dust entering a lunar habitat) and if mitigation strategies are used to reduce the particle count. Mitigation strategies could also be used in reducing risk *R*-values.

In summary, assuming that the suggested non-dimensional index value is established to directly correlate with increasing potential for material wear (i.e., a higher index indicates a greater potential abrasive impact to the system), the four input parameters result in the following trends. Higher *R*, *H*, and *F* values would increase the abrasion index as follows. *R* is determined on a system-by-system basis as a function of the level of risk that is associated with excess abrasive wear on the component. A larger *R*-value implies greater functional criticality that would be impacted by abrasion. *H* and *F* are dependent on the operational environment in terms of the minerals present and the concentration that a given system is exposed to. An increase in either factor presents the potential for greater abrasion to occur. S is a function of the specific tribology effects dependent on how surfaces come into contact with dust in terms of interaction mode and loading profile. The value of *S* increases as classical two-body abrasion is approached, representing a worst-case scenario for particle interaction and resultant wear. Therefore, defining an abrasion index in this manner gives designers a systematic method for combining operational environment factors with system functionality to determine the overall effect of abrasion, which can then be used to predict expected lifetime and performance impacts.

Additional variables can be added as deemed useful, with further work required to determine the most appropriate inputs for a given application. A complete abrasion index should ultimately include weighting criteria and a definition of how the variables relate, i.e., are they a weighted sum, or are some variables multiplied or divided by each other. This work presents the concept and lays a foundation for defining an abrasion index, with suggested potential relationships that can be used to quantify a single, non-dimensional index value.

Conclusions

By characterizing the concerns of lunar abrasion encountered during the Apollo era, future exploration systems can be designed to reduce the potential risk of failure or undesirable degraded performance. Planning for abrasive interactions can help to ensure that field equipment is optimized for the environment it will be used in, taking into account the concentration and hardness of the mineralogy found in the desired exploration region. Terrestrial laboratory and industrial experience can also be used to compile analogous data needed to quantify the level of severity expected for the different interaction modes of abrasion under specified normal loads. The frequency of interactions can be added to predict expected life cycles of the components and systems to ensure safe and efficient operations. Combining these variables, a non-dimensional abrasion index value can be defined that takes all the above into account to aid with mission and hardware design and to ensure proper testing and material selection occurs. The next step in defining this index is to quantify the input variables, establish the appropriate relationships and weighting factors, and determine a suitable, relative index scale.

References

ASTM (1997): "Friction and wear testing: source book of selected references from ASTM Standards and ASM Handbooks." ASTM and ASM International, West Conshohoken, PA and Materials Park, OH.

ASTM (2005): "Standard Terminology Relating to Wear and Erosion." G 40-05, Annual Book of ASTM Standards, ASTM.

Belden, L., Cowan, K., Kleespies, H., Ratliff, R., Shah, O., and Shelburne, K. (1991): "Design of Equipment for Lunar Dust Removal." Mechanical Engineering Department, The University of Texas at Austin. NASA N90–25496.

Budinski, K.G., and Ives, L.K. (2005): "Measuring abrasion resistance with a fixed abrasive loop." Wear, 258, pp. 133–140.ASTM (2003): "Standard Test Method for Scratch Hardness of Materials Using a Diamond Stylus." G 171–03, Annual Book of ASTM Standards, ASTM.

Budinski, K.G. (2007): "Guide to Friction, Wear, and Erosion Testing." ASTM International, West Conshohocken, PA. MNL56.

Calle, C.I., Mazumder, M.K., Immer, C.D., Buhler, C.R., Clements, S., Lundeen, P., Chen, A., and Mantovani, J.G. (2006): "Electrodynamic Dust Shield for Surface Exploration Activities on the Moon and Mars." International Astronautical Congress, Valencia, Spain. IAC–06–A5.2.07.

Colaprete, A., Asphaug, E., Bart, G., Elphic, R., Ennico, K., Goldstein, D., Hermalyn, B., Heldmann, J., Korycansky, D., Landis, D., Wooden, D., Ricco, T., Schultz, P., Sollitt, L., Summy, D. and the LCROSS Team (27 Jan 2010): "A Review of the Lunar Crater Observation and Sensing Satellite (LCROSS) Impact Results" (presentation). "Lunar dust, plasma and atmosphere: The next steps" 1st Workshop, Jan 27–29, Boulder, CO.

Colwell J. E., Batiste S., Horányi M., Robertson S., and Sture S. (2007): "Lunar surface: Dust dynamics and regolith mechanics." Rev. Geophys., 45, RG2006, doi:10.1029/2005RG000184.

Dunbar, B. (2007): "World Book at NASA: Moon." Accessed online 18 Mar 2010, last updated 29 Nov 2007. URL: http://www.nasa.gov/worldbook/moon_worldbook.html

Gaier, J.R. (2007): "The Effects of Lunar Dust on EVA Systems During the Apollo Missions." NASA, Glenn Research Center, Cleveland, OH. NASA/TM—2005-213610/REV1.

Harrington, D., Havens, J., and Hester, D. (1990): "Design of a device to remove lunar dust from space suits for the proposed lunar base." Mechanical Engineering Department, The University of Texas at Austin. NASA N90–25496.

Hyatt, M., Greenberg, P., Pines, V., Chait, A., Farrell, W., Stubbs, T., and Feighery, J. (2007): “Lunar and Martian Dust: Evaluation and Mitigation.” NASA Glenn Research Center at Lewis Field. AIAA 45th Aerospace Sciences Meeting, Session 47–GPSE2, Reno, NV.

Kobrick, R.L., and Klaus, D.M. (2008): “Characterizing Physical Properties and Induced Motion of Lunar Dust Affecting Surface Exploration Missions.” Lunar and Planetary Science XXXIX. Abstract No. 1439.

Kobrick, R.L., Street, K.W., Klaus, D.M., Greenberg, P.S., and Hyatt, M.J. (2008): “Developing Abrasion Testing Hardware to Evaluate Effects Caused by Lunar Dust on Construction Materials.” 59th International Astronautical Congress. Space Exploration Symposium, Interactive Session on Moon Exploration, IAC–08–A3.2.INT3, Glasgow, UK.

Kobrick, R.L., Klaus, D.M., and Street, Jr., K.W. (2009): “Developing Abrasion Test Standards for Evaluating Lunar Construction Materials.” 39th International Conference on Environmental Systems 2009, Savannah, GA. SAE Technical Paper 2009–01–2377.

Kobrick, R.L., Klaus, D.M., and Street, Jr., K.W. (2010a, In Review): “Standardization of a volumetric displacement measurement for two-body abrasion scratch test data analysis.” J. WEAR. Manuscript number: IH–6025. Elsevier.

Kobrick, R.L., Klaus, D.M., and Street, Jr., K.W. (2010b, In Review): “Validation of proposed metrics for two-body abrasion scratch test analysis standards.” J. WEAR. Elsevier. Manuscript number: IH–6173. Elsevier.

Kobrick, R.L., Budinski, K., Street, Jr., K.W., and Klaus, D.M. (2010c, In Review): “Three-Body Abrasion Testing using Lunar Dust Simulants to Evaluate Surface System Materials.” 40th International Conference on Environmental Systems 2010, Barcelona, Spain. AIAA Control ID: 753630.

Lang, K.R. (2003): “Lunar interior.” Fig. 5.22. Tufts University. Accessed online 18 Mar 2010, last updated 2009. URL: http://ase.tufts.edu/cosmos/view_picture.asp?id=389

Mitchell, J.K., Houston, W.N., Scott, R.F., Costes, N.C., Carrier, III, W.D., and Bromwell, L.G. (1972): “Mechanical properties of lunar soil: Density, porosity, cohesion, and angle of internal friction.” Proceedings of the Third Lunar Science Conference (Supplement 3, Geochimica et Cosmochimica Acta) Vol. 3, pp. 3235–3253.

Plescia, J. (2008): “Lunar Regolith Formation and Properties.” Presentation, Lunar Regolith Community of Practice (LunRCoP) Webinar, 26 Feb 2008.

Rickman, D., and Street, Jr., K.W. (2008a): “Expected Mechanical Characteristics of Lunar Dust: A Geological View.” Proceedings of the Space Technology and Applications International Forum, Albuquerque, NM.

Rickman, D., and Street, Jr., K.W. (2008b): “Expected Mechanical Characteristics of Lunar Dust: A Geological View.” Presentation, Space Technology and Applications International Forum, Albuquerque, NM.

Sunshine, J.M., Besse, S., Petro, N.E., Pieters, C.M., Head, J.W., Taylor, L.A., Klima, R.L., Isaacson, P.J., Boardman, J.W., Clark, R.C. and the M3 Team (2010): “Hidden in Plain Sight: Spinel-Rich Deposits on the Nearside of the Moon as Revealed by Moon Mineralogy Mapper (M3)” (abstract). 41st Lunar and Planetary Science Conference. Abstract No. 1508. The Woodlands, Texas.

Taylor, L.A., and Hill, E. (2005): “JSC–1A “Exposed” Petrography, Mineralogy, and Geochemistry". Planetary Geosciences Institute, The University of Tennessee Knoxville.

Taylor, L.A., Schmitt, H.H., Carrier, W.D., and Nakagawa, M. (2005): “The Lunar Dust Problem: From Liability to Asset,” AIAA 1st Space Exploration Conference: Continuing the Voyage of Discovery. Orlando, FL. AIAA–2005–2510.

Walton, O.R. (2007): “Adhesion of Lunar Dust.” Dept. Research & Technology Directorate. NASA Contract NNC06VC87P. NASA/CR—2007-214685. NASA Glenn Research Center.

REPORT DOCUMENTATION PAGE						*Form Approved* *OMB No. 0704-0188*
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.						
1. REPORT DATE *(DD-MM-YYYY)* 01-10-2010		**2. REPORT TYPE** Technical Memorandum				**3. DATES COVERED** *(From - To)*
4. TITLE AND SUBTITLE Defining an Abrasion Index for Lunar Surface Systems as a Function of Dust Interaction Modes and Variable Concentration Zones						**5a. CONTRACT NUMBER**
						5b. GRANT NUMBER
						5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Kobrick, Ryan, L.; Klaus, David, M.; Street, Kenneth, W., Jr.						**5d. PROJECT NUMBER**
						5e. TASK NUMBER
						5f. WORK UNIT NUMBER WBS 936374.03.05.03.03
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191						**8. PERFORMING ORGANIZATION REPORT NUMBER** E-17414
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001						**10. SPONSORING/MONITOR'S ACRONYM(S)** NASA
						11. SPONSORING/MONITORING REPORT NUMBER NASA/TM-2010-216792
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited Subject Categories: 42 and 48 Available electronically at http://gltrs.grc.nasa.gov This publication is available from the NASA Center for AeroSpace Information, 443-757-5802						
13. SUPPLEMENTARY NOTES						
14. 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.						
15. SUBJECT TERMS Abrasion; Lunar exploration; Lunar dust; Surface systems						
16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**		**19a. NAME OF RESPONSIBLE PERSON** STI Help Desk (email:help@sti.nasa.gov)
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	UU	21		**19b. TELEPHONE NUMBER** ***(include area code)*** 443-757-5802