BOOK OF ABSTRACTS

LUNAR REGOLITH SIMULANT MATERIALS WORKSHOP

JANUARY 24-26, 2005

Organized By:

Marshall Space Flight Center
Johnson Space Center

Sponsored By:

NASA's Human System Research
and Technology Development Program

Hosted By:

Exploration Science and Technology Division
at the NASA Marshall Space Flight Center

Marshall Space Flight Center
Huntsville, AL   USA

The Lunar Regolith Simulant Materials Workshop

January 24 – 26, 2005

Marshall Institute

Madison, Alabama

Foreword

On behalf of the Scientific Organizing Committee, we welcome you to the 2005 Lunar Regolith Simulant Materials Workshop. This workshop is jointly sponsored by Marshall Space Flight Center and Johnson Space Center, and is being held January 24-26, 2005, at the Marshall Institute in Huntsville, AL. We have invited experts in a number of disciplines in order to identify and define lunar regolith simulant materials that are, and will be, needed for research and development of the next generation lunar technologies. The absence of widely-accepted lunar simulant standards that represent the different potential lunar landing regions is the urgent issue that dictates the timing of this workshop. Following the address of President G.W. Bush, which defined the National Vision for Space Exploration in January 2004, NASA has adopted an aggressive schedule to return a human presence on the moon and on to Mars for the long term. Hence, this workshop approaches the problem of simulant materials from the perspective of the technology developers and scientists who will prepare and support these missions.

In September 1989, a workshop entitled "Production and Uses of Simulated Lunar Materials" was convened at the Lunar and Planetary Institute in Houston, Texas, to define the needs for simulated lunar materials and examine related issues in support of the Space Exploration Initiative launched by then-President G.H. Bush. This effort led to the development of lunar simulants JSC-1, and MLS-1 which were widely distributed, but are no longer in production and supplies have been exhausted. Several organizers and participants of the 1989 workshop have contributed to the organization of the 2005 workshop and the excellent results achieved in 1989 form the foundation upon which we will build during the next few days. We look forward to working together on these goals.

Laurent Sibille   Paul Carpenter
Chair   Co-chair

On behalf of the Scientific Organizing Committee

Laurent Sibille   Paul Carpenter
BAE Systems   BAE Systems
Analytical & Ordnance Solutions   Analytical & Ordnance Solutions
Marshall Space Flight Center   Marshall Space Flight Center

David S. McKay   Lawrence A. Taylor
Astromaterials Research & Exploration Science   Planetary Geosciences Institute
Johnson Space Center   University of Tennessee, Knoxville

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Department of Geology   Lunar Geotechnical Institute
University of Texas at Dallas   Lakeland, FL

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Posters

THE STATUS OF LUNAR SIMULANT MATERIALS, WORKSHOP OVERVIEW AND OBJECTIVES.

L. Sibille, BAE Systems Analytical and Ordnance Solutions, NASA Marshall Space Flight Center, XD42, Huntsville, AL, 35812, Laurent.Sibille@msfc.nasa.gov.

Introduction: As NASA turns its exploration ambitions towards the Moon once again, the research and development of new technologies for lunar operations face the challenge of meeting the milestones of a fast-pace schedule, reminiscent of the 1960's Apollo program. While the lunar samples returned by the Apollo and Luna missions have revealed much about the Moon, these priceless materials exist in too scarce quantities to be used for technology development and testing. The need for mineral materials chosen to simulate the characteristics of lunar regoliths is a pressing issue that must be addressed today through the collaboration of scientists, engineers and program managers. The workshop on Lunar Regolith Simulant Materials being held this week brings together experts from a wide range of disciplines to define the nature of the simulants needed and offers guidelines for the sustainable availability of these reference materials.

Present Status of Lunar Simulant Materials: No coordinated program currently exists in the U.S.A. to define reference materials to be used as analogs of lunar materials. Such coordinated efforts have existed at different times in the past to either provide these materials to specific technology development programs such as the Apollo Landing Module and Lunar Rover or when NASA policies showed a renewed interest in lunar missions as was the case in 1989 and the early 1990's. While no Apollo lunar simulants remain today, the more recent efforts led to the development and distribution of materials such as MLS-1 [1], a titanium-rich basalt from Minnesota and JSC-1 [2], a glass-rich basaltic ash from the volcanic fields of the San Francisco mountains of Arizona. Both of these simulant materials were successful in the sense that they provided known source materials for researchers and engineers but were only adequate for certain applications. These deficiencies led to efforts to ameliorate their characteristics, particularly to better duplicate the content of glassy agglutinates in lunar regoliths (MLS-2). The lack of funding and the waning interest from NASA in the 1990's resulted in disappearing stocks and the resurgence of a variety of 'home-made' lunar simulants and independent commercial materials. Today, neither of the simulants mentioned above are available from their manufacturers. In parallel to NASA-funded simulants, the Japanese space agency NASDA, which is now the Japan Aerospace Exploration Agency, has funded a development program for lunar simulant materials for the past decade. As a result, simulants such as FJS-1, MKS-1 are used in Japan, but are not well known or used in the USA [3]. These materials have been characterized extensively in terms of bulk chemical composition, mineralogy, geotechnical properties and are available in modest quantities. The chaotic situation concerning lunar simulant materials calls for a focused and coordinated development of large quantities of simulant materials in the near future to meet the needs of present and future efforts to develop technologies and test new hardwares for lunar precursor missions and lunar base development.

Workshop Overview and Objectives: Building from the results and conclusions of the 1989 Workshop on Production and Uses of Simulated Lunar Materials [4], we have adopted the following two main objectives for this workshop; 1) To obtain a consensus from expert participants on the requirements for the definition, production, validation and distribution of Lunar Regolith Simulant Materials based on the needs of technology developers and the knowledge of lunar mineral resources and their environment, and 2) To propose strategies to the Exploration Systems Mission Directorate to assure that all R&TD programs for lunar surface systems adopt the same lunar simulant reference materials.

After a day of presentations on how the various characteristics of the lunar regolith affect a wide range of lunar operations from landing a spacecraft to extracting resources and affecting human health, the participants will be asked to work in separate groups to examine the applicability and importance of specific properties of the lunar materials that must be duplicated in simulant materials. This initial session will be followed by the definition of requirements to specify the level of accuracy with which these properties should be duplicated. The scientific organizing committee will then guide the discussion to identify a family of potential simulant materials. Finally, the participants will be asked to examine the critical issues of production feasibility, quality control, storage and distribution, and prioritization of these materials based on spiral development of the exploration capabilities.

References: [1] Weiblen P.W., Murawa M.J., and Reid K.J. (1990) "Preparation of simulants for lunar surface materials" *Engineering, Construction and Operations in Space II*, ASCE, 428-435; ; [2] D.S. McKay, J.L. Carter, W.W. Boles, C.C. Allen & J.H. Allton (1997) "JSC-1: A new Lunar Regolith Simu-

lant", *Lunar and Planetary Science* XXIV, 963; [3] Kanamori, H., Udagawa, S., Yoshida, T., Matsumoto S., and Takagi, K. (1998) 'Properties of Lunar Soil Simulant Manufactured in Japan', Space98, ASCE, 462-468.; [4] D.S. McKay, J.D. Blacic (1991) LPI/Technical Report 91-01.

PHYSICAL AND CHEMICAL CHARACTERISTICS OF LUNAR REGOLITH: CONSIDERATIONS FOR SIMULANTS.

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Introduction: It is obvious that many factors must be considered in making lunar simulants for various ISRU projects. This subject is of major importance as we move into the near-future endeavors associated with a return to the Moon. Herein, detailed geologic specifics of lunar soil are addressed and geotechnical properties are addressed that should be considered before we produce simulants for definitive study purposes.

Formation of Lunar Soil: The lunar soil formed by space weathering processes, the most important of which is micrometeorite (< 1mm) impact dynamics. Although of small mass, these particles possess large amounts of kinetic energy, impinging on the lunar surface with velocities up to 100,000 km/hr. Much of the impacting energy goes into breaking and crushing of fragments into smaller pieces; however, due to the high energy of many of the impacts, the lunar soil is partially to completely melted on a local scale of millimeters. The melted soil incorporates soil fragments and quenches to glass. These aggregates of minerals, rocklets, and glasses are welded (i.e., cemented) together into "agglutinates" [1]. It is the glass in these fragile agglutinates that further becomes comminuted into smaller pieces making for ever-increasing amounts of glass to the lunar soils. Portions of these silicate melts also vaporize, only to condense upon the surfaces of all soil grains. Other cosmic, galactic, and solar-wind particles also perform minor weathering, largely by sputtering; but many of these particles remain imbedded in the outer portions of all lunar soil grains. As demonstrated by Taylor & McKay [2], as the number of lithic fragments decreases, the amount of liberated free minerals increases to a point, with continuing exposure to impact processes actually decreasing the abundance of these mineral fragments. With these changes in rock and mineral fragments, the major accompanying process is the formation of the glass-welded agglutinates; and the abundances of agglutinitic glass increase significantly with decreasing grain size (Fig. 1, [3]), as well as increase in maturity of the soil. Due to complicated interactions of the impact melts with the solar wind, as well as productions of vaporized chemistry, the glass of the lunar soil contains myriads of nano-sized $Fe°$ grains (4-33 nm), with the soil containing 10X more $Fe°$ than the rocks from which it was derived. As a result of all this space weathering, the resulting lunar soil consist of rocklets, minerals, and agglutinates, with major amounts of glasses, impact-produced but also volcanic in origin.
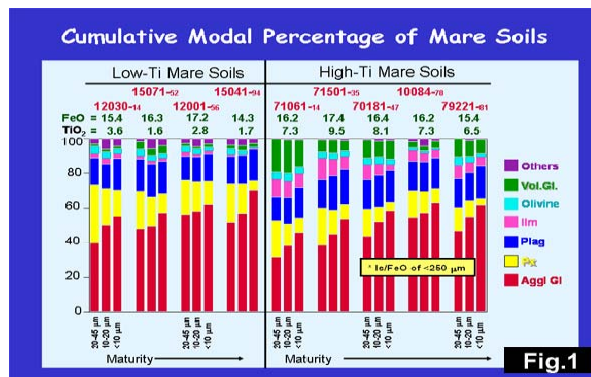
Fig.1

The abundances of glass in lunar soil increases with decreasing grain size, such that the "dust" (i.e., <50 µm) portion of the lunar soil contains over 50% glass [Fig. 1], present as sharp, abrasive, interlocking, fragile glass shards and fragments. It is this same "dust" at <50 µm that constitutes approximately 50% of mature lunar soils, as a rule-of-thumb for size distributions. It is the mainly the presence of these huge quantities of glass that contributes to the unusual engineering properties of lunar soil [4].

"THE Sourcebook": Figure 2 shows "The Lunar Bible" in which the geologic and engineering properties of lunar regolith are presented in detail, by 'lunatic' authorities. This should be the first stop in anyone's search for data about the rocks and soils of the Moon.

Fig. 2

References: [1] McKay, D.S., and A. Basu, 1983, The production curve for agglutinates in planetary regoliths. Jour. Geophys. Res. 88, B-193-199;   [2]

Taylor, L.A., and D.S. McKay, 1992, Beneficiation of lunar rocks and regolith: Concepts and difficulties. In <u>Engineering, Construction, Operations in Space III</u>, Vol. I, ASCE, New York, 1058-1069; [3] Taylor, L.A., Pieters, C., Keller, L.P., Morris, R.V., McKay, D.S., 2001, Lunar mare soils: Space weathering and the major effects of surface-correlated nanophase Fe. *Jour. Geophys. Lett. 106,* 27,985-27,999; [4] Taylor, L.A., Pieters, C., Keller, L.P., Morris, R.V., and McKay, D.S., 2001, The effects of space weathering on Apollo 17 mare soils: Petrographic and chemical characterization. . *Meteor. Planet. Sci. 36*, 285-299; [5] Carrier, W.D., III, Olhoeft, G.R., and Mendell, W., 1991, Physical properties of the lunar surface. in *Lunar Sourcebook*, ed. by G. Heiken, D. Vaniman, and B. French, Cambridge University Press, New York, 475-594.

EVOLUTION OF THE LUNAR REGOLITH. David S. McKay, Johnson Space Center, Mail Code KA, Houston TX 77058, david.s.mckay@nasa.gov

Introduction: In order to properly design and produce simulants, it is necessary to have some insight into the evolution of the lunar regolith. In particular, the physical and engineering properties of the lunar regolith result from the complex processes that produce it and make it unique. In addition, the chemistry of the lunar regolith depends not only on the chemistry of the bedrock underlying it, but also on the evolution paths that produced it. In general, the chemistry of the regolith does not exactly correspond to the chemistry of the underlying bedrock. Furthermore, the chemistry of a given grain size fraction is likely to be different from that of another fraction. To understand these complexities, we must consider how lunar regolith has formed over geologic time.

The lunar regolith. The lunar regolith is the fragmental layer that overlies nearly all rock formations on the moon. It varies in thickness from less than a meter in some areas to 10s of meters elsewhere. The maximum thickness is not known but is likely to be less than 100m and certainly less than 200m. Meteorite bombardment and secondary processes related to bombardment mainly produce the regolith. However the regolith is not simply ground up or milled bedrock. It is a dynamic material, sometimes becoming finer and other times becoming coarser in grain size. At any site the regolith may reach a steady state grain size but this grain size will likely differ from site to site. One type of regolith, represented by the black and orange glass at Apollo 17, is not the primary product of meteorite bombardment, but was produced by volcanic eruption of pyroclastic ash. In some places it constitutes the main regolith and is termed dark mantle. Dark mantle has many qualities that make it an attractive resource target for lunar propellant production.

Typical lunar regolith contains rock fragments, mineral fragments, and glass. The primary glass type is agglutinates, which are constructional particles produced by small impacts. Because constructional particles are produced, the lunar regolith is not simply a product of grinding; its grain size distribution is much more complex. Figure 1 [1] shows the mean grain size and graphic standard deviation for 42 Apollo 17 soils.
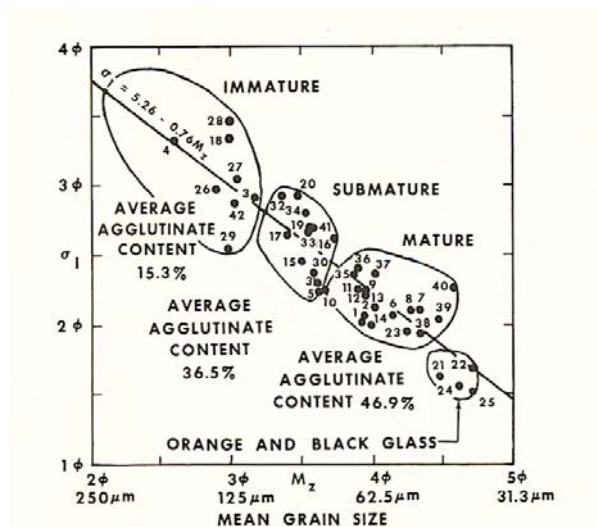
Fig. 1. Graphic mean grain size (Mz) versus inclusive graphic standard deviation (σ_1) for 42 Apollo 17 soils (subcentimeter data). The strong inverse correlation between grain size and sorting is apparent. Samples are divided into arbitrary fields corresponding to the soil maturity; average agglutinate content of the samples within each field is shown. Numbers on the graph correspond to the following samples:

Finer Soils. These parameters show an inverse correlation; finer soils are better sorted. The maturity of lunar soils was first defined by this figure based on grain size parameters. Maturity is an important parameter because it determines how much solar wind components (hydrogen, carbon, nitrogen, etc.) are present. Independent measurements of agglutinate content showed that more mature soils have more agglutinates. This correlation is also shown in Figure 2.
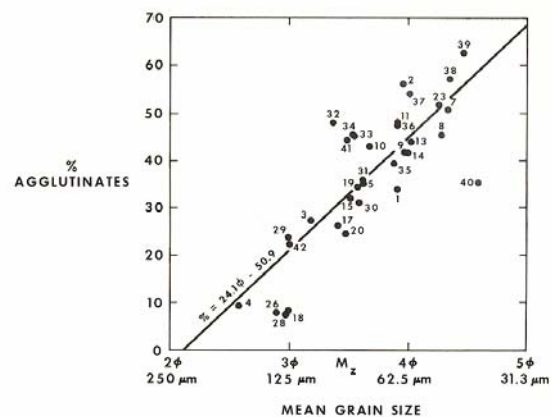
Fig. 2. Graphic mean grain size (Mz) versus the percentage agglutinates in the 90-150 μm fraction. Numbers on graph correspond to the same samples shown in Fig. 1. Agglutinate data from Heiken and McKay (1974). The standard error of estimate of the regression equation is ±8.7% agglutinates.

Mature Soils. The most mature soils contain more than 60% agglutinates in the intermediate size fraction 90-150μm. Extrapolation to 100% agglutinates would predict a mean grain size of 13μm. This is much finer grained than any Apollo soil; a soil this fine is unlikely

to exist on the moon. Figure 3 shows complete size distribution histograms for a number of soils and for several kinds of reference material.
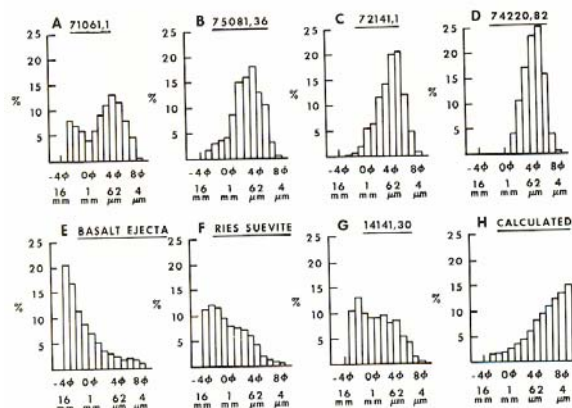
Fig. 3. Grain size histograms: A. Typical immature soil; B. Typical submature soil; C. Typical mature soil; D. Orange glass; E. Single impact in basalt from Gault et al. (1963); F. Wornitzostheim suevite from Fig. 6 in van Engelhardt et al. (1971), part of coarse tail not included; G. Cone Crater soil; H. Possible distribution from prolonged comminution of E., adapted from Fig. 11 in Shoemaker (1971).

Immature Soils. Immature soils (e. g. 71061) are often bimodal and mature soils are usually single modal with narrower standard deviation. The volcanic soil 74220 is more fine grained and has the lowest standard deviation of any measured lunar soil. Yet it has no agglutinates. This radical disconnect between maturity-related properties means it was clearly produced by a radically different process compared to typical soils. Also note that lunar soils do not match the size distribution of either single impact comminution or of calculated multiple impact comminution. The essential difference is mainly the result of the role of constructional particles.

Figure 4 illustrates the end-member path that soils take on the moon with repeated bombardment.

Fig. 4. Soil evolution path 1 in which fresh ejecta of size distribution E is reworked to a mature soil. Along this path, all size fractions of the soil have had the same exposure history at any point and the soil can be considered to have type 1 homogeneous maturity.
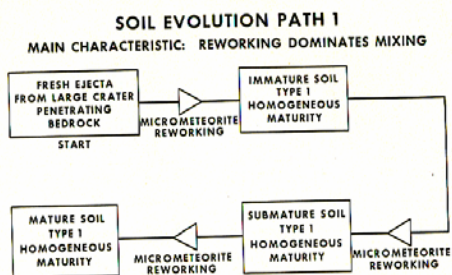
Mixing of Soils. Large blocks produced from bedrock are ground down and become more mature. The final result is a balance between destructional particles and constructional particles. In this path, essentially all components have the same maturity. The other end member (Figure 5), represented by many soils, includes significant mixing of soils of differing maturities.
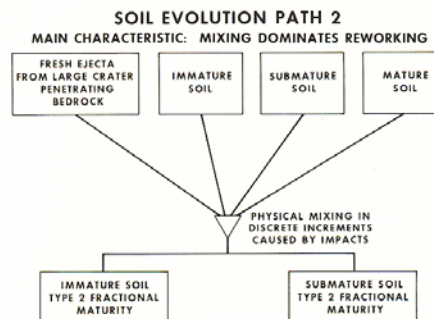
Fig. 5. Soil evolution path 2 in which mixing of soils dominates reworking. Soils can be mixed by impact in any combination and proportion. In the resulting soils, some components may have had different exposure histories compared to other components. The maturity of each fractional component must then be considered separately and the soil has a type 2 fractional maturity.

One result of this mixing is that different grain size fractions may consist of subsets of differing maturity; these subsets or fractions of the complete soil may then have their own fractional maturity. Figure 6 shows the resultant of the mixing of two soils of differing maturity.
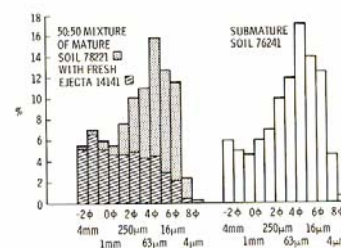
Fig. 6. Hypothetical soil (left) made by mixing in equal parts fresh ejecta 14141 with mature soil 78221. It can be seen that the coarser size fractions are dominated by 14141 and the finer fractions are dominated by 78221. Submature soil (76241) is shown for comparison to the overall shape of the histogram of the hypothetical soil.

The fine-grained part is dominated by one soil and the coarse-grained part is dominated by the other soil. If the parent soils are different initial compositions, the chemical and mineral composition of the resulting size fractions may differ radically from coarse to fine.

Because communition and agglutination may occur at differing rates, a typical soil may reach equilibrium between the two processes (Fig. 7).
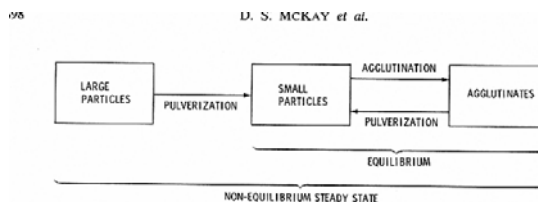
Fig. 7. Diagram of components of the steady-state model showing the agglutinate equilibrium reaction (right) and the large particle pulverization (left). Not indicated in the diagram but necessary for the steady-state model is the replenishment of large particles (left) from an outside source.

However, if the supply of coarse particles is greater for one soil, its equilibrium point may be different from another soil. Hence, this equilibrium is really a dynamic steady state set by the supply of coarse

grained material which is in turn a function of the regolith thickness (Fig 8).
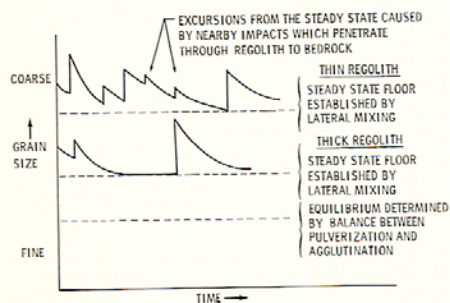
Fig. 8. Diagrammatic representation of the relation between grain size, regolith thickness, and time as predicted by the steady-state model. See text for discussion.

In regions of thin regolith, the supply of coarse-grained material will be greater and the steady-state grain size floor will be higher. No soil in that region is likely to be finer than a certain limiting value. Conversely, in regions of thick regolith, bedrock is reaching much less frequency by impacts so the supply of fresh coarse ejecta is lower and the mean grain size may reach lower values. If no new coarse material were added, a result of an infinitely thick regolith, the equilibrium mean the balance between communition and agglutination would establish the mean grain size. This suggests a relationship between regolith thickness and mean grain size. Figure 9 shows the regolith thickness estimated by various techniques plotted against the mean grain size and the maximum and minimum grain size at each Apollo site.
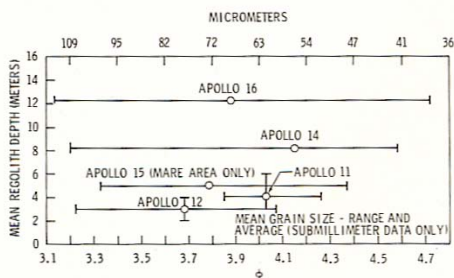
Fig. 9. Regolith depth from Watkins and Kovach (1973) plotted against mean grain size of analyzed samples at each site. A total of 48 samples is represented on this graph; at each site the coarsest sample is the left terminus of the bar, the finest sample is the right terminus of the bar, and the average of analyzed samples or splits is the circle. All data are from the same group: King *et al.* (1971); King *et al.* (1972); Butler *et al.* (1973a); Butler *et al.* (1973b).

No correlation is obvious between mean grain size and regolith thickness. However if only the finest-grained soil sample at each site is used, a strong correlation is seen with regolith thickness. This finest grain size may represent the steady state baseline at each site as shown in Figure 8.
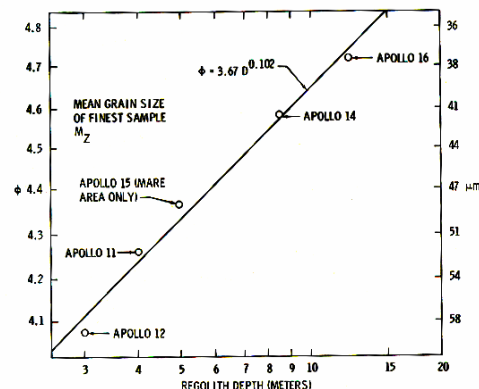
Fig. 10. Most fine grained sample at each site from Fig. 8 plotted against regolith on a log scale. The strong correlation is apparent. The equation of the line is fr[o] linear regression equation relating the log of ϕ to the log of D.

The correlation shown in Figure 10 can be used to predict the finest grain size from estimation of regolith thickness, something that can be done from orbit. It can also be used to estimate the regolith thickness if a number of grain size analyses is available for a site.

In summary, the evolution of the lunar regolith has been complex and has resulted from a dynamic system producing several systematic correlations and relationships. Understanding those relationships may allow us to produce more appropriate simulants and allow us to understand how our simulants may differ from actual lunar regolith.

References: All figures are from D. S. McKay et al., 1974, Grain size and the evolution of lunar soils, Proceedings of the Fifth Lunar Conference, Supplement 5, Geochemica et Cosmochemica Acta, Vol. 1, pp 887-906.

THE GEOTECHNICAL PROPERTIES OF THE LUNAR REGOLITH: FROM EQUATOR TO THE POLES.

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Introduction: It is obvious that many factors must be considered in making lunar simulants for various ISRU projects. This subject is of major importance as we move into the near-future endeavors associated with a return to the Moon. Herein, detailed geologic specifics of lunar soil are addressed and geotechnical properties are discussed that should be considered before we produce simulants for definitive study purposes.

Geotechnical Soil Properties for Consideration in Simulants: "The Lunar Bible" in which the geologic and engineering properties of lunar regolith are presented in detail, by 'lunatic' authorities, is the place to go for most scientific and geotechnical data on lunar regolith. This should be the first stop in anyone's search for data about the rocks and soils of the Moon. Figures 1 & 2 give some important geotechnical properties of lunar regolith culled from a chapter in the _Lunar Sourcebook_ by Carrier et al. [5]. Data such as these must be used in any approach to ISRU of lunar materials.

Lunar Simulants: It was a general consensus at the 6th Space Resources Roundtable meeting that there is need for at least three (3) 'root' simulants produced: 1) a typical mare soil; 2) a highland soil; and 3) a South Pole soil simulant. The basic properties should be similar for all simulants: grain size, grain size distribution, a mixture of lithic fragments, mineral fragments, and glassy particles, a chemistry judged to be appropriate. Figure 5 shows that there is a necessity of several different simulants depending upon the nature of the ISRU study being addressed, emphasizing the conclusion that "One Simulant Does Not Fit All Needs." [6].
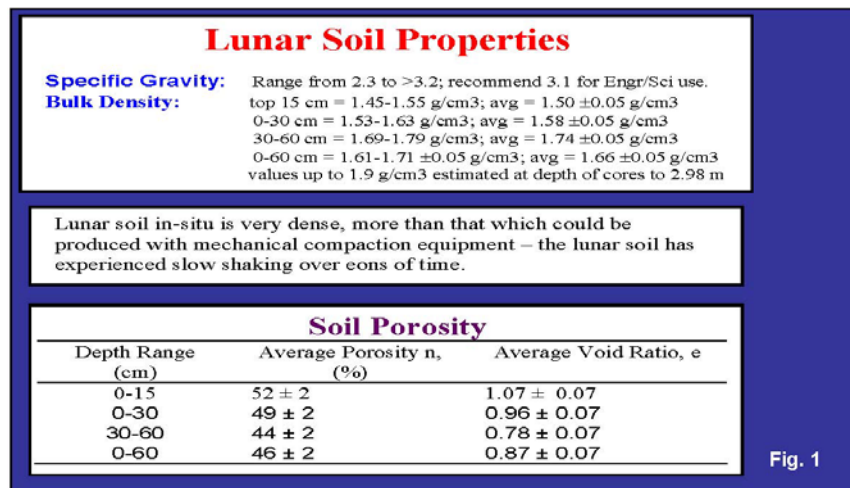
References: [1] McKay, D.S., and A. Basu, 1983, The production curve for agglutinates in planetary regoliths. Jour. Geophys. Res. 88, B-193-199; [2] Taylor, L.A., and D.S. McKay, 1992, Beneficiation of lunar rocks and regolith: Concepts and difficulties. In Engineering, Construction, Operations in Space III, Vol. I, ASCE, New York, 1058-1069; [3] Taylor, L.A., Pieters, C., Keller, L.P., Morris, R.V., McKay, D.S., 2001, Lunar mare soils: Space weathering and the major effects of surface-correlated nanophase Fe. _Jour. Geophys. Lett. 106,_ 27,985-27,999; [4] Taylor, L.A., Pieters, C., Keller, L.P., Morris, R.V., and McKay, D.S., 2001, The effects of space weathering on Apollo 17 mare soils: Petrographic and chemical characterization. _Meteor. Planet. Sci. 36_, 285-299; [5] Carrier, W.D., III, Olhoeft, G.R., and Mendell, W., 1991, Physical properties of the lunar surface. in _Lunar Sourcebook_, ed. by G. Heiken, D. Vaniman, and B. French, Cambridge University Press, New York. 475-594; [6] Taylor, L.A., McKay, D.S., Carrier, W.D. Car-rier, Carter, J., and Weiblen, P., 2004, The Nature Of Lunar Soil: Considerations For Simulants. Abstr. 6th Space Resources Roundtable, Colorado Sch. Mines, 46.

Lunar Soil Properties

Specific Gravity:	Range from 2.3 to >3.2; recommend 3.1 for Engr/Sci use.
Bulk Density:	top 15 cm = 1.45-1.55 g/cm3; avg = 1.50 ±0.05 g/cm3
	0-30 cm = 1.53-1.63 g/cm3; avg = 1.58 ±0.05 g/cm3
	30-60 cm = 1.69-1.79 g/cm3; avg = 1.74 ±0.05 g/cm3
	0-60 cm = 1.61-1.71 ±0.05 g/cm3; avg = 1.66 ±0.05 g/cm3
	values up to 1.9 g/cm3 estimated at depth of cores to 2.98 m

Lunar soil in-situ is very dense, more than that which could be produced with mechanical compaction equipment – the lunar soil has experienced slow shaking over eons of time.

Soil Porosity

Depth Range (cm)	Average Porosity n, (%)	Average Void Ratio, e
0-15	52 ± 2	1.07 ± 0.07
0-30	49 ± 2	0.96 ± 0.07
30-60	44 ± 2	0.78 ± 0.07
0-60	46 ± 2	0.87 ± 0.07

Fig. 1

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Fig. 2

Fig. 3. "One Simulant Does Not Fit All Needs"

	Chemi-stry	Geotech/ Engr	Simulant
Facilities Construction Regolith Digging and Moving Trafficability (e.g., Roads) Microwave Processing Conventional Heat Treatment Oxygen Production Dust Abatement Mineral Beneficiation Solar-Wind Gas Release Cement Manufacture Radiation Protection	X XX X X X X X XX X	XX XX XX X X X X X X X	JSC-2 JSC-2 JSC-2 NP-1+JSC-2+MLS-2 JSC-2+MLS-2 JSC-2+MLS-1+MLS-2 NP-1+JSC-2 ??? JSC-2+Ion Implant MLS-1+MLS-2 JSC-2+MLS-1+MLS-2

Slope Stability (Fig. 9.39; LSB, 1991)

Calculated stability of artificial slopes constructed in lunar surface material. Data are presented for 3 situations:

(1) an excavation in lunar soil
(2) a compacted pile of excavated lunar soil;
(3) a dumped pile of lunar soil

The data show that a vertical cut can safely be made in lunar soil to a depth of about 3m, while an excavated slope of 60° can be maintained to a depth of about 10 m.

Fig. 4

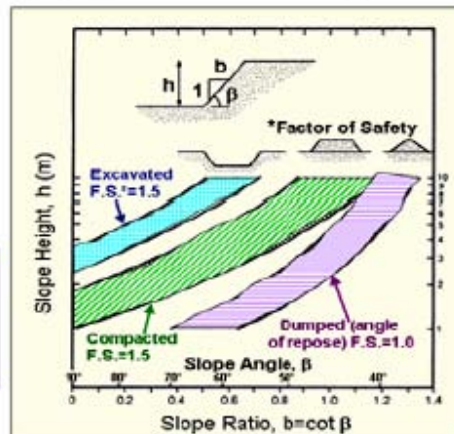| Mare Soil:	JSC-2	= JSC-1 in chemistry + Geotech Prop.
	MLS-1	= Chemistry only of Apollo 11 soil (no glass)
Highland Soil:	MLS-2	= Anorthosite = Chemistry only
Magnetic Soil:	NP-1	= Magnetic properties only

Fig. 5

NEW LUNAR ROOT SIMULANTS: JSC-2 (JSC-1 CLONE) AND JSC-3. James L. Carter[1], David S. McKay[2], Carlton C. Allen[3], Lawrence A. Taylor[4]; [1]Department of Geology, University of Texas at Dallas, Richardson, TX 75083-0688 (jcarter@utdallas.edu), [2]Planetary Exploration, Johnson Space Center, Houston, TX 77058 (david.s.mckay@nasa.gov), [3]NASA Johnson Space Center, Houston, TX 77058 (carlton.c.allen@nasa.gov), and [4]Planetary Geosciences Institute, University of Tennessee, Knoxville, TN 37996 (lataylor@utk.edu).

Introduction: The 2005 Marshall lunar simulant workshop builds on a workshop held in 1991 [1] to evaluate the status of simulated lunar material and to make recommendations on future requirements and production of such material based on the experiences over the past decade using the resultant simulant, JSC-1. As an outgrowth of the original workshop, a group centered at Johnson Space Center headed by David McKay and Carlton Allen teamed with James Carter of the University of Texas at Dallas and Walter Boles of Texas A&M University to produce and distribute a new standardized lunar soil simulant termed JSC-1. James Carter supervised the field collection, shipping, field processing, homogenization, initial packaging, transportation, and laboratory documentation of JSC-1. About 25 tons of relatively homogeneous simulant were created and ultimately distributed to the lunar science and engineering community, the academic community, museums, and individuals. JSC-1 is now essentially depleted and none is left for distribution; therefore, a replacement of JSC-1 is needed. It was proposed at the 6th Space Resources Utilization Roundtable that both a lunar maria and a lunar highland simulant be made in large quantities (100 tons minimum) [2].

JSC-1: The JSC-1 lunar maria regolith fines simulant developed a decade ago served an important role in concepts and designs for lunar base and lunar materials processing. The basic parameters of JSC-1 are described by McKay et al. [3]. Its geotechnical properties are described by Klosky et al. [4]. While other lunar soil simulants were produced before JSC-1 [5], they were not standardized, and results from tests performed on them were not necessarily equivalent to test results performed on other simulants. JSC-1 was designed to be chemically similar to a low titanium lunar mare soil, have a maximum grain size of 1 mm (with 50% less than 0.1 mm), a grain size distribution similar to sub-mature lunar mare regolith fines, and contain a mixture of lithic fragments, mineral fragments, and irregular vesicular glassy particles. The glass-rich character and grain size distribution of JSC-1 produced quite different properties compared to other simulants that were made entirely of comminuted solid rock. These properties closely duplicated lunar maria near surface regolith.

Standardized Root Simulant: At the 6th Space Resources Utilization Roundtable the concept of a standardized root simulant was proposed in which large quantities of a lunar regolith simulant (100 tons minimum) would be produced in a manner that homogenizes it so that all sub-samples would be equivalent [2]. A standardized root simulant would be similar chemically and mineralogically, along with grain components and grain size distribution, to the lunar regolith it was chosen to simulate. Specialized properties would be difficult and, therefore, probably too expensive to be produce in large enough volumes to be incorporated in the root simulant. From a root simulant, however, other more specialized simulants could be made in small volumes to closely approximate certain properties of lunar regolith needed for specific tests and experiments. Examples include the addition of various components such as ilmenite, metallic iron, carbon, organics, or halogens, the implantation of solar wind, or the addition of ice in various proportions. In all cases, the specialized simulant would be traceable to the root simulant and so designated. Moreover, finer fractions or coarser fractions of a root simulant could be made relatively easily. The specialized simulant would be labeled so as to avoid any confusion; for example, JSC-2i, JSC-2f, and JSC-2c, for ilmenite enriched, fine fraction, and coarse fraction, respectively, of JSC-2.

Mare Root Simulant (JSC-2). We propose that the new mare regolith root simulant be a clone of JSC-1 and labeled JSC-2. This is because of the large body of data that has been generated on JSC-1, which can be used for reference and comparison purposes. Even though it may be impossible to duplicate JSC-1 exactly, it can be duplicated closely.

Root Highland Simulant (JSC-3). While JSC-1 and its clone, JSC-2, are a mare simulant, a root highland simulant may be desirable [2, 6]. Many of the proposed landing sites are in highland terrain, and the properties of lunar highland regolith have some fundamental differences compared to mare regolith. Consequently, it may be important to produce a root highland simulant and labeled JSC-3. However, this simulant probably would not have a vesicular glassy component similar to lunar agglutinates, because of the lack of appropriate vesicular volcanic materials on earth and the technical difficulties and expense re-

quired to produce large volumes of appropriate vesicular glassy materials in the laboratory, which would significantly affect the mechanical properties and melting characteristics of the lunar highland simulant. Otherwise, the basic properties of the lunar highland root simulant, JSC-3, should be similar to the chemistry, grain size, average grain size distribution, and mixture of lithic fragments, mineral fragments, and non-vesicular glassy particles of a lunar highland regolith soil, and, therefore, would be a good simulant for some tests.

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LUNAR REGOLITH SIMULANT MLS-1: PRODUCTION AND ENGINEERING PROPERTIES. S. N. Batiste[1]

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Introduction: Researchers at the University of Minnesota produced a lunar regolith simulant, Minnesota Lunar Simulant #1 (MLS-1) from a basaltic rock with bulk chemistry resembling Apollo 11 mare soil sample 10084 [1,2]. A quantity of the material was distributed to the University of Colorado, where geotechnical testing was performed, including determination of several engineering properties [3]. The characteristics of MLS-1 and its use as a lunar regolith simulant will be discussed.

Mineralogy: MLS-1 comes from a basalt sill of an abandoned quarry in Duluth, Minnesota. The high-titanium basalt contains plagioclase, olivine, pyroxene and ilmenite, crystallized simultaneously. It has a grain size similar to coarser lunar mare basalts. MLS-1 contains less pyroxene than the Apollo 11 lunar mares, more feldspar, a small amount (<3% by volume) of biotite, surface ferric iron (3.5% by wt) in ilmenite and mafic silicates, 0.4% water, and surface oxidation [1,2]. The quarried basalt contains no glass or agglutinates, which made up approximately the majority of 10084.

Production: One thousand kilograms of basalt was quarried, then crushed and ground at the University of Minnesota Mineral Resources Research Center [1]. Portions of the ground basalt were passed through a high temperature plasma furnace to form glass particles [2]. The material was made available for distribution, and used in plant growth, glass, and concrete fabrication studies and geotechnical research.

The Center for Space Construction at the University of Colorado at Boulder received a quantity of MLS-1 in 1988, without the particles processed to form glasses or agglutinates, for geotechnical research. The lack of glasses is not considered to have a significant impact on engineering properties. The lack of agglutinate particles may have a significant effect on the stress-strain properties of the soil because the particles would tend to break in shear. Although glass particles had been produced at the time, a process proven to form the intricate and delicate shapes of agglutinates had not been developed [4]. The grain-size distribution of 10084 falls at the lower bound of the Apollo 11, 12, 14, 15 samples [3]; therefore, the material was regraded to better represent the range of sample grain sizes. It was first sieved into its respective sizes, and the larger particles were brought to the United States Bureau of Reclamation in Denver, Colorado where it was ground in a rodding mill to create a sufficient quantity of fines.

The soil was then recombined to produce a simulant more representative of all Apollo missions [4], which was then used for determination of physical and geotechnical properties (Figure 1).
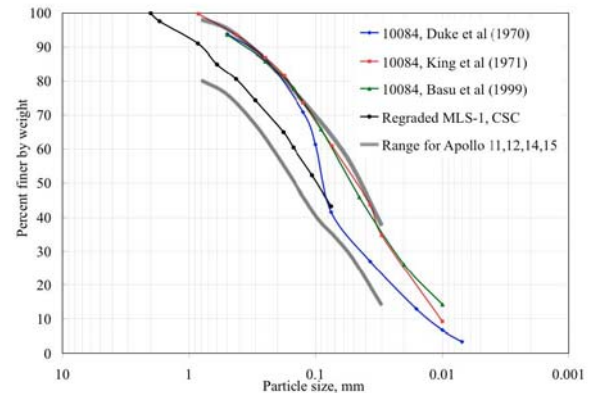
Figure 1. Particle size distribution curve for Apollo 11 sample 10084, CU-Boulder regraded MLS-1, and the range of distributions for Apollo 11, 12, 14, and 15.

Physical Properties: Specific mass was measured to be 3.2. Maximum and minimum index unit weights of 2.20 and 1.50 g/cm^3 were found for the particle-void composite, with the maximum taken from vibratory compaction techniques. Figure 2 compares the range of densities for lunar regolith and terrestrial simulants found using similar static compaction methods. The low maximum void ratio for MLS-1 is believed to be a result of the lack of agglutinates. An increase in maximum void ratios for Apollo 12 (Surveyor 3), Apollo 15, and Apollo 14 samples follows the trend of increasing average agglutinate contents of 15%, 33% and 52%, respectively. The highly irregular shape of the agglutinate particles would allow for much looser packings, but would not have as much effect as compaction energy is increased [4].

Engineering Properties: A series of triaxial compression experiments were performed on MLS-1 and compared to lunar regolith data, with both sets of experiments performed in Earth's 1-g atmospheric environment (Table 1). The stiffnesses and softening behavior were comparable, indicating the CU-Table 2.

Comparison of Cohesion Parameters. [4] Boulder MLS-1 closely matches the strength and

stiffness properties of lunar regolith. For two confining stress levels, the results for friction angle are quite close; however, when examining the cohesion terms from direct shear experiments on MLS-1 with *in situ* regolith, a discrepancy exists. Table 2 gives average density, and cohesion for *in situ* regolith at shallow (0-15 cm) and deep (30-60 cm) depths [5], and direct shear experiment results for two extreme densities of MLS-1, indicating the cohesion is low for MLS-1. Figure 5 combines the friction and cohesion information from tests performed on MLS-1 [4] and while results from MLS-1 do tend to bracket data from *in situ* lunar regolith, the cohesion intercept is low. This may be due to the lack of electrostatic charging and absence of agglutinate particles [4].
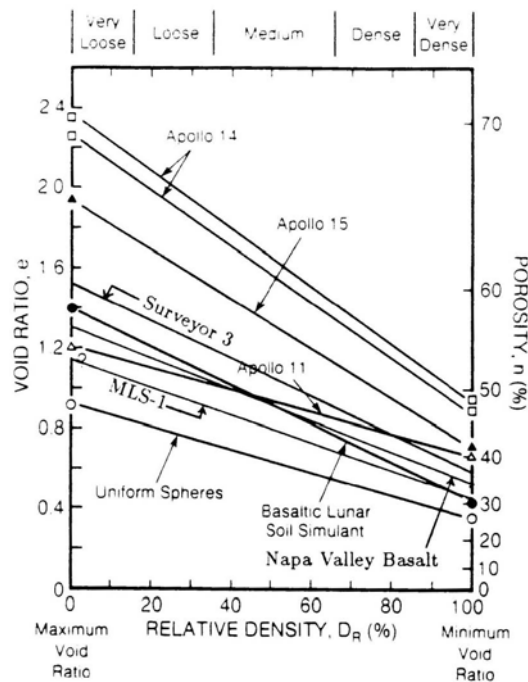
Figure 2. Maximum and minimum void ratio from lunar soil and simulants. From [5]

Table 1. Comparison of Triaxial Test Results. [4]

Material	Density, g/cm3	Confining Stress, kPa	Friction Angle, deg
Lunar Regolith [6]	1.89	26.0	48.8
	1.71	52.6	40.7
MLS-1 [4]	1.90	13.8	49.8
	1.90	34.5	48.4
	1.70	34.5	42.9
	1.70	68.9	41.4

Table 2. Comparison of Cohesion Parameters. [4]

Material	Density, g/cm3	Cohesion, kPa
Lunar Regolith	1.50	0.52
	1.75	3.0
MLS-1	1.70	0.10
	2.17	1.5
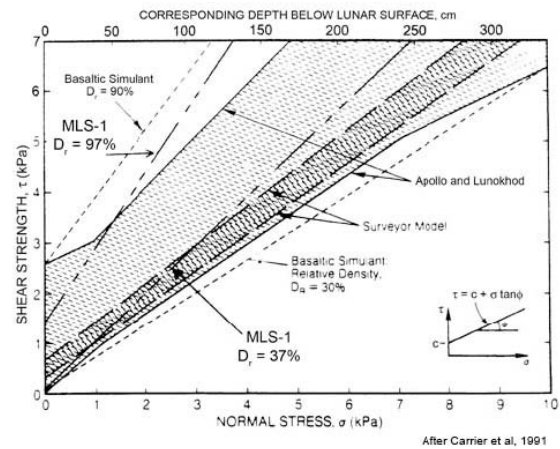
Figure 3. Mohr-Coulomb Peak Strength Envelopes for Lunar Regolith and MLS-1. From [5]

Conclusions: A comparison of data between lunar mare regolith and the simulant MLS-1 indicates that MLS-1 is a reasonable simulant of the lunar basalt, similar in both chemistry and engineering properties. However, it lacks the cohesion properties of lunar regolith.

To be a more realistic simulant, agglutinates should be added to MLS-1 and subsequent tests performed to check cohesion properties.

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CHARACTERIZATION STRATEGIES AND REQUIREMENTS FOR LUNAR REGOLITH SIMULANT MATERIALS. Paul Carpenter, BAE Systems, Analytical & Ordnance Solutions, NASA, Marshall Space Flight Center, XD42, Huntsville, AL 35812, paul.carpenter@msfc.nasa.gov.

Introduction: Lunar samples returned from the Apollo missions represent diverse geological materials and processes, and have been studied in considerable detail using numerous characterization techniques. Developing lunar simulants presents a challenge in matching terrestrial materials to lunar soils and rocks. Existing lunar simulants such as JSC-1 [1] and MLS-1 [2,3] have been utilized as engineering test materials with primary emphasis placed on determining geotechnical properties, and secondary emphasis on supporting chemical and mineralogical analysis. Implementation of a comprehensive suite of lunar simulants will require a diverse set of mineral, rock, and synthetic materials coupled with processing technologies and characterization by both geotechnical and chemical/mineralogical techniques. Presented here is a brief roadmap of analytical characterization approaches coupled with development requirements for lunar simulants that support anticipated NASA missions.

Lunar Simulants: Lunar soils are comprised of materials that are predominantly basaltic and anorthositic, reflecting mare and highland source regions, respectively. Meteorite impact events have mixed these materials over large areas, and have produced significant fragmentation, melting, and glass formation. These actions are evidenced in the texture, chemistry, mineralogy, and presence of significant glass fraction as well as vapor-deposited reduced iron. Lunar simulants can in principle be matched to lunar source materials by means of selecting root components that when mixed and processed appropriately, duplicate the characteristics of the lunar target materials. Potential root simulants are basalt, anorthosite, mineral and glass separates, and size-fractions such as dust and Fe nanophase material. Meteoritic material clearly exists in lunar soils based on trace element chemistry, but also represents a challenge in identifying equivalent terrestrial materials to use as meteorite simulants. Quantitative modeling of root simulant materials to match Apollo soil chemistry can be performed by choosing sets of simulants, then determining a least-squares fit to the Apollo bulk chemistry and iterating the mix proportions. One primary goal of this workshop is to determine which lunar materials need to be simulated, and the accuracy with which the simulant needs to match the target lunar material.

Characterization Techniques: Characterization of simulant materials is necessary using physical, chemical, and mineralogical methods. Lunar samples are

scientifically precious and non-destructive characterization was calibrated against baseline measurements on selected material, then applied more widely. Modern analytical techniques allow one to bridge the spatial range from "bulk" to "microanalytical" by means of microsampling. Researchers that need to study processes that occur over different size scales can use these techniques to monitor the beginning of a reaction which likely begins at the micro scale and proceeds to larger sample volumes. Failure analysis of a wide range of natural and synthetic materials reveals that the physical, chemical, and phase-specific properties at the micro-scale determine the failure of, and subsequently, the material behavior of the bulk sample.

Electron-probe microanalysis: Electron-probe microanalysis (EPMA) has been used to obtain nearly all mineralogical analyses of returned lunar samples and the development of the technique and application to lunar materials represents a milestone in quantitative microanalysis. In addition to microanalysis of lunar minerals, the bulk chemistry of lunar samples was obtained using EPMA by means of a point count measuring protocol based on a grid of sampling points on the polished sample [4]. As the number of grid points was increased, both the individual mineral chemistry and the bulk chemistry estimates improved in comparison to baseline bulk chemistry techniques. Modern microprobe systems have benefited from numerous improvements in instrumentation and automation in the 35 years since Apollo, and current systems can routinely collect digital backscattered-electron and x-ray maps using beam deflection as well as stage point counting methods. Digital images can be used for size analysis, in which derivative images are analyzed in order to extract grain size and shape measurements. This can be coupled with simultaneous chemical typing of grains, and serves to support other bulk measurements made using geotechnical methods. This parallel analysis can readily illustrate the need, for example, to grind simulant MLS-1 to establish a finer grain size fraction and bring the simulant in line with targeted Apollo soil characteristics. In the last decade, secondary-ion mass spectrometry has been used extensively to perform trace element analysis of lunar materials, and can also support lunar simulant characterization needs.

Bulk chemical analysis: Lunar materials have been analyzed by non-destructive techniques wherever possible. X-ray fluorescence spectrometry can be utilized

for major and trace analysis of bulk lunar simulant materials, and real-time analysis is possible for process monitoring. Newer microsource x-ray tubes with a 10-50 μm spot size permit a similar mapping strategy as discussed for EPMA. Instrumental neutron-activation analysis (INAA, non-destructive) and inductively coupled plasma spectrometry (ICPMS, requires sample digestion) can also be used for trace analysis.

Powder X-ray Diffraction: Advances in powder x-ray diffraction (XRD) include Rietveld analysis, a whole-pattern fitting technique which provides a powerful tool for characterization of lunar simulants when coupled with quantitative phase analysis. Real-time phase and structural changes at elevated temperature can be monitored using a high temperature XRD furnace attachment.

Oxidation State of Fe and Oxygen Fugacity Control: In general, lunar materials equilibrated at the more reducing Fe-FeO buffer, whereas terrestrial igneous rocks have equilibrated at the more oxidizing Fe_2SiO_4-Fe_3O_4-SiO_2 buffer. High temperature processing experiments using lunar simulant materials that aim to duplicate conditions on the lunar surface require experimental control of vacuum and oxygen fugacity to the appropriate values. The definitive determination of the oxidation state of Fe is accomplished using Mössbauer spectroscopy, where the measured spectra indicate the valence in the phases examined. This measurement capability can also be added to high temperature experimental apparatus.

Simulant Development, Production, and Calibration: The production of lunar regolith simulants will require a coordinated effort beginning with source material selection and ending with a final standardized simulant product. This requires identification of terrestrial materials in existing regions that are actively mined or amenable to extraction, and test evaluation of small batches to screen materials prior to commitment of large-scale development. Materials selected for simulant use next need to be processed by necessary physical and chemical techniques in order to duplicate the textural, compositional, and mineralogical characteristics of the targeted lunar material. This processing is followed by characterization using physical, chemical, and mineralogical techniques both at the bulk and microanalytical scales. This characterization is necessary both for development and quality control during sub-division of master batches for deployment to end-users. Quality control issues must be established at each step of simulant development. These issues are well known in the geological community based on experience with standard reference rock powders. Storage, curation, and shelf-life monitoring of materials should be handled in cooperation with requests for distribution and implementation of simulant materials. Proposals to use simulant materials and establishment and/or monitoring of proper experimental protocol should be carried out by an oversight committee that includes individuals having relevant expertise.

Quality Control of Simulant Materials: The distributed MLS-1 simulant required additional grinding based on grain size matching to Apollo soils. The consistency of bulk chemistry also depends on a consistent fine grain size. Bulk chemical analysis of small sample populations of MLS-1 reveal wide variations at the major and trace element level [5], which reflects improper sampling of material as well as grain size issues. This aspect is important for standard reference rock powders, where occasional large grains of an accessory phase cause spike values in analyses (e.g., Cr variation due to modal variations in chromite). Likewise, the presence of grains of quartz in an anorthosite powder would cause uneven measurements of geotechnical properties that depend on mineral hardness. Homogenization is important for both physical and chemical properties of simulant materials, and it is necessary to address both aspects in quality control during simulant production.

Lunar Highland Simulant: In anticipation of a lunar polar mission, the development of a lunar highland simulant should be a priority. Two localities are being discussed as sources for anorthosite. The banded zone of the Stillwater intrusion is attractive because extensive studies of the geology, mineralogy and chemistry exist, active mining is being conducted, and access to fresh material is possible. The Duluth complex in Minnesota is also a possible source for anorthosite. An evaluation of these localities should be pursued based on existing research on the chemistry and mineralogy of the anorthosite bodies, coupled with logistics concerning mining, crushing, other processing, and transportation from the site.

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CHARACTERIZATION OF CHEMICAL AND PHYSICAL PROPERTIES OF PROPOSED SIMULANT MATERIALS.

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The requirements for planetary soil simulants are based on the need to provide *in situ* resource development for sustainable missions to the Moon and Mars. These requirements go far beyond the need for materials with mechanical properties that would match specific planetary soils. It is expected that planetary soils will be used for a wide range of activities including oxygen generation, food production, and materials manufacturing. As such, it is critical that simulated materials match specific properties that will be found in planetary soils as closely as possible [1].

In order to develop simulated soils with the desirable properties it will be necessary to characterize prospective source materials and final products on the micro and macro scales for chemistry, mineralogy, grain size, grain morphology, and other properties as required by investigators. It will be necessary to insure a level of homogeneity for the properties measured within and between production units of the simulant.

An additional concern for the production and use of simulated soils is safety. Source materials and final products must be characterized for any hazardous materials that could be inhaled, ingested, or absorbed. This could be a significant issue when materials will need to be produced with ultra-fine grain size similar to lunar soils and will, therefore, contain a high proportion of respirable (< 3 μm) particles.

It is anticipated that characterization will include x-ray fluorescence, x-ray diffraction, x-ray microanalysis, ICP-MS, and ICP-AES for mineralogy and of major, minor and trace elements. Scanning electron microscopy, and particle size analysis will be required for morphology. It will also be necessary to measure electrostatic properties of the materials. Additional characterization could include neutron activation analysis, secondary ion mass spectrometry, transmission electron microscopy, thermal ionization mass spectrometry, leachate analysis, mossbauer spectroscopy, mid- and near-infrared spectroscopy differential thermal analysis, and other techniques depending on stimulant requirements.

One example of the type of characterization necessary for production of stimulant materials is x-ray microanalysis using both wavelength dispersive and energy dispersive techniques (EDS). X-ray microanalysis combined with scanning electron microscopy and possibly transmission electron microscopy will be required for accurate determination of source material and simulant chemistry and mineralogy, fine particle chemistry, and identification of any possibly hazardous particulate material.

Figure 1 shows a terrestrial soil point count analysis used to quantify soil particles for mineralogy, chemistry, morphology and particle size. Area-percentage coverage of total sample is determined using binary representations of backscattered electron images. Area fraction of individual particles is determined by direct measurement of each particle. The chemistry of particles is determined and binned according to particle type. This process can be performed at several magnifications depending on requirements dictated by particle size distribution of the material. Multiple randomly selected fields of view at each magnification are analyzed for each sample. The number of particles counted on each sample can be adjusted depending on the density of coverage and statistics required. Recent advances in microanalysis hardware and software should allow this type of analysis to be performed in an automated mode.
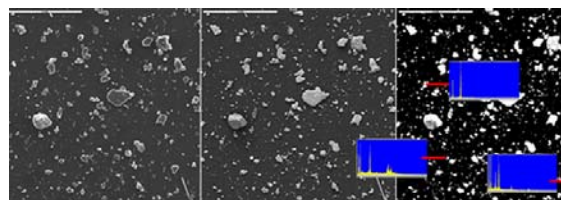
Figure 1. Particle field shown by secondary electron image (left), backscattered electron image (center), and binary (right). Individual particles are identified by energy dispersive x-ray analysis. Scale bar = 100 μm.

The characterization of simulants will require laboratories that are familiar with the analysis of rock and mineral materials, have appropriate standards, and can deal with large volumes of material to ensure representative aliquots. It is desirable that characterization be conducted in close proximity to or at the production facility in order to make possible efficient interaction between those trying to meet specific production requirements and those monitoring requirements in a QA/QC role.

The U.S. Geological Survey, Minerals Program, has for decades, produced and analyzed large quantities of rock and mineral reference materials for the analytical community, NIST, and other groups in need of specific, homogeneous reference standards. Production and characterization are performed primarily

in the USGS analytical laboratories in Denver where a large array of analytical equipment is available for rapid turn around analysis. The USGS has significant expertise in the handling and analysis of all types of rock and mineral materials. In addition, the USGS Minerals and Human Project has, for the last five years, provided rapid turn around, health-related information to agencies such as U.S. Environmental Protection Agency and U.S. Public Health Service on issues including characterization of asbestos in soils to characterization of the dust generated by the collapse of the World Trade Center buildings.

References: [1] McKay D. S. and Blacic J.D., 1991, *Workshop on Production and Uses of Simulated Lunar Materials.* LPI Tech. Rpt. 91-01, Lunar and Planetary Institute, Houston. 82 pp.

DEVELOPMENT OF GEOCHEMICAL REFERENCE MATERIALS AT THE UNITED STATES GEOLOGICAL SURVEY.

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Introduction: Since its inception in 1995, the USGS reference materials project (RMP) has been responsible for the development of matrix matched reference materials in support of programmatic needs. In this role the project is responsible for the development and distribution of 32 different materials covering the range from silicate rocks, to soils, to coal, to manganese nodules. Efforts have focused on providing materials with well characterized chemical compositions, which are homogeneous over the typical twenty year supply (5000 units) of a given material. These objectives required the development or procurement of customized equipment which is designed to reduce sample particle size to less than 90 micron, blend the material ideally as a single batch, and then split the material into 30-50g portions.   This preparation process is done with minimal contamination through the use of ceramic lined grinding equipment, industrial-sized V-blenders, and a customized spinning riffler.

In addition to its specialized preparation procedures, the USGS also performs initial homogeneity assessment on each reference material at its Denver, Colorado laboratories. Samples from the final set of bottles are selected using a stratified random sampling approach and subjected to both within and between bottle analysis. Multiple analytical techniques are utilized and the final data set evaluated for its total major and trace element composition. Reference material preparation is considered successful if precision results (%RSD) for major and trace elements are <3% and <10% respectively. After homogeneity assessment is complete, a select group of international laboratories is invited to participate in an intra-laboratory certification study for the material. Results from this study are compiled, the data statistically evaluated, and a certificate developed which lists both certified and recommended total element concentrations. It is this attention to detail and experience gained over 55 years that allows the USGS RMP to meet its programmatic needs, and be one of the principal international distributors of geochemical reference materials.

THE MOON AS A BEACH OF FINE POWDERS. Masami Nakagawa[1], Juan H. Agui [2] , and Heather Angel[3]; [1]Mining, Engineering, Colorado School of Mines, 1500 Illinois Street, Golden, Colorado 80401 mnakagawa@mines.edu, [2] NASA Glenn Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135 Juan.H.Agui@nasa.gov, [3] Division of Engineering, Colorado School of Mines, 1500 Illinois, Golden, Colorado 80401 hangel@mines.edu.

Introduction: Neil Armstrong described the Moon as a beach of fine powders [1]. Material and mechanical properties of fine powders under terrestrial environment is an on-going active research area. However, the same cannot be said in terms of dust research in space exploration. In this paper we address the needs of new regolith simulants specifically dedicated to the investigation of behavior of Lunar and Martian dust in a simulated Lunar and Martian environment. The lunar dust investigation requires a simulant with the micron to sub-micron size particles that are electrostatically or magnetically charged in extreme environments of the Moon and Mars.

There is some direct evidence in the past Apollo Missions and the recent Mars Missions that fine dust affected the performance of instruments and threatened crew health (Figs 1a and 1b). During the EVA excursions using the Lunar Rover in Apollo Missions, it was reported that the rover kicked-off significant dust (Fig. 1c), and batteries and radiators had to be brushed clean at each stop. The power output of the photovoltaic cells on the Sojourner rover was measured to decrease by 0.2 percent per sol (Martian day). Radiators covered with insulating dust will lose much of their ability to cool sensitive electronics.
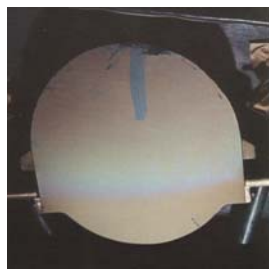

Fig.1a: Surveyor 3's mirror is coated with dust after 31 months on the lunar surface.

Fig.1b: Apollo 17 astronaut commander Eugene Cernan, grimy with lunar soil fromthree days of exploration.

Fig.1c: The dust plume from drive wheel.

A Brief Description of the Project Dust: "The Project Dust" (in response to the NASA Broad Agency Announcement 2004: Mitigation of Dust and Electrostatic Accumulation for Human and Robotic Systems for Lunar and Martian Missions) has a set of coherent dust mitigation protocols as its final product. However, during the course of four-year investigation, a number of unique and innovative low TRL (Technology Readiness Level) research works are being planned. The Dust on the surfaces of the Moon and Mars will be disturbed and becomes loosened by various surface activities ranging from the astronauts' walk to Martian storms. The kick-off mechanisms and UV levitation are investigated. Once the dust becomes mobile, it transports to adhere to surfaces of space suits and other space structures. The dust transport mechanisms, adhesion, accumulation, deposition, abrasion and tribocharging effects are planned to be investigated. Effective filter designs for the airlock and habits will be investigated. The knowledge accumulated in these different areas of investigation will converge to form and improve the mitigation protocols.

Space Simulation Chamber: After the first phase, the Project Dust will make a cryogenic vacuum chamber (the Space Simulations Chamber:SSC) available to the program team members to conduct experiments that require realistic Lunar and Mars environment. The SSC can achieve hard vacuum (up to 10^{-12} torrs) and cryogenic temperature 83°K and offer about 100 ft^3 space available for experiments. A series of experiments ranging from dust levitation to dust abrasion have been proposed.

Material properties of Dust: Due to its diverse nature, the Project Dust requires simulants to be targeted to different aspects of dust mitigation. In terms of crew health, the project will first investigate the effectiveness of currently existing dust monitoring devices. This requires both the effectiveness of measuring the particle size distribution and mass count. The challenge will lie in dealing with extremely small dust, possibly as small as 50 nm. The size distribution information is crucial in other areas of investigation such as dust levitation, transport, deposition and filtration. In addition to size distribution, the particle shape will be a crucial factor in investigating the impact abrasion damage. In modeling the dust accumulation process, the adhesion properties are required. The bulk density

is also a fundamental property but for regions below 3 m no direct data about the density of the lunar regolith exists [2].

Mechanical Properties of Dust: The standard properties identified in soil mechanics may be required: compressibility, shear strength, permeability, bearing capacity, slope stability, and trafficability. In addition, we will investigate the effects of extreme vacuum and temperature environment on these properties. Under extreme environment, the interaction between dust and metallic surfaces may be unexpectedly altered and should also be investigated. This includes the investigation of tribocharging due to particle-particle interactions and also particle interaction against other surfaces. Due to insulating nature of the surface of the Moon, once the charge is accumulated, the discharge is expected to be a serious problem. Grounding will be investigated in conjunction with weakly conductive coating.

Shaking the Space Suit: an example of mitigation strategy: It was reported many times that the conventional "brushing-off" the dust never worked once the dust adhered to the Apollo astronauts' suit. Many dust removal methods have been suggested, including the possibility of manufacturing new fabric that possesses repelling capability at nanoscale. Manufacturing new materials will be the ultimate solution. In parallel to the development of the potential dust repelling materials, we will pursue several dust removal techniques including shaking, airbrushing, and electrostatic/magnetic wands sweep. This paper shows our preliminary approach of dust removal by shaking that was initiated by two undergraduate students from Colorado School of Mines who participated in the 2004 summer internship program offered by the NASA-Glenn research center.

When removing sand on a beach towel, we usually first shake it giving a large sinusoidal motion. This removes most sand grains with the help of significant gravitational pull. At a closer look at the towel, however, you will notice smaller sand grains embedded in the towel fabric. These are usually removed by washing with the help of surfactant influenced fluid motion. On the surface of the Moon or Mars, we do not anticipate the luxury of using water to wash off dust every time an astronaut returns to his/her habitat. The question of releasing fine dust from the beach towel will still remain as a problem there. We pursued very localized shaking of fabric after a general shake. Different modes of local shaking were tried. We arrived at a conclusion that a mixed mode between vertical and horizontal shaking should produce the results we expect. To accomplish this task at a preliminary stage, a small motor used to vibrate a cell phone was used. It

seemed to release fine dust effectively. However, after a closer look at the dust-contaminated fabric under the microscope, we found finer dust still adhered to the fabric even after magnetic sweep (Fig.3).

A series of preliminary experimental data will be shown at the time of presentation.

Fig. 3. A magnified view of the space suit fabric contaminated by dust.

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THE EFFECTS OF LUNAR DUST ON ADVANCED EVA SYSTEMS: LESSONS FROM APOLLO. J.R.

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Introduction: NASA's Vision for Space Exploration has as its fundamental goal the advancement of "…U.S. scientific, security, and economic interests through a robust space exploration program."[1] The Vision is based around a spiral development that extends "…human presence across the solar system, starting with a human return to the Moon by the year 2020…"   The Advanced Extravehicular Activity (AEVA) program has been charged with developing both the technology and the flight hardware required for spacesuits, tools, and vehicular interfaces that will enable astronauts to work on the lunar surface.

Apollo Lessons: One of the lessons learned from the Apollo program is that lunar dust has the potential to degrade EVA systems through a variety of mechanisms. Mission documents from the six Apollo missions that landed on the lunar surface reveal dust degradation effects that can be sorted into nine categories: vision obscuration, false instru-ment readings, dust coating and contamination, loss of trac-tion, clogging of mechanisms, abrasion, thermal control problems, seal failures, and inhalation and irritation. The properties of lunar dust with respect to these adverse effects must be understood and replicated if the AEVA systems are to be designed to operate effectively on the lunar surface.

The first dust-related problem experienced by the Apollo astronauts occurred when they attempted to land the Lunar Module (LM). The Apollo 11 crew reported that "Surface obscuration caused by blowing dust was apparent at 100 feet and became increasingly severe as the altitude decreased."[2] This was even more of a problem for Apollo 12 where there was total obscuration in the last seconds before touchdown to the extent that there was concern that one of the landing feet could land on a boulder or in a small crater[3]. For Apollo 14 the landing profile was adjusted to be steeper, and the astronauts reported little difficulty in seeing the landing site[4]. However, this may have been due in part to the Apollo 14 landing site being intrinsically less dusty, because Apollo 15 and Apollo 16 also used the higher landing pro-file, and both reported difficulties seeing the landing site in the critical last seconds [5, 6].

In Apollo 12 the velocity trackers gave false readings when they locked onto moving dust and debris during de-scent [3]. The Apollo 15 crew also noted that landing radar outputs were affected at an altitude of about 30 feet by mov-ing dust and debris [5]. But the Apollo 17 crew reported no lock-up on moving dust or debris near the lunar surface [7]. This again points out the differences in the amount of dust at the different landing sites, with it being high at the Apollo 12 and 15 sites, and low at the Apollo 17 site.

The Apollo experience then reveals that the extent that vision and radar obscuration is a problem on landing is de-pendent on the amount of loose dust in the specific landing zone. Thus, it will probably remain a variable as long as spacecraft are landing in previously unexplored territory.

In addition to vision obscuration on landing, the dust caused minor problems with photography. The Apollo 15 crew reported problems with a halo effect on the television camera transmission. This was remedied by brushing the dust off of the lens [5].

Neil Armstrong reported dust material adhering to his boot soles caused some tendency to slip on the ladder during ingress back to the LM [2]. However, this slipperiness was not reported by any of the other crew members, and there are specific references in the Apollo 12 record that this was not a problem for them [3]. It became standard practice for the astronauts to kick the excess dust off of their boots on the ladder before they re-entered the LM in an attempt to keep as much dust as possible out of the spacecraft, and it is likely that this measure was enough to keep this from happening.

Dust was found to quickly and effectively coat all sur-faces it came into contact with, including boots, gloves, suit legs, and hand tools. Consequences included the Apollo 11 astronauts repeatedly tripping over the dust covered TV cable [2], and a contrast chart on Apollo 12 becoming unusable after being dropped in the dust [3]. This was particularly troublesome on Apollo 16 and 17 when rear fender extensions were knocked off of the Lunar Roving Vehicle (LRV) and dust showered down on top of the astronauts [6,7]. Dust coating is the precursor to other problems such as clogging of mechanisms, seal failures, abrasion, and the compromising of thermal control surfaces. In addition, valuable astro-naut time was spent in ordinary housekeeping chores like brushing off and wiping down equipment – which often proved ineffective.

Equipment was compromised by dust clogging and jamming in every Apollo mission. This included the equipment conveyor [2], lock buttons [3], camera equipment [5], and even the vacuum cleaner designed to clean off the dust[6]. Dust made Velcro® fasteners

inoperable [7], and was a particular problem in trying to use duct tape to repair a broken fender extension [7]. The dust also clogged Extravehicular Mobility System (EMS) mechanisms including zippers [3] wrist and hose locks [6], faceplates [5], and sunshades [6].

The most alarming characteristic was how quickly and irreversibly this could happen. One short ride on the rover with a missing fender extension, or standing where the equipment conveyor dumped dust on the EMS and difficulties began immediately. All of the astronauts experienced this to some degree, even those with the shortest stays on the surface. Several remarked that they could not have sustained surface activity much longer or clogged joints would have frozen up completely [3, 6, 7].

Lunar dust also proved to be particularly abrasive. Pete Conrad and Alan Bean report that their EMS were worn through the outer layer and into the Kapton® multi-layer insulation above the boot [3]. Gauge dials on the LRV were so scratched up during the Apollo 16 mission as to be unreadable [6]. Harrison Schmitt's sun shade on his face plate was so scratched that he could not see out in certain directions [7], and the cover gloves worn by the Apollo 17 astro-nauts when they were working the core drill were worn through after drilling cores in only two of their three EVAs [7].

A layer of dust on radiator surfaces was impossible to remove by brushing and caused thermal control problems. On Apollo 12, temperatures measured at five different locations in the magnetometer were approximately 68 °F higher than expected because of lunar dust on the thermal control surfaces [3]. Similarly, on Apollo 16 and 17 the LRV batteries exceeded operational temperature limits because of dust accumulation [5] and they did not cool appreciably after they accumulated even a thin film of dust. A high quality thermal/vacuum test facility is needed to provide "believable", correlated simulation and verification of dust mitigation methods and techniques.

John Young remarked that he regretted the amount of time spent during Apollo 16 trying to brush the dust off of the batteries – an effort that was largely ineffective. (This was contrary to ground-based tests which indicated that dusting the radiator surfaces would be highly effective.) This led him to later remark that "Dust is the number one concern in returning to the moon."[8] In addition to difficulties with communications equipment and TV cameras, some of the scientific instruments on both Apollo 16 and 17 had their performance degraded by overheating due to dust interfering with radiators [6, 7].

The ability of the EMS to be resealed after EVA was also compromised by dust on the suit seals. The Apollo 12 astronauts experienced higher than normal suit pressure decay due to dust in fittings [3]. Another indicator is that the environmental sample and gas sample seals failed because of dust [3]. By the time they reached earth the samples were so contaminated as to be worthless. This does not bode well for a long duration habitat where several astronauts will be passing through air locks and unsealing and resealing their EMS routinely.

Perhaps the most serious consequence of lunar dust is the possibility of compromising of astronaut health by inhalation and resultant irritation caused by lunar dust. The Apollo 11 crew reported that the dust gave off a distinctive, pungent odor, suggesting that small particles were suspended in the spacecraft, with perhaps the presence of reactive volatiles on the surface of the dust particles as well [2]. Dust found its way into even the smallest openings, and when the Apollo 12 crew removed their clothes on the way back to earth, they found that they were covered with it [3]. Dust was also transferred to the Command Module during Apollo 12 and was an eye and lung irritant during the entire trip back [3]. Given the toxicity of even inert particles with sizes less than about 5 μm, the need to monitor the concentrations of dust particles within the EMS, the airlock, the habitat, and the spacecraft is acute.

Plans to Return: In the summer of 2004 the Advanced Integrated Matrix (AIM) Program undertook a study to identify systems on both the lunar and Martian surfaces that would be affected by dust, how they would be affected, the associated risks, the requirements that need to be developed, and knowledge gaps that need to be filled [9]. The group generated a list of potential problem areas in EVA systems that included those experienced by the Apollo astronauts plus possible electrical problems such as power drains and shorts caused by conductive paths of dust particles.

Part of the evaluation for the Spiral 2 Surface Suit and other AEVA components will be to determine how well they hold up in the dusty environment. The evaluation of components, materials and full-up tests will be defined by the testing requirements developed by the Environmental Protection Project Plan. Test Plans will also define the appropriate lunar simulants. The evaluation is envisioned to be a three-stage process. The first stage will be an evaluation of candidate suit materials that would be exposed to the dust. New mitigation strategies will be tested at this level, and their effectiveness will be quantified. The second stage is component-level testing. This is particularly important for joints and connections, and to test out new designs which incorporate the best materials identified in the first stage. The third stage is full-up suit tests, to try to identify system problems that are not obvious from the component tests.

Different simulants may be required to simulate different functional properties of the dust which include optical, tribological, adhesive, abrasive, thermal and electrical properties. For example, to quantify the abrasion resistance of candidate suit materials, what is required is a substance with similar abrasion properties to lunar dust and soil. It is not important for this abrasion evaluation whether the chemical or optical properties are similar to lunar regolith material. Similarly, the best simulant for each of the other degradation mechanisms must be determined and optical and other material properties will be important.

The required characteristics of the best AEVA lunar simulants for each functional property have yet to be defined. It must be recognized that the properties that are required to test the survivability of AEVA system components in the lunar environment do not necessarily correspond to those of the best *in situ* resource utilization (ISRU) simulant. Although it is important that communication between the AEVA and ISRU teams be maintained on this subject, it would just be a fortunate coincidence if the simulants required by both efforts are identical.

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Introduction: From research conducted on the ground and in low earth orbit over the past 30 years, it appears that the gas exchange function of the human lung adapts well to microgravity. However, the particle clearance function of the lung involves a different set of mechanisms and remains relatively unstudied in the space environment. The return of humans to the moon as part of the Vision for Space Exploration (VSE) will refocus interest on this topic, since the lunar (and Martian) regoliths include a large component of dusts characterized by unusual mineralogies and the potential for unwanted biological effects.

Apollo astronauts reported that lunar dust was one of the major problems encountered during the moon missions. Harrison Schmitt, the only scientist/geologist to go to the moon, describes the unique chemistry and physical properties of the dust, including its tendency to adhere to surfaces, its abrasiveness and damaging effects on the astronauts' EVA suits, as well as its irritational effects on body surfaces such as the eyes and nasal mucosa. At the end of every excursion onto the lunar surface, dust was brought into the lunar excursion module, where it was mobilized from the EVA suits to contaminate equipment and the astronauts. Once back in lunar orbit and microgravity, the dust floated about the interior of the vehicles, causing further problems.

The effects of this material on equipment are well-enough recognized to have stimulated work for new designs for EVA and habitation systems, but the impact on the astronauts themselves is less well appreciated. No long-term toxicity studies on simulated or real lunar dust have been carried out in the 30 years since the last Apollo moon mission. Lunar regolith dust is produced under conditions not naturally replicated on earth, but the resulting unique physical chemistry produces silicate-based particles similar enough to that seen in the mining and other industries to raise the specter of serious pulmonary disease. Silicates on earth can cause both acute and chronic pulmonary disorders that could become established in the 90-day time frame being considered for lunar missions under the VSE.

Silicosis is a debilitating disorder originally called "stone-grinder's disease" because it resulted from chronic inhalation of quartz and other silicate mineral dust produced in certain industrial environments. Key to the pathogenesis of this disease is the size of the particles inhaled. Grains in the 1-micron size range are able to remain suspended in air long enough to reach the terminal airways and gas exchange components of the lung (the alveolar ducts and the alveolar sacs), where they can stimulate both a damaging acute inflammatory reaction, and cause ongoing responses that can result in chronic and crippling fibrosis leading to pulmonary insufficiency and in some cases, death.

Compounding the unknown toxicity of lunar dust are the as yet uncertain behavior of pulmonary particle clearance mechanisms in fractional gravities, such as that on the moon or Mars. John West and his colleagues at the University of California at San Diego [1] have conducted human studies in 0-g parabolic KC-135 flights and have discovered that the 1-micron range inert test particles are deposited in the lung in increased numbers in 0-g compared to 1-g controls. This is a disturbing finding when coupled to the known size distribution of lunar dust samples brought back by Apollo astronauts, which showed as much as 5% of the grains by weight to be in the hazardous 1 micron size range. While additional KC-135 flights simulating fractional gravities are planned, as of this date nothing is known of the efficiency of particulate clearance mechanisms in lunar and Martian gravitational fields.

It is fortunate that samples of actual lunar regolith dust are available in the repository collection at Johnson Spaceflight Center; however, this material is of limited quantity and so authentic simulants will likely be needed to conduct adequate acute and chronic toxicity studies. Because the mineral chemistry of the dust grains are important in determining their toxicity, lunar dust simulants designed for biological study will have to be produced under more stringent requirements than that meant for testing of equipment, such as that intended for testing of in-situ mining and manufacturing equipment. Because the micromineral composition of lunar dust is determined by micrometeorite impacts which produce a complex glass-like composite, replicating this unusual material for biological testing will be challenging; however, the potential health affects of this material should justify a detailed look at its characteristics in the human organism.

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SINTERING, MELTING AND CRYSTALLIZATION OF LUNAR SOIL WITH AN EXPERIMENTAL PETROLOGIC POINT OF VIEW. G. E. Lofgren, Code KT, NASA-JSC, Houston, TX 77058,

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Introduction: Lunar soils have many unique properties that affect their sintering, melting, and crystallization behavior.   Previous experimental studies of lunar soil and basalt material can provide insight into these behaviors for future utilization as an engineering material.

Procedures: The procedures for sintering, melting and crystallization and the desired end products from each of these processes are different.

Sintering. Sintering requires temperatures between the glass transition and solidus temperatures for glass agglutinate rich soils (glass spherules can contribute, but not as much). The final products can have only a limited variation in physical properties with porosity being one of the important ones. The variations result from variations in the time and temperature of sintering, but also the grain size, composition, and physical state of the soil.

Melting. Melting is a simple process that requires temperatures between the solidus and liquidus and superliquidus temperatures, if total melting is required.   A totally melted lunar soil would have limited uses and would not be a desirable product.

Crystallization. Crystallization is the important step to producing a custom product. It is a complex and variable process that can produce a wide variety of products with different physical properties. Tailoring the physical properties of the crystallized product to desired uses requires extensive experimentation.   Such characteristics as tensile strength, surface toughness, resistance to fracturing and insulation properties could all be controlled. Unfortunately, they cannot all be optimized simultaneously.

A dynamic crystallization study completed on lunar soil 15301 [1] demonstrates some of the variations in crystallization properties that can be obtained. The lunar soil was melted for 10 minutes to 96 hours at temperatures in the range of 1230-1280°C and either quenched or cooled slowly at approximately 2°C/hr. Melting at 1280°C produced a glass while melting at 1230°C produced a partially crystalline melt with numerous small crystals.

Melting at 1230°C for the different times produced different degrees of melting and distributions of crystals. Resulting textures varied from poikilitic to fine intersertal to more coarsely intersertal to even coarser intergranular to subophitic texture with increasing melting time. The array of texture will result in different physical properties for the final products. Two obvious properties that will vary are porosity and strength or toughness. This study was not designed to determine the variation in physical properties and none were measured. This study does show what is required to vary the textural properties of the final product and how one would systematically vary those properties.

Requirements: The best soils to sinter or crystallize would be ones with the lowest solidus temperatures   and   a   relatively   low   liquidus temperature. Soils with high glass content, either agglutinates or spheres, will be the most easily sintered.   Glass content is not as important for melting and crystallization processes, except possibly with regard for the total energy input for large quantities. The more glass, the less energy needed to totally melt a soil from a kinetic point of view.

The energy to produce melting is significant and probably would have to be supplied locally, such as with a solar furnace with the direct use of focused sunlight, or by solar collectors and stored power.

Important Simulant components: What would be the important simulant properties for experimental studies? Bulk composition controls the liquidus and solidus temperatures. Both are important for energy input considerations (latent heat of fusion). It would be desirable to simulate the lower melting soils or soils at a projected landing site as accurately as possible.

Bulk composition also dictates the minerals that are stable, their ratios, what crystallization textures are possible, and ultimately the physical properties of the material. It would be more difficult to simulate the array of minerals and glassy particles. Naturally high FeO and TiO2 basalt like some found in Columbia Plateau basalts would be a good base material. Hawaiian glassy ejecta could be used to simulate agglutinates and spherules.

The unique grain size distribution of lunar soils would also be important for determining their melting properties as the fine-grained component melts most readily. This property is particularly important for sintering applications.

Thus, experimental studies would require a very faithful simulant, but would not require large quantities. For some experimental studies that can be done with a few grams, actual lunar soil could be used.   If extensive physical testing of the final products is required, simulants would be necessary.

An additional source of information: Basalt has a long history of use as the raw material for casting ceramic products for a wide variety of uses

[2-4]. This technique was used in Eastern Europe in the early part of the 20th century. An extensive knowledge of casting techniques was developed in order to produce basalt casting with known properties. This industry provides insight into the crystallization histories necessary to produce desired physical properties. An examination of this acquired knowledge would be an excellent starting place to develop an understanding of how to produce useful products from lunar soil on the moon.

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TOWARDS LUNAR SIMULANTS POSSESSING PROPERTIES CRITICAL TO RESEARCH AND DEVELOPMENT OF EXTRACTIVE PROCESSES. D.R. Sadoway[1], D.C. Lynch[2], L. Sibille[3], and K.A. Debelak[4]; [1] Department of Materials Science & Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Room 8-203, Cambridge, MA 02139-4307, dsadoway@mit.edu, [2] Department of Materials Science and Engineering, The University of Arizona, Harshbarger Bldg., Room 16B, Tucson, AZ 85721-0012, dclynch@engr.arizona.edu, [3] BAE Systems, Analytical & Ordnance Solutions, NASA Marshall Space Flight Center, Exploration Science and Technology Division XD42, Huntsville, AL 35812, Laurent.Sibille@msfc.nasa.gov, [4] Department of Chemical Engineering, Vanderbilt University, Box 1604 B, Nashville, TN 37235, kenneth.a.debelak@vanderbilt.edu.

Introduction: Extractive processes rely heavily on the chemical and physicochemical properties of feedstocks. Accordingly, the design of lunar simulants must take this subset of materials properties into account if laboratory studies are to yield useful data. This paper presents an analysis of stimulant needs from three different perspectives, each involving a branch of chemical processing.

Pyrometallurgical Extraction Processes: Previous work by David C. Lynch at the University of Arizona's Space Engineering Research Center for Utilization of Local Planetary Resources on recovery of oxygen by pyrometallurgical processing of lunar regolith will be reviewed (see Figure 1). Specific chemical and physicochemical properties of significance to pyrometallurgy will be enumerated.

Supercritical Fluid Extraction Processes: Recent work by Kenneth A. Debelak at Vanderbilt University on the use of surfactants to enhance the extraction of metals in supercritical carbon dioxide from feedstock resembling compounds found in Martian soil will be reviewed (see Figure 2). Specific chemical and physicochemical properties of significance to processing in supercritical fluids will be enumerated.

Metal Extraction and Oxygen Production by Molten Oxide Electrolysis: Recent work by Donald R. Sadoway at MIT on the use of molten oxide electrolysis to directly decompose lunar regolith into oxygen and metal will be reviewed (see Figure 3). Specific chemical and physicochemical properties of significance to high-temperature electrolytic processing in molten salts will be enumerated.

Overarching Themes in Extraction Processes: On the basis of the ideas presented in the previous three sections of the paper, the scientific underpinnings will be expressed with a view to trying to develop a design paradigm that applies broadly to chemical processes.
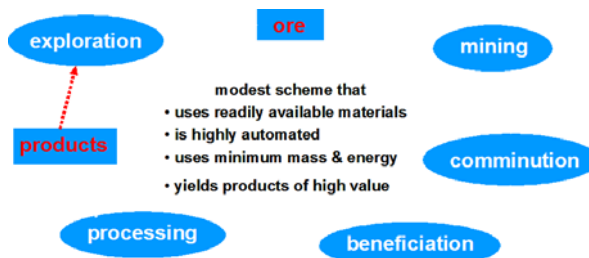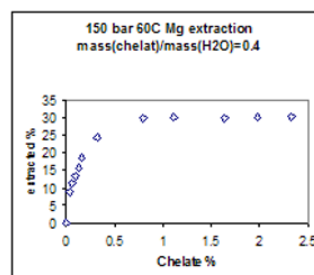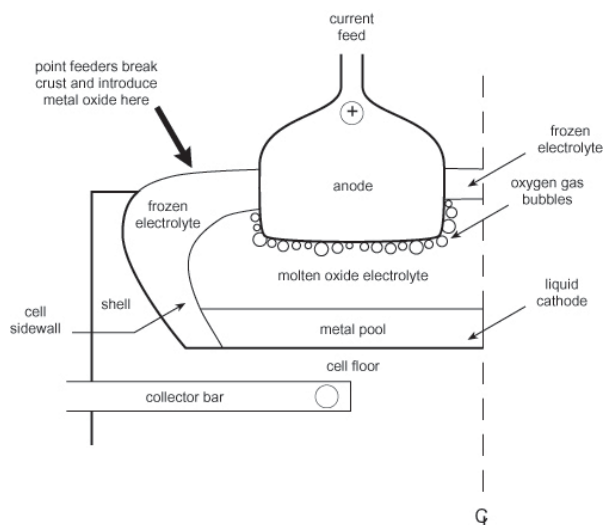

Figure 1.

Figure 2.

Figure 3.

THE IN-SITU STATE: THE ELUSIVE INGREDIENT IN LUNAR SIMULANT. E. S. Berney IV[1] and J. F.

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Introduction: The next generation of lunar exploratory vehicles will encounter problems unlike any of those posed by past missions. The bold mission of exploring *in-situ* resource utilization (ISRU) will require the insertion of instrumentation, excavating equipment, and permanent structures at depths below the lunar surface where little data on performance is available. While previous studies by J. Mitchell and W. Carrier [1] on lunar regolith have determined a range of material properties for the remolded regolith material on earth, in-situ material response is still an unknown. Research has shown that very dense particulate regolith found at shallow depths, less than 20cm, has substantial strength [1]. Further, lunar regolith strength is partly derived from agglutinates, which tend to become compressible under heavy loading conditions, a phenomena typical of a loessial soil. The combined mechanisms of agglutination and particle interlocking can generate a particulate body not easily replicated by commonly used methods of reconstitution. These mechanisms strengthen the soil beyond that of simply compacted simulant whose high frictional strength can be attributed to low confining pressure [2]. Terrestrially, the in-situ strength of many soils including glaciated tills, quick clays, loess and silty-sand deposits [3], is difficult to replicate in reconstituted specimens. In these soils, in-situ structure and interparticle bonds create a stronger, more durable base than observed in laboratory investigations on disturbed samples. Therefore, ISRU exploration will need to account for the potential resistance to subsurface boring at even shallow depths in calculation of instrument power requirements and design methodology. Evidence of this behavior is supported by Apollo missions that experienced difficulty in boring probe insertion [1] as a result of the regolith fabric. High relative densities and tight interlocking along a bored shaft can bind or minimize the effectiveness of improperly designed tools. Further excavation of regolith may prove very difficult owing to the forces required to break regolith interlock.

Methods to recreate the effects of structure and inter-particle bonding are needed for reliable design of drilling and excavation equipment. A key requirement is to establish a very uniform density sufficient to match a mature lunar regolith as slight variations in density can cause considerable change in volume stability and resistance to subsurface boring [4]. The discrete element method (DEM) could be used to simulate the effects of particle interlocking and excavation of irregularly shaped particles packed into tight arrangements. Model reliability could be assessed through a laboratory study of regolith simulant bonded with an agent such as a polymer or cement during compaction. The computer simulation provided by DEM helps to extrapolate the behavior of the imperfect lunar simulant to the lunar environment.

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LUNAR REGOLITH SIMULANT REQUIREMENTS: MECHANICAL PROPERTIES CONSIDERATIONS.

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Introduction: Two upcoming projects under NASA's HRT program address the characterization of the physical and mechanical properties of the regolith, and the development of regolith-handling construction equipment. Both efforts will require the use of a lunar regolith simulant to support the physical testing of a number of the regolith characterization instruments, and for testing prototypes or scale models of the regolith-handling equipment. The presentation outlines the physical and mechanical properties of a regolith simulant that are of greatest interest to these two projects, and gives some consideration to the quantities that will be required to support instrument testing and equipment development.

Physical properties considerations: The physical properties considerations fall into the broad categories of individual particle characteristics, particle size distributions, and packing. For regolith that may be bonded (e.g., cemented by water ice, for example,) there are additional considerations related to the concentration of water and its distribution in the pore space. Although properties such as mineralogy and thermal characteristics are important in some applications, they are of secondary significance in the context of mechanical behavior (provided that the simulant is in roughly the same class as actual lunar material with respect to the cohesive/fracture strength of the particles and ice adhesion). The surface roughness and angularity of particles are key features of lunar material that must be adequately relected in the simulant. These properties have a strong impact on the grain-scale mechanics of granular media, and hence on the material's bulk behavior.

Mechanical properties considerations: The needs of the HRT program encompass a broad spectrum of engineering problems that require knowledge of geotechnical and geophysical properties such as the effective elastic and dynamic moduli, and time-dependent (e.g., creep) properties of the regolith. The design of equipment for drilling and excavating in the regolith, and handling excavated material for ISRU requires knowledge of frictional characteristics and granular media flow. Since detecting and recovering regolith that contains water ice is of prime concern, the mechanical properties of ice-bonded material are an issue as well.

Characterization of the simulant: It will be important that the simulant used in any terrestrial prototype experiment not only provide an acceptable level of similitude with the lunar regolith, but also that the mechanical properties of the simulant be well understood and documented over a range of physical scales. Since it is anticipated that a strong emphasis will be placed on the use of either detailed numerical or perhaps physically based analytical models of the deformation processes of interest, it will be important to characterize the simulant in ways that adequately support the analytical efforts associated with the various experimental/testing activities of the overall program.

It will be necessary to fully characterize the above mentioned physical properties of any simulant used in terrestrial testing. The mechanical properties characterizations should be considered on both the micro scale and the bulk or aggregate scale (e.g., specimen sizes that are typical of geotechnical laboratory test-in). Additionally, it will be important to examine the bulk behavior over a range of relative densities and specimen preparation methods. Apart from supporting the critical testing of proposed instruments and equipment under realistic conditions, any testing conducted in well characterized simulant will add important information to the developing data base for the HRT program.

The presentation covers the specific mechanical properties of interest in greater detail and describes the physical requirements for testing the proposed drilling system, and various surface and sub-surface geophysical and geomechanical testing instruments.

COMPOSITION OF THE LUNAR HIGHLAND CRUST: A NEW MODEL. Paul D. Lowman Jr., Goddard

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Introduction: This paper presents a synthesis of Apollo remote sensing data, Earth-based reflectance spectroscopy, returned sample analyses, and Apollo EVA photographs, pointing to a new model for the composition and origin of the oldest lunar highland crust.   The petrology of the lunar highlands has been a difficult problem because of the deep and apparently continuous regolith mantle, a mixture of breccias, impact melts, and exotic rock fragments.   However, a re-examination of EVA photographs of highland structure taken on the Apollo 15, 16, and 17 missions reveals pervasive layering similar to terrestrial lava flows such as those of the Columbia Plateau.   X-ray fluorescence surveys point to a high-alumina basaltic composition for the highland crust, an interpretation consistent with earth-based reflectance spectroscopy and analyses of returned highland samples, especially from Apollo 17. It is concluded that the highland crust is largely high-alumina hypersthene basalt, formed by global fissure eruptions during the first few hundred million years of the Moon's existence.   Anorthosites, troctolites, and similar plutonic rocks were formed by magmatic processes in intrusions, and are exposed chiefly in large craters, occurring as minor constituents of the exposed highland crust.

SPACE RADIATION AND LUNAR REGOLITH. James H. Adams, Jr[1]. and Manojeet Bhattacharya[2]; [1]NASA Marshall Space Flight Center, NSSTC, 320 Sparkman Dr., Huntsville, AL 35805, james.h.adams@nasa.gov . [2]University of Alabama at Huntsville, Huntsville, AL 35899, manojeet.bhattacharya@msfc.nasa.gov

Radiation hazards on the Moon are influenced by the character of lunar regolith is several ways. It is likely that lunar regolith will be used as radiation shielding. By burying a habitat under perhaps two meters of lunar regolith one can obtain a significant reduction in the radiation exposure to galactic cosmic and a great reduction in the radiation hazard from solar energetic particle events. Radon gas resulting from the decay of ^{238}U in the regolith can, in principle, pose a radiation hazard in a buried habitat. Several factors including the rate at which radon escapes from the lunar fines surrounding the habitat will determine the extent of this hazard. Finally, the smallest lunar dust particles appear to be capable of lodging in the lungs. If these particles contain a sufficient abundance of alpha-emitting nuclei such as Th and U, they can pose a health hazard. The properties of regolith that are relevant to radiation hazards will be discussed.

SUPERCRITICAL EXTRACTION OF METALS USING BINARY LIQUID MIXTURES WITH A CONSOLUTE POINT. James K. Baird, Department of Chemistry, University of Alabama in Huntsville, Huntsville, AL 35899, chemch@email.uah.edu

Introduction: A mixture of 38.8 weight percent isobutyric acid + water has a critical solution temperature at 26 ^{o}C. Above this temperature, isobutyric acid and water are miscible in all proportions. Below 26 ^{o}C, a meniscus appears separating a water rich liquid phase on the bottom from an isobutyric acid rich phase on the top. The critical composition, 38.8 weight percent, and the critical temperature at 26 ^{o}C define the consolute point of the mixture. We have been using the 38.8 weight percent mixture (pH = 2) at temperatures just above the critical solution temperature as a medium for extracting metals from their oxides. This is a supercritical extraction process, which is analogous to the supercritical extraction of caffeine from coffee using carbon dioxide at a temperature just above its liquid-vapor critical temperature. Whereas supercritical extraction at the liquid-vapor critical point requires pressures of 10 atmospheres or more, our liquid-liquid extraction process using isobutyric acid + water operates at 1 atmosphere. This is a major advantage of our method for space processing. Also, we are able to dissolve the metal and purify it using a temperature change of just one degree Centigrade. This means that our process is very energy efficient, which is another advantage for space processing.

The solubilities of both MnO_2 and Al_2O_3 in 38.8 weight percent isobutyric acid + water are strong functions of the temperature near the critical solution temperature. The measured solubility, *s,* is plotted in Fig. 1 for MnO_2 and in Fig. 2 for Al_2O_3. Since MnO_2 goes into solution endothermically, a plot of ln *s* vs. *1/T,* where *T* is the absolute temperature should make a straight line with negative slope at temperatures above the critical temperature (small values of *1/T*). In Fig. 1, we see that the solubility of MnO_2 indeed obeys this law until the critical temperature is approached. At the critical temperature, however, the solubility falls below the extrapolated straight line by a factor of *ten*. By contrast, Al_2O_3 goes into solution exothermically, and a plot of ln *s* vs. *1/T* should make a straight line with positive slope. In Fig. 2, we see that this is indeed the case above the critical temperature, but as the critical temperature is approached, the solubility increases by a factor of *two*. In the cases of both MnO_2 and Al_2O_3, the solubility effect at the critical point is produced by temperature change of just *one* degree Centigrade.

Because so little heat is required to change the solubility near the critical point, we can imagine using this principle to design a very *energy efficient* plant for extracting metals. A diagram of the proposed the plant is shown in Fig. 3. Consider the purification of MnO_2 for example. On the left in the figure, the impure solid MnO_2 is brought into contact with the isobutyric acid + water mixture at a temperature, T, which is one degree above the critical temperature T_c. According to Fig. 1, the solubility of MnO_2 is high above T_c, so manganese readily goes into solution. If the mixture with dissolved manganese is then pumped to the chamber on the right and cooled to T_c, the MnO_2 will readily precipitate. The depleted liquid mixture, which is left over, could then be pumped through a heater back to the left hand chamber and the process repeated.
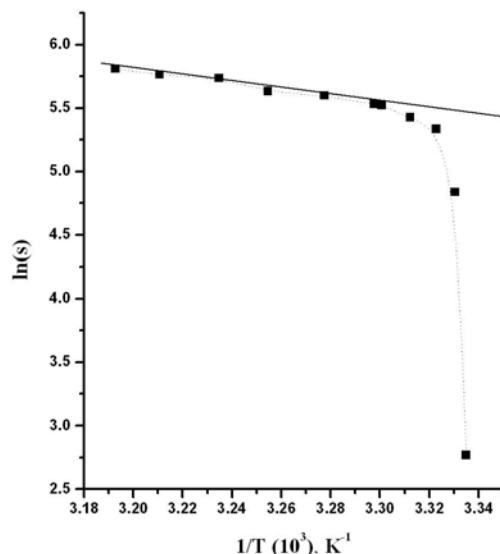
Figure 1. The Logarithm of the Solubility of MnO_2 in Isobutyric Acid + Water as a Function of Absolute Temperature.

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sobutryric acid + water is not the only binary liquid mixture with a consolute point. Triethylamine + water (pH = 12) is another example. Since triethylamine + water is basic, it can be used to extract metals from their carbonates, phosphates, and sulfides. Although our laboratory is at atmospheric pressure, these mixtures should work equally well at total pressures equivalent to their vapor pressures which are in the range of 0.05 atm. Thus, both isobutyric acid + water and triethylamine + water can be used as low pressure, very energy efficient media for extraction of metals from their compounds.
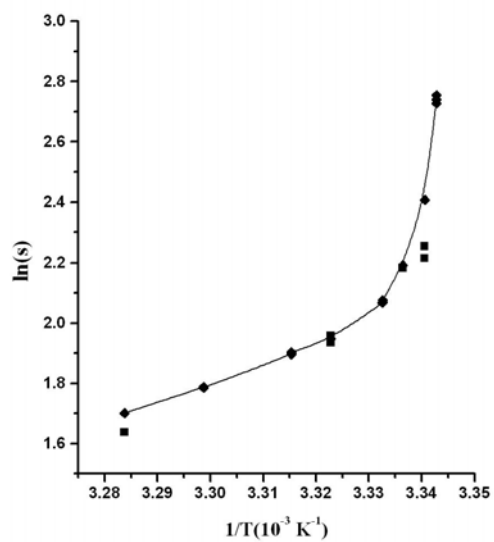
Figure 2. Logarithm of the Solubility of Al_2O_3 in Isobutyric Acid + Water as a Function of the Absolute Temperature
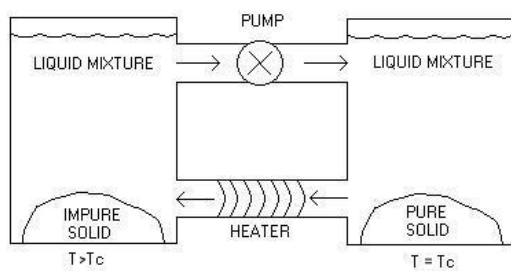

Figure 3. Schematic Diagram for an Energy Efficient Plant for Extracting and Purifying MnO_2 Using a One Degree Centigrade Temperature Change in the Mixture, Isobutyric Acid + Water, Near Its Critical Point of Solution

THERMODYNAMIC MODELING AND EXPERIMENTAL STUDIES ON PLANETARY MATERIALS.

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Development of modular systems in processing of planetary materials based on experimental and modeling results is being investigated.

Thermodynamic calculations on NASA simulant material (JSC 1 lunar simulant composition) were made in the temperature range of 100^0C-1500^0C with and without argon gas. Thermodynamic equilibrium concentrations for species were determined based on the Gibbs energy minimization method. The moles of each possible species were calculated. These species except Oxygen gas, whose moles are less than 10^{-4} kmol at equilibrium, were not considered.

The material balance results are: 1) product compositions are the same with and without Argon atmosphere in the feed materials; 2) moles of only SiO_2, TiO_2, Fe_2O_3, FeO and MgO major element compositions are more than 10^{-4} kmole; moles of the other major element compositions are less than 10^{-4} kmole in the temperature range of 100^0C-1500^0C in product compositions; 3) The gas phase analysis showed that oxygen gas is not significant (less than 10^{-5} kmole) until temperature reaches 1500^0C.; 4) the temperature range of 400^0C to 600^0C is critical and many product compounds showed maximum in their composition in the temperature range of 400^0C to 600^0C.

Energy balances were carried out as a function of temperature in the range of 100^0C-1500^0C with and without Argon in the feed materials. Energy released or needed for melting of the materials were determined. Results showed that ΔT decreased with increase in temperature. A significant decrease in amounts of ΔT and heat needed is observed above 500^0C.

Carbothermal reduction reactions were carried out using JSC-1. Different phases were identified using XRD and the amount of each phase was quantified using electron microscopy. A comparison of the experimental results with the model predictions will also be presented.

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Monday January 24

Time	Length	Speaker	Subject
7:30 AM	1:00		Registration
8:30 AM	:15	Raymond Clinton	Welcoming remarks from Chief, Exploration Science and Technology Division, MSFC
8:45 AM	:15	Tom Morgan and Mike Wargo	Perspectives from NASA Headquarters (by telecon) Chief Lunar Scientist Science Directorate, Chief Lunar Scientist Exploration Systems
9:00 AM	:15	Audience	Telecon Questions
9:15 AM	:30	Laurent Sibille	The Status of Lunar Simulant Materials, Workshop Overview and Objectives
9:45 AM	:30	Break	
10:15 AM	:30	Larry Taylor	Physical and Chemical Characteristics of Lunar Regolith: Considerations for Simulants
10:45 AM	:30	David McKay	Evolution of the Lunar Regolith
11:15 AM	:30	Larry Taylor	The Geotechnical Properties of the Lunar Regolith: From Equator to the Poles
11:45 AM	:30	Audience	Discussion
12:00 PM	1:00	Lunch	
1:00 PM	:30	James Carter	New Lunar Root Simulants: JSC-2 (JSC-1 Clone) and JSC-3
1:30 PM	:30	Susan Batiste	Lunar Regolith Simulant MLS-1: Production and Engineering Properties
2:00 PM	:30	Paul Carpenter	Characterization Strategies and Requirements for Lunar Regolith Simulant Materials
2:30 PM	:30	Break	
3:00 PM	:30	Greg Meeker	Characterization of Chemical and Physical Properties of Proposed Simulant Materials
		Steve Wilson	Development of Geochemical Reference Materials at the United States Geological Survey
3:30 PM	:30	Masami Nakagawa	The Moon as a Beach of Fine Powders
4:00 PM	:30	Ron Creel	The Effects of Lunar Dust on Advanced EVA Systems: Lessons From Apollo
4:30 PM	:30	Russ Kerschmann	Biological Effects of Lunar Surface Mineral Particulates
5:00 PM		End of session	
5:15 PM		EMS Dry Run for Science Committee	

Tuesday January 25

Time	Length	Speaker	Subject
8:00 AM	:30	Gary Lofgren	Sintering, Melting, and Crystallization of Lunar Soil With An Experimental Petrologic Point of View
8:30 AM	:30	Donald Sadoway	Towards Linear Simulants Possessing Properties Critical to Research and Development of Extractive Processes
9:00 AM	:20	Ernest Berney	The In-Situ State: The Elusive Ingredient in Lunar Simulant
9:20 AM	:20	David Cole	Lunar Regolith Simulant Requirements: Mechanical Properties Considerations
9:40 AM	:20	Break	
10:00 AM	:20	Paul Lowman	Composition of the Lunar Highland Crust: A New Model
10:20 AM	:20	Jim Adams	Space Radiation and Lunar Regolith
10:50 AM	:25	Larry Taylor	Group Discussion, Larry Taylor Moderator, Simulant Requirements
11:15 AM	:45	Working Groups	Sub-session 1A Group: Sub-session 1B Group: Sub-session 1C Group
12:00 PM	1:00	Lunch	

Tuesday, January 25 (cont'd)

Time	Length	Activity
1:00 PM	1:30	Session 1
1:30 PM		
2:00 PM		
2:30 PM		
3:00 PM	:30	Break
3:30 PM	:30	Gate 1 Summary
4:00 PM	1:00	Session 2
4:30 PM		
5:00 PM		Adjourn

6:30 PM   **Informal dinner at Holiday Inn – Speaker, Owen Garriott, Former Skylab II and Spacelab 1 Astronaut**

Wednesday January 26

Time	Length	Activity
8:00 AM	2:00	Session 2
8:30 AM		
9:00 AM		
9:30 AM		
10:00 AM	:30	Break
10:30 AM	:30	Gate 2 Summary
11:00 AM	1:00	Session 3
11:30 AM		
12:00 PM	1:00	Lunch
1:00 PM	1:30	Session 3
1:30 PM		
2:00 PM		
2:30 PM	:30	Break
3:00 PM	:30	Gate 3 Summary
3:30 PM	1:30	Executive Summary
4:00 PM		
4:30 PM		
5:00 PM		Workshop Adjourn