STATUS OF LUNAR REGOLITH SIMULANTS

AND

DEMAND FOR APOLLO LUNAR SAMPLES

Report from the

Simulant Working Group

of the

Lunar Exploration Analysis Group

and

Curation and Analysis Planning Team for Extraterrestrial Materials

to the

Planetary Science Subcommittee

of the

NASA Advisory Council

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Executive Summary

The large number of requests for Apollo samples to the Curation and Analysis Planning Team for Extraterrestrial Materials by in situ resource utilization and other technologies initiated an assessment of lunar regolith simulants by the LEAG-CAPTEM Simulant Working Group. The Simulant Working Group was chartered to report on the number and types of available lunar regolith simulants, the properties lacking in current simulants that are necessary for specific tasks and must still be developed, protocols for proper usage of simulants, and which technologies require the use of Apollo samples in lieu of simulants to adequately prove the design for lunar surface interaction. Simulants currently offered are exceedingly variable in all properties and available quantity, as well as fidelity when compared to actual lunar regolith. Some simulants are more suitable for specific tasks than others. That is, a successful geotechnical simulant is generally not also prudent for geochemical or mineralogical tests. To assure proper usage of simulants or to determine the need for new simulants and provide the lowest possible mission risk, simulant users are advised to discuss their tests with the Simulant Team at Marshall Space Flight Center and appropriate lunar experts prior to acquiring simulant.

Unfortunately, it is difficult, expensive, and time-consuming to produce adequate simulants. This has spurred other simulant users to produce their own "simulants" or materials quickly and cheaply, without the advice of simulant experts. Although this outside development cannot be prevented, it can ultimately add to the mission risk if an improperly designed simulant is used. Industry, with input from NASA, has also stepped up to the simulant production task; however it is viewed as a high risk/low reward venture. Suggested ways for industry to be included in the simulant production effort for NASA studies include: having NASA pay for some or all development costs; having NASA buy a significant amount of new simulant(s) from commercial vendors and distribute these simulants to the research community; and educating the user community that the cost of simulants is high and that they must plan their budgets accordingly. To illustrate the significant cost of simulant, it was suggested that research requiring simulants should budget up to 10% of their total cost for purchasing simulant(s). This would severely impact some technology research costs. Thus, it was also suggested that the NASA Directorates might work together to plan an integrated simulant-needs assessment, and consider adding funding to projects that require simulants.

The Simulant Working Group determined that only certain tasks require the use of Apollo samples to verify technology, and even those tests must be sufficiently miniaturized so as not to require large quantities of Apollo samples. These tasks include the characterization of biological interactions, particularly those dealing with human health and toxicity; mineral beneficiation technology dependent on the magnetic and electrostatic properties of the lunar regolith; and dust mitigation by magnetic and electrostatic means.

Additional comments, such as the need for sufficient funding of simulant development prior to the needs of the next generation of surface missions and the suggested creation of a planetary surface expert committee (Planetary Simulant Advisory Panel) to complement the Marshall Space Flight Center Simulant Team, are included for consideration by the NASA Advisory Council.

Introduction

It is generally held by the In-Situ Resource Utilization [ISRU] research community, as well as other areas such as the Human and Robotics Systems community, that testing at some scale or level with Apollo lunar regolith (soil ≤1 cm; dust ≤20 μm) is required to validate computer programs that model regolith behavior, critical design attributes, and/or minimize the risk of operating critical hardware on the Moon. This perceived need is to advance their development efforts to the next Technology Readiness Level [TRL] in preparation for launch of their technology. It is also thought that characterization of lunar regolith behaviors and interactions with the structures, chemistry, and biology of exploration and habitation on the Moon, should be similarly validated. These perceptions have led to many requests to the Curation and Analysis Planning Team for Extraterrestrial Materials [CAPTEM] for large amounts of lunar soil/dust. However, with the availability of appropriately designed, developed, and produced lunar regolith simulants, most of these lunar sample requests would not be necessary or justified. This report begins to address this issue.

Due to the precious nature of Apollo lunar samples and potential use for non-scientific purposes, the Planetary Science Subcommittee [PSS] of the NASA Advisory Council [NAC] recommended **"that a comprehensive study be undertaken by LEAG [Lunar Exploration Analysis Group] and CAPTEM to define the types of lunar simulants that the various communities require in order to facilitate important lunar investigations, as well as to preserve the Apollo lunar sample collection for future generations."** Subsequently, the LEAG-CAPTEM group was asked to form a committee, namely the Simulant Working Group [SWG], to study this subject, gather existing data, evaluate the number and nature of the lunar simulant needs, and report back with recommendations. It should be noted that the Regolith Simulant Team managed by NASA/MSFC had already collected much of this information from various NASA projects via a Lunar Regolith and Simulant User Survey before the SWG was created. The SWG (see **Appendix 1** for SWG membership and charter) consists of experts in lunar soil, lunar engineering, and lunar biology, in addition to NASA managers and industry representatives. *The SWG was charged with compiling a report within three months and this report addresses the following : 1) what is needed for lunar simulants; 2) what lunar simulants already exist; 3) protocols for their proper usage; and 4) needs for Apollo lunar samples.*

Numerous inputs into this report were accumulated and evaluated. The SWG Chair and a member visited the Lunar Simulant group at NASA/MSFC to consult with the Simulant Team and gather available lunar simulant documentation from their files. Several of the SWG members have participated in workshops or conferences (e.g., Lunar and Planetary Science Conference) and obtained valuable knowledge with which to evaluate and review this report. In addition, the first Lunar Applications of Mining and Mineral Beneficiation [LAMMB] Workshop was convened at Montana Tech in Butte in early October. The purpose of this Workshop was to discuss beneficiation technologies and the requirements for lunar regolith simulants in order to investigate and advance ISRU technologies. Many of the major simulant users' project managers, simulant developer managers and workers, as well as academia and industrial representatives, were present at this apropos workshop. Jerry Sanders, ESMD-ISRU Chief Engineer, chaired a round table discussion on the topic of Lunar Regolith Simulants at the Workshop. A synopsis of the discussion was written and distributed to the Workshop attendees. The round table was extremely helpful in further defining the many challenges and difficulties in preparing simulants, particularly those of high-fidelity, including characterization and assessment of the simulants' fidelity levels; assessment of the production and distribution of simulants; investigation of the influence of cost; acquisition of simulant feedstock; and the determination of a responsible organization for developing, producing, and characterizing/evaluating simulants. Importantly for this report were the major concerns of CAPTEM for the numerous requests they had been receiving and evaluating the last several years for lunar samples for engineering (e.g., ISRU) endeavors.

Simulant History:

For a decade prior to January 2004, no NASA simulant program existed; however, various users were producing simulants. In 2004, the ESMD funded the In-Situ Resource Utilization Project, which included the establishment of a Lunar Simulant Project. The genesis of this simulant effort was for MSFC to provide a centralized focal point for all NASA lunar simulant user requirements collection, development, production, and characterization activities. This project was initiated in response to the then-newly-announced Vision for Space Exploration [VSE], which included returning humans to the Moon and establishing an outpost. The VSE required simulants for advancing technologies and performing hardware certifications. Over the past six years, the Simulant Project has made good progress in gathering data on the needs of the simulant community within the ESMD Exploration Technology Development Program (ETDP) and the Constellation Program, evaluating physical and chemical criteria for the production of appropriate simulants; developing recipes and process controls for production of regolith simulants; and being responsible for production of lunar regolith simulants for NASA ISRU and

Dust Mitigation Projects since those projects were the primary funding sources for the last six years. **Appendices 2 and 3** contain two of the several MSFC-generated Reports.

It is not a simple or easy task to produce lunar simulants for particular purposes, or even to represent a particular Apollo lunar mission region. One must understand the requisite lunar material properties well enough to set simulant requirements, and understand the users' hardware and test objectives well enough to advise on the appropriate simulant to use or to develop a new simulant if the existing ones do not meet the user's needs. However, it is also necessary to develop adequate process production techniques and controls that meet the simulant fidelity requirements. Last but not least, measurement techniques and test protocols must be established and implemented to verify that the requirements have been met within acceptable tolerance levels (i.e., quality control). It is generally felt by the SWG that the concept that "one size does not fit all" for lunar simulants has *not* been effectively understood by many in the simulant user community. In the future, this should be more strongly conveyed and emphasized.

The unique nature and diversity of actual lunar soil (i.e., Apollo samples) is not necessarily well-understood or appreciated by many of the potential simulant users; this has resulted in unadvised individuals selecting and using materials as "simulants" for their test purposes. The use of these simulants, especially for advanced TRLs, can lead to potentially misleading results that could have disastrous consequences resulting in hardware that does not function properly in the actual lunar environment. Industrial, academic, and NASA researchers commonly misuse lunar simulants that were designed and produced for other specific purposes, primarily due to lack of knowledge on the user's part. This is largely due to the lack of communication with the simulant experts who could provide advice and recommendations in the proper selection and usage of simulants. It is also a possible effect that the original JSC-1 was somewhat "over-sold" as a multi-use lunar soil simulant. The general conception that a simulant such as JSC-1A, the "new" JSC-1, made primarily for its geotechnical properties, also has all the chemical and mineralogical properties of real lunar mare has led to several questionable uses. Such wastes of time and resources could have been prevented with more communication between the simulant users, the Lunar Simulant Office at MSFC, and lunar regolith experts.

It is felt by the SWG that there is need for more education of the simulant users, with regards to lunar soil scientific and engineering parameters. A suggestion was made that each container of simulant dispersed by a producer should have a large "warning label" outlining the types of experiments for which it is qualified, and warnings or cautions to check with the Lunar Simulant Office before utilizing it for any other experiments. Users need to be advised to read and understand the Characterization Sheets and the Material Safety Data Sheets [MSDS] that come with each simulant as well, but this should not take the place of direct communication with the simulant experts.

Lunar Simulants

Existing Lunar Simulants:

There are >30 lunar simulants that have been produced to date, some of which have been exhausted – **Appendix 4** lists simulants currently known by the MSFC Simulant Development Team. Because of the depletion of former JSC-1 simulant, originally produced and distributed by Johnson Space Center [JSC], a subsequent simulant (JSC-1A) was produced near the start of the VSE to provide developers with an initial simulant to begin development activities; this simulant has only been available for 5 years. Besides JSC-1A, there is another NASA-produced simulant series [NASA/U. S. Geological Survey - Lunar Highlands Type (NU-LHT) and its derivatives] for highland soils, which were made available recently due to the VSE interest in the polar region of the Moon. Due to several factors such as the lack of selection of simulants, limited supply of the new NU-LHT simulant, and costs, users have developed a tendency to make their own simulants to use in their test programs. This can be good or bad depending on their knowledge of lunar regolith, materials processing, and appropriate simulant use. Indeed, because of the prohibitive cost for obtaining large quantities of JSC-1A and NU-LHT, Glenn Research Center [GRC] created and produced GRC-1 and 3 as simulants for excavation and wheel/soil interaction testing. Recently, material from the Black Point lava flow near Flagstaff, AZ, called BP-1, was used for performing excavation tests and will be utilized for an upcoming excavation challenge at Kennedy Space Center in 2011. While neither the BP nor GRC simulants can be considered good for most lunar development activities, they are reasonable first approximations for the development tasks for which they were created. Whereas Appendix 4 contains a large number of past and current simulants, it is suspected that there are many other users, both internal and external to NASA, developing their own simulants unbeknownst to the Simulant Group at MSFC. As also depicted in Appendix 4, other countries besides the U.S. continue to develop simulants to support their own hardware development efforts (e.g., Canada, Japan, China, and South Korea). Some of these countries have also inquired into purchasing U.S. simulants and/or obtaining assistance with developing their own simulants.

Various natural and man-made materials have been used as feedstock for the simulants: from crushed volcanic tuffs with abundant glass (e.g., JSC-1 & JSC-1A), to anorthosite with added fayalitic (Fe silicate) slag (e.g., OB-1), to synthetic agglutinates, to synthetic nanophase metallic iron (Fe^0). Although some of the simulants produced to date have served well for important studies and tests, other simulants do not have the proper lunar soil properties for which they have been applied or utilized – e.g., JSC-1A has a large amount of nanometer-sized magnetite ($Fe^{2+}Fe^{3+}{}_2O_4$), so this would definitely not be the feedstock for the laborious effort to produce nanophase Fe in a simulant of lunar magnetic properties. It may be suitable as it is for preliminary experiments. Lunar simulant production is not an easy process and will become more difficult as simulants with more accurately produced lunar regolith properties (known as higher fidelity simulants) are required, especially the more lunar properties that are involved/required for specific tests.

Need for Lunar Simulants:

It was recognized early on that there were more users for lunar simulants than in the original NASA ISRU Project, from which the restarted Lunar Simulant Project was funded. The Lunar Simulant Project at MSFC has generated a compilation [**Appendix 5]** of various aspects that must be considered for the production of quality simulants. The data in Appendix 4 are cumulative results of previous Lunar Simulant Workshops, information from the lunar community, and the Lunar Sourcebook (Heiken et al., 1991). It is believed by the Lunar Simulant Project at MSFC that these are the specific things that need to be considered for a simulant to be viable and of real use for hardware development projects.

The need for simulants is driven by what technology and development efforts require the simulants. In turn, the simulant needs are controlled by specific lunar properties or exploration architecture objectives that most affect the engineering and scientific objectives. As the TRL of a project increases, the need for more closely controlled lunar properties in the simulants also becomes more important. A symbiosis of science and engineering is a major factor that needs further work in order to be successfully implemented in the scheme of lunar simulant development. Combined efforts and communication between ESMD and SMD [possibly through CAPTEM] is imperative; this collaboration might be the catalyst needed to stimulate this forging of relationships.

The numerous technologies and discipline areas require lunar simulants; the physical and chemical characteristics that may be important in their application; and the estimated quantities of simulant required were collected by MSFC via a user-survey and discussions, and it is summarized in **Appendix 6**. (*It must be noted that these simulant demands were gathered prior to the recent announcement of NASA's new Flexible Path space policy which has much less focus on the Moon and more on Mars, asteroids, and other planetary bodies. This new space vision will most likely change many of the demands currently delineated in Appendix 6*). It should be noted that while the data gathered provide information on what users believe are important regolith parameters for their research/hardware development efforts, it does not define the relative importance of each parameter and when in the development cycle that parameter will be more or less important. In addition, there may be need for a lunar simulant with certain properties, yet the capability may not *yet* exist to produce a simulant with these properties. **Appendix 7** lists the existing capabilities for reproducing certain characteristics of lunar soil; however, it should be acknowledged that lunar simulants will never fully replicate lunar soil properties due to the uniqueness of lunar soils and the necessitated use of weathered/oxidized terrestrial materials.

Based on discussions with current lunar simulant developers, production and sale of simulants can be a very high-risk/ low-reward endeavor. The costs to develop new, high-quality simulants are quite high, and the potential market is completely unknown. However, it is strongly believed by SWG members that some of the processes for generating simulant feedstock and for producing the simulants could provide several spin-offs benefitting various commercial industries, such as mining, pharmaceuticals, glass, and metal refineries. Some in the user community expect appropriate, high-quality simulants to be available for little or no direct cost. This means there is a lot of risk for a commercial company to develop a new simulant with little chance of reward. The uncertainty over the future of NASA has only made this problem worse. Will there be a return to the Moon? If so, when and where? How much simulant will be needed and when will it be needed? What are the requirements for this simulant(s)? These are questions yet to be answered.

Despite the above concerns, there are ways to improve the risk/reward balance. The following three ways were considered by the SWG, but should not be regarded all inclusive: 1) have NASA pay for some or all of the development costs; 2) have NASA buy a significant amount of new simulant(s) from commercial vendors and distribute them to the research community; and/or 3) educate the user community of simulants, their cost, and the impact on their research, such that appropriate simulant selection and procurement is performed. The first option has been done already to a certain degree, but it still does not satisfy the market need for more simulants. The second option would establish a market for simulants and allow NASA more control over what simulants are used for research projects. However, once a simulant has been procured by NASA, improvements to the simulant or production of a new simulant to perform the same function would be discouraged, in order to achieve a cost payback for the investment in the existing stockpile. The third option does nothing to discourage individual simulant users from developing their own simulant, and in fact may encourage them. The simulant costs will likely be higher under this option since simulants will only be produced on an as-needed basis. It is important to emphasize that the advice of the Lunar Simulant Office should be sought for future NASA-funded research that requires lunar simulant use, which would help to ensure that the most appropriate simulants are used for NASA-funded research.

Alternatively, NASA-funded research projects requiring lunar simulants might be encouraged to include an allowance in the budgets for simulant development or purchase (notionally 1 to 10%). The NASA Directorates might work together to plan an integrated simulant-needs assessment including, but not limited to, test beds that require large amounts of simulants. Investigators that are selected for Small Business and Innovation Rewards (SBIRs), Lunar Institutes, Research Opportunities in Space and Earth Sciences (ROSES), etc., must account for simulant needs and the costs to procure those simulants when they develop their proposals. NASA/HQ must be cognizant of this issue and develop a means to ensure that the costs of development and procurement of simulant costs are considered for research that involves the use of lunar simulants.

Need For Apollo Lunar Samples

While the MSFC Lunar Regolith and Simulant Survey conducted in 2008 and 2009 revealed requests for actual lunar regolith samples (presented at the 2009 LEAG meeting), it is believed by members of the SWG that there are few needs for the use of a real lunar specimen with which to experiment on, especially for large-scale testing. That consensus is becoming gradually accepted by the engineering community as well. Real needs do exist for studying interactions between lunar samples and terrestrial chemistries and biology, which will require small amounts of lunar samples for study. During the LEAG meetings and the Lunar Beneficiation Workshop/Simulant Round-Table in Butte and after considerable discussions in other forums, it was agreed that the real needs for testing with lunar regolith/soil/dust are few. These needs include: 1) characterization of biological interactions at all levels, including but not limited to human health and toxicity issues; 2) mineral beneficiation studies using magnetic and electrostatic processes; and 3) dust mitigation by electrostatic/magnetic means. New developments in the area of nano-sized metallic iron may have also negated apparent needs for lunar samples. Nanophase iron (Fe^0) additive has been developed for incorporation into lunar simulants for research such as the study of microwave heating, sintering, and melting of lunar soil (L.A. Taylor, pers. comm., 12/2010.). As the available simulants become more precise representatives of particular and diverse lunar soil samples, the demand for and use of lunar samples will be reduced, thereby, preserving more of the lunar samples and ensuring they remain intact.

Requests for lunar samples to use for engineering studies must follow the application instructions in the Astromaterials Research and Exploration Science Directorate (ARES) at JSC, available on the internet. The application is both to the Lunar Sample Curator and CAPTEM. A sub-committee of CAPTEM interfaces with members of the engineering community at JSC, and outside reviews of proposals are obtained as well. CAPTEM evaluates the proposal in light of these reviewers' inputs, and the Lunar Curatorial personnel also suggest possible lunar samples for use. CAPTEM then makes a recommendation to NASA Lunar Sample Curator regarding the lunar sample request. Notably, requested Apollo samples for engineering studies are often fairly large due to the perceived need to reproduce test results with the full size of the equipment. Therefore, past experience with engineering requests for lunar sample has demonstrated that the mass of requested sample is typically too large, with regards to use of these precious samples. CAPTEM may suggest that the applicant *miniaturize* the experiment, in order to reduce the absolute mass of sample needed. This has led to approved sample requests for engineering studies. The approval of the sample request will designate exactly how the sample should be used, including its possible destruction. In addition, the applicant must establish that their laboratory protocols, procedures, and facilities are suitable for the use and storage of the Apollo samples.

Suggestions for the Future

Although it is not in the purview of the SWG tasks, several issues regarding lunar simulant design, production, and distribution were addressed in our deliberations. The following views should be taken in light of the fact that the Constellation Program no longer exists and NASA's apparent direction does not involve human presence on the Moon in the immediate future (e.g., 20-30 years), although robotic missions and orbiters are still planned. The following are considerations for the simulant program in the future, for ESMD and SMD to consider, especially when a renewed interest in U.S.-led, long-term, manned missions to the Moon occurs. It could be argued that the postponement of human return to the Moon for a long period of time may effectively increase the value of lunar simulants because the ability to replenish the exisiting supply of actual lunar material is also postponed accordingly. Lunar, asteroid, and planetary simulants may become central to many kinds of new technology development for the future.

The Lunar Regolith/Soil/Dust Simulant Project's tasks were to design, develop, produce, and provide simulants for use in the ESMD ETDP and Constellation Projects, such as lunar surface system technology development, as funding allowed. In addition, the project was also to provide advice and consultation to the simulant users in the proper selection, handling, and use of simulants for both NASA and non-NASA studies. For the future, the SWG advises that *it is imperative that the various NASA directorates, projects, and tasks within projects coordinate with the Lunar Simulant Project and continue communication to maintain current simulant requirements and needs as situations change*.

At this time, with the demise of the Constellation Program, there is need for re-evaluation of the placement of lunar simulant production in the ISRU Project, as this affects the simulant needs of the community. Because of limited funding to the ISRU Project, funds dedicated to simulant development have been focused primarily on the needs of the ISRU Project and not the simulant users' community in general. Also, much of the data on the needs for various lunar simulants compiled by MSFC and included in this study will need to be re-evaluated with NASA's new space-policy direction.

There are several things that investigators and technology developers need to be aware of and understand when using simulants in lieu of actual regolith. These include: 1) how the regolith and simulants differ and what the implications are; and 2) how those differences will interact with the experimental conditions. The first awareness is related to pure geology, while the second awareness requires both geology and the biological, chemical, or structural experiment under consideration. This is especially true for production scale experiments that move beyond model biological, chemical, or mineralogical systems. Robust regolith simulants for both maria and highlands should provide sufficient material that accurately mimics these regoliths upon which an extended outpost would depend. In addition, exacting regolith simulants may need specialized processing and storage to most accurately reflect the type of material astronauts would manipulate *in situ*, and some portion of simulant manufacture should be reserved for high-fidelity, specialized purposes.

Planetary Simulant Advisory Panel:

The SWG has perceived a need for a bridge between a good knowledge of the science and engineering properties of lunar regolith, within the context of the Moon, and the user community and the MSFC Simulant Program. *It is highly recommended that a Planetary Simulant Advisory Panel (PSAP) be established.* This panel should consist of experts with knowledge in the physical/chemical characteristics and general science of planetary regoliths/soils and in their surface-system engineering (e.g., civil engineering) and other engineering disciplines as needed. The PSAP would complement the Simulant Team and assist in ascertaining and interpreting users' requirements for both simulants and actual regolith samples leading to the development of various types and fidelities of simulants. This panel would also participate in defining the appropriate applications for the different simulants and be available to consult with users in the proper selection, use, handling, and preparation of the simulants for specific tests. In addition, the PSAP would assist in collecting data on simulant users and their test needs that would be used to further characterize and improve simulants as necessary.

The SWG has considered the variety of lunar regolith/dust simulants that exist, not only in the USA, but also in several foreign countries, where requests for Apollo sample may originate. It has readily become obvious that, because of the large variety of simulants and their unique properties, this is a complicated matter with major ramifications for NASA scientists and engineers, as well as those in industry and academia. The MSFC Simulant Team has already made noble efforts in considering several of these factors. In addition, the Simulant Team has performed characterization tests on several simulants and materials, thereby, starting to assimilate a library of known simulant properties. Though the Team has made significant strides in the areas of developing recipes for various simulant uses (e.g., oxygen extraction, excavation, dust mitigation, et cetera), there is still much to do. The formation of the PSAP would be a tremendous source of knowledge and capability and in working with the Simulant Team to complement their endeavors, the simulant users would greatly benefit from this partnership.

It is generally felt by the SWG that NASA needs the knowledge and capability to provide its ISRU and other technology rapid access to appropriate simulants. This requires funding for the project to stockpile current simulants and develop new high-fidelity simulants for use in future ISRU or NASA projects. Thus, it is of vital importance to fund the Simulant Project *prior* to the time when simulants are needed for testing technologies that will be used on lunar, martian, or asteroid surfaces. The higher-fidelity simulants that the Simulant group is able to design and produce (or direct the production of), the less risk there will be in a NASA surface mission.

Unfortunately, funding for the Simulant Project has been less than ideal for the task it was assigned. Much of the simulant work for the group at MSFC was started and funded through the ISRU Program to meet ISRU development and test needs. Later, the project was moved to the ESMD ETDP Dust Mitigation project, managed at Glenn Research Center. When Constellation was cancelled, the Simulant Project moved back under the direction of the ISRU Project. Minimal funding has been provided for FY11, which does not allow the Simulant Project to procure or produce simulant, and additional meager funds are planned for allocation in the future under ISRU. Sufficient simulant development requires investment from both SMD and ESMD to assure both NASA Directorates mission success. Thus, the procurement and production budget for the Simulant Project should be increased, and the funding for the PSAP should be made independent of the simulant procurement and production budget to prevent the demise of one for the preservation of the other.

A suggestion was made in the SWG that NASA consider locating the PSAP in the Astromaterials Acquisition and Curation Office, in the Astromaterials Research and Exploration Science Directorate (ARES) at JSC. This division curates and conducts research on extra-terrestrial materials: 1) lunar rocks and soils; 2) meteorites from Antarctica; 3) cosmic dust collected in the stratosphere; 4) samples collected by the Genesis Mission; and 5) cometary dust collected by Stardust Mission. Many of the scientists in ARES are world-class in lunar sample research and are among the most knowledgeable in the science/engineering of lunar rocks and soils, the subject of this report. In addition, ARES is the home of the Lunar Sample Curator and Facilities and CAPTEM, the committee that evaluates and recommends applications for lunar samples for scientific and engineering research.

Regardless of the location of the PSAP, it should be responsible for complementing the MSFC lunar simulant program, working closely with and assisting in the evaluations of simulant users' needs. The planetary materials expertise of the PSAP combined with the engineering and simulant-production expertise of the MSFC program would make for a united and efficient planetary simulant program, ready to continue to develop and produce simulants now and into the future. This combination of the PSAP and MSFC Simulant Program should be largely proactive, with scientific and engineering advice to simulant developers and users, as well as general education of the lunar simulant community. This mode of operation will insure the close alliance of both the scientists (SMD) and engineers (ESMD), and bring these two NASA Directorates together in a common cause.

As extra-terrestrial sample research progresses in the near future, simulants of soils of Mars, asteroids (Near Earth Objects [NEOs]), and Phobos will be needed. The next generation of robotic sample return missions will provide scientists and researchers with an entirely new selection of small samples from the Moon, the surface of an asteroid, and from Mars. The detailed properties of these new samples will provide data enabling the production of new simulants, which in turn will enable the development of lower-risk new technologies.

Relevant Findings

The needs for lunar simulants and a list of existing simulants are currently available in documents by the MSFC Simulant Program (Appendices 3, 4, and 6). The current needs will definitely be modified as a result of the cancellation of the Constellation Program and an evaluation of the role that the new discoveries of water on the Moon will have for future ISRU endeavors. There are >30 lunar simulants around the world, many produced by the users themselves that are potentially suitable for unique tasks, if used appropriately and properly.

It is generally recognized that the protocols for the proper usage of lunar simulants have not been effectively conveyed to the potential users, though not due to a lack of effort or concern from the MSFC Simulant Team. The education of the users in the science/engineering of lunar regolith is a critical part of the simulant problem and must be resolved. For the education of potential simulant users, it is suggested that an additional **Regolith Simulant Team website** (http://isru.msfc.nasa.gov) be established that is specifically dedicated to the education of potential simulant users (e.g., scientists, engineers, and teachers). The website should be user friendly, and contain a good selection of lunar soil science and engineering topics and tutorials, with many suggested readings. Public contact information on the website for the MSFC Simulant Program and the Planetary Simulant Advisory Panel will encourage the users to query and correspond with the experts to assist the proper choice and usage of a simulant. Appreciation must be fostered that each simulant is different, and it takes a great deal of knowledge to determine the appropriateness of a simulant for different experiments.

The engineering ISRU community and [illegible]nt activities that are designed to interface with planetary surfaces have few needs for actual Apollo lunar samples; appropriate simulants will provide sufficient data. However, a few activities, because of the known or anticipated extreme complexity of potential interactions with lunar regolith, require allocations of lunar material from the Apollo collection. Currently only three types of activities have been identified in this category: 1) characterization of biological interactions at all levels, including but not limited, to human health and toxicity issues; 2) mineral beneficiation studies using magnetic and electrostatic processes; and 3) dust experiment development and dust mitigation by electrostatic or magnetic means. We recommend that Apollo allocations be restricted to these three categories unless an extremely strong case can be made that simulants are inadequate.

Education of the engineering community to the requirement that whatever process or use for lunar samples is proposed, miniaturization of the overall experiment or equipment must be undertaken to minimize the quantity of Apollo sample required. It might be appropriate to have a member from the ESMD technology development office (possibly from the MSFC Simulant Team) become a member of the CAPTEM lunar allocations subcommittee.

ISRU and other NASA technology development projects typically have definite test milestones. Timely funding for the Simulant Group and PSAP is required in order to produce and deliver appropriate simulants sufficiently in advance of such project dates. This is vital for meeting mission deadlines and assuring the lowest possible mission risk. If NASA developed or approved simulants are not available when needed, users will once again fall into the trap of developing their own material to substitute as simulants which could have dire consequences to hardware functionality and reliability and, thus, overall NASA mission success.

Lawrence A. Taylor 12/18/2010

Lawrence A. Taylor, SWG Chair date

APPENDIX 1. Charter for Simulant Working Group, Members, and Contact Info.

Charter for the LEAG-CAPTEM Simulant Working Group.

LEAG and CAPTEM have been tasked by the NASA Advisory Committee, Planetary Sciences Subcommittee to undertake a study of the need for lunar simulants in the following recommendation:

"The PSS recommends that a comprehensive study be undertaken by LEAG and CAPTEM to define the types of simulants that the various communities require in order to facilitate important lunar investigations as well as to preserve the Apollo lunar sample collection for future generations."

The Working Group will report three months after it has been formed and is charged with the following tasks:

1) **Identify all available lunar simulants** along with their physical and chemical characteristics, the reason that they were made, the process by which they were made, who made them, and the quantity available (along with where/how they can be acquired) to the broader lunar community;
2) **Identify all potential areas of study** (e.g., engineering, biomedical and ISRU) that could require large quantities (10s of grams to kilograms) of lunar samples, thus creating a critical need for lunar simulants. For each area of study, (a) define the physical and chemical characteristics that would be required for the appropriate simulant and (b) estimate a projected quantify that would be needed for each area of study the foreseeable future (i.e., the next 10 years).

The product will basically address 1) what is needed for lunar simulants; 2) what lunar simulants already exist; 3) protocols for their proper usage, and 4) needs for Apollo lunar samples.

This working group will leverage its report by using existing resources including, but not limited to, those available on ISRU simulant web site at Marshall Space Flight Center (http://isru.msfc.nasa.gov/simulantdev.html).

Timeline: by Thanksgiving 2010

Simulant Working Group members (Chip Shearer (ex-officio) LEAG Chair):

- **Larry Taylor,** Univ. of Tenn., LADTAG, Lunar Soil Expert (Chair)
- **Jennifer Edmunson,** MSFC, Simulant Engr.
- **Rob Ferl,** Univ. of Florida, KSC, Molecular Biologist
- **Bob Gustafson –** ORBITEC, Simulant Engr.
- **Yang Liu,** Univ. of Tenn., Lunar Soil & Simulant Characterizer
- **Gary Lofgren,** JSC, Lunar Sample Curator
- **Carole McLemore**, MSFC, ISRU/Dust Project Manager
- **Dave McKay**, JSC, LADTAG, Lunar Soil Expert (Dust/Biomedical)
- **Doug Rickman,** MSFC, Simulant developer and tester
- **Jerry Sanders,** JSC, ISRU Head Honcho
- **Mini Wadhwa,** (ex-officio) CAPTEM Chair, Lunar Expert

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Appendix 2

Lunar Regolith Simulant User's Guide

National Aeronautics and
Space Administration

Simulant-Doc-007
Revision 2
Draft Date: 1/16/2010
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George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

VP33

Lunar Regolith Simulant Development & Characterization Project

Lunar Regolith Simulant User's Guide

Revision 2

Distribution Unlimited

[To Larry Taylor from Carole McLemore, 9-1-10]

Signature Page

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11/25/08

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Draft Revision	**1**	**11/25/08**	**On 1/16/09 - Revision v.1.21**
Draft Revision	**2**	**TBD**	**On 1/20/10 - Revision 2.2** **Updated Contact information to include Jennifer Edmunson**
			2/18/10 – Changed the document naming structure. Former was DUST-Sim-Doc-001, new one is Simulant-Doc-001. No content changes were made.

Lunar Regolith Simulant User's Guide, 2010

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1 Purpose

This document summarizes information on existing lunar regolith simulants. We focus on primary characteristics of the simulants, i.e., the inherent properties of the material rather than their responses to behavioral (geomechanical, physiochemical, etcetera) tests. We define these inherent, or primary, properties to be particle composition, particle size distribution, particle shape distribution, and bulk density. When data allow, we quantitatively compare simulant properties to those of a lunar highlands regolith reference material by use of Figure of Merit algorithms and software.

Some of the simulants mentioned in this guide are no longer available for use. However, if any simulant has been analyzed, used in a proof-of-concept study, or used for hardware testing, it is necessary to understand that simulant's properties relative to the lunar regolith.

NOTE: Before choosing or using a simulant, we strongly encourage simulant users to contact one of the members of the MSFC simulant program listed at the end of this document. We do not intend for the Figure of Merit scores or the Simulant Use Matrix to substitute for consultation with experts. Where we lack expertise we can guide you to the appropriate resources.

2 Definitions

All definitions for minerals are based on *Dana's New Mineralogy* (Gaines et al., 1997). Definitions for rock types are based on IUGS classifications found in *Igneous Rocks: A Classification and Glossary of Terms* (Le Maitre, 2005). Particle type definitions for the sub-millimeter portion of lunar regolith are based on Basu and McKay (1981).

3 Figures of Merit (FoM)

The Figure of Merit (FoM) mathematics and algorithms (Rickman et al, 2007, and MSFC-RQMT-3503 (DRAFT)) provide a means for formal, quantitative comparison of two particulate materials composed of geologic components. A reference material serves as the benchmark against which a second material is compared. In this case, the reference material is an average of lunar subsamples within a lunar core (see below). The simulants are compared against this reference. Though it is beyond the scope of this work, it is worth mentioning that the FoM can be used to compare multiple batches of simulant, multiple samples of lunar regolith, or any other two materials.

3.1 Objective of FoM

The FoM was designed as a practical and efficient way to characterize and compare materials. Towards this end the parameters for evaluation are chosen to be:

- definable: many characteristics of materials are not yet rigorously defined – we use only properties defined in MSFC-RQMT-3503 (DRAFT);
- measurable: parameters were chosen that can be measured economically, in a timely fashion, and with results reproducible across laboratories;
- useful: for simplicity of design, parameters were chosen that correlate to properties important to the functioning of simulant under expected conditions; and
- primary versus derivative: this concept recurs throughout the FoM logic; some characteristics are inherent to a material, like the composition of its constituents, be they minerals or glass, while other properties like the behavior of a material during heating are derivative of the composition, all else being equal.

3.2 Figure of Merit Composition

Composition describes attributes of a particle that exist without regard to size or shape. Here, we use the term *particle* to mean a piece of solid matter mechanically separable from others, such as by use of a sieve. All particles in lunar regolith or simulant will be comprised of glass and/or mineral "grains", but particles may be amalgams of grains that result in lithic fragments (rock particles) or agglutinates.

Therefore, the first order of classification of constituents includes mineral grains, glass grains, lithic fragments (which include breccia fragments), and agglutinates. Measuring proportions of particle types by volume is known as a "modal analysis" and is usually reported in modal% by each constituent. Although not required by the Figure of Merit, it is ideal that modal analyses be obtained for a material in several different size fractions. This is because the percentages of constituents of any bulk material will tend to vary by size due to differential susceptibility to grinding and crushing.

3.3 Figure of Merit Particle Size Distribution

For the Figure of Merit, particle size is measured on a particle by particle basis and reported as a distribution. The number of bins and the size of the bins are defined by the user, but a more precise FoM evaluation is rendered by an approximation to the lunar regolith dataset. These data can be found in, for instance *The Lunar Soils Grain Size Catalog* (Graf, 1993).

3.4 Figure of Merit Shape and Density

We have preliminary definitions for particle shape distribution and bulk density with regard to Figures of Merit, and we are developing algorithms and metrics. These FoMs are not included in this User's Guide.

3.5 FoM software

The software used here for size FoM ratings is Figure of Merit v.1.0, released in 2007, and v.2.0, released in 2009. The composition FoMs presented here were calculated using the algorithm of Figure of Merit Revision v.2 software.

4 Lunar Regolith Reference Material

The reference material used here for the Figure of Merit calculations is the integrated suite of subsamples from Apollo core 64001/64002, which is a sample of lunar highland regolith from Apollo 16 Station 4. A highland sample was chosen in line with the current lunar architecture which calls for an outpost in the polar region – a region best approximated by highland regolith (to the best of our current knowledge). A lunar core was chosen as opposed to a soil sample because it provides an integration of the surface and shallow subsurface, thus at least partially countering the bias lent by surface processes like "space weathering". 64001/64002 was specifically chosen because it is a complete and intact core, it is deemed representative of Apollo 16 site regolith (Houck, 1982) and it has been reasonably well-studied.

5 Composition

5.1 Lunar Regolith Data Used for composition FoM

The Figure of Merit v.2 software combines particle type data, as described above, with limited mineral composition data for comparison. Mineral composition data are measurements of the average chemistry of mineral phases with variable compositions. Many minerals, including the most common ones in lunar regolith – plagioclase feldspar, clino- and orthopyroxene, and olivine – have chemical compositions that vary between fixed points. This is called *solid solution* and it varies between *endmembers*. Figure of Merit v.2 software allows incorporation of solid solution chemistry into the composition comparison, but only for plagioclase feldspar is there sufficient data available for reasonable comparison. The other solid solution minerals are either undifferentiated, as with olivine, or grouped into subclasses, as with clino- and orthopyroxene and the spinel minerals.

5.1.1 Literature Data

We averaged modal particle type data for sample 64001, the lower ~30 cm of the core, from Basu and McKay (1984) and from 64002, the top ~30 cm of the core, from Houck (1982) for use as the basis for the FoM lunar reference material. Each study examined six size fractions from 20 to 500 µm of six subsamples of the core at ~5 cm interval. They classified particles according to the system of Basu and McKay (1981). They calculated a weighted average, by weight% of the size fractions, of the compositions of each subsample. We then combined these subsample averages to a single mean particle type composition of the 20-500 µm portion of the 64001/64002 core.

This particle classification (Basu and McKay, 1981) has primarily been used with data generated by optical microscopy of very fine particles, and thus some mineral types are not classified to the level of specificity we desire. For instance, pyroxenes are not differentiated to clino- and orthopyroxene, and all spinel minerals (chromite, spinel, and ulvöspinel), ilmenite, and sulfides are undifferentiated as "opaques".

More than 90% of the particles by weight of most lunar regolith samples fall below 500 µm (Graf, 1993). An average of ~20 wt.% of most regolith falls below 20 µm, but modal data for this fraction are scarce. Therefore, we consider this to be the most reasonable available dataset for our purposes.

5.1.2 Scanning electron microscope/energy dispersive spectroscopy data (SEM/EDS)

We generated modal data from electron beam analysis of Apollo 16 samples from drive core 64001/64002. The analyzed lunar samples were thin sections 64002,6019 (5.0-8.0 cm depth) and 64001,6031 (50.0-53.1 cm depth) and sieved grain mounts 64002,262 and 64001,374 from depths corresponding to the thin sections, respectively. We analyzed four size fractions from each grain mount sample: 500-250 µm, 150-90 µm, 75-45 µm, and <20 µm fractions. These data are not particle type modal data but rather total area modal% by phase, such as by mineral type and glass.

For the lunar reference composition, we use the ratios of certain mineral classes from these SEM/EDS data to augment our particle type modal data from the literature. For instance, when the Houck (1982) and Basu and McKay (1984) data report only "pyroxene", we subdivide these into clinopyroxene and orthopyroxene based on the electron beam-generated ratio. Furthermore, we divide their "opaques" into ilmenite, Fe-sulfide, and spinels (not further differentiated).

5.1.3 Plagioclase composition

Plagioclase feldspar is the only mineral for which we currently evaluate chemical compositional variability in the FoM algorithm. We use the generally accepted composition of An95 (Heiken et al., 1991) for lunar highland regolith plagioclase. This means the plagioclase is 95 molar% of the $CaAl_2Si_2O_8$ (anorthite) end-member and only 5 molar% of the $NaAlSi_3O_8$ (albite) end-member. We include plagioclase composition in the FoM because:

- it is the most abundant mineral in the highlands regolith (e.g., Houck, 1982);

- it is the only mineral for which we have reasonable compositional data in both the regolith and the simulants; and
- lunar highlands plagioclase is more calcic than almost any terrestrial plagioclase, and we view closeness to lunar plagioclase composition as a significant marker of simulant fidelity.

5.1.4 Populating the lunar reference for Figure of Merit

The literature and SEM/EDS data are combined so as to yield a highlands lunar regolith reference composition, which is shown in Table 1 along with simulant data.

Table 1. Particle type modal data and plagioclase molar% Anorthite for the lunar reference material and regolith simulants. See text for data sources.

	64001/ 64002	**NU-LHT-1M**	**NU-LHT-2M**	**OB-1**	**JSC-1**	**JSC-1A**	**JSC-1AF**	**FJS-1**	**MLS-1**
Lithic Fragments	31.1				90.9	90.9	91.9	80.2	52.3
Glass	8.9	22.4	7.2	52.6				0.5	36.6
Agglutinates	32.5	29.0	23.5						
Plagioclase	23.3	38.8	54.9	43.9	1.5	1.5	3.4	14.1	2.6
(Plag. An%)	*95*	*80*	*80*	*75*	*68*	*70*	*70*	*50?*	*47*
Olivine		2.9	9.5	0.0	5.6	5.6	4.1	1.1	0.0
Clinopyroxene	0.6	2.0	4.0	0.1	1.3	1.3	0.4	1.2	2.2
Orthopyroxene	3.2	4.4	0.2						
Spinel minerals	0.03	0.05	0.01	0.19		0.04	0.02	0.05	0.03
Fe-sulfide	0.01	0.00	0.04						
Ca-phospates	0.12		0.43						
Ilmenite	0.1	0.3	0.2	0.0		0.1	0.0	0.1	1.1
Native Iron	0.01								
Other (sim. only)		0.2	0.1	3.1		0.5	0.1	2.6	5.2
Total	100	100	100	100	100	100	100	100	100

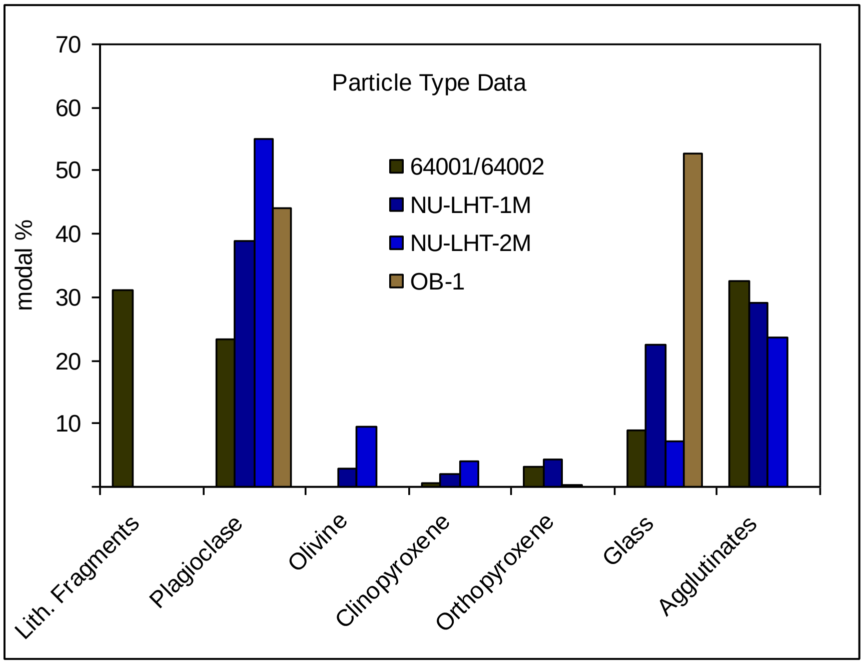
5.2 Simulant data used for composition FoM

Particle type modal data for the regolith simulants is from electron beam analysis. Plagioclase composition is based on the limited data of feedstock analysis or, when available, electron microprobe analysis of the simulant itself.

5.2.1 Scanning electron microscope/energy dispersive spectroscopy data (SEM/EDS)

All simulants analyzed have been considerably less complex, texturally, than the analyzed lunar regolith. We have been able to obtain consistent particle type data on the simulants by QEMSCAN® SEM/EDS analysis. The software used for textural analysis and particle identification is the iDiscover 4.2 package developed by Intellection, Ltd.

and incorporated into QEMSCAN® technology. It differentiates and classifies basalt as



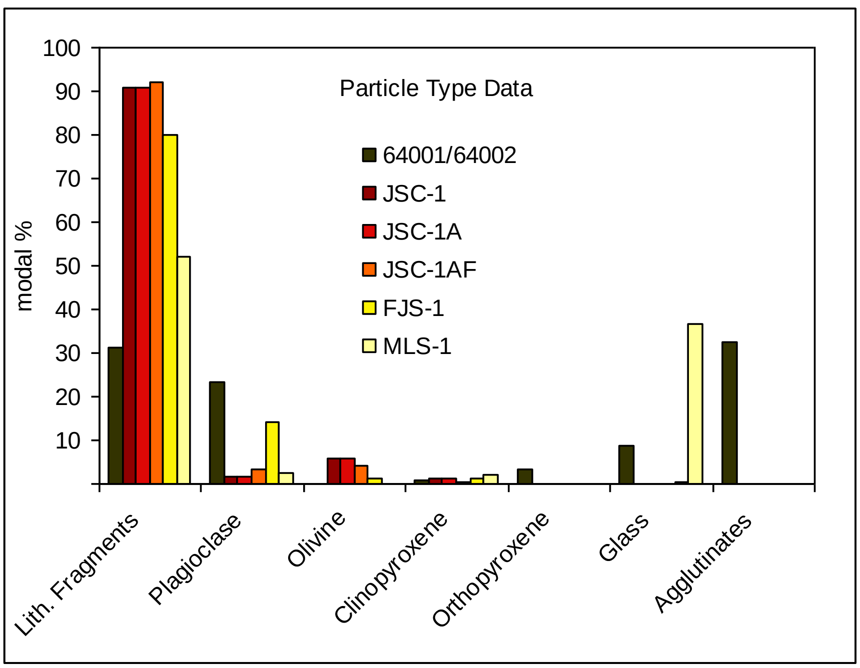


Figure 1A & B. Particle-type compositional data for highlands regolith simulants and the lunar reference 64001/64002. **1A** and **1B** contain highland and mare simulant data, respectively.

lithic fragments in mare simulants and the pseudo-agglutinate fragments (identified as agglutinates) in the NU-LHT series highland simulants. It is these particle type modal analyses that are used in the FoM v.2 composition routines. The data for major particle types are shown in plots with the lunar reference data in Figure 1. Tabulated data are shown in Table 1. In addition, the SEM/EDS analysis yields total modal area% for the simulants as it does for the lunar material. For numerous reasons, the FoM composition definitions and algorithms use the particle type modal data, but the area modal data for simulants and the lunar reference material are presented in Figure 2 (major phases) and Figure 3 (minor and trace minerals) for completeness.

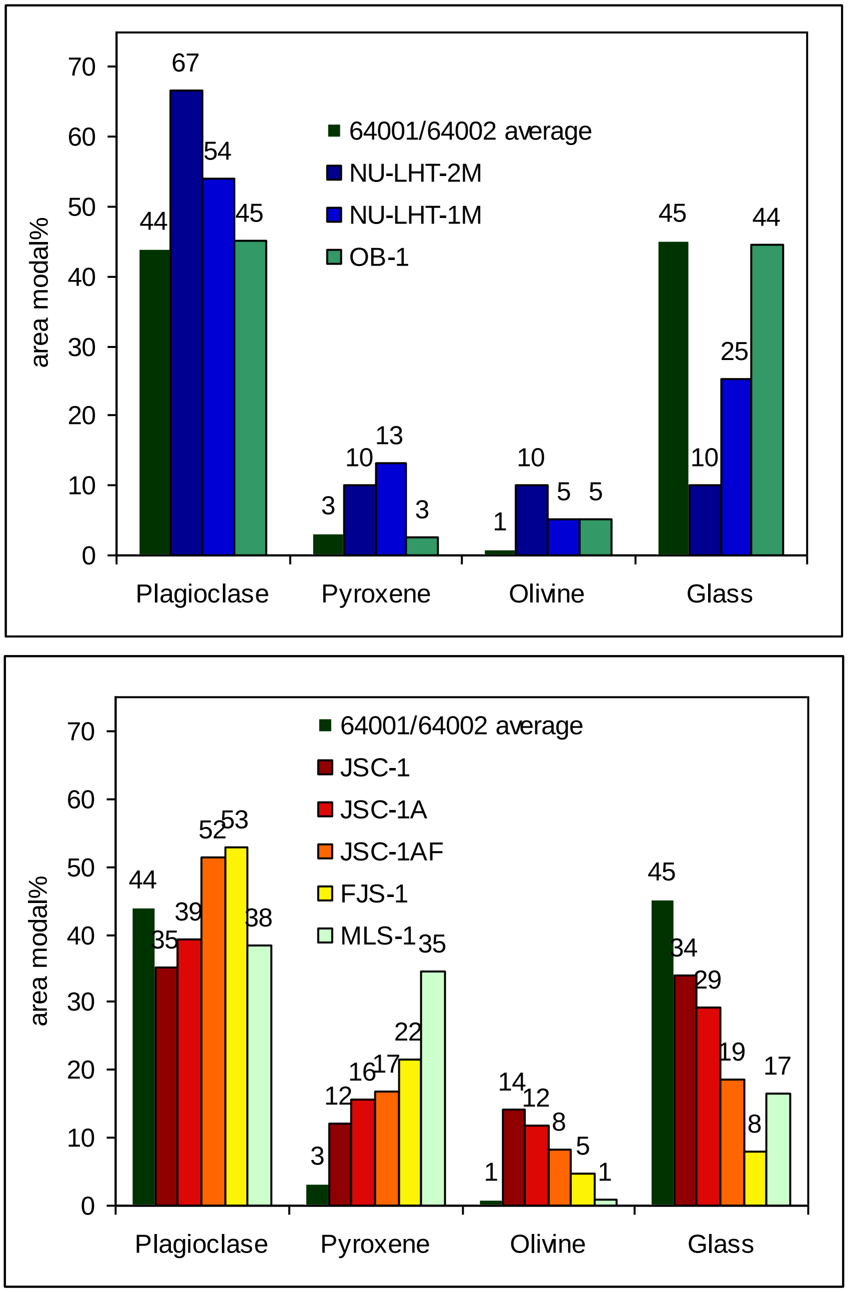
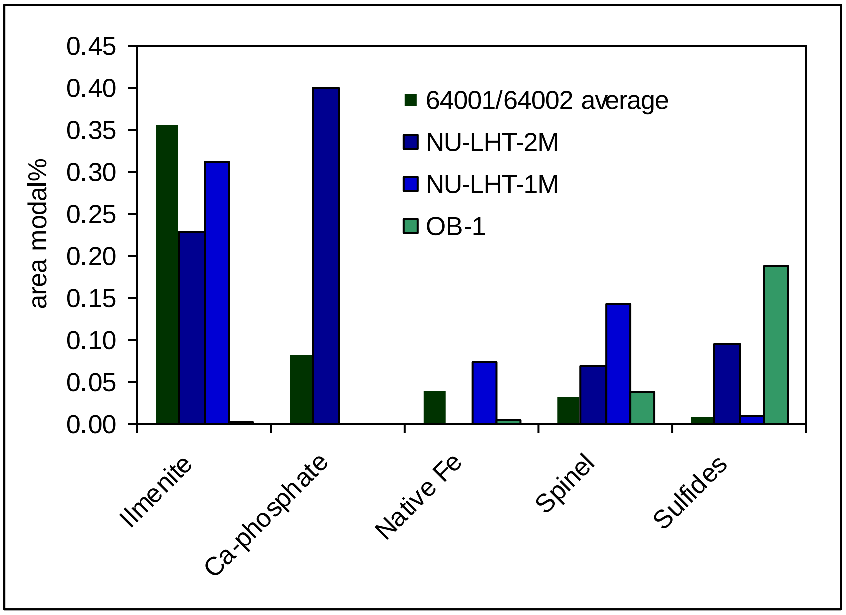


Figure 2A & B. Area modal data for major phases in mare regolith simulants and the lunar reference 64001/64002. **Figures A** and **B** contain highlands and modal data, respectively.



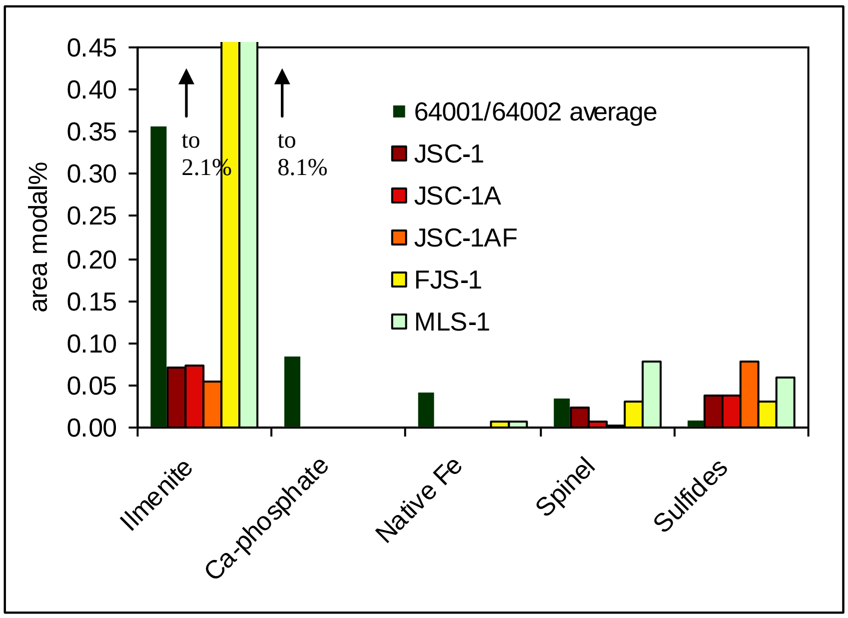


Figure 3A & B. Area modal data for minor phases in mare regolith simulants and the lunar reference 64001/64002. **Figures A** and **B** contain highlands and modal data, respectively.

There are some apparent inconsistencies between the particle type and the area modal data. For instance, the area modal data (Figure 2) show simulant OB-1 to contain measurable amounts of the mafic (Fe- and Mg-bearing minerals) olivine and pyroxene while the particle modal data (Table and Figure 1) show neither as free minerals. An examination of the phase maps indicate that this is due to pixels in the OB-1 olivine slag glass being reported as mafic phases. These may be crystals, on the scale of microns to

10's of microns, formed by devitrification of the slag glass or they may be compositional inhomogeneities in the glass. The processing by the iDiscover software classified these as glass particles.

5.2.2 Plagioclase composition

Table 1 contains the values we used in the FoM analysis for plagioclase composition for simulants and lunar regolith.

The particle type composition of the Chenobi simulant is not shown in Table 1 because it has not been analyzed. However, it incorporates the same anorthosite feedstock used in OB-1 and thus has plagioclase with An75%.

5.3 Composition Figure of Merit Results

All composition FoMs were run using Figure of Merit FoM v.2 data entry forms and algorithms. We calculated the FoMs using *Matlab* software because the final user version of v.2 was not released at the time this document was produced.

See Table 2 for Figure of Merit v.2 composition results for all simulants tested against the 64001/64002 lunar reference material.

Table 2. Results of Figure of Merit composition analysis. Figure of Merit Revision 1 algorithm used with lunar reference material 64001/64002.

simulant	64001/64002 reference
NU-LHT-1M	0.65
NU-LHT-2M	0.55
OB-1	0.28
JSC-1	0.33
JSC-1A	0.35
JSC-1AF	0.43
MLS-1	0.35
FJS-1	0.36

5.4 Comments

The Figure of Merit is a powerful tool still in development. We continue to innovate and update the approach, algorithms, and software. Composition is a complicated concept for granular geologic materials, as it may capture particle type and chemistry (as reflected in and controlling the mineralogy and phase assemblage), etcetera.

5.4.1 Lithic Fragments and Agglutinates

It is a complex problem to consistently classify fragments of rock and breccia in lunar and terrestrial material. In regolith, they form a spectrum of particle types composed of varying amounts of minerals and glass and of varying and unknown mechanical competency. For this reason, all rock fragments and breccias are classified as lithic fragments and compared to the abundance of all rock and breccia fragments in the regolith.

Agglutinates are a member of the particle spectrum including lithic and breccia fragments, but we interpret them to be sufficiently unique in their properties and abundance as to be worth differentiating. Furthermore, their characteristics as irregularly shaped, often vesicular particles composed of minerals in a glass matrix makes it possible to identify them with automated beam technology.

Because the lunar regolith reference 64001/64002 is composed of ~32 modal% agglutinates and 31 modal% lithic fragments, simulants that do not approximate these abundances will score a low composition FoM score. They may still be appropriate simulants for many purposes by virtue of their chemistry, shape, or size distribution. Conversely, a simulant with appropriate abundances of these particles may be inappropriate for some uses.

5.4.2 Glass composition

Glass is an amorphous material with no crystalline structure which can have an almost unlimited range of chemical composition. The lunar regolith has a range of glass populations of different origins and different chemical compositions. Various approaches to evaluating glass compositions are being evaluated for incorporation into FoM v.3. This FoM analysis (v.2) treats all glass particles as the same and compares them to the 8.9 modal% in the lunar reference material.

Most glasses behave broadly similarly for geomechanical purposes. Simulant users who need certain chemical fidelity to lunar material will need to take glass composition into consideration and consult with experts. Table 3 contains an overview of glass contained in simulants. Quantitative analyses are not available but a consideration of feedstock sources presents some constraints.

Table 3. Qualitative description of glass found in simulants.

Simulant	Qualitative Glass Description
NU-LHT series	Glass is derived by melting of noritic feedstock in a plasma stream. Si-Al-Ca with moderate Fe and Mg.
OB-1	Glass is an olivine slag. Si-Fe-Mg.
Chenobi	Glass is derived by melting of the anorthosite feedstock in a plasma stream Si-Al-Ca.
JSC-1 series	Natural basalt glass. Si-Al-Ca-Fe-Mg with lesser Na.
FJS-1	Natural basalt glass. No analyses available.
MLS-1	In the sample analyzed, glass is derived by plasma melting of basaltic feedstock. Si-Al-Fe-Mg-Ca.

6 Size

6.1 Lunar Regolith Data Source

The particle size distribution data (PSD) for 64001/64002 is taken from Graf (1993). It is an average of 12 subsamples by weight% of each size fraction.

6.2 Simulant Data Sources

We used multiple sources of simulant size distribution data, and in most cases multiple data sources are represented per simulant. Data methods are clearly listed in our results.

6.2.1 Dry Sieving

Some data are from dry sieving methods and reported by weight%. The data for OB-1 comes from Trow Analytical, Ltd. The analyses for JSC-1A and NU-LHT-1M were performed in the lab of Susan Batiste at the University of Colorado.

The dataset for NORCAT's Chenobi simulant is s combination of dry sieve data above ~75 µm and laser diffractometry data for the finer portion.

Particle size distribution data is available for NU-LHT-2C, but the bin sizes are skewed to show the coarse fractions and are too broad to use for FoM analysis

6.2.2 SEM and image processing

We have size data from QEMSCAN® SEM/EDS analysis, reported by weight%, for all simulants except for NU-LHT-1D. It should be said that grain mounts used for SEM imaging are polished and thus provide a sectioned sample, and that most particles will not be sectioned at their plane of greatest diameter equivalent. For this reason such results are sometimes referred to as an SSD *(sectional size distribution)* rather than a PSD. The high number of particles counted partially offsets this effect, but there will always be a slight bias towards finer particles in an SSD. This can be partially compensated for by stereological techniques and we are pursuing this approach. For now, we caution the users to take this into account, but also remind them that all simulants were measured by this method and thus any problems will be consistent across that portion of the dataset.

6.2.3 Liquid dispersion and laser diffractometry

We have data for NU-LHT-1M, -2M, and -1D, and JSC-1A from liquid dispersed laser diffractometry. Susan Batiste at the University of Colorado measured NU-LHT-1M and JSC-1A, while the Bureau of Mines analyze NU-LHT-2M and -1D.

These data are presented as volume% rather than as weight%. If the particle composition distribution were consistent across the size fractions then the data would be equivalent, but this is not true for lunar regolith and is likely not to be true for simulants. However, we judge it likely that the deviations in density across the size fractions are of small effect. We leave it to the user to evaluate these ratings until more data are gathered and analyses are presented. Again, the method is consistent for the four simulants measured and thus is of comparative value.

The <75 μm portion of the Chenobi simulant dataset is determined by laser diffractometry and converted to weight%.

This analytical method yields more bins of data (smaller size fractions) than the FoM software allows. We have summed the bins to best match the Graf (1993) bins.

6.3 Figure of Merit PSD results

Table 4 contains FoM size results for all simulants against the lunar reference material 64001/64002. Several subsets of reference data are compared to simulant size datasets obtained by different methods.

Table 4. Figure of Merit size results for all simulants against 64001/64002 lunar reference material. Simulant datasets were compared against the bulk average of 64001/64002, the <1mm subset of the data and the <90 µm subset of the data; both reference subsets were recalculated to 100%. Analytical method is in parentheses.

	64001/2 bulk average	64001/2 <1 mm average	64001/2 average to 90 µm
OB-1 (section image analysis)	0.23	0.54	
NU-LHT-1M (section image analysis)	0.23	0.58	
NU-LHT-2M (section image analysis)	0.17	0.48	
JSC-1 (section image analysis)	0.22	0.53	
JSC-1A (section image analysis)	0.25	0.56	
JSC-1AF (section image analysis)	0.06	0.23	0.60
MLS-1 (section image analysis)	0.20	0.29	
FJS-1 (section image analysis)	0.26	0.45	
OB-1 (dry sieve)	0.59		
NU-LHT-1M (dry sieve)	0.26	0.75	
JSC-1A (dry sieve)	0.35	0.74	
Chenobi (dry sieve + laser diffractometry)	0.77	0.73	
NU-LHT-2M (laser diffractometry)	0.29	0.82	
NU-LHT-1D (laser diffractometry)			0.54
NU-LHT-1M (laser diffractometry)	0.26	0.64	
JSC-1A (laser diffractometry)	0.28	0.74	

6.3.1 Comparison to the entire 64001/64002 PSD

The range of size bins for 64001/64002 from Graf (1993) is broader than for any of the simulants. All simulant PSD's are compared to the entire 64001/64002 PSD and the results are shown in the first column of Table 2.

6.3.2 Against normalized subsections

6.3.2.1 <1mm fraction

Most of the simulant PSD's only extend to ~1mm. The second column of Table 8 shows comparisons of all simulants to the <1mm fractions of 64001/64002. These fractions were recalculated to sum to 100 weight%.

6.3.2.2 <90 μm fraction

For the two simulants specifically intended to be dust simulants, another normalized subset of Graf's (1993) data was used for comparison, this time recalculating the <90 μm fraction to sum to 100 weight%. We show the results for this subset in column 3 of Table 8.

6.4 Comments

Of the simulant PSD's run in the FoM size analysis, only OB-1 sieve data and the Chenobi sieve + laser diffractometry data had particles in the larger fraction that matched the bins of the reference data. The simulant NU-LHT-2C contains particles to 10 cm and the PSD apparently matches well with Apollo regolith; however, as mentioned above (section 6.2.1), the resolution of NU-LHT-2C PSD data is insufficient for FoM analysis.

The FoM size analysis is sensitive to how data are binned. Within any one method/data type, all datasets have identical binning, so comparison within groups is reliable.

7 Shape

Figure of Merit Revision 1 software is capable of comparing aspect ratio and angularity of particle shape distributions, but we have not yet completed defining the metrics and parameters for analysis.

As part of the QEMSCAN® analysis, the iDiscover software returned shape metrics for all simulants, which are shown in Table 5, and compared graphically in Figure 4. These are given in terms typical for geological studies, but should provide a qualitative comparison between simulants. No data in these terms exist for lunar regolith. However, the moon lacks the flowing water and wind that cause rounding in terrestrial sediments, and thus only glass spherules are likely to be rounded or well-rounded.

Table 5. Shape parameters of simulants derived by QEMSCAN© analysis. Units are in weight% of typical geologic classification bins, from very angular to well-rounded.

	weight %							
Particle Shape Classification	**NU-LHT-1M**	**NU-LHT-2M**	**OB-1**	**JSC-1**	**JSC-1A**	**JSC-1AF**	**FJS-1**	**MLS-1**
very angular	2.4	1.5	1.7	2.9	4.7	1.1	2.0	0.4
angular	4.2	1.8	2.3	5.1	7.0	3.1	4.2	3.0
sub-angular	15.3	7.3	10.4	17.0	16.3	13.0	20.9	11.5
sub-rounded	43.3	36.2	40.7	42.9	40.0	39.2	49.2	37.5
rounded	34.4	52.8	44.5	31.9	31.6	43.4	23.6	30.8
well-rounded	0.2	0.6	0.3	0.1	0.3	0.3	0.1	16.9
Total	100	100	100	100	100	100	100	100

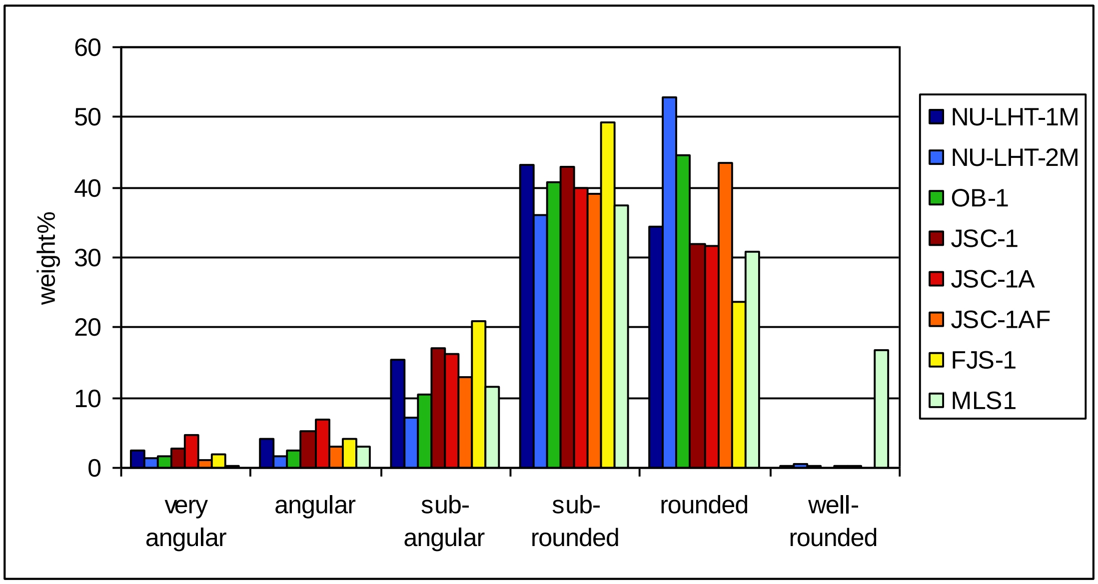


Figure 4. Qualitative graphical comparison of shape parameters for simulants derived by QEMSCAN© analysis. Units are in weight% of typical geologic classification bins.

8 Conclusions

There are a number of studies documenting other properties of simulants, including geomechanical properties, abrasiveness, behavior during oxygen production procedures, etcetera. We recommend users consult these when relevant to their needs.

We encourage users to contact the authors at Marshall Space Flight Center for advisement as to simulant use. We predict that this document will be updated at least annually, but new information is available constantly. These evaluations are ongoing, as is Figure of Merit development. Most importantly, simulant development is continuing.

9 References

Basu, A. and McKay, D.S., 1981, Classification of lunar highland's submillimeter particles, in *Workshop on Apollo 16,* edited by O.B. James and F. Hörz, LPI Technical Report 81-01, Lunar and Planetary Institute, Houston, pp. 36-39.

Gaines, R.V., Skinner, H.C.W., Foord, E.E., Mason, B., and Rosenzweig A., 1997, *Dana's New Mineralogy: The System of Mineralogy of James Dwight Dana and Edward Salisbury Dana*, 8th ed. Wiley, New York.

Graf, J.C., 1993, Lunar Grain Size Catalog, NASA Reference Publication 1265, 464 p.

Heiken, G., Vaniman, D., and French, B.M., 1991, Lunar Sourcebook: A User's Guide to the Moon, Cambridge University Press, Cambridge [England], New York.

Houck, K.J., 1982, Modal petrology of six soils from Apollo 16 double drive tube 64002, Proceedings of the 13th Lunar and Planetary Science Conference, Part 1, Journal of Geophysical Research, v. 87, supplement, pp. A210-A220.

Le Maitre, R.W. and International Union of Geological Sciences, 2005, Subcommission on the Systematics of Igneous Rocks., Igneous Rocks: A Classification and Glossary of Terms: Recommendations of the International Union of Geological Sciences, Subcommission on the Systematics of Igneous Rocks, 2nd ed. Cambridge University Press, Cambridge, U.K., New York.

Rickman, D., MSFC-RQMT-3503 Lunar Regolith Simulant Requirements, Pre-Decisional Draft, Effective date: 08-31-2006, 90 p.

Rickman, D., Hoelzer, H., Carpenter, P., Sibille, L., Howard, R., and Owens, C., 2007, A Quantitative Method for Evaluating Regolith Simulants, Space Technology And Applications International Forum, Albuquerque, New Mexico, Feb. 11-15, 2007.

Sibille, L., Carpenter, P., Schlagheck, R., and French, R.A., 2006, Lunar Regolith Simulant Materials: Recommendations for Standardization, Production, and Usage, NASA Technical Paper 2006-214605, 118 p.

10 Addendum to the Lunar Regolith Simulant User's Guide: Simulant Fit-to-Use Matrix

> NOTE: Before choosing or using a simulant, we strongly encourage simulant users to contact one of the members of the MSFC simulant program listed at the end of this document. We do not intend for the Figure of Merit scores or the Simulant Use Matrix to substitute for consultation with experts. Where we lack expertise we can guide you to the appropriate resources.

This document represents a best estimate of each simulant's appropriateness for common types of investigations. The material behaviors important to these investigations are largely derived from the four "primary" properties captured in the Figure of Merit for simulant evaluation (MSFC-RQMT-3503 (DRAFT)). These material properties are particle composition, particle size distribution (PSD), particle shape distribution, and bulk density.

Two simulants are included in the matrix, NU-LHT-2C and Chenobi, that are not included in particle type FoM evaluations in the User's Guide. Further, NU-LHT-2C is not included in the PSD section, either, though we have PSD data for it. Chenobi is included in the matrix because the composition is understood to be composed of the same material as the anorthosite fraction of the OB-1 feedstock; a portion of this anorthosite was then melted to make the glass portion of Chenobi. NU-LHT is derived from the same materials as NU-LHT-2M, but a portion of the material was partially fused to make a coarser fraction that is added back in after milling and grinding. Thus, though these simulants were not analyzed in the same fashion of other simulants included in the User's Guide, the authors feel that these simulants are sufficiently understood to be evaluated for the Fit-to-Use matrix.

In assembling this matrix we attempt to extrapolate from the known primary characteristics of simulants to their behavior under the relatively complex conditions of these investigative environments. The behavior of a simulant during excavation may be affected by, for instance, its abrasiveness and angle of repose: these properties in turn result from the hardness and cleavage behavior of its particles (particle composition), its PSD, its particle shape distribution, and its maximum packing density. The response of a simulant to heating in the presence of hydrogen for oxygen extraction will be largely a result of its particle type composition – neglecting reaction rates that may be due to its PSD and packing/density properties.

We have a reasonably good understanding of these simulant's particle compositions and PSD's (see Simulant User's Guide, 2009), though more detail is needed in some areas. We have only a rudimentary survey of their particle shape distributions or density properties. We are aided by having some initial studies on oxygen extraction, angle of repose, and abrasiveness.

It is very important to remember that all simulants are here measured relative to the highland lunar reference sample Apollo core 64001/64002 (see Simulant User's Guide (2008) for justification). Some simulants that may be appropriate for investigations pertaining to, for example, a high-Ti mare regolith deposit, will be judged poorly by our standards. It is equally important to remember the necessarily speculative nature of some of these judgments. They have been made in some cases without the benefit of direct measurement. This document will be updated with input from the user community and the engineering and scientific community.

10.1 Oxygen Production

There are many approaches to oxygen production for ISRU, but three primary methods are currently being investigated: H_2-reduction, carbothermal reduction, and Molten Oxide Electrolysis (MOE). The first requires heating to the point of sintering and partial melting while the latter two require total melting of the material.

There are intricacies to the methods and the oxygen yield/energy input depends on a number of material compositional details and methodologies. It is our judgment that a simulant to be used for oxygen production should have reasonable compositional fidelity to the reference lunar material in the following ways:

1. Chemically, it should contain FeO wt.% (% by weight) close to the FeO wt.% of the lunar reference material. (Here, FeO is not a phase but the chemical species Fe^{2+}-O found in minerals, glasses, and the melt.)

   Justification: Oxygen is liberated by breaking metal-oxygen bonds, and the amount of energy required to break them is inversely proportional to their free energy of formation. Of the major lunar chemical oxides, FeO has the highest free energy and CaO the lowest. For this reason, during H_2-reduction oxygen yield correlates to FeO wt.% in the starting material (e.g., Allen et al., 1996). Some SiO2 (chemical) and TiO2 (chemical) are reduced as well.

   In processes involving melting, i.e., carbothermal reduction and MOE, these chemical species are more completely reduced. It is generally possible to reduce all of the Fe^{2+} through these methods.

2. The oxidation state of the Fe in a simulant should be as close as possible to that in lunar regolith. *Practically speaking, no natural rock, and thus no non-synthetic simulant, can emulate the oxidation state of lunar rocks*. It is important for users to be aware of this.

   Details: On the moon, Fe dominantly occurs as Fe^{2+} (FeO) with lesser Fe^0. In terrestrial rocks, Fe occurs as a combination of Fe^{2+} (FeO) and Fe^{3+} (Fe_2O_3).

   During H_2-reduction, Fe_2O_3 will initially reduce to FeO and thus produce more O per unit Fe than will lunar regolith. During MOE, reaction with Fe^{3+} behaves parasitically with regard to electronic conduction and reduces the efficiency of the process by 20-30% relative to Fe^{2+}.

3. The Fe-bearing phases, i.e, its assemblage of Fe-bearing minerals and glasses, should be similar in kind and abundance to the reference material. This is true especially for H_2-reduction work and less so for MOE or carbothermal.

   Justification: The oxygen is liberated primarily from Fe-bearing phases. In the case of H_2-reduction, the oxygen is derived most efficiently from the mineral ilmenite ($FeTiO_3$), then from the glass phase, and then, and only partially, from the Fe-bearing silicate minerals olivine and pyroxene (Allen et al., 1996).

   Although oxygen yield during H_2-reduction is proportional to FeO wt.% when run to completion [3 hours for Allen et al.'s (1996) study], almost 75% of the oxygen is extracted relatively quickly (Allen et al., 1994) due to the efficiency of liberating it from ilmenite and glass. Therefore, the phases in which the Fe resides exert a strong control on yield/energy input, especially for the H_2-reduction method.

4. The presence of hydrous or hydrated (OH^- or H_2O-bearing) minerals in a simulant is undesirable, especially if it is to be used for H_2-reduction work.

   Justification: There are no hydrous or hydrated materials on the moon, except possibly in shadowed craters. In the H_2-reduction method oxygen is liberated as H_2O, so any water or OH^- present will skew results of the test.

5. Simulants should have an assemblage of trace minerals, especially halogen-bearing (F^- and Cl^-) and S-bearing phases, similar to the lunar reference material in kind and abundance. Halogens are especially important to H_2-reduction work, while sulfur is particularly significant for MOE.

   Justification: F and Cl occur in minor amounts in trace minerals (fluorapatite, primarily) in the lunar regolith. However, at high temperature these elements, Cl especially, are strongly partitioned into the vapor phase yielding HCl and possibly HF. It has been demonstrated that these can have a corrosive effect on equipment even in the short-term.

   Sulfur occurs in troilite (FeS) in the lunar regolith. For MOE, S acts parasitically regarding electronic conductivity and diminishes the efficiency of the process.

11 Simulant Fit-to-Use Matrix References

Allen, C.C., Morris, R.V., and McKay, D.S., 1994, Experimental reduction of lunar mare soil and volcanic glass, *Journal of Geophysical Research*, V.99, n. E11, pp. 23,173-23,185.

Allen, C.C., Morris, R.V., and McKay, D.S., 1996, Oxygen extraction from lunar soils and pyroclastic glass, *Journal of Geophysical Research*, V. 101, n. E11, pp. 26,085-26,095.

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13 Records

Records shall be identified in accordance with MPR 1440.2. These records shall be retained and dispositioned in accordance with NPR 1441.1, Schedules 7 and 8. All record custodians shall have approved records plans in accordance with MPR 1440.2 with copies of those plans submitted to the applicable program/project office.

Simulant Fit-to-Use Matrix

	excavation/flow*	drilling*	abrasion/wear
NU-LHT-1M	**recommended:** it has been demonstrated that pseudo-agglutinates affect geomechanical behavior that may be important to excavation	**recommended**: fidelity to mineral and glass% should yield appropriate abrasiveness; presence of pseudo-agglutinates may aid fidelity to regolith	**recommended**: fidelity to mineral and glass% should yield appropriate abrasiveness; presence of pseudo-agglutinates may aid fidelity to regolith
NU-LHT-2M	**recommended:** it has been demonstrated that pseudo-agglutinates affect geomechanical behavior that may be important to excavation	**recommended**: fidelity to mineral and glass% should yield appropriate abrasiveness; presence of pseudo-agglutinates may aid fidelity to regolith	**recommended**: fidelity to mineral and glass% should yield appropriate abrasiveness; presence of pseudo-agglutinates may aid fidelity to regolith
NU-LHT-1D	**not recommended**: unrealistically fine PSD	**not recommended**: unrealistically fine PSD	**recommended with reservations**: unrealistically fine PSD for many uses
NU-LHT-2C	**most recommended:** it has been demonstrated that pseudo-agglutinates affect geomechanical behavior that may be important to excavation	**most recommended**: fidelity to mineral and glass% should yield appropriate abrasiveness; presence of pseudo-agglutinates may aid fidelity to regolith, good PSD	**recommended**: fidelity to mineral and glass% should yield appropriate abrasiveness; presence of pseudo-agglutinates may aid fidelity to regolith
OB-1	**recommended:** good PSD at coarse end; lack of lithic fragments or pseudo-agglutinates may affect flowability or angle of repose -- this should be examined	**most recommended**: fidelity to mineral and glass% should yield appropriate abrasiveness; best PSD for coarse fractions	**most recommended**: fidelity to mineral and glass% should yield appropriate abrasiveness; best PSD for coarse fractions
Chenobi	**recommended:** good PSD at coarse end; lack of lithic fragments or pseudo-agglutinates may affect flowability or angle of repose -- this should be examined	**most recommended**: fidelity to mineral and glass% should yield appropriate abrasiveness; best PSD for coarse fractions	**most recommended**: fidelity to mineral and glass% should yield appropriate abrasiveness; best PSD for coarse fractions

* We lack quantitative data on shape, and shape is important to geomechanical behavior

Simulant Fit-to-Use Matrix

	excavation/flow*	drilling*	abrasion/wear
JSC-1, -1A	**recommended:** relatively angular particles, reasonable PSD	**recommended with reservations**: uncertain but probably reasonable fidelity to highland abrasiveness	**recommended with reservations**: uncertain but probably reasonable fidelity to highland abrasiveness
JSC-1AF	**not recommended**: unrealistically fine PSD	**not recommended**: unrealistically fine PSD	**recommended with reservations**: unrealistically fine PSD for many uses
FJS-1	**recommended:** low-g tests show it has a high angle of repose; relatively angular particles, reasonable PSD	**recommended with reservations**: uncertain but probably reasonable fidelity to highland abrasiveness, low glass	**recommended with reservations**: uncertain but probably reasonable fidelity to highland abrasiveness, low glass
MLS-1 (processed for glass component)	**not recommended:** relatively poor PSD; shape distribution is skewed towards well-rounded particles	**not recommended:** high pyroxene/plagioclase may adversely affect particle cleavage behavior; rounded grains	**not recommended:** high pyroxene/plagioclase may adversely affect particle cleavage behavior; rounded grains

* We lack quantitative data on shape, and shape is important to geomechanical behavior

Simulant Fit-to-Use Matrix

	oxygen production**	human health studies
NU-LHT-1M	**recommended for highlands**: chemistry: slightly low FeO relative to lunar reference (~4 vs. 5 wt.%), but significantly closer than other simulants; mineralogy: contains ilmenite; high Fe in silicates relative to reference, which will slow reduction	**suitable composition** though it lacks the added phosphates and sulfides of NU-LHT-2M; **reasonable PSD** but too coarse in fine fraction
NU-LHT-2M	**most recommended for highlands**: chemistry: slightly low FeO relative to lunar reference (~4 vs. 5 wt.%), but significantly closer than other simulants; mineralogy: contains ilmenite, phosphates and sulfides, the presence of which are realistic but possibly hazardous to ISRU processes; high Fe in silicates relative to reference, which will slow reduction	**most suitable composition**; **reasonable PSD** but too coarse in fine fraction
NU-LHT-1D	**recommended for highlands**: should be similar to NU-LHT-1M, but possibly with lower FeO	**suitable composition** though it lacks the added phosphates and sulfides of NU-LHT-2M; **good PSD** in fine fraction
NU-LHT-2C	**recommended for highlands**: chemistry: slightly low FeO relative to lunar reference (~4 vs. 5 wt.%), but significantly closer than other simulants; mineralogy: contains ilmenite, phosphates and sulfides, the presence of which are realistic but possibly hazardous to ISRU processes; high Fe in silicates relative to reference, which will slow reduction	**most suitable composition**; **good PSD**
OB-1	**not recommended:** it is expected that the abundance of Fe-rich glass will result in unrealistically high oxygen yields per energy input; no glass analyses are available	**unsuitable composition** due to high Fe-glass; may be acceptable for testing where abrasiveness is of primary importance
Chenobi	**recommended for highlands with reservations**: will serve, in a way, as a worst-case example of the highlands regolith with the highest anorthositic fraction and that with the least mare contamination (i.e., very low FeO)	**partially suitable composition** though it lacks added phosphates and sulfides, and it represents one end-member of regolith composition; **good PSD** in fine fraction

** See associated text for details on different oxygen production methods

Simulant Fit-to-Use Matrix

	oxygen production**	human health studies
JSC-1, -1A	**recommended with reservations**: chemistry: FeO is significantly high relative to lunar reference (~11 vs. 5 wt.%); mineralogy: contains natural phosphates, Ti-magnetite instead of ilmenite; use will likely result in unrealistically high oxygen yields; may be a good mare simulant (e.g., Apollo 14) for this use	**possibly suitable composition**; **reasonable PSD** but too coarse in fine fraction
JSC-1AF	**recommended with reservations**: should be similar to JSC-1A	**possibly suitable composition**; **good PSD** in fine fraction
FJS-1	**recommended with reservations**: chemistry: FeO is significantly high relative to lunar reference (~11 vs. 5 wt.%); mineralogy: contains natural phosphates, Ti-magnetite instead of ilmenite; use will likely result in unrealistically high oxygen yields; may be a good mare simulant (e.g., Apollo 14) for this use	**possibly suitable composition**; **poor PSD** in fine fraction
MLS-1 (processed for glass component)	**not recommended for highlands**: chemistry: FeO is very high relative to lunar reference (>14 vs. 5 wt.%); mineralogy: contains abundant ilmenite but also hydrous minerals; may result in extremely unrealistically high oxygen yields; may be an acceptable high-Ti (Apollo 11) simulant, but hydrous minerals are still problematic	**unsuitable composition**; **unsuitable PSD** in fine fraction

** See associated text for details on different oxygen production methods

Appendix 3

Lunar Regolith/Simulant Users' Needs Survey Report

National Aeronautics and
Space Administration

Simulant-Doc-011
Draft Baseline
Draft Date: 06/30/2010

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

VP33

Lunar Regolith Simulant Development & Characterization Project

Lunar Regolith/Simulant Users' Needs Survey Report

Draft Baseline

June 2010

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Document History Log

Status (Baseline/ Revision / Canceled)	Document Revision	Effective Date	Description
Draft Baseline	**Basic**	**TBD**	**Draft Initial baseline to be approved by Dust Project Management. (Note: This document started under the In-Situ Resource Utilization (ISRU) Task.)**
			Updates were added in August 2009 to include new survey responses. Note: Troy Hudson was deleted from the data, he previously had requested a large amount of simulant.
			2/18/10 – Changed the document naming structure. Former was DUST-Sim-Doc-001, new one is Simulant-Doc-001. No content changes were made.
			6/30/10 – Updates were added to include new survey responses.

1 Introduction

Three organizations, Exploration Technology Development Program (ETDP), Constellation Project (CxP), and Human Health, were surveyed to collect estimated lunar regolith and simulant demands per an action at the ETDP 2007 Integrated Baseline Review (IBR) to the Marshall Space Flight Center (MSFC) Lunar Simulant Development and Characterization Team. The MSFC developed a web-based survey and an overview/tutorial presentation to provide an explanation of the current status of simulant development and other pertinent information to assist the potential regolith/simulant users in completing the survey and to assist the simulant developers in understanding the applications/conditions that the simulants will be used. Specific test applications will drive simulant fidelity and, thus, the number of types and quantities of simulants that must be developed. Typically, higher fidelity simulants will be more complex to develop and, therefore, require a longer delivery time and perhaps be more costly. The goal of the MSFC Lunar Simulant Development and Characterization Team is to develop simulants in a timely manner with the right fidelity (e.g., properties) in the most economical method possible.

Several individuals were solicited to ensure that this effort was communicated to the community which contributed to the successful gathering of data. The ETDP Program Element Managers (PEMs), Dr. Dana Gould and Ms. Diane Hope both from Langley Research Center (LaRC), assisted in notifying their Project Managers about the upcoming Survey. Ms. Sandy Wagner/JSC, Constellation Environments and Constraints (E&C) Systems Integration Group (SIG), served as the contact between MSFC and the Constellation Project Leads. She also provided access to Dr. Noreen Khan-Mayberry/JSC of the Human Health Program.

A kick-off webex conference was held May 21, 2008, with various representatives from ETDP, CxP, and Human Health. Surveys were received over the next few months with some arriving just recently. A total of thirty-five (35) surveys have been received to date. This data is presented and discussed in Section 2.0. It is believed, however, that there are many more NASA projects and tasks that will require regolith and/or simulants to perform not only development testing for technology enhancements/advancements or early engineering tests, but also verification and certification testing for future flight hardware. A potentially large group of individuals external to NASA, but associated with NASA Exploration via contracts, grants, proposal awards, and other means will most likely need simulants too. This population has not yet been surveyed, but MSFC strongly recommends that this be undertaken in order to provide a more accurate picture of forecasted demands. Now the results of the current survey data in hand will be presented below.

2 Survey Results/Analysis

2.1 Simulant Demand

2.1.1 Total Simulant Demand

Across the three organizations, a total of 137,739.68 kg (303027.3 lbs) of simulant has been requested over a six year period. Table 1 shows the number of requests and amount of simulant requested per year for ETDP, CxP, and Human Health organizations. Figures 1 and 2 show the results in graphical form.

Table 1: Total Simulant Demand across All Organizations.

Total Simulant Demand (CxP, ETDP, HH)		
Year	**Requests**	**Amount (kg)**
2008	9	72.5
2009	14	4371.1
2010	20	9424.08
2011	11	113068
2012	7	9993
2013	4	396
Unspecified	14	415
TOTAL	**79**	**137739.68**

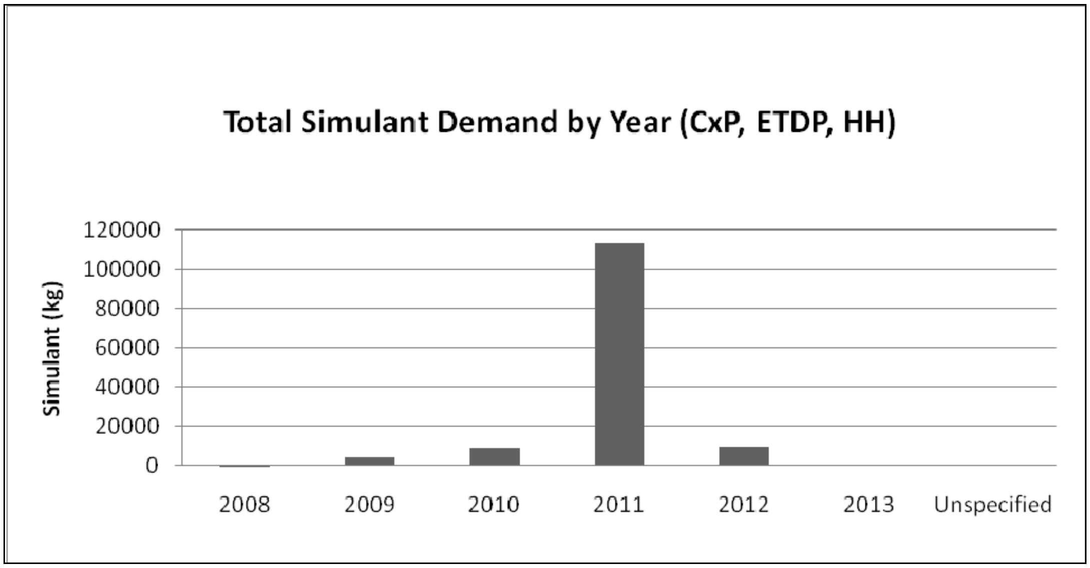

Figure 1: Total Lunar Simulant Demand for ETDP, CxP, and Human Health
Note: 2008 quantity is not visible on this chart due to the small quantity.

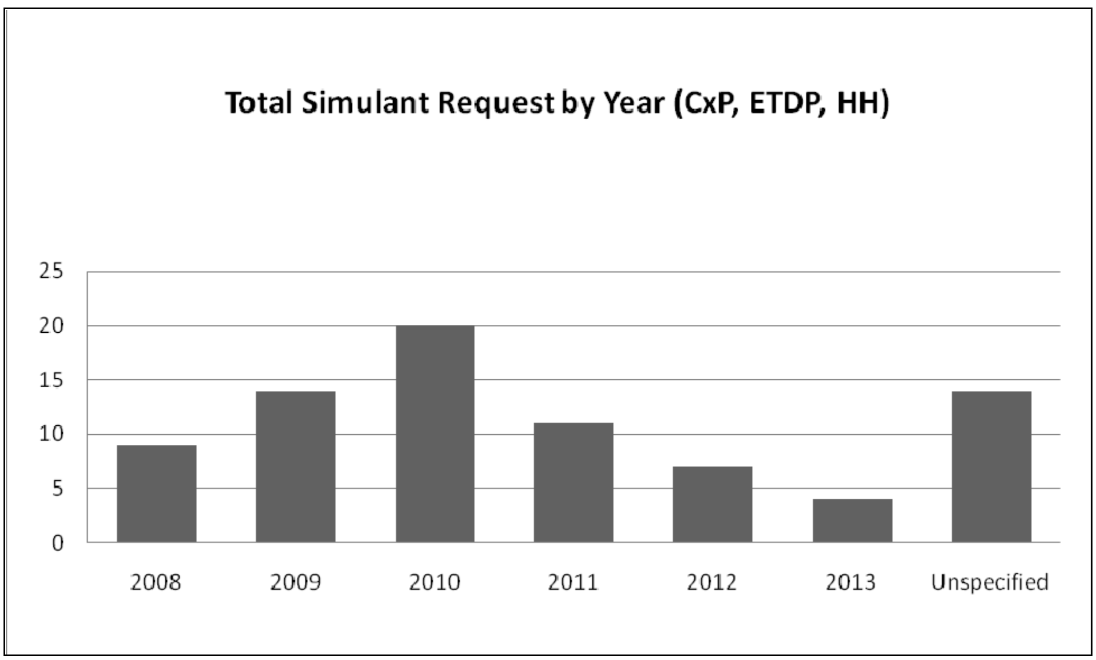

Figure 2: Total Lunar Simulant Requests from ETDP, CxP, and Human Health

2.1.2 Simulant Demand Among Organizations (ETDP, CxP, and Human Health)

Over a six year period, Constellation projects require the most simulant- a total of nine requests comprising 119,462 kg of simulant is estimated. ETDP had the largest number of requests – 65 requests for a total of 18241.18 kg of simulants. Human health had the least number of requests and also the smallest simulant demand – 5 requests for 36.5 kg of simulant. Table 2 summarizes the results of this demand within each organization. Figures 3 and 4 illustrate the demands by year for the organizations compared by quantity and percentages (%), respectively. Since Constellation requires the most simulant by a large margin, individual charts by organization are also delineated. Figures 5, 6, and 7 illustrate the demands of Constellation, ETDP, and Human Health, respectively. Also, Figure 8 chronologically summarizes the amount of requests within each organization.

Table 2: Simulant Demand within each Organization by Year

	Constellation		**ETDP**		**Human Health**	
Year	Requests	Amount (kg)	Requests	Amount (kg)	Requests	Amount (kg)
2008	0	0	4	36	5	36.5
2009	3	3726	11	645.1	0	0
2010	1	5000	19	4424.08	0	0
2011	2	110718	9	2350	0	0
2012	0	0	7	9993	0	0
2013	0	0	4	396	0	0
Unspecified	3	18	11	397	0	0
TOTAL	**9**	**119462**	**65**	**18241.18**	**5**	**36.5**

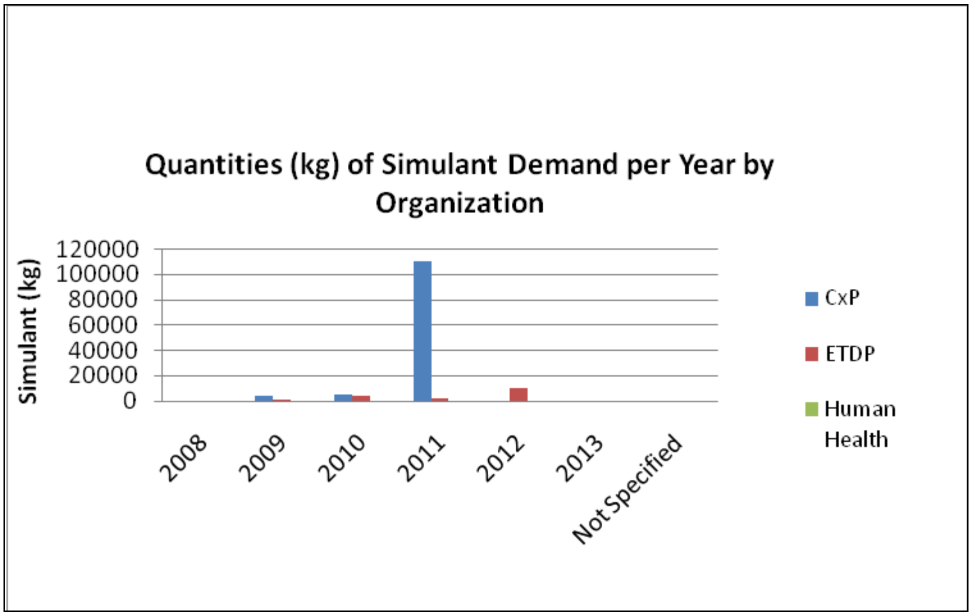

Figure 3: Overall Lunar Simulant Demand per Year by Organization

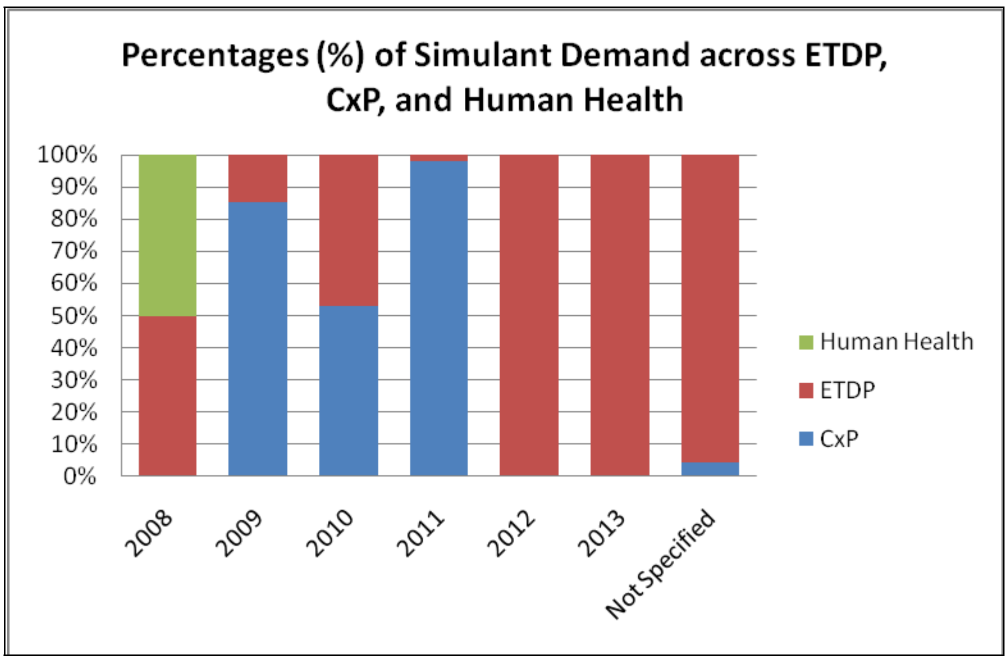

Figure 4: Overall Lunar Simulant Percentage Demand per year by Organization

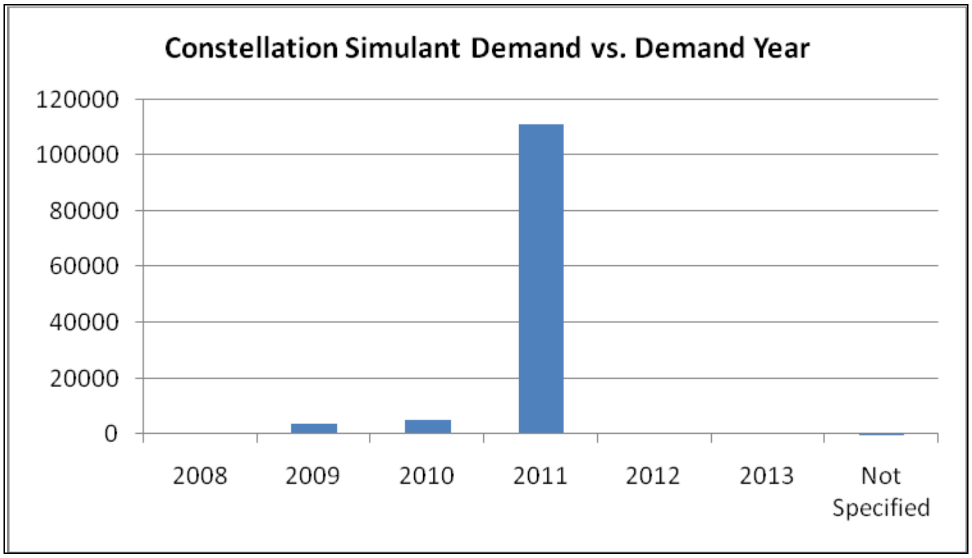

Figure 5: Lunar Simulant Demand within Constellation Project

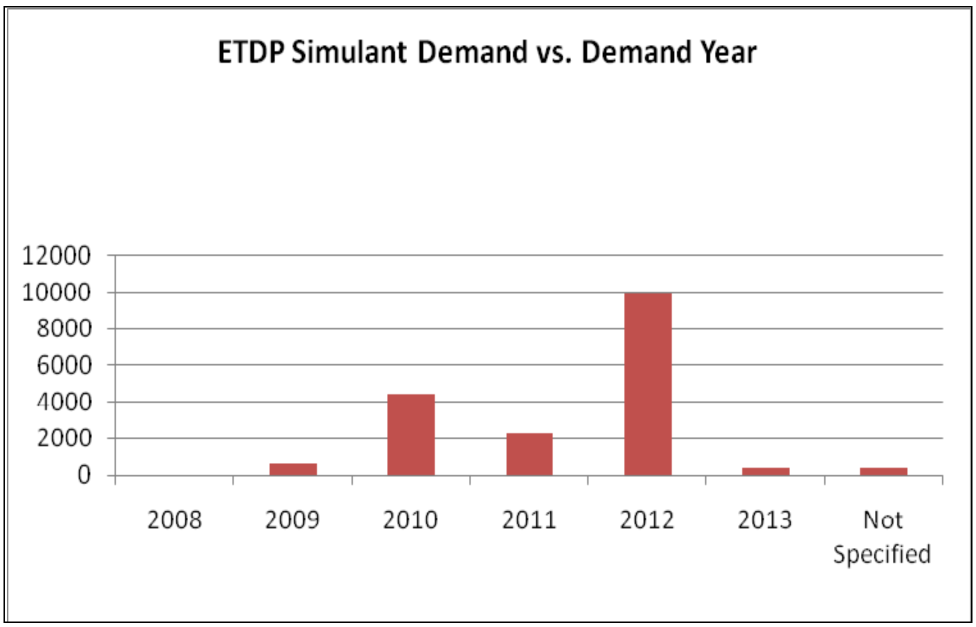

Figure 6: Simulant Demand within ETDP

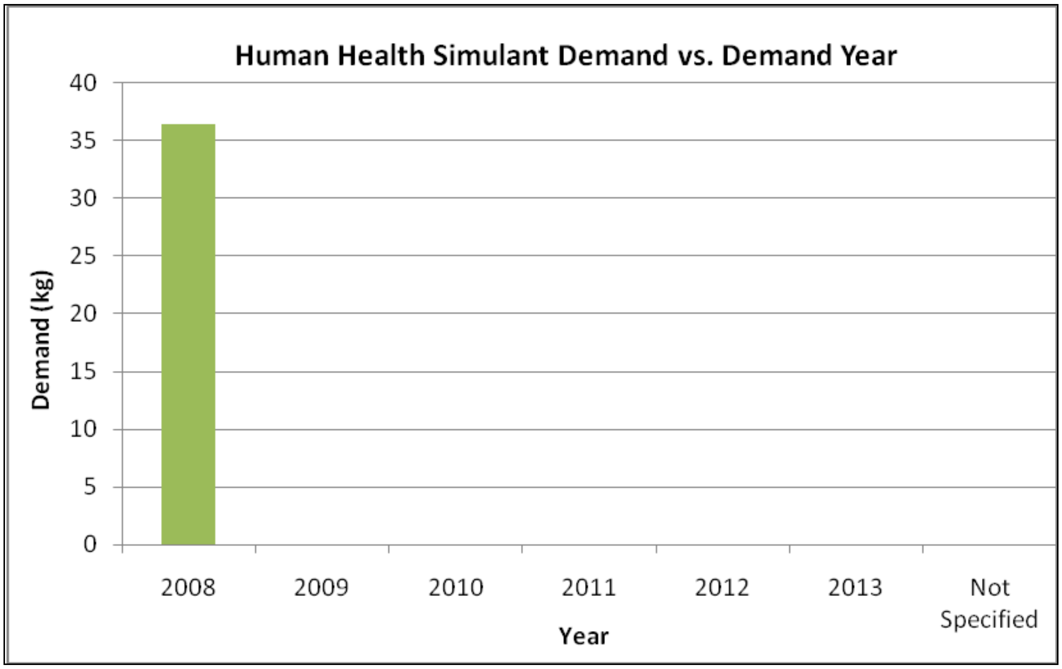

Figure 7: Simulant Demand within Human Health

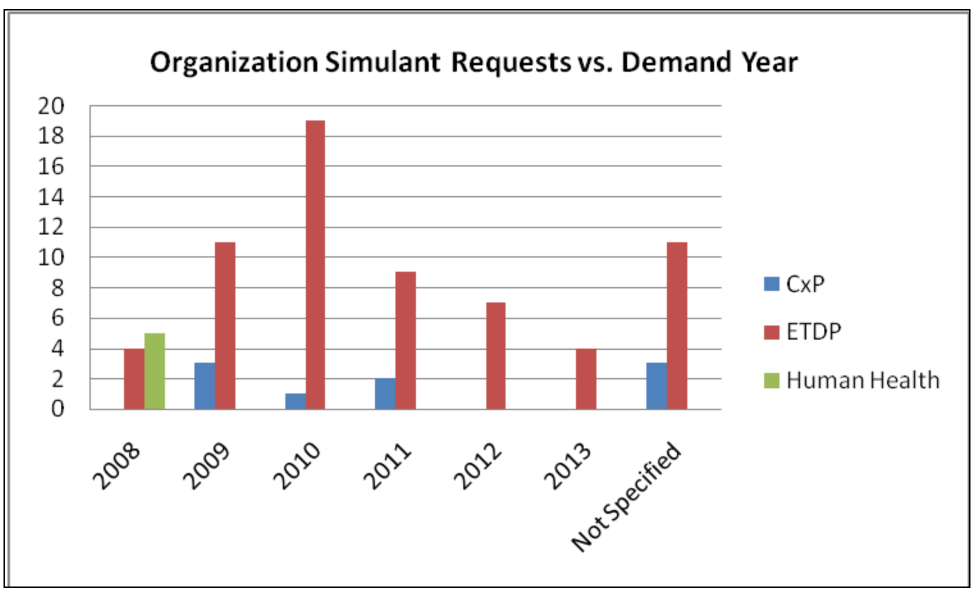

Figure 8: Simulant Requests across ETDP, CxP, and Human Health by Year

2.1.3 Simulant Demand of Projects Within Each Organization

2.1.3.1 Constellation Projects

Constellation projects demanded the most simulant over six years compared to all other organizations. Particularly, Lunar Excavation and Lunar Surface Systems (LSS) both requested the most simulant, with 100,000 kg and 20,000 kg requests respectively. Figure 9 summarizes the results of the Constellation Projects demand. Figure 10 summarizes the number of requests from the different projects within Constellation.

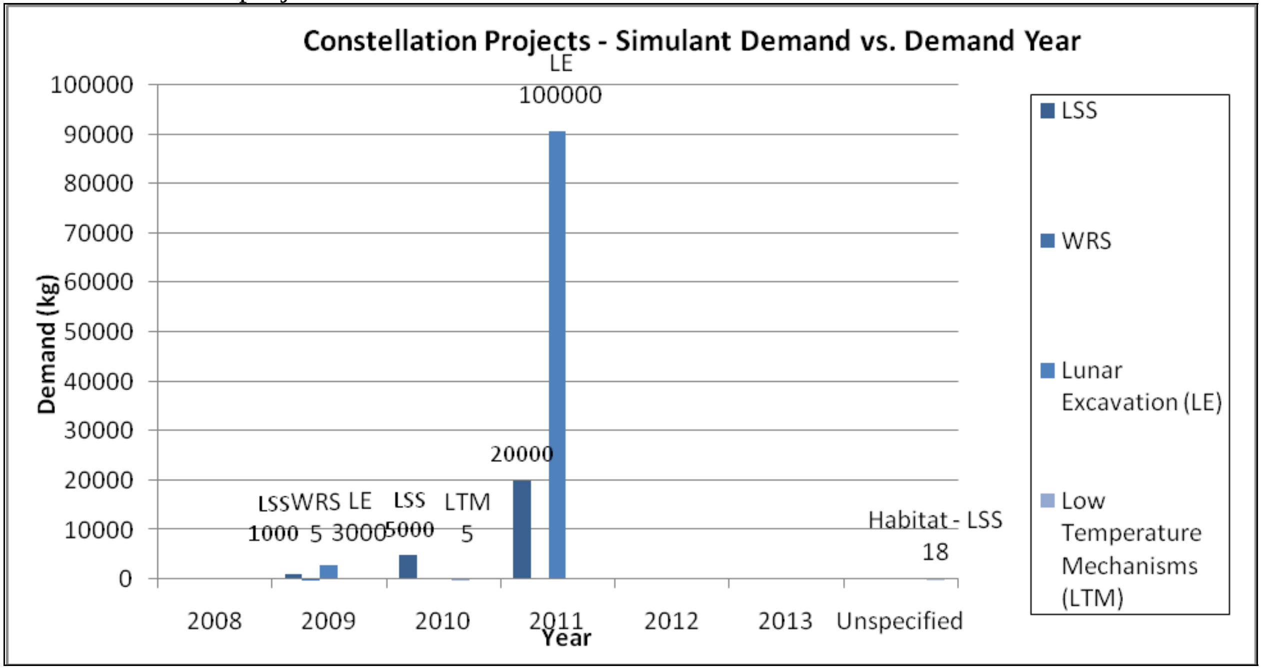

Figure 9: Simulant Demand from Constellation Projects

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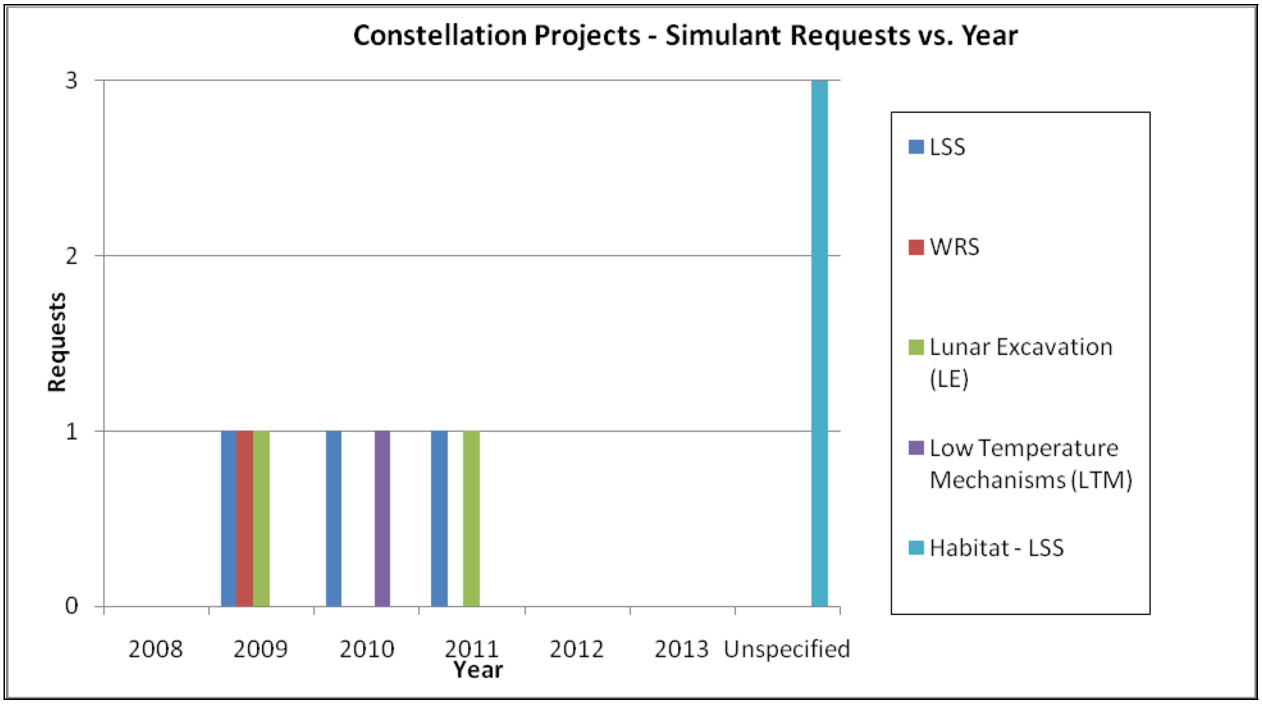


Figure 10: Simulant Requests from Constellation Projects

2.1.3.2 ETDP Projects

ETDP projects ranked second in requesting the most simulant over a six year period compared to the other organizations. Particularly, ISRU requested the most simulant; 2000 kg are requested in 2011 and 5000kg in 2012. Figure 11 summarizes the results of this ETDP's demand. Figure 12 summarizes the amount of requests from the different projects within ETDP.

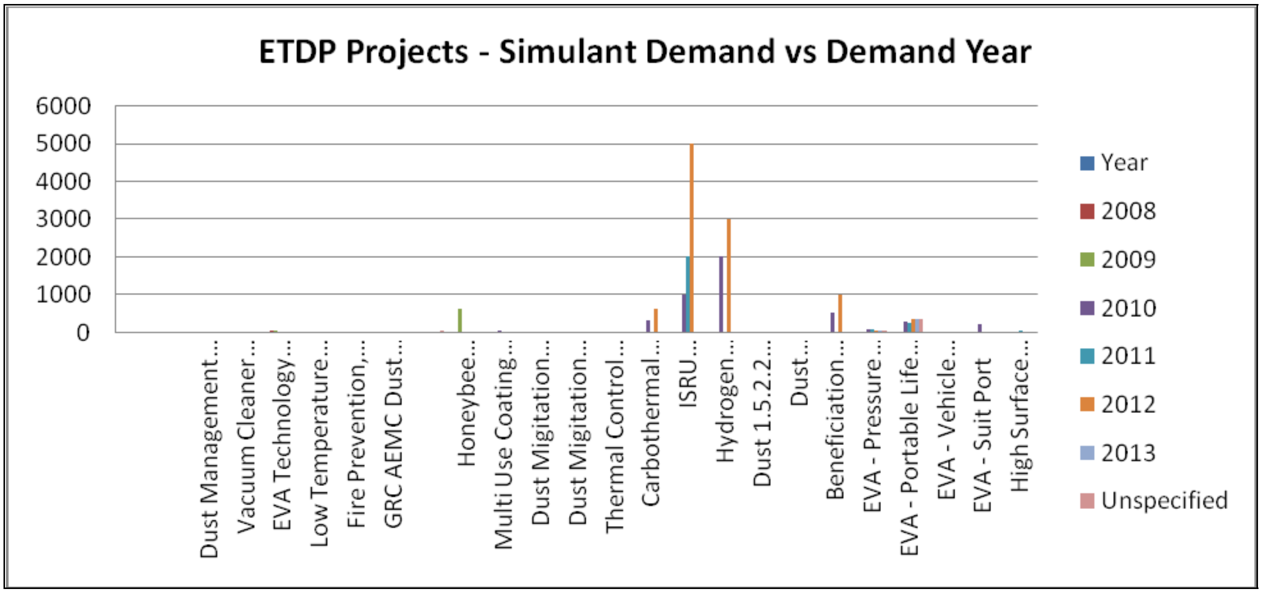


Figure 11: Simulant Demand from ETDP Projects

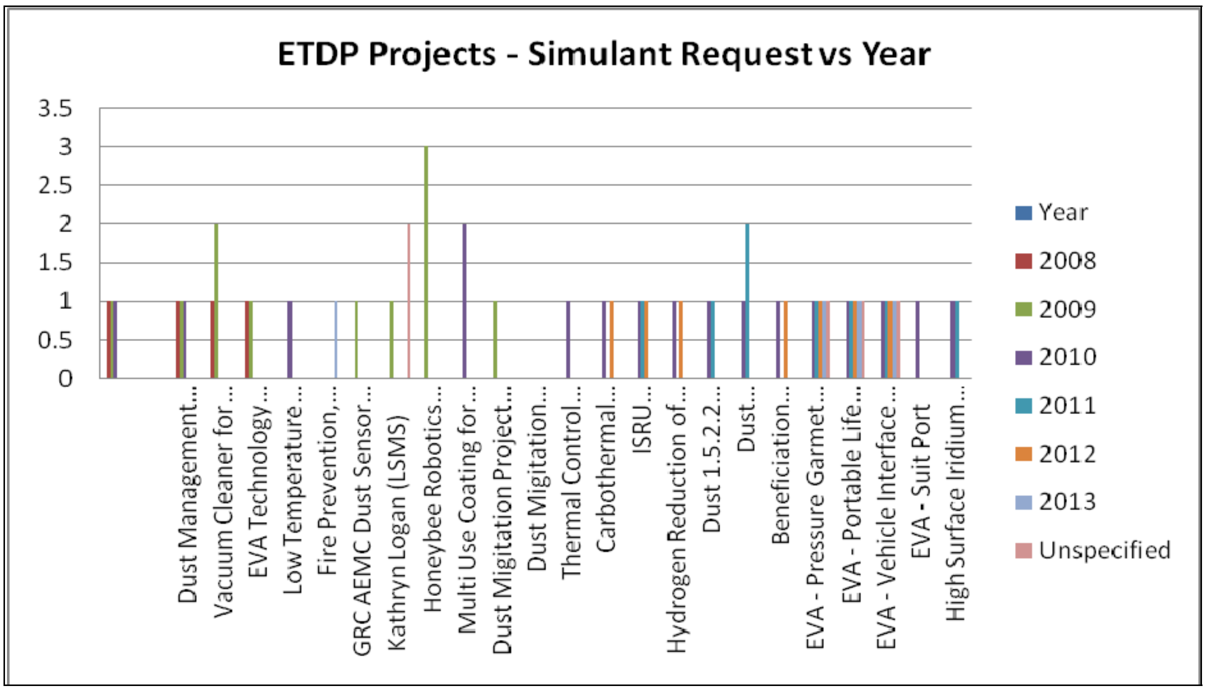


Figure 12: Simulant Requests from ETDP projects

2.1.3.3 Human Health

Human Health projects demanded the least simulant of all other organizations over a six year period. The LADTAG requested the most simulant totaling 36.5 kg from two separate areas. Figure 13 summarizes the results of this simulant demand. Figure 14 summarizes the amount of requests from the different projects within Human Health.

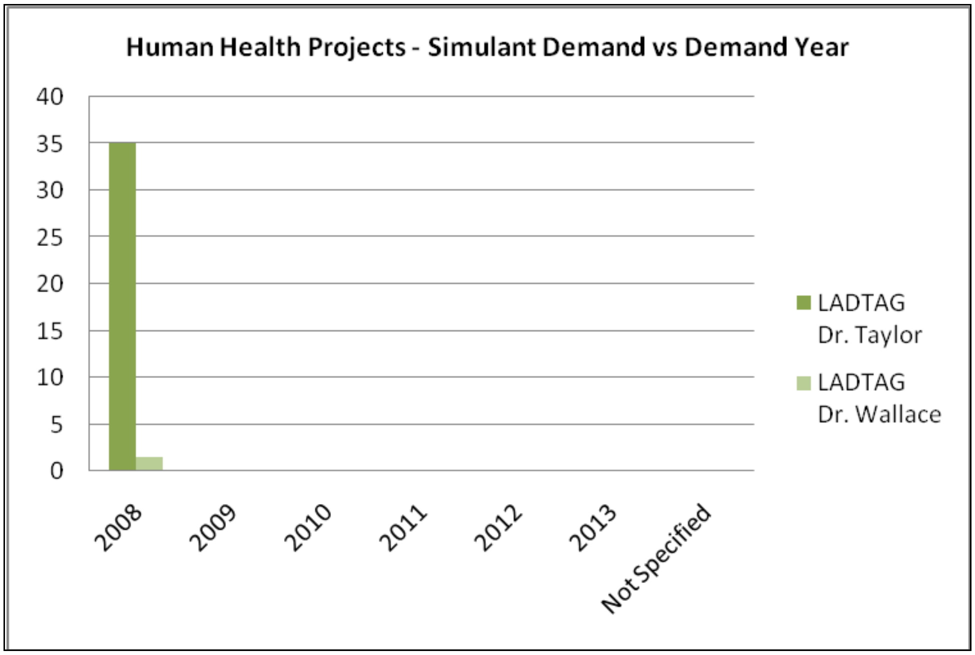


Figure 13: Simulant Demand from Human Health Projects

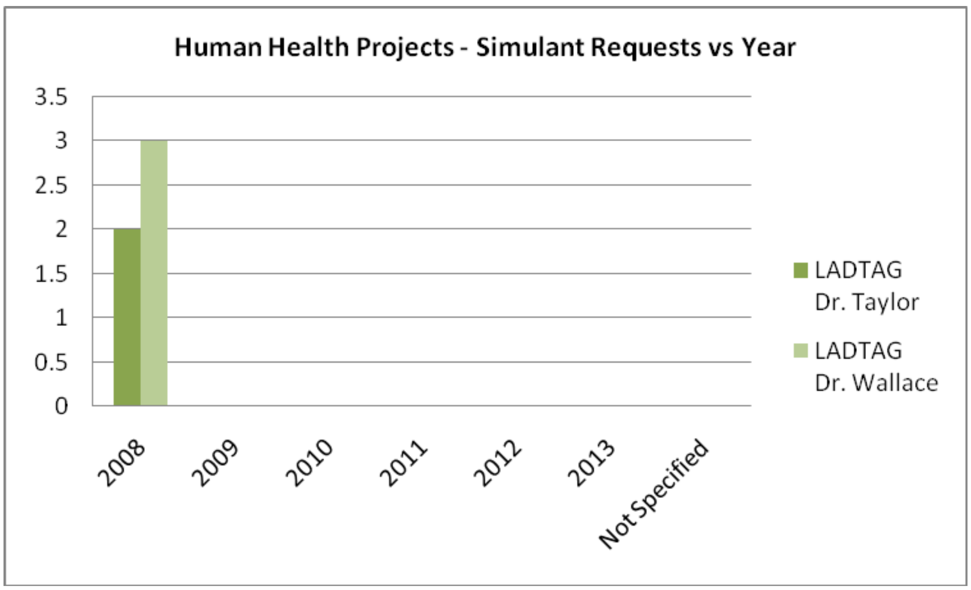


Figure 14: Simulant Requests from Human Health Projects

2.2 Simulant Reuse

Of the thirty-five projects that participated in the survey, over half of them plan on reusing the simulants more than once for their experiments (assuming the application(s) or use has not altered the critical properties of the simulant that are needed for that test or investigation). It is imperative that users consult with knowledgeable experts such as lunar geologists and scientists to ensure that the used simulant is still fit to be used in further testing applications. Table 3 summarizes the number of projects who plan to reuse their simulants.

Table 3: Number of Projects Plan to Re-Use Simulants

Projects that Plan on Reusing Simulants	
Number of Projects	Percent of Projects
19	54.29%

2.3 Simulant Needs According to Specific Applications

The thirty-five survey respondents relayed information about the need for simulants based on their particular applications or processes. As previously stated, the fidelity of the simulant and the properties that are critically important are correlated to the specific application or process that the simulant will be used in. The responses are shown in Table 4. Note that the total number of projects is greater than 35. This is because some projects need simulant for multiple processes. Figure 15 displays the percentage of this need in graphical form.

Table 4: Number of Projects Needing Simulant by Specific Process

Simulant Need for Specific Process

Process	**Number of Projects**	**Percent of Projects**	**Percent of Need**
Chemical - Oxygen Production	9	25.71%	17.65%
Chemical - Propellant Production	4	11.43%	7.84%
Manufacturing - Glass/Semiconductor Substrate Production	2	5.71%	3.92%
Construction - Brick or Road Production	7	20.00%	13.73%
Excavation - Burying Items or Moving Dirt for Berms, Etc.	9	25.71%	17.65%
Mobility - Transportation (Rovers), Etc.	13	37.14%	25.49%
Other	7	20.00%	13.73%
Total	51		100.00%

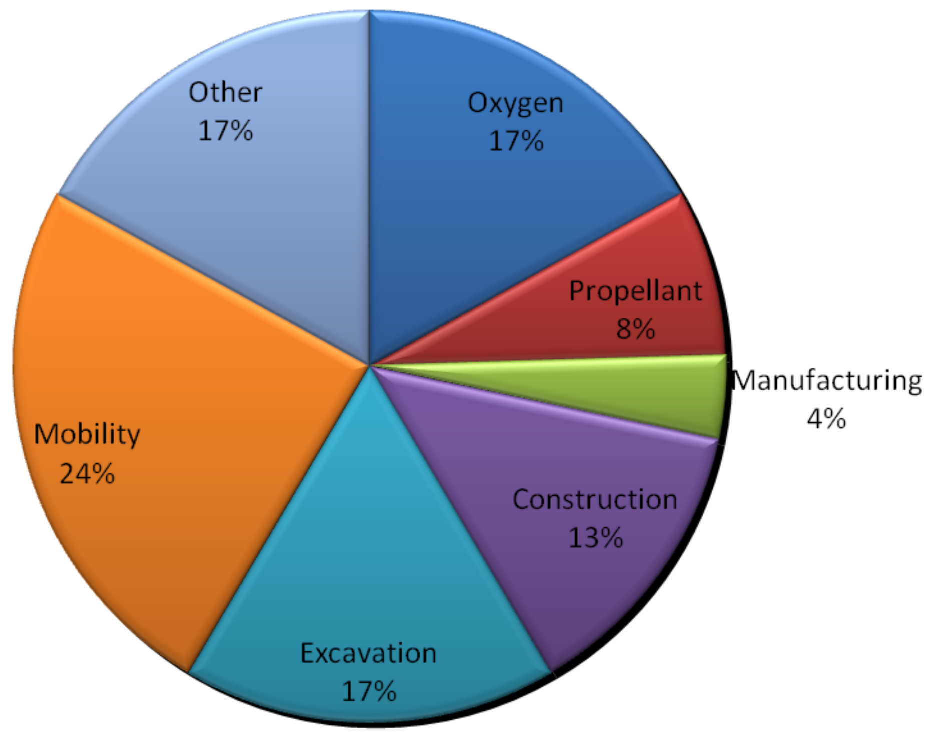


Figure 15: Pie-Chart Summarizing Simulant Needs by Specific Applications/Processes

As illustrated in the above figure, mobility and excavation comprise over 40% of the processes that will use simulants. For these types of applications, physical properties are of definite importance. For the processes involving oxygen and propellant production, chemical composition is of utmost importance. Processes included in the “other” category comprised of environmental dust sensing; cleaning of regolith (in 4 projects), abrasion/wear and removal testing, and educational purposes. However, all properties or characteristics will need to be considered while developing the various types of simulants in order to ensure the proper fidelity.

2.4 Importance of Simulant Characteristics

The thirty-five survey respondents relayed what simulant characteristics they believe to be of importance for their needs out of a choice of 56 properties. These properties include the 32 properties that were stated to be important to simulant users from the 2005 Lunar Regolith Simulant Workshop held by MSFC. The users' responses are shown in Table 5**.** These results illustrate that projects chose physical characteristics, size, shape, and grain size distribution as the most important characteristics in a simulant.

Table 5: Characteristics of Importance to Projects

Survey Results - Characteristics			
Total Respondents	35		
Total Characteristics	56		
Total Needs	676		
Respondents Who Felt That…	**Number of Respondents Who Said "Yes"**	**Percent of Respondents Who Said "Yes"**	**Total Percent of "Yes" Responses**
Physical Characteristics are Important	32	91.43%	4.73%
Size is Important	29	82.86%	4.29%
Shape is Important	29	82.86%	4.29%
Particle Size is Important	27	77.14%	3.99%
Grain Size Distribution is Important	25	71.43%	3.70%
Electrostatic Characteristics are Important	21	60.00%	3.11%
Abrasion is Important	21	60.00%	3.11%
Particle Shape Distribution is Important	21	60.00%	3.11%
Mineral/Chemical Characteristics are Important	19	54.29%	2.81%
Magnetic Characteristics are Important	19	54.29%	2.81%
Non-Visible Particles are of Concern	19	54.29%	2.81%
Electrostatic Charging is Important	18	51.43%	2.66%
Composition is Important	16	45.71%	2.37%
Conductivity is Important	16	45.71%	2.37%
Magnetic Grain Properties are Important	16	45.71%	2.37%
Thermal Characteristics are Important	15	42.86%	2.22%
"Smoke"-sized Particles are of Concern	15	42.86%	2.22%
Bulk Density is Important	15	42.86%	2.22%
Hardness is Important	15	42.86%	2.22%
Thermal Properties are Important	15	42.86%	2.22%
Particle Density is Important	14	40.00%	2.07%
Density is Important	14	40.00%	2.07%
Glass Composition is Important	14	40.00%	2.07%
Hardness is important	14	40.00%	2.07%
Bulk Characteristics are Important	13	37.14%	1.92%
Reflectivity is Important	13	37.14%	1.92%
Particle Shape is Important	12	34.29%	1.78%
Bulk Chemistry is Important	12	34.29%	1.78%
Agglutinates with Nanophase Iron are Important	12	34.29%	1.78%
"Dust Layer on Table"-sized Particles are of Concern	11	31.43%	1.63%
Soil Texture is Important	11	31.43%	1.63%
Coefficient of Friction is Important	11	31.43%	1.63%

Surface Reactivity (inc. Damage) is Important	10	28.57%	1.48%
"Cement Powder"-sized Particles are of Concern	9	25.71%	1.33%
Absorptivity is Important	9	25.71%	1.33%
Surface Area is Important	9	25.71%	1.33%
Permeability is Important	8	22.86%	1.18%
Porosity is Important	7	20.00%	1.04%
Angle if Repose is Important	7	20.00%	1.04%
"Sandpaper"-sized Particles are of Concern	6	17.14%	0.89%
Comprehensive Strength is Important	6	17.14%	0.89%
Hue is Important	5	14.29%	0.74%
Emissitivity is Important	5	14.29%	0.74%
Shear Strength is Important	5	14.29%	0.74%
Tensile Strength is Important	5	14.29%	0.74%
Mineralogical Comp. as Fn of Grain Size is Important	5	14.29%	0.74%
Modal Mineralogical Composition is Important	5	14.29%	0.74%
"Fine Sand"-sized Particles are of Concern	4	11.43%	0.59%
Fracture Behavior is Important	4	11.43%	0.59%
Friability is Important	3	8.57%	0.44%
Impact Resistance is Important	3	8.57%	0.44%
Reactivity as Volatile/Soluble Minerals is Important	3	8.57%	0.44%
Rheology is Important	2	5.71%	0.30%
Implanted Solar Particles are Important	2	5.71%	0.30%
"Coarse-Sand"-sized Particles are of Concern	0	0.00%	0.00%
Saturation is Important	0	0.00%	0.00%
Total	676		100.00%

2.5 Concern for the Grain Sizes in Lunar Regolith Samples

The thirty-five respondents also relayed information about their concern with certain grain sizes that the lunar regolith and/or simulant may exhibit. These responses are shown in Table 6. The results show that projects are most concerned with non-visible particles (which comprise much of the lunar dust) and "smoke"-sized particles.

Table 6: Grain Sizes Concerns to Project Respondents

Concern	Number of Respondents Who Said "Yes"	Percent of Respondents Who Said "Yes"	Total Percent of "Yes" Responses
Non-Visible Particles	19	54.29%	29.69%
"Smoke"-sized Particles	15	42.86%	23.43%
"Dust Layer on Table"-sized Particles	11	31.43%	17.19%
"Cement Powder"-sized Particles	9	25.71%	14.06%
"Sandpaper"-sized Particles	6	17.14%	9.38%
"Fine Sand"-sized Particles	4	11.43%	6.25%
"Coarse-Sand"-sized Particles	0	0.00%	0%
Total	64		100.00%

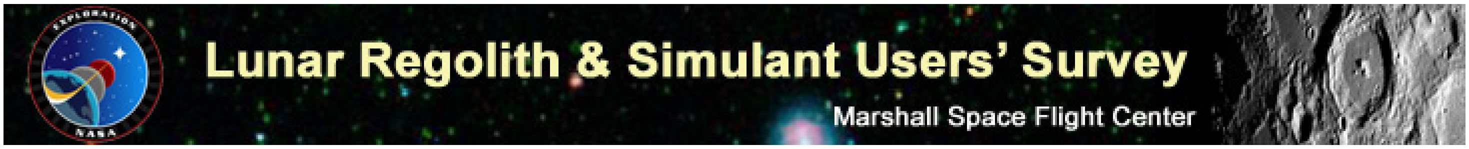
3 Recommendations

As previously pointed out in the Introduction section, it is highly recommended that the external NASA community be surveyed regarding their potential demand for regolith and simulants, especially those organizations that are NASA contractors and awardees of grants, proposals, and other NASA monies. In addition, it is suggested that all of these potential simulant users be surveyed annually. This will allow adjustments to be made to the Simulant Development Project based on the most recent forecast for simulant types and fidelities, quantities, and schedules.

It is also strongly recommended that simulant users consult with a lunar geologist or lunar scientist prior to ordering or using simulants. This will ensure proper selection, use, and handling of simulants which will, in turn, prevent or at least lessen the risk to the user in the collection of erroneous or misleading test data that could have major impacts later in the form of hardware performance and failures or human health issues.

Appendix A

Lunar Regolith & Simulant Users' Survey



4 Lunar Regolith & Simulant Users' Survey

The purpose of this survey is to assimilate lunar regolith simulant requirements as well as Apollo sample requests for the ETDP and Constellation projects and test facilities. Lunar simulants will be needed for development testing as well as verification and certification of hardware and human health. Your input will assist the simulant developers in determining when and what types (fidelities) and quantities of simulants will be needed based upon your objectives and uses of the simulant.

User Background Information

1. Project Name:

2. Project Description:

3. Point of Contact:

First Name Last Name

Area Code Phone Number E-Mail Address

Alternate Point of Contact:

First Name Last Name

Area Code Phone Number E-Mail Address

4. What project within Constellation does your work support? Check all that apply:

- ☐ ***Ares Launch Vehicle***
- ☐ ***Orion Crew Vehicle***
- ☐ ***Altair Lunar Lander***
- ☐ ***Surface Systems***
- ☐ ***Other*** Please specify:

5. What project within ETDP does your work support? Hold Ctrl and click for multiple selections.

- Structures/Mechanisms/Materials
- Advanced Composite Technologies
- Ablative Thermal Protection System Tech.
- Dust Mitigation
- Habitation Systems Technologies
- Radiation Protection Technologies

6. Describe how your project will utilize Regolith Simulant or Lunar Regolith (Apollo Samples).

7. Specify project or task schedule dates that are drivers for simulant or regolith needs. (Ex: Lab tests, demos, PDR, CDR, etc.)

8. Do simulant and/or Regolith Apollo sample requirements change based on schedule dates? (ie., Does the simulant fidelity required increase as hardware development proceeds?)

Simulants

9. Please fill out the amount of simulant needed using the following example.

	Quantity (kg)	Date Required	Purpose	Location
	12 kg	12/01/08	Oxygen Extraction	MSFC
	Quantity (kg)	Date Required	Purpose	Location
1st Order:				
2nd Order:				
3rd Order:				

More / Special Instructions:

10. Does your project have different simulant requirements during the life of the project? If so, please explain:

Lunar Regolith Simulant Requirements:

11. Which simulant characteristics are important to your project or activity. (Check all that apply)

- ☐ Physical- size, shape, hardness(used for excavation, flow, abrasion)
- ☐ Mineral/chemical - minerals, hardness (used for reactors)
- ☐ Thermal - emissitivity, conduction (used for reactors, heat exchange, sintering)
- ☐ Electrostatic - (used for attraction, grounding, shorts, communication interference)
- ☐ Magnetic - (used for attraction/removal, microwave sintering)
- ☐ Bulk - Density, compaction, tractability (used for rover/wheel interaction, digging)

12. Mark any of the following which may be of concern for design or health issues:

☐ Size not visible with the human eye ☐ Sand on 150 grade sand paper size

- [ ] Smoke particle size
- [ ] Dust layer on table size
- [ ] Cement powder size
- [ ] Fine sand
- [ ] Course sand
- [ ] Other (please identify)

13. Identify the regolith properties that are important to your work. (Check all that apply)

☐ Size	☐ Composition	☐ Absorptivity	☐ Hue	☐ Particle Density
☐ Shape	☐ Abrasion	☐ Emissivity	☐ Saturation	☐ Bulk Density
☐ Density	☐ Hardness	☐ Conductivity	☐ Porosity	☐ Thermal Properties
☐ Permeability	☐ Grain Size	☐ Reflectivity	☐ Surface Area	☐ Friability
☐ Glass Composition	☐ Grain Size Distribution	☐ Grain Shape	☐ Bulk Chemistry	☐ Hardness
☐ Soil Texture	☐ Grain Shape Distribution	☐ Comprehensive Strength	☐ Coefficient of friction	☐ Shear Strength
☐ Magnetic Grain Properties	☐ Electrostatic Charging	☐ Tensile Strength	☐ Rheology	☐ Angle of repose
☐ Fracture behavior	☐ Impact resistance	☐ Implanted solar particles	☐ Reactivity as volatile/ soluble minerals	
☐ Agglutinates with nanophase iron	☐ Surface Reactivity (inc. damage)	☐ Mineralogical composition as function of grain size	☐ Modal mineralogical composition	

14. Are there any specific elements (chlorine, fluorine, etc.) or minerals (ilmenite, etc.) or glass that are important and of concern to your research/work? If so, please identify them.

15. Are there any other simulant characteristics/attributes that are needed for your applications?

16. Do you plan to reuse the simulant during testing?

○ Yes ○ No If so, please explain:

Process

17. Does your project involve using simulants in a chemical process such as oxygen production? If so, please specify process (e.g. H2 reduction, carbothermal, etc.)

Yes No If so, please explain:

18. Does your project involve using simulants in a chemical process such as propellant production?

Yes No If so, please explain:

19. Does your project involve a manufacturing process such as glass or semiconductor substrate production?

Yes No If so, please explain:

20. Does your project involve a construction process such as brick or road production?

Yes No If so, please explain:

21. Does your project involve an excavation process such as burying items or moving dirt for berms etc.?

Yes No If so, please explain:

22. Does your project involve a mobility process such as transportation (rovers) etc.?

Yes No If so, please explain:

23. Any other processes not covered above?

Yes No If so, please explain:

Lunar Regolith (Apollo Samples) Requirements

Note: Per direction, we have been requested to collect regolith requirements but have no influence over the CAPTEM Board (Curation and Analysis Planning Team for Extraterrestrial Materials).

24. Quantity Needed:

25. Need by (date):

26. How will the Apollo samples be used?

27. Will this be for development testing or verification/certification testing?

28. Do you expect the sample(s) to be returned intact or destroyed?

29. Additional Comments / Questions:

This file cannot be saved, so please make a copy/print for your records.

Submit

Thank you for your input. We will contact you should we have any questions regarding your responses.

4.1 Contact Information:

Technical:

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Lead Project Scientist for Simulants
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Doug.Rickman@nasa.gov

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Geologist
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Project:

Carole McLemore
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Carole.A.McLemore@nasa.gov

John Fikes
MSFC Deputy Project Manager, ISRU and Dust
256-544-5570
John.C.Fikes@nasa.gov

Check out the simulant website at:
http://isru.msfc.nasa.gov

More information coming soon on the Annual Lunar Simulant Workshop for 2008!

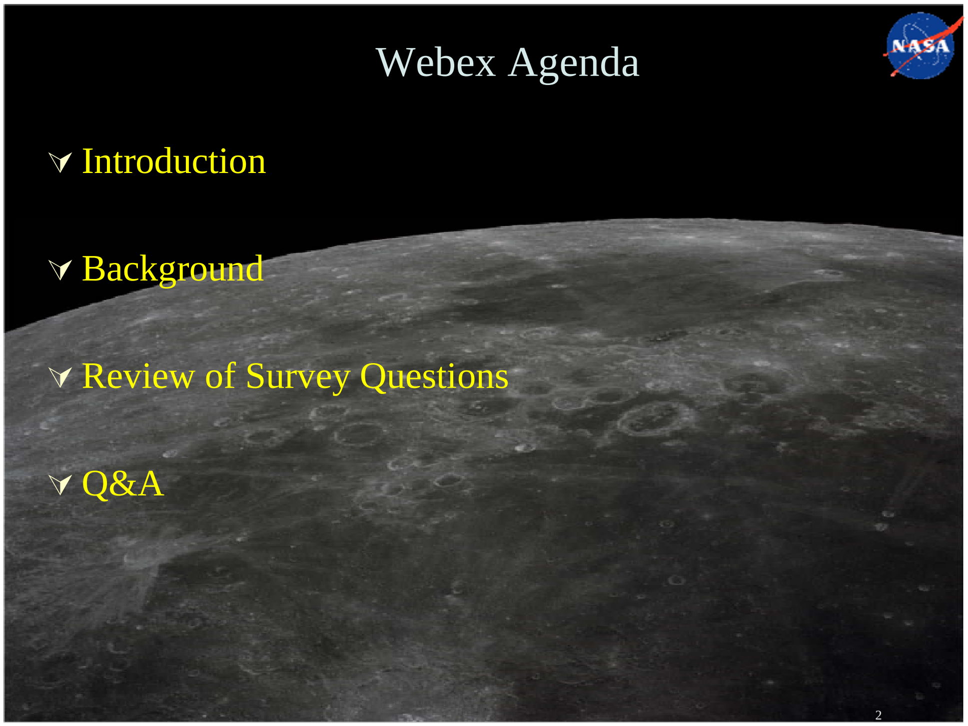
Thank you for completing the survey!

Date last revised: 05/21/08

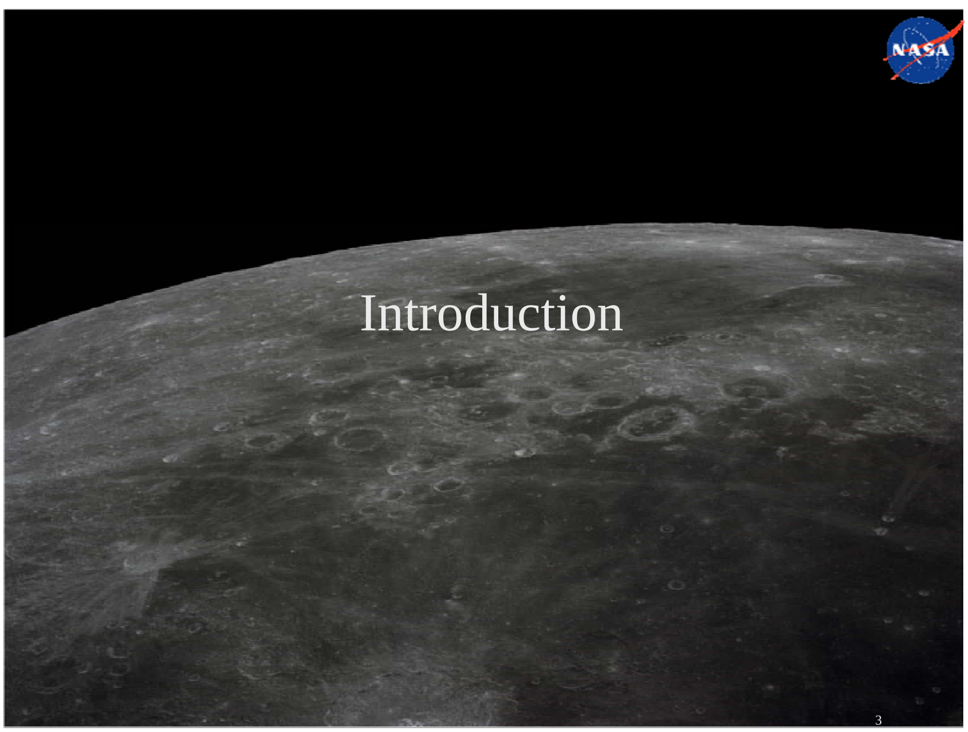
Appendix B

Lunar Regolith & Simulant Survey Kick-Off Presentation

National Aeronautics and Space Administration
NASA
Lunar Regolith and Simulant
User's Survey Kick-Off
Webex Package
NASA/Marshall Space Flight Center
May 21, 2008
Carole McLemore/VP33
carole.a.mclemore@nasa.gov
http://isru.msfc.nasa.gov



Webex Agenda
Introduction
Background
Review of Survey Questions
Q&A
2



Introduction
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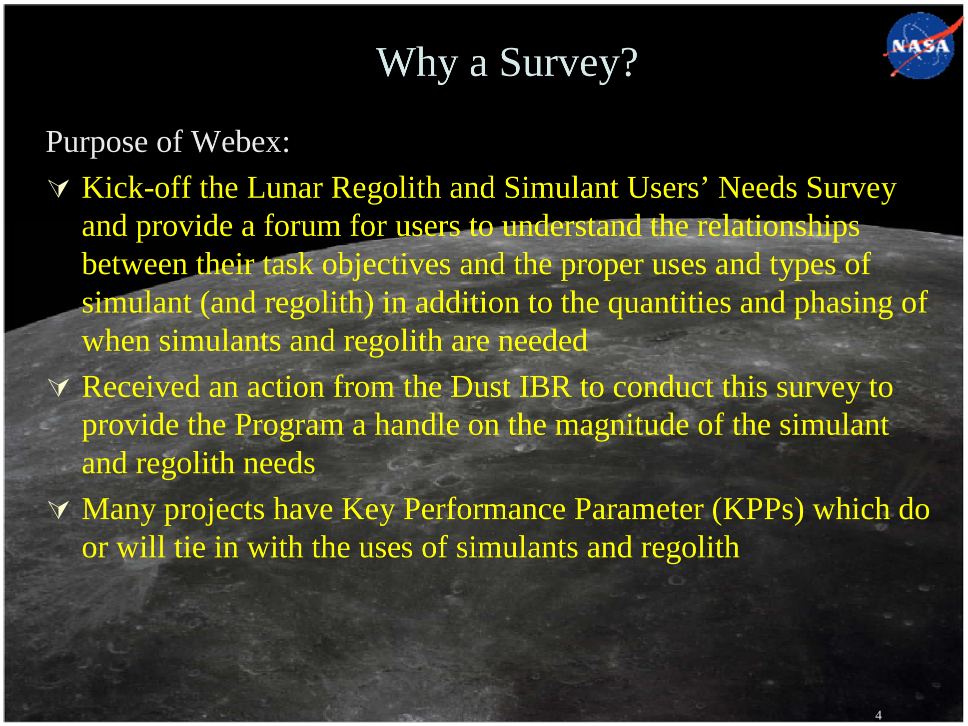
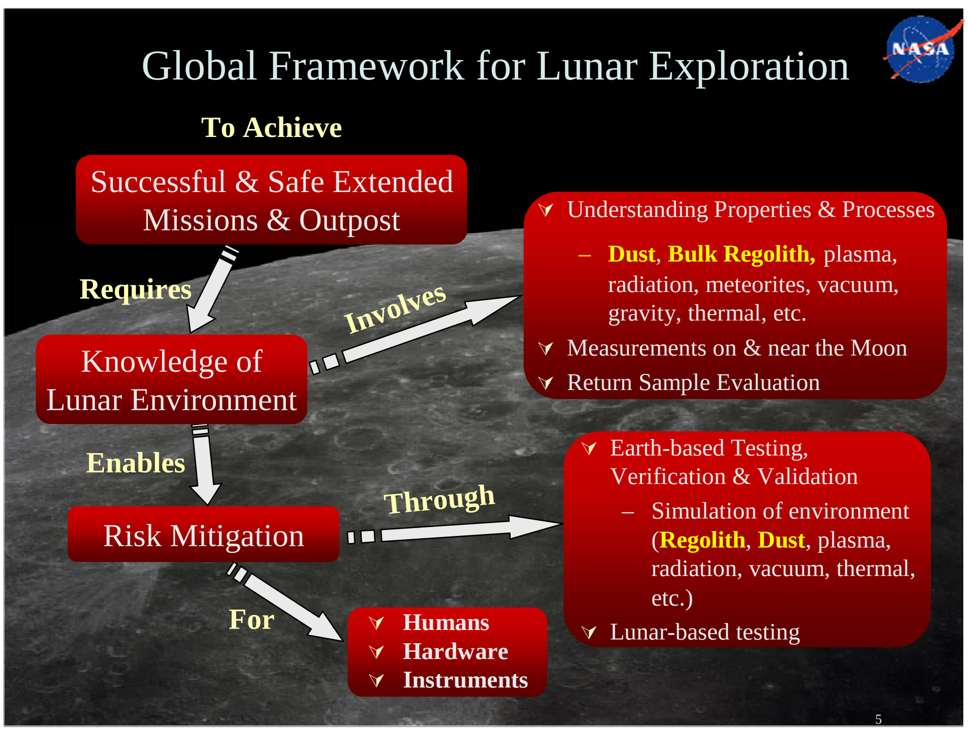
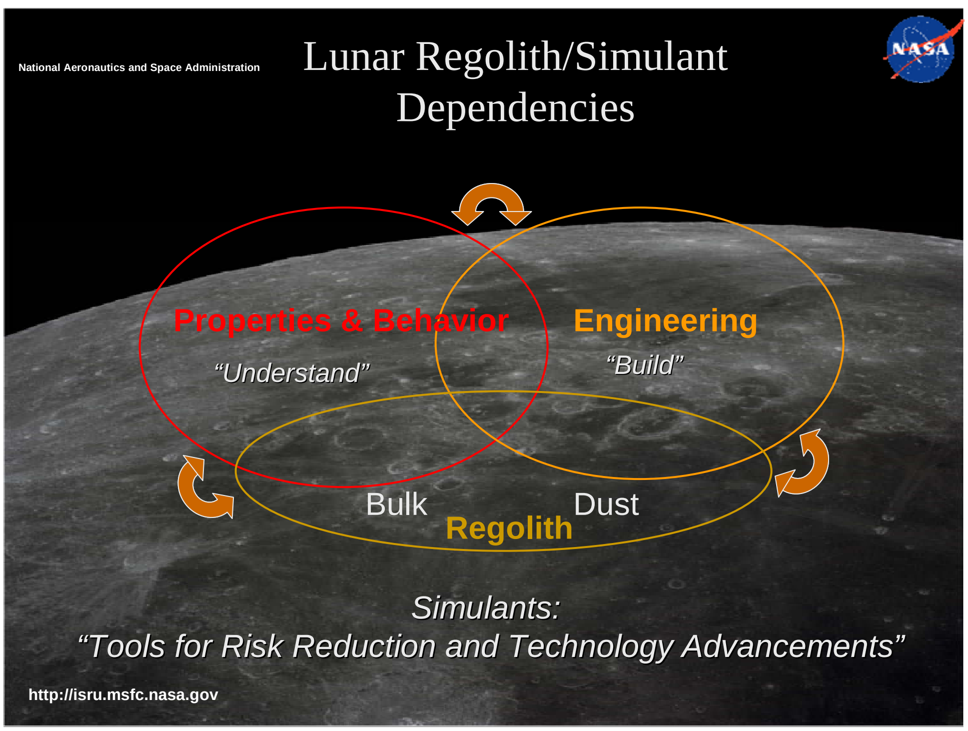


Why a Survey?
Purpose of Webex:
Kick-off the Lunar Regolith and Simulant Users' Needs Survey and provide a forum for users to understand the relationships between their task objectives and the proper uses and types of simulant (and regolith) in addition to the quantities and phasing of when simulants and regolith are needed
Received an action from the Dust IBR to conduct this survey to provide the Program a handle on the magnitude of the simulant and regolith needs
Many projects have Key Performance Parameter (KPPs) which do or will tie in with the uses of simulants and regolith
4

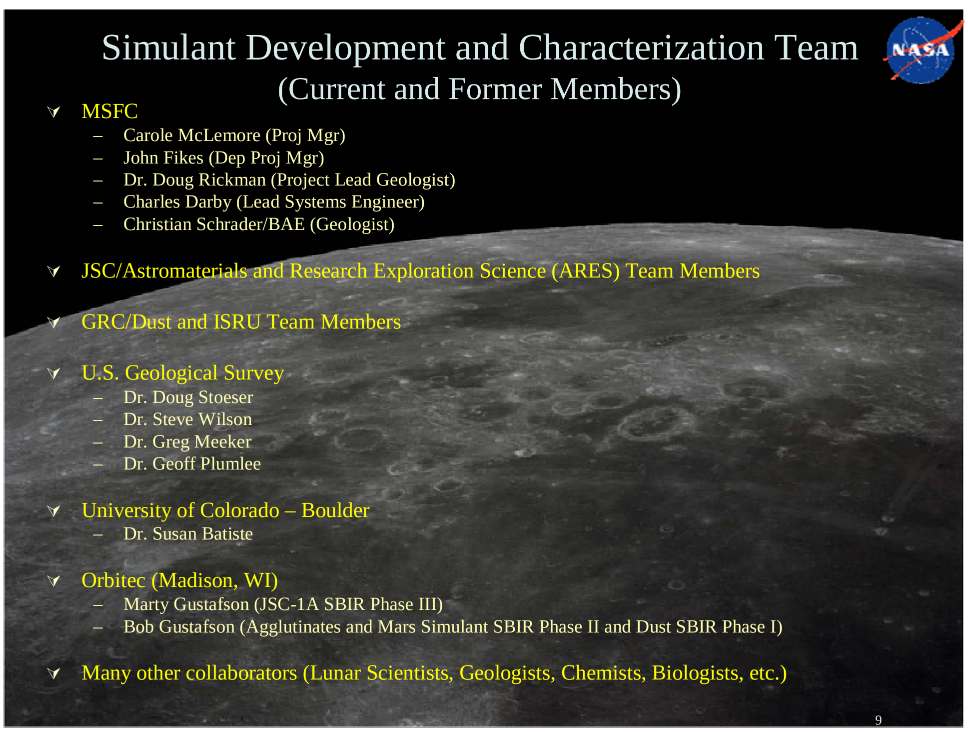


Global Framework for Lunar Exploration
To Achieve
Successful & Safe Extended Missions & Outpost
Requires
Knowledge of Lunar Environment
Involves
Understanding Properties & Processes
– Dust, Bulk Regolith, plasma, radiation, meteorites, vacuum, gravity, thermal, etc.
Measurements on & near the Moon
Return Sample Evaluation
Enables
Risk Mitigation
Through
Earth-based Testing, Verification & Validation
– Simulation of environment (Regolith, Dust, plasma, radiation, vacuum, thermal, etc.)
Lunar-based testing
For
Humans
Hardware
Instruments
5


Specific Framework for Lunar Regolith
Role of Regolith
It Touches Everything
3 Aspects – (1) Understand It, (2) Deal With It, (3) Utilize It
Interrelationships & Connectivity
Science (Properties & Processes)
Engineering (Design, Test & Operations)
Knowledge
Environment Simulation
Resource Utilization
Regolith Simulants (ESMD/SMD)
Dust Simulants
Bulk Simulants
Earth Based Environmental Testing
Human Health
HW/System Development &Verification
6


National Aeronautics and Space Administration
Lunar Regolith/Simulant Dependencies
Properties & Behavior
"Understand"
Engineering
"Build"
Bulk
Dust
Regolith
Simulants:
"Tools for Risk Reduction and Technology Advancements"
http://isru.msfc.nasa.gov

Background
8



Simulant Development and Characterization Team
(Current and Former Members)
MSFC
– Carole McLemore (Proj Mgr)
– John Fikes (Dep Proj Mgr)
– Dr. Doug Rickman (Project Lead Geologist)
– Charles Darby (Lead Systems Engineer)
– Christian Schrader/BAE (Geologist)
JSC/Astromaterials and Research Exploration Science (ARES) Team Members
GRC/Dust and ISRU Team Members
U.S. Geological Survey
– Dr. Doug Stoeser
– Dr. Steve Wilson
– Dr. Greg Meeker
– Dr. Geoff Plumlee
University of Colorado – Boulder
– Dr. Susan Batiste
Orbitec (Madison, WI)
– Marty Gustafson (JSC-1A SBIR Phase III)
– Bob Gustafson (Agglutinates and Mars Simulant SBIR Phase II and Dust SBIR Phase I)
Many other collaborators (Lunar Scientists, Geologists, Chemists, Biologists, etc.)
9

Useful Definitions

- ***Regolith***: General term for the mantle of loose, incoherent, or unconsolidated rock material, of whatever origin, size or character, that nearly everywhere forms the surface of rocky planetary bodies
  - Definition adapted from the Glossary of Geology, 1972
  - Most lunar regolith was formed by hypervelocity impacts
  - Lunar regolith is spatially very heterogeneous in composition and particle size distribution compared to terrestrial regolith
- ***Regolith Simulants***: Synthetic analogs that approximate, to a known extent, one or more properties of a regolith
- ***Lunar Regolith Simulant***: Regolith Simulant that approximates one or more regolith properties at a particular lunar location or region
- ***Dust***: An informal term - the EPA and OSHA have set regulatory definitions for "dust" related health concerns at particle sizes smaller than 2.5µm & 10µm
- ***Lunar Dust***: Particles from the Moon which are less than 10µm in size
  - The departure from American regulatory definitions in part reflects the lower surface gravity of the Moon.
- ***Lunar Dust Simulant***: A regolith simulant where virtually all particles are less than 10µm in size (Note: NEDD and DSNE Documents define dust this size)

10

Regolith Simulant Background

September 1989 Workshop on Production and Uses of Simulated Lunar Materials @ LPI/Houston hosted by David McKay and James Blacic

Three Key Recommendations:

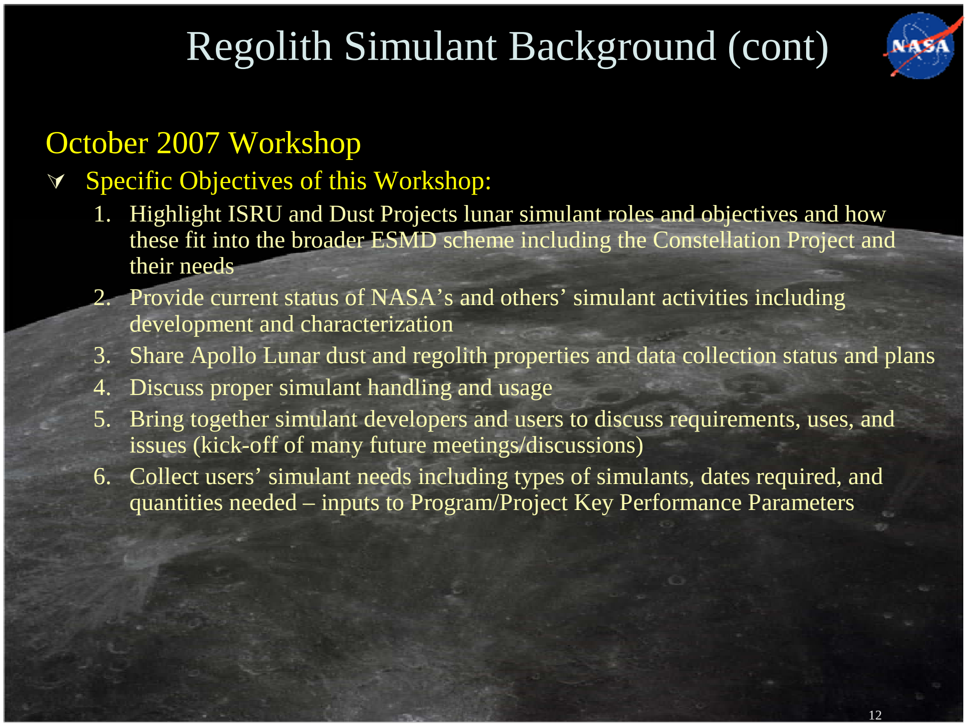
- 1) It is strongly recommended that lunar simulant components be produced and made available to researchers as soon as possible.
- 2) NASA should immediately designate a lunar simulant curator and establish a lunar simulant advisory committee.
- 3) Every effort should be made to assist the research community with appropriate knowledge transfer concerning the feasibility and design of specific experiments requiring simulants.

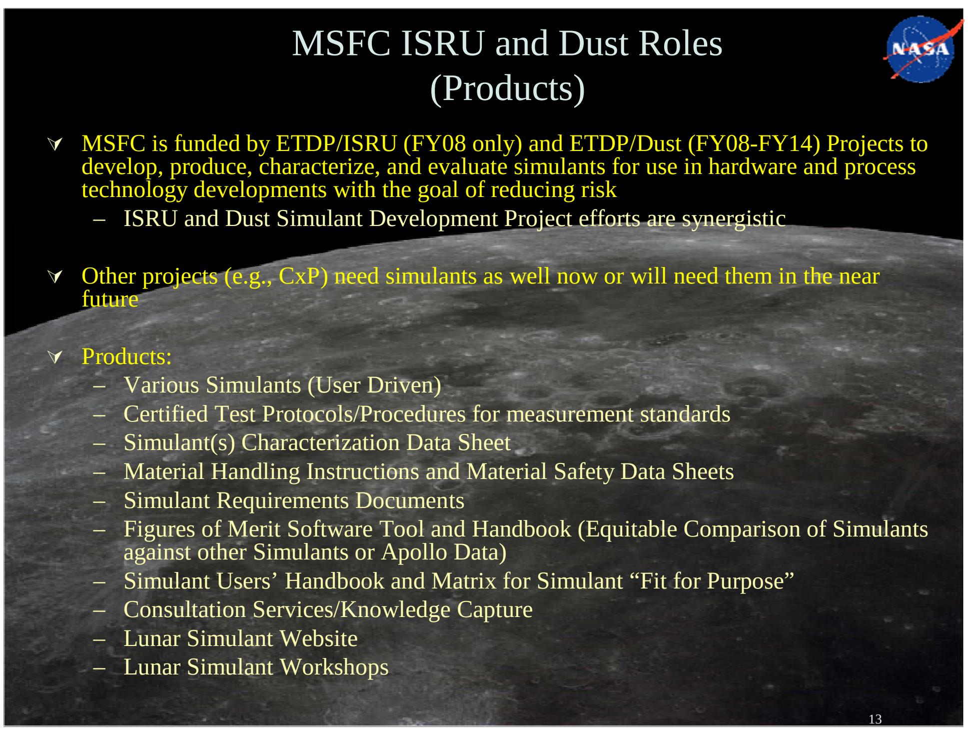
January 2005 Simulant Workshop held in Huntsville and sponsored by ESMD and MSFC in collaboration with JSC

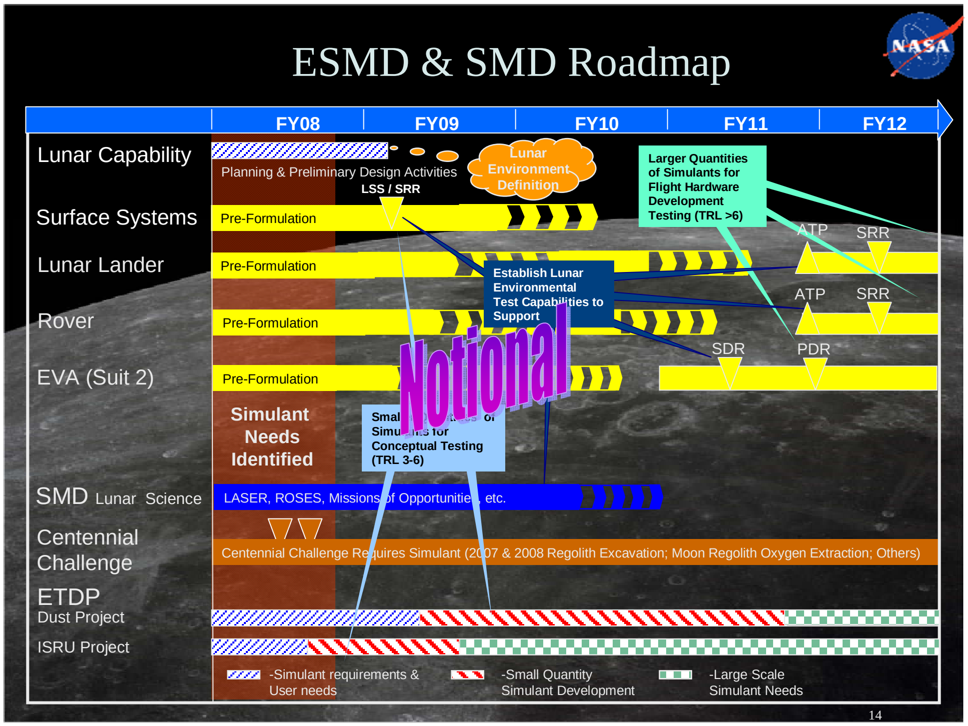
Four Recommendations:

- 1) Establish a common set of standards for simulant materials for NASA sponsored projects.
- 2) Establish a process for the development, production, and certification of simulant materials.
- 3) Develop a long-term simulant acquisition strategy.
- 4) Proceed as quickly as possible with a unified, near-term ESMD simulant acquisition through an immediate redeployment of lunar mare simulant JSC-1.
- Thirty-two (32) Lunar Regolith Properties were identified and ranked by importance based on consensus count by attendees

11


Regolith Simulant Background (cont)
October 2007 Workshop
Specific Objectives of this Workshop:
1. Highlight ISRU and Dust Projects lunar simulant roles and objectives and how these fit into the broader ESMD scheme including the Constellation Project and their needs
2. Provide current status of NASA's and others' simulant activities including development and characterization
3. Share Apollo Lunar dust and regolith properties and data collection status and plans
4. Discuss proper simulant handling and usage
5. Bring together simulant developers and users to discuss requirements, uses, and issues (kick-off of many future meetings/discussions)
6. Collect users' simulant needs including types of simulants, dates required, and quantities needed – inputs to Program/Project Key Performance Parameters
12


MSFC ISRU and Dust Roles (Products)
MSFC is funded by ETDP/ISRU (FY08 only) and ETDP/Dust (FY08-FY14) Projects to develop, produce, characterize, and evaluate simulants for use in hardware and process technology developments with the goal of reducing risk
– ISRU and Dust Simulant Development Project efforts are synergistic
Other projects (e.g., CxP) need simulants as well now or will need them in the near future
Products:
– Various Simulants (User Driven)
– Certified Test Protocols/Procedures for measurement standards
– Simulant(s) Characterization Data Sheet
– Material Handling Instructions and Material Safety Data Sheets
– Simulant Requirements Documents
– Figures of Merit Software Tool and Handbook (Equitable Comparison of Simulants against other Simulants or Apollo Data)
– Simulant Users' Handbook and Matrix for Simulant "Fit for Purpose"
– Consultation Services/Knowledge Capture
– Lunar Simulant Website
– Lunar Simulant Workshops
13



Current MSFC-Managed Lunar Simulant Status

JSC-1A:

- Under SBIR Phase 3, Orbitec delivered 16 tons of JSC-1A (Mare type simulant)
  - Fines (1MT), Bulk (14MT), and Coarse (1MT)
- Eight tons of additional JSC1A simulant were delivered to the California Space Authority (CSA) for Centennial Challenge in Spring 2007
- Compiled JSC-1A Fines Characterization Report with input from Simulant Science Advisors and Experts

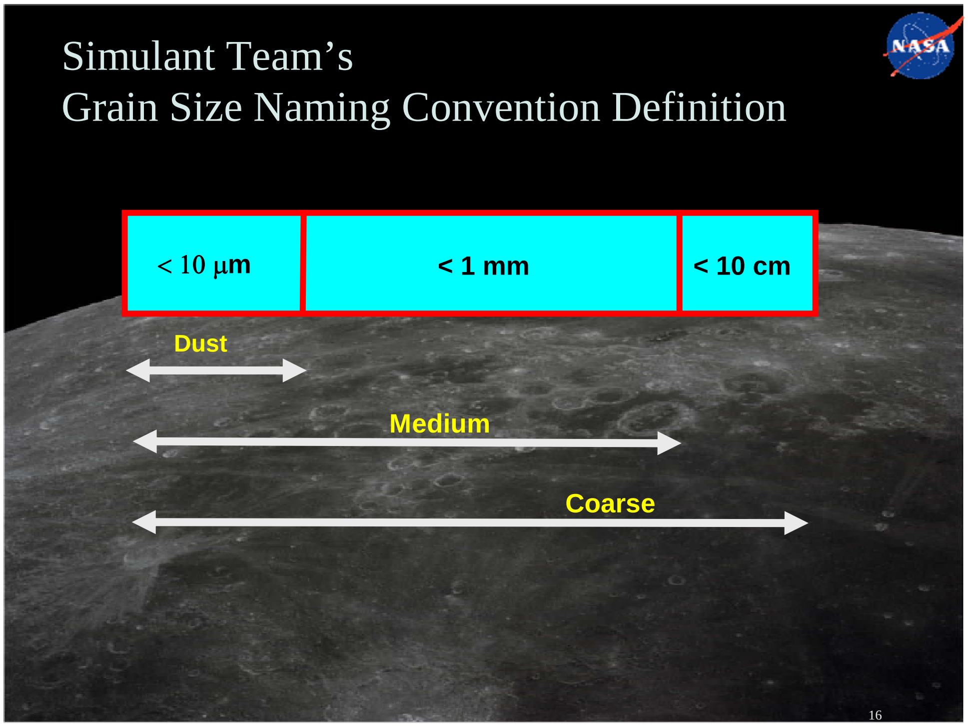
NASA/U.S. Geological Survey Lunar Highland Type Medium (NU-LHT-M):

- Simulant Requirements Document
- Identified sites to obtain feedstock material for manufacturing LHT simulants
- Selected an Apollo 16 core sample as the official reference for the LHT
- Developed a method for evaluating specific properties of simulants to compare against a reference such as an Apollo sample or other simulants (i.e., Figures of Merit (FOMs)) – 4 FOMs (Size, Shape, Distribution, and Composition)
- Developed and produced NASA/U.S. Geological Survey Lunar Highland Type (NU-LHT-1M) Pilot material and NU-LHT-2M (Prototype) 1300 #
- Draft NU-LHT-M Characterization Data Sheet

Dust:

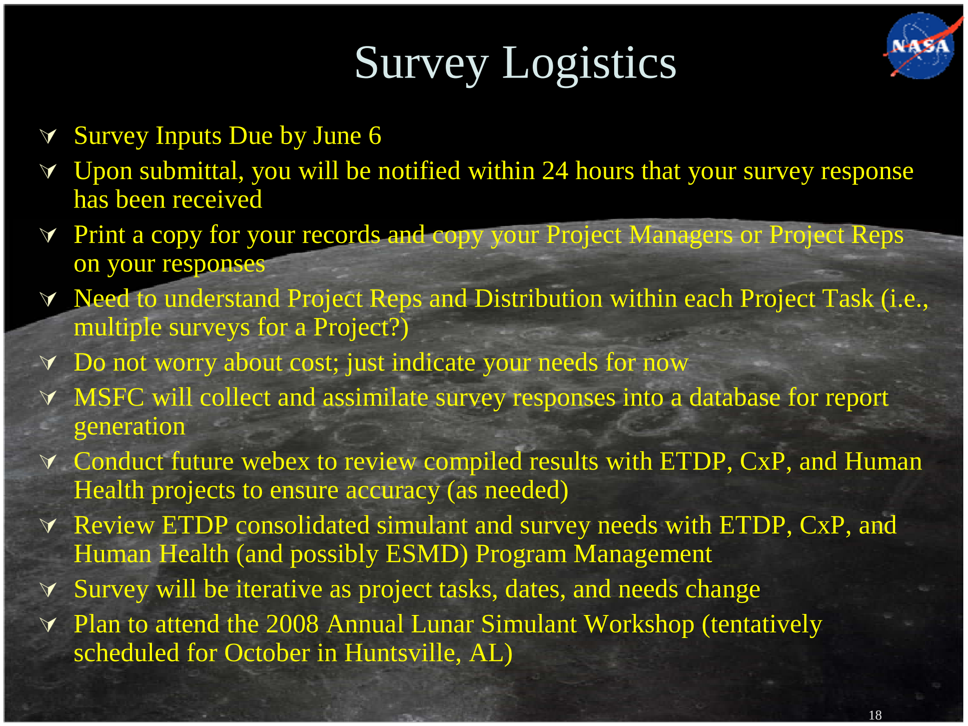
- FOMs in development
- Developed small quantity (~ 1 kg) of Pilot Dust Simulant (NU-LHT-1D)

15

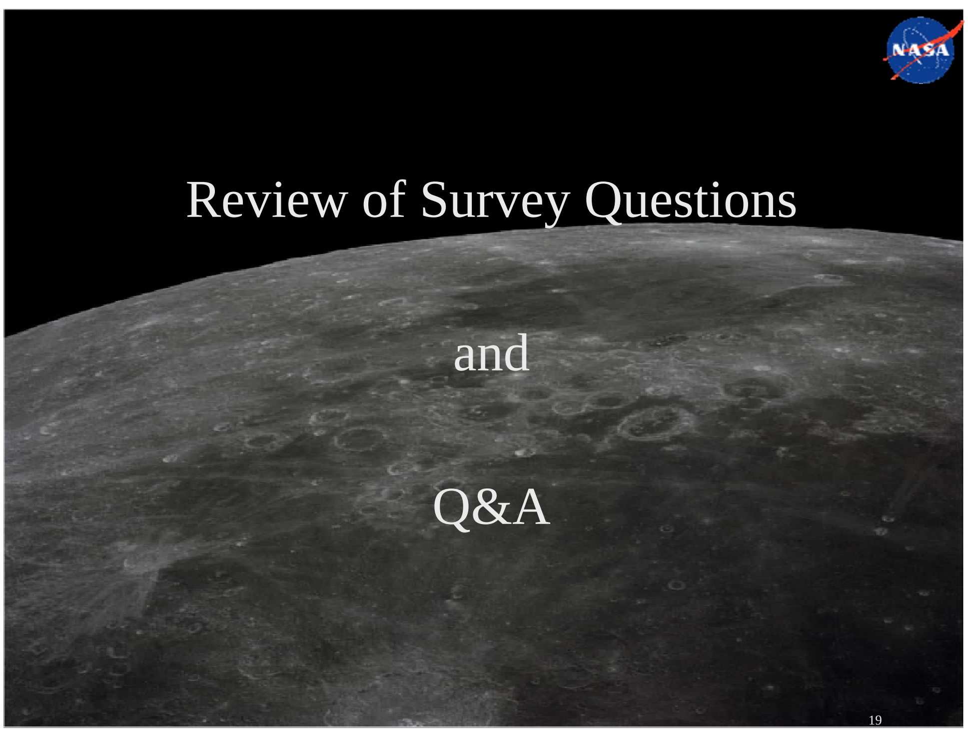


Simulant Team's
Grain Size Naming Convention Definition
< 10 µm
< 1 mm
< 10 cm
Dust
Medium
Coarse
16

Lunar Regolith and Simulant User Needs
Results of this Survey will drive …..
Where we go from here
17



Survey Logistics
Survey Inputs Due by June 6
Upon submittal, you will be notified within 24 hours that your survey response has been received
Print a copy for your records and copy your Project Managers or Project Reps on your responses
Need to understand Project Reps and Distribution within each Project Task (i.e., multiple surveys for a Project?)
Do not worry about cost; just indicate your needs for now
MSFC will collect and assimilate survey responses into a database for report generation
Conduct future webex to review compiled results with ETDP, CxP, and Human Health projects to ensure accuracy (as needed)
Review ETDP consolidated simulant and survey needs with ETDP, CxP, and Human Health (and possibly ESMD) Program Management
Survey will be iterative as project tasks, dates, and needs change
Plan to attend the 2008 Annual Lunar Simulant Workshop (tentatively scheduled for October in Huntsville, AL)
18



Review of Survey Questions
and
Q&A
19

Records

Records shall be identified in accordance with MPR 1440.2. These records shall be retained and dispositioned in accordance with NPR 1441.1, Schedules 7 and 8. All record custodians shall have approved records plans in accordance with MPR 1440.2 with copies of those plans submitted to the applicable program/project office.

APPENDIX 4. List of Lunar Regolith/Soil/Dust Simulants. Red = Developed under the MSFC Simulant Project to date (10/28/10). Blue= no longer available

SIMULANTS			TYPE
MLS-1	Minnesota Lunar Simulant, Weiblen et al., 1990	USA	High-Ilmenite mare (general use)
MLS-1P	Weiblen et al., 1990	USA	High-Ti mare (experimental, not produced in bulk although small quanitites were distributed)
MLS-2	Tucker et al., 1992	USA	Highlands (general use)
ALS	Arizona Lunar Simulant Desai et al., 1993	USA	Low-Ti Mare (geotechnical)
JSC-1	Johnson Space Center McKay et al., 1994	USA-**JSC**	Low-Ti mare (general use)
FJS-1 (type 1) **FJS-1 (type 2)** **FJS-1 (type 3)**	Fuji Japanese Simulant Kanamori et al., 1998	Japan	Low-Ti mare Low-Ti mare High-Ti mare (general use)
MKS-1	Carpenter, 2005	USA-**MSFCS**	Low-Ti mare (intended use unknown)
JSC-1A **JSC-1AF**	Dr. James Carter, see http://www.orbitec.com/store/JSC-1A_Bulk_Data_Characterization.pdf, http://www.orbitec.com/store/JSC-1AF_Characterization.pdf	USA-**MSFC** ORBITEC	Low-Ti mare (general use) JSC-1A was intended to replicate JSC-1 by using the same source material and similar processing
OB-1	Anorthosite + Fe Olivine Glass, Battler & Spray, 2009	Canada	Highlands (general use geotechnical)
CHENOBI	Undocumented, see http://www.evcltd.com/index_005.htm	Canada/Norcat	Highlands (geotechnical)
CAS-1	Zheng et al, 2008	China	Low-Ti mare (geotechnical)
GCA-1	Goddard Space Center, Taylor et al, 2008	USA - GSA	Low-ti mare (geotechnical)
NU-LHT-1M **NU-LHT-1D**	NASA/USGS Lunar Highlands type Stoeser et al, 2009	USA-**MSFC** USGS	Highlands (general use)
NU-LHT-2M **NU-LHT-2C**	Stoeser et al, 2009	USA-**MSFC** USGS	Highlands (general use)
Oshima	Base simulant, Sueyoshi et al, 2008	Japan	High-Ti mare (general use)
Kohyama,	Base stimulant, Sueuoshi et al, 2008	Japan	Between highlands and mare (general use)
NAO-1	Li et al, 2009	China	Highlands (general use)
CLRS-1	Chinese Lunar Regolith stimulant (Chinese Acad. Of Sciences, 2009)	China	Low-Ti mare (general use)
CUG-1	He et al, 2010	China	Low-Ti mare (geotechnical use)
GRC-1 **GRC-3**	Glen Research Center, Oravec et al, In press	USA-**GRC**	Geotechnical: standard vehicle mobility lunar simulant
TJ-1 **TJ-2**	TongJi University, Jiang et al, in press	China	Low Ti mare (geotechnical)
KOHLS-1	Koh, Lunar sumulant, Jiang et al, 2010	China	Low-Ti mare (geotechnical use)
BP-1	Black Point Rahmatian & Metzger, in press	USA-**KSC**	Low-Ti mare (geotechnical use)
CSM-CL	Colorado School of Mines-Colorado Lava unpublished	USA	Geotechnical

<u>APPENDIX 5.</u> What is needed for production of quality Lunar Simulants:

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Things needed in order to have a viable simulant of real use to real engineers

The need for simulants is driven by the uses of the simulant. In turn, the uses are controlled by the engineering and scientific objectives. Objectives inherent in a brief landing on the Moon are radically different from a permanent base. For a brief landing, such as with Apollo, engineering needs are probably well satisfied using something like the JSC-1 series materials or any of several equivalents: OB-1, CAS-1, FJS-1, etc. All of these are grossly inadequate in larger particles, but this is readily remedied. The following is based on the assumption that something more than a repeat of Apollo is envisioned.

1. Factors affecting Cost of Simulants

Cost elements pertaining to simulants:

1.1. Feedstock
1.2. Design
1.3. Production
1.4. Evaluation/characterization
1.5. Storage
1.6. Shipping
1.7. Consultative expertise to advise usage

2. Need for multiple simulants

Two major facts drive this. 1) The known variation in the lunar regolith is large enough to require adaption in the engineering. 2) The range of needs is extremely large in terms of both fidelity and quantity. It is not realistic in terms of cost to meet needs for bulk quantities needing low fidelity with high fidelity material. Nor can low quality material be substituted where high fidelity is needed.

3. Knowledge Required for Simulant Production and Use

The uses of simulant are extremely varied. The factors that will affect a given use of simulant are also extremely varied and are experiment specific. The engineers do not understand the regolith; and, they do not understand the geology used to explain the characteristics of the regolith. To use simulant in place of actual regolith one must understand 1) how the regolith and simulant differ, and 2) how those differences will interact with the experimental conditions. The first is pure geology, the second requires both geology and the ability and time to understand the experimental conditions. Anyone filling the role should have the following skills:

3.1. Detailed knowledge of existing and ongoing lunar geology research.
3.2. Experience with lunar samples.
3.3. Detailed knowledge of feedstocks used to make the simulants.

3.4. Detailed knowledge of how the feedstocks are processed to make the simulants.
3.5. An ability to understand engineers and others using simulants, foresee the implications of experimental conditions, and to communicate useful guidance to the users of simulants.

4. Apollo/Lunar research

There remain substantial areas where specific knowledge about the lunar regolith is inadequate to meet the known or anticipated needs of simulant users. Geologically, much can be reasoned from the available data, but engineers are prudently hesitant to accept hypotheses as substitutes for data. Following are several topics that are known or can reasonably be expected to require specific, focused research.

4.1. In a statistical sense what is the spatial variation of most properties? For example, in a given location, how likely is there to be a particle big enough to interfere with a specific design.
4.2. Remote sensing of places you want to go to.
4.3. What is the mechanical strength of particles at all sizes?
4.4. Shape data for lunar particles.
4.5. Data for particle size distribution for >1mm is inadequate.
4.6. The interlocking of different phases within a particle can be very important for beneficiation and other *in situ* handling operations. Very little is known about this.
4.7. Minor and trace phases and elements can be quite important in certain situations. Very little is known in detail about what phases, how much, associated phases that hold them, and the potential to mobilize them under various conditions. Minor and trace elements, such as As, Se, Sb, S, P, F, Cl, probably C also, are specific concerns.

5. Develop new knowledge

It is a given that as engineering and science progresses, the sophistication of their needs increases. This is already observed over the coarse of the last 4 ½ years. Therefore, the knowledge and technology base of the simulant designers must also increase. And this really needs to lead the users, because it takes so long to get the necessary knowledge.

It should be noted that in order to "stay ahead" of the users, the simulant designers have to maintain familiarity with what the engineers are doing and plan to be doing. Related to the above are known areas needing research.

5.1. Most importantly – mineral separation technology. This should permit reductions in cost for higher fidelity simulants, improve the fidelity, increase the range of regoliths that can be readily matched, and remove contaminating phases, such as hydroxyl- and H_2O-bearing minerals.
5.2. Density values for the existing simulants are generally not known.
5.3. Shape distributions for existing simulants are generally not known. Further, the significance of variations is shape is not understood quantitatively.

5.4. For various mechanical measures, such as flow and shear strength, how sensitive are the measures to factors that can be controlled in production of the simulants?
5.5. Spectroscopy at differing wavelengths for the existing simulants is generally not known.
5.6. Amount and nature of volatiles as function of temperature needs to be known. Also the energy requirements for various phase transitions. This kind of information can be obtained using DTA and TGA in vacuum linked to FTIR.
5.7. How significant is particle texture for engineering applications? Is this something we need to worry about?

6. Stocks

In addition to supplies of simulants for engineering and scientific users, there is a need to have stocks for research on the simulants, as per 5 above. 1 kilogram reserve of each simulant is the current amount recommended for this purpose. These stocks are also used to supply gram quantities for various research purposes.

- 6.1. Samples of each simulant, both the series and the specific products.
- 6.2. Relatively pure end member phases
  - 6.2.1. Synthetics
    - 6.2.1.1. Glass
    - 6.2.1.2. Anorthite
    - 6.2.1.3. Breccia
    - 6.2.1.4. Agglutinates with nanophase Fe
    - 6.2.1.5. Ilmenite
    - 6.2.1.6. Whitlockite/Merrilite
  - 6.2.2. Minerals
    - 6.2.2.1. Olivine
    - 6.2.2.2. Orthopyroxene
    - 6.2.2.3. Clinopyroxene
    - 6.2.2.4. Natural plagioclase
    - 6.2.2.5. Minor minerals
      - 6.2.2.5.1. Apatite
      - 6.2.2.5.2. Pyrite
      - 6.2.2.5.3. Spinel

Suggestion: We need to offer order of magnitude estimates of what any of the above, or other, recommendations might cost. Also we should consider providing estimates of time requirements to do the work.

APPENDIX 6. List of Technologies used for research with lunar simulants, Characteristics that may be important, and estimated amounts of simulant needed.

Technology	Method	Important Regolith Characteristics		Quantity Needed (per 10 years)
Excavation	Regolith Movers	Size Distribution Particle Density Bulk Density Friability Compressive Strength Rheology Shear Strength Angle of Repose	Shape Abrasion Hardness Soil Texture Coefficient of Friction Soil Texture Tensile Strength	500 tons (103 tons/2y)
	Drilling	Size Distribution Shape Bulk Density Porosity Compressive Strength Friability Tensile Strength Fracture Behavior Rheology	Particle Density Abrasion Hardness Permeability Coefficient of Friction Shear Strength Angle of Repose Impact Resistance	2000Kg (600Kg/3y)
	Beneficiation	Size Shape Bulk Mineralogy Magnetic Properties Glass Composition Agglutinates with Nanophase Iron Abrasion Rheology	Distribution Hardness Electrostatic Charging Surface Area Bulk Chemistry Bulk Density	13,000 Kg (4000kg/3y)
Oxygen Extraction	Magma Electrol-ysis	Bulk Chemistry Glass Composition Reactivity/Surface Reactivity Thermal Properties Size Distribution	Bulk Mineralogy Implanted Solar Particles Surface Area	50kg
	Ilmenite Reduction	Bulk Chemistry Glass Composition Implanted Solar Particles Surface Area Reactivity/Surface Reactivity	Bulk Mineralogy Bulk Composition	50kg
	Acid Dissolution	Bulk Chemistry Fracture Behavior Glass Composition Implanted Solar Particles	Bulk Composition Friability Modal Mineralogy	50kg

		Size Distribution Surface Area Reactivity / Surface Reactivity	
	Hydrogen Reduction of Silicate Glass	Agglutinates with Nanophase Iron Bulk Chemistry Size Distribution Shape Hardness Bulk Mineralogy Emissivity Conductivity Electrostatic Charging Magnetic Properties Glass Composition Reflectivity Surface Area Implanted Solar Particles	30,000kg (9000kg/3y)
	Pyrolysis	Size Distribution Hue Shape Bulk Density Hardness Conductivity Porosity Thermal Properties Reflectivity Bulk Chemistry Soil Texture Compressive Strength Coefficient of Friction Angle of Repose Implanted Solar Particles	6,000kg (1900kg/3y)
Dust Mitigation	Filter	Sub-micron Size Distribution Magnetic Properties Electrostatic Charging Absorptivity Particle Density Shape Abrasion Emissivity Conductivity Porosity Permeability Reflectivity Surface Area Glass Composition Agglutinates with Nanophase Iron Reactivity/Surface Reactivity	60kg (18kg/3y)
	Vacuum System	Size Distribution Shape Abrasion Hardness Glass Composition Magnetic Properties Electrostatic Properties Conductivity Friability	10kg (3kg/3y)
	Coatings (1)	Size Distribution Particle Density Shape Abrasion Bulk Density Hardness Reflectivity Compressive Strength Electrostatic Charging Tensile Strength Angle of Repose Fracture Behavior Modal Mineralogy Magnetic Properties Reactivity/Surface Reactivity	10kg
	Coatings (2)	Size Distribution Electrostatic Charging Abrasion Thermal Properties Hue Shape Hardness Magnetic Properties	60kg (6kg/2y)

		Absorptivity Conductivity Soil Texture Agglutinates with Nanophase Iron	Emissivity Reflectivity Surface Reactivity	
	Dust Removal (1)	Bulk Chemistry Modal Mineralogy Shape Abrasion Conductivity Magnetic Properties Surface Reactivity Agglutinates with Nanophase Iron	Bulk Composition Size Distribution Thermal Properties Hardness Coefficient of Friction Electrostatic Chargng	10kg (1kg/1y)
	Dust Removal (2)	Bulk Chemistry Modal Mineralogy Shape Electrostatic Properties Conductivity Surface Reactivity	Bulk Composition Size Distribution Hardness Abrasion Magnetic Properties	10kg (3kg/3y)
	Thermal Effects	Modal Mineralogy Bulk Composition Hue Abrasion Hardness Permeability Surface Area Glass Composition Electrostatic Charging Implanted Solar Particles Surface Reactivity	Size Distribution Absorptivity Shape Emissivity Thermal Properties Reflectivity Bulk Chemistry Coefficient of Friction Angle of Repose Agglutinates	10kg (1kg/y)
Human Health and Biological Interaction	Toxicity (1)	Size Distribution Bulk Mineralogy Abrasion Glass Composition Electrostatic Charging Hardness Agglutinates with Nanophase Iron	Bulk Composition Shape Bulk Density Magnetic Properties Surface Reactivity	150kg (35kg/2y)
	Toxicity (2)	Size Distribution Surface Area Bulk Chemistry Magnetic Properties Agglutinates Reactivity / Surface Reactivity	Shape Glass Composition Bulk Mineralogy Implanted Solar Particles	50kg (15kg/3y)
	Water Filtration	Particle Size Distribution Absorptivity Shape Porosity	Bulk Composition Particle Density Bulk Density Permeability	1000kg

		Surface Area Bulk Chemistry Reactivity / Surface Reactivity Agglutinates with Nanophase Iron Bulk Mineralogy Friability	Glass Composition Soil Texture Fracture Behavior	
	Mineral bio-availability	Size Distribution Bulk Mineralogy Bulk Chemistry Bulk Composition Glass Composition Bulk Density Particle Size Distribution Friability	Surface Area Shape Magnetic Properties Implanted Solar Particles Surface Reactivity Agglutinates Nanophase Iron Absorptivity	200kg each of three sieve sizes : (<50um), (<1mm) and (<5mm).
Mobility	Bearings and Seals Testing (1)	Size Distribution Particle Density Bulk Density Surface Area Compressive Strength Shear Strength Angle of Repose Bulk Mineralogy	Bulk Composition Abrasion Bulk Mineralogy Bulk Chemistry Coefficient of Friction Tensile Strength Friability Fracture Behavior	90,000kg (26,000kg/3y)
	Bearings and Seals Testing (2)	Size Distribution Hardness Bulk Chemistry Friability Bulk Density Shear Strength Tensile Strength	Shape Coefficient of Friction Bulk Mineralogy Abrasion Surface Area Compressive Strength	50kg (5kg/1y)
	Bearings and Seals Testing (3)	Bulk Composition Electrostatic Properties Shape Hardness Coefficient of Friction Bulk Density Compressive Strength Tensile Strength	Bulk Mineralogy Size Distribution Abrasion Soil Texture Friability Surface Area Shear Strength	50kg
	EVA Power, Communications, Avionics, and Informatics	Size Distribution Absorptivity Abrasion Conductivity Permeability Reflectivity Hardness Magnetic Properties Surface Reactivity	Bulk Mineralogy Shape Hardness Thermal Properties Grain Size Glass composition Coefficient of Friction Electrostatic Charging	300kg (60kg/2y)

Power	Nuclear Housing	Size Distribution Particle Density Bulk Density Conductivity Bulk Chemistry Magnetic Properties	Bulk Composition Shape Density Thermal Properties Compressive Strength Electrostatic Charging	5,000kg
Simulant Design	All Techniques	All Properties Available		20kg (3kg/3y, 1 location)
Habitat Design	Environmental Monitoring (1)	Dust-Size Distribution Absorptivity Particle Density Abrasion Bulk Density Conductivity Permeability Reflectivity Magnetic Properties Reactivity/Surface Reactivity Modal Mineralogy Agglutinates with Nanophase Iron	Bulk Composition Hue Shape Emissivity Hardness Thermal Properties Size Distribution Bulk Chemistry Electrostatic Charging	40kg
	Environmental Monitoring (2)	Size Distribution Shape Reflectivity	Absorptivity Emissivity	30kg (3kg/1y)
	Environmental Monitoring (3)	Size Distribution Bulk Mineralogy Particle Density Abrasion Conductivity Surface Area Magnetic Properties Agglutinates with Nanophase Iron Surface reactivity	Bulk Composition Absorptivity Shape Bulk Density Reflectivity Bulk Chemistry Electrostatic Charging	(0.1kg/1y)
	Airlock	Size Distribution Bulk Composition Particle Density Angle of Repose Electrostatic Properties	Shape Hue Soil Texture Abrasion	(18kg/3y – estimates made for single, not multiple, tests)
	Building Materials	Size Distribution Particle Density Emissivity Conductivity Permeability Surface Area Bulk Chemistry Rheology	Bulk Composition Shape Bulk Density Thermal Properties Reflectivity Glass Composition Soil Texture Bulk Mineralogy	100kg (29kg/3y)

		Modal Mineralogy Reactivity / Surface Reactivity Agglutinates with Nanophase Iron	
	Roads	Size Distribution Absorptivity Shape Emissivity Hardness Porosity Permeability Surface Area Glass Composition Soil Texture Coefficient of Friction Rheology Fracture Behavior Agglutinates with Nanophase Iron Bulk Mineralogy Particle Density Abrasion Bulk Density Conductivity Thermal Properties Reflectivity Friability Bulk Chemistry Compressive Strength Shear Strength Angle of Repose	(8000kg/3y)
Science	Penetrometers	Size Distribution Shape Bulk Density Hardness Compressive Strength Shear Strength Angle of Repose Impact Resistance Particle Density Abrasion Porosity Soil Texture Coefficient of Friction Tensile Strength Fracture Behavior Friability	10,000kg

The important characteristics are what the user defined as something that could influence their results. The Characteristics are those to be considered when recommending simulant. Note that the estimated quantities are for 10 years with uninterrupted research and consistent need (and are guesstimates). Some of these amounts are unlikely with any single unrepeated project. Hence, in parentheses, is the estimated quantity over a specific time of a study.

<u>APPENDIX 7.</u> What capabilities presently exist to produce Lunar Simulants

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1. **Things we have demonstrated we can reproduce**
   - **1.1. Agglutinates**
   - **1.2. Mono-mineralic particles with the correct mineralogy**. Minerals we have used are:
     - 1.2.1. Plagioclase up to An_{82} (natural, synthetic is higher)
     - 1.2.2. Orthopyroxene
     - 1.2.3. Clinopyroxene
     - 1.2.4. Olivine
     - 1.2.5. Ilmenite (contains Fe_2O_3)
     - 1.2.6. F-Apatite
     - 1.2.7. Pyrite
     - 1.2.8. Spinel
   - **1.3.** Particle size distributions between ~5 µm and 5 mm.
   - **1.4.** Synthesis of
     - 1.4.1. High Ca plagioclase An_{95} and An_{100}. (but contains trace contaminants)
     - 1.4.2. Pyroxenes (but contains minor contaminants)
     - 1.4.3. Glasses
     - 1.4.4. Breccias
     - 1.4.5. Whitlockite (commercial)
     - 1.4.6. Ilmenite
   - **1.5.** Compositional range covering anorthosite to basalt
2. **Things we probably can reproduce, but have not proven it**
   - **2.1.** Glass beads, smaller is probably harder. Very small may be very hard.
   - **2.2.** Particle size distributions outside ~5 µm and 5 mm.
   - **2.3.** Simulants with <0.1 LOI in quantities greater than a few kilograms.
3. **Things we currently can not reproduce**
   - **3.1.** Textures within particles other than agglutinates
   - **3.2.** Vapor deposited rims
   - **3.3.** Trace element patterns (containing phases, abundance either absolute or relative)
   - **3.4.** Much of the minor and most of the trace mineralogy
   - **3.5.** Shocked nature of the particles
   - **3.6.** Ratio of ortho/clino is not within control
   - **3.7.** Some nuances of specific mineralogy, such as high Fe feldspars.
4. **Things we don't know if we can reproduce due to a lack of data**
   - **4.1.** Particle shapes and shape distributions
   - **4.2.** Any relationship between particle size or shape and composition