CAPTEM-LEAG ANALYSIS DOCUMENT

Review of Sample Acquisition and Curation During Lunar Surface Activities.

September 1, 2010

This report was prepared by the members of the Lunar Sample Acquisition and Curation Review Group that was organized by the Lunar Exploration Working Group (LEAG) and the Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM):

- **Charles Shearer**, University of New Mexico, Co-chair (former chair CAPTEM)
- **Clive Neal,** University of Notre Dame, Co-chair (chair LEAG)
- **Lou Allamandola**, Ames Research Center
- **Jacob Bleacher**, Goddard Space Flight Center
- **Jesse Buffington**, Johnson Space Center
- **Simon Clemett**, Johnson Space Center
- **Dean Eppler**, Johnson Space Center
- **Fred Hörz**, Jacobs Technology
- **Lindsay Keller**, Johnson Space Center
- **Sarah Noble**, Marshall Space Flight Center
- **Dimitri Papanastassiou**, Jet Propulsion Lab
- **Scott Sandford,** Ames Research Center
- **Allan Treiman**, Lunar and Planetary Institute

Ex officio

- **Marilyn Lindstrom,** NASA Headquarters
- **Carlton Allen,** Johnson Space Center
- **Gary Lofgren,** Johnson Space Center
- **Karen McNamara,** Johnson Space Center

Contributors

- **Judith Alton,** Johnson Space Center
- **Mary Sue Bell,** Johnson Space Center
- **Cindy Evans,** Johnson Space Center
- **John Gruener,** Johnson Space Center

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Section 1. Executive Summary

The exploration of the Moon that climaxed with Apollo resulted in a paradigm shift in not only our understanding of the Moon but in our scientific appreciation of fundamental processes at work in the solar system. The collection and return of lunar samples was critical to this immense intellectual step. As we look forward to a new period of lunar exploration, the importance of samples looms even larger. This importance is tied to three concepts: (1) Apollo explored and sampled a small, near-side, equatorial area of the Moon and, therefore, our understanding of the Earth-Moon system is incomplete, (2) Sample analysis in terrestrial labs provides a unique perspective unavailable using other exploration tools, and (3) The symbiotic relationship among orbital, surface in situ, and sample observations is invaluable for the exploration-habitation of the Moon and feeds forward to the exploration of the solar system.

A CAPTEM-LEAG team reviewed the guiding principles for the acquisition and curation of samples during future human lunar surface activities. This review included: (1) The implications of sample acquisition, preservation, return, and curation on critical engineering requirements for Constellation or any other follow-on design for exploration of the Moon or other planetary body, (2) The need for sample documentation, acquisition, packaging, preservation and contamination control at all stages, (3) Usefulness of field analysis in sample selection, (4) sample acquisition tools and protocols, (5) Curation, analysis and "high-grading" at the Moon, (6) Training levels for astronauts and scientists, and (7) Curation requirements and required facilities on Earth.

This document identifies 58 findings tied to the acquisition and curation of samples during lunar surface activities. An additional 25 findings are tied to curation on Earth of extraterrestrial materials. These findings should be implemented during various stages of the future architecture designed to transport humans to the Moon and beyond. Findings that are relevant to the earliest stages of development of such an architecture are:

(1) The architecture should be able to accommodate a return mass of 250 to 300 kg of geological samples and sample containers (per mission). A volume of 0.10-0.12 m^3 is required per 100 kg of lunar samples.

(2) Relevant to accommodating this sample volume in the architecture is the usefulness of soft containers to return lunar samples. A hard Apollo-type “rock-box” is inefficient at packing samples, increases the volume needed per 100 kg of sample mass, and is inflexible in storage.

(3) Contamination of lunar samples has many potential sources and could be introduced through many processes and activities. Therefore, there is a need to establish programmatically acceptable guidelines for general materials selection and control protocols for specific manufacturing and surface finishing processes.

(4) A joint advisory committee consisting of both science and engineering community stakeholders is required to facilitate communication and formal decision making that is required to maintain and enforce the standards established in recommendation 3 (above).

(5) For all science involving thermally sensitive samples (geology, planetary science, biology) refrigeration units must be accommodated within the returning space craft and the outpost. Cryofreezers providing a level of capability similar to GLACIER, developed for the ISS, are representative of the capacity and level of thermal control required.

(6) The scientific exploration of the Moon and associated sampling mandate efficient transfer of voice, navigation, imagery and analytical instrument data from the surface to the ground and vice versa. These needs have detailed implications for the Communication Architecture.

(7) Reducing sample return mass by "high-grading" samples on the lunar surface that is based on scientific criteria requires well-trained astronauts and key analytical instruments. The former requires well thought out astronaut selection and training, while the latter dictates power requirements for sortie and outpost operations.

Section 2. Introduction

2.1 Preface to the analysis

One of the intents of the charter for this analysis was to provide insights into the impact of sample acquisition, preservation, return, and curation on critical engineering requirements for the Constellation Program and future lunar surface operations. Near the end of this analysis, the Constellation program was canceled. Throughout the text of this document the relevance of the findings are often placed within the context of the Constellation Program as requested by our charter. However, all of the findings are critical to any manned exploration program which has the goal of returning to the Moon. In addition, many of these finding are highly relevant to the design and operation of manned exploration of the surface of other planetary bodies. This includes Near Earth Objects and Mars.

2.2 Importance of lunar samples

The level of understanding the Moon prior to the Apollo Program is perhaps best depicted in a lament attributed to J.J. Cook in 1967 only two years prior to Apollo and quoted by S.R. Taylor (1975): "No conclusions can be drawn (about the Moon) other than that the interpretation of the existing experimental data leads to many ambiguities". The exploration of the Moon that climaxed with the Apollo Program resulted in a paradigm shift in not only our understanding of the Moon but in our scientific perception of fundamental processes at work in the solar system and in the view of our place in the solar system. Critical to this immense intellectual step forward was the collection of lunar samples. As we look forward to a new period of lunar exploration, what is the importance of samples in future lunar surface activities by humans? The importance of samples is illustrated by three key concepts: (1) Apollo explored and sampled only a relatively small area of the Moon and, therefore, the understanding of the Earth-Moon system given to us by Apollo is incomplete, (2) Return of samples for analysis in terrestrial labs provide a unique perspective unavailable by any other exploration method, and (3) The symbiotic relationship among sample, surface, and orbital observations aids the exploration-habitation of the Moon and feeds forward to the exploration of the solar system.

Our current knowledge of the Moon indicates that its surface terrain is geologically diverse (Figure 1). The Apollo Program only explored and sampled a limited region facing the Earth. Therefore, our scientific knowledge of the Moon, and by extrapolation the early Earth and the solar system, is biased by this limited perspective.

The unique planetary perspectives based on lunar samples returned to Earth have a strong symbiotic relationship to orbital and surface observations/measurements. This unique perspective is closely tied to the use of terrestrial laboratories that have capabilities exceeding those of instrumentation currently associated with spacecraft surface (i.e., in situ) measurements. The terrestrial labs provide higher analytical accuracy and precision, afford a higher degree of spatial resolution (to angstroms), offer a high degree of

sample manipulation, and facilitate multiple analytical approaches. These analytical attributes result in copious contrasts between sample return missions and other types of missions: (1) The best instruments can be used to analyze returned samples, not the best available at the end of mission design reviews.

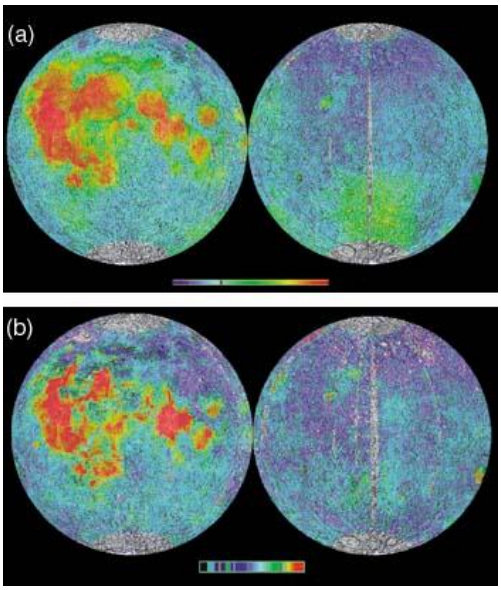


Figure 1. The crustal heterogeneity of the Moon is illustrated in (a) iron and (b) titanium maps of the nearside and farside of the Moon. The Apollo Program sampled only a small portion of this exposed terrane. Maps constructed from data derived from the Clementine mission. The highest concentrations are shown in red and the lowest concentrations are shown in blue.

(2) Instrumentation is not limited by mass, power, reliability, data rate, the requirement to work autonomously, etc. This results in much lower cost to do an analysis**.** (3) Analyses are iterative and not limited by preconceived ideas at the time of the mission design. (4) Unexpected or ambiguous result can be tested with additional measurements or modified experiments. A new mission is not required to retest results. (5) The diagnosis of analytical instrument technical problems and instrument repair can be better facilitated in a terrestrial lab, (6) The ability to modify experiments as scientific problems and technology evolve over an extended period of time. (7) "Samples are the gift that keep giving" to future generations of planetary scientists. (8) Large numbers of scientists can *usefully* participate. This includes not only scientists involved in sample measurements, but also scientists who will place these data into a planetary context using orbital and surface measurements, and conversely the sample data will add value to the orbital and surface in situ measurements by providing a greater measure of ground truth. The end result of all of these positive attributes of sample analysis and

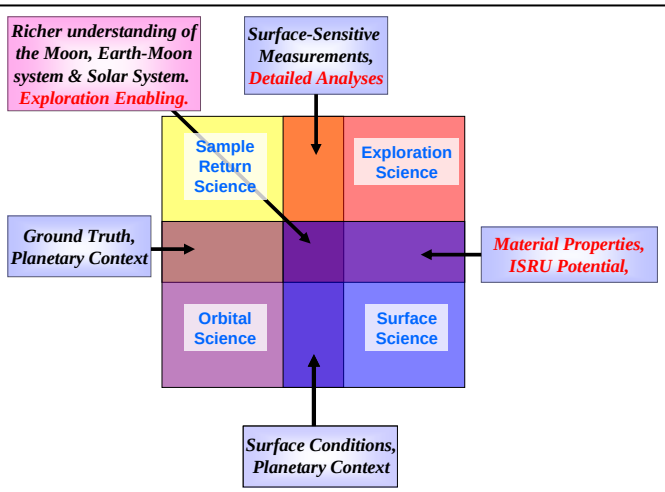


Figure 2. Overlapping relationships among sample return science, exploration science, orbital science, and surface science.

sample return missions is in a large science return and the establishment of a firm foundation, on which to base other sample return and non-sample return missions. For example, the Moon is the best understood extra-terrestrial object because of the samples returned by the Apollo Program and the planetary-scale context in which these samples could be placed through both orbital and surface observations**.** Numerous examples of the usefulness of samples in studying a planetary body and the importance of placing the samples with a planetary context are contained in "New Views of the Moon" (Jolliff et al., 2006).

The symbiotic relationships among sample return, orbital, surface, and exploration science enriches the data collected by any single approach and affirms that the integration of these approaches provides a logical and balanced scientific approach to exploring the Moon (Figure 2). Samples from the Moon's surface provide ground truth for orbital data, while orbital data allow samples from a local area to be placed into a regional and even planetary context. Establishing a lunar chronology from samples allows calibration of crater counting on the surface of the Moon and other planetary surfaces. Surface material derived from a planetary interior (through volcanism or impact processes) can be inverted to interpret surface geophysical measurements, whereas surface measurements made by geophysical networks place the sample data within a context of planetary structure and dynamics. Finally, samples provide an initial foundation for understanding the in situ resource utilization potential and health hazards for human exploration of a planetary surface, while in situ measurements of mechanical properties of materials in a planet's environment will provide insights into their behavior during exploration and utilization.

As with the Apollo Program, sample acquisition and curation will be an important human activity during future surface exploration. Since the Apollo Program, technologies have evolved that will make surface activities on the Moon more efficient and insightful. Further, Apollo provided a outstanding point of reference to continue the exploration of the Moon. The intent of this review is to integrate lessons learned from Apollo with new scientific and technological advancements to define surface activities tied to sampling the Moon and the impact of these activities on the Constellation architecture.

2.3 Charter for the CAPTEM-LEAG LSAC Review

2.3.1 Background

The NASA Science Mission Directorate, in coordination with the Optimizing Science and Exploration Working Group (OSEWG) requested that CAPTEM and LEAG jointly conduct an end-to-end review of sample acquisition and curation during the next stage of human exploration of the Moon (APPENDIX I). This should address all aspects of curation recommended by the NAC (S-07-C-9) and the NRC (Recommendation 4R) as well has assisting with the definition of scientific requirements needed by engineers designing spacecraft and missions and future government or commercial activities related to lunar resource recovery and use.

The NAC recommended (NAC S-07-C-9 Sample Collection, Documentation, Containment and Curation) that NASA should:

(1) Establish well-defined protocols for collection, documentation, containment, return and curation of lunar samples;
(2) Collect lunar samples of various types and purposes with maximum diversity of location and required *in situ* documentation;
(3) Optimize scientific return while protecting sample integrity.

The NRC recommended (4R Updating Lunar Sample Collection Techniques and Curation Capabilities) that NASA should:

(1) Conduct a thorough review of all aspects of curation;
(2) Take into account differences in sortie and outpost mission approaches;
(3) Consider documentation, collection, curation on Moon and in facilities and laboratories on Earth;
(4) Enlist broad scientific input with CAPTEM and LEAG to assist the review.

2.3.2 Charter

The charter for this review is located in APPENDIX II. In the charter, CAPTEM and LEAG, jointly, are requested to review lunar sample acquisition, curation and the potential distribution for scientific studies, with consideration including, but not limited to the following:

(1) The impact of sample acquisition, preservation, return, and curation on critical engineering requirements for Constellation and future lunar operations.
(2) Sample preservation and contamination control at all stages.
(3) Sample documentation, acquisition, and packaging at all stages.
(4) Potential for and advantages of field analysis in sample selection, including technologies needed.
(5) Scientific value of integrated investigations of a variety of different sample types.
(6) Sample acquisition techniques, tools, procedures, photography and description, including hand samples, regolith, drill core, and volatile-rich samples.
(7) Sample curation and analysis on the Moon including selective sample size and quantity reduction prior to return to Earth.
(8) Sample transfer from spacecraft to curatorial facilities at Earth.
(9) Sample curation, shipment, and investigator handling requirements at Earth.

2.3.3 Report

The need for samples that will meet scientific requirements to support Constellation and future engineering development challenges, including lunar resource acquisition, are to receive special emphasis in this review. Given that activities on the Moon can impact curation at Earth, a preliminary report on the review of activities conducted on the Moon will be completed in one year from January 1, 2009, with the final report that includes review of curation at Earth to be completed within 18 months (June 30, 2010). In addition to the specific items listed above, the final report will include discussion and recommendations on the following more general topics:

(1) Contamination prevention and packaging requirements;
(2) Definition of mass, volume, power, communications, crew time, crew skills, and flight control requirements for curation on the Moon and return to Earth (noting differences between a sortie mission and an outpost);

(3) Assessment of differing degrees of *in situ* or laboratory sample analysis on the Moon and associated equipment, technology, skill, training, and professional experience needs;
(4) Protocols for collection, documentation, analysis, and curation on the Moon;
(5) Definition of existing, new or modified capabilities and techniques for curation at Earth, including the required skilled personnel.

2.4 Approaches to the Review

The first organizational meeting of the LSACR was held at the LPI on October 15, 2008 to define its charter and discuss possible membership. During the 2008 annual LEAG meeting (October 28, 2008), co-chairs of the LSACR meet with OSEWG co-chairs and members to further discuss the role of LSACR and its charter. The organizational teleconference was held on December 9, 2008. Teleconferences were held approximately every month until mid-June. The work product of each teleconference was clearly spelled out prior to each meeting and products were assembled into powerpoint charts. The review group met at the Lunar and Planetary Institute for a total of 6 days during January 2009, June 2009, and January 2010. APPENDIX III contains the agendas of those two meetings. During teleconferences and meetings, additional experts were invited to provide input into the review process.

This analysis was conducted in the following stages:

Phase 1:

(1) Contamination prevention and packaging requirements;

(2) Definition of mass, volume, power, communications, crew time, crew skills, and flight control requirements for curation on the Moon and return to Earth (noting differences between a sortie mission and an outpost);

(3) Assessment of differing degrees of *in situ* or laboratory sample analysis on the Moon and associated equipment, technology, skill, training, and professional experience needs;

(4) Protocols for collection, documentation, analysis, and curation on the Moon and on Earth;

Phase 2:

(1) Definition of existing, new or modified facilities, capabilities and techniques for curation on Earth, including the required personnel skills.

The results of Phase 1 and 2 are included with this single whitepaper.

2.5 Assumptions of the Review

2.5.1 Introduction

The review has several assumptions tied to the general Constellation architecture presented to the review group in January 2009. These assumptions are broken down into Sortie and Outpost assumptions. In most cases, slight deviations in these assumptions due to the evolving Constellation architecture will not significantly change our recommendations or findings.

2.5.2 Sortie Missions

This review made the following assumptions concerning the nature of sortie missions to the lunar surface:

(1) Seven days on the ground, with crew EVAs on Days 2, 3, 5 & 6, with a potential additional EVA on Day 4 if crew and ground operations personnel agree.

(2) Two rovers are available during sortie missions.

(3) Four crew members are on the lunar surface and organized in teams of two.

(4) Total traverse time is equal to 8 hours per crew member per day during the 4 days of EVA.

(5) There are no science assets within the lander to do analysis. This review does consider the potential of simple field instruments that can be used by astronauts during EVA for sample selection and "high-grading".

2.5.3 Outpost operations:

(1) Four crew members per increment with increments initially from 14 days evolving to 180 days.

(2) Exploration traverses will initially be short excursions up to 3 days, evolving to a mix of 14 day-2 pressurized rover excursions intermixed with shorter 3 day excursions

(3) Outpost facility to have the capability to perform first order sample examination in the habitat. This capability could evolve during the life-time of the habitat. Crewmembers will work shirt sleeve, although the samples will be in a glove box or other environment to minimize contamination.

(4) EVA per crewmember will be 24 hours every week; it is expected that 2 person teams will go out every other day, dovetailed with their counterpart crewmembers to give 2 person EVAs every day.

(5) Availability of small pressurized rovers will allow the radius of exploration to evolve eventually to a 500 km radius

2.6 Outline of white paper

This white paper follows the outline:

(Section 3.0) Requirements for lunar sample acquisition and curation on the lunar surface. Themes discussed in this section include ***Sample Acquisition Tool Requirements, Instrumentation Requirements, Sample Packaging and Preservation Requirements, Sample Contamination Control Requirements***, ***Sample Mass and Volume Requirements***, ***Power Requirements for Sample Acquisition and Curation, Crew Requirements for Sample Acquisition and Curation,*** and ***Communication and Flight Control Requirements.*** Each theme portion is divided into: Lessons learned from the Apollo Program, Advancements since the Apollo Program, Capabilities for sampling the lunar surface, Specific engineering recommendations and Analyses required prior to establishing recommendations.

(Section 4.0) Protocols for Sampling and Curation within the context of Sortie missions and Outpost operations.

(Section 5.0) Lunar Sample Curation on Earth.

(Section 6.0) Summary of Recommendations and Findings.

(Section 7.0) References

(Section 8.0) Appendices that include detailed calculations and discussions and additional organizational documentation.

Section 3. Requirements for Lunar Sample Acquisition and Curation on the Lunar Surface.

3.1 Sample Acquisition Tool Requirements

3.1.1 Lessons Learned from the Apollo Program

Over the course of NASA's manned space program, EVA tools have been present since the first US EVA conducted by Ed White on Gemini IV. The majority of the early EVA tools were to aid the task of the EVA. In the Apollo Program, a dramatic increase in scientifically oriented EVA tools and equipment was seen, including both crew-actuated sample acquisition devices and crew deployed science packages. The Apollo Program used an array of field geology style tools for sample acquisition (Allton, 1989). These tools included items such as the Geology pick/hammers, manual & power core samplers, trenching tool, rakes, tongs, and the gnomon photo reference device. These tools evolved during the Apollo Program in response to surface activities and they provide, in combination with gained knowledge of the mechanical properties of the lunar surface and samples, a foundation for the engineering design of tools for future lunar exploration by humans.

The tools used during Apollo were deployed and operated with varying degrees of success in the lunar environment. The dusty environment of the Moon affected the ability to quickly assemble or exchange removable tool heads. The Apollo 17 mission hinted at the potential difficulty to systematically and efficiently collect samples from large boulders such as Tracy's rock at Station 6 at the Apollo 17 landing site (or presumably from outcrops). The more successful tools included the rake, tongs, trenching tools, and the geologic pick/hammer. Additionally, several of the Apollo missions illustrated the usefulness of collecting samples by coring as well as the potential pitfalls (decreased efficiency, contamination, core extraction issues revealed during curation). Finally, the Gnomon photo reference device provided important information, yet it was clumsy to set up and substantially decreased the efficiency of surface operations. The information the Gnomon provided is doubtless important to future surface exploration efforts, but updated technology may provide a more efficient alternative.

Beyond specific individual tools, an overarching Apollo lesson is that communication is critical between the science community (as the end users of the acquired samples) and the engineering community (as the sample acquisition hardware provider) is paramount. This statement will be reiterated and expanded upon in the "Specific Engineering Requirements" section as well as promulgated in the primary

"findings". The need for this coordination is demonstrated in that the majority of issues identified by the science community were not "failure to function" type events wherein hardware failed to acquire samples but that several Manufacturing & Processing (M&P) disconnects occurred wherein sampling tools contained materials or came into contact with processes that inadvertently contaminated the samples and were not identified until the samples were returned to Earth for detailed analysis and curation. At this point many of the specific science questions to be addressed by these samples were compromised and were re-oriented for alternative topics of investigation.

Physical actuation of equipment and "failure to function" type issues will certainly be concerns for hardware designers providing lunar sample acquisition and curation tools and equipment for the Constellation Program. However, as in Apollo, the expectation is that many of these issues will be successfully identified and resolved through design verification and validation tests conducted in support of certification. This leaves the community with the challenge to learn from the disconnects of the past and impose proper contamination control requirements (especially M&P constraints) in such a way as to improve upon the success of the Apollo Program.

3.1.2 Improvements since the Apollo Program

During the Space Shuttle and the International Space Station Programs, EVA Tools have been developed for a tremendously wide and varied array of needs. Most of these needs were of the engineering/construction genre. Throughout these programs, a tremendous knowledge base has been developed to support the task of identifying the function (requirements) of each "tool" and certifying these tools to meet said requirements. However, these tools have been developed in the dust free micro gravity environment of Low Earth Orbit (LEO). Thus, there must be a merging of contemporary design and analysis methods with lessons learned from Apollo. It is our recommendation that the engineering community seek collaboration with lunar soil mechanical experts and with scientists knowledgeable about lunar sample collection goals and handling challenges on the Moon early in the concept evaluation and development phases to facilitate this merging.

Ultimately, the goal of a hardware provider in any program is to supply a solution that meets all requirements within scope, schedule and budget constraints. For EVA Tools, "certification" is the act of verifying the particular design capability to meet the previously described requirements and hence provide certainty and confidence that it will fulfill its function and thereby contribute to mission success. This has perhaps been the area of the most development since the Apollo Program in that theoretical time to a given design solution has been reduced with the aid of computer based design, modeling and advanced analysis (thermal, stress, etc.) as well as progress in management of project lifecycle models. However, the major cost of a given piece of flight hardware is still in the validation phase (as in the Apollo Program) due to testing and documentation costs. Even with advanced analytical techniques developed with input from

several decades of experience in LEO, a certain subset of hardware qualification and acceptance testing is still required and cannot be deleted from the certification process .

Additionally, existing program level requirements for contribution limits to Probability Risk Assessments (PRA's) drive stringent Configuration Management (CM) practices. The practices facilitate Safety and Mission Assurance oversight that are critical to mission success but may offset the schedule advances made with updated design and analysis methods. The result is that a much, much deeper understanding of the hardware capability and "as built" configuration will be available but at a zero sum gain in terms of time to certification and delivery as compared to Apollo era development projects.

The previously mentioned knowledge base has correspondingly led to an evolving process followed for designing, developing, testing and certifying an EVA Tool. In the context of the Shuttle Program and ISS assembly, the EVA community has implemented a system for Government Furnished Equipment (GFE) whereby common or "generic" requirements that apply to all EVA Tools are cataloged in what is aptly called the "Generic Design Requirements Document" or GDRD (JSC26626A). The GDRD is thus a place where unchanging parameters that impact design (such as environmental factors or crew interface needs) are held and levied against every piece of hardware. It is also a place where some fundamentally important "lessons learned" are also captured, leading to requirements that drive design from a "best practice" standpoint. It should be noted that there is a separate but very similar document for Contractor Furnished Equipment (CFE) that acts as a similar vehicle. This document is JSC28918, but for the purposes of this discussion the GDRD will be referenced as the illustration. Additionally, as of the writing of this document work is underway to release the first revision to the Constellation Program equivalent of these Shuttle/ISS documents, entitled the "Constellation EVA Design and Construction Specification" (EVA D&C, CxP 70130). This document derives many engineering requirements for EVA hardware designs from the GDRD and JSC28918 and is being used as the mechanism to communicate requirements across the Constellation Program.

In practice, unique situations require unique tools and pose unique requirements of a given task. Efforts are commonly made to "delta certify" a given tool for a new purpose if the newly defined unique requirements can be met by a pre-existing design solution, which depends on the compromise between modifying a given existing design or simply starting from scratch. Thus, we see that "unique requirements" are the drivers for the complexity of design beyond what is minimally required by system-wide "generic requirements". With this approach of cataloguing generic requirements applicable to all tools used in a specific environment at hand, we can consider a similar method of requirements decomposition for a sampling system.

3.1.3 Developing capabilities for sampling the lunar surface

The set of tools required for sample acquisition must have the capability to acquire a broad range of sample types (i.e. regolith from varying depths, rocks, chips and fragments off of boulders-outcrops) in a fairly efficient manner within well-defined contamination control restrictions. Further, as with Apollo, we anticipate that tool design will be responsive to both astronauts using the tools, sample curators, and the science community. We anticipate that tools used during surface operations for sortie missions and outpost operations should be similar in capability, utilization, and material. Therefore, discussion under this section will be applicable to both styles of surface operations.

When considering the generation of requirements outlining the features and capabilities necessary to enable lunar sample acquisition and curation, the fundamental task for the hardware provider is to understand the practical issues of handling samples and the needs of the science community with regards to minimum contamination. At an engineering level, the challenge is then to identify the unique requirements derived from the goal of the sample acquisition and curation tasks required of a given tool or device and then meet those specific requirements along with the generic requirements also levied on the entire system. If the generic requirements are developed *once* at an engineering level and are made applicable across the entire EVA System on all EVA Geology Tools, the process then frees the non-engineering stakeholders (i.e. science community, vehicle team, habitat project, etc) from becoming overly concerned with requirements other than those specific (unique) to their needs. The project team creating a given EVA tool must consider interplay between the generic and unique requirements but in general this method of documenting the "generic" as a standing list and the "unique" on a per device basis will streamline the development process and reduce/eliminate concerns over inadvertent sample contamination through poor materials/process selection.

It is therefore apparent that when "Science Tools" for lunar sample acquisition and curation are discussed there are several sources from which requirements will come from, and they can be grouped into "generic" and "unique". The generic will be well developed and understood as they are applicable to all EVA certified science devices, regardless of task, and the stakeholder needing the tool must then only focus on communicating the special needs a given device must fulfill. <u>This is where the heart of the challenge and opportunity for collaboration exists between the engineering team developing and certifying the hardware solution and the science stakeholder driving the design</u>. The engineering team must understand the overall vision of what the tool or device needs to do and not do and then aid in translating these requirements into verifiable "shall statements" that a design can be tested, analyzed, or in some other acceptable means verified to meet.

Thus, what we have done is to bracket the known genres of requirements that would not be defined in a generic requirements document at present and use that as a blueprint by which to guide future efforts as sample acquisition/curation goals are finalized. This will provide a matrix by which to check off genres

of requirements as either applicable or non-applicable to a science package, leaving behind a punch-list of unique requirements to flesh out into solid, verifiable "shall" statements for a given science tool. Careful review of this matrix will undoubtedly reveal that some certain subset of these genres are applicable to almost every EVA Science Tool, thereby leading the community to a first order list of topics for a "Science Hardware GDRD". Regardless, this section will establish this list of unique genres, the culmination represented in a sample worksheet as shown in APPENDIX IV. Ultimately it is intended that this sample worksheet and rationale form would be implemented in order to facilitate communication between all stakeholders as EVA Tools and Equipment for lunar sample acquisition and curation in the Constellation Program are developed.

The successes and challenges of tools during the Apollo Program provide critical insights into sampling tool capabilities for lunar surface activities. First, it is important that a baseline kit of tools be developed that are useful for both sortie and outpost style missions. This dual mission purpose for the baseline tool set will decrease training time and increase efficiency of surface activities.

3.1.4 Specific Engineering Recommendations

Disconnects between science community stakeholders and engineering hardware solution providers occurred during the Apollo Program that, while not resulting in "Loss of Mission" events negatively impacted some lunar samples' viability. Such disconnects can be prevented and/or overcome by communication between the two parties. At a fundamental level, several specific recommendations are made to leverage the lessons learned from the Apollo Program, and advancements since, while addressing these disconnects:

(1) M&P concerns are paramount in sampling activities and dictate that a strict program of stock/process material sample coupon curation must be implemented. This is critical as launch/return mass limitations will most likely dictate that the majority of sampling tools will never return to Earth from the lunar surface. After-the-fact questions and concerns about pre-flight contamination cannot be addressed without retaining samples of stock material or process products indefinitely. This implies that a secondary curation protocol and facility be established to maintain the recommended stock samples.

(2) Establishment of a standard process for documentation and communication of any uniquely derived science requirements levied against hardware design should be executed and requirements found to be common across the majority of hardware in the sampling system should be captured as "Generic Geology Hardware Requirements". As illustrated by disconnects in the Apollo Program, communication is paramount to reducing inadvertent sample contamination through uninformed design decisions, and tracking, application and verification of these two bodies of requirements will facilitate this communication.

(3) Establishment of a convening body possessing authority and scientific/technical insight to oversee and decide integration issues between science community stakeholders and engineering hardware solution providers should be executed to support development of the "Sample Collection System". This is important as recommendations 1 and 2 will be difficult if not impossible to implement without a parent body under which they are enacted and sustained. Cognizance of the overall approach and methodology towards these goals must be continuous and intentional and cannot be maintained without an authoritative body governing their execution.

3.1.5 Analyses required prior to establishing recommendations

The Apollo Program illustrated a number of tools that functioned well in the lunar environment with limited sample contamination. Potential refinements of these otherwise successful designs could reasonably start with an effort to reduce sample system mass, especially focusing on components that provide logistics support such as tool management and stowage. Since the Apollo Program a number of composite materials have been developed, and these materials may provide important mass savings. However, there may be issues of sample contamination due to non-metallics in these composite materials and their stability in the harsh lunar environment. Within the context of the above engineering recommendations, it is important to assess the contamination potential of composite materials prior to their use in geologic sample system hardware.

Findings:

(1). A joint forum between science and engineering community stakeholders is required to facilitate communication and formal decision making events to achieve elimination of disconnects that will lead to sample contamination and decrease in the efficiency of sampling activities. The forum must be delegated authority to oversee the "Sample Collection System" for acceptability and compliance with requirements levied against sample acquisition and curation hardware where contamination issues are concerned.

(2) New materials for sampling tools should be tested and evaluated within the context of Finding 1, prior to implementation in any future sampling system.

(3) A baseline collection of tools should be developed that are common for both sortie and outpost style missions. This will decrease training time and increase efficiency of surface activities.

(4) The Apollo Program provided insights into tools that worked well in the lunar environment. These included the rake, tongs, trenching tools, and hammer. Developing the capability to easily exchange tool heads in a dusty environment would decrease tool mass but must be done with the increased cycle life of outpost missions in mind.

(5) The Apollo Program illustrated the usefulness of collecting samples by coring. The close integration of the core sample and the coring device require strong coordination for the end to end lifecycle of the device, with intentional effort levied on designing for post-return curation activities.

(6) The Gnomon photo reference device provided important information in photo documentation, yet it substantially decreased the efficiency of surface operations. The development of an alternative device is important.

(7) A distinction must be made between tools on which astronaut survival depends and tools used solely for sample handling and science. Requirements on the latter should be less restrictive. This should allow for some more experimentation with tool design, without breaking the bank.

3.2 Analytical Instrumentation Requirements for Sample Acquisition and Curation

3.2.1 Introduction

There are numerous differences between the Apollo Program and future human surface activities that will require additional information-observations in selecting samples during sortie missions and outpost activities. Due to Apollo and subsequent missions our scientific understanding of the Moon is much more sophisticated than it was prior to the Apollo Program. Therefore, sample selection during surface activities will be, in many cases, much more focused to specific scientific problems. EVA hours during future sortie and outpost surface operations will be significantly longer than EVAs during Apollo. Based on a simple comparison between Apollo EVAs and the projected duration of surface activities during a simple 7 day sortie involving 4 astronauts, future activities have the capability to collect over 700 kg of sample (Shearer et al., 2007). Longer EVAs during sortie and outpost activities have the capability of acquiring substantially higher masses of lunar samples. This potential total mass cannot be accommodated for return to Earth by the capabilities of the Apollo architecture (~110 kg), initial sample mass capabilities proposed for the Constellation architecture (~30-40 kg) or the larger sample mass capability requirements proposed by Shearer et al. (2007) and advocated in this analysis (~250-300 kg). Therefore, additional observations that surpass the Apollo Program must be incorporated into future sample acquisition to essentially "high-grade" samples.

3.2.2 Lessons Learned from the Apollo Program

During the Apollo Program, samples were selected based on astronaut training and visual observations. Science support room discussions provided overall concepts for sample selection during EVAs, but input into the selection of specific samples was not available. Although sample collection approaches were very minimal, the Apollo Program experience provides fundamental concepts that will influence decision-making processes during future missions. First, the Apollo Program provided a working knowledge of surface operations and its linkage to the decision making process of selecting samples. Second, the Apollo Program returned a wide variety of samples that provided us with a foundation for identifying sample properties that will allow us to design appropriate instruments, which will give us the ability to better distinguish between and to select the most scientifically relevant samples. Third, the Apollo Program provided a scientific foundation upon which future sample selection decisions can be placed.

3.2.3 Improvements since the Apollo Program

There are three areas of improvements since Apollo that will aid in the development and utilization of instrumentation for the selection of samples. First, many analytical instruments have been or have the capability of being miniaturized. Second, substantial geochemical and mineralogical data exist for lunar samples. This data base can be used to design instruments that will be useful in distinguishing among

samples and selecting samples that are scientifically important. Final, with an increase in communication capabilities, the science support room (equivalent to the science back room of the Apollo Program) on Earth will be able to interpret and store analytical data. This will allow the science support room to respond to astronauts questions in real time and create a sample data base during the mission to guide sample selection and high-grading.

3.2.4 Capabilities for sampling the lunar surface

Sortie missions: There are 5 important concepts tied to the utilization of analytical instrumentation on the lunar surface for high-grading samples:

- threat of instrumentation to safety and ability to carry out efficient surface activities,
- ease of use and interpretation of data,
- threat of contamination of the sample,
- linkage of analytical data to sample macroscopic characteristics (texture, mineralogy),
- sample documentation, and ability to transfer data to the science support room,
- power requirements and capability to recharge instrumentation

The analytical instrumentation must not be burdensome during surface activities or pose a threat to astronauts safety or their ability to carry out efficient surface activities. The instrument must be of a relatively low mass, and tie rather simply into other suit subsystems. Instrumentation that is associated with the rover and works relatively independently of astronaut activities would be valuable if tied to science support room planning (i.e. multispectral panoramic imager on a rover mast). A high mass, bulky instrument will hinder surface operations, tax the astronauts as operations are carried out and ultimately provide a source of risk to the astronauts and mission. In addition to high mass and volume providing an element of risk, instrument design must consider safety as an important element. For example, poorly designed instruments with a laser or radioactive source could pose additional risk. An instrument that requires substantial time to perform an analysis (>1 minute) and/or provides complex output to the astronaut will severely slow surface operations and its use will be abandoned by the astronaut.

Instrumentation must be easy to operate and provide the astronaut with quick (~1 minute or less) and easy to interpret results. One way to fulfill the ease (to use and interpret), and quickness requirements for analytical instrumentation would be to identify fingerprint traits (chemistry, mineralogy) that would be relevant to selecting the appropriate samples. These fingerprints could be relevant to the whole Moon, a specific landing or outpost site, or to a specific scientific problem. For example, the combination of a high-resolution camera, a micro-imager and a geochemical analyzer capable of the analysis of fingerprint elements such as Th could be used to differentiate among KREEP basalts, mare basalts, and impact melt rocks at a landing site.

Rover-mounted science instruments could include devices concerned with the bulk composition of rocks and the nature of their major rock forming minerals (some multispectral instrument; the latter may even be mounted on the rover's mast to obtain a first-order "map" of specific rock-types at a given station). Instruments such as a multispectral panoramic imager on the rover's mast may allow the science support room to assist in planning an EVA and place samples within a local geologic context. The rover is also a suitable platform for the in situ measurement of lunar surface properties via, for example, a magnetometer or ground penetrating radar. Lastly, the lunar exploration rover (LER) may be used to deploy a network of diverse geophysical instruments to learn about the Moon's interior.

It is critical that the measurements-observations made on the lunar surface do not pose a contamination threat to the sample. Most megascopic- microscopic observations should not pose a threat. Potential threats could stem from extensive sample handling, extensive abrasion between sample and instrument if analysis requires analytical tool to be placed against sample, or interactions between sample and instrument source (i.e. laser, x-rays, radioactive source). Most of these concerns can be remedied with careful instrument design and training if instrument design and definition teams are made aware of these issues.

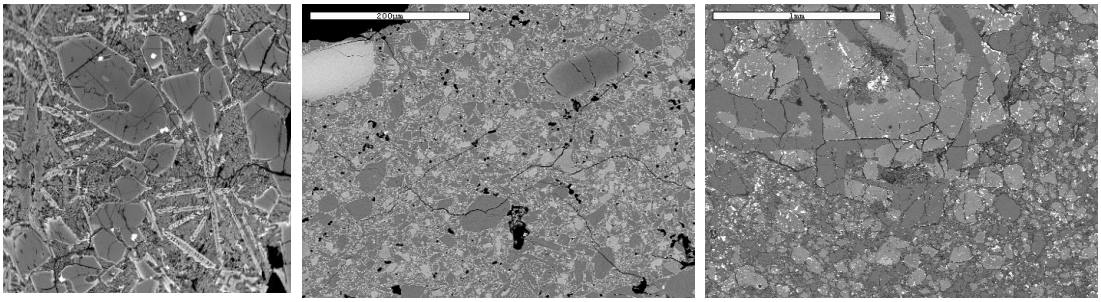


Figure 3. Three different types of lunar lithologies with similar geochemical characteristics that could be best distinguished with combined textural and geochemical observations: mare basalt, melt rock and breccia from left to right).

In most cases, chemical data combined with megascopic- microscopic observations will provide a much more powerful method for distinguishing among lunar rock-types. For example, Figure 3 illustrates that three types of lunar lithologies may have similar compositions (within the confines of selected fingerprint elements). Yet, these lithologies have substantially different origins, their "crystallization" ages reflect different processes, and they exhibit different textures. Therefore, the capability to link instrument data with sample megascopic- microscopic observations and sample documentation (field relationships, sample number) is critical in the decision making process to select the most scientifically relevant samples during a sortie.

Finally, the capability for downloading instrument data and sample observations to the science support room will enhance sample collection and surface activities. We do not propose that these data be

used by the science support room (on Earth or at the outpost) to micromanage surface activities during the EVA. This would pose a threat to the astronauts ability to carry out efficiently surface activities. The astronaut should be trained (see 3.7 Crew Requirements for sample acquisition and curation) to make sampling decisions in real time using the tools provided. The importance in having these data downloaded to the science support room would be in planning sampling activities during the EVA or for follow on EVAs.

Outpost Operations: Analytical instrumentation to identify and select samples in the field during outpost surface operations should be similar to sortie missions. Differences between outpost operations and sortie missions tied to sample acquisition, selection, and curation differ in time and instrument sophistication due to the availability of outpost facilities. Outpost analytical capacities should be viewed in two stages: Stage 1: preliminary analysis, selection and curation of samples, and Stage 2: scientific analyses performed by astronauts. Outpost planning should focus upon activity 1 during the initial stages of outpost activities with the outpost having the capability of evolving into Stage 2. In this discussion, we focused upon Stage 1. The goals of outpost operations during stage 1 should be selecting the most scientifically relevant samples for return to Earth, providing preliminary analyses for planning outpost-based EVAs, and performing analyses of sample properties that potentially could be modified during transport to Earth.

3.2.5 Specific engineering recommendations

(1) In order to select the scientifically most valuable samples, a combination of macro-imaging, micro-imaging, and geochemical instrumentation must be designed and developed for sortie or outpost field investigations.

(2) These analytical instruments should have the following characteristics:

They cannot be a threat to safety and ability to carry out efficient surface activities;

They must be easy to use and the data must be easy to interpret;

They cannot be a threat to the contamination of the sample;

The geochemical data must be linked to sample macroscopic characteristics (texture, mineralogy);

It is important to be able to transfer the sample data to the science back room (Sections 3.8 and 3.9 discuss the function and importance of the science back room).

(3) Outpost analytical capacities should be viewed in two stages: (Stage 1) analysis, selection and curation of select samples and (Stage 2) analyses performed by astronauts for specific scientific and exploration goals. The goals of outpost operations during stage 1 should be selecting the most scientifically relevant samples for return to Earth, providing fundamental analyses for planning outpost-based EVAs, and performing analyses of sample properties that potentially could be modified during transport to Earth.

3.2.6 Analyses required prior to establishing recommendations

NASA should convene a panel or panels or an NRC study to identify useful types of instruments and their mode of operation and use.

Findings:

(1) The large sample mass that could potentially be collected during sortie missions requires selection of samples for return to Earth that are of the highest scientific and exploration importance.
(2) Such sample collection can be accomplished with easy to use instruments that provide mineralogical and geochemical fingerprints of samples that enhance astronauts' geological training. These instruments must fulfill a number of requirements tied universal applicability and intrinsic value of data obtained? And also to safety, efficiency, and avoidance of sample contamination.
(3) In addition to astronaut operated analytical instrumentation, remote controlled instrumentation (i.e. multispectral panoramic imager on rover mast) may provide both observations to plan efficient EVAs and place samples within a local geologic context.
(4) All data for a given sample should be linked and the linked data be made available to the science support room.
(5) The habitat should be designed to handle an evolving suite of analytical instrumentation. As most measurements can be best made on Earth, initial instrumentation should assist in selection of the most relevant samples for return to Earth and planning EVAs in real time. These instruments could be more complex versions of instruments used during sorties (i.e. multiple elemental analysis rather than fingerprint and elements). Safety and contamination issues must be addressed.
(6) Habitat analytical instrumentation could evolve to test properties of lunar materials that could be compromised during transport to Earth, planning long duration EVAs, exploring potential resources, and evaluating ISRU processes.

3.3 Sample Packaging and Preservation Requirements

3.3.1 Lessons Learned from the Apollo Program

Apollo missions Apollo 11, 12 and 14 returned all lunar samples in sealed aluminum boxes called Apollo Lunar Sample Return Containers (ALSRC) (see Figure 4). The design for and use of these containers were based on sample quarantine requirements. The boxes were machined out of single blocks of 7075 AA aluminum alloy (all data on Apollo sample return containers comes from Allton, 1989) and were lined with metal mesh padding knitted from 2024 aluminum alloy. The groove portion of the locking interface between container lid and the body of the container contained a sealing surface that was made from an In-Ag alloy and a fluorosilicone compound designated L608-6 that formed two additional sealing rings. The lid was closed with an over-center cam latch type mechanism that brought a knife edge from the upper lid in close, intimate contact with In-Ag metal seal and the L608-6 seals, thereby sealing the box. Of the 12 ALSRCs returned from the Moon, 8 maintained a substantially high vacuum, while 4 of the boxes had their integrity compromised by either lunar soil or sample bag hardware that interfered with the

sealing mechanism. The boxes weighed an average of 6.7 kg empty, were 48 cm x 30 cm x 20 cm, had an internal usable volume of ≈16,000 cm^3 and an external volume of ≈29,000 cm^3.

On the Apollo 15, 16 and 17 missions, ALSRCs were used for a portion of the returned samples. However, the completion of the quarantine phase of the post-mission procedures after Apollo 14 meant that the samples did not need to be sealed against leakage of potentially harmful biological organisms into the terrestrial environment. Consequently, a significant number of samples were returned in soft-sided Sample Collection Bags (SCB[1]) that were made of TFE Teflon cloth vulcanized between two sheets of FEP Teflon film (NASA, 1972, cited in Allton, 1989). Each SCB had a light metal framework sewed into the lay-up that maintained the SCB's shape, and the bottom of each bag was lined with metal mesh padding. SCBs were designed to be strapped to the side of a crewmember's Portable Life Support System (PLSS) and/or stashed at any convenient location on the Lunar Roving Vehicle (LRV). The lid of each bag could be used in two ways: in addition to being opened by a soft-goods "hinge", each lid was constructed with a slit that could be pushed open to stash samples within the SCB without the necessity of opening the lid (Figure 5). As inferred in the footnote, the SCBs had internal dividers made of the same fabric lay-up that allowed drive tubes and Teflon sample bags to be segregated internally. In addition, the SCBs were used to stow various sample collection hardware, such as drive tubes, to be packed for transit to the lunar surface. On each of the Apollo 15-17 missions, two SCBs were returned inside the ALSRCs, with the remaining SCBs returned as loose cargo. Each SCB weighed 762 g, were 42 cm x 22 cm x 15 cm in size, with an internal capacity of ≈13,900 cm^3.

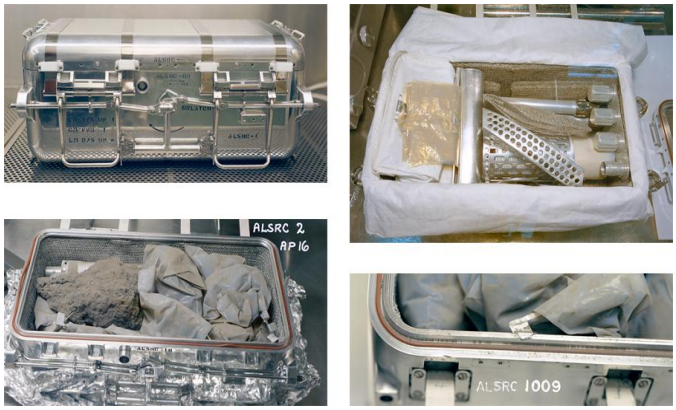


Figure 4. Apollo Sample Return Containers in Various Configurations. Upper left, a closed ALSRC in a dry nitrogen glove box prior to shipment to Kennedy Space Center for loading on the Lunar Module (NASA Photograph S72-37196). Upper right, an ALSRC loaded with clean sample containers and other hardware; note the Nomex ® (http://www2. dupont.com /Nomex/en _US/index.html) fabric drape, designed to protect the container seal, and the woven mesh inner lining (NASA Photograph S70-52550). Lower left, ALSRC after being opened on return to the Lunar Receiving Laboratory after being loaded on the lunar surface by the Apollo 16 crew; note that opening the box has lifted the L608-6 fluorosilicone seal off the sealing track in several places (NASA Photograph S72-36984).

[1] An additional SCB, called the Extra Sample Collection Bag (ESCB) was also carried on Apollo 15-17. Its construction differed slightly from the SCBs in that it had no internal dividers, but otherwise it was identical in size and material construction.

Lower right, ALSRC SN:1009 after a twist tab on a sample bag inadvertently fell across the inner sealing surface when being closed on the lunar surface, leading to an incomplete seal (NASA Photograph S72-37550).

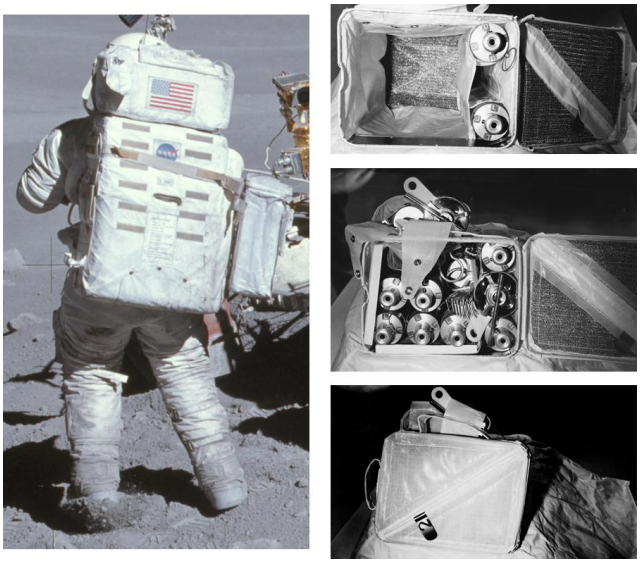


Figure 5. Apollo Sample Collection Bags. Left, SCB strapped to the right side of a lunar crewmember's Portable Life Support System (NASA Photograph AS16-107-17446). Upper right, open SCB during packing prior to being transferred to the Lunar Module; note the divided slots on the right side into which 2 drive tubes have been placed, as well as the woven wire mesh bottom of the bag (NASA Photograph S88-52671). Middle right, SCB completely loaded for flight, including drive tubes, special environmental containers and sample bags (NASA Photograph S88-52662). Lower right, closed SCB, showing the lateral spring loaded opening that would allow a crewmember to stuff a sample bag into his fellow crewmembers SCB without having to open the SCB lid (NASA Photograph S88-52763).

In addition to the primary sample containers, there were a variety of smaller containers that were used to contain certain types of samples in a pristine environment, or segregate them from other samples, preventing mixing, as in the case of soil samples. The vast majority of samples were returned in documented sample bags made of Teflon that could hold roughly a kilogram of soil (Allton, 1989) or rocks 10-15 cm in their long dimension. Some of these bags were padded, although the majority were not. These bags were held open by two metal strips that could be pulled against each other to seal the bag, and had tabs on either end to allow the bag lid to be rolled up and sealed as a twist bag. Each bag had a unique identity number that was called down by a crewmember when depositing rocks or soil into the bag (Figure 6).

A variety of special environmental containers were used to collect small soil samples or drive tubes that could then be sealed on the lunar surface in a manner similar to the ALSRCs. The smaller of these containers were up to ≈10 cm long, and were used for collecting soil. A larger version was ≈40 cm long, and could be used to seal a complete single drive tube. Each of these containers was <500 g in weight (Figure 7).

3.3.2 Improvements since the Apollo Program

Since the Apollo Program, NASA has had to store and transfer a considerable volume of cargo to and from Low Earth Orbit (LEO) on both stand-alone Shuttle missions and on ISS logistics resupply missions. In order to accommodate a variety of cargo that does not need stringent environmental conditioning nor strict contamination control, NASA developed soft goods cargo containers called Cargo

Transfer Bags (CTBs) (data drawn from a presentation by Angela Hart, International Space Station Integration and Operations Office, titled, "Internal Cargo Integration"). Cargo transfer bags are Nomex storage bags that have removable dividers that can be internally reconfigured to accommodate a variety of sizes and conditions of cargo (Figure 8). They are available in half, single, double and triple sizes (Table 1). Each bag is closed by a zipper (Figure 9), and has removable mesh netting inside the CTB.

Figure 6. Apollo sample bags. Left, sample bags being manipulated by an Apollo 16 crewmember prior to inserting a documented sample (NASA Photograph AS16-116-18649). Right, documented sample bag with a soil sample in the Lunar Receiving Laboratory (NASA Photograph S73-15061).

Figure 7. Special Environmental Sample Container. Left, the SESC held by an Apollo 12 crewmember on the lunar surface, showing the size of the container. Similar containers, core sample vacuum containers were used on the Apollo 15-17 missions to seal up selected drive tubes that were essentially the same design, but long enough to hold a single drive tube (41 cm) (NASA Photo AS12-49-7278). Right, an SESC after opening in the Lunar Receiving Laboratory. Note the sharp rim of the container, which was designed to cut into the top when the three dogs on the cap were engaged with the raised rim on the container (NASA Photo S88-52666).

The Apollo experience suggests that the vast majority of the returned samples will not need to be returned in a hard vacuum, like Apollo samples returned in ALSRCs. CTBs are space-flight rated

equipment that can be used to pattern development of soft stowage elements for lunar sample return where the requirements for hard seals, such as used on the ALSRC, can be relaxed. For that small subset of samples that require transport in hermetically sealed containers such as the SESCs referenced above.

While the majority of samples returned will not need to be contained under vacuum, prudence would dictate the need to manage the sample environment to limit exposure to the relatively humid, oxidizing atmosphere of Lander return cab and the command module of Orion. This may be possible using soft goods bags, similar to CTBs, fitted with a gas-sealing zipper enclosure similar to those used on soft-goods-based pressure garments that would be sealed on the lunar surface, as was done on with the ALSRCs. Soft-goods-based pressure garments use special zippers that forcibly bring two sides of a rubber bladder material into solid contact, forming, in effect, a zipper-closed gasket. Although the standard approach with pressure garments is to seal the pressure environment into the garment, in this case, the atmosphere would be sealed out. No pressure garment is ultimately leak-proof, and it is not known how well this concept would work in keeping samples temporarily secure against the vehicle cabin atmospheres. The next step in this process would be to develop a prototype sample return bag that could be sealed in vacuum, and to conduct testing as to the validity of the concept.

Figure 8. Single-sized Cargo Transfer Bag

ISS science required the refrigeration of samples stored on the ISS and returned via the Shuttle. Such a capability may be important for fulfilling science goals during sortie and outpost activities. The Shuttle refrigerator (15 kg) and freezer (20 kg) units have a capacity of producing temperatures of 4 degrees C and -80 degrees C, respectively. Their approximate dimensions are 46 cm x 23 cm x 23 cm. A single freezer is capable of holding 18 SESCs. The requirement for maintaining and transporting lunar

samples under refrigeration are not addressed here but may be addressed in a follow-on study, which addresses also lighter refrigeration units.

CTB Type	Approximate Dimensions	Maximum Load (Strapped to a Bulkhead)	Maximum Load (Secured in a Locker)
Half [SEG33111836]	25 cm x 43 cm x 24 cm	13. 6 kg	27.2 kg
Single [SEG33111837/838]	50 cm x 43 cm x 25 cm	27.2 kg	45.3 kg
Double [SEG33111839]	50 cm x 43 cm x 50 cm	54.4 kg	81.7 kg
Triple [SEG33111840]	75 cm x 43 cm x 50 cm	81.7 kg	81.7 kg

Table 1. Cargo Transfer Bag Basic Specifications. The documentation that covers CTB usage, loading, design, installation, ground handling, packaging and stowage requirements is JSC 39207 - Cargo Transfer Bag Certification and Acceptance Requirements, and JSC 39233, Rev D. – Cargo Transfer Bag (CTB) Interface Design Document (IDD).

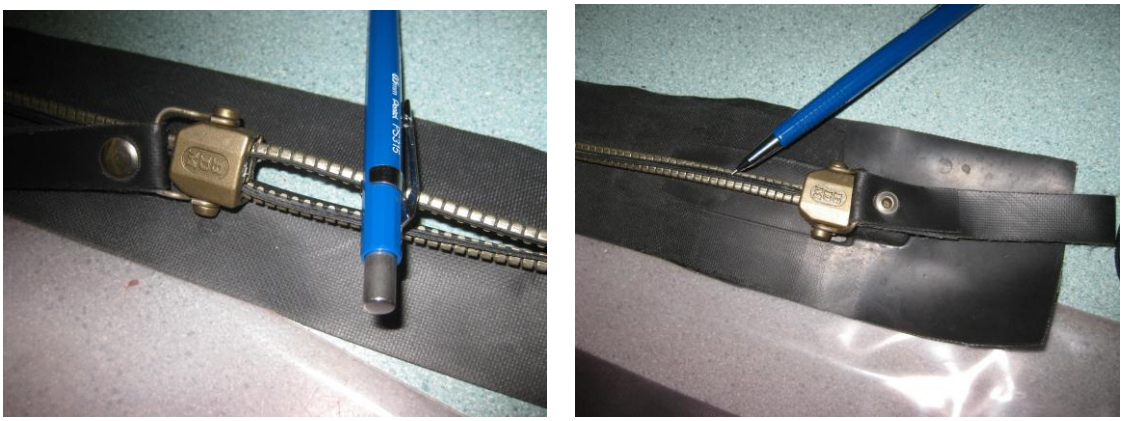


Figure 9. Pressure-sealing Zipper used in the present generation of soft-sided pressure garments

3.3.3 Capabilities for sampling the lunar surface

Sortie missions: The expected timeline for sortie missions will not allow much more time for sample sorting and selection than was available on the Apollo missions. Given that, in a 7 day sortie, it is likely that a well-trained crew could collect more samples than there would be return mass to accommodate, it will be important for the crew to take a certain level of care in sample selection during traverses and on outcrops to ensure that sample mass does not exceed return mass limitations. This implies a level of

geologic training, and the ability to discriminate the scientific importance of samples in the field, that is at least as effective and thorough as was done on Apollo. At the end of the surface mission, the crew would secure the samples in the variety of sample return containers provided, with samples segregated as to their specific sensitivity to atmospheric humidity and oxygen levels.

We envision that during a sortie mission a majority of the rock samples would be initially stored in Sample Collection Bags (SCB) similar in function to those used in the Apollo Program. Rather than using ALSRC, SCBs would be stored in CTBs. In addition to this standard sample container, there are scientific problems that require more unique containers that would be used to preserve particular sample characteristics (i.e. volatile content, minerals that could react to conditions in a non-lunar environment). General use containers for these types of samples could be similar to the Special Environmental Sample Containers (SESC) used during the Apollo Program. Volatile-rich samples collected from permanently shadowed regions of the lunar environment could be collected in SESC containers and stored in a small freezer unit similar to those units used in the ISS and Shuttle. Although we realize that these freezer units cannot reproduce the extremely low temperatures of lunar cold traps (freezer temperatures of approximately -80 degrees C compared to temperatures that are not well documented but probably exceed -100 degrees C) and some sample degradation will take place, they may be adequate for the collection and storage of the first cold trap samples to be returned to Earth. Further documentation of cold trap environments is required before storage and preservation can be discussed in more detail. As with tools, other sample containers will become developed as they fulfill the needs of the proposed or applicable scientific investigations. Selection of materials and container design should occur under the guidance of a joint advisory committee consisting of science community stakeholders and engineering hardware solution providers as discussed in the sample tools section (section 3.1).

Outpost Operations: Outpost operations will provide the crewmembers with greatly increased time to do field work, additional surface time to conduct some level of preliminary examination in a pressurized laboratory, but no significant increase in return mass and more demands on that return mass from biological samples. However, it is expected that return sampling provisions for geological materials will be identical to those used on sortie missions. One accommodation will likely be the practice of splitting samples outside the habitat on the surface, with one portion of the sample being brought into a pressurized laboratory and the remaining portion being retained the outside habitat, to minimize the potential for contamination (e.g., see the work of Treiman, 1993). Sample containers or their utilization may be modified to facilitate this operation without contaminating the sample or sample splits.

Freezer requirements in the outpost may evolve from observations made during initial sampling of cold traps. If sample degradation compromises important science, freezers with the capability to store samples at temperatures greater than -100 degrees C may be important to have in the outpost facility.

3.3.4 Specific engineering recommendations

A prototype soft goods sample return bag for storage on the return spacecraft should be fabricated similar to a CTB that would be, in effect, a pressure garment with a rectilinear volume. The fabric layers used on the soft-goods assemblies of the present Shuttle and ISS Extravehicular Mobility Unit (EMU) are, from the interior pressurized environment to the exterior, space environment (weblinks provide the basic material properties and composition of the materials used):

1) Gas-retentive bladder, fabricated from polyurethane-coated nylon (polyurethane - http://en.wikipedia.org/wiki/Polyurethane; nylon - http://en.wikipedia.org/wiki/Nylon)
2) Restraint layer (responsible for keeping the garment in the proper shape while pressurized; this may not be a necessary layer, as our bags will be under negative pressure) – polyester (http://en.wikipedia.org/wiki/Polyester)
3) Thermal-Micrometeorite Garment liner - neoprene-coated nylon (neoprene - http://en.wikipedia.org/wiki/Neoprene)
4) Multi-layer insulation - 5-layers of reinforced aluminized mylar [this will probably not be required, as thermal management will probably not be an issue]
5) Ortho-fabric - Nomex and Teflon (PTFE) with Kevlar reinforcement (Nomex - http://en.wikipedia.org/wiki/Nomex; Teflon - http://en.wikipedia.org/wiki/PTFE) [ortho-fabric is extremely abrasion resistant, which is why it is used a lot on space hardware exposed to the exterior environment, such as the Space Shuttle payload bay]

The prototype soft sample bag could be fabricated out of layers 1, 3, and 5. One way to manage the scuffing that might be induced by samples within the bag would be to have an inner-to-outer layer configuration of 5-1-3-5, with the orthofabric as both an inner scuff-resistant layer to protect the bladder from any loose rocks or regolith, and as an outer layer to protect the whole bag from both the lunar environment and the usual abuse that happens when a soft good is stowed and unstowed in a hard-sided environment. The bag would be sealed with a gas retentive zipper, identical to those used on the present generation of Advanced Crew Escape System launch escape suits. Part of the fabrication process would be to provide internal instrumentation to monitor internal pressure during a test. Once the bags were developed, a vacuum chamber test could proceed where the bag is backed and sealed in vacuum, then brought into the exterior pressure environment to determine the efficiency of the sealing zipper and the rate and degree to which the interior volume of the bag changes over a time period roughly equivalent to departure from the lunar surface and return to a terrestrial laboratory.

3.3.5 Analyses required prior to establishing recommendations

There are several analyses that are required prior to the use of any sample container during a lunar mission.

(1) The new material and design for the soft goods sample return containers proposed in this review must be investigated in terms of sample contamination control and sample preservation.

(2) New designs for one or more general SESCs must be developed. These containers must be easy to use during surface operations, easily sealed to preserve sample integrity, and at least one design will need to be readily accommodated in freezer units in Orion and outpost facilities.

Findings:

(1) A joint advisory committee consisting of science community stakeholders and engineering hardware solution providers is required to facilitate communication and formal decision making events to achieve elimination of disconnects that will lead to sample contamination and decrease in the utility of sampling containers. The committee must be delegated authority to oversee the "Sample Collection and Storage Systems" for acceptability and compliance with specific "science unique" requirements levied against sample acquisition and curation hardware.

(2) To reduce sample container volume, we find that soft goods sample return containers may provide an alternative to the ALSRC. Prior to the use of this style of container, it is imperative that sample preservation and contamination issues be investigated and resolved.

(3) A general use Special Environmental Sample Container should be designed based on lessons learned from their use during the Apollo Program.

(4) Sortie and Outpost operations should use similar sample containers.

(5) It is anticipated that unique containers will be requested by the science community to specific scientific needs. The process stated above in (1) should be used in the evaluation of materials and design.

(5) The preservation of samples will require the availability of ISS-type freezers during sortie and outpost activities. Scientific need will drive the evolution of freezer requirements.

(6) Freezer sample storage protocol must be established to accommodate geological and biological samples and prevent sample cross contamination.

3.4 Sample Contamination Control Requirements

3.4.1 Lessons Learned from the Apollo Program

Sample contamination control during the Apollo Program relied on the use of tools made from approved materials and on the storage of samples for transport to Earth in special containers, under vacuum and in bags (see section 3.1 and 3.3). Contamination problems arose from the gaskets used (In-Ag), from leaks in the seals, and from exposure to the return vehicle environment for samples brought back in excess of the capacity of the sample containment boxes (Table 2).

3.4.2 Improvements since the Apollo Program

Extensive experience in the original Lunar Receiving Laboratory resulted in abandoning the attempt to handle lunar samples under vacuum in favor of establishing techniques and tools for handling samples in stainless steel glove boxes in a GN2 atmosphere with very low limits for oxygen and water contents. This experience is integrated in the design of the current Lunar Curatorial Facility at JSC and in the extensive experience of sample curation personnel and in a body of standard operating procedures.

Table 2. Contamination. Lessons learned from the Apollo Program

Contamination Issues:

- Indium (10% Ag) seals in sample containers resulted in indium contamination.
- Apollo 15 drill core were a Ti alloy and threads were canadized in Pb bath.
- Core bit with WC cutters brazed to drill stem (potential W,Ni, Pb contamination issues)
- MoS_2 grease used in LRL up to about 1972. Source for organic contamination
- Xylan (complex blend of organics with PTFE) replaced MoS_2 grease in 1972. Source of N and organic contamination.
- Band saw blade diamonds adhered in electroplated Ni; sawing is dry, causing heating.
- Moisture & oxygen in N_2 usually ~5 ppm, but rises during processing, gloves leak; samples in containers are protected during storage.

Contamination in transit:

- Many samples in bags with twisty seal were partially exposed to crew module and Earth atmosphere from leaving lunar surface to containment at JSC.
- Rocks are their own best container.
- Soils in core tubes were well protected, but quantities small.
- Some samples were well protected in their special sealed containers.
- Samples acquired from Apollo 15 to 17 have a better chain of custody for cleanliness once at JSC.

3.4.3 Guidelines for contamination control during sortie and outpost operations

The current tasks and challenges for sample collection and handling on the lunar surface are:

- to retain the pristine character of the samples;
- to document the potential sources of contamination and to quantify the potential for sample contamination for each sample handling procedure on the lunar surface and for the return trip to Earth and the LCF;

- to provide clean procedures for splitting samples and for preservation of representative splits, if detailed processing of samples on the lunar surface cannot preclude contamination to acceptable levels, based on current and future analytical capabilities in terrestrial facilities.

The possible contamination of lunar samples is pervasive. Without controls, contamination can be introduced at many stages and from sources directly designed for sample handling and from more general spacecraft components and lunar surface equipment and procedures, only remotely connected with sample collection and handling. Hence there is a need for general guidelines. These include the need for guidelines, particularly in the following general areas of concerns:

- Contamination from landing and ascent from the Moon, e. g., rocket exhaust;
- Contamination from spacecraft components (structural materials, surface finishes, and coatings, greases, abrasion products from moving parts, incl. exfoliation from space greases
- Contamination from sample handling tools and containers, including drilling and coring mechanisms;
- Contamination in complex habitats, created and used on the lunar surface; the preservation of samples becomes more critical if SOPs include physical or chemical processing of samples (e. g., surface cleaning of soil from rock surfaces, preparation of thin sections, sample dissolution and chemical processing, exhaust from equipment and instruments;
- Contamination from exposure to human activities, especially in a long range, pressurized rover, and in lunar base habitats;
- For these considerations we will need to address inorganic and organic/biological contamination individually.

3.4.5 Specific engineering recommendations

1. The engineering design must incorporate ongoing advice from a standing advisory committee composed of sample scientists, sample curation experts, and experts on the physical and mechanical properties of materials for space components. The components and the sources of contamination for any mission are vast in numbers, so that any list of approved materials must be a living document, continuously updated, especially as compromises for optimum use will be necessary.

2. A list of approved materials will be maintained and updated. Multiple lists will be needed for materials that come into direct contact with the samples and for peripheral materials, for which exposure of the samples may be controlled by appropriate operating procedures.

3. A list of all materials used, and amounts will be maintained.

4. Consideration will be provided for the use, analysis, and preservation of coupons, to establish the levels of contamination to which samples may become exposed.

5. Design of major mission components, such as the living quarters (and standard operating procedures) for rovers, pressurized long range rovers, lunar base habitats needs to address and minimize the potential for sample contamination.

6. Protocols must be established for sample handling and curation during outpost "high-grading" and science activities.

7. The preservation of volatile rich samples under cryogenic conditions must include protocols to address contamination.

3.4.5 Analyses required prior to establishing recommendations

Defining more detailed contamination control guidelines and protocols will assist in establishing more detailed recommendations tied to Constellation architecture.

Findings:
(1) The possible contamination of lunar samples has many sources and may be introduced during many processes. It is possible that, without controls, contamination can be introduced at many stages and from many sources. Therefore, there is a need for both general guidelines for materials control of contamination control and of specific manufacturing and surface finishing processes during many aspects of design specifications and fabrication.
(2) Contamination control protocols must be established for sample handling and curation during sortie mission activities.
(3) Contamination control protocols must be established for sample handling and curation during outpost "high-grading" and science activities.

3.5 Sample Mass and Volume Requirements

3.5.1 Lessons Learned from the Apollo Program

An analysis of sample mass requirements was first conducted in preparation for the Apollo Program. The 1967 summer study of lunar science and exploration that was held in Santa Cruz, California made the following recommendation regarding sample mass:

"*One important, if not the most important, scientific result from the AAP (Apollo Applications Program) missions will be the return of lunar samples. The amount returned must increase as the capabilities of the vehicles allow. It is recommended that the total returned payload from the Moon in AAP missions increase to 400 pounds* (181.6 kg) *so that a minimum of 250 pounds* (113.5 kg) *of lunar samples can be returned."*

The Apollo Program returned a total 381.7 kg of geological material from the lunar surface during 6 missions (Table 3). Apollo 11 returned the smallest sample mass from a limited geological area within 100 m of the lunar module, yet had the highest sample mass per EVA hour (for a crew of 2) of all the Apollo missions (Figure 10). This was due to several factors. Sampling and sample diversity was

secondary to safety during the first lunar surface mission. Therefore, the "rock box" (Apollo Lunar Sample Return Container, ALSRC) was filled with lunar soil at the end of the mission in order to

Table 3. Sample Mass Returned by the Apollo Program (Vaniman et al. 1991).

Apollo 11	21.6 kg	47.6 lbs
Apollo 12	34.3 kg	75.6 lbs
Apollo 14	42.3 kg	93.3 lbs
Apollo 15	77.3 kg	170.5 lbs
Apollo 16	95.7 kg	211.0 lbs
Apollo 17	110.5 kg	243.7 lbs
Total Return Mass	**381.7 kg**	**841.7 lbs**

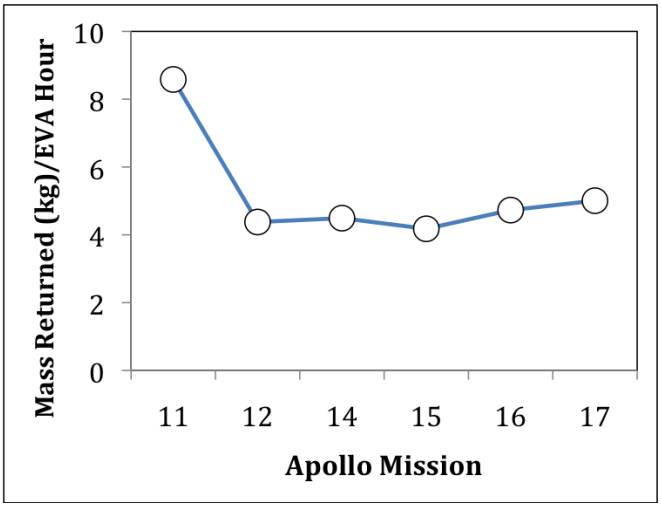


Fig 10: Mass returned (kg) per EVA hour (2 crew) for the Apollo missions.

maximize sample return. Apollo 17 returned the largest amount of diverse material from 22 locations over traverses totaling 36 km in the Taurus-Littrow Valley. The Apollo 17 mission is our closest approximation for the base level of science and sample acquisition to be accomplished during the sortie missions in the Constellation Architecture.

The samples returned during the Apollo Program were collected and stored using a variety of techniques devised to facilitate particular types of measurements and to take advantage of differences in astronaut mobility on the lunar surface (see Allton, 1989). Relatively large individual hand samples of breccias (i.e., 14321, 9.0 kg), basalt (i.e., 15555, 9.6 kg), and plutonic rocks (i.e., 60015, 5.6 kg) were collected (Figure 11). By contrast, the collection of rake samples was designed expressly to return large numbers of relatively small mass samples (> 1 cm^3; ≈ 0.2 to 1.0 g), enhancing the lithologic diversity of the returned material, and helping to maximize sample collection storage and return efficiency. Regolith samples were collected in order to provide a record of both surface evolution and volcanic history (i.e., the Orange Soil 74220, 4.57 kg). In addition, approximately 54 feet of core tube and drill core samples were collected to determine changes in characteristics with depth and to investigate impact processes (e.g.

regolith gardening) and space-weathering processes. A subset of samples was collected and stored in specially designed containers (SESCs) to preserve them in a "lunar environment".

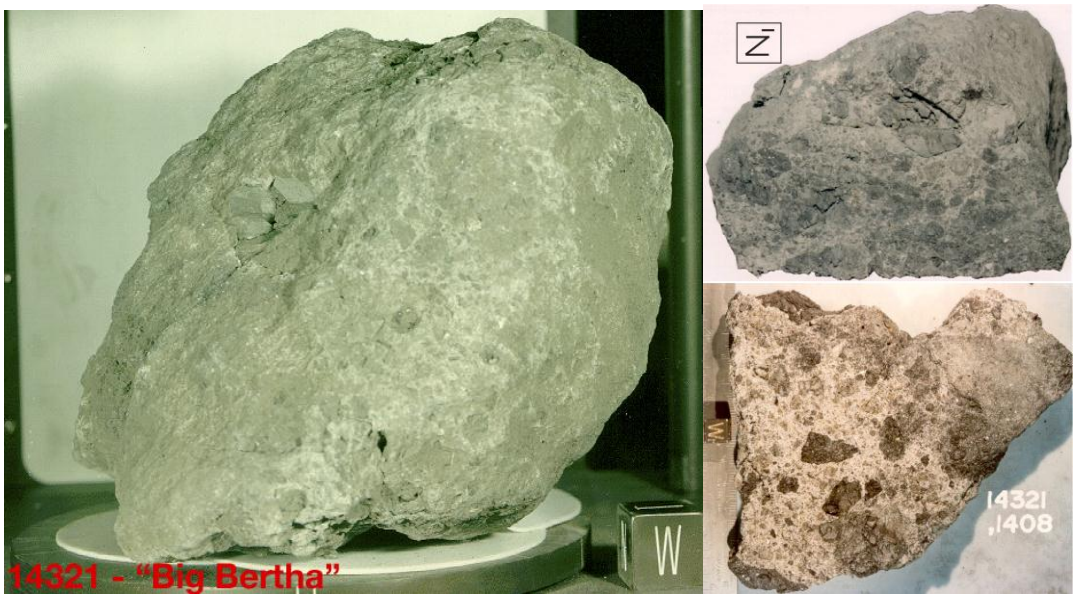


Figure 11. Photographs of 14321,0 "Big Bertha" and cut surfaces illustrating diverse dark clasts embedded in a light breccia matrix. These clasts represent a large number of different crustal rocks unsampled by any other rocks returned by Apollo. This image illustrates the value of returning large samples.

The analysis of sampling during the Apollo Program provides many insights into sampling for future human missions to the Moon:

1) Illustrates a near linear relationship between sample mass and EVA hours for sortie missions (Figure 12).

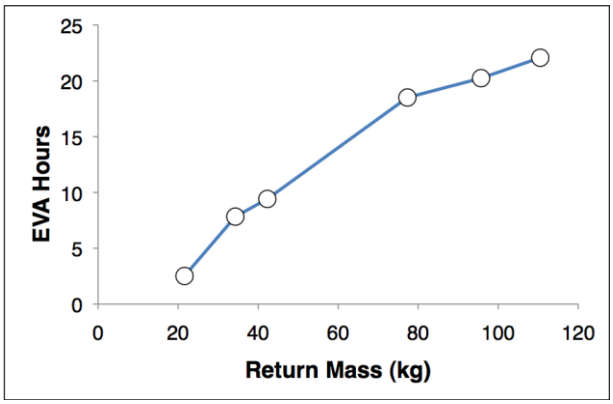


Fig 12: Return Sample Mass vs. number of EVA Hours.

2) Provides documentation to establish relationships between sample mass and container mass and volume.

3) Provides documentation illustrating the relationship among sample mass, sample type, and science productivity.

It should be noted that the Apollo crews, especially the J mission crews, were trained to achieve a given sampling mass rate per hour that would allow the selected samples to fit in the sample container mass and volume constraints. However, if the new architecture expands EVA times but

reduces the sample return mass, more emphasis on sample selection (training and tools) will be need to be incorporated into astronaut training.

3.5.2 Improvements and observations since the Apollo Program

Post-Apollo Program improvements in technology and scientific observations will influence the types of samples that can be collected during future missions and the sample return mass and volume. The development of new materials for sample containers may reduce volume/mass ratio for traditional geologic samples relative to Apollo (see Section 3.3). Recent scientific observations will influence the types of samples that will be returned and this will influence container types and the volume to mass ratio. These scientific observations/conclusions include: the existence of possible volatiles in polar regions, the existence of fragile volatile coatings on grain surfaces, the diversity of the lunar crust, the potential reactivity between samples and "terrestrial environment". In addition, studies of the Apollo collection have shown that while large basalt samples may not be required for most scientific studies, large polymict breccia samples have high scientific value because of the diversity of lithologies that they contain.

3.5.3 Capabilities for sampling the lunar surface

A previous analysis carried out by CAPTEM concluded that for scientific rationale the Constellation architecture must accommodate between 250-300 kg of sample related mass (samples, sample containers, etc.) during sortie missions (Shearer et al., 2007; http://www.lpi.usra.edu/captem/analysis.shtml). This review agrees with the conclusions reached from this analysis. However, the current Exploration Architecture Requirements Document (EARD) states that the upmass from the Moon is "at least 100 kg" with an objective of 250 kg, which is still low given the scenarios currently used for both sortie and outpost surface operations.

An analysis of sample volume was carried out during this review based upon the Apollo experience. A full description of the analysis is presented in APPENDIX V The Apollo containers were not uniformly packed and the ALSRCs had the lowest packing density relative to the soft Sample Collection Bags or SCBs (the average ratio of sample mass returned, m_{smp}, to total return mass or sample + container, M_{RET}, is 0.58 and 0.92, respectively; see Figure 13 and Appendix V. The data presented in Figure 13 for the Apollo J missions demonstrate the advantages of the SCBs over the ALSRCs: even though the packing density of some SCBs covers the range of the ALSRCs, the ratio of m_{smp}:M_{RET} is much higher. Given that the SCB Packing Density extends to much higher values than the ALSRCs, the conclusion is that the soft containers are preferred in terms of packing efficiency and the fact that there is less of a mass penalty with these containers. The volume analyses show that 250-300 kg mass will occupy approximately 0.30-0.36 m^3, assuming a soft container akin to the SCB from the Apollo era is used. If a hard contain akin to the ALSRC is used, and using the average packing density of the hard Apollo Lunar Sample Return Containers (ALSRCs) returned by the Apollo J missions, the volume to accommodate 250-

300 kg of lunar samples increases to 0.7-0.9 m^3. Considering the technological developments since Apollo, it is certainly feasible to have the new generation of SCBs have gas impermeable closures, to protect the samples from any reactivity with the human return capsule environment or the terrestrial environment in general. Given the experience of Apollo in returning samples, *it is recommended that soft containers be used for typical Apollo-like lunar sample returns* as they can be packed with samples more efficiently than hard containers, and then the bags themselves do not need to be altogether in one place (i.e., they can be distributed throughout the return module). *Special Environmental Sample Containers (SESCs) of the size and mass used in Apollo will be useful in the next stage of lunar exploration for obtaining environmentally sensitive samples*. These could then be stored in a gas tight soft container on the lunar surface.

Sortie missions: Sortie missions have the potential to collect samples that would significantly exceed the 250-300 kg total return mass defined in the CAPTEM study (Shearer et al., 2007). The current sortie mission scenarios plan to place 4 astronauts on the surface for a total of 7 days undertaking surface EVAs in teams of two (a total of eight 8 hour EVAs or 64 EVA hours). If the astronauts are trained to achieve an Apollo 17 collection rate of 5 kg/EVA hour (Figure 10), the sortie missions under the current plan can collect a ***minimum*** of 320 kg. While high grading of samples during sorties will aid in the selection of sample mass with high scientific value, it will depend on the length of sortie missions along with mission goals to see just how much high grading of samples can be conducted. In addition, the equipment needed to conduct the high grading will need to be taken to the lunar surface for each sortie mission.

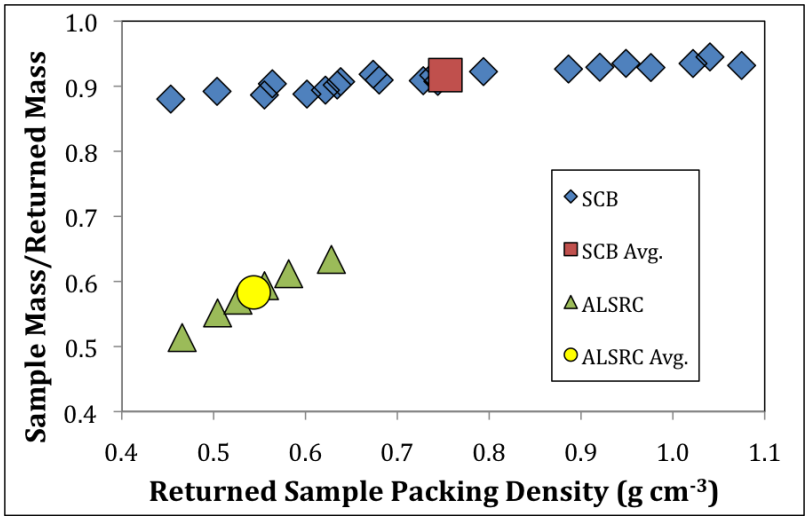


Figure 13. Ratio of Sample Mass to Returned Mass plotted against Returnied Sample Packing Density for the Apollo J missions (15, 16, 17).

Outpost Operations: The sample mass and volume estimates given above will be applicable to both sortie and outpost scenarios. However, outpost operations will have the capability to acquire substantially more sample mass than sorties. A high-grading facility would need to reduce sample return mass to a maximum of ~230 kg (Shearer et al., 2007) for a total return mass of 250 kg per human return flight if the objective in the current EARD is met. If only 100 kg is possible, there will be even more emphasis on the high grading facility and/or robotic sample return technology (as was accomplished by the Soviet Luna

missions 16, 20, and 24). Robotic sample return is a technology development highlighted in the LEAG Lunar Exploration Roadmap, Science Goal A, Objective 2 and is recommended here, as it will be critical for maximizing science return from the next stage of lunar exploration.

3.5.4 Specific engineering recommendations

Based upon the Apollo experience, it is recommended that:

1. A volume of 0.10-0.12 m^3 is required per 100 kg of lunar samples;
2. Soft containers should be used to return lunar samples – a hard ALSRC-type "rock-box" is inefficient at packing samples and should not be used;
3. Development of air tight closures for the soft containers (bags) should be implemented so sensitive (volatile-rich) samples can be returned without experiencing contamination from the atmosphere of the return module;
4. The hard-sided Special Environmental Sample Container (SESC) of the Apollo era will also be useful in this stage of lunar exploration and it can be stored in a vacuum-sealed soft container;
5. Robotic sample return technology should be developed to enable robotic sorties and also supplement sample return from an extended stay outpost mission. This technology has important feed forward implications for sample return from Mars, Mercury, asteroids, etc.

Findings:
(1) Constellation architecture should be able to accommodate a minimum return mass of 250 to 300 kg of sample and sample containers.
(2) A volume of 0.10-0.12 m^3 is required per 100 kg of lunar samples.
(3) Soft containers should be developed, and used to return lunar samples. A hard ALSRC-type "rock-box" is inefficient at packing samples, increases the volume needed per 100 kg of sample mass, and is inflexible in storage.
(5) "High-grading" samples is required for both sortie and outpost surface activities (see section 3.2), but will be critical for Outpost operations.

3.6 Power Requirements for Sample Acquisition and Curation

3.6.1 Lessons Learned from the Apollo Program

The Apollo Program had minimum power requirements for sample acquisition. Apollo's 15, 16 and 17 utilized an electric drill for coring. This was the only power tool used during the Apollo Program for sample acquisition or *in situ* analysis. The drill, built by Martin Marietta, required about 430W of power. No power was used during Apollo for sample preservation until after the samples arrived at curation facilities.

3.6.2 Improvements since the Apollo Program

Since the 1970s, there have been advances in drills for both cores and rock samples. Several groups have been working on developing drills for ~7-10 m cores, and all are considerably lower in power than the Apollo drill (Table 4).

Handheld field analysis tools, such as portable spectrometers, have become commonplace in terrestrial field work and can be adapted for use on the Moon. Instruments developed for robotic (rover) use on Mars or other planetary surfaces may also be adapted for astronaut use on the lunar surface.

It may be desirable for some geologic samples, particularly polar volatile samples, to be returned under environmentally controlled conditions. Non-reactive and hermetically sealed containers (i.e. SESC) would preserve volatiles but not chemical speciation. While SESC combined with refrigeration could preserve volatiles and speciation. Such freezers are also highly desired by the biomedical community for returning samples. Cryofreezers like GLACIER, developed for the ISS, can be easily adapted for lunar needs, provided that the power infrastructure in Constellation vehicles matches those of Shuttle and ISS. The current GLACIER configuration draws about 180 W at 28V, aircooled on ascent in the STS middeck.

Some assumptions need to be made about which instruments will be book kept under "science" as opposed to those which fall under situational awareness, communication, etc. While helmet cameras or rover-mounted cameras, for example, may be co-opted for science, these are not considered science instruments. However, a handheld camera or microscopic imager whose main purpose was science would be considered a science instrument (See Table 5 in section 3.8).

3.6.3 Capabilities for sampling the lunar surface

Sortie missions: Handheld and rover-mounted power tools (see section 3.1) and instruments (see section 3.2) will be utilized on missions of all durations. Handheld analytical instruments (see Section 3.2) and power tools for sampling rocks (i.e. rock corer) will require power. These tools and instruments should be battery operated with the ability to recharge from the rover. Rover-mounted power instruments might include ground penetrating radar (GPR), spectral imager, and magnetometers. A drill capable of reaching several meters into the soil could be rover mounted or stand alone.

Outpost Operations: Long stays at an outpost will provide the opportunity to collect more samples and the luxury of time that sortie missions do not afford. It will therefore be advantageous to have tools and instruments available at the outpost to assist in high-grading samples, in addition to those used on sorties. Such instruments and tools will likely initially include a microscope with camera and a rock splitter, neither of which requires large amounts of power. More sophisticated equipment may also be desired, particularly as outpost capabilities expand. These may include more sophisticated laboratory versions of the field analytical instruments (XRF, XRD, Vis/NIR spectrometers). Power planning for the outpost should be designed so as not to preclude such instruments from operating in the future.

Table 4. Power requirements for instruments of interest

Power needs	Apollo	ISS	Earth	Begin designed/Mars instrument		
EVA						
XRF	n/a	n/a	~200-600W	CMIST >5W	CHEMin ~10W	MOXTEK XRD/XRF ~5W[6]
Vis/NIR spectrometer	n/a	n/a	ranges from >100W to <3W			
Drill	430W[4]	n/a	10s of kWs	Swales ~90W	Honeybee MARTE ~150W[2]	JSC/Baker Hughes ~60W
rock corer	n/a	n/a	100s of Watts to 10s of kWs	Mars Rock Corer >2W[1]	USDC >5W[3]	Honeybee CRUX ~10W[2]
microscopic imager	n/a	n/a		Athena/MER rover 0.1 W[8]		
GPR	n/a	n/a	>10W to <100W[5]	CRUX mini GPR ~1W		
In hab						
Microscope/ camera	n/a	n/a	20-30W Halogen/7-15W Fluorescent			
Rock splitter	n/a	n/a	Up to 10s of kWs	Manual - No power needed?		
XRD	n/a	n/a	ranges from several thousand Watts to ~100W[7]	MOXTEK XRD/XRF ~5W[6]		
Raman	n/a	n/a	100s of Watts (benchtop) to 10s of Watts (handheld)	Athena rover 2.5 W[8]		
Return						
Refrigeration	n/a	GLACIER 180W				

[1]http://www.lpi.usra.edu/meetings/lpsc2002/pdf/1419.pdf

[2]http://www.lpi.usra.edu/meetings/lpsc2008/pdf/1355.pdf

[3]http://ndeaa.jpl.nasa.gov/ndeaa-pub/SPIE-2001/Paper-SPIE-4327-55-USDC.pdf

[4]Familiarization and Support Manual for Apollo Lunar Surface Drill, MCR-71-35 (1971) Martin Marietta Corp.

[4]Final Report of Apollo 17 Lunar Surface Drill Mission Performance, MCR-73-18 (1973) Martin Marietta Aerospace.

[5]http://www.geophysical.com/sir20.htm

[5]http://mission.sfgov.org/OCA_BID_ATTACHMENTS/FA2495.

[6]http://www.moxtek.com/PDF/Publications/SIMULTANEOUS_XRDXRF_WITH_X-RAY_TUBES.pdf

3.6.4 Specific engineering recommendations

There are currently two requirements in the EARD dealing with providing power for science use: Ex-0074 and Ex-0077.

> "[Ex-0074] The Constellation Architecture shall have the capability of supplying outpost surplus power to systems or payloads.
>
> *Rationale: Power systems are designed to meet a nominal power requirement plus a design margin throughout the power system's lifecycle. Depending on the power system design, there may be times when a power system generates power that is not required by nominal systems. For example, a solar array with a battery backup would be designed to meet power requirements for the worst case illumination lunar cycle (local winter) at end-of-mission. For all other times of the year, surplus power would be generated. The power system should be designed such that such surplus power could be made available to any additional new payload or system. The power system would provide access (i.e. ports) but the new systems or payloads would need to include any additional subsystems, such as thermal radiators that are needed to use the surplus power.*"

> "[Ex-0077] The Constellation Architecture shall provide at least (TBD-EARD-031) of power to support requirements other than infrastructure and logistics needs (e.g., scientific research, commercial, Education and Public Outreach (EPO), International Partners, etc.) during crewed lunar missions.
>
> *Rationale: This requirement provides a power allocation to enable transport of material to and from the Moon in support of scientific research and other external users. The requirement helps to block the tremendous pressures that occur during the operational phase of a program that push out scientific research and other external users in a critical manifest. A significant portion of this allocation is expected to be used by science, including conditioned biomedical, although the exact makeup will not be known until the operational phase of the Architecture. The allocation could be used by International Partners, commercial users, as well as for EPO activities. ISRU demonstration products fall within this category, but ISRU production products do not.*"

The statements above are generic and the levels are stated as TBDs (To Be Determined). Several more specific engineering recommendations for power requirements resulted from this review.

(1) Rovers must have sufficient power to run rover-mounted instruments throughout the duration of an EVA. Some tools will be used continuously on traverse, others will be used intermittently at targets of opportunity.

(2) Rovers must have the capability to provide power to recharge battery-operated handheld tools and instruments. Small handheld tools, such as rock corers, and instruments, such as cameras and spectrometers, will rely on battery packs, which will need to be recharged from the rover.

(3) The return vehicle must have the capability to support the power needs for environmental control (refrigeration at or below -80 C) for geologic and biologic samples.

(4) The outpost laboratory needs to provide sufficient power to support near-term needs, with the ability to expand to support future needs. The rationale behind this recommendation is that early outpost geologic science will likely include power-consuming equipment such as computers and a glovebox with imaging capabilities. As the outpost grows, the laboratory needs will also grow with more complex and

powerful analytical instruments that will require greater power. This increased laboratory capability will help high-grade samples, help plan and prepare for future traverses, help satisfy feed-forward needs, and allow some special samples to be analyzed immediately on the Moon rather than transported to Earth.

3.6.5 Analyses required prior to establishing recommendations

Power needs are derived from an understanding of the tools and instruments that will be utilized. Therefore, instrument and infrastructure design teams must effectively communicate their power needs as tools and equipment are agreed upon. Prior to that, sufficient reserves for power must be carried.

Findings:
(1) The rovers must have sufficient power to supply rover-mounted instruments and have the capability to recharge battery-operated handheld tools and instruments.
(2) Rovers should have sufficient power to also run rover-mounted science instruments (e.g., drill, GPR, etc.).
(3) Return vehicles must support the power needs for environmental control (refrigeration) for geologic and biologic samples. These needs are to be determined.
(4) The outpost should provide sufficient power to support near-term needs tied to "high-grading" samples, using sample analyses to provide data for planning future EVAs, and sample science, with the ability to expand to support future needs.

3.7 *Crew Requirements for Sample Acquisition and Curation during the Geological Exploration of the Moon*

3.7.1 Lessons Learned from the Apollo Program.

The scientific exploration of the Moon requires crews that have the abilities to identify and select scientifically important samples for return to Earth (i.e. recognize sample diversity, capable of high-grading samples) and to place these samples within the context of geological observations (i.e. identify location, relationship of samples to surface geology). These abilities require highly skilled and experienced observers. Many of these observational skills can only be acquired by extensive, hands-on field work in a variety of geologic settings. This is how academia trains professional geologists, and how the Apollo astronauts were trained. Future crews will have to undergo similar field- and class room training to become proficient and competent geologic observers and explorers. Obviously, geologic field operations will differ dramatically between Earth's shirt-sleeve environment and that of the Moon, the reason why all crews, even professional geo-scientists, will also have to undergo extensive training related to operational aspects and constraints. The following section addresses the basic approach and infrastructure needed to develop and acquire the observational and operational skills necessary for future lunar explorers.

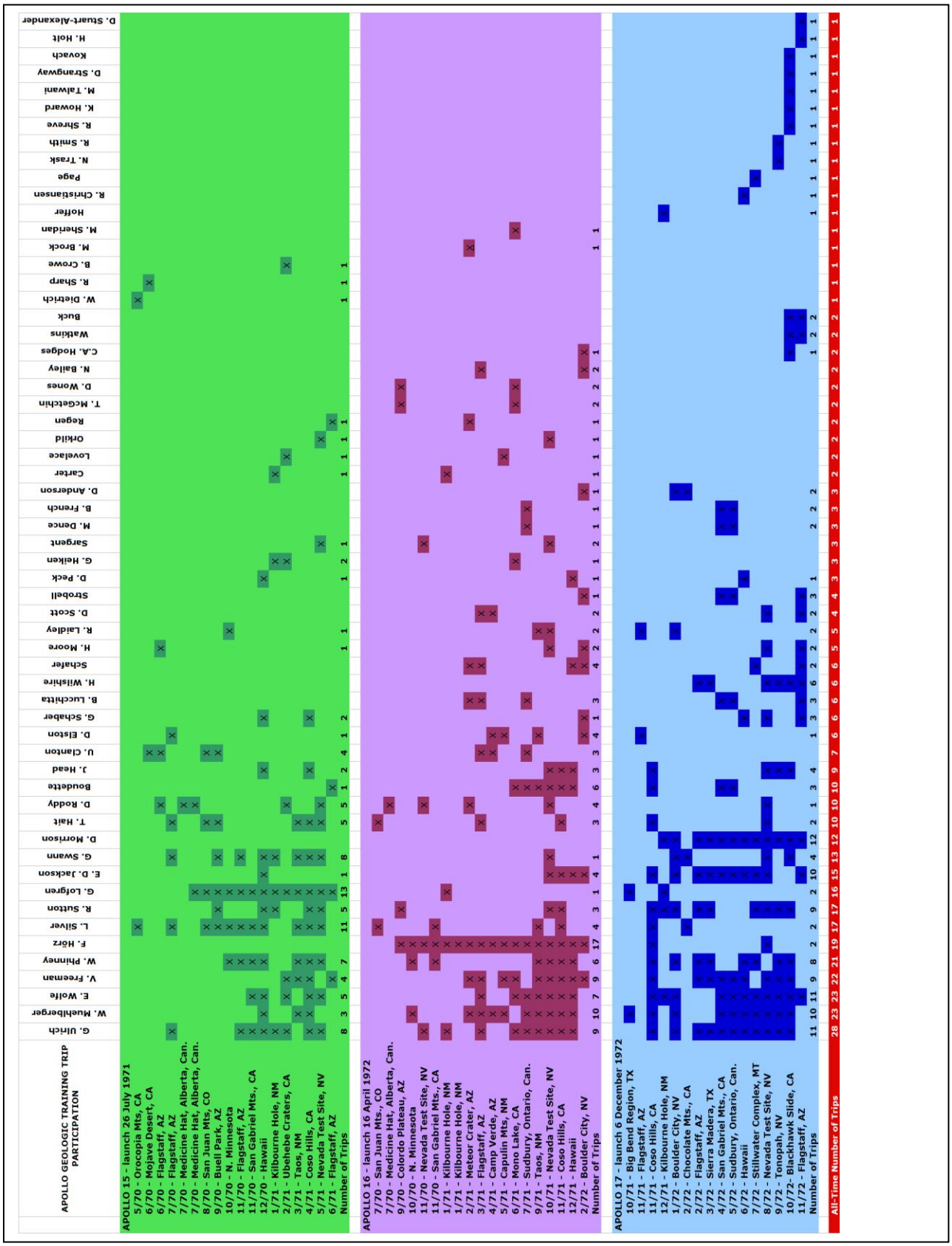
This review identified the position of *Field Geology Principal Investigator (PI)* as a critical role in the success of surface science operations during Apollo. The Field Geology PI was responsible for the direction of field training, traverse design, and overall final decisions related to field operations. Under the

direction of the Field Geology PI a rigorous training campaign was implemented to provide all potential lunar astronauts with a thorough field geology background prior to their actual mission. Figure 14 shows the Apollo 15, 16, and 17 field training sites and the geologists that took part in each field excursion. Between May, 1970 and June 1971, 29 geologists trained the Apollo 15 crew and backup crew during 18 field trips to 13 different field sites. Between July, 1970 and February, 1972, 40 geologists trained the Apollo 16 crews during 19 trips to 15 different sites, and between October, 1971 and November, 1972, 44 geologists trained the Apollo 17 crews during 16 trips to 14 sites. A total of 59 geologists were involved in the Apollo 15-17 crew field geology training, collectively taking a total of 375 individual trips to a total of 27 different locations.

Here, we reference the total science training for the Apollo 15 crew (Per. Coms. Dean Eppler, 2009). Comparable training hours were devoted to the Apollo 16 and 17 crews (Figure 15). Prior to mission selection and subsequent mission specific training each Apollo astronaut experienced ~ 375 hours of general scientific training. Following mission assignment, each crew and backup crew went through mission specific science training. These curriculums involved ~ 80 hours of general science lectures, ~ 20 hours of PI briefings, ~ 80 hours of orbital geology training, ~ 12 hours of lunar sample training, and ~ 470 hours of geologic field training at the sites listed in Figure 15. As a result, each Apollo astronaut had experienced 1030-1040 hours of science training when they arrived at the Moon. These values include the protocol/procedure training, but each astronaut received additional training in the use of and deployment of science packages and instruments (e.g. ALSEP, penetrometer device, neutronprobe, etc.).

Apollo science instrument tests and crew training activities can be divided into different training styles: 1) equipment tests under conditions relevant to crew operations on the lunar surface, 2) basic training of crew members in geology, both from a general perspective and at a professional level of expertise for landing site specific analog terrains, and 3) integrated simulations of science traverses, including operational procedures and constraints, at relevant analog field sites. The success of this approach was the result of focusing on a specific training aspect or goal for each activity so as not to confuse the participants between training objectives. For example, ALSEP deployment and operations were generally practiced in pressure suits to train the participants in mission relevant conditions (training style 1 listed above), whereas non-mission specific geology training was conducted in a “shirt sleeve” fashion (training style 2). Mission-specific simulations and traverses were conducted with Portable Life Support Systems (PLSS) volumetric simulators, and with camera equipment and sampling tools that exercised the conditions under which the crew would have to work on the lunar surface. These field-based, mission-specific training simulations were conducted with CAPCOMs and science support rooms to support the crew. This level of interaction was critical for the success of the surface operations on the

Figure 14. This chart (Personal Communications, Dean Eppler, 2009) displays the science analog and training sites used during the Apollo 15 (green), 16 (purple), and 17 (blue) missions. For each field site an X marks which participants (listed at the top) were involved in the training exercise. This level of involvement for crew training should serve as a starting point from which Constellation astronaut surface science training begins.



Moon, was important both for training the astronauts, as well as the mission operations participants in Mission Control at MSC/JSC, Houston.

3.7.2 Improvements since the Apollo Program

Lunar surface operations should build from the success of the Apollo Missions, but will involve new technologies. Apollo tool functionality has been discussed (Allton, 1989). Some Apollo tool designs are likely to be enhanced or altered and some new tool designs might be developed (see section 3.1 in this document). The development of crew requirements will also likely involve the use of new analytical instruments, both handheld and rover mounted, as well as inside the lunar outpost. These instruments will play an important role in sample identification. Recommendations from this group for the development of such instruments are presented in section 3.2 of this document. Crew interactions with the CAPCOM and science support room will greatly differ from Apollo. Technology advances in communications, cameras, and video feeds will enable near real-time observation of astronaut activities by a science support room and hand-held instruments might provide near real-time analyses. Furthermore, some rover-mounted instruments might be remotely controlled by the science support room independently of astronaut operations.

Technological advances will result in new rover and equipment designs. In as much as the rovers will control the ability of astronauts to identify, document, collect, and curate samples, these advances will certainly influence the new crew skills and requirements. Beyond the vehicle and equipment, a lunar outpost should include analytical capabilities that increase through time. The ability to analyze samples on the lunar surface prior to decisions related to sample return to the Earth involve new skills related to science analysis and curation procedures. Likewise, outpost operations will also involve astronaut interactions with the CAPCOM and science support room.

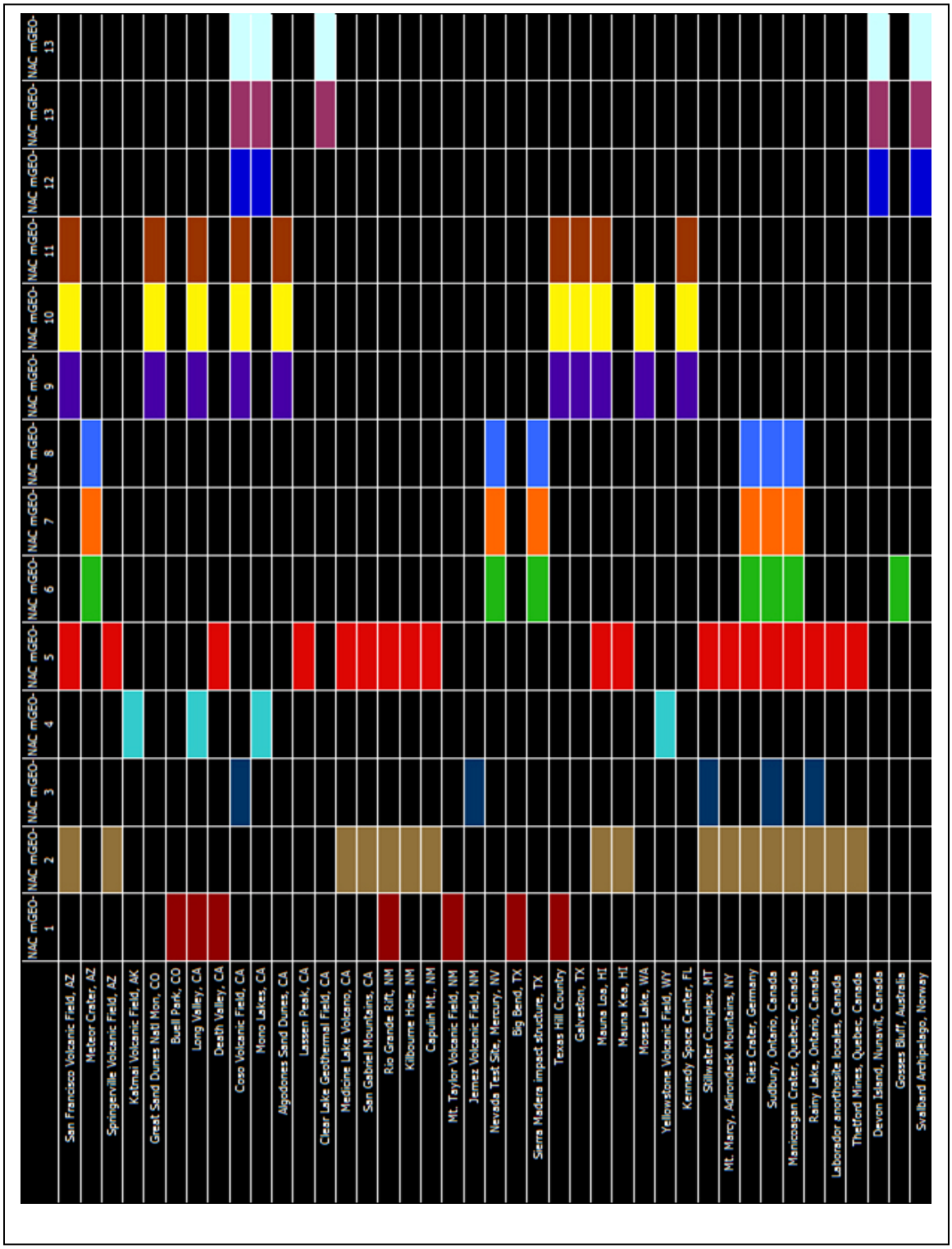
3.7.3 Capabilities for sampling the lunar surface

Sortie missions and Outpost Operations: As presented in Sections 3.1 -3.4, astronauts will be required to be trained in a number tasks tied to sampling. These tasks include the utilization of sampling tools, analytical instruments, and sample containers. They must also be concerned about following contamination control, selecting diverse samples, creating a sample inventory, and making geologic observations that are tied to the collected samples.

3.7.4 Specific recommendations

Our recommendations for crew requirements are focused on crew training. Crews returning to the Moon must have a level of scientific training that is, at a minimum, comparable to the Apollo crews. Although several sections in this document are divided into Sortie and Outpost specific recommendations, we recommend that all Constellation astronauts be trained to the same scientific level regardless of their background training or potential planned participation in sortie or outpost missions. It is reasonable to

Figure 15. This chart (Personal Communications. Dean Eppler, 2009) shows the results of a workshop designed to define appropriate science analog field sites to match the NAC lunar science objectives. This type of study should also be conducted to match the LEAG objectives to sites that will be used in the Constellation Program Office astronaut training curriculum.



assume that outpost science operations might differ from sortie science operations, but all astronauts should be proficient in the skills needed to achieve the science objectives in both styles of missions. It is also reasonable to assume that crews will include science or curation leads or experts. Therefore, we recommend that each science mission include at least one crew per every two astronauts with background training (prior to astronaut science training mentioned in recommendation 1) as a geology expert. This recommendation is consistent with current ESMD field tests and ensures that every rover mission will have at least one geology expert per rover. We also recommend that each outpost mission include at least one curation/inventory management expert. For example, the Apollo 17 crew included Jack Schmitt who was trained as a geologist prior to the Apollo missions. However, he also participated in all Apollo science training sessions. Therefore, he was trained to the same level as all other Apollo crew members in operational matters, but he also possessed a geology background beyond that required for other Apollo crews.

The success of Apollo surface science operations was the result of the leadership of the Field Geology PI. Therefore, we recommend that a Lunar Surface Geology Principal Investigator position be established and filled as soon as possible to oversee all surface science operations on the Moon. As in Apollo, The Lunar Surface Geology PI will be responsible for directing the field training campaign for the astronauts, lunar surface traverse design, and will make final decisions for most field operations. Under the guidance of the Lunar Surface Geology PI all astronauts should be trained for efficiency in the following areas: 1) fundamental field geology skills, 2) hand specimen petrography, 3) sample collection tool use and protocols (see section 3.1), 4) science instrument use (see section 3.2), 5) navigation and rover operation, 6) sample collection protocols (see section 4.0), 7) outpost laboratory analytical capabilities, and 8) science support room interaction.

The Constellation astronaut training program must also begin identifying sites where their personnel will be educated. As in Apollo, the Constellation training can be broken down into three categories, 1) instrument/tool training, 2) basic geology training, and 3) integrated simulations. Equipment tests under conditions relevant to crew operations on the lunar surface need not require specific scientific analogs in remote locations. Training the crew to use specific instruments or tools can be conducted in pressurized suits to simulate lunar conditions while at NASA field centers both in laboratory high-bays or "rock yards". Analog science curriculum will require geology and petrography classrooms in the field and therefore the identification of appropriate geologic sites. For each site a specific geologic problem should be clearly identified and the approach to teaching those geologic principles should be well drawn out. Integrated simulations of science traverses at relevant analog field sites will again require travel to the appropriate geologic sites, but must also include those team members who are to be trained for participation as science support room personnel.

Basic geologic training can occur over a significant number of sites in North America, and advanced geologic training tied to specific mission plans will require unique sites to be identified. Thus, we recommend that once a Lunar Surface Geology PI is identified, a training curriculum be established and the proper sites identified for all three training and teaching categories. However, we caution against the temptation to send crews to any and all lunar analog geology sites. Each analog site must have a well defined teaching/training goal. The logistics cost of using multiple sites for the same purpose could be detrimental to the program. The cost/benefit balance of any potential site should be well established and should always be a critical factor in site selection. Efforts should be made now to revisit the Apollo analog and training sites to determine if they remain unmodified and appropriate for the education and training of the next generation of lunar astronauts. For example, some of the man-made crater fields in Flagstaff are known to be eroded and one was converted into a residential neighborhood. These represent educational losses from the Apollo-era that must be accounted for in the new training campaign.

As well as field geology education/training, petrographic training of the Apollo astronauts relied not only on field trips, but class room activities introducing rock forming minerals and hand specimen petrography. The Apollo collections of minerals and rocks must be replenished and expanded to include more crustal lithologies and rock specimens. In this endeavor the lunar rock collection must be consulted extensively. Furthermore, astronaut science education and training during Apollo was essentially a collaborative effort between NASA MSC (JSC) and USGS Flagstaff personnel. The ability of NASA and USGS personnel to lead the astronaut training effort for Constellation should be assessed. Personnel needs within NASA and the USGS should be identified and addressed, both through personnel hires and the inclusion of participants from within academia to ensure that a well rounded education and training team is in place as Constellation moves forward. Developing the training team at an early stage ensures a knowledgeable base of participants from which the Lunar Surface Geology PI can form a science support room with experience in all stages of astronaut education and training activities.

3.7.5 Analyses required prior to establishing recommendations

Some scientific analog and training sites that were used during the Apollo missions are likely still useful while some might no longer be reasonable due to urban development or other types of changes. As such, a review of which geologic principles are no longer easily taught at the available sites should be compiled. This will serve as a starting point for selection of Constellation science analog and training sites to educate or train for specific purposes within the training curriculum. Although many USGS and NASA technical reports were written prior to and during Apollo, designed as field guides for science analog and training sites, this style of documents has not been supported in the subsequent 3 decades. This style of report, however has become a method of teaching in academia during that same time period and as such an effort should be made to review science analog sites that are currently in use among scientists to enable the

education of the next generation of planetary scientists. This review would complement a review of Apollo sites and provide a strong base from which to design the Constellation science analog and training site curriculum. At this time the Lunar Exploration Analysis Group is developing a set of scientific objectives for the exploration of the Moon that will likely serve as the primary exploration roadmap. As these goals are established and accepted within the scientific community a review of LEAG goals with respect to analog science sites should be established.

Findings

1) All Constellation astronauts must undergo scientific and operational training regardless of their background or potential planned participation in sortie or outpost missions. The level of training all astronauts must be exposed to needs to be established.
2) Each science mission must include at least one crew per two astronauts with background training as a geology expert, and outpost missions should include at least one curation/inventory management expert.
3) A Lunar Surface Geology Principal Investigator position should be established within the Constellation Program Office.
4) All astronauts should be trained for efficiency in/with the fundamental field geology skills, hand specimen petrography, sample collection tool use and protocols (see section 3.1), science instrument use (see section 3.2), navigation and rover operation, sample collection protocols (see section 4.0), outpost laboratory analytical capabilities, inventory and data management, and science support room interaction.
5) A training curriculum needs to be established and the proper sites need to be identified for all three training and teaching categories. Establishing the curriculum should involve identifying geology trainers, reviewing the Apollo field sites for their current utility to teach astronauts the above skills, and identifying potential science analog training sites that are currently in use within academia.

3.8 Communication Requirements for Sample Acquisition and Curation

3.8.1 Introduction

Compared to Apollo, modern electronic and digital capabilities will revolutionize how we operate on the lunar surface with crews and machines, and how we communicate observations and instrument data to Earth. These vastly improved capabilities will be highly beneficial to all aspects of lunar surface operations, including sample acquisition and related science.

Note for instance, that Apollo used film-based Hasselblad cameras to document all of the local geology, rocks, and surface operations; not only did each mission have a limited film budget (approx. 1000 frames for all surface activities for each of the J-missions), but the film had to be returned to Earth for development, days after the actual lunar surface operations. While there was a TV camera on the Apollo-rover, primarily as a navigation tool, it was not suited to document most science activities; all of the science support room thus relied substantially on voice communications to follow the crew's progress, as practiced and practiced and practiced during numerous field trips. The future astronaut will have a helmet-

or suit-mounted, continuous-stream video-device that can capture the geologic context at a variety of scales in real time, that portrays which specific rock was collected, and that can reveal surface texture or grain size of individual rocks. Modern capabilities seem thus wildly improved over Apollo, yet even modern communication devices have their limits in terms of size, mass, power, and especially data rate, as well as crew time to activate and operate each system.

Communication in the present report refers to the transfer of four types of information from the Moon to Earth:

1) Voice transmission of crews operating on the lunar surface
2) Navigation data for diverse mobile assets and crews
3) Transmission of diverse imagery form both still- as well as video cameras
4) Measurements and data from science instruments.

Obviously, some of this information must be available in real time, such as voice loop or navigation, but some may be stored temporarily for later transmission at more suitable times, such as certain images or specific instrument data. All communication loops with crews, rovers and science instruments must also operate in reverse, going form Earth to the Moon, yet the latter exchanges and transmissions will be of much smaller scope than the former. Most of the Moon-to-Earth communication, commonly refered to as "surface-to-ground" must be available to the science support room, presumably at JSC, yet possibly also at distributed locations in the form of a virtual support room (e.g. robotic precursor missions or a specific science instruments).

Details of the overall communication architecture for Constellation and specifically for lunar surface operations are currently being defined and evaluated. Given the rapidly changing capabilities of modern electronic devices, this is obviously an evolving and major undertaking beyond the scope of this report. A number of communication devices, such as essentially all audio loops, navigation information, and many video streams will also be needed by general Mission Operations, as they relate to situational awareness, hazard recognition, and ultimately to the safety of crews and machines. Many of these communication devices will also be critical for the science operations, and it is expected that many can be shared among diverse users, including science. As a consequence, we distinguish in this report among 1) "operational" devices (e.g., voice loop, navigation, diverse cameras, etc.) that are already being designed and integrated into the overall communication architecture, and 2) additional devices and instruments entirely dedicated to the conduct of science, that will also have to be accommodated by the overall communication architecture. All of these science-related devices are currently in development; estimates and projections about some of their resource needs can be found in the instrument chapter of this report.

3.8.2 Capabilities for sampling the lunar surface

Introduction: A brief summary of the communication needs currently recognized by the science community is presented in Table 5. The report below will enlarge on this table and provide details about

the general purpose and need for individual systems. The latter merely represent first order, general descriptions and lack technical detail; they must be viewed as generic placeholders. This is in part on purpose and in part by necessity; the general field of communications and science-instrument design is simply evolving so rapidly that it is difficult to predict specific capabilities and resource needs for the specific time frame(s) by which the electronic design of these systems has to be frozen in. As a consequence, all of the cameras and science instruments listed in Table 5 are still under evaluation, if not development. Also, the option must be kept open for new systems that come on line that are not even part of current plans. Clearly, Table 5 needs periodic updating as both the operational systems and those needed by the science community evolve and mature. This updating should be conducted jointly by all stake holders of the overall communication architecture, with science being a critical part thereof, as it will have to support the science-driven objectives of future lunar surface operations.

Table 5 and this report are organized by major communication requirements: 1) Voice, 2) Navigation, 3) Imaging, and 4) Science Instruments. Emphasis is on the imaging and instrument categories, with each category being organized by the surface system, such as rover, crew, robot etc., that serves as "*platform*" of a specific device; the "*location*" specifies, where possible, a desirable mounting location within a specific platform. We also distinguish in Table 5 among systems that are 1) most likely provided by diverse operational elements within ESMD, and that hopefully can be shared with "science", and 2) systems that are exclusively dedicated to science, and thus most likely provided by SMD and/or other science organizations. We denote these differences for brevity by their expected provider/owner as "*ops*" (= Missions Operations/Constellation) and "*science*" (= Science Organizations). There are also suggestions of which devices will have to operate "*continuously*", and which will operate intermittently "*on demand*". Where possible some typical optical characteristics, such as "*focal plane*" and "*resolution*" are also presented, as well as which data must be transmitted in "*real time*" and/or in "*delayed*" fashion. Finally the "*power source*" is identified as well as the number ("n") of devices for 2 paired crews/2 rovers, and a single Geostation or robotic explorer. Also, a single set of handheld analytical instruments may readily be shared among a crew of two.

1) Voice communication. Science needs access, in real time, to all voice communications between crews and ground that involve the topic of science and lunar surface exploration. It is also paramount that the science support room on Earth has the means of communicating in real time with the crew on the Moon to provide timely assistance and guidance on their activities. It is hoped that the Constellation astronauts have a less hurried surface schedule than those of Apollo, and that they exercise their geologic judgment more freely and more often, necessitating on occasion intense interaction with the science support room. Ready access to some transcript of the voice communications is also a must for the efficient conduct of the science support function.

Table 5. Elements of communication that must be in place for the successful conduct of lunar exploration science.

	Platform/Device	Location	"owner"	Operation	Foc.Plane	Res.	Real time	Delayed	Power source	n
1)	VOICE	Multiple	ops	continuous			yes		varies	1
2)	NAVIGATION	Multiple	ops	continuous		< 10 m	yes		varies	1
3)	IMAGING Systems									
3a)	ROVER									
3a.1)	Video 1, Gigapan	Mast	ops	continuous	1m	1 cm	yes		Rover	2
3a.2)	Video 2	Aft-pointg	ops	continuous	1m	1 cm	yes		Rover	2
3a.3)	Video 3	Forwd. Pointg.	ops	continuous	1m	1 cm	yes		Rover	2
3a.4)	Digital Microscope	on chassis	science	on demand	Special	< 5 um	yes	yes	Rover	2
3a.5)	Video 4, hand held	Inside	ops	on demand	0.1- 0.2 m	<1 mm	yes	yes	Rover	2
3a.6)	Still, hand held	Inside	ops	on demand	0.1 m	10 um	yes	yes	Rover	2
3b)	SUITED CREW									
3b.1)	Video, Helmet	helmet	ops	continuous	0.1 m	<20 um	yes		PLISS	4
3b.2)	LED Display	visor? TBD	ops	on demand	n/A	n/A	yes	no	PLISS	4
3b.3)	Still Camera	chest mounted	science	on demand	0.1m	<10 um	yes	yes	PLISS	4
3c)	OUTPOST									
3c.1)	Video 1, swiveled	exterior, central	ops	on demand	1 m	1 cm	yes	yes	OUTPOST	1
3c.2)	Video 2, hand held	interior, central	ops	on demand	0.5 m	1 mm	yes	yes	OUTPOST	1
3c.3)	Video 3, hand held	interior, Geostation	science	on demand	0.2 m	100 um	yes	yes	OUTPOST	1
3c.4)	Still, hand held	interior; Geostation	science	on demand	0.1 m	10 um	yes	yes	OUTPOST	1
3c.5)	Digital Microscope	interior; Geostation	science	on demand	Special	<5 um	yes	yes	OUTPOST	1
3d)	ROBOTIC EXPLORER									
3d.1)	Video 1, swiveled	Mast	science	continuous	> 1m	1cm	yes	yes	Expl. Robot	1
3d.2)	LIDAR	Mast	science	on demand			yes		Expl. Robot	1
3d.3)	Still Camera (Close up)	chassis	science	on demand	> 0.1 m	0.5 mm	yes	yes	Expl. Robot	1
3d.4)	Digital Microscope	chassis	science	on demand	special	<5 um	yes	yes	Expl. Robot	1
4)	SCIENCE INSTRUMENTS									
4a)	ROVER									
	Bulk Composition	chassis/mast	science	on demand			yes	yes	TBD	2
	Mineral Composition	chassis/mast	science	on demand			yes	yes	TBD	2
	Geophys. Instruments	chassis	science	on demand			yes	yes	TBD	2
	Geophys. Instruments	surface deployed	science	continuous			yes	yes	TBD	2
4b)	SUITED CREW									
	Bulk Composition	Crew, hand held	science	on demand			yes	yes	self/battery	2
	Mineral Composition	Crew, hand held	science	on demand			yes	yes	Self/battery	2
4c)	OUTPOST									
	Bulk Composit.	Geostation	science	on demand			yes	yes	OUTPOST	1
	Trace Elements	Geostation	science	on demand			yes	yes	OUTPOST	1
	Mineral Composit.	Geostation	science	on demand			yes	yes	OUTPOST	1
4d)	ROBOTIC EXPLORER									
	Bulk Composit.	Geostation	science	on demand			yes	yes	Expl. Robot	1
	Mineral Composit.	Geostation	science	on demand			yes	yes	Expl. Robot	1
	Geophys. Instruments	chassis	science	on demand			yes	yes	Expl. Robot	1
	Geophys. Instruments	surface deployed	science	continuous			yes	yes	Expl. Robot	1

2) Navigation: A variety of navigation methods are currently being evaluated by Constellation; we consider any system with an accuracy of 10 m sufficient for general exploration objectives and geological

field activities by suited astronauts. The latter assumes continuous video coverage, such that additional triangulation and positioning is possible should a more accurate position, within Constellation's reference coordinates, be needed for special purposes.

It is likely that improved suit designs will permit individual astronauts to conduct most sample-related surface operations independent of their paired partner, unlike Apollo; separation distances among crew members of 100 m, possibly more, may thus be allowed, and it seems highly desirable that each astronaut carry his or her own navigation tool/position sensor (which should also have an accuracy of 10 m) while conducting geologic field work.

3) Imaging: As stated in the introduction, science has vital interests in most any imaging system that provides situational awareness at all times and that therefore contributes to the safe conduct of lunar surface operations by both men and machines. As a consequence, most any major surface asset involved in surface exploration already contains a camera, in most cases even multiple imaging systems.

4) Analytical instrumentation data: As was stated in section 3.2, analytical instrumentation will be available with individual astronauts, on rovers, and in the outpost. During various stages of the evolution of lunar exploration, it may be necessary to communicate this data among numerous individuals involved in the mission (i.e. astronauts, the science support room, and the outpost).

Rover Capabilities during sortie and outpost operations: The Lunar Electric Rover (LER) is equipped with a number of cameras, all related to situational awareness, some contributing to navigation. The following 3 cameras are of specific interest to science that can be accommodated on the LER during sortie and outpost surface activities.

1) The LER Mast Camera is located on top of the LER Mast; its current incarnation is commonly referred to as "Gigapan" camera, as it can be rotated 360^0 and elevated between 0 and 90^0. It typically takes many individual images that are being stitched together into a seamless mosaic via onboard software. The size and resolution of individual images is controlled by selection of the camera's focal length; a full panorama at maximum resolution may be composed of hundreds of images and may take some 30 min to complete; lower resolution panoramas may take as little as 5 minutes. Also, physical movement of the camera head can be controlled to provide partial panoramas and high resolution images of select areas that may be visited and explored by the crews. Line of site permitting, this camera is highly suitable to provide a high-resolution overview of a prospective sampling "station" and will thus be of great scientific use.

2) The LER, Forward Pointing Video camera will operate while the rover is moving; it will provide a continuous video stream of the local scene in the forward direction; it is mounted, however, on a swivel and can look sideways as well. This camera will thus capture most of the local geology during LER drives. Its viewing angle can be adjusted remotely as well as by the crew inside the pressurized cabin. This

camera is thus of great utility to image the local scenery and to establish the geologic context for either predetermined or spontaneous, sampling stations.

3) The LER, Rearward Pointing Video camera is identical to the forward pointing device and fulfills the same operational as well as scientific role(s). Additionally, this camera will be particularly useful in documenting a specific station which the crew is about to explore. Note that the suit-ports are also pointing rearwards. Once a crew determines that a specific "station" was reached and is indeed worthwhile to be explored on foot, they will position the rover such that its rear points towards the prospective station. This will allow for two things: 1) the rear camera can be used to document the sampling station during the 10 min egress and 2) having the suit ports facing towards the rear, the crews themselves will have some time to observe the local scene, once in the suit. Video images and crew observations will enable the support room to greatly assist in the crew's development of a sound sampling strategy before egress is complete.

In addition to these three cameras on the rover, it will be important for the astronauts to have a microscopic imager and handheld cameras. As discussed in section 3.2 (analytical instruments), on occasion it will be necessary to transmit a microscopic image to the support room for a more detailed understanding of the component minerals and/or texture of rocks and soils. For this purpose, a Digital Microscope will have to be incorporated on the rover's chassis, preferably in vicinity of the tool pallet. Suitable compact devices are available commercially and need detailed evaluation; all will take minimal handling by the crew.

The geologically skilled and trained astronauts will observe the local scenery during extended drives, some lasting as long as 60 min, if not longer (during the more mature phases of lunar surface exploration). They are thus the major source of information about any changes in the local geologic setting and they need a hand held video camera to document specifics. The geologic observations made by the crew and documented via hand held video will be greatly augmented by a still camera that has more powerful optics, possibly different lenses, suitable to provide close up images of the local ground as well as details in the far distance. This camera may be especially useful to evaluate rock statistics, both in real time as well as during long term analysis, thus placing the samples actually collected and returned to Earth within a broader and possibly more meaningful context. Images obtained from inside the cabin will also be useful in evaluating whether it makes sense to stage any planned or impromptu sampling activity.

<u>Suited crew during sortie and outpost sampling activities:</u> The actual process of selecting and acquiring samples will have to be documented by the crew itself. Their geologic judgment about the significance of any given sample will be the most critical ingredient in this process, yet photographic documentation of a sample's orientation and relationship to its immediate and local environment is critically important as well. For example, detailed textures and variable rock-types composing a large breccias boulder are best

documented photographically for more detailed analysis on the ground; such documentation may also include the track in the local regolith if the boulder rolled down some local slope; this track obviously may be used to reconstruct the boulder's source stratum. Photographic documentation is simply an integral part of geologic field work and especially of sample acquisition. All crews must therefore have suitable photographic equipment at their display in the field.

1) Helmet or Suit-Mounted Video Camera: Akin to the suit-mounted Hasselblads of Apollo, the Constellation astronauts will have a suit mounted imaging system, i.e. a capable video camera with freeze-frame features. This camera should be capable of taking close up images of rock surfaces at working distances of some 10-20 cm, and resolutions of better than 20 um. Ideally, this camera has wide-field optics, such that "aiming" of the camera and composing a specific image becomes relatively easy, even at close up range. These requirements are met by current devices that are being tested during Desert RATS field exercises. The specific documentation protocols for any given sample-acquisition are currently under development; they will, however, be more efficient than those of Apollo, leaving more crew time for observations and synthesis of the local geological setting.

2) LED Display: Having the above video camera mounted in either the helmet or on the suit implies that the crews will have to compose specific images simply by pointing the camera into a desired direction, akin to the "blind" shooting with the Apollo Hasselblad. This blind shooting took considerable practice for Apollo, yet was on rare occasions not accomplished very well. Desert RATS field tests have revealed, that this is a particular problem for close-up photography, say of a specific rock held at arm's length. Additionally, the crew does not know what images they produced and what is available to the support room. It is for this reason that we strongly encourage the development of an LED display, located either in the helmet's visor or on the crew's wrist. This display will allow the crew to truly "compose" specific images that contain the critical feature(s) of interest, and they will positively know what is being transmitted to the ground, especially for the individual "freeze frame" images that are intended to show important details. This display will also assist diverse operational aspects, the major reason why it is currently being considered for development. The simple point here is: "science" is keenly interested in such a display as well for the reasons mentioned above.

3) Handheld Still Camera: The need for a hand held still camera, most likely a capable SLR device, is currently being evaluated; its need is based on the assumption that it will yield superior images relative to the system as previously described. This assumption seems valid currently, but may not apply if sufficiently capable video cameras emerge in the next few years. We are thus only suggesting that a still camera be considered, if the development of video cameras are below expectations. The most cogent argument for inclusion of still cameras, however, is an operational one: they will serve as back-up imaging system in case the video camera fails. Documentation of geologic features and sample properties is simply

such an important aspect of lunar surface operations and sample acquisition, that a single point failure of the imaging system appears unacceptable.

Outpost capabilities for sampling the lunar surface

We consider both the exterior and interior of the Outpost as important locations related to the acquisition and processing of lunar samples for return to Earth. Clearly, many aspects of these operations are currently under development and poorly defined. Nevertheless, we are in a position to define some first-order, generic imaging requirements.

1) Video Camera monitoring Outpost's Exterior: This camera is mounted at some central location on the Outpost's exterior; its purpose is to monitor and document such things as manifesting the LER with the appropriate science equipment and documenting their stowage locations. Upon return from an EVA, no matter what duration, the collected samples will have to be transferred into suitable containers for Earth return and/or for additional processing in the Outpost's Geostation. Some Outpost scenarios entail a "rock garden", i.e. samples temporarily stored outside the Outpost and its Geostation; this sample collection will have to be photo-documented for inventory and curation purposes. Additionally, some science instruments may be deployed in close proximity to the Outpost, such as a geophysics package akin to the Apollo Lunar Surface Experiment Package (ALSEP). All of these operations will benefit from a video camera mounted on a suitable vantage point. It is further assumed, that detailed documentation, where needed, is accomplished by the crew-mounted video camera.

2) Handheld Video Camera in the Outpost's Interior: This camera is intended to compliment the above, exterior camera. It will be operated by a shirt-sleeved astronaut to document additional details of diverse, exterior operations, and it will monitor the sample transfer into the Geostation inside the Outpost.

3) Handheld Video Camera in the Geostation: The Outpost will be equipped with a Geostation; the latter is a small laboratory capable of supporting more detailed characterizations of individual samples via a modest compliment of analytical instruments. It also serves as a processing facility for lunar samples under the direction of the Curator, with the objective to select and ready specific samples or their subsplits for Earth return. A handheld video camera seems inescapable to document these activities; the Geostation is conceived as a stand-alone clean room, the reason why this camera will have to remain inside this station and be entirely dedicated to science.

4) Still Camera in the Geostation: Still cameras are an integral part of curatorial operations, documenting details of a sample's nature, such as grain-size, texture, distribution of microcraters and related lunar surface orientation of a rock etc. Such cameras are also needed to document the detailed step-by-step processing of individual samples. Highly capable SLR devices, with a selection of suitable lenses, seem superior to video devices in accomplishing these, on occasion rather demanding, tasks.

5) Digital Microscope: A digital microscope is essential for the Outpost's Geostation as it reveals surface details of any sample that cannot be duplicated by any other device. It will thus be the work horse in characterizing and selecting samples for more detailed studies by the Geostation's suite of analytical instruments. It is also indispensible for many sample processing operations aimed at selecting and preparing samples for Earth return. A number of seemingly suitable devices are commercially available and part of modern laboratories, as their digital output may be processed in numerous ways, unlike traditional, optical microscopes.

Robotic Explorer: Reconnaissance by unmanned robots should be an important part of both sortie missions as well as of more extended traverses from the Outpost. The proponents of unmanned explorers suggest that there are approximately 30 hours of unmanned robot time for every hour of manned surface activities; while these numbers may ultimately be incorrect, there is no doubt that robotic precursors can significantly assist in the planning and execution of manned activities. Imaging systems on board such robots, and other remote sensing instruments, will gather some first order ground information that will significantly improve upon the traverse planning that is otherwise solely based on remote sensing data, the latter exclusively obtained from diverse platforms in lunar orbit. Robotic explorers, provided they are capable of traversing the large distances commensurate with the LER capabilities, will thus be an important ingredient for the conduct of manned activities. This document is not the place to address the cons and pros of robotic versus manned exploration. We merely envision that unmanned robots will be part of the exploration mix. We thus must assure that their cameras and sensors are accommodated by the communication architecture of Constellation. Although some robotic exploration may be conducted on behalf of In Situ Resource Utilization (ISRU), possibly some operational objectives (e.g., trafficability) we nevertheless assume in this report that most cameras and sensors will be provided by science and for science.

1) Mast-Mounted Camera: Any robotic explorer will have a mast that houses instruments intended to survey the local surroundings from some vantage point. The Gigapan Camera described in 3a.1) is a natural candidate for such robotic reconnaissance, as there is ample time (TBD; hours) to produce complete panoramas at the highest resolutions. The latter should prove a valuable aid in refining and modifying the traverse planning based on orbital data. The utility of such camera systems is currently being tested during the Desert RATS field simulations.

2) Mast Mounted LIDAR system: While not a camera per se, this system nevertheless produces a 3-dimensional "image" of the local topography; the latter is not only useful in its own right, but may also be used for navigation purposes by acquisition and precise location of specific topographic features and landmarks.

3) Close-up Still Camera: The Gigapan Camera may be complimented by a capable SLR camera, especially one that can be pointed downwards to take close-up images of specific rocks and soils. The Gigapan Camera may be geometrically shielded from such a viewing geometry.

4) Digital Microscope: For the reasons outlined in 3.2 and above in 3.8, a digital microscope appears mandatory for any robotic explorer; such a system is essential to learn about a rock's minerals and texture, both combining in many instances into some first order assessment of the rock's formative processes and possible origins, such as volcanic, impact or sedimentary processes.

Science Instruments: An extensive suite of potential science instruments is described in section 3.2 of this report. The sole purpose of including them in this chapter is to assure that they are accommodated in Constellation's Communication Architecture. These analytical instruments may be associated with the suited crew, rover, outpost and a potential robotic exploer.

3.8.3 Specific recommendations

Most of the imaging systems and science instruments mentioned above are of fairly mature design; some even have considerable flight-heritage. Nevertheless, their detailed band-width(s) and duty cycles, which feed into the Constellation Communication Architecture, remain poorly defined at present. While some anecdotal information may be available for some devices, this information is not systematic, much less complete at present. Also note that to date neither a single camera nor science instrument has been selected for flight, as additional refinements are being envisioned and implemented in the near future. It is paramount that this development continue at a vigorous pace, and that a series of candidate cameras and instruments, or at least the specifications thereof, emerge. The latter may well vary from mission to mission, depending on specific mission objectives and the overall evolution of the major lunar science goals over the lifetime of Constellation. It is also paramount that all of these systems undergo rigorous field-testing in lunar analog environments, and that they be integrated into the operational scenarios of Constellation.

The specific requirements for the suite of science-sponsored imaging systems and analytical or geophysical instruments on the Constellation Communication Architecture are poorly known at this time; they can only be addressed with rigor once specific cameras and instruments are selected for flight and their duty cycles are known. As a consequence, their mention in this report should merely be viewed as a place holder(s) for devices to come on line over the next 5 to 10 years. Obviously, some sequencing and staging is mandatory in this development, as not all of the devices and instruments mentioned in this chapter need to be ready at the same time.

Findings:

1. The scientific exploration of the Moon and associated sampling mandates efficient transfer of voice, navigation, imagery and analytical instrument data from the lunar surface to the Earth and vice versa; detailed implications for Constellation's Communication Architecture are difficult to define, currently.
2. The navigation data should be accurate to 10 m or better.
3. The communication system must also accommodate a minimum of 6 continuous video-streams from 4 surface crews and 2 LER mast cameras.
4. We also conclude that NASA should accelerate the development of handheld instruments, to be operated by suited crews in the field, that measure the composition and mineralogy of rocks and soils, such that their communication requirements may be better defined.
5. Table 5 should be viewed as place holder for many individual devices that ultimately must be integrated into the Constellation Communication Architecture.

3.9 Flight Control Requirements for Sample Acquisition and Curation

3.9.1 Introduction

Communication and flight control are the two hallmarks of manned spaceflight. The image in most people's mind of how manned spaceflight is done involves, at one end, a human crew in a spacecraft or an EVA suit and, on the other end, a flight control team maintaining operational control over the overall mission. This control is managed through voice contact with the crewmembers, visual images of crewmembers in space, and data from systems and instruments that provide knowledge to a collection of experts about the minute-by-minute status of the spacecraft and the crewmembers in it and the activities of the crew in free space or on a planet's surface.

Throughout the history of manned spaceflight, the system of mission management has been based on a hierarchical system of rooms, all under the control of the mission's Flight Director, beginning at the "front room" with the principal Flight Controllers for each spacecraft system, such as the propulsion system or a particular mission function, such as navigation. "Behind" this front room is a series of "support rooms" where each principal flight controller is backed up by a group of experts with levels of detailed understanding not necessarily needed full-time in the front room, but whose expertise is important at critical times in a given flight. During Apollo, and when we return to the lunar surface, one of these support rooms will be devoted to science operations on the lunar surface.

The principal role of this "Science Support Room" (SSR for short, yet commonly referred to as "support room") in Mission Control is to assist the astronauts in the exploration of the lunar surface and to maximize the science return. Obviously, this mandates intense interaction in real time between surface crews and ground operations. While the discovery-driven acquisition of scientifically sound and useful data is of overriding interest to the science support room, it is recognized that crew safety is the highest priority concern at all times; none of the mission objectives can be accomplished without a safe and healthy crew and well maintained vehicles and other operational systems.

Major elements of the ground support infrastructure refer to the monitoring of the crew's health, of life-supporting consumables, accurate navigation data, status reports on suit-performance and lunar surface vehicle(s), communication links, and other equipment needed while exploring the lunar surface. As a consequence, the science support room not only interacts with the crews, but it must do so also with all other operational elements under the control of the Flight Director. This real time interaction among diverse ground support elements is also very intimate and commonly proceeds in highly iterative fashion; although well structured, this iterative decision-making process commonly mandates face to face meetings - the prime reason why the major decision makers should be co-located. It is our considered judgment, that the SSR be part of Mission Control at JSC in Houston; within this infrastructure, the SSR must be viewed as the final authority in rendering science-related recommendations and/or decisions to Mission Control and its Flight Director.

The remainder of this document deals with the specific roles and functions of this science support room. Commensurate with the specific lunar surface activities that may be pursued in parallel, such as reconnaissance via unmanned robots or activities within the Outpost's geological laboratory facilities, subsidiary support rooms can be envisioned. Specific teams of experts will compose these support rooms, yet allowance must be made for some overlap of personnel among these teams, to assure continuity of the contemplated science tasks. We also do not exclude that major support functions may be widely distributed geographically, but we recommend that the executive decision-making team reside in Mission Control, in a single facility, to enable timely decision making and implementation of optimized plans in this time-constrained and discovery-driven environment. All concepts to be described below depend heavily on the successful implementation of an efficient communication system that is detailed separately (Section 3.8).

3.9.2 Lessons Learned During the Apollo Program

The Apollo Program operated under a tightly managed operational environment. Operations on the lunar surface were fairly scripted, and crews followed well-defined procedures. This level of control was essential to manage the limited time and limited supplies available for actual lunar surface operations. The Apollo 11 crew spent <3 hours on the lunar surface in a single EVA and, while both the time on the lunar surface and the number of surface science EVAs increased as the program progressed, the longest duration on the lunar surface, the Apollo 17 J-Mission, was around 71 hours with 3 EVAs, the longest of which was slightly longer than 7.5 hours. The scientific success of the program attests to the efficacy of this approach with a tightly constrained mission timeline.

In addition to time constraints, there were mass and volume constraints as well. The internal volume of the lunar module and its ability to bring mass both down to the lunar surface, as well as back to Earth, did not leave room for analytical equipment or pressurized sample acquisitions on the lunar surface.

In addition, this affected items such as the amount of film the crewmembers had on board to take photographs of the lunar surface, and the requirement to leave everything not required for the return trip dumped on the lunar surface before liftoff.

Lastly, visual communication was one way, from the lunar surface to the ground and, while voice communications were two-way. Access to the crew on the lunar surface went through a constrained hierarchy of Flight Director to CAPCOM; in particular, the only person that spoke with the crew was the CAPCOM. While various operations entities could see the operations on the lunar surface, there was no way for the support room scientists to interact freely with the crew. Although this was, at times, frustrating to the science personnel on the ground, it was consistent with the operations constraints under which the Apollo missions operated.

The decision to land at specific lunar location was made by the Apollo Site Selection Team, a committee composed of scientists and engineers, all nationally if not internationally recognized experts. The committee conducted the trade-off studies between science potential and engineering constraints, both evolving dynamically with time, as insights into lunar geologic processes accumulated, and as confidence in the capabilities of the remarkable flight systems increased. Preliminary traverse plans, provided by the Field Geology Principal Investigator (FGPI for short in this report), supported these deliberations, and illustrated which features could be accessed and investigated by the crews. Additionally, a separate peer-review system selected a complement of science instruments that was to be accommodated on a specific mission.

Once a specific landing site was selected, the FGPI and his team refined the preliminary traverse plans for review by yet another committee, the Surface Working Group (SWG). SWG was predominantly composed of scientists, but it had good representation of engineering interests, specifically of flight operations experts, intimately familiar with the capabilities and limitations of vital systems, such as suits or rovers. The scientists prominently included the FGPI, the PIs of the selected instruments, and representatives of the sample analysis community, such as petrographers, geochemists, solar physicists etc. The major purpose of this committee was to coordinate and accommodate all science efforts approved by NASA, and the generation of specific protocols and time lines for each of these approved efforts including, for example, detailed procedures for sample acquisition and photo documentation. SWG was also the final authority to mediate conflicts among science interests as well as between science and operational constraints. The final products of this committee were 2 documents: a) Lunar Surface Procedures (separate documents for each mission) and b) a nominal “Flight Plan” for each EVA, to be used in real time by both crew and the entire ground support structure. While both of these documents were penned by mission operations personnel, it was nevertheless SWG that oversaw and ultimately approved these

documents. The SWG committee was thus the major facilitator and final arbitrator of all science-related activities during Apollo.

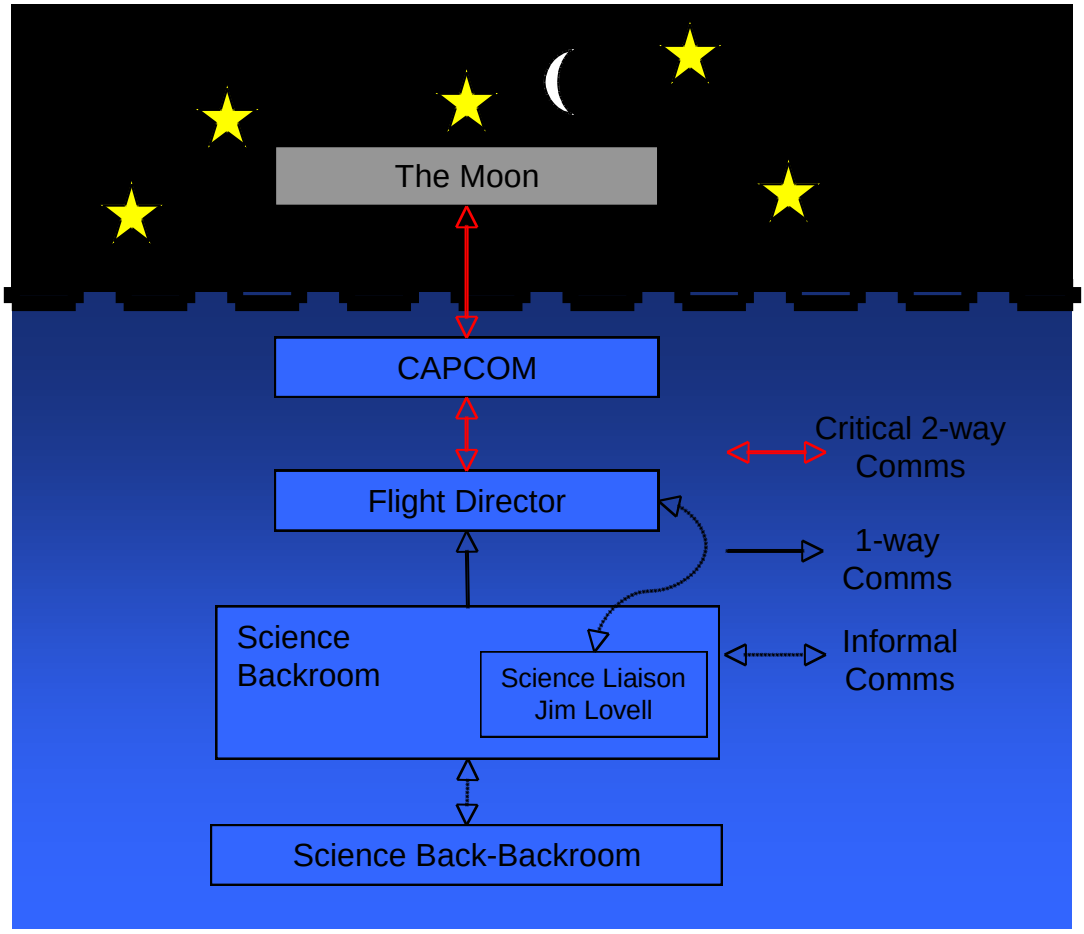


Figure 16. Schematic Diagram Showing Operational Flow between Science Support Rooms and the Apollo Crew on the Lunar Surface. Not shown is the support room that supported orbital science operations.

As shown in Figure 16, the actual Apollo science support room may be viewed as the executive arm of SWG. The support room was charged with implementing all tasks, procedures, and timelines established by SWG. This included major contingency planning based on extensive paper simulations; the latter pretended major anomalies to be dealt with (in real time) by the entire ground support system; the results formed the basis for a detailed Contingency Plan that was available for each mission. Although heavily guided by SWG, the support room, nevertheless, had final authority to deal with all science-related issues, especially those that deviated from the nominal Flight Plan.

Interestingly, for reasons related to logistics and space, there were 3 support rooms related to sciences during the Apollo J missions (Apollo 15, 16 and 17), one for the field geology operations, one for the surface instruments, and one for orbital science. Field geology and surface instruments were the

responsibility of SWG; orbital sciences were organized by a separate ad-hoc panel of participating scientists. The field geology support room is generally referred to as *the* Support room, as it monitored and guided all of the geology and sample-related activities of the crew. The FGPI was the logical Lead of this Support room, supported by his deputy PI and some additional members of the Field Geology Team, typically structural geologists and sample-oriented petrographers. Additional science personnel included representatives of SWG, the Lunar Sample Analysis Planning Team (LSAPT), and the Chief of the Geology Branch at MSC/JSC, who was in charge of the MSC-provided component of the crew's geology and general science training. All told, this support room consisted of some 10-12 individuals. It is important to note that all of them, without exception, participated in many field trips and paper-simulations; all had hands-on field experience with diverse sampling protocols, operational constraints, suit and rover capabilities, etc., and all were intimately familiar with pertinent documents, flight rules, nominal schedules and contingency plans.

We emphasize the Apollo experience where all participants were deeply involved and immersed in the planning of the mission(s) and individual EVAs, and all had participated in numerous field trips and simulations filling the role and function that they ultimately occupied during the real mission. A final operational readiness test occurred within weeks of launch, with the fully suited crew conducting a representative EVA at Kennedy Space Center's rock yard. With years of planning and training, the Apollo Science Support room operated as a well-trained and exceptionally efficient unit that was intimately familiar with all science objectives, numerous operational constraints, and all contingency planning. The success of this approach during the Apollo Program reinforces the need to initiate a comprehensive astronaut and mission control (with associated support rooms) early in the next stage of lunar exploration.

While science-related discussions, chaired by the FGPI, were conducted freely and in an ad hoc manner in the Apollo support room, there was no direct communication with the surface crew. Any communication with the crew had to go through the support room's Science Liaison, typically an astronaut more familiar with all flight systems than the scientists. Interestingly, the Science Liaison (Jim Lovell) also happened to be the Chair of SWG for Apollo's 16 and 17, attesting to the significance of SWG. It was this Science Liaison that forwarded potential questions or advice to the Flight Director, who in turn informed the CAPCOM to transmit specific messages to the crew on the lunar surface. This line of communication worked reasonably well, yet some messages were modestly distorted by the time they were received by the crew, having gone through a number of channels/individuals. Also, a significant number of the messages reached the crew too late, as they had already moved on to another observation or activity. More direct communication between crew and the science ground support seems highly desirable in the future.

Consistent with the technology of the late 60's/early 70's, the only communications received in the support room from the lunar surface was the voice link and a rather grainy TV image by modern standards, displayed via a single, central monitor. While this TV camera represented an almost miraculous technology break through at the time, its primary purpose was to augment the navigation system and to provide situational awareness about the lunar surface. The TV camera also provided useful overviews of individual stations, yet it was not able to document details of sample acquisition, much less of the samples themselves. These details were documented via Hasselblad still cameras. The latter did not figure in real time decisions, however, because the exposed film had to wait return to Earth for development.

3.9.3 Improvements since the Apollo Program

The digital revolution, including laser/optical communications to cope with the high data rate, will have a dramatic effect on future SSR operations. The amount of information received in real time will be much more extensive and detailed, and may be complemented by additional data that will be transmitted in delayed fashion. Within the context of the lessons learned from Apollo, much planning, practice and experimentation will be needed to effectively manage this increased information flow, both in terms of the astronaut on the lunar surface and in support room deliberations and communications.

3.9.4 Specific Operational Recommendations

Science Working Group: It is highly recommended that a Science Working Group be instituted that is the equivalent of the Surface Working Group during Apollo. This committee should be composed of scientists and Mission Operations experts, and should be in place as soon as the earliest mission priorities and activities are selected. This will be in the timeframe of 3-5 years prior to the earliest mission. Protocols for the selection of members for this working group should be well defined. Committees defining specific subsets of science and operational requirements prior to the implementation of SWG should be represented on SWG. Examples of earlier, long standing committee work may relate to curatorial concerns and associated sample containers, or to the photographic documentation of sampling procedures using video- instead of still cameras, or to the type of observations and science tasks that can be accomplished while driving in a pressurized rover or while egressing through a suit port, etc. The SWG committee will have to receive fairly mature protocols and timelines regarding the operation of individual subsystems or of specific science tasks, such as sample acquisition or the field analysis of a rock via hand-held instruments.

The charter of this SWG committee will be to integrate these relatively mature and detailed requirements into a realistic flight plan that is consistent with the science objectives of the entire mission and of individual EVAs, if not of specific stations. This entails that SWG will be the final arbitrator among conflicting science requirements, as well as between science interests and operational considerations. The SWG deliberations will be manifested in the formal Lunar Surface Operations document for each mission, as well as in detailed EVA Plans, the latter being the equivalent of a Flight

Plan, detailing all mission operations and their sequencing for each crew member. This committee should also be involved in the development of adequate Contingency Plans and it should be instrumental in setting up a suitable ground support system for all science operations, including the SSRs.

Science CAPCOM: The science-support functions of current Shuttle and Space Station operations allow for more streamlined, if not direct communications, by individual scientists with the crews, compared to Apollo. We strongly encourage further development of these operational concepts with the ultimate goal of having a CAPCOM function *(= SCICOM*) actually reside in the SSR during those mission phases that are substantially devoted to science, such as the detailed exploration and exploitation of a predetermined EVA station; the SCICOM would also handle all detailed traverse pre-briefings, as well as the post-traverse de-briefings related to science. These concepts are currently being tested during the Desert RATS field simulations, where the Mission Control's operational CAPCOM (= *OPSCOM*) hands over the microphone to the Science-CAPCOM (=SCICOM) following egress from the rover vehicle. The SCICOM in turn will hand back the microphone to the OPSCOM once the crew commences to ingress into the pressurized vehicle. Conceptually, the SCICOM is permitted to directly talk to the surface crew during "boots on the ground" time, a period where intimate ground-to-surface interaction seems particularly beneficial for the overall science productivity; the SCICOM would also conduct all daily science briefings.

Assuming that the concept of direct communications with the surface crews via SCICOM is implemented, the major functions of the primary SSR will be as follows:

1) Science Liaison: This function will be critical and remains essentially unchanged from that of Apollo. It represents a single individual that is authorized to communicate the needs of the SSR to the Flight Director and thus to all elements of Mission Operations, as per approved channels of communication. This individual will coordinate the hand-over between the OPSCOM and the SCICOM, during those periods where the SSR is permitted to communicate directly with the crew. The individual will also advice the SSR about detailed time lines and other operational constraints that he receives from Mission Operations, such as how much time is left on a specific station or the status of critical consumables, and any other information which will assist the SSR in its forward planning. This seems a particularly critical function in the planning of the next, upcoming EVA, which may or may not proceed along nominal plans. The Science Liaison will specifically convey all new operational constraints that must be taken into account should it become necessary to modify the nominal operations. In short: the Science Liaison is the single link to all non-science operational elements that are involved in the conduct of lunar surface operations; he communicates directly with the Flight Director and defines the operational constraints for the SSR.

2) Science CAPCOM (SCICOM): This role –if approved as recommended above- will be occupied by individuals intimately familiar with the science objectives and procedures of a specific

mission or EVA, as well as with the diverse mechanical systems, communications assets, and operational constraints. Familiarity with operations and nuanced operational dialog of the flight crew dictated that Apollo CAPCOMs were recruited from the astronaut corps; the CAPCOM function during actual lunar EVAs were specifically occupied by scientist-astronauts. This may or may not be the case for the future SCICOM.

Whether recruited from the astronaut corps or not, the SCICOM must have an Earth-sciences back ground and he/she will be highly trained in parallel with the flight crew by participating in the field trips, general lectures, and mission-specific briefings attended by the crews. Intimate familiarity with the crew's background, observational skills, and idiosyncrasies of verbal communications is a must for all CAPCOMs, as is familiarity with all surface procedures and operational systems. These qualifications can only be met with years of training and intense interactions with the surface crew as well as with major SSR personnel, especially the FGPI.

3) Field Geology Principal Investigator: The role of the FGGPI will remain unchanged from that of Apollo and he/she will be the Chairperson of the entire SSR. This individual will be responsible for training the crew in all matters related to major science objectives, detailed surface procedures, nominal traverse plans, and detailed rationale for each traverse station. He/she will be a prominent member of SWG. In order to successfully lead the support room, he/she must also be intimately familiar with the detailed expertise and responsibilities of all support room members. While a significant number of support room members will indeed be part of the Field Geology Team, presumably handpicked by the FGGPI, this will not be the case for all support room members as detailed below. It will be the role of the FGGPI to resolve any conflicts between these additional science interests that reside in the SSR. As stated above, most of these conflicts should have been foreseen, however, and solved by SWG, and the FGGPI will in most cases merely implement the recommendations of the latter. As Chairperson of the SSR, he/she will, however, be the final decision maker in case of unforeseen contingencies.

The FGGPI position is one of enormous responsibilities and that he/she must be involved in all mission planning activities, beginning with the evaluation of diverse landing sites, the selection of a specific site, and the definition of associated science objectives via preliminary traverse plans. As a consequence, the FGGPI is a critical component in the earliest planning stages for renewed lunar surface exploration, even more so as he/she will also have to play an instrumental role in the geologic training of prospective crews. Obviously, all of this can only be accomplished if the PI is supported by competent collaborators who will become core members of the Field Geology Team. All of these seem to be long lead items, ergo we recommend that NASA appoint the FGGPI in the near future. His/her immediate task would be to coordinate and consolidate a large number of currently ongoing activities, many of which are currently being pursued independently and in seemingly uncoordinated fashion.

4) Deputy Field Geology Principal Investigator: The deputy PI will fulfill all functions and responsibilities of the Principal Investigator, should the latter not be able to do so. This individual will be appointed by the FGGPI and must have participated in all mission planning activities, the training of the crew, and the development of operational concepts and constraints. He/she should be an *ex officio* member of all committees that the PI is involved in.

5) Field Geology Team Members: A number (TBD) of field geology team members will support the FGGPI. This may include individuals who designed the daily traverse or specific station objectives, who designed specific surface protocols, who are experts in lunar surface processes, such as regolith evolution, igneous processes or impact experts, all capable to assist in optimizing the science return from a specific station or EVA, and all capable to guide and advise on the crew observations and sampling activities. Importantly, it is these experts that will attempt in real time to reconstruct the local and regional geologic settings that are being described by the crew and that are being extracted from the imagery available in the SSR. The latter will include rock descriptions and detailed images of their surfaces, revealing textural and mineralogical detail far beyond that available to the Apollo support room.

6) Instrument PIs: The need for rapid mineralogical or compositional analyses via hand-held instruments and/or instruments potentially carried on the rover is a recurring theme, if not a requirement, throughout this document. It seems obvious that competent operators of these instruments must reside in the SSR as well if the analytical results are to affect any decision on which sample(s) to collect or to reject in the field. These experts are not only operating the instruments, but must also be versed in interpreting the data in real time, and without outside assistance. A minimum of 2 instrument PIs is expected; one for mineralogical and one for compositional analysis. While these instrument PIs could be part of the field geology team, this must not be a necessity, as long as they are thoroughly integrated into the operation.

7) Additional Experts: As was the case for Apollo, one or two representatives of the SWG committee should be part of the science support room. These individuals will assure compliance with the priorities and procedures established by SWG and thus, by the science community in general. Unlike Apollo, some representative of the Curatorial Office should also reside in the SSR. Good curation simply begins with sample acquisition. This is particularly critical for all special-purpose samples that may have dedicated containers and that will typically mandate non-standard collection and documentation procedures. This role was occupied during Apollo by an ad-hoc group of scientists under the Curator's guidance, convened in Building 31 of MSC/JSC, which had a direct telephone line to the Support room in Mission Control (Building 30).

Todays distributed communications via web-based applications, and DVIS voice communications enable additional real-time expertise to tie into the control center from distributed locations. The

possibility to have recognized outside experts contribute in real time to the SSR deliberations and operations must be evaluated and exploited to its fullest.

3.9.5 Conceptual support room operations

Identification of the major support room functions is obviously the first step in defining the operation of this ground support group. The currently recognized functions are substantially patterned after the Apollo Program protocols, albeit somewhat modified by more recent operational protocols from Space Shuttle and ISS operations, as well as ongoing Desert RATS field simulations. The transmission of diverse imagery as well as of instrument data will lead to an overall information flow that is orders of magnitude larger than during Apollo. Management of this information flow is possible only with workstations that are manned by science experts with considerable experience in modern image processing, analysis, and synthesis. The operational scenarios will thus deviate considerably from those of Apollo, and may more closely resemble Space Shuttle and ISS operations. Additionally, purely robotic missions, such as MER or PHOENIX on Mars provide valuable models for the management of large amounts of data, and the forward looking, day-by-day planning of the science operations. For example, these robotic missions engage two mission support teams, a tactical and a strategic component. The tactical team conducts the daily activities (= an ongoing EVA), whereas the strategic component does all of the (daily and long term) forward planning, taking into account what was learned during the tactical shift(s) Tactical and strategic support teams are also part of the science planning of ISS.

Based on the above, there is currently no good, much less firm, understanding of how the future lunar SSR will be operated in detail, how the data stream will be managed and archived, and what specific expertise has to reside in the SSR, and how it can be put to best use. This uncertainty relates largely to the circumstance that the actual amounts and types of data to be received and processed by the SSR are poorly known at present. Also, there is currently no recognized FGGPI, apposition that will obviously have a major role in the detailed and efficient set up of this science support function. First-order SSR concepts are currently being tested during the Desert RATS field exercises; also, we have initiated discussions about the detailed operations of the STS and ISS science ground support structures and support rooms, as well as with the robotic MER and Phoenix Mars missions. These interactions will hopefully reveal those operational elements most suitable for future manned lunar science operations.

Although we cannot provide details, it seems clear that the enormous data stream coming from the lunar surface will, at some stage, have to be subdivided into volumes and packages that can be managed by individual experts who manipulate, process, analyze, and interpret the data at dedicated work stations (= “seats”) in the support room. Further, this data will need to be archived for future use by both mission planners and the science community. Based on preliminary assignments of real-time positions during Desert RATS tests, we estimate below the number of individual “seats” for the future support room.

While this exercise helps to conceptualize the physical size of a support room, the assignment of individual monitors to some specific function and/or expertise may also convey some sense of how the support room might be organized, and how the data stream might be managed conceptually.

All of the seats and "monitor" positions indicated below are conceptual; some may eventually be arranged differently, possibly grouped, or eliminated; only practical experience –over years- will result in a final SSR configuration. EV1 refers to one individual and EV2 to the other of a paired crew of 2 astronauts.

Monitor 1: Science Liaison

Monitor 2: SCICOM

Monitor 3: Field Geology, PI

Monitor 4: Field Geology, Deputy PI

Monitor 5: Field Geology, Traverse Planner/Navigator

Monitor 6: Field Geology, Geologist (GigaPan Camera)

Monitor 7: Field Geology, Structural Geologist (Helmet-Video; EV1)

Monitor 8: Field Geology, Structural Geologist (Helmet-Video; EV2)

Monitor 9: Field Geology, Petrographer/Geochemist/Mineralogist (Still images; rock close ups; EV1)

Monitor 10: Field Geology, Petrographer/ Geochemist/Mineralogist (Still images, rock close ups; EV2)

Monitor 11: Field Geology, Sample Inventory/Note taker

Monitor 12: Instrument PI (Mineralogy)

Monitor 13: Instrument PI (Composition)

Monitor 14: Instrument PI (Digital Microscope)

Monitor 15: SWG-Representative 1

Monitor 16: SWG-Representative 2

Monitor 17: Curation Representative

Monitor 18: real time imagery support (image processing/manipulation/data base) 1

Monitor 19: real time imagery support (image processing/manipulation/data base) 2

The above estimates are based on a single rover and a 2 man crew (EV1; EV2); if 2 rovers and 4 astronauts (EV3 and EV4) were operating simultaneously, seats/monitors # 5-14 would have to be duplicated, possibly # 18 and 19.

Based on the above, some 20 seats/monitors and associated workspaces seem required for the science support room to conduct manned surface operations with a single rover and 2 astronauts; some 30 seats are needed to monitor the simultaneous activities of 2 rovers and 4 astronauts.

Many of the support room functions described above are based on Apollo and the evolving Desert RATS experience, the latter constituting a vital and necessary ingredient into the future planning of all surface and ground operations. Participation of prospective SSR member in these Desert RATS simulations seems a must, as hands-on experience and intense, real time interaction with other operational elements is a prerequisite for any successful support room. Additional extensive training and simulations are required for each individual support room member. The SSR will only operate smoothly and efficiently, if each member has extensively practiced his or her role and is thoroughly familiar with most of the other SSR functions; each SSR member must also be thoroughly familiar with many surface systems and the operational constraints they impose on an ongoing EVA. Sustained training as individuals and as teams (with feedback) for each support room scientist will be critical for mission success.

3.9.6 Additional Science Support Functions in Mission Control

The above considerations refer to the primary SSR only that monitors the manned lunar surface operations. As briefly mentioned, most Apollo instrument PIs (especially those of ALSEP) had their dedicated support room, as did those involved in orbital sciences. Similar, additional ground support functions are envisioned and planned for the future.

New arrays of geophysical instruments will be emplaced and distributed on the lunar surface. They will need ground support in real time, including possible interaction with the crew, while being emplaced, initialized and/or operated. Additional instruments may have to be accommodated that investigate the lunar environment, such as dust impact sensors or instruments that monitor the volatile elements of a tenuous lunar atmosphere, etc. Additionally, instruments related to solar activity are currently being developed. Finally, the moon is perceived as ideal platform for a wide variety of astronomical observations and instruments. Undoubtedly, most of these instruments will need real time ground support. It is recommended that all instruments that do not generate information in direct, real time to support for ongoing EVAs be accommodated in a separate “Science Instrument” support room.

Orbital sciences will largely be conducted in unmanned fashion and prior to manned landings; suitable ground support rooms to support these remote sensing missions will have to operate prior to manned surface activities and should readily accommodate the observations and measurements of moon-orbiting astronauts and instruments carried onboard their flight vehicles.

Unlike Apollo, there will be the need for a science support room dedicated to robotic precursor missions. Current exploration scenarios provide for unmanned systems to operate for months reconnoitering the general traverse areas planned for the manned activities. The objective is to provide

ground truth that will enhance (or diminish) the significance of individual traverse objectives and stations as perceived from the analysis of remote sensing information only. Such robots will be capable of carrying cameras with analytical and/or geophysical instruments. Such long duration robotic missions will have to be supported by a dedicated science support room.

Also unlike Apollo, the Outpost will house a geological sample analysis capability that is dedicated to the characterization of specific samples beyond the information gathered in the field. This Geostation facility will be equipped with analytical instruments and associated sample preparation devices; additional sample processing gear will need to be capable to prepare specific samples or their subsplits for return to Earth. Again, these specialized operations in the Outpost's Geostation are best accomplished by some dedicated support room, the latter most likely under the guidance of the Lunar Sample Curator.

Many of the above functions can in principle be supported through geographically distributed facilities and virtual support room operations in view of modern communications capabilities. The latter options have to be evaluated carefully, and could include specific functions of the field geology SSR and/or any other of the above science operations. However, the real time interaction of experts, residing in a single room, will probably not be duplicated by any distributed system. It is for this reason that we suggest that NASA install and operate a substantial SSR at JSC, dedicated to manned field exploration of the lunar surface.

Findings:

1) Important to establish a primary Science Support Room (SSR) at JSC that accommodates some 30 individuals and associated monitors and workspaces.
2) Real time communications from the ground to the EVA crews are critical, the reason why we suggest that a Science-CAPCOM reside in the SSR that would communicate directly with the crew during "boots-on-the-ground" times.
3) It is critical that a Field-Geology Principal Investigator be appointed soon who would establish sound concepts for traverse planning, crew training, sample acquisition, and SSR operations.
4) Participation of prospective SSR members in field exercises is paramount and time-critical to generate a cadre of some 8-12 experienced geoscientists that will assist the Field Geology PI in the development and advancement of diverse operational concepts.
5) A separate backroom should be established for orbital sciences, surface instruments, the Outpost Geostation, and robotic reconnaissance operations.
6) The potential role and utility of distributed support room functions should be investigated.
7) A committee should be formed that integrates science requirements and operational constraints akin to the Apollo Surface Working Group.

Section 4. Protocols for Sampling and Curation

4.1 Introduction

Several studies conducted during the 1980s and 1990s analyzed scenarios of human return to the Moon, using the Apollo Program experiences to extrapolate to future strategies and protocols for sample

acquisition, handling and curation. One result was a report, Treiman (1993), on strategies for curation of geological samples on lunar outpost missions (APPENDIX VI). Treiman summarized earlier discussions and presented a sample handling and curation process, selected from among several options and sequences for sample handling (with some discussion of the trade spaces of the respective options).

Here, we expand on and update the conclusion of Treiman (1993), correcting some inconsistencies and recognizing the vast unimagined improvements in imaging, data handling, and analytical instrumentation. In particular, current imaging and non-destructive field analytical technologies allow real-time acquisition of significant data for select (if not all) geological samples collected during lunar traverses. We assume these data streams will be tracked and archived as part of the sample documentation, and do not further consider these data, except to recommend early development of image and geographic databases. We also do not consider sample handling and curation on Earth. Our focus is on sample handling during both sortie missions (prior to outpost or not originating from the outpost) and outpost surface operations (including sorties and roving that originates from outpost) from initial collection, including sub-sampling, containment, transport on the lunar surface, temporary or long-term storage on the Moon, and return to Earth.

4.2 Apollo Experience

The overarching strategy during Apollo was to collect samples and return them to Earth; minimal sample handling was employed while on the Moon and sample selection was based on astronauts observational skills. Samples were documented through photography, astronaut verbal comments (transcripted), and discussions with the science support room. All samples were tracked in pre-labeled bags and containers, a field task that also minimized sample cross-contamination. The data collected in the field were used on Earth with the samples to reconstruct other pertinent information (orientation, etc). The Apollo model is still valid as the basic foundation for sample handling and curation on the lunar surface.

4.3 Sample Acquisition

During both sortie missions and exploration traverses from outposts, surface operations for documenting and acquiring samples operations and strategies will be similar. Generally, most sample acquisition tools will be similar and have the capability of acquiring a wide range of different samples (see section 3.1). Many of the tools for sample acquisition will have their heritage with the Apollo Program. Pressurized rovers and robotic rovers will allow sample acquisition to occur over a much larger area than Apollo. The outpost infrastructure and pressurized rovers can be used to accomplish sampling on a much larger scale than Apollo or simple sorties. Under these scenarios, large scale trenching or deep drilling could provide access to samples unreachable by any other sampling technique.

4.4 High-grading

Sortie Missions: As stated in section 3.2, high-grading to yield high priority scientific samples will be required during sortie missions. During a sortie mission, samples can be high-graded at several times or stages. The first stage of high-grading will come during surface EVAs, and will based on an astronauts geologic skills enhanced with hand held and rover based analytical instrumentation, and real-time consultation with science support. The second stage of sample high-grading will be before the return to Earth, and will be based on astronaut-science back room consultations and a "virtual cache" of samples documented by the science support room from image and mineral-geochemical fingerprints collected by the astronauts. This decision making process will include input from the science backroom based on more extensive analysis of images and mineral-chemical data collected by the astronauts.

Outpost Operations: Within the outpost scenario, there is the capability of acquiring a large mass of samples and there will be more infrastructure available for high-grading. We suggest that the temptation to high-grade large volumes of samples at the outpost be ignored and that the high-grading process should be kept simple. The first steps in high-grading will be accomplished along traverses in a similar manner to sortie missions. After establishing a virtual cache of samples, high-grading samples for return to Earth could involve further analysis in the outpost Geolab. The sample analyzed in the Geolab should be made on a sample split and in most cases, the Geolab split should not be returned to Earth. We do not envision the outpost stage of high-grading as a requirement for the return of all samples to Earth. Rather, this stage in high-grading should be used to identify additional high priority samples to be returned.

4.5 Curation

Sortie Missions: The overarching philosophy of lunar sample return regardless of style of mission (sortie versus outpost) is that curation starts prior to the mission and continues long after the mission has been completed. This philosophy is critical to contamination control and sample documentation during all phases of sample return. There are differences in curation operations among the Apollo Program, future sortie missions, and future outpost activities. Curation during sorties will be similar to Apollo missions but with an enhancement in preliminary characterization of the samples prior to return. Unlike Apollo, sortie missions will result in increased sample documentation (images, links to orbital data, mineralogical and geochemical information) that will be available to the science support room during the EVA. This data can be used during preliminary examination and curation on Earth.

Outpost Operations: Due to the long term nature of the outpost and its facilities, the outpost and the backroom will have the capability of curating samples during their residence on the lunar surface and prior to their return to Earth. Curation activities on the Moon must establish contamination control criteria, preserve samples, retain sample documentation established during EVAs, and provide access to samples for Geolab measurements and sample return to Earth.

4.6 Functional Flow for Acquisition and Curation on the Moon

Sortie Missions: It is anticipated that sample acquisition and curation during sortie missions will be similar in nature to the Apollo Program. However, there will be some differences. These differences are described throughout section 3.0

- Analytical instruments that will be available to enhance astronaut capabilities for selecting and high-grading the most significant samples.
- Real-time interactions between astronauts and the science support room, facilitated by digital imagery and rapid data streams, will improve sampling and sample documentation.
- The geological contexts of collected samples will be known, rapidly, far better than was possible in the Apollo Program. At the larger scales (planetary, local, and regional), geological contexts will be known from orbital data that was unavailable to the Apollo Program (e.g., Kaguya, Chandraya'an),. And at the smaller scales of traverse and outcrop, improved surface imaging from landers, orbiters and rovers (i.e., with a multispectral reflectance imager on a rover's mast) will provide first-order "maps" of specific rock-types, and improved navigation will augment local documentation of the sample sites.
- Exploration coverage and sample variety will be enhanced due to the increased duration of EVAs (longer missions and more astronauts) and improved mobility (multiple rovers, pressurized rovers).

A simplified flow diagram for sample acquisition on sortie missions (Figure 17) shows the fundamental actions of acquisition and the crucial decision points based on scientific requirements. The basic concept of this diagram is modified from Treiman (1993) into the context of a sortie mission, and includes sample selection, collection, documentation, tracking, splitting, high-grading, storage, and EVA planning. During these stages in sample acquisition, interactions with the science support room will aid in high-grading and EVA planning during the mission. Curation or preliminary examination will not be done on the surface by astronauts. However, with the anticipated advancements in communication and flight control virtual curation and preliminary examination could be accomplished on Earth in the science support room during the mission.

Outpost Surface Activities:

Although traverses during EVAs originating from the outpost may be similar to sortie traverses in sampling activities, there will be fundamental differences (Section 3.0).

- The ability to use larger and more capable sampling tools adjacent to the outpost. For example, this could take the form of large trenching tools that would enable a more detailed study of the regolith.
- Analytical instrument available at the outpost that would be more capable than hand held or rover instrumentation. This instrumentation will enable "high-grading" of samples, planning future EVAs,

conducting science adjacent to outpost (i.e. regolith stratigraphy within trenches) or on samples sensitive to changes in environment, and improve yields during ISRU experiments-production. Clearly, instrumentation and their utilization will evolve with time, and continually enhance astronaut observations for selecting and "high-grading" samples.

- A different level of high-grading and curation can be accomplished in the outpost mode of operation.
- The outpost provides a source for extended robotic exploration that may include a sample return component. As noted in section 3.4, contamination control requirements must be established during all of these staging of sampling.

Simplified flow diagrams for sample handling during outpost missions, Figures 17 and 18, show the fundamental actions of acquisition and the crucial decision points based on scientific requirements. The basic concepts are modified from Treiman (1993), and include sample collection, documentation, tracking, splitting, and preliminary examination. This enables decisions about subsequent transport and storage on the lunar surface, and potential for expanded preliminary examination in a geosciences lab on the Moon. Considering the Functional Flow Chart (Treiman 1993, p13. Scheme 6), we focus on returning subsamples of high priority samples. Figure 16 presents a stylized flow that illustrates the pathway of a lunar sample from the point of collection. Figure 17 expands the concept into a flow chart, and presents basic decisions points for each sample collected. The decision making process for prioritizing samples involve field observations, virtual examination and curation during science support room activities, and sample observations made at the outpost. The decision process for prioritizing sample return will evolve with time and outpost maturity.

Although firm decisions about lunar rover and habitat configurations have not been made, we assume that there will be a progression of capabilities for sequential missions, which enable long duration missions on the lunar surface, and that a geosciences laboratory, in some form, will be part of the design implementation from an early stage of the outpost. We also assume that lunar surface science will include sampling from the first mission, and that long duration missions will collect more samples than can be brought back to Earth on return vehicles, given the current lunar architecture. Finally, as lunar sample handling matures with well-developed lunar operations, we envision the evolution of more sophisticated sample handling and examination protocols to test and prepare for Mars sample handling (Figure 18).

4.7 Elements for Acquisition and Lunar-Based Curatorial Functions

We identified requirements— hardware, basic facilities, and data handling infrastructures—that are critical to successful lunar-based sample acquisition, handling and curation and subsequent Earth-based curation.

1) Sampling at field location:

Activities - sub-sampling, imaging, preliminary descriptions and/or examination, sample containment, tracking and documentation;

Requirements - sample splitter, appropriate sample containers with accommodations for multiple sub-samples, imaging systems, field-based analytical tools, field-based data streams for recording, documentation and tracking.

2) Transport from field site:

Requirements - Containment and transportation for collected samples.

3) Lunar Storage:

Activities - Sample placement, documentation and tracking of location;

Requirements - storage location, storage and retrieval procedures, appropriate protection for sample containers and samples from space environment and lunar activities.

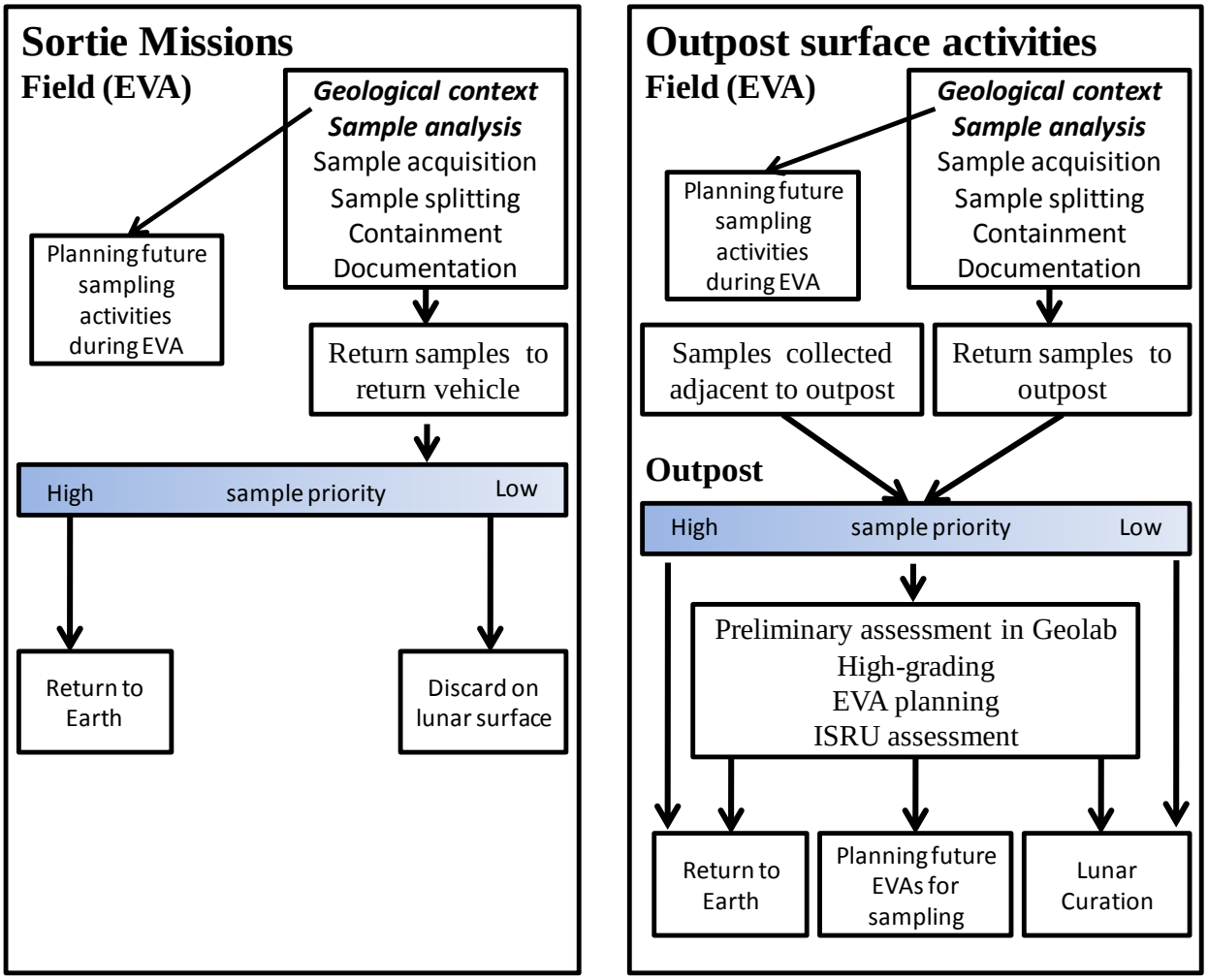


Figure 17. Flow chart illustrating decision points for samples collected on a planetary surface during sortie and outpost activities.

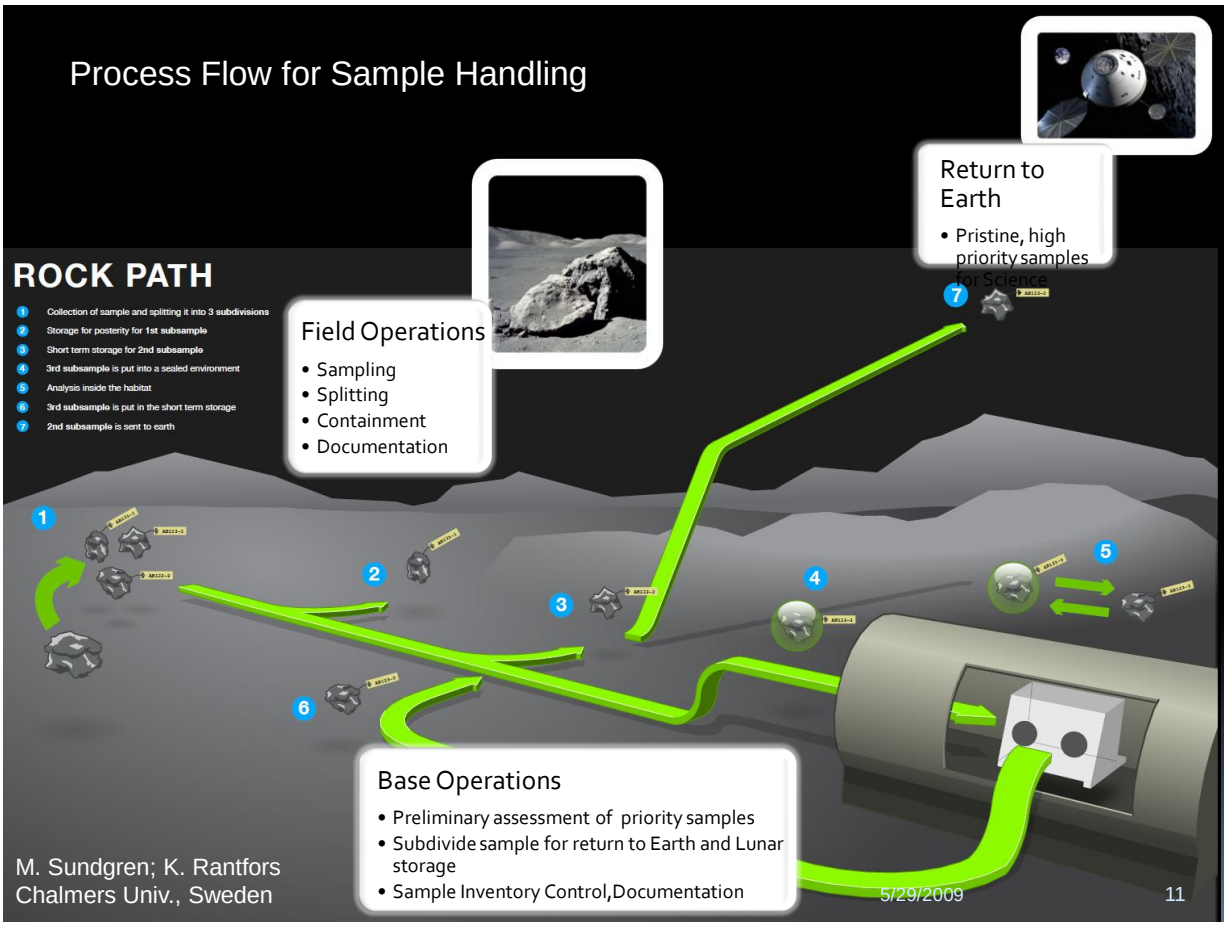


Figure 18. Schematic for handling of a lunar sample, based on work by Treiman (1993) and adapted by Rantfors et al. (2009). From field operations (left), transport to a lunar storage site (2), lunar base examination of subsample (5, Base Ops), sample selection for return to Earth (3) and Earth based study (7).

4) Lunar examination:

Activities - Retrieval of subsample, transport to examination site, examination, documentation, re-containment, return to storage, tracking;

Requirements - Criteria for lunar examination, sample retrieval and transport tools, procedures for accessing appropriate sub sample, sample handling tools, Geoscience lab equipped with analytic tools and sample containment (e.g., glovebox), post-examination storage of subsample, documentation and tracking data.

4.8 Feeding Forward to Mars and Beyond

The environments of the Moon and Mars are dramatically different and may require different tools and sample storage containers. However, there are a variety of sampling challenges for both planetary bodies that are similar or even identical, like coordination of surface operations, contamination control, analytical instrumentation, data integration, and collaboration. Therefore, planning for sample acquisition and curation on the lunar surface during sorties and outpost activities feeds forward to similar human

operations on Mars. These activities allow the integration of sampling philosophy of Apollo with 21st century technology. As such, a variety of Mars-based human sampling scenarios can be explored and fine-tuned on the Moon.

Findings:

(1) A detailed process for sample handling on the lunar surface must be developed that includes well defined protocols for utilization of tools and sample containers, sample tracking, contamination control, high-grading, and curation. It is important to keep the implementation of the sample handling processes simple and yet maintain the integrity of the samples.

(2) Sample curation will be improved by a reliable data streams from the field that can be maintained in a database (i.e., curated) and that track samples associated with specific field-based data (imagery, analyses, geographic data). Designs should include image and geographically based databases to support field exercises.

(3) Sample acquisition and curation would be enhanced by the development of field-based splitting tools and analytical instruments that can be used for simple sample characterization, sample selection, and high-grading. It is critical that the use of such tools and instruments make surface activities safe and efficient and do not compromise the integrity of the samples. For both sortie and outpost activities, new analytical technologies should be actively researched, and robust, easy-to-use tools (splitting, mass measurements, analysis) that facilitate high-grading should be developed and tested.

(4) The examination of samples in real time enables improved exploration/research activities (EVA planning). These data may allow planning of EVAs during a mission and allow science driven selection of samples.

(5) If samples that are brought into the Outpost are assumed to be sacrificial (i.e., not intended for return to Earth) it may be possible to relax sample handling protocols in the Outpost for ease of execution. This concept must be further explored and protocols for these activities must be well established.

(6) Sample curation requires a well thought out lunar surface storage scheme that protects samples and allows tracking and retrieval for later scientific studies. Sample storage should be protected from the Outpost to prevent contamination from activities endemic to the habitat (e.g., spacecraft flight paths, contamination emanating from the habitat, etc.). Research and develop preliminary external (outside habitat) curation facility designs: location, configuration, materials and organization scheme

(7) Long duration lunar missions will test protocols for Mars exploration, and will likely challenge existing sampling strategies. New technologies for enhanced (advanced) curation should be actively pursued to enable future science for difficult or special samples (cryogenic samples, volatiles, etc) **.**

(8) Feed-forward to Mars activities that demonstrate protocols satisfying more rigorous requirements for contamination control and monitoring should be phased into the lunar surface curation protocols when the Outpost crew can appropriately accommodate them.

(9) Prototyped sampling and lab hardware provide a mechanism for testing and refining sampling protocols. The sampling and handling process and conceptual hardware should be prototyped and an operational concept developed for continued critical assessment of the sampling and curation process and definition of requirements. Begin tool and procedure design to better test concepts for sample handling.

(10) Assemble placeholder design requirements for lunar curation that includes imagery and other analytical data, mass, volume, power for support equipment, and environment requirements (e.g., cryogenic stowage and return).

Section 5. Lunar Sample Curation on Earth.

5.1 Introduction

The charter for this CAPTEM-LEAG document (located in APPENDIX II) includes a request to review current terrestrial lunar sample curation facilities and evaluate potential future needs if larger volumes of material (see findings under section 3.5 and Appendix V) or "special samples" are returned by future human missions to the Moon. Here we evaluate protocols, contamination issues, and infrastructural needs under these sample return scenarios.

5.1.1 History of Lunar Sample Curation Facilities

When Apollo 11 completed its historic trip to the moon, the first lunar samples were brought to the Lunar Receiving Laboratory (LRL) at the Manned Spacecraft Center (now Johnson Space Center) in Houston, Texas. By the end of Apollo 17 in 1972, approximately 382 kg of lunar rocks and soil, comprised of 2196 individual specimens were in the custody of NASA and the science community.

The LRL was constructed as a state of the art facility comprised of biological quarantine and geological testing facilities, crew isolation area, gas analysis laboratory, and radiation counting laboratory. Adding to the cost and complexity of the facility, the planetary science committee had decided some samples should be processed in a high vacuum environment. After Apollo 12, the vacuum facility was abandoned as an impractical operation. The remaining samples were processed in the sterile nitrogen atmosphere processing line (SNAP) and the nonsterile nitrogen processing line (NNPL.)

As the Apollo missions progressed, it became obvious the LRL did not have enough space to process and store the lunar samples from multiple missions properly. Part of a nearby building (Building 31) was remodeled to form the Sample Storage and Processing Laboratory (SSPL). The SSPL processed the samples securely and cleanly under nitrogen and had room to prepare requested samples for PI's. After the work of the Apollo 17 Preliminary Examination Team was completed, all of the samples were processed in the Building 31 SSPL. To maintain the security of the samples, they were placed in bolt top cans which were stored in vaults in other buildings at JSC. Each day, processors would retrieve samples for the day's work and return them at the end of the workday.

In addition to the SSPL, an additional storage facility was required to protect the entire collection's exposure to natural disasters or other hazards occurring in one location. A bunker at the Brooks Air Force Base in San Antonio, Texas, was renovated to serve as a remote storage space. In 1976, 14% of the lunar sample collection was relocated to this secure military facility.

After years of careful planning, an annex was added to Building 31, the Lunar Sample Curatorial Facility. Using experience gained from curating the lunar samples since return, scientists worked carefully with the building designers, engineers and construction crews to create a building complementary with good science. The laboratory was constructed of materials screened to be

chemically "clean" as to not interfere with the analysis of the samples and the air was kept clean by high efficiency air filtration. The building was engineered to withstand man-made disasters and the extreme weather, such as hurricanes, that frequent the Texas Gulf Coast. Security measures were designed to protect the sample collection from unauthorized access. Within the building, the samples were stored in cabinets with positive nitrogen pressure and placed in bank vaults for secure storage.

In the years since the establishment of the remote storage facility at Brooks Air Force Base, changes in the military presence impacted the level of security available for the facility. In 2001, plans were initiated to move the lunar samples from Brooks to the White Sands Test Facility (WSTF) in Las Cruces, New Mexico. A new remote storage facility was constructed within an existing building in a very secure area of WSTF. A clean room, vault, alarm systems, and associated equipment were procured and installed. The facility was operational in October 2002 and the lunar samples were moved from Brooks Air Force Base to WSTF by a caravan of curation and security personnel.

5.1.1 Current Facilities

The Lunar laboratory is a tribute to its planners, designers, and builders. After decades of use caring for the Apollo lunar samples, the facility continues to function as intended. Recent improvements to the infrastructure including a new roof, a new nitrogen tank and piping, new security monitors, as well as new air handlers and controls have upgraded the laboratory's basic functionality. This laboratory suite is in excellent condition, and should continue to operate for decades. Details concerning the dimensions and capabilities of these facilities are in section 5.2.3.

The current configuration of the Lunar Laboratory available for lunar work is:

First floor
Sample Information Center (Room 1110)
Return Preparation Laboratory (Room 1105)
Return Processing Laboratory (Room 1106)

The Sample Information Center is comprised of office work space, work areas for sample transit packaging (Sample Control Center and Education Sample Center), and shelving for information and records storage. It is actively engaged in curation work across all collections.

The Return Preparation Laboratory contains desks, lab furniture with shelves and drawers, a safe containing radioactive samples, file cabinets with returned samples, and other varied items. Currently, this area is not actively used for curation work since returned samples are not being processed at this time.

The Return Processing Laboratory is presently being used by a non-Curation ARES research group to process a lunar allocation. This group is expected to conclude its work in early 2010. The room contains a cold glovebox cabinet, a small nitrogen processing cabinet, and a flow bench.

Second Floor
Pristine Sample Vault (Room 2108)
Return Sample Vault (Room 2110)

Pristine Sample Laboratory (Room 2107)
Observation Room (Room 2105)
Change Rooms (Rooms 2102SB and 2106)
Pristine Corridor (Room 2102C)
Core/Bandsaw Lab (Room 2107A)
Transfer Room (Room 2103)
Science Room (Room 2109)
Visitor Viewing Area (Room 2112)

The Pristine Sample Vault (PSV) has 7 banks of positive pressure nitrogen sample cabinets dedicated to each of the Apollo missions, 2 banks of positive pressure cabinets containing core samples and one bank partially filled with a limited number of fragile samples. The vault is protected by a double combination lock vault door.

The Returned Sample Vault (RSV) has numerous cabinets filled with returned lunar samples. As Astromaterials Curation has evolved to include collections in addition to Apollo lunar samples, the RSV has become a repository for portions of other sample collections. Genesis, Stardust, and Meteorite collections have cabinets located in the RSV and/or plumbing lines to receive cabinets during a hurricane shutdown.

The Pristine Sample Laboratory (PSL) has eight positive pressure nitrogen processing cabinets and a display cabinet. A few small pieces of ancillary lab furniture are also located in the room.

The Observation Room is used to monitor the environmental safety of the controlled laboratory space, to communicate with staff inside the contamination barrier, and to serve as a command post during hurricane preparation activities.

The Change Rooms are used to don the protective garments required for entry into the lunar laboratory areas. The room consists of storage bins for protective clothing, a change bench, and containers for soiled garments and other waste.

The Pristine Corridor surrounds the three of the four exterior walls of the Pristine Sample Laboratory and provides access to both the Pristine Sample Laboratory and the Pristine Sample Vault. There are eight ports leading from the Pristine Corridor into the eight processing cabinets in the PSL for the transfer of samples into the cabinets for processing.

The Core/Bandsaw Laboratory has a cabinet with equipment dedicated to processing lunar core samples and cutting rocks.

The Transfer Room is used to move cabinets or other large pieces of equipment into and out of the Pristine Sample Laboratory and the Core Bandsaw Laboratory.

The Science Room contains two processing cabinets, a flow bench, and other pieces of lab furniture. This area is used to prepare returned samples for allocation, prepare display samples, support the annual inventory, and provide space for special studies conducted by in house or visiting scientists.

The Visitor Viewing Area (VVA) looks into the Pristine Sample Laboratory and the Core Bandsaw Laboratory. It is accessed by an exterior building door and staircase. It does not have a penetration into the lunar laboratory area. The VVA allows visitors to view the facility without the need to don protective garments.

The WSTF Remote Storage Facility houses 6 sample cabinets. Three cabinets contain the set of lunar samples originally stored at Brooks Air Force Base. Subsets of the Genesis and Stardust collections are stored in separate cabinets and another cabinet is available for other sample storage.

Curation operations are governed by an extensive set of policy documents and procedures:

- Management Procedures
- Laboratory Operating Procedures
- Sample Control and Data Procedures
- Sample Processing Procedures
- Technical Support Procedures

These procedures govern all operations in the lunar laboratory including but not limited to functions such as contamination control, sample numbering, sample security, sample handling, and laboratory access. The policy documents and procedures are located on the curation server and are available in a series of notebooks in the Sample Information Center. The documents are all assigned numbers and are reviewed and revised every couple of years.

Lunar curation performs three general categories of sample processing: rock processing, soil processing, and core processing. Rock processing by several methods is routinely conducted on a regular basis. The use of a band saw to cut rocks is an infrequent activity; however the skill has been maintained due to training new personnel when a sample request requires cutting a rock. The sieves and other equipment required to conduct soil processing exist and are available. No core processing has been done for many years, but the equipment required to perform core processing still exists.

The PSV has ample floor space available to conduct the activities required to remove samples to and from storage and to begin the steps associated with allocation. The PSV has room to house additional sample cabinets. Floor space in the Return Sample Vault is constrained for additional equipment or furnishings. As previously stated, this area provides a space to safeguard other astromaterials collections during the threat hurricanes.

At the present time, pristine lunar sample processing is conducted by three contractor lunar processors and one contractor processor splitting time between lunar and meteorite duties. The laboratory is maintained by a technician team which also performs maintenance for other laboratories in the organization. Included in this maintenance function are the environmental monitoring and cleaning of all curation laboratories and the precision cleaning of tools, containers, and processing cabinets.

5.2 Future Protocols and Infrastructural Needs

5.2.1 Protocols from landing site on Earth to preliminary examination

Protocols during the Apollo Program: Sample handling during Apollo 11 provides some insights into the initial challenges to curation of the return of the first lunar samples. Here we summarize some of the documentation assembled by W. David Compton for "Where No Man Has Gone Before: A History of Apollo Lunar Exploration Missions". This documentation was augmented by reminiscences of JSC curation staff that participated in the Apollo Program. As expected curation and preliminary examination evolved during the Apollo Program.

In the early morning hours of July 24, 1969 (8 days, 3 hours, 18 minutes, and 18 seconds after leaving Kennedy Space Center), Apollo 11, crew and samples landed in the Pacific Ocean about 200 nautical miles south of Johnston Island. Recovery crews from the U.S.S. Hornet arrived quickly and tossed the biological isolation garments into the spacecraft. After the cocooned astronauts emerged from the spacecraft the swimmers swabbed the hatch down with an organic iodine solution. The astronauts and recovery personnel decontaminated each other's protective garments with sodium hypochlorite solution. The recovery crews brought *Columbia* on board and connected it to the astronauts' temporary home by means of a plastic tunnel. Through this, the film magazines and sample return containers were taken into the quarantine trailer, then passed out through a decontamination lock. Sample return container no. 2 was packed in a shipping container along with film magazines and tape recorders and flown to Johnston Island, where it was immediately loaded aboard a C-141 aircraft and dispatched to Ellington Air Force Base near MSC. Six and a half hours later the other sample return container was flown to Hickam Air Force Base, Hawaii, and then on to Houston. During Apollo 11 or follow on Apollo program missions, the curation staff from the receiving lab in Houston was not present at the landing site and were not involved in sample handling until materials arrived at the Manned Spacecraft Center, Houston.

The first sample container arrived in Houston late in the morning on July 25, 1969 and was delivered to the receiving laboratory shortly before noon. The second arrived from Hawaii that afternoon. After initial inspection the sealed sample return container was transferred to the vacuum laboratory and weighed (33 pounds, 6 ounces; 15.14 kilograms). Technicians in the vacuum laboratory then started the container through the process of preliminary examination. Before admitting it to the vacuum system, they passed it through a two-step sterilization, first with ultraviolet light, then with peracetic acid (a liquid biocide), after which it was rinsed with sterile water and dried under nitrogen. Next it was passed through a vacuum lock into the main vacuum chamber. At 3:45 p.m. on July 26, the cover was removed from the sample return container. Initial observations of samples were hindered because they were covered with fine dust that obscured their surface characteristics. On July 27 technicians removed a rock from the box

for low-level radiation counting, dislodging much of the dust from its surface. In addition to the rocks and dust, the sample return container held a solar-wind collector and two core tubes. Core tubes and solar-wind collector were sealed in stainless-steel cans, sterilized, and transferred out of the vacuum laboratory.

The following week the lunar sample preliminary examination team (LSPET) and the lunar sample analysis planning team (LSAPT) examined, characterized, photographed, and cataloged the specimens and allocate samples to the 142 principal investigators. The two groups worked two shifts a day during the initial stages of PE. They determined how the larger rocks would be divided and which ones should be sectioned, basing their judgment on the requirements of the investigators and the availability of the different types of samples. While many members of these teams were later involved in specific investigations, their purpose at this stage was to match samples with research projects to make most effective use of the samples.

Preliminary examination of samples and preparation of material for the investigators continued throughout August, aiming at distribution of experimental material as soon as the quarantine protocols were completed. For the first few days work in the laboratory went on as planned; some minor malfunctions in the waste disposal system briefly threatened to break the biological containment but were corrected without incident. About the only potential equipment problem was the torn glove in the vacuum chamber. Since replacement was a time-consuming process, technicians jury-rigged a repair by slipping another glove over the damaged one and taping the two together. But before the first week was out the gloves ruptured, exposing most of the samples in the system to the atmosphere and sending two technicians into quarantine. Work in the vacuum laboratory was suspended while scientists and laboratory managers decided what to do. Problems with the vacuum system had been experienced during premission simulations and provision had been made to fill the chamber with sterile nitrogen gas; that alternative was now adopted.

Protocols during Genesis and Stardust Missions The Genesis and Stardust missions were the first United States sample return missions since the Apollo Program. Although robotic in nature, they posed some of the same challenges to Curation as the Apollo Program. Curation facilities for handling both Genesis and Stardust samples were designed based on interactions among mission PIs and science teams, CAPTEM, curation staff at JSC, and facility engineers.

The Genesis sample return capsule entered Earth's atmosphere at 16:55 UTC September 8, 2004 over northern Oregon with a velocity of approximately 11.04 km/s. Due to a design flaw in a deceleration sensor, parachute deployment was never triggered, and the spacecraft descended slowed only by its own air resistance. The planned mid-air retrieval could not be carried out. The spacecraft crashed into the desert floor of the Dugway Proving Ground in Tooele County, Utah at about 86 meters per second (311 km/h (193 mph)). The capsule broke open on impact, and part of the inner sample capsule was also

breached. The damage was less severe than might have been expected given its velocity; it was to some extent cushioned by falling into fairly soft muddy ground. Unfired pyrotechnic devices in the parachute deployment system and toxic gases from the batteries delayed the recovery team's approach to the crash site. Once all was made safe, the damaged sample-return capsule was secured and moved to a clean room for inspection; simultaneously a crew of trained personnel scoured the site for collector fragments and sampled the local desert soil to archive as a reference by which to identify possible contaminants in the future. Recovery efforts by Genesis team members at the Utah Test and Training range – which included inspecting, cataloging and packaging various collectors—took four weeks. Science team members and JSC curation staff members were members of the recovery team. The samples returned by the Genesis spacecraft were flown by military transport from Utah to Ellington Air Force Base in Houston, Texas, then transferred by road to the Johnson Space Center in Houston, Texas. Preliminary examination plan for the genesis samples is discussed by Stansbery and McNamara (2005)

In 2006, the *STARDUST* sample return capsule (SRC) returned to Earth (at the Utah Test and Training Range), and was immediately flown by military transport from Utah to Ellington Air Force Base in Houston, Texas, then transferred by road to the newly constructed Stardust Laboratory at the Johnson Space Center. Once safely at JSC, the canister was opened and the aerogel and its comet and interstellar dust harvest were inspected. The SRC contents, including the aerogel and contained samples, were maintained at a class 100 cleanroom environment or better during this deintegration. Particulate and non-volatile residue (NVR) witness plates were used to monitor the environment during the times aerogel was open to the laboratory air, and monitored daily for visible particulate contamination. The recovery of the SRC and sample curation plans were discussed by Sandford et al. (2006). Preliminary examination organized by the mission P.I. was an inclusive examination involving a large number of members from the national and international community. The preliminary examination led to a sample documentation website that could be accessed by the larger community.

Protocols during future human sample return There are numerous lessons that can be learned from the sample return missions and preliminary examination programs outlined above. It is extremely important to have curation and sample advisory groups involved in the initial stages of planning for spacecraft return to Earth. During the Apollo Program representatives of the science community and curation staff did not participate in sample handling at the landing site. In contrast, for both Stardust and Genesis missions both mission team members and curation staff were represented at the landing site. Curation should have at least one representative at the landing site and accompany the samples to their final destination at the JSC. The design of the final sample handling facilities, sample handling protocols, and the planning of the preliminary examination must involve input from the curation staff at JSC and the science community. The latter can be organized through CAPTEM. Earlier in this document, we introduced the concept of a

"virtual sample cache" that would consist of measurements, images, and observations made by astronauts on a planetary surface that could be utilized by the science backroom to "high-grade" samples. This surface data and results from the preliminary examination should be integrated and made available to the science community via electronic media for adding sample requests and allocations.

Findings:

1. Curation should be represented at spacecraft landing site and accompany samples back to the curation facility.
2. Sample handling protocol from landing site through preliminary examination should involve the scientific community through committees such as CAPTEM.
3. Preliminary examination and sample distribution should involve curation staff and members of the scientific community.
4. Results of preliminary examination should be integrated with surface observations and measurements and be made available to the scientific community via electronic media for sample requests.

5.2.2 Contamination issues

Improving current procedures/materials: The current procedures for lunar curation have been quite effective in preserving the integrity of the lunar samples over several decades. However, analytical techniques have become much more precise in recent years and levels of contamination that were previously below the limits of detection are no longer so easily ignored. One source of these contaminants are the small impurities in the nitrogen gas in which the samples are stored, particularly H_2O, which is present in the N_2 at a level of about 10 ppm. Due to the recent results concerning water on the lunar surface (Pieters et al., 2009; Clark et al., 2009, Sunshine et al., 2009), there is strong interest in the community to understand the native water contents of lunar soils, unfortunately, the ability to do that is hindered as a result of the current standards.

There are ways to remove impurities from the N_2, including H_2O, down to the <1 ppb level. The Genesis sample curation facility has adapted commercial point-of-use nitrogen purifiers like those used by the semiconductor industry. The purifiers, however, can also put additional elements into the process line and therefore, may themselves become a possible source of contamination, although the purifier chemicals are upstream of a 0.003 nm particle filter. These filters are consumables, making such a system prohibitively costly on a large scale, but should be investigated for maintaining a small subset of samples, particularly soils. Alternatively, efforts to understand water or other surface processes might be

considered “special investigations” and special sample collection containers could be designed to meet those needs. This approach, however, would likely not allow samples to be maintained for future investigators.

Impact of the Preliminary Examination Team on Contamination: Preliminary examination is a crucial step in understanding the sample collection and providing the necessary information to guide potential investigators. These needs have to be balanced with the potential for contamination incurred through this process. Unlike Apollo, in the next era of exploration, a lot of information may be gathered at the time of collection or during high-grading exercises on the surface, including high-resolution imagery and even chemistry. In most cases, this will not provide sufficient information, but will be useful for strategizing and guiding preliminary examination efforts. This preliminary data will allow the PET to asses in advance, for example, which samples will require thin sections be produced or other complex operations, and which do not, which should minimize the necessary handling.

Processing Cabinet Usage: The current lunar curation facilities are equipped with eight processing cabinets in the clean room, plus two additional cabinets in the science experiment room. One of the eight cabinets is currently used to showcase lunar rocks to those visiting the observation room; the other seven are used for processing Apollo samples to be distributed. Although only one sample in a cabinet is ever open at a time, those cabinets are currently each assigned to a particular Apollo mission to avoid cross-contamination. This mission-specific situation cannot continue to be maintained with the introduction of new samples from new missions, and probably doesn’t need to be. Cabinets can be used to process samples from different missions, although an intermediate level cleaning procedure should be developed along with guidelines for determining when one sample is sufficiently different from the previous to trigger that intermediate level cleaning (whether that is based on mission, or rock type, or some combination).

It is recommended, however, that at least two cabinets remain Apollo-specific, one for Apollos 11 and 12, and one for 14 - 17. Because different tools and collection methods, and possibly storage methods will be used for the collection of new samples, maintaining separate Apollo processing cabinets is prudent. Furthermore, during the Apollo 13 downtime, the lunar processing lab was completely refurnished. This included removal of heating equipment, gas testing chromatography, plastics, wires and plugs, metals/lead, glass bottles containing oils, tools which were not pure "as advertised", and organics. The cabinets were changed from individual cabinet to the SNAP line (sterile nitrogen) connected cabinets we continue to use today. Thus, Apollo 11 and 12 missions were exposed to higher levels of contaminants. For example, studies have confirmed that there is terrestrial lead contamination in some samples. Because there is a marked difference in the level of contaminants in the early missions vs. the later missions, we recommend maintaining a separate cabinet for 11 and 12.

A processing cabinet should also be set aside, either permanently or temporarily, for dealing specifically with samples containing possible organics. This cabinet would have to be held to a much higher standard of cleanliness than the others and new cleaning and testing procedures need to be developed. This topic is expanded upon in the following section.

Advanced Samples- Organics, Cryo, Volatiles: The procedures for handling Apollo lunar samples and acceptable tools and materials were developed over a number of years. As we are considering collection of samples with potentially significant levels of organics and volatiles, including water, new procedures need to be identified. For this purpose, we will emphasize the case where the levels of organics, water, and volatiles are extremely low. If these levels, for specific collected samples (e. g., from permanently shadowed areas on the Moon)), are in fact not low, then the concerns about contamination become more easily addressable.

For the following we will refer to volatile content to include potential organic components, water, and any other volatiles. The tool and procedures need to address both direct contamination of volatiles and the potential for partial loss of volatiles from a collected sample. Such loss would affect the measurement of concentrations as well as key isotopic ratios. We consider different stages of handling potentially volatile rich samples:

a. Individual sample collection;
b. Extraction of components volatile at room temperature;
c. Handling of samples with absorbed volatiles, at room temperature;
d. Handling samples under cryogenic conditions.

In controlling contamination of volatiles and potential loss of volatiles, it is important to develop first clean, vacuum tight containers, free of organics and water. Such containers must also include a valve or other mechanism for sampling the volatiles without having to open the sample container, except in a controlled way. Such containers must also allow the collection of a sample, followed by the ability to close and seal the container hermetically. The closure mechanism must address the process of sealing in the presence of soil particles. A design effort will be required. The constraints are:

a. Sample container must cleanable to be free of volatiles (e. g., electropolished 304 stainless, bakeable, and sealable, on Earth to preserve this condition);
b. It must be possible to open the container and reseal it, at the temperature at which the sample will be collected. This means the sample collection mechanism and the sample container should not modify the sample volatile content at the time of sample collection and of sealing of the container;
c. Sealing of the sample container must operate in the presence of lunar soil particles;

d. For the first collection of potentially volatile rich samples, we believe containment of the sample is important. However, it is not necessary to preserve the sample containers under cryogenic conditions.
e. It must be possible to sample the volatiles in the sample container, through a valve and vacuum sealed lines to instruments of interest.
f. The containers should be bakeable to extract at least adsorbed volatiles.

Once the volatiles have been extracted through the valve provided in the design, it is possible to handle the sample "in the open", in a sample cabinet flushed with GN2. As discussed above, the gaseous nitrogen in such a cabinet must have a water content potentially much lower than the current 10 ppm level in the lunar processing cabinets. This may involve cleaning the nitrogen being introduced in the sample cabinets, but more importantly modifying the cabinets to obtain a much lower leakage rate than currently possible. It is observed that water levels increase in sample cabinets when there is sample processing activity in the cabinet. It is believed that operating the neoprene gloves results in some leaks of atmosphere into the cabinets. Lowering the level of water may require active traps/cleanup of gaseous nitrogen as well as a redesign of a sample cabinet for use with volatile rich lunar samples. It is possible that this design will employ robotic sample handling, although at this time is not known that robotic components can be sufficiently degassed of water and organics. This too will require significant research and design and experimentation.

We consider that at this time there is almost no experience of clean sample containment and handling under cryogenic conditions. The closest analog of containment and handling of ice cores is not applicable. The problem is that cold surfaces become sinks for water and organics, so that samples held at cold temperatures may become significantly contaminated, simply by being held (and handled) at cryogenic temperatures. The standard operating procedures for ice cores offer little guidance. When one wants a clean ice core sample, one shaves off the surface ice and uses the internal parts of an ice core. Such a procedure is not applicable to lunar soils and rocks.

Significant experience will have to be gained before cryogenic sample handling is developed. We also believe that individual investigators, with an interest in cryogenic samples, must take the lead in developing the proper equipment and procedures.

Findings:

5. Nitrogen purifiers should be investigated for maintaining a small subset of samples, particularly soils.
6. For small volumes, nitrogen purifiers may be simple cold fingers, or cold traps for the incoming gas nitrogen. For example gas nitrogen can be introduced in a sample cabinet through a U-trap, cooled with liquid nitrogen or with a CO_2-alcohol mixture.
7. Sample cabinets must be developed with lower leak rates
8. Cold traps, inside the sample cabinets are contraindicated, as they may also pump out some of the volatiles in the samples.
9. Processing cabinets can be used to process samples from multiple missions, although an intermediate level cleaning procedure should be developed along with guidelines for determining when one sample is sufficiently different from the previous to trigger that intermediate level cleaning (whether that is based on mission, or rock type, or some combination).
10. A minimum of two processing cabinets should remain Apollo-specific, one for Apollo missions 11, 12, and 14, and one for Apollo missions 15, 16, and 17.
11. A processing cabinet should be set aside for handling organic-sensitive samples and new cleaning and testing procedures should be developed for this cabinet.
12. Develop sample containers that will be opened and closed on the Moon, at cold temperatures (as in permanently shadow areas sample collection activities) and in the presence of lunar soil, which may adversely affect hermetic sealing
13. Develop mechanisms (bakeable valves) for sampling the volatile atmosphere in a sample container at room temperature and up to 120°C.
14. Develop sample cabinets with very low leak rates. This may require new types of gloves or assemblies and potentially robotics
15. Initiate a research and development effort for sample containers and sample cabinets for volatiles (potential water and organics, at the level down to 1 ppm).

5.2.3 Future infrastructural curation needs on Earth

Introduction: We concluded above that generally the current sample processing infrastructure at JSC are adequate, but this may not be the case for the *storage* of future samples, especially when "special" samples (i.e., those requiring different storage and handling environments from those already in use at JSC) are considered. Storage of new samples must be as secure and subject to the same contamination controls as is the case for the current Apollo collection. The only facilities that qualify are those currently in use: the *Pristine Vault* and the *Sample Return Vault* at JSC, (Building 31 N), and the *Remote Storage Facility* (RSF) at White Sands Test Facility (WSTF). Once all three facilities are at maximum capacity, the construction of additional storage space becomes unavoidable. All 3 facilities are under the direct administrative control of JSC, an important aspect when considering possible expansion of facilities. The intent of this chapter is to determine the maximum capacity of the existing facilities and to plan for the future, as well as staffing issues.

Assuming that present capacities will not suffice, we evaluate cost effective options to generate additional storage space via relatively modest modifications of the existing facilities. However, future human missions to the Moon may return some hundreds of kilograms of lunar rocks annually, and construction of new facilities may become necessary in the long term, the reason why we suggest that NASA undertake engineering and cost studies to evaluate different approaches to new construction(s).

The present report details current storage-practices of the Apollo collection and evaluates options to consolidate the entire collection into the least amount of space; this then determines the space left in all 3 facilities for additional, future samples. The report also focuses on the "special samples" could be comprised of rocks, regolith, and/or drill cores collected from areas where the potential preservation of volatiles exists. Analysis of evolved gas and volatiles from "special samples" is required to satisfy a variety of scientific goals:

- Cryogenically and stratigraphically preserved sampling from regolith (on Earth, permafrost could be analogous)
- Determining presence of refractory volatile-bearing species including water-bearing minerals, complex organics, and clathrates.
- Determining elemental composition, especially hydrogen, for immediate surroundings of sampling sites.
- Determining local stratigraphy for sample context

It must also be noted that the Apollo collection has been utilized by the science community for 40 years; many rocks and soils have been split and processed into numerous, on occasion hundreds, of individual samples, each in its dedicated container. As a consequence, the storage volume needed for Apollo increased with time and continues to grow, as is the case for any active sample collection. New missions will initially require less space per unit mass of sample, as the subdivision of samples is at an early stage. As a consequence, we assume that these new returns will initially occupy some 30% less space per unit sample mass than the current Apollo collection.

The section of the report is structured such that we first evaluate the capacity of the present facilities before we proceed to major modifications thereof, and ultimately to the construction of new facilities. This structure attempts to mimic estimated costs, starting with the most economic approach and progressing from there to increasingly more costly options. Actual cost estimates are not part of this report, as they demand detailed study by NASA. We also examine what was done with the "special" Apollo samples to investigate improvements that may need to be made for the return of future special lunar samples.

Curation Capacities: The Pristine Vault is 36 x 34 ft in size and accommodates currently 268 kg of lunar rocks and soils, representing 70.1 % of the entire Apollo return. The vault houses 24 stainless steel

cabinets, each equipped with shelves and sample storage trays into which individual sample containers were placed; 18 cabinets have samples transfer ports, allowing the insertion or withdrawal of samples without compromising the environmentally controlled (N_2; O_2; H_20) cabinet interior; there are also 6 "dead storage" cabinets that lack a transfer port; if opened, these cabinets are exposed to the ambient atmosphere; upon closing, they will have to be flushed with dry N_2 until their interior complies with specifications. Each Apollo mission has dedicated cabinets to prevent cross-contamination.
To estimate the full capacity of the facility, we must define a common denominator that relates sample mass to storage volume. We suggest that the most practical measure for storage volume is at the level of individual storage trays; the latter are stainless steel surgical trays that come with a flat lid; they are 6" (15.2 cm) high, some $12^{3/4}$"(32.4 cm) long, and some $10^{3/8}$" (26.4 cm) wide, representing a volume of 13 001 cm^3 or 13 liters; the shelving in the cabinets is dimensioned such that the trays are as closely packed as practical, leaving no dead space; the number of lunar samples in individual trays ranges from < 5 to > 100, depending on the size of sample container(s). The current collection utilizes a total of 541 trays; most of these trays are full, yet some are not; with some modest rearrangement of the current trays, the Apollo collection could be housed in 500 trays; this would then amount to some 500 g of sample mass/tray (268 kg : 500); note that each tray has a volume of 13 liters; most (> 95%) of a tray's volume is thus taken up by container and packaging materials, as the sample volume is < 0.25 liters for materials with density > 2 g/cm^3. Considering the less processed nature of the future returns, we will assume throughout this report that each tray of samples from future missions will house on average some 700 g of lunar rocks or soils.

Note that each Apollo mission mandates dedicated cabinets; 16 cabinets are small accommodating 30 sample trays each; 8 cabinets are double that size, each housing 60 trays. The actual use of the current cabinetry is portrayed in Table 6, with the Apollo collection in black and the number of cabinets and associated trays potentially available for future samples in red. Accordingly, the current Apollo collection is housed in 6 small cabinets and 8 large ones, yielding a total of 660 trays (541 actually in use and some 119 being empty and ready for further expansion of the collection). The 6 "dead mode" cabinets are of the small type and basically empty, thus providing room for an additional 180 trays for future samples. An additional 4 cabinets are underused, housing special samples and core-tubes; their contents are readily consolidated into 2 cabinets, freeing another two cabinets and thus 60 trays for future samples. Thus: total present capacity is 900 trays, 240 of which can be dedicated to future samples by simply using 6 empty cabinets and consolidating the 4 underused ones.

Additional consolidations of the Apollo collection seem possible, yet any consolidation must preserve dedicated cabinets for each of the Apollo missions. We consider two possible scenarios, termed consolidation a) and b) in Table 6. Consolidation a) leaves Apollo 11-14 "as are" and reduces the Apollo

15-17 collections by 60 trays each, consolidating each mission into 2 double cabinets. This decreases the Apollo collection to 480 trays and increases the number of trays available for future samples to 420. The maximum condensation of the Apollo collection is portrayed as Consolidation b) in Table 6, giving Apollo 11-14 each a small cabinet and Apollos 15-17 each a double cabinet; this would reduce the need of Apollo to 270 trays and increase the unused capacity to 630 trays. Much of these consolidations are accomplished by transferring samples to the Remote Storage Facility at WSTF. Consolidation a) seems readily accomplished, yet Consolidation b) will occupy the RSF to its maximum capacity (see below). A minor variant (not listed in Table 6) of Consolidations a) and b) includes the possibility to remove the 6 dead-mode cabinets and replace them with new, and substantially taller cabinets, thus gaining space for an additional 100 trays in the pristine vault.

In summary, maximum capacity of the Pristine Sample Vault is approximately 1000 sample trays, after purchase of new cabinets that eliminates all dead storage in the vault. Consolidation of the current collection into some 270 trays seems possible in combination with sample transfers to the existing WSTF remote facility (see below). This will generate space in the Pristine Sample Vault for approximately 700 trays and thus some 450 -500 kg of additional samples.

The Remote Storage Facility at WSTF consists of a commercial bank vault, some 10 X 12 ft in plan view and a similar sized anteroom for gowning and supplies that were installed inside the RSF. The total sample mass residing at RSF is 52 kg, some 13.5 % of all of Apollo. The RSF building itself is of considerable size, with the Remote Storage Facility occupying < 10 % of its floor plan. Inside the vault are 6 “dead mode” storage cabinets; 2 are devoted to lunar samples, with 1 fully occupied, the other approximately half; one cabinet is devoted to Genesis and another to Stardust; 2 cabinets are empty. The samples are stored inside bolt top containers rather than trays, allowing for more sample mass per storage volume; some 52 kg are housed in 1.5 cabinets at RSF, at 35 kg/cabinet. Filling the partially occupied cabinet as well as the 2 empty cabinets to full capacity allows for the transfer of a considerable fraction (2.5 x 35 kg = 87.5 kg) of the Apollo collection. Such a transfer seems consistent with Consolidation b) of Table 6. However, after completion of this transfer, the Remote Storage Facility will be at full capacity, unable to receive any “posterity” samples from the new returns. Stardust and Genesis could possibly be combined into a single cabinet, a suggestion that should be explored by the Curator with the help of CAPTEM. It follows that the RSF capacity is either 4 or 5 dead-mode cabinets, amounting to 140 kg or 175 kg of lunar rocks or soils.

Table 6. Current and possible future use of sample cabinets and sample trays in the Pristine Sample Vault between the Apollo (black) and future (red) collections. See text for the significance of "Consolidation a" (= modest consolidation of Apollo collection) and "Consolidation b" (most severe consolidation).

Mission	Small Cabinet 30 trays ea	Large Cabinet 60 trays ea	Current Apollo total trays	Consolidation a	Consolidation b
Apollo 11	1		30	30	30
Apollo 12	1		30	30	30
Apollo 14	2		60	60	30
Apollo 15	2	2	180	120	60
Apollo 16		3	180	120	60
Apollo 17		3	180	120	60
Totals, Current	6	8	660		
Dead Stor.	6	0 (180)		180	180
Underused	4	0 (60)		60	60
Total Capacity			900		
Consolidation a)					
Apollo	6	6		480	
Constellation	10	2		420	
				900	
Consolidation b)					
Apollo	5	3			270
Constellation	11	5			630

The sample return vault is some 36 x 22 ft in size and houses numerous conventional 2-door cabinets with adjustable shelves; the cabinet interiors are not environmentally controlled, but exposed to clean, well filtered air. This laboratory is essentially a class 1000 clean room with all returned samples exposed to the ambient environment. The total returned sample mass is 29 kg, some 7.6 % of the total collection, with the remainder (3.4%) "consumed" during processing and the production of public and educational displays. This vault also houses some miscellaneous materials from other missions, such as Stardust and Genesis, as well as cosmic dust samples and associated collectors, some unprocessed, some processed. It is also the temporary receptacle, during hurricane threats, of rare meteorites, all Stardust and some Genesis samples. It is thus a multipurpose facility, with some 70% of its floor space devoted to returned lunar samples, yet the remaining 30% of great utility to the Curator that is not readily duplicated. Consolidation of existing collections and cabinets, combined with the purchase of additional cabinets on an as needed basis (there is sufficient floor space) suggests that a factor of 2 more returned lunar samples may be accommodated in this vault than is the case presently, after 40 years of Apollo. This facility is thus capable to support the Apollo and future sample collections for some time to come, much longer than the 2 facilities concerned with the storage of pristine samples. It is difficult to derive an absolute time

scale by which this facility may reach maximum capacity, yet if it does, the suggestion is to generate a new sample return vault at WSTF at relatively modest costs (see below).

In summarizing the capacities of the current facilities, we suggest that the Remote Storage Facility at WSTF be used to capacity by re-locating part of the Apollo collection currently in the Pristine Sample Vault. Additional rearrangement and condensation of the Apollo collection will free as much as 60-70% of the current Pristine Vault capability for future collections; some 300 sample trays remain occupied by Apollo and some 700 new trays will be available for future samples, with full vault capacity defined as 1000 total sample trays. We estimate that some 400-500 kg of new samples can be accommodated, together with some 150 kg of Apollo materials. Assuming 2 sample return missions of 150 kg each per year, the Pristine Vault and the WSTF will thus be at full capacity after the first 2 years.

It is clearly desirable to evaluate additional options for increased sample storage capacity. We consider two scenarios: 1) Modification of Existing Facilities and 2) New Construction.

Modification of existing facilities: A promising way to increase the capacity of the Pristine Sample Vault is to replace the current storage cabinets with cabinets that are modestly taller and more efficient in housing individual sample trays, and that would also utilize the overall floor space more efficiently. Such cabinets are commercially available, with minor modifications. Using these more efficient cabinets, as many as 45 individual units could be installed, each housing some 20 sample trays, 4 on each of 5 shelves; this would amount to 1800 sample trays and thus almost double current capacities; extra tall cabinets (approximately 7 ft tall) by adding an additional shelf and thus 4 trays, could increase this number by another 200 trays, yielding a total capacity of 2000 trays. This then would amount to approximately 1700 trays devoted to future samples and a total storage capacity of about 1200 kg (1700 x 0.7 kg) for these samples, sufficient for some 4 years of continued sample returns at 300 kg/annum. A possible drawback of this suggestion is that these cabinets would not have sample ports; instead, each shelf unit housing 4 trays would be essentially a sealed container that is separated from the rest; once its door is opened, all 4 trays would be exposed to the ambient environment, albeit shortly, as the unit would be flushed and re-pressurized immediately after withdrawal (or insertion) of the desired tray. On the other hand, having 4 trays per individual storage "cabinet" allows for extremely efficient use of storage space.

As alluded to earlier, the present facility is likely at maximum capacity when the first new samples return. It is thus not possible to accommodate any posterity sample(s) that may be generated from any new return; generation and preservation of such a posterity suite seems of high priority. It seems that the storage capacity at WSTF must be increased. This will be accomplished most economically by adding an additional vault to the current facility. Vault size should be as large as the current facility to accommodate an additional 200 – 250 kg of rock. The current "dead mode" storage

units that will be surplussed from the Pristine Vault are similar to those currently operated at WSTF and they could be installed in this new vault, resulting in a substantial cost savings. The addition of a new vault also opens the possibility to relocate the Genesis and Stardust samples from the present to the new vault, thus permitting the storage of additional Apollo samples in the old vault, making Consolidation scenario "b" more realistic.

It seems obvious, that modular expansion of the WSTF facility, adding one vault after another, is a highly cost effective approach to storage capacity, as individual vaults could be added and sized on an as needed basis. No major new construction is needed, other than the relative economic installation of a stand-alone vault, installation of suitable sample cabinets, and relatively modest plumbing to assure an environmentally acceptable cabinet interior. The installation of the present Remote Storage Facility at WSTF cost about $200 K, including supervision during construction and an operational shake down by personnel from the JSC Curation Office. It is thus concluded that expansion of the remote storage capabilities at WSTF are the most economic means to expand overall storage capacity for pristine lunar samples.

The major drawback of this option relates to the obvious fact that some of the current (non-Curation) users of the RSF building would have to be relocated to make space for the new curatorial facilities. We suggest that JSC develop a short- and long-term plan for the use of this building. The short term plan relates to the addition of a single vault that will not only be needed for new posterity samples, but that also will be useful during the re-arrangement of the existing Apollo collection, an activity that will obviously precede the arrival of new samples, and that may benefit from some generous temporary storage capability. Ideally, this short-term plan should be in place within the next 2-3 years and construction of a new vault should be completed within two years prior to any new sample return. The long-term plan will relate to the installation of additional vaults on an as needed basis, with the curatorial facilities occupying progressively more floor space, as much as half of the building, possibly the entire building, with each vault accommodating some 300 kg of samples.

In this "modification" scenario, all of the sample processing would still be accomplished at JSC; as a consequence, sample transfers from Houston to WSTF and from WSTF to Houston would have to occur much more frequently than is currently the case; while somewhat of an operational nuisance, these transfers are not a major obstacle. Indeed they seem outweighed by sample safety issues: NASA's major lunar sample storage facility would be in an environmentally safer place than Houston's hurricane-prone location. In the long run, only the "active" collection, in need of processing, would be housed in Houston; most of the sample mass would reside at RSF in White sands.

Other than adding new cabinetry and using the available floor space more efficiently, this facility will support all lunar samples for a relatively long time to come. Once it is at full capacity, it may become necessary to install a vault at WSTF that is dedicated to returned lunar samples.

New Construction: We concluded above that existing sample processing capabilities suffice to support an Apollo-type demand for lunar samples from the international community; Apollo satisfied over 200 individual investigators. We also suggest, that the Pristine Vault (after installation of new cabinets), housing some 1000-1200 kg of materials adjacent to the processing facilities, suffices to support this throughput; the "active" collection to be housed in the Pristine Vault will be a function of newly arrived samples and those under ongoing investigation, all in need for processing. We consider the above sample mass, representing a few thousand samples, sufficient to support the incoming sample requests and associated processing; samples residing at the RSF in White Sands can readily be added in a timely fashion to this active collection. In brief, the capabilities of the processing lines and sample storage in the modified Pristine Vault seem internally self-consistent and adequate to serve the science community for a long time to come.

Consequently, the major issue related to the capacity of all curatorial facilities is substantially related to the generation of additional sample storage, specifically "dead storage" that does not need access on a frequent basis. This storage will accommodate those samples that were selected for posterity, and samples that are of diminishing interest to the sample community and that can be removed from the "active" collection in the Pristine Vault. We argued above that this storage capability is best installed at WSTF, by modular installation of vaults on an as needed basis, inside an existing building that is structurally sound.

It is also recommended that NASA undertake an engineering and cost study to expand the current facilities in Houston, by adding a new Pristine Sample Vault to Building 31N that is structurally as safe as the present vault, of comparable size and at a similar elevation above sea level. This study should include the equivalent of the present Sample Return Vault on the 2nd floor, akin to the current Sample Return Vault. This study will be needed in case the above estimates regarding total capacity for the "active" collection at JSC are insufficient; the additional Return Vault may be needed to not only house additional lunar materials from either Apollo or new lunar missions, but it may also become the major receptacle of extraterrestrial samples returned from other missions, such as Genesis, Stardust, the Cosmic Dust collection, valuable meteorites, and future asteroid and comet missions (note that two of the three of the current New Frontiers selections that have been chosen to go to Phase A, at the time of writing, are sample return missions). The primary purpose of this study, however, is to compare the cost estimates for new construction with the cost estimates for the modular expansion, vault by vault, of the Remote Storage

Facility at WSTF. This study should also consider the building of a cold storage and processing facility as part of future curatorial needs (see below). This cost estimate is also needed in case there is no room in the RSF building for additional vaults.

Special Samples: A suite of Apollo 17 samples were collected from Taurus- Littrow on December 10 – 11, 1972 and returned to Earth to then be kept frozen. Surface samples were collected from locations transiently shadowed and in ~1-3m cores. No attempt was made to contain the samples in a "cold" environment during collection and transport and the thermal history of the returned Apollo samples was not documented either during collection, transport from the surface of the moon to Earth, or during curation in Houston, TX (Allton, 1989). As a result, the frequency and duration of thermal excursions experienced by the samples is unknown. As might be expected, the Apollo 17 rocks have not been of much interest to researchers who require pristine samples for scientific analysis. Durrani et al., (1976) is the only investigator to have studied the Apollo 17 "cold" samples. See Butler (1973) for details of sample containment and transfer.

Areas considered to be "cold traps" on the Moon (such as permanently shadowed areas at the poles) are considered possible regions that concentrate volatiles and are modeled at temperatures of approximately -220°C (Vanada et al., 1999). The change in ice structure with rising temperature and loss of volatiles as ice sublimes (-123°C in vacuum) necessitate sample containment at the coldest possible temperatures. However, sample containment and handling are considerably more complicated and costly at temperatures below approximately -80 ^{o}C (Ehrenfreund & Irvine, 2006). In situ analysis may be required for research involving highly volatile species (e.g. CO & N_2) and highly specialized protocols would be required for such studies.

Technologies exist to contain and store samples thereby preserving most volatile species in geologic samples. The Cold Stowage Payloads on NASA's International Space Station and Space Shuttle are capable of preserving samples at temperatures ranging from -80 ^{o}C to -160 ^{o}C and consist of both active and passive refrigeration systems. Most importantly, thermal histories of the samples can be documented. The Minus Eighty Laboratory Freezer for ISS (MELFI) is an active cooling system that consists of four identical dewars each of which can be controlled independently at certain set points as long as dewar 1 is at -95°C. The three set points for dewar temperatures are -95 ^{o}C, -35 ^{o}C, and +2 ^{o}C and total capacity is 175 liters. MELFI is continuously powered on-orbit when supporting science and can maintain temperature below -68 ^{o}C with a power off duration of 8 hours. The General Laboratory Active ISS Experiment Refrigerator (GLACIER) is an active cooling system that consists of a vacuum insulated cold volume that can support a selectable temperature range of -160 ^{o}C to +4 ^{o}C and total capacity of 11.35 liters. GLACIER can maintain samples below -68 ^{o}C for a maximum of 20 hours without power if

operating at -160 °C and 75% full. Passive cold stowage resources for Shuttle and ISS consist of cold bags that contain icepac and ice brick assemblies. Maximum mass that can accommodated by current cold bag configurations is 24.4 kg (sample and icepacs). The icepacs are standard solid-liquid phase change material encapsulated in hard plastic. They are available for specific melting temperatures: +4 °C, 0 °C, -16 °C, -21 °C, -32 °C. Temperature hold time depends upon the icepac type and quantity but range from 4 to 10 days.

Currently large volume refrigerated facilities exist for storing ice cores and other cold samples. The US Army Cold Regions research and Engineering Laboratory (CRREL) in Hanover, NH (http://www.crrel.usace.army.mil/facilitieslabstestsites/coldrooms.html) maintains 24 specially equipped cold laboratories served by a central refrigeration system to store and examine ice samples at -30 °C. The National Ice Core Lab (NICL) in Denver, CO occupies 8,000 ft^2 at the Denver Federal Center and is managed by The Climate Change Research Center, Institute for the Study of Earth, Oceans and Space, University of New Hampshire, Durham, NH (http://nicl.usgs.gov/about.htm). The main storage area of the facility is held at -35 °C to promote the longevity of the cores and to minimize sublimation and diffusion. NICL also has lab space for processing and preliminary analysis of cores and sub-samples at -20 °C. The Kochi Core Center (KCC) is a research facility jointly managed by the Kochi University and Japan Agency for Marine-Earth Science and Technology (http://www.kochi-core.jp/en/aboutus/index.html). KCC maintains four large refrigerated storage areas at about 4˚C and humidity of about 80% for most core sections and a separate storage area at -20˚C. In addition, KCC has twelve 430-liter liquid nitrogen tanks. The tanks are continuously monitored by a central control system, which automatically supplies liquid nitrogen to keep temperature stable below -160˚C (Fig.19).

Figure 19. Each tank is capable of storing 398 sample vials, each of which can contain ca. 50 cc core sample.

Curating samples under cold conditions poses unique challenges to traditional curation practices; however, this ability lies on the critical path of enabling future sample return missions from the nuclei of comets, permanently-shadowed lunar craters, the surface of Mars and other icy bodies. Humans processing samples in a -25°C laboratory are exposed to temperatures capable of causing frostbite on exposed skin in 45 minutes or less (USARIEM Tech note, 2001). Personal protection equipment required to comfortably operate in such an environment severely limits hand sample manipulation and static electricity levels inherent in cold, dry environments present considerations for equipment operations as well. The cost of construction and maintenance of cold processing facilities is related to size and temperature requirements for the storage environment. Construction and maintenance of a glovebox-sized cold processing environment is considerable less than that for a complete laboratory and the scientific integrity of the sample in an isolated environment can be preserved as well. In preparation for receipt of cold samples, Johnson Space Center (JSC) has designed and installed a cold curation glovebox within a JSC Advanced Curation Facility to develop this technology (Fletcher et al., 2008). This glovebox was designed to store and manipulate frozen samples while quantifying and minimizing contamination levels throughout the curation process.

Figure 20. A. The stainless steel, nitrogen purged Cold Curation glovebox. B. Ultrapure water samples on cold plate and sample balance located inside glovebox.

The JSC cold glovebox system is a custom designed stainless steel glove-box outfitted with a cold plate for sample manipulation and freezer for sample storage (Figure 20). The cold plate and freezer

hold their -35°C temperature within +/- 2°C, while our overall glovebox environment maintains the temperature of the incoming curation-grade dry nitrogen gas (22°C +/- 2°C). A room temperature box allows the operator to easily see and manipulate tools and samples; however, the large temperature gradients surrounding the cold plate could impact the sample structure. The temperatures surrounding the -35°C cold plate reach 0°C just 3 mm away from the plate surface on all sides. On the horizontal plane 10 cm from the plate, the temperature is 20°C. In the vertical direction, 20°C is reached 20 cm above the plate. As the sub-freezing temperatures are only maintained very close to the plate surface, sample manipulation must be done very quickly or within metal containers resting on the plate such that the cold plate will transfer that temperature up the walls of the container and increase the volume of the sub-freezing environment. In addition to the cold plate and freezer, the cold curation glovebox contains probes to measure the temperature of the cold plate, freezer and overall box environment, a microscope and camera mounted outside of the box, sample balance and heat sealer for initial processing and storage, touch screen to control and display temperature data and environmental conditions and a laptop with software for logging glovebox environmental conditions and sample data. The gloves are made of Hypalon and seals are made of Viton. A glovebox environment that can maintain -35°C (or greater) throughout requires double wall construction and refrigerated gas as well as insulated gloves which greatly reduce dexterity. Robotic manipulation is required to handle samples in cryogenic environments safely and efficiently, as has been demonstrated in the semi-conductor industry. Appropriate manipulator tools, dexterity, and user interfaces must be developed for the specific tasks associated with geologic sample handling. Cold samples act as cold traps for contaminants and this presents problems for certain types of scientific investigations. Solutions to contamination management in cryogenic isolation environments are needed to facilitate scientific investigations involving cryogenic samples. Cold storage and processing is best developed at JSC and only once the techniques have been developed, should off-site cold storage at WSTF be developed.

Water ice begins to sublimate at around -125 ^{o}C and will sublime quickly at -80°C under vacuum (Vasavada et al., 1999). Containers for storage and transport of volatile-rich samples will be required to accommodate large head space pressures (Gooding, 1990) and should be designed to interface with instrument-specific sample introduction systems for the measurement of any head space gas that is evolved during transport and storage. It is recognized that an insufficient number of facilities are currently available to analyze head space volumes of specially contained cryogenic samples and this is a concern for the scientific community. No one laboratory is able to analyze the full complement of volatile species that may be preserved in extraterrestrial samples and many of the techniques and hardware developed for analysis of volatiles in the head-space volumes of Apollo returned sample containers are no longer in use or even in existence (Don Bogard personal communication).

Staffing: The situation at the time of writing of this report is that there are currently 2 dedicated lunar processors and the meteorite curator sometimes helps out. Over the past several years the number of lunar sample requests has increased due to re-emphasis of the Moon in solar system exploration. This has brought pressure on the skeleton lunar curatorial staff at JSC. This is exemplified by the fact that returned lunar samples continue to build up as there has not been the time to address the backlog of these samples. At this time, there is a pressing need for 2 lunar processors to process the returned sample backlog.

For the Apollo missions, there were far more persons involved in the processing and curation of lunar samples (e.g., data clerks to set up paperwork, QC experts, photographers, etc.) With the advent of new technology (e.g., voice recognition software, digital photography, etc.), the number of FTEs needed for processing and curating the next era of lunar return samples will be much lower than needed during Apollo. However, Apollo should be taken as the baseline the level of detail recorded and the procedures taken to avoid sample contamination and cross-contamination.

The present situation has a total of 8 cabinets for processing, so future needs should allow for simultaneous operations of all benches. One more processing cabinet could be put in the pristine laboratory and two more could be put in the experimental laboratory. This gives a total of 11 processing cabinets. If this is the case, then the total number of technicians needed would be 11 (including processers, database, photography, etc.) and assuming that scientists would be involved in the preliminary examination of the returned samples. Preliminary examination of a sample return will probably be done in the processing laboratory in parallel with processing of the previous return. A sequence of what goes into the database still needs to be developed and documentation needs to be all inclusive.

Findings:

Recommendations for Current and Future Lunar Sample Curation:

1. We conclude that the current curatorial facilities are at full capacity with the return of 450-500 kg of materials from future lunar sample return missions, possible after 2 years of supporting such operations.
2. The installation of more efficient cabinets in the Pristine Sample Return Vault and relocation of some 100-150 kg of Apollo samples to the RSF at WSTF would increase the space for new samples inside the Pristine Vault to some 1000-1200 kg, provided a new vault is added to the RSF.
3. Approximately 5 years into a new program of lunar sample returns, additional vault space must be made available, either at WSTF or at JSC. **We suggest that NASA conduct engineering and cost studies to generate additional storage at WSTF and/or at JSC that includes cold storage and processing facilities at JSC**. WSTF is preferred, as it may offer the more cost-effective approach and because it is the safer site, less prone to natural catastrophes than Houston.

Findings (continued):

Recommendations for Cold Sample handling and Curation: Cold sample collection, containment, and curation require special considerations with regard to sample science preservation. The following recommendations summarize the findings herein:

1. There needs to be a stepwise approach to returning cryogenic samples from planetary bodies. Some samples could be analyzed in situ and other samples could be stored/contained in situ and then returned for cold curation and analysis on Earth.
2. Cold curation and storage need to be factored in to the discussion of storage capacity and any new storage facility construction. A study is required to estimate the volume of samples that would require cold storage.
3. A custom designed new facility for cold storage and processing is needed rather than trying to meld it into an existing facility.
4. If total special sample volume is small (1-2 kg) the support structure would be approximately the size of a small car, if current technologies are used (compressors, liquid nitrogen) but the facility could be mobile. A mobile facility could dock to Building 31N and then takes the sample to the PI. Such a facility could also pick samples up from the landing site.
5. Cold processing and curation capabilities need to be developed to at least -125˚C to prevent sublimation of volatiles.
6. Every sealed special environmental sample container must be able to retain volatiles and to accommodate head space gas analysis through a valved gas port. A gas analysis facility is also needed.
7. PET of special samples will have an influence on future needs, but protocols need to be looked at in more detail. Cryogenic conditions create contamination control issues that must be addressed in the context of life detection techniques that apply to Mars sample return as well as for volatiles that may be sampled on the Moon.

Recommendations for Staffing Needs:

1. At this time, there is a pressing need for 2 lunar processors to process the returned sample backlog.
2. If the sample return reaches the level of 300 kg of samples being returned per year, the number of technicians trained in lunar sample processing and curation needs to be increased to a minimum of 8 if no new processing cabinets are added.
3. If new sample processing cabinets are added to the JSC curatorial facility, there should be an increase of one trained technician per sample processing cabinet.

Section 6. Summary of Findings.

This document contains 58 findings tied to the acquisition and curation of samples during lunar surface activities. Further, the document identifies 25 additional findings tied to future curation needs on Earth. Although many findings are relevant to both sortie and outpost activities, there are several that are linked to one or the other. Several findings are highly relevant to the early stages of the evolving exploration architecture tied to human exploration of the Moon or other planetary body:

(1) The architecture should be able to accommodate a return mass of 250 to 300 kg of sample and sample containers (per mission). A volume of 0.10-0.12 m^3 is required per 100 kg of lunar samples.

(2) Relevant to accommodating this sample volume in the architecture is the usefulness of soft containers to return lunar samples. A hard Apollo-type "rock-box" is inefficient at packing samples, increases the volume needed per 100 kg of sample mass, and is inflexible in storage.

(3) Contamination of lunar samples has many potential sources and could be introduced through many processes and activities. Therefore, there is a need to establish programmatically acceptable guidelines for general materials selection and control protocols for specific manufacturing and surface finishing processes.

(4) A joint advisory committee consisting of both science and engineering community stakeholders is required to facilitate communication and formal decision making required to maintain and enforce the standards established in recommendation 3 (above).

(5) For all science involving thermally sensitive samples (geology, planetary science, biology) refrigeration units must be accommodated within the returning space craft and the outpost. Cryofreezers providing a level of capability similar to GLACIER, developed for the ISS, are representative of the capacity and level of thermal control required.

(6) The scientific exploration of the Moon and associated sampling mandate efficient transfer of voice, navigation, imagery and analytical instrument data from the surface to the ground and vice versa. These needs have detailed implications for Communication Architecture.

(7) Reducing sample return mass by "high-grading" samples on the lunar surface that is based on scientific criteria requires well-trained astronauts and key analytical instruments. The former requires well thought out astronaut selection and training, while the latter dictates power requirements for sortie and outpost operations.

In addition to these findings that are highly relevant to the design of human planetary exploration architecture there are several findings that identify further studies and development. These include:

(1) Design and testing of general use sample containers.
(2) Investigation of new materials for tools and sample containers.
(3) Investigation, design, and testing of easy to use analytical instrumentation for surface operations, sample selection, and high-grading.

(4) Using the Apollo Program as a starting point to establish a rigorous astronaut training program applicable to exploration, and sampling of planetary surfaces.
(5) Establish surface operations protocol for sampling which considers contamination control, high-grading, and curation.

Section 7. References

Allton, J.H. (1989) Catalog of Apollo Lunar Surface Geological Sampling Tools and Containers. JSC-23454, LESC-26676.

Butler (1973) Lunar Sample Information Catalog Apollo 17. MSC 03211.

Compton, W. D. (1989) Where No Man Has Gone Before: A History of Apollo Lunar Exploration Missions. Published as NASA Special Publication-4214 in the NASA History Series.

Duke M.B and Nagle J.S. (1976) Lunar Core Catalog. JSC09252

Durrani (1972) Refrigeration of Lunar Samples destined for Thermoluminescence Studies. Nature 240, 96-97.

Durrani S.A., Karzal K.A.R. and Ali A. (1976) Temperature and duration of some Apollo 17 boulder shadows. Proc. 7th Lunar Sci. Conf. 1157-1177.

Ehrenfreund, P., Irvine, W.M. & , e.a. (2006). Future Perspectives and Strategies in Astrobiology. *Orig. Life Evol. Biosphere*.

Fletcher, L. A. et al. (2008) LPSC XXXIX, Abstr. # 2202.

Jolliff BL, Wieczorek, MA, Shearer, CK, and Neal CR (2006) New Views of the Moon. Reviews in Mineralogy and Geochemistry v. 60, 721p.

Räntfors, K, Sundgren M, Rucker M, (2009) Chalmers University Geolab presentation to Houston.

Rummel JD, Race MS, deVincenzi DL, Schad PJ, Stabekis PD, Viso M, Aceved SE, (2002) A Draft test Protocol for Detecting Possible Biohazards in Martian Samples Returned to Earth. NASA/CP 2002-211842, 112 p. [http://www.marsinstitute.info/epo/docs/draft_protocol.pdf].

Sandford, S.A., McNamara, K., and Zolensky, M. (2006) The recovery of the STARDUST sample return capsule. LPSC XXXVII, abstract # 1123.

Shearer, C., Neal, C., Borg, L., Jolliff, B., Papanastassiou, D., Treiman, A., Floss, C., Rutherford, M., Norman, M., Farquhar, J. (2007) Analysis of Lunar Sample Mass Capability for the Lunar Exploration Architecture Unpublished white paper, 14 p, posted May 2007 by the Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM) at http://www.lpi.usra.edu/captem/.

Stansbery, E.K. and McNamara, K.M. (2005) Genesis Preliminary Examination – Ellipsometry Overview. LPSC XXXVI, abstract # 2145.

Taylor SR (1975) Lunar Science: A post-Apollo View, Pergamon.

Treiman AH (1993) Curation of Geological Materials at a Lunar Outpost, JSC-26194 and Office of the Curator Publication #187.

UASRIEM Tech Note (2001) Sustaining health and performance in cold weather operations.

Vasavada, A.R., Paige, D.A., and Wood, S.E. (1999) near-Surface Temperatures on mercury and the Moon and the Stability of Polar Ice Deposits. *Icarus* 141, 179-193.

Section 8. APPENDICES

APPENDIX I. Letter from Associate Administrator Acknowledging Review

Dr. Charles Shearer
Chair, Curation and Analysis Planning
Team for Extraterrestrial Materials
University of New Mexico
MSC03 2050
Albuquerque, NM 87131-0001

Dr. Clive R. Neal
Chair, Lunar Exploration and Analysis Group
Department of Civil Engineering
And Geological Sciences
156 Fitzpatrick Hall
University of Notre Dame
Notre Dame, IN 46556

Dear Drs. Shearer and Neal:

NASA's plans to return humans to the moon present many opportunities for science and numerous challenges. The return of lunar samples collected by astronauts allows the precise analyses needed to answer long-standing questions about the history of the moon and solar system. The dual challenges of preserving sample integrity and selecting from a larger group of samples than we can return determine the quality of scientific results.

NASA's Science Mission Directorate requests the help of the Curation and Analysis Planning Team for Extraterrestrial Materials and the Lunar Exploration and Analysis Group in evaluating these challenges by conducting a review of requirements and options for collection and curation processes on the moon and in curation labs on Earth. In conducting the review we ask that you consider all likely users for the lunar samples.

Enclosed is a description of the task that I understand has been negotiated with you. NASA and the NASA Advisory Council will be most interested in the results of this review. Dr. Marilyn Lindstrom will serve as your point of contact in the Science Mission Directorate's Planetary Science Division. Thank you for your efforts to advance the scientific exploration of the moon.

Sincerely,

Edward J. Weiler
Associate Administrator
Science Mission Directorate

Enclosure

APPENDIX II. LSAC Review Charter.

2.2 Charter for the CAPTEM-LEAG LSAC Review

The NASA Science Mission Directorate, in coordination with the Optimizing Science and Exploration Working Group (OSEWG) requests that CAPTEM and LEAG jointly conduct an end-to-end review of sample acquisition and curation during the next stage of human exploration of the Moon. This should address all aspects of curation recommended by the NAC (S-07-C-9) and the NRC (Recommendation 4R) as well has assisting with the definition of scientific requirements needed by engineers designing spacecraft and missions and future government or commercial activities related to lunar resource recovery and use.

Background

NAC S-07-C-9 Sample Collection, Documentation, Containment and Curation

NASA should

(1) Establish well-defined protocols for collection, documentation, containment, return and curation of lunar samples;
(2) Collect lunar samples of various types and purposes with maximum diversity of location and required *in situ* documentation;
(3) Optimize scientific return while protecting sample integrity.

NRC 4R Updating Lunar Sample Collection Techniques and Curation Capabilities

NASA should

(1) Conduct a thorough review of all aspects of curation;
(2) Take into account differences in sortie and outpost mission approaches;
(3) Consider documentation, collection, curation on Moon and in facilities and laboratories on Earth;
(4) Enlist broad scientific input with CAPTEM and LEAG to assist the review.

2.22 Charter

CAPTEM and LEAG, jointly, are requested to review lunar sample acquisition, curation and the potential distribution for scientific studies, with consideration including, but not limited to the following:

(1) The impact of sample acquisition, preservation, return, and curation on critical engineering requirements for Constellation and future lunar operations.
(2) Sample preservation and contamination control at all stages.
(3) Sample documentation, acquisition, and packaging at all stages.
(4) Potential for and advantages of field analysis in sample selection, including technologies needed.
(5) Scientific value of integrated investigations of a variety of different sample types.
(6) Sample acquisition techniques, tools, procedures, photography and description, including hand, regolith, drill core, and volatile-rich samples.
(7) Sample curation and analysis at the Moon including selective sample size and quantity reduction prior to return to Earth.
(8) Sample transfer from spacecraft to curatorial facilities at Earth.
(9) Sample curation, shipment, and investigator handling requirements at Earth.

Report

The need for samples that will meet scientific requirements to support Constellation and future operational engineering, including lunar resource acquisition, are to receive special emphasis in this review. Although activities on the Moon can impact curation at Earth, a preliminary report on the review of activities conducted on the Moon will be completed in one year from January 1, 2009, with the final report that includes review of curation at Earth to be completed within 18 months (June 30, 2010). In addition to the specific items listed above, the final report should include discussion and recommendations on the following more general topics:

(1) Contamination prevention and packaging requirements;
(2) Definition of mass, volume, power, communications, crew time, crew skills, and flight control requirements for curation on the Moon and return to Earth (noting differences between a sortie mission and an outpost);
(3) Assessment of differing degrees of *in situ* or laboratory sample analysis on the Moon and associated equipment, technology, skill, training, and professional experience needs;
(4) Protocols for collection, documentation, analysis, and curation on the Moon;
Definition of existing, new or modified capabilities and techniques for curation at Earth, including the required skilled personnel.

APPENDIX III. Agendas from January 2009, May 2009 and January 2010 meetings of the LSAC Review.

MEETING OF THE
CAPTEM-LEAG LUNAR SAMPLE ACQUISITION AND CURATION REVIEW

January 22-23, 2009

Lunar and Planetary Institute

Thursday, January 22, 2009, 8:30

8:30 AM — Welcome and Introductions (Neal & Shearer)
Goals for 1st Meeting (Shearer & Neal)

8:45 AM — Sample Acquisition and Curation. Lessons Learned from the Apollo Program.

8:45 AM — Sample Tools (Allton)
9:15 AM — Sampling surface operations (Hörz and Lofgren)
9:45 AM — Sample Packaging, Preservation, and Storage (Lofgren and Allton)
10:15 AM — Sample Contamination Control (Lofgren)

10:45 AM — Coffee Break

10:55 AM — Sample Return within the context of the Constellation Architecture, sorties and outpost (Gruener)

11:25 AM — ISS operations and relevance to sampling on the lunar surface (Eppler)

11:55 AM — Lunch

1:05 PM — LEAG Lunar Science Roadmap and Relevance of samples (Neal)
1:35 PM — Conditions of Lunar "cold traps" and sample collection and storage (Allamandola)
1:50 PM — Preserving the lunar record in fragile or environmentally sensitive samples (Keller, Lofgren)

2:15 PM Coffee Break

2:30 PM Discussion on Theme Linkages
Contamination Control, Packaging, Tools (Discussion Lead: Papanastassiou)
Sample Mass and Volume, Packaging, Sample High-grading (Discussion Lead: Neal)
Crew Requirements, Communication, Flight Control (Discussion Lead: Eppler)

4:00 PM Setting Engineering Requirements I
Sample Acquisition Tools (Discussion Lead: Buffington)
Packaging and Preservation (Discussion Lead: Eppler)

Contamination Control (Discussion Lead: Papanastassiou)

5:30 PM— Adjourn for the day

Friday, January 23, 2009, 8:30

8:30 AM — Revisit and Modify Friday's Agenda

8:45 AM — Setting Engineering Requirements II

Sample Mass and Volume (Discussion Leader: Neal)
Power Requirements (Discussion Leader: Noble)
Crew Requirements (Discussion Leader: Bleacher)
Communication and Flight Control Requirements (Discussion Leader: (Hörz and Eppler).

10:30 AM Coffee Break

10:45 AM Setting protocols for collection, documentation, analysis, high grading and curation during sortie missions (Breakout).

12:05 PM — Lunch Break

1:15 PM — Setting protocols for collection, documentation, analysis, high grading and curation during sortie missions.

1:45 PM — Setting protocols for collection, documentation, analysis, high grading and curation during outpost missions.

3:00 PM — Revisit Phase 1 themes in light of protocol discussions.

3:45 PM — Timeline, writing assignments, LSACR "Workshop"

4:15 PM— Adjourn for the day

AGENDA
2nd MEETING OF THE
CAPTEM-LEAG LUNAR SAMPLE ACQUISITION AND CURATION REVIEW

May 7-8, 2009

Lunar and Planetary Institute
Berkner Room

Thursday, May 7, 2009, 8:30

8:30 AM — Welcome and Introductions (Neal & Shearer)
Goals for 2nd Meeting (Shearer & Neal)

8:45 AM — **Discussion of sample acquisition and curation protocol during surface operations**

(15 minute presentation of Strawman protocols, 45 minute discussion)

8:45 AM — Protocol for sample acquisition during sortie and outpost operations (Fred and Gary).

9:45 AM — Protocols for sample acquisition and curation during sortie missions (Jake)

10:45 AM — Coffee Break

11:00 AM — Protocols for sample acquisition and curation during outpost operation missions (Allan, Mary Sue, Cindy)

12:05 PM — **Lunch**

1:05 PM — **Breakout Group I**

Sample Mass and Volume (Clive (L), Allan, Chip, Fred, Carl)
Sample packaging and preservation requirements (Dean (L), Dimitri, Gary, Jesse, Simon, Cindy)
Power requirements for sample acquisition and curation (Sarah (L), Lindsay, Jake, Mary Sue, Karen)

3:30 PM — **Coffee Break**

3:45 PM — **Breakout Groups Report**
5:30 PM — **Adjourn for the day**

Friday, May 8, 2009, 8:30

8:30 AM — **Discussion of Friday's Agenda**
8:45 AM — **Breakout Groups II**

Sampling acquisition tools (Jesse(L), Fred, Lindsay, Lindsay, Karen, Cindy)
Sample contamination control requirements (Dimitri(L), Clive, Chip, Simon, Gary)
Crew Requirements (Jake(L), Sarah, Mary Sue, Dean, Allan)

10:30 AM — **Coffee Break**

10:45 AM — **Breakout Groups III (continue through lunch).**

Communication and Flight Control Requirements (Fred (L), Dean, Sarah, Karen, Gary, Cindy).
Analytical Instrumentation Requirements for Sample Acquisition and Curation (Chip (L), Jake, Clive, Allan, Jesse, Dimitri, Carl, Lindsay, Simon, Mary Sue)

1:30 PM — **Morning Breakout Groups Report**

2:45 PM — **Coffee Break**

3:00 PM — **Breakout Group IV**

Protocols for sample acquisition and curation during sortie missions (Jake(L), Karen, Jesse, Dean, Clive, Fred, Simon)

Protocols for sample acquisition and curation during outpost operations missions (Allan (L), Mary Sue, Cindy, Carl, Chip, Dimitri, Lindsay, Gary)

4:00 PM **Discussion of Breakout Group IV and Timeline**

5:00 PM **Adjourn for the day**

3rd MEETING OF THE CAPTEM-LEAG LUNAR SAMPLE ACQUISITION AND CURATION REVIEW

January 7-8, 2010

Hess Room at the Lunar and Planetary Institute and Johnson Space Center

Thursday, January 7, 2010

9:00 AM -noon — Tour of Lunar Curation Facilities (Shearer, Borg, Buffington, Horz, Lindstrom, Noble, Papanastassiou)

Noon-1:15 PM — Lunch

1:15 PM — Goals for 3rd Meeting (Shearer & Neal) Future lunar curation on Earth

1:30 PM — History of curation facility and curation proceedures during the Apollo Program (JSC Curation and Discussion)
Topics:Pathway for handling samples from recovery on Earth to curation facility, initial Apollo sample curation

2:30 PM Current state of lunar curation at JSC (JSC Curation and Discussion)
Topics: Description of current facility, current sample mass, curation capabilities and capacities, staff size, curation and allocation proceedures.

3:30 PM Coffee Break

3:45 PM Future Needs (JSC Curation and Discussion)
Topics: Future needs for sample capacity, advanced curation, engineering requirement, contamination control and sample preservation issues (given the latest results from M3 and LCROSS).

4:30 PM Discussion of Friday's agenda

5:00 PM Discussion of changes to Phase 1 whitepaper
5:30 PM Adjourn for the day

Friday, January 8, 2010, 8:30

8:30 AM	Potential outlines for LSAC Review phase 2 whitepaper
9:30 AM	Writing Teams and Assignments
10:00 AM	Coffee Break
10:15 AM	Writing Teams Breakout
12:05 PM	Lunch Break
1:15 PM	Reports from Breakout Groups
3:00 PM	Timeline, writing assignments,
3:15 PM	Adjourn Meeting

APPENDIX IV. Sample "Unique Science Requirements Worksheet".

Lunar Science Tools - Unique Requirements Worksheet Example					
Number	**Requirement**	**Applicable (Y/N)**	**Design Impact (Y/N)**	**System Requirement (Y/N)**	**Specific Need**
1.0	**Derived**				
1.1	Mass				
1.2	Volume				
1.3	Configuration				
1.4	Volatiles				
1.5	*TBD*				
2.0	**Fundamental Geology**				
2.1	Core Sample Stratigraphy Management				
2.2	Clast Size Distribution				
2.3	*TBD*				
3.0	**Thermal**				
3.1	Cryogenic				
3.2	Thermal Limit				
3.3	*TBD*				
4.0	**Materials**				
4.1	Cleanliness				
4.2	Tool Contamination				
4.3	Sample Specific Materials Exclusions				
4.4	*TBD*				
5.0	**Manufacturing Processes**				
5.1	Feedstock Coupon Retention/Curation				
5.2	Process Consumables Retention/Curation				
5.3	*TBD*				
6.0	**Electromagnetic Preservation**				
6.1	Heliophysics				
6.2	Magnetophysics				

Worksheet explanation.

As outlined in the above sample worksheet, the "science unique" requirements matrix concept can be utilized as a tool to document the broad spectrum of concerns the science community may have related to sample acquisition and containment tools. Furthermore, itself may be used as a medium to communicate the particular unique science requirements for a given piece of hardware or system to drive the design of an EVA Science Tool. Thus, the worksheet above is only half of the needed "science unique" requirements, the other half of which is documentation of the spirit of each requirement and what is to be "filled in" for a given tool or system. The following represents this documentation for the draft requirements captured in Figure 1:

1.0 Derived Sample needs- This section defines requirements ultimately imposed on a given sample collection or containment device or system by implication from other unique requirements as outlined below.

1.1 Mass- The mass of the sample collected shall be XXX (TBD).

1.2 Volume- The volume of the sample collected shall be XXX (TBD).

1.3 Configuration- The configuration of the sample collected shall be maintained as XXX (TBD).

1.4 Volatiles Collection/Containment- The device shall collect or maintain volatiles as XXX (TBD).

1.5 *TBD*- This requirement and following subsection requirements reserved for expansion of subsection.

2.0 Fundamental Geology- This section defines requirements related to the fundamental geology needs of the sample collection/containment device.

2.1 Core Stratigraphy- The sample collection/containment device shall maintain stratigraphy of sample throughout XXX (TBD) phases of acquisition/storage.

2.2 Clast Size Distribution- The sampel collection/containment device shall preferentially sort a bulk volume of sample to retain a XXX (TBD) clast size distribution.

2.3 *TBD*- This requirement and following subsection requirements reserved for expansion of subsection.

3.0 Thermal- This section defines requirements related to thermal state or limits on a sample prior to, during, or after the sample collection event or on the sample collection or containment device prior to, during, or after the collection event.

3.1 Cryogenic- The sample or collection/containment device shall be at cryogenic temperatures during XXX (TBD).

3.2 Thermal Limits – The sample or collection/containment device shall be maintained within the thermal extremes of XXX (TBD).

3.3 *TBD*- This requirement and following subsection requirements reserved for expansion of subsection.

4.0 Materials- This section defines requirements related to the materials compatibility and contamination prevention/mitigation concerns on sample collection tools and containers.

4.1 Cleanliness- This requirement shall establish specific cleanliness levels of type XXX (TBD) when requirements exceed minimum generic engineering cleanliness statements.

4.2 Tool Contamination – The sample collection/containment device shall not impart contamination to the sample of type XXX (TBD).

4.3 Sample Specific Materials Exclusion- The sample collection/containment device shall not utilize material XXX (TBD) to preclude contamination of the sample.

4.4 *TBD*- This requirement and following subsection requirements reserved for expansion of subsection.

5.0 Manufacturing and Manufacturing Processes- This section defines requirements related to manufacturing process limitations relevant to sample contamination prevention/mitigation through manufacturing process control on collection tools and containers as well as retention of sample coupons.

5.1 Feedstock Coupon Retention/Curation- The manufacturer of the sample collection/containment device shall retain XXX (TBD) sample coupons from lot/batch/parent feedstocks (such as bar stock, sheet, etc) used in the manufacture of the device.

5.2 Process Consumables Retention/Curation- The manufacturer of the sample collection/containment device shall retain XXX (TBD) samples from lot/batch/parent process consumables (such as cutting fluids, passivation/anodize baths, etc) used in the manufacture of the device.

5.3 *TBD*- This requirement and following subsection requirements reserved for expansion of subsection.

6.0 Electromagnetic Preservation- This section defines requirements related to the control of electromagnetic contamination of the sample.

6.1 Heliophysics- The sample collection/containment device shall preclude XXX (TBD) to facilitate heliophsics analysis.

6.2 Magnetophysics- The sample collection/containment device shall preclude XXX (TBD) to facilitate magnetophysics analysis.

6.3 Solar Particle- The sample collection/containment device shall preclude XXX (TBD) to facilitate charge distribution analysis.

6.4 Conductivity- The sample collection/containment device shall preclude XXX (TBD) to facilitate electrical property analysis.

6.5 *TBD*- This requirement and following subsection requirements reserved for expansion of subsection.

7.0 Highgrading-_This section defines requirements related in-situ high-grading capability.

7.1 In-Situ Curation- The sample collection/containment device shall provide for XXX (TBD) in-situ curation.

7.2 In-Situ Analysis- The sample collection/containment device shall provide for XXX (TBD) in-situ analysis.

7.3 Splits- The sample collection/containment device shall provide for XXX (TBD) in-situ splitting.

7.4 *TBD*- This requirement and following subsection requirements reserved for expansion of subsection.

8.0 Post-Return Curation- This section defines requirements related to post Earth-return and handling/curation of samples

8.1 Long Term Storage- The sample collection/containment device shall provide for XXX (TBD) long term storage post Earth-return.

8.2 Subdivision- The sample collection/containment device shall facilitate for XXX (TBD) subdivision post Earth-return.

8.3 Allocation- The sample collection/containment device shall provide for XXX (TBD) allocation post Earth-return.

8.4 Known Analytical Techniques- The sample collection/containment device shall facilitate XXX (TBD) analysis post Earth-return.

8.5 *TBD*- This requirement and following subsection requirements reserved for expansion of subsection.

9.0 Novel Science Methods- This section defines requirements facilitating use of novel analytical techniques

9.1 *TBD*- This requirement and following subsection requirements reserved for expansion of subsection.

APPENDIX V: Relationship of Lunar Sample Mass to Earth Return Mass and Volume: Empirical Case Study Using the Apollo J Missions.

Introduction:

As was the case for Apollo, future lunar sample returns will be constrained by sample mass and volume, consistent with the capabilities of the Earth return vehicle. The present document consults the Apollo J missions (Apollo 15, 16 and 17) with the objective to derive empirical packing-densities (g cm^{-3}) that relate absolute sample mass to total Earth return mass and volume for the major Earth-return containers housing multiple samples that were used by Apollo. These empirical relationships may serve as guides for Constellation.

The J-missions were selected because they more closely resemble the lunar surface operations envisioned for Constellation than the earlier Apollo missions. The J missions included substantial surface mobility via a rover and lunar surface activities spread over 3 individual EVAs, each approximately 8 hours long. In contrast, the Apollo 11, 12 and 14 EVAs were on foot and employed sampling tools and protocols that were not as mature as those employed by the later J missions. Also, the crews or Apollo 15-17 underwent more extensive geological training than those of Apollo 11-14, and exercised considerable geologic judgment when selecting rocks and soils for Earth-return. It is for these reasons that we consider the J-missions to be more representative of future lunar surface operations than those of Apollo 11-14. It seems paramount that the Constellation crews will be as proficient in exploring the lunar surface and selecting representative samples as those of Apollo 15-17.

The present study considers two types of sample-return containers, both of well defined geometry and housing multiple samples. One container, the Apollo Lunar Sample Return Container (ALSRC for short), was a sophisticated vacuum vessel made of aluminum; the purpose of the vacuum seal was to eliminate potential sample-contamination by exposure to the crewed cabin-environment during Earth-return, as well as by exposure to the terrestrial atmosphere before the samples could be placed into environmentally controlled processing cabinets at JSC's Curatorial Facilities. The other container type was the Sample Collection Bag (SCB for short) made of woven Teflon. The latter was potentially open to the cabin environment and terrestrial atmosphere until it also was placed into a processing cabinet at JSC. The two types of container thus differ in the potential level of contamination, although no systematic study has been conducted today to quantify these differences.

Based on the above, the present analysis not only addresses the relationship of sample return mass to total return mass and volume, but it also explores the trade-offs between "hard" vacuum vessels made of metal and "soft" good containers made of Teflon or any other acceptable fabric. Current technology developments suggest that it may be possible to vacuum-seal soft good containers. The choice between hard or soft sample containers will obviously have significant implications for the total sample Earth return mass and volume.

Each of the J missions employed 2 ALSRCs and up to 8 SCBs, providing a total sample of 6 ALSRCs and 22 SCBs for the present analysis. The latter reconstructed the sample mass (m_{ump}) returned by each of the 28 containers, and uses their well defined weights and volumes to determine total Earth return mass (M_{RET}) and volume (V_{RET}).

APOLLO SAMPLE CONTAINERS:

An extensive report by Allton (1989) describes a wide variety of lunar sample containers as well as the tools used to collect samples on the lunar surface. This report also details the dimensions and weights of each individual item, as well as the material(s) it was made of. We excerpt and summarize as follows:

Each individual rock or soil sample was placed into a *Documented Sample Bag* (DB) as part of the lunar surface sampling protocol. The latter was made of Teflon, weighed 10.2 g, and measured some 20 x 19 cm in flat configuration. It also contained an aluminum strip at its open end, with sizeable tabs on the sides that were grabbed by the crew to fling the loaded bag around this strip, essentially rolling up the bag's open end; once rolled up, the tabs were bent around the rolled up end, thus positively stabilizing the latter, and providing a good seal for particulates and a crude seal for gases. Most DBs housed individual

rock and soil samples, but some contained multiple rocks and a few a mixture of soils and rocks; some contained numerous, walnut-sized rocklets collected with the rake tool.

After sealing an individual DB, it was placed into a *Sample Collection Bag* (SCB) which was attached to a crew's life-supporting back pack; the purpose of the SCB was to house multiple samples as they were being collected in the field. It was made of Teflon cloth, draped over a light weight metal frame to maintain its shape. It weighed 760 g, was 42 cm high, 22 cm wide and 15 cm deep, with a total capacity of about 14 000 cm^3. Ideally, each of these SCBs was filled to capacity with individual sample bags or Special Sample containers (see below), stowed on the rover, and ultimately transferred into the crew cabin for Earth return.

After returning to the Lunar Module at the end of an EVA, a single, full SCB was typically placed inside the *Apollo Lunar Sample Return Container* (ALSRC) vacuum vessel for Earth return; one Apollo 16 ALSRC contained individual sample bags only, as the crew felt the need for repacking. The inside dimensions of ALSREC were such to snuggly accommodate a full SCB; the bottom and walls of the ALSRC were padded by metal mesh which had some give. The container was machined from a monolithic block of aluminum 7075 AA alloy. The outside dimensions were 48 x 30 x 20 cm; the weight varied between 5900 and 7700, depending on design and wire-mesh padding, yet 6400 g seems a good average mass for the typical ALSRC used by the J missions.

Allton (1989) also describes a wide variety of additional containers, all housing special purpose samples, termed *Special Samples* for short in the present report. The latter include regolith profiles collected via drive tubes or drill cores, soil samples housed in special, vacuum sealed containers (e.g. Core Sample Vacuum Container (CSVC), Special Environmental Sample Container (SESC), Gas Analysis Sample Container (GASC) and others) or soils collected from different depth via the Contact Soil Sampling Device (CSSD). Common to all of these samples is a dedicated, self-containing (if not sealing) metal container. With the exception of most drill samples, the Special Samples were mostly returned inside SCBs, a few inside ALSRCs.

METHOD:

Each Apollo Mission produced a *Lunar Sample Information Catalog* (web site) which describes the findings of the Preliminary Examination Team for every single rock or soil sample. The frontispieces of these catalogs summarize the weight of each sample, identify the DB it resided in, and the ALSRC or SCB in which any given DB was returned to Earth. It is thus possible to reconstruct the entire content of each ALSRC and SCB for Apollos 15-17 with considerable fidelity.

In detail, a spreadsheet was generated for each ALSRC or SCB, differentiating among four sample types: 1) *rocks* ranging in mass from < 1 to > 10 kg. g), 2) *soils* (typically > 100 g), 3) DB and SCB "*residues*", i.e. poorly characterized fines that resulted from abrasion and breakage of soft rocks inside a DB or SCB (on occasion as large as 150 g), and 4) *"Special Samples"* that were returned in dedicated metal containers, such as regolith drive tubes, SESC, CSVC or CSSD etc. Most of the latter containers remained unopened for some time, the reason why the sample catalogs list their total mass, i.e. container + content. It is possible in principle to subtract the container mass from this total, to derive the pure sample mass. We have not done so, however, for two reasons: 1) the special purpose container is such an intrinsic part of the sample that it must be listed under sample mass; without appropriate container there simply would be no special sample; 2) it is expected to have similar special samples and their dedicated containers in the future and their total M_{RET} -as given in the sample catalog- should be viewed as useful generic representation of future Special Samples. Also, these samples and their containers constitute < 10% of the total sample mass; a more detailed treatment will thus not greatly affect the conclusions reached below.

We excluded the deep drill cores from this analysis as they were typically not returned in ALSRCs or SCBs; again, their mass is < 5% of the total return and thus of little consequence for the major conclusions reached. Also, we exclude all large rocks that were not returned in either an ALSCRC or a SCB. The purpose of this report is not to provide a complete sample inventory of Apollo 15-17, but to analyze the contents of ALSRCs and SCBs, the major sample return containers of well known dimensions, volume and mass.

RESULTS:

Table A1 lists the summary findings for 6 ALSRCs, while Table A2 presents those of 22 SCBs. Figure A1 summarizes the major findings and simply plots total sample mass (m_{SMP}) of rocks, soils, residues and Special Samples as per yellow column in Tables A1 and A2 for individual ALSRCs and SCBs. Since the interior storage volume of a rock box approximates that of an SCB, this figure may be viewed as returned sample mass at essentially constant container volume (some 14 000 cm^3). On average, the ALSRCs contained some 9130 g of sample, the SCBs some 9655 g, a difference of some 5%. However, there is considerable scatter, with the ALSRC data ranging from 6891 g to 11476 g (factor of 1.67) and the SCB data from 5586 g to 14023 (factor of 2.51). This variance obviously relates to packing density; e.g. A16 SCB5 contained essentially only one rock (no soils and no Special Samples), ditto A17 SCB 2, as can be deduced from the small number of DBs in Table A2. Other SCBs of low weight were demonstrably not as full as others, because each crew started an individual EVA with new SCBs on their back packs. Substantial variation is thus to be expected from SCBs, as many were simply not filled to capacity. The ALSRCs were packed more consistently, and all seemed "full", and yet they vary substantially in total sample mass as well. The 2 heaviest ALSRCs and the 5 heaviest SCBs (all marked in blue) yield an average of 10860 and 13255 g, respectively; these differences are difficult to rationalize, as both relate essentially to the volume of an SCB; however the heaviest SCBs bulged and did not fit inside the ALSRC; they thus represent the maximum packing density achievable in modestly pliable, soft containers.

A detailed break down of the container's contents is presented in the cumulative histograms of Fig. A1. It illustrates that the total sample mass in any given container is not a strong function of sample type. While most mass is dominated by rocks (occasionally exclusively) a few SCBs contained > 30% of soil, and some had > 25% of Special Samples by mass. However, the relative proportions of these sample types vary widely for individual SCBs. We have constructed correlation diagrams plotting the specific sample type against total sample mass per SCB and find no systematic correlation. It is thus suggested that the

Table A1: Contents and associated masses for Apollo 15, 16, and 17 ALSRCs.

			Returned Sample Mass					**D. Bags**		**M RET**
			Rocks	**Soils**	**Resid.**	**Sp.Sp.**	**mSMP**			
			g	**g**	**g**	**g**	**g**	**n**	**g**	**g**
Ap.15	**ALSREC 1**		**3948**	**2712**	**73**	**1278**	**8011**	**11**	**112**	**14523**
	ALSREC 2		**7756**	**251**	**9**	**645**	**8661**	**10**	**102**	**15163**
Ap.16	**ALSREC 1**		**7431**	**3652**	**384**		**11467**	**22**	**225**	**18092**
	ALSREC 2		**4071**	**2159**	**116**	**3147**	**9493**	**10**	**102**	**15995**
Ap.17	**ALSREC 1**		**4149**	**2560**	**182**		**6891**	**12**	**122**	**13413**
	ALSREC 2		**2633**	**4365**	**33**	**3220**	**10251**	**10**	**102**	**16753**
	sums		**29988**	**15699**	**797**	**8290**	**54774**	**75**	**765**	**93939**
ALSRC, Averg.			**4998**	**2617**	**133**	**1382**	**9130**	**12.5**	**128**	**15656**
ALSRC, full			**5032**	**4009**	**209**	**1610**	**10860**		**164**	**17424**

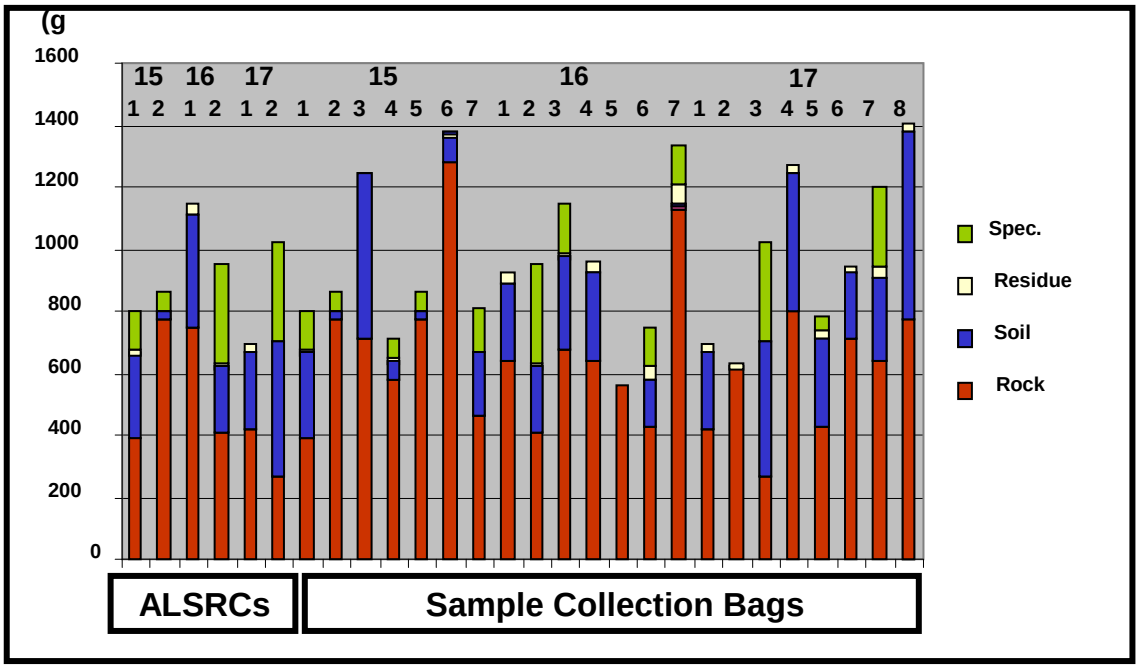


Figure A1: The sample content of 6 ALSRCs and 22 SCBs returned by the Apollo J missions (Apollo15, 16, and 17); the single digit numbers refer to the assignmnt of individual containers for each mission as per the Lunar Sample Cataloge.

TableA2: Contents and associated masses for Apollo 15, 16, and 17 SCBs.

		Returned Sample mass					Doc.Bags		SCB	MRET
		Rocks	Soils	Resid.	Sp.Sm.	mSMP				
		g	g	g	g	g	n	g	g	g
Ap.15	SCB 1	3948	2712	73	1278	8011	11	112	760	8883
	SCB 2	7769	214		678	8661	1	10	760	9431
	SCB 3	7096	5327			12423	10	102	760	13285
	SCB 4	5772	608	89	666	7135			760	7895
	SCB 5	7756	251	9	645	8661	10	102	760	9523
	SCB 6	12816	849	99		13764	4	41	760	14565
	SCB 7	4596	2039	76	1394	8105	7	71	760	8936
Ap.16	SCB 1	6437	2472	353		9262	17	173	760	19195
	SCB 2	4071	2159	116	3147	9493	10	102	760	10355
	SCB 3	6780	2973	150	1593	11496	15	153	760	12409
	SCB 4	6362	2845	390		9597	13	133	760	10490
	SCB 5	5574		12		5586			760	6346
	SCB 6	4300	1471	492	1215	7478	18	184	760	8422
	SCB 7	11413	96	539	1328	13376	7	71	760	14307
Ap.17	SCB 1	4149	2561	182		6892	12	122	760	7774
	SCB 2	6245		46.1		6291	1	10	760	7052
	SCB 3	2633	4365	32.9	3220	10251	10	102	760	11113

	SCB 4	**8012**	**4469**	**210**		**12691**	**21**	**214**	**760**	**13665**
	SCB 5	**4272**	**2856**	**212**	**441**	**7781**	**16**	**163**	**760**	**8704**
	SCB 6	**7106**	**2161**	**186**		**9453**	**10**	**204**	**760**	**10417**
	SCB 7	**6403**	**2669**	**359**	**2542**	**11973**	**15**	**153**	**760**	**12886**
	SCB 8	**7764**	**5981**	**278**		**14023**	**26**	**265**	**760**	**15048**
	sums	**141274**	**49078**	**3904**	**18147**	**2E+05**	**234**	**2487**		**2213610**
SCB, Average		**6422**	**2231**	**177**	**825**	**9655**	**9.7**	**113**	**760**	**10528**
SCB, full		**9420**	**3344**	**225**	**266**	**13255**		**139**	**760**	**14168**

diverse sample types have similar "*packing densities*", i.e. similar mass per unit volume of packed (!) container material, no matter whether they are angular rocks (with considerable voids in between individual specimen-bags), soils (of lower bulk density, yet individual sample bags conform and pack without significant voids), and ultimately special purpose soils in rigid, albeit thin walled and light-weight metal containers (that may have high bulk density yet that also have sizeable gaps between them). All seem to pack at approximately the same effective bulk density. Also note that total sample mass does not depend systematically on the number of individual sample bags (from n = 0-26; see Table A2) that resided in a given SCB.

We now address the containers and their masses (= tare) in which the samples were returned. We obviously have to account for the DB material, some 10.2 g per sample bag. The weight of individual ALSRCs varied modestly based on Allton (1989), as their interior configuration varied, yet a good average value for the boxes used for the J-Missions is some 6400 g. Similarly, individual SCBs varied somewhat depending on their specific configuration, yet some 760 g per SCB is a conservative average value based on Allton (1989). Adding all of these container masses to that of the samples (m_{SMP}) ultimately yields the *Earth return mass* (M_{RET}) per individual container as listed in Table A1 and illustrated in Fig.A2. It seems

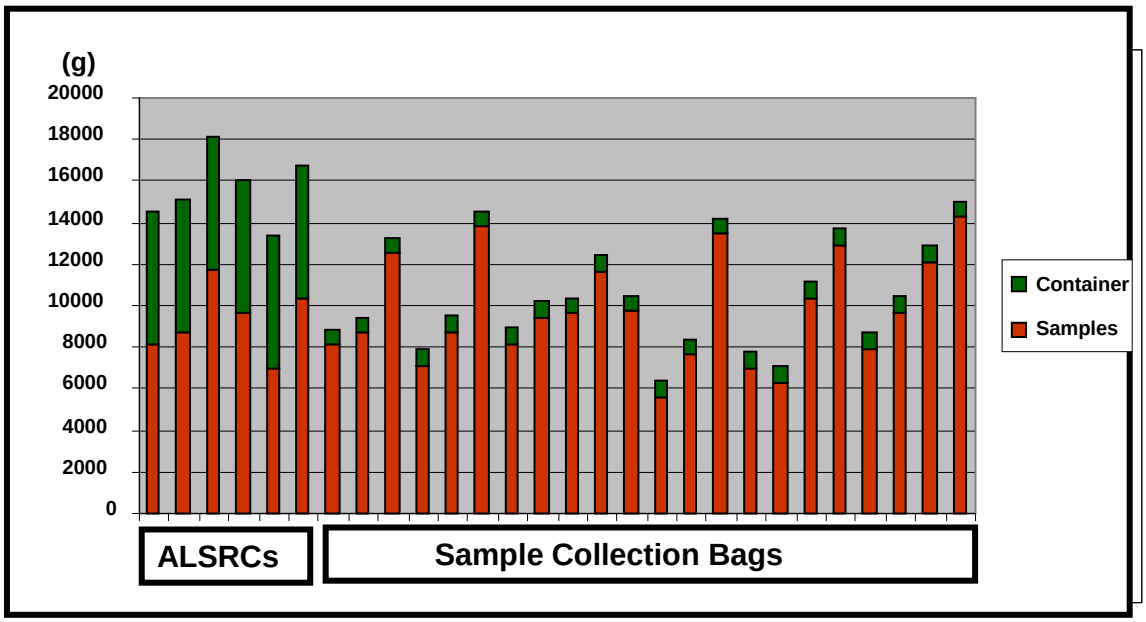


Figure A2: Total Earth return mass, broken into sample and container mass, for 6 Apollo ALSRCs and 22 SCBs.

obvious that the Earth return mass for the ALSRCs is systematically higher than that for SCBs, averaging some 15656 g for ALSRCs and some 10528 g for SCBs. The 2 heaviest ALSRCs averagesome 17.5 kg, the 5 heaviest SCBs some 14 kg (see Tables A1 and A2) .

EFFECTIVE PACKING DENSITY

Having determined the mass parameters for ALSRCs and SCBs, we now address effective packing densities by placing these masses into the appropriate volumes of their respective containers as defined by their outside dimensions, some 28800 cm^3 for an ALSRC and some 14000 cm^3 for an SCB. Table 3 lists these calculations. We determine two packing densities, PD_{SMP} and $PD_{RET.}$ Both are referenced to V_{RET} with one expressing the effective density of the samples within the nominal container volume (PD_{SMP}; regardless of container mass), the other accounting for container and sample mass, and thus reflecting PD_{RET}. Obviously, the ratio of PD_{SMP}/PD_{RET} must correspond to the ratio of $m_{SMP}/M_{RET.}$

Using some subjective judgment related to partly versus completely full containers, we recommend for planning purposes to use PD_{RET} = 0.58 gcm^{-3} for (full) "hard", box-like, vacuum-sealed containers and PD_{RET} = 0.92 gcm^{-3} for (full) "soft" good containers; the recommended values for PD_{SMP} are 0.35 and 0.85 gcm^{-3} for box-like and softgood containers, respectively. These are modestly conservative densities, demonstrably less than the *average* (!) of the most densely packed Apollo items, but noticeably more dense than the grand average of ALSRECs and SCBs, some of which were demonstrably not packed to capacity. The recommended densities thus

		m_{SMP}	**M_{RET}**	**V_{RET}**	**PD_{SMP}**	**PD_{RET}**	**m_{SMP}/M_{RET}**
		g	g	cm^3	gcm^-3	gcm^-3	
average	ALSRC	9130	15656	28800	0.317	0.544	0.583
full	ALSRC	10860	17424	28800	0.377	0.605	0.623
recommended					**0.35**	**0.58**	**0.60**
average	SCB	9655	10528	14000	0.690	0.752	0.917
full	SCB	13255	14168	14000	0.947	1.012	0.936
recommended					**0.85**	**0.92**	**0.92**

Table A3: Effective packing densities for samples only and loaded ALSRCs and SCBs.

seem fairly realistic for planning purposes and are on the modestly conservative side relative to fully loaded Apollo containers. The reason why we define these densities to 2 significant numbers relates to the m_{SMP}/M_{RET} ratio; the latter ratio must also be bracketed by the observed values. This can not be accomplished, however, with only a single significant number, say PD_{RET} = 0.6 and 0.9, or PD_{SMP} = 0.9 in Table A3; such simplified values for packing density would yield mass ratios (m_{SMP}/M_{RET}) that are not consistent with observations; to make m_{SMP}/M_{RET} consistent with observations, we needed a second digit for the recommended values.

GENERAL RELATIONSHIPS OF SAMPLE MASS TO EARTH RETURN MASS AND VOLUME

In the following we develop some implications for these packing densities. Assume a hard or soft container to have a volume of 1 ltr ; its total Earth return weight would be some 580 and 920 g, respectively, using the recommended PD_{RET} values (x 1000 cm^3). The m_{SMP}/M_{RET} ratios of 0.60 and 0.92 imply that some 348 g of samples (580 x 0.6) reside in the hard box and some 846 g of sample (920 x .92) are accommodated by the soft good container. These sample masses correspond directly to the recommended PD_{SMP} of .35 and .85 g cm^{-3}. The packing densities containing the volume term, must obviously be consistent with the observed, yet dimensionless, mass ratios. In the following we present figures that illustrate the general relationships of sample mass, Earth return mass, and Earth return volume,

with the slope of individual lines corresponding to the recommended (!) packing densities of Table A2. Recall, that the latter are on purpose modestly smaller than the most densely packed ALRCs and SCBs, and thus somewhat on the conservative side.

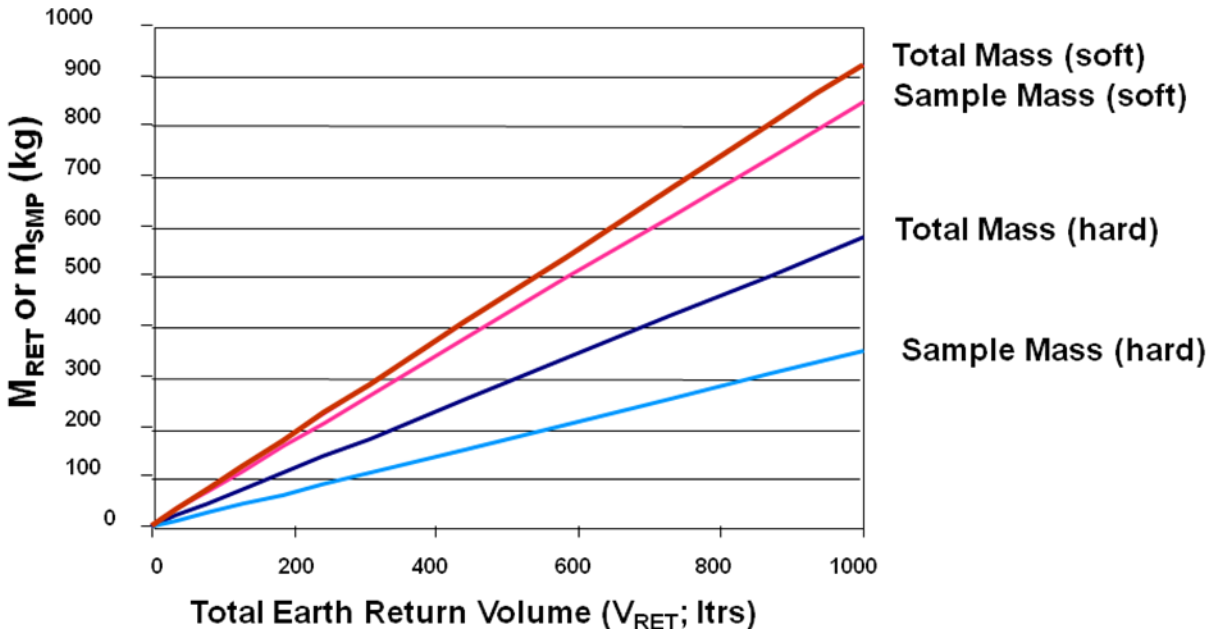


Figure A3: The general relationship of sample mass (m_{SMP} and total Earth return mass (M_{RET}) for hard and soft good containers at a given Earth return volume (V_{RET}).

The generalized relationships of container volume (V_{RET}) to sample mass (m_{SMP}) and total Earth return mass (M_{RET}) are illustrated in Figure 3. This figure illustrates the case were the sample return is controlled by available volume in the Earth return vehicle; it my be used to deduce sample mass (m_{SMP}), as well as total mass for Earth return (M_{RET}), for both metal-based "hard" sample containers, as well as those based on fabrics and "soft"-good technologies. Note that at constant container volume, the total mass (M_{RET}) for soft good containers is approximately a factor of 1.5 ($PD_{RETsoft}/PD_{REThard}$ = 0.92/0.58) higher than that for hard containers. This higher return mass for soft-good containers reflects the substantially inefficient and bulky volume of the ALSRCs relative to the SCBs. Importantly, the soft good containers will accommodate a factor of approximately 2.5 ($PD_{SMPsoft}/DP_{SMPhard}$ = 0.85/0.35) more sample mass than a hard metal container of identical volume. As a consequence, soft good containers will substantially outperform sealed metal-vessels in terms of returnable sample mass as well as in terms of total Earth return mass at constant volume.

The amount of samples to be retuned to Earth will obviously also be limited by mass, the latter becoming part of the return-vehicle's finite lift-off mass. We thus constructed Fig. A4, which portrays the relationship of total Earth return mass to total return volume, as well as to sample mass for both "hard" and "soft" containers. Not surprisingly, the volume mandated by soft containers is approximately a factor of 1.5 smaller than that of hard containers. Despite this relatively small volume, the actual sample mass is some 50% larger in the soft good containers. It is obvious by now, that soft good containers are superior to metal boxes. We finally portray the packing densities at constant sample mass and solve for the resulting return masses and volumes. This is probably the most useful plot, as most considerations regarding sample return tend to begin with estimates of total sample mass collected and ready to be returned.

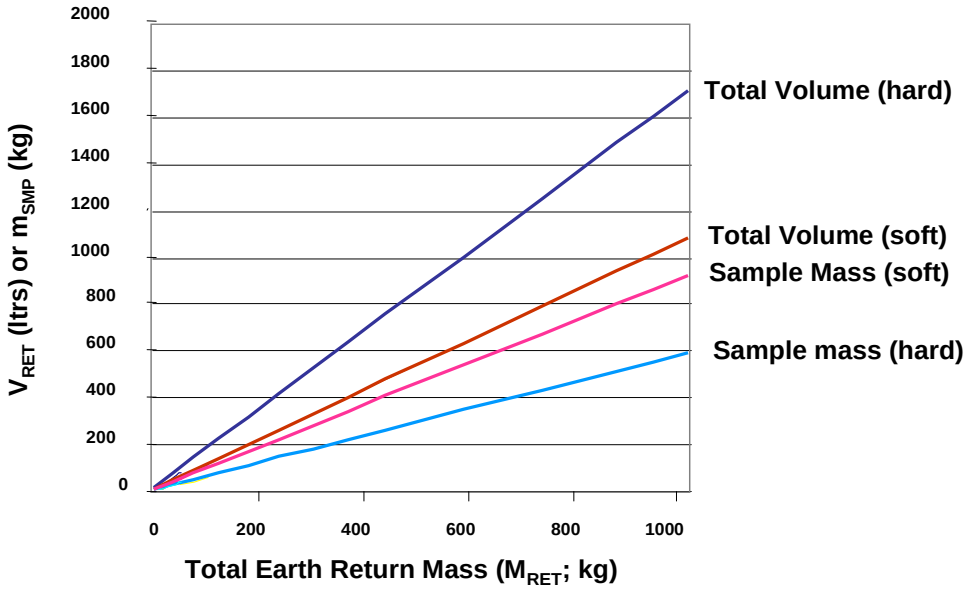


Figure A4: Total Earth return mass and associated volumes and sample masses for "hard" and "soft" sample containers based on Apollo 15-17 ALSRCs and SCBs.

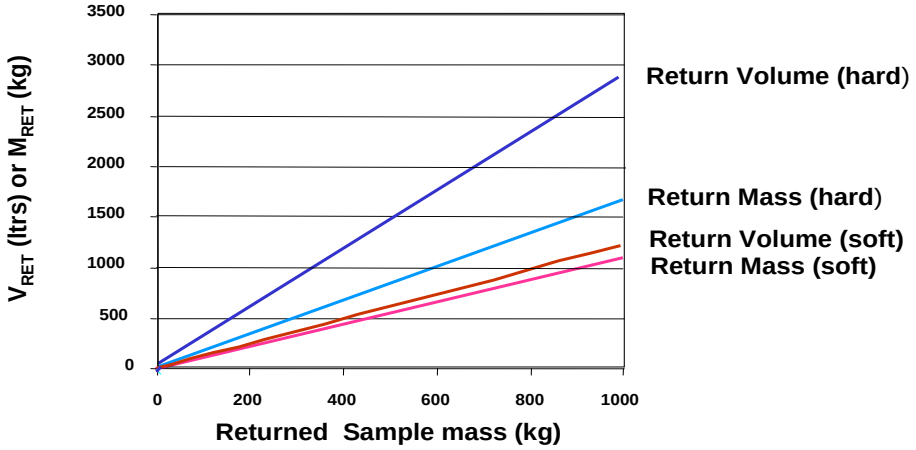


Figure A5: Total sample mass and its relationship to Earth-return volume (VRET) and mass (MRET) or hard metal and soft-good containers akin to the Apollo Lasers and SCBs.

We finally portray in Fig. A5 the quantitative relationship of sample mass to total return mass and volume. This is probably the most useful plot, because total sample mass that is to be shipped to Earth seems to be the most critical, initial parameter in most manifesting activities. Fig. 5 may be used to solve for Earth return volume and mass for any arbitrary sample mass. Again soft-good containers substantially outperform the hard metal boxes, as they accommodate approximately a factor of 2.5 more sample mass per unit volume and because they allow for the return of some 1.4 times more sample mass at any given total return mass.

CONCLUSIONS:

There are significant differences in the type of sample containers one chooses for future sample return missions. Assuming that they somewhat resemble those used by Apollo, soft-good. containers will significantly outperform typical hard containers in most operational aspects of Earth return; the latter favor high packing densities, i.e. small return volumes per unit mass. Soft good containers will return approximately 2.5 times more mass per unit volume to Earth and they will be a factor of 1.6 smaller in volume at constant Earth return mass. If the container performance were judged on the basis of identical lunar sample mass that is being returned to Earth, the soft containers mandate a factor of 1.5 less Earth return mass and would occupy a factor of 1.4 less volume than the hard vessel. These seem significant operational advantages.

Nevertheless, major science-related trade off studies is warranted, because the sealed, "hard" vacuum vessel obviously preserves the integrity of the returned samples somewhat better than the unsealed soft-good bag. Nevertheless, a number of small, vacuum-sealed vessels akin to the Apollo Special Sample containers seems more efficient, as they could be returned inside soft good containers, thus avoiding the weight and volume penalty inherent in ALSRC-type, large boxes. It is possible also to envision a single ALSRC-like container, possibly a relatively small one, containing only those samples that relate to investigations that can be affected by e.g. the gaseous environment in the return-vehicle or upon exposure to the Earth's atmosphere etc.

Once this mix of containers is established, one may readily calculate the associated Earth return mass and volume for any given lunar sample mass and container type using the above observations and associated packing densities. We suggest that the packing densities to be used for Constellation are those based on fully loaded Apollo containers, rather than on their average values, because the latter include containers that were demonstrably not filled to capacity. We list the recommended values in Table 3 and utilized them to derive Figures 3, 4 and 5.

Note that the highest packing density for samples only (PD_{SMP} in Table 3) may approach 1 g cm^{-3} for the most fully loaded and densely packed SCBs (e.g. AP.17; #8 SCB weighed in at 14023 g at 14 ltrs volume; see Table 2), suggesting that any mixture of rock and soil may not be packed more densely. Thus: 1 g cm^{-3} seems to be an empirical, maximum packing-density for pure sample mass only that may not be exceeded by Constellation. The heaviest SCB containing rocks, soils and Special Sample containers was that of Ap.16, SCB #7, weighing in at 13327 g. Both cases are significant: they illuminate not only that a packing density of 1 g cm^{-3} represents an absolute upper limit, but that the recommended values of 0.85 g cm^{-3} seem realistic and modestly on the conservative side. Both values refer to essentially pure sample mass that is contained by some minimal Teflon fabric.

References for Appendix V:

Allton, J. H. (1989) Catalog of Apollo Lunar Surface Geological Sampling Tools and Containers, NASA JSC Report JSC-23454, 97 pages.

Lunar Sample Information Catalog, Apollo 15 (1971), Lunar Receiving Laboratory Report, MSC 03209, 303 pages.

Lunar Sample Information Catalog, Apollo 16 (1972), Lunar Receiving Laboratory Report, MSC 03210, 376 pages.

Lunar Sample Information Catalog, Apollo 17 (1973), Lunar Receiving Laboratory Report, MSC 03211, 448 pages.

APPENDIX VI Treiman AH, (1993) Curation of Geological Materials at a Lunar Outpost, JSC-26194 and Office of the Curator Publication #187.

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Publication #87

CURATION OF GEOLOGICAL MATERIALS AT A LUNAR OUTPOST

Allan H. Treiman
Lockheed Engineering & Sciences Company
Houston, Texas

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CONTENTS

ABSTRACT

If geological materials collected at an outpost base on the Moon are to be used for their greatest value, they will need to be curated: documented, tracked, split, protected from contamination, examined, and stored. Many schemes for curation have been proposed, most recently in planning for the NASA "First Lunar Outpost" mission, FLO. As part of that planning, curation schemes have been analyzed to determine which serve the uses (and users) of geological samples: preliminary examination, detailed analyses, and storage for posterity.

The flow of functions in curation was studied to determine which sequences of functions could best serve the users of lunar samples. Documentation, sample tracking, contamination control, and storage are common to all schemes for sample curation. Sample splitting, preliminary examination, and storage permit a range of options. The preferred scheme for the flow of these functions is: sample splitting, then preliminary examination of a subsample, followed by decision on transport to Earth. This scheme permits delivery of the most suitable samples, and is consistent with earlier studies of sample curation on the moon and with FLO planning. However, it requires both a geosciences laboratory and a sample storage facility on the Moon.

Cost and sample contamination dictate where curation functions should be performed. The contamination inherent in preliminary examination is inconsistent with the sample requirements for the uses of detailed analysis and storage for posterity. Thus, samples should be split into representative sub-samples before preliminary investigation: one for preliminary examination, one for detailed analysis, and one for storage for posterity. Splitting should be done at the site of collection. Because the sub-samples for detailed analysis and storage would be minimally contaminated, there would no need for extreme care in treating the sub-sample for preliminary examination. Preliminary examinations could be performed in the outpost (habitat) under desiccated habitat atmosphere.

This scheme and sites for curation functions are applicable to rocks, rake samples, and regolith samples, although criteria for splitting might depend on rock type. The scheme would not be appropriate for volatile-rich samples, core samples (drill or drive tube), nor those in specialized containers.

INTRODUCTION

This work is an investigation of options for curation of geological samples at a lunar outpost. It is based on the specifications of the "First Lunar Outpost" as defined by NASA planning exercises in 1991-1993, but should be applicable to spartan lunar outposts which include capabilities for collecting geological samples and transporting them to Earth.

The mission of curation is to protect, preserve, and distribute materials for study.

> "Maintaining samples in a pure state is critical to extracting scientific information [from them]. Equally important, however, is making the [samples] available for scientific study and education, because it is these activities that give the samples their true value. It is also wise to reserve portions of the samples for future studies that will become possible with new or improved ideas and techniques." Office of the Curator (1992).

Within the context of a lunar outpost, the goal of curation is to ensure that geological samples are treated so that they: are available for exploration, research and educational use; are as little contaminated by human activities as is consistent with their intended uses; and satisfy the objectives of the nation's space program (and thereby serve the interests of the country as a whole).

Curation of geological samples can be divided into the following distinct, but interconnected, functions:

- documentation of sample histories;
- sample tracking;
- control of contamination and sample environment;
- sample handling;
- preliminary examinations;
- secure storage; and
- allocation for detailed investigations (Taylor and Spudis, 1990; Dietrich, 1989, 1990).

The last function is not likely to be done at a lunar outpost, but would be conducted on Earth.

Maintaining histories for every sample is critical for understanding what human activities may have affected samples and subsequent analyses of them. A sample's history would begin with documentation of its location, orientation, and surface setting before collection, and would record in detail <u>everything</u> that was done to the sample and its sub-samples.

Sample tracking involves knowing the current location and status of each sample and sub-sample and all of their documentation. This function is critical to all other phases of curation.

Environmental and contamination control are critical in curation, as they directly affect the end uses and users of the samples. As with the Apollo samples, much contamination can be controlled by limiting the types of materials that can come in contact with the samples. These contamination controls would apply to astronaut pressure suits (EMUs), tools, containers and instruments, and all procedures of handling, preliminary examination, allocation, and storage. Environmental control would include the ambient atmosphere surrounding the samples during curation and handling (e.g., N_2 gas in the Lunar Curatorial Facility at JSC), sample temperatures, and exposure to radiation, magnetic fields, etc.

Handling of samples is an unavoidable and integral part of curation. Controls on sample handling begin at the time of collection, and continue to include sample splitting, preliminary examination, storage, repackaging, and transport to Earth.

Preliminary examination of a sample is crucial for knowing what a sample is, identifying its potential uses and users, and defining the curatorial activities it requires. Preliminary examination may be highly variable, and depends on the analytical equipment available, the sample collection strategy, and the constraints on return of samples to Earth.

Secure storage is essential to preserving samples for posterity and subsequent analyses. Storage, and its documentation through sample histories and tracking, must provide physical security to avoid mixing or loss of samples, a ready means to retrieve samples, and protection from contamination and environmental hazards. There may be different levels or areas of storage, depending on the histories of samples or their eventual uses. For instance, at the Lunar Curatorial Facility at JSC, samples which have been returned to the facility by investigators are kept under less stringent contamination controls than are "pristine samples," most of which have never been exposed to air. In another example, Dietrich (1990) suggests storage categories based on eventual use: interim, for unstudied samples; pre-transfer, for Earth-bound samples; and long-term, for samples to be held at a curatorial facility on the Moon.

HISTORY: CURATION OF GEOLOGICAL SAMPLES ON THE MOON

Apollo

Curatorial activities beyond documentation, sample tracking, and contamination control were generally considered inappropriate for the Apollo missions. The operational concept for Apollo was to do nothing on the Moon that could be done on Earth: " . . . the only tasks which should be accomplished on the Moon are those that must be done in situ." (NASA, 1967, p. 92). This was consistent with the mission plans of not revisiting sites, and of deriving the maximum return from the available time on the Moon. Thus, curation on the Moon was limited to documentation of sample collection, tracking samples with tagged bags and containers, and contamination control. "Selection and documentation of samples will be one of the most critical tasks of men on the lunar surface. Ideally, the site at each sample should be documented by stereophotographs taken before and after the sample is acquired, supplemented by verbal description of relationships not shown in the pictures and of effects of the sampling process on the sample and its environment. In many cases, it will be desirable to mark the sample in situ or provide some other control to recover information about the original orientation of the sample." (NASA, 1967, p. 43)

Apollo had no provision for use of samples on the lunar surface, and it was not expected that findings from samples would affect the choreography of geological exploration. No samples were left on the moon in "minimally contaminated storage," although thought was given to preserving a sample free from organic and biological contamination (NASA, 1965, p. 239).

The curatorial functions of preliminary examination, allocations, and storage were to be done on Earth. "Upon return of the lunar samples to Earth, they will be prepared at a Lunar Sample Receiving Laboratory (LSRL[later the LRL]) for distribution. Here they will be logged in, cataloged, checked for outgassing, measured for low-level radiation, and examined for pathogenic agents. Only those tests which must be done immediately will be conducted at the LSRL. The portion of samples to be distributed will be packaged and initial distribution to the selected scientific investigators will be made." (NASA, 1965, p. 12). However, it was recognized that preliminary examination on the Moon might be necessary. "In the final step of packing the samples for return to Earth, further judgment may be necessary to select the most important samples to be returned to Earth, in the event that more samples are collected than can be accommodated in the Apollo spacecraft." (NASA, 1965, p. 43)

To "Geoscience and A Lunar Base"

Operational concepts for lunar outposts were studied intensely in the 15 years following the Apollo missions, with emphases on the great rewards and the technical problems involved (Lowman, 1985; Johnson and Leonard, 1985). These efforts were brought together in 1984 at conference on lunar bases (Mendell, 1985), and a second conference in 1988 (Mendell, 1992). However, there was very little consideration of sample curation.

Following the 1988 conference on lunar bases (and complementary to it), the workshop "Geoscience and a Lunar Base" (Taylor and Spudis, 1990) considered requirements and operations for geological sciences at a lunar base. Sample science was of great concern, and they devoted a full chapter to their recommendations on curation and analytical facilities at a lunar base.

The workshop participants envisioned a complete curatorial facility at a lunar base, similar in concept to the Lunar Curatorial Facility at JSC, but of smaller scale. Sample documentation and tracking would be computerized. Samples would be split on collection, with part used for preliminary

examination, and the remainder reserved for detailed examination or storage. Sample handling and preliminary analyses would be done outside the habitat, in a dust-controlled structure (a "shed"), using robotic and telerobotic operation as much as possible. Samples would be stored in tagged containers, and tracked through the curatorial computer system. The whole system would be automated as much as possible.

Lunar Science Strategy Workshop, 1989

This workshop (Duke, 1989) represented the input of the scientific community to NASA as part of the 90-day study report. The lunar geosciences team, led by M. Cintala, was responsible for sample science and curation. They recommended that a lunar outpost (a base in the Emplacement Phase) should have a sample curation facility, at ambient lunar surface conditions, robotically operated with full photo-documentation and computer database facilities, and capable of processing 200 kg of samples per day. This facility was to be complemented by a preliminary examination laboratory, presumably also at ambient lunar conditions, teleoperated or partially automated, with a stereomicroscope, X-ray fluorescence analysis capability, and a scanning electron microscope (SEM).

90-Day Study: Human Exploration of the Moon and Mars

This report (Cohen, 1989) barely mentions sample science, handling, or curation at a lunar base. It recognizes the need for preliminary examination on the Moon, but concerns itself much more with Martian than with lunar samples.

Human Exploration Initiative

In 1989-1990, considerable effort was expended at SN/JSC toward defining the requirements for science activities at a hypothetical lunar outpost as part of the "Human Exploration Initiative" and the "Lunar Outpost and Mars Initiative." This work apparently was preserved only as personal memos and as unpublished "white-paper" case studies. Their recommendations for sample curation and handling on the Moon closely follow those of Taylor and Spudis (1990). Sample collection was again assumed to follow Apollo-like procedures. Sub-sampling, preparation for analysis, and preliminary analyses were to be done under lunar ambient conditions, perhaps telerobotically. The need for a work-shed (Taylor and Spudis, 1990) was called into question. Preliminary analyses were assumed to include visual and stereomicroscopic examination and major element bulk composition. Sample storage on the lunar surface was to be under ambient conditions, perhaps in a shed, but the details of storage were not investigated. Unfortunately, this effort did not yield a consensus conclusion or a report.

"America at the Threshold"

The Synthesis Group (1991) report contains essentially nothing on sample science, handling or curation at a lunar base. Collection and scientific examination of geological samples is implicit in most of its architectures, particularly the second "Science Emphasis for the Moon and Mars." However, lunar samples and sample science, except for their use in resource extraction, are mentioned only in the Appendix under the Waypoint of Lunar Exploration.

LExSWG: Planetary Science Strategy

In 1992, The Lunar Exploration and Science Working Group (LExSWG) published their recommendation for "A Planetary Science Strategy for the Moon." Although LExSWG recognized the importance of geological samples in scientific research, they did not address specifics of operations at a lunar outpost. They did envision that preliminary analyses would be done on the Moon (LExSWG, 1992, p. 22), and recognized the potential for extensive geologic studies from a lunar outpost. However, there was no mention of where or how sample examination would be done, nor of whether or how geological samples might be stored and curated on the Moon.

The "FIRST LUNAR OUTPOST" Mission

The most detailed scheme for handling and curation of geological samples is included within the "First Lunar Outpost Mission," FLO, studied in detail at Johnson Space Center in 1990-1992. The present study is based on work requested in support of the FLO mission.

The FLO mission, as defined in the *FLO Requirements and Guidelines* and the *Detailed Assumptions Document* (Neubeck, 1992a,b) and the *FLO Conceptual Surface Mission* (Joosten, 1992), involves four humans staying and working at a single site on the lunar surface for 42 days, or two lunar days and one lunar night. The mission would begin with an uncrewed launch from Earth of a living-space module, a habitat, which would land autonomously at the site of the lunar outpost. Later, a crew of four people in their piloted lander/return vehicle would land near the habitat early in the lunar day. Crew operations would be transferred to the habitat within 24 hours.

Samples for geological study would be collected on EVAs throughout the mission, both on foot and using an Apollo-style rover. Collection of geological samples at FLO would follow the concepts and methods used in the Apollo program. For example, sample collection tools are all derived from, or extensions of, the Apollo geoscience instruments (Allton, 1989; Eppler, 1991; Wilson, 1992). Sample documentation and tracking would also follow the Apollo model. In the 42-day mission, more than 1000 kg of geological samples could be collected.

In the FLO mission, preliminary examinations of geological samples would be performed on the Moon in the pressurized habitat, as "intravehicular activity," or IVA. "Laboratory IVAs include activities such as basic analysis, sorting, and packaging of samples for return to Earth . . ." (Joosten, 1992). These activities would be done in a geoscience laboratory (Neubeck, 1992b, Detailed Assumption #177; Joosten, 1992; Treiman, 1992). Following earlier reports on the evolution of science capabilities at a lunar outpost (e.g., Taylor and Spudis, 1990), the initial FLO geoscience instruments would be: a binocular microscope (presumably to approximately 100 X, useful for the natural surfaces of rocks); a simple chemical analysis device (currently favored is a combination X-ray fluorescence and Mössbauer spectrometers); and simple physical (e.g., magnetic) properties instruments (Eppler, 1991; Joosten, 1992; Treiman, 1992; Neubeck, 1992b; Detailed Assumption 607). There was no explicit consideration of transferring samples transfer from EVA (extra-vehicular activity) to IVA, the configuration of the geoscience laboratory, nor sample transfer from IVA to EVA.

Containment of geological samples on FLO is presumed to follow the Apollo model. The FLO manifest includes geological sample containers among the Geological Field Equipment Package, which is derived from the Apollo tools (Allton, 1989; Eppler, 1991; Wilson, 1992). However, there is no explicit consideration of containers for samples after they have been examined, nor of containers for long-term storage on the lunar surface.

The need for storage and curation of geological samples at a lunar base is explicitly recognized in the FLO mission requirements (#484, Neubeck, 1992a), and the issues involved were studied by Treiman (1993). That work forms the basis for the present report.

The FLO mission would end after 42 days on the lunar surface. At that time, the crew would re-occupy the lander/return vehicle, transfer return cargo to it, and begin the return to Earth. Return cargo of geological samples would be limited to 200 kg, including all sample containment and environmental controls.

THE STUDY

Six questions (or issues) have been identified as having the greatest importance in determining the functions, sites, and procedures for curation of geological materials at a lunar outpost.

1. What are the uses (and users) of geological materials originating at a lunar outpost?
2. What schemes, sequences, or flows of curation functions are compatible with the requirements of exploration and research?
3. Which functions are best performed on the Moon, and which on the Earth?
4. In the recommended curation scheme, where should the individual functions be performed?
5. In the recommended curation scheme, should humans, robots or telerobotic operators perform the curation functions?
6. What kind of storage and curation should be provided for samples that are not selected for transport to Earth?

These questions suggest that analyses of curation by use, function flow, and site be applied in order. Questions 2-3 are the most crucial, as they includes the decisions of whether to do preliminary examination on the Moon, and whether to store and curate samples on the Moon. In addition, issues of less critical importance at this stage were studied within the recommended scheme of functions and their locations.

Concepts for curation and handling of geological samples at a lunar outpost were evaluated for whether they: enable significant geoscience research on Earth and on the lunar surface; provide a capability to curate geological samples; and permit evolution of knowledge and capability within and between missions to a lunar outpost. These criteria are essentially as proposed by the scientific community as high-level requirements and assumptions for FLO (Neubeck, 1992a,b). The expense of curation is considered in terms of whether specific costly capabilities (e.g., a geoscience laboratory or a sample storage facility) are required. I did not perform costing estimates. Similarly, technology development is important in considering robotic and autonomous functions, but I did not perform a detailed assessment of technology readiness.

USES FOR GEOLOGICAL MATERIALS FROM THE MOON

The principal constraints on handling and curation of samples at a lunar outpost should be eventual uses of the samples. Ideally, no potential uses of the samples would be compromised in any way by collection, handling and curation. For geological materials, three broad categories of uses have been identified:

- Preliminary Examination,
- Detailed Analysis, and
- Storage for Posterity.

Preliminary Examination

Preliminary examinations of geological samples at a lunar outpost would include visual inspection and simple analytical procedures. In FLO, preliminary examinations would include inspection by eye and through a binocular microscope, simple physical tests, and simple non-destructive chemical analysis. Preliminary examinations are useful for: support in selecting samples for detailed analyses; real-time understanding of geologic relationships as an aid to planning exploration and research; and long-term understanding (at the lunar base) of the findings of previous missions.

Detailed Analysis

Typically, detailed analyses of lunar samples are end uses within the engineering and research communities. In the past, these studies have included chemical analysis, thin section examination and determination of mineralogy and petrography, isotope analysis, gas analysis, magnetic properties measurement, chemical processing for oxygen extraction, etc. Few of these analyses could be done at lunar outpost within current concepts, so use for detailed analysis would imply transport to Earth. Only a small proportion of geological samples could be transported to Earth. For example, the conceptual FLO mission provides for collection of up to 1000 kg of geological samples, but only 200 kg of return mass (which must include sample containers).

Storage for Posterity

As a resource and legacy for the future, samples of geological materials should be stored in safe, secure, minimally contaminating environments. These samples would preserve the record of past exploration and research, and ensure that it need not be repeated. In addition, they would preserve materials pre-dating any global atmospheric modification caused by extensive human activities on the Moon. The samples could be retrieved from storage for additional detailed analyses or additional preliminary examinations (e.g., for comparison with newly collected samples).

FUNCTION FLOW IN CURATION

Curation can be considered as set of functions, suggesting that options in curation at a lunar outpost can be explored through function flow analysis. The functions of curation and related activities at a lunar outpost would likely include:

- sample collection,
- sample documentation,
- sample tracking,
- preliminary examination,
- splitting (breaking or dividing a sample into representative portions),
- deciding whether to return a sample to Earth or store it on the Moon (decision to be made by a science support segment, and nominally a portion of the allocation function),
- preparation for transport to Earth, and
- storage in a curatorial facility on the Moon.

Sample allocation would likely be done on Earth, at least during the outpost phases of a lunar base. The functions of sample collection, sample documentation, sample tracking, and preparation for transport to Earth would have to be done under any circumstance, and so do not suggest options for curation at a lunar outpost.

Functional Schemes

The remaining functions suggest options for sample curation at a lunar outpost: to split or not, to examine or not, to decide on Earth return or not, and to store on the Moon or not. Among these functions, many schemes or flows are possible, and the most reasonable are shown in Figure 1. These schemes range from "do nothing" (#1), to a full utilization of laboratory, storage, and decision-making capabilities (#5 and #6).

Evaluation of Schemes

These curation schemes can be evaluated by how well they serve the end uses of geological samples (embodying the goals of sample science) and how much they cost (e.g., mass to surface, astronaut time, volume in a habitat, etc.). High-level programmatic criteria need not be of considered directly because the goals sample science can be justified in terms of high-level requirements. The most important criteria, expressed as positive attributes, are:

1. enable examination of samples in real time to improve exploration/research activities;
2. enable examination of previously collected samples in real time to improve exploration/research activities;
3. enable selectivity in return of samples to Earth for detailed study;
4. enable preservation of minimally contaminated samples or sub-samples;
5. require no laboratory facility; and
6. require no sample storage facility.

These criteria are discussed briefly below, and Table 1 shows how the schemes of Figure 1 meet the criteria.

Real-time Sample Analyses. Examination of samples <u>during</u> a lunar outpost mission would enable significant improvements in its program of exploration and research. Examinations could define promising or interesting sites, and exploration and research could be redirected to those areas. Otherwise, interesting areas or rock types might remain undetected until long after the mission when analyses were performed on Earth.

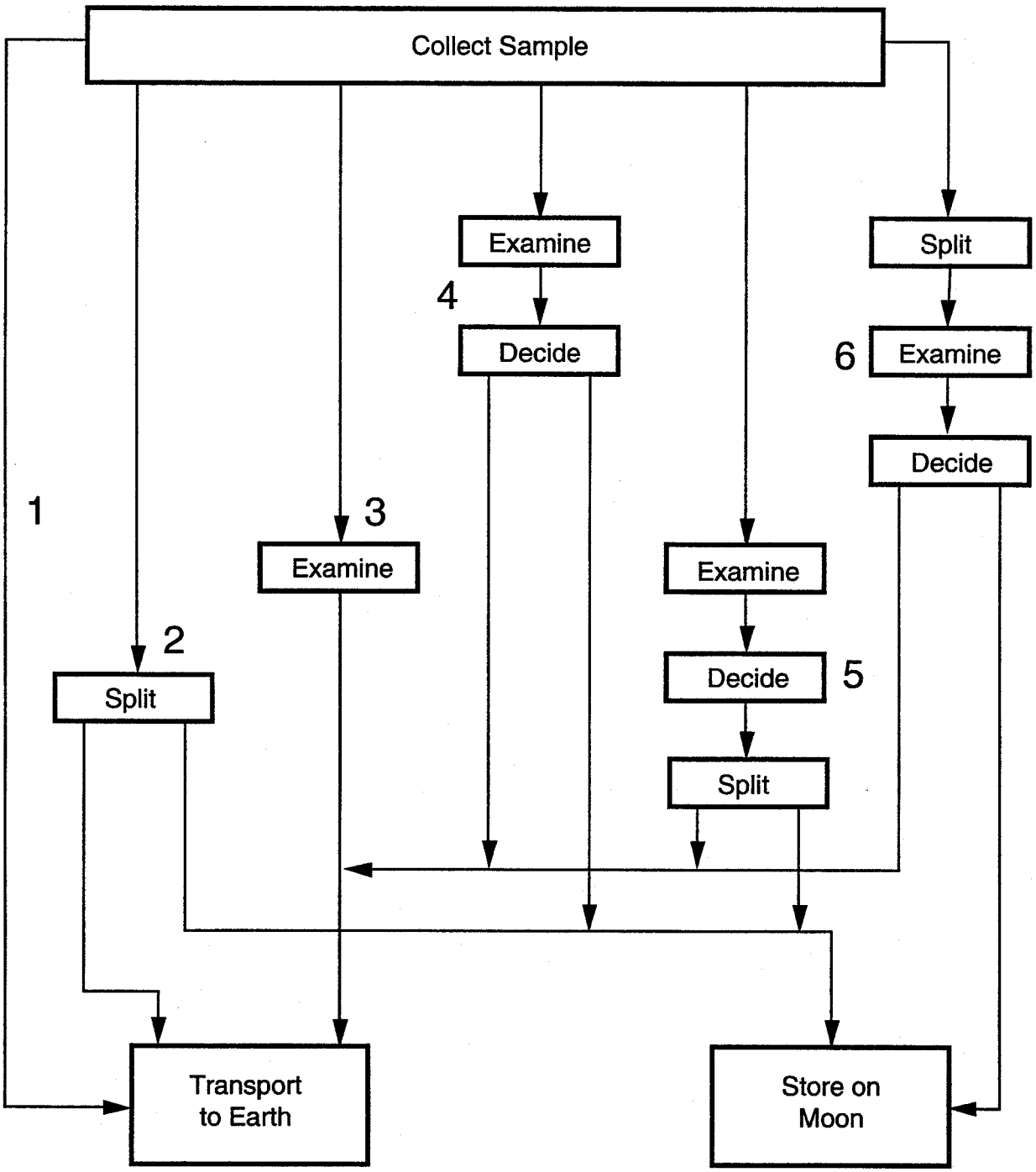

Figure 1: Schemes for curation functions at a lunar outpost.

Table 1: Evaluation Matrix of Proposed Scheme for Sample Curation at a Lunar Outpost. Symbol indicates that the Criterion to Left is Satisfied by that Scheme.

	1	2	3	4	5	6
Permits Sample Examination on Moon in Real Time			X	X	X	X
Permits Examination on Moon of Previously Collected Samples					X	X
Permits Selective Sample Return to Earth				X	X	X
Permits Retention of Minimally Contaminated Sample		X				X
Requires No Laboratory on Moon	X	X				
Requires No Storage on Moon	X	X				

Long-term Sample Availability. If a lunar outpost is to serve exploration and research for more than a single mission, it becomes important that each mission have access to knowledge and samples acquired by the preceding missions. If that knowledge and samples are not available, each mission would need to begin again in learning the geological materials in region around the outpost. There is also a risk that different missions may apply different criteria in identifying geological materials. As is done in geoscience exploration on Earth, it would be important to maintain "type" specimens of geological materials and units in a form easily accessible by the astronauts.

Selectivity of Sample Return. It is a fact of exploration and research that some samples are more valuable than others, because they can yield unique, critical data upon detailed analysis. The scientific and exploration value of a lunar outpost would be enhanced if the most valuable samples could be identified and returned to Earth for detailed analysis. The extra value of such samples may derive from their locations, rock types, structures, ages, etc. Some of these factors can be determined at the site of collection by visual clues, others can be determined by preliminary examinations, and others only become apparent after detailed analysis.

Minimally Contaminated Sample. "Minimally contaminated" is taken to mean exposed only to contamination derived from sample collection and sample storage. The mere act of collecting samples on the Moon contaminates them, e.g., by outgassing from astronaut pressure suits (EMUs) and EVA machinery. This level of contamination is unavoidable under Apollo collection procedures, but has not impeded or prevented most detailed analyses. However, bringing samples into an environment of higher gas pressure (near or in a habitat) will induce significant adsorption of gases onto their surfaces. Even though the environmental gas may be inert, reactive contaminants in that gas will become concentrated on the geological materials because of their reactivity. This level of contamination, while unavoidable and acceptable for Earth-based studies, could be avoided and is therefore unacceptable for minimally contaminated lunar samples. In addition, bringing samples near a habitat or near machinery may expose them to unnatural physical conditions, like temperature or magnetic fields.

No Laboratory Facility. A geosciences laboratory at a lunar outpost would require mass, power, and volume, and would likely be the most costly facility associated with sample curation. The baseline geosciences laboratory for FLO would be in the habitat, would occupy approximately 0.5 m^3, weigh 46 kg, consume 181 watts power (Eppler, 1991; Wilson, 1992; Detailed Assumption 607, Neubeck, 1992b), and require astronaut time in the habitat. If the geosciences instruments were outside the habitat, they would perform the same analytical functions, and might consume more or less mass, power or volume depending on the particular instruments. The baselined geological instruments for FLO, a binocular microscope, simple physical properties instruments, and a simple bulk chemical analyzer, would probably consume essentially the same mass, power and volume inside and outside the habitat. If a laboratory outside the habitat were operated by astronauts on EVA, their time would be needed. If a laboratory outside the habitat were operated robotically or telerobotically from inside the habitat, it would require mass and power for robotic instruments. If a laboratory outside the habitat were operated telerobotically by astronauts in the habitat, it would require a robot manipulator interface in the habitat with its mass, power and volume requirements.

No Sample Storage Facility. A sample storage facility would be required for access to, and recovery of, collected samples. A sample storage facility is required for FLO. At a minimum, storage could consist of placing tagged samples at known locations on the lunar surface (i.e., a "rock garden"). A more sophisticated facility might have samples on shelves or in bins (perhaps from used consumables storage containers), pending an understanding of sample contamination that they might cause. Also required would be astronaut time to package, file and retrieve samples and computer power to maintain a curatorial database and tracking system.

Evaluations of Schemes

Scheme 1: Apollo. The first scheme of Figure 1 is the "return everything" option of Taylor and Spudis (1990), and was the philosophy followed on the Apollo missions: "do nothing on the Moon that can be done on the Earth." This scheme requires the minimum sample handling and curation on the Moon, and yields satisfactory returned samples with minimum expenditures of mass-to-Moon and astronaut time.

The advantages of this scheme are purely economic: minimum cost and minimum astronaut time. This scheme would require no laboratory facility, no laboratory instruments, no storage facility, and no astronaut time devoted to sample examinations. On the other hand, it provides the least return to exploration and research, with no provisions for selectivity of sample return, sample examination on the moon, or storage of minimally contaminated samples. In addition, it requires extreme selectivity during EVAs in choosing samples, as the baselined return cargo for FLO is only 200 kg, which includes sample containers.

Scheme 2. In scheme 2, geological samples would be split on the Moon without preliminary examinations (vis. Dietrich, 1990). Sub-samples would be transported Earth, and others would be stored on the lunar surface.

The advantages of this scheme are almost entirely economic: no laboratory facility or laboratory instruments, and no astronaut time devoted to sample examination. This scheme would send minimally contaminated sub-samples to the Earth, and retain minimally contaminated sub-samples on the Moon. Storage on the Moon would be required, and astronauts at the lunar outpost would be unable to examine the samples. In effect, minimally contaminated samples would be stored in the expectation that later missions might carry equipment for sample examination. As in scheme 1, however, it would require extreme selectivity

during EVAs in choosing samples because the return cargo mass is small.

Scheme 3. In this scheme, astronauts would examine all samples for real-time assistance in exploration/research, and then package them whole for transport to Earth.

The advantages of this scheme are in permitting real-time examination of samples, and in not having to establish a storage facility. A geosciences laboratory (and instruments) would be required. However, this scheme would have all samples exposed to the contamination of preliminary examination, and thereby ignore detailed analysis as a use of samples. In addition, this scheme would not permit examination of samples collected on previous missions. And, as in scheme 1, it would require extreme selectivity during EVAs in choosing samples because the return cargo mass is small.

Scheme 4. This scheme is like scheme 3 except that some samples are left on the lunar surface after examination. All samples will have been contaminated by sample handling and examination.

The advantages of this scheme are in permitting real-time examination of all samples, and preserving some samples on the moon for future use. Both a laboratory and a storage facility would be required. As above, this scheme would have all samples exposed to the contamination of preliminary examination, and thereby ignore detailed analysis as a use of samples. Also, astronauts on future missions to the Moon would be unable to examine those rocks that had been transported in toto to Earth.

Scheme 5. This scheme modifies scheme 4, in that sub-samples, not whole samples, would be transported to Earth. Other sub-samples would be retained on the Moon. Taylor and Spudis (1988) seemingly advocate this procedure: " . . . to adopt a dual packaging technique, whereby each sample is split at the sampling site into a large specimen (most of the sample) . . . and a small one to be subjected to preliminary examination at the Base," although elsewhere they clearly advocate storage of samples on the moon.

The advantages of this scheme are in permitting real-time examination of all samples, and preserving some samples on the moon for future use. Both a laboratory and a storage facility would be required. However, this scheme would have all samples exposed to the contamination of preliminary examination; as above, the end use of detailed analysis is ignored.

Scheme 6. The final scheme, "bring back subsamples of only the most interesting samples" (Taylor and Spudis, 1990), involves the most extensive sample curation and handling. Samples would be split, and minimally contaminated sub-samples would be placed in storage. Other sub-samples would be given preliminary examination. Based on those preliminary examinations, decisions would be made about transporting sub-samples to Earth. The chosen sub-samples would be readied for Earth transfer, and the remainder placed in storage on the moon.

This scheme satisfies all of the criteria for exploration and research (and consequently all of their programmatic requirements): preliminary examination, preservation of minimally contaminated samples, and selectivity of return to Earth. It is also consistent with the scenario advocated by Taylor and Spudis (1990),

> ". . . adopt a dual packaging technique, whereby each sample is split at the sampling site into a large specimen (most of the sample), which will remain in a sealed container . . ., and a small one to be subjected to preliminary examination at the Base. . . . Even with liberal sample payloads to Earth, a considerable number of samples will be stored indefinitely on the Moon."

This scheme is, with #5, the most costly of those considered. It requires both a laboratory facility on the Moon and a storage facility on the Moon.

The Preferred Scheme for Curation on the Moon

Table 1 shows that the tradeoff in curation on the Moon is of cost versus capability. The lowest cost scheme (#1) has the least capability, while the greatest capability (#5, 6) costs the most. A lunar geosciences laboratory, with instrumentation and its power requirements, seems likely to be much more costly than a storage facility. Thus, schemes 3 through 6 would be comparably costly. Of these, #6 provides the most capability for the cost. Schemes 1 and 2 provide very little flexibility and advantage from the exploration/research viewpoint, but are preferable from a cost standpoint.

From this analysis, the Office of the Curator prefers scheme #6, which best facilitates known potential uses for lunar samples. Scheme #6 is consistent with sample handling and curation in the First Lunar Outpost Conceptual Surface Mission (Joosten, 1992), and with the recommendations of Cohen (1989,), Taylor and Spudis (1990), and LExSWG (1992). Quoting in turn:

> "Samples collected . . . will be examined at the outpost, and preliminary assessments will be made of their character and importance." (Cohen, 1989).
>
> "Preliminary examination [of geological samples] will be an important activity at the Base. Results of preliminary examinations will be used to plan additional sample collecting activities and to decide whether and how much of a sample is to be sent to Earth for extensive study, studied further on the Moon, or simply stored for future use. For limited sample transport capability, preliminary examination will be essential to identify and isolate the most significant samples." (Taylor and Spudis, 1990).
>
> "Initial analyses might be simple (e.g. major element chemical composition) and could be used to prioritize the selection of samples to be shipped back to Earth for detailed analysis." (LExSWG, 1992)

In particular, splitting each sample on collection was specifically mentioned by Taylor and Spudis (1990).

If the cost of a geoscience laboratory is too great, scheme #2 is recommended, although it is <u>much</u> less desirable than #6. Scheme #2 requires a near-minimum of mass-to-Moon, astronaut time, and laboratory volume, and would feed samples into a well-established curation system on Earth. The sample splits remaining on the moon would be seen as a resource (not commitment) for future geological exploration at the outpost site. However (as seen in Table 1), scheme #2 does not satisfy the need for real-time examination of samples on the Moon, nor reap the benefits of selective sample return to Earth.

PROCEDURES FOR CURATORIAL FUNCTIONS

Having selected scheme #6 as best facilitating the three categories of sample use, it is important to consider procedural guidelines for the curatorial functions. The procedures for each function would not affect the availability of samples to users, but would have significant impacts on the quality of the samples delivered (in terms of contamination) and in the costs of curation.

Some curatorial functions at a lunar outpost could be done under a variety of procedures and at a variety of sites, while others do not admit significant options. For instance, sample tracking and documentation must be done wherever the samples are, from collection to final storage. Decisions on transporting samples to Earth will likely be made inside the habitat and on Earth.

The curatorial functions that present significant options (or require discussion) are sample handling (splitting), preliminary examinations, and storage. Storage is considered first, as its stringent requirement for contamination control influences decisions on how to split and examine samples. Sample splitting is considered last, as it must serve all three uses.

Storage of Geological Samples

The purpose of curatorial storage is to maintain samples in as pristine (minimally contaminated) and secure a condition as possible, so they can be accessed readily for future users. At a lunar outpost, security is not likely to be a significant issue, but contamination will be.

Contamination: Site. Storage on the Moon could be inside a habitat, near a habitat, or distant from a habitat. Only the last is suitable. Storage in a habitat would contaminate the samples with volatiles and organic matter from the habitat, and physical effects (vibration, electrical and magnetic fields) associated with habitat activities. In addition, storage in a habitat would require allocation of pressurized volume, which certainly could be utilized for other purposes. Storage out on the lunar surface near a habitat is also inappropriate, as gasses emitted from the habitat and activity surrounding the habitat would likely contaminate the local environment. Storage under spacecraft flight paths would also be contaminating, as tons of gases are emitted on each landing and launch.

So, a site distant from the habitat, other structures, and flight paths would be optimal for sample storage. It is not clear how far is "distant" in terms of contamination. The minimal storage facility would have tagged samples placed at known locations on the lunar surface (e.g., a "rock garden"). Storage and tracking would be facilitated by having a building, structure or container dedicated to storage. This concept, a sample storage "shed," was considered optimal in 1988 (Taylor and Spudis, 1990) and retained currency at least through 1990 (Dietrich, 1990; Lindstrom, 1990). Unfortunately, a curation storage structure might also increase the contamination level of the stored samples, and might have considerable cost in terms of mass to the Moon. It might be possible to re-use a spent food or fuel resupply container as a curatorial structure, if the container would not cause the stored samples to become unacceptably contaminated. However, the first lunar outpost mission might not have such a container available.

Contamination: Containment. Containment of samples in a storage facility is desirable, if for nothing other than to prevent cross-contamination between samples. The containment materials must themselves cause minimal contamination, and FLO has baselined teflon sample collection bags like those used in the Apollo missions (Allton, 1989; Wilson, 1992). The choice of container materials needs further study, as Teflon like that of the Apollo bags abrades and rips easily (J. Allton, pers. comm.), and can lose much of its strength from long exposure to solar radiation (Rousslang et al., 1991).

Accessibility. Samples in lunar storage must be accessible and retrievable for study and analysis. A systematic method of filing and tracking samples is required. This could be achieved easily in a curatorial storage "shed," and less easily for samples exposed on the lunar surface. A "rock pile" of samples would provide inadequate accessibility.

Preliminary Examination

The function of preliminary examination presents the most options for its sites and procedures, the most opportunities to contaminate samples, and the greatest potential costs to a lunar outpost mission. Preliminary examinations could be done as IVA, EVA near the habitat, or EVA far from the habitat; they could be done by humans, by telerobotics, or by robots. Sample contamination is unavoidable in preliminary examination, because even the most stringent control procedures will expose samples to higher gas pressures and more chance for contamination than those of collection or storage. Astronaut EMUs, machinery and analytical instruments emit gasses, may contribute to sample cross-contamination, and may contribute particulates and electromagnetic contamination.

Preliminary Examination during EVA. It has been recommended, principally by the geoscience community, that preliminary examinations be performed outside of the habitat, and far from the habitat to reduce sample contamination. For example,

> "For minimum contamination, the [sample] processing facility ought to be located outside the artificial atmosphere of the base habitats. A relatively simple shed could be constructed for this purpose . . . ." (Taylor and Spudis, 1990),

> "Preliminary Examination Laboratory: Teleoperation . . . ." (Cintala, 1989)

> "Subsampling, preparation for analysis, and preliminary analysis of samples is best done remotely under lunar ambient conditions, i.e., . . . outside the habitation module." (Lindstrom, 1990)

Performing preliminary examinations during EVA would prevent the contamination attendant on examinations in the habitat, but would contribute contamination from astronaut EMU suits, robotic manipulators, examination instruments, etc. As shown below, doing preliminary examinations as EVA could also be very costly.

Human Crew Operation. Preliminary examinations performed by astronauts during EVAs would be costly in terms of their time, mass-to-surface, and technology development. Using human operators on EVAs would require allocation of EVA time (likely to be scarce at any lunar outpost, and known to be scarce in the FLO mission: Joosten, 1992; Treiman, 1992), emplacement of a horizontal work surface (e.g., bench) for examinations, development of non-contaminating procedures for dust removal on the lunar surface, and development of analytical instruments usable by suited and helmeted astronauts (e.g., a stereomicroscope), and stable in the varying environmental conditions of the lunar surface.

Telerobotic Operation. Preliminary examinations could be performed on the lunar surface by telerobotic operation, with the astronaut operators in the habitat. This option would require the equipment and technology development in the above option, **plus** the mass and technology development of highly dexterous robotic manipulators rated for use in the lunar surface environments, **plus** allocation of IVA space for the human interface to the telerobotic system.

Fully Robotic Operation. Preliminary examinations could be performed by a fully automated robotic facility, without the intervention of humans. Implementation of this option would require all of the mass and technology development of the telerobotic option, **minus** the IVA space for human operators, but **plus** the technology development and computation power to fully

automate preliminary examinations. I suspect that most geologists who have examined samples critically would despair of a fully robotic system making the inferences and judgments required to adequately evaluate geological samples.

Preliminary Examination in the Habitat. It has been recommended or assumed, principally by the engineering and management communities, that preliminary examinations at a lunar base would be done in the habitat. For example,

> "When the pressurized laboratory module is emplaced, geochemistry . . . research will begin." (Cohen, 1989),
>
> "Provide a means to maintain samples in a controlled atmosphere while inside the laboratory for: storage, sample manipulation, breaking chips off rock samples, viewing under binocular microscope . . . ." (Budden, 1990)
>
> "A pressurized laboratory may be provided for scientific experiments and observations, processing and archiving of materials . . . . [S]ub-samples [would be] taken and examined in laboratory modules... ." (PSS, 1991), and
>
> "Laboratory IVAs include activities such as basic analysis, sorting, and packaging of samples for return to Earth." (Joosten, 1992).

Performing preliminary examinations in the habitat would not consume EVA time, would not require development of technology for use on the lunar surface and (for FLO) would utilize baselined laboratory space in the habitat. These benefits would come at the cost of moderate to extreme contamination of samples, and controls to keep the samples from contaminating living spaces. There are a number of options for doing preliminary examinations in the habitat.

Examination in Vacuum. In this option, samples would be held, manipulated, and examined in a vacuum chamber in the habitat. This option eliminates the problems associated with astronaut EVA or robotic systems outside the habitat, but has little else to recommend it. To create a vacuum environment in the habitat would require either pumps or a vent to the outside. An airlock system for sample transfer would be required. Instruments capable of functioning in a vacuum would have to be developed.

The lunar vacuum is better than that which could be reasonably produced in the habitat, so samples in a laboratory vacuum would be contaminated compared to those left outside the habitat. Similarly, it was the experience in the Apollo Lunar Receiving Laboratory that manipulation and examination of samples in a vacuum are unsatisfactory. If samples are to be maintained in a vacuum, it would seem much more reasonable to use the ambient lunar vacuum, i.e. do preliminary examinations during EVAs (McKay et al., 1992).

Examination Under Inert Gas. In this option, preliminary examination would be done under purified inert gas, comparable procedures now used at the Lunar Curatorial Facility, Johnson Space Center. Use of an inert gas would complicate analyses of indigenous abundances and isotopes of that gas, and possibly others because of adsorption onto grain surfaces. An inert gas system would require a source of gas, an airlock system for sample transfer, a gas-tight laboratory module, and procedures to keep the samples, instruments, and tools clean. There may be little technology development, as instruments have been developed for use in similar facilities on Earth.

Examination Under Desiccated Habitat Atmosphere. In this option, preliminary examination would be done under dried habitat atmosphere in a desiccator glove-box environment in the habitat. In this

option, samples would be contaminated with breathing gas, but possible chemical reactions are likely to be slow in the absence of water. The overhead involved in vacuum or inert gasses would be avoided, and there would be little technology development for instruments. The desiccating medium could be regenerated in the habitat cooking oven.

Examination Under Ambient Habitat Atmosphere. In this option, preliminary examination would be done in the habitat without any controls on the sample atmosphere. This is the most contaminating of the options, exposing the samples to the water vapor, oxygen, carbon dioxide, etc. As in the Apollo samples, metallic iron could be expected to react with the moist air to form the hydrous iron oxide akaganéite, ß-FeOOH (Taylor et al., 1973, 1974). Similarly, this option presents the most chance for contamination of the habitat by the rocks. However, this option would require by far the least cost in terms of mass to surface, astronaut time (i.e., ease of operation), sample transfer system (airlocks), consumables (e.g., inert gas), and technology development.

Conclusion. The fundamental question here is whether the requirements of preliminary examination are consistent with the requirements of detailed analyses and of minimally contaminated storage. It seems clear that these two sets of requirements are fundamentally irreconcilable. Sample examination is inherently a contaminating procedure, and a sample that been examined is not suitable for uses that require a minimally contaminated sample. The only possible accommodation of the demands is through **multiple splits** of a sample, **one committed for examination,** and **the others kept minimally contaminated.**

Accepting that multiple sample requirements demand multiple sample splits, it is wasteful to expend significant effort keeping the preliminary examination (sacrificial) sample free from contamination. The scientific value of a sample will be essentially the same following any of the preliminary examination procedures above, except the last which involves exposing the sample to water. Thus, cost is the primary guide to our recommendation here, and it is **recommend that preliminary examinations be performed inside the habitat under desiccated habitat atmosphere.** We chose this over ambient gas because of the rapidity with which iron reacts with water in the air, and the effect that the resultant "rust" might have on the colors of the samples. However, it may be possible to examine the samples briefly in ambient air and store them in a desiccator without degrading their value significantly.

Splitting Geological Samples

Because the recommended procedures involves splitting samples, the sites and procedures of splitting must be considered. To serve uses that require minimally contaminated samples, initial splitting must be at the site of least contamination, the site of collection. At collection, at least two sub-samples of each rock type need to be split: one for preliminary examination, one for minimally contaminated storage, and possibly a separate split for detailed examination. If three sub-samples are made, each category of use would have a separate sub-sample, to be disposed of as needed. If two sub-samples are made and if the sample is chosen for detailed analysis, no minimally contaminated sub-sample would be retained on the Moon.

Splitting a sample after collection seems to offer few advantages. This contamination from a second splitting would likely not be significant for the sub-sample destined for detailed analysis, because transport to Earth and curation on Earth would cause contamination well beyond that caused by a second splitting on the Moon. However, the sub-sample left behind in lunar storage would also have been significantly contaminated.

Sample mass must also be considered. For a small sample, less than approximately 250 gm, it may be necessary to transport the whole mass to Earth to adequately satisfy the demands of detailed analysis. In

this case, further splitting is not recommended, and the whole mass could be transported to Earth.

If mission and program goals would be best served by retaining minimally contaminated samples on the Moon, **it is recommended that samples be split into three sub-samples on collection**: one for preliminary examination; one for potential transport for detailed analyses, and one for storage. However, it will always be easier to retrieve a sample from storage than to obtain a new sample, particularly from a distant location.

Summary of Recommendation

It is recommend that geological samples, rocks in particular, be split at the time of collection into three sub-samples: one for preliminary examination, one for detailed analyses; and one for minimally contaminated storage. Samples destined for minimally contaminated storage should be placed there as soon as possible after collection. To reduce contamination, the storage system should be distant from the habitat, other structures and incoming and outgoing flight paths. The storage system must include easy access to samples, and a comprehensive tracking system. Infrastructure for such storage could be minimal, e.g., placing tagged sample containers at known locations on the lunar surface. Samples for detailed analysis would be stored outside the habitat soon after collection, and retrieved later for transport to Earth.

Samples for preliminary examination would be brought into the habitat to a geosciences laboratory. These samples would be prepared (e.g. dusted) and examined under desiccated breathing air. If required, samples could be split in the lab module. After use, these preliminary examination samples would be tracked and stored, either inside the habitat or out on the lunar surface.

OTHER ISSUES

Curation of Various Rock Types

A wide range of rock types occur on the Moon. The preceding discussion assumed that the samples were monomict rocks, i.e. a single recognizable rock type. However, many lunar samples are not monomict, but mixtures of rock fragments cemented together in a finer-grained matrix, i.e., polymict breccias.

Should polymict breccias be curated and examined in the same manner as monomict rocks? The lunar samples contain many types of polymict breccias: dimict (black and white), fragmental, granulitic, regolith, and impact melt and probably others (Taylor, 1982). The breccias show significant variations both in the sizes of fragments and in the diversity of rock types represented among the fragments. It is fortunate that the breccias with the greatest diversity usually contain mostly small fragments. Hence, it may be necessary to sample dimict or impact breccias (large fragments of few lithologies) by taking separate samples of fragments and matrix, and to sample regolith and fragmental breccias (small fragments of many lithologies) by taking whole rock samples. The decision on sample collection strategy should be made by the astronauts at the collection site.

As above, the curation strategy for breccias should be dictated by the end uses and users. In laboratories on Earth, these breccias have found most value for the rock fragments within them; the breccias are carefully dissected, and the fragments individually analyzed for composition, age, isotope ratios, etc. The matrices of the breccias have received significantly less attention. However, on the Moon, different breccia types may be most useful to the lunar geoscientist as geologic units. In this case, the major fragment types and the character of the matrix may be the most important characteristics.

This dichotomy of uses for breccias is conceptually the same as encountered above with monomict rocks: detailed analyses and preliminary examinations have different needs. However, users of breccias also have different needs for sample types. The analyst on Earth might prefer a non-representative sample containing the greatest variety of usable rock fragments (perhaps 0.5-3 cm diam.?) and little matrix. The field geologist on the Moon might prefer to have a characteristic sample of matrix and small splits of the most abundant clast types. Both of these goals could be achieved by selective sampling at the time of collection.

Curation of Various Geological Samples

It is important to know if different types of geological samples could be curated under the scheme and procedure outlined above. As a baseline, one can consider the types of samples collected during the Apollo missions: rocks, regolith (soil), rake samples from regolith, drill samples, and drive tube samples (Allton, 1989). In addition, a number of specialized sample containers were used during Apollo, including: contact regolith samples, core vacuum containers, gas analysis sample containers, magnetically shielded containers (apparently never used), and special environmental sample containers (Allton, 1989). Rock samples were discussed above.

Rake Samples. Rake samples consist of rock fragments >10 mm diameter gleaned from their host regolith. Ryder et al. (1988) showed that such rocklets can be identified under procedures like those of preliminary examination here. Thus, it appears that rake samples may be examined and curated under the same protocols as rock samples, except that individual rocklets are too small to split.

Regolith Samples. Samples of unconsolidated material from the lunar surface, the regolith, may be handled under protocols similar to those outlined above for rocks. Regolith samples may be extremely useful in real-time planning of exploration,

particularly for potential lunar resources. Dust contamination of the habitat may be a significant concern with regolith samples, as they are by definition rich in dust.

Cores, Drill and Drive Tube. Cores from drills and drive tubes have been handled similarly in the Lunar Curatorial Facility on Earth. Under controlled environments, cores are extruded, excavated in three stages, and sampled continuously over their whole lengths. This level of handling and processing would be essentially impossible at a lunar outpost, and would likely require a significant expenditure of resources at a developed lunar base. If nothing else, the equipment and core segments currently used are physically larger than the laboratory volume baselined for FLO (of Space Station Freedom heritage). The question of dealing with cores is serious, as 1) subsurface information derived from cores would likely be significant in real-time planning of exploration and research, and 2) mining engineering and planning will likely generate many core samples (see below) and 3) will require rapid interpretations of their materials and compositions.

Specialized Containers. Specialized containers (like the gas analysis sample container) are designed for specific detailed analyses that would be impossible on samples that experienced the normal treatment accorded lunar samples. Thus, it is likely that samples in these containers would be transported directly to the site of detailed analyses, and would not be examined or stored on the Moon.

Site Of Lunar Outpost

It is possible that the choice of site for a lunar outpost could affect the schemes of curation and sample handling. For FLO, the baseline outpost site is in Mare Smythii on the eastern limb of the Moon; although the site is attractive (Morrison, 1990) no firm decision has been made.

To a first approximation, outpost site is likely to have no influence on curation of geological materials. The synoptic views of the Moon given by Earth-based astronomy and the Lunar Orbiter, Apollo, and Galileo missions suggest that the geological processes that acted at the Apollo sites are likely to have acted over the whole lunar surface, and that bulk compositions of the lunar surface fall within fairly restricted ranges. From similar processes and similar bulk compositions, it is likely that the geological materials all over the moon are grossly similar (vis. Taylor, 1982). At any site on the Moon, astronauts are likely to find coherent rocks and boulders (monomict and polymict breccias), regolith, and dust. Given the same broad classes of materials site-to-site, it seems unlikely that curation of geological materials would be influenced by outpost site.

The one known exception to this invariance of curatorial procedures would be an outpost site at a lunar pole. It is possible that the polar regions may contain significant, recoverable quantities of water and other volatiles trapped in permanently shadowed regions. In this case, there would be a need for curation (including preliminary examination) of very cold, volatile-rich samples. The recommended scenarios for curation would not be adequate, and new scheme would have to be developed.

Curation Of Other Types of Samples

In the mature phases of a lunar base (consolidation or utilization, as in Cohen, 1989; Synthesis Group, 1991), it will likely become advantageous to curate materials beyond geological samples for scientific use. Although highly speculative, it would be helpful if curation activities planned for a lunar outpost could evolve gracefully to include other types of materials, and accommodate the range of interfaces required by other user communities.

ISRU Materials. ISRU (indigenous space resource utilization) activities on the moon will likely generate great numbers of geological samples, all requiring documentation, tracking, and storage.

> "Geologic sampling may take many forms, but the most common tool by far is the core drill. Cores are taken

> at an interval small enough to sample accurately both ore reserves and any geologic formations that can affect mining operations . . . sampling continues throughout the life of the mine." (Gertsch, 1992)

On Earth, exploration samples are typically split, with one portion going for analysis, and the other going to storage (usually in a core shed on the mine site). The interface between curation of geoscience samples and curation of mining exploration samples is a point of potential concern. First, the mining samples may also hold significant geological information, and should be accessible and usable by the exploration and research community. Second, the number of mining samples could potentially overwhelm an inadequately prepared curatorial facility. And third, the needs of mining engineering, commercial enterprises, and exploration/research are not completely compatible, and may require accommodations by all communities.

Artifacts. Human artifacts exposed to the lunar environment for extended times could provide information on the lunar environment, as was the case with Surveyor III materials returned by Apollo 12. If more artifact materials became available on the Moon, it might be possible to use a geosciences curation facility to preserve the materials and select the most useful portions for detailed analyses on Earth.

Cosmic Dust. A large cosmic dust collection facility has been proposed as an exobiology experiment for FLO, despite potential contamination by indigenous lunar dust. Should such a collector be built, it will likely require a curation facility on the Moon, because the collection plates themselves will be much more massive than the sum of all cosmic dust particles.

Planetary, Asteroidal, and Cometary Samples. It has been suggested that the Moon would be an good site for initial curation of samples returned from elsewhere in the solar system. Initial curation on the Moon would provide biological isolation of the Earth from the samples (and vis. versa), could easily provide a high vacuum (e.g. for asteroidal samples) and could provide constant cold (e.g., in permanently shaded areas) for icy or volatile-rich samples. The demands of curating extra-lunar samples exceed those of curating lunar materials (except possible volatile-rich polar materials), and would require specially designed facilities.

RECOMMENDATIONS FOR CURATION OF GEOLOGICAL MATERIALS AT A LUNAR OUTPOST

These recommendations summarize the curatorial functions and procedures that would be required at a lunar outpost base in order to ensure that collected geological samples are adequate for the known groups of users. These recommendations should be applicable to a spartan lunar outpost like FLO, and could be expanded or elaborated should a more capable lunar outpost or base become feasible.

1. All geological samples must be completely documented and tracked.
2. Contamination of geological samples must be limited according to potential uses, and all potential contaminating events and environments must be documented.
3. The following scheme for handling and curation of rocks (crystalline, monomict, or breccias), rake samples, and regolith samples should be followed.
   a. Upon collection, a geological sample (not including specialized samples or cores) should be split into three sub-samples, reserved for preliminary examination, detailed analyses, and minimally contaminated storage on the Moon.
   b. The minimally contaminated sub-sample(s) should be placed in storage on the lunar surface as soon as possible.
   c. Storage on the lunar surface should ensure that samples receive minimal contamination, and be readily retrievable. These requirements imply storage far from the habitat, other human operations, landing areas, and flight paths.
   d. Preliminary examination of the designated sub-sample should take place in a geosciences laboratory space in the habitat.
   e. Preliminary examination should be performed with the sample under desiccated habitat atmosphere.
   f. Adequate safeguards should be used to prevent human danger and equipment damage from lunar dust.
   g. The decision to transport a sample to Earth should be based in part on preliminary examination.
   h. Preliminary examination samples not selected for transport to Earth should be curated on the Moon. It may be prudent to store examined samples separate from minimally contaminated samples.
   i. Geological samples previously subjected to preliminary examination should be readily available for further examination during subsequent missions to the lunar outpost.
4. Core samples (drill or drive tube) and samples in specialized containers should be transported to Earth, not stored or examined on the Moon. The requirements for examination of cores and specialized samples on the Moon deserve analysis.
5. Strategies for sampling breccias should be studied in more detail, not only for lunar samples but also for samples from other planetary bodies.
6. The preceding scheme is inadequate for curation and handling of volatile-rich materials, such as might be found at the lunar poles. Further study for that case is recommended.
7. The preceding scheme may be inadequate for curation and handling of geological materials generated by ISRU activities. Further study is recommended, including that of managerial and informational interfaces between potential resource extraction operations on the Moon and the exploration/research community.

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REFERENCES

Allton J. (1989) Catalog of Apollo lunar surface geological sampling tools and containers. JSC-23454; LESC 26676. 97 p. Johnson Space Center, Houston, TX.

Budden N.A. (1990) *Logistical requirement on Planet Surface Systems for sample collection, documentation and handling.* Dated 1-9-90. Unpublished draft, Housed in Office of the Curator's Data Center, Johnson Space Center, Houston TX.

Cintala M. [team lead] (1989) Lunar Geoscience. in Duke M.B. ed., *Lunar Science Strategy Workshop: Science Strategy for the Exploration and Development of a Lunar Outpost and the Moon. Final Report.* NASA/Johnson Space Center, unpaginated. Housed in Office of the Curator's Data Center, Johnson Space Center, Houston, TX.

Cohen A. (1989) *Report of the 90-day Study on Human Exploration of the Moon and Mars.* U.S. Government Printing Office.

Dietrich J. (1989) *Sample Curation for Lunar Outpost and Mars Sample Return* Unpublished viewgraphs dated Dec.14, 1989; prepared in connection with planning for the Human Exploration Initiative in the Space Sciences and Exploration Division, Johnson Space Center. Housed in Office of the Curator's Data Center, Johnson Space Center, Houston, TX.

Dietrich J. (1990) *Elements of Sample Curation at a Lunar Outpost* Unpublished memo, dated 2/7/90. Housed in Office of the Curator's Data Center, Johnson Space Center, Houston, TX.

Duke M.B. (1989) *Lunar Science Strategy Workshop: Science strategy for the exploration and development of a lunar outpost and the Moon.* Final Report of a conference; prepared in connection with planning for the Human Exploration Initiative in the Space Sciences and Exploration Division, Johnson Space Center. Housed in Office of the Curator's Data Center, Johnson Space Center, Houston, TX.

Eppler D.B. (1991) *SEI Science Operations Planning.* NASA/XI In-house document. Housed in the Exploration Program Office Library, Johnson Space Center, Houston, TX.

Gertsch (1992) To Build a Mine: Prospect to Product. p. 4-14 in McKay et al. (1992).

Johnson S.W. and Leonard R.S. (1985) Evolution of concepts for lunar bases. 47-56 in Mendell (1985).

Joosten K. (1992) *First Lunar Outpost Conceptual Surface Mission.* NASA Exploration Program Office. In Press.

LExSWG (1992) *A Planetary Science Strategy for the Moon.* JSC-25920. 73 p. Johnson Space Center, Houston, TX.

Lindstrom D.J. (1990) Subsampling and Analysis of Lunar Rocks at a Lunar Outpost. Unpublished Memo. Housed in Office of the Curator's Data Center, Johnson Space Center, Houston, TX.

Lowman P.D. (1985) Lunar bases, a post-Apollo evaluation. 35-46 in Mendell (1985).

McKay M.F., McKay D.S. and Duke M.B. (1992) *Space Resources*. NASA SP-509, U.S. Government Printing Office.

Mendell W.W. ed. (1985) *Lunar Bases and Space Activities of the 21st Century*. 865 p. Lunar and Planetary Institute, Houston, TX .

Mendell W.W. ed. (1992) *The Second Conference on Lunar Bases and Space Activities of the 21st Century*. NASA Conference Publication 3166. 705 p. NASA Scientific and Technical Information Program.

Morrison D. (1990) *A Site Selection Strategy for a Lunar Outpost: Science and Operational Parameters*. Conclusions of a Workshop, Johnson Space Center, Houston. 80 p. Housed in Office of the Curator's Data Center, Johnson Space Center, Houston, TX.

NASA (1965) NASA 1965 Summer Conference on Lunar Exploration and Science. NASA SP-88. U.S. Government Printing Office.

NASA (1967) NASA 1967 Summer Study of Lunar Exploration and Science. NASA SP-157. U.S. Government Printing Office.

Neubeck D., ed. (1992a) *First Lunar Outpost Requirements and Guidelines (FLORG)*. NASA Exploration Program Office. In Press.

Neubeck D., ed (1992b) *First Lunar Outpost Detailed Assumptions Document (DAD)*. NASA Exploration Program Office. In Press.

Office of the Curator (1992) *Office of the Curator, NASA/JSC*. Pamphlet for public distribution. Available from Office of the Curator's Data Center, Johnson Space Center, Houston, TX.

PSS (1991) *Planetary Surface Systems Operations Study*. JSC-24824. Johnson Space Center, Houston, TX.

Rousslang K., Crutcher R. and Pippin G. (1991) Results of examination of silvered teflon from the Long Duration Exposure Facility. 847-859 in *LDEF -- 69 Months in Space. First Post-Retrieval Symposium*. (ed. A.S. Levine) NASA Conf. Pub. 3134. NASA Scientific and Technical Information Program.

Ryder G., Lindstrom M. and Willis K. (1988) The reliability of macroscopic identification of lunar coarse fines particles and the petrogenesis of 2-4 mm particles in Apennine Front samples 15243. *Proc. 18th Lunar Planet. Sci. Conf.*, 219-232. Lunar and Planetary Institute, Houston, TX.

Synthesis Group (1991) *America at the Threshold: America's Space Initiative*. 114 p. U.S. Government Printing Office.

Taylor G.J. and Spudis P.D. eds. (1990) *Geosciences at a Lunar Base: A Comprehensive Plan for Lunar Exploration*. 73 p. NASA Conference Publication 3070. NASA Scientific and Technical Information Division.

Taylor L.A., Mao H.K. and Bell P.M. (1973) Rust in the Apollo 16 rocks. *Proc. Lunar Sci. Conf. 4th*, 829-839.

Taylor L.A., Mao H.K. and Bell P.M. (1974) ß-FeOOH, akaganéite, in lunar rocks. *Proc. Lunar Sci. Conf. 5th*, 743-748.

Taylor S.R. (1982) *Planetary Science: A Lunar Perspective*. Lunar and Planetary Institute, Houston, TX.

Treiman A. (1992) *First Lunar Outpost Conceptual Science/Payloads Mission, and a Strawman Implementation at the Mare Smythii Site.* NASA Exploration Program Office internal report. Housed in Office of the Curator's Data Center, Johnson Space Center, Houston TX.

Treiman A.H. (1993) Lunar Surface Curation Trade Study. NASA Exploration Program Document, Trade Study FLO-92:57. In Press.

Wilson T. (1992) *Conceptual Science Payloads for the First Lunar Outpost.* NASA Exploration Program Office internal report. Housed in Office of the Curator's Data Center, Johnson Space Center, Houston TX.

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To preserve their maximum scientific value, geological samples collected at a lunar outpost will require curation at the outpost. Documentation, tracking and contamination control will be required under all outpost scenarios. Rock and soil samples should be split, at the time of collection, into three subsamples for minimally contaminated storage on the Moon, preliminary examination, and transport to Earth. At a minimum, storage on the Moon would involve placing samples in tagged containers at known locations on the lunar surface, far from normal outpost activities and flight paths. Preliminary examinations (to include visual examination with a binocular microscope, simple physical tests, and rough chemical analyses) would be done in the habitat, in a geosciences laboratory, under desiccated habitat atmosphere. Preliminary examination would render these subsamples unsuitable (contaminated) for transport to Earth, and they would be preserved on the Moon to support future exploration. Specialized samples and samples in specialized containers (including cores) should not be examined at a lunar outpost, but be transported to Earth for detailed analyses.

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