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CURATION OF GEOLOGICAL MATERIALS AT A LUNAR OUTPOST

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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 be 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 everything 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., N₂ 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 include 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 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 during 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.

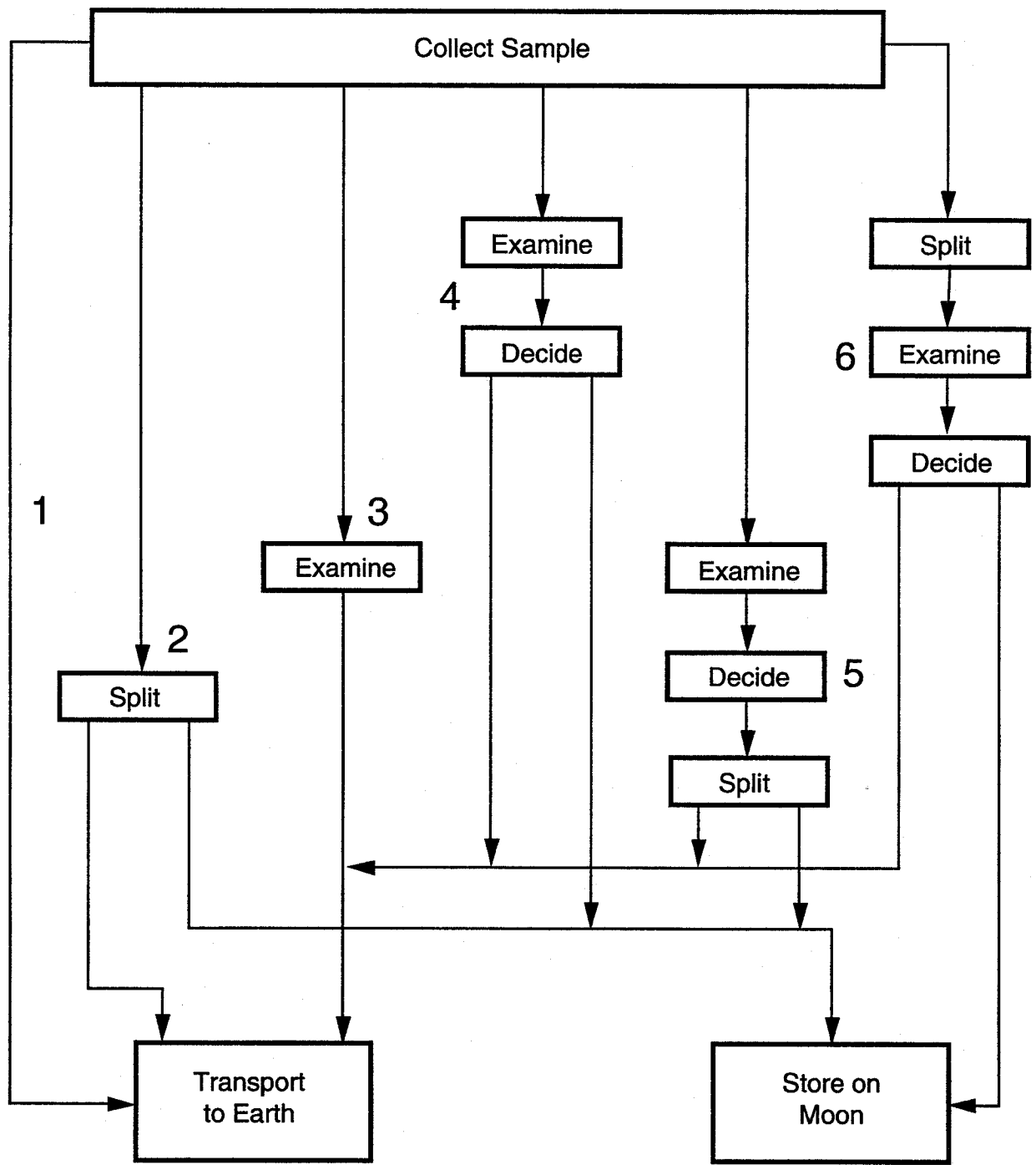


Figure 1: Schemes for curation functions at a lunar outpost.

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 m³, 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 much 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, β -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 **recommended 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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13. ABSTRACT (Maximum 200 words) 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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