



Curation and Analysis Planning Team for Extraterrestrial Materials

*“Dedicated to Maximizing
Planetary Sample Science
While Protecting the Integrity
of NASA Collected
Extraterrestrial Materials”*

CAPTEM ANALYSIS DOCUMENT

Analysis of Lunar Sample Mass Capability for the Lunar Exploration Architecture

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Executive Summary

The Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM) was requested by the NASA Advisory Council (NAC) to conduct an analysis of the mass of returned lunar samples that must be accommodated within the Lunar Exploration Architecture to fulfill lunar science goals. This analysis was conducted in three manners that evaluated sample mass with regards to previous Apollo Program surface activity, scientific productivity, present-day scientific rationale as defined by the LAT, and samples (mass, diversity) required to fulfill the scientific objectives.

The findings of this study are (1) lunar exploration architecture should accommodate **150 kg** of traditional geological samples for return to Earth, not including sample containers and environmentally sensitive samples. (2) This geological sample mass exceeds that of the Apollo 17 mission by only 35%. It is exceedingly important that the sample return capability of this architecture exceeds that of the Apollo Program to demonstrate we have progressed beyond Apollo. (3) Using the Apollo sample containers as a guideline, container mass needed to accommodate 150 kg of traditional lunar samples is approximately **30 kg**. Decreasing the sample container mass without compromising sample integrity should be explored. (4) The science requirements also dictate the need to preserve certain types of volatile-bearing samples beyond that available during the Apollo Program. To accommodate the preservation of these samples, an additional **36 kg** of samples and containers need to be included in the architecture capability. (5) It is essential that mission operation requirements build in capabilities for the future exploration of the solar system. The current nominal return mass requirement of 100 kg will not meet basic needs of either human exploration or science over projected lifetime of the CEV and VSE.

Introduction

The Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM) was requested by the NASA Advisory Council (NAC) to conduct an analysis of the mass of returned lunar samples that must be accommodated within the Lunar Exploration Architecture to fulfill lunar science goals. The current architecture for lunar exploration calls for a total return capability of 100 kg of material from the lunar surface. This mass includes lunar samples and their containers, and materials taken to the lunar surface and then returned to Earth for diverse reasons, including any biological materials and refrigeration units capable of biological sample preservation, and whatever additional materials necessary to support the Exploration agenda.

This request originated from the NAC-sponsored Lunar Science Workshop in Tempe, Arizona that was held February 27 – March 2, 2007 in which the NAC Planetary Science Subcommittee stated:

“The PSS views the sample mass allocation in the current exploration architecture for geological sample return as too low to support the top science objectives. We are asking that CAPTEM undertake a study of this issue with specific recommendations for sample return specifications.”

Below we present a historical background for sample return mass associated with the Apollo program and then discuss the current mass requirements in the context of both this previous experience and present-day scientific rationale. The overall objective of this analysis is to define sample requirements necessary to achieve science goals, which are recognized by NASA as one of the key drivers for lunar exploration.

Historical Background

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 381.7 kg of geological material from the lunar surface during 6 missions (Table 1). Apollo 11 returned the smallest sample mass from a limited geological area within 100 m of the lunar module. Apollo 17 returned the largest amount of diverse material from 22 locations over traverses totaling 36 km in the Taurus-Littrow Valley.

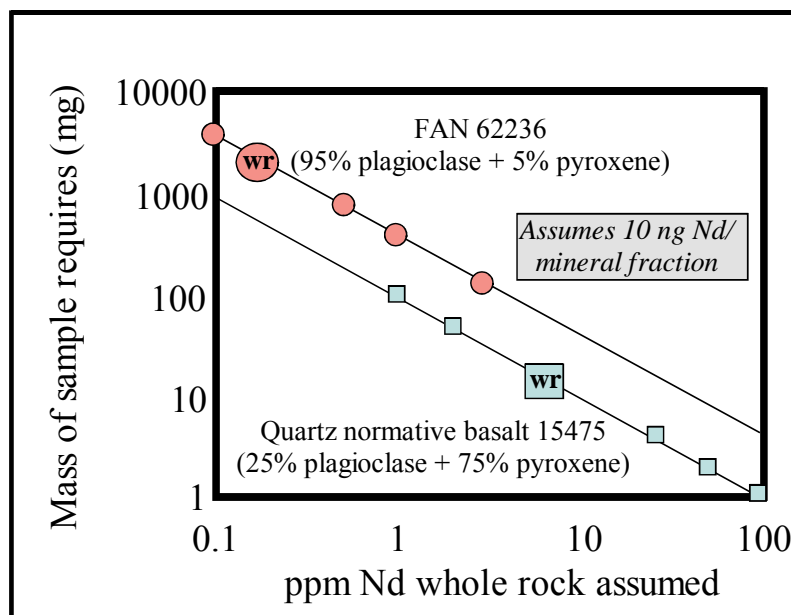
TABLE 1. Sample mass returned by the Apollo program (Vaniman et al., 1991).

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 Mass	381.7 kg (841.7 lbs)

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. 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. The collection of rake samples was designed expressly to return large numbers of relatively small mass samples ($> 1 \text{ cm}^3$; ≈ 0.2 to 1.0 g), contribute to lithologic diversity of the returned material, and help 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 and space-weathering processes. A subset of samples was collected and stored in specially designed containers to preserve them in a “lunar environment”.

The sample size required to fulfill science goals depends critically on the measurements to be made and the rock type. Furthermore, in order to maximize scientific return, numerous analytical measurements are typically required on individual samples. For example, as illustrated in Figure 1, in order to use the Sm-Nd isotopic system to determine age and the Sm-Nd systematics for a quartz normative basalt (15475) and a ferroan anorthosite (FAN; 62236) as little as 10 mg of the basalt are required whereas at least 2000 mg of the FAN are needed.

FIGURE 1. Calculations of the minimum sample mass required to produce a single Sm-Nd isochron for a quartz normative lunar basalt (15475) and a ferroan anorthosite (62236). The amounts given represent the material dissolved; a larger starting mass is required to obtain mineral separates of sufficient mineral purity, as required for the work. Large symbols labeled wr represent whole rock, whereas small symbols represent mineral fractions.



Since Apollo, analytical techniques have been improved and new techniques developed. However, it is a common misconception that because analytical techniques have dramatically improved and therefore there is no need to return rocks as large as was done during Apollo. This statement is incorrect for two

reasons that are related to the complexity and grain sizes of lunar rocks. First, many lunar rocks are breccias – rocks made of many fragments of other rock types (including other breccias) that have been agglomerated together by impact processes. The Apollo 14 breccia 14321, "Big Bertha" is a case in point. This remarkable sample has a mass of 9 kg and is up to 23 cm across. It contains clasts that represent an extensive diversity of lunar lithologies (Figure 2) that include some of the oldest lunar basalts, troctolites, anorthosites, and granites (i.e., Phinney, 1981; Shervais and Taylor, 1983; Shervais et al., 1984; and Salpas et al., 1985). Collection and investigation of such rocks is essential to decipher relationships between their diverse components. Impact breccias are likely to be the most abundant rock type present at any given outpost site other than a site in a volcanic terrain. Exploration objectives and sample-return requirements must explicitly consider the return of this type of material when defining mission operation requirements.

Second, for most lunar rocks, small samples are not likely to be representative because their mineral grains can be large and irregularly distributed. Terrestrial studies have long appreciated the statistical requirements for collecting representative samples (Larsen, 1938; Wager and Brown, 1960; Grant and Pelton, 1973). Ryder and Schuraytz (2001) demonstrated that a multiple-gram-sized sample is required to obtain a fully representative chemical analysis of a typical lunar basalt (< 1 cm). A chemical analysis of an unrepresentative sample may produce misleading results (e.g., underestimating the amount of ilmenite in a potential mining feedstock). To give an idea of how grain size affects the minimum mass of sample required for a representative whole-rock analysis, we represent the sample mass as a cube with the dimensions of the maximum grain size. Using returned highlands samples from the Apollo 15 mission, 15415 (ferroan anorthosite, the "Genesis Rock") has a maximum grain size of 3 cm and using a density of 2.85 g/cm³ approximately 77 grams would be required for one representative whole-rock analysis. Additional mass would be needed for other geochemical analyses, such as geotechnical studies.

FIGURE 2. Photographs of 14321,0 "Big Bertha" and cut surfaces illustrating diverse dark clasts embedded in a light breccia matrix.



Sample containers contributed to the overall mass of material returned from the Moon during Apollo. A catalog of Apollo lunar surface geological sampling tools and containers was prepared by Allton (1989). A subset of the dimensions and weights of Apollo sample-return containers are shown in Table 2. The Apollo Lunar Sample Return Container (ALSRC or rock box) was an aluminum box with a triple seal. Two ALSRCs were used on each Apollo mission. Two 4-cm drive tube core samples were sealed in a Core Sample Vacuum Container (CSVC) on the Apollo 16 and Apollo 17 missions. Special Environmental Sample Containers (SESC) were designed to ensure that samples were not exposed to

terrestrial atmosphere or spacecraft cabin gases. They were used on all of the Apollo missions. The configuration and size of sample bags changed during the Apollo program. Only the sample bags from Apollo 17 (including dispenser) are described in Table 2. The Gas Analysis Sample Container (GASC) was designed to hold a small amount of lunar soil within a large volume. The GASC was used only on the Apollo 11 and 12 missions.

TABLE 2. Apollo sample containers with packing.

Containers	Weight	Dimensions	Interior Volume
ALSRC	6800-8900 g	48x30x20 cm	1600 cm ³
4cm Drive Tube	410 g	42 cm length, 4.4 cm od	470 cm ³
CSVC	493 g	41 cm length, 6.1 cm od	703 cm ³
SESC	360 g	21 cm length, 6.1 cm od	360 cm ³
Soil Sampler Bags	358 g/48	13 cm length, 8 cm od	
Sample Bags	10.2 g/bag	20x19 cm	

Other sample containers were used on single missions for particular scientific purposes. For example, the magnetic shield sample container was used during the Apollo 14 mission. The sizes and masses of these more unique containers are not discussed here.

Estimates of Sample Mass

Unlike the pre-Apollo estimates of return sample mass required to fulfill science goals, we have an advantage based on surface operations during the Apollo Program and over 38 years experience of lunar sample study. We have used two approaches to estimate the mass of geological sample that should be accommodated within the Lunar Exploration Architecture: estimates based on Apollo surface operations and estimates linked to sample-based science yield. In addition to these estimates of sample mass, we have also estimated the sample and container mass required for returning and preserving lunar volatiles that may be associated with some types of lunar surface material.

Apollo surface operations: Calculating sample mass based on Apollo surface operations provides a mechanism to compare the amount of sample returned from the Apollo mission with the proposed lunar architecture. This simple calculation is based on the relationship between [Extra-Vehicular Activity \(EVA\)](#) time, lunar sample mass, and number of humans on the lunar surface. Sample mass returned during Apollo was highly correlated to EVA time (Figure 3A). Except for Apollo 11, the mass returned was approximately 4 kg per EVA hour (Figure 3B). Apollo 11 looks much more efficient, in part because mobility was restricted (limited walking and no driving) and at the end a sample container was filled with regolith. Assuming that the architecture for lunar missions includes 4 humans on the surface rather than 2, and that the EVA time is 4 times that of Apollo 17, the mass of sample that could potentially be collected by astronauts on the lunar surface is approximately 800 kg (Figure 3C). Improved spacesuits (i.e., improved astronaut mobility and dexterity) will further increase this number, if all EVA time is dedicated to the exploration of the lunar surface.

We do not necessarily advocate the capability for returning 800 kg of geological material per mission, but this exercise illustrates the capability of humans for sampling the Moon over the duration of a mission planned in the current exploration architecture. The Apollo mission goals were explicitly geological exploration of the Moon and so capabilities were shaped to maximize sample return mass. The “Vision for Space Exploration (VSE)” goals differ from those of the Apollo Program and will include more time for infrastructure development activities (relative to total mission time) and other scientific activities and less for geologic characterization of the outpost site and region. Given the longer durations of nominal missions in the current architecture, however, the total amount of EVA time allocated to lunar surface characterization and science should certainly not be less than that of the Apollo missions. The surface activity of Apollo 17 mission may be the closest approximation to the surface activity anticipated by the lunar architecture for an outpost site, especially in the early missions. As the most complex of the Apollo missions, Apollo 17 included a scientist in the crew, had the greatest EVA times, and had expanded mobility and experience with which to explore the lunar surface. Total sample mass collected by this mission was 110.5 kg and the sample containers had a mass of approximately 23 kg. Thus Apollo 17 returned a total of 133.5 kg from the lunar surface, which we recommend should be a *minimum* capability for the lunar exploration architecture. It is very important that the sample return capability of the lunar exploration architecture exceeds that of Apollo 17 to demonstrate progression beyond the Apollo Program.

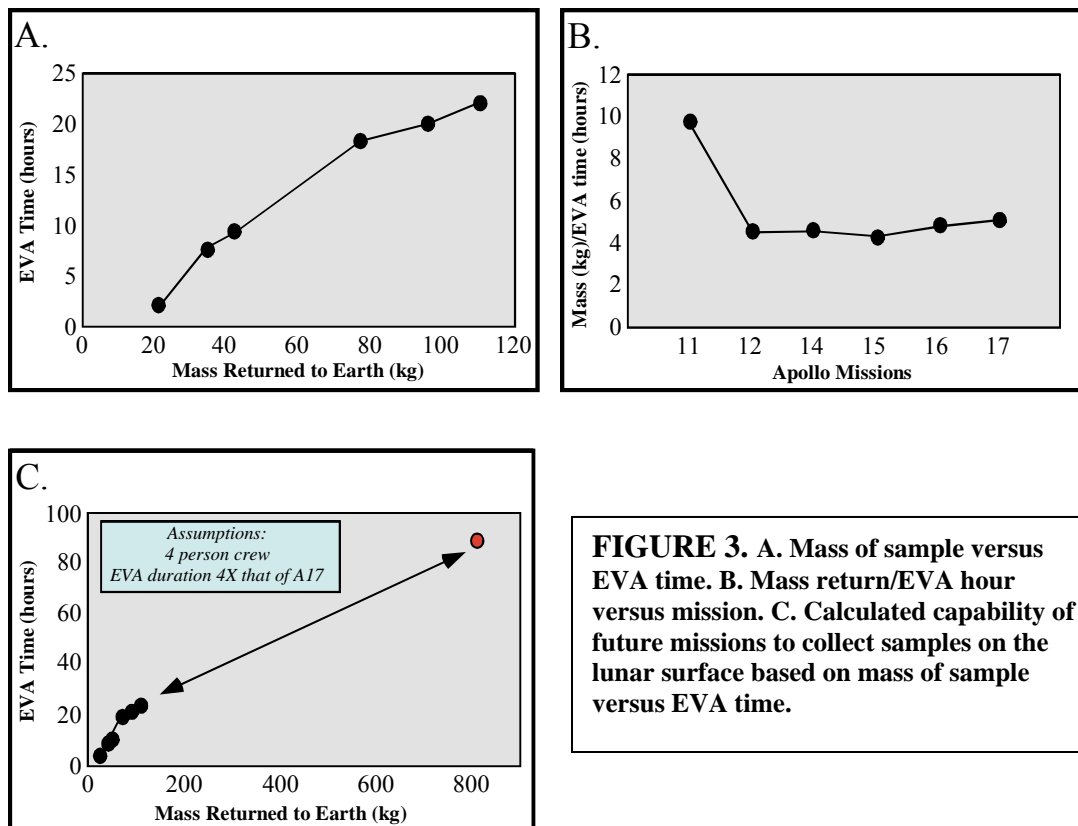


FIGURE 3. A. Mass of sample versus EVA time. B. Mass return/EVA hour versus mission. C. Calculated capability of future missions to collect samples on the lunar surface based on mass of sample versus EVA time.

Sample mass- science yield: A second type of analysis to determine sample mass is tied to the sample type and mass required to fulfill specific scientific objectives. We have approached this analysis in two ways. The first analysis is tied to the relationship between sample mass and scientific output. The second

analysis ties sample type and mass to the objectives of the lunar architecture science (with Apollo 17 as a model), and analytical needs to fulfill science objectives. It should be emphasized that there is an inherent uncertainty with this type of analysis because it depends on the complexity of the site. For example, a site located on a widespread basalt flow would require fewer samples than a site located at the juncture between basalt, impact-ejecta deposits, and feldspathic highlands. Likewise, a site near the edge of a large, fresh crater could contain a diversity of materials excavated from different depths by the impact event.

TABLE 3. Scientific output based on sample return mass.

	Number of Studies	# of studies	Number samples used per study	Minimum Number of samples	Maximum Number of samples	Average
Number A17 Studies	173					
Number studies desired (A17x 1.25)	216					
Types of studies	Percent study by type					
Geochronology	30%	65	4-6	260	389	
Petrology/Min Chem	35%	76	4-6	303	454	
Geochemistry	8%	17	15-25	260	433	
Isotope	16%	35	5-15	173	519	
Other	11%	24	15	357	357	
Total Studies		216				
Average samples				270	430	
Individual Unique number of samples						350

Input: (1) 173 A17 studies. (2) Types of studies are in proportions listed in column C.
 Assume: (1) Want to have 25% greater scientific output for new missions.
 Calculate 216 total studies
 Calculate 350 samples required for 216 studies assuming number of sample/study similar to Apollo and listed in columns D-E-F

Samples	Number homogeneous rocks required	Number individual samples	Mass	kg	Volume/sample (cm ³)
breccias	375	75	1	75	33.3
large rocks	150	150	0.2	30	6.7
small rocks	300	300	0.05	15	1.7
soils	50	50	0.2	10	6.7
TOTAL	875	525		130	
Percent unique/usable	0.4	350			

(1) Assume sample collection similar to Apollo and made up of breccias, large homogeneous rocks, small homogeneous rocks, and soils.
 (2) Following Apollo assume 40% sample yield due to archiving and inadvertent repeat sampling of same rock. Therefore need $350/0.40 = 875$ total samples required
 (3) Number of breccias, lrg. sm. and soil samples adjusted to yield 350 samples.
 Note fragmental breccias assumed to contain 5 individual samples each
 (4) Assume mass of breccias = 1 kg, lrg = 0.2 kg, sml = 0.005kg, and soil = 0.2 kg
 (5) TOTAL MASS CALCULATED FROM 525 ROCKS TIMES MASS OF EACH ROCK

Estimating sample mass based on scientific productivity is outlined in Table 3. The assumptions used in these calculations are based on scientific productivity following Apollo 17. Within four years subsequent to the return of 110.5 kg of sample by Apollo 17 on December 1972 there were at least 173 published manuscripts based directly on the returned samples. These studies focused on physical and geophysical properties, petrology, geochemistry, isotopes, and geochronology. Included in this total are additional manuscripts that are indirectly related to the analyses of Apollo 17 samples, but use the Apollo 17 data to ascertain the origin and evolution on the Moon. Within that period of time, fragments of approximately 230 samples were used in research, with at least 68 samples used in geochronological studies.

As outlined in Table 3, if 215 scientific manuscripts (1.25 x Apollo 17) are to be produced per mission (breakdown are listed per discipline), approximately 350 unique samples are needed, requiring approximately 130 kg of samples. This mass is equivalent to a volume of approximately 4350 cm³. This volume of sample could be accommodated within 3 sample containers similar in size to the ALSRC. Because each ALSRC has an average mass of 7.8 kg, this increases the minimum return mass to 153.4 kg. If core tubes are used to sample regolith an additional 410 g/core tube (4 cm diameter, 42 cm in length) must be considered, assuming Apollo 17 tube masses. For example, Apollo 17 return ~7.5 kg of core samples in seventeen core tubes (Apollo 17 Preliminary Science Report, 1973), making the minimum sample return mass ~138 kg and the total return mass (samples + containers) of ~170 kg.

An alternative method for estimating required sample mass involves analyzing the relationship between sample type and mass, and other variables such as fulfilling the lunar architecture science objectives (Table 4), sample return approaches from Apollo 17, characteristics of lunar samples, the scientific requirements for sample diversity, and sample requirements for analyses that are needed to fulfill science objectives (for example see the requirements for the analysis of Sm-Nd in Figure 1). This analysis is illustrated in Table 5 with a list of limitations and assumptions. The analysis includes the return of relatively homogeneous hand samples such as basalts and clast-free impact melt rocks, heterogeneous, monomict and polymict breccias, rake samples, unsieved regolith, and drill core. The proportions of these samples will be site-dependent with basalts decreasing in abundance at the lunar poles. Further, it does not include the sampling and return of polar hydrogen-rich deposits that might occur in permanently shadowed regions of the Moon. Based on this analysis approximately 150 kg of lunar samples are needed to fulfill the science for a mission. The result of this calculation agrees well with the calculation based on scientific output, and requires approximately 180 kg of return capability for lunar samples and containers (including core tubes).

Sample Mass Required for the Preservation of Lunar Volatiles: The mass calculations made in the previous analyses assumed a traditional Apollo model for the types of lunar materials that would be returned. However, several of the science objectives defined in the Lunar Architecture and further evaluated for their scientific importance by the LEAG and the NAC may not be fully achieved with the return of these types of geological materials (Table 4). In particular, mGEO12 (Characterize lunar volatiles at the poles to reveal the nature of impactors on the Moon), mGEO13 (Characterize transport of volatiles to understand the processes of polar volatile deposit genesis and evolution) and mGEO14 (Characterize resources to understand their potential for exploration utilization) require special sample containment and preservation. Furthermore, if the lunar outpost is sited at one of the poles in proximity to volatile-element deposits in permanently shaded craters, sampling these types of lunar materials and maintaining them in a very cold environment will be a high priority.

TABLE 4. Lunar science objectives defined in the Lunar Architecture and ratings [x] of scientific importance as defined by the LEAG and NAC. Rating is based on a scale of 1 (low)-10 (high).

mGEO1: Use passive seismic data to determine the internal structure and dynamics of the Moon to constrain the origin, composition, and structure of the Moon and other planetary bodies. [10]

mGEO2: Determine the composition and evolution of the lunar crust and mantle to constrain the origin and evolution of the Moon and other planetary bodies. [10]

mGEO3: Characterize the global lunar geophysical state variables to constrain the origin, composition, and structure of the Moon and other planetary bodies. [9]

mGEO4: Determine the origin and distribution of endogenous lunar volatiles as one input to understanding the origin, composition, and structure of the Moon and other planetary bodies. [7]

mGEO5: Characterize the crustal geology of the Moon. [9]

mGEO6: Characterize the impact process on the Moon and other planetary bodies. [9]

mGEO7: Characterize impact flux over the Moon's geologic history, to understand the impact history of the inner solar system. [10]

mGEO8: Study meteorite impacts on the Moon to understand the early Earth history and origin of life. [7]

mGEO9: Study the lunar regolith to understand the nature and history of solar emissions, galactic cosmic rays, and the local interstellar medium. [9]

mGEO10: Determine lunar regolith properties to understand the surface geology of the Moon and other planetary bodies. [7]

mGEO11: Characterize the lunar regolith to understand the space weathering process from different crustal environments. [6]

mGEO12: Characterize lunar volatiles at the poles to reveal the nature of impactors on the Moon. [8]

mGEO13: Characterize transport of volatiles to understand the processes of polar volatile deposit genesis and evolution. [7]

mGEO14: Characterize resources to understand their potential for exploration utilization. [7]

mGEO15: Provide documentation and curatorial facilities and technologies to ensure contamination control for lunar samples. [10]

mGEO16: Provide sample analysis instruments on the Moon to analyze selected lunar samples before returning them to Earth. [9]

The assumption in this analysis is based upon: (1) the need to minimize phase changes in volatile compounds potentially preserved in the permanently shaded regions of lunar craters. (2) accommodate regolith core samples that may be collected in or adjacent to such environments, (3) ensure that samples are not exposed to terrestrial atmosphere or spacecraft cabin gases, and (4) container mass and dimensions are based on past and current sample preservation technologies such as the Special Environmental Sample Containers (SESC) used during the Apollo Program and refrigerator-freezer units currently used on the Shuttle for moving samples back and forth to the International Space Station. As shown in Table 2, the SESC has a mass of 360 grams, length of 21 cm, an outer diameter of 6.1 cm, and is capable of holding 360 cm³ of regolith (approximately 540g). 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 SESC's. The total mass of preserving environmentally sensitive samples is 36.25 kg and includes 9.75 kg of sample, 6.5 kg of sample container, and a 20 kg freezer.

TABLE 5. Relationships among sample type, mass, science rationale (LAT,PSS), and analytical techniques. All sample return fulfills LAT objectives mGEO15 and mGEO16.

Sample category and lithology	Science Rationale	Mass(g)	Samples (n)	Total Mass(kg)	Analytical Approach ¹
A Large Hand samples					
A1 Homogeneous rocks		500	40	20 kg	
Basalts	mGEO1,2,3,4,7				1,2,4,6
Clast-free impact melt rocks	mGEO6,7,8				1,2,4,6
A2 Breccias	mGEO1,2,3,4,5,6,7,8,9	5000	18	90 kg	1,2,4,6
polymict breccias					
monomict breccias					
B Rake Samples	mGEO1,2,3,4,5,6	0.5	20000	10 kg	1,2,6
C Unsieved Regolith Samples	mGEO4,5,6,9,10,11,12,13	2000	5	10 kg	1,4,5,6,7
D Drill Core	mGEO4,6,9,10,11,12,13	700/core	24 cores	16.8kg	1,3
TOTAL				146.8 kg	

Assumptions used in estimating mass.

(A1) Basalt samples from A17 range in mass from 0.57 to 8110 grams. Thirteen basalts had a mass greater than 400g. As illustrated in Figure 1, for most lunar rocks a single Sm-Nd analysis requires between 20-2000 mg of useable material. Based on samples returned by Apollo mare basalts have grain sizes that range from 5 cm³ to near glass. For petrologic and geochemical studies, to analyze a representative samples with a grain size of 100 mm³ a mass of 500 grams must be collected (Larsen, 1938; Wager and Brown, 1960). Following the approach of Ryder and Schuraytz (2001) approximately 50-100 grams of mare basalt may produce a representative sample for a single analysis..

(A2) Apollo 14 breccia 14321, "Big Bertha" is an example of the usefulness of large breccias. This sample has a mass of 9 kilograms. Samples from Apollo 17 range in mass from 1 to 3640 g.

(B) Using the Apollo 15 collection of 4-10 mm fragments for calibration, the average particle mass is 0.2 g (mean model diameter = 5 mm). Reasonable average particle mass for 4-20mm fragments is estimated to be 0.5 g (mean model diameter = 7mm). Approx. 2000 particles are needed to have a 90% probability of detecting a population present at the 0.1% level (2 particles in 2000). At an average of 0.5g per particle, 2000 particles will have a mass of 1000 g.

(C) Estimates based on previous spectral, physical properties, and ISRU experiments.

(D) Sample volume of 4-cm drive tube is approximately 470 cm³. Average regolith density is approximately 1.5 g/cm³. Apollo 17 collected 6 cores (in 17 core tubes) with a maximum depth of 292 cm. Total weight of the Apollo 17 core samples was 7.3 kg (Apollo 17 Preliminary Science Report, 1973). We doubled the mass of the Apollo 17 core samples based on the conclusion that core analyses may be extremely valuable to outpost construction. Also assumes 100% recovery.

¹Analytical Approaches: (1) petrology and mineralogy, (2) geochronology, (3) solar history (4) spectral studies (5) physical properties, (6) geophysical properties, (7) ISRU.

Sample Return and Lunar Exploration

From the perspective of returning samples, a key advantage of human missions to the Moon is the ability to assess the local geologic environment and to thus place sample materials within context of the site geology. Humans can facilitate the collection and documentation of a wide variety of materials ranging from regolith scoop samples to cores to irregularly shaped and large rocks. Whereas robotic sample returns might be constrained in design to collect simple samples and minimal sample mass to address specific and limited science objectives, human missions to an outpost can exploit the tremendous capabilities of the astronaut field geologist to collect suites of samples that can most effectively be used to address a wide range of scientific and engineering objectives. The scientific, engineering, and public engagement returns on investment in sample collection and return to Earth will be many fold, as they were with the Apollo Program.

Findings:

- (1) On the basis of these analyses, surface operations would conceivably have the capability of sampling at least 800 kg of lunar material per sortie mission.
- (2) The lunar exploration architecture should accommodate **150 kg** of traditional geological samples for return to Earth, not including sample containers and environmentally sensitive samples. This mass estimate is based on considering previous lunar surface operations that may come the closest to approximating future exploration missions, known rock types, contributions of sample size and lithology to previous lunar science investigations, sampling of diverse lunar rock types, sample mass required for analytical measurements, and major science objectives identified by the LAT.
- (3) This geological sample mass exceeds that of the Apollo 17 mission by only 35%. It is exceedingly important that the sample return capability of this architecture exceeds that of the Apollo Program to demonstrate a progression of capability beyond that of Apollo.
- (4) Using the Apollo sample containers as a guideline, container mass needed to accommodate 150 kg of lunar samples is approximately **30 kg**. This includes 3 ALSRC and drill core. Assuming that all samples and sample containers could be accommodated into 3 “ALSRC”, 4800 cm³ of volume are required for the return of traditional lunar samples. Decreasing the sample container mass without compromising the samples through contamination should be explored.
- (5) The science requirements also dictate the need to preserve certain types of volatile-bearing samples beyond capabilities available during the Apollo Program. To accommodate the preservation of these samples, an **additional 36 kg** of samples and containers need to be included in the architecture capability.
- (6) It is essential that mission operation requirements build in capabilities for the future exploration of the solar system – current nominal return mass requirement of 100 kg will not meet basic needs of either human exploration or science over the projected lifetime of the CEV and VSE. On the basis of our analysis, a total mass capability of 250 to 300 kg is appropriate to accommodate all materials (biological, geological, engineering) and associated containers from the lunar surface.

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David Kring of the Lunar and Planetary Institute provided the calculations that are illustrated in Figure 3. Marc Norman of the Australian National University provided the initial calculations that are the basis for Table 6. We appreciate their contributions.

List of Acronyms Used In Text

AAP	Apollo Applications Program
ALSRC	Apollo Lunar Sample Return Container
CAPTEM	Curation and Analysis Planning Team for Extraterrestrial Materials
CEV	Crew Exploration Vehicle
CSVC	Core Sample Vacuum Container
EVA	Extra-Vehicular Activity
FAN	Ferroan Anorthosite
GASC	Gas Analysis Sample Container
ISS	International Space Station.
LEAG	Lunar Exploration Analysis Group
LAT	Lunar Architecture Team
NAC	NASA Advisory Council
PSS	Planetary Science Subcommittee
SESC	Special Environmental Sample Containers
VSE	Vision for Space Exploration