Appendix S

EVA Geologic Sample Mass

For the Constellation Program, LPI conducted an analysis of EVA geologic sample mass and presented the results to a NASA Advisory Council Meeting (Kring, 2007c). The results were re-released for the Artemis program (Kring, 2020b). The objective of the study was to determine the mission sample mass returned to Earth as a function of EVA time. This is information was needed to size the lunar ascent vehicle and crew return capsule. We had a boundary condition: This was to be a mission-level assessment to provide a baseline for ascent vehicle requirements. Station-level and traverse-level assessments would need to be made separately to provide baselines for crew and surface vehicle requirements and the development of suitable operational protocols. The analysis began with a review of Apollo lunar sample return data (**Table S1**).

Table S1. Lunar sample inventory. From Kring (2007c).

Mission	Mass (kg)	Number	EVA Length (hr)	Distance (km)
Apollo 11	21.5	58	2.2	0.5
Apollo 12	34.4	69	7.6	2.0
Apollo 14	42.3	227	9.2	3.4
Apollo 15	77.3	370	18.3	23.0
Apollo 16	95.7	731	20.1	20.7
Apollo 17	110.5	741	22.0	31.6
Total Apollo	382.0	2196	89.0	81.0
Soils	80	167		
Breccias	133	79 over 300 g each		
Basalts	80	134 over 40 g each		
Cores	20	24 holes (total length is 15 m with 52 segments)		
Other	69	Mostly small breccias		
Luna 16	0.101	35 cm core		
Luna 20	0.050	27 cm core		
Luna 24	0.170	160 cm core		
Total Luna	0.321			

The data were then reviewed in the context of evolving mission capability, from the Apollo 11 G-type mission (land and return, to the Apollo 12 and 14 H-type missions (deploy ALSEP, two EVAs, and longer surface duration), to the Apollo 15, 16, and 17 J-type missions (to a complex geologic terrain and with EVAs supported with an unpressurized rover) (**Fig. S1**). The analysis showed (**Fig. S2**) that the sample mass per EVA hour per crew member was a constant in the Apollo 12 through 17 missions. The exception is Apollo 11 when the Commander famously filled the sample box with nine scoops of additional soil, providing an invaluable sample (10084; ~10 kg) for a broad range of scientific and *in situ* resource utilization (ISRU) studies. (Sadly, lunar curatorial staff report that a picture of the regolith filled box does not exist.)

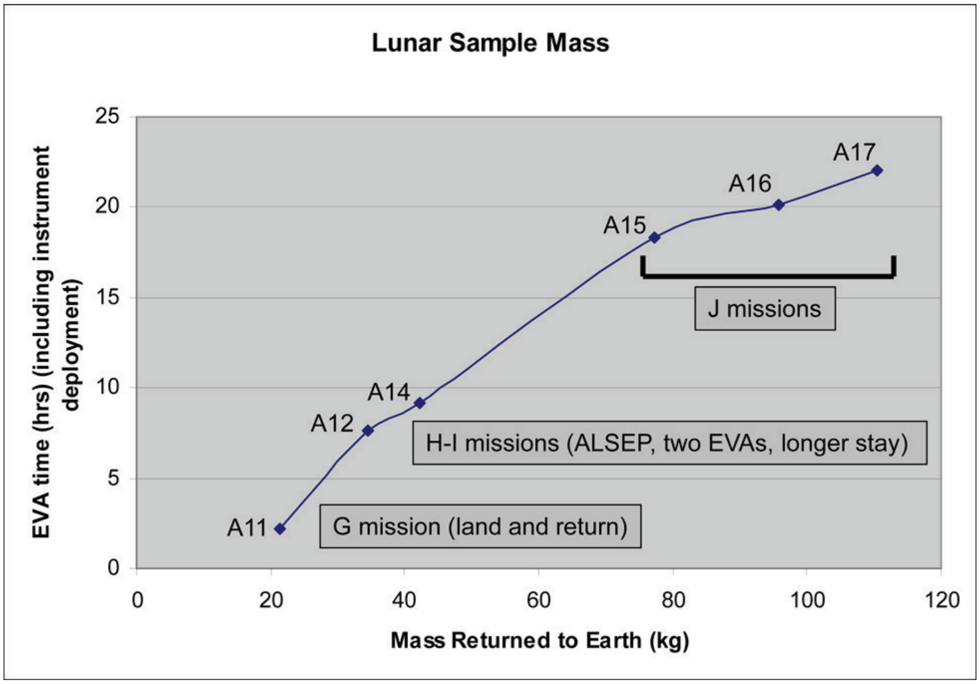

Figure S1. *Mass of geologic samples returned to Earth plotted as a function of EVA time for each of the Apollo surface missions. From Kring (2007c).*

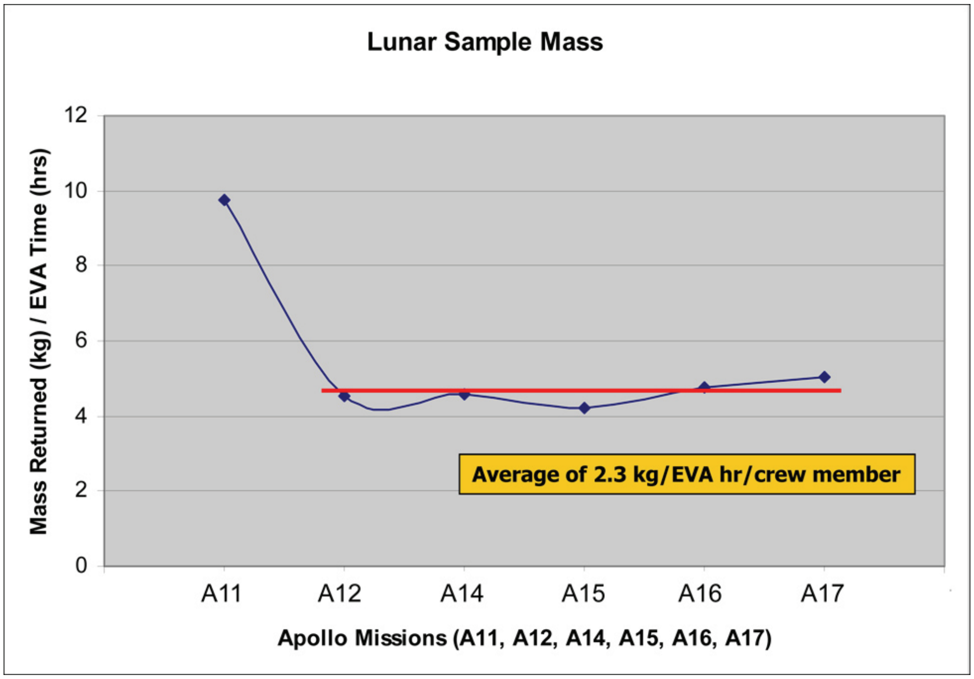

Figure S2. *Geologic sample mass per EVA hour per crew member for each of the Apollo lunar surface missions. From Kring (2007c).*

The LPI finding was not a model result. Rather, it was drawn from actual lunar surface mission data and could not be disputed. The near constant average value is 2.3 kg/EVA hr/crew member, although, if one scrutinizes the data, one detects a 20% increase in the sampling rate between the Apollo 15 and 17 missions. The near-constant sampling rate occurred regardless of the terrain; *e.g.*, mare (Apollo 12), highland (Apollo 14, 16), and a juxtaposition of mare and highland materials (Apollo 15, 17). Thus, a value of 2.3 kg/EVA hour/crew member could be reliably used to predict geologic sample mass for the Constellation Program. The method was incorporated into a recommendation by the Curation and Analysis Planning Team for Extraterrestrial Materials (Shearer *et al.*, 2007).

The result posed a problem, because the anticipated ascent mass for the lunar lander, then called Altair, was of order 10 kg. Based on the 2007 finding, efforts were initiated to increase the return mass capability. As of December 2008, it was 100 kg with a goal of reaching 250 kg. That was likely still too low a mass for ≥14 day missions being planned for Constellation, but the value was moving in the right direction because scientists and engineers were communicating together.

That average value can be usefully applied to estimate the sample mass of Artemis missions.
For example, a 6.5 day surface mission with two astronauts (*e.g.*, NASA, 2019b) conducting 24 hours of EVA will have an estimated sample mass of 110.4 kg, comparable to that from the Apollo 17 mission.

We note that one of the findings of the Artemis III Science Definition Team (NASA, 2020c) is "The high-priority Investigations described in this report require the collection of a diverse set of sample types, collected from geographically diverse locations broadly representative of the complex geology of the south polar region, and a total return sample mass from the Artemis III south polar site exceeding the average return mass for the Apollo missions." But as the report also notes, the requirements for the Artemis III Human Landing System is to "return a minimum of 35 kg (or a goal of 100 kg) of scientific payloads (*e.g.* samples, inclusive of tare) to lunar orbit for return to Earth (NASA, 2019c). Tare is expected to consume 9 kg of the upmass allocation in the minimum case, and 20 kg in the goal case." That corresponds to a minimum scientific upmass of 15 to 26 kg. A 80 to 91 kg scientific mass goal approaches a suitable range for a first mission, although that value depends on the other sources of mass that will need to be returned to Earth. Geologic samples may not be the only items to be returned to Earth. The lander and ascent vehicles for Artemis missions beyond Artemis III have not yet been selected and, thus, their capabilities are not yet known. There also needs to be a corresponding mass capability in the Orion crew vehicle.

A second method for estimating geologic sample mass is available. We refer readers to Shearer *et al.* (2007) for those details and a brief discussion of the method as it might be applied to Artemis (Kring, 2020c).

It is important to understand that well-trained astronauts familiar with mission objectives will collect the samples needed to address those objectives. They will not unnecessarily collect excess sample mass. Field geologists are faced with similar mass limitations when conducting expedition-scale studies. For example, I was part of a team studying the Triassic-Jurassic boundary on the Pacific coast of the island Haida Gwai. It was a remote location accessed by helicopter, so we had a helicopter-limited sample return constraint. Assuming traditional best practices are followed, a well-trained astronaut who is familiar with mission science objectives and sample mass restrictions is only going to collect the samples needed to meet mission science objectives. If a well-trained astronaut, flown all the way to the Moon collects a sample, then that sample should be returned to Earth. It has already been high-graded.

This issue sometimes becomes confused if scientists involved are not field geologists and only have the experience of lunar mission simulations. In a lunar mission simulation, we may have multiple stations along a lava flow, for example, to practice the crew's and the science support team's capabilities to assess sampling options in the context of a station location, how the sample is collected, and whether it is the best sample to meet mission science objectives. During a lunar mission, however, a well-trained astronaut is not going to collect multiple samples of the same lava flow unless there is a scientific reason to do so (*e.g.*, collecting ejecta from craters of different sizes to determine the thickness of an underlying lava flow).