A Carbonaceous Chondrite Based Simulant of Phobos

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ABSTRACT

In support of an ESA-funded concept study considering a sample return mission, a simulant of the Martian moon Phobos was needed. There are no samples of the Phobos regolith, therefore none of the four characteristics normally used to design a simulant are explicitly known for Phobos. Because of this, specifications for a Phobos simulant were based on spectroscopy, other remote measurements, and judgment. A composition based on the Tagish Lake meteorite was assumed. The requirement that sterility be achieved, especially given the required organic content, was unusual and problematic. The final design mixed JSC-1A, antigorite, pseudo-agglutinates and gilsonite. Sterility was achieved by radiation in a commercial facility.

INTRODUCTION

In support of an ESA-funded concept study considering a sample return mission, a simulant of the Martian moon Phobos was needed. A premise of the concept mission was Phobos is likely to have accumulated material ejected from Mars by hypervelocity impacts. As the mission concept has implications for planetary protection, the NASA Office of Planetary Protection agreed to fund development of the required simulant as part of a collaborative effort with ESA.

Using the logic of Rickman et al. (2013a) four characteristics were needed to specify the simulant: composition, size distribution, shape distribution, and packing density. There are no samples of the Phobos regolith, therefore none of the four characteristics are explicitly known for Phobos. Because of this, specifications for a Phobos simulant must be based on spectroscopy, other measurements, and judgment.

There were two additional requirements derived from experimental design. First, three different size fractions of the simulant were needed. Second, the simulant must be sterile when each individual test began. This presented multiple technical challenges in the design, manufacture and use of the simulant.

COMPOSITION

In a review of available information about the surface of Phobos (Pearson et al., 2015) a fundamental decision was made that the formation of Phobos regolith is likely to be akin to similar regolith forming processes on other small Solar System bodies (Ramsley and Head, 2013). Spectra from cameras and spectrometers on board Phobos 2 showed that the Phobos surface was spectrally heterogeneous (Murchie and Erard, 1996) and showed regions that could be geologically defined; the areas around the satellite's largest crater, Stickney, appeared spectrally bluer than the remaining redder surface. HST-FOS (Zellner and Wells, 1994) and NASA IRTF (Rivkin et al, 2002), also identified these blue and red units, indicating two spatially distinct units. The data indicated the two units were compositionally similar to P- and D-type asteroids respectively. These asteroid types both have low albedos with featureless, red spectra, possibly due to the presence of organic compounds. Although no meteorites have been linked directly to P-type asteroids, an example of a D-type asteroid is believed to be the Tagish Lake meteorite (Brown et al., 2000).

The meteorite is highly heterogeneous, both mineralogically and texturally. Brown et al. (2000), Zolensky et al. (2002), and Blinova et al. (2009) provide mineralogical and textural information, though not modal abundance, for the Tagish Lake material. The most abundant minerals in the meteorite appear to be phyllosilicates (Mg-rich serpentine, saponite), Mg-rich olivine, magnetite, Fe-Ca-Mg carbonates, and Fe-Ni sulfides. The organic carbon abundance of the meteorite is on the close order of a percent. A review of its organic chemistry is provided by Pizzarello et al. (2006).

Assuming the Tagish Lake meteorite provides guidance was quite distinct from assuming it provides a detailed template to understand the surface of Phobos. The surface of Phobos is likely to have been meteoritically gardened in the same way as the Moon, with consequent large-scale replacement of meteoritic or hypothetical asteroidal textures and minerals by vesicular glasses (Christou et al., 2014; Fraeman et al., 2014). Further, the level of certainty linking the composition of the surface of Phobos with the composition of the Tagish Lake meteorite is not overwhelming. Further, there were significant practical technical and cost constraints on what could be done in manufacturing a simulant, especially with respect to replicating textures (Rickman et al., 2013b). Finally, the tests for ESA using the simulant were not expected to be sensitive to most textures.

All components in the design had to be reasonably available in sufficient mass, at an affordable cost, and in a timely manner. It was also desired that they be both internally consistent and as well characterized as practical. These would greatly simplify subsequent work. Finally, the components and their mixtures had to be safe to handle. The compositional design of the Phobos simulant agreed on by the team reflects the above considerations and is shown in Table 1.

Table 1. Composition of Phobos Simulant

Component	**Wt. %**
JSC-1A	46
Antigorite	35
Pseudo-agglutinate	15
Gilsonite	4

JSC-1A was used to provide a glassy and microcrystalline fraction of basaltic composition. It has the advantage of being extremely well known and well characterized within the community of user's experimenting with lunar simulants.

Commercially available antigorite from a Canadian producer was used to provide a phyllosilicate. A major consideration in selection of this material was the requirement that it be certified as free of asbestos. The material was checked at the United States Geological Survey and confirmed to be asbestos-free.

The pseudo-agglutinates were produced by Zybek Advanced Products of Boulder, CO, under contract with the United States Geological Survey. This was done as part of the simulant development research led by a team at MSFC (Weinstein et al., 2012; Rickman et al., 2013b). The starting material for this component was a noritic mill-sand produced by the Stillwater Mine of Nye, Montana. The pseudo-agglutinate provides a highly vesicular, glassy component with mineral grains of varying sizes, which replicates many of the textures found in lunar agglutinates. The synthetic material lacks the nano-phase iron characteristic of the lunar material, hence the term pseudo-agglutinate.

Gilsonite, *sensu stricto*, is an naturally occurring asphaltite produced from vein deposits near the Colorado – Utah border. The deposits are large and have been mined for approximately 100 years, with large remaining reserves (Boden and Tripp, 2012). Asphaltite is used as it chemically approximates the complex structure of the organic materials present in carbonaceous chondrites, such as the Tagish Lake meteorite. Chondritic organic species are predominantly insoluble macromolecules consisting of polycyclic aromatic cores linked by aliphatic and functionalised (N, O, S-bearing) species. Terrestrial counterparts are kerogens, but kerogens are heat sensitive (see below), are not generally available as pure, well-characterized and uniform products. Asphaltites represent a good compositional approximation, are less heat sensitive than other alternatives, and the asphaltities are available as pure, well characterized and uniform products. Gilsonite is also brittle, which is important in the simulant manufacturing process. Brittle materials are easy to mill to the necessary size distribution (see below) and to handle or mix with other components without problems such as caking. Finally, gilsonite has a long track record of use and is known to be safe with respect to human exposure.

STERILIZATION

The requirement that the simulant be sterile prior to each experimental test presented a significant design challenge, especially given the need for the required organic component. The biologists working on the experiment needing the simulant initially suggested that sterilization should be achieved by heating the simulant in the experimental sample chamber to reach an internal temperature of 170 °C for 1 hour, or 150 °C for 4 hours, or 140 °C for 6 hours. Monitoring internal temperature would need a probe, which could not remain in place during the subsequent experiment. Therefore, the temperature probe would have to be withdrawn after heating, which would disturb the packing, another important experimental parameter. To assure proper heating without a probe the target temperature would have to be held for substantially longer than the minimum time, which would become a logistical problem. Also, there was a concern that at high enough temperatures the asphaltite would soften and effectively glue the other material into a solid once cooled. These problems could be addressed by either using an asphaltite with a higher melting point or sterilizing using either radiation or chemicals.

Higher melting point asphaltites, grahamite and ipsomite, do exist and have previously been mined (Carman and Bayes, 1961; Cornelius, 1987). Production in the United States, which ended ~90 years ago, was from Oklahoma and West Virginia. According to Brian J. Cardott of the Oklahoma Geological Survey (pers. comm. April 14, 2015), it is likely that sufficient ipsomite, an asphaltite with a very high softening temperature, can still be culled from the old mine dumps for the immediate needs of the ESA experiments. However, this is a clearly limited supply. Also acquisition would be exceedingly expensive per pound, as it would require someone to hike into a forested region and backpack the material out. The eponymous Grahame mine in West Virginia is now part of a State park and no material is available from that source. While there are non-domestic producers of asphaltites roughly equivalent to gilsonite, sources for asphaltites with higher softening temperatures were not found. Without an asphaltite with a high enough softening temperature, thermal sterilization was judged to be an impractical option.

Chemical sterilization was also considered. However, the high surface area of the finer simulant, the vesicular nature of components and the organic fraction make chemical sterilization impractical.

Sterilization by radiation was finally chosen as the best solution. It is a commercially available service, and relatively inexpensive. One of our team, S. Wilson, uses it for production of sterile soil standards. The process will not damage the constituents of the simulant. In practice, the simulant is split into aliquots at the producing facility. Each aliquot is sealed in a plastic bag sized to insert into the experimental sample chamber. The sealed bags are then irradiated and then shipped to the experimental facility.

PARTICLE SIZE DISTRIBUTION

Particle size distribution for Phobos has not been directly measured and the available imagery is not sufficient to directly establish particle size characteristics. Therefore, it is prudent to make multiple size fractions of the simulant, should particle size be a significant experimental parameter. For the ESA experimental needs three size fractions were made of the Phobos simulant: Fine, <425 µm, Medium, 1.2 to 3.3 mm, and Coarse, >5. Indirect methods provided, in part, the rationale for these size ranges.

Thermal inertia is related to particle size distribution (Gundlach and Blum, 2013). These authors provide an estimate of the mean particle size of approximately 1 mm for Phobos. The accuracy of is estimate is affected by the measured thermal inertia of the object, the surface temperature of the body during observation and the material properties of the regolith. Accuracy specifically for Phobos is not known, but no better than a factor of two according to Gundlach and Blum. Basilevsky et al. (2014) suggest there could be a depletion in regolith components of grain size < 300 µm. Ramsley and Head (2013) predict a minimum size of 3 mm, since impact ejecta of sizes below this are rapidly decelerated and fall into Mars' atmosphere, rather than re-colliding with Phobos.

PARTICLE SHAPE DISTRIBUTION

Particle shape in the simulant is controlled by the duration of milling and the grinding media present.

With the exception of a few particles from Itokawa (Tsuchiyama et al., 2011), the only relevant and directly measured particle shapes in the µm to cm size regime are those for lunar samples. The lunar particles exhibit highly variable shapes ranging from spherical to extremely angular (Heywood, 1971). They are generally elongated and subangular to angular (Rickman, 2012; Kiekhaefer et al., 2013). Demidov and Basilevsky (2013) measure average boulder aspect ratio of 0.6 in two dimensions for Apollo surface panoramas. Itokawa and Eros boulders, at much larger sizes, will be eroded by collisions and possibly thermal cycling. They have shape properties that appear independent of size in the ~10 cm to ~100 m range. They also have typically highly elongated shapes but with a wide variation of major axis ratios b/a from 0.25 to 1. The mean b/a = 0.7, with a standard deviation of 0.15 (Michikami et al., 2010). Impact experiments produce axis ratios a:b:c typically of $2:\sqrt{2}:1$ (Capaccioni et al., 1984). The 2-D shapes provide a close match to the asteroid shape distributions. The limited number of boulders above the resolution limit of available global images means a comparison with Phobos data has not yet been performed, but given the similar evolutionary processes we expect to have a similar wide range of shapes and textures. The regolith analogue should therefore have a wide range of shapes and subangular to angular textures to be representative of the expected surface.

PACKING DENSITY

Packing density on the surface of Phobos is poorly constrained. It can crudely be estimated from density and composition estimates. With the small gravitational forces and, hence, small internal pressures, there will be relatively high porosities are possible (e.g. the C-type asteroid Mathilde has a mean density of just 1.3 g cm-3 (Yeomans et al., 1997), implying a porosity of about 40%). The total porosity of Phobos (micro- & macro-porosity) has been estimated at between 12-30% (Thomas et al., 2011, Andert et al., 2010). However, this porosity is greatly increased if the interior is a rubble pile structure (Michel et al., 2009). Estimates of macroporosity of the regolith range from 40-50% to 15% based on rotational characteristics (Rambaux et al., 2012) and likely compositional analogues (Rosenblatt, 2011) respectively. Microporosity adds an additional porosity measurement, and for Phobos this has been estimated based on likely compositional analogues. Microporosity has been estimated to represent between 10 and 40% grain volume for a carbonaceous chondrite-like analogue (Consolmagno et al., 2008; Rosenblatt, 2011). Porosities of carbonaceous chondrites have been measured at 23% (Macke et al., 2011), however it should be noted that this is the porosity of a solid fragment (Phobos interior) and not an unconsolidated powder (surface regolith).

Very importantly, packing density is an experimentally adjustable parameter. How the simulant is handled can change the density at the time of measurement by relatively large amounts.

AVAILABILITY

Information about the design and performance of the simulant, “fit for purpose,” can be obtained from D. Rickman, doug.rickman@nasa.gov. Given the likely interest within the community, especially given the simulant is both a Phobos and a carbonaceous chondrite simulant, more simulant was manufactured than was needed by the ESA-motivated work. Availability and purchase of this material can be ascertained by contacting Steve Wilson, swilson@usgs.gov.

CONCLUSION

A simulant of the Martian moon Phobos has been created. Lacking samples of the Phobos regolith or a surface lander, spectroscopy and informed judgment has been used to guide the design of the simulant. The Tagish Lake meteorite was taken as an approximate guide for the target composition, adjusted for the effects of space weathering at the surface of the moon. The design calls for a mixture of JSC-1A, antigorite, pseudo-agglutinate and gilsonite. JSC-1A and the pseudo-agglutinate provide glass with microcrystals and mineral grains. The pseudo-agglutinate provides vesicular particles, providing micro-porosity, and entrained grains of relevant minerals. Asbestos-free antigorite from a commercial source was used to represent the phyllosilicates found in the meteorite. Gilsonite is used to emulate the complex organic constituent.

The requirement that sterility could be achieved, especially given the required organic content was unusual and problematic. Sterility is achieved in this simulant by radiation in a commercial facility.

Particle size characteristics for the simulant is based largely on estimates for the Phobos regolith using thermal inertia adjusted by prudent respect for the limitations of the estimates. The desired particle shape characteristics are taken from the lunar regolith, data from hypervelocity impact studies, and observed boulders on rocky planetary surfaces.

Packing density on the surface of Phobos is poorly constrained. But as it is a parameter under experimental control over a wide range of values, it was not a major design constraint.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support for this work by the NASA Planetary Protection Program and the support of the European Space Agency, which has funded a study entitled "Feasibility studies and tests to determine the sterilization limits for sample return planetary protection measures, SRE-F/2014.021/SOW_Feasibility Sterilisation, 2014", under Contract 4000112742/14/NL/HB.

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