Scientific requirements for a possible Mars Science Laboratory sample cache[1]

Christopher P. McKay[2] (Chair), David W. Beaty[3], Catherine A. Conley[4], Joy A. Crisp[3], David J. Des Marais[2], John P. Grotzinger[5], John S. Karcz[6,2], Lawrence G. Lemke[2], Steven W. Squyres[7], Carol R. Stoker[2], and Allan H. Treiman[8]

September 2007

NASA is currently considering providing the 2009 Mars Science Laboratory (MSL) rover with a container for caching geological samples as a means to simplify a future Mars Sample Return (MSR) mission. At the minimum, a cache must perform two tasks: accept samples of some sort acquirable by the host rover and provide some means by which a future mission can retrieve it or its contents. The cache would provide MSR the option of returning a set of known, previously characterized samples. MSL has the potential to cache a particularly diverse set of samples due to its anticipated endurance and extensive analytical capabilities. MSL is designed to last for one Mars year and to be able to drive 20 km (Vasavada et al. 2006).

The proposed cache would need to be designed to be an unobtrusive payload on MSL, in terms of its demands on both the spacecraft's systems and operations. It would be more tightly constrained than previously proposed caches due to the late stage in development at which its addition to the rover is being considered. Previous caching mission concepts included equipment specifically dedicated to collecting and storing samples. The Athena instrument suite, for instance, originally included a coring drill and a container for 104 individually held samples (Squyres et al. 1998).[9] Unfortunately, while a sample container may be added to MSL, dedicated sample acquisition tools—such as a coring drill—may not. Caching would need to employ—unmodified—the systems intended to acquire samples for MSL's onboard instruments.

---

[1]NASA Ames Research Center document A9SP-0703-XR04. Suggested citation: McKay, C. P., Beaty, D. W., Conley, C. A., Crisp, J. A., Des Marais, D. J., Grotzinger, J. P., Karcz, J. S., Lemke, L. G., Squyres, S. W., Stoker, C. R., & Treiman, A. H. 2007, Scientific requirements for a possible Mars Science Laboratory sample cache, posted by the Mars Exploration Program Analysis group at `http://mepag.jpl.nasa.gov/reports/MSL_cache_sdd.pdf`. This document was requested by NASA's Associate Administrator for the Science Mission Directate.

[2]NASA Ames Research Center, Moffett Field, CA 94035

[3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109

[4]NASA Headquarters, Science Mission Directorate, 3X63, 300 E Street Southwest, Washington, D.C. 20546

[5]Division of Geological and Planetary Science, California Institute of Technology, Pasadena, California 91125

[6]SETI Institute, 515 North Whisman Road, Mountain View, CA 94043

[7]Department of Astronomy, Cornell University, Ithaca, NY 14853

[8]Lunar and Planetary Institute, 3600 Bay Area Boulevard, Houston, TX 77058

[9]The drill and container were not flown with the other Athena instruments on the 2003 Mars Exploration Rover missions.

The cache would be located on the exterior of the rover and would accept samples delivered by MSL's Sample Acquisition/Sample-Processing and Handling (SA/SPaH) system. It would hold several samples, collected as desired over the course of MSL's traverse. The cache would remain attached to MSL until possible retrieval, which even optimistically would not occur until several years beyond the anticipated lifetime of MSL. After removing the sample container from MSL, the MSR rover would place it in the MSR ascent stage for return to Earth.

Inclusion of the cache on MSL would not imply a commitment by a future MSR mission to retrieve it. That decision would not be made until later—perhaps well after MSL's mission is complete—based on the perceived value of the contents of the cache relative to samples obtainable from other sites. If retrieved, we do not anticipate that the cached samples would comprise the totality of the returned set. They would likely be complemented by fresh samples acquired during MSR.

An important concern is how a desire to maintain the accessibility of the cache for retrieval by MSR might influence strategic MSL mission planning, such as site selection and high-level traverse decision making. Given the secondary-payload nature of the cache on MSL, we suggest that it should not be a factor in such decisions—they should be based on the risk to, and the existing primary science priorities of, MSL. The eventual accessibility of the cache should instead be factored into the decision by MSR of whether to retrieve the cache.

Given that a future team undertaking MSR would only choose to retrieve and return the cache if its contents were deemed to be of sufficient value, we have assembled a small set of scientific requirements intended to make the contents as scientifically attractive as possible under the constraints on the cache due to schedule, budget, MSL capabilities, and expected MSR capabilities.

In §1 we list noteworthy constraints which apply to the cache. A discussion of the scientific objectives for the cache follows in §2. The section starts by reviewing the high-level goals of Mars sample return in general, and then narrows down to consider—in §2.1—the set of objectives toward which the contents of this particular cache would be best suited. We then present in §3 a small set of requirements for the cache—chosen to maintain the suitability of the samples for those applications—along with a brief rationale for each.

1. Constraints

Two precepts have been imposed on the cache: it must be "minimalist," and it must impose no new requirements on MSL other than those strictly necessary for its accommodation. Due to the late date at which the cache has been proposed and the limited funds available for its development, fabrication, and testing, its scope and design are tightly constrained. It must be designed to take best advantage of MSL's capabilities, rather than to collect samples satisfying all of the goals of a dedicated, purpose-built sample-return mission.

The cache and the samples it contains will need to tolerate a long, uncontrolled stay on the surface of Mars. A sample return project has not yet started. Even given a fast-paced project, it is likely that the cache would spend at least six Earth years on the surface of Mars, roughly triple the one Mars year design life of MSL. A conservative plan must assume that the cache will spend a significant duration—perhaps 6–10 years—inert on the surface prior to retrieval (if it is retrieved). The samples toward which the cache is targeted should be chosen with this in mind. Certain objectives, such as detailed analysis of gas components in the samples, appear incompatible with such uncontrolled storage. Fortunately, a future MSR would not be restricted to returning just the cached samples. They may be supplemented by fresh samples (e.g., intact rock cores or soil scooped using ultra clean tools), either from near the MSR landing site or from revisits to particularly attractive sites previously identified by MSL, which may be stored, sealed, and returned to Earth under conditions monitored and controlled as necessary.

Further constraints arise from a desire to avoid complicating a future MSR mission. While not required, the Mars Program Office at JPL and our MSL Sample Cache Science Definition Group prefer that the cache be designed for accommodation by the most recent (see, e.g., Mattingly et al. 2004) MSR orbiting sample (OS) container designs. If feasible, the MSL cache should only occupy a fraction of the capacity of the OS to leave room for samples freshly obtained by MSR. Specifically, it should fit within a cylinder 7 cm in diameter and 2–3 cm in height (roughly the size of a hockey puck) and have a total mass of no more 200 g, 40 % of the nominal sample volume and mass accommodated by the current OS design.

2. Scientific goals for Mars sample return

The scientific objectives and value of the cached samples should be considered in the broader context of the general goals for Mars exploration. The return of samples from Mars can contribute to a wide range of Mars science goals (MEPAG Next Decade Science Advisory Group Report, in prep, hereafter ND-SAG). The return of rock, soil, and atmosphere samples from Mars could contribute to all four of the high level Mars Exploration Program Analysis Group (MEPAG) goals (MEPAG 2006):

I. Determine if life ever arose on Mars,

II. Understand the processes and history of climate on Mars,

III. Determine the evolution of the surface and interior of Mars, and

IV. Prepare for human exploration.

The search for evidence of life on Mars would be greatly aided by studies of certain kinds of returned samples. The MEPAG Goals Document (MEPAG 2006) describes three life-related scientific objectives: a) assess the past and present habitability of Mars, b) characterize carbon cycling in its geochemical context, and c) assess whether life is or was present on Mars. Each of these is further broken down into four investigations, such as, for characterizing the carbon cycle, 1) determining the distribution and composition of organic carbon on Mars, 2) characterizing the distribution and composition of inorganic carbon reservoirs on Mars through time, 3) characterizing the links between carbon and hydrogen, oxygen, nitrogen, phosphorous, and sulfur, and 4) assessing the preservation of reduced compounds on the near-surface through time. All of these investigations can be advanced by the analysis of returned samples. Different kinds of samples are required to advance each (ND-SAG), including sedimentary rocks that span the range of depositional and diagenetic environments, rocks that have experienced water/rock interactions under different kinds of conditions and at different times in martian geologic history, igneous rocks, samples of the regolith and the aeolian dust, samples of ice, and others. The kinds of measurements that would be done on these samples in terrestrial laboratories would include detailed characterization of the texture (e.g., Fisk et al. 2006), mineralogy, and chemistry, at a scale, accuracy and precision that is not possible via missions in situ.

MEPAG's goals related to the martian climate and atmosphere can most effectively be addressed by returned samples in three ways: reading the sedimentary record to interpret paleoclimates and paleoenvironments, analyzing gas inclusions in rocks and minerals of different age to interpret the origin and evolution of the atmosphere, and returning an ice sample.

The geological objectives presently defined by MEPAG can be advanced with the same kinds of samples as described above for the "life" goal (ND-SAG, Jones & Treiman 1998). We could make productive use of the products of all rock-forming and rock-altering processes on Mars, and the wider the range of natural variation covered by the sample collection, the more effective the scientific analysis and interpretation will be. Whereas scientists pursuing the life goal have put a higher priority on sedimentary and hydrothermal rocks, the scientists involved in the "geology" goal can make use of a wider variety of igneous, sedimentary, hydrothermal, and other kinds or rocks, along with granular materials derived from them. The scales of interest range from atomic to outcrop to planetary.

The prospect of human exploration of Mars raises questions related to properties of Martian surface materials (see Hauck et al. 2002). The most important questions that need to be addressed via returned samples relate to the possible presence of biohazards in the airborne dust, and the possible adverse effect of martian granular materials (dust and regolith) on both engineering systems (deterioration of seals, corrosion, electrical effects, etc.) and human explorers. Of particular interest for the latter are intracorneal, intratracheal, and ingestion effects. Finally, identification and characterization of possible resources is of significant interest.

2.1. Scientific objectives of the MSL cache

Here we consider which objectives among the broad goals above can be addressed well by samples cached on MSL.

The proposed cache will likely make some contribution to all of the high-level MEPAG goals. However, the specific scientific objectives for this cache are limited by the constraints described in §1. Given these limitations, the cached samples would be best suited for investigation of the evolution of the surface and interior of Mars (MEPAG Objective III). This aim is the least sensitive to the storage conditions of the samples, particularly to exposure to many years of diurnal thermal cycling. Conversely, explicitly accommodating investigations addressing the possibility of life on Mars—the top MEPAG goal—with the appropriate level of care would demand a more sophisticated cache than the imposed constraints allow. Although the cached samples would likely be analyzed for volatiles, organics and evidence for life, we suggest that samples freshly obtained during MSR would present better targets for such study.

Thus, we recommend as the scientific objective for this cache to *extend the understanding of the geological context and surface evolution of the region explored by MSL beyond the level achievable using the rover's onboard capabilities.* The value of samples for unravelling surface and interior evolution has been demonstrated by the returned lunar samples (e.g., Shearer & Borg 2006). Return of the cache would allow the complete suite of laboratory petrological analyses to be applied to the samples, rather than the small set provided by MSL's instruments. Terrestrial laboratories are superior in virtually all aspects to rover-borne instruments, including sensitivity and breadth of analyses. Among the analyses which can be performed terrestrially but which will not be addressable in situ by MSL or other foreseen missions are examinations of:

- rock petrography to determine rock/soil history via analysis of mineral shapes, sizes, relative orientations, and spatial relationships using, e.g., optical and electron microscopy;
- mineral chemical compositions by electron & ion microprobe, laser-ablation ICPMS, etc., to examine the chemical histories of rocks and soil, and to find crucial constraints for understanding bulk chemical analyses;
- nano-scale chemical composition and structure using, e.g., transmission electron microscopy and nano-SIMS to determine textural, chemical, and mineral structural data on the smallest grains, especially in clays;
- bulk light-element (H, Li, Be, B, C, O, N, etc.) elemental and isotopic geochemistry;
- bulk trace element (rare earth and platinum-group elements, tungsten, molybdenum, etc.) geochemistry at part-per-million to part-per-trillion levels;
- absolute age dating of rocks via the K(Ar)–Ar, Rb–Sr, and U–Th–Pb methods, cosmic ray exposure, etc. (While MSL is not expected to be targeted at a region containing large igneous

features, crucial age information may be available from sedimentary rocks and impactites.[1])

These analyses are fairly insensitive to the anticipated long-term environmental exposure of the cache. Each benefits from MSL's anticipated sampling of a diverse set of sites, and none requires any further capabilities from MSL.

Within this objective, there still remains a choice of sampling strategy. Recent orbital and in situ investigations of Mars have determined that it has a surprisingly diverse surface composition, including basalts (and their altered equivalents), sediments laid by wind and water, and impactites from its numerous impact craters. Minerals detected from orbit or by rovers (e.g., Ming et al. 2006), beyond the high-temperature minerals of igneous rocks, include sulfates (of Ca, Mg, and Fe), phyllosilicates, silica, phosphates, and iron oxides like hematite. Given this diversity, the MSL cache should focus on collection of samples representative of the fundamental rock types and/or mineral associations along its traverse route. Returning samples of this nature would allow definitive correlation between past global mapping campaigns and precise characterization of those map units. In addition, this advance choice of caching targets would allow MSL to proceed with its investigations without being encumbered, necessarily, with searching for unusual rock and mineral types. This strategy does not preclude collecting unusual types, but it shifts the ultimate responsibility on collection of those types to MSR, which might retrieve the MSL cache of Mars fundamentals and then proceed to a select number of waypoints (recorded by MSL) for collection of additional samples, determined at the close of the MSL mission to be uniquely different.

3. Science requirements on the cache

The following requirements were formulated to maximize the scientific value of the returned samples subject to the constraints on the cache. They are all consistent with the minimalist nature of the cache. Requirements needed for planetary protection will come from NASA's Planetary Protection Office and are not addressed in this document, which pertains only to the science requirements.

---

[1]It may be possible to derive formation age dates for chemical sedimentary rocks (from, for instance, Rb–Sr in alkali-rich evaporites or U–Th in carbonates). In clastic sediments, ages of constituent rock or mineral grains (such as zircon) provide upper age limits on deposition. Many authigenic and alteration minerals (such as jarosite and feldspars) are potentially datable (e.g., Vasconcelos et al. 1994; Lueth et al. 2005) and may provide lower age limits to the altered sediments while being useful regardless. Impactites can be dated (using, e.g., the Ar–Ar method), and would provide a lower age limit to the rock unit that hosts the source crater.

3.1. Sample types

The types of samples available for caching will depend on SA/SPaH's capabilities. SA/SPaH is designed to acquire samples in two ways: using a pulverizing drill or a soil scoop. It is designed to provide measured portions of material sieved to grain sizes less than either 1 mm or 150 μm to MSL's Sample Analysis at Mars (SAM) and Chemistry and Mineralogy (CheMin) instruments. It is also thought to be capable of delivering unsieved drill and soil samples to the cache. The scoop may be able to acquire some rocks with diameters greater than a few millimeters if they are located in soft soils. Even if it can acquire rocks of that size, whether it will be able to reliably scoop up *particular* rocks of that scale is uncertain. The scoop is not expected to be effective at picking up rocks located on hard surfaces. Careful use of the current design may allow some centimeter-scale sieving.

The cache should be able to accommodate either rocks or powders acquirable by SA/SPaH. Each has particular value. Cached powders would allow terrestrial analysis of the samples fed to MSL's onboard instruments. Intact rocks contain information (e.g., textures, gradients) absent in powdered rock. We would like a capability to cache both types of samples. If, however, the constraints on the cache drive it toward a design capable of holding only one type, we would prefer to cache rocks, particularly if covering the samples is infeasible.

- **Caching of both rock and powder samples is preferred, but caching either alone is acceptable.**
- **If rocks alone are cached, rocks spanning at least a factor of ten in volume should be accommodatable.** This is intended to ensure some breadth in the set of sizes that can be accommodated. A larger range would be preferred.

3.2. Sample containment

- Sample isolation & identification:
  - **The cache should store each powdered or soil sample in a dedicated container.** The provenance of powdered samples will be unknown unless they are stored separately.
  - **Samples other than intact rocks should be capped.** The sample containers should be covered somehow, to mitigate contamination and loss of samples during their stay on Mars, as well as loss during MSL's traverse. Hermetic seals are not required, but an effort should be made to exclude transfer through seals by grains with diameters larger than 10's of microns, to allow containment of powders delivered by the 150 μm sieve. The lids should prevent the entry of ambient dust during long-term storage. Lids for environmental protection may be omitted for bulk rock if necessary to significantly simplify the cache or increase the rock number, mass, or volume capacity of the cache.

- **Rock samples should be photo-documented.** If multiple rock samples are stored in a common container, the rocks should be imaged by rover cameras before and after storage in the cache. Imaging of a rock before storage will allow it to be identified on return to Earth and thus to be tied to its site and geology of origin. Imaging after placement in the cache may provide a different view of the rock than that exposed while it was on the ground and will permit operators to know whether caching has been successful. Rock samples in the cache should be re-imaged at intervals during long-term operations, especially after actions with great enough accelerations to have bounced rocks around in the cache. This re-imaging will enhance the value of the cache by providing additional views of rocks to enhance chances of identification on return to Earth, and by allowing operators to determine if rocks have settled (or disaggregated) to permit caching of additional samples

  Imaging should be performed sufficiently well to provide a reasonable chance of re-identification of samples upon return to a terrestrial laboratory. Re-identification of samples does not need to be guaranteed.

- **For powders, the level of sample–sample cross contamination contributed by the cache system should be limited to the same level as that contributed by SA/SPaH, which is required to be less than ~ 5 %.** Since laboratory analysis will already need to accommodate that level of cross contamination, stricter control will provide little benefit.

• Sample number: **The cache should accommodate at least five separately collected samples, but ten or more would be preferred.**

• Sample size: **If powdered samples are targeted, the sample cups should be able to accept at least six grams of the powder provided by the 150 μm sieve.** Experience from lunar and meteoritic samples indicates that extensive petrological analysis can be obtained from ~ 3 g samples, with little reserve for future analysis (Treiman et al. 1999). The cache should accept a sufficient quantity of sample to allow extensive scientific analysis, while holding roughly half in reserve for future examination.

  This sample mass is also similar to the maximum which can be provided by the pulverizing drill.

• Container materials:

- **The material(s) that will be in direct contact with the samples inside the cache should be chosen to minimize contamination of the samples during their long stay on Mars, subject to the cost-constraints of the mission.** The material(s) should be well characterized in composition, as pure as possible, and of as few types as possible. Advice from the Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM) on the materials should be considered by the cache engineers on a best-efforts basis. Relevant concerns include, for example, trace element contamination and sample–container reactivity (see Neal 2000).

– **Samples of the materials that will be in direct contact with the samples inside the cache should be delivered to the appropriate parties for curation.** These materials would be available for later reference to understand contamination of the returned samples. Advice from CAPTEM should again be considered when determining what to curate, who should preform the curation, and how to deliver the samples.

3.3. Sample emplacement

- Rover attitude during caching: **The cache inlet should support deposits under the same range of orientations as possible with delivery of solid samples to SAM and CheMin.** A lower range may be acceptable if it increases the number of cachable samples.
- Cache imaging: **The cache's inlet and any exposed covers should be visible by at least one science or engineering imager.** Imaging will allow characterization of cross contamination, assessment of the success of caching operations, and assessment of the condition of the cache.

4. Summary

The proposed cache presents an inexpensive means to give a future MSR the option of retrieving a diverse, previously characterized set of samples. Even a minimalist cache exploiting MSL's sample acquisition capabilities should be able to accommodate samples potentially worthy of later return. They might be well suited to advancing our understanding of the evolution of the surface and interior of Mars, and may contribute toward advancing other high-level goals for Mars exploration as well. Adherence to a small set of requirements will maintain the scientific suitability of the samples and their attractiveness for eventual return.

REFERENCES

Fisk, M. R., Popa, R., Mason, O. U., Storrie-Lombardi, M. C., & Vicenzi, E. P. 2006, Astrobiology, 6, 48

Hauck, F. H., McSween, H. Y., Bennett, D. H., Breazeal, C., Clark, B. C., Eshleman, V. R., Haas, J., Reid, J. B., Richmond, J., Turner, R. E., & Whittaker, W. L. 2002, Safe on Mars: Precursor Measurements Necessary to Support Human Operations on the Martian Surface (Washington, DC: National Academy Press)

Jones, J. H. & Treiman, A. H. 1998, LPI Bulletin, 85, 12

Lueth, V. W., Rye, R. O., & Peters, L. 2005, Chemical Geology, 215, 339

Mattingly, R., Matousek, S., & Jordan, F. 2004, in Aerospace Conference, 2004. Proceedings., Vol. 1 (IEEE), 492

MEPAG. 2006, Mars Scientific Goals, Objectives, Investigations, and Priorities: 2006, J. Grant, ed., 31 p., posted at `http://mepag.jpl.nasa.gov/reports/index.html`

Ming, D. W., Mittlefehldt, D. W., Morris, R. V., Golden, D. C., Gellert, R., Yen, A., Clark, B. C., Squyres, S. W., Farrand, W. H., Ruff, S. W., Arvidson, R. E., Klingelhöfer, G., McSween, H. Y., Rodionov, D. S., Schröder, C., de Souza, P. A., & Wang, A. 2006, Journal of Geophysical Research (Planets), 111, 2

Neal, C. R. 2000, J. Geophys. Res., 105, 22487

Shearer, C. K. & Borg, L. E. 2006, Chemie der Erde, 66, 163

Squyres, S. W., Arvidson, R., Bell, J. F., Carr, M., Christensen, P., Des Marais, D., Economou, T., Gorevan, S., Klingelhöfer, G., Haskin, L., Herkenhoff, K., Knoll, A., Knudsen, J. M., Malin, M., McSween, H., Morris, R., Rieder, R., Sims, M., Soderblom, L., Wänke, H., & Wdowiak, T. 1998, in Lunar and Planetary Institute Conference Abstracts, Vol. 29, Lunar and Planetary Institute Conference Abstracts, 1101

Treiman, A. H., Allton, J., & Lindstrom, M. 1999, in Programme d'exploration de Mars et missions de retour d'échantillons (CNES)

Vasavada, A. R. & the MSL Science Team. 2006, in Lunar and Planetary Institute Conference Abstracts, Vol. 37, 37th Annual Lunar and Planetary Science Conference, ed. S. Mackwell & E. Stansbery, 1940

Vasconcelos, P. M., Brimhall, G. H., Becker, T. A., & Renne, P. R. 1994, Geochim. Cosmochim. Acta, 58, 401