

Developing Tools and Technologies to Meet MSR Planetary Protection Requirements

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Abstract— This paper describes the tools and technologies that need to be developed for a Caching Rover mission in order to meet the overall Planetary Protection requirements for future Mars Sample Return (MSR) campaign. This is the result of an eight-month study sponsored by the Mars Exploration Program Office. The goal of this study is to provide a future MSR project with a focused technology development plan for achieving the necessary planetary protection and sample integrity capabilities for a Mars Caching Rover mission.

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1. INTRODUCTION

The Planetary Science Decadal Survey released on March 7, 2011 recommended the Mars Sample Return (MSR) be the top priority mission of the next decade in the NASA Mars exploration program [1]. MSR would, for the first time, bring samples to Earth from a planet that is known to have the possibility of a habitable environment for life. The returned samples would allow thorough scientific investigation and exploration, well beyond the capabilities of in situ instruments. Advancement in molecular detection instrument technologies provides increasing sensitivity and enabling tools for in situ life detection, Planetary Protection (PP) biohazard testing at the Sample Receiving Facility, or for sample analyses in laboratories [2]. These sophisticated instruments would be extremely susceptible to contamination, which can compromise science measurements and biohazard testing confidence. As a result, great care must be taken to ensure that spacecraft and instruments meet stringent cleanliness requirements when in proximity of or in direct contact with extraterrestrial samples.

A possible scenario of Mars Sample Return campaign would consist of four major elements: a Caching Rover, an Orbiter, a Lander/Fetch Rover/Ascent Vehicle, and a

Sample Receiving Facility. The Mars Caching rover mission would acquire Mars samples on the surface of Mars, and store them in a sample canister. A subsequent Lander mission would land a Mars Ascent Vehicle (MAV) and a fetch rover. The fetch rover would retrieve the sample canister and return it to the Lander. The canister would be transferred to the Orbiting Sample (OS) container on the MAV. The MAV would be launched and releases the OS into Mars orbit. A MSR Orbiter would rendezvous with the OS and transfer it into an Earth Entry Vehicle (EEV), part of the Earth Return Vehicle (ERV) on the MSR Orbiter. After the EEV lands on Earth, the samples and the EEV would be retrieved and transported to a Sample Receiving Facility (SRF) for initial Planetary Protection hazardous testing to determine how the samples could be distributed for further scientific investigations, either labs within the SRF or labs around the world.

The Mars Caching Rover would probably have a high level of heritage from MSL. The rover design, avionic, Entry, Descent Landing (EDL) system likely would be very similar to MSL. This gives us the advantage of knowing a large portion of the hardware and the mechanism of the operational scenarios. The architectural details have not been decided yet. The rover payloads would probably be very different from MSL. Most of the PP technologies in our plan do not require a detailed architecture.

A draft version of the MSR Planetary Protection requirements guideline was released in July 2011 by the NASA Planetary Protection Officer [3]. It defines the proposed Mars Sample Return mission as a PP Category V mission and the outbound Cache Rover mission as Category IVb [4]. Because all returned samples must go through the PP biohazard and life detection “test protocols”, any biological or organic contamination must be kept below 50 ng/g of total organic carbon. We also expect the mission science requirements would specify contamination limits on individual biosignature molecules at parts per billion (ppb) levels.

As a sample return mission, MSR would also have to address the back contamination planetary protection issues that protect the Earth’s biosphere from possible harmful Martian substances. Ambiguous results of the initial PP biohazard tests on the returned sample could jeopardize subsequent scientific investigations. Setting a maximum

contamination limit would not only ensure the successful achievement of the mission science objectives, but it would also comply with the international agreement of planetary protection and ensure the health of our own planet. NASA, and the MSR project in particular, must provide necessary investments to ensure that the capabilities are there to meet the challenges [5-10].

2. MSR PP TECHNICAL CHALLENGES

The two main PP challenges for MSR are to meet the forward PP category IVb and the new microbial and organic contamination limits in the Martian sample. Past PP technology investments can be summarized into two groups (a) investment in improving the current IVa and IVb implementation processes, such as developing faster bioburden assay methods, new H₂O₂ sterilization method, expanded temperature ranges of dry heat sterilization methods, biobarrier, vehicle burnup, breakup analysis, and (b) investment in MSR related microbial contamination to samples, such as far field and near field contamination transport models, clean-to-sterility, and genetic inventory. There also exist technologies used by semiconductor and pharmaceutical industries for cleaning and containment. Our survey concluded that there are a lot of technologies in the containment areas we could adapt or modify for the Mars returned sample handling (MRS) area of MSR, but not much in the cleaning and sterilization area needed for a Mars Caching Rover mission.

Due to budget constraints and other technical challenges, meeting the IVb requirement for the whole spacecraft by Viking-like system sterilization is less likely, though still possible. The proponents of a system-level sterilization argue that the MSR lander would then be able to land in special regions where the chance of finding metabolic life are much higher. However, even a sterilized lander may not be able to satisfy the organic contamination requirement in samples unless it also would be cleaned to a very high standard. It is not realistic to assume with the current budget and resources that NASA would have a completely ultra-cleaned and sterilized spacecraft. The most probable scenario would be to have a IVa rover with a IVb compliant ultra clean sample acquisition subsystem.

Sources and impact of spacecraft contaminants

There are two types of contaminants residing on spacecraft surfaces relevant to the MSR life detection: microbial and molecular.

In the past, planetary protection only addressed microbial contamination. The main focus was placed on viable and cultivable microbes that might propagate under certain Martian environments (in order to protect Mars). With the increased knowledge of life as we know it and the advancement of astrobiology instrumentation, we now realize that there are many forms of life that exist on Earth and possibly on Mars. Some hardy microbes can survive

very harsh conditions for thousands of years with little metabolic activity. Virus particles can be as small as 100 nm. The definition of life detection has evolved from detecting metabolic activity to the search for biosignature molecules. The definition of contamination for PP has correspondingly extended to biosignature molecules. We view the overlapping and merging interests between mission science, planetary protection, and contamination control as a positive development. It would allow better consolidation and coordination for a mission project to address related issues at the same time. This could potentially save money and other resources for the project.

The following lists some common types of contaminants:

- Spore – Hardy, dormant type of microbes, 1 um in size, 10% are cultivable
- VEM – Viable Earth Microbes. Microbes that are alive and can be cultivated. The ratio between spore and VEM is around 1 to 1000, could be much higher if include non cultivable microbes other than bacteria
- Dead microbes and their debris – Contribute to TOC (total organic carbon).
- Organic molecules – Hydrophobic and hydrophilic
- Inorganic molecules – Mineralogical significance

Microbial contaminations on spacecraft surfaces come from manufacturing parts, cleanroom facility air, human operators, soil tracked into cleanrooms from the outside, etc. For example, the JPL Spacecraft assembly facility may have different species of microbes than the Payload Hazardous Servicing Facility at KSC even though the two facilities have the same cleanliness classification. The ratios among the microbes also vary. The total amount of microbes a spacecraft can carry is specified by the PP requirement and it depends on the mission category.

Organic contaminants come from the same sources as microbes. The only difference is that it can also come from additional and never ending sources of the nonmetallic outgassing materials on the rover, such as lubricants, cables, adhesives, coatings, and joint sealing materials.

Total organic carbon (TOC) is contributed by all the organic materials, from all microbes (dead or alive) and all organic molecules (oily or water soluble). This is because TOC is measured by high temperature, automated, dry combustion techniques which turns organic carbon into CO₂. Figure 1 shows the mechanism of TOC measurement.

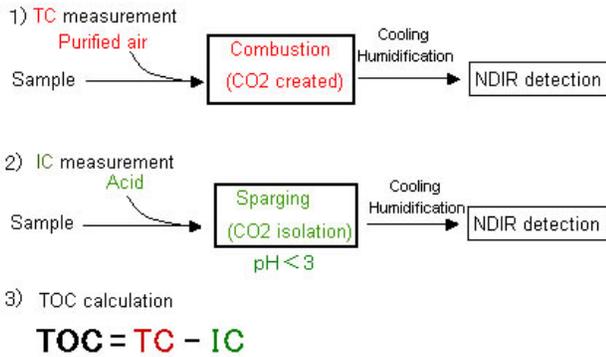


Figure 1. Mechanism of measuring TOC

A back-of-the-envelope calculation (BOTE) estimation of the microbial contribution to TOC on a category IVa spacecraft is between 1-10 ng/cm². Microbial contamination = spores + VEM + dead microbes and their debris. With a IVa level hardware, we would have 0.03 viable and cultivable spores per centimeter square. That is ~30 viable Earth microbes (VEM) per centimeter square. Consider only 1% microbes are cultivable, that will be 3000 live microbes. Adding to the dead cells, the debris, mammalian cells (considering humans shed 600,000 skin particles/hr!), and other microorganisms, conservatively we could have ~10⁵ biological particles/cm² on the spacecraft surfaces. If one cell has a dry weight of 0.2 pg and half of them are carbon, we would have ~10ng/cm² TOC. Since the sample tube's interior surface area is ~ 23 cm², potential TOC contribution by microbes would be 23-230 ng/sample. Unlike single molecules that can be dissolved or cleaned by water or organic solvents, cells and cell debris are insoluble to organic solvents and have to be physically removed by mechanical forces. Since they are submicron in size, there has not been a readily available cleaning method to solve this problem.

Contamination transport pathways

There are at least three pathways by which contaminants can be transported into samples:

1. Direct contact – microbial and molecular contaminants are transferred from the hardware surfaces to samples by direct contact.
2. Particle transport - Microbes and molecular contaminant-containing particles are dislodged from spacecraft hardware surfaces by wind or by mechanical forces and are then carried by wind to the sampling ground or into the sample tube.
3. Volatile organic carbon (VOC) transport – outgassed volatile organic compounds from nonmetallic parts will diffuse or be carried by wind to condense on the sampling ground, sample contacting hardware, and samples.

We analyzed the possible events that can cause particle dislodgement and transport pathways. We identified the landing site particle shedding as the far field contamination source if the proposed rover would drive several kilometers before taking the first sample. Here are three scenarios:

1. The best-case scenario is that if the particle adhesion coefficient is very low, all the contamination particles from the rover and the decent stage (sky crane) are taken off during landing, if we drove the rover to a site, say, 10 km away, we may have very little contamination risk.
2. The opposite case is that the particle adhesion coefficient is very high. Not many particles are shed and there may not be a need for the rover to drive far. Samples can be taken not far from the landing site. The risk of the contamination is also not very high, unless a gusty wind or dust devil occurs before or during the sampling events. We would need to take into account the statistical data of dust devil occurrences on Mars.
3. The most likely scenario is that the rover sheds small amounts of particles over a long time. Thus the rover carries the rest of the contaminants to the sampling site no matter how far it is from the initial landing site. Because the rover still carries the majority of the contaminants and the particle dislodge rate may increase because of the sampling operations, one would expect this to be the highest sample contamination risk. In other words, the possible worse-case scenario is in this category.

BOTE estimate on contamination transport risk

To illustrate a worst-case scenario, we did a BOTE analysis on the probability of finding 1 microbe on 1 cm² sampling area using a IVa cleanliness level spacecraft. It has been recognized that the far field contamination can be partly mitigated by moving the rover far away from the landing site. So a rover operation scenario is illustrated in Fig. 2, where the rover moves 1 km away from the landing site before drilling/coring.

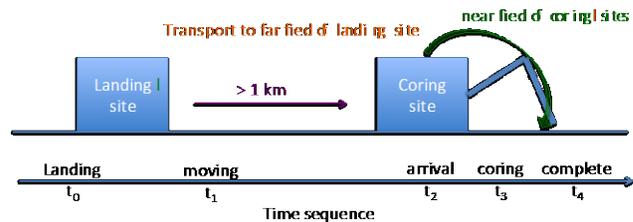


Figure 2. Illustration of an event sequence after the rover landing and the related particle contaminant transport

To estimate the particle transport after landing, we first assume that there is an average particle dislodgement

probability rate, R (%/hr), under the Martian surface wind conditions. Currently, we don't have a precise knowledge of this rate, as it depends on the wind profile, particle size, and particle adhesion properties (some studies were done in this area, but they are not complete). So we will vary this parameter to look for the worse-case scenario. This rate will give us the number of particles coming off from the rover after a given time t . It's not difficult to show then that the total number of particles dislodged into the surrounding between times t_i and t_j is $\Delta N(t_{ij}) = N(t_i) \exp(-Rt_i) - N(t_j) \exp(-Rt_j)$, and the particles remaining on the rover is simply $N(t) = N(t=0) \exp(-Rt)$.

To determine where the dislodged particles go, we use the probability distribution from a prior study by Beaudet, et al [11]. This model assumes steady unidirectional wind condition. If the rover drives along this wind direction, it would give an upper limit of the probability in the far field. For the BOTE estimate, we use specifically the probability under 7 m/s steady wind and 1 km away from the landing site. With this number, we can calculate the number of VEM carried by particles with a given time sequence from landing to coring, assuming the initial total spores on the rover is 3×10^5 and the corresponding VEM is 3×10^8 .

As an example, consider the rover moves to the sampling site 48 hours after landing, and another 24 hours at the sampling site before the completion of sample acquisition. Fig. 3 shows a plot of the VEM/cm² found at the coring site as a function of the average particle dislodgement rate.

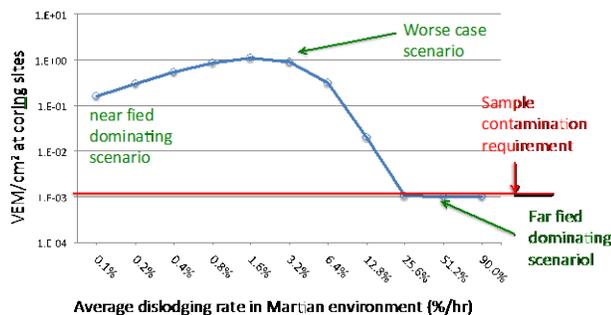


Figure 3. Probability of VEM per cm² 1 km away from the landing site versus possible particle dislodgement rate. See text for more details.

Clearly, if the dislodgement rate is very high, then one assumes that all contaminants have been dispersed a short time after landing. The VEM density at distant coring sites is totally determined by the initial dispersion. Moving the rover away from the landing site is a very effective way to reduce the risk. Even with the unlikely unidirectional wind assumption here, the resulting density probability of VEM at the coring site already meets the anticipated requirement of 10^{-3} VEM/cm².

On the other hand, if the dislodgement is not very high, one can understand that the rover would carry the contaminants with it to wherever it goes. The contamination level would

be determined by the near field transport. A maximum would be reached when the coring site time is about equal to the “lifetime” of particles on the rover. In the specific case, the contamination level is far beyond the MSR VEM requirement in samples. We should point out that the peak probability is not very sensitive to the dwelling time nor the averaged rate. They merely shift the peak position to the left or right on the plot in Fig. 3 over a wide range. In this region, unfortunately, moving the rover is not as effective.

Although the above simple estimate has a lot to be questioned, it illustrates that the risk of sample contamination is not as low as one might think. It also shows that understanding accurately the initial particle load, particle dislodgement mechanisms, and the Martian weather conditions are critical to the overall contamination risk. It should be clear that the BOTE exercise here only includes one of several contamination pathways. Other significant pathways include (1) transport from lander (crane) to far field coring sites, (2) transport to near field surfaces at coring sites, (3) near field transport directly to sample/tools during operations, and (4) direct hardware contact through surface contaminants.

We need a combination of focused efforts that include reducing the bioburden on the spacecraft, improving the accuracy of the models, and obtaining experimental physical parameters for more quantifiable, reliable tools to evaluate the contamination risk to the sample. This is the most viable way that Mars Caching Rover project can demonstrate that it meets the sample microbial contamination requirements.

In addition, most of the VOC comes from rover outgassing materials; it stays with the rover and probably would continually release VOC during sampling operations. VOC can also arise from other unexpected sources, such as lubricants on top of the drill bits. There are lubricant materials in the sample acquisition and caching (SAC), where samples are being capped and sampling tubes are stored. Significant work needs to be done both by modeling and by experimental measurement to quantitatively assess the contamination transport mechanisms. Again, without high quality tools/method to systematically quantify the contributions to sample contamination, we cannot determine if the project will be able to meet the contamination requirements in samples and risk to the MSR science objectives as well as the possibility of cross contaminating Mars and Earth.

Developing a system-level engineering contamination risk assessment can also provide the Mars Caching Rover project with design guidance on material selection, flow-down hardware cleanliness requirements, and containment needs.

The Mars technology program has recognized the importance of the contamination risk analysis since 2004. Some particle contamination modeling efforts were funded; the results of these efforts provide a good starting point.

There is a wealth of experience and knowledge from previous studies. We have identified what is still missing and what needs further development.

How clean does the spacecraft hardware have to be?

Although the precise answer to this question needs to wait until we finish the contamination risk analysis described in the previous section, we already know some basic answers. We know that we would have to meet the IVb cleanliness of microbes on sample acquisition subunits, we also know we need to keep the sampling hardware surface TOC cleanliness at ng/cm^2 level, both constraints are specified in the draft PP requirements for MSR [3]. We know that methods are needed to not only kill microbes but also to remove all the debris ion surface, which contribute to the TOC. It is not only desirable but also necessary to develop safer and environmentally friendly precision cleaning methods to replace the complicated organic solvent cleaning methods, which are not effective in cleaning biogenic and cell debris. Since alcohol wiping and even swab sampling on some critically cleaned hardware will only introduce more contaminants, a hand-held touch-up cleaning device such as CO_2 pellet jet cleaning technology (currently under development) may be used for cleaning after rework, or before subsystem assembly. We currently do not have sensitive enough methods to directly measure the hardware surface TOC level at ng/cm^2 to evaluate cleaning protocols. It is one of the technology gaps identified by this study

One example of what needs to be closely looked at is the cable debris generated from pyro-activated cable cutter devices. Large cable bundles are hard to clean. Locations of these cables need to be identified and contamination risk assessed. Another example is the SHEC, which may contain complicated mechanical components that are in close proximity to the sample and sample contacting hardware.

Contamination isolation and recontamination prevention

There are two strategies to prevent contamination transport. One is to isolate the contamination source or install contamination barriers on the cleaned hardware or sample that needs to be protected. For the Mars Caching Rover mission, the contamination sources would be either from the cleanroom environment on Earth or from the dirtier part of the spacecraft on Mars. Isolating the dirtier part of the spacecraft can mean the entire IVc rover or any exposed instruments that are difficult to clean due to their complex geometry and function. Some of the most challenging issues for the Mars Caching Rover mission that previous missions do not have would be:

1. Containment system: no matter what form they are (e.g. a bag, box, etc.) the containment system must be a molecular barrier, not just a microbial barrier like the one used for Phoenix's arm. The limited molecular permeability may cause pressure problems unless a properly vent system is put into place.

2. The barrier cannot be opened before sampling operations, since the samples and the hardware have to be protected during the entire operation to meet the PP requirement.
3. There might be a need to cover the top of the rover at the landing event since the sky crane might deposit contaminants from its engine exhaust system.
4. Organic contamination is one of the foremost challenges; contamination can accumulate on surfaces of the barrier bags and boxes that would become new contamination sources.
5. Other disadvantages of putting an enclosure on dirtier components are the added mass and power, and possible tangling causing mechanical failure.

Based on this analysis, we think putting the contamination barrier on dirtier spacecraft approach is not as feasible as trying to isolate the clean spacecraft components from recontamination. Since there are fewer critical hardware elements that need to be kept clean, it is more manageable to isolate the clean hardware from recontamination, though it is not easy. Depending on the level of cleanliness at which the hardware surfaces or sample have to be maintained, the level of contamination and the methods to achieve the required level need to be defined. For the sample tubes, for example, hermetic sealing may be required, while for others a simple sealed Amerstat bag may suffice.

The contamination isolation strategy for implementation should start at the component level. It is much easier to clean a simple piece part than a more complex component. The cleaned piece parts would be kept in a clean cabinet or glovebox. A cleanroom inside a cleanroom can be used to lower the recontamination risk.

Although the detailed implementation would need to be worked out after the MSR architecture is determined, there are a few approaches that should be considered as a general strategy for the PP implementation. The general approaches are spelled out in the PP guideline and have either required or suggested implementation approaches. For example, the recontamination prevention measures must be implemented throughout the course of the entire mission. The sample acquisition and handling hardware elements that have the potential to contaminate the sample with terrestrial material must be sterilized and cleaned to levels dictated by the sensitivity of the life detection instrumentation. After incorporating feedback from the hardware engineers on the practicality of implementation for both component and system level assembly during ATLO, the following is one of the possible implementation plans for the sample handling subsystem of MSR:

- At the piece part level - Conduct clean to sterility (aggressive solvent sonication, supercritical CO_2 /plasma, laser plasma cleaning, etc) at the piece

- part level and keep the cleaned hardware under a contamination barrier before the next level of assembly.
- At the component level – Assemble the piece parts in a clean bench (e.g class 100) in a class 100,000 cleanroom. Conduct touch up cleaning after assembly (e.g. CO₂ jet/plasma cleaning) and store the component inside a contamination barrier or a clean cabinet.
- At the subsystem level - Assemble the components in a class 10,000 cleanroom inside a regular class 100,000 spacecraft assembly facility. Conduct touch up cleaning after assembly. Store the subsystem in a contamination barrier which contains molecular getters and sensors to ensure the VOC from the subsystem inside the barrier will not contaminate the cleaned, assembled subsystem hardware.
- At the system level – Assemble the component in a class 10,000 cleanroom in a spacecraft assembly facility. Conduct touch up cleaning after assembly.
- Keep in mind that unlike MSL, the Mars Caching Rover recontamination prevention system has to be in place before launch, during cruise, and during Mars surface operation until the samples are hermetically sealed and secured in the cache.

The MSR campaign intends to continue to develop the PP implementation strategies. The focused technology program team should work closely with the MSR project to adjust and refine the technology needs based on the new strategies and new information when they emerge.

Protect sample integrity and its containment system on Mars

The sample integrity preservation is an important aspect of meeting the MSR scientific objective. A compromised sample not only would jeopardize the integrity of the scientific investigation, it also poses a risk of interfering with the planetary protection sample biohazard assessment. Two technological issues will be addressed here. One is the sample tube, sealing material, and sample compatibility. The other is the sealing integrity during the long storage on Mars.

The current baseline for sample containment is that samples are hermetically sealed until they are returned to earth and opened at the SRF. Two key factors affecting the lifetime of both the seals and the container material are the temperature gradients over the duration of the mission and the effect of the rocks and soil on the container (e.g. corrosion). Furthermore, the potential for contamination from both the container material and seals must be addressed to guarantee that sample integrity is preserved. The amount of complexity needed in the proposed tests extends far beyond simple tests of seals and container materials. However, it is our goal to optimize and perform only those tests which will

reveal the most information regarding the lifetime and potential contamination.

3. SUMMARY

A Mars Caching Rover mission could be the first life detection mission since Viking, and it would carry a sample acquisition and caching system on board. One of the conclusions from this study is that the current state-of-the-art PP tools and technology used by previous Category IVa or IVc missions such as Phoenix and MSL will not be sufficient to address the more stringent requirements for the sample return campaign, which would be a Category V overall and also consists of a series of Category IVb, IVa, and III outbound missions. More specifically, existing PP capabilities will not meet the predicted Mars Caching Rover IVb requirements. The MSR PP organic contamination requirement of < 50 ng/g total organic carbon (TOC) in sample is significantly different than the MSL contamination control (CC) requirements. Significant gaps have been found in the following four areas:

1. Tools and methodologies needed to predict and validate the TOC and microbial contamination levels in cached samples, and to demonstrate the ability to meet the PP requirements.
2. Need robust clean-to-sterility capability to achieve ultra-clean sample-handling hardware from both oily hydrophobic and biogenic hydrophilic molecules to avoid contamination by direct sample contact.
3. Containment technology for re-contamination prevention, containment of the motor joint lubricants of the drill and in sample handling and encapsulation (SHEC).
4. Sample integrity preservation strategy for cached samples over a long period of storage time (>10 years) on Mars.

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BIOGRAPHY



Dr. Ying Lin is the program manager of JPL Planetary Instrument Concept Office, Solar System Exploration Directory. She has a BS in chemical engineering and a Ph.D. in Organic Chemistry. She has extensive research experiences in chemistry, biology, and chemical engineering. She has been leading planetary protection and contamination control element for the Mars Technology Program since 2004. She is currently managing JPL's Planetary Protection Research, Astrobiology Research, and Planetary Instrument Development program

