Planetary protection and Mars sample return

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Abstract: Mars sample return (MSR) mission planning requires a high level of planetary protection in order to break the chain of contact between Mars and the terrestrial biosphere. As a focus of MSR is the search for life, it is also imperative that a minimal amount of terrestrial contamination is taken to Mars on the mission. For these reasons, spacecraft cleaning of up to Viking levels will be needed, adding to the cost and complexity of the mission. Experience gained in Mars missions in the USA and Europe including and after Viking will be used. New technologies such as sample sealing in Mars orbit are also required. The recent identification of special regions on Mars where liquid water may have been present within the recent geological past has led to a revision of planetary protection constraints for missions such as MSR which might wish to visit them. Approximately 500 g (five to eight samples) are envisaged in the first MSR within the 2020s. This requires a sample receiving facility to assess the threat to the terrestrial biosphere prior to analyses of the samples by the wider scientific community. This will be operated at biohazard level 4 – the highest level. Long-term curation of returned samples has planetary protection constraints but also challenges in maintaining the pristine nature of the samples as far as possible as they are moved from the oxidizing, reactive Mars surface to Earth.

Keywords: planetary protection, Mars, Mars sample return

1 INTRODUCTION

Mars has long been considered the next most Earth-like planet in the solar system, and therefore is likely to have a high probability of hosting either its own life or providing a home for contaminating Earth life. In the 1960s and 1970s, the international community determined that missions to Mars should be carried out in such a way that there was no more than a 1:1000 probability that Earth organisms would contaminate Mars over the 'period of biological exploration' and this resulted in a series of Committee on Space Research (COSPAR) papers (for example, see references [**1**] and [**2**]). This was expected to last until a strong scientific consensus was reached regarding the possibility of finding native life on Mars. The international community is now within the period of biological exploration of Mars.

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Upcoming missions within the NASA Mars exploration programme and the ESA Aurora programme are planned to be collaborative between the two agencies, leading up to Mars sample return (MSR) in the 2020s [**3**]. When searching for life on Mars, it is absolutely essential to control for the possibility that hitchhiking Earth life might accidentally be discovered instead. This has been recognized since the beginning of Mars exploration, and all NASA and ESA missions to Mars have met the pertinent constraints at the time of mission selection.

In this article, the authors review how the requirements of planetary protection for life-detection missions have evolved since Viking and, in particular what is required for an MSR mission. Planetary protection considerations have implications for the design and preparation of missions, the locations on Mars from which samples can be taken, the sealing of sample containers, transportation of samples, and design and operation of a sample receiving facility (SRF). COSPAR planetary protection guidelines (for example, see reference [**4**]), divide space missions into categories I to V, where I is where the mission is to a target body which is not of direct interest for understanding the process of chemical evolution or the origin of life. Category V includes all Earth-return missions including MSR. Here the authors elaborate on the background and practical implications of a category V MSR mission.

2 DEVELOPMENT OF PLANETARY PROTECTION REQUIREMENTS FOR MARS

For the Viking lander missions that NASA sent to Mars in the 1970s, it was decided that the most effective method for meeting the probabilistic requirement of no more than a 1:1000 probability of contamination would be to 'sterilize' the entire lander spacecraft, after it had been encased in its heat shield and back shell. This was done by cleaning the lander hardware to stringent levels and then baking the completed hardware assembly in a vacuum oven for several days. The goal was to ensure that the coldest point within the apparatus had achieved temperatures that had been demonstrated to reduce the numbers of heat-resistant viable organisms on spaceflight hardware by four orders of magnitude, a process termed 'dry heat microbial reduction' (DHMR). After baking, the spacecraft assembly was protected from recontamination by Earth microbes until after it was launched into space. Although DHMR is currently the only qualified procedure for bioburden reduction, it does come with cost implications. As experienced by the Viking programme, a large investment is needed in qualifying components and subsystems for heat sterilization that rises with the scale of the system being sterilized. Small units can often be qualified for sterilization by considering the heat tolerance of their components (e.g. MIL (US Military standard components) specification electronics), but the process becomes more involved with larger and more critical systems such as entry and descent components. Another cost consideration is the application of planetary protection at later stages. Planetary protection must be considered from the earliest design phases of the mission so that it can be incorporated in the design at all levels. Attempting to incorporate planetary protection at a later date would lead to cost and schedule impacts as the system must be adapted to fit the new requirements.

The 'failure' of the Viking life-detection experiments in 1976, although the spacecraft themselves functioned almost flawlessly, influenced subsequent planetary protection policy revisions. After a 20-year hiatus in landed Mars exploration, the Pathfinder mission (1997) was put forward in the context of a better scientific understanding of Martian surface conditions largely based on Viking orbiter and lander results. Because the Martian surface is in general cold, dry, and relatively inhospitable to Earth life, COSPAR revised the requirements for lander missions, such that the Pathfinder landed hardware was required to be cleaned to the levels that Viking had reached before the terminal DHMR step, but Pathfinder was not subjected to a final heat treatment [**5**]. Thus, the Pathfinder mission almost certainly did deposit a small number of viable Earth organisms on the Martian surface, but conditions at the location where that rover landed (Ares Vallis, 19.3 °N, 324 °E) would have killed those organisms quite rapidly. Although the surface of Mars should be mostly cold and dry, data from Pathfinder, Mars Global Surveyor (1998), and the follow-on Mars exploration rovers (MER, 2004) suggested that some small regions on Mars might not always be so cold and dry. Those landed missions have provided direct evidence that rocks on Mars encountered liquid water at some point in Mars' past. For instance, a widely held interpretation is that a sabkha-lake type deposit [**6**] formed at what is now the opportunity landing area during the Noachian epoch.

The orbiting missions, with their global view of Martian terrain at an increasingly high resolution – for instance, the HiRise stereo camera on board the Mars reconaissance orbiter is returning images at 25 cm/pixel resolution – have provided visual and spectral evidence for the effects of water on the Martian surface within the last few million years. In particular, gullies on pole-facing slopes ~30 °S have been interpreted as forming through the melting of near-surface water ice during slightly warmer climatic periods [**7**]. The geomorphology of the gullies shows a high probability of the action of liquid water or water-lubricated debris flows. Repeated orbital imaging of some Martian gullies has documented changes that must have been created by material flowing downhill within the past few years [**8**].

Large volumes of water ice exist permanently in the Martian northern and southern polar ice caps. Subsurface ice is also likely at lower latitudes [**9**]. Glacial and periglacial features have been imaged on the surface landscapes of the planet and in the subsurface by radar [**10**]. Liquid water is currently unstable on the surface of the planet because of the low temperature and average of 6.5 mbar atmospheric pressure on the surface. However, in a recent study, Balme and Gallagher [**11**] showed that much of the equatorial regions of Mars had periglacial landscapes indicating surface ice with some meltwater within the last few million years.

Upon consideration of the presence of youthful gullies, COSPAR again modified [**4**] the planetary protection requirements for Mars to protect locations that could be more likely to provide habitats for Earth life – or Mars life, though it is recognized that currently there are no data to suggest where those might be. Missions targeting such 'special regions' must meet the full Viking-style requirements including terminal microbial reduction [**12**]. Initially, special regions were defined on the basis of morphology and/or a (lack of) knowledge regarding their possible composition. Under these guidelines, the Phoenix mission was required to perform a terminal DHMR on the robot arm used to access the icy polar subsurface of Mars, after the arm had been protected from recontamination behind a biobarrier [**13**]. Subsequent Earth-based modelling and analysis has led to the adoption of two parameters that provide useful information about the conditions that might be hospitable to Earth life. Temperature and 'water activity' (which describes the availability of water to participate in chemical reactions) are now used to define special regions on Mars [**12**]. iMars [**3**] suggested that an MSR mission could achieve its aims without sampling a special region. However, it is conceivable that an MSR mission may incorporate novel technology which allows sampling over many hundreds of kilometres [**14**], thus making the sampling of a special region more likely.

2.1 Particular concerns for life-detection experiments

One component of the Viking mission that was of considerable interest for both scientific investigation and planetary protection was the 'life-detection package' – this hardware was designed with the objective of culturing Martian organisms, should any be present in collected samples [**15**]. The design of this experiment was based on the authors' best understanding of Earth life at the time, prior to the discovery off the Galapagos Islands of 'extremophiles' or hydrothermal vent communities (which were discovered while one of the Viking landers was en route to Mars, for example, see reference [**16**]). The life-detection package provided water and other chemical compounds that were thought to be appropriate 'food' for Martian life, with detectors that could identify breakdown products if that 'food' were to be 'eaten'. In fact, some breakdown products were detected in the Viking experiments, but subsequent work provided strong evidence that this was the result of purely chemical processes [**15, 17, 18**].

Missions, including MSR, based around life-detection experiments are of particular concern from the standpoint of planetary protection, because the results of any life-detection experiment will have implications for the development of future planetary protection policies. Planetary protection requirements and implementation approaches are 'determined by the best multidisciplinary scientific advice' according to international policy [**19**]. If a Martian life-detection experiment were to be contaminated with biological material from Earth, but mistakenly identify those contaminants as biological products from Mars, this would not only mislead the scientific understanding of Mars but also result in the imposition of much more stringent requirements on all future Mars missions. For this reason, any sample return or other life-detection missions to Mars must take particular precautions to ensure that biological contamination from Earth is not introduced into samples collected for analysis.

2.2 Constraints imposed by perennial heat sources

It is now known that ice is present in the near subsurface of Mars over large fractions of polar regions and in some locations at lower latitudes [**9**]. If targeting these locations, missions that carry their own permanent heat sources (e.g. radio-thermal generators or radioisotope power generators) have the potential to create habitats for Earth organisms – a 'warm little pond' – in some mission failure scenarios [**4, 20**]. For this reason, constraints based on the full Viking-level terminal microbial reduction are imposed on isotope-powered missions that are accessing locations on Mars that might reach water-bearing subsurface strata in the event of a mission failure.

3 MSR MISSION

Although the planetary protection requirements for performing life-detection experiments or accessing special regions on Mars pose additional challenges for MSR, planetary protection constraints do not represent the most stringent limitations on mission activities. Due to the thin atmosphere of Mars and the dictates of orbital mechanics, the engineering constraints on entry, descent, and landing are likely to impose more stringent limitations on landing site selection and access to target locations for sample return. MSR has a high degree of support within the scientific community because it will provide an opportunity to use the most sophisticated equipment and replicate analyses within terrestrial laboratories on carefully selected samples. Initial handling of the samples within a specially designed SRF will allow planetary protection rules to be maintained in addition to making sure that experiments (e.g. organic molecule characterization, designed to check for signs of extinct or extant life), are not compromised.

The MEPAG and iMars reports into sample return planning [**3, 21**] suggest that about eight samples giving a total mass of 500 g would be collected. These would include cored samples (e.g. from 2 to 3 m depth), soil samples and an atmospheric sample. Samples to be returned may have been collected and cached over a series of missions (i.e. ExoMars (arriving at Mars in 2019) and Mars Science Laboratory (2012)). In addition, the MSR mission itself would have the capability to sample and analyse rocks in order to ensure that the highest priority samples were selected for return to Earth. Samples have to be encapsulated to prevent the loss of volatile compounds.

A likely MSR mission [**3**] would include a lander (with rover and Mars Ascent Vehicle (MAV)) and an orbiter launched separately from Earth. The lander composite would include a rover giving 10 s km movement across Mars or other methods of movement for greater mobility (see reference [**13**], this volume, for a discussion of such technologies which would allow movement over many hundreds of kilometres on Mars). The rover or other vehicles would include a scientific package for rock characterization and a drill to take samples from below the uppermost irradiated zone. The lander would also include a MAV which would take collected samples in a capsule back up into Mars' orbit where it would rendezvous with the Mars orbiter for return to Earth via a parachute or hard landing. This would then be transferred to a SRF on Earth. iMars [**3**] suggested that the time span from the initial launch of the lander parts of MSR would be 5 years.

4 PREPARATION OF THE SPACECRAFT, FORWARD AND BACKWARD CONTAMINATION ISSUES

The technologies required to successfully fly an MSR mission complying with all the planetary protection requirements have already been under study for many years. The mission will need to face up to challenges imposed by both the 'forward contamination' issues; minimizing transport of viable organisms to the surface of Mars, and 'backward contamination'; the control of potentially hazardous Martian material upon return to Earth.

4.1 Forward contamination reduction

The forward contamination technologies have already been studied, and put into practice, on several missions to Mars. As already discussed earlier, the original planetary protection precautions were put in place on the NASA Viking missions in the 1970s, placing the entire spacecraft in an oven to effectively sterilize the spacecraft via DHMR. The parameters used were 125 °C for 48 h, a challenging environment for any hardware, let alone spacecraft. It has been estimated by the NASA Mars Science Laboratory team that to achieve the Viking levels of sterility by system level DHMR, necessary to visit a special region, would cost $60–170 million [**22**]. The more complicated MSR mission would undoubtedly require more. Other techniques have been investigated for terminal sterilization (e.g. H_2O_2 and gamma sterilization), but all suffer from being only surface or close-to-surface techniques that will not reduce bioburden encapsulated in materials. Post Viking, in the light of the new information, the requirements for landed systems not visiting special regions were revised to meet Viking pre-sterilization levels. This set a quantitative target of 500 000 total bacterial spores (i.e. those bacteria capable of forming spores that are believed to have the greatest chance of surviving the interplanetary journey) [**23**]. This includes surface contamination and spores encapsulated in materials that are planned to crash land on Mars (e.g. elements of the descent system).

To meet this requirement, a variety of techniques have been used, even on the same spacecraft. The key to minimizing spores has been continual control of the spacecraft assembly, integration and verification or AIV environment for microbial contamination. For missions since Viking, including NASA's Mars Pathfinder, and the NASA MER rovers, isopropyl alcohol (IPA) has been used in the clean room environment to remove spores from surfaces. The IPA does not act as a sporicide, but rather is a physical removal process that requires a formal wiping process to be followed to ensure reduction [**23–25**]. For those articles of the spacecraft that cannot be wiped, either due to sensitivity, or inaccessibility within the spacecraft, a sterilization process can be applied (that the hardware can withstand) and the area protected by temporary barriers to prevent microbial fallout from the clean room environment.

MSR will need to meet additional criteria for the control of contaminants that may disrupt later life-detection experiments. This problem was addressed on the NASA Phoenix lander, as discussed earlier, by encapsulating the sampling arm in a removable bio-barrier [**9**]. A similar approach is being considered by the joint ESA/NASA ExoMars project, enclosing the sample handling chain and instruments within an 'ultraclean zone' to protect them from contamination [**26**].

An alternative approach was employed by the Beagle 2 project, where the entire lander was assembled 'aseptically' in an International Organization for Standardization (ISO) class 100 clean room. Access to the process was strictly controlled and personnel were continually monitored to minimize the volume of contamination they introduced [**27**]. For MSR, the first approach is likely to be the better, as only the sample handling equipment (e.g. drill) and sample containers need to be ultra-clean. The aseptic approach was only necessary, and indeed possible, due to the small size of the Beagle 2 lander.

4.2 Containment of samples

Once the mission enters the return phase, the issue becomes one of containing the sample to prevent its uncontrolled release. The philosophy is one of 'breaking the chain of contact' between Mars and Earth (i.e. letting no Martian material come into contact with the terrestrial biosphere until its safety has been determined). The technology to achieve this is much more in its infancy than the practices and procedures used to reduce bioload or the outward journey. The break in the chain of contact can be achieved by utilizing two stages of sample sealing.

The initial stage of containment is to seal the samples within individual canisters on Mars. The baseline architecture for the MSR mission outlined in reference [3] calls for the sealed samples to be released from the ascent vehicle to rendezvous in orbit with the Earth return vehicle. A second sealing around the group of canisters will then be performed in orbit on the return vehicle. The second sealing process must therefore be carried out autonomously, and in microgravity conditions. One possible method for achieving a high-integrity seal is via explosive welding [**28**], here explosives are used to seal the sample canisters within a biocontainer that is placed within a capsule for entry into the Earth's atmosphere. Additional methods studied include heat-brazed foil seals and shape memory alloy seals.

Upon leaving Mars orbit, it is not planned to make a direct return to Earth, but rather to place the spacecraft on a trajectory that will miss Earth. The vehicle will then be put on an entry trajectory late on in the return, only if the integrity of the seal has been confirmed. Options for validating the second seal range from a validation of the application process, to the monitoring of pressure levels, induced with inert gas inside the seal, to detect leaks. Once the seal has been verified, the return vehicle places the entry capsule on a return trajectory, and then avoids the Earth itself to ensure any Martian material that might have transferred from the samples during the rendezvous in Mars orbit does not enter the biosphere. The entry capsule itself should be designed to reach high temperatures on all external surfaces during entry, to destroy any Martian material. The capsule itself would complete entry without assistance from a parachute, since the potential failure of a parachute system requires for the capsule to be able to survive a 'hard landing', rendering the parachute unnecessary in the first place.

4.3 Sample return and curation facilities and how samples should ideally be stored

Once retrieved, the samples shall be quickly recovered to a prepared SRF. The purpose of the facility will be to perform an assessment of the level of threat to the terrestrial biosphere. Unless this assessment has been completed, the samples cannot be released to the wider scientific community for study [**3**]. The facility has to fulfil two main functions, the juxtaposition of which makes the design somewhat novel. First, the facility must contain the sample, preventing its release. It is recommended that the sample be treated as a hazard level 4 (Center for Disease Control classification) [**4**]. This requires that the facility conforms to the highest level of containment; this is nominally a biosafety level 4 (BSL-4) laboratory; however, the nature of the materials contained requires that standard BSL-4 practices and procedures be reviewed carefully during the early phases of design. For instance, BSL-4 facilities are designed to handle infectious diseases in liquid form, whereas the SRF will be handling rocky, dusty, and gaseous samples, and thus, the standard practice of maintaining pressure differentials in the facility using high airflow may not be acceptable when handling loose Martian regolith, especially given its incalculable scientific value.

The second function is to preserve the scientific value of the sample. The environments and protocols required within the facility to achieve this are discussed below, but the main conflict that requires novel design solutions is in the conflict between the pressure requirements of containment and contamination control. In a containment environment, negative pressures are maintained to ensure any leakage in the primary containment barrier (e.g. an isolator) will result in air flowing in not out. In clean environments, however, positive pressure is used to keep contamination out. One potential design solution is the use of double-walled isolators with a negative pressure interior space and a positive pressure outer jacket [**4, 29**]. This meets both contamination and containment requirements, but requires for operation on the sample to be performed remotely via robotics, as double-gloved operation in a double-walled isolator would likely be too strenuous, and also prone to failure.

4.3.1 Curation environment

The curation environment must be maintained in order to best preserve the sample science during the period the samples are stored and assessed within a facility. This environment not only ensures that the biohazard assessment of the sample can be accurately and reliably performed, but must also preserve as much of the additional science that will be of interest once the sample is identified as safe for release to the wider scientific community. This environment need only apply to the pristine samples. Any subsamples that undergo tests that will affect the condition of the subsample should be maintained in an environment most suited to the relevant test. Preservation of Mars surface samples is particularly challenging due to their oxidizing and potentially reactive nature.

4.3.2 Temperature

In order to preserve the maximum amount of science, any form of artificial thermal cycling is undesirable at best and may cause further damage to the sample, especially for those that may have been originally below freezing on the Martian surface (all the time e.g. in a polar region or in some sort of other cold environment, e.g. in permanent shadow). A practical engineering solution must be reached that allows the greatest flexibility of the facility in response to the unknowns in the condition of the samples throughout their life, both prior to and post collection.

1. There is no firm landing/collection site decision.
2. It is not known for sure which types of rocks will be collected – will they even contain species susceptible to T changes? Will there be some samples which are frozen, partially frozen (e.g. ice coatings on mineral grains?)
3. It is not known whether the rocks will be subjected to thermal cycling/the degree of thermal cycling either on the Martian surface post collection or during transit to Earth.

There is currently no firm decision on what materials will be collected, and from where on the Martian surface. Surface temperatures at equatorial sites, such as Nili Fossae, are predicted by then to reach >273 K (0 °C) for several hours a day during spring and summer [**30**]. Drilled cores from a few metres below the surface will have been at lower temperatures (circa several tens of degrees) when buried. Additionally, there is a great diurnal temperature cycling of approximately 60 K that present on the equatorial Mars surface. It is also currently unclear what temperature regulation there will be during transport to Earth and the MSR facility. It is likely, based on experience from previous studies of the MSR mission, that temperatures will be constrained to remain below 293 K (20 °C) if possible [**3**]. Given these unknowns, it is likely to be desirable to have a facility that is capable of curating the samples at different temperatures, should the specific character of them require it. A suggested regime might be to store and process most of the samples at 'room temperature' (i.e. ~18 °C) and have the option to store and process some of the samples at a colder, subzero temperature (e.g. −20 °C).

4.3.3 Pressure

While a low-pressure environment is perhaps beneficial in preserving some very specific science within the samples (e.g. sulphates), it is not viewed as a necessity for the majority of the science within the samples. The use of a low-pressure environment is also of doubtful benefit for several practical engineering issues. The pressure inside the sample vessels (SVs) may rise significantly during the return journey via outgassing into a confined, sealed volume, although this will depend on the design of the vessel and the environmental control of the SV. This is especially likely given the thermal cycling currently expected to be experienced by the sample in Mars orbit. Reducing the pressure in the SVs after a potential pressure rise may indeed be detrimental to sample integrity in causing further structural and crystallographic defects in minerals such as clays. Apollo experience suggests that ambient pressure, inert atmosphere curation does not harm the lunar samples. Although the scientific considerations are somewhat different here, inert gases such as nitrogen or argon are generally considered to be non-harmful to Martian samples, provided their composition and cleanliness are known and are highly controlled during operations [**31**]. It is generally thought that drilling (e.g. to 2 or 3 m depth) is desirable in the search for life because it has the potential to get below the most oxidized and irradiated zone. Three-metre depth is equivalent to ~1 bar pressure on Mars and this pressure is probably suitable for any life. However, sampling on Mars (e.g. drilling and putting into a return capsule will immediately reduce the pressure to ambient Mars conditions, e.g. 6.5 mbar). Thus, even at an early stage of an MSR mission, a pressure drop is likely and this may cause a problem for returning extant life.

4.3.4 Gas and humidity

The atmospheric composition of the curation and handling environments must be carefully controlled to prevent reactions between the atmospheric gases and the sample chemistry, and to allow the identification of SRF atmospheric gases from those trapped in the samples from Mars. An inert gas environment should therefore be selected (e.g. nitrogen or argon), to minimize reactions. This is particularly important for Mars samples given their potentially reactive, oxidizing nature. The engineering practicality of an inert gas environment is mainly related to monitoring of the gas environment, and the difficulty in using people in such an environment (which may lead towards a more robotic handling of the sample). The atmosphere should also control humidity to low levels to prevent saturation of the sample with water vapour.

4.3.5 Contamination

The contamination levels in the facility (particulate and organic) will ultimately be driven by three factors:

(a) the sensitivity of the instrumentation used in the biohazard assessment;
(b) the level of contamination introduced by the flight hardware;
(c) the ability to verify the levels attained.

Determination of the species of contamination to be controlled must take into account all the science aims of the MSR mission. Such an analysis can be found in reference [**3**]. Above all, it is desirable that any contamination to which the samples are exposed is low level, inert, and identifiable so as to be easily screened out if present.

4.3.6 Physical environment

The environment of the sample should also be controlled to avoid physical damage to the sample.

Potential sources of damage are the following.

1. Vibration and shocks. The handling of the sample should not introduce vibrations to the sample, or induce short-term shocks while moving and analysing the sample. These could destroy the structure within the sample that may be vital for future scientific analysis.
2. Electromagnetic contamination (EMC). The EMC environment of the samples must be controlled for two reasons. First, any strong electromagnetic fields may physically affect the electromagnetic properties of the sample, which are important to the science, and second, electrostatic charge may cause dusty sample to cling to surfaces and make recovery of the sample after analysis problematic, leading to loss of some of the sample.
3. Orientation. Given the high G-loads expected on landing, it may be necessary to maintain the landed orientation of the samples in order to preserve structure. It is necessary to preserve structures so that, for instance, the sedimentary environment of samples can be characterized accurately.

5 CONCLUSIONS

Planetary protection requirements of Mars space missions have evolved as one's understanding of the planet has increased. After the Viking landers it was assumed that the oxidizing nature of the Mars surface rendered dry microbial heat treatment that Viking was prepared with was unnecessary. However, within the last 12 years, the possibly for near surface water within the recent geological past has been learnt. This has led to the definition of special regions where landers – including potentially MSR – require Viking mission levels of sterilization. In addition, additional controls to limit contaminants which could disrupt life and organic detection experiments are necessary. These constraints are a significant part of the cost of an MSR mission.

In order to bring back samples (e.g. ~500 g) to Earth from Mars, it is necessary to break the chain of contact so that Earth's biosphere is not contaminated by Martian material. This is one of the major unresolved challenges of MSR, requiring new autonomous technologies including the sealing of samples in Mars orbit and ability to check for leaks. An SRF is required to perform an assessment of the level of threat to the terrestrial biosphere. This will be operated at biohazard level 4, which is the highest level.

The oxidizing and reactive nature of the Mars samples poses particular challenges to their long-term preservation. It is envisaged that samples will be stored in an inert, dry atmosphere (e.g. nitrogen gas with strictly controlled contamination, physical environment, temperature, pressure, and humidity). Further research will be required to ascertain the optimum storage conditions with minimum sample degradation.

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