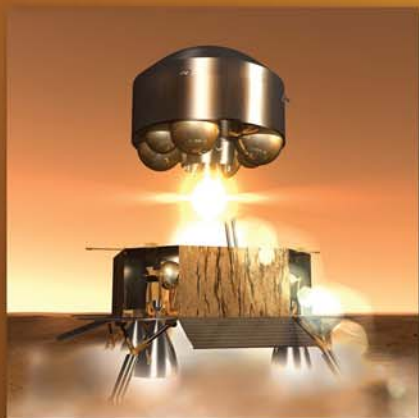


iMARS

Preliminary Planning for an International Mars Sample Return Mission

Report of the International Mars Architecture for the Return of Samples (iMARS) Working Group
June 1, 2008



Caption for cover images:

Left: Artist's conception of the Mars Ascent Vehicle lifting off of the martian surface. Image credit: ESA.

Middle: Sampling sites across stratigraphy encountered on Mars by the Opportunity rover. This is an excellent illustration of the concept of a suite of samples of known geologic context, which has far greater scientific value than individual samples without context. (Image details: False color Pancam mosaic acquired by the Opportunity rover on Sol 173 using the 753nm, 535 nm and 432 nm filters. The image shows the ingress route into Endurance crater. The false color rendering highlights the sedimentary layering and locations examined by the rover's contact instrument suite (rock abrasion tool, APXS, Mössbauer and microscopic imager.) Image provided by Dr. Scott McLennan.

Right: Artist's conception of the Mars Exploration Rover. It seems likely that a rover of similar size and capability would best meet the needs of Mars sample return. Image credit: NASA/JPL.

Preliminary Planning for an International Mars Sample Return Mission

Report of the iMARS (International Mars Architecture for the Return of Samples) Working Group

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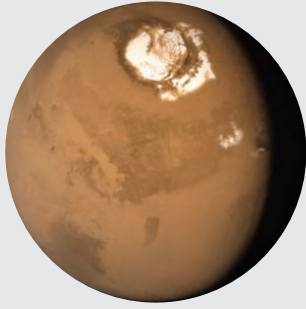
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Preliminary Planning for an International Mars Sample Return Mission

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Executive Summary

The international Mars Architecture for the Return of Samples (iMARS) Working Group was chartered by the International Mars Exploration Working Group (IMEWG) in mid-2006 to develop a potential plan for an internationally sponsored and executed Mars sample return (MSR) mission. Its purpose is to outline the scientific and engineering requirements of such an international mission in the 2018–2023 time frame. The Terms of Reference of iMARS are given in Appendix I.

This report is a summary of Phase I of iMARS' efforts, which were carried out between September 2007, and May 2008. Over this period, the iMARS team developed: scientific objectives; an understanding of the kinds, quantities, and conditions of samples needed to achieve those objectives; draft requirements associated with the objectives; analyses of flight and ground system implementation options and priorities to meet the requirements; a preliminary timeline for MSR for planning long-lead elements and approximate budget phasing; and an analysis of some identified management issues. The result of this effort was consensus on a potential architecture for an international MSR mission, as well as several conclusions regarding MSR and the next steps to achieving it.

The team worked with and was represented on a Next-Decade Science Assessment Group (ND-SAG), which developed guidance regarding the merits of different sample types to achieve high-priority Mars science goals. Engineering analysis included studies of launch opportunities and mission design, along with assessments of the requirements for mobility and time on the surface necessitated by the goal to collect diverse samples from scientifically important sites. The iMARS team also considered the requirements and options associated with planetary protection implementation, which will be more significant for this mission than for any other ever flown.

The primary conclusions of the iMARS analysis include:

- In order for MSR to be broadly acceptable to the international scientific community, it would need to be able to return carefully selected, diverse samples from Mars. It would need to return these samples in a controlled way to maintain the sample's scientific integrity. These considerations have significant implications for the design and operations of the end-to-end Mars sample return mission including both the flight and ground systems.
- Between the flight elements, ground systems, and scientific analysis, iMARS identified approximately 20 primary building blocks that could be led or supported by different international participants.
- Five high-priority mission design options have been identified, all of which would make use of the launch opportunities from 2018–2022. All options would involve two launches and at least one Sample Receiving Facility (SRF) certified prior to return of the sample.
- The development timeline for MSR has two long-lead aspects that must be planned for: New technology development for the flight elements and the SRF(s), and site selection for the latter. In both cases, substantive effort must begin at least 10 years before launch of the flight segment.
- The iMARS architecture and plans provide a path towards a fully international, affordable MSR mission.
- Public outreach and communication require particular attention due to the nature of this mission and need to be addressed in an open and well-managed way from the very beginning.

I. Introduction



HOLDEN CRATER

This image, taken by HiRISE on MRO, shows a proposed Mars Science Laboratory landing site in Holden Crater. Erosion of deep alcoves into the walls of Holden Crater provided sediment to alluvial fans, which have coalesced into a large deposit called a bajada. Most Martian impact craters that contain large alluvial fans are clustered between 18 degrees and 29 degrees South, and the Holden bajada is the largest of these deposits recognized to date.

iMARS

I-I Introduction

Mars has been an object of fascination for humanity since the time of the ancients. Notable milestones have included the early telescopic observations of Galileo and Huygens, the later telescopic descriptions of the martian surface by Schiaparelli and Lowell, and the fictional writings of authors like Edgar Rice Burroughs. In the modern era of spacecraft-based exploration, since the Mariner 4 fly-by in 1964 returned 21 images, there have been several dozen spacecraft sent to Mars, of which 15 have been successful. Public interest remains extremely high—for example, as of this writing there have been 900 million hits on the Mars Exploration Rover (MER) web site. As is typical of the progress of science, these investigations have raised more questions than they have answered. Mars remains a high-priority target for ongoing exploration for the following primary reasons:

- Mars is the most Earth-like planet in the Solar System. The first 700 million years of Earth's history are not preserved in its geologic record, but this history is preserved on Mars. Since life got started on Earth during this period of time, we have very little information about its origins and early evolution—the critical rocks are missing on our home planet. What could Mars tell us about the early evolution of water-rich terrestrial planets, and its relationship to the evolution of habitable environments?
- Of the various places of interest for evaluating whether or not life exists or has existed elsewhere in the universe, Mars is by far the most accessible. We can afford to send a regular series of missions that progressively build the exploration technology and which respond to the discoveries of previous missions. This accessibility allows us to address the life question in a systematic fashion.
- Mars is a potential target for eventual human exploration. Of our nearest planetary neighbors, Mars is the most compatible with crewed missions, and the scientific questions at Mars would most benefit from the attention of human explorers.

Our current specific goals for Mars have been best codified by the Mars Exploration Program Analysis Group (MEPAG), which has framed goals which go by the nicknames of Life, Climate, Geology, and Preparation for Human Exploration (MEPAG, 2006). These goals can be further broken down into prioritized lists of objectives and investigations. Although MEPAG is formally a part of NASA's advisory structure, it has a long tradition of carrying out its discussions with international participation—the science of Mars is something that transcends international boundaries, and the MEPAG list of scientific objectives has been judged to be valuable by non-US scientists.

The multiple objectives and investigations contained in the MEPAG summary could be advanced through many different kinds of missions, including orbiters, fixed landers (e.g., Phoenix), rovers, penetrators, airplanes, and several other kinds of missions. However, it has long been recognized that the mission that would have the single greatest scientific return is one that would return samples from the martian surface. In fact, several of our scientific objectives could not be advanced at all without this mission. The National Research Council (USA) has made this case on a regular basis for at least 30 years (see NRC, 2007 and the references therein), and for this reason has consistently assigned a high priority to MSR. Similar arguments have been advanced within ESA (Messina et al., 2006; ESA, 2006), France (Bonneville and Favier, conclusions of the national workshop on exploration, 2007), and Italy (Colangeli et al., 2004).

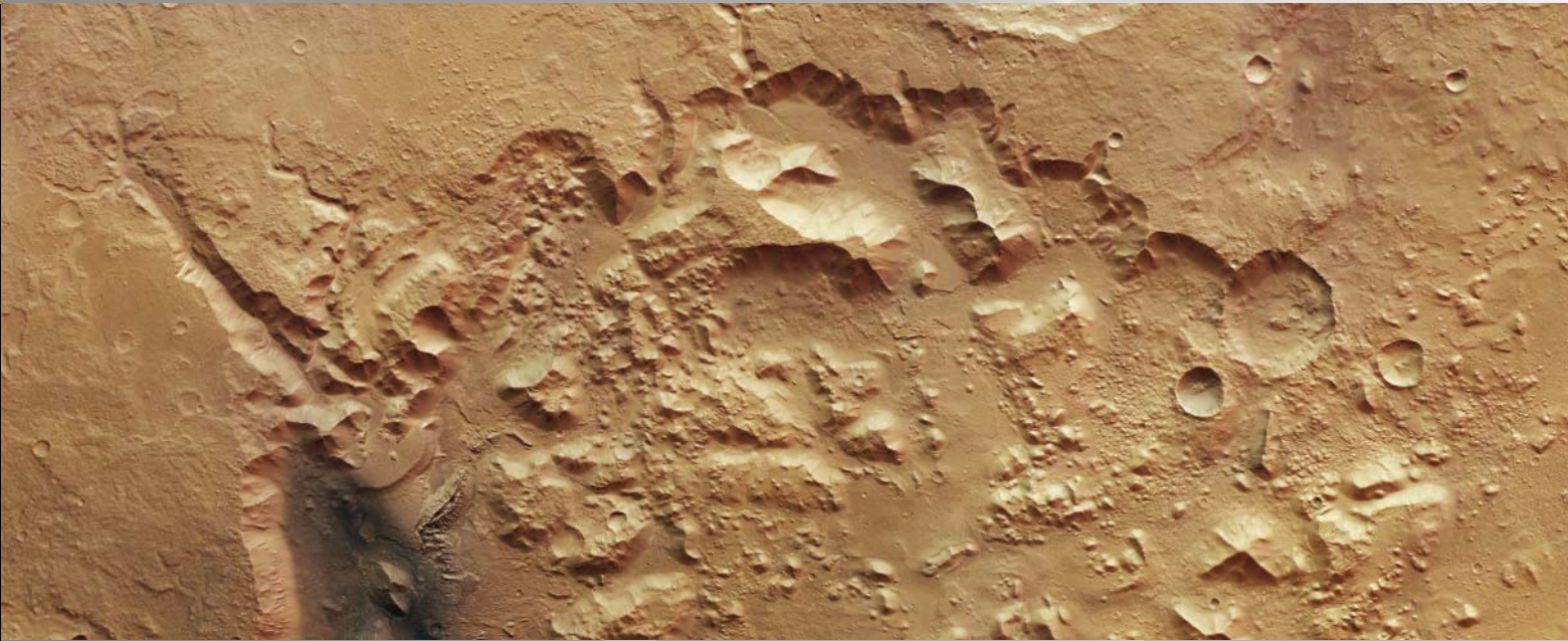
For MSR to proceed and become a reality one day soon, we would need to ensure that the public understands our goals and priorities. It would be essential to keep the public up to date with information about the progress of the international Mars exploration program. When the Apollo samples returned to Earth in 1969, people queued up in cities all over the world to see for themselves tiny fragments of Moon rock. Even today, with all the sophisticated computer games available to them, young people are still thrilled to touch and see rocks from beyond the Earth. We must not underestimate the interest that the first Mars rocks to be returned directly from the planet would engender in the general public, and the capability that an MSR mission has for inspiring interest in science and space research in students.

This Study

In addition to the high scientific value of MSR, it has long been recognized that MSR also would have high cost and implementation risk. In order to be politically viable, it would probably be necessary to share the cost and risk among multiple international partners. To support possible partnership-formation discussions, the International Mars Exploration Working Group (IMEWG) requested the formation of a Mars Sample Return Working Group in mid-2006 (see Terms of Reference, Appendix I). When the group met for the first time in September 2007, it chose for itself the name “International Mars Architecture for the Return of Samples” (iMARS). IMEWG is “an international interagency forum set up with the overall goal of fostering international scientific and technical cooperation for the development of Mars exploration” (IMEWG Terms of Reference). This voluntary cooperation has provided a forum for international cooperation and dialog. The specific charge to iMARS was to propose an architecture and planning structure required for a first truly international Mars mission.

There are many questions about conducting Mars Sample Return as an international mission, such as who is in charge? Is there a senior partner? Who does what? Who would decide where to go and what to bring back? Who would pay for it? The iMARS team, although selected to contain reasonable international and technical diversity, is a team of scientists, engineers, strategic planners, and managers, not a team of budget decision makers, diplomats, or politicians. The iMARS focus has been on developing a potential plan suitable for partnership-forming discussions for an internationally sponsored and executed Mars sample return mission. As such, the potential plans described in this report have yet to be approved for implementation by any agency or country.

II. Science Objectives



NEPENTHES MENSAE

The High Resolution Stereo Camera on board ESA's Mars Express orbiter imaged Nepenthes Mensae in a region lying at approximately 3 degrees north and 121 degrees east.

iMARS

2-1 Introduction

There are many ways in which MSR could make a contribution to our primary goals for the exploration of Mars. However, these multiple possibilities are not of equal priority, either from the point of view of the intrinsic value of the scientific question, or from the point of view of the progress that might be made towards the question if samples were not returned. In addition, many relatively specific scientific questions under consideration would require relatively specific samples. We need to recognize the dual realities that the first MSR mission could not collect all of the samples that would be useful, but that it must collect samples that support enough of a diversity of investigations that broad support from the scientific community could be achieved. This leads to important debate regarding how broad or narrow MSR's scientific objectives should be; this in turn drives the number and character of the samples needed.

2-2 Scientific Objectives

Eleven candidate scientific objectives for MSR were recently identified by MEPAG ND-SAG (2008). The iMARS team considers ten of these to be serious candidates for the first MSR mission (the eleventh relates to ice samples). However, it is important to note that the choice of landing site would play a critical role in determining how many of these objectives end up as part of the mission plan and the level of detail to which each would be pursued. These ten objectives, listed below in approximate priority order, would make an enormous contribution to our high-level goals for Mars. In each case, further detail relating to the context and the significance of the objective can be found in the ND-SAG report (p. 8–12).

- Determine the chemical, mineralogical, and isotopic composition of the crustal reservoirs of carbon, nitrogen, sulfur, and other elements with which they have interacted, and characterize carbon-, nitrogen-, and sulfur-bearing phases down to submicron spatial scales, in order to document processes that could sustain habitable environments on Mars, both today and in the past.
- Assess the evidence for prebiotic processes, past life, and/or extant life on Mars by characterizing the signatures of these phenomena in the form of structure/morphology, biominerals, organic molecular and isotopic compositions, and other evidence within their geologic contexts.
- Interpret the conditions of martian water-rock interactions through the study of their mineral products.
- Constrain the absolute ages of major martian crustal geologic processes, including sedimentation, diagenesis, volcanism/plutonism, regolith formation, hydrothermal alteration, weathering, and cratering.
- Understand paleoenvironments and the history of near-surface water on Mars by characterizing the clastic and chemical components, depositional processes, and post-depositional histories of sedimentary sequences.
- Constrain the mechanism and timing of planetary accretion, differentiation, and the subsequent evolution of the martian crust, mantle, and core.
- Determine how the martian regolith was formed and modified, and how and why it differs from place to place.

- Characterize the risks to future human explorers in the areas of biohazards, material toxicity, and dust/granular materials and contribute to the assessment of potential *in situ* resources to aid in establishing a human presence on Mars.
- For the present-day martian surface and accessible shallow subsurface environments, determine the preservation potential for the chemical signatures of extant life and prebiotic chemistry by evaluating the state of oxidation as a function of depth, permeability, and other factors.
- Interpret the initial composition of the martian atmosphere, the rates and processes of atmospheric loss/gain over geologic time, and the rates and processes of atmospheric exchange with surface condensed species.

2-3 Samples Needed to Achieve the Objectives

The wide range of potential science objectives would require the sampling of a range of lithologies—sedimentary, hydrothermal, and igneous. This arises from the variety of significant processes (igneous, sedimentary, hydrothermal, aqueous alteration, etc.) that played key roles in the formation of the martian crust and atmosphere. Each process creates materials that differ in their composition, location, etc. and that collectively could be used to interpret that process. The iMARS team has defined a “sample suite” as the set of samples required to determine the key process(es) that formed them. Within each suite of samples, we seek to maximize variation within the class, with only a small number of samples.

There is presumably not any single landing site on Mars that could produce all of the samples necessary to support all of the above objectives. How much could be achieved at a single landing site would depend on the magnitude of the rover’s mobility and its ability to do scientific sample selection and context documentation. The landing site selection process would, therefore, be an essential part of the scientific planning for MSR. The NASA and ESA Mars exploration programs have put us in the position of being able to identify—and land on—the best sites.

On Earth, suites typically consist of a few to hundreds of samples, depending on the nature, scale, and detail of the process(es) being addressed. However, suites of about 5 to 8 samples represent a reasonable compromise between scientific needs and mission constraints for MSR samples. The following kinds of sample suites are under consideration for the iMARS reference MSR, although it would almost certainly not be possible to collect all of them during a mission to any single landing site.

- Sedimentary materials rock suite
- Hydrothermal rock suite
- Low-temperature altered rock suite
- Igneous rock suite
- Regolith
- Atmospheric gas
- Dust
- Depth-resolved suite
- Other samples of opportunity

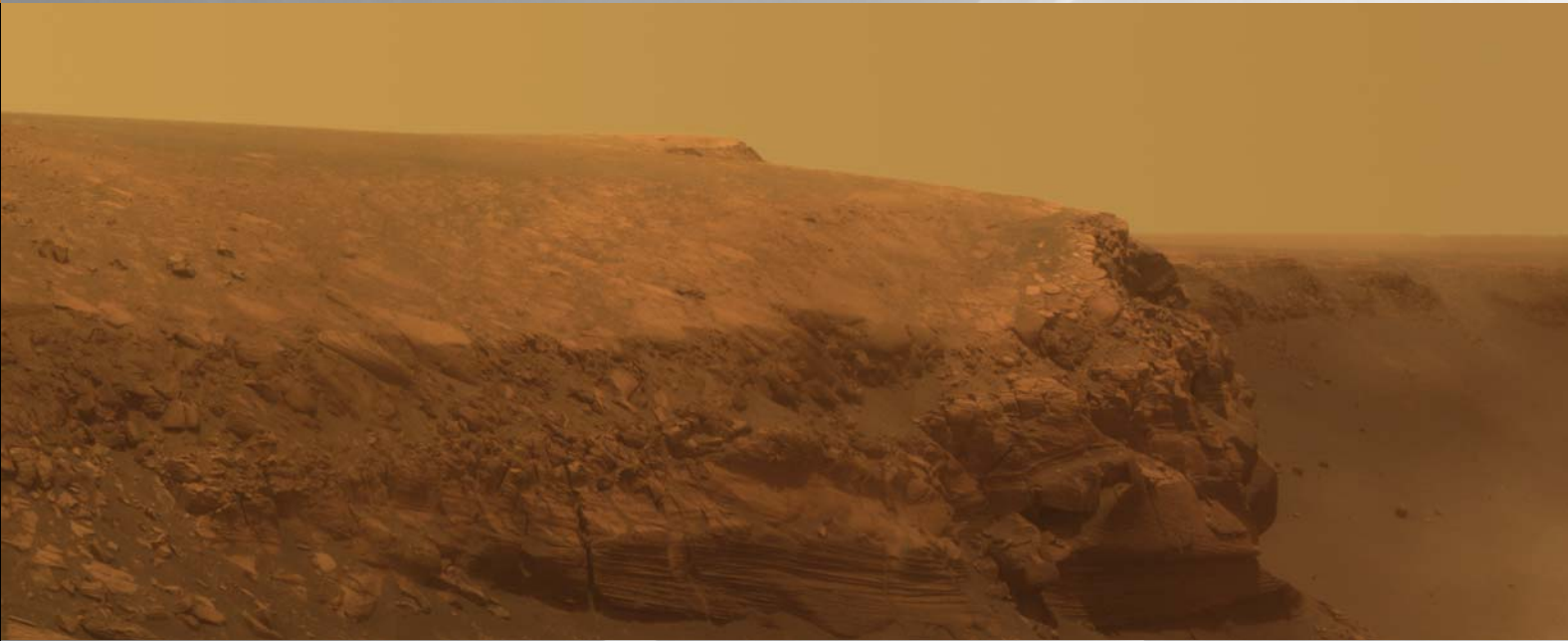
2-4 The Unique Value of Returned Samples

Because MSR would be an expensive mission, it is worth asking whether its objectives could alternatively be achieved either by *in situ* investigations or by study of the martian meteorites.

In 2006, MEPAG identified 55 important future science investigations related to the exploration of Mars. Carrying out these investigations would all be dependent on our ability to make measurements, and a wide range of spacecraft types and targets is implied. The ND-SAG (2008) concluded that about half of the MEPAG investigations could be addressed to one degree or another by MSR. In fact, MSR is the single mission that would make the most progress towards the entire list. Moreover, given the scope of what is realistically achievable via *in situ* exploration technology, a significant fraction of these investigations cannot be meaningfully advanced without returned samples. There are four primary reasons why MSR is of such high value to science:

- **Complex sample preparation.** Several of the high-priority investigations would involve sample preparation procedures that would be too complicated for *in situ* missions. For example, many of the methods of geochronology (see Objective #4 above), require high-purity mineral separations followed by extraction and concentration of trace elements such as Rb, Sr, Nd, and Sm under clean conditions. The procedures to do this in terrestrial labs are well established, but we are nowhere close to figuring out how to do this at Mars. Other investigations would require extensive heating to high temperatures (>1000 C); extraction using a sequence of polar and non-polar organic solvents, followed by chemistry on the extracts to produce derivatives for organic analysis; freeze-drying, etc. Another critical example is the preparation of thin sections—this involves a degree of interactivity that is not possible with simple robotic systems.
- **Instrumentation that would not be suitable for flight to Mars.** Certain kinds of instrumentation would not be amenable for mounting on a Mars lander, because they are too large, require too much power, require too much maintenance, or have complex procedures (e.g. sample loading/manipulation). An example would be a Computed Tomography (CT) scanner.
- **Instrument Diversity.** *In situ* missions to date have been limited to 5–10 scientific instruments. However, we may be able to analyze returned samples using 50–100 instruments, including future instruments that have not yet even been designed. This could significantly amplify our ability to make initial discoveries, to respond to initial discoveries with follow-up tests, and to increase the degree of definitiveness to which a scientific question could be answered (which commonly is dependent on whether a preliminary result could be confirmed by a different kind of measurement).
- **Mars meteorites are useful for some, but not all questions.** It has been widely accepted for approximately two decades that the shergottite, nakhlite, and chassigny (SNC) class of meteorites is from Mars, and there are now approximately 40 known meteorites of this type. All of them are relatively fresh igneous rocks, derived from either thick basalt flows or subvolcanic intrusive rock. However, current high-priority scientific questions, particularly related to the life goal, also require the analysis of sedimentary rocks, hydrothermally altered rocks, and evolved igneous rocks, all of which are absent in the meteorite collection. Also not represented in the meteorite suite are regolith, dust, and atmospheric gas, three sample types needed to address several key objectives. Finally, the Mars meteorites are from unknown localities on Mars—we don't know exactly what they have sampled.

III. High-level Requirements



CAPE VERDE

A promontory nicknamed "Cape Verde" can be seen jutting out from the walls of Victoria Crater in this approximate true-color picture taken by the panoramic camera on NASA's Mars Exploration Rover Opportunity.

iMARS

The iMARS team has compiled a detailed set of draft high-level requirements in three categories—science, planetary protection, and mission/programmatics. These are listed in their entirety in Appendix II and are summarized in Table 1 below.

TABLE 1

High-level requirements summary

Category	Requirement
Sample types to meet science objectives	MSR would have the capability to collect samples of rock, granular materials (regolith, dust) and atmospheric gas
Sample mass	MSR would return a minimum of 500 g of sample mass
Sampling redundancy including contingency samples at landing site	MSR would have both a rover-based sampling system and a lander-based sampling system
Sample encapsulation	MSR would have the capability to encapsulate each sample in an airtight container to retain volatile components of solid samples with the associated solid samples and protect samples from commingling
Cache retrieval	If Mars Science Laboratory (MSL) ends its mission in an accessible location with a cached sample on board, MSR should be designed to have the capability to recover the cache(s)
Horizontal mobility to acquire diverse samples needed to meet science objectives	In order to sample various geological sites, MSR would have the ability to rove to the edge of its landing error ellipse (“go-to” capability), carry out a 2.5 km sample acquisition traverse, then return to the lander.
Landing site latitude range	MSR would be able to access landing sites within +/- 30 deg latitude
Planetary protection	All MSR flight and ground elements would meet the planetary protection requirements established by COSPAR; an MSR mission is classified as category V, restricted Earth return
International cooperation	MSR mission planning would enable international cooperation
Timing	The launch of Lander Composite would be no later than 2020, and MSR would return the samples within 5 years after the launch of the first element

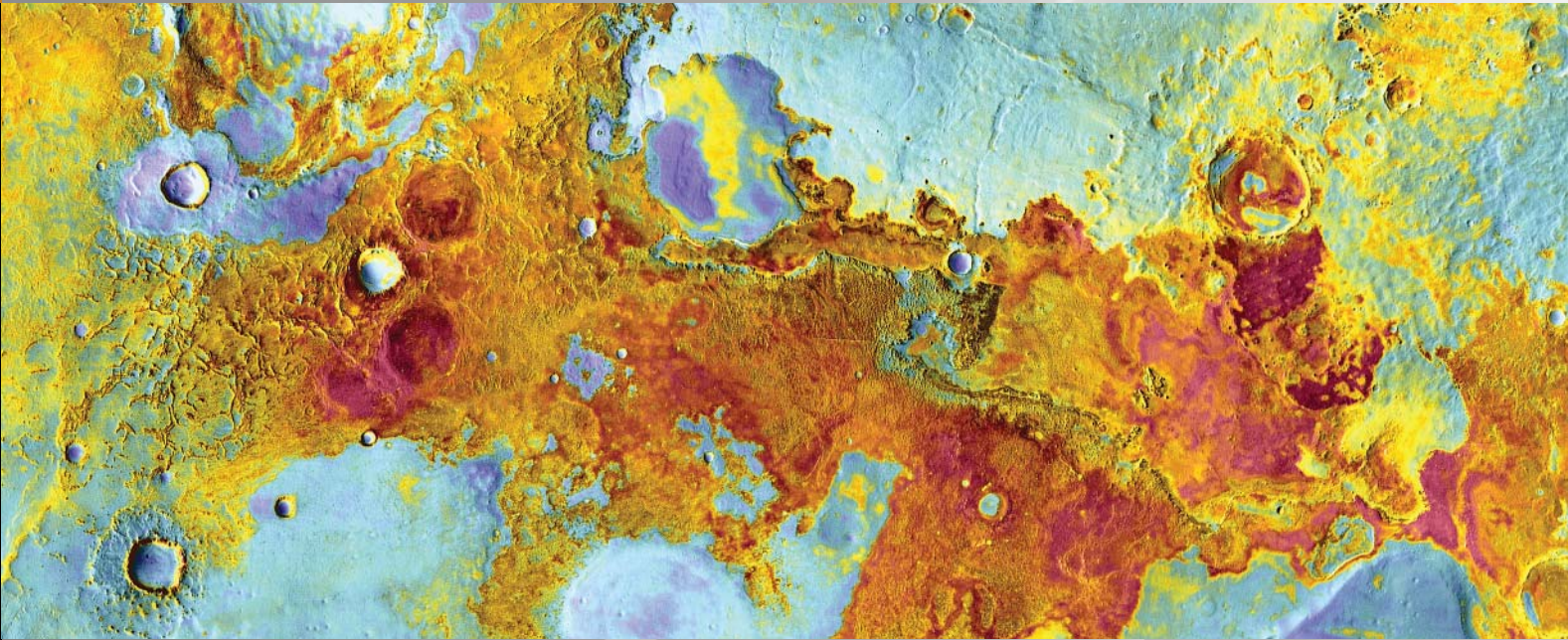
The science requirements include the characteristics of the samples, the requirements for characterizing the sites from which samples are to be collected, the characterization of the samples as they are collected, and protection and preservation of the samples.

The planetary protection (PP) requirements originate in the treaty obligations of space-faring nations and are maintained by the Committee on Space Research (COSPAR) in the form of a planetary protection policy document. A Mars sample return mission would need to comply with planetary protection requirements more demanding than for any mission flown to date. There are aspects of planetary protection that are unique to MSR, which may not be familiar to Mars mission planners and potential sponsors. These requirements can be summarized as follows (the definitions of the PP categories are presented in Appendix IV):

- MSR would be classified as Category V, restricted Earth return. Such a mission would require the highest degree of containment of the samples and all returned hardware that had been in direct contact with Mars. The requirement is to break the chain of contact between Mars and Earth, which needs to be reflected in both mission and spacecraft design.
- Landed assets involved in acquiring the samples to be returned must meet the requirements for Category IVb (see Appendices II and IV for details), missions performing life-detection analyses. The Category IVb requirement for sample return missions is intended to minimize the likelihood of false positive detection due to contamination of a Mars sample by Earth organisms, especially during life-detection and biohazard assessments that would be performed on the samples.
- Orbital elements of an MSR mission must meet the requirements for Category III, either via orbital lifetime or bioburden control. Additionally, any orbiter hardware that might potentially contaminate the returned samples would be required to meet cleanliness levels equivalent to the landed assets (i.e., Category IVb).

The mission/programmatic requirements aim to specify an international mission that would be technically feasible and affordable from a schedule and cost viewpoint. These would include requirements for mission sequence and planning to enable international participation.

IV. Implementation of Mars Sample Return



MERIDIANI

The Meridiani area has a long sedimentary history; this false-color image shows rockier areas in redder hues, and dustier ones in cool tones. This image, 260 km (161 miles) wide, was taken by the Thermal Emission Imaging System (THEMIS) on the Mars Odyssey spacecraft in 2004.

iMARS

4-1 Implementation Considerations Related to the Science System

4.1.1 Surface Mobility

Achieving the scientific objectives of MSR would be critically dependent on the types of sample that would be collected, which in turn would depend on the sample collection mechanism being able to reach specified samples. Two separate sampling systems are envisioned: 1) a rover-based sampling system and 2) a lander-based sampling system. Having these different opportunities would ensure sampling redundancy and would decrease part of the risk to mission success (Appendix II, Req't. # 3)

- MSR would have the ability to rove to the edge of its landing error ellipse (“go-to” capability), carry out a 2.5 km sample acquisition traverse, and then return to the lander. (Appendix II, Req't. #13). Within the scope of this requirement would be the ability for the rover to visit multiple locations within a single site (for example, taking material from different positions within a single outcrop of rock, where the locations would be between 1 cm and 1 m apart, depending on the structure of the outcrop), as well as visiting different sites that might be several tens to hundreds of meters apart. The rover-based sample acquisition system would have the capability of collecting rock samples, granular materials (regolith, dust) and atmospheric sample(s) (Appendix II, Req't. #2), as well as single cores to depths of ~5 cm below the surface (Appendix II, Req't. #4a). Again, being able to collect different types of material would require mobility.
- The lander-based sampling system could collect samples from different vertical depths (Appendix II, Req't #5). The lander-based system would be able to collect contingency samples shortly after landing, and would also be designed to collect samples from within the landing site including core samples from regolith or soft rock, as well as an atmospheric sample.

In addition, if NASA's Mars Science Laboratory (MSL) ends its mission in an accessible location with a cached sample on board, MSR should be designed to have the capability to recover the cache (Appendix II, Req't. #1). This may be a third class of sample that could be returned by MSR.

4.1.2 Selection of Samples and Documentation of Field Context

Achieving diversity in the sample collection would require enough knowledge to be able to select wisely the few samples that could be returned (Appendix II; Req't #24). Correctly interpreting the diversity of a suite of samples typically requires that the field context of the samples is known (Appendix II; Req't #26). In order to achieve these two functions, on-Mars sample-related measurements are needed. If MSR were sent to a previously unvisited landing site, or it got “off the beaten track” of a previous mission's operations, the value of sample data is straightforward. Even if the MSR rover were to “follow in the footsteps” of a previous rover that has already established the field context, sample-related data would be useful, although the number of measurements could perhaps be reduced.

Although there are some differences in perspective by different scientists, five measurements are generally thought to add significantly to the value of the sample collection (ND-SAG, 2008):

1. High-quality color panoramic imaging would be essential to identify samples of interest and to determine their local geological context (e.g., Grotzinger et al., 2005).
2. A microscopic imager (with resolution of 10s of microns or better) that examines rock and sediment textures for clues about processes and environments of formation. In addition, microbially induced textures are one of the key indicators of life (e.g., Herkenhoff et al., 2004).
3. The mineralogy would need to be determined to discriminate one rock from another and to establish geologic context of the samples (e.g., Christensen et al., 2004). For example, phyllosilicates, sulfates, carbonates and silica-rich minerals are excellent for retaining evidence of aqueous processes and of habitable environments and life.
4. Measurements of elemental abundance have been critically important during the MER mission (e.g., Ming et al., 2006; McSween et al., 2006) and would be essential in understanding the range of variability within a field site, and in identifying the effects of geologic processes.
5. Reduced carbon measurements would be essential for understanding prebiotic chemistry, habitability, and life (e.g., Schopf, 1983). Parts-per-million-level sensitivity might be sufficient for screening for sample selection on Mars.

A rock abrasion tool would also be essential for characterizing the rocks adequately, as many rocks on Mars have dusty or weathered surfaces.

4.1.3 Sample-Acquisition System

Rock Samples

In order to maximize the scientific value of rock samples, the rover-based sample acquisition system (Appendix II; Req't #4) should be able to:

- Take samples from outcrops where the geologic context is well-known, and also from loose rocks of interest.
- Sample both the weathered exterior and unweathered interior.
- Sample specific sites (e.g., designated beds within a stratigraphic sequence, such as the Burns Cliff at Meridiani Planum).
- Deliver samples of an appropriate size and form.

These priorities would be served with a “mini-corer” capable of accessing unweathered terrains and acquiring small samples. An example geometry of about the right size is a small core of about 1 cm in diameter and 2 to 3 cm in length; how to optimize the combination of parameters is still under discussion. To distinguish this from larger drills with depth capability of 2–3 m, iMARS has adopted the generic term “mini-corer” for this tool.

Regolith/Dust Samples

The simplest and probably most effective way to sample granular materials, such as regolith and dust, might be using a scoop. However, it might be possible to engineer a mini-corer so that it could also be used to sample granular materials.

Atmospheric Gas Sample

Because of the wide range of concentration of the various gas species in the martian atmosphere, the quantity of atmospheric gas needed for measurement would vary greatly among the different major species. The ND-SAG (2008) recommended that a minimum returned gas sample should be 10 cm³ at a pressure of 0.5 bar (Appendix II; Req't #9). This would provide enough gas material for robust analyses. As martian atmospheric pressure is about 0.006 bar, this implies a compressed gas sample with a compression ratio of about 100:1. The gas sample should be isolated from the rock samples. The sampling system should, therefore, consist of a small compressor and a small vessel, preferably with a valve. The latter would make the sample much easier to deal with on Earth without being contaminated by the Earth's atmosphere.

Contingency sample

The delivery of samples from a rover-mounted sampling system would be vulnerable to failure of the rover—it would have to complete a round trip in order to deposit samples in the return system. The risk of not having rover-acquired samples could be mitigated by adding a second, redundant sampler on the landed platform, so that even if the rover would fail, some quantity—perhaps even up to as much as filling the sample container—of solid sample could be collected (Appendix II; Req't #5). It would be desirable if this platform-mounted sampler took the form of a drill, possibly with depth capabilities of 2–3 m (still under discussion).

4.1.4 Returning the Samples in a Scientifically Useful State

The iMARS team concluded that it would diminish the value of the overall MSR mission greatly if the samples could not be analyzed fully once returned to Earth. Key characteristics must be preserved in order to make sense of the results of any analysis done on the samples. Even if the samples are altered by the long trip to Earth, exposure to conditions that are very different from the surface and subsurface of Mars, and the impact of landing at Earth, it would be critical to be able to piece together the changes that might have occurred during the voyage in order to understand the samples as they were collected. To do this, each sample must be individually packaged or “encapsulated”.

Secure and appropriate packaging would be required to ensure that samples would not become mixed (Appendix II; Req't #10), damaged, or contaminated. To prevent mixing and cross contamination of rock samples and granular materials, an implementation like a capped vial is envisioned. In addition, some of the samples would contain volatile components, and, if they escape to the next sample, there would be potential for chemical reaction that would degrade **both** samples. Thus, the caps on the sample vials should be airtight.

Also, for rock samples, the internal structure is critical to the scientific value and would be severely compromised if the sample were pulverized. One of the major themes of the 2008 MSR conference in Albuquerque, NM (USA) (Shearer, et al., 2008) was the value of rock samples with intact mineral structure. Sample handling and packaging should ensure that samples would not be pulverized or crushed during collection, encapsulation, and transport from Mars to Earth (Appendix II; Req't #17a).

For a gas sample, having a valved vessel would be an advantage (Appendix II; Req't #9) because this would be by far the best way to 1) maintain sample integrity when the spacecraft is opened in the Earth's atmosphere, and 2) split the sample and introduce aliquots into the appropriate instruments.

Proper attention is required to ensure that the sample extraction (i.e. opening of all layers of sample containment) could be done in a way to preserve the sample integrity.

4.1.5 Sample-Related Contamination Concerns

MSR would need to limit contamination of the samples by at least three categories of contaminants: 1) Earth-sourced organic molecules; 2) Earth-sourced inorganic substances; and 3) live Earth-sourced organisms. Although dead Earth-sourced organisms would also be of interest and concern, if they were detected by molecular methods, they would be covered by the first of these categories. Note that the contamination concerns in all three categories would apply from the time the samples are collected on Mars until they are analyzed in a laboratory on Earth, giving rise to requirements on both the flight and ground systems. Note that for issues of sample contamination, the concern is solely with the contaminants that could transfer to the samples—the contaminants that do not transfer from sample contact surfaces to the samples are not relevant to this issue,

- For organic compounds, Mahaffy et al. (2004) proposed an overall limit of 40 parts per billion (ppb), with sub-limits for each of six main classes of organic molecules of interest; and MacPherson et al. (2005) recommended that this be reduced for MSR by a factor of 4, to a total of 10 ppb (Appendix II; Req't #18).
- For inorganic contaminants, MacPherson et al. (2005) recommended that the levels be set at 0.1% of the concentration in Shergotty and Nakhla, two of the martian meteorites. This led to the calculation of Table 7 in their report, which has specific recommendations for about 30 elements of interest (Appendix II; Req't #19).

- For terrestrial biological contamination (Appendix II; Req't #20), constraints are established based on the planetary protection category IVb for the flight system. The intention of the category IVb requirement is to avoid false positives in the planetary protection test protocol (see § 4.3.4). One important strategy to achieve this would be to fully characterize the bioload on the outbound spacecraft (informally called the “passenger list”). Early approaches have been applied to differing extents to NASA’s Phoenix and MSL missions. A bioload characterization is also planned for ESA’s ExoMars (Appendix II; Req't #21).

4.1.6 Terrestrial Sample Analysis Laboratories

It is intended that the returned martian samples would be analyzed using the full power and diversity of the world’s research laboratories. As has been our experience with the lunar samples returned by Apollo, this would allow for adapting the investigation program to respond to discoveries, for making critical measurements by different methods, and for bringing new instruments to bear as they are developed in the future. Of critical importance, the returned samples would allow the usage of large instruments that cannot be miniaturized or ruggedized (a prerequisite for consideration by *in situ* missions) and investigation methods that require complex sample preparation procedures. Because relevant instruments and professional expertise are distributed throughout the world, including in laboratory fields traditionally unrelated to space science, MSR could engage a very wide spectrum of the scientific community on an international basis.

4-2 Summary of Architecture and Mission Elements

A “mission architecture” is a set of mission elements, in sequence, that collectively describe the complete mission. In the case of MSR, there are many theoretically possible architectures. The iMARS architecture described here draws from the combined efforts and results of previous national and international designs for MSR and represents the consensus high-level approach for the implementation of this mission.

4.2.1 General Design

The iMARS reference mission architecture would include two flight elements, referred to for the purpose of this report as the Lander Composite and the Orbiter Composite, launched separately to Mars, which would work together to return at least a single Mars sample container back to Earth. In addition, there would be significant ground elements in operations centers, at least one sample receiving facility, and at least one curation facility.

One flight element, the Lander Composite, would perform a direct entry and land on the surface of Mars, as did the Mars Exploration Rovers and Phoenix and as is planned for the 2009 Mars Science Laboratory mission. After entry through the martian atmosphere, the Lander platform, with both a surface rover and Mars Ascent Vehicle (MAV), would perform a soft landing on the martian surface. The rover would drive away from the Lander platform to acquire samples from the surface, including rock cores, and then return to the Lander platform, which would have mechanisms to load the samples into a sample container on the MAV. The Lander platform would also have the capability to acquire samples. When collection is complete, the sample container would be launched by the MAV into low-Mars orbit for retrieval by the Orbiter Composite.

The second flight element, the Orbiter Composite, would detect, rendezvous with, and capture the sample container in Mars orbit. The Orbiter Composite, which would include propulsion, the capture system, and Earth return capability, would jettison its main propulsion module upon return to Earth during the next Mars to Earth transfer window. At Earth, the Earth Return Vehicle (ERV) would release an Earth Entry Vehicle (EEV)—much like those employed on the NASA Stardust and Genesis sample return missions—that would contain the sample container during entry and descent through the Earth’s atmosphere and a landing on the Earth’s surface. The ERV would divert away from Earth in a non-return trajectory.

The proposed flight sequences of the Orbiter/Earth Return and Lander Composites are depicted in Figure 1. Both of the flight sequences could be launched in the same launch opportunity, or they might be launched sequentially, one or more opportunities apart. In the case where the Orbiter Composite launch follows the Lander Composite launch, another spacecraft with telecomm capability would be required at

Mars to ensure data relay for the Lander, particularly for the critical landing events. Regardless of launch order, the time from the launch of the last flight element to the return of the sample to Earth would be approximately three years.

The ground segment would consist of the facilities required to control and operate the flight elements including science decision support, as well as the SRF(s) and curation facility(ies). The SRF(s) would provide adequate containment for the flight hardware and samples returned from Mars to meet PP requirements (see Appendix II). The SRF primary function is to protect the Earth from potentially hazardous materials or harmful effects from the samples while the necessary test protocols are conducted to determine if the samples are safe for release. The other ground elements would be the mission and control centers for both flight composites, as well as a set of telecommunication ground stations.

4.2.2 Summary of Primary Mission Components

In an international MSR mission, different countries, agencies, and institutions would consider contributing in different ways. The iMARS team has broken the MSR elements into the building blocks listed in Table 2. This table includes a short description of each building block and some of the challenging technologies identified by iMARS as being critical for that block.

FIGURE 1

iMARS reference architecture. The figure shows the launch of, and interactions between, the Lander Composite and the Orbiter Composite in the iMARS two-launch MSR architecture. Mission ground segment building blocks are also identified. The launch vehicles and launch order are examples, pending further refinement of the mission concept, but the functions depicted—including sample acquisition with a rover on Mars' surface, launch of the sample container by the MAV, and capture of the sample container by the orbiter—would be the same in any scenario.

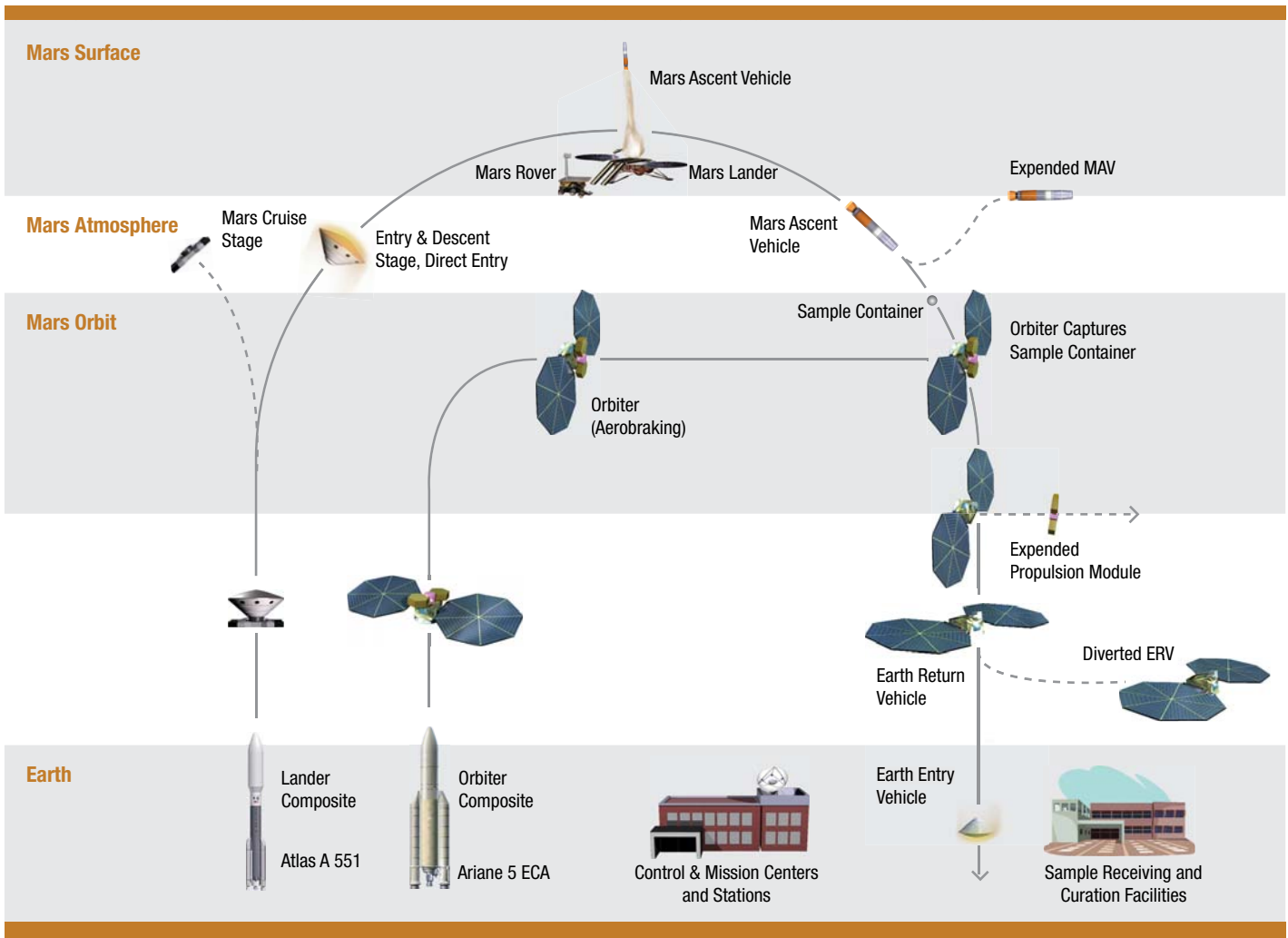


TABLE 2
Proposed Primary MSR building blocks

Name	Functional Description	Technology Development Needed
Orbiter Composite		
Launch Vehicle for Orbiter Composite	Launches Orbiter Composite	- None: conventional launch vehicle would suffice
Orbiter	<ul style="list-style-type: none"> - Performs data relay with the Lander and rover from Mars orbit - Carries rendezvous and capture system and ERV with EEV - Captures sample container in Mars orbit - Releases ERV/EEV 	- Autonomous rendezvous sensors, GNC, algorithms and operations
Earth Return Vehicle (ERV)	<ul style="list-style-type: none"> - Carries and releases the EEV - Diverts to a non-Earth impact trajectory 	- None
Earth Entry Vehicle (EEV)	<ul style="list-style-type: none"> - Is carried by ERV - Re-enters Earth's atmosphere and lands with samples returned from Mars 	<ul style="list-style-type: none"> - Sample thermal protection - End-to-end system: no entry done from Mars
Propulsion Module	<ul style="list-style-type: none"> - Provides propulsion/fuel to reach Mars and insert into orbit - Performs rendezvous maneuvers - Propels the ERV from Mars orbit. 	- None
Rendezvous & Capture System	- Detects and captures sample container in Mars orbit	<ul style="list-style-type: none"> - Low-light detection - Autonomy
Sample Containment and Verification	- Seals sample container and verifies flight containment on return trip	- Robust sealing and containment verification technologies
Lander Composite		
Launch Vehicle for Lander Composite	- Launches Lander Composite	- None: conventional launch vehicle would suffice
Mars Cruise Stage	- Carries the Lander from launch to its entry point in the Mars atmosphere [MSL type EDL]	- None
Lander, including EDL	<ul style="list-style-type: none"> - Carries landed systems including rover, MAV, and sample container to the surface of Mars - Provides landing within accuracy requirements - Carries contingency sample collection and containment system 	- Sample collection and containment system, precision landing, sample transfer system
Rover	<ul style="list-style-type: none"> - Mobile system to acquire samples [MER class rover] - Carries instruments and tools - Carries sample collection and containment system - Transfers samples to Lander 	<ul style="list-style-type: none"> - Sample collection and containment system - Sample transfer system
Rover Instrument Payload	- Characterizes the sample site and sample targets	- None
Sample Acquisition System: Rover	<ul style="list-style-type: none"> - Includes tools to acquire samples of soil, rock, regolith, and atmosphere - Puts samples into encapsulation system 	<ul style="list-style-type: none"> - Coring tools - Other sample-acquisition tools

Name	Functional Description	Technology Development Needed
Lander Composite (continued)		
Sample Acquisition System: Lander	<ul style="list-style-type: none"> - Carries tools to acquire, at a minimum, soil and atmosphere samples, possible subsurface sample acquisition. - Carries sample encapsulation system - Transfers samples to Sample Container 	<ul style="list-style-type: none"> - Sampling tools, sample transfer system - Possible 2-3 m drill
Mars Ascent Vehicle (MAV)	<ul style="list-style-type: none"> - Carries sample container to Mars surface on Lander - Launches sample container into Mars rendezvous orbit 	<ul style="list-style-type: none"> - Propellant and materials for long-duration storage and performance in Mars environment - Launch from low-mass landed platform - Low-mass avionics
Sample Container	<ul style="list-style-type: none"> - Arrives at surface of Mars empty - Is filled by rover and/or lander sample transfer system - Is launched by MAV 	<ul style="list-style-type: none"> - Orbital detection - Reliable containment but low mass - Cleanliness
Ground Facilities		
Ground Recovery	<ul style="list-style-type: none"> - Monitors Earth Entry Vehicle landing - Accesses landed EEV - Transports Sample Container to SRF(s) 	<ul style="list-style-type: none"> - Safe transportation technology
Sample Receiving Facility(ies) (SRF)	<ul style="list-style-type: none"> - Provides containment and contamination control for returned samples - Contains instruments and tools for cataloguing samples and conducting PP protocols 	<ul style="list-style-type: none"> - Sample handling in containment with strict contamination control - Optimized PP test protocol
Curation Facility(ies)	<ul style="list-style-type: none"> - Provides for documentation, storage, and distribution of samples once it has been determined that the samples harbor no life or threat to human health or the environment - May be collocated with SRF(s) 	<ul style="list-style-type: none"> - None
Science Support	<ul style="list-style-type: none"> - Participates in requirements development, landing site selection, sample selection during Mars surface ops, and science analysis of returned samples. - Evaluates extended mission opportunities for landed assets on Mars' surface after sample return 	<ul style="list-style-type: none"> - None
Mission Ops Center—Orbiter	<ul style="list-style-type: none"> - Performs mission operations by commanding and controlling the Orbiter Composite 	<ul style="list-style-type: none"> - None
Mission Ops Center—Lander/ Rover	<ul style="list-style-type: none"> - Performs mission operations by commanding and controlling the Lander Composite, including rover operations on the surface 	<ul style="list-style-type: none"> - None
Research Laboratories	The world's laboratory infrastructure	<ul style="list-style-type: none"> - None, unless sample is found to be hazardous

4-3 Analysis of the Flight System

4.3.1 Past Studies

There have been a number of past studies on MSR missions on both sides of the Atlantic Ocean, and the work of the engineering subteam greatly benefited from previous efforts. In 1998, NASA and the Centre National d'Etudes Spatiales (CNES) joined to initiate a sample return mission set, for launches in 2003 and 2005, with a contribution from the Agenzia Spaziale Italiana (ASI). After cancellation of the effort in 2000, NASA reviewed and improved the US mission architecture and cost estimates through several industry studies, resulting in an improved overall mission architecture with updated cost estimates. Since 2003, ESA has included MSR as a flagship mission within its Aurora Exploration Programme and has conducted several internal and industrial assessment studies. Although based on slightly different sets of requirements, all the above studies independently selected—from a large range of options—a similar mission architecture baseline.

The primary conclusion from these studies is that any sample return mission benefits from having at least two distinct mission elements in order to fit within current and near-future technologies and launch vehicle capabilities. Mass estimates indicate that any flight element capable of performing the end-to-end MSR mission from a single launch would exceed the launch capabilities of the US and ESA, as well as the capability of any current entry, descent, and landing technology for Mars. One flight element is required to acquire the sample from the surface of Mars and launch it to Mars orbit. A second flight element is required to acquire the sample in Mars orbit and return it to Earth.

4.3.2 Mission Analysis

A joint mission analysis activity was carried out in order to develop a common understanding of potential MSR mission scenarios in terms of orbital mechanics, launch vehicle capabilities, and feasible launch vehicle-flight element combinations over the 2018–2022 timeframe. The following assumptions were considered in the analysis:

- Two heavy-launch vehicle (Ariane 5 ECA or Atlas V 551 class vehicles) launches either in the same or in consecutive Mars launch opportunities and in any order.
- One launch would carry the Orbiter/ERV and the EEV flight elements (“Orbiter Composite”), the other launch would include a Mars Cruise Stage and the Lander with the MAV and a sample-acquisition rover onboard (“Lander Composite”).
- Preference was for direct Earth-to-Mars transfer trajectories (type T1 and T2); Earth swing-by and type T3 transfers were also considered to increase mass performance.
- Orbiter staging with jettison of a propulsion module in Mars orbit before Earth return.
- Lander entry at Mars would be direct from the hyperbolic arrival trajectory.
- Mars target orbit for Orbiter Composite and MAV payload delivery is 500-km circular, 45-degree inclination, reached by the Orbiter via nine-month-duration aerobraking.
- Rendezvous and capture would also be in this Mars target orbit.
- Assume direct Mars-to-Earth transfer for the return leg, always assuming the use of the earliest available return window (i.e., mid-2023 or mid-2025 Earth arrivals).
- Earth Entry Vehicle re-entry would be direct from Earth hyperbolic arrival trajectory.

In terms of required delta-V, the 2018 launch opportunity represents the most desirable option. The 2020 and 2022 opportunities are almost equivalent in terms of delta-Vs, but slightly less favorable than 2018. However, the 2022 launch window allows only for a maximum of eight months on Mars’ surface, if return to Earth by mid-2025 were required.

In terms of launch mass, the Lander Composite would be the more critical element, because of the large entry mass that would be required to land the MAV and rover. Launch vehicle performance and the composite masses are launch period and trajectory dependent. However, for architecture-development

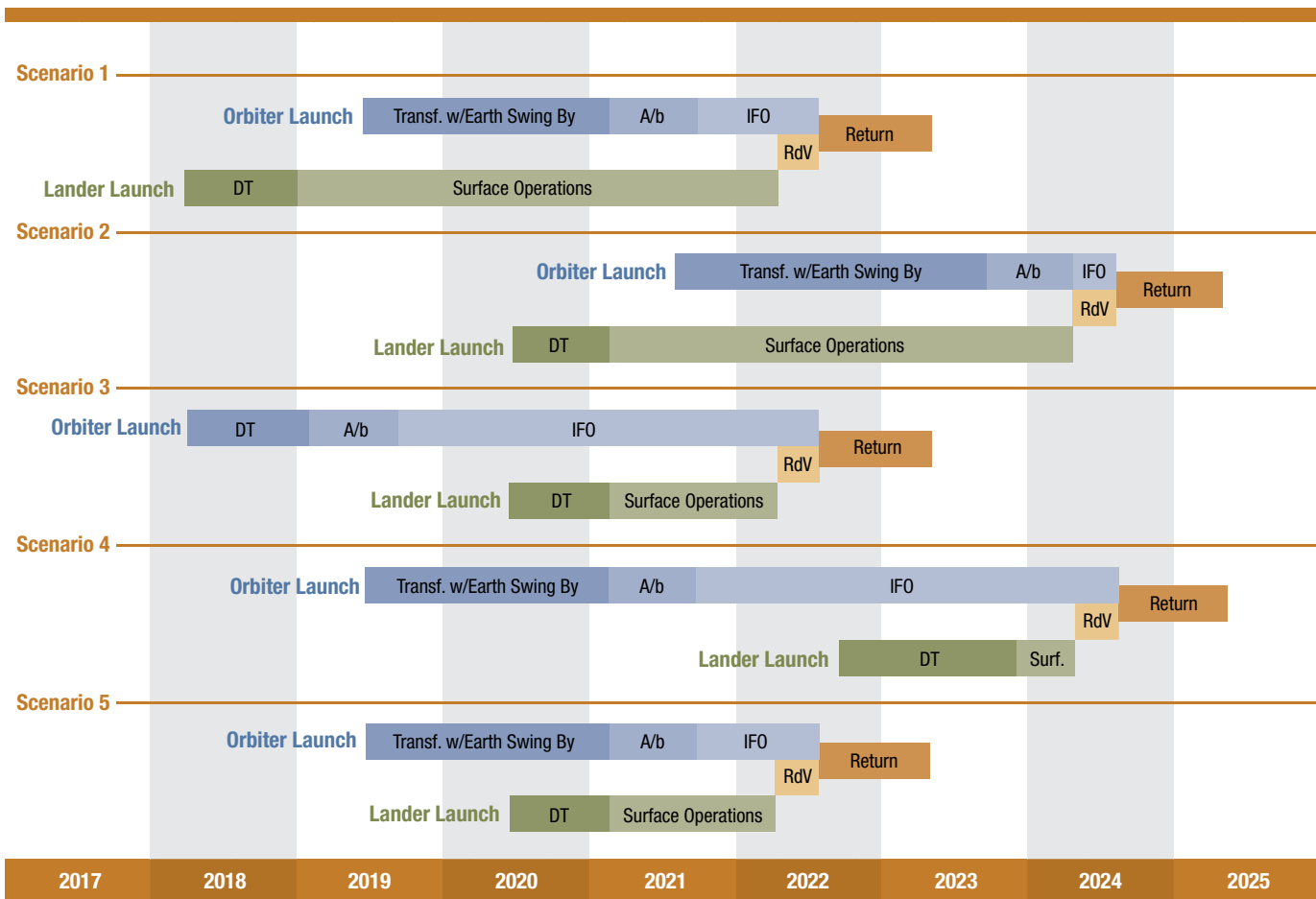
purposes, the following launch mass estimates were used: 4300 kg for the Lander Composite and 3500–4000 kg for the Orbiter Composite. Based on these mass estimates, the joint mission analysis revealed that an Atlas V 551-class vehicle would have positive launch margin for launching either composite, allowing the use of direct transfers in all considered launch dates. However, the current Ariane 5 ECA performance is sufficient only for the proposed Orbiter Composite. Moreover, it would require the addition of Earth swing-by transfers to enhance launch margin. This implies a launch one year earlier than the nominal direct-transfer launch window (e.g., 2019 and 2021 instead of 2020, 2022). An enhanced version of Ariane 5, if available at that time, would improve the situation.

Based on the analysis above, the following mission scenarios were discussed (see Fig. 2). For these scenarios, example launch vehicle options are discussed for illustrative purposes only to provide planning examples supported by a specified class of launch vehicle (e.g., Atlas V or Ariane 5) available today.

- Launch of the Lander Composite in May 2018 by Atlas V 551 would be followed by launch of the Orbiter Composite by Ariane 5 ECA in August 2019. The Lander Composite would land before the Orbiter would be launched; therefore, this scenario would require the presence in Mars orbit of another spacecraft (ESA Mars NET or NASA Scout 2013 for example) for initial data relay and coverage during critical landing events.
- Same as 1 but with the launches in 2020 and 2021, respectively. Another spacecraft for Lander Composite initial data relay would be required

FIGURE 2

MSR mission scenarios and timing. Abbreviations: A/b: aerobraking; DT: Direct Transfer (no Earth swing-by); RdV: Rendezvous and Capture; IFO: In-flight operations.



- Launch of the Orbiter Composite in May 2018 by Ariane 5 ECA would be followed by launch of the Lander Composite in July 2020. This scenario would not require any additional support spacecraft.
- Launch of the Orbiter Composite in June 2019 by Ariane 5 ECA would be followed by launch of the Lander Composite in September 2022. This scenario would not require any additional support spacecraft, but implies either reduced Mars surface operation time or late return to Earth (2027).
- Launch of the Orbiter Composite in June 2019 by Ariane 5 ECA would be followed by launch of the Lander Composite in July 2020. This scenario would require another spacecraft for Lander initial data relay.

4.3.3 Landing Accuracy Analysis

Current Mars landing accuracies are on the order of 100-km radius with unguided ballistic aero-entry systems and 10 km with guided aero-maneuvering such as that planned for the 2009 MSL mission. With improvements in parachute-deployment timing, but no significant technology development, ~3-km accuracy could be reached. Improvements in accuracy to better than 3 km would require guided parachutes, lateral guided powered terminal descent, or potentially both.

Based on 3-km landing uncertainties (3-sigma), sample acquisition on Mars' surface would be confined to regions near the actual landing site or would require the use of valuable surface time either to seek more scientifically interesting sites outside of the safe landing area or to retrieve a cache from a prior mission. Average traverse mobility rates, estimated from experiences with the Mars Exploration Rovers, might approach 100 m per martian day or "sol", making time on surface a trade against the ability to collect a diverse suite of samples. The choice between close-in sampling and target-oriented sampling would ultimately depend on science sampling strategies and the nature of the chosen landing site.

4.3.4 Planetary Protection Implementation Related to the Flight System

Implementing the planetary protection requirements to prevent contamination of Mars and the samples to be returned by Earth organisms associated with flight hardware includes reduction and control of the bioburden on flight hardware by cleaning, sterilization and recontamination prevention. Recontamination prevention would also need to cover the return phase of the mission. Flight hardware intended for a hard landing on Mars (e.g., heat shield) would be required to further reduce the encapsulated bioburden. Impact probability constraints would apply to flight elements (e.g., launch vehicle upper stage, cruise stage, and orbiter) throughout all mission phases, including Mars orbit insertion. If these impact probability constraints could not be met, additional bioburden control for such flight elements would need to be implemented. All these approaches have been applied in various forms in past and ongoing Mars missions (e.g., Viking, Pathfinder, MER, Phoenix, MSL, ExoMars).

The numerical bioburden limits do not scale with the size of the flight system; thus, larger flight systems must take greater care to control the contamination. The size and complexity of the MSR flight system—as well as the need for recontamination prevention once the sample handling chain is cleaned, sterilized, and prepared for launch from Earth, through to sample acquisition on Mars, plus the requirements for sample containment before return to Earth—might require sterilization of the fully assembled flight system prior to launch. This is known as "terminal sterilization". Based on current knowledge, it is recommended to address this issue in iMARS Phase II, particularly to assess the need to start technology developments of critical long-lead components and sub-systems with respect to sterilization compatibility and the necessity to keep the trade space open until the planetary protection implementation approach is confirmed at the Preliminary Design Review (PDR).

Implementing the planetary protection requirements to prevent contamination of Earth by potentially hazardous martian material would require highly reliable sample containment throughout all mission phases including Earth entry and landing, transport of the returned hardware and samples to an SRF, and operations carried out in the SRF until samples and returned flight hardware would be declared safe for release. The process for timely conduct of the planetary protection test protocol and the ability to decontaminate and sterilize the returned flight hardware and samples need to be in place at the SRF.

Even if a terminal system-level sterilization of the flight system would not be necessary to meet the planetary protection requirements, general bioburden and (re)contamination control would affect the material

and process selection, design, model philosophy and qualification program to a greater extent than a traditional one-way mission to Mars.

4-4 Analysis of the Ground Facilities

4.4.1 Sample Receiving Facility (or Facilities)

Based on planetary protection requirements, the SRF must provide adequate containment for the flight hardware and samples returned from Mars until they could be tested for possible biological hazards.

Facility design, construction, and operation must utilize existing experience and best practices for Bio Safety Level 4 facilities, which is the most stringent containment level for biological hazards. Requirements for contamination control would add unique complexity in all phases. Considering the stringent contamination control constraints, together with the small size of samples that need to be manipulated, robotic systems may be a good choice as an integral part of the sample handling chain. Based on the functions that would need to be performed on the returned flight hardware and samples, a combination of full-suit laboratories, glove-box lines, and robotic manipulation would likely to be necessary. A capability to decontaminate flight hardware, equipment used in the high-containment zone, and the samples must be provided.

Consensus from this and previous studies is that the SRF site should be in proximity to a relevant research environment (e.g., other high-containment facility or research cluster of relevance). The SRF should not be geographically or intellectually isolated.

The extent to which oversight committees may be required would depend on the legal framework of the host country within which the SRF is sited. Regardless of legal obligations, it is likely that some form of Institutional Biosafety Committee would be essential, to oversee proper implementation of the planetary protection test protocols and to ensure public confidence in the facility. Such a committee should be constituted several years in advance of the target operating date for the SRF.

4.4.2 Sample Curation Facility (or Facilities)

Proper curation of martian samples brought to Earth by spacecraft would require one or more dedicated laboratories and associated staff (Appendix II; Req't #29). Extraterrestrial samples collected on space missions are generally stored and prepared in positive pressure nitrogen glove boxes, operated in high-level clean rooms. Martian samples would likely impose new requirements involving temperature, pressure, gas composition, and extreme organic cleanliness. Significant technology development would be required to meet these requirements, and the resulting laboratories might be considerably more complex than previous curation facilities. The curation facilities would also need to provide physical security and to support allocation to the international research community.

In addition to recognizing the need for dedicated curation facilities, iMARS has also discussed the advantages in setting up more than one facility, located in different countries. If there were multiple facilities, it might be advantageous to set them up in a complementary rather than identical way. In addition, dividing the sample set might improve overall sample security (e.g. vulnerability to a single catastrophic event) and take advantage of the specific expertise of international partners. The locations and configurations of possible Mars curation facilities are yet to be determined. The operations could be conducted in stand-alone buildings or within dedicated curation laboratories associated with the SRF(s). In any case, curation would represent a long-term investment, since the scientific need for martian research samples would extend for years or decades, long after the flight mission ends.

V. Development Timeline



BECQUEREL CRATER

The layers shown in this image formed by loose sediment accumulating within Becquerel Crater. The layers are interesting in that there are repeated cycles of thick and thin layers. These cyclic changes in layer thickness shows that some environmental conditions varied in a repeated way as each subsequent layer was deposited. The image was taken by the HiRISE camera on MRO.

iMARS

5-1 Mission Development

One of the challenges facing an MSR mission implemented within an international framework would be coordination of the Orbiter and Lander Composite engineering, development, and operations activities. Indeed, the early phases (O, A and B) must be done in parallel to optimize the overall mission design and the interface definition. It is generally considered that the Lander Composite would be the more complex to design, develop and test, and the Lander and Orbiter development and test phases (C and D) would not necessarily have the same length, particularly if the two composites would not be launched in the same opportunity.

The iMARS team generated two development plans to address the synchronization issues. Each is based on the results of the mission design studies conducted by the engineering subgroup and includes coordination across the mission elements. They are distinguished by whether or not a telecomm relay asset would be in place at Mars in time for the arrival of the Lander Composite.

The first option (see Fig. 3) supposes that telecomm support would not be available and, therefore, the MSR Orbiter Composite would have to be in place prior to the arrival of the Lander Composite. This corresponds to scenario 3 of the mission analysis (see § 4.3.2). On the other hand, in option 2 (see Fig. 4), such support would be available, and the MSR Orbiter Composite would arrive after the Lander Composite. In this example, to address the launch performance limitations of an Ariane 5 ECA (for example), an Earth gravity assist would have to be performed. Thus, the MSR Orbiter Composite would also be launched before the Lander Composite. With a more powerful launch vehicle, the launch sequence might be different. This option corresponds to scenario 5 of the mission analysis (see § 4.3.2).

In both options, the following points are important to note:

- To insure perfect coherency between the Orbiter and Lander Composites, a mission-level PDR and an Interface PDR are planned, in addition to the normal PDRs for the Orbiter and Lander,
- There is a need to initiate technology maturation activities as soon as possible to reach the relevant Technology Readiness Levels (TRLs) at the start of Phase A and at PDR for all MSR elements including the SRF(s),
- The activities related to the SRF(s) would need to be started well in advance of the sample return, since they would have to deal with public engagement and facility approval processes, as well as with technical aspects. The site selection of the SRF(s) is identified as a critical early step.

5-2 SRF Development Plan

The timelines shown in Figures 3 and 4 illustrate that the development of the SRF(s) would be eight years from the start of site-specific design to the completion of the building commissioning and another three years for move-in and a test phase before it would be ready to receive the samples from Mars. Although recent experience with the construction and commissioning of BSL-4 laboratories shows that if things go well, commissioning could be achieved in less than 8 years, we need to allow for the possibility of schedule challenges. There are two additional long-lead aspects of the SRF development that would need to be planned in advance of this eight-year development schedule.

- **Site selection.** The process of selecting the site(s) of the SRF(s) would need to be completed. This would require both compliance with the regulatory environment of the country (or countries) where the SRF is located and proactive communication with the local citizens. If the site is to be selected by a proposal process involving communities who want the facility(ies), it would take time to generate and evaluate those proposals. All told, this site selection process could take at least two years.
- **Technology Development.** Technical research and development efforts relating to the containment system would need to be completed before the start of detailed facility design. Additional technology would also be needed in the areas of sample handling and technical solutions to allow stringent contamination control in a high-containment environment, protecting both the terrestrial environment and the samples.

5-3 Technology Maturation Plan

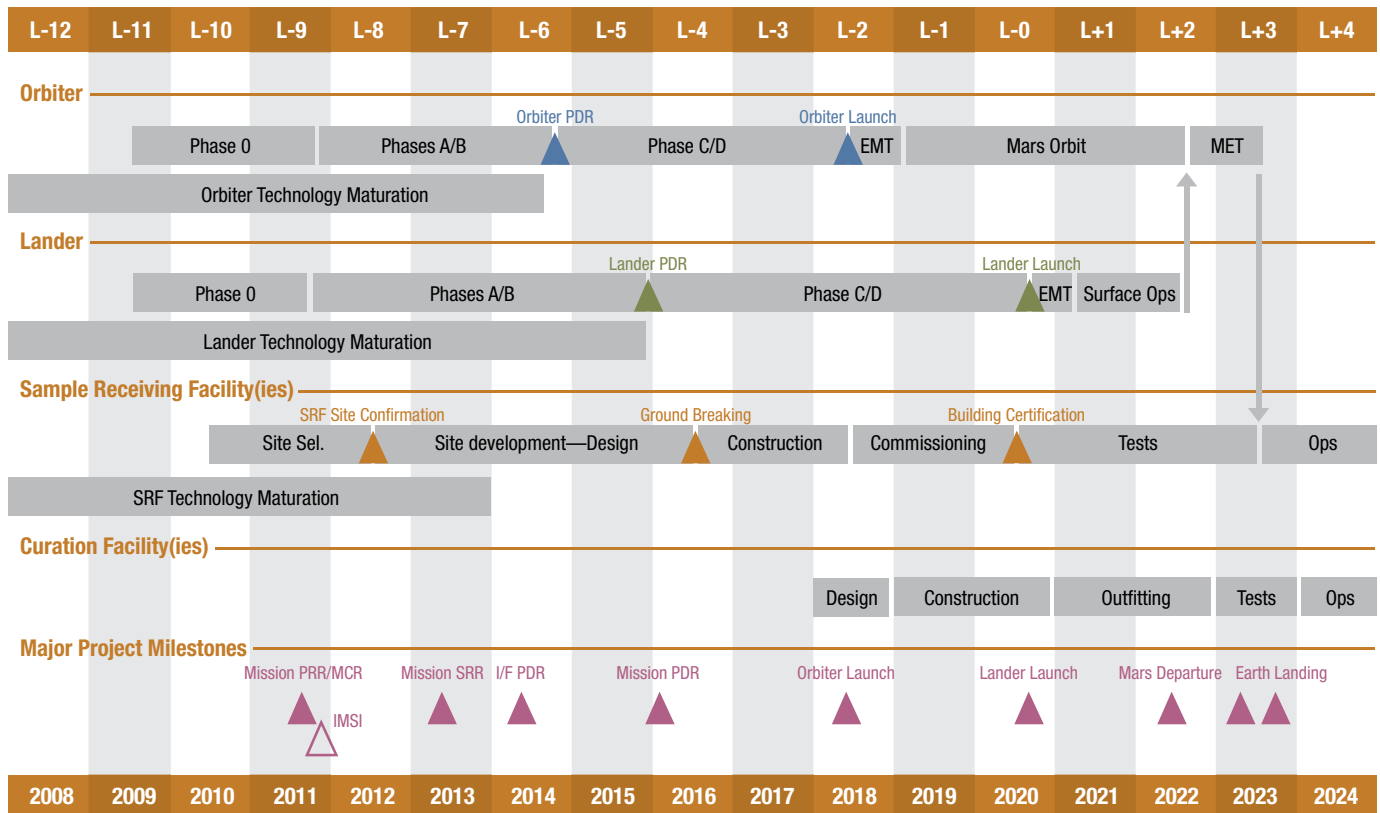
Even if the desire to minimize technical risk places high priority on the use of existing or partially developed technologies, some new developments are unavoidable for MSR. These critical new technologies have been carefully mapped. Their development would require significant effort in the short/medium terms to reach sufficient maturity (TRL of 6; see Appendix III for definitions) by the time of the PDR for the overall mission and/or for the MSR elements they enable.

- Precision Landing capability to land near scientific targets of interest;
- Hazard Avoidance to avoid obstacles that could endanger the lander’s platform;
- Forward Planetary Protection to satisfy the flight system bioburden constraints as well as to assure that martian samples would not be contaminated with Earth-sourced organisms;

FIGURE 3

Development plan assuming there is NOT telecomm support from another mission. Abbreviations: CY: Calendar Year, EMT : Earth/Mars Transfer, MarsSurf: Mars surface operations, MET: Mars/Earth Transfer, SRF: Sample Receiving Facility, IMSI : International MSR Science Institute, PDR: Preliminary Design Review, PRR: Preliminary Requirements Review, MCR: Mission Concept Review, SRR: System Requirements Review, I/F: Interface

Year, with respect to Lander launch



Reference Timeline (CY), assuming Lander launch in 2020

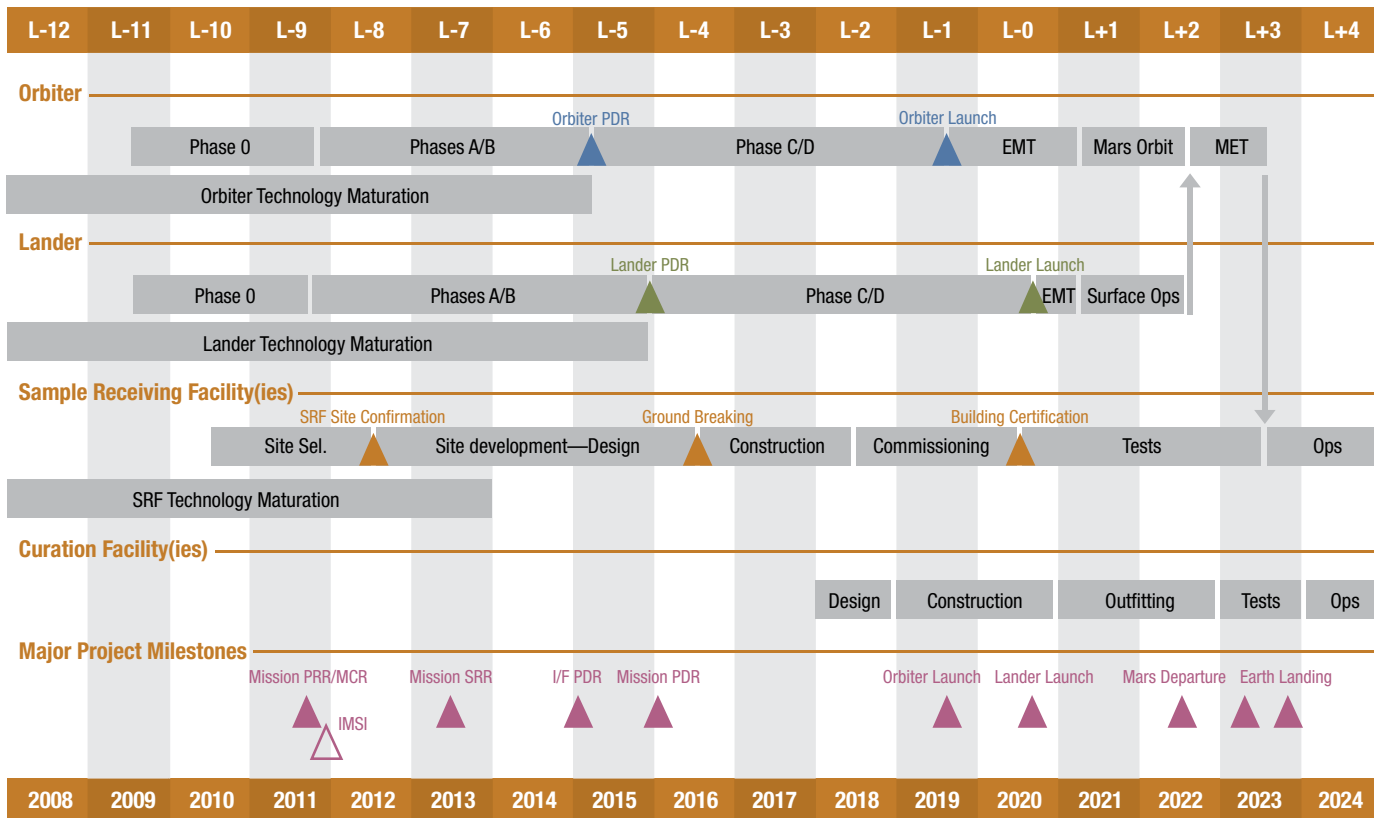
- Sample Acquisition, Handling, Encapsulation, and Transfer to obtain cores and other samples, encapsulate them to avoid cross contamination, and transfer them to a sample container located on the MAV using a midsize mobility system (i.e., MER/ExoMars class rover vehicles);
- Faster Mobility to increase the speed of the rover for traversing between the lander and the science targets in order to reduce the required time for surface operations;
- Mars Ascent Vehicle to launch the sample container to the Mars rendezvous orbit;
- Autonomous Rendezvous and Capture to ensure successful detection, approach and terminal capture of the sample container in Mars orbit;
- High-Speed Earth Re-Entry to comply with the extreme heat loads during the atmospheric phase and protect the samples through the high stresses encountered upon landing;
- Back Planetary Protection (Bio-Containment) break the chain of contact with Mars and assure that there is a very low probability of contaminating Earth’s biosphere with martian particles;
- Sample Receiving Facility technologies to safely handle martian samples (containment and contamination) and to perform the planetary protection test protocol.

In particular, the technology maturation program would have to develop engineering units of specific key elements such as the MAV, EEV, and rendezvous and capture system in time to test them in relevant environments. Also, a major mobility/sampling testbed would have to be developed to validate capabilities to perform traverses to sampling sites, end-to-end sample acquisition, sample transfer, and encapsulation for

FIGURE 4

Development plan assuming there is IN PLACE telecomm support from another mission. Abbreviations as in Figure 3.

Year, with respect to Lander launch

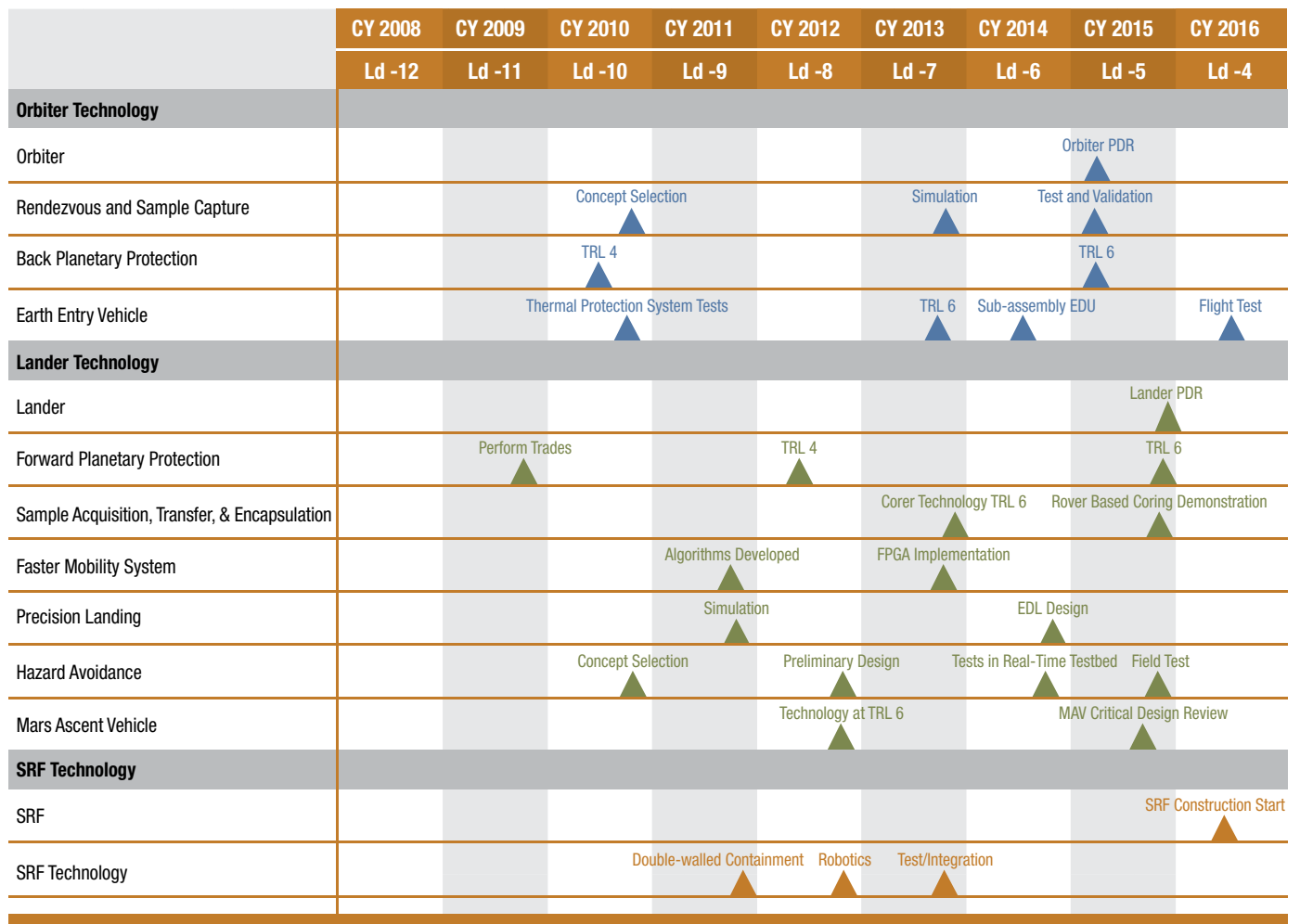


Reference Timeline (CY), assuming Lander launch in 2020

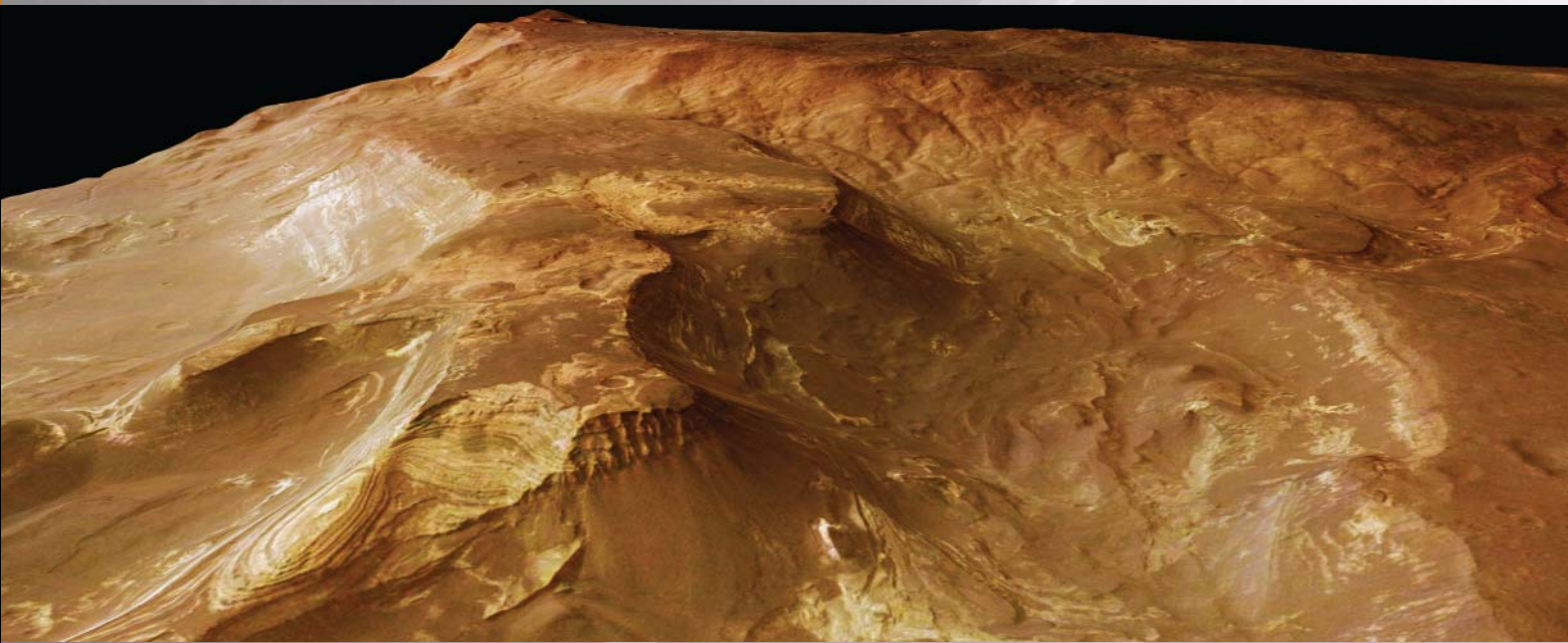
FIGURE 5

Mars Sample Return Technology Development Schedule shows major milestones that must be achieved by the PDRs of the Orbiter, Lander, and SRF, depicted by red triangles. This figure indicates that a 5–6 year lead time would be required to develop the critical technologies before the start of mission development.

a variety of sample types. Figure 5 below shows a schedule to mature these technologies. This corresponds to the mission development plan that assumes the existence of a telecomm orbiter from another mission (See Fig. 3); in the case of no existing telecomm orbiter, the Orbiter technology development schedule would need to be advanced by six months. It is important to note that, since many of the capabilities and technologies would either be new and/or would be required to address particularly challenging requirements in the frame of MSR, significant effort in terms of hardware development and testing would be required prior to the selection of the best technological concept in each area.



VI. Management Planning



TERBY CRATER

The High Resolution Stereo Camera (HRSC) on board ESA's Mars Express orbiter imaged the Terby crater on Mars. The region is of great scientific interest as sediments there hold information on the role of water in the history of the planet.

iMARS

The management of such an ambitious and highly international project would present significant challenges in scientific, engineering, and political aspects. These challenges would need to be addressed among the stakeholders involved in the project.

6-1 Management of Project Elements

The magnitude of the challenges in term of management, decision-making, regulatory, and organizational issues would be greatly dependent upon how many international partners choose to be involved in MSR, the scope of their commitments, and the complexity of the interfaces between their various contributions. For example, there would be a need for overarching mission-level reviews (see § 5), carried out by internationally configured review panels. The iMARS team has not had a chance to discuss these issues and possible solutions, since this international sharing is currently open. These topics will be addressed in the proposed iMARS Phase II.

The iMARS team did discuss the possible management of one or more Sample Receiving Facilities. The team concluded that, for an international sample return mission, all of the SRF management positions within an SRF, except the Biosafety Officer, could be filled by personnel from any country. The Biosafety Officer should be a resident the country in which the SRF is sited or, at a minimum, have comprehensive knowledge of local biosafety codes and control authorities.

6-2 Management of MSR Science

6.2.1 Managing an International Science Team

A significant challenge for an international MSR mission would be the process by which a large, diverse, international science team would be managed. For example, how would international participation in the following critical science-related decisions be managed?

- Where to land
- Which samples to collect
- Mars surface operations strategy
- How the samples would be subdivided once back on Earth
- How the samples would be allocated for scientific research

One possibility considered by iMARS is the formation of an International MSR Science Institute (IMSI). This is envisioned to be a virtual institute, a confederation of Mars science agencies or countries that are substantially involved in MSR, from missions to sample analysis to curation. The purpose would be to establish a close, productive interaction among its members, analogous to what exists in a classical, collocated institute, even though the members would be geographically separated. The benefit would be the coordination of joint international missions and the maximization of scientific return from, what would then be, the most precious samples on Earth. The advantages for members would be direct involvement and access to the missions, laboratories, and samples themselves.

6.2.2 Managing the Asset (the samples)

The general process by which the samples would be tracked, protected, and made available to the international research community is referred to as sample curation. This must be planned on an international basis. Sample curation can be divided into distinct, but interconnected, functions:

Documentation and tracking

All primary samples and subsequently produced subsamples would be documented and tracked.

Handling and subdivision

Samples would be subdivided as necessary to permit initial examination and to prepare subsamples for life / biohazard assessment and subsequent detailed research. All handling and subdivision would be conducted under extremely clean conditions.

Contamination and environmental control

To the extent possible, samples would be maintained under conditions that would not alter the samples in any way. Inorganic, organic, and biological contamination of the samples would be minimized.

Secure storage

Samples would be stored under a high level of physical security in order to prevent theft or damage.

Allocation for detailed research

Following release from the SRF(s), the samples would be transferred to one or more Mars curation facilities for long-term storage and allocation to the international research community.

6-3 Cost Estimation for MSR

The current consensus for the end-to-end MSR mission costs range from \$4.5B to \$8B or B€3 to B€5.3, depending on the final requirements and international cooperative structure. These rough-order-of-magnitude costs are based upon past MSR studies, as well as actual cost data from recent Mars missions, including the Mars Exploration Rovers, MSL, and ExoMars.

Current estimates are of necessity high level and would be refined continuously in the future, based on further requirements definition, results of technology investments, and the sharing of responsibilities between the partners. One of the more important activities in Phase II of iMARS will be to support the development of a reliable estimate of the end-to-end costs and funding requirements for an international MSR.

However, nations, agencies, and institutions that intend to participate in MSR can start now to gauge the required near-term investment based on the long-lead technologies as described in section 5.3 and associated with building blocks summarized in section 3.2. The requirement to have these technologies proven in a relevant environment prior to the applicable PDR dates necessitates early investment and invites parallel development.

VII. Public Outreach and Education



COLUMBIA HILLS

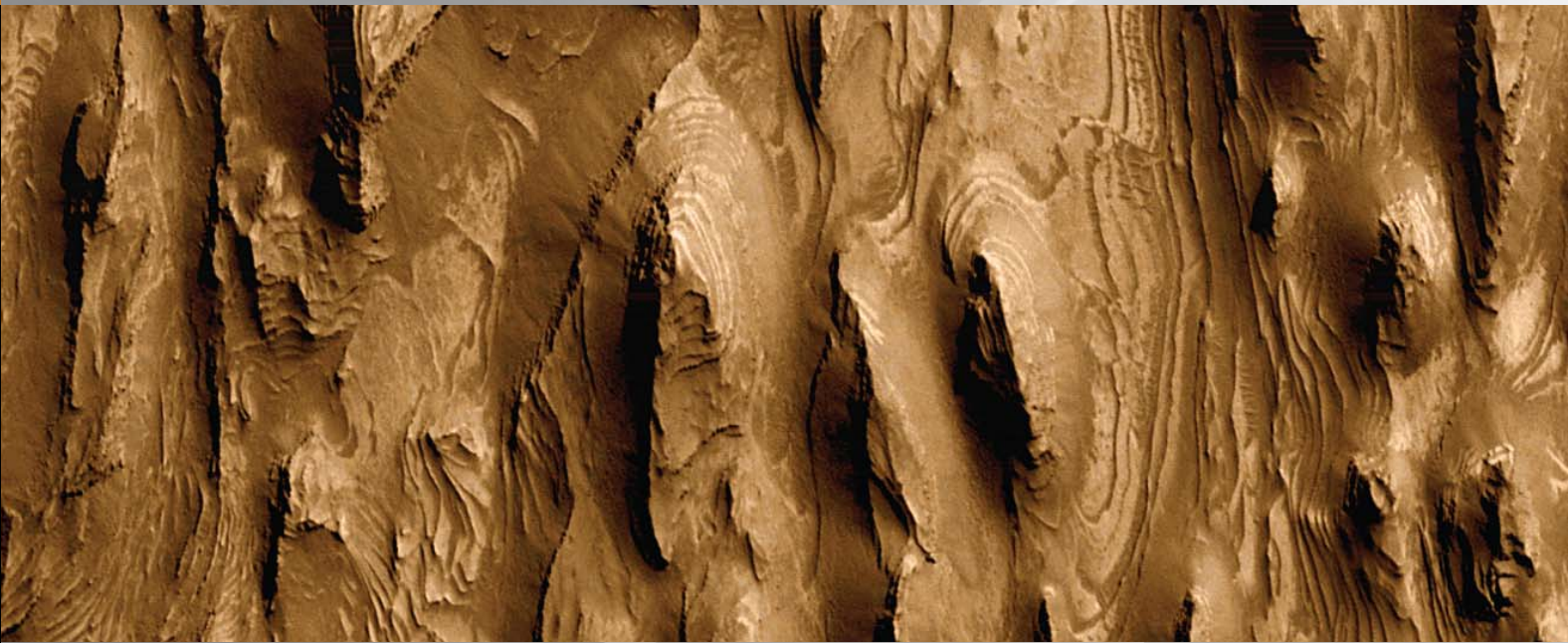
Portion of approximate true-color panorama taken by NASA's Spirit rover after it successfully trekked to the top of "Husband Hill," in the "Columbia Hills" of Gusev Crater.

iMARS

During Phase I of iMARS, there was very little opportunity to promote an MSR mission to the general public or to produce any educational materials. The iMARS team did, however, recognize that public outreach and education would be essential components of any future mission and have highlighted this issue as an important part of the work of the IMSI.

Several planning aspects for a possible MSR mission were discussed by iMARS with peer groups at international conferences. Papers were given at the Astrobiology Science Conference in California and at the European Geosciences Union Meeting in Vienna, both in April 2008. Presentations will also be made at the COSPAR Congress in Montreal in July 2008, the International Astronautical Federation Congress in Glasgow in September 2008, and the Geological Society of America General Assembly in Houston in October 2008. Abstracts for these presentations are attached in Appendix V.

VIII. Conclusions and Next Steps



SEDIMENT PATTERN

The uniform pattern seen here—similar layers repeated over a hundred times—suggest that the deposition of the layers was interrupted at regular intervals. Patterns like this, when found on Earth usually indicate the presence of sediment deposited in dynamic, energetic, underwater environments. This image from Candor Chasma was taken by Mars Global Surveyor in 2000.

iMARS

8-1 Conclusions

As a result of its Phase I work, iMARS has reached the following conclusions:

- The first MSR mission would make an enormous contribution to many of our fundamental scientific questions. However, the ultimate scientific return of the mission would be dependent on the character, diversity, and quality of the samples returned. There are important trade-off discussions between implementation/cost and benefit in this area that still need refinement.
- Even if a large set of existing or under-development technologies could be reused or adapted, a limited number of critical technologies need new development, including the MAV, automatic rendezvous and capture in Mars orbit, biosealing, hazard avoidance, and Earth Entry Vehicle system design and test. They would require a substantial effort in the short/medium terms to reach a correct maturity level in the early phases of the project.
- Planetary protection challenges for an MSR mission would be beyond those encountered for one-way Mars missions, particularly as related to the containment of martian samples from the point of entry into the Earth's environment until the potential for biological hazards could be definitively assessed. There would be some significant technological planetary protection challenges, including aseptic sample transfer, redundant containment of the flight system, and biohazard assessment after the samples return to Earth.
- The implementation of PP and contamination control requirements to the end-to-end mission system is identified as critical and is not fully analyzed today,
- Two launch vehicles would be required to separately launch the lander/MAV composite and the orbiter/return vehicle composite. Mars aerocapture would not be required for either composite; the needed entry, descent and landing system could be based on a slightly enhanced MSL system; the horizontal mobility specification could be satisfied with an enhanced MER class sampling rover; and the lander-based sampling system could be based on the one planned for ExoMars.
- MSR could be divided into approximately 20 separate elements that could be considered for funding by different international entities. However, a clear challenge for an international MSR would be the management of the interfaces between these different elements. Determining "who does what" would be partly a technical and partly a political question, and this would not be something iMARS could do on its own.
- If the resources are available and decision making at international level is efficient, the mission could be started in ~2013 (phase B start) for launches around 2020 and receiving a sample back on Earth three years later (see § 5.1).

8-2 iMARS Phase II—Forward Planning

Although iMARS was able to summarize some of the high-level issues associated with developing a potential plan for an international MSR, progress is needed in several technical and management areas before entering into a structured Phase 0. Additional analysis would be helpful in the partnership-forming phase. Thus, an extension of the work of the iMARS group is recommended—this is referred to as iMARS Phase II.

8.2.1 General Objectives

There are six primary areas associated with generating the necessary support for an international MSR in which iMARS could make a significant contribution if the committee were to continue its work for at least another year:

- The current fundamental basis such as the high-level requirements and the reference architecture must be consolidated, particularly to take into account the international aspects of this mission and assess the PP and contamination control implementation.
- Continue to refine the interplay between science and engineering. We need to understand the trade-offs between feasibility, cost, and value in order to find ways to optimize the flight and on-Mars systems given the multiple programmatic and technical constraints. As part of this, there is consensus building still to be done within the science community—their strong advocacy is absolutely essential.
- Understand in more detail how to break the mission down into components that would be potentially led by different financial and implementation entities and understand the issues associated with managing the interfaces between these components, along with keeping these interfaces as simple as possible while achieving correct performances.
- Improve confidence in our cost estimates, and this would require maximizing and focusing early technology and analysis investments/efforts.
- Develop a mechanism to engage potential sponsors, to assess degree of interest, and appropriateness of technical fit.
- Initiate public engagement. We need to get early information out about the value of the mission and our approaches to risk management.

8.2.2 iMARS Phase II Proposed Organization

For iMARS Phase II to be most productive, it clearly needs continued work from the Phase I science and engineering teams, perhaps with some expansion of membership. iMARS also needs a means of working with IMEWG on the political issues and defining coordinated strategies for getting the MSR messages out to the public.

Concerning the critical issues of planetary protection and sample facilities, we propose a different approach than in the iMARS Phase I, in which there was a “Facilities” subteam that evolved to also encompass “Planetary Protection.” In the area of planetary protection, it is critically important to keep the setting of policy separated from the implementation of policy. Thus, we propose the following improved structure:

- Agency Planetary Protection Officers would lead the development of Version 2 of the Draft Test Protocol, independent of iMARS. iMARS’ job would be to implement what is required for planetary protection compliance, not to develop the requirements.
- Form a relatively small Earth Operations Subteam within iMARS that would have, as their first task, requirements definition in the areas of ground recovery operations, Earth surface transportation, sample receiving/testing, and curation. This team should focus on risks associated with sample handling, transfer, and preservation.
- Incorporate some of iMARS’ PP experts into the engineering subteam, to help with the design of PP-compliant solutions to the flight system. PP needs to be integrated into the design of the flight system from the very beginning.
- Have two agency Planetary Protection Officers participate in iMARS in *ex officio* roles and have them provide guidance to both the Engineering and Earth Operations subteams.

8.2.3 Engineering Subteam—Forward Planning

At the end of its Phase I work, the Engineering Subteam identified the following fields where deeper technical studies are deemed necessary in order to pave the way for an efficient start of a project Phase 0 technical activities:

- Consolidate architectural and system aspects, according to the updated high-level mission requirements and initial ideas regarding potential sharing of responsibilities;
- review and analyze the possible PP implementation options and contamination control implementation;
- elaborate detailed sampling strategies (linked with candidate landing sites);
- refine engineering of the most critical building blocks and identified critical technologies;
- update of the technology challenges and needed capabilities (“roadmap”, strategies, etc.); and
- specific open points (precursor mission(s), ITAR, organization of Phase 0).

The proposed approach, in addition to the collaborative work within the team and with the other iMARS subgroups, is to organize large audience workshops in the following areas: MAV concept and rendezvous strategies, biosealing and EEV design, sample acquisition strategy and systems, Entry Descent and Landing (EDL) System.

8.2.4 Science Subteam—Forward Planning

Develop a draft Science Management Plan including the following topics: sample management rules and processes, “Stuck in the SRF” science planning, surface science team and management, and selection processes for various teams. In addition take up the following issues:

- IMSI definition—develop a proposal
- Begin landing-site selection process and its execution
- Refine open questions re: lander-based sampling system
- Surface operations planning, impact on requirements
- Lower priority in first year: Update contamination requirements
- Ground based sample measurements in laboratories

The proposed approach is to form a long-lead MSR science team and conduct 1–2 meetings, but predominantly use telecons and e-mail.

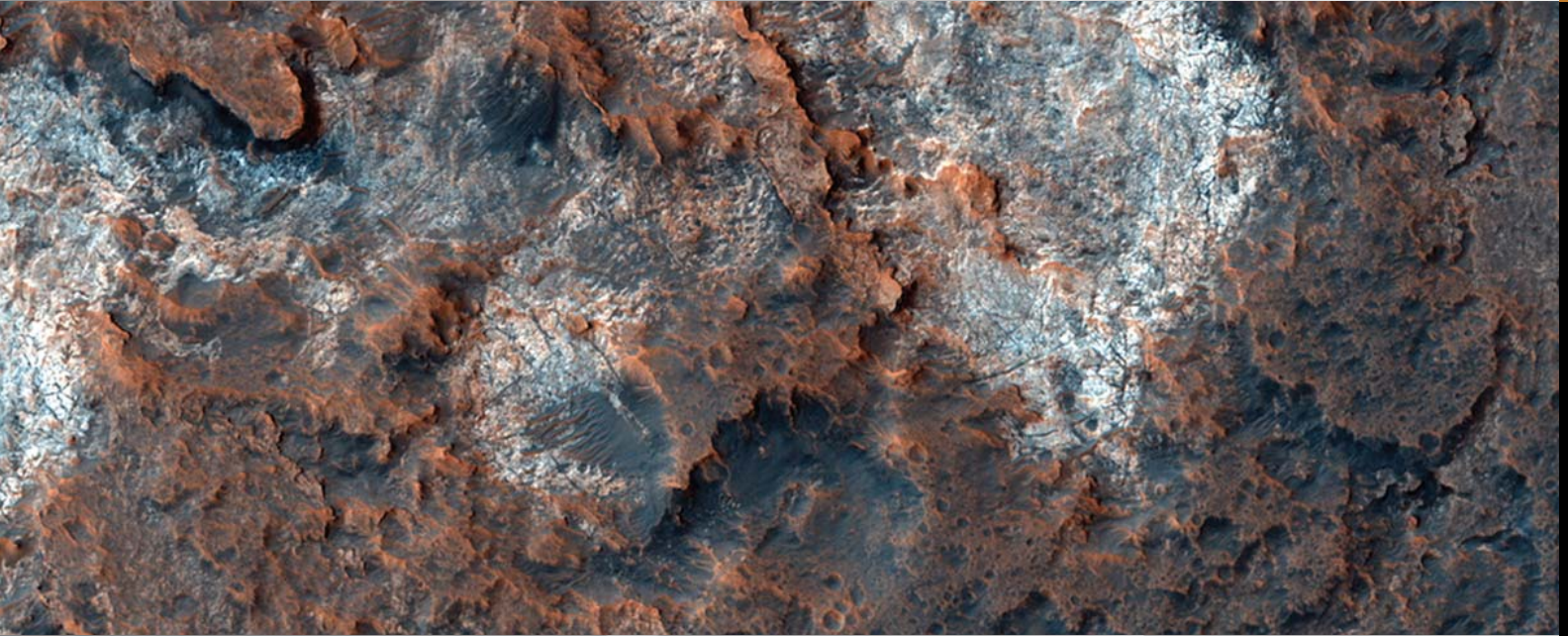
8.2.5 Earth Operations Subteam

It would be most useful at this time to have the Earth Operations Subteam focus on requirements definition (other than the planetary protection requirements that take the form of policy). In order to make our description of the mission complete, we should include ground recovery operations at the Earth landing site and transportation from there to the SRF(s). Thus, we need requirements in four areas:

- landing site operations,
- Earth surface transportation,
- SRF(s), and
- curation.

The proposed approach is to conduct 1–2 meetings, but predominantly use telecons and e-mail.

Acknowledgements, References and Appendices



MAWRTH VALLIS

Mawrth Vallis has a rich mineral diversity, including clay minerals that formed by the chemical alteration of rocks by water. The CRISM instrument detects a variety of clay minerals here, which could signify different processes of formation. The high resolution of the HiRISE camera on MRO helps us to see and trace out layers, polygonal fractures, and with CRISM, examine the distribution of various minerals across the surface.

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APPENDIX I. Terms of Reference

International Mars Exploration Working Group (IMEWG)
Charter for an International Working Group On the Return of Samples from Mars

Phase I

The overarching goal of this activity is to identify how international cooperation might enable sample return from Mars, document the existing state-of-knowledge on return of samples from Mars, develop international mission architecture options, identify technology development milestones to accomplish a multi-national mission, and determine potential collaboration opportunities within the architecture and technology options and requirements, and current Mars sample return mission schedule estimates of interested nations. The activity will also identify specific national interests and opportunities for cooperation in the planning, design, and implementation of mission-elements that contribute to sample return. The Working Group's final product(s) is expected to be a potential plan for an internationally sponsored and executed Mars sample return mission.

Phase I of this working group is limited to the following activities to develop a common international understanding and go-forward plan for follow-on sample return mission studies:

- Concisely document the rationale for the benefits of Mars Sample Return, in terms of
 - the scientific objectives; and
 - the role in human exploration.
- Develop and document a detailed understanding of the current state-of-knowledge for Mars sample return, including studies and reports, conceptual architectures and mission elements, general technology maturity, and national interests.
- Earth-based return/receiving facilities related to the current state-of-knowledge will be included in this research.
- Identify critical challenges and opportunities for Phase II (including technical, scientific, programmatic and public understanding and awareness issues).

The Sample Return Study Group (SRSG) will be an activity supporting the International Mars Exploration Working Group (IMEWG):

- The chair, appointed by IMWEG, with approximately 15 members from the international Mars community (by appointment) would constitute the SRSG;
- SRSG members will be scientists, engineers and technologists as appropriate; and
- The working group shall complete the initial study within 12 months, with an interim report to IMEWG approximately half way through the study.

Deliverables:

A report and related presentation material covering the study/research topics outlined above for Phase I of the SRSG.

Future Phases:

Future phases of the SRSG will be determined by the members of the IMEWG, but are anticipated to build on the Phase I initial research to eventually develop a detailed set of science priorities, mission requirements, critical technologies and development timelines, opportunities for international cooperation, and a range of technically and financially feasible mission architectures.

Additional phases will be defined and scheduled by IMEWG as results of Phase I are received.

APPENDIX II. Draft requirements for a possible international MSR mission.

Requirement Type	Ref.	Title	Description
Science			
<i>Sample Acquisition</i>	1	Cache retrieval	If MSL ends its mission in an accessible location with a cached sample on board, MSR should be designed to have the capability to recover the cache(s)
	2	Sample types	MSR will have the capability to collect rock, granular materials (regolith, dust) and atmospheric sample(s)
	3	Sampling redundancy	MSR will have both a rover-based sampling system and a lander-based sampling system
	4	Rover-based sampling system	MSR will have a rover-based sample-acquisition system
	4a		
	5	Lander-based sampling system	MSR will have the capability to collect samples at the landing site
	5a		The lander-based system will have the capability to collect contingency samples within TBD time of landing. [Note: to be defined in Phase II]
	5b		The lander-based system will have the capability to collect core samples of TBD cm from a depth of up to TBD m in regolith or soft rock and an atmospheric sample [Note: to be defined in Phase II]
	7	Rock Samples: number and volume	MSR will collect at least 20 samples of at least 3.5 cc each
	8	Granular Materials: number and volume	MSR will collect at least 4 samples of at least 3.5 cc each
	9	Gas Sample: number and volume	MSR will collect at 1 sample of 10 cc at a pressure of 0.5 bar
	10	Sample encapsulation	MSR will have the capability to encapsulate each sample in an airtight container to retain volatile components of solid samples with the associated solid samples and protect samples from commingling
	10a		MSR will have the capability to encapsulate atmospheric samples
	11	Total sample mass	MSR will return a minimum of 500 g of sample mass
	13	Horizontal mobility	MSR will have the ability to rove to the edge of its landing error ellipse ("go-to" capability), carry out a 2.5 km sample acquisition traverse, then return to the lander.
	16	Sampling site (latitude band)	MSR will be able to access landing and sampling sites within +/- 30 deg latitude
<i>Sample preservation</i>	17	Sample temperature (max C for duration t)	The end-to-end MSR mission will retain samples at a maximum temperature of +20C and will record sample temperature with TBD frequency up to the Earth landing [Note: to be defined in Phase II]

APPENDIX II. (Continued)

Requirement Type	Ref.	Title	Description
<i>Sample preservation (Continued)</i>	17a	Sample integrity	All sample handling and transfer components including the Sample Container will be designed to prevent crushing or pulverization of collected rock samples
	18	Maximum allowable contamination of samples	DRAFT: The maximum allowable contamination of samples by Earth-sourced organic contaminants prior to analysis will be <10ppb total organic carbon [Note; to be defined, following additional data from MSL and ExoMars]. Additional limits by classes of molecules at 25% of the levels specified by Mahaffy et al. (2004, Table 2).
	19	Maximum allowable contamination of samples	DRAFT: The maximum allowable contamination of samples by Earth-sourced inorganic contaminants prior to analysis will be 0.1% of the concentration in the SNC meteorites. Specific levels summarized in Table 7 of MacPherson et al. (2005)
	20	Maximum allowable contamination of samples	DRAFT: The scientific requirement for maximum allowable contamination of samples by live Earth-sourced organisms prior to analysis is equivalent to that specified by planetary protection [Ref #104]
	21	Recognize contamination background	MSR will establish and implement procedures to recognize and characterize the contamination background.
	23	Sample cross-contamination by Mars-sourced contaminants mitigation	TBD [Note: to be defined in Phase II]
<i>Additional measurements</i>	24	Sample characterization capability	DRAFT: MSR will have the capability to document the appearance, characterize the mineralogy and bulk chemistry, and identify the presence of organic carbon
	26	Site characterization capability	DRAFT: MSR will have the ability to characterize prospective sample-collection sites to enable site selection and the ability to document physical and environmental characteristics at each sample-collection site.
	29	Long-term storage	The MSR ground facilities will provide storage for all samples and subsamples, as well as test coupons of all materials that could come in contact with the samples under TBD security, TBD environmental, and TBD cleanliness, conditions for a period of not less than TBD (proposed 30) years
Planetary Protection			
<i>Forward control</i>	101	Total bioburden limit and impact probability limit	Total bioburden control (<5E5 bacterial spores) or lifetime requirement (<1E-2 impact probability) shall be applicable for flight systems (i.e. orbiter, hard impacting hardware for all mission phases).
	102	Bioburden limit for landed systems (per IVb category)	The bioburden of the landed system shall be equal or less than Viking post-sterilization level, or at a level driven by the nature and sensitivity of the particular biohazard investigation, whichever are more stringent, OR the subsystems which are involved in the acquisition, delivery, and analysis of samples used for biohazard assessment shall have a bioburden at that level, and a method of preventing their recontamination and the contamination of the samples to be analyzed is in place. Recontamination prevention is applicable until and including analysis in SRF(s).

Requirement Type	Ref.	Title	Description
<i>Backward control</i>	103	Probability for Earth contamination	Meet COSPAR requirements. The probability that a single unsterilized particle of 0.2 microns in diameter or greater shall be released into the Earth environment shall be less than 1×10^{-6} . (TBC)
	104	Break the chain of contact	The mission and the spacecraft design shall provide a method to break the chain of contact between Earth and Mars. No uncontained hardware that contacted Mars, directly or indirectly, shall be returned to Earth.
Mission			
<i>Launch and Earth-to-Mars trajectory</i>	201	Number and type of launchers	MSR mission planning will allow international cooperation
	202	Launch sequence	MSR mission planning will allow international cooperation
<i>Mars arrival and landing</i>	203	Launch constraints	TBD depending on the selected launch vehicle
	204	Landing period	MSR element landings should not occur during conjunction periods and global dust storms (probability less than 20 % of optical depth > 1) [Note: to be confirmed in Phase II]
	205	Mars arrival sequence	There will be an orbiting asset with telecomm relay capability at Mars for critical event telemetry for any landed mission. This relay capability may be provided by an element of the MSR mission or another spacecraft.
	206	Landing accuracy	The baseline landing accuracy is ± 3 km (3-km landing ellipse radius, 3 sigma)
	206b	Safe landing	The probability of a safe landing will be TBD.
	207	Surface operations period	The MSR landed element will be capable of surviving and maintaining communications through global dust storms [Note: Number and duration TBD]
<i>Mars Operations</i>	209	Surface mission duration (from landing to MAV launch)	The MSR sample-acquisition elements will be capable of operating on the surface of Mars for a minimum of TBD months [Note: to be derived from traverse and sample-acquisition times]
	210	Detection, rendezvous and capture duration	The MSR orbital rendezvous and capture will take no more than TBD months [Note: to be derived based on lander and orbiter launch opportunities and trajectories to/from Mars]
<i>Earth return</i>	211	Maximum Earth entry velocity	The maximum Earth entry velocity will be < 12 km/s [Note: to be derived in Phase II based on engineering studies]
	212	Return abort requirement	The MSR Earth return and entry systems will meet COSPAR planetary protection requirements (see 101)
	213	Earth landing location	TBD. No strong requirement, but impacts transportation from the landing site to the SFR
	214	Max time for EEV recovery after landing	TBD hours [Note: to be derived from thermal-control profiles and security requirements]

APPENDIX II. (Continued)

Requirement Type	Ref.	Title	Description
Programmatic			
<i>Program timing</i>	301	Launch dates	TBD [Note: to be derived from funding profiles and launch opportunity characteristics] Launch of Lander Composite no later than 2020
	302	Total mission time	MSR will return the samples within 5 years after the launch of the first element
<i>Sharing of responsibilities</i>	303	Mission element responsibility	MSR mission planning will allow international cooperation
	304	Launch vehicle(s)	MSR mission planning will allow international cooperation
	305		MSR mission planning will allow international cooperation
<i>Risk mitigation</i>	306	Sample Receiving Facility(ies) responsibility and location	MSR mission planning will allow international cooperation
	309	Duplication of sample containers	TBD. [Note: To be determined based on assessment of the cost vs. benefit of sample redundancy]

APPENDIX III. Definition of Technology Readiness Levels (TRLs)**Introduction**

Technology Readiness Levels (TRLs) provide a system that supports assessment of the maturity of a particular technology and consistent comparison of maturity between different types of technologies. The European Space Agency, NASA, and the Japanese Aerospace Exploration Agency have adopted these definitions to facilitate collaboration on international missions.

Technology Readiness Levels Summary

TRL 1 Basic principles observed and reported

TRL 2 Technology concept and/or application formulated

TRL 3 Analytical and experimental critical function and/or characteristic proof-of-concept

TRL 4 Component and/or breadboard validation in laboratory environment

TRL 5 Component and/or breadboard validation in relevant environment

TRL 6 System/subsystem model or prototype demonstration in a relevant environment (ground or space)

TRL 7 System prototype demonstration in a space environment

TRL 8 Actual system completed and “flight qualified” through test and demonstration (ground or space)

TRL 9 Actual system “flight proven” through successful mission operations

APPENDIX IV. Summary of COSPAR Planetary Protection Classifications

COSPAR guidelines impose requirements on spaceflight missions according to five categories of target body and mission type combinations [Ref. COSPAR PLANETARY PROTECTION POLICY (20 October 2002; Amended 24 March 2005)]

Category Definitions

Category I includes any mission to a target body, which is not of direct interest for understanding the process of chemical evolution or the origin of life. No protection of such bodies is warranted. The requirements are for simple documentation only.

Category II missions comprise all types of missions to those target bodies where there is significant interest relative to the process of chemical evolution and the origin of life, but where there is only a remote chance that contamination carried by a spacecraft could jeopardize future exploration. The requirements are for simple documentation only.

Category III missions comprise certain types of missions (mostly flyby and orbiter) to a target body of chemical evolution and/or origin of life interest or for which scientific opinion provides a significant chance of contamination, which could jeopardize future exploration. Requirements will consist of documentation (more involved than Category II) and some implementation procedures, including trajectory biasing, the use of cleanrooms during spacecraft assembly and testing, and possibly bioburden reduction.

Category IV missions comprise certain types of missions (mostly surface missions) to a target body of chemical evolution and/or origin of life interest or for which scientific opinion provides a significant chance of contamination, which could jeopardize future exploration. Requirements imposed include rather detailed documentation (more involved than Category III), and an increased number of implementing procedures. The implementation procedures required may include trajectory biasing, the use of cleanrooms during spacecraft assembly, bioburden control and sterilization processing.

Category V missions comprise all Earth return missions. The concern for these missions is the protection of the terrestrial system, the Earth and the Moon. The Moon shall be protected from backward contamination to retain freedom from planetary protection requirements on Earth Moon travel.

- For solar system bodies deemed by scientific opinion to have no indigenous life forms, a subcategory “unrestricted Earth return” is defined. Missions in this subcategory have planetary protection requirements on the outbound phase only, corresponding to the category of that phase (typically Category I or II).
- For all other Category V missions, in a subcategory defined as “restricted Earth return,” the highest degree of concern is expressed by the absolute prohibition of destructive impact upon return, the need for containment throughout the return phase of all returned hardware which directly contacted the target body or unsterilized material from the body, and the need for containment of any unsterilized sample collected and returned to Earth. Post-mission, there is a need to conduct timely analyses of the unsterilized sample collected and returned to Earth, under strict containment, and using the most sensitive techniques. If any sign of the existence of a non-terrestrial replicating entity is found, the returned sample shall remain contained unless treated by an effective sterilizing procedure. Category V concerns are reflected in requirements that encompass those of Category IV plus a continuing monitoring of project activities, studies and research (i.e., in sterilization procedures and containment techniques).

APPENDIX V. iMARS Conference Presentations

European Geosciences Union (EGU) (Vienna, April 2008)

Title: Planning for an International Mars sample Return Mission

Authors: M. Grady and the iMARS team

Abstract:

The return of samples from Mars, although technologically challenging, is essential for answering critical scientific questions that cannot be addressed by purely *in situ* mission. It is only through detailed terrestrial laboratory study of carefully chosen rock, regolith, ice and atmosphere samples that information related to habitability and life (including geological context, geochronology, and planetary evolution) can be obtained. Furthermore, it is only through careful analysis of returned samples that most of the surface conditions relevant for human exploration can be characterized.

The importance and complexity of such a mission necessitates a multinational effort, with particular collaboration between NASA and ESA, as well as the participation of space agencies from other countries. To this end, the International Mars Exploration Working Group (IMEWG) formed an international study group to investigate the architecture of an International Mars Sample Return mission (iMARS). iMARS has been supported by a MEPAG-sponsored multi-disciplinary science team with about 30 members, known as ND-SAG. Building from the efforts of previous groups, new concepts have emerged. The new vision for MSR emphasizes the integration of sample selection and study of the considerable data base that already exists since the Viking mission of 1976.

It is envisaged to return about 500 g of rock, regolith, dust, and atmosphere materials, individually packaged and separated from each other. However, it is obvious that no one landing site on Mars can satisfy all the science objectives, and the currently proposed mission is best thought of as the first sample return.

Astrobiology Science Conference (AbSciCon) (California, April 2008)

Title: Preliminary Findings Related to the Use of Sample Return to Advance our Life-Related Goals for Mars.

Authors: Beaty, D.W., ND-SAG and iMARS planning teams

Abstract:

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, each of which is further broken down into four investigations. Although each of these investigations could be advanced by the analysis of returned samples, the approaches are different, and different kinds of samples are implied.

Sample types that would be of interest include sedimentary rocks that span the range of depositional and diagenetic environments, rocks that have experienced water/rock interactions under different kinds of conditions, igneous rocks, samples of the regolith and dust, samples of ice, and a gas sample. The kinds of measurements that would be done on these samples in terrestrial laboratories would include detailed characterization of the texture, mineralogy, and chemistry, and at a scale, accuracy and precision that is not possible via *in situ* missions.

The potential scientific value of returned samples would be dependent on several factors, including the size of the samples, the kind and number of samples, the method by which the samples are acquired, the way they are packaged, their mechanical integrity after Earth return, their maximum temperature, and the amount of information available for sample selection and documentation of sample context at the collection site. Each of these areas should be considered as possible requirements for the MSR engineering system are discussed, as the MSR-related advance technology development program is planned, and as the overall budget of the mission is estimated.

COSPAR (Montreal, July 2008)

Title: Potential International Collaboration for Mars Sample Return

Authors: Doug McCuiston, Bruno Gardini, and the iMARS Team

Abstract:

The Mars Sample Return (MSR) mission has been of interest to the world's space agencies for more than two decades. However, the mission has a number of technical challenges that would make it difficult for any single space agency to achieve on its own. Fortunately, the mission can be broken down into multiple discrete components with definable

interfaces, and this lends itself to the splitting up of these components on an international basis. To evaluate these options, the International Mars Exploration Working Group (IMEWG) has convened the International Mars Architecture for the Return of Samples (IMARS) task force. The IMARS team has systematically evaluated three aspects of MSR: the science, the system engineering and technology development, and the necessary ground facilities, including the sample receiving and containment facility. The goal has been to produce a single, integrated plan for MSR that could be submitted for participation and funding consideration to multiple international space agencies. The IMARS team has been working since September, 2007, and delivered its Phase I analysis to the IMEWG in July, 2008. This paper describes the results of the IMARS analyses, outlines the scientific objectives and a potential international architecture for sample-return collaboration. The objectives for Phase II of IMARS will be also presented.

International Astronautical Federation (IAF) (Glasgow, September 2008)

Title: The Road to an International Architecture for Mars Sample Return—The IMARS Team view (reference: IAC-08-A3.1.3)

Authors: Denis Moura, Frank Jordan, Alain Pradier, Andrea Santovincenzo, Richard Mattingly, Stuart Kerridge, Michael Khan, Bruno Gardini, Doug McCuiston, Lisa May and the iMARS Team

Abstract:

The Mars Sample Return (MSR) mission represents a milestone in the exploration of the solar system and, in particular, in the investigation of the planet Mars and specific questions regarding its potential habitability. For many years, this technically challenging mission has remained as a long-term goal of many of the world's space-faring nations and agencies. This paper will present the recent efforts of the International Mars Architecture for the Return of Samples (IMARS) group, created under the auspices of the International Mars Exploration Working Group (IMEWG), to establish a common, international reference architecture for this landmark mission.

This paper will present an initial consensus international architecture for Mars sample return. It will outline the work performed in establishing and assessing, in a common framework, the major requirements of the mission and their translation into engineering challenges that must be addressed. The major trade-offs arising from the preliminary architecture consideration will be discussed, including their relationship to the mission's ambitious science objectives and strict planetary protection constraints.

In particular, this paper documents the initial analyses performed to identify suitable mission architectures based on the evaluation of Earth-to-Mars and return trajectories, launch vehicle performances, and mission element masses. The next steps after these first cooperative efforts on the MSR mission will be outlined, along with their relationship to broader planning for Mars exploration.

Geological Society of America (GSA) (Houston, October 2008)

Title: Sampling Strategy for a Possible Mars Sample Return Mission

Authors: Gian Gabriele Ori, Carlton Allen, and iMARS Team

Abstract:

Mars Sample Return (MSR) would be a mission devoted to the collection of rock and regolith samples from the martian surface, and their transport back to Earth. The iMARS Working Group is developing potential plans for MSR that could be implemented on an international basis. A critical subsystem for MSR would be the sample collection hardware that would need to operate on the martian surface. The landed package is proposed to consist of a fixed platform and a mid-range rover. In order to avoid surficial weathering, primary sampling would be achieved by a coring device, placed on the rover, that would be able to penetrate rocks to a depth of several cm. The selection of the sampling sites would need to be supported by an array of instruments in order to provide geo-mineralogical context. These instruments would provide large- to medium-scale data about the sampling area in order to identify the main geological units, their geometries and their stratigraphic relationships. Close optical investigation would reveal the gross lithologies and fine-scale structures (e.g. stratification). Geochemical and mineralogical analysis would complement these observations. The sampling strategy would be very similar to the way in which "terrestrial" geologists map an area and sample rocks. In addition, it would be valuable to have a platform-mounted subsurface system (a drill) able to collect samples of regolith, unconsolidated sediment and rocks to a depth of a few meters.

APPENDIX VI. Acronym List and Glossary

Acronym	Definition
A/b	Aerobraking
APXS	Alpha Particle X-Ray Spectrometer
ASI	Agenzia Spaziale Italiana
BSL-4	Bio Safety Level 4, the highest level of containment
CNES	Centre National d'Etudes Spatiales
COSPAR	Committee on Space Research
CT	Computed Tomography
CY	Calendar Year
DT	Direct Transfer
ECA	Evolution Cryotechnique type A (Ariane 5 ECA)
EDL	Entry, Descent and Landing System
EDU	Engineering Development Unit
EEV	Earth Entry Vehicle
EGU	European Geosciences Union
EMT	Earth-Mars Transfer
ERV	Earth Return Vehicle
ESA	European Space Agency
ExoMars	Exobiology on Mars (ESA mission under development for a 2013 launch)
FPGA	Field-Programmable Gate Array
GNC	Guidance, Navigation & Control
GSA	Geological Society of America
IAF	International Astronautical Federation
I/F	Interface
IFO	In-Flight Operations
iMARS	international Mars Architecture for the Return of Samples
IMEWG	International Mars Exploration Working Group
IMSI	International MSR Science Institute (a possible organizational structure that does not yet exist)
ITAR	International Traffic in Arms Regulations
MAV	Mars Ascent Vehicle
MCR	Mission Concept Review
MEPAG	Mars Exploration Program Analysis Group
MER	Mars Exploration Rovers (NASA mission in operation)
MET	Mars-Earth Transfer
MRO	Mars Reconnaissance Orbiter (NASA mission in operation)
MSL	Mars Science Laboratory (NASA mission under development for a 2009 launch)
MSR	Mars Sample Return
NASA	National Aeronautics and Space Administration (US)
ND-SAG	Next Decade Science Analysis Group
NRC	National Research Council (US advisory body)
PDR	Preliminary Design Review

Acronym	Definition
PP	Planetary Protection
ppb/m	parts per billion/million
PRR	Preliminary Requirements Review
RdV	Rendezvous
SNC	Shergottite, nakhlite, and chassigny
SRF	Sample Receiving Facility
SRR	System Requirements Review
SRSG	Sample Return Study Group
TBC	To be confirmed
TBD	To be defined/derived/determined
TRL	Technological Readiness Levels

