Strategic Technology Development for Future Mars Missions (2013-2022)

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[*] An expanded version is posted on the MEPAG web site, and may be referenced as follows:
Samad Hayati, et al. (2009). "Technology Development for Future Mars Missions," White Paper posted September 2009 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.jpl.nasa.gov/decadal/index.html

References are compiled in a separate document at the following web site: http://mepag.jpl.nasa.gov/decadal/index.html.

Introduction

The intent of this white paper is to provide concise information regarding enabling technologies, together with the associated cost and schedule, for the following candidate missions: Trace Gas Orbiter Mission (TGM) [1], Mars Net Lander Mission [2], and missions associated with a Mars Sample Return (MSR) campaign [3] including Mars Astrobiology Explorer-Cacher (MAX-C) [4].

Technologies identified and discussed in this document are those that would be enabling for the missions identified above and could be developed in the 2011-2020 timeframe. Costs provided are estimates (in FY 09 dollars) to bring each technology to NASA Technology Readiness Level (TRL) 6 [5]. It would be essential for key technologies to be at this maturity level at the time of Preliminary Design Review (PDR) in order to reduce mission cost and schedule risks. Cost estimates for possible MSR-related missions were derived from the 2004 Mars Sample Return Technology Program and were recently updated via a NASA Workshop on MSR technologies in 2008 at the Lunar and Planetary Institute.

Some of the technology challenges associated with a potential MSR campaign would be particularly difficult. These include the Mars Ascent Vehicle (MAV); sample acquisition and handling; and back planetary protection (Back PP). The MAV, in particular, stands out as the system with highest development risk, pointing to the need for an early start to complete trade-study analysis, retire component technology risks, and develop and flight-test a flight-like engineering unit in a relevant environment before an MSR Lander (MSR-L) PDR.

Enabling technologies for the candidate missions that are discussed in this white paper

TGM	Net Landers	MAX-C	MSR-Lander	MSR-Orbiter
No new enabling technologies would be needed	Technologies depend on mission architecture and would require further study	Entry Descent & Landing: precision landing and hazard avoidance	MAV	Rendezvous and sample capture
		Sample acquisition and handling	Back PP	Back PP
		Rover technologies: faster traverse	Low-mass, low-power avionics for fetch rover	Earth Entry Vehicle (EEV)
		Avoidance of Earth organisms in returned samples (round trip PP)		Mars Returned Sample Handling (MRSH)

Technologies for Mars Trace Gas Orbiter Mission (TGM) Concept

There are no new and enabling technologies required for this candidate mission.

Technologies for Mars Net Landers Concept

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Technology needs would depend on the architecture of the mission concept. Soft landers would not require new technologies. Rough landers would require developments to ruggedize the lander, the engineering subsystems, and the instruments. In 2008, a lander and penetrator request-for-information yielded a number of candidate technologies, but the costs to develop them varied widely, both in fidelity and magnitude.   Further study of technology needs for a Net Lander Mission would be needed in the future.

Technologies for a Mars Astrobiology Explorer-Cacher (MAX-C) Concept

Entry, Descent, and Landing (EDL)

NASA has invested heavily in developing EDL capabilities in the past. Current capabilities include airbag landing for surface payloads that weigh less than ~200 kg and propulsive landing for more massive landers. The Mars Science Laboratory (MSL), scheduled to launch in 2011, will demonstrate several EDL technology advances that will provide a capability to land heavier payloads (930 kg) with a smaller landing error ellipse (10km radius) than on previous missions. However, there are candidate rover and lander missions that would require an increase in landing precision, hazard avoidance, and the capability to deliver a landed mass exceeding that of MSL. (Current mission architectures deliberately limit any increase of landed mass to ~10% over MSL to avoid the significant expense associated with a step up in launch vehicle capability to the Delta IV Heavy class.) The EDL technologies that would be needed are discussed below.

1) Precision landing: Landing within ~5-7 km of the target could be achieved by several techniques. Based on recent studies, this level of precision could be realized by reducing the initial entry-attitude initialization error and using a range trigger for deployment of the parachute. Ramifications of adopting a range trigger on site elevation would need to be fully understood in order to satisfy both the requirement for increased precision and the requirement for increased landed mass [6].

2) Hazard avoidance: This capability could be achieved by using a three-part approach: terrain-relative navigation using descent images to update the location of the spacecraft; use of orbital images to identify safe areas prior to landing day; and minimum-fuel powered descent guidance to execute divert maneuvers to a safe site [7].

3) Increased landed mass: Future Mars missions would be likely to have designs based on MSL’s landed-payload capability of about 930 kg. Methods to accommodate landed system mass increases (up to10%) could include increased entry vehicle lift-to-drag ratio (L/D) (from 0.24 to 0.3), parachute system enhancements, and reduction in mass of the (anticipated) heritage skycrane descent system.

Sample Acquisition and Handling

NASA has very limited experience in planetary sample acquisition. On Mars, the experience is limited to Viking and Phoenix scoops for sampling regolith. Any future MSR mission would most likely require small core samples (~1cm in diameter and ~5 cm in length) [4]. This would require the development of a coring tool to acquire the samples and a mechanism to transfer the core samples in sealed cases to a sample container. In addition, a sample-acquisition rover would most likely be planned to be mid-sized—smaller than MSL and larger that the Mars Exploration Rovers. Thus, the rover-based sampling systems would have to be sized accordingly.

1) Coring Tool: Shallow coring technology would be needed to acquire rock cores from a wide range of rock types. Examples of current state-of-the-art technology are the Honeybee Corer Abrader Tool [8], the Mini-corer developed for the 2003/2005 MSR baseline mission [8], the Alliance Space Systems Low-Force Sample Acquisition System [9], and MSL’s Powder Acquisition Drill System. While specific tool functions have been demonstrated in prototype tools, no tool provides an integrated set of functions satisfying all of the MAX-C mission concept needs. A significant effort would be needed to develop and validate a coring tool with required overall functionality that would also have low enough mass to enable core acquisition from a small to mid-sized rover on sloped terrain.

2) Sample Transfer, Sealing, and Caching: Technologies would be needed to transfer samples from the coring tool into individual sample tubes, seal the tubes, and store the tubes in a canister on the rover. A significant effort would be needed to develop and validate a system that would work on the wide variety of rock types anticipated and handle cores even if broken during acquisition, as well as satisfy stringent planetary protection and contamination control requirements.

Rover Technologies

The candidate MAX-C mission would deliver a solar-powered rover to the martian surface. The proposed sampling requirement would be to collect 20 samples at four sites outside the landing ellipse within one Earth year. The rover would then drive to a safe location to deposit the 20-sample cache for a fetch rover to potentially retrieve sometime after 2020. For such a scenario, the MAX-C rover would be expected to traverse 10 km in 150 driving sols, i.e., ~67 m/sol on average. Although the Mars Exploration Rovers (MERs) are mechanically capable of faster speeds (up to 252 m/sol), their speed is limited to 29 m/sol when full hazard avoidance and visual odometry, which are required for safe traverse, are functioning. Improved rover autonomy would be needed for the candidate MAX-C mission.

The autonomy cycle for the MERs, which is similar to the planned cycle for MSL, consists of a "sense, think, and drive" cycle. Each cycle, which typically covers a half-meter step, takes as long as three to four minutes for sensing, assessing the traversability of the terrain, completing the traverse step, and measuring the resultant slippage. The energy usage for autonomous drive represents a five-fold increase relative to continues driving, primarily because of the sensing and computational requirements. Advances in rover autonomy would include an increase in sensing and computation throughput through the parallelization of computation. Additionally, it would include algorithmic advances to reduce the amount of computation while increasing robustness. A further advancement to the traverse speed would include the parallelization of the sequential process to enable "thinking while driving" and adaptation for the amount of computation based on terrain difficulty.

Round-Trip Planetary Protection

Forward planetary protection technologies developed over the past decade for MER, Phoenix, and MSL missions would be adequate to satisfy the anticipated MAX-C mission concept's forward planetary protection requirements, i.e., to protect Mars from harmful contamination from Earth. However, since the MAX-C mission concept would be assembling a cache of samples with the intent that it would be returned by a potential future MSR mission, the samples and the associated hardware would have an additional requirement to be kept free of "round-trip" Earth organisms that could interfere with biohazard and life-detection testing of martian samples upon return to Earth. This "round-trip" requirement is not new; it traces to COSPAR and NASA planetary protection policies [10]. Life-detection or sample return missions would have to meet this "round trip" planetary protection requirement, independent of the site on Mars or what *in situ* science were to be conducted.

Overall, there are two distinct approaches to meeting the stringent planetary protection requirements for round-trip PP: system sterilization, or component and subsystem level sterilization, along with associated biobarriers. The technologies that would be needed are discussed below.

1) System sterilization approach: This approach is similar to the terminal sterilization used on Viking by heat treatment, or Dry Heat Microbial Reduction (DHMR), of the entire flight system after assembly and before launch. The advantage of the system sterilization approach is its conceptual simplicity. The disadvantage lies in the issue of hardware compatibility. Further technology investments would be needed to eliminate risks of component or subsystem failure due to incompatibility with DHMR or other treatments.

2) Component and subsystem level approach: An alternative approach would be to conduct cleaning and sterilization at the component level followed by a clean-assembly strategy. Nested subsystem sterilization approaches would need to be used, including aseptic assembly and recontamination prevention, with sensitive subsystems being protected from sterilizing agents or processes later in assembly.

Technologies for a Mars Sample Return Lander (MSR-L) Concept

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Mars Ascent Vehicle

The MAV is a critical part of the MSR mission concept. Although there is extensive terrestrial experience and knowledge in rocket engineering, the US has never launched an unmanned rocket from a planetary surface. NASA conducted industry studies in 2002, from which a baseline design using solid motors was shown to be the best solution [11]. To date, no engineering MAV unit has been developed, thus the MAV as a system is at a very low TRL.

It is anticipated that the MAV would have fundamental requirements to launch from +/- 30^{o} latitude with inclination accuracy to +/- 0.2^{o} and deliver a 5-kg, 16 cm diameter Orbiting Sample (OS) to a 500 +/- 100 km orbit. Continuous telemetry during operation would be required. The MAV would need to be compatible with storage for up to one Earth year on the Mars surface.

Fundamental challenges to a MAV system would be mass, g-loads during EDL, storage on Mars surface, and operation in the martian environment. The current baseline MAV design mass is ~300 kg, but mass growth would be possible due to its low TRL. Alternative options may exist, but additional technology development and testing would be required to assess their feasibility. To reduce risk, a MAV unit would need to be developed and flight tested in a relevant environment (including landing g-loads and Mars environment simulation) 4–5 years prior to launch of the proposed MSR-L. Therefore, the component technologies would need to be at TRL 6 and ready for integration into a flight-test unit 7–8 years prior to launch.

The solid rocket motor approach has significant flight heritage, but the following new developments would need to be addressed if this approach were to be used: the thrust vector control system is not qualified for the proposed MSR mission environments and would need to be qualified for cold temperature and propellant grain design would require analysis and testing for both the high lateral g-loads and long-term storage.

Back Planetary Protection (for MSR Lander and MSR Orbiter)

Back planetary protection deals with the need to assure containment of all returned martian samples, as well as flight hardware that has been exposed to martian material, until they could be tested for possible biohazards. The potential biohazard risk has led to a requirement that samples returned from Mars by spacecraft should be treated as though potentially hazardous until proven otherwise [12]. Back planetary protection would require new technologies for three high-level functions: break the chain of contact with Mars; preserve containment of the sample; and assess sample safety [13]. Back planetary protection technologies would be required for the proposed MSR-L, MSR Orbiter (MSR-O), and the Sample Receiving Facility (SRF). Specific technologies for the lander and orbiter would vary depending on where the “break the chain of contact” would be implemented—lander and orbiter, or orbiter only. As such, the technologies are included in this section, but in reality, some would belong to the orbiter. Technologies for proposed SRF are discussed separately in this document in the Mars Returned Sample Handling section.

The first part of containment assurance would require “breaking the chain of contact” with Mars, i.e., the exterior of the sample container and the spacecraft that would return it to Earth would need to be uncontaminated with Mars material. Next, the sample container and its seals would need to survive the worst-case Earth impact corresponding to the candidate mission profile; the Earth Return Vehicle (ERV) must provide safe and accurate delivery to the Earth entry corridor; and the EEV would need to be designed to withstand the thermal and structural rigors of Earth atmosphere entry, all with an unprecedented degree of reliability. Finally, containment would have to be maintained after the samples were safely received on Earth.

Low-mass, Low-power Avionics

The proposed MSR-L would land a small fetch rover to perform a surface rendezvous with the cached sample container from the proposed MAX-C rover. Current models show that the surface rendezvous would require the fetch rover to traverse approximately 12 km at an average speed of 80 m/sol. To keep the overall MSR lander mass within the (anticipated) heritage MSL EDL capability and increase the speed of the fetch rover, the fetch rover would require low-power, low-mass, and high-throughput avionics. A study conducted by the Mars Technology Program in September 2008 indicated that a Command and Data Handling (C&DH) system based on the path-to-flight high-performance and high-density Xilinx Virtex 5 FPGA (flight programmable gate array) device would satisfy a sub-10 kg requirement. This new C&DH technology would be composed of a double-sided 3U processor board with two embedded Power PC 440 CPUs in the FPGA and a number of other FPGA boards.

Technologies for a Mars Sample Return Orbiter (MSR-O) Concept

Rendezvous and Sample Capture

Orbital rendezvous and sample capture would be a complex series of distinct operations that would extend over a period of up to a month during the capture phase of an MSR mission. The following series of operations would be required: search and detection; tracking and approach; and capture and sample transfer. This last step would consist of physically capturing the OS and moving it to the EEV on board the proposed MSR-Orbiter.

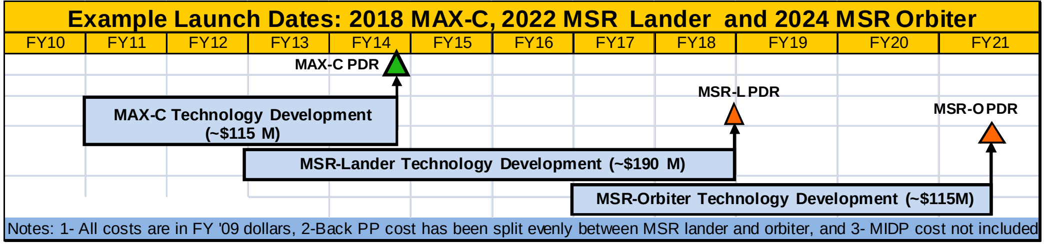
A number of missions have demonstrated technologies that could be adapted for use on the proposed MSR-O. These include the *navigation imaging systems* of Mars Reconnaissance Orbiter and Orbital Express (OE); the *LIDAR systems* of the Air force XSS-11 and OE; the *onboard navigation systems* of Deep Space 1, Deep Impact and OE; the *rendezvous systems* of the Shuttle, the next generation version to fly on Orion, and that of XSS-11. The Mars and other NASA technology programs have also made advances in capture mechanisms [14], LIDARs, software architecture [15], and other areas that could be applied. Nevertheless, in order to accomplish the above proposed MSR functions, a range of technologies would need to be developed or existing technologies would need to be adapted and matured to TRL 6 by MSR-O PDR. Key technology elements would be: autonomously actuated mechanisms for OS capture; optical sensors; OS radio beacon; autonomous rendezvous guidance, navigation and control (GN&C); and ground validation tests. A ground testbed would be required to validate an integrated system.

Earth Entry Vehicle (EEV)

An EEV that would return Mars samples would be required to have extremely high reliability to preserve sample integrity, as well as to meet back planetary protection requirements. For these reasons, the EEV would need to possess particular design attributes. First, the vehicle would need to be "self-righting," so that it would quickly stabilize itself in a heat shield-forward orientation should the release from the Earth return vehicle, a micrometeoroid impact, or some other anomaly cause it to enter the atmosphere in any other orientation. Second, the EEV would be designed to have no parachute or other deployable drag device, since the reliability of such a device would be much less than the required system-level reliability.

In the 2000 timeframe, NASA developed a detailed conceptual design of the MSR EEV. All of the component technologies are available today, with the exception of a limited supply of the carbon phenolic heat shield material that provides the required confidence to meet the planetary protection requirements [16]. However, if the current supply is used for other missions, new heat shield materials that are available today would be considered. The current EEV design would require the construction of an Engineering Development Unit and a flight test, to validate the systems engineering and rigorous ground testing to ensure sufficiently high EEV reliability to meet the PP requirements.

Cost & schedule example for MAX-C, MSR-L, and MSR-O technology development for candidate launch dates



Notes: 1- All costs are in FY '09 dollars, 2-Back PP cost has been split evenly between MSR lander and orbiter, and 3- MIDP cost not included

Technologies for Mars Returned Sample Handling (MRSH)

MRSH denotes the "ground segment" of an MSR mission, i.e., the activities that would occur after landing of an EEV on Earth [17]. After landing, the EEV would be transferred to an SRF, where it would be opened and samples extracted. The SRF would provide containment, contamination control, and capabilities for assessing the possible presence of life or biohazards in representative portions of the samples. The SRF would also have capabilities to preserve the remaining samples for later scientific use. The principles and techniques that would be required for a Mars SRF are generally mature; biosafety laboratories, the NASA Lunar Sample Facility, pharmaceutical laboratories, and electronic fabrication cleanrooms each contain many of the required technical elements. However, specific capabilities unique to the MSR mission would need to be developed: transport of samples, biological safety combined with sample protection, ultra-clean sample manipulation, and sample sterilization.

Science Instrument Technologies for Potential Future Mars Missions

No new science instruments would be needed for the TGM concept mission. The network lander concept mission might require heat flow probes and atmospheric trace gas detectors. Furthermore, depending on the mission architecture, some existing instruments would have to be ruggedized. For the MAX-C concept mission [18], the 2-D in situ micromapping instruments would need development, especially for mineralogy and organic detection. The proposed MSR flight elements would not require any instrument technologies beyond those needed for the MAX-C concept.

NASA has PIDDP and ASTID programs to competitively select and advance science instruments to TRL 3-4. The MIDP program then develops technologies to TRL 6 for Mars missions. Prior experience indicates that without substantial instrument funding, TRL 6 is unlikely to be achieved, which results in an increase in cost and risk for the mission.

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