

# Mission Concept Study

## Planetary Science Decadal Survey MSR Lander Mission

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# Data Release, Distribution, and Cost Interpretation Statements

This document is intended to support the SS2012 Planetary Science Decadal Survey.

The data contained in this document may not be modified in any way.

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Cost reserves for development and operations were included as prescribed by the NASA ground rules for the Planetary Science Decadal Survey. Unadjusted estimate totals and cost reserve allocations would be revised as needed in future more-detailed studies as appropriate for the specific cost-risks for a given mission concept.

# Planetary Science Decadal Survey

## Mission Concept Study Final Report

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# Executive Summary

The Mars Sample Return (MSR) concept is a campaign of three missions: a sample acquisition/caching rover mission, a lander mission to fetch the cache and deliver it to Mars orbit via a rocket, and an orbiter mission that would capture the orbiting sample (OS) container and deliver it to Earth via an Earth Entry Vehicle (EEV). A fourth component is the Mars Returned Sample Handling (MRSH) element that would include a sample receiving facility (SRF) and a curation facility. These elements are represented in three separate mission concept study reports:

- *Mars 2018 MAX-C Caching Rover* [1]
- *MSR Lander Mission*
- *MSR Orbiter Mission (including MRSH)* [2]

The Lander Mission concept is the subject of this report.

The overall objective of the proposed MSR campaign would be to collect samples of Mars (mainly rock cores) and return them to Earth for in-depth analysis in terrestrial laboratories. The objective of the MSR Lander Mission would be to retrieve a cache of rock cores left by the MAX-C rover, collect local samples of regolith and atmosphere, package them in a container suitable for orbit, and launch that package into orbit for subsequent capture by the MSR Orbiter Mission.

While the MSR campaign might be an international endeavor, this report assumes that the complete Lander Mission would be performed by NASA.

## Mission Concept

The MSR lander would be launched on an intermediate-class vehicle on a trajectory that would reach Mars in approximately eleven months. It would enter directly into the martian atmosphere and land using an entry, descent, and landing (EDL) system inherited from the Mars Science Laboratory (MSL) planned for launch in 2011. While MSL is a rover that lands on its wheels, the proposed MSR lander would be a pallet that touches down on the surface. The lander, as currently envisioned, would carry a fetch rover and a Mars Ascent Vehicle (MAV) and would have some capability to locally collect regolith and atmosphere.

The proposed MAX-C caching rover (which would have nominally been at Mars for six years) would have deposited a small cache container of rock cores on the surface for pickup. The MSR lander would target a landing ellipse containing the cache and dispatch its single-purpose fetch rover to retrieve and return the cache to the lander. This process could take as long as 6 months and would involve a round-trip traverse of over a dozen kilometers. While the fetch process is underway, regolith samples would be collected via a scoop on the lander's arm. The sample cache, regolith, and atmosphere would then be packaged in an OS container for transfer to orbit.

The MAV would launch the OS container (a ~17 cm sphere) into a 500 km circular orbit, releasing it with a significant separation velocity. The MSR Orbiter Mission, which would have been launched earlier and would have monitored these events, would then assume responsibility for rendezvous and capture of the OS for return to Earth.

## Key Technologies and Risks

The MSR Lander Mission would primarily use EDL capabilities that will be demonstrated on MSL. Current plans have the MAX-C rover landing on a pallet similar to that planned for MSR and in approximately the same landing ellipse. Thus, it is assumed that accommodation of surface features and/or avoidance of landing hazards would have been demonstrated on the MAX-C mission. The fetch rover would be similar to the Mars Exploration Rovers sent in 2003. The only new feature would be more efficient driving, which would have been developed for and demonstrated on the MAX-C mission. The new challenge for the

MSR Lander Mission would be the ascent, which has never been performed from a planetary surface. Current plans start technology and advanced development for the MAV in 2011, culminating in an Earth-based flight demonstration at high altitude (similar dynamic pressures as Mars) prior to the MSR Lander mission Preliminary Design Review (PDR).



# 1. Scientific Objectives

## Science Questions and Objectives

The current emphasis of the Mars Exploration Program is to answer the question “Did life ever arise on Mars?” Exploration for life on Mars requires a broad understanding of integrated planetary processes in order to identify those locations where habitable conditions are most likely to exist today or to have existed in the past and where conditions are or were favorable for preservation of any evidence of life. Therefore, this endeavor must also investigate the geological and geophysical evolution of Mars; the history of its volatiles and climate; the nature of the surface and subsurface environments, now and in the past; the temporal and geographic distribution of liquid water; and the availability of other resources (e.g., energy) necessary for life.

Accordingly, assessing the full astrobiological potential of martian environments would require much more than identifying locations where liquid water was present. It would also be necessary to characterize more comprehensively the macroscopic and microscopic fabric of sediments and other materials, identify any organic molecules, reconstruct the history of mineral formation as an indicator of preservation potential and geochemical environments, and determine specific mineral compositions as indicators of coupled redox reactions characteristic of life. The requirement for such information guides the selection, caching, and return of relevant samples in order to address the life question effectively using sophisticated laboratories on Earth.

The acquisition and return to Earth of martian materials has been a high science priority since the 1970s. The proposed MAX-C rover would start the sequence of missions to enable Mars sample return to be accomplished in a way that effectively would address the search for evidence of life.

To ensure access to the scientifically most valuable samples, the MAX-C rover would be designed to traverse up to approximately 20 km over a 500-sol nominal lifetime. It would feature mast-based remote sensing instrumentation, arm-based in-situ measurement capability, and the ability to obtain rock cores for a primary and contingency pair of sample caches. These caches would be retrieved during the proposed MSR Lander Mission, via a fetch rover, for return to a Mars Ascent Vehicle (MAV) and eventual delivery to Earth.

In addition to returning the proposed MAX-C rover rock-core cache, the MSR Lander Mission would have two additional objectives:

- Collect and return several samples of regolith to add to the rock-core cache collected by the MAX-C rover.
- Collect an atmospheric sample.

As identified in the Technical Overview section (Section 3), the MSR Lander Mission concept includes a copy of the Phoenix arm, scoop, and camera. The concept includes a dual use of this system to facilitate transfer of the sample cache from the fetch rover to the MAV and to collect local regolith within reach of the arm. The samples would require sealing similar to the rock cores.

The details of collecting an atmospheric sample have not been determined. Envisioned is a small (tens of grams) pump to compress a sample into a void in the lid of the sample canister. The minimum amount recommended by the most recent MSR-related SAG was equivalent to 10 cm<sup>3</sup> at 0.5 bar. Alternatively, atmospheric samples captured at Mars ambient pressure will be assessed in future trade studies.

## Science Traceability

The science traceability matrix is not included in this report because there are no science instruments planned for the proposed MSR Lander Mission. The science would be performed using laboratories on Earth once the samples are returned.

# 2. High-Level Mission Concept

## Overview

The MSR concept is a campaign of three missions: a sample acquisition/caching rover mission (MAX-C rover), a lander mission to fetch the cache and deliver it to Mars orbit via an ascent vehicle, and an orbiter mission that would capture the orbiting sample (OS) container and deliver it to Earth via an Earth Entry Vehicle (EEV). A fourth component is the Mars Returned Sample Handling (MRS) element that would include a sample receiving facility (SRF) and a curation facility.

The Lander Mission concept is the subject of this report.

The overall objective of the proposed MSR campaign would be to collect samples of Mars (mainly rock cores) and return them to Earth for in-depth analysis in terrestrial laboratories. The objective of the MSR Lander Mission would be to retrieve a cache of rock cores left by the MAX-C rover, collect local samples of regolith and atmosphere, package them in a container suitable for orbit (the OS), and launch this package into orbit for subsequent capture by the MSR Orbiter Mission.

The proposed MSR Lander Mission would nominally be the third mission in the MSR campaign. The mission assumes that the MAX-C rover would have deposited a cache of rock cores on the surface for retrieval by the Lander Mission and that the MSR orbiter would be in place to provide telecommunications relay and critical event coverage and to perform rendezvous with an OS. The MSR lander would be launched using a medium-class vehicle on a trajectory that would reach Mars in approximately eleven months under the control of a cruise stage. It would then enter directly into the martian atmosphere and achieve touchdown using an entry, descent, and landing (EDL) system inherited from the Mars Science Laboratory (MSL). While MSL is a rover that lands on its wheels, the proposed MSR lander would be a pallet that touches down on the surface. The lander, as currently envisioned, would carry a fetch rover and a MAV and would have some capability to locally collect bulk regolith and atmosphere.

The proposed MAX-C caching rover (which would have nominally been at Mars for six years) would have deposited a small cache container of rock cores on the surface for pickup. The MSR lander would target a landing ellipse containing the cache and would dispatch its single-purpose fetch rover to retrieve and return the cache to the lander. This process could take as long as six months and would involve a round-trip traverse of over a dozen kilometers. While the fetch process is underway, regolith samples would be collected via a scoop on the lander's arm. The sample cache, regolith, and atmosphere would then be packaged in an OS for transfer to orbit.

The MAV would then launch the OS (a ~17 cm sphere) into a 500 km circular orbit, releasing the OS with a significant separation velocity. The MSR Orbiter Mission, which would have been launched earlier and would have monitored these events, would then assume responsibility for rendezvous and capture of the OS for return to Earth.

## Concept Maturity Level

Table 2-1 summarizes the NASA definitions for concept maturity levels (CMLs). The lander is a new point design produced by JPL's Advanced Project Design Team (Team X) that has been assessed to be at a CML 4. The cruise and EDL systems are assumed to be identical to the MSL systems and are assessed to be at CML 5. The MAV concept is assumed to be the baseline identified here, studied by both industry and Team X. It should be considered at CML 4 since this is the preferred point design at present and it is assumed that alternate designs that might emerge from the technology program would be easier to accommodate and be overall less costly to the project. The fetch rover is assessed at CML 4 as well since it is a preferred point design developed by a full Team X design study and the proposed design has significant heritage from the Mars Exploration Rover (MER) and MSL missions.

**Table 2-1. Concept Maturity Level Definitions**

<b>Concept Maturity Level</b>	<b>Definition</b>	<b>Attributes</b>
CML 6	Final Implementation Concept	Requirements trace and schedule to subsystem level, grassroots cost, V&V approach for key areas
CML 5	Initial Implementation Concept	Detailed science traceability, defined relationships and dependencies: partnering, heritage, technology, key risks and mitigations, system make/buy
CML 4	Preferred Design Point	Point design to subsystem level mass, power, performance, cost, risk
CML 3	Trade Space	Architectures and objectives trade space evaluated for cost, risk, performance
CML 2	Initial Feasibility	Physics works, ballpark mass and cost
CML 1	Cocktail Napkin	Defined objectives and approaches, basic architecture concept

## Technology Maturity

The proposed MSR Lander Mission plans to use some capabilities that have not yet been flown. With the exception of the MAV, risks are anticipated to be retired by MSL or the proposed MAX-C mission by the time of flight system development.

MSL (planned for launch in 2011) is the largest technological contributor having developed the landing capability of delivering 1 metric ton to the surface of Mars that would be needed by an MSR campaign. The MSR Lander would depend on the success of MSL; all systems needed from launch through descent of the platform to the surface plan to use the MSL technology. Current plans have the MAX-C rover landing on a pallet similar to MSR and in approximately the same landing ellipse. Current studies are examining potential methods for accommodating any landing hazards. MAX-C has a technology plan to produce any augmentation needed; thus, these capabilities would be demonstrated on MAX-C before they would be needed by the MSR lander.

The fetch rover would be similar to the Mars Exploration Rovers sent in 2003. The only new feature would be more continuous driving, incorporating less time processing navigation data between small driving increments. This feature, which would also be required for the proposed MAX-C rover and is planned in its technology program, would be demonstrated on the MAX-C mission before it would be needed by the MSR lander.

The new challenge for the proposed MSR Lander Mission is the MAV. Ascent from the surface of Mars to orbit has never been performed. Current plans include the initiation of MAV technology and advanced development in 2011, culminating in an Earth-based flight demonstration at high altitude (similar dynamic pressures as Mars) prior to the mission Preliminary Design Review (PDR). This development is described in the Technology Development Plan section of this report.

## Key Trades

An extensive set of trade studies related to the MSR architecture have been performed over the last decade to find the best balance of science, risk, and cost. The mass of the MAV is a key driver for landing a surface package on Mars. To minimize the mass of the MAV, the orbiter would perform the rendezvous and the rendezvous would be performed in low Mars orbit as opposed to further out (even deep space). Another architectural result of the trade studies is that the original two-mission MSR architecture has evolved into a campaign of three separate missions. This would enable an incremental approach to MSR, which would reduce implementation and mission risk. Separating the difficult task of sample selection and collection from the challenge of Mars ascent would spread the technology risk across the proposed MAX-C rover and MSR lander missions. This would also allow as much time as would reasonably be needed to

find and acquire the samples and would minimize the amount of time the MAV would be exposed to the martian environment.

One of the primary open trades involves methods for accommodating landing hazards. The current approach assumed in this study is to be able to land on hazards that are expected in the sites of interest and then adjust to them with movable legs or jack-screws to facilitate rover egress and to provide a stable platform for sample handling and MAV launch. The proposed MAX-C mission, which also would include a rover landing on a pallet, is currently assessing the trade amongst accommodation of surface features, avoidance of surface hazards during descent by diverting to one of several previously mapped-out safe zones, and actively detecting and avoiding hazards by small maneuvers during descent. This MAX-C assessment will take into consideration MSR lander specific needs. It is expected that the solution developed for MAX-C will be sufficient for MSR.

# 3. Technical Overview

## Instrument Payload Description

There are currently no science instruments planned for the proposed MSR Lander Mission.

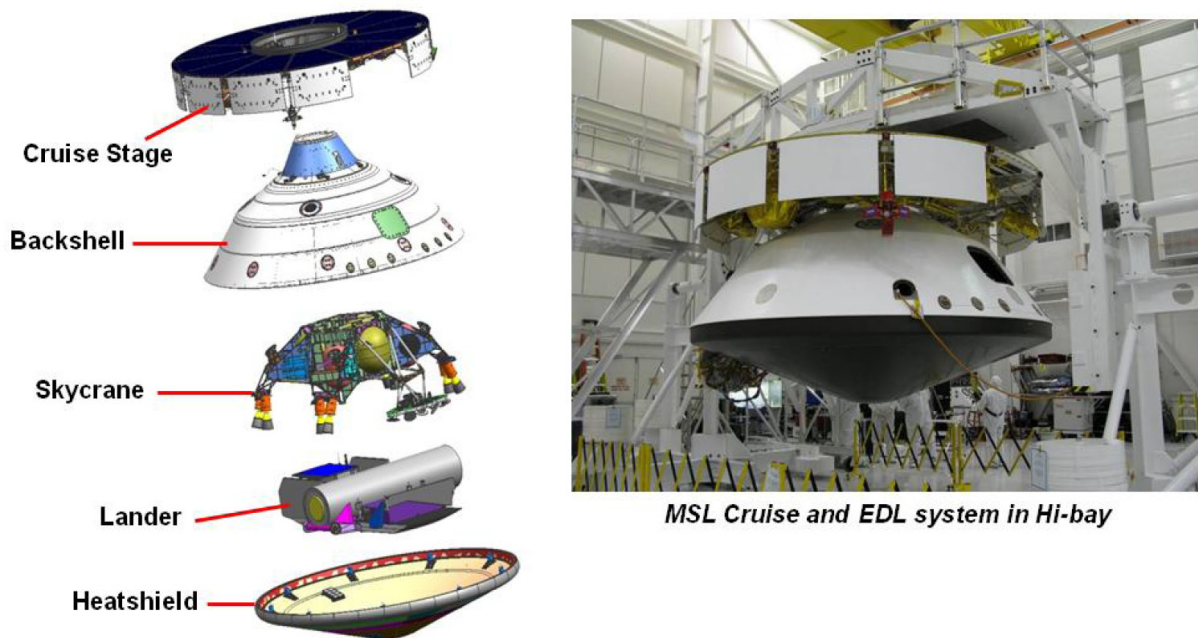
## Flight System

The flight system concept is divided into four flight systems: 1) the cruise, entry, descent, and landing (CEDL) system; 2) the lander; 3) the MAV; and 4) the fetch rover.

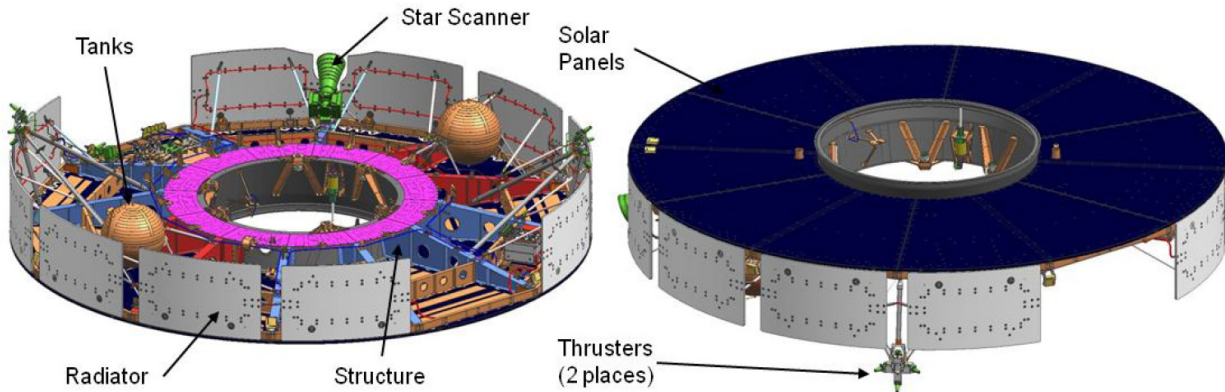
### ***Cruise, Entry, Descent, and Landing (CEDL) System***

The lander would be delivered to the Mars surface by the CEDL system directly inherited from MSL. Figure 3-1 shows the MSL CEDL system in the JPL Hi-bay. The proposed MSR would use a nearly identical system, except that the MSL Curiosity rover would be replaced with the MSR lander. The system could be launched on an Atlas V-551 (MSL is scheduled to launch on an Atlas V-541).

The cruise stage would deliver the EDL system to Mars, release the system prior to entry, and then divert into a trajectory for burn-up in the atmosphere. As depicted in Figure 3-2, it is envisioned to be essentially the same design used for MSL and the proposed MAX-C. It would be spin-stabilized until just before release of the EDL system. It would have a blow-down monopropellant hydrazine propulsion system for attitude control and trajectory correction maneuvers (TCMs), utilizing eight MSL heritage 4.5 N thrusters and dual monolithic titanium diaphragm propellant tanks. Redundant sun sensors and star scanners would provide sensing for the attitude control, with processing and control utilizing the command and data system (CDS) on the lander through a remote engineering unit (MREU). Solar panels, nominally sun-pointed and located on the back of the cruise stage, would provide power to the entire CEDL system and



**Figure 3-1. Proposed MSR Lander CEDL System**



**Figure 3-2. Cruise Stage Concept (Inherited from MSL)**

lander stack during cruise with batteries on the lander being utilized for power storage. Heat dissipation for the lander during cruise would be provided by the cruise stage radiators and a mechanical pump and fluid loop identical to MSL. A cruise stage medium-gain antenna would be connected to the descent stage X-band telecommunication subsystem for use during cruise. Tables 3-1 and 3-2 list preliminary mass and power estimates and system characteristics; Appendix C provides the preliminary master equipment list (MEL).

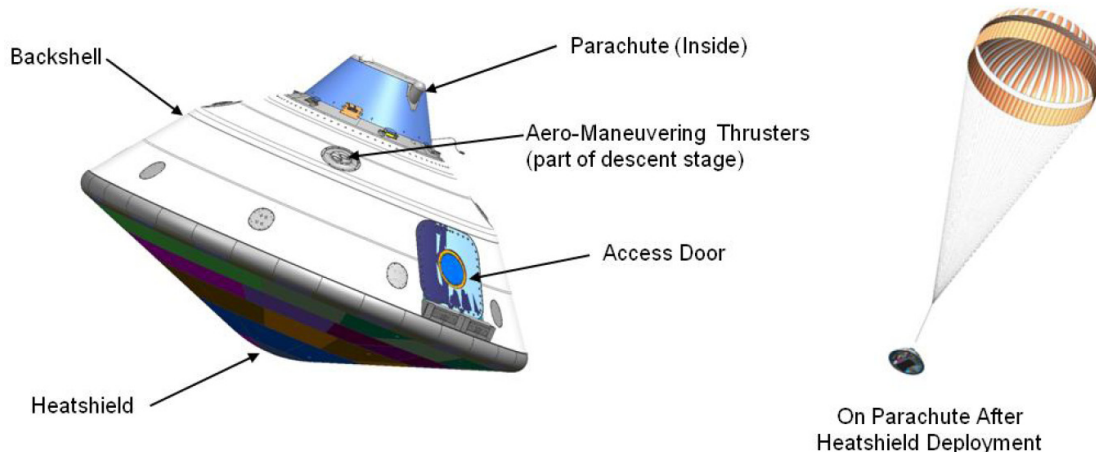
The cruise stage would be attached to the entry stage until shortly before entry. The entry stage would consist of a heatshield, backshell, parachute, and ballast for cruise spin balance (Figure 3-3). The MSL design is baselined for use. Entry velocity is predicted to be lower than that planned for MSL. Guided entry aeromaneuvering would be performed by rolling the vehicle, which would have a center-of-gravity offset to produce lift in desired directions (called bank-angle guidance). Roll would be performed via reaction control system (RCS) thrusters on the descent stage, protruding through the backshell. Approximately 15 kg of descent stage fuel would be consumed. The aeroshell TPS would be Phenolic Impregnated Carbon Ablator (PICA) and the backshell would be SLA-561V. The Viking-shaped 4.5 m diameter heatshield and the MSL supersonic 21.5 m parachute would be used. At about Mach 2, the parachute would be deployed from the backshell and the heatshield released once the subsonic regime is achieved. The descent stage with lander would then be released. Tables 3-3 and 3-4 list mass and power estimates and system characteristics; Appendix C provides the preliminary MEL.

**Table 3-1. Cruise Stage Mass and Power Preliminary Estimates**

	Mass			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)
Structures and mechanisms	210.3	30%	273.4	-	-	-
Spacecraft side LV adapter	45.8	30%	59.5	-	-	-
Thermal control	56.3	7%	60.5	33	43%	47
Propulsion (dry mass)	19.0	26%	24.0	25	43%	36
Attitude control	7.8	10%	8.5	7	43%	10
Command & data handling	1.2	30%	1.6	4	43%	6
Telecommunications	0.7	2%	0.7	-	-	-
Power	33.8	30%	43.9	50	43%	71
Cabling	24.7	30%	32.1	-	-	-
System contingency	-	-	67.1	-	-	-
<b>Total Dry Mass</b>	<b>399.5</b>	<b>43%</b>	<b>571.2</b>	<b>119</b>	<b>43%</b>	<b>170</b>

**Table 3-2. Proposed Cruise Stage Characteristics**

Flight System Element Parameters (as appropriate)	Value/ Summary, units
<b>General</b>	
Design life, months	11 months
<b>Structure</b>	
Structures material (aluminum, exotic, composite, etc.)	Aluminum, titanium, composites
Number of articulated structures	0
Number of deployed structures	0
<b>Thermal Control</b>	
Type of thermal control used	Passive; heat-loop and radiators for lander heat dissipation
<b>Propulsion</b>	
Estimated delta-V budget, m/s	30 m/s
Propulsion type(s) and associated propellant(s)/oxidizer(s)	N <sub>2</sub> H <sub>4</sub>
Number of thrusters and tanks	(8) 4.5 N thrusters (2) N <sub>2</sub> H <sub>4</sub> tanks
Specific impulse of each propulsion mode, seconds	228 s
<b>Attitude Control</b>	
Control method (3-axis, spinner, grav-gradient, etc.)	Spinner
Control reference (solar, inertial, Earth-nadir, Earth-limb, etc.)	Inertial, anti-solar
Attitude control capability, degrees	50 arcsec
Attitude knowledge limit, degrees	6 arcsec
Agility requirements (maneuvers, scanning, etc.)	–
Articulation/#-axes (solar arrays, antennas, gimbals, etc.)	None
Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	0.35 deg sun sensors, 50 arcsec star scanners, 0.005 deg/hr MIMU
<b>Command &amp; Data Handling—Uses Lander CDS</b>	
	MREU and multiplex card only
<b>Power</b>	
Type of array structure (rigid, flexible, body mounted, deployed, articulated)	Body mounted
Array size, meters x meters	5.4 m <sup>2</sup>
Solar cell type (Si, GaAs, multi-junction GaAs, concentrators)	GaAs
Expected power generation at beginning of life (BOL) and end of life (EOL), watts worst case	1725 W BOL, 665 W EOL
On-orbit average power consumption, watts with 43% margin.	~665 W
Battery type (NiCd, NiH, Li-ion)	On lander
Battery storage capacity, amp-hours	N/A



**Figure 3-3. Entry System Concept (Inherited from MSL)**

**Table 3-3. Entry Stage Mass and Power Preliminary Estimates**

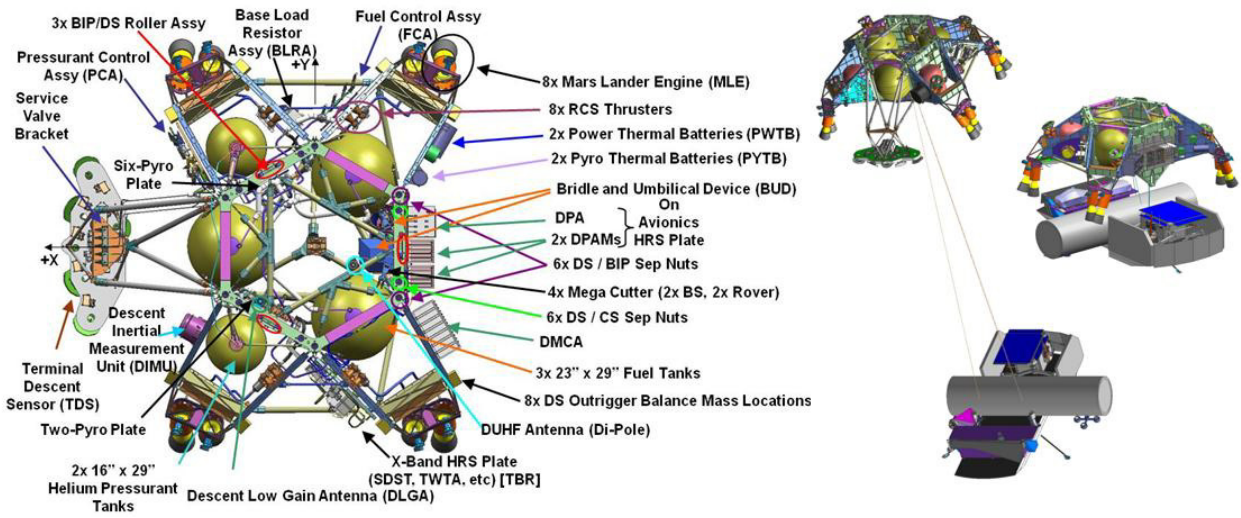
	Mass			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)
Structures and mechanisms	1290.7	30%	1678.0	-	-	-
Thermal control	23.8	8%	25.7	39	43%	56
Telecommunications	12.4	10%	13.7			
Cabling	5.5	30%	7.2	-	-	-
System contingency	-	-	181.0	-	-	-
<b>Total Dry Mass</b>	<b>1332.5</b>	<b>43%</b>	<b>1905.6</b>	<b>39</b>	<b>43%</b>	<b>56</b>

**Table 3-4. Proposed Entry System Characteristics**

Flight System Element Parameters (as appropriate)	Value/ Summary, units
<b>General</b>	
Design life, months	<1 hour
<b>Structure</b>	
Structures material (aluminum, exotic, composite, etc.)	Aluminum, titanium and composites
Number of articulated structures	0
Number of deployed structures	Parachute, heatshield, ballast mass
<b>Thermal Control</b>	
Type of thermal control used	Passive with heaters, PICA for heatshield, SLA-561V for backshell
<b>Propulsion</b>	Provided by descent stage RCS
<b>Attitude Control</b>	Provided by descent stage
<b>Command &amp; Data Handling</b>	None
<b>Power</b>	None



The proposed descent stage design (Figure 3-4) is assumed to be identical to MSL, utilizing a high-throughput throttleable monopropellant hydrazine system (and He pressurant) with eight 3000 N engines for slowing descent. In addition, it has eight 267 N thrusters for not only lateral movement and attitude control during descent but also for aeromaneuvering during entry. Lightweight composite tanks being developed for the proposed MAX-C rover mission could be used to save mass, if needed. An inertial measurement unit (IMU) would be used for guidance and the MSL terminal descent radar for altitude measurement. In addition to the vertical deceleration, a ~100 m lateral maneuver would be integrated to ensure separation of the landing of platform from the backshell and parachute. The lander platform attached to the descent stage would be released and lowered to the surface in a Sky Crane mode via three tethers as the descent stage hovers approximately 10 m above the surface. Upon touchdown, the lander would cut the tethers and the descent stage would fly away to a safe distance and impact the surface. Approximately 400 kg of fuel would be consumed, including that used for entry aeromaneuvering. While descent would be controlled through the CDS on the lander, engine controllers, radar electronics, and an IMU would be part of the descent stage. Thermal batteries and an X-band telecomm system would be used during descent, while the lander X-band could be patched-in for backup and the lander UHF telecomm would be available through a UHF antenna on the descent stage. Tables 3-5 and 3-6 list mass and power preliminary estimates and system characteristics; Appendix C provides the preliminary MEL.



**Figure 3-4. Proposed Descent Stage (Inherited from MSL)**

**Table 3-5. Descent Stage Mass and Power Preliminary Estimates**

	Mass			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)
Structures and mechanisms	266.6	30%	346.6	-	-	-
Thermal control	19.0	25%	23.7	36	43%	51
Propulsion (dry mass)	214.0	2%	218.3	44	43%	63
Attitude control	46.0	3%	47.2	334	43%	478
Command & data handling	1.2	13%	1.3	3	43%	4
Telecommunications	12.9	4%	13.4	215	43%	307
Power	24.1	30%	31.3	82	43%	117
Cabling	37.4	6%	39.7	-	-	-
<b>Total Dry Mass</b>	<b>621.1</b>	<b>16%</b>	<b>721.5</b>	<b>714</b>	<b>43%</b>	<b>1020</b>

Note: Fuel estimated at 389 kg for a total descent stage mass of 1110 kg.

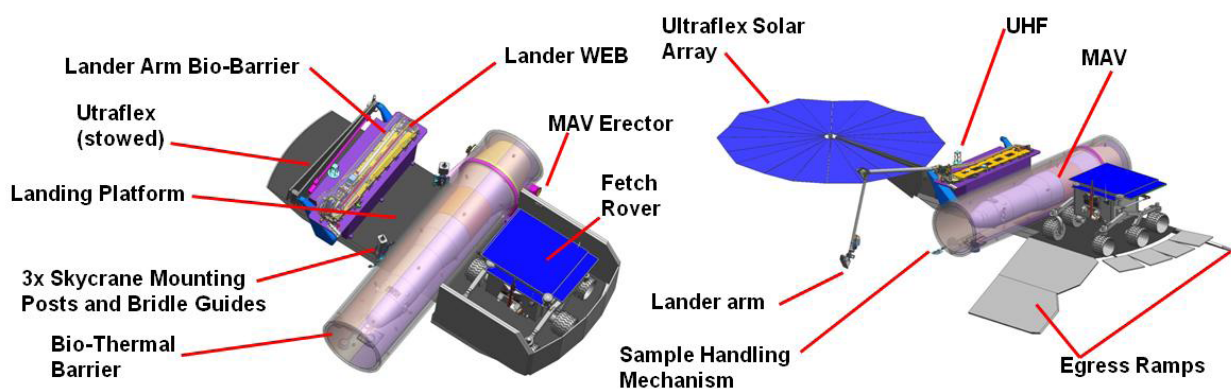
**Table 3-6. Proposed Descent Stage Characteristics**

Flight System Element Parameters (as appropriate)	Value/ Summary, units
<b>General</b>	
Design life	Minutes of operation
<b>Structure</b>	
Structures material (aluminum, exotic, composite, etc.)	Aluminum, titanium, composites
Number of articulated structures	None
Number of deployed structures	Bridal lowering pallet
<b>Thermal Control</b>	
Type of thermal control used	Passive with heaters
<b>Propulsion</b>	
Estimated delta-V budget, m/s	389 m/s
Propulsion type(s) and associated propellant(s)/oxidizer(s)	N <sub>2</sub> H <sub>4</sub> , He pressurant
Number of thrusters and tanks	(8) 2000 N descent (8) 267 RCS, 3 N <sub>2</sub> H <sub>4</sub> tanks, 2 He tanks
Specific impulse of each propulsion mode, seconds	217 s descent, 225 s RCS
<b>Attitude Control</b>	
Control method (3-axis, spinner, grav-gradient, etc.)	3-axis
Control reference (solar, inertial, Earth-nadir, Earth-limb, etc.)	Inertial
Attitude control capability, degrees	–
Attitude knowledge limit, degrees	–
Agility requirements (maneuvers, scanning, etc.)	Control terminal velocity to ~1 m/s
Articulation/#-axes (solar arrays, antennas, gimbals, etc.)	None
Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	0.005 deg/hr MIMU
<b>Command &amp; Data Handling</b>	
Uses lander C&DS	
<b>Power</b>	
Expected power generation at beginning of life (BOL) and end of life (EOL), watts	Long-term power from cruise stage array
On-orbit average power consumption, watts	283 W typical 714 W peak during EDL
Battery type (NiCd, NiH, Li-ion)	Li-ion
Battery storage capacity, amp-hours	4 thermal batteries, 9 A-Hr each for EDL

## **Lander**

The lander platform concept is a new structural design. The concept, developed by JPL's Team-X, is shown in Figure 3-5. The platform could have crushable aluminum honeycomb on the bottom and jack-screws or legs that would be deployed after touchdown for stabilizing and leveling the platform. The avionics would be inherited from the MSL rover and would be redundant where practical. The avionics would control the CEDL systems as the rover avionics do for MSL. Like MSL, communications would be performed by UHF Electra-lite transceiver for relay to an orbiter and by a small deep space transponder (SDST) for a direct-to-Earth (DTE) X-band. Power would be provided by a 6.2 m Ultraflex solar array—

similar to that used on Phoenix and planned for the MAX-C rover—with two 50 A-Hr Li-Ion batteries. A sampling system consisting of the arm, scoop, and camera baselined to be identical to that flown on Phoenix would be utilized to collect regolith and dust samples and a contingency sample, including small rocks, as backup in case rover-collected samples are not collected and returned. The Phoenix biobarrier would be used to isolate this sterilized sampling system from the rest of the lander in order to meet planetary protection requirements. The lander would carry a fetch rover, which would egress soon after landing to retrieve the sample cache left by the MAX-C rover. Upon return, the cache would be transferred to the lander using the lander arm. One of the primary functions of the lander would be to keep the MAV in a controlled thermal condition throughout the mission. The approach envisioned is to keep the MAV in an igloo of high-efficiency CO<sub>2</sub> insulation (same type used on MSL) and nominally 27 radioisotope heater units (RHUs). Very little electrical heater power would be required, except when preparing for launch of the MAV. Preliminary analysis indicates that the MAV can be kept above its -40°C requirement while limiting thermal cycling to within half a dozen degrees. This igloo could also serve to isolate the MAV from Mars dust particles through HEPA filters as an aid to back planetary protection implemented on the orbiter. Tables 3-7 and 3-8 list mass and power preliminary estimates and system characteristics; Appendix C provides the preliminary MEL.



**Figure 3-5. Proposed Lander Concept**

**Table 3-7. Lander Mass and Power Preliminary Estimates**

	Mass			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)
Cameras	3.4	12%	3.8	-	-	-
Structures & mechanisms	212.0	30%	275.6	-	-	-
Thermal control	45.0	30%	58.4	40	43%	57
Propulsion (dry mass)	0	0%	0	-	-	-
Attitude control	11.2	10%	12.3	1	43%	1
Command & data handling	11.2	30%	14.6	5	43%	7
Telecommunications	15.3	13%	17.3	1	43%	1
Power	49.3	30%	64.0	19	43%	27
Cabling	39.9	30%	51.9	-	-	-
System contingency	-	-	55.8	-	-	-
<b>Total Dry Mass</b>	<b>387.2</b>	<b>43%</b>	<b>553.7</b>	<b>66</b>	<b>43%</b>	<b>94</b>

**Table 3-8. Proposed Lander Characteristics**

Flight System Element Parameters (as appropriate)	Value/ Summary, units
<b>General</b>	
Design life, months	2 years
<b>Structure</b>	
Structures material (aluminum, exotic, composite, etc.)	Primarily aluminum and aluminum honeycomb
Number of articulated structures	1 arm and scoop, sample handling mechanisms, antenna gimbal
Number of deployed structures	1 solar array, 2 rover egress ramps, MAV erector, 4 stabilizing legs
<b>Thermal Control</b>	
Type of thermal control used	Passive with heaters, CO <sub>2</sub> insulation + 27 RHUs baselined for the MAV
<b>Propulsion</b>	
N/A	
<b>Attitude Control</b>	
Control method (3-axis, spinner, grav-gradient, etc.)	3-axis
Control reference (solar, inertial, Earth-nadir, Earth-limb, etc.)	Local horizontal
Attitude control capability, degrees	N/A
Attitude knowledge limit, degrees	0.75 deg
Agility requirements (maneuvers, scanning, etc.)	N/A
Articulation/#-axes (solar arrays, antennas, gimbals, etc.)	2 DOF 0.28 m X-band antenna
Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	0.4 deg sun sensors, 0.005 deg/hr MIMU
<b>Command &amp; Data Handling</b>	
Flight element housekeeping data rate, kbps	2 kbps
Data storage capacity, Mbits	4 GB
Maximum storage record rate, kbps	20 Mbps
Maximum storage playback rate, kbps	2 Mbps
<b>Power</b>	
Type of array structure (rigid, flexible, body mounted, deployed, articulated)	Deployed UltraFlex
Array size, meters x meters	6.2 m <sup>2</sup>
Solar cell type (Si, GaAs, multi-junction GaAs, concentrators)	GaAs
Expected power generation at beginning of life (BOL) and end of life (EOL), watt-hours/sol (sol=24.6 hours)	3301 W-Hr BOL 2982 W-Hr EOL
Worst case daily power consumption, watts	100 W
Battery type (NiCd, NiH, Li-ion)	Li-ion
Battery storage capacity, amp-hours	100 A-Hr

## Mars Ascent Vehicle (MAV)

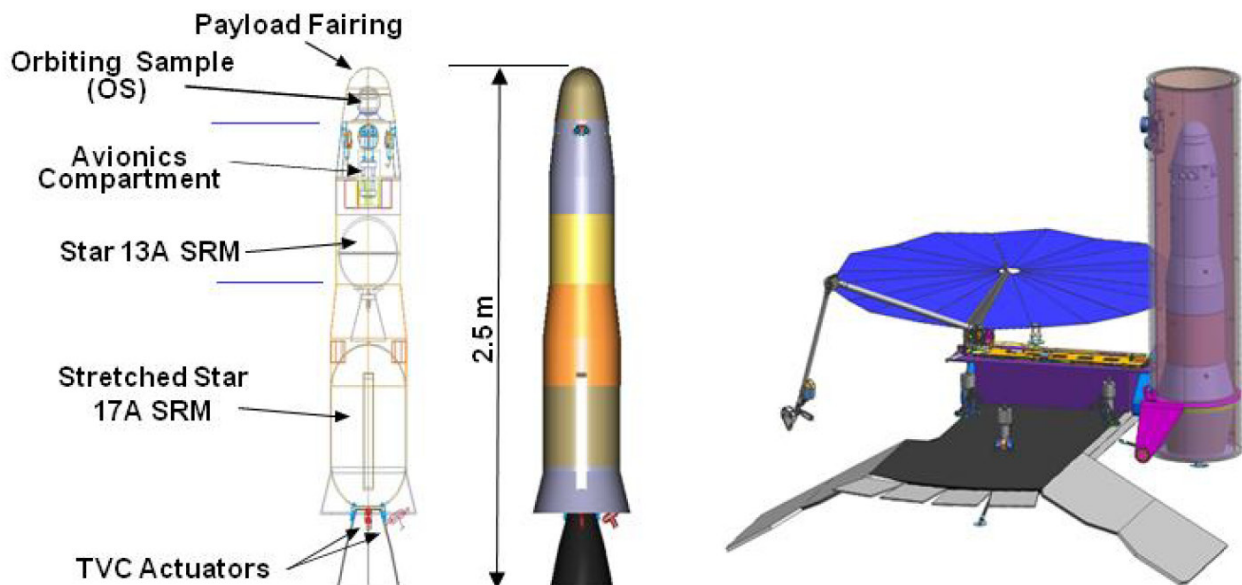
The baseline MAV, depicted in Figure 3-6, is a two-stage solid-motor design based on modifications to existing motor designs. The MAV would be housed in an igloo, while on the surface, to keep it thermally stable and fairly immune to seasonal or diurnal effects. Full-system model testing in relevant environments, including shock, storage at expected temperatures, and launch at high altitude from a balloon platform to simulate the Mars environment, is planned as part of the technology program.

The current MAV concept is based on MAV industry studies from 2002 and has been cross-checked by running the design through JPL's Team X in 2004. Both designs had a mass of approximately 285 kg, but have been scaled to 300 kg to include 43% margin for this study. The industry studies are described in [3] and cover MAV designs based on solid, liquid, and gel propellants. The vehicle concept is 3-axis stabilized to avoid issues with payload center-of-gravity variation and nutation. The OS concept is a 17 cm sphere, estimated to weigh 5 kg, which is included in the MAV mass allocation. The concept has two stages—the first using thrust vector control for steering and the second using front-end steering using RCS. Other MAV approaches will be explored in the technology program with an emphasis on mass reduction, ease of accommodation, and reliability.

The current approach has a loose injection accuracy ( $\pm 70$  km), which is accommodated by targeting a 500 km orbit; a 400 km altitude is compatible with the OS remaining in orbit for well over several decades. The maneuvers for rendezvous with these variations are included as part of the orbiter propulsion budget. The OS would be released with a small spring-produced delta-V once orbit is attained so that over time, capture could be performed outside the realm of the MAV as part of the breaking-the-chain, planetary protection process.

Launch of the MAV would be a critical event that would require telemetry monitoring, transmitted during and after flight. This would necessitate that either the MSR orbiter be in place or another reliable telecommunication relay asset be available.

Tables 3-9 and 3-10 list mass and power preliminary estimates and system characteristics, which are based on the Team X version of the MAV. The detailed MEL contains proprietary and ITAR-sensitive information and is therefore not included in this report.



**Figure 3-6. Two-Stage Solid Motor MAV Concept, in Proposed Launch Configuration**

**Table 3-9. MAV Mass and Power Preliminary Estimates**

	Mass			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)
Structures & mechanisms	10.3	28%	13.2	-	-	-
Thermal control	0.8	30%	0.9	-	-	-
Propulsion dry mass (all but fuel)	25.7	30%	33.6	-	-	-
Attitude control	5.5	22%	6.7	4.4	43%	6.3
Command & data handling	1.0	30%	1.3	1.8	43%	2.6
Telecommunications	3.0	13%	3.9	40	43%	57.2
Power	5.6	30%	7.2	48.3	43%	69.1
Cabling	2.1	24%	2.6	-	-	-
System contingency	-	-	7.8	-	-	-
<b>Total Dry Mass</b>	<b>54.0</b>	<b>43%</b>	<b>77.2</b>	<b>94.5</b>	<b>43%</b>	<b>135.1</b>

Note: Fuel estimated at 218 kg for total MAV mass of 300 kg (including 5 kg OS).

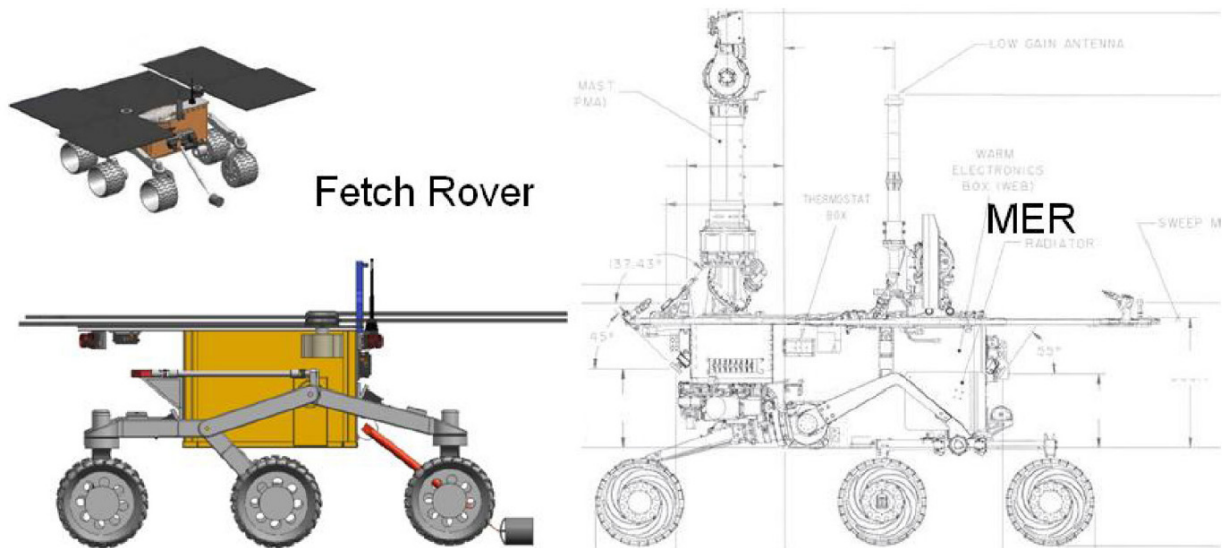
**Table 3-10. MAV Concept Characteristics**

Flight System Element Parameters (as appropriate)	Value/ Summary, units
<b>General</b>	
Design life, months	2 years on-orbit and surface storage; operation < 1 week
<b>Structure</b>	
Structures material (aluminum, exotic, composite, etc.)	Primarily aluminum
Number of articulated structures	Gimbaled nozzle
Number of deployed structures	OS, fairing, staging
<b>Thermal Control</b>	
Type of thermal control used	Passive with heaters (igloo on lander provides control during storage)
<b>Propulsion</b>	
Estimated delta-V budget, m/s	3,690 m/s
Propulsion type(s) and associated propellant(s)/oxidizer(s)	Solid propellant for 1 <sup>st</sup> and 2 <sup>nd</sup> stage; N <sub>2</sub> H <sub>4</sub> for RCS
Number of thrusters and tanks	(8) 22 N for steering, (4) 5 N for fine control RCS, 1 N <sub>2</sub> H <sub>4</sub> tanks, STAR 13A, Stretched STAR 17A
Specific impulse of each propulsion mode, seconds	-
<b>Attitude Control</b>	
Control method (3-axis, spinner, grav-gradient, etc.)	3-axis
Control reference (solar, inertial, Earth-nadir, Earth-limb, etc.)	Inertial
Attitude control capability, degrees	±1.4 deg
Attitude knowledge limit, degrees	±0.18 deg

<b>Flight System Element Parameters (as appropriate)</b>	<b>Value/ Summary, units</b>
Agility requirements (maneuvers, scanning, etc.)	–
Articulation/#-axes (solar arrays, antennas, gimbals, etc.)	–
Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	IMU 1 <sup>st</sup> stage thrust vector control
<b>Command &amp; Data Handling</b>	
Flight element housekeeping data rate, kbps	Low
Data storage capacity, Mbits	4 GB
Maximum storage record rate, kbps	8 Mbits/s
Maximum storage playback rate, kbps	8 Mbits/s
<b>Power</b>	
Type of array structure (rigid, flexible, body mounted, deployed, articulated)	None
Array size, meters x meters	–
Solar cell type (Si, GaAs, multi-junction GaAs, concentrators)	–
Expected power generation	–
Average power consumption, watts	135 W
Battery type (NiCd, NiH, Li-ion)	Li-ion primary charged from lander and 1 thermal battery
Battery storage capacity, amp-hours	1 A-Hr

## ***Fetch Rover***

After the rock cores have been cached by the proposed MAX-C rover mission, a single-purpose fetch rover would be utilized to retrieve the cache. A concept emerging from a concept study team led to a Team X point design study in September 2009. The concept is similar to MER but without instruments. A 1-DOF arm would be used to pick up the cache from the surface, using rover positioning to insert the arm end-effector into loops envisioned on the cache. Figure 3-7 shows the fetch rover concept in relation to a MER. MSL heritage avionics would be used with low-temperature distributed motor-controllers to save mass, which are currently being developed and should have been demonstrated on the MAX-C rover. Selective redundancy, consistent with its short mission duration, would be implemented for key components to address fault tolerance. It would have similar trafficability as MER, but would utilize enhanced avionics and driving capability to increase effective speed, planned as part of the technology program for the MAX-C rover mission. These upgrades would enable close-to-continuous driving unlike the low duty cycle of MER, where most of the time would be taken for computation between short moves. Even with the lander targeting the MAX-C rover cache location, ~14 km traverse might be needed, which would be possible with the proposed MAX-C rover developed upgrades. MSL-heritage mobility actuators would be used, which are designed for MSL's 20 km distance requirement. Four navigation cameras (MER nav cams) would be mounted as stereo sets on the front and back of the chassis, rather than on a mast; four hazard cameras (MER haz cams) would also be mounted on the lower end of the front and back. With the MSR orbiter planned to be in place before the MSR Lander Mission, reliance on UHF relay communications to the orbiter is assumed, eliminating the need for the MER X-band DTE system. Since the mast and X-band antenna could be eliminated, the upper deck of the rover would be open, allowing unique rotating solar array deployment that could be used not only to save stowed configuration space, but also to potentially provide a means of cleaning dust accumulation. Tables 3-11 and 3-12 list mass and power preliminary estimates and system characteristics; Appendix C provides the preliminary MEL.



**Figure 3-7. Fetch Rover Concept in Relation to MER**

**Table 3-11. Fetch Rover Mass and Power Preliminary Estimates**

	Mass			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)
Structures & mechanisms	67.2	30%	87.3	8	43%	11.4
Thermal control	1.0	22%	1.2	10	43%	14.3
Propulsion (dry mass)	-	-	-	-	-	-
Attitude control	2.6	7%	2.8	4	43%	5.7
Command & data handling	8.5	12%	10.3	13	43%	18.6
Telecommunications	3.3	10%	3.7	1	43%	1.4
Power	21.6	30%	28.1	10	43%	14.3
Cabling	5.8	30%	7.6	-	-	-
System contingency	-	-	16.3	-	-	-
<b>Total Dry Mass</b>	<b>110.0</b>	<b>43%</b>	<b>157.3</b>	<b>46</b>	<b>43%</b>	<b>65.8</b>

**Table 3-12. Proposed Fetch Rover Characteristics**

Flight System Element Parameters (as appropriate)	Value/ Summary, units
<b>General</b>	
Design life, months	<1 year cruise, <1 year on surface
<b>Structure</b>	
Structures material (aluminum, exotic, composite, etc.)	Primarily aluminum
Number of articulated structures	6 wheels, 4 wheel steering (1) 1-DOF arm
Number of deployed structures	4 solar array panels

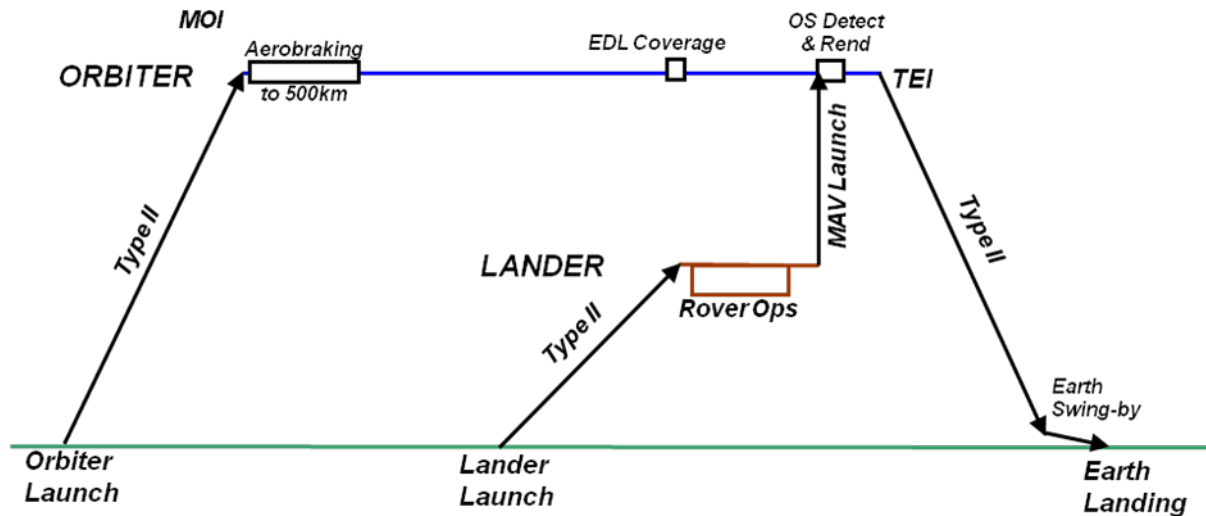


<b>Flight System Element Parameters (as appropriate)</b>	<b>Value/ Summary, units</b>
<b>Thermal Control</b>	
Type of thermal control used	Passive with heaters, CO <sub>2</sub> insulation
<b>Attitude Control</b>	
Control method (3-axis, spinner, grav-gradient, etc.)	3-axis
Control reference (solar, inertial, Earth-nadir, Earth-limb, etc.)	Inertial & surface features
Attitude control capability, degrees	-
Attitude knowledge limit, degrees	-
Agility requirements (maneuvers, scanning, etc.)	Wheel steering
Articulation/#-axes (solar arrays, antennas, gimbals, etc.)	None
Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	4 navigation cameras 4 hazard cameras LN-200S IMU
<b>Command &amp; Data Handling</b>	
Flight element housekeeping data rate, kbps	Low
Data storage capacity, Mbits	64 Mbytes
Maximum storage record rate, kbps	1.6 Mbits/s
Maximum storage playback rate, kbps	1.6 Mbits/s
<b>Power</b>	
Type of array structure (rigid, flexible, body mounted, deployed, articulated)	Rigid, deployed and body mounted
Array size, meters x meters	2.7 m <sup>2</sup>
Solar cell type (Si, GaAs, multi-junction GaAs, concentrators)	GaAs
Worstcase average power available dependent on latitude, time of year, dust coverage and cell degradation.	75 W
Average power consumption, watts	70 W
Battery type (NiCd, NiH, Li-ion)	Li-ion
Battery storage capacity, amp-hours	46 A-Hr

## Concept of Operations and Mission Design

The nominal sequence of the proposed MSR campaign would start with the MAX-C rover mission that would be launched in 2018, resulting in a sample cache left on the martian surface roughly 2 years later in 2020. The MSR Orbiter Mission would be nominally launched in 2022, followed by the lander in 2024. Figure 3-8 shows a representative timeline. Table 3-13 provides the parameters that reflect the 2024 opportunity.

The proposed MSR lander would launch from Cape Canaveral on 10/2024 on an Atlas V-551 or comparable vehicle with a C3 of approximately 12.2. On a Type-II trajectory, the lander would arrive at Mars in September 2025. Once on the surface, the fetch rover would be dispatched to retrieve the cache left by the MAX-C rover. The plan is to have the MAX-C rover deliver the cache to a location that would be well within the landing ellipse of the MSR lander. The fetch rover might have to traverse 14 km round-trip in a worst case of landing in relation to the cache. It is anticipated that the cache return could be accomplished within 3 months. Collection of a regolith sample at the lander would be performed during that time. In order to leave adequate time for the MSR Orbiter Mission to accomplish rendezvous with the OS and set up for Earth return, the MAV should launch around May 2026, approximately eight months after arrival. In the event that surface operations would take more than eight months, the MSR Orbiter Mission would have the fuel to wait for an opportunity before return.



**Figure 3-8. Representative Lander Mission Timeline in Relation to the Orbiter Mission**

**Table 3-13. Mission Design Concept**

Parameter	Value	Units
Mission lifetime	<2	Years
Maximum eclipse period	14	Hours
Launch site	CCAFS	–
Total flight system mass <b>with</b> contingency	4598	Kg
Propellant mass <b>without</b> contingency	–	Kg
Propellant contingency	–	%
Propellant mass <b>with</b> contingency – for cruise only	70	Kg
Launch adapter mass <b>with</b> contingency <i>(included in cruise stage mass)</i>	60	Kg
Total launch mass	4668	Kg
Launch vehicle	Atlas V-551	Type
Launch vehicle lift capability	5130	Kg
Launch vehicle mass margin	462	Kg
Launch vehicle mass margin (%)	9	%

Communications for the proposed lander would be through the Deep Space Network (DSN) once per day and up to two passes of relay through the MSR orbiter. DSN coverage for the orbiter relay is included in the MSR Orbiter Mission concept study report [2]. DSN near-continuous coverage would be needed for tracking around TCM maneuvers while enroute to Mars and during the critical events of EDL and MAV launch. All fetch rover communications would be through UHF relay to the MSR orbiter. Table 3-14 summarizes the need for coverage. Without science instruments, data volume would be low; therefore, X-band would be adequate. The Decadal Survey guidelines indicate that Ka-band should be used post-2016. It is believed that X-band might still be available. However, Ka-band could be used (at a cost of \$5M–\$10M) and would have insignificant mass and volume impacts.

**Table 3-14. Mission Operations and Ground Data Systems**

Downlink Information	Nominal Phases	EDL & Maneuvers & MAV Launch
Number of contacts per week	7	Continuous
Number of weeks for mission phase, weeks	Throughout	6 days each x 6
Downlink frequency band, GHz – 8.4 GHz	X-band	X-band
Telemetry data rate(s), kbps	10 kbps	10 kbps
Transmitting antenna type(s) and gain(s), DBi	0.28 m HGA	0.28 m HGA
Downlink receiving antenna gain, DBi	34 m DSN	34 m DSN
Transmitting power amplifier output, watts	15 watts	15 watts
Total daily data volume, (MB/day)	<b>170 Mb</b>	<b>170 Mb</b>
Uplink Information		
Number of uplinks per day	1 per day	Several
Uplink frequency band, GHz – 7.2 GHz	X-band	X-band
Telecommand data rate, kbps	2 kbps	2 kbps
Receiving antenna type(s) and gain(s), DBi	1.0 m HGA	1.0 m HGA

## Planetary Protection

This proposed mission would be classified as Category IVb. The proposed approach would be a IVb-subsystem implementation, where all hardware that might touch the sample must be sterilized and cleaned, with bio-barriers to protect that hardware from recontamination from other sources. The affected hardware would be the regolith arm and scoop and any sample handling and transfer hardware. The use of the Phoenix Mars arm/scoop and biobarrier design would meet this need. The sample handling transfer and packaging mechanisms must be enclosed in a biobarrier that would be only opened as needed.

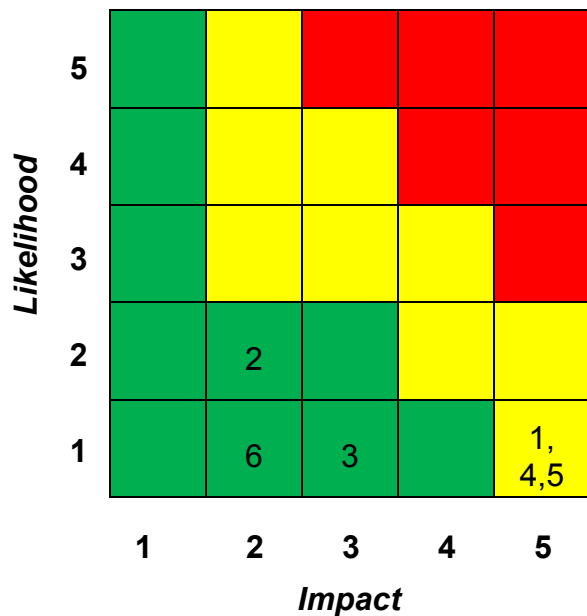
## Risk List

Table 3-15 lists the top mission and implementation risks for the proposed MSR Lander Mission. Figure 3-9 correlates the likelihood and impact on a 5 x 5 risk matrix (with risk level color coding of green = low, yellow = medium, and red = high). Table 3-16 is a key to risk assessment.

**Table 3-15. Top Risks for the Proposed Lander Mission**

Risk	Level	Description	Impact	Likelihood	Mitigation
1. Lander is late in delivery of the OS for rendezvous.	M	Difficulty in cache retrieval or delayed events leading to MAV launch might delay planned Earth return of the orbiter. The return would be delayed by 2 years.	5	1	Orbiter Mission to carry the fuel to support a 2-year slip in return. Fuel impact is small. Operations cost would be extended 2 years.
2. MAV development is more difficult than planned.	L	MAV development is new. Significant mass or accommodation growth might cause redesign / rescope of the lander.	3	1	Implement a technology program to develop and flight test MAV prior to the mission PDR, and start early with incremental qualification steps. Current plan starts 7 years prior to the PDR.

Risk	Level	Description	Impact	Likelihood	Mitigation
3. Sample handling on lander proves more difficult than planned.	L	The necessary hardware to package the regolith has not been designed, nor has the OS design been updated since 2000. Phoenix has shown that handling loose material can be challenging.	2	2	Carry multiple solutions and back-off positions. Develop strawman designs in Pre-Phase A. Revisit previous designs from 1999 project. Consider using the proposed MAX-C core packaging design.
4. MAX-C rover does not bring cache back into the potential landing ellipse	M	The current design assumes the traverse for a round-trip fetch rover within the design distance of MSL (actuator lifecycles) of 20 km. Outside this distance is considered unacceptable risk.	5	1	Build in constraints on proposed MAX-C exploration envelope.
5. MAX-C rover fails with cache attached	M	The current fetch rover is designed for surface cache pickup, not removal from MAX-C.	5	1	Add feature to MAX-C design that would allow simple release of cache to ground from a non-operating rover.
6. MAX-C EDL solution is not applicable to MSR-L	L	MSR-L landing needs might be different than that implemented on MAX-C	2	1	EDL and platform design process for MAX-C will take into account MSR-L considerations and seek common solutions



**Figure 3-9. 5 x 5 Risk Matrix**

**Table 3-16. Risk Level Definitions**

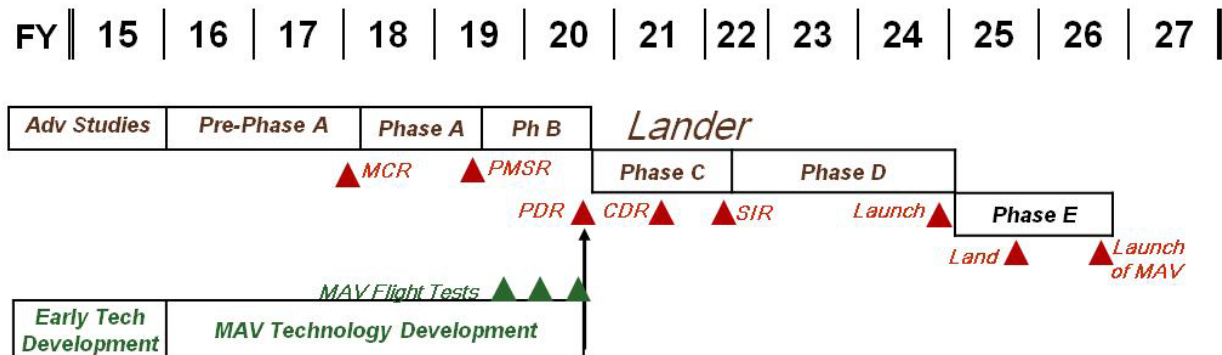
Levels	Mission Risk		Implementation Risk	
	Impact	Likelihood of Occurrence	Impact	Likelihood of Occurrence
5	Mission failure	Very high, >25%	Consequence or occurrence is not repairable without engineering (would require >100% of margin)	Very high, ~70%
4	Significant reduction in mission return (~25% of mission return still available)	High, ~25%	All engineering resources will be consumed (100% of margin consumed)	High, ~50%
3	Moderate reduction in mission return (~50% of mission return still available)	Moderate, ~10%	Significant consumption of engineering resources (~50% of margin consumed)	Moderate, ~30%
2	Small reduction in mission return (~80% of mission return still available)	Low, ~5%	Small consumption of engineering resources (~10% of margin consumed)	Low, ~10%
1	Minimal (or no) impact to mission (~95% of mission return still available)	Very low, ~1%	Minimal consumption of engineering resources (~1% of margin consumed)	Very low, ~1%

# 4. Development Schedule and Schedule Constraints

## High-Level Mission Schedule

Figure 4-1 shows the development and schedule for the proposed MSR Lander Mission (planned for launch in 2024) and the associated technology development phase of the MAV culminating in flight tests.

Table 4-1 lists the duration of key phases of proposed Lander Mission development.



**Figure 4-1. Development Schedule for the Proposed Lander Mission**

**Table 4-1. Proposed Key Phase Duration**

Project Phase	Duration (Months)
Phase A – Conceptual Design	18 months
Phase B – Preliminary Design	13 months
Phase C – Detailed Design	20 months
Phase D – Integration & Test	26 months
Phase E – Primary Mission Operations	20 months
Phase F – Extended Mission Operations	None
Start of Phase B to PDR	11 months
Start of Phase B to CDR	23 months
Project total funded schedule reserve	Built in to schedule (~1 month/year)
Total development time Phase B–D	59 months

## Technology Development Plan

Only one technology would not have been addressed by the proposed MAX-C and prior missions—the development of the MAV. While the component-level technology needed is relatively minor, the qualification of the elements for the mission environments, and the MAV as a system, is planned as part of the MSR technology program and would be completed prior to the mission PDR.

A NASA Research Announcement (NRA) has been released this year as part of NASA’s Research Opportunities for Space and Earth Sciences (ROSES), sponsored by the NASA-GRC In-Space Propulsion (ISP) program. This plan begins with MAV system studies, initiated by the end of this fiscal

year (FY) and culminates in the demonstration of at least one MAV propulsion system within three years. Results of a MAV request for information (RFI) issued last year indicate that several concepts might be worth pursuing. If current plans are sustained over the three-year period, either the baseline concept (described in this report) or an alternate concept or variation will be selected and enough propulsion system-level testing will have been accomplished to have confidence in starting full-fledged MAV system development.

The MAV technology program is designed to provide the project with a qualified MAV system, ready for manufacture and acceptance testing of the flight unit with minimal change. While the baseline MAV concept relies on existing technologies, the reliable operation of those technologies as a system under the environmental conditions required by a Mars mission still needs to be demonstrated. The technology program is envisioned to incrementally qualify components, then systems (such as motors), then stages, and finally a full flight system. Environmental qualification at each of these levels would include not only low temperature and thermal cycling over mission lifetimes, but also tolerance to loads that would be experienced during launch, entry, and landing. Ground-based performance testing, potentially including surface launch of the first stage, would be performed. Ultimately, a full MAV system would be flight tested at high altitude (62,000 feet) from a balloon platform. Three tests are planned prior to the mission PDR with at least two successful flights required, one of which must have been through full environmental qualification.

For the purposes of this report, the full MAV technology program is budgeted in the project in parallel with pre-Phase A through Phase B development activities, starting in FY16. The total cost budgeted is \$274M (RY) with a five-year profile as shown in Section 5.

## **Development Schedule and Constraints**

There is nothing unusual about the proposed MSR Lander Mission that would indicate schedule issues at this point in planning. Care has been taken to adequately plan MAV technology development to start next year and to achieve environmental qualification and high-altitude flight test prior to the mission PDR.

Launch opportunities to Mars occur roughly every 26 months; thus, if the spacecraft was not ready for launch, a two-year slip would occur.

# 5. Mission Life-Cycle Cost

## Costing Methodology and Basis of Estimate

The proposed MSR Lander Mission design and cost have been developed by JPL's Team X using their quasi-grassroots process. Combinations of grassroots, parametric analysis, and analogy models are used by each of the discipline chairs representing their implementing organizations. These models have been validated against actual costs of prior JPL missions.

The Team X study was performed in October 2009. Costs have been modified to meet the Decadal Survey guidelines of 50% reserves for development (Phases A–D) and 25% for operations (Phase E).

A separate fetch rover Team X study was performed in September 2009, the results of which were rolled into the MSR lander study, the following month.

The MAV was studied by Team X in 2004 and those costs have been carried forward into subsequent Team X studies, including the October 2009 lander study. The development (Phases A–D) costs for the MAV assume that technology development for the MAV (funded at \$250M [FY15]) would take a flight-like unit through full environmental qualification and high-altitude flight testing.

All costs have been inflated to FY 2015 dollars and real year (RY) dollars for a 2024 launch, as requested by the Decadal Survey.

Launch vehicle cost is as specified in the Decadal Survey ground rules for mission studies.

Technology development cost estimates for the MAV are based on modification of MAV industry study results from 2002 [3], two MSR technology reviews (in 2005 and 2008), and most recently an independent review by Aerospace Corporation. MAV technology development costs include 50% reserve.

## Cost Estimates

Table 5-1 summarizes the total mission estimated costs for the proposed MSR Lander Mission.



**Table 5-1. Total Estimated Mission Cost Funding Profile**

(FY Costs in Real Year Dollars, Totals in Real Year and 2015 Dollars)

FY	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	Total RY	Total FY15
<b>Pre-Phase-A</b>	6	10										16	15
<b>Technology Development</b>	15	27	86	86	60							274	250
<b>Development A–D</b>													
Proj Mgmt/SE/MA			2	6	16	38	48	50	45	4		209	171
Flight Sys Mgmt/SE			2	4	7	21	26	26	26	2		114	94
Mars Ascent Vehicle						13	11	11	12	1		48	39
Fetch Rover			1	4	20	42	59	60	20	4		210	172
Lander			2	6	24	63	77	79	75	5		331	272
Descent Stage			2	4	10	28	40	41	29	3		157	129
Entry (with analysis)			1	1	8	21	29	29	16	3		108	89
Cruise Stage			1	2	7	22	27	27	20	2		108	89
MSI&T				2	6	10	24	28	29	1		100	82
Ground Data System Dev				1	3	8	10	10	11	1		44	36
MOS Prep & Mission Design				1	5	12	15	15	15	2		65	53
Prelaunch Science					1	2	3	3	3	1		13	11
Total A_D w/o Reserves			11	31	107	280	369	379	301	29		1507	1238
A-D Reserves			5	15	54	140	184	190	150	15		753	619
<b>Total A–D Cost</b>			<b>16</b>	<b>46</b>	<b>161</b>	<b>420</b>	<b>553</b>	<b>569</b>	<b>451</b>	<b>44</b>		<b>2260</b>	<b>1857</b>
<b>Launch Services</b>							<b>38</b>	<b>150</b>	<b>140</b>	<b>6</b>		<b>334</b>	<b>272</b>
<b>Phase E</b>													
<b>Phase E Science</b>										6	6	12	9
Other Phase E Costs										35	31	66	50
Phase E Reserves										10	10	20	15
<b>Total Phase E</b>										<b>51</b>	<b>47</b>	<b>98</b>	<b>74</b>
<b>DSN</b>									4	7	7	18	14
<b>Education/Outreach</b>					1	1	1	1	2	8	8	22	17
<b>Total Mission Costs</b>	<b>21</b>	<b>37</b>	<b>102</b>	<b>132</b>	<b>222</b>	<b>421</b>	<b>592</b>	<b>720</b>	<b>597</b>	<b>116</b>	<b>62</b>	<b>3022</b>	<b>2499</b>

Notes: MSI&T—Mission System Integration and Test and preparation for operations.

Includes all costs to NASA including estimated DSN costs.

# Appendix A. Acronyms

BOL	beginning of life
CBE	current best estimate
CDS	command and data system
CEDL	cruise, entry, descent, and landing
CML	concept maturity level
DSN	Deep Space Network
DTE	direct-to-Earth
EDL	entry, descent, and landing
EEV	Earth Entry Vehicle
EOL	end of life
FY	fiscal year
IMU	inertial measurement unit
MAV	Mars Ascent Vehicle
MEL	master equipment list
MEV	maximum expected value
MREU	MSAP remote engineering unit
MRSR	Mars Returned Sample Handling
MSR	Mars Sample Return
OS	orbiting sample
PDR	Preliminary Design Review
PICA	Phenolic Impregnated Carbon Ablator
RCS	reaction control system
RFI	request for information
RHU	radioisotope heater unit
RY	real year
SAG	Science Advisory Group
SDST	small deep space transponder
SRF	sample receiving facility
TCM	trajectory correction maneuver
TPS	thermal protection system
UHF	ultra-high frequency

# Appendix B. References

- [1] National Aeronautics and Space Administration. March 2010. *Mission Concept Study: Planetary Science Decadal Survey—Mars 2018 MAX-C Caching Rover*.
- [2] National Aeronautics and Space Administration. March 2010. *Mission Concept Study: Planetary Science Decadal Survey—MSR Orbiter Mission (including Mars Returned Sample Handing)*.
- [3] Stephenson, D., “Mars Ascent Vehicle—Concept Development,” NASA-Marshall Space Flight Center, Huntsville, AL, 38th Joint Propulsion Conference and Exhibit, July 7–10, 2002, Paper #4318.

# Appendix C. Lander Mission Master Equipment Lists from Team X Studies

The following MELs are included in this appendix:

- Cruise Stage
- Entry System
- Descent Stage
- Lander
- Fetch Rover

## Cruise Stage Preliminary MEL

Component	Fit Units	CBE/Unit (kg/unit)	CBE (kg)	Cont.	CBE + Cont. (kg)
<b>Attitude Determination and Control System</b>					
Sun Sensors	2	2.40	4.80	10%	5.28
Star Trackers	2	1.48	2.95	10%	3.25
<b>Command and Data System</b>					
Telemetry Multiplex Card (TMC): CRC Card (NR)	1	0.40	0.40	30%	0.52
MREU: MSAP Analog/Discrete MREU	1	0.80	0.80	30%	1.04
<b>Power</b>					
Solar Array	1	7.73	7.73	30%	10.05
Chassis	1	3.93	3.93	30%	5.11
Array Segment Switches* - Array Interface Slice Boards	2	2.22	4.44	30%	5.77
Load Switches - LCC Boards	4	1.00	4.00	30%	5.20
Thruster Drivers* - GID Boards	2	1.10	2.20	30%	2.86
Houskeeping DC-DC Converters* Boards	2	1.13	2.26	30%	2.94
Power/Shunt Control* - Shunt Driver Slice Boards	2	4.00	8.00	30%	10.40
Shielding	1	1.24	1.24	30%	1.62
<b>Propulsion</b>					
Gas Service Valve	2	0.23	0.46	2%	0.47
Temp. Sensor	1	0.01	0.01	5%	0.01
Liq. Service Valve	1	0.28	0.28	2%	0.29
LP Transducer	2	0.27	0.54	2%	0.55
Liq. Filter	1	0.40	0.40	2%	0.41
LP Latch Valve	2	0.35	0.70	2%	0.71
Temp. Sensor	34	0.01	0.34	5%	0.36
Lines, Fittings, Misc.	1	3.00	3.00	50%	4.50
Monoprop Main Engine	8	0.38	3.04	10%	3.34
Pressurant Tanks	1	0.00	0.00	0%	0.00
Fuel Tanks	2	5.13	10.26	30%	13.34
<b>Structures</b>					
Primary Structure	1	100.63	100.63	30%	130.82
Secondary Structure	1	21.77	21.77	30%	28.30
Thruster Support Structure	1	5.22	5.22	30%	6.79
Prop Support Structure	1	2.98	2.98	30%	3.87
Radiator Panels	1	53.06	53.06	30%	68.98
Separation Devices	1	16.27	16.27	30%	21.15
Cruise Stage PAI & CM	1	9.90	9.90	30%	12.87
Purge Hardware	1	0.44	0.44	30%	0.57
Cabling Harness	1	24.70	24.70	30%	32.11
Adapter, Spacecraft side	1	45.75	45.75	30%	59.48
<b>Telecomm</b>					
X-MGA (19dB) MER	1	0.37	0.37	2%	0.38
Other	1	0.28	0.28	2%	0.29
<b>Thermal</b>					
Multilayer Insulation (MLI)	20	0.40	8.00	20%	9.60
Paints/Films	10	0.25	2.50	15%	2.88
General	1	0.49	0.49	0%	0.49
Custom	4	0.28	1.10	20%	1.32
Propulsion Tank Heaters	2	0.10	0.20	20%	0.24
Propulsion Line Heaters	6	0.10	0.60	20%	0.72
PRT's	78	0.00	0.12	5%	0.12
Mechanical	4	0.01	0.05	20%	0.06
Thermal Radiator (Area=m2)	1	7.50	7.50	5%	7.88
CIPAS	1	22.65	22.65	2%	23.10
HRS Tube Assy	1	6.11	6.11	5%	6.42
HRS CFC-11	1	6.34	6.34	10%	6.97
HRS Tube Epoxy	1	0.20	0.20	20%	0.24
Fluid (P-Clamp+Bulk Jam Nut)	1	0.46	0.46	5%	0.48

## Entry System Preliminary MEL

Component	Flt Units	CBE/Unit (kg/unit)	CBE (kg)	Cont.	CBE + Cont. (kg)
<b>Structures</b>					
Backshell	1	484.52	484.52	30%	629.88
Heatshield	1	420.50	420.50	30%	546.65
Parachute	1	88.22	88.22	30%	114.69
Cruise Ballast	1	138.70	138.70	30%	180.31
Entry Ballast	1	158.80	158.80	30%	206.44
Cabling Harness	1	5.52	5.52	30%	7.18
<b>Telecomm</b>					
X-LGA MER/MPF CWG	2	0.41	0.82	2%	0.84
UHF-MGA array	1	7.86	7.86	7%	8.41
Waveguide Transfer Switch (WGTS)	2	0.44	0.88	2%	0.90
Polarizer	2	0.27	0.54	25%	0.68
Other	2	0.05	0.10	30%	0.13
Other	2	0.03	0.06	10%	0.07
WR-112 WG, rigid (Al)	4	0.45	1.80	30%	2.34
Coax Cable, flex (190)	1	0.26	0.26	2%	0.27
Coax Cable, flex (120)	1	0.12	0.12	2%	0.12
<b>Thermal</b>					
Multilayer Insulation (MLI)	5	2.05	10.25	15%	11.79
General	1	0.73	0.73	0%	0.73
Isolation (G-10)	1	0.00	0.00	0%	0.00
High Conductance	1	0.00	0.00	0%	0.00
Catalogue	1	0.05	0.05	0%	0.05
Custom	1	0.05	0.05	0%	0.05
Propulsion Tank Heaters	1	0.10	0.10	0%	0.10
Propulsion Line Heaters	1	0.10	0.10	0%	0.10
Temperature Sensors	1	0.00	0.00	0%	0.00
Thermistors	1	0.02	0.02	0%	0.02
PRT's	1	0.01	0.01	0%	0.01
Mechanical	1	0.02	0.02	0%	0.02
Electronic	1	0.01	0.01	0%	0.01
Thermal Louvers	1	0.98	0.98	0%	0.98
Thermal Radiator (Area=m2)	1	10.50	10.50	0%	10.50
Ext SLI	1	1.03	1.03	30%	1.34

## Descent Stage Preliminary MEL

Component	Flt Units	CBE/Unit (kg/unit)	CBE (kg)	Cont.	CBE + Cont. (kg)
<b>Attitude Determination and Control System</b>					
IMUs	1	4.00	4.00	10%	4.40
Terminal Descent Sensor	1	23.60	23.60	2%	24.07
Descent Motor Controller	1	18.39	18.39	2%	18.76
<b>Command and Data System</b>					
Telemetry Muiltiplex Card (TMC): CRC Card (NR)	1	0.40	0.40	30%	0.52
MREU: MSAP Analog/Discrete MREU	1	0.80	0.80	5%	0.84
<b>Power</b>					
Thermal Battery (Thermal Battery)	4	0.51	2.04	30%	2.65
Chassis	1	3.54	3.54	30%	4.61
Load Switches (LCC) Boards	6	1.00	6.00	30%	7.80
Thruster Drivers* - MSL GID Boards	2	1.10	2.20	30%	2.86
Pyro Switches* (DPRA) Boards	4	1.64	6.56	30%	8.53
Houskeeping DC-DC Cnvrttrs* (HPCU) Boards	2	1.13	2.26	30%	2.94
Shielding	1	1.45	1.45	30%	1.89
<b>Propulsion</b>					
Gas Service Valve	4	0.23	0.92	2%	0.94
HP Transducer	1	0.27	0.27	2%	0.28
Gas Filter	1	0.75	0.75	2%	0.77
NC Pyro Valve	2	0.67	1.34	2%	1.37
NC 3/8" Pyro Valve	2	0.30	0.60	2%	0.61
Press Regulator	1	1.60	1.60	15%	1.84
Temp. Sensor	2	0.01	0.02	5%	0.02
Rectify to MSL PCA mass of 8.94kg	1	1.70	1.70	0%	1.70
Liq. Service Valve	3	0.28	0.84	2%	0.86
Test Service Valve	1	0.23	0.23	2%	0.24
LP Transducer	3	0.27	0.81	2%	0.83
Liq. Filter	1	0.45	0.45	2%	0.46
LP Latch Valve	2	0.35	0.70	2%	0.71
NC Pyro Valve	6	0.67	4.02	10%	4.42
NC 3/8" Pyro Valve	2	0.30	0.60	10%	0.66
Mass Flow Control	4	0.03	0.12	50%	0.18
Temp. Sensor	10	0.01	0.10	5%	0.11
Water flow test bed	1	0.00	0.00	0%	0.00
Lines, Fittings, Misc.	10	5.40	54.00	10%	59.40
Monoprop Main Engine	8	9.10	72.80	10%	80.08
Monoprop Thrusters 1	8	0.74	5.92	10%	6.51
Pressurant Tanks	2	9.12	18.24	30%	23.71
Fuel Tanks	3	15.99	47.97	30%	62.36
<b>Structures</b>					
Primary Structure	1	178.30	178.30	30%	231.79
Secondary Structure	1	15.76	15.76	30%	20.48
Separations	1	10.41	10.41	30%	13.53
BUD	1	32.28	32.28	30%	41.96
Prop Structure	1	17.20	17.20	30%	22.36
DS Centering Mass	1	11.80	11.80	30%	15.34
Purge Hardware	1	0.84	0.84	30%	1.09
Cabling Harness	1	37.42	37.42	30%	48.65

Component	Flt Units	CBE/Unit (kg/unit)	CBE (kg)	Cont.	CBE + Cont. (kg)
<b>Telecomm</b>					
X-LGA MER/MPF CWG	1	0.35	0.35	2%	0.36
UHF-LGA Monopole	1	0.60	0.60	2%	0.61
SDST X-up/X down	1	3.01	3.01	2%	3.07
X-band TWTA RF=100W	1	2.46	2.46	2%	2.51
Waveguide Transfer Switch (WGTS)	2	0.44	0.88	2%	0.90
X-band Isolator	1	0.52	0.52	2%	0.53
Filter, low power	2	0.07	0.14	2%	0.14
Filter, high power	2	0.38	0.76	2%	0.78
X-band Diplexer, high isolation	1	0.63	0.63	2%	0.64
Polarizer	1	0.26	0.26	2%	0.27
Other	1	0.06	0.06	2%	0.06
Coax Transfer Switch (CXS)	1	0.12	0.12	5%	0.13
Other	1	0.05	0.05	2%	0.05
WR-112 WG, rigid (Al)	4	0.56	2.22	10%	2.44
Coax Cable, flex (190)	4	0.14	0.56	10%	0.61
Coax Cable, flex (120)	1	0.29	0.29	10%	0.31
<b>Thermal</b>					
Multilayer Insulation (MLI)	26	0.38	9.75	30%	12.68
Paints/Films	5	0.02	0.12	20%	0.14
General	1	0.71	0.71	20%	0.86
Custom	46	0.10	4.60	20%	5.52
PRT's	140	0.00	0.21	5%	0.22
Mechanical	20	0.01	0.26	20%	0.31
HRS Tube Assy	1	2.23	2.23	20%	2.68
HRS Epoxy	1	0.56	0.56	10%	0.62
HRS Fluid (CFC-11)	1	1.10	1.10	30%	1.43
Fluid System P-Clamps	12	0.01	0.12	5%	0.13
Fluid System Mech Jt Jam Nuts	9	0.01	0.09	5%	0.10



## Lander Preliminary MEL

Component	Flt Units	CBE/Unit (kg/unit)	CBE (kg)	Cont.	CBE + Cont. (kg)
<b>Instruments</b>					
Lander Cameras	3	0.30	0.90	2%	0.92
Robotic Arm Camera	1	1.60	1.60	15%	1.84
Sample Insertion Camera	1	0.30	0.30	15%	0.35
Descent Cameras	2	0.30	0.60	15%	0.69
<b>Attitude Determination and Control System</b>					
Sun Sensor 1	3	0.06	0.17	30%	0.22
IMU 1	1	4.00	4.00	10%	4.40
SA Gimbal Drive Electronics	2	1.00	2.00	10%	2.20
HGA Gimbal Drive Electronics	2	1.00	2.00	10%	2.20
Lander arm Electronics	2	1.00	2.00	10%	2.20
Sampling handling Electronics	1	1.00	1.00	10%	1.10
<b>Command and Data System</b>					
Processor: MSAP Enhanced SFU (3U) 133MHz	2	0.55	1.10	30%	1.43
MTIF: MSAP MTIF Card (6U)	2	0.77	1.54	30%	2.00
CRC: CRC Card (NR)	2	0.40	0.80	30%	1.04
NVMCAM: MUC (Mission Unique Card) (NR)	2	1.00	2.00	30%	2.60
1/2 Sized Backplane & Chassis: MSAP Backplane with 1/2 Enclosure	2	1.30	2.60	30%	3.38
PCC: MSAP PCC DC-DC Converter: 5 V, 3.3V and +/-12V.	2	0.80	1.60	30%	2.08
MREU: MSAP Analog/Discrete MREU	2	0.80	1.60	30%	2.08
<b>Power</b>					
Solar Array	1	11.21	11.21	30%	14.58
Li-ION (Secondary Battery)	2	9.60	19.20	30%	24.96
Chassis	1	5.59	5.59	30%	7.26
Array Segment Switches* - MSL/MSAP Array Interface Slice Boards	2	0.80	1.60	30%	2.08
Load Switches - MSL Load Control Card (LCC) Boards	4	0.80	3.20	30%	4.16
Pyro Switches* - Pyro Firing Card (PFC) Boards	2	0.80	1.60	30%	2.08
Houskeeping DC-DC Converters* (HPCU) Boards	2	1.00	2.00	30%	2.60
MSI/MSAP Power Bus Controller Boards	1	1.00	1.00	30%	1.30
Battery Control - MSL Battery Control Board Boards	3	0.80	2.40	30%	3.12
Shielding	1	1.45	1.45	30%	1.89
<b>Structures</b>					
Primary Structure	1	68.85	68.85	30%	89.50
Secondary Structure	1	19.00	19.00	30%	24.70
Solar Array Latch/Release/Deploy Hinge	1	1.75	1.75	30%	2.28
Antenna Gimbal Assemblies	1	6.70	6.70	30%	8.71
Rover Egress	2	7.00	14.00	30%	18.20
Rover Mobility Tie-Downs	6	1.50	9.00	30%	11.70
Rover Lift Mechanism	1	5.20	5.20	30%	6.76
Rover Umbilical Cutter, Retractor & Tower	1	2.60	2.60	30%	3.38
MAV Support Releases	1	3.50	3.50	30%	4.55
MAV Erection Mechanism	1	15.00	15.00	30%	19.50
MAV Barrier Support Structure	1	10.00	10.00	30%	13.00
Sample Transfer Mechanism to MAV	1	15.00	15.00	30%	19.50
Lander Arm and Bio Barrier	1	5.56	5.56	30%	7.23
Lander Arm Launch Locks	2	0.50	1.00	30%	1.30
Lander Electronics Box	1	8.50	8.50	30%	11.05
Lander Bridle & Umbilical Cutters with Towers	1	6.60	6.60	30%	8.58
Lander Balancing Mechanism	3	3.50	10.50	30%	13.65
HGA Launch Locks	1	0.50	0.50	30%	0.65
Integration Hardware	1	4.82	4.82	30%	6.27
Balance Mass	1	3.90	3.90	30%	5.07

<b>Telecomm</b>					
X-HGA (22dB) MPF	1	1.60	1.60	10%	1.76
X-LGA MER/MPF CWG	1	1.00	1.00	10%	1.10
UHF-LGA MSL Helix	1	0.56	0.56	10%	0.62
SDST X-up/X down	1	2.70	2.70	10%	2.97
Electra-Lite	1	3.15	3.15	10%	3.47
X-band SSPA, RF=15W*	1	1.50	1.50	10%	1.65
Waveguide Transfer Switch (WGTS)	2	0.38	0.76	10%	0.84
X-band Diplexer, moderate isolation	1	0.35	0.35	10%	0.39
Filter, low power	2	0.20	0.40	10%	0.44
Coax Transfer Switch (CXS)	1	0.13	0.13	10%	0.14
Coax Cable, flex (190)	7	0.16	1.15	25%	1.43
WR-112 WG, rigid (Al)	4	0.43	1.72	25%	2.15
Coax Cable, flex (120)	3	0.09	0.25	25%	0.32
<b>Thermal</b>					
CO-2 Surface Insulation	5.4	0.38	2.03	30%	2.63
Paints/Films	2.9	0.15	0.44	30%	0.57
Isolation (G-10)	100	0.01	0.50	30%	0.65
Custom	20	0.02	0.30	30%	0.39
PRT's	120	0.00	0.18	10%	0.20
Mechanical	20	0.02	0.30	10%	0.33
Mechanical Pump Loop System	1	10.00	10.00	30%	13.00
Inter-Connect Tubint	1	6.29	6.29	30%	8.18
Shoulder	1	0.50	0.50	30%	0.65
Elbow	1	0.50	0.50	30%	0.65
Wrist/Sctuator	1	0.50	0.50	30%	0.65
HRS H/W	1	6.30	6.30	30%	8.19
0	1	0.00	0.00	30%	0.00
MAV Enclosure	1	14.50	14.50	30%	18.85
MAV Temperature Sensors	20	0.00	0.08	10%	0.09
MAV RHU's	26	0.10	2.60	30%	3.38

## Fetch Rover Preliminary MEL

Component	Flt Units	CBE/Unit (kg/unit)	CBE (kg)	Cont.	CBE + Cont. (kg)
<b>Attitude Determination and Control System</b>					
IMU 1	1	0.73	0.73	5%	0.77
Nav Camera	4	0.22	0.88	10%	0.97
Hazard camera	4	0.25	0.98	5%	1.03
Shielding:	1	0.00	0.00	0%	0.00
<b>Command and Data System</b>					
Processor: RAD750	1	0.55	0.55	5%	1.60
Telecom_I_F: MTIF	1	0.73	0.73	5%	0.77
Custom_Special_Function_Board: MDM ASIC (Fetch)	1	0.13	0.13	30%	0.17
Analog_I_F: MREU	1	0.82	0.82	6%	0.87
Custom_Special_Function_Board: Image, motor drive,	1	0.71	0.71	30%	0.92
Power: CEPCU	1	1.15	1.15	10%	1.27
Backplane: CPCI backplane (6 slots)	1	0.60	0.60	30%	0.78
Chassis: CDH chassis (8 slot)	1	3.83	3.83	2%	3.91
<b>Power</b>					
Solar Array	5	0.77	3.84	30%	4.99
Li-ION (Secondary Battery)	1	13.80	13.80	30%	17.94
Chassis	1	0.00	0.00	30%	0.00
Load Switches - Represents Power Switch Board Boards	1	1.80	1.80	30%	2.34
Power/Shunt Control* - Represents Solar array & Battery Board Boards	1	2.00	2.00	30%	2.60
Shielding	1	0.21	0.21	30%	0.27
<b>Structures</b>					
Primary Structure	1	10.06	10.06	30%	13.08
Secondary Structure	1	6.54	6.54	30%	8.50
Solar Array Structure	1	12.75	12.75	30%	16.57
Solar Array Latch/Release (Pyro)	3	0.09	0.27	30%	0.35
Mobility - Suspension & Differential	1	9.56	9.56	30%	12.43
Mobility - Wheels	6	1.16	6.97	30%	9.06
Mobility - Drive & Steering Actuators	10	1.57	15.70	30%	20.41
Chassis - Solar Panel Motors & Brackets	2	1.05	2.09	30%	2.72
Mast - Haz Cam Bar & Spt Struc	2	0.24	0.48	30%	0.62
Sample Acquisition	1	1.75	1.75	30%	2.28
Mast - Additional Nav Cam Support Structure	4	0.25	1.00	30%	1.30
Cabling Harness	1	5.80	5.80	30%	7.54
<b>Telecomm</b>					
UHF-LGA Monopole	1	0.10	0.10	15%	0.12
Electra-Lite	1	3.15	3.15	10%	3.47
Coax Cable, flex (120)	1	0.07	0.07	25%	0.09
<b>Thermal</b>					
Heaters	0	0.00	0.00	0%	0.00
Custom	8	0.02	0.14	30%	0.18
PRT's	15	0.01	0.18	30%	0.23
Thermostats	0	0.00	0.00	0%	0.00
Mechanical	16	0.02	0.32	30%	0.42
Other Components	1	0.00	0.00	0%	0.00
Camera Heaters	8	0.04	0.32	10%	0.35
CO-2 Shield	2	0.03	0.06	2%	0.06