Continuing Evolution of Mars Sample Return[1,2,3]

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Abstract—In 2001, JPL commissioned four industry teams to make a fresh examination of Mars Sample Return (MSR) mission architectures. As new fiscal realities of a cost-capped Mars Exploration Program unfolded, it was evident that the converged-upon MSR concept did not fit reasonably within a balanced program. Therefore, along with a new MSR Science Steering Group, JPL asked the industry teams plus JPL's Team-X to explore ways to reduce the cost. A paper presented at last year's conference described the emergence of a new, affordable "Groundbreaking-MSR" concept [1].

This paper addresses the continued evolution of the Groundbreaking MSR concept over the last year. One of the tenets of the low-cost approach is to use substantial heritage from an earlier mission, Mars Science Laboratory (MSL). Recently, the MSL project developed and switched its baseline to a revolutionary landing approach, coined "skycrane" where the MSL, which is a rover, would be lowered gently to the Martian surface from a hovering vehicle. MSR has adopted this approach in its mission studies, again continuing to capitalize on the heritage for a significant portion of the new lander.

In parallel, a MSR Technology Board was formed to reexamine MSR technology needs and participate in a continuing refinement of architectural trades. While the focused technology program continues to be definitized through the remainder of this year, the current assessment of what technology development is required, is discussed in this paper. In addition, the results of new trade studies and considerations will be discussed.

Adopting these changes, the Groundbreaking MSR concept has shifted to that presented in this paper. It remains a project that is affordable and meets the basic science needs defined by the MSR Science Steering Group in 2002.

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1. PROGRAM BACKGROUND

NASA has considered a sample return mission from Mars since the 1960s. The most recent series of studies of the Mars Sample Return (MSR) concept (circa 2001) established a trade space framework for the evaluation of various mission architectures and established a baseline plan for a 2013 mission. Because technology development will lower the risk and cost of a sample return and thereby enable a reasonable mission, these studies also endeavored to define the required technology. While it remains uncertain when a sample return mission might occur, the current Mars Exploration Program (MEP) includes an eventual sample return as a goal. Precursor missions that demonstrate various required aspects of a sample return mission must be included in any plan. Without precursor missions and technology development to reduce risk and cost, a sample return mission could remain too ambitious.

MEP Overview

Let's take a moment and review the current MEP plan in the context of its contribution toward a MSR. The Mars Pathfinder and the Mars Global Surveyor (MGS) were launched in 1996. Mars Pathfinder demonstrated that a rover could maneuver in a limited fashion on the surface of Mars and make scientific measurements. The mission, which lasted approximately 90 days, proved that a rover could be an essential part of a Mars surface mission.

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[1] 0-7803-8155-6/04/$17.00 © 2004 IEEE
[2] IEEEAC paper #1238, Version 1, Updated January 21, 2004
[3] The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.
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MGS continues to return a stunning set of pictures of the globe. MGS not only provides a huge amount of global science, but also provides a crucial relay function for the 2003 Mars Exploration Rovers (MER)

With MGS continuing, new missions in the current decade provide additional capabilities (see Figure 1). 2001 continued the legacy of global scientific return with the Odyssey orbiter mission, which features a moderate imaging capability combined with a multi-band thermal imaging spectrometer. This combination enables the highest resolution near-infrared investigation to date.

In addition, a gamma-ray spectrometer and neutron detector survey the planet for hydrogen (and consequently liquid or ice water) at coarse resolution. Odyssey also provides UHF data relay for MER and has been the main conduit thus far in the mission.

2003 shows a step function increase in roving capability with the launch of two Mars Exploration Rovers. MER uses a Mars Pathfinder heritage entry, descent, and landing (EDL) airbag system to place a much more capable rover on the surface. MER will be the first time a rover will move over the horizon from its landing point. This is consistent with the capability needed for the original MSR concepts established in 2001, which at some point could re-emerge.

The European Mars Express mission in 2003 joined the suite of NASA's mission in pursuit of better understanding of Mars.

2005 sees another increase in the resolution of imaging from an orbiter. MRO will carry a camera capable of 30- to 60-cm resolution images at possibly hundreds of 10-km-square sites. MRO will also return more data than all other Mars missions combined and enable better resolution images to complement MGS and Viking orbiter global imaging data sets. MRO also has a hyperspectral imager and an Agenzia Spaziale Italiana (ASI, the Italian Space Agency) radar (follow up to the 2003 European Space Agency Mars Express mission).

A Mars Scout is planned for 2007 (NASA Discovery analog, see 2003 IEEE Aerospace Conference paper # 1525 by Matousek for more details [2]). The Phoenix mission was selected, which uses the Mars Surveyor Program's 2001 lander that has been in storage since 2000. This stationary mission will land in high northern latitudes where we expect near-surface ice for study of water and potential habitability.

The plan for 2009 calls for a surface mission: the Mars Science Laboratory (MSL). MSL would demonstrate precision landing (within 5 km of nominal), hazard avoidance, and hazard tolerance. MSR studies assume inheritance of the MSL accurate/safe landing capabilities. MSL is planning a suite of advanced analytical instruments based on a large rover capable of greater mobility that can move outside the 10-km precision landing ellipse.

NASA is also planning a Mars Telecommunications Orbiter (MTO) in 2009. This communications asset would last ten years and support the MSL and other missions in the next decade. In numerous Mars Program studies in recent years, a dedicated telecommunications spacecraft enables future science missions of increased scope. MTO would also demonstrate a key MSR function that will be discussed later.

Past the 2009 time frame, the current MEP plan becomes uncertain. The earliest MSR would naturally occur after 2009 would be 2013 to ensure proof of feed-forward technology of the 2009 MSL mission. A series of pathways through the next decade have been studied to be responsive to new discoveries made in this decade. Figure 2 shows a potential of MSR in an example pathway.

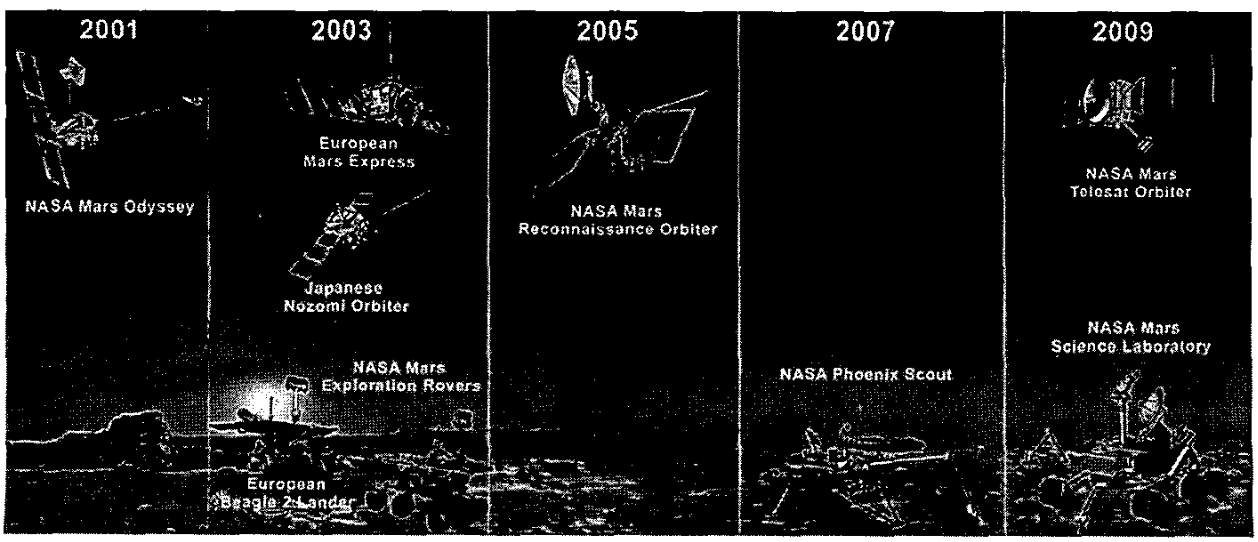

Figure 1. This decade of Mars Missions are planned.

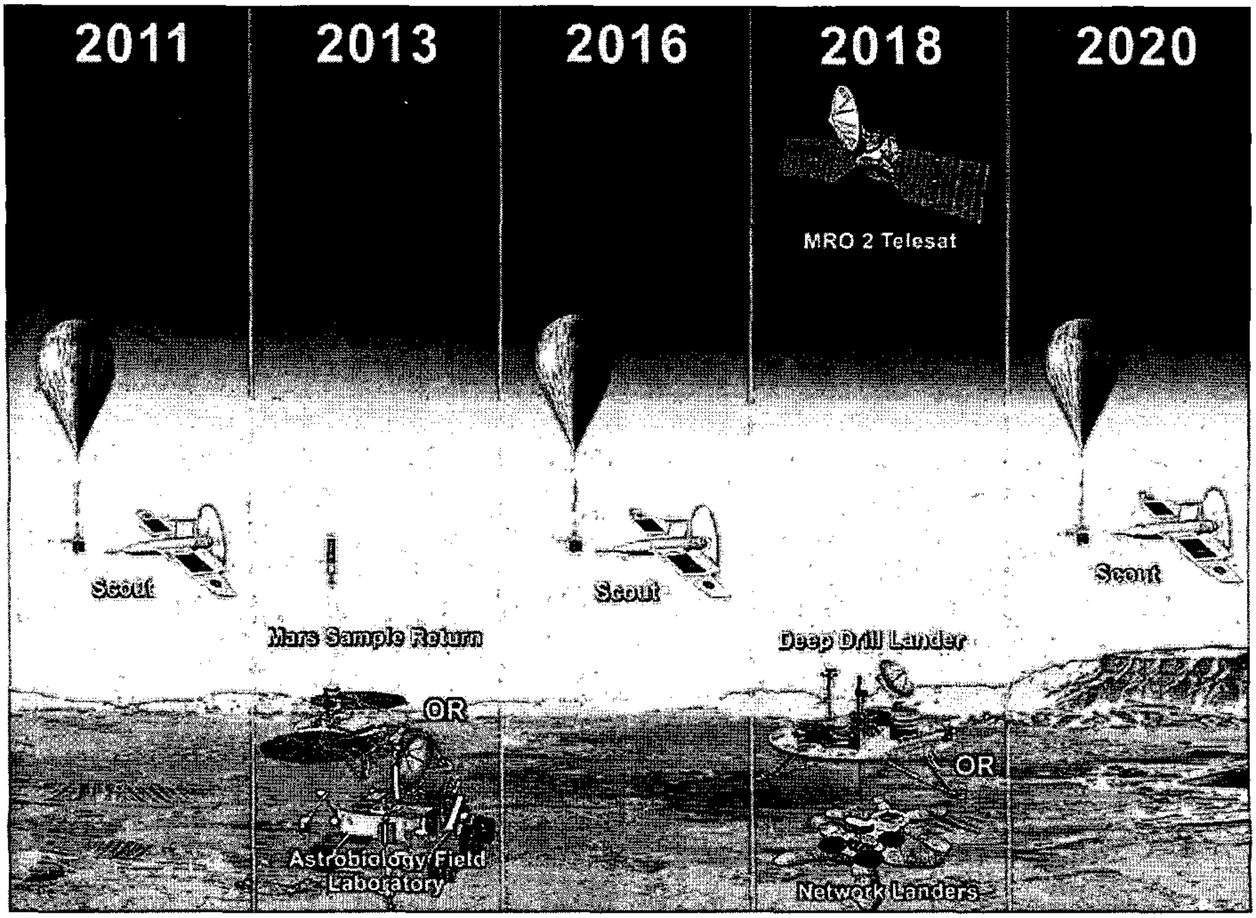

Figure 2. Example pathway through the next decade

2. Evolving to Groundbreaking MSR Concept

Original MSR Studies

In 2001, we performed industry studies to take a fresh look at MSR implementation.

Four teams conducted the studies, each having substantial involvement by industry and academic partners. More than 20 institutions and companies were involved. The teams were led by:

- Ball Aerospace & Technologies Corporation (BATC), Boulder, Colorado.
- The Boeing Company, Huntington Beach, California.
- Lockheed Martin Corporation, Denver, Colorado.
- TRW, Redondo Beach, California. The significant partners are identified in each of the papers written two years ago by each team (see References in this paper).

The studies were performed in two parts. First as a broad trade study and second as a focused study on down selected concepts.

The results of these studies are discussed in depth in papers written for the 2002 IEEE Aerospace Conference. Six papers were presented, one by each industry team, one by JPL's Team X, and an overview paper (see References [3] through [8]). Concepts varied significantly, including a variety of surface mobility (roving) capabilities and the use of Solar Electric Propulsion (SEP), aerobraking and aerocapture at Mars, variety of Mars Ascent Vehicles (MAV), etc.

Establishing the Groundbreaking Approach

In 2002, new fiscal realities of a cost-capped Mars Exploration Program unfolded and it was evident that these MSR concepts defined in 2001 did not fit reasonably within a balanced program. As a result, a MSR Science Steering Group (as one of several Mars program science steering groups) was formed to reevaluate the science requirements for MSR and recommend an approach to a "first" MSR mission that might have a better chance of fitting.

The basic change in requirements was to eliminate mobility on the surface and any "sophisticated" sample collection process. By selecting the right kind of site, "mobility" to get sample diversity could potentially be provided by the planetary processes (weathering, outflows, etc.) themselves. Using a scoop on an arm, subsurface access to a few tens of centimeters might be adequate. With a sieve, rocks (key to pristine sample collection) could be collected. Use of a context camera would help "catalog" the samples to be sorted out on Earth from a bulk sample container rather than individual samples kept segregated throughout the mission.

Emerging Concepts

What has emerged is a reduced mission concept called the Groundbreaking MSR. A generic version of which is depicted in Figure 3. The notations on the figure should be self-explanatory.

Unlike the previous concept, the lander has neither a rover nor a drill. The surface stay is about two weeks, where the previous version collected samples for about three months before departing for Mars orbit. The payload has been simplified to a flight-proven arm with a scoop and sieve and a basic context camera. The samples are bulk stored in the Orbiting Sample container, rather than individually. Differences in the two mission concepts are shown in Table 1.

Each team developed a new mission concept, which retained some of their basic differences in approach. Table 2 indicates some of the basics.

All the teams have eliminated their rover to keep the cost down, and all reduced their landed system to a single system; in the previous study, three of the 5 teams doubled up on the landers and MAV.

To assure ourselves that we had credible costs estimates, we retained the services of both Aerospace Corporation and SAIC to provide independent cost assessments of each of the teams' concepts. At no time prior to our concept review did any of the teams know what costs the other teams had arrived at, nor did Aerospace or SAIC. Thus, we ended up with 12 independent cost estimates for this new mission. These estimates are remarkably consistent, ranging from 0.9 to 1.4 billion dollars for development in $FY02.

The SSG then embarked on confirming and building a case for the adequacy of the floor-level mission; the results are discussed in the following paragraphs.

Science Steering Group Conclusions

While the results of the MSR SSG were reported last year, it is important to keep them at the forefront of the evolving missions. Indicated above, the MSR SSG evaluated the adequacy of this new floor-level mission. With the benefit of industry team study results and focused investigation on the science adequacy of these reduced requirements, the MSR SSG published a final report of their findings that was later approved by the Mars science community (represented by the Mars Exploration Payload Analysis Group (MEPAG). The following is a condensation of key science findings identified in the report.

1) The first Groundbreaking MSR mission must support the science objectives of Astrobiology; it will do so by simply landing at a site shown by prior missions to contain information about the current and past Mars climate and habitability. Mobility is not required.

2) Landing precision comparable to that of Mars 2009 MSL (~10 km) and sufficient to ensure landing safely is adequate for the first mission if geologic units having lateral extents of >10s to 100s of km are targeted. Analyses of returned samples can be generalized to the rest of each unit.

3) By collecting samples of fines (fine grained regolith and wind-blown dust), small regolith rock fragments, and atmosphere, the Groundbreaking MSR mission will achieve science goals fundamentally important to the Mars Exploration Program as defined by MEPAG.

4) Assuming a site similar to the Pathfinder site and assuming an extendable arm with 2-meter reach and ~20-cm depth capacity, there is a high probability that the mission will succeed in achieving the stated sampling requirements.

5) A simple context imager, an extendable robotic arm with arm-camera, a simple sampling devices (for example, a scoop + sieve), and a sealable gas-tight sample canister are sufficient on-board sensing and sampling systems for Groundbreaking MSR.

6) The first MSR should be flown at the earliest possible time following the completion of those missions now identified through the 2009 MSL.

7) The science requirements for the first Mars Sample Return Mission, having been defined by the science community itself, must not be permitted to escalate. KEEP IT SIMPLE.

8) NASA should establish a program architecture that minimizes risk through selected redundancy, even though this likely will increase mission cost.

9) The MSR SSG considers risk reduction to be so important that it should have a higher priority than any additional science capabilities beyond those of the revised science requirements.

A primary driver for the mission has not changed, and that is the planetary protection requirements — forward, back and round-trip as follows:

- The need to control the amount of <u>sample contamination</u> by round-trip Earth organisms to avoid false positives in life detection tests (for the purposes of this study we assumed a goal of sterilization of the entire Lander to Viking levels, or proof of <10e-2 chance of a single Earth organism in the sample).

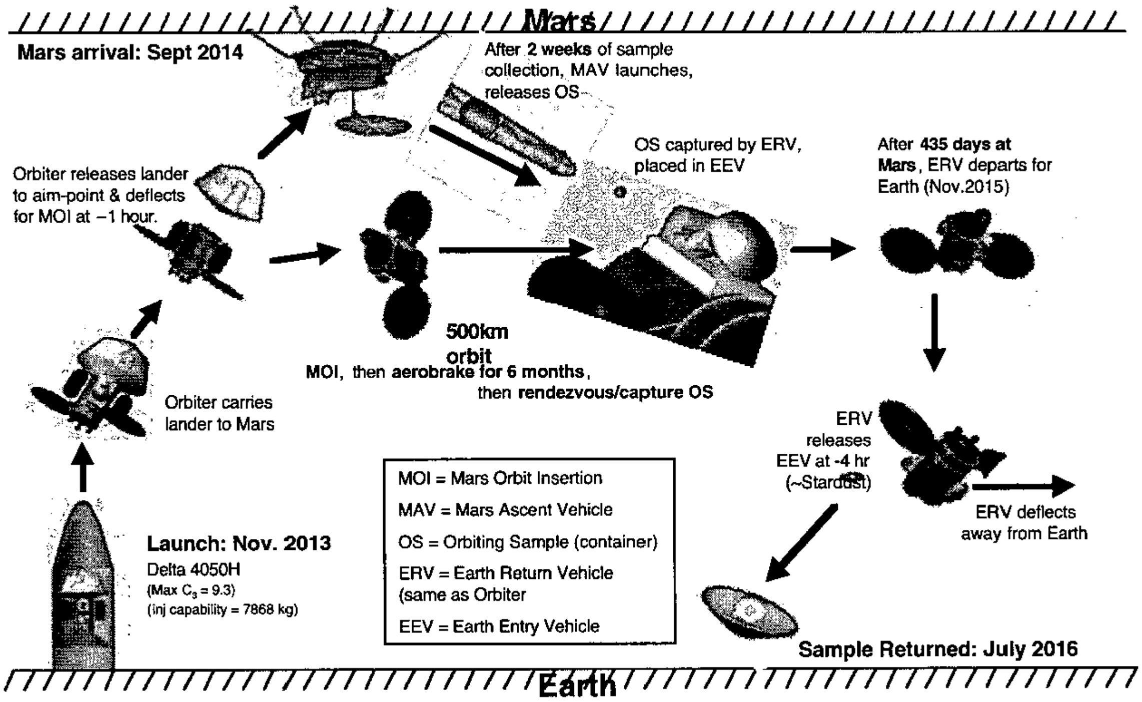

Figure 3. Generic Groundbreaking MSR mission

Table 1. New concepts versus old concepts.

New First "Groundbreaking"	Previous "MER"-Class Mobility
Sample collection over a **few square meters** with stable Lander and arm	Sample collection over a few square km **with rover**
Sample collection within a few 10's of cm of surface with **scoop**	Sample collection within a few meters of surface with a **drill**
Lander-based collection simplicity with **single camera** to aid scoop and sieve	Rover-based collection complexity with **multiple in-situ instruments** to aid rock corer
Samples mixed in single container	**Samples segmented**, documented, and isolated in multiple containers
Lander surface operation a **few weeks** duration	Lander/Rover surface operation a **few months** duration
Lander payload mass (MAV, collection equipment, avionics, power) ~ 600 kg	Lander payload mass (ditto plus 200 kg Rover ~ 800 kg)
Total landed mass ~ 1100 kg	Total landed mass ~ 1600 kg
Aeroshell diameter: 4.05 m	Aeroshell diameter = 4.57 m
LV ~ Delta 4050H with increased margin	LV ~ Delta 4050H
Mission development cost ~ 1 B ('02 $'s)	Mission development cost: ~ 1.6 B ('02 $'s)

Notes: **a) Basic Mission Architecture is Common**
b) Masses are from JPL Team-X studies

Table 2. Summary of new concept attributes.

(All concepts have a stationary lander, no Rover)

Ball • 1 lander – 1 sample • All chemical propulsion • Mars orbit rendezvous • Return to Earth -- direct atm orbit	**Boeing** • 1 lander – 1 sample • All chemical propulsion • Mars orbit rendezvous • Return to Earth orbit – direct atm entry
LMA • 1 lander – 1 sample • All chemical propulsion • Deep space rendezvous • Return to Earth – direct atm entry	**TRW** • 1 lander (released from orbit) – 1 sample • SEP propulsion • Mars orbit rendezvous • Return to Earth – direct atm entry
Team-X • 1 lander – 1 sample • All chemical propulsion • Mars orbit rendezvous • Return to earth – direct atm entry	

– Sample containment assurance: The requirement that the integrated probability of back contamination be kept below a specified level (with a lack of a specific requirement, for the purposes of this study we assumed a goal of probability of release of Mars material to the Earth's biosphere to being less than 1 in a million).

3. MOVING TO THE SKYCRANE

The Team-X concept was a result of distilling the industry concepts with input from the multinational, multi-agency Mars Program Systems Engineering Team (MPSET). Recognizing that variations have merit, this concept has been maintained this year as a reference for further studies.

One of the premises of keeping the cost and risk down for MSR, was the use of the landing implementation that would be adopted by the '09 mission of the Mars Science Laboratory. MSL plans to demonstrate precision landing, robust/safe landing and delivering a much higher usable landed mass than previous missions. The ground-breaking MSR concept and cost indeed reflected building another copy (to the extent practical) of the MSL entry/descent/landing (EDL) system, as well as the lander platform. Over the last year, MSL's concepts evolved from a traditional legged platform to support the rover laboratory to one where the landing system suspends the rover from above and lowers the already hazard-robust rover to the surface via a 10-meter tether. This landing system is coined the "skycrane". Figures 4 and 5 depict this current MSL landing concept. The difference in descent configuration is shown in Figure 6. The rover is the base for the MSL science laboratory, which traverses over-the-horizon from the landing location. Thus, a landed platform serves no utility for the mission once landed, and further, the main motivation for considering the skycrane implementation is to eliminate the rover egress difficulties of this large rover from a raised platform. Unlike MER with its air-bag landing system where the landed platform sits on the surface, a powered-descent platform requires propulsion elements underneath with enough clearance to tolerate substantial surface rocks.

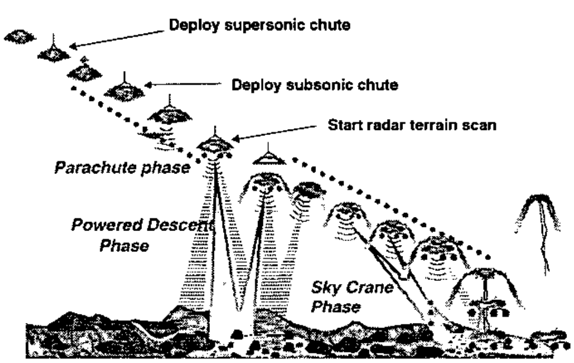

Figure 4. MSL EDL concept

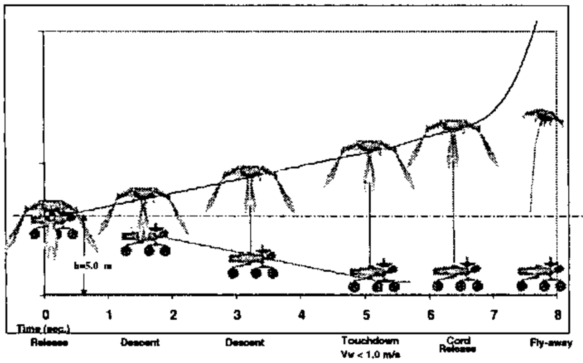

Figure 5. MSL rover lowered to the surface

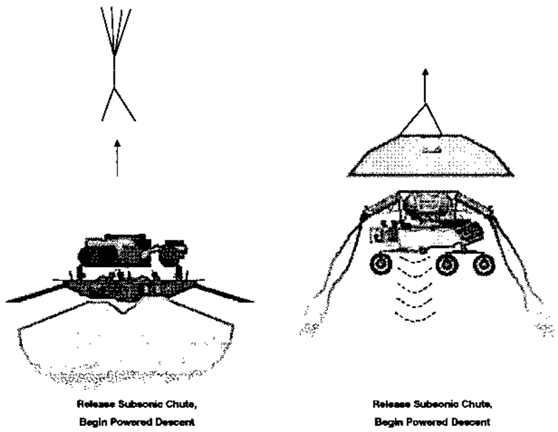

Figure 6. Pallet versus skycrane descent for MSL

We conducted studies with JPL's Team-X to understand the impact of changing to the skycrane on MSR implementation. We found that we were able to maintain the build-a-second-copy approach from the MSL EDL system. However, we no longer have a platform to inherit from MSL. While we expect a small cost increase as a result, the major benefits of MSL inheritance remain, including the avionics and telecom systems from the MSL rover. Figure 7 depicts an MSR platform being lowered by the skycrane.

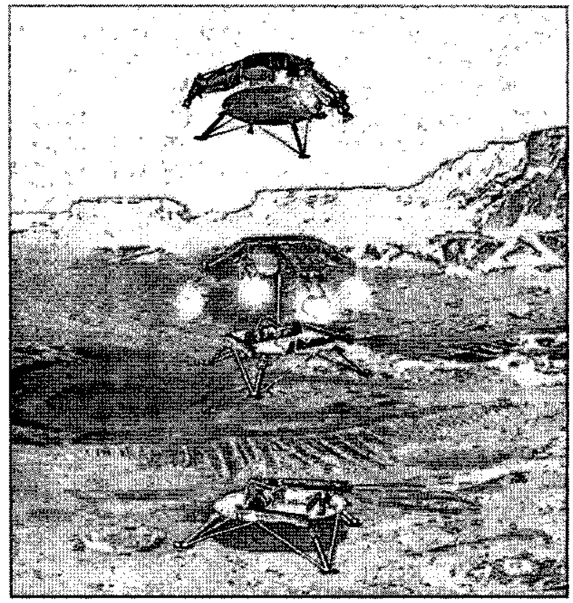

Figure 7. MSR lander lowered by skycrane

4. Latest MSR Reference Concept

As already described in the generic groundbreaking MSR mission concept (Figure 3), there are numerous system elements required to carry-out a MSR mission. And again, while the industry studies have a variety of differences in design, the Team-X design is currently carried as the reference design.

Table 3 shows the latest mass breakdown for the major mission elements.

Table 3. Top-level mass breakdown for MSR

	Lander		Descent Stg		Entry Sys		Orbiter/ERV	
	(kg)	(%)	(kg)	(%)	(kg)	(%)	(kg)	(%)
CBE Dry Mass	786		458		564		910	
Subsystem Heritage Contingency	146	29%	125	27%	128	23%	230	25%
System Growth Contingency	5	1%	13	3%	41	7%	43	5%
DV Propellant	0		203		0		3215	
RCS Propellant	0		0		15		0	
Propellant mass growth contingency	0	0%	0	0%	0	0%	0	0%
Wet Mass	937		799		748		4398	
Launch Mass	6882							
L/V Performance Margin	828				11%			
Mission Unique LV Contingency	0				0%			

The launch vehicle is assumed to be a Delta 4050H with the standard 5-meter fairing.

The EDL/Lander System

The MSR Skycrane design is shown in Figure 8. The system is monopropellant, and utilizes engines inherited from Viking. Minimal avionics are included, the heart being provided by the lander avionics (or the rover avionics in the case of MSL). Power is provided by an internal "thermal" short-term/high-output battery lasting through the EDL process.

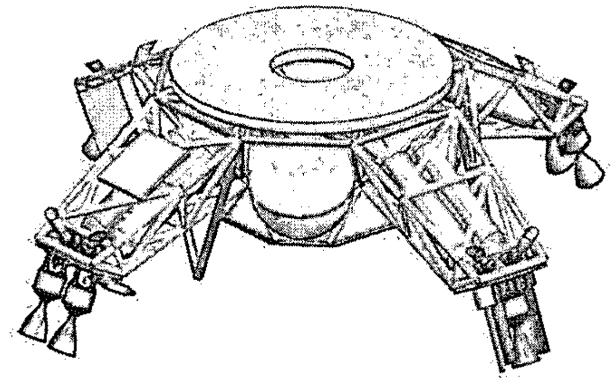

Figure 8. MSR skycrane

The Skycrane and Lander packaged in the heatshield (bottom) and backshell is shown in Figure 9. Figure 9 shows an optional cruise stage attached which would be needed if a second copy of the lander were to be launched separately for system redundancy. The cruise stage would have significant build-to-print heritage from MSL. The aeroshell is 4.5 m in diameter to take advantage of the full dynamic envelope of heavy-lift launch vehicles (5-meter fairings). While the previous version of MSR performed within a 4.05 m aeroshell, heritage of build-to-print from MSL makes the 4.5 m economical. The shapes of aeroshell and backshell are similar those used on Viking, preserving that heritage.

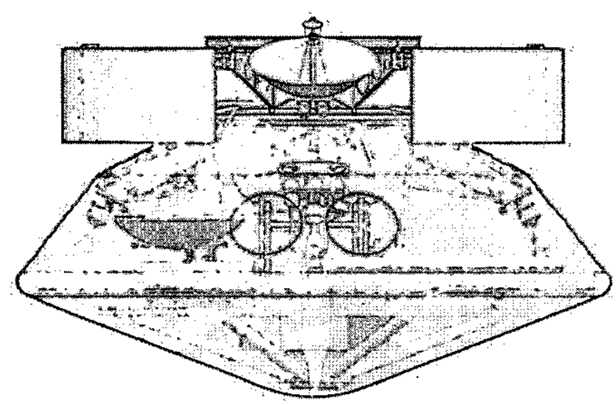

Figure 9. EDL system with optional Cruise Stage

The lander shown in figures 10 and 11 is a new design, but assumes some MSL heritage. An avionic package is shown sitting on the lander deck, which is inherited from MSL with modest modifications (reductions). The dish on top of the package is an X-band direct-to-earth high-gain antenna identical to the MSL design. In addition both systems have UHF "Electra-lite" communications packages linked to orbiting assets (including the planned MTO and, if still functional, MRO and even Odyssey). Redundant arms (about a meter long), each with a scoop and sieve, are used to acquire samples from the immediate area. Trenching to a few 10s of centimeters will be required to obtain sample free from lander contamination and natural surface oxidation. While previous contemporary landers use a stereo camera on a mast to view the trenching and collection area, we believe that simple arm mounted cameras can be used effectively. The method of measured filling of the Sample Container is yet to be definitized, but is believed to be easily within current technical capabilities. Transfer of sample container to the Orbiting Sample (OS) (a 16cm sphere) is described in the technology section.

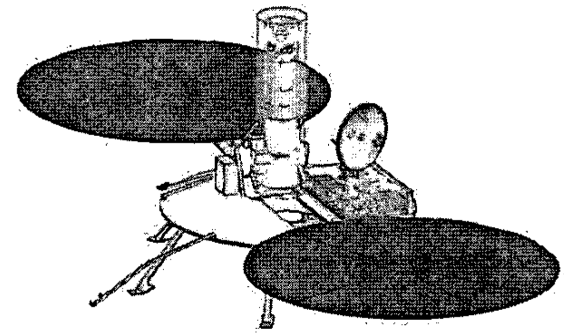

Figure 10. MSR Lander – deployed, MAV erect

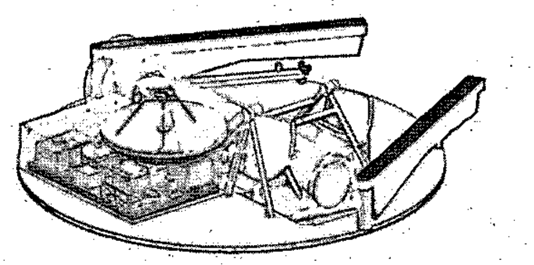

Figure 11. Lander stowed in EDL configuration

The MAV would be enclosed in an igloo that is kept internally clean from Mars dust, and provides an acceptable thermal environment. A solid-propellant MAV must be kept above minus 50 C. The power required for keeping the MAV warm would be substantial, and more detailed trade studies will be performed in the near-future to optimize power versus thermal insulation and the benefit of the potential use of Gel propellant technology which can tolerate much colder temperatures (see technology section).

Mars Ascent Vehicle

The MAV is baselined as a solid-propellant, two-stage, three-axis stabilized vehicle, weighing about 285 kg (including the 5 kg OS). Figure 12 shows to MAV configuration, with the smaller second stage with thrusters for 3-axis control and the OS mounted on a spin-eject mechanism inside the nosecone. It launches the OS into a circular orbit of 500 km+/- 100 km and within 0.2 degrees of inclination. The MAV would transmit enough telemetry during ascent to allow reconstruction of events in case of failure. In addition, it carries a UHF beacon for location by orbiting assets to aid in location of the OS. The OS may stay with the MAV for perhaps a month, unless risk analysis indicates immediate release.

Figure 12. Mars Ascent Vehicle with OS

Orbiter/Earth Return Vehicle

The Orbiter/ERV would function as a cruise stage for the Lander. After carefully targeting and releasing the Lander at about an hour before encounter with Mars, the Orbiter prepares itself for a propulsive Mars Orbit Insertion (MOI) maneuver, into an elliptical 1-3 day orbit with a 240 km periapsis (apoapsis 35,000 km to 75000 km), setup for aerobraking. For this maneuver and the departure from Mars, the orbiter would require over 3000 kg of mono-propellant. Aerobraking would be used (to save fuel) over the next 6 months to circularize the orbit to 500 km for rendezvous with the OS. Future studies will examine the possibility of eliminating the need for aerobraking, which is viewed as an additional risk for an already complex mission.

In addition to delivering the Lander for entry, the Orbiter/ERV (see Figure 13) would carry the Earth Entry Vehicle (EEV), the equipment for detection/rendezvous/capture of the OS and transfer of the OS to the EEV, the spin/release mechanism for the EEV, and the propulsion for earth return. Once in circular orbit, the Orbiter/ERV would maneuver to, rendezvous with, and capture, the OS. The MAV would most likely lift the OS into orbit within a month of entry. Aerobraking maneuver design can be optimized to end-up in the same plane, phased correctly with the OS with a minimum of additional propellant. The OS would be detected and tracked by the Orbiter/ERV by a visible-band narrow-angle camera developed for optical navigation, called the OpNav Camera (see technology discussion). In addition, an Electra UHF receiving system for detection and tracking of a UHF beacon on the upper stage of the MAV would be included. The current thinking is to keep the OS attached to the MAV for a month as additional aid in locating the OS. Adding a beacon to the OS is also being considered, but ii not currently in the reference design. As a back-up, the MTO would also have the same OpNav camera and Electra system, and would have already demonstrated that it can track an OS with the camera.

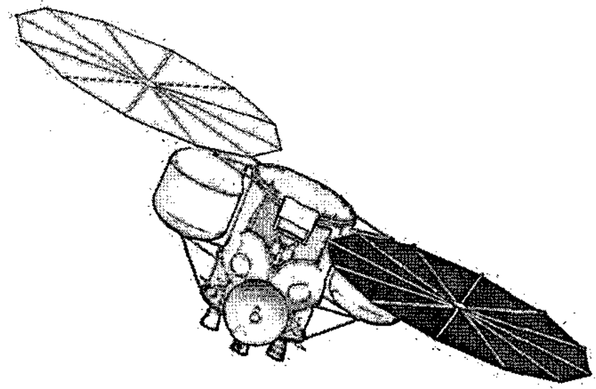

Figure 13. ERV/Orbiter concept

The capture of the OS would be performed through autonomous maneuvering of the Orbiter to the OS, in a non-linear closing trajectory called a football orbit (for its shape), until the OS is sensed to be inside a basket and constrained. A wide angle camera would be used in this proximity phase, and other sensors are being explored to potentially augment the camera. Several concepts are being considered as shown in figures 14 and 15 (discussed in the technology section). The OS would be transferred to the EEV and sealed for earth entry. If a redundant second Lander were flown in the mission, the Orbiter may have to maneuver to a second OS as well. Trades are yet to be completed on the pros and cons of recovering and returning both OS's vs. rendezvousing with/returning only one of the OS's. Figure 14 shows a capture basket on a pallet with 2 EEV's as an optional design. A single transfer mechanism is used to load OS's into both EEV's.

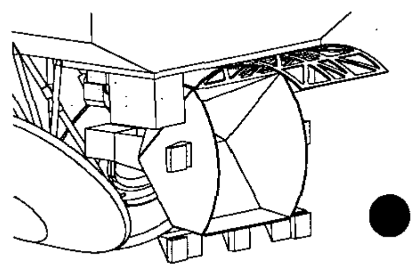

Figure 14. Baseline capture basket concept

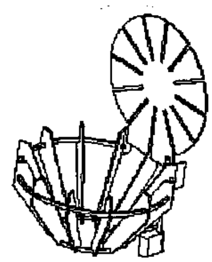

Figure 15. Alternate capture basket concept

If six months is taken to aerobrake, there still remains about a year to affect the capture of the OS(s), and prepare for departure for Earth. A propulsive maneuver then would initiate a Type-I cruise to Earth. Initially targeted to pass by Earth, the Orbiter would be retargeted in the last few days to release the EEV toward earth entry about four hours out, then would perform a divert maneuver into a non-earth-returning trajectory.

Earth Entry Vehicle Concept

The EEV as conceived is a self-righting, 0.9 m diameter, 60 degree sheer-cone blunt-body atmospheric entry vehicle. The cross-section is shown in Figure 16. The central cylinder is the sample container, inside a spherical OS. Aside from another sealed container (essentially a Kevlar bag) around the OS, called Containment Vessel, the remainder of the spherical part of the EEV is crushable material and carbon-carbon composite shells. The early state of development of the EEV is discussed in the technology section. The front of the EEV is standard ablative material. The EEV is completely passive, except for self-contained beacons used as a backup tracking aid. For purposes of this study, the Utah Test and Training Range (UTTR) has been used as the reference landing site.

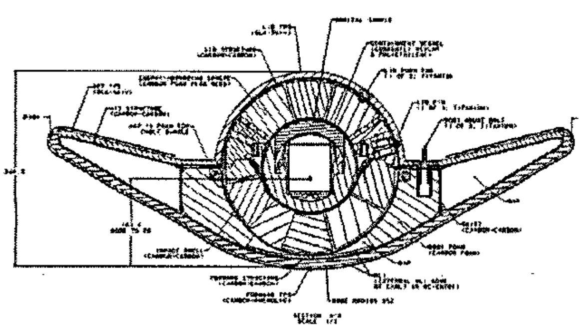

Figure 16. Cross-section of EEV concept

Orbiting Sample Concept

The OS concept calls for a a 16 cm diameter sphere. It contains the sample container that would be filled and sealed prior to insertion into the OS. The OS contains an internal structure that locks the sample container in place and protects it (see Figure 17). The outer surface is a smooth spectular surface for efficient detection with the visible OpNav camera. As we study OS detection further, we might add a UHF beacon for this design concept; low power solutions are being pursued that would not require solar arrays on the OS surface which would degrade its optical properties.

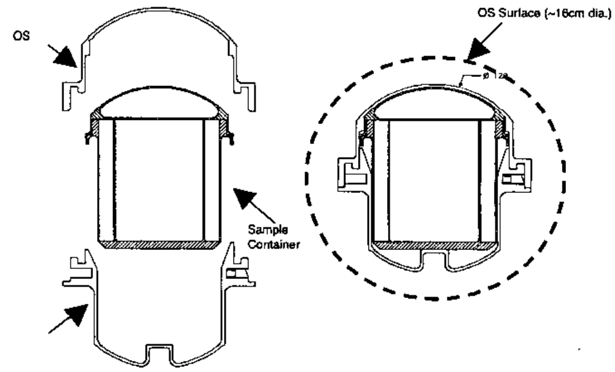

Figure 17. Sample Container inside OS structure within the OS shell

5. Technology Development Planning

Technology Board Formed

In recognition of the need to start preliminary MSR technology development this coming year (FY'05), a technology board was formed to solidify the plans required. The Board consists of representatives from JPL, NASA LaRC, and NASA MSFC covering each of the key areas identified. We are about mid-way in the board activities at the time of writing this paper. The following defines preliminary results and identifies the challenges ahead.

MSR Lander

The Entry, Descent and Landing system for MSR would be expected to be highly inherited from the planned MSL'09 mission. Technology development for robust/safe landing is currently underway and expected to be completed within the next year. They include guide entry (hypersonic aeromaneuver guidance), hazard detection and avoidance (phased array terrain radar, autonomous crater detection and avoidance, and the addition of a subsonic parachute for longer hang time), and an efficient, large mass capability touchdown system (skycrane concept and development of a modified Viking engine for descent).

The landed platform planned for MSR will be a new design. While the design will be challenging, we anticipate that there is no new technology required. The planned avionics, including telecom, are all existing technology, with high-heritage from MSL and early programs.

The design of the cruise stage (if needed) would be expected to be inherited from MSL, and would have already incorporated the optical navigation capability currently being developed for MRO '05.

MSR Orbiter

The orbiter would be expected to be highly inherited from an industry bus. There are no new technologies envisioned.

OS Detection, Rendezvous and Capture

Detection of the OS once in orbit is baselined to be via the OpNav camera being developed for optical navigation from MRO and MTO. Analysis has shown that locating a lost OS from a medium altitude orbit can be achieved within a few days. If MSR in fact uses aerobraking, the relative orbital configurations may make that process difficult. As discussed previously, the OS may be kept attached to the upperstage of the MAV with a UHF beacon for an extended period of time. It is desirable to also have a UHF beacon on the OS that could last several years; miniature designs are being investigated which may be already close to available commercially. Operating an OS beacon on battery is desirable since population of the OS surface with solar cells will degrade the optical detectability

A wide angle visible camera (already flown on MER for other purposes) is planned for close proximity operations

Semi-autonomous rendezvous algorithms have been extensively studied by both JPL and Draper Laboratory, and solutions are available.

Designing the capture of the OS has been through many concepts. A couple of basket concepts were previously described. JPL is currently performing trades to converge on a single concept with which the technology program can move forward. Payload Systems (Cambridge, MA) has a SBIR contract to develop and build a capture mechanism test facility for the International Space Station as part of an augmentation to the SPHERES formation flying testbed. A free-flying OS, which is an adaptation of one of the SPHERES test articles, would be flown in controlled trajectories into a capture mechanism to study contact and capture dynamics.

The Mars Technology Program is funding MTO to fly a OS detection and tracking demonstration that would release an engineering version of the OS and track the OS in orbit using their already existing OpNav camera. In addition, MTO would serve as a second asset to detect and track the OS during the MSR mission. MTO's Electra communications payload would have the capability to also track the UHF beacon on the MAV (and possibly on the OS).

Other mission applications/demonstration of rendezvous in earth orbit are being investigated for benefits to understanding MSR. Other sensor suites such as lidar are being considered, even though not believed at this point to be required.

Mars Ascent Vehicle

A focused study on MAVs by three industry teams resulted in a good understanding of the technologies needed (see Reference [10]). A solid propellant vehicle is the baseline currently, with greater packing efficiencies than liquids. The technology is readily available, except for the need to further develop thrust vector controlled engine nozzles. As discussed earlier, Gel propellants have benefits that should not be ignored, both in the ability to better tolerate the cold temperatures on the surface of Mars and provide the potential for restart of the engines. Gel technology is mature for tactical uses by the Army; MSFC is further investigating for promising application to MSR.

The MAV, however, is a new development for the Mars environment. We have chosen to include two Earth-based developmental test flights as part of the project costs. MAV design would be performed pre-project (Pre-Phase A) and qualified before entering Phase C/D. Trying to match dynamic pressure and flight timeline to that of Mars is difficult and requires that the test launches be performed starting from high altitude balloon flights (62,000 ft).

Planetary Protection Technologies

Forward Planetary Protection is at this stage believed to be consistent with that required by MSL. This is another area where technical feed-forward is assumed. While further understanding and analysis is needed, the MSR requirement to not return earth spores carried to Mars (to avoid false-positives) is roughly consistent with the need to not contaminate measurements made by in-situ missions on Mars. Current MSL and Base Technology Programs are assessing and developing techniques for cleaning and sterilization (including hydrogen peroxide vapor techniques and the effects of heat sterilization on modern (post-Viking) electronics). In addition, validation technologies and procedures to be applied to the spacecraft during assembly need to be further developed. The MSR technology program has a small amount of funding ear-marked to cover any work needed beyond that inherited from MSL.

Sample Containment

Fundamental to the design of this mission is a need to not allow Mars material to enter the earth's biosphere. In 1999 and 2001, SAIC produced Probability Risk Assessments (PRA) to aid in determining what technologies were needed to be in-place to enable development of an adequately reliable system. Reliable earth entry was a major area that will be discussed in the next section. "Breaking the chain" of contact with Mars as well as measures to ensure that the sample remain sealed are also essential elements of sample containment.

Breaking-the-chain occurs in two places in the mission design. The first is to arrange for the sample canister to be placed in the OS without carrying any contamination to the OS or MAV which would have remained in an earth clean environment since launch. An ingenious scheme has been devised that would not only allow for a clean transfer, but would also effect a series of seals (one being welding the lid to the container). The process is depicted in Figure 18. The scheme calls for the exterior of the sample canister to be kept isolated from the Mars environment by an outer shell (like a thermos bottle) until it is sealed shut and inside the earth-clean environment. The second place where the chain is broken is in Mars orbit. The OS is ejected from the MAV and captured by the ERV.

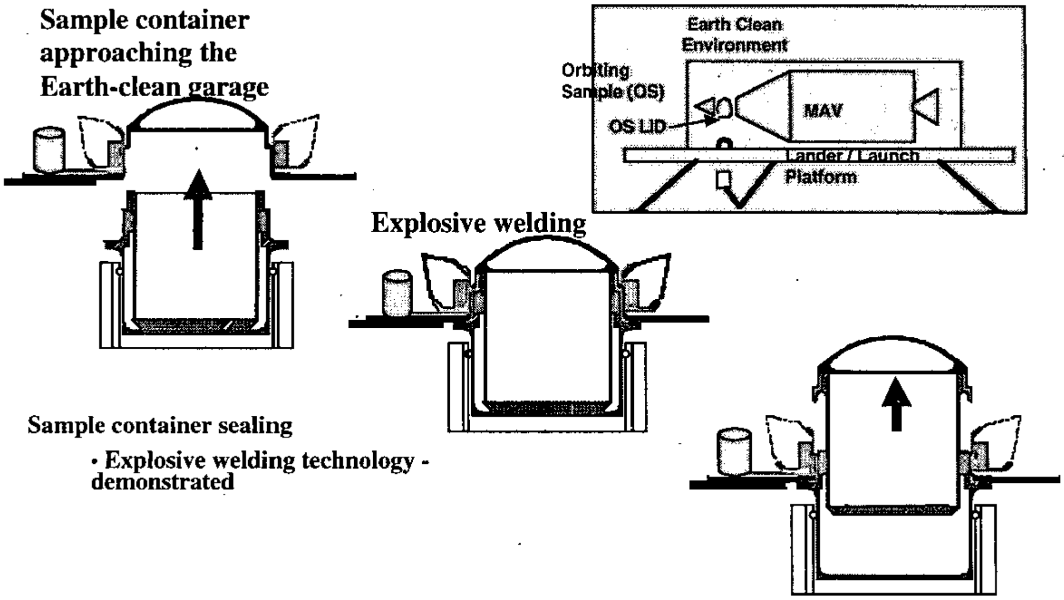

Figure 18. Breaking the chain of contact with Mars

The OS is clean, and the potential of contaminating the OS from atmospheric dust that the outside of the MAV might have picked up is minimized. Analysis of potential migration of any dust is underway. Probability is high further steps will not have to be taken, such as using a pyrolytic paint on the MAV fairing that would burn off any residual. Except for the OS, nothing that was in contact with Mars would be in contact the ERV. Additional measures would be taken as "belt-and-suspenders" including placing the OS inside a Kevlar soft containment vessel in the EEV which is sealed shut with enough heat to sterilize the seams, and designing the shape of the EEV so that all exterior surfaces will reach temperatures high enough for sterilization (>500 C).

Sample Acquisition Concept

Acquiring the sample would utilize experience and inheritance of hardware from both Phoenix and MSL. Both spacecraft plan to use end-effectors (scoops and/or other devices that should be applicable to MSR). Arm mounted cameras are planned for sample selection and operations; both Phoenix and MSL have applicable hardware and software. Software for visualization needed for planning and monitoring the trenching operation interactively with mission planners will have been well established and proven by Phoenix and MSL and is currently being used on MER. The new challenge for MSR would be methods of sorting through bulk sample and measured methods of transferring sample to the sample container. This needs to be done without introducing earth microbes. Experience will be gained with Phoenix and MSL, but we expect to have residual issues for MSR. Technology funding may be needed for lab mock-up of processes to assure ourselves that no new technology is needed. Included is evaluating the ability of an arm-mounted camera to provide enough context to plan and monitor the sample collection.

Earth Entry Concept

Reliable earth entry is key to sample containment, and LaRC has completed significant development to date. The EEV design was indicated in Figure 16.

The aerodynamic characteristics of the design have been analyzed and tested to show that aero-heating is reasonable, even to the extent that soak-back would not cause the sample container to rise above 50 C. While the study considered newer ablative materials for the heat-shield, carbon-phenolic was chosen for test and flight heritage, and knowledge of failure modes. Trajectory entry angles have been selected that limit the heat flux to within well-understood testable regime for verification. In addition high fidelity simulations have shown that the if the EEV was released incorrectly (even backwards) or tumbled from a large micro-meteoroid hit, that it would right itself prior to the entry heat-pulse. Micro-meteoroid impact protection of the heatshield was indicated as necessary by the PRA mentioned earlier. Design of protective shielding is the subject of current analysis; several concepts look promising. Aerodynamic trajectory analysis has been performed to assure that landing would occur in a safe area of UTTR (the reference landing site used for these studies). These analyses will be updated for the full set of mission opportunities over the next decade. The only aerodynamic design issue open is the shape of the backshell. As discussed in the Sample Containment section, the current shape does not assure that all the surfaces get heated to >500 C sterilization for yet another (functionally redundant) layer of protection. Later this year, the design will be tweaked to obtain full sterilization coverage.

The other function that the EEV has is protecting the sample containment. The sample would be in a multiple-seal container inside a protective OS, now conceived as a pliable sealed Containment Vessel. The landing of the EEV would be a direct impact with the surface at a site like UTTR. Referring to Figure 19, the OS/Containment Vessel as conceived is surrounded by a Kevlar and graphite cell wall impact sphere, which deforms to keep the OS loading to reasonable levels. The shell of the EEV is a carbon-carbon composite (the potential benefit of titanium will also be examined). Extensive analysis, verified by testing at the LaRC impact dynamics facility, have verified impact resistance effectiveness. In addition, a full-scale drop test (from a helicopter) of an engineering model EEV reached terminal velocity at UTTR and again validated the design. Figure 20 shows the EEV after impact being held by the LaRC team, and Figure 21 shows the impact area on the ground.

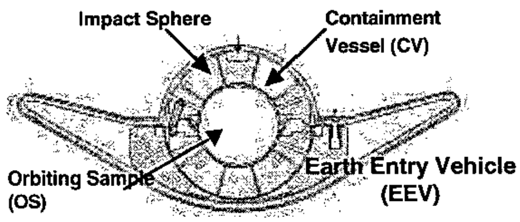

Figure 19. OS/Containment Vessel

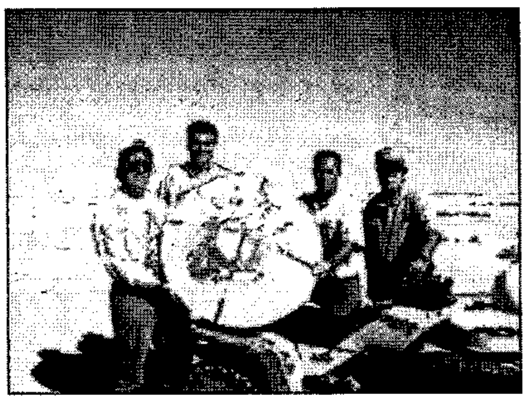

Figure 20. EEV after impact

Figure 21. Impact area

Technology Development Schedule

The plan assumes that an array of technology development and demonstrations take place before embarking on the development (see Figure 22). These would be key to being able to implement the project at the cost estimated. This year the MSR Technology Board will complete the planning for the technology tasks that would need to be completed over the four years to be ready at TRL-6 for the Project Preliminary Design Review (PDR). In parallel, system trade studies continue to be performed that are interdependent on the technology selections. This year, industry studies are on-going to define any development of Mars Returned Sample Handling (MRSH) facilities and processes that would be necessary to assure safe containment of the samples while keeping them pristine from earth-borne contaminates.

6. Project Plan

The Mars Sample Return mission study is currently being carried in the Mars program plan as an option for a 2013 launch. The nominal schedule studied for the project takes into account the complexity of the development of MSR with a substantial development phase (Figure 23).

7. Summary

It is believed that the scope of the "Groundbreaking" MSR is well understood and fits within a balanced Mars Exploration Program budget. The move to the EDL skycrane approach currently baselined by MSL would still retain significant heritage and feed-forward to MSR. Technology planning is well underway and, by the end of this year, the balance of technology development that would be required should be initiated.

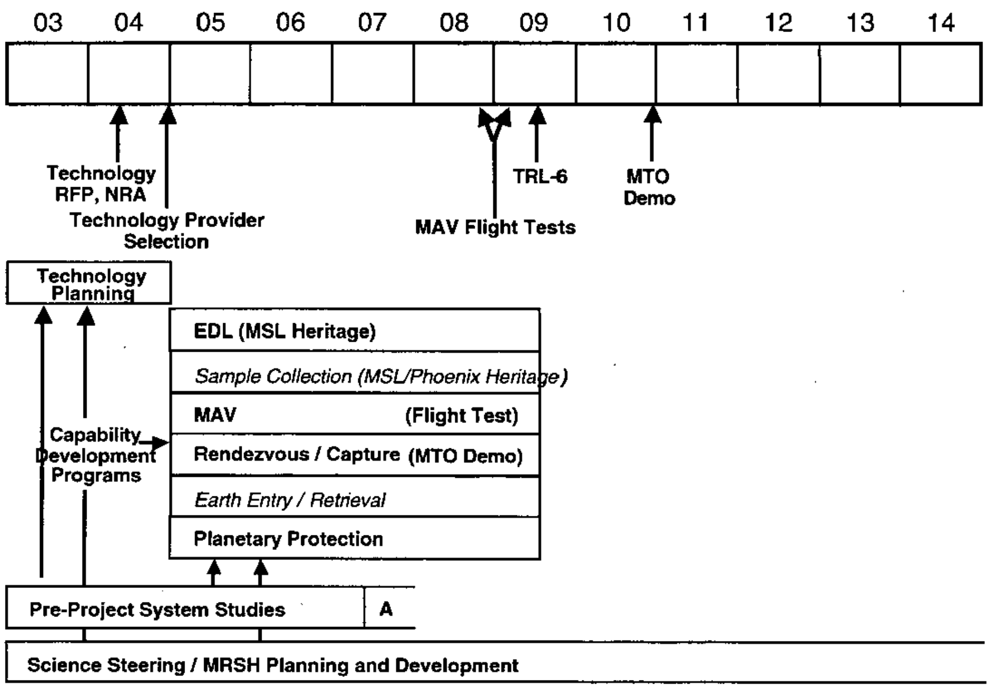

Figure 22. Groundbreaking MSR pre-project activities

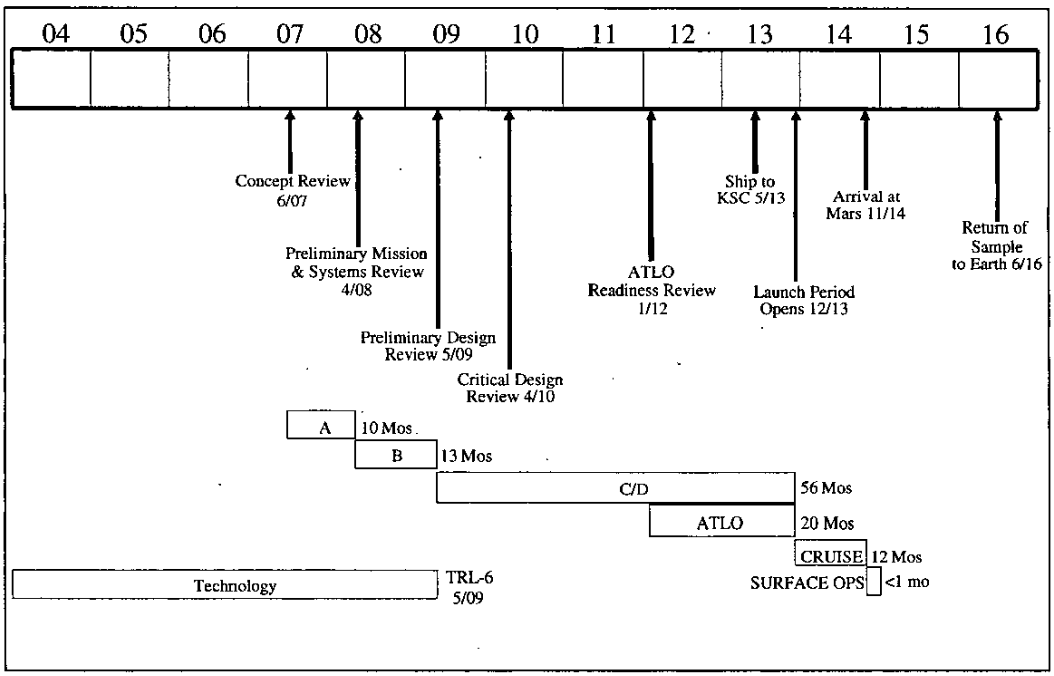

Figure 23. Nominal Groundbreaking MSR project schedule.

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Acronyms

ASI	Agenzia Spaziale Italiana
BATC	Ball Aerospace & Technologies Corporation
CNES	Centre Nationale d'Etudes Spatiales
CSA	Canadian Space Agency
EDL	Entry, descent, and landing
EELV	Evolved Expendable Launch Vehicle
EEV	Earth Entry Vehicle
ERV	Earth Return Vehicle
ESA	European Space Agency
ISPP	In situ Propellant Reduction
JPL	Jet Propulsion Laboratory, California Institute of Technology
L/D	Lift-to-drag
LEO	Low-Earth Orbit
LMA	Lockheed Martin Astronautics
MAV	Mars Ascent Vehicle
MEP	Mars Exploration Program
MEPAG	Mars Exploration Payload Analysis Group
MER	Mars Exploration Rover
MGS	Mars Global Surveyor
MOI	Mars Orbit Insertion
MOLA	Mars Orbiting Laser Altimeter
MOR	Mars Orbit Rendezvous
MPSET	Mars Program System Engineering Team

MRO	Mars Reconnaissance Orbiter
MRSH	Mars Returned Sample Handling
MSL	Mars Science Laboratory
MSR	Mars Sample Return
MTO	Mars Telecommunications Orbiter
MTP	Mars Technology Program
NASA	National Aeronautics and Space Agency
NPD	NASA Policy Directive
NPG	NASA Procedures and Guidelines
OS	Orbiting Sample
RFP	Request for Proposal
ROM	Rough Order of Magnitude
RPS	Radioisotope Power Source
SEP	Solar Electric Propulsion
SPHERES	Synchronized Position Hold Engage and Reorient Experimental Satellites.
SSG	Science Steering Group
STS	Shuttle Transportation System
TMOD	Telecommunications and Mission Operations Directorate
US	United States
UTTR	Utah Test and Training Range

BIOGRAPHIES

Richard Mattingly received a B.S. degree in Engineering from California State University, Los Angeles in 1970. He has been with JPL for more than 20 years. Currently, he is the Studies Manager for the MSR Studies and recently supervised a systems engineering group for JPL's projects implemented in partnership with industry. He has also managed systems engineering groups for instrument and payload development. Richard has been involved in the formulation and development of numerous planetary and Earth-orbiting spacecraft and payloads. His career started with systems integration on the Apollo program for North American Rockwell.

Steve Matousek is currently the Mars Scout Program Manager. During the period of these MSR Studies, he was Deputy Manager of Solar Exploration Advanced Studies and Pre-projects at JPL. In that capacity, he studies and creates study teams for advanced concepts for solar-system exploration. His prior work includes supervising the Mars and Microspacecraft Mission Architecture Group as well as numerous Discovery, MIDEX, and SMEX proposal management jobs. He started his career at JPL in 1985 by having the honor of working on the Voyager navigation team as a trajectory engineer for the 1985 Uranus encounter and the 1989 Neptune encounter. Steve's first space job was as a student command controller for the Solar Mesospheric Explorer at the University of Colorado. He also serves AIAA as a member of the Space Systems Technical Committee

Frank Jordan has a Ph.D. in Engineering Mechanics from the University of Texas at Austin. He has been a member of the technical staff at JPL since 1966. During his career at JPL, he has served as Supervisor of the Precision Orbit Determination Group, Manager of the Navigation Systems Section, and Manager of the Systems Division. He currently leads the Advanced Studies and Pre-Projects Office in JPL's Solar System Exploration Program Directorate. Frank has received the Magellanic Premium from the American Philosophical Society, the Bronze Medal from the Royal Institute of Navigation, the Weems Award from the Institute of Navigation, and two NASA Awards.