

Mars Sample Return – Studies for a Fresh Look^{1,2}

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Abstract—Mars Sample Return (MSR) is a key mission in the plan for Mars Exploration. During 2001, NASA issued contracts to four industrial teams to conduct a broad trade study of what they envisioned to be the best implementation of MSR; the teams were subsequently tasked with focusing on a specific concept and fleshing-out a design sufficiently to provide a cost for the mission. Finally, the teams were asked to identify any technology development or demonstrations that are prerequisite to the mission. This paper describes the breadth of rich trade space that exists for this mission. Included in the paper are both the themes resulting from the industry studies and the general scope of the focused concepts used to assess the current planning for the mission and precursor missions. Included in this conference are papers by the four industrial teams, as well as a fifth study by JPL's Team-X to provide further corroboration of study results. The results suggest that a scientifically justifiable mission is possible, and that technology and precursor mission demonstration plans currently in the Mars Program are justified (with some modifications).

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1. MEP OVERVIEW

NASA has considered a sample return mission from Mars since the 1960's (see the Extended Bibliography). The most recent series of studies of the Mars Sample Return (MSR) concept seeks to establish a trade space framework for the evaluation of various mission architectures. Since technology development will lower the risk and cost of a sample return and thereby enable a mission, these studies also seek to define the required technology. While it

remains unclear 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 will remain too ambitious.

Under the current MEP plan, 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 around the surface of Mars and make scientific measurements. While the goals of Pathfinder were limited, the mission, which lasted approximately 90 days, proved that a rover could be an essential part of a Mars surface mission. As a result of the success of this mission, future surface missions (including sample return) require mobility to accomplish scientific objectives.

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 (see Figure 1).

2001 continues 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.

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. Later in this paper, a summary of MSR mobility requirements will posit that the MER mobility capability is probably the minimum acceptable capability for a first sample return.

¹ IEEEAC paper #384, Updated January 31, 2002.

² 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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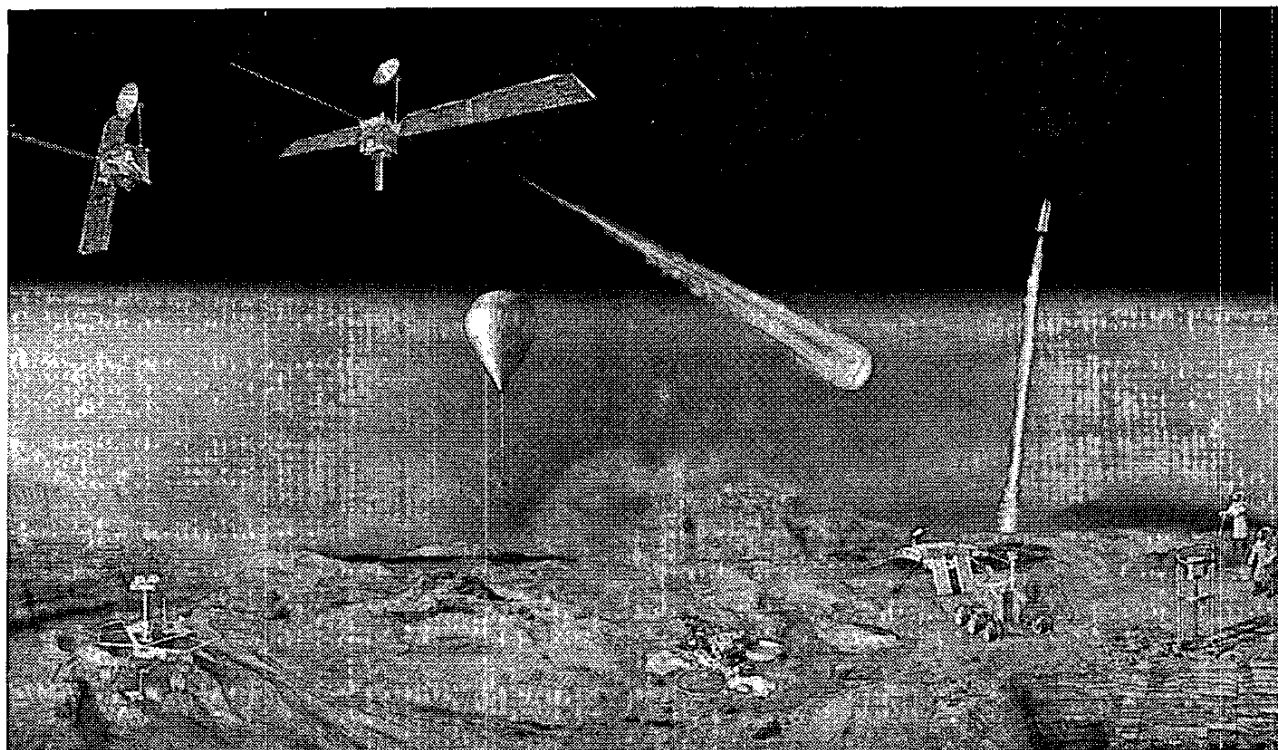


Figure 1. A collection of current and potential future MEP missions in artist's concept. Clockwise from upper left are: 1) 2001 Odyssey orbiter, 2) Mars Reconnaissance Orbiter (MRO), 3) Potential future human missions for which robotic missions pave the way, 4) Mars Sample Return large rover and Mars Ascent Vehicle (MAV), 5) Mars Exploration Rover (MER) (1 of 2) with heritage Mars Pathfinder airbag system, 6) MER rover, 7) balloon mission, and 8) aeroshell streaking through the Mars atmosphere.

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 the 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).

Any missions beyond 2005 are currently only in the planning stages and subject to change. Three missions are planned for 2007: 1) a Mars Scout (NASA Discovery analog, see 2002 IEEE Aerospace Conference paper 384 by Matousek for more details), 2) a Centre Nationale d'Etudes Spatiales (CNES — the French Space Agency)/NASA orbiter that also delivers the European Space Agency (ESA) Netlander probes and carries scientific instruments, and 3) an ASI/NASA telecommunications and navigation support orbiter. The plan for 2009 calls for a surface mission to demonstrate precision landing (within 5 km of nominal), hazard avoidance, and hazard tolerance. Mobility requirements for the 2009 surface mission are unclear at this time. Most likely, the mission will have a MER-class rover with enhanced autonomy or a larger rover capable of greater mobility that can move outside the 10-km precision landing ellipse. More details of the MSR precision landing, hazard

avoidance, and hazard tolerance requirements are located later in this paper and the industry and Team X papers. 2009 may also have an ASI/NASA science orbiter with undetermined science. Past the 2009 time frame, the current MEP plan becomes even more uncertain. A sample return mission is a possibility in the next decade. However, the earliest MSR could occur after 2009 would be 2013: one opportunity in between missions will be required to ensure that the techniques and technology demonstrated in the 2009 mission for precision landing and hazard avoidance/tolerance work correctly before building the hardware for MSR. During the spring of 2002, the MEP will examine the options and produce a plan for 2011 and beyond.

2. STUDY PURPOSE

The MEP needed to take a fresh look at MSR in 2001. Several factors combined to warrant the breadth and scope of the studies. Chief amongst them are:

- The Mars Technology Program (MTP) needed to determine the technologies required for MSR and any precursor missions, such as the (then) large lander/rover in 2007 that is referred to in the previous section as the 2009 surface mission (see footnote 7 on the next page). The studies needed to finish and provide input on these technologies by October 2001 so as to aid the planning

of the Fiscal Year 2002 and beyond Mars Technology Program⁶.

- The Mars 2007⁷ surface mission was conceived as a combined effort of the 2007 project and the MTP. Because the mission has a long implementation schedule (to facilitate the infusion of advanced technologies), the 2007 surface mission required determination of the characteristics of those technologies by spring, 2002. To determine the required technologies, NASA/JPL decided to "leave no stone unturned" and embark on MSR studies tapping into the considerable capabilities of the US aerospace industry.
- Potential foreign partners required inputs on the MSR architecture so as to ensure adequate funding from their governments. In particular, the long lead schedule for the 2007 CNES/NASA orbiter mission required a decision by the fall of 2001 from the French government with regard to funding and the parameters of MSR cooperation.
- NASA and JPL needed to know the potential cost of MSR. Previous efforts at MSR studies (Mars 03/05, MRSR, etc. — see the extended bibliography at the end of this paper for historical MSR studies) included some assumptions that are no longer valid. Technologies and program parameters have changed greatly over the past several years. To proceed with MEP program planning requires an understanding of the cost and schedule requirements for a MSR mission; it seemed logical to enlist US industry in the effort to determine MSR cost and schedule.

Consequently, the Solar System Advanced Studies Office at JPL was commissioned by the MEP to begin the process of assembling a Request for Proposals, evaluating subsequent study proposals, monitoring progress of the industry studies, choosing appropriate study parameters for Phase 2 from the wide range of trades presented at the end of Phase 1, and assembling the data for the MEP to aid in determining when MSR can occur in the current program.

The next section details the specifics of the study requirements with respect to information required by MEP to make informed decisions about MSR planning.

3. OVERVIEW

Structure

Four industry teams were each funded \$1M to conduct a six-month study, divided into two steps: the first providing a broad trade study culminating in a variety of concepts that

covered the waterfront of what a reasonable mission might be, the second being a focused study of a concept (different for each team) in enough detail to identify cost, schedule, technology needs, and the prerequisite mission demonstrations that would be needed. The study was performed under the schedule shown in Figure 2.

To obtain fresh ideas, the teams' activities were kept isolated from the others; with regard to information concerning previous work, only information contained in the open literature was made available to the teams. The teams were allowed to request information on the state of technology development and were briefed on Mars-related technology plans at the outset of the study. In addition, mission design and NASA infrastructure information was provided initially and by request. All requested information was sent to all four teams.

In Phase 1, each team conducted a broad trade study addressing a diverse set of potentially viable technical approaches, with rationale behind each trade. Phase 1 required each team to generate at least two mission concepts based on the selected approaches that would rank highly when evaluated against the following selection criteria:

1. Performance relative to sample return objectives.
2. Development and life cycle costs.
3. In-flight mission risks and overall reliability.
4. Risks of technology readiness.
5. Technology legacy provided to future Mars missions.

Phase 1 culminated in a review for each team, the viewgraphs serving as a NASA-proprietary interim report.

For Phase 2, JPL selected one of the mission concepts (or a modification thereof) for each team. JPL's process of mission concept selection is discussed further in Section 6. The teams were asked to provide an in-depth study of the technical approach selected and a technical description of the resulting mission concept(s). In addition, a development cost estimate was required for the (1) formulation, (2) implementation (including mission operations system), and (3) launch phases for each concept, excluding the costs of the science payloads. Each team had to identify the technology development and demonstrations needed and the mission operations cost elements, all of which were not to be included in the estimate. Finally, each team had to provide requirements on technology development consisting of:

- A listing of technology needs.
- Recommendations for the required testing and/or flight validations.

As was done after Phase 1, Phase 2 culminated in a final review for each team, with annotated briefing books delivered as a NASA-proprietary final report.

⁶ Cutts, J., Hayati, S., et. al., "The Mars Technology Program." Proceedings of The 6th International Symposium on Artificial Intelligence, Robotics and Automation in Space. Key note speech, Montreal, Canada, June 18-22, 2001.

⁷ It looks very likely that the Mars 2007 Smart Lander surface mission will be delayed to 2009. At the time of the writing of this paper the date for the mission is not determined. This paper will assume the mission will occur in 2009. When referring to the last year of MSR work, the Smart Lander surface mission was always assumed to occur in 2007.

- Any landing site within 15 degrees of the equator and at any altitude below +1.5 km (with respect to the MGS/MOLA-based mean reference) shall be accessible.
- Landing accuracy shall be no worse than 50 km (semi-major axis of the three-sigma landing ellipse).

For the first phase of the study (trade study), desired increases and potential decreases were specified and were intended to bring out trade sensitivities and allow a greater range of mission options:

- Desired Increases in Science Content
 - Survival of surface science assets after the sample has left the surface of Mars, extending in situ investigations to a total of at least two years.
 - Extended mobility beyond the 1-km sample return mobility requirement to at least beyond the perimeter of the landing uncertainty footprint.
 - Improve landing accuracy to < 5 km.
 - A sample from a depth of at least 10 m.
 - Landing site accessibility to ± 45 degrees from the equator.
- Potential Decreases in Science Content
 - Reduced or eliminated mobility: collect sample at >10 m from Lander
 - Reduce sample depth requirement to $\frac{1}{2}$ m.
 - Reduced landing accuracy: < 200 km

In addition, all lander designs had to allocate at least 50 kg for science instruments, including those to be used for:

- Sample selection.
- In situ science.
- Experiments supporting future human exploration.

Constraints and assumptions

A set of constraints and assumptions were also specified:

- A MEP overall budget of \$500M/year (Real Year Dollars).
- MSR (2011) development between \$1B and \$2B, including launch vehicle(s) and the mission operations system.
- Cost Estimates not to include technology development, flight validation demonstrations, mission operations, or preparation for and implementation of handling the returned sample on Earth.
- Telecommunications and operations assets in place and available for MSR.
- Design margins to standard JPL guidelines.
- Premium on safe landing on Mars using:
 - Robustness of landing system design to potential surface hazards.
 - and/or
 - Systems for hazard avoidance during landing.
- Technology Readiness Level Achievement schedule constraints are specified as follows (see Technology Readiness Level Definitions, Figure 4):

- TRL 5 — by Preliminary Mission System Review (before Phase B start).
- TRL 6 — by Preliminary Design Review (before Phase C start).
- TRL 7 — by Critical Design Review (if required) (before Phase D start).
- Deep Space Network available.
- At least one Mars orbiter in place to support sample return elements with telecommunications relay and proximity navigation support.
- Full core mission operations services typically supplied by the JPL Telecommunications and Mission Operations Directorate (TMOD) Mission Management Office.
- Delta and Atlas family launch vehicles and STS available.
- Planetary Protection Requirements — forward, back and round-trip (see below).

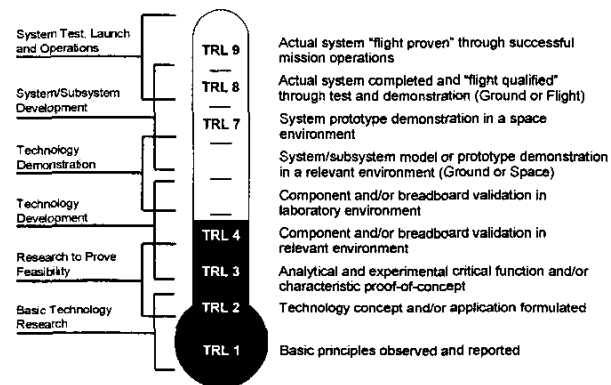


Figure 4. Technology Readiness Levels.

The Toughest Challenge – Planetary Protection

Planetary Protection constraints are mandated by international treaty, and specified by NASA Policy Directives (NPDs) and NASA Procedures & Guidelines (NPGs). Most of the requirements for sample return are derived from two general concerns, which have the potential to drive the system:

- The need to control the amount of sample contamination 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).
- 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).

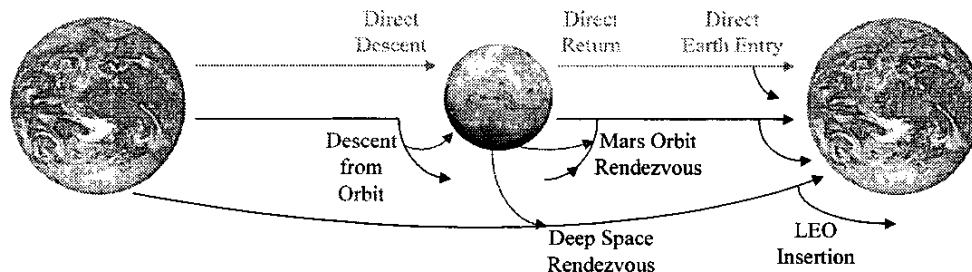


Figure 4. Mars Sample Return Trade Space.

While dry heat is the only sterilization technique officially recognized by NASA, most spacecraft designers believe it would be extraordinarily expensive to build a spacecraft with modern avionics that could be heat sterilized the way Viking was. As an alternative, the capability to sterilize the appropriate elements of the MSR spacecraft with hydrogen peroxide H_2O_2 is being developed. In a “local sterilization and isolation” option, the sample collection and containment gear would be sterilized using heat, H_2O_2 , or other means, and then isolated from other parts of the spacecraft. The isolation includes bio-barrier enclosures and modeling of contaminant migration patterns. Another key development is a technique for collecting clean samples from beneath a Martian surface possibly contaminated by migration of Earth microbes from a lander or rover.

Many elements of the MSR mission must be designed for high reliability in order to meet the containment assurance requirements and many of these elements will require development of new technology. The exterior of the sample container cannot be contaminated with Martian material. Breaking the chain of contact with Mars will be key and involves one or more sample handoff steps that pass forward a clean container on the Mars surface, during ascent, during Mars orbit rendezvous, and/or in Earth orbit. The sample container and its seals must survive Earth impacts corresponding to the candidate mission profiles. The Earth Entry Vehicle(s) (stand-alone in the Direct Entry case or a vault for a Shuttle entry case to mitigate Shuttle accident effects) must also withstand thermal and structural rigors of Earth atmosphere entry and be protected from micro-meteoroid or space debris impacts. In the Direct Entry case, the mission profile needs to be robust enough to mitigate risks to the EEV arising from entry, navigation, or maneuver errors. In the Shuttle option, risks arising from failure modes in which the Shuttle is unable to retrieve the sample container must be well understood and mitigated in the design.

5. PHASE 1 – TRADES STUDIES

Figure 4 graphically shows the mission approaches that are available to MSR and can be referred to in the following generic description, as well as the Trade Space discussion.

Generic Mission Synopsis

Generically, a MOR⁸ Mars sample return mission would consist of a Mars orbiter and lander launched together or separately (lander on a cruise-carrier if not part of the orbiter). The orbiter inserts into low Mars orbit (via chemical, aerobraking, or aerocapture) and the lander goes in entry/descent/landing directly from the Earth-Mars trajectory or is released for entry from the orbiter. The lander has a rover for sample collection mobility, a MAV for getting the sample off the Martian surface, sample handling equipment, and science instrumentation. Samples are obtained and packaged into a small Orbiting Sample (OS) container that is lifted into low Mars orbit by the MAV. The orbiter effects a rendezvous and capture of the OS, which is returned to Earth on an Earth Return Vehicle (ERV) (probably a subset of the orbiter). At Earth, the sample enters directly via an Earth Entry Vehicle (EEV) or goes into Earth orbit for rendezvous with another vehicle (e.g., the shuttle). Post-landing sample handling is outside the scope of the MSR studies.

The Trade Space

During Phase 1, each team was asked to perform a broad trade study addressing at least a minimum set of trades. Those trades, in mission-chronological order, are:

- Launch.
 - Separate spacecraft launches on expendable launch vehicles.
 - Combined spacecraft launch on an expendable launch vehicle.
 - Shuttle launches with spacecraft assembly on-orbit.
- Earth-to-Mars cruise and approach.
 - Earth-to-Mars transit.
 - Ballistic flight.
 - Low-thrust flight.
 - Approach navigation.
 - Radio data types.
 - Optical data.
- Mars orbit.
 - Orbit insertion.
 - Chemical propulsion.

⁸ This description is for a mission that utilizes Mars Orbit Rendezvous (MOR) for sample exchange from the MAV to an earth return vehicle. Other architectures are possible including deep-space or libration-point rendezvous or even direct return of the MAV without rendezvous.

- Aerobraking.
 - Aerocapture.
- Mars atmosphere entry, descent, and landing.
 - Lander entry.
 - Lander entry direct from cruise.
 - Lander entry from Mars orbit.
 - Entry/descent techniques.
 - Entry aeroshell shape.
 - Chutes.
 - Powered descent.
 - Landing techniques.
 - Hazard detection and avoidance.
 - Impact attenuation.
- On the surface.
 - Sample collection.
 - Mobility.
 - Sub-surface.
 - Collection options.
 - Sample handling.
 - Number of exchanges.
 - Risks.
 - Contamination chain.
 - Communications requirements and infrastructure.
 - Post-sample collection long surface life, lateral and subsurface range.
- Ascent from Mars surface.
 - Return profile.
 - Mars rendezvous.
 - Deep space rendezvous.
 - Direct return to Earth.
 - Mars ascent vehicle.
 - Solid propellant.
 - Unguided.
 - Guided.
 - Liquid propellant.
 - Cryogenic propellant.
 - In situ propellant production (ISPP).
 - Mars ascent vehicle.
 - On rover.
 - On lander.
 - Options for ground asset survival after MAV launch.
- Mars-to-Earth cruise.
 - Mars-to-Earth transit.
 - Ballistic flight.
 - Low-thrust flight.
- Return to Earth.
 - Earth atmosphere entry capsule.
 - Direct entry from cruise trajectory.
 - Entry from Earth orbit.
 - Shuttle rendezvous.
- Program phasing.
 - Launches in same opportunity.
 - Launches in separate opportunities.

The teams also identified additional trades: the most significant were one versus multiple landers and the use solar power versus Radioisotope Power Source (RPS) on the surface of Mars.

Each team was required to produce a concept in Phase 1 that met the baseline science requirements detailed earlier⁹. If that concept had its associated MSR rough-order-of-magnitude (ROM) cost in the \$1B to \$2B range (see Figure 5 (1)), the second concept should strive for the “baseline +” (see Figure 5 (2)) science to determine the science-to-cost sensitivity. If the MSR ROM cost for baseline science was near or greater than \$2B (see Figure 5 (4)), the second concept should strive to meet the “baseline science –” (see Figure 5 (3)) to determine the science-to-cost sensitivity over the \$1B to \$2B range. One million to 2 billion dollars was selected as the desired range because previous studies indicated that MSR would certainly cost more than \$1B; \$2B was felt to be a programmatic limit given current and projected budget constraints.

This sensitivity analysis worked better in theory than in the actual results after Phase 1. The main reason the sensitivity analysis did not work was that the absolute cost ROMs were overly optimistic. This led to Phase 1 results stating that “baseline +” science fit easily within \$2B. When further analysis in Phase 2 showed they did not, the relative ROMs for Phase 1 were useful in determining the selected Phase 2 concept for each team.

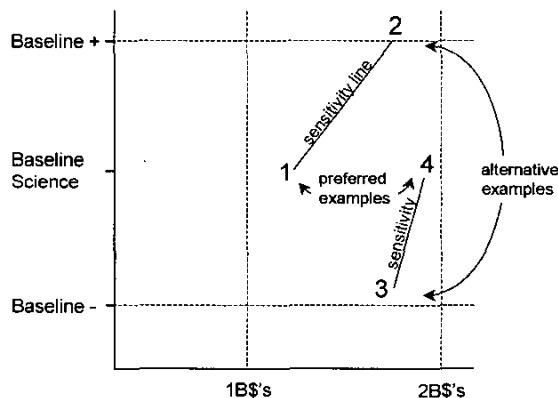


Figure 5. Sample Return Trade Space.

Phase 1 Results

Figures 6a-d summarize the elements and features included in the teams' approaches. Of the total number of approaches presented, the figures indicate the percentage of inclusion of a feature, color coded by team. The results for each team are reflected in each team's individual paper (previously cited).

Creative mission approaches ranged from “grabbing” a sample and returning quickly to Earth to multiple landers in varying sites returning more than one OS. Many creative ideas were presented for surface mobility.

One of the pervasive qualitative assessments made was that for the most part, mission costs estimates were way too optimistic; and the final results showed that to be true.

⁹ Science requirements were derived from Mars Exploration Payload Assessment Group (MEPAG) measurements, MPSET input, discussions with the MEP scientists at NASA headquarters, and discussions with the MEP chief scientist at JPL.

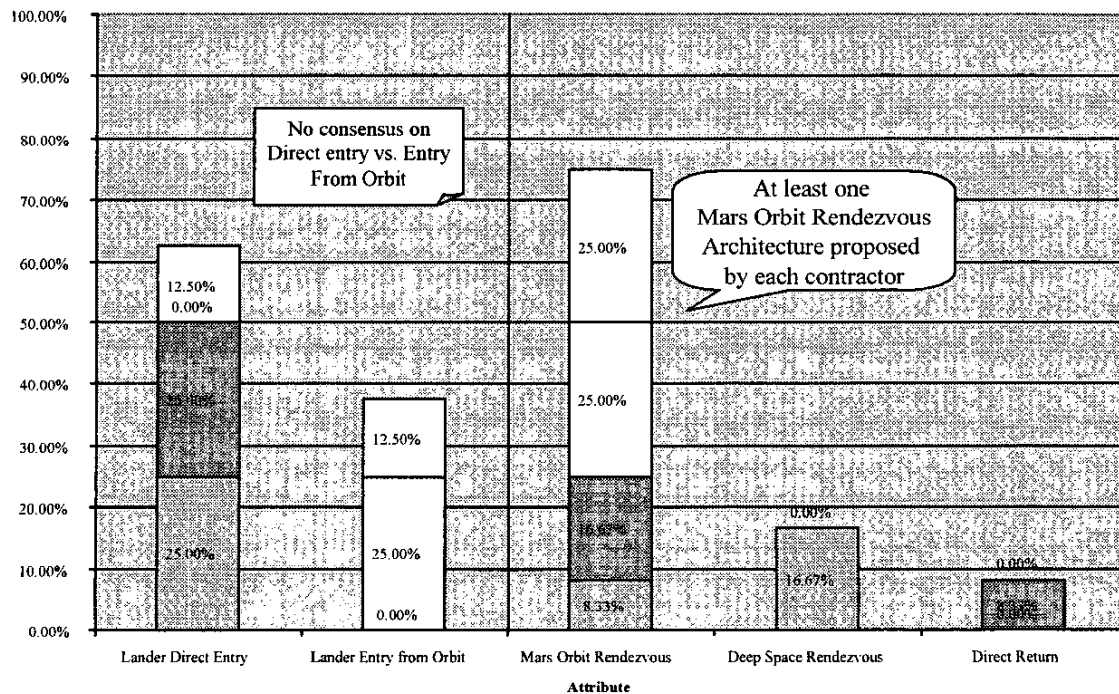


Figure 6a. Key architectural trades.

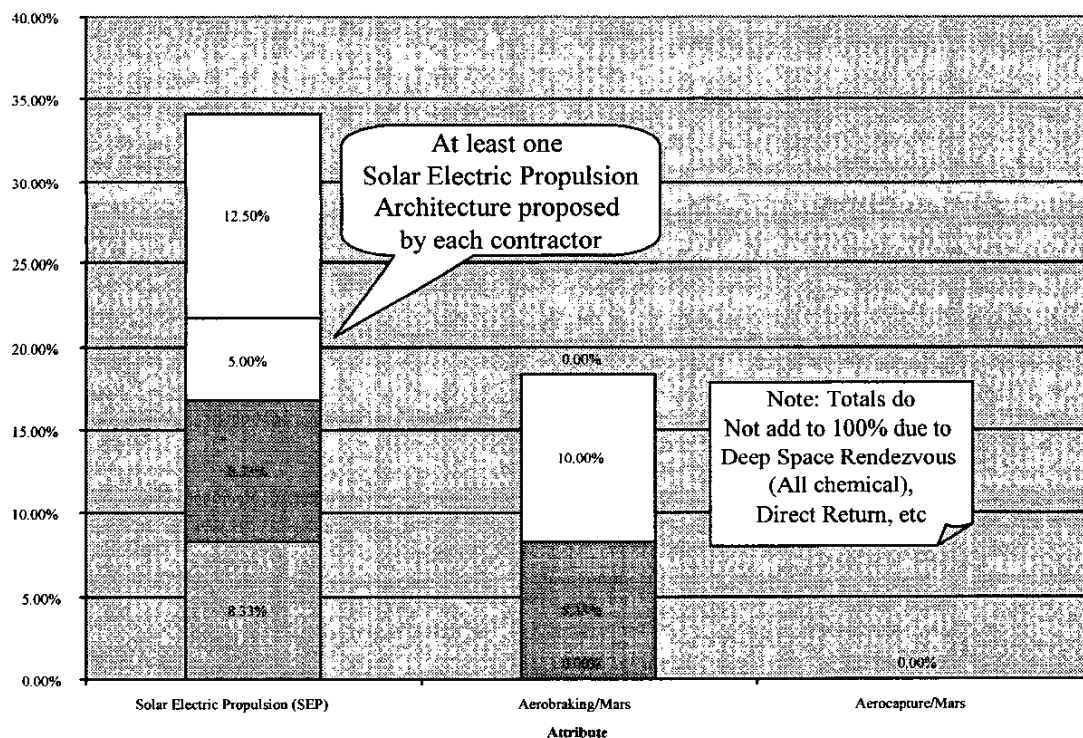


Figure 6b. Orbiter Transportation Mode.

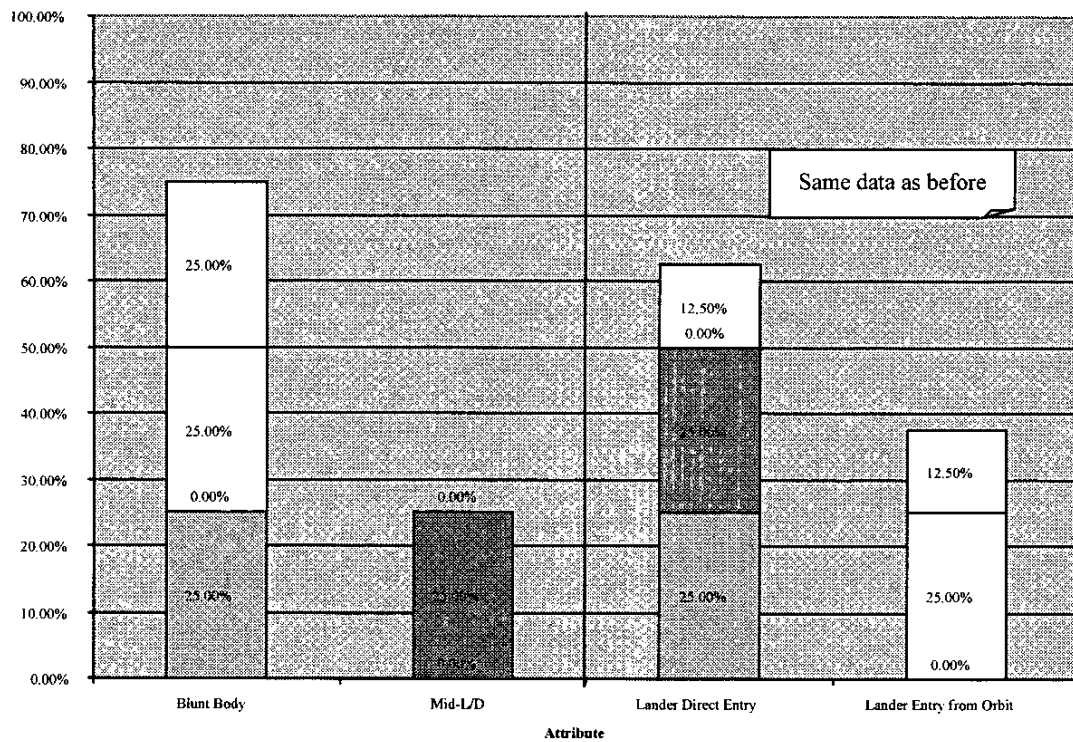


Figure 6c. Entry, Descent, and Landing.

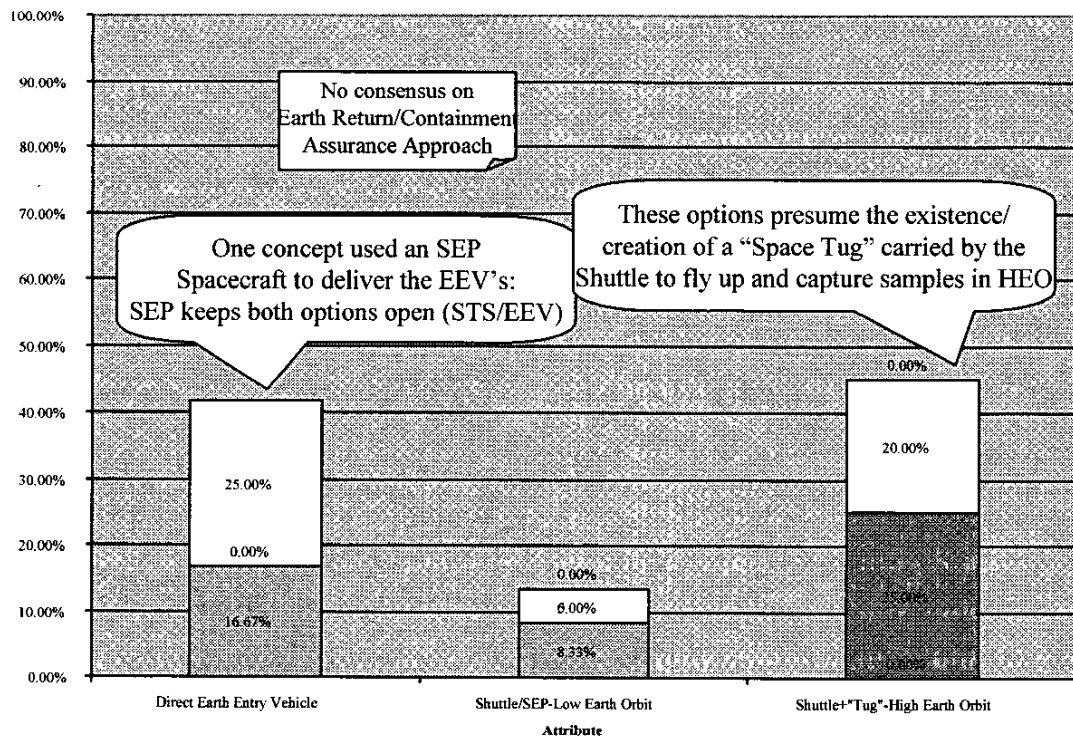


Figure 6d. Earth Return.

6. PHASE 2 – FOCUS STUDIES

After Phase 1, the Advanced Studies Office at JPL in conjunction with the MEP and the Mars Program System Engineering Team¹⁰ (MPSET) directed the four industry teams to narrow down the scope of their studies. This direction took into account:

- MEP goals for MSR, including required technology definition and precursor missions.
- MPSET advice on the scope and content of the MSR trade space.
- Industry team technical capabilities.
- Industry team desires.
- Any areas that were not examined as part of previous or current MSR studies.

Within a few days of the Phase 1 industry team briefings, JPL directed each of the teams for Phase 2. Additionally, whereas each team had considerable freedom to interpret the MSR program requirements¹¹ in Phase 1, much more specific guidance was provided in Phase 2. Specifically, each team was to assume the Science Baseline Objectives, as previously listed, with 2 modifications:

- A sample from a **single hole** of a depth of at least 2 m shall be returned.
- Landing accuracy shall be no worse than **10 km** (the previous objective was 50 km) (semi-major axis of the three-sigma landing ellipse). (This was based on assuming that the precursor lander mission will have already demonstrated this accuracy.)

A few additional requirements were given with regard to the use of MEP assets to further reduce the risks associated with MSR. These requirements were:

- An optical navigation camera should be on all orbiters and any direct-entry landers (design and cost were supplied by JPL¹²). The orbiter optical navigation camera should be capable of being used to detect an un-powered Orbiting Sample in the unlikely event the OS becomes un-powered and fails to emit a beacon.
- An OS beacon shall be detectable by the existing orbital telecommunications/navigation asset (nominally the 2007 ASI/NASA telecom/nav orbiter).

¹⁰ MPSET advises the MEP on technical issues. MPSET membership currently consists of respected technical experts at the NASA centers, the NASA HQ program executive for MSR, and representatives of the French, Italian, and Canadian space agencies.

¹¹ Program requirements are used here as the requirements that MSR must meet. These requirements are developed through a process of developing the science requirements via the science community (using such groups as the Mars Exploration Payload Assessment Group, or MEPAG), interacting with the technology community, and determining what MEP needs from MSR.

¹² The 2005 Mars Reconnaissance Orbiter mission is slated to fly an MEP optical navigation camera that could be used, unchanged, for all future Mars missions. This is a direct result of MEP instituting multiple approach navigation data types to make Mars missions more robust after the Mars Climate Orbiter loss of mission in 1999.

- The OS design shall include (as a back-up capability) the ability to be detected while the OS is un-powered.
- All landers shall have terminal hazard avoidance and be capable of tolerating 1.0-meter obstacles and 30-degree slopes.
- All landed assets (landers, rovers and MAVs) shall have the capability to communicate with (and be tracked by) an existing orbital communications asset (nominally, the 2007 ASI/NASA telecom/nav orbiter). Lander telemetry shall be continuously sent to the orbital communications asset during EDL. MAV telemetry shall be continuously sent to the orbital communications asset during ascent from the Martian surface.
- No mid-L/D EDL¹³, use Viking heritage EDL.

Besides these general Level 1 requirements, the teams were to study the subjects detailed in the sections that follow.

Ball

Study MSR consisting of a single launch on a NASA Evolved Expendable Launch Vehicle (EELV), direct entry of the lander at Mars, chemical propulsive Mars Orbit Insertion (MOI) with aerobraking of the orbiter/ERV, surface mobility consistent with the Science Baseline requirements, single OS to low Mars orbit rendezvous, chemical propulsive return of the ERV to High-Earth Orbit (HEO), and rendezvous with an EEV deployed by/returned to the US Space Shuttle or used for direct entry to the surface of the Earth.

Boeing

Study MSR consisting of a dual-launch (two separate launches of an EELV), ballistic lander cruise, solar electric propulsion (SEP) ERV transfer, propulsive capture of the lander in elliptical Mars orbit or a direct Mars entry, SEP spiral ERV to low Mars circular orbit, one rover with RPS, 2-meter drill and 1 km range, MAV to ERV for transfer of OS, SEP spiral ERV from Mars and spiral into low Earth orbit (LEO) for shuttle pick-up.

LMA

Selected for study are two variations of MSR. The first variation is the "Libration Point Rendezvous", which includes a single launch for ballistic cruise, direct entry of a single lander and propulsive capture of ERV, MAV rendezvous with an ERV in a Mars Libration Region, ballistic return, and direct entry at Earth (ala, Genesis/Stardust). The second variation performs the MAV rendezvous with an ERV at Low Mars Orbit. The LMA Phase 2 study compared and contrasted these two MSR architectures.

¹³ Mid L/D refers to Lift/Drag ratios of greater than about 0.25. Viking heritage EDL was specified due to the large cost and uncertainty associated with qualifying a new EDL technology. Also, mid L/D is not needed when MSR can be accomplished with a precision landing ellipse of ~ 10 km (3 sigma). The precision landing is slated to be demonstrated on the 2009 lander/rover surface mission.

TRW

Study MSR consisting of a single launch on an EELV, SEP cruise and Mars orbit capture (via spiral into Mars orbit with SEP system), 2 landers (with MAVs) deployed from low circular orbit, return of one OS, SEP departure and cruise to Earth, and a direct entry at Earth.

At the end of Phase 2, each of the teams presented the results of their studies. Figure 7 represents a summary of the architectures studied by each of the teams. After the results were compiled from each team by the JPL Advanced Studies Office, it became clear that another quick-turnaround study would be needed to corroborate the results of each of the teams. To this end, JPL's Team X (Advanced Mission Design Team) studied two options of MSR under the same study assumptions that each of the industry teams had for Phase 2. The results of the Team X studies are included in the last two columns of Figure 6, and are discussed in depth in paper.

Some general observations after Phase 2 are:

- MSR, using Mars orbit rendezvous, is possible with near-term small improvements to Viking heritage EDL systems.
- US industry felt that MSR should use the largest EELV available and launch everything on one launch vehicle.
- US industry did not feel that aerocapture at Mars is enabling.

- SEP appears to have benefits in terms of delivered mass capability. However, it is still to be determined whether the longer flight times inherent in MSR missions utilizing SEP are acceptable.
- A scientifically justifiable MSR is possible with current MER surface mobility capabilities.
- MSR appears to be a \$1.5B to \$3.0B class mission. This breaks down to \$1.5 to 2.0B for a one-lander mission, and \$2.5 to 3.0B for a two-lander mission (preferred by industry). Sample handling methods needed for planetary protection are the largest uncertainties in these estimates.
- It has not yet been determined whether the sample should be brought directly to the surface of the Earth or should enter Earth orbit and be brought from Earth orbit down to the surface via some other flight system (such as the Space Shuttle).
- A precursor mission to reduce the risk of MSR, including precision EDL, hazard avoidance, and hazard tolerance, is necessary.
- By and large, the MTP is concentrating on the correct technologies to reduce the risk, complexity, and cost of MSR. Some of these technologies include rendezvous/capture, the Mars Ascent Vehicle, and sample handling.

Further observations specific to each of the studies will be given by each of the industry study teams via their papers and presentations in this session (see references).

# of Launches	Ball	Boeing	LMA	TRW	TeamX Option A	TeamX Option B
AV for E-M Cruise	Chemical	SEPERV, Chem Lndrs	Chemical	SEP	Chemical	Chemical
# of Veh E-M	One	Two	One / Two	One	Two	Three
Orbiter Capture	Chemical with aerobraking	SEP spiral	Chemical	SEP spiral	Chemical with aerobraking	Chemical with aerobraking
Mars Lander EDL	Direct	Direct	Direct	Two Landers from orbit	Direct	Direct
Surface Ops	2 x (Lander + MAV + drill, RPS rover)	2 x (Lander + MAV, RPS rover + drill)	Lander + MAV + Drill, MER rover	2 x (Lander + MAV + drill, rover)	Lander + MAV + Drill, MER rover	2 x (Lander + MAV + drill, MER rover)
Mars Orbit Rendezvous	LMO	LMO	Libration Pt Rend / LMO	LMO	LMO	LMO
M-E Cruise	Chemical	SEP	Chemical	SEP	Chemical	Chemical
Direct or Earth Orbit Insertion (EOI)	EOI to HEO, rendezvous with separate launch EO, 2 sample canisters returned	EOI with SEP spiral to LEO, shuttle mission to return 2 sample canisters	Direct, one sample canister returned with EEV	Direct entry of 2 sample canisters returned on two separate EEVs	Direct via one EEV with one sample canister	Direct, 2 EEV's with one OS each

Figure 7. An overview of the results of the Phase 2 industry studies plus post-Phase 2 studies with JPL Team X. Details of each of these studies are in the papers given by each of the industry study teams plus the paper by JPL's Team X.

7. SUMMARY

MSR is a complex robotic mission. The best of NASA, industry, and academia will be needed to accomplish the mission. Additionally, MSR will most likely require international partners. Given these realities, it seems appropriate to ask US industry to examine MSR trades and a likely architecture in more depth. US industry had not been engaged as a whole in MSR studies since the late 1980s when MRSR was studied by NASA together with industrial partners (see the extended bibliography at the end of this paper for some relevant references to MRSR). Consequently, the JPL Advanced Studies Office commissioned industry study teams to examine MSR with a fresh look. Ball, Boeing, LMA, TRW, and their numerous partners should be commended for providing outstanding value for the money spent on these studies. Additionally, these studies should provide a future model for engaging industry and academia in MEP advanced studies. The input is valuable to the program and will help advance the cause of MSR.

Finally, while it is uncertain as to an exact date for MSR, all of the steps are being taken to lay the foundation for a successful mission some time next decade. The studies outlined in this paper take a big step forward in making MSR a reality.

ACKNOWLEDGMENTS

The authors would like to thank Frank Jordan and Dan Low. Without their guidance and support, these studies would never have been started. Thanks also to the many dedicated men and women of NASA, MPSET, the industry study teams and their partners, and NASA's international partners. The technical competence, dedication, and energy devoted over the years to Mars exploration, and in particular to these studies, continue to amaze and inspire us. Finally, we wish to thank our families for putting up with the late nights and weekends required to keep these studies on track, to complete this paper, and to organize the MSR studies session at the conference.

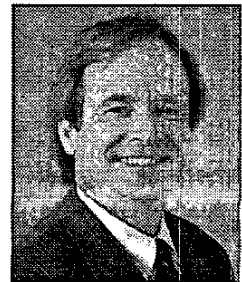
This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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BIOGRAPHIES

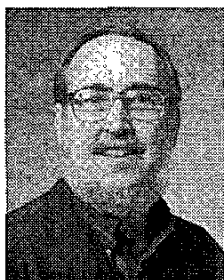
Richard Mattingly received a B.S. degree in Engineering from California State University, Los Angeles in 1970. He has been with JPL for more than 20 years. Currently, he is the Contract Technical Manager for the MSR Industry Studies and the Supervisor of systems engineering of JPL's projects implemented 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 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 and as Chair-Elect for the San Gabriel Valley section.

Robert Gershman is a Principal Engineer in the Systems Division at JPL. Recent JPL assignments include serving as Planetary Protection Manager for the Mars Sample Return Project, Planetary Advanced Missions Manager, Deputy Manager of the Galileo Science and Mission Design Office, and Supervisor of the Mission Engineering Group. Before coming to JPL, he was a Senior Research Engineer at Ultrasystems, Inc. and a Group Engineer in the Propulsion Department at McDonnell Douglas Astronautics Co.



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on the study of flight hardware materials' compatibilities with hydrogen peroxide vapor sterilization processes; (4) a summary of the results of our mapping of the microbial diversity of JPL's Spacecraft Assembly Facility; and (5) a summary of our maintenance technology development efforts, which include determination of the sources of biological contamination in JPL cleanroom facilities, and models developed for flight hardware biological cross-contamination in the Martian environment.

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2003 mission will be launched on a Delta-III-class launch vehicle in May/June 2003 and arrive at Mars in December 2003/January 2004. The Lander deploys the Rover to collect surface samples from several sites and return them to the Lander where they are transferred to a sample canister onboard the MAV. The MAV is launched into a low Mars orbit (targeted for 600 km circular, 45 deg inclination) and releases the sample canister to await retrieval by an Orbiter launched in 2005. (The sample canister is a passive vehicle with no maneuvering capability.) The duration of Mars surface operations is at most about 90 days. The 2005 mission consists of two separate spacecraft: a Lander/Rover/MAV spacecraft identical to that used for the 2003 mission and an Orbiter carrying an Earth Entry Vehicle (EEV). Both spacecraft will be launched on a single Ariane-5 in August 2005 and arrive at Mars in July/August 2006. A second sample canister is delivered to Mars orbit using the same scenario as was used for the 2003 mission. The Orbiter uses aerocapture for insertion into Mars orbit (targeted for 250 x 1400 km, 45 deg inclination). During its approximately one-year stay at Mars, the Orbiter will search for and attempt to rendezvous first with the 2003 sample canister and then with the 2005 sample canister. After retrieval, each sample canister is transferred to the EEV. The Orbiter departs Mars in July 2007 and returns to Earth in October 2008 on a trajectory targeted for landing at the Utah Test and Training Range (UTTR). After deploying the EEV, the Orbiter performs a deflection maneuver to avoid reentry into Earth's atmosphere.

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Haynes, N. R., *The NASA Mars Exploration Program*, IAF, International Astronautical Congress, 49th, Melbourne, Australia, Sept. 28-Oct. 2, 1998, 6 p., 1998. **Abstract:** The goals and the current status of the Mars Surveyor Program are discussed. The main objectives of the program are to (1) understand the potential for life on Mars, (2) understand the relationship between Mars and Earth climate change processes, and (3) understand the solid planet, how it evolved, and its resources for future exploration. The architecture developed for the MSP will provide the following: acquisition and return of the first sample from Mars by 2008; acquisition and return of three sets of samples by 2012; a continuous flow of scientific information about Mars present and past; injection of technology and new science investigations every two years; strong international participation; and public engagement in the evolving Mars exploration story.

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Jordan, J. F. ; Miller, S. L., *Mars Exploration Architecture*, Jet Propulsion Lab., Pasadena, CA., 6 p, 2000. **Abstract:** The architecture of NASA's program of robotic Mars exploration missions received an intense scrutiny during the summer months of 1998. We present here the results of that scrutiny, and describe a list of Mars exploration missions which are now being proposed by the nation's space agency. The heart of the new program architecture consists of missions which will return samples of Martian rocks and soil back to Earth for analysis. A primary scientific goal for these missions is to understand Mars as a possible abode of past or present life. The current level of sophistication for detecting markers of biological processes and fossil or extant life forms is much higher in Earth-based laboratories than possible with remotely deployed instrumentation, and will remain so for at least the next decade. Hence, bringing Martian samples back to Earth is considered the best way to search for the desired evidence. A Mars sample return mission takes approximately three years to complete. Transit from Earth to Mars requires almost a single year. After a lapse of time of almost a year at Mars, during which orbital and surface operations can take place, and the correct return launch energy constraints are met, a Mars-to-Earth return flight can be initiated. This return leg also takes approximately one year. Opportunities to launch these 3-year sample return missions occur about every 2 years. The figure depicts schedules for flights to and from Mars for Earth launches in 2003, 2005, 2007 and 2009. Transits for less than 180 deg flight angle, measured from the sun, and more than 180 deg are both shown.

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results for the first approach are presented along with preliminary results for the second approach (Author)

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Lee, W., D'Amario, L., Roncoli, R., Smith, J., *Mission Design for the Mars 2003/2005 Sample Return Mission*, Astrodynamics 1999; Proceedings of the AAS/AIAA Astrodynamics Conference, Girdwood, AK, Aug. 16-19, 1999 (A00-35032 09-12), San Diego, CA, Univelt, Inc. (Advances in the Astronautical Sciences. Vol. 103, pt. 1), 190, p. 85-102. 2000. **Abstract:** NASA in conjunction with CNES, and will utilize launches in both 2003 and 2005 with an expected sample return in October 2008. The baseline mission mode selected for the MSR mission is Mars orbit rendezvous, analogous in concept to the lunar orbit rendezvous mode used for Apollo. Specifically, MSR will employ two NASA-provided landers of nearly identical design and one CNES-provided orbiter carrying a NASA payload of rendezvous sensors, orbital capture mechanisms, and Earth return capsules. The high-level concept is that the landers will launch surface samples into Mars orbit, and the orbiter will retrieve the samples in orbit and then deliver them to Earth. This paper provides an overview of the preliminary mission design for the Mars Sample Return mission.

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and design approach of the Earth Entry Vehicle is significant. A simple Earth entry vehicle is described which can meet these requirements and safely transport the Mars Sample Return mission's sample through the Earth's atmosphere to a recoverable location on the surface. Detailed analysis and test are combined with probabilistic risk assessment to design this entirely passive concept that circumvents the potential failure modes of a parachute terminal descent system. The design also possesses features that mitigate other risks during the entry, descent, landing, and recovery phases. The results of a full-scale drop test are summarized.

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O'Neil, William (JPL, Pasadena, CA); Cazaux, Christian (CNES, Toulouse, France), *The Mars Sample Return Project - A Status Report*, IAF, International Astronautical Congress, 51st, Rio de Janeiro, Brazil, Oct. 2-6, 2000, 24 p. 2000. **Abstract:** At last year's Congress the authors presented the design overview of the joint NASA/CNES Mars Sample Return (MSR) Project, then about one year into its development. A major restructuring of the NASA Mars Program resulted from the loss of the Mars '98 Climate Orbiter and Polar Lander missions. This restructuring has resulted in the cancellation of the 2003/2005 Mars Sample Return Project. This paper describes the highlights of progress made since last year's Congress up to the point of project termination. It is offered as a legacy for the next attempt at a Mars Sample Return Project.

O'Neil, William J., Cazaux, C., *Mars Sample Return Project Selected Proceedings of the 50th International Astronautical Federation Congress*, *Acta Astronautica*, Vol 47, p 453-465, 2000. **Abstract:** The Mars Sample Return (MSR) Project is underway. A 2003 mission to be launched on a Delta III Class vehicle and a 2005 mission launched on an Ariane 5 will culminate in carefully selected Mars samples arriving on Earth in 2008. NASA is the lead agency and will provide the Mars landed elements, namely, landers, rovers, and Mars ascent vehicles (MAVs). The French Space Agency CNES is the largest international partner and will provide for the joint NASA/CNES 2005 Mission the Ariane 5 launch and the Earth Return Mars Orbiter that will capture the sample canisters from the Mars parking orbits the MAVs place them in. The sample canisters will be returned to Earth aboard the CNES Orbiter in the Earth Entry Vehicles provided by

NASA. Other national space agencies are also expected to participate in substantial roles. Italy is planning to provide a drill that will operate from the Landers to provide subsurface samples. Other experiments in addition to the MSR payload will also be carried on the Landers. This Paper will present the current status of the design of the MSR missions and flight articles.

Price, H.; Cramer, K.; Doudrick, S.; Lee, W.; Matijevic, J.; Weinstein, S.; Lam-Trong, T.; Marsal, O.; Mitcheltree, R., *Mars Sample Return Spacecraft Systems Architecture*, 2000 IEEE Aerospace Conference Proceedings, Vol. 7, p. 357-75, IEEE, Piscataway, NJ, USA, 2000. **Abstract:** The Mars Sample Return mission plans to collect sets of samples from two different sites on Mars and return them to Earth in 2008. The mission consists of 15 different vehicles and spacecraft plus two launch vehicles, with elements being provided by the U.S., France, and Italy. These vehicles include two U.S. provided Landers, each with a sample collection Rover, Mars Ascent Vehicle, and an Orbiting Sample satellite. France is providing the sample return Orbiter that carries a U.S. payload for sample detection and capture plus two Earth Entry Vehicles for landing the samples on Earth. The Orbiter also delivers four NetLanders to Mars for performing unique surface science. Significant in-situ science is included. New technologies are being developed to aerocapture into Mars orbit, to collect and safeguard the samples, to launch the samples into Mars orbit, and to enable autonomous Mars orbit rendezvous and capture for return to Earth.

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Smith, Bruce A., *NASA Invests Heavily in New Technology*, *Aviation Week & Space Technology* (ISSN 0005-2175), Vol. 153, no. 24, p. 63,66-67, 2000. **Abstract:** NASA's plans to develop a series of second-generation Mars landers and rovers intended to provide safer and more accurate landings and the capability to cover far greater distances over the surface of the planet are reviewed. This work is aimed at providing future technology options, beginning with a proposed validation mission during the 2007 Mars launch opportunity intended to prove some of the new designs.

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Congress, 41st, Dresden, Federal Republic of Germany, Oct. 6-12, 1990. 9 p., 1990. **Abstract:** None available.

Taverna, M., *Mercury and Venus Sample Returns Eyed*, Aviation Week & Space Technology (ISSN 0005-2175), vol. 150, no. 7, Feb. 8, 1999, p. 23, 24., 1999. **Abstract:** In addition to the Mars Sample Return Mission program, a number of other missions are being planned by NASA and ESA to recover samples from other places in the solar system. The missions will use the new aerobraking/aerocapture techniques and rely on lightweight spacecraft technologies. The planned missions include the Stardust project, a mission to bring back debris cloud particles from the Comet Wild-2, and Japan's Muses-C, intended to recover samples from the near-Earth asteroid Nereus. Among other bodies being considered are comet nuclei, Martian moons, Mercury, and Venus.

Taverna, Michael A., *Europe to Have Major Sample Return Role*, Aviation Week & Space Technology (ISSN 0005-2175), Vol. 153, no. 24, p. 60,62,63, 2000. **Abstract:** The participation of France, Italy, and several other European countries in the Mars sample return missions and the demonstration flight that will precede them is discussed. The French national space agency, CNES, will provide two orbital vehicles, one for a demonstration mission in 2007, and the other for the first Mars Sample Return (MSR) flight. It will also provide a network of four Netlander probes to accompany the 2007 mission, as well as the launch for the 2007 mission. The Italian space agency, ASI, will supply a separate telecommunications relay orbiter for the MS missions and is discussing some payloads as well.

Volpe, R.; Baumgartner, E.; Scheaker, P.; Hayati, S., *Technology Development and Testing for Enhanced Mars Rover Sample Return Operations*, 2000 IEEE Aerospace Conference Proceedings Vol. 7, p. 247-57, IEEE, Piscataway, NJ, USA, 2000. **Abstract:** This paper describes several Jet Propulsion Laboratory research efforts being conducted to support Mars sample return in the coming decade. After describing the 2003/05 mission scenario, we provide an overview of new technologies emerging from three complementary research efforts: Long Range Science Rover, Sample Return Rover, and FIDO Rover. The results show improvements in planning, navigation, estimation, sensing, and operations for small rovers operating in Mars-like environments.

Williams, S., Coverstone-Carroll, V., *Mars Missions Using Solar Electric Propulsion*, Journal of Spacecraft and Rockets (ISSN 0022-4650), vol. 37, no. 1, Feb. 190, p. 71-77. 2000. **Abstract:** Successful demonstration of solar electric propulsion on the Deep Space 1 technology demonstration mission has paved the way for the use of this technology on future planetary missions. Currently there is much interest in retrieving Mars surface samples for scientific exploration, as well as developing the technology to enable human missions to Mars sometime in the next few decades. Solar electric propulsion trajectories for Mars opportunities in the 2004-2011 time frame are examined. All of the trajectories shown were optimized with a gradient-based calculus-of-variations

tool. In addition, a genetic algorithm was used to search for more nonstandard trajectories. Mission performance is presented as burnout mass along contours of constant flight time. The superior specific impulse of these propulsion systems results in a larger delivered mass at Mars than a conventional chemical mission. A very curious feature of these missions is that for longer flight times, solutions exist that permit a nearly continuous launch opportunity over an entire Earth-Mars synodic period.

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
HEO	High-Earth Orbit
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
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
MSR	Mars Sample Return
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
STS	Shuttle Transportation System
TMOD	Telecommunications and Mission Operations Directorate
US	United States

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