FINAL!

Mars Sample Return, Updated to a Groundbreaking Approach[1,2,3]

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Abstract — A Mars Sample Return (MSR) mission is a goal of the Mars Program. Recently, NASA and JPL have been studying the possibility of a Mars Sample Return some time in the next decade of Mars exploration.

In 2001, JPL commissioned four industry teams to make a fresh examination of MSR architectures. Six papers on these studies were presented at last year's conference. As new fiscal realities of a cost-capped Mars Exploration Program unfolded, it was evident that these MSR concepts, which included mobility and subsurface sample acquisition, did not fit reasonably within a balanced program. Therefore, at the request of NASA and the science community, JPL asked the four industry teams plus JPL's Team X to explore ways to reduce the cost of a MSR. A NASA-created MSR Science Steering Group (SSG) established a reduced set of requirements for these new studies that built upon the previous year's work. As a result, a new "Groundbreaking" approach to MSR was established that is well understood based on the studies and independent cost assessments by Aerospace Corporation and SAIC. The Groundbreaking approach appears to be what a contemporary, balanced Mars Exploration Program can afford, has turned out to be justifiable by the MSR Science Steering Group, and has been endorsed by the Mars science community at large.

This paper gives a brief overview of the original 2001 study results and discusses the process leading to the new studies, the studies themselves, and the results.

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1. 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 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 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.

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) (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.

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2 IEEEAC paper #1392, Updated November 14, 2002.

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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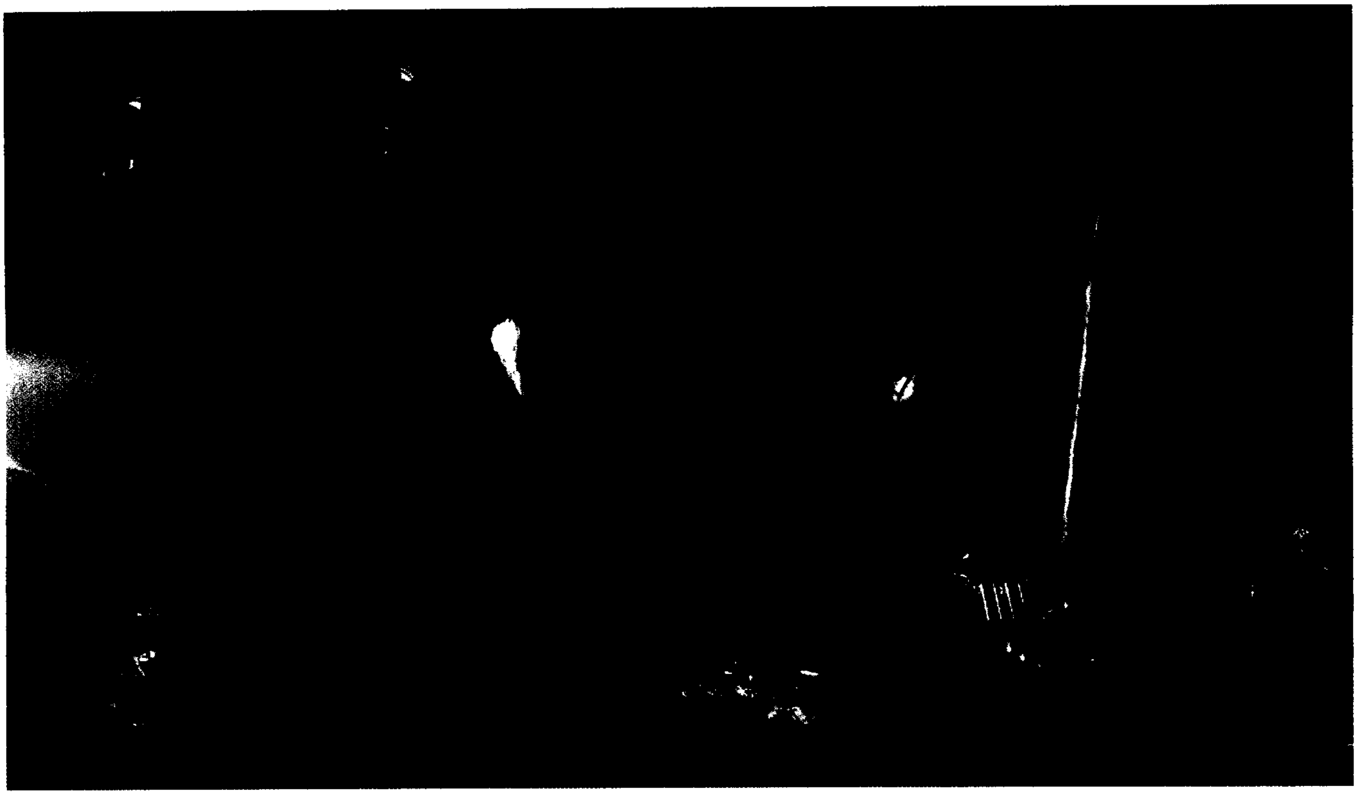

Figure 1. A collection of current and potential future MEP missions in artist's concept. Clockwise from upper left are: 1) 2001 Odyssey orbiter, 2) Mars Reconnaissance Orbiter (MRO), 3) Potential future human missions for which robotic missions pave the way, 4) Mars Sample Return large rover and Mars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

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. This is consistent with the capability needed for the original MSR concepts established in 2001.

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).

Missions beyond 2005 are currently only in the planning stages and subject to change.

A Mars Scout is planned for 2007 (NASA Discovery analog, see 2003 IEEE Aerospace Conference paper # 1525 by Matousek for more details).

The plan for 2009 calls for a surface mission (Mars Science Laboratory (MSL)) 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 either 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. MSR is assumed to inherit the MSL accurate/safe landing capabilities.

At this time, previously planned missions by the Centre Nationale d'Etudes Spatiales (CNES, the French Space Agency) and ASI for 2007 are delayed or cancelled due to budgetary difficulties in France and Italy. NASA is currently planning a telecommunications orbiter 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 network enables future science missions of increased scope.

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 would naturally occur after 2009 would be 2013; this time is necessary to ensure that the techniques and technology demonstrated in the 2009 MSL mission for precision landing and hazard avoidance/tolerance work correctly before building the hardware for MSR.

2. The 2001 MSR Studies — Old News

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

- To aid the planning of Mars Technology Program.
- To determine the feed-forward requirements on the MSL project to ensure EDL technology for MSR has been demonstrated.
- To identify potential foreign partners' required inputs on the MSR architecture so as to ensure adequate funding from their governments.

Consequently, in early 2001, the Solar System Advanced Studies Office at JPL was commissioned by the MEP to conduct industry-centric studies to acquire data for the MEP to aid in determining when MSR can occur in the current program.

Structure

In the summer of 2001, four industry teams were each funded $1 M 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.

To obtain independent views and fresh ideas, each 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.

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. 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 cost estimate was required and technology needs were identified.

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.

The Teams

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 last year by each team (see References in this paper).

The teams had varied amounts of involvement in previous MSR studies and represented a broad range of space mission implementation viewpoints, ranging from previous Mars missions to the Space Station.

Study Requirements and Challenges

A fundamental guideline for the study was for the teams to assume a MSR mission implemented by the US without consideration of international partners. Even though international participation by ASI, CNES, and the Canadian Space Agency (CSA) is likely, this US-only approach led to a comprehensive study of the full mission, the results of which could later be manipulated to include international partners.

Science Requirements

The science baseline objectives were as follows:

- The objective of the mission was to return Martian samples to Earth for analysis. However, Earth handling and analysis of the samples was deemed to be outside the scope of these studies.
- The total mass of samples returned by a first mission greater than 500 g.
- Returned samples were to include rock, regolith, and atmosphere and selected using a payload of scientific instruments and sub-surface sampling tools.
- Sample diversity ensured by providing mobility for the sample selection and collection payload of no less than 1 km, measured as a radial-distance from the landing site. The 1-km radial distance could be achieved over a period of a few months.

- A sample from a depth of at least 2 m.
- 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).
- Landing accuracy no worse than 10 km (semi-major axis of the three-sigma landing ellipse).

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

For these 2001 studies, a set of constraints and assumptions were also specified:

- Launch in 2011 (with option of 2013).
- 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, but not including:
  - Technology development.
  - Flight validation demonstrations.
  - Mission operations.
  - Preparation for and implementation of handling the returned sample on Earth.
- 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 specified as follows:
  - TRL 5 by Preliminary Mission System Review (component and/or breadboard validation in laboratory environment).
  - TRL 6 by Preliminary Design Review (system/subsystem model or prototype demonstration in a relevant environment).
  - TRL 7 by Critical Design Review (System prototype demonstration in a space environment).
- 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.
- 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).
  - <u>Sample containment assurance</u>: 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).

Phase 2 Direction

After Phase 1, the Advanced Studies Office at JPL in conjunction with the MEP and the Mars Program System Engineering Team[7] (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 advise 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.

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 on all orbiters and any direct-entry landers (design and cost were supplied by JPL[8]). 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 to be detectable by existing orbital telecommunications/navigation assets.
- The OS design that includes (as a back-up capability) the ability to be detected while the OS is un-powered.
- All landers to have terminal hazard avoidance and be capable of tolerating 1.0-meter obstacles and 30-degree slopes.
- All landed assets (landers, rovers and MAVs) to have the capability to communicate with (and be tracked by) an existing orbital communications asset. Lander telemetry to be continuously sent to the orbital communications asset during EDL. MAV telemetry to be continuously sent to the orbital communications asset during ascent from the Martian surface.

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[7] 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.

[8] 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.

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-m 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.

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.

Study Results

At the end of Phase 2, each of the teams presented the results of their studies. Table 1 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 Table 1 and are discussed in depth in this paper.

Table 1. **Old Concepts**. An overview of the results of the 2001 Phase 2 industry studies plus post-Phase 2 studies with JPL Team X. Details of each concept are in the papers presented by each team at last year's conference.

	BOEING	BALL	LMA	TRW	TEAM X Option A	TEAM X Option B
# OF LAUNCHES	One	One	One / Two	One	One	Two
EARTH-MARS VEHICLES	One	Two	One / Two	One	Two	Three
EARTH-MARS TRANSIT	Chemical	SEP, ERV, Chem Lndrs	Chemical	SEP	Chemical	Chemical
MARS ORBIT CAPTURE	SEP Spiral	Chemical + Aerobrake	Chemical	SEP Spiral	Chemical + Aerobrake	Chemical + Aerobrake
MARS LANDER EDL	Direct Entry	Direct Entry	Direct Entry	Two Landers from Orbit	Direct Entry	Direct Entry
SURFACE OPERATIONS	2× (Lander + MAV, RPS, Rover + Drill)	2× (Lander + MAV, Drill, RPS Rover)	Lander + MAV + Drill, MER Rover	2× (Lander + MAV + Drill, Rover)	Lander + MAV + Drill, MER Rover	2× (Lander + MAV + Drill, MER Rover)
SAMPLE RENDEZVOUS	Low Mars Orbit	Low Mars Orbit	Libration Pt Rend / Low Mars Orbit	Lander + MAV + Drill, MER Rover	Low Mars Orbit	Low Mars Orbit
MARS-EARTH TRANSIT	SEP	Chemical	Chemical	SEP	Chemical	Chemical
EARTH ENTRY	EOI with SEP Spiral to LEO, Shuttle	EOI to HEO, rendezvous with separate launch EOV, 2 sample canisters returned	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 EEVs with one OS each

Some general observations after Phase 2 were:

- 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 was enabling.
- SEP appeared to have benefits in terms of delivered mass capability. However, it was still to be determined whether the longer flight times inherent in MSR missions utilizing SEP were acceptable.
- MSR appeared to be a $1.5 B to $3.0 B class mission. This broke down to $1.5 to 2.0 B for a one-lander mission and $2.5 to 3.0 B for a two-lander mission (preferred by industry). Sample handling methods needed for planetary protection were the largest uncertainties in these estimates.
- It had 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, was necessary.
- By and large, the MTP was concentrating on the correct technologies to reduce the risk, complexity, and cost of MSR. Some of these technologies included rendezvous/capture, the Mars Ascent Vehicle, and sample handling.

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 1 through 6).

3. Establishing New Requirements

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.

In February 2002, the MSR SSG met with the Mars studies office and the industry teams to embark on reformulating the scope of MSR. Industry presented the results of the 2001 studies and identified the cost drivers on the mission.

The major cost drivers from science included:

- Mobility needed to collect samples from a variety of locations at the site (> 1-km radius from the lander).
- Drilling needed for subsurface access to greater than 2 meters.
- Carefully caching many samples, keeping them segregated and cataloged.
- Time on the surface to search, evaluate, and collect promising samples.
- Accommodating 50 kg of science instruments to perform in-situ evaluation and science.

It was unclear at that point whether any MSR mission could be affordable. After much debate, a floor-level set of requirements were defined that could be used as a starting point for a mission architecture. The SSG didn't know whether they could advocate these floor-level requirements; however, a stake needed to be put in the ground for a floor-level mission.

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.

The SSG would then embarked on confirming and building a case for the adequacy of the floor-level mission; the results are discussed in Section 7.

Armed with the elimination of the requirements for:

- Mobility.
- A sophisticated in-situ science package.
- Drilling.
- Segregation of the samples.

the study teams embarked on a process of defining a floor-level mission. They were also directed to keep the mission as inexpensive as prudent (by their own judgment).

The new Level-1 requirements were defined as

- 500 gm.
- Rock, regolith, atmosphere – capability.
- Landing <10 km.
- Context camera for sample collection, selection, and knowledge.
- Samples held at temperatures below <50°C.
- Mission launch by 2013.
- Mission duration <5 years.
- Option to break apart the mission, with elements launched from earth in separate launch opportunities (for example 2013, 2016).
- Planetary protection requirements:
- Forward.
- Backward.

The change to a 2013 launch date was due to the MSL pre-cursor mission being slipped to 2009 (as previously discussed, skipping a bi-annual opportunity is necessary to feed-forward the mission results).

The requirement listed above to be able to split the mission enabled a way to spread the cost of the mission over a longer period if that was necessary to keep within a yearly cost cap.

4. EMERGING CONCEPTS

What has emerged is a reduced mission called the Groundbreaking MSR. A generic version of which is depicted in Figure 2. 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 2.

Since we couldn't afford to start from scratch (funds and schedule), the study teams started with their previous concepts as a basis for their floor-level mission study. They understood their previous concepts in-depth, including the cost drivers.

As a result, each team retained some of their basic differences in approach. Table 3 indicates some of the basics. For example, TRW retained the use of Solar Electric Propulsion (SEP) and LMA continued to use a deep space rendezvous (previously at Libration Point), rather than rendezvous in Mars orbit, as the other teams did.

As shown, all the teams have eliminated their rover. In addition, to keep the cost down, 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.

Comparisons of the Mission and Implementation Characteristics are shown in Tables 4a and 4b.

5. ESTABLISHING CREDIBILITY

One of the concerns that we had is making sure that the development cost estimates for the new mission were credible. We approached the issue two ways.

First, we required the teams to provide traceability between the cost estimates for this new concept and their 2001 concept. All the teams invested a lot of the study resources in 2001 to costing that mission. All have substantial costing models and involved their financial organizations. Having

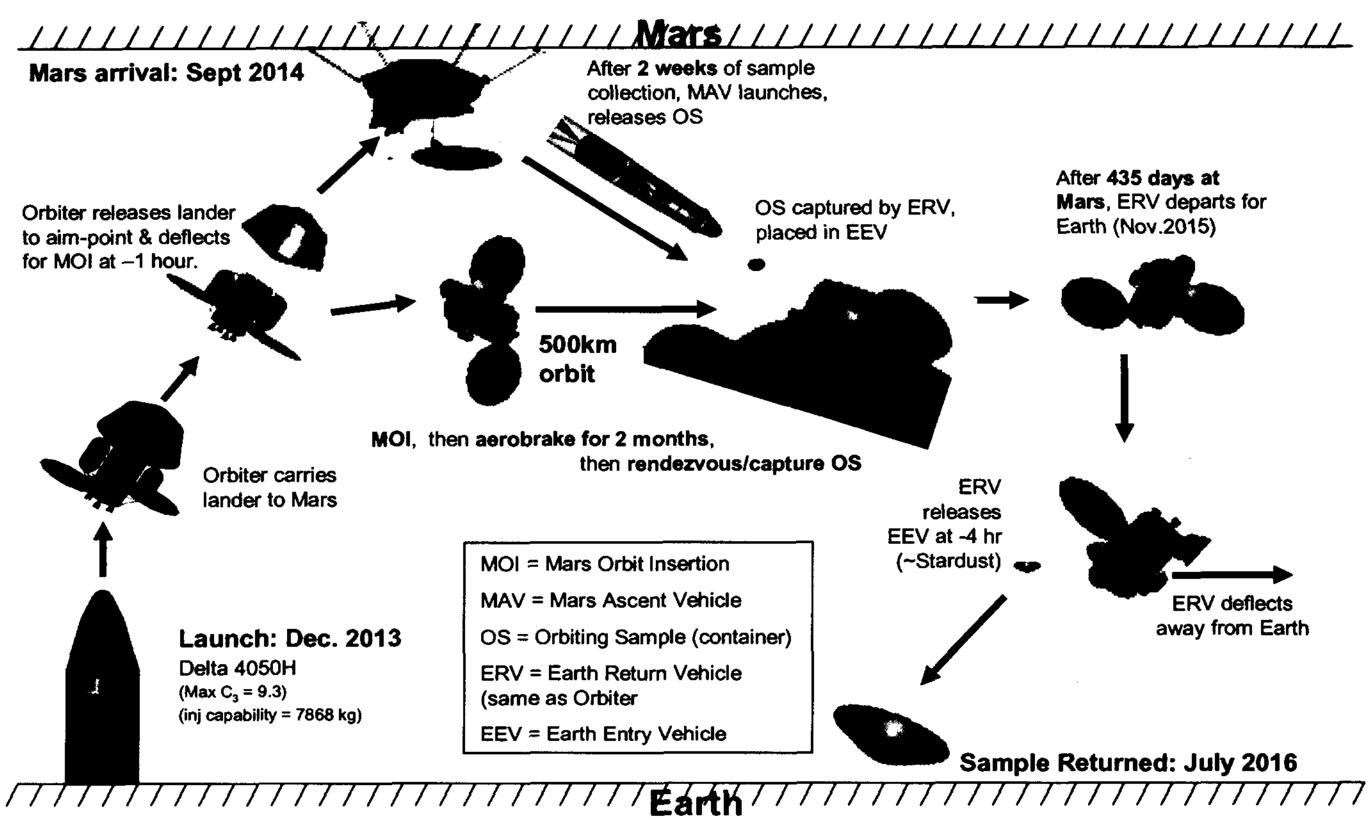

Figure 2. Generic Groundbreaking MSR mission.

Table 2. 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 3. 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	

Table 4a. Groundbreaking MSR concepts: mission characteristic.

	BOEING	BALL	LMA	TRW	TEAM-X
LAUNCH VEHICLE	Delta IVH	Delta IV	Atlas V	Atlas V	Delta IVH
EARTH-MARS VEHICLES	1 Orbiter/ERV + Lander	1 Orbiter/ERV + Lander	1 ERV + Lander	1 Orbiter/ERV + Lander	1 Orbiter/ERV + Lander
EARTH-MARS TRANSIT	Ballistic	Ballistic	Ballistic	SEP	Ballistic
MARS ORBIT CAPTURE	Chemical + Aerobrake	Chemical	N/A (ERV Flyby)	SEP Spiral in	Chemical + Aerobrake
MARS LANDER EDL	Direct Entry Sep: E-2 days	Direct Entry Sep:	Direct Entry Sep: E-12 hrs	From orbit (1250x500km)	Direct Entry Sep:
SURFACE OPERATIONS	Stationary 8 weeks	Stationary <2 weeks	Stationary 2 weeks	Stationary 2 weeks	Stationary 8 weeks
SAMPLE RENDEZVOUS	Low Mars Orbit	Low Mars Orbit	Heliocentric Orbit (M +150days)	Low Mars Orbit	Low Mars Orbit
MARS DEPARTURE	Chemical	Chemical	Swing-by	SEP spiral out	Chemical
MARS-EARTH TRANSIT	Ballistic	Ballistic	Ballistic	SEP	Ballistic
EARTH ENTRY	Direct	Direct	Direct	Direct	Direct
MISSION TIME	~3 yrs	2.7 yrs	3.2 yrs	2.2 or 5 yrs	2.5 yrs

Table 4b. Groundbreaking MSR concepts: implementation characteristic.

	BOEING	BALL	LMA	TRW	TEAM-X
SURFACE PAYLOAD	Arm w/ scraper, sieved scoop, context camera	Arm w/ scoop, grasper, context camera	Arm w/ scoop, context camera	Arm w/ scoop, context camera	2 Mars'01 arms w/ scoop, context camera
MARS ASCENT VEHICLE (MAV)	2 stage solid w/ head-end stage for 3-axis stab 215 kg	2 stage solid 3-axis stab 265 kg	2 stage solid 1 3-axis, 1 spun 260 kg	2 stage GEL 3-axis stab 220 kg	2 stage solid 3-axis stab 285 kg
RENDEZVOUS & CAPTURE SENSORS	Optical camera LIDAR Vis/Nav system	RDF LIDAR Optical Camera	RDF Optical/IR LIDAR	RF Transponder Video(laser) guidance sensor	UHF Beacon Optical WAC for terminal
OS DESIGN	3.6 kg sphere	6 kg sphere	6 kg cylinder with solar arrays	Sample container attached to upper stage (5kg back)	4.6 kg reflective sphere
EARTH ENTRY VEHICLE (EEV)	LaRC EEV design	LaRC EEV design + parachute	Stardust derivative w/vault	LaRC EEV design mod. for for sample container	LaRC EEV design
PP BREAKING THE CHAIN	Mars surface and atmos. Isolation	Mars surface isolation + in-orbit transfer	Mars surface isolation + ashing + in-orbit transfer	Mars in-orbit transfer + chem & heat decontam.	Mars surface isolation + in-orbit transfer
MSL HERTIAGE	MSL EDL system design (incl s/w)	MSL EDL system design (incl s/w)	None	MSL EDL system design w/o steerable aeroshell	MSL EDL system design
LANDED PAYLOAD MASS	<300 kg	337 kg	350 kg	~300 kg	608 kg incl. lander utilities
LAUNCHED MASS	3600 kg	4057kg	3039 kg	3848 kg	6362 kg

the teams justify the reductions in cost provided more confidence that the less-expensive mission was not under-estimated.

Second, 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. As can be seen in Table 5, the estimates are remarkably consistent.

6. THE BIG DEBATE

One of the issues that emerged from the study was the additional mission risk inherent in using only one landed system, rather than doubling-up on all the landed elements. The probability of mission success is an additive process of a string of events that have to work, which goes beyond a typical Mars mission. During the 2001 studies, several of the teams doubled-up on entry systems and the Mars Ascent Vehicle (MAV) feeling that these are the most risky elements of the mission.

Each team made their best attempt at estimating the probability of mission success. The estimates varied widely and great debate ensued on the process, the basis of the numbers, and even the significance of the results. Most agree that analysis of this kind is best used for comparative trades and assessing the strengths and weaknesses of systems, rather than using the results in an absolute sense. A common refrain in the debate was, "If you believe the final numbers and take them literally, you would probably never launch any mission". This debate needs to be further pursued. In the mean time, it is prudent for Mars program planning to earmark a budget that would allow adding a second landed system in the event the potential need is solidified.

7. SCIENCE STEERING GROUP CONCLUSIONS

As indicated in section 4, 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.

Table 5. Groundbreaking mission development cost estimates ($B).

	Industry Team				Team X
	a	b	c	d	
Cost Estimate from Source	1.1	1.1	0.8	1.4	0.9
Independent Cost Estimate by Aerospace Corp	1.0	1.0	1.0	1.3	1.0
Independent Cost Estimate by SAIC	1.1	1.2	1.0	1.3	1.1

Notes:
- In FY '02 dollars, including launch vehicle, and averages of ~200 M in reserves
- Not including mission operations estimated at 44 M by Team-X
- Not including technology program or ground sample handling facilities
  - Technology at 122 RY $'s in 2003 through 2009
  - MRSH provided Science support to mission (1 M/yr pre-launch - 5 M post-launch)

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 listed in the revised science requirements.

8. Project Plan and Technology

The Mars Sample Return mission is currently being carried in the Mars program plan as a 2013 launch. The nominal schedule for the project takes the complexity of the development of MSR into account with a substantial development phase (Figure 3). For a detailed development schedule, see Figure 4, which is the schedule developed by Team-X.

The plan assumes that an array of technology development and demonstrations take place before embarking on the development (see Figure 5). These are key to being able to implement the project at the cost estimated.

Chief among them is the EDL development and flight on MSL in 2009. The safe and accurate landing capabilities needed by MSR is a major development undertaken by MSL. The Groundbreaking MSR landing capability is assumed to be the same as demonstrated on MSL; in deed, MSR might target the same or similar site. MSL currently is designing to being able to have full planet access (any altitude). If in the future, limitation are accepted in the MSL design, MSR most likely could accept the same limitations.

In addition, the project is counting on demonstration of rendezvous and capture methodology and hardware/ software/algorithms. The Mars technology Program is currently developing a rendezvous/capture demonstration to be flown either on the CNES/NASA Orbiter scheduled to launch in 2009 or a NASA-only telesat also launched in 2009. An instrumented OS will be acquired and tracked as the orbiter maneuvers to close proximity, all in applicable low Mars orbit. In addition, a ST-6/XSS-11 joint NASA/DOD mission in 2004 will demonstrate instrumentation and techniques in Earth orbit.

The MAV 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 will be performed pre-project (Pre-Phase A) and qualified before entering Phase C/D.

In addition to the developments/demonstration already discussed, the Mars Technology Program has approximately $125 M budgeted for other focused MSR technology development. Included is:

- Forward Planetary Protection — to develop cleaning, sterilization, and validation technologies and delivering a set of procedures that, when applied to the spacecraft during assembly, will satisfy forward planetary protection requirements.

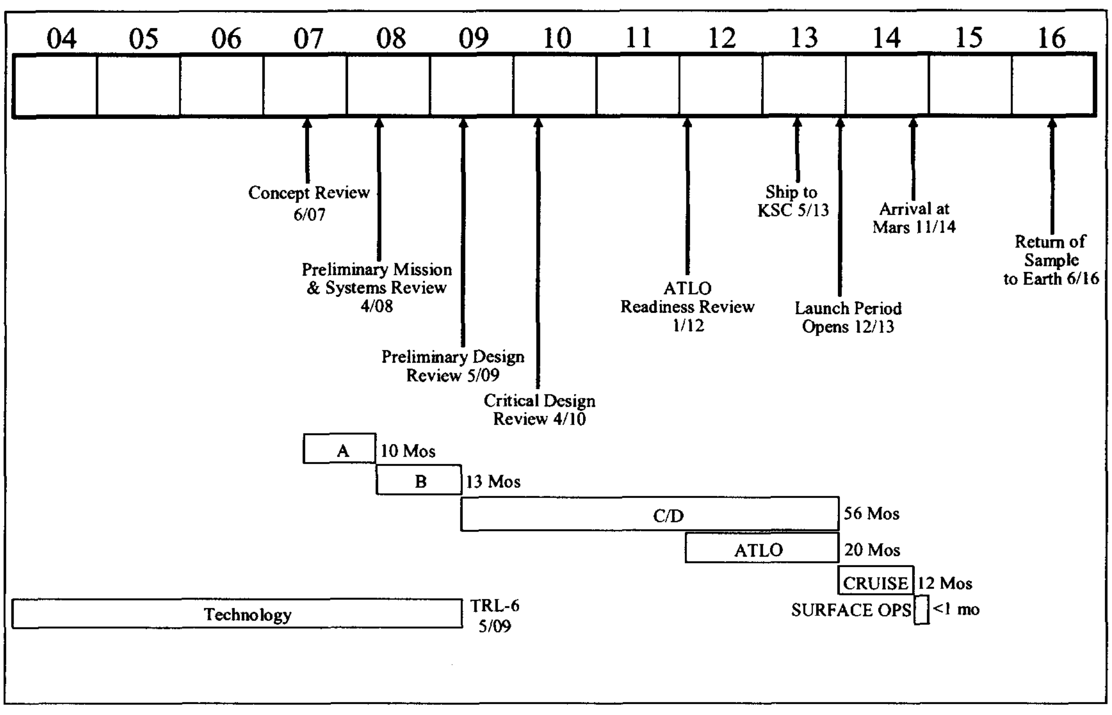

Figure 3. Nominal Groundbreaking MSR project schedule.

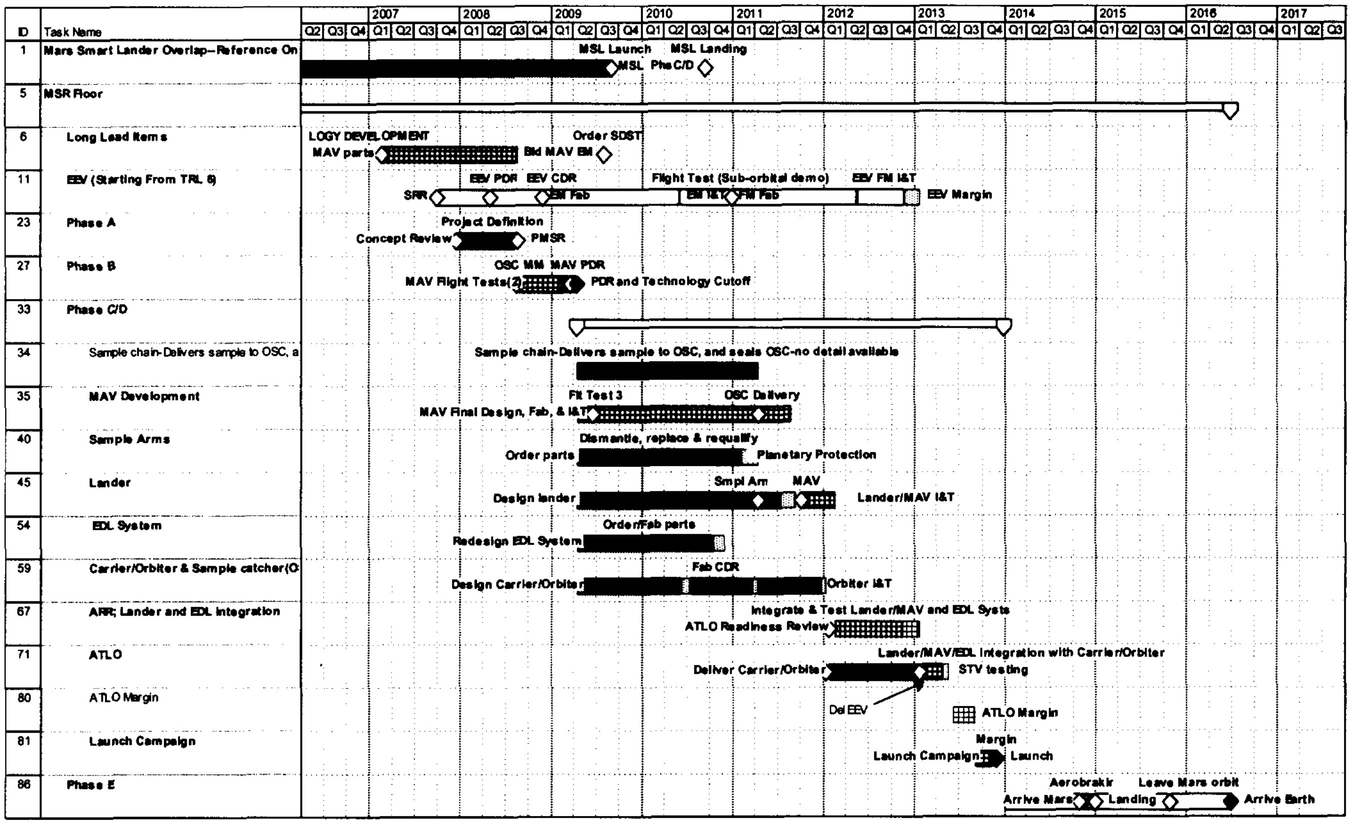

Figure 4. Team-X version of 2013 MSR schedule.

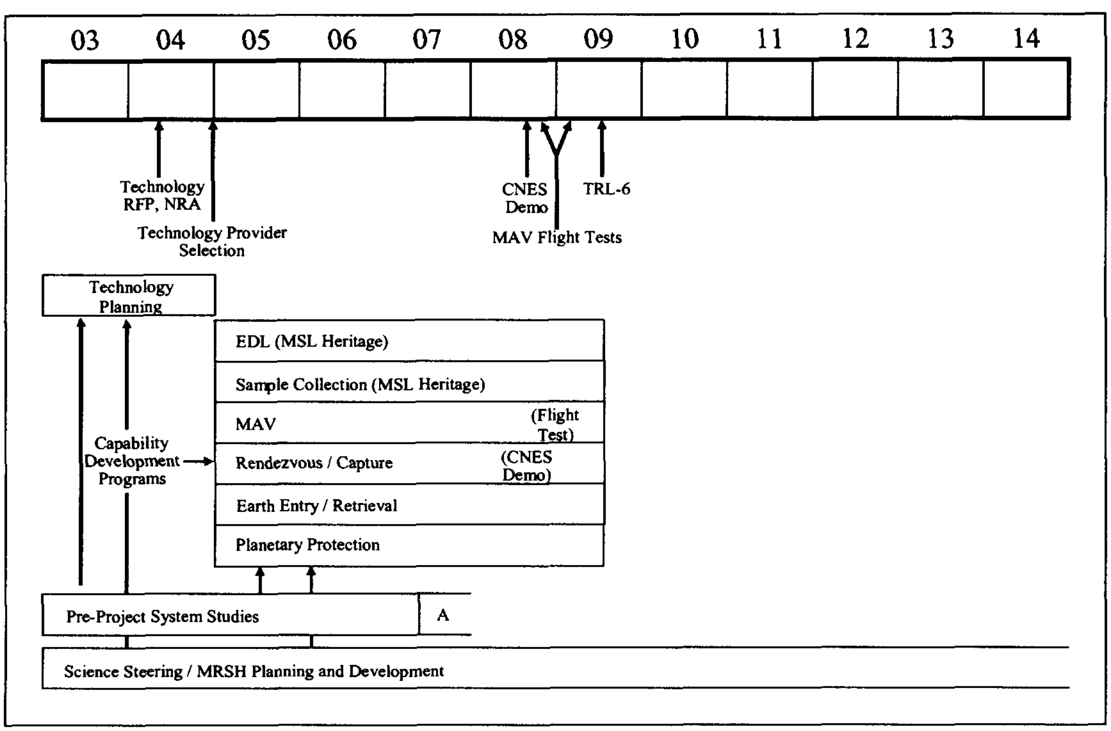

Figure 5. Groundbreaking MSR pre-project activities.

- Sample Acquisition — covers qualification of arm and scoop/sieve (inherited from MPL mission).
- MAV — for specific "device-level" qualification dependent on MAV propulsion type selected.
- Rendezvous and Sample Capture — this is to coalesce the results of the flight demonstrations and "fill-in the gaps" as necessary.
- Back Planetary Protection (or Sample Containment and Earth Return) — covers a number of areas that will enhance some of the following areas prior to pre-project start:
  - Dust migration and mitigation (fairing dust mitigation).
  - Sample container sealing (break-the-chain of contact).
  - Containment vessel sealing and possible dust mitigation.
  - Earth return vehicle (flight dynamics, thermal protection, structure, sterilization, and impact protection).
  - Earth return targeting (analyze containment assurance risk and propose innovative designs for spacecraft, navigation and mission operations).
  - Meteorite protection.
  - System analysis and PRA.

Drop testing of the Earth Entry Vehicle is included in the project costs.

9. SUMMARY

It is believed that the scope of this new "Groundbreaking" approach to MSR is well understood by the studies and independent cost assessment by Aerospace Corporation and SAIC. It appears to be what a contemporary, balanced Mars Exploration Program can afford; has turned out to be justifiable by the MSR Science Steering Group, and is endorsed by the Mars science community at large.

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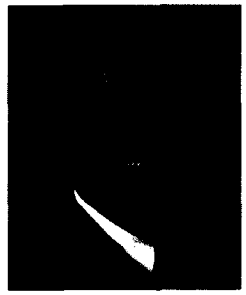
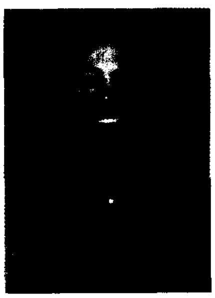
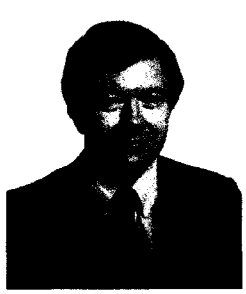
BIOGRAPHIES



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 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.

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
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
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
SSG	Science Steering Group
STS	Shuttle Transportation System
TMOD	Telecommunications and Mission Operations Directorate
US	United States