Mars Ascent Vehicle
Key Elements of a Mars Sample Return Mission

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[1,2] *Abstract*—The Mars Sample Return mission is being planned to return samples of Martian rock, soil, and atmosphere to Earth for scientific analysis. A Mars Ascent Vehicle (MAV) will be brought to the Martian surface within a lander; receive samples delivered by a mobile surface vehicle; and launch the samples into Mars orbit for return to Earth. The MAV is being designed as a two-stage solid-fuel vehicle with a head-end steering capability, packaged within an erectable launch tube for thermal and environmental stability during the various mission phases of cruise to Mars; entry, descent, and landing; surface and pre-launch operations; and launch. Key features of the MAV operations and design are discussed, including the thermal, environmental, and structural requirements and their conceptual design solutions during each phase; concepts for insertion of the orbiting sample into the payload bay inside the launch tube; and pre-launch operations. MAV launch to orbit details will be discussed, and key technology development challenges will be identified.

TABLE OF CONTENTS

1. INTRODUCTION
2. MAV SYSTEM ARCHITECTURE
3. LAUNCH TUBE
4. SAMPLE INSERTION
5. ERECTION
6. GAS EJECTION
7. LAUNCH OPERATIONS
8. KEY TECHNOLOGY CHALLENGES
9. DESIGN TRADES
10. SUMMARY
REFERENCES
BIOGRAPHIES

1. INTRODUCTION

Background - Exploration of Mars continues to hold a unique position in our understanding of the origins and development of the Solar System. As the planet with the closest climate and atmospheric conditions to those of the Earth, it holds a special interest in our understanding of terrestrial evolution. As a water-bearing planet, at least in solid and vapor form if not currently in liquid form, it holds great interest in the possibility that life has formed, or in fact currently resides, there.[1] In addition to the potential for past or current life, it holds the most attractive possibilities for sustaining long-term human life in many credible scenarios of human evolution beyond the planet Earth.

Exploration of Mars has proceeded according to a long-range plan of spacecraft fly-bys, orbiters, landers, and mobile rovers. The current generation of Mars exploration missions, shown in Figure 1, includes Mars Odyssey, the two Mars Exploration Rovers (MER) – Spirit and Opportunity – on the Martian surface, the Mars Express in polar orbit, and the Mars Reconnaissance Orbiter currently en route to Mars with orbit insertion anticipated during the month of this conference in March 2006. The next two windows of opportunity for Mars missions – in 2007 and 2009, will include the Mars Phoenix Scout mission and the Mars Science Laboratory (MSL). The Mars Science Laboratory mission will be highlighted by a long-life, high-mobility rover that is planned to operate for at least one Martian year (1.9 Earth years) with a capability to traverse large distances from the landing site.

[1] 0-7803-9546-8/06/$20.00 © 2006 IEEE
[2] IEEAC paper #1009, Version 3, Updated February 10, 2006

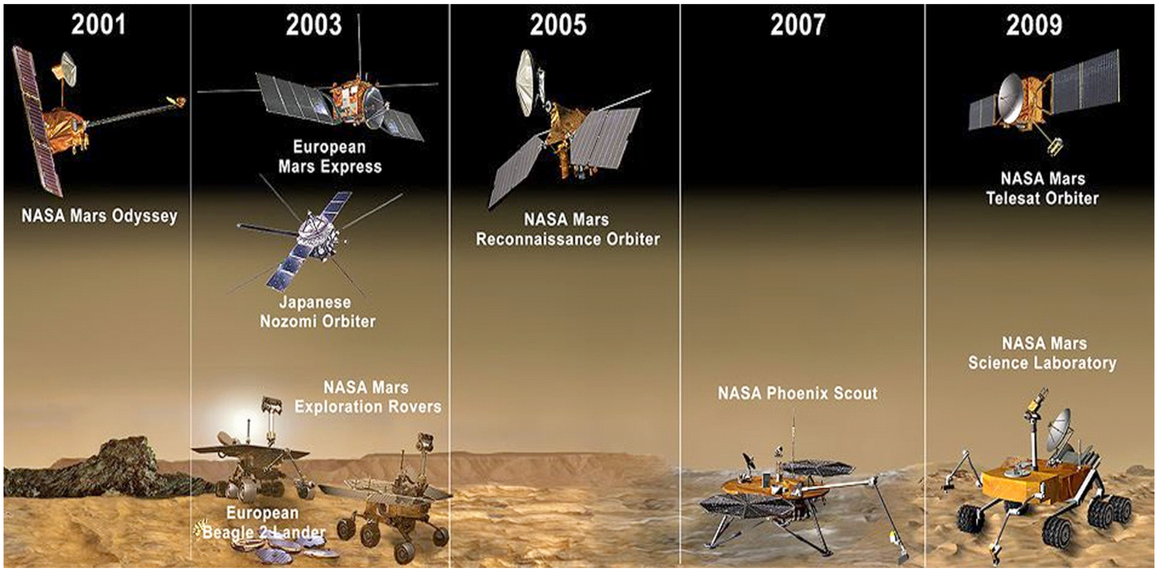

Figure 1 – Mars Exploration Timeline in Current Decade

Mars Sample Return Overview

By the end of this decade, we will have completed a coordinated survey of at least four sites on the Martian surface with mobile rovers, including Pathfinder, MER, and MSL. These rovers have had improving capabilities to examine samples of the Martian surface, including visual analysis and drilling of rock and soil samples, as we have also improved the scientific instruments. There has been a number of studies of Mars missions that could fly in the next decade. A leading candidate for the next decade is a Mars Sample Return mission. A Mars Sample Return (MSR) mission would land on the Martian surface, collect samples of Martian soil, rocks, and atmosphere, and return the samples to Earth. This approach to scientific investigation of Martian samples allows for more detailed analyses in terrestrial laboratories with more capable instruments than those that fit within the launch constraints of a Mars mission. For optimum scientific value, the sites would be carefully selected based on criteria related to scientific objectives, mission risk, and spacecraft capabilities. Multiple missions, or at least multiple landing sites, would enhance the scientific return.

There has been a series of studies of Mars Sample Return missions, beginning in 1998. A series of MSR workshops were conducted at the Jet Propulsion Laboratory (JPL) during the summer of 1998. At these workshops, the feasibility of an MSR mission with a Mars Ascent Vehicle (MAV) placing an orbital sample into Mars orbit for recovery by an Ariane-5-launched orbiter/Earth return vehicle was evaluated. This led to a systems architecture study performed by JPL and its contractors in 1999, when it was determined that the sample mass returned to Earth was likely to be in the range of 0.5 – 5 kg of Mars samples.[2]

A series of contractor studies was performed in 2001, and updated in 2003. During these studies by Ball Aerospace, Boeing, Lockheed Martin, and TRW, a broad range of mission architectures was evaluated and several options were selected as feasible by each contractor.[3] The architectures considered a range of mission objectives, technologies, landers, rovers, ascent vehicles, orbital rendezvous, Earth return technologies, and Earth entry scenarios. Each contractor then selected one or more system architecture concepts for further study, and prepared a rough cost estimate and technology development plan for the selected concepts. The Advanced Project Design Team (Team-X) at JPL also conducted an MSR design study in 2001.[4] Another round of studies was conducted in 2003 with JPL and the same contractors to establish a baseline for what can be accomplished within tighter cost constraints than were allowed in 2001. This round of studies, called the "Groundbreaking" approach to MSR, developed the current set of requirements for the MSR mission.[5]

The key requirements for an MSR mission include the following:

- Select samples of rock, regolith, and atmosphere using a payload of scientific instruments and sub-surface sampling tools.
- Safely return a mass of selected samples of at least 0.5 kg to Earth.
- A sample from a depth of at least 2 m shall be returned.
- Meet defined planetary protection requirements for forward and back contamination.

Mars Ascent Vehicle

The vehicle to lift the selected Mars samples off the Martian surface is the Mars Ascent Vehicle. A series of contractor studies by Lockheed Martin, Boeing, and TRW examined various concepts for the MAV in 2001-2002, including liquid, solid, and hybrid fuels of varying technology readiness.[6] The requirements for the MAV system are a subset of the overall MSR mission requirements. They can be summarized by receiving an Orbiting Sample Container (OSC) into the MAV payload interface and placing the OSC into Mars orbit for retrieval by an Earth Return Vehicle (ERV). The OSC includes the returning samples with back-contamination barriers within a sterile container, in a package that can be retrieved by the ERV. The ERV is placed into Mars orbit on an earlier mission with a periapsis of 400-500 km. The MAV includes the vehicle itself, with the engines, avionics and communications systems, and payload interfaces for the OSC. In addition to the vehicle, the MAV system includes the supporting systems for maintaining an operational environment throughout the MSR mission; for interfaces with the Mars lander; for retrieval, insertion, and integration of the OSC into the payload fairing; for pre-launch preparations to place the MAV into a raised attitude; and for ejection of the MAV from the launch tube.

MAV system requirements include:

- Accommodate earth launch, in-space transit cruise, Martian entry-descent-landing, and surface environment.
- Receive the OSC and integrate it into the MAV as a payload for secure launch into Mars orbit.
- OSC payload mass to be at least 5 kg.[3]
- Place the OSC into a stable Mars orbit altitude of at least 500 km, from anywhere on the Martian surface between $\pm 45^{o}$ latitude.

Scope

The scope of this report is to summarize key features of the Mars Ascent Vehicle, and to discuss the supporting subsystems. The subsystems addressed here include the thermal, environmental, and structural support subsystems; those for transfer and insertion of the OSC into the payload integration mechanisms; the launch tube; and associated thermal, structural, and inertial measurement subsystems. The following sections address: 2. The overall MAV system architecture, including the MAV as an MSR system, operations analysis, and key MAV subsystems; 3. The launch tube with its required thermal protection, impact resistance to Mars entry, parachute deployment, and lander touchdown; 4. Handover and insertion of the OSC into the payload attach location; 5. Erection of the launch tube with the MAV prior to launch; 6. Gas ejection of the MAV from the launch tube; 7. Launch operations; and 8. Key technology challenges.

2. MAV SYSTEM ARCHITECTURE

MAV as an MSR System

During launch from Earth and transit to Mars, the MAV is basically a dormant package within the cruise stage spacecraft. This spacecraft will be launched into trans-Mars injection by an Evolved Expendable Launch Vehicle. As a minimum, this spacecraft contains entry, descent, and landing subsystems and a lander. Various options still under study for the MSR architecture include the following decisions:

- *Orbiter* – The Mars samples will rendezvous in Mars orbit with an Earth return vehicle. This vehicle will be placed into Mars orbit either as part of the same spacecraft that delivers the MSR surface package – with MAV – or on a separate mission, perhaps by the European Space Agency. A variety of rendezvous techniques, of Earth return trajectories, and of Earth entry architectures are under consideration. The orbiter will actively locate, rendezvous, and capture the OSC in Mars orbit prior to trans-Earth insertion.
- *Surface Rover* – There are several options for how the Mars samples will be collected. One option is for the MSR mission to carry a mobile surface rover with the instruments and tools to collect samples and to place them within the MAV. Other options include collecting the samples on an earlier mission, such as the Mars Science Laboratory (MSL), and storing them for delivery to the MAV during the MSR surface mission. A third option is to collect the samples with manipulator arms mounted directly on the lander.

During the cruise to Mars, the MAV and its supporting subsystems are integrated into the lander system, which is fully enclosed with the spacecraft. As this spacecraft approaches the Martian atmosphere, the lander is gradually exposed during the entry, descent, and landing phase as the entry shield is released and the parachutes are deployed. After landing, the MAV and its support systems are mounted horizontally on the MSR lander, as shown in Figure 2.

The MAV itself is planned as a two-stage vehicle with solid rocket motors. A preliminary design concept[6] is shown in Figure 3. Initial wet mass is about 250 kg, including the OSC payload. The first stage uses a stretched STAR 17A solid rocket motor to achieve a 500 km apoapsis. The second stage uses a STAR 13A motor to circularize the orbit. The second stage jettisons the OSC after achieving orbit, and the Mars orbiting vehicle rendezvous and captures the OSC for return to Earth.

The total MAV wet mass at launch is about 250 kg, including the OSC payload. The OSC payload mass is 5 kg. The MAV length is 2.56 m, including the payload fairing. The diameter is 0.442 m.

[3] The Orbiting Sample Container mass shall not exceed 5 kg for a returned sample of 0.5 kg of Martian material, i.e. the sample of rock, regolith, and atmosphere shall be at least 0.5 kg, contained within an OSC with mass not to exceed 5.0 kg.

MAV Operations Phases

During Earth to Mars transit, the MAV is secured within the MSR spacecraft. It draws minimal power, simply to monitor systems and communicate with Earth through the spacecraft. Important thermal requirements indicate that the solid rocket motor fuel (CTPB) must be maintained above -40°C, and that the reaction control system (RCS) fuel tanks, with HPB 1808 fuel (74% hydrazine/18% hydrazinium nitrate/8% water), must be maintained above 0°C to prevent water freezing during the dormant surface phase. During surface operations prior to MAV launch, the MAV draws power from the lander to maintain a thermal environment to protect the solid rocket fuel and two-phase reaction control fuels, and it communicates vehicle health status through the lander. It is located on the lander in a horizontal position.

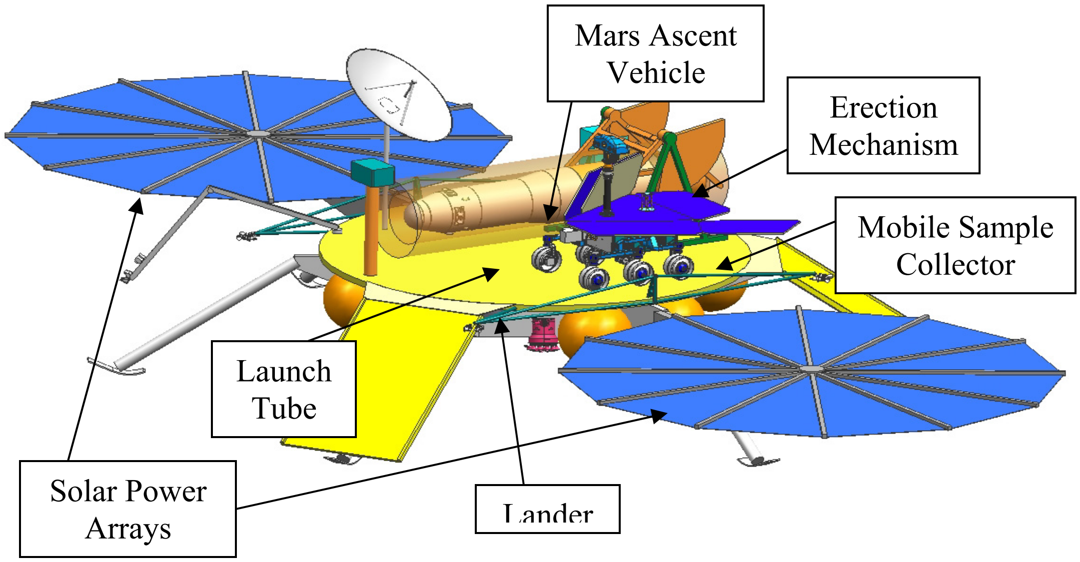

Figure 2 - Mars Sample Return Lander with MAV

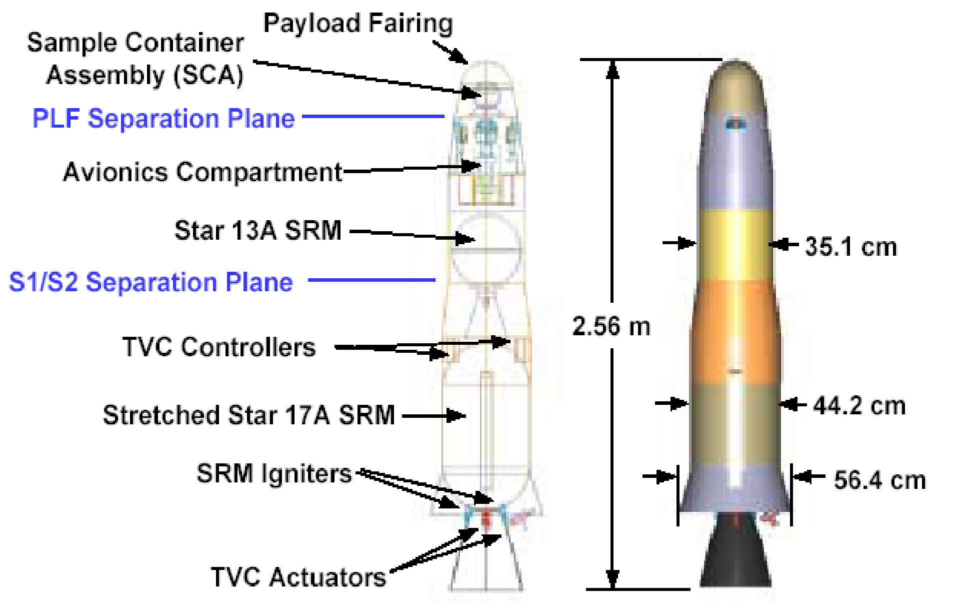

Figure 3 - Baseline MAV Design Concept

Landing requirements indicate that we should design to allow landing anywhere on the Martian surface between 45° North and 45° South latitudes. The MAV is mounted horizontally on the lander deck, and will be approximately 1 m above the Martian surface at lander touchdown. This means that we must design for a Mars atmospheric temperature as low as -123°C, and a wind speed of up to 20 m/s.[7] The MAV must be heated and surrounded with insulation within the launch tube. 3200 W-hr/sol (131 W average continuous power) of heating is required for the solid rocket motors with 2.5 cm of foam insulation. The RCS fuel and nozzles will likely be heated with radioisotope heating units (RHUs).

Prior to launch, Martian samples of atmosphere, regolith, and soil are transferred from the surface vehicle which collects the samples – assumed for this discussion to be a mobile rover – to the MAV. They are secured within the Orbiting Sample Container (sphere shaped), which is attached to the forward section of the MAV. The MAV, contained in the launch tube, is then raised to a launch attitude that is near vertical and the launch tube is vertically exposed to the Martian environment. The MAV then is ejected from the launch tube by a release of a high-pressure gas ejection mechanism, with ignition at a safe distance from the lander (if required), and the two-stage, solid fuel rocket ascends into low Mars orbit. To achieve optimum fuel performance, the MAV solid propellant bulk temperature should be raised to -10°C before launch. With the launch tube open in a vertical position, heating the MAV to this temperature will require an average of 180 W of continuous power, or 325 W of power during daytime only, for a period of 4.5 sols.

Supporting Subsystems – There are several subsystems that support the MAV, in addition to the vehicle itself, and these will be the focus of the next four sections of this report. These include the following:

- *Launch Tube* – This provides environmental protection from the Martian temperatures, dust, and winds during the MAV stay on the Martian surface. It also contains the sample retrieval arm, the inertial measurement system, the gas ejection system, and structural support to survive the loads during entry, descent, and landing. These loads include entry and parachute deployment loads up to 20 g, and surface impact.
- *Sample Retrieval Subsystem* – This is the arm that retrieves the OSC and secures it within the payload integration bay of the MAV.
- *Launch Tube Erection Subsystem* – During surface operations, the MAV is contained within the launch tube, which lies horizontally on the lander. Just prior to launch, this subsystem raises the launch tube to its launch position, perpendicular to the lander surface and approximately vertical.
- *Gas Ejection Subsystem* – This is a pressurized gas container mounted in the base of the launch tube that ejects the MAV from the launch tube to a height of 20-50 m as the first step in ascent.

3. Launch Tube

The lander and MAV systems are located on the Martian surface, with the MAV about one meter above the surface. A landing site has not yet been specified, so there is a requirement that these systems must be operable for landing sites within 45 degrees of the Martian equator. Daily minimum temperatures at the limits of these latitudes range from -124°C to -64°C, with daily maxima ranging from -100°C to -10°C.[7] The wide variations relate to the seasons, as well as the regional climates. Wind speeds up to 20 m/s have been measured. Because of these cold temperatures and wind speeds, the MAV resides within a cylindrical launch tube while on the Martian surface. The launch tube provides four functions to the MAV:

- Shock damping from atmospheric entry, parachute deployment, and landing.
- Thermal and dust isolation from the Martian atmosphere.
- Support for pre-launch erection.
- Orbiting sample manipulator and insertion mechanisms.
- Inertial measurement calibration.

The launch tube will be a high-strength alloy, probably a titanium alloy, with a thickness of 1 mm. A cylindrical tube design with a gas ejector in the base and an end cap above the nose cone has been considered. Later designs have favored a somewhat shorter tube, which reach to the second stage-payload fairing interface. The launch tube length is then 2.375 m, including lower end cap and gas ejector. This design results in lower tube mass, while leaving the payload fairing exposed. This is acceptable as long as the reaction control thruster tanks and nozzles are heated by RHUs. Within the launch tube, the MAV is thermally and structurally isolated by a foam Sabot, with thickness of 5 cm. Five cm of foam insulation is required to maintain the solid rocket CTPB fuel above -40°C, with 131 W of average continuous electrical heater power. The Sabot also supports the MAV during atmospheric entry and parachute deployment, with a mechanical support arm assisting during lander touchdown. Structural support is designed to protect MAV for lateral loads up to 20 g during atmospheric entry, parachute deployment, and lander touchdown.

4. Sample Insertion

Design of the sample insertion subsystem involves a number of trade options. The OSC is a spherical package, with a diameter of 16 cm and a mass of 5 kg. The samples are collected by a rover that is beyond the scope of this study. As discussed in Section 2 above, options under consideration include collection of the samples by the Mars Science Laboratory and long-term storage until the MSR lander is in place with the MAV, and a variety of landers or manipulators/scoopers associated with the MSR mission. The OSC is transferred from the collection device to the payload integration location in the upper stage of the MAV while the MAV is within the launch tube in the horizontal position. Earlier studies have considered options with an upper end cap on the launch tube, to better protect the MAV from the Martian environment. To save launch tube mass, the design has been modified to remove the end cap and the upper 12 cm of the launch tube, so the payload fairing is located beyond the open end of the tube, with a thin protective layer between the second stage and the payload fairing.

Sample insertion is a three-step process, beginning with sample positioning within the range of a manipulator. The OSC is transferred to the manipulator for insertion into the payload interface location, and then securely integrated into the MAV payload interface. Options considered for sample transfer include:

- Dexterous manipulator aboard the rover
- Dexterous manipulator aboard the lander
- Dexterous manipulator attached to the launch tube
- Single degree-of-freedom arm attached to the rover, with the rover manipulating to align the insertion to the MAV
- Single degree of freedom arm attached to the lander
- Arm attached to the rover with a chute attached to the launch tube to receive the OSC
- Telescoping rod from the top of the launch tube

All these options have been considered, with a variety of options for actual insertion into the payload interface. The option with the lowest mass and highest reliability appears to be the telescoping rod mounted to the top of the launch tube, working with a simple arm on the rover, as shown in Figure 4.

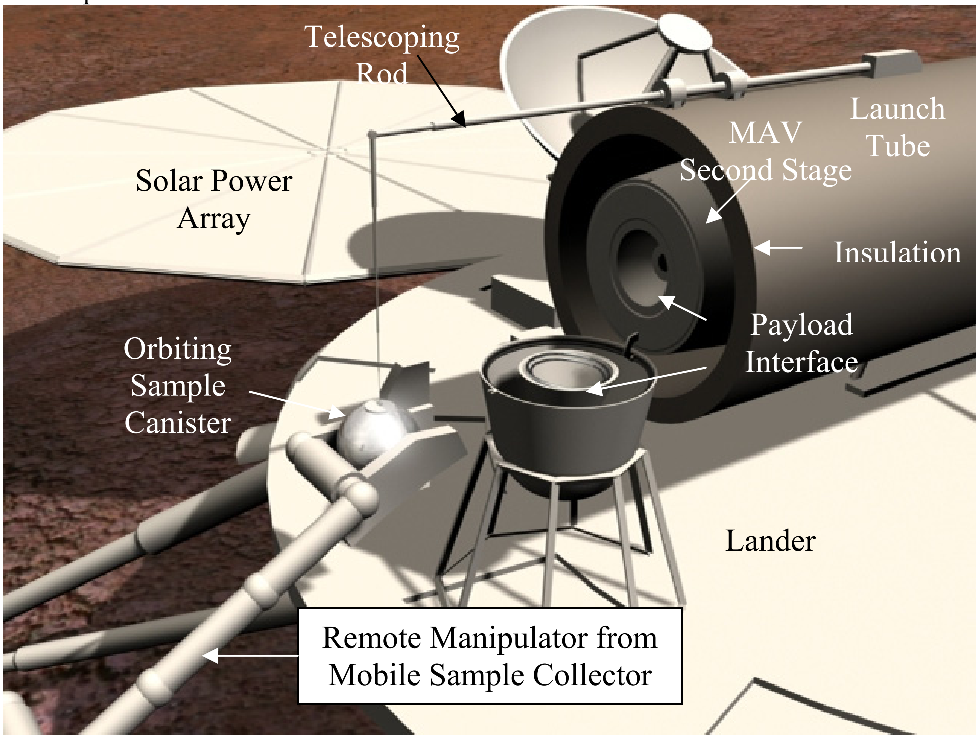

Figure 4 - Sample Insertion Mechanisms

The samples are assumed to be collected by mechanisms aboard the rover and placed within the OSC. The rover places the OSC within the reach of a telescoping arm mounted on the top of the launch tube. The arm reaches out to the rover and lifts the OSC with a magnetic attachment. The arm then raises the OSC to the location of the payload fairing, and retracts to a position where it lowers the OSC into the payload fairing. The payload is then secured into the payload fairing and the interfaces verified, before the retrieval mechanism reaches down to a latch on the outside of the payload fairing, and closes the payload fairing into the launch configuration. This completes the payload integration process, and the MAV is then prepared for launch.

5. Erection

Prior to launch, the MAV and launch tube must be erected to the launch position. The ideal launch position would be eastward-facing, at 50 to 60 degrees elevation. The entry, descent, and landing systems allow landing within about a ten-kilometer ellipse of the target site. Since this landing ellipse does not allow pinpoint landing to a specific terrain, the erection system must be designed with an uncertainty of inclination in mind. We have assumed that we can select a landing site such that the inclination is no greater than 30 degrees, in an orientation that is not known a priori. Thus, rather than requiring either a strictly vertical orientation or an eastward-facing orientation, we have selected a design option that erects the launch tube to an orientation which is perpendicular to the lander platform. This guarantees an orientation that is within 30 degrees of vertical, with attitude control assigned to the MAV reaction control thrusters.

For the erection mechanism, three options were considered: springs, pneumatics, and motor-driven gears. Springs were attractive from a power conservation perspective, but were dismissed because of mass and the risk of premature release. Space flight history use of pneumatic mechanisms could not be identified, leading to concern for dryout and failure of the mechanisms when required – the MAV launch tube is to be erected between two weeks and six months after landing on Mars. Including the trans-Mars flight and the spacecraft integration process, this means that the mechanisms will be untouched for at least a year, in California and Florida conditions, in long-duration space conditions, and in Mars surface conditions.

The design option that was selected was a single-string, motor-driven device with a single gear mounted at the base of the launch tube, and a redundant motor. The dimensions are shown in Figure 5. This system requires 670 W to erect in six minutes. This single gear could place the launch tube in an attitude perpendicular to the lander surface. Strictly vertical orientation would require two degree-of-freedom gears to adjust the attitude in two dimensions, which would add mass to the erection subsystem.

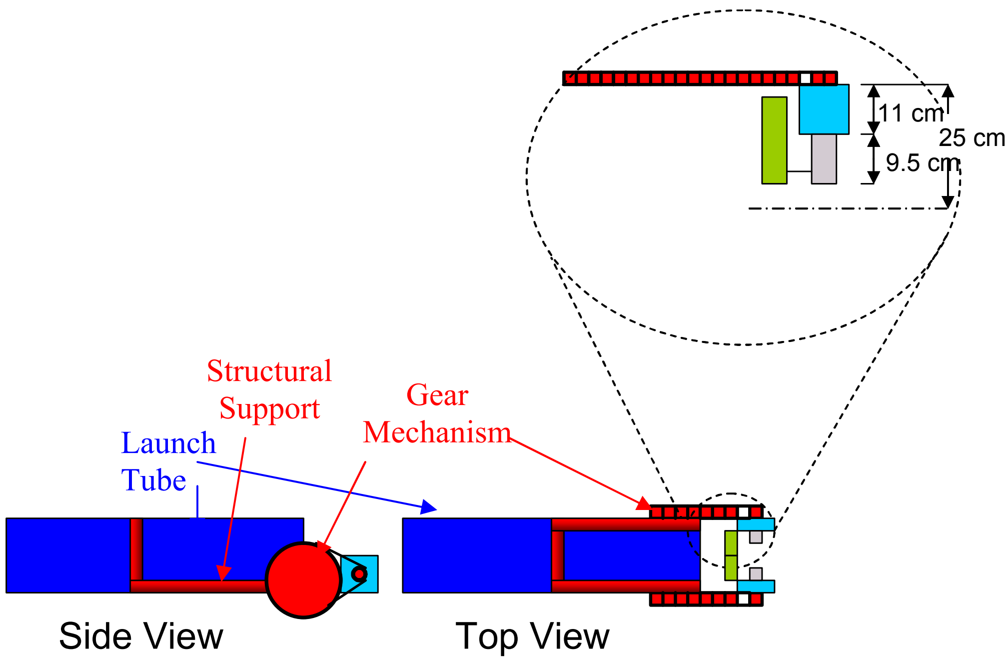

Figure 5 - Erection Gear Mechanism

6. Gas Ejection

The MAV is ejected out of the launch tube after it has been erected. If there are no scientific instruments on or near the lander, the MAV will likely be ignited within the launch tube. If there is instrumentation on the lander that should survive the exhaust from the MAV, then the MAV will be ejected out of the tube. This will be done by either a spring, a rapidly-pressurized canister such as an air bag, or by a pressurized gas. Pressurized gas ejection systems were selected for further study. With this concept, a pressurized gas canister resides in the base of the launch tube. When the MAV is ready for launch, a pyro latch is released, and the upper cap of the pressurized gas canister exerts force on the MAV, ejecting it from the launch tube. The higher the pressure and the more gas volume, the higher the MAV is ejected. Figure 6 shows the maximum altitude that a 250 kg MAV will reach before falling back under Martian gravity. The first stage rockets will ignite near the maximum altitude and the attitude control thrusters will orient the rocket. From Figure 6, we see that we can easily reach an altitude of 20-50 m with either helium or nitrogen gases at 1.3 to 4 MPa (200 to 600 psia) before ignition. This should protect the lander instruments from the blast of the rocket thrusters. Adiabatic expansion was allowed in these calculations until the gas cap reached 2.4 m from its initial position, i.e., the pressure was reduced at a rate inversely proportional to the expanded volume, and then the MAV was allowed to fall back under Mars gravity until it reached maximum altitude.

7. Launch Operations

When the OSC payload has been inserted into the payload section of the upper stage, the MAV is prepared for launch. The specific time of launch depends on several factors, including the Martian weather and the location of the Mars orbiting telecommunication satellites. Communications with Earth ground control will verify the flight readiness of the key MAV systems and their supporting systems, including the lander power and the satellite. Two conditions required before the launch tube is erected are a favorable forecast of Martian weather – daylight with minimal winds and minimal dust – and timing for the telecommunications satellite to be within range from the moment of launch until orbit insertion.

The launch tube is erected upon command from ground control. A single gear mechanism located on the lander surface near the aft end of the launch tube is used to raise the tube. It uses 670 Watts of electrical power from the lander to rise in six minutes. If lander power is a constraint, the power can be decreased by increasing the erection time. Erection is complete when the launch tube is perpendicular to the lander surface – this may be off-vertical by as much as 30 degrees, depending on the lander orientation with respect to the Martian surface.

The inertial measurement unit (IMU) is calibrated prior to launch, while the launch tube and MAV are in their launch orientation. The final launch command may be before erection or after IMU calibration is complete, depending partially on the power available for MAV heating. Heating requirements for the MAV are higher when the launch tube is vertical, due to increased thermal convection and higher exposure to wind. The round-trip communications time with ground control is at least ten minutes. Once erection is complete, the end cap of the gas canister is released by a pyrotechnic device, and the MAV is ejected from the launch tube by pressurized gas. The reaction control thrusters orient the roll, pitch, and yaw, and the first stage engine ignites once the MAV is at the required distance from the lander. This required distance has not yet been defined, since the lander instrument package (if any) has not yet been selected.

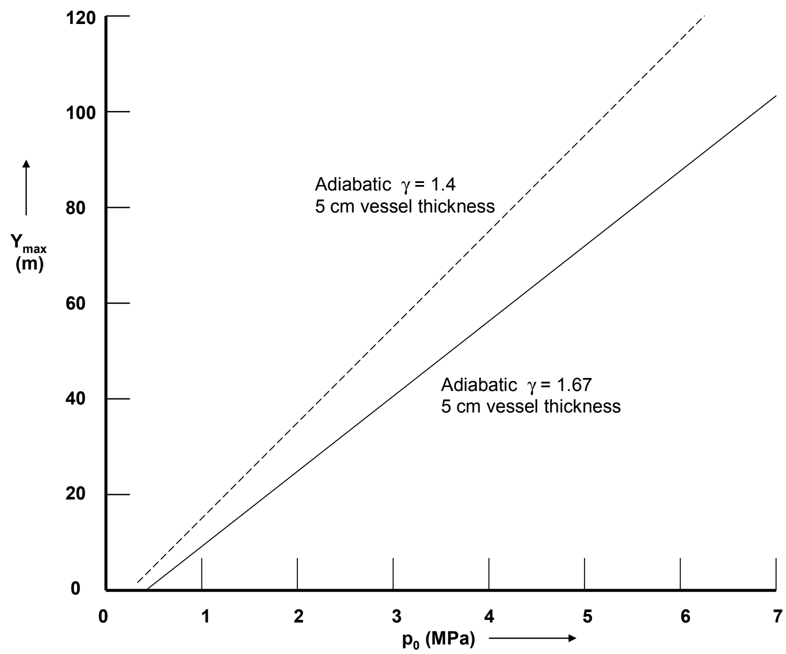

Figure 6 - Ejection Altitude vs. Gas Pressure

The complete ascent operations take about 700 seconds, from launch tube ejection until OSC release in Mars orbit. The timing requires direct communications with a telecommunications satellite throughout the launch operations, from verification of launch tube erection to OSC release. Telemetry is required, from a risk mitigation standpoint, to assist with orbit location determination of the OSC in the event it does not reach the expected altitude orbit, and in the event failure analysis is required.

8. KEY TECHNOLOGY CHALLENGES

There are a number of key technology challenges that will be addressed before actual flight certification. In general, current technologies allow solutions to these issues, at the expense of either increased mass or power requirements. Since mass, power, and reliability will be key factors in the design selection, the technologies should be raised to higher readiness levels, and a flight demonstration of a complete Mars Ascent Vehicle should be conducted under conditions relevant to the Martian environment.

- *MAV Mass Reduction* - There is a strong desire to keep the entry, descent, and landing (E-D-L) mass of the MSR mission to something no greater than that of the E-D-L mass of the MSL mission. Meeting this requirement would allow the use of the same parachute(s) design for both missions. This would be a major cost reduction for the MSR mission. Since the MSL mission does not utilize a MAV, much attention is being given to reducing the mass of the MAV system. The current configuration of the MAV contains the avionics section on the MAV second stage. This is driven by the requirement for telemetry coverage during mission critical events. The current avionic design is single fault tolerant for mission success. Going to a single string avionics design can significantly reduce launch mass because of the second stage sensitivity factor on overall launch mass. This change will be approached cautiously, especially if the MSR mission only has one MAV. **It should be remembered that all components of the MSR mission can be demonstrated on Mars precursor missions with the exception of the MAV.** Other avenues for mass reduction such as use of MEMS technology, higher performance solid propellants, composite propellant cases, etc. will be investigated in the near future.

- *Flight Engine Demonstration* – For risk mitigation, the MAV is expected to have a number of Earth test launches that represent many of the critical conditions expected during actual Martian conditions. Launch of the MAV from a high altitude balloon (higher than 20 km) will approximate the atmospheric dynamic pressure of Mars during a large portion of the flight time, especially during the critical events between the 1st and 2nd stage (1st stage burnout, separation, and 2nd stage ignition). This Earth altitude test will be an excellent test of vehicle dynamics and controllability. An altitude test will also replicate the trajectory /mission profile for a Mars launch for much of the ascent profile. By these tests, confidence in motor ignition and burns, vehicle controllability, separation events and event sequences, and telemetry acquisition can be acquired before the actual flight event at Mars.

- *Temperature Limits* – There are two principal temperature limits for the MAV and its subsystems. These are that the solid fuel must be maintained above -40°C, and that the RCS fuel tanks and thrusters must be maintained above 0°C. This imposes heating requirements during surface operations and pre-launch operations. Qualification testing will be required to verify that these are the correct temperatures, and that the respective subsystems can survive extended periods at these cold temperatures, and be ready for design operation when required.
- *Sample Insertion* – A sample insertion process was described in Section 4 above. This process should be validated under a range of operating conditions in a Mars-simulated environment. The test conditions should include the thermal and atmospheric conditions to be found on Mars, including wind and dust. Failure modes and effects analyses should be performed on the rover that delivers the OSC, the manipulator that retrieves the OSC, the transfer to the nose cone, the integration of the OSC into the payload integration interfaces, and the closing of the nose cone. It is likely that this process can be accomplished under teleoperated control from the ground, with pre-scripted commands and verification of each step.
- *Planetary Protection* – Both forward and back contamination issues need to be addressed with the complete Mars Sample Return mission. This is currently being addressed under a Focused Technology program.
- *Erection and Gas Ejection* – These are both well-established technologies. Launch tube erection should be analyzed for failure modes and risk assessment, and tested in a simulated Martian operating environment. Gas ejection is a common method of pre-ignition operations for missiles.

9. DESIGN TRADES

The Mars Sample Return mission is still in a pre-Phase A status, so design options and required technology development are still being examined. Each of the supporting subsystems described in the previous sections has been selected as the result of trade studies of design options based on available information at the time. Additional design trades are warranted in most cases, particularly when we focus on optimum system mass. Three key design trades that will enable system mass reduction include:

- Relocate launch tube further into the lander surface
- Shift pivot point for erection system
- Alternatives to sample insertion

Relocate Launch Tube – A key requirement on the MAV is that the solid rocket fuel must maintain temperature above -40°C. The power required to maintain this temperature during surface operations is 131 W of continuous electrical power, based on an assumption of radiation to the atmosphere at a temperature of -123°C, and a wind speed of up to 20 m/s. This can be significantly reduced by embedding the launch tube within the lander, i.e. placing it partially below the lander surface, rather than one meter above the surface. This reduces the convection losses due to wind. It should also reduce radiative losses, assuming that the lander itself is maintained at some temperature above the atmospheric temperature of -123°C. Saving thermal power reduces required MSR power system mass.

Shift Pivot Point for Erection System – The analysis of Section 5 was based on a gear mechanism at the aft end of the launch tube. Once again, this decision was based on an assumption that we could not cross the plane of the lander surface. If this is allowed, so the aft end of the launch tube can drop below the plane of the lander surface, the pivot point can be moved more toward the center of gravity of the launch tube with MAV. This would significantly lower the required torque, and therefore both the gear mass and the power required for erection.

Alternatives to Sample Insertion – A wide variety of options are available for both the manipulator that retrieves the OSC and the sample insertion device. For the insertion device, this includes the following:

1. *Open, hinged payload fairing*
2. *Payload fairing that extends longitudinally to allow sample insertion*
3. *Open launch tube end cap with hinged payload fairing*
4. *Open sidewall to the launch tube for sample insertion*
5. *Pivot-rotated payload fairing*
6. *Payload fairing carried aboard the rover*
7. *Payload fairing carried aboard the lander*

For the manipulator, the options include:

1. *One degree-of-freedom (DOF) manipulator on the lander with normal insertion*
2. *Dexterous manipulator on lander with normal insertion*
3. *One DOF manipulator on the lander with perpendicular insertion*
4. *Manipulator attached to the launch tube*
5. *Drop chute attached to the launch tube for the OSC to slide to payload insertion point*
6. *Dexterous manipulator attached to the rover*

A trade study was conducted on the pros and cons of each option, and the chosen concept was Insertion Device #7 with Manipulator Device #4, as discussed in Section 4. Placing the payload fairing aboard the lander allows flexibility in the sample insertion while minimizing requirements for the rover manipulator. The rover manipulator must simply place the OSC within reach of the manipulator attached to the launch tube. A single DOF manipulator on the launch tube removes requirements from the rover manipulator, and minimizes mechanisms risk.

OSC Source - One additional design trade that is currently being addressed is the source of the orbiting sample. Most of the ongoing MSR analyses have been based on the assumption that a capable rover is delivered to the Martian surface aboard the lander, and drives off the lander platform to search for and collect samples at a distance of 50 meters or more, up to several kilometers, from the lander. This rover then packs the samples into the orbiting sample container, and delivers the OSC to the manipulator arm of the MAV.

There are a number of alternatives that have been considered, to save both mass and funding. One concept is for the MSL to collect the samples for Earth return during its long-term, long-traverse surface mission. The MSL would then "cache" the samples, i.e., store them in a safe place near the future MSR landing site, for later retrieval. When the MSR then lands on Mars, either the MSL would deliver the samples to the MSR lander, or a mini-rover would be released from the lander and retrieve the already-stored samples. This option makes several assumptions that add risk to the program: the MSR will land within the rover range of the cache, or the MSL will still be operational when the MSR lands. Another alternative is that the MSR lander simply has a long manipulator arm that can reach the surface near the lander, and scrape surface materials from the immediate vicinity. This assumes that the materials of interest are accessible to the manipulator arm, and that the landing itself does not contaminate the materials collected.

10. SUMMARY

As the planet that is most similar to Earth in terms of climate, Mars holds a particular fascination to understanding the past – and potentially the future – development of Earth's geology and climate. A Mars Sample Return mission would allow scientists to analyze materials from known locations on Mars with the best instruments available on Earth. Such a mission would certainly expand our knowledge of Mars geology, climate, potential biology, and prepare us for later human exploration.

Key to a successful Mars Sample Return mission is the successful operation of the Mars Ascent Vehicle and its supporting subsystems. We have described the overall MAV system architecture and some of the key subsystems that support the MAV, including the launch tube, its thermal protection and its erection mechanism; the subsystems for retrieving the samples and integrating them into the payload integration location; and the gas ejection subsystem. Studies are underway to reduce the technology risk, the overall cost, and the mass of these systems.

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David Stephenson works at the Marshall Space Flight Center in Huntsville, Alabama, where he is a Project Manager in the Space Transportation Directorate.

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Current areas of research: Mars Exploration Concept studies and low cost launch vehicle technology development.

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