PROJECT MINERVA: A LOW-COST MANNED MARS MISSION BASED ON INDIGENOUS PROPELLANT PRODUCTION

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Abstract

Project Minerva is a low-cost manned Mars mission designed to deliver a crew of four to the Martian surface, using only two sets of two launches. Key concepts which make this mission realizable are the use of near-term technologies and *in-situ* propellant production, following the scenario originally proposed by R. Zubrin of Martin Marietta. The first set of launches delivers two unmanned payloads into Low Earth Orbit (LEO): one consists of an Earth Return Vehicle (ERV), a propellant production plant, and a set of robotic vehicles, and the second consists of the upper stage/trans-Mars injection (TMI) booster. In LEO, the two payloads are joined and inserted into a Mars transfer orbit. The landing on Mars is performed with the aid of multiple aerobraking maneuvers. On the Martian surface, the propellant production plant uses a Sabatier/electrolysis-type process to combine six tons of hydrogen brought from Earth with carbon dioxide from the Martian atmosphere to produce 100 tons of liquid oxygen and methane, which are later used as the propellants for the rover expeditions and the manned return journey of the ERV. Once the *in-situ* propellant production is completed, approximately two years after the first set of launches, the manned portion of the mission leaves Earth. This set of two launches is similar to that of the unmanned vehicles; the two payloads are the Manned Transfer Vehicle (MTV) and the upper stage/TMI booster. The MTV contains the manned rover and the habitat which houses the astronauts *enroute* to Mars and on the Martian surface. During the 180-day trip to Mars, artificial gravity is created by tethering the MTV to the TMI booster and inducing rotation. Upon arrival the MTV performs aerobraking maneuvers to land near the fully-fueled ERV, which will be used by the crew a year and a half later to return to Earth. The mission entails moderate travel times with relatively low-energy conjunction-class trajectories and allows ample time for scientific exploration. This set of missions can be repeated every two years in order to continue exploration at a variety of sites and gradually establish the infrastructure for a permanent base on Mars.

Introduction

For centuries humans have pondered the nature of Mars and developed many theories to support what was observed. Speculation on the presence and extent of life on Mars has long held the interest of both the scientific community and the general public. For the past 28 years Mars has been explored by unmanned space probes, beginning with the Mariner series in the late 1960's and followed in the mid-1970's by Viking I and Viking II. These missions have answered some of the questions surrounding Mars and have given rise to new ones. With the Mars Observer establishing the return to exploration of the red planet in 1993, Mars is currently receiving attention as a possible target for manned exploration in the early 21st century.

The National Space Council (NSC) has the responsibility of defining the future objectives of America's space program in what is known as the Space Exploration Initiative (SEI). NASA, the Department of Defense, and the Department of Energy are the primary participants that assist the NSC with forming the SEI, which includes a plan for the manned exploration of Mars. SEI's plans require in-orbit construction and multiple launches, and consequently would be extremely complex and costly. This is one reason why SEI did not receive any funding from Congress for fiscal year 1991, and why it continues to have difficulty in drawing support.[1] Therefore, an opportunity exists to develop a simple, low-cost alternative to SEI's present concept of placing humans on Mars for the purpose of effective exploration.

Such a mission has been suggested by R. Zubrin of Martin Marietta.[2,3] His so-called Mars-Direct Mission Architecture is based on the premises of using near-term technologies, going to Mars directly from Earth's surface on a conjunction class trajectory (thus circumventing in-space construction and dependence on Space Station Freedom), and manufacturing the propellant for the return journey on Mars from indigenous materials, i.e., the Martian atmosphere.

This year's Advanced Design Program at the University of Washington designed the Minerva manned mission to Mars, based on the Zubrin scenario and incorporating a number of new ideas. These range from the selection of the heavy lift vehicle and the design of the trans-Mars injection booster to the design of the manned habitat, the Mars rovers, and the Earth return vehicle.

The mission is undertaken in two main segments; in the first an unmanned spacecraft delivers a propellant production plant and the Earth Return Vehicle (ERV) to the surface of Mars. During the year and a half following the arrival of the unmanned spacecraft, the propellant production plant manufactures methane and oxygen by combining hydrogen brought from Earth with carbon dioxide from the Martian atmosphere, using a Sabatier-type chemical process complemented by water electrolysis. This process is very effective, converting only 6 tons of H_2 into 78 tons of O_2 and 22 tons of CH_4.

Once it has been confirmed that the necessary propellant for the return journey has been successfully produced and stored (about 2 years after the unmanned launch), the manned mission leaves Earth. To alleviate the problems of extended zero-gravity (~ 180 days) a 2.5 km tether is connected between the manned vehicle and its spent Trans Mars Injection (TMI) booster, and the two are spun at 1 RPM to produce artificial gravity. The capture of both the unmanned and manned vehicles at Mars is effected via aerobraking and a modest retro-rocket maneuver. Once on the surface, the crew of four astronauts uses CH_4-O_2 powered manned and unmanned rovers and a rocket propelled hopper to explore Mars.

One of the advantages of the Mars-direct scenario based on conjunction class trajectories is that the surface stay time on Mars is much longer than in the case of a high energy opposition class mission, i.e. ~ 1.5 years vs. ~35 days. Thus the astronauts will have ample time to carry out an in-depth exploration of a large area of the planet.

This summary report discusses the basic mission architecture and its major components, including the orbital analysis, the Unmanned Mars Transfer Vehicle (UMTV), the Manned Transfer Vehicle (MTV), Earth Return Vehicle (ERV), aerobrake design, life sciences, guidance, communications, power, propellant production, surface rovers, and Mars science. Also presented is an evaluation of the cost per mission over an assumed 8-year initiative. Although the scope of this report covers only the exploration of Mars, many of the same technologies and philosophies can apply to lunar and other planetary mission concepts.

Mission Scenario

The Mars mission model described here is arbitrarily based on an 8-year Mars exploration initiative, as shown in Fig. 1. The program consists of an unmanned mission to Mars followed two years later by simultaneous manned and unmanned missions. This launch procedure is then repeated every two years for a total of 8 years, ending with a manned mission to Mars in the eighth year. This model results in four manned and four unmanned missions to Mars.

Our proposed program will benefit by using a relatively small number of large, low-cost heavy lift launch vehicles (HLLV's). Although any HLLV capable of lifting at least 70,000 kg into LEO can be used, the single-stage-to-orbit (SSTO) vehicle Antares VII, which was developed during our 1991 design study,[4] has been chosen for the Minerva mission. The Antares system is a partially reusable, modular system based on a single unit vehicle. This unit uses a Dual Mixture Ratio Engine (DMRE), a new type of rocket engine studied by Pratt and Whitney specifically for SSTO applications.[5] The single Antares units can be clustered together to provide variable payloads to LEO, ranging from 10,000 kg to 70,000 kg, and beyond. Figure 2 shows the basic Antares I and the Antares VII vehicles with their standard payload fairings.

Project Minerva uses the Antares VII vehicle to place the Mars transfer vehicles (both manned and unmanned) and their TMI booster stages into orbit. No in-orbit assembly is required, other than the straightforward rendezvous, docking, and connection of the spacecraft and their TMI boosters.

All launches proceed from the Kennedy Space Center and insert their payloads into a 150 x 300 km elliptical orbit of 28.5° inclination. This orbit is then circularized to a 300 km parking orbit, where rendezvous and docking maneuvers occur. The program OPGUID, which was provided by NASA's Marshall Space Flight Center, was used to analyze all mission launches.

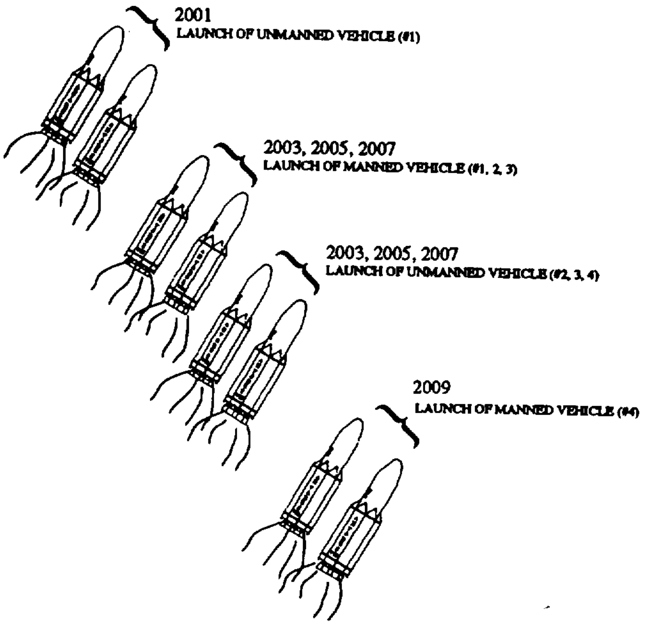

Fig. 1 Mission model

To boost each transfer vehicle to Mars, 105 metric tons* of propellant are required. Since the Antares VII has a payload of 70 tons, an upper stage is required to deliver the necessary propellant to LEO. This upper stage also doubles as a TMI booster (see Fig. 5). For the manned segment the spent TMI booster stage is used as a countermass for the rotating tether that supplies artificial gravity to the crew. The unmanned spacecraft simply discards the spent TMI booster once it is on its way to Mars.

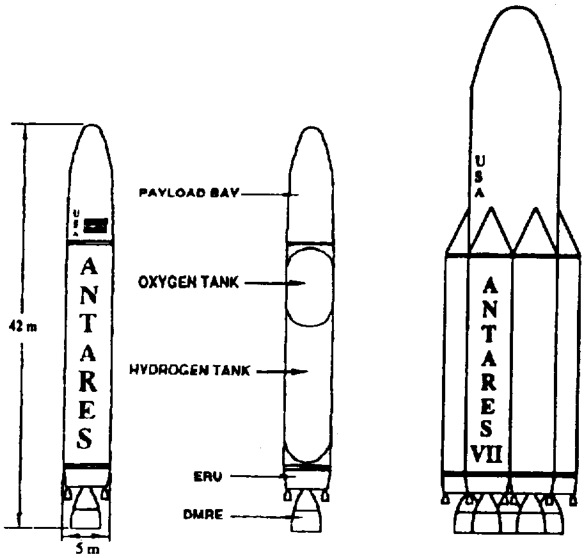

Fig. 2 Antares vehicle configurations

In both the unmanned and manned missions the TMI booster is placed into LEO first. The propellant tanks of the Antares VII vehicle are partially filled in order to allow it to lift off with its fully fueled 250 ton upper/TMI stage. At an altitude of 109 km the upper stage separates and delivers itself to a 300 km circular parking orbit with the 105 tons of propellant needed for the TMI burn. After the upper/TMI stage has been successfully delivered to LEO, the transfer vehicle is launched directly by an Antares VII operating as an SSTO vehicle. The two are joined using an Apollo-Soyuz type docking procedure and, after deployment of the aerobrake and a functionality test of all major systems, the journey to Mars is initiated.

The unmanned segment of the mission has the primary purpose of producing propellant for the manned return trip, and delivering the ERV. It also has the secondary purpose of deploying an unmanned rover to scout around for areas of interest, deploy scientific instruments for a variety of measurements, and collect Martian samples for later analysis.

After about 1.4 years, all of the propellant for the return trip will have been manufactured and stored on Mars in the ERV and the minimum energy window for the manned mission will be available. The manned mission is launched in the same manner as the unmanned mission. Since the

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*Henceforth, "ton" will be understood to mean metric ton.

astronauts would be appreciably weakened by a six-month stay in zero-gravity, artificial gravity at 0.4 g is generated by tethering the MTV to its spent TMI booster and rotating the assembly at 1 RPM.

Abort Capabilities

Abort capabilities are crucial for the manned mission. However, the direct to Mars mission architecture does not allow a return to Earth without the *in-situ* propellant manufactured using CO_2 from the Martian atmosphere.

If any system fails during or shortly after the TMI burn, the landing retro-rockets can be used to slow the MTV and place it in a highly elliptical, 300 km perigee orbit about Earth. Since the ΔV capability of the retrorockets is small, the window of opportunity to abort after the TMI burn is only about two hours. A short burn at first apogee decreases the perigee altitude to within the Earth's atmosphere, where the already deployed aerobrake is used to lower the apogee to LEO. A further maneuver circularizes the orbit at 300 km, where the astronauts wait until the Space Shuttle can rendezvous for rescue at a later time.

Astrodynamics

There are many factors that influence the type of transfer trajectory from LEO to low Mars orbit (LMO) and vice-versa. Some examples are the type of propulsion system used (chemical, nuclear, or electric), life support mass for the manned vehicle, sensitivity to radiation, tolerable solar flux, and desired stay time on the surface of Mars. Minimizing the required energy is an important factor in defining the capability of any mission. Energy savings ultimately result in a savings of propellant and an increase in payload capacity.

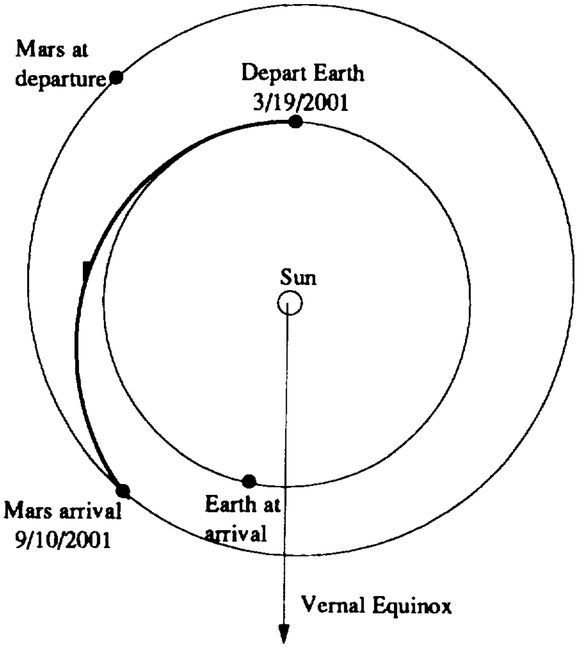
The first design consideration is opposition versus conjunction class missions. Although the quickest round-trip time to Mars would be an opposition class mission, there are many drawbacks to that type of trajectory. An opposition class mission is defined as a high energy trajectory in which the departure position of Earth and arrival position at Mars are on generally the same side of the sun. Because of the high energy involved, a very large mass of propellant is required. This class of mission would take approximately 1.6 years, with only 0.1 year on the Martian surface. In addition, it would require an extended period of time closer to the sun than Earth's orbit on the return journey.[2] The increased particle radiation levels at this distance from the sun would be hazardous to the astronauts and would require additional shielding. The solar heat load to the vehicle would also be very high. This type of mission also requires a high-energy aerocapture at Mars, submitting the astronauts to between 8 and 10 g of acceleration. It is for these reasons that a conjunction class mission was selected for Project Minerva.

Conjunction class missions are close to minimum energy transfers, in which the departure position of Earth and the arrival position of Mars are approximately on opposite sides of the sun. The total mission time using a conjunction class trajectory is approximately 2.6 years.[2] The risks involved are longer radiation exposure and an extended period of zero gravity for the astronauts. Solar radiation exposure will be limited, since the mission will remain outside the Earth's orbit at all times. In addition, the vehicle will rotate about a tether to provide the astronauts with artificial gravity.

The following windows, excess velocities, and energy values for manned and unmanned segments have been specified utilizing Jet Propulsion Laboratory data.[6] Two types of missions will be flown, an unmanned flight followed by a manned flight. The first unmanned mission will depart from Earth in 2001 and the first manned mission will depart in 2003, as shown in Figs. 3 and 4. The launch windows have been identified by the minimum departure energy limits. The departure energy, C_3, is equal to the square of the hyperbolic excess velocity. The first manned and unmanned flight windows are assumed to be limited by a maximum C_3 value of 10 km^2/s^2. For a near-minimum energy conjunction class mission, the launch window for the unmanned mission opens March 4, 2001 and closes April 2, 2001. For a minimum energy transfer, the unmanned departure date would occur March 19, 2001, with arrival at Mars on September 10, 2001. The arrival window at Mars is from August 18, 2001 to October 17, 2001. The maximum hyperbolic excess velocity for the given launch window is 6.3 km/s at Martian arrival and the corresponding maximum entrance velocity in the Martian atmosphere at 100 km altitude is 7.95 km/s.

The manned mission, as shown in Fig. 4, has a minimum departure C3 of 8.81 km^2/s^2. The launch window for Earth departure, limited by a maximum C3 value of 10 km^2/s^2, is from May 22, 2003 to June 22, 2003. The minimum C3 departure date from Earth is June 7, 2003 with a Mars arrival date of December 25, 2003. The Mars arrival window is from November 17, 2003 to January 27, 2004. The maximum arrival hyperbolic excess velocity for the given launch window is 3.6 km/s.[6]

The mission dates and Earth to Mars trajectory have been selected by performing trade studies between the energy of the transfer orbit and the stay time on Mars.[7] If minimum energies for arrival at Mars and departure to Earth are used, the manned vehicle will arrive at Mars on December 25, 2003 and the return trip will begin on June 28, 2005. This results in a total surface time of 1.44 years (526 days), which should be ample to complete a considerable amount of scientific experimentation and exploration. (The low energy windows for the conjunction class missions discussed above allow a range of 1.35 to 1.55 years (493 to 566 days) of surface stay time).



NOTE: planets' size not to scale

Fig. 3 Outbound unmanned transfer trajectory

The window for Mars departure with a maximum C3 of 14 km^2/s^2 is June 17, 2005 to July 9, 2005. For the return vehicle, the departure date from Mars for a minimum departure energy is June 28, 2005, with an Earth arrival date of January 6, 2006. The Earth arrival window is from December 28, 2005 to January 15, 2006.[8] The maximum Earth arrival hyperbolic excess velocity for the given launch window is 3.6 km/s. The capture at Earth will be similar to that used in the Apollo program, i.e., a ballistic reentry. The entrance velocity will be 11.6 km/s at an altitude of 100 km.[8]

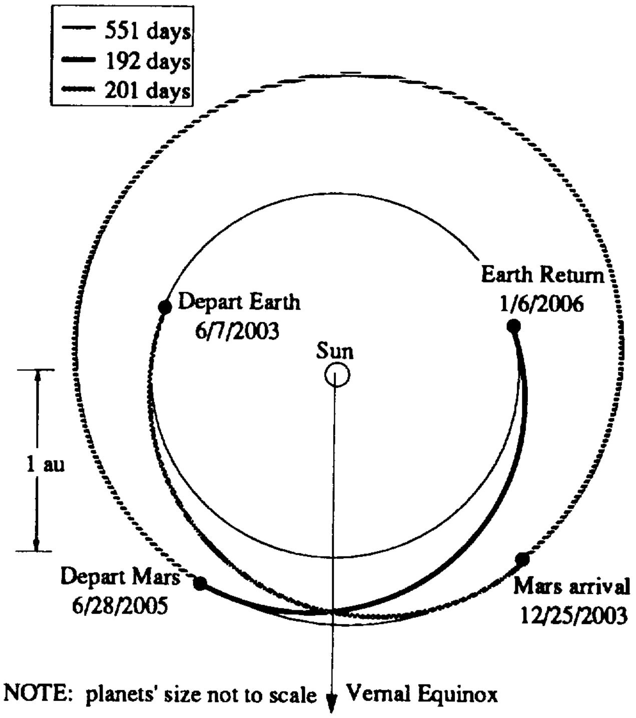


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Fig. 4 Manned mission transfer trajectories

Design Of Transfer Vehicles

Upper Stage/TMI Booster Vehicle

In addition to performing the burn to LEO, the upper stage also has the role of performing as the TMI booster (see Fig. 5). It carries 105 tons of propellant for the TMI burn. The upper stage also requires a propulsive system with a high thrust and high specific impulse. To allow for redundancy and eliminate the possibility of a single point failure, at least two engines need to be used. Pratt and Whitney's RL10-A4 and the Space Shuttle Main Engine

(SSME) were considered, but Japan's Mitsubishi LE-7 engine[9] was found to have the characteristics most desirable for this mission.

This engine is similar to the SSME but smaller, and is used as a first stage engine in the Japanese H-2 launch vehicle. The LE-7 operates on a staged combustion cycle and has a vacuum thrust of 1180 kN and vacuum specific impulse of 449 sec.[9] It burns liquid oxygen and liquid hydrogen at a ratio of 6:1. The LE-7 has already been designed, built, and tested, and is scheduled for first flight in 1993, after which it will become available in the U.S.

The upper stage/TMI booster has a diameter of 8.2 m and a length of 29.4 m. The payload fairing length of the Antares VII is increased by 5 m to accommodate this configuration. A docking mechanism is attached to the top of the TMI stage via a stub adapter.

An orbital maneuvering system (OMS) is used for the orbital circularization and rendezvous maneuvers. The OMS and reaction control systems are similar to those used on the Space Shuttle.

Unmanned Mars Transfer Vehicle

The mission requires that two types of vehicles be placed safely on the surface of Mars. The first vehicle sent is the unmanned Mars transfer vehicle (UMTV), shown in Fig. 6. The UMTV has a diameter of 9.1 m and a height of 32.0 m. At the base (in stowed position) the aerobrake is folded up against the vehicle with an effective diameter of 11.1 m. The vehicle consists of the ERV stage atop the UMTV descent stage. The ERV contains a habitat in which the astronauts live during the return trip to Earth. Centered in the middle of the ERV habitat is the Earth Re-entry Module (ERM). The astronauts and their payload re-enter the Earth's atmosphere in the ERM, while the ERV detaches and continues on its hyperbolic trajectory back out to deep space. Below the habitat are two hemispherical propellant tanks which will carry 96 tons of methane and oxygen that the propellant production unit will make on the Martian surface. The ERV sits atop the UMTV and has a height of 20 m, including its 5.5 m-long nose cone, and a diameter of 9.1 m. The ERV is attached to the UMTV by studs and pyrotechnic separation nuts so that the two vehicles can be separated just prior to launch of the ERV.

The payload bay comprises the main section of the UMTV, and houses the unmanned rover, science equipment, and propellant production unit. Shuttle-like tiles shield the latter from the ERV exhaust at the start of the return journey. Protecting the unit will enable it to be used in subsequent missions, should the need arise. The UMTV also carries eight tons of hydrogen, six for propellant production and two for descent maneuvers. The oxygen required for landing is contained in the ERV LOX tank and is piped to the two descent engines in the UMTV. Using this tank for both descent and take-off reduces the vehicle mass. Table 1 lists the mass breakdown of major unmanned system components.

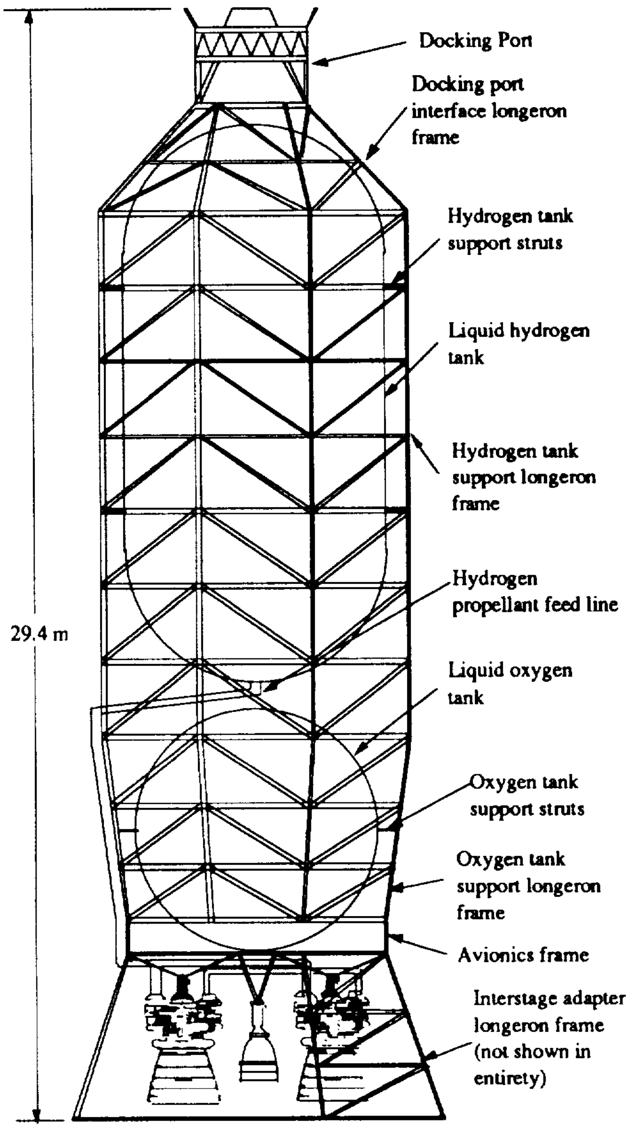


Fig. 5 Schematic of upper stage/TMI booster

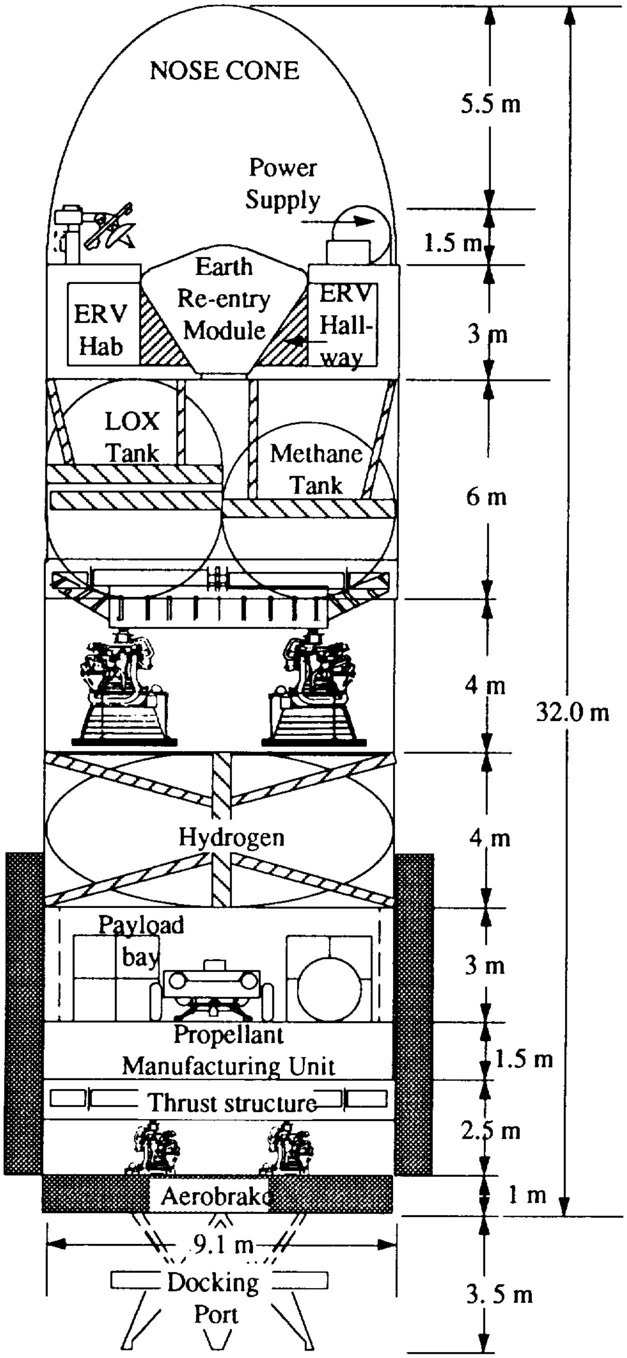


Fig. 6 Unmanned Mars transfer vehicle (UMTV)

Earth Re-entry Module

Re-entering the entire ERV into the Earth's atmosphere at the end of the mission would incur unacceptable mass penalties. This consequence led to the concept of using a smaller Earth re-entry module (ERM) just large enough for the astronauts and any returning Martian samples. The ERM is similar to the command module of the Apollo lunar missions; however, it is based on a Boeing design capable of returning four astronauts.[10] Prior to re-entry at Earth it separates from the ERV. Two small solid rockets located on the ERV provide sufficient ΔV to the ERV so that its trajectory does not overlap that of the ERM. After re-entering with the use of an ablator heat shield and deployable parachutes, the ERM splashes down for a water recovery. The ERV remains in a hyperbolic trajectory, continuing back out into deep space. (It is not desirable to have the ERV re-enter and break up in the atmosphere because of the danger of scattering plutonium from its dynamic isotope power system).

Table 1 Mass breakdown of unmanned transfer vehicle

SYSTEM COMPONENT	Mass (ton)
Earth Return Vehicle	18.0
Structure of Payload Bay and Engine Supports	10.0
Propellant for Landing (LH_2 & LOX)	10.0
Hydrogen Feed Stock	6.0
Propellant Tanks	3.0
Aerobrake	9.0
Power Supply	7.6
Propellant Manufacturing Unit	2.0
Retro-Rocket System for Martian Descent	0.7
Piping and Wiring	1.0
Reaction Control System	0.5
Unmanned Rover	1.0
Science Equipment	0.5
TOTAL	69.3

The ERM re-entry velocity is 11.6 km/sec and is comparable to that of the Apollo missions. It has a ballistic coefficient of $280\ \mathrm{kg/m^2}$, L/D of 0.5, and an angle of attack of 25 degrees. This type of design was chosen due to its cross range capability, simple structure, and reliable recovery method (water landing). The shield is made of a brazed stainless steel honeycomb and filled with an ablative type carbon-carbon composite.

Mars Descent and Earth Return Engines

The UMTV, as well as the MTV, use retrorockets for final descent after atmospheric entry at Mars. The engines required to successfully complete this part of the mission must be highly reliable. This requirement is satisfied by the Pratt and Whitney RL10A-4 engine, due to its simple cycle and conservative design. As for the reliability of the engine, "the RL10 has accumulated over 20 hours of operation in space; 174 engines have produced 282 in-space firings without a single engine failure, and the engine has demonstrated the highest reliability of any operational liquid rocket engine."[11] The two RL10A-4 engines used for the descent stage use LOX/LH_2 as propellant. These engines have a specific impulse of 449 sec, a thrust of 185 kN, and a mass of 167.8 kg each. In addition, the ERV uses four RL10A-4's modified to burn LOX/LCH_4 propellant, which incurs a reduction in specific impulse to 376 sec and an increase in engine mass to 363 kg.[11]

Manned Transfer Vehicle

The Manned Transfer Vehicle (Fig. 7) is similar to the UMTV, except that instead of an ERV there is the habitat which houses the astronauts enroute to Mars and on the Martian surface. In the MTV payload bay are carried the manned rover, more science equipment, and three more tons of hydrogen for additional propellant production on Mars. The manned vehicle has a height of 15.6 m and a diameter of 9.1 m (not including the aerobrake, which is similar to that of the UMTV). Table 2 shows the mass breakdown of the major system components.

Artificial gravity is provided during the manned voyage from Earth to Mars by tethering the MTV to the expended TMI booster in a "dumbbell" configuration, as shown in Fig. 8, using a 2.5 km tether made from Spectra 1000. The entire system is designed to rotate at one RPM which produces 0.4 g, approximately the same as the gravity on Mars. Without this artificial gravity, the crew would require significant recovery time upon arrival at Mars.

The habitat module and TMI booster are rigidly connected during the TMI burn. Immediately after this burn, the MTV separates from the spent TMI stage, rotates 180°, and attaches to the tether mechanism on the TMI stage. Subsequently, the tether is deployed using a tension control device to prevent tether snap oscillations. The reorientation of the MTV before deployment keeps the apparent artificial gravity force vector in the same direction as during engine firing and aerobraking.

Table 2 Mass breakdown of manned transfer vehicle

SYSTEM COMPONENT	Mass (ton)
Habitat	28.0
Structure of payload bay and engine supports	5.0
Propellant for landing	10.0
Propellant Tanks	3.5
Aerobrake	9.0
Power on Mars	2.0
Manned Rover	3.0
Science Equipment	1.5
Reaction Control System	0.5
Retro-Rocket System	0.7
Piping and Wiring	1.0
Tether	2.0
Hydrogen	3.0
TOTAL	**69.2**

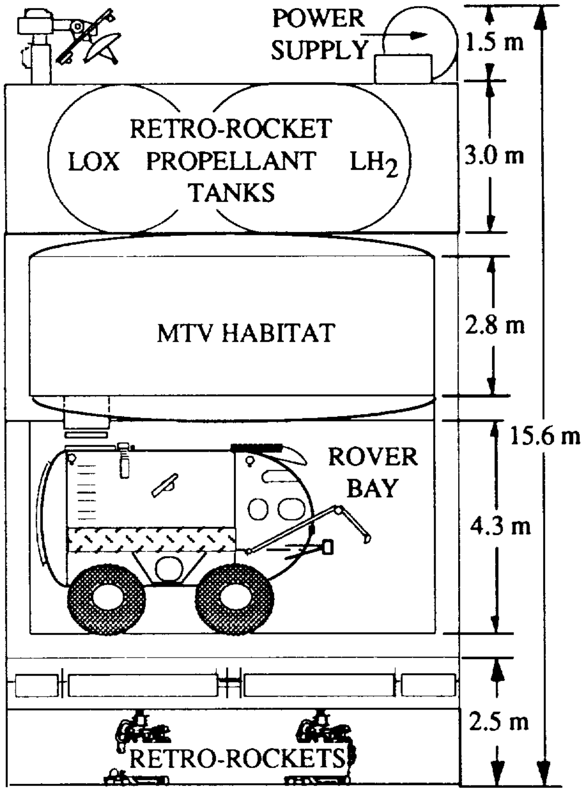


Fig. 7 Cutaway view of manned transfer vehicle

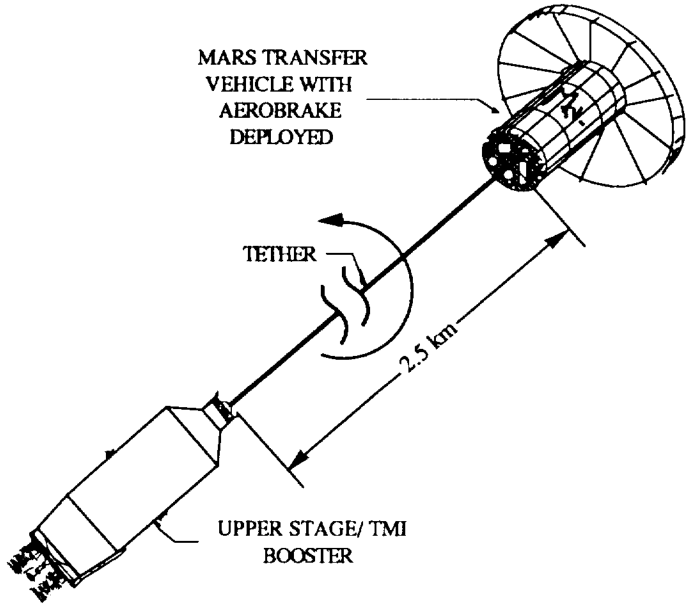


Fig. 8 Deployed tether

Prior to entry into Mars orbit, the tether and spent TMI booster are detached. A tether system is not used on the ERV for the return journey to Earth, since the crew will have plenty of time to recover from the effects of ~180 days of zero gravity once they are back on Earth.

Habitat

The MTV habitat is designed to shelter four astronauts on the two-year mission. This crew size was selected to provide the minimum psychological stress to individual crew members, while keeping life support requirements manageable and realizable. The MTV habitat provides the four astronauts with a safe, "shirt-sleeve" environment in which to live and work. In addition, all systems are closed and self-supporting (see Fig. 9). To these ends, it uses chemical regeneration systems instead of biological systems. Chemical systems have been proven reliable in the past and are well understood, whereas biological systems, although very promising, are not yet scaled for such long term missions.[12]

To protect the crew from harmful radiation and space debris, the MTV has galactic cosmic radiation and meteor shielding. Solar flare and radiation belt protection comes from a special water jacket that surrounds the airlock and can be filled when needed. Another consideration which influences the design of the MTV is the effect of zero gravity. Without artificial gravity the crew would require significant recovery time upon arrival at Mars. This concern led to the design of the tether system described earlier to provide artificial gravity at 0.4 g.

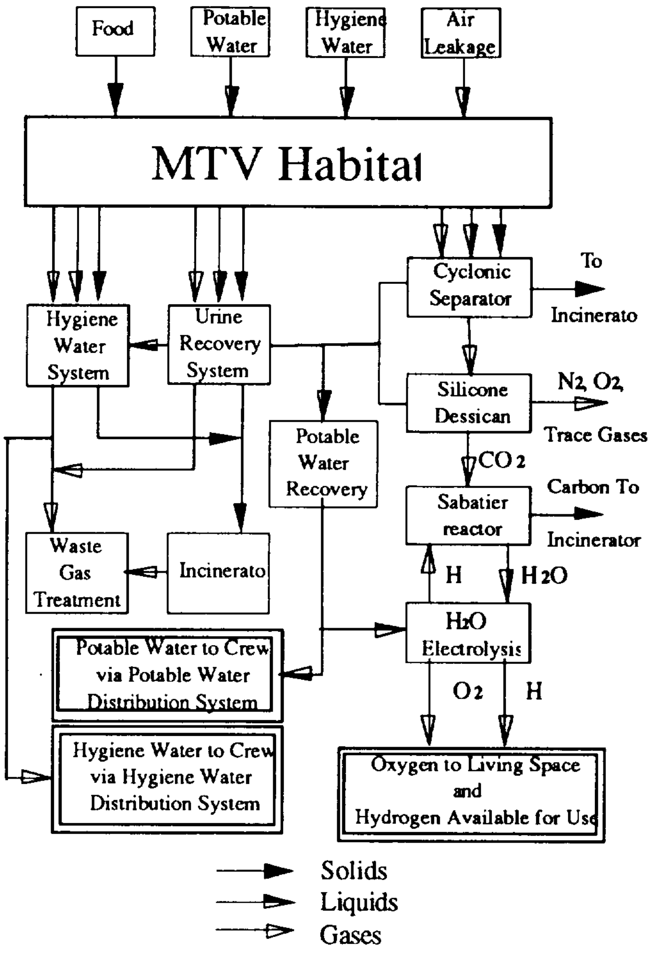


Fig. 9 Chemical regeneration system schematic

The habitat level on the MTV has a floor area of 51 m^2 and consists of eight rooms, as shown in Fig. 10. The MTV has one 3.51 m^2 stateroom for each member of the crew. The staterooms have a fold-out bed, desk and chair, storage space for personal items and clothing, and a small window. The bathroom is equal in size to a stateroom and houses the shower, toilet, and laundry equipment. The science room (11.4 m^2) is the main control center for the MTV and contains the analysis lab used to perform experiments. The airlock is where the astronauts will seek safety during solar particle events (SPE), in which case a

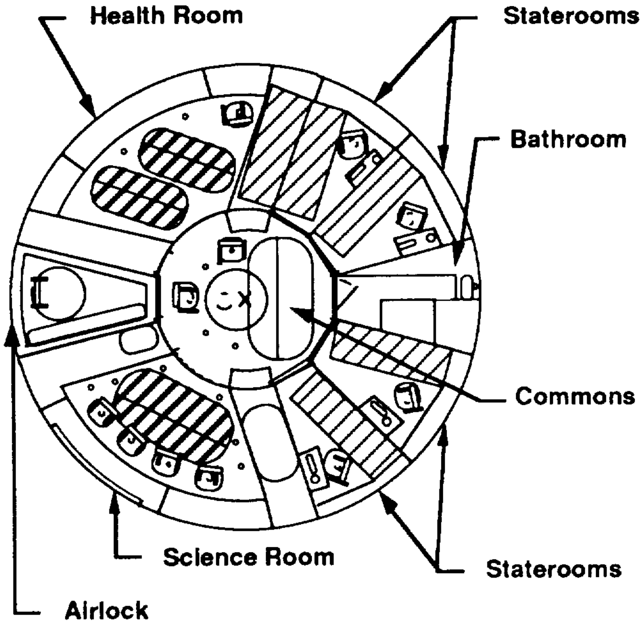


Fig. 10 Habitat floor plan

Once on Mars, the crew will use the airlock to enter the rover or payload bay (see Fig. 7). The airlock is the same size as a stateroom (3.51 m^2) and contains a three-day food supply for the crew during a SPE. The health room (11.4 m^2) will enable the astronauts to exercise, conduct biological and space-flight experiments, and use medical equipment and supplies. The commons area (7.68 m^2) is in the center of the MTV habitat level and contains the cooking facilities, the ship's library, and the table and chairs.

Aerobrake

The aerobrake is an integral part of both the manned and unmanned missions. The aerobrake geometry selected is a blunt body with low lift to drag (L/D) ratio. It serves to slow the incoming craft at Mars and ensure capture, and to provide thermal protection of the craft within its wake zone. The aerobrake is folded up like an umbrella around the TMI stage during launch from Earth (see Fig. 11). It is opened and locked firmly into place in LEO, before the journey to Mars is initiated.

The deployed aerobrake (Fig. 12) has a symmetric modified conical shape with a cone half-angle of 60°. The middle section is a spherical shape with a radius of curvature of 9.1 m. This aerobrake has a coefficient of drag of about 1.8 and a lift to drag ratio of approximately 0.5.

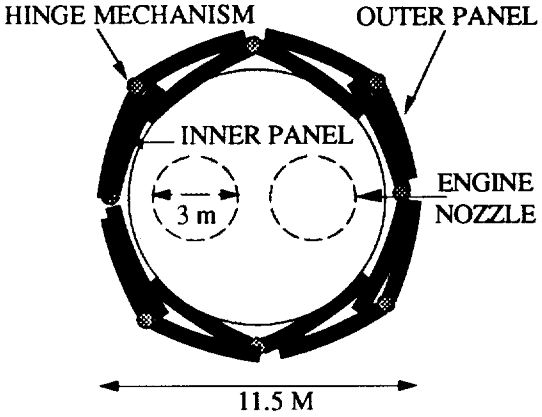


Fig. 11 Top view of aerobrake launch configuration

The cross-sectional diameter of the aerobrake is 22.5 m (with 6.7 m extended outward from the vehicle), providing a total cross-sectional area of 398 m^2. Protecting the entire vehicle by having it within the aerobrake's 25° wake angle would have required a much larger, extremely heavy aerobrake. Instead, protection outside the wake zone is provided by thermal tile shielding on the vehicle, as shown in Fig. 12.

Heat Shielding

For the unmanned mission a heating rate of approximately 35.2 W/cm^2 will exist at the stagnation point. The manned mission will have a heating rate of approximately 15.7 W/cm^2. To withstand these heating rates both missions will use AETB-8 (Alumina Enhanced Thermal Barrier)[13] which can withstand heat fluxes up to 53.4 W/cm^2. This material has a density of approximately 128 kg/m^3 and will result in a heat shielding mass of 1800 kg. The upper part of the vehicle not shielded by the aerobrake is protected by Shuttle tiles, as noted earlier.

Structure and Operation

The aerobrake is stored against the side of the spacecraft during Earth launch in a flower petal format. The aerobrake consists of eight identical "petals" that are folded around the transfer vehicle (see Fig. 11). Each petal has four main support struts, four radial ribs, and two sets of circumferential members to provide rigidity. In LEO the aerobrake is deployed by opening up the petals by means of the main support struts, fastening the petals together, and locking the support struts into place. The aerobrake doors for the retro-rocket engines, located at the bottom of the spacecraft, are then tested to ensure all systems are operating properly. A manual override system for the aerobrake doors is provided on the manned spacecraft in the event of mechanical failure. The aerobrake petals are discarded when the retro-rockets are fired at Mars and fall away from the vehicle. The main support struts are then lowered to provide landing legs for the vehicle.

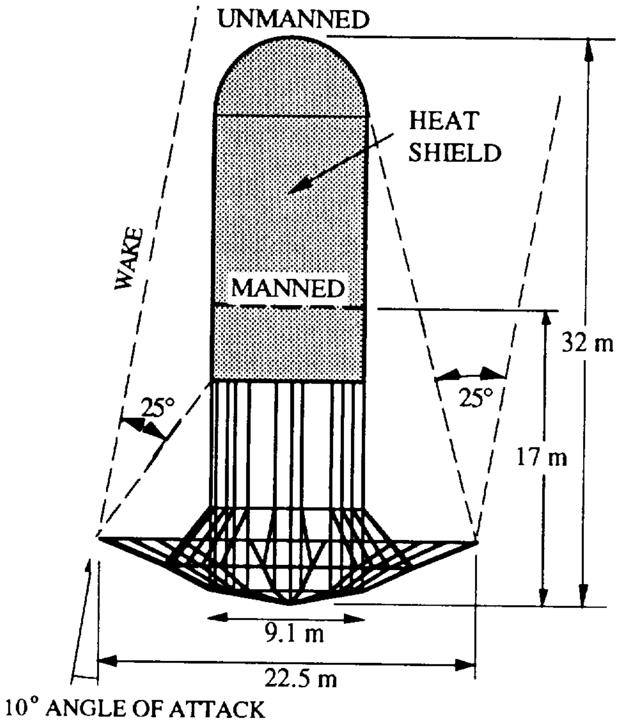


Fig. 12 Deployed aerobrake and transfer vehicle

The structural components of the aerobrake are made of Graphite/Epoxy (fiber volume of 55%) which has a density of 1490 kg/m^3. This composite has a very low coefficient of thermal expansion (-0.36×10^{-6} K^{-1}) which is necessary because the aerobrake experiences high heating rates. The aerobrake structure was designed to withstand 8.3 g deceleration. For minimal displacements, diameters of 20 cm for the main tubular support struts and 10 cm for the other structural elements are needed to provide adequate rigidity. A thin graphite/epoxy sheet attached to an aluminum honeycomb core covers the structural members of the aerobrake; to this is attached the heat shielding material. The overall mass of the aerobrake, including structure, heat shielding, and thermal tiles on the vehicle body, is approximately 9000 kg.

Aerocapture

Upon completing the transfer orbit to Mars, both the manned and unmanned missions will make a first close pass within the Martian atmosphere (at approximately 50 km and 45 km, respectively) to ensure aerocapture into a highly elliptical 24.6-hour, one-Martian-day orbit (MDO). The altitude for this first pass is determined by the hyperbolic excess velocity. The manned mission, with a lower hyperbolic excess velocity, needs to pass through less atmosphere than the higher energy unmanned mission. The corridor height, which is similarly defined by hyperbolic excess velocity, defines the acceptable margin of error in periapsis altitude for a given mission pass. The manned mission has a corridor height of approximately 55 km, whereas the unmanned mission has a 25 km corridor.[14]

After this initial aerobrake at a close altitude a small adjustment burn is made at apoapsis to raise the periapsis to 250 km. This one MDO matches the rotation period of the planet and has an apoapsis radius of 37,180 km (see Fig. 13). The MDO is not a necessity, but a precautionary measure to ensure that all equipment is functioning properly prior to descent and that the landing site is confirmed to be clear of dust storms and large boulders. It is unlikely that the aerobrake would suffer any atmospheric dust-related damage, even during the close first pass. Dust storm effects are believed to occur only at altitudes below 40 km, which is below the first pass altitude for both missions.[15]

Descent for both missions is initiated by a small impulsive retro-burn at apoapsis to reduce the periapsis altitude from 250 km to an altitude within the atmosphere again. Although both the manned and unmanned spacecraft could then descend directly to the Martian surface, they are placed into a second elliptical orbit in order to launch a small communications satellite into a Mars synchronous circular orbit at 20,406 km radius. This orbit allows communication between the habitat and the rover while on Mars. Insertion of the satellite into this orbit is accomplished by a small booster. After the satellite is deployed the spacecraft makes a final periapsis pass and descends at an angle of attack of 10° below the local horizontal.

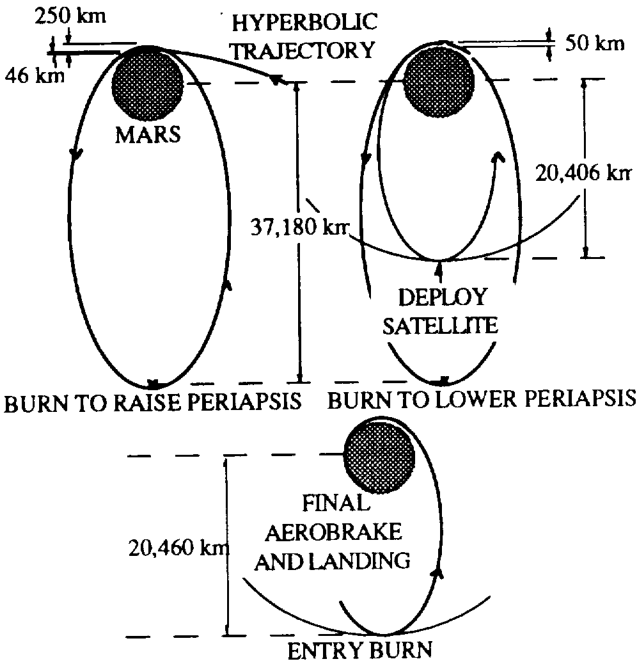


Fig. 13 Aerocapture and descent at Mars

Guidance, Communications, And Controls

The tasks of communication, navigation, guidance and control of a mission such as this encompass a wide range of requirements, constraints, objectives, and solutions, some of which are unique to this mission. One such requirement is the need for artificial gravity during the outbound leg of the manned mission. The solution, as already stated, is to tether the manned Mars transfer vehicle (MTV) to the spent TMI booster, and slowly spin the vehicles about the center of mass. Although this poses some difficulties, especially for the onboard navigation and control, it requires no new technologies. In fact, most of our objectives are achieved with existing off-the-shelf systems.

Landing Capabilities

The manned MTV must land relatively close to the previous unmanned landing site, where the fully fueled ERV is waiting. The MTV will be carrying a rover with a 500 km radius of operation or a one-way range of 1000 km that, if necessary, can transport the astronauts to the Earth return vehicle (ERV). A "homing" beacon at the unmanned site will help guide the MTV to the landing site. Control during entry is provided by attitude thrusters that adjust the angle of attack of the vehicle.

Communication

Guidance and navigation of both the outbound and return trips will be made possible with the use of the Deep Space Network (DSN)[16] and onboard guidance control systems that will work in conjunction with the DSN. The onboard system includes navigation devices such as Sun and star sensors, rate-integrating gyros for attitude determination, and computer systems that continually check and compare the trajectory of the vehicle against the desired trajectory.

The DSN will also form the backbone of our communication scheme. A high gain antenna will be in constant contact with the DSN, allowing communication and data transmission to occur at all times.

The small communication satellite, deployed at Mars during the aerobraking maneuver, will allow the habitat to communicate with the manned and unmanned rovers during excursions. It will also be used as an emergency communication link between the habitat and Earth during the periodic 12.5-hour blackouts that occur when the habitat is not in a direct line of sight with Earth.

Power Systems

The MTV and ERV power needs are supplied by Dynamic Isotope Power Systems (DIPS). Each DIPS system consists of a spherical plutonium dioxide ($^{238}PuO_2$) heat source surrounded by a tungsten gamma ray shield. The gamma ray shield is, in turn, surrounded by a lithium hydride neutron shield. Two Stirling engines are connected to the spherical (4π) heat source/radiation shield assembly by heat pipes. Waste heat is taken from the Stirling engines by a pumped loop heat exchange system which is connected to the spacecraft's heat pipe radiators, located on the outer cylindrical wall.

Heat is generated by the plutonium dioxide through radioactive decay. The harmful decay products are weak gamma rays and neutrons. The gamma rays are blocked by the thin layer of tungsten and the neutrons are blocked by the substantially thicker lithium hydride shield. Each DIPS is designed so that the crew will receive no more than 10 rems per year from the PuO_2 decay.[17]

Each DIPS has two Stirling engines for redundancy. Normally, the two Stirlings will run at 50% power, but in the event that one fails, the remaining Stirling engine can run at 100% power and supply the vehicle with the power it needs. Table 3 shows the characteristics of the 15 and 20 kWe DIPS for the manned and unmanned spacecraft, respectively.

Table 3 DIPS characteristics

	MTV	UMTV
Number of DIPS	1	3
Output Power per DIPS	15 kWe	20 kWe
Thermal Power (BOL)	54 kWt	108 kWt
Thermal Power (EOL)	50 kWt	100 kWt
Total Output Power	15 kWe	60 kWe
Total Thermal Power (BOL)	54 kWt	216 kWt
Total Thermal Power (EOL)	50 kWt	200 kWt
Operating Lifetime	10 years	10 years
Stirling Engines	2	6
Stirling Engine Efficiency	30%	30%
Mass per DIPS(kg)		
Shield and Heat Source Mass	1250	1550
Stirling Engines	240	320
Radiator Mass	300	400
Structural Mass	210	280
Total	2000	2550
Total Power System Mass	**2000**	**7650**

(BOL) - Beginning of Life
(EOL) - End Of Life

In-Situ Propellant Production

In-situ propellant production is used to produce the propellant needed for the ERV because of its huge mass savings. Taking hydrogen to Mars on the unmanned spacecraft allows all propellant for the return trip to be produced before the astronauts leave Earth. The ERV uses methane/LOX engines because of the ease in producing methane by combining hydrogen with the Martian atmosphere, which is mostly carbon dioxide (CO_2). The unmanned spacecraft carries the propellant production unit to make methane and oxygen at Mars. Table 4 shows the major characteristics of the propellant production system.

Methane and oxygen are produced by utilizing already proven technologies: an enhanced Sabatier type reaction and electrolysis (see Fig 14).[18] The Sabatier process produces methane by the reaction $CO_2+4H_2 \Rightarrow CH_4+2H_2O$. The electrolysis process produces oxygen by: $2H_2O \Rightarrow 2H_2+O_2$. The methane and oxygen are produced and then liquefied and pumped into storage tanks on the ERV.

Table 4 Propellant production characteristics

Total Propellant Produced	100 tons
Fuel (Methane)	22 tons
Oxidizer (Oxygen)	78 tons
ERV Mixture Ratio (mass ratio)	3.5:1
Production Time	550 days
Power Required	60 kWe
Initial H_2 Feed stock (from Earth)	6 tons
Propellant Plant Mass	1.5 tons

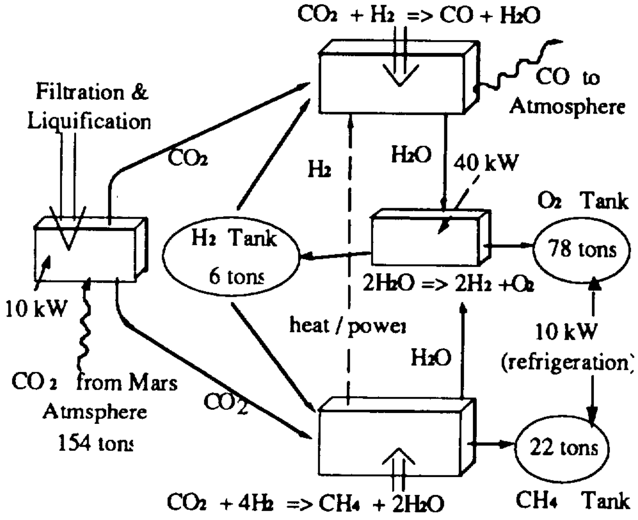


Fig. 14 Schematic of propellant production process

The propellant manufacturing unit is singly redundant. Two identical chemical plants will run at 50% capacity, but in the event that one fails, the remaining one will run at 100%, producing the propellant in the allotted time (before the manned mission leaves Earth).

All the propellant can be produced from a feed stock of 5.5 tons of H_2. Six tons are taken from Earth to account for boil-off during the Mars transfer. The manned mission will take three more tons of hydrogen for the production of propellant for the manned rover, which also runs on methane and oxygen.

Rovers And Robotics

On any mission aimed at the exploration of Mars, it is desirable to collect samples and conduct experiments at a wide variety of sites. To do this, Project Minerva has a group of four rovers designed to facilitate a detailed exploration of the Martian surface.

Unmanned Rover

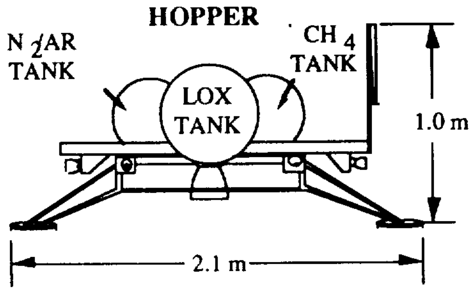
The unmanned rover (Fig. 15) has a mass of 1000 kg and is powered by a methane/oxygen internal combustion engine. Its dimensions are 3.5 m long, 2.5 m wide, and 1.5 m high, with a maximum ground clearance of 65 cm. The payload bed can be tilted fore and aft to facilitate loading and unloading of cargo. The rover has a maximum radius of exploration of 200 km. Before the manned spacecraft arrives, the rover will deploy seismic detectors and survey the Martian terrain. The unmanned rover will also have the task of transferring the extra hydrogen brought by the manned vehicle to the propellant manufacturing unit of the unmanned vehicle. This extra hydrogen is for manned and unmanned rover use during the 1.44 year stay time on Mars. Afterwards, the unmanned rover will primarily act as a "mother ship" for the hopper and minirover. It will be able to be teleoperated from both the manned rover and habitat.

Hopper

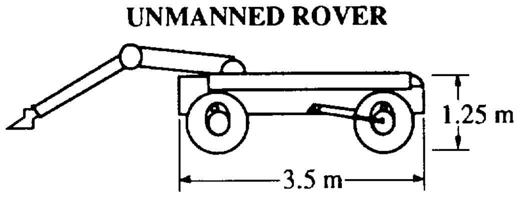
The hopper travels to inaccessible regions of Mars via ballistic trajectories and soft landings. The hopper has a dry mass of 250 kg and is powered by an 8000 N methane/oxygen, pressure-fed rocket engine. It has a nominal round trip range of 15 km. The hopper can accommodate the mini rover or a single bucket seat on its payload bed. This will allow the minirover or an astronaut to journey where the manned rover cannot. The dimensions of the hopper are 2.1 m long, 1.6 m wide, and 1.25 m high.

Manned Rover

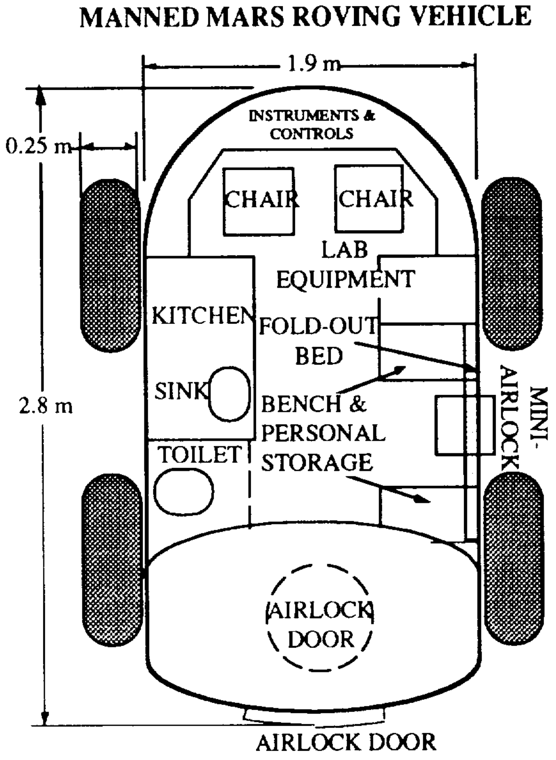
The manned rover (Fig. 15) is the prime instrument used in the exploration of the Martian surface. This rover is capable of taking core samples to a depth of 10 m, delivering scientific experiments, collecting samples, and performing limited sample analysis. Powered by a 35 kW methane/oxygen internal combustion engine, the rover has the capability of traversing 1000 km with a maximum radius of exploration of 500 km. The manned rover has a ground clearance of 1 m.



Range: 11km
Mass: 250 kg
Methane/Oxygen Engine
Specific Impulse: 370 sec
Thrust: 8000 N



Range: 400 km
Mass: 1000 kg
Ground Clearance: 0.65 m
Internal Combustion Engine
Fuel Methane/Oxygen
Speed: 8 km/hr



Range: 1000 km
Mass: 2250 kg
Ground Clearance: 0.5-1.0 m
Internal Combustion Engine
Fuel: Methane/Oxygen
Speed: 15 km/hr

Fig. 15 Overview of rovers and hopper

With a dry mass of only 2250 kg, the manned rover provides a versatile tool for the exploration of Mars. The shirt-sleeve environment of the rover can accommodate two astronauts for up to two weeks and has an emergency back-up capability of supporting all four astronauts for up to a week. An airlock located at the rear of the rover allows easy access to the MTV habitat, through the ceiling airlock door, and to the surface of Mars through the back airlock door. The manned rover stores its life support end products for processing and distillation at the habitat.

Mini Rover

The mini rover, which has a three-section articulated design,[7] has a mass of 50 kg, and is powered by rechargeable nickel hydride batteries, which give it a range of about 2 km, depending on the terrain. The dimensions are 1.5 m long, 1 m wide, and 0.8 m high. It has 6 conical shaped wheels, allowing a high level of mobility. It can be used to scout around the outside of the habitat, to piggyback aboard the unmanned rover for remote scouting, or as the primary payload of the hopper for reaching normally inaccessible areas of Mars.

Mars Science

While the overall mission rationale is to explore Mars, potential landing sites had to be determined and a scientific payload package put together. In late 1992, Mars Observer will begin its mission to further explore Mars robotically. Minerva will seek to increase the knowledge of Mars, as well as to provide manned exploration of the "Red Planet."

The ideal landing site was determined by the number of scientific questions that could be answered, the safety of landing, and the establishment of a site near the equator to facilitate an easier orbital insertion. The four sites considered were the Lunae Planum, the Mangala Vallis, the Chryse Planitia, and the Argyre Planitia regions (see Fig. 16).

The primary site is located on the southern edge of the Lunae Planum, so that the rovers can reach the Juventae Chasma and the Ophir Chasma, which are within the Vallis Marineris. Figure 17 shows the Lunae Planum ideal landing site. The area also offers possible river basins and cratered areas.[19] Goals relating to site selection are the determination of elemental composition, tectonic activity (past or present), geologic/morphologic studies, and exobiological analysis. The existence of carbonates would give evidence of past life and that liquid water once existed on Mars.

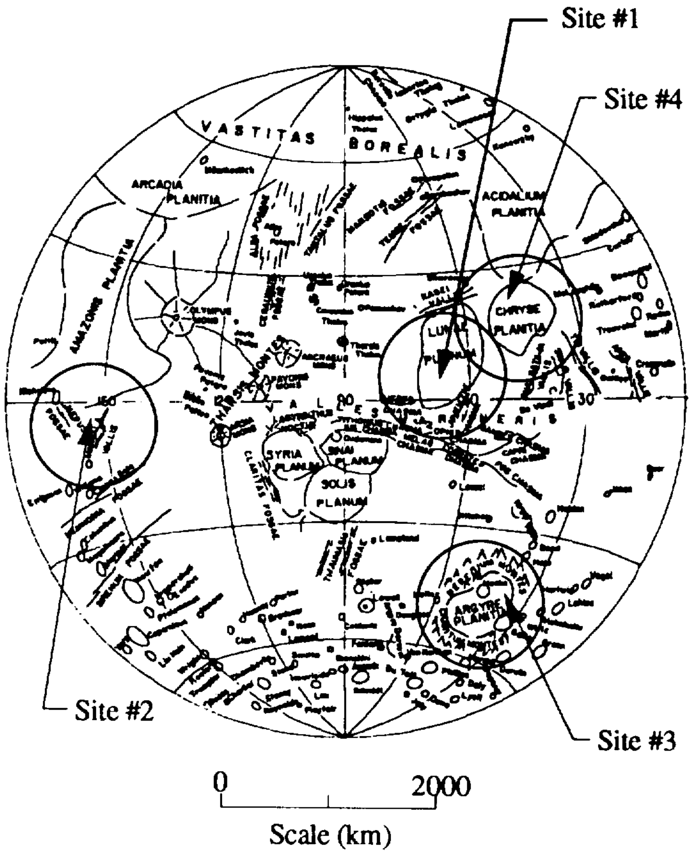


Fig. 16 Possible landing sites on Mars

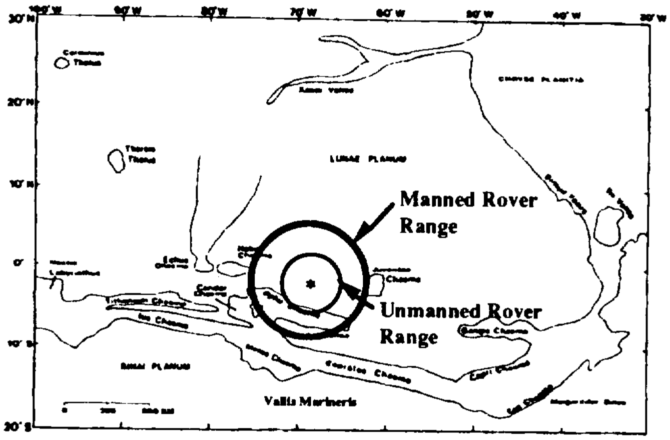


Fig. 17 Lunae Planum. Landing site is denoted by asterisk

The scientific package includes field equipment, exobiology and geoscience measuring instruments of various types, and sample collection containers for both field use and for possible Earth return.[20] Also included are astronomical instruments to be used during the space flight to Mars.

Economics

The mission model for the Minerva project is based on an assumed eight-year Mars exploration initiative. The eight-year initiative begins with an unmanned mission to Mars in 2001, followed two years later by a manned and an additional unmanned mission. This launch procedure is then repeated every two years for eight years, resulting in a total of four unmanned and four manned missions to Mars (see Fig. 1). This model is assumed to end after eight years for cost analysis purposes but could continue as long as desired.

The vehicle costs have been broken down into three categories: Research and Development (R&D), Production Costs, and Operations and Support (O&S). The vehicle costs are the costs necessary to produce the number of launch vehicles required. A cost was estimated for each of these categories on a per year basis, based on previous missions. The R&D costs were assumed to last for 28 years and the O&S costs were assumed to last for 18 years, while the production costs were calculated on a per vehicle basis. The total for the vehicle costs amounts to $12 billion (in 1992 dollars).

The unmanned mission costs were calculated by dividing the mission into different components and estimating the cost based on previous space systems. The unmanned mission also contains its own R&D and O&S costs. These costs are also assumed to last for 28 and 18 years respectively. A cost was then estimated for each of these categories and the amount was summed. The total for the unmanned mission vehicle costs amounts to $23.5 billion.

The manned mission costs were estimated based on the same method as the unmanned mission, allowing for differences in components. These costs were also assumed to last for 28 and 18 years, respectively. The total for the manned mission amounts to $20.5 billion.

By summing these costs we can come up with a total mission cost. The total cost for our eight year Mars Exploration Initiative is $56 billion (see Table 5). This cost is considerably lower than other manned Mars missions suggested by NSC.[21]

Table 5 Total mission cost in billions of dollars

	Vehicle	Unmanned	Manned	Total
Mission1	3	7	5.5	$15.5
Mission2	3	5.5	5	$13.5
Mission3	3	5.5	5	$13.5
Mission4	3	5.5	5	$13.5
Total	12	23.5	20.5	**$56**

Conclusion

Project Minerva is a viable and low-cost approach to the manned exploration of Mars. The mission architecture follows the proposal recently expounded by R. Zubrin of Martin Marietta for a class of Mars direct mission based on near term technologies and *in-situ* propellant production. The mission scenario that has been presented here involves an unmanned mission followed two years later by a manned mission. Both use the Antares VII heavy lift launch vehicle that was the subject of the 1991 University of Washington advanced design project.

The unmanned mission delivers a propellant production unit, six tons of liquid hydrogen feed stock, and an Earth return vehicle to Mars. The hydrogen is combined with carbon dioxide from the Martian atmosphere using a Sabatier and electrolysis process to produce a total of 100 tons of liquid methane and oxygen which are needed for the return journey to Earth and by the rovers. The manned mission carries with it a manned rover capable of exploring an area within a 500 km radius of the landing site. Both missions use low energy conjunction class trajectories to Mars. Artificial gravity at 0.4 g is provided for the manned spacecraft by connecting it to the spent trans-Mars injection booster with a 2.5 km long tether and rotating the system at 1 RPM. Both the unmanned and manned spacecraft make use of aerobraking maneuvers followed by retrorocket firing to effect a soft landing on Mars. The Lunae Planum area of Mars is proposed as an optimal landing site for maximum scientific return.

After a 1.44 year stay on the Martian surface, the crew returns to Earth aboard the fully fueled Earth Return Vehicle, again on a low energy trajectory, and re-enters the Earth's atmosphere six months later in an Apollo-like capsule. The total mission cost for an eight year program involving four unmanned and four manned flights is on the order of $56 billion.

Acknowledgments

The AA 420/421 class of 1992 completed this project with invaluable help from many sources. Most importantly, thanks go to Prof. Adam Bruckner and to Prof. Abraham Hertzberg for guidance and encouragement through the year, and to teaching assistant Hobie Anderson. We also wish to thank David Carlile, last year's teaching assistant, for his very helpful comments and suggestions. Project Minerva was put together by a class of 32 students over a six-month period. The entire class deserves recognition for the many hours and hard work that they put into this effort.

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