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MANNED MARS MISSION

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INTRODUCTION

Terrapin Technologies is pleased to propose a Manned Mars Mission (M^3) design study. The purpose of M^3 is to transport ten people and a habitat with all required support systems and supplies from low Earth orbit (LEO) to the surface of Mars and, after an eight-man surface expedition of three months, to return the personnel safely to LEO. The proposed hardware design is based on systems and components of demonstrated high capability and reliability. The mission design builds on past mission experience but incorporates innovative design approaches to achieve mission priorities. Those priorities, in decreasing order of importance, are safety, reliability, minimum personnel transfer time, minimum weight, and minimum cost. The design demonstrates the feasibility and flexibility of a waverider transfer module.

MISSION OVERVIEW

The M^3 begins with the departure of the Landing/Launch Vehicle Module (LLVM) from LEO on a transfer trajectory to Mars. The LLVM is comprised of three submodules: (1) the LLVM Departure/Return Stage, (2) the Lander/Launcher/Habitat Submodule, and (3) the Supply Stage (SS). The Departure/Return Stage provides propulsion and control for the burn out of LEO, as well as propulsion and control for primary burns to achieve a low Mars orbit (LMO) and propulsion and control for the burn to return the waverider to LEO. The Lander/Launcher/Habitat Submodule provides all life support, logistics, and equipment for the surface expedition as well as propulsion, thermal protection, parachute braking system, and control for descent to the Mars surface and propulsion and control for liftoff and rendezvous with the Departure/Return Stage in LMO. Finally, the SS carries supplies for the Waverider Orbital Personnel Module (WOPM) return to LEO.

Following departure of the LLVM from LEO and checkout of all systems in Mars orbit, the WOPM departs LEO for Venus. The WOPM is composed of two submodules: (1) the WOPM Departure Stage, which provides propulsion and control for the burn out at LEO and separates after that burn is complete, and (2) the waverider, which provides propulsion and control for transfer into LMO, thermal protection for an aeroassist maneuver in the Venus atmosphere, guidance for all phases of the mission, and accommodations for the ten passengers on both departure and return legs of the mission. After separation from the WOPM near Venus, the Departure Stage, with propulsion produced by a nuclear generator, will return autonomously to LEO to be reused for future missions. The LLVM Departure/Return Stage and the WOPM Departure Stage are of the same design, and, for generic discussions, will be referred to as "the booster."

After transferring from Venus to LMO, the WOPM performs an aerobrake maneuver and carries out a rendezvous with the LLVM, already in Mars parking orbit at 170 km. Systems are checked out, and the waverider, SS, and Return Stage, now docked together, are separated from the Lander/Launcher, which then descends to the martian surface with eight of the ten crewmembers. The other two crewmembers remain on board the waverider to monitor the habitat on Mars and maintain frequent communication with the ground stations on Earth. They will also be responsible for performing scientific experiments and transferring supplies for the return voyage from the SS portion of the LLVM.

After the three-month expedition is complete, the Liftoff Submodule rejoins the WOPM in LMO. Personnel transfer to the waverider, and the empty SS is jettisoned. This allows the WOPM to return to Earth without the added weight of the SS, thereby decreasing the necessary amount of return fuel. Finally, the WOPM departs for Earth with the Return Stage providing propulsion.

VEHICLE DESIGN AND FUNCTION

The LLVM is designed to carry all necessary supplies for the surface mission and return voyage since the crew would not have need of them until LMO is achieved. In addition, the thin, aerodynamic structure of a waverider of reasonable proportions is not capable of transporting such large volumes and still achieving the high values of L/D required for the Venus flyby portion of the mission.

As noted previously, the boosters for the WOPM and the LLVM are of identical design and will be recovered at the end of the mission.

The Launcher/Lander/Habitat is a blunt, lifting cone and thus provides a compact, efficient volume for the crew dwelling on the surface.

The WOPM is designed to carry the ten-person crew and all the supplies and equipment needed to reach LMO from LEO. When the Liftoff Subsystem returns to LMO for rendezvous, the WOPM must be capable of adjusting its trajectory to meet that of the Liftoff Module. Once the remaining crew reenters the waverider, it will dock with the booster portion of the LLVM in the proper configuration for the return trip.

TRAJECTORY

The trajectory of the waverider consists of leaving Earth orbit on an elliptical transfer orbit to Venus, performing an aero-gravity assist (AGA) maneuver at Venus, and then traveling to Mars on a new, elliptical orbit. After the three-month surface mission, the waverider is placed on an elliptical transfer orbit back to Earth, where a velocity increment is applied to slow the vehicle down and place it into orbit about the Earth.

The advantage of using the waverider for this application lies in the fact that it is a lifting body. A waverider is a vehicle built so that it can create a shock wave that does not separate from the leading edge. Because it "rides" on its own shock wave and avoids the usual pressure losses, the vehicle can achieve much better aerodynamic performance for a given high-speed condition.

Since its structure is tailored to "ride" the shock wave at a certain flight condition, the waverider can enter and fly through the planet's atmosphere without experiencing excessive velocity loss due to drag. Also, it can remain at a constant altitude during the atmospheric passage, thus allowing almost any desired angular deflection. Thus an AGA maneuver can be used to provide a high angular deflection about Venus with minimal loss in velocity.

Considering all the variables, the Earth-Venus-Mars trajectory was then determined by trial and error runs of a computer code. This trajectory allows the waverider to reach Mars in 135 days, with a required deflection angle of 82° through the atmosphere of Venus. An elliptical transfer orbit with a duration of 137 days was selected for the return trip to Earth. The manned mission totals only 362 days. This trajectory meets the requirements of the Request for Proposal, in that it provides the minimum time of flight to Mars within two years of the specified year, 2025. Table 1 describes the final trajectory for the entire mission of the waverider.

Table 1. Final Trajectory of Waverider

Launch Date	Planet	V_∞*	Bend angle
8/22/2026	Earth	6.6 km/sec	—
10/28/2026	Venus	16.0 km/sec	82°
1/02/2027	Mars	-13.2 km/sec†	—
4/02/2027	Mars	6.0 km/sec	—
8/17/2027	Earth	-5.0 km/sec†	—

*V_∞ is given as the relative velocity to the corresponding planet.
† The negative sign indicates the velocity is to be lost at the given planet.

The SS trajectory will consist of placing the vehicle on a Hohmann transfer orbit to Mars, where it will then be placed in a circular orbit about Mars and remain there until it docks with the waverider. The time of flight to Mars via a Hohmann transfer is 258 days.

The entry phase of the landing trajectory was chosen for moderate entry velocity and heating alleviation. A shallow flight path at entry is maintained to reduce heating and increase range to permit drag to reduce velocity. As a means of reducing propellant required for landing, parachutes will be deployed. The final profile chosen involves a moderate entry initiated from a 170-km circular parking orbit, entry velocity of 3.61 km/sec at 90 km, guidance for thermal control and velocity reduction from 90 km until conditions are reached to allow parachute deployment, three-stage parachute deployment beginning at Mach 2.6, and a final powered flight, hover/landing phase initiated at 0.5 km.

The Launcher Submodule is contained within the Launcher/Lander Module and provides the transfer from the martian surface to a parking orbit where it will rendezvous with the waverider to transfer personnel and scientific samples for the return to Earth. The final launch trajectory determined iteratively by computer requires a gravity turn of 200 sec after an initial period of 0.4°/sec constant turn rate to gain altitude.

WAVERIDER STRUCTURES AND MATERIALS

Design of the size and shape of the waverider was done by computer generation. A program written at the University of Maryland allows the user to input the expected flight conditions and desired physical characteristics (i.e., length, size constraints) for a vehicle and will output the size, shape, and aerodynamic characteristics of a corresponding waverider. In order to accomplish our trip in the shortest possible time, volume optimizing and designing for an L/D of at least 7 was found to produce the best final design. The final design for the waverider is shown in Fig. 1. The vehicle had a L/D of 6.89 and an internal volume of 5300 m^3.

The waverider will experience severe heating rates, temperatures, and structural loading when it passes through the atmospheres of Venus, Mars, and Earth. These will vary on different surfaces of the waverider, so different parts of the waverider are designed accordingly.

The upper surface of the waverider will experience relatively low temperatures, since it is parallel to the freestream air flow. It will be protected with a hot structure system.

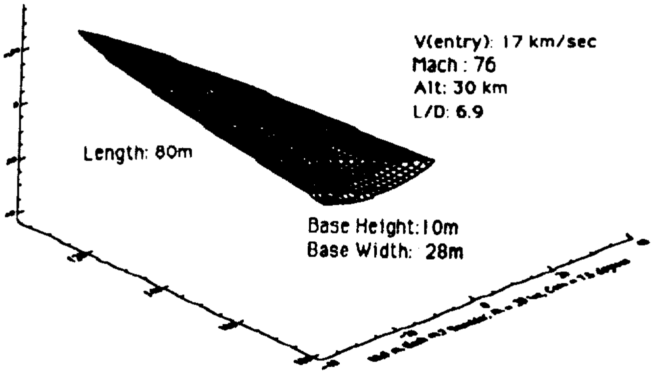

Fig. 1. Waverider Design

The lower surface of the waverider will experience different temperatures and heating rates at different locations. The inner part of the surface that experiences temperatures below 2500 K will be covered with a thermal protection system consisting of thermal tiles made of three-dimensional carbon-carbon composites, the structural material with the highest specific strength above 1200 K.

Since carbon-carbon can only withstand temperatures up to 2500 K, the area behind the nose and leading edges will need an active cooling system. The structure will consist of carbon-carbon composites surrounding refractory metal heat pipes. Liquid hydrogen will pass through these pipes, absorbing heat from the structure and carrying it to the rear where it can be expelled out of a nozzle to provide a propulsive thrust to help overcome some of the drag. To protect the structure during the encounter with Venus, 5000 kg of hydrogen will be needed and an additional 5000 kg will be needed for Mars. The hydrogen will be heated to a temperature of 1000 K and expelled through two nozzles at a mass flow rate of 13.89 kg/sec. This will provide an extra 75,000 N of thrust.

The nose and the leading edges of the waverider will experience heating rates of up to 33,500 W/cm^2. This corresponds to a temperature of 9000 K, the highest experienced anywhere on the vehicle. Carbon phenolic, the ablative material used on the Galileo probe, was selected to protect the vehicle because it can withstand temperatures over 11,000 K. During the martian encounter, the last of the ablative material will burn away, exposing the active cooling system. This will reduce the L/D ratio for the martian aerobraking, which will allow for a quicker reduction in speed.

The hot structure making up the upper surface of the waverider will have a mass of 19.6 kg/m^2. The thermal protection system and active cooling system on the lower surface will have a mass of 34.2 kg/m^2. The total structural mass of the waverider will be 93,050 kg.

WAVERIDER PROPULSION

In order to meet mission requirements, our propulsive system—embodied in a booster—can be used for both the SS and the waverider by changing the amount of fuel. Since the main showcase of this mission will be the use of the waverider, it is in this area that development costs will be the highest. To counterbalance this, our propulsion systems emphasize cost and development efficiency over risky technologies.

The propulsion requirements for this mission are primarily safety, reusability, and low development cost. Because we are using nuclear engines, it is extremely important that the mission be safe and successful for the future of space exploration.

Our final engine choice was a solid core nuclear rocket. The major safety hazard of this system is from radiation, which is easily shielded by use of a shadow shield—a barrier of shield material that is between the reactor and the endangered areas. The reactor will be of bimodal design, i.e., the engine generates electricity as well as thrust, but does not do so simultaneously. Such an output would require 3500 kg of helium. The specifications for the waverider booster are given in Table 2. The acronym NEBIT refers to Nuclear Engine Booster for Interplanetary Travel, and WR stands for the waverider.

Table 2. Waverider Booster Specificationss

Booster Length	40 m	Tank Length	30 m
Booster Width	22 m	Truss Length	35 m
Booster Mass (fueled)	556,440 kg	Miscellaneous Mass	15,000 kg
Fuel Mass (maximum)	426,440 kg	Reactor Mass	15,000 kg
Thrust	2,352,000 N	Tank Mass	20,000 kg
Specific Impulse	1,200 sec	Tank Diameter	8.7 m
Delta V (with WR)	10,523 m/s	Truss Diameter	4 m
Total Mass (NEBIT + WR)	856,440 kg		

A CerMet (ceramic metal) fuel element was selected for our reactor. The mass of the core, pressure vessel, and reflector will be approximately 20,000 kg. The specifications of the supply ship boosters are given in Table 3.

Table 3. Supply Ship Booster Specifications

Booster Length	40 m	Tank Length	30 m
Booster Width	35 m	Truss Length	35 m
Booster Mass (fueled)	1,032,880 kg	Miscellaneous Mass	15,000 kg
Fuel Mass (maximum)	852,880 kg	Reactor Mass	15,000 kg
Thrust	2,352,000 N	Tank Mass	20,000 kg
Specific Impulse	1,200 sec	Tank Diameter	8.7 m
Delta V (with SS)	5,621 m/sec	Truss Diameter	4 m
Total Mass (NEBIT + SS)	1,332,880 kg		

WAVERIDER LIFE SUPPORT

One of the major problems that the astronauts on the Mars mission will have to overcome is the effect that a zero-gravity environment will have on the human body. The effects of prolonged weightlessness on the human body include: decalcification of bones, shrinkage of the heart, decrease in blood volume, and loss of muscle mass.

As a solution to the problem, the crew will make use of both an exercise program (interactive) and an artificial gravity system (passive).

For the exercise program, each astronaut will be scheduled for up to 2 hr of strenuous exercise per day. The familiar treadmill and exercycle will appear on the ship, as well as fluid resistance workout machines.

For the artificial gravity system, the Terrapin Technologies gravity-bed system is being planned. This device is essentially a rotating disk to which the astronaut will be strapped while sleeping. An 8-hr sleep shift while strapped to the gravity bed will provide the needed stress on the bones. This stress will be an axial force acting primarily on the long, load-bearing members (arm, leg bones, and spine). In addition to the bones, the heart and other muscles will gain benefit from the pull of gravity. The primary design of the gravity bed calls for all parts to be made of aluminum.

Another of the major problems that will have to be dealt with is the exposure of the astronauts to radiation. This radiation will come from several sources: radiation from the nuclear engines on the ship, radiation from primary cosmic rays, and radiation from solar flares. This radiation could be of four main types: energetic protons, fast neutrons, X-rays, and gamma rays.

The fast neutron radiation from the nuclear engines on the ship is taken care of by means of a shadow shield discussed above. According to our radiation model, no additional shielding is required to protect the waverider crew from cosmic rays.

The problem of solar flares is slightly more complicated to deal with, since the only way to protect against these high-energy protons is to have a large amount of shielding. By orienting the waverider so that the reactor (with its own shielding) is between the sun and the astronauts, the amount of lead shielding needed to protect the astronauts would be reduced. A protective wall that the astronauts can hide behind during a solar flare was also designed.

SUPPLY STAGE STRUCTURES

The size of the SS was based on supply volumes and the need to accommodate the ascent/descent module. However, the SS was designed to be as low in volume and weight as possible to facilitate the transport from LEO to LMO and to minimize costs.

Since the SS must dock with the waverider in LMO, the configuration was developed in conjunction with the waverider and booster systems. The supply ship must be 25 to 30 m long. Since nothing large will be brought back from the surface of Mars, it is sufficient that the entrance/exit of the ascent/descent module be 2 m. The SS configuration is shown in Fig. 2.

LANDER/LAUNCHER STRUCTURES

During the planning phase of the landing segment of the mission, a decision was made to perform only one landing. This was based on the need to keep all the supplies centrally located on the planet surface. A low-mass structure is also desired since the lander must be transported to Mars. Since fuel requirements and overall cost increase with mass, lightweight, composite materials will be used.

Atmospheric entry at hypersonic speeds will produce high heating due to the viscous effects of atmospheric molecules interacting with the surface of the vehicle. An aeroshell similar to that used on the Viking spacecraft will be employed to protect the lander from the heat loads. Carbon-carbon composites will be used for the aeroshell, eliminating the need for an ablative material. The aeroshell will be designed as a lifting body that will decelerate the lander until parachutes can be used to further slow the descent.

A single atmospheric entry dictates the need for the lander to contain an ascent module as well as the supplies for the three-month stay and the necessary living and working space within the habitat. The fuel tanks for the ascent module are placed above the combustion chamber and nozzle. The design employs the ascent engine during the descent phase of the mission.

The ascent stage has a mass of 1150 kg. The radius of the module is 2.1 m. While the eight astronauts may be cramped, they will be able to fit into this module for the duration of its flights. The astronauts will lie on their backs such that they will radiate from the center of the craft like spokes on a wheel.

The lander vehicle will be utilized as the crew's living quarters for the three-month stay on the surface of Mars. The power system will consist of GaAs solar arrays during daylight hours in tandem with regenerative fuel cells and NiH_2 batteries

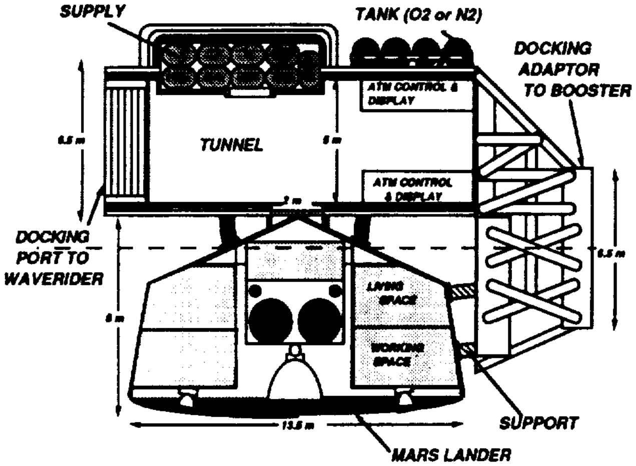

Fig. 2. Supply Vehicle Configuration, Cross-Sectional View

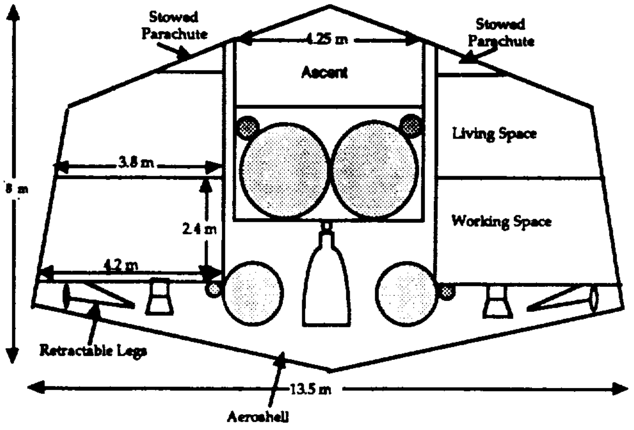

Fig. 3. Lander/Launcher Module, Cross-Sectional View

at night and during dust storm periods. The entire system will weigh 196.5 kg (Fig. 3).

LANDER/LAUNCHER PROPULSION

The primary design goal of the ascent and descent module propulsion systems is reliability. In propulsion systems, the pumps are the most common and likely failure. This weak link is eliminated by using a blowdown system.

The lander and ascent module will be aboard the supply ship for up to a year and a half before being used. Therefore, storable fuels like hydrazine or its derivatives [specifically a 50-50 mix of unsymmetrical dimethylhydrazine (UDMH) and hydrazine] are utilized. Because of its relatively high freezing point, the oxidizer tanks will have to be temperature controlled by a heater/thermal blanket. There will be three small descent engines as well as one large ascent/descent engine included in the configuration.

Since this engine is used for descent deceleration, some maneuvering to adjust the landing site is desirable. This requires variable thrust capabilities; therefore, thrusters are included in the design.

LANDER LIFE SUPPORT

Life support concerns for the Mars lander are simplified due to the 0.38-*g* martian environment. Even though the duration of the visit to the surface will be short, an emphasis on regenerative systems, particularly for water, is still critical. These and other requirements were considered in developing a life support system to accommodate the needs of the crew.

Two types of radiation are present on the surface of Mars: ultraviolet and ionizing. Since the astronauts will never be exposed directly to the atmosphere, ultraviolet radiation is not a major concern. However, ionizing radiation in the form of solar flares is a major problem. Equipment will be placed on the waverider to constantly monitor the sun to warn of threatening solar activity.

Mars has a weak electromagnetic field and a thin atmosphere, so most of the incident radiation due to a solar flare will arrive at the surface. Shielding to protect against solar flares would make the lander too heavy to fly (and land safely). The only reasonable solution seems to be to abort the mission in case of a solar flare that would affect the lander. The lander would boost to orbit and dock with the waverider, which would be in the safety configuration.

The lander will have two levels. The upper deck will be the private quarters and contain the bathroom; the lower deck will have work stations and the galley. The galley unit will contain a washer, dryer, microwave oven, sink, trash compactor, refrigerator, freezer, and storage space. This level will contain the airlock for outside excursions as well as work space, an exercise area, and storage space for the EVA suits. Total life-support weight for the lander and ascent modules is 3904 kg.

While on Mars, the astronauts will collect rock and soil samples from different depths to determine composition and water content. The trip to Mars will most likely be a precursor to a permanent base, and this mission will show how well people can adapt to the environment. Therefore, the need to assess resource potential is the most critical for this mission.

COMMUNICATIONS

Terp Tech's philosophy is to keep the ground crew in contact with the flight crew as long as possible. The LLVM will be directed by Mission Control and thus needs to be in contact with Earth at all times. Communications with the waverider will be lost during the AGA at Venus and during aerobraking at Mars.

LLVM

The LLVM must carry a sophisticated communications system. It will be used as a platform to do in-depth studies of martian geology, meteorology, and atmosphere to be transferred to Earth before the waverider arrives.

Waverider

Communications, the only link between crew and Earth, will be fundamental to completing the mission. Especially before the critical maneuvers, AGA and aerobrake, the crew will compare instrument readings with ground control. Lag time is a significant problem. The maximum lag time will be 20 min, but the combination of lag and AGA blackout time will result in longer periods without communication.

The M^3 system must be light, low in power consumption, able to handle large amounts of data, transmit with minimal error, and be reliable.

COST

Cost for the M^3 was estimated from costs for a Mars reference mission with similar hardware complexity (all costs in 1990 dollars). The waverider and hardware costs were determined by scaling the STS orbiter development cost by mass. Costs of the LLVM and the WOPM Departure Stage were determined by scaling costs from the reference mission by mass. The WOPM and LLVM would be launched into LEO by a large, expendable vehicle. The STS/Centaur G′ was selected as the most cost effective. In summary, the total program cost is $105 billion. This compares to $96 billion development cost for the Apollo program.

SUMMARY

In summary, Terrapin Technologies has met the requirements of the RFP, as demonstrated by the following key features of the proposed design:

Minimum time of crew flight. The waverider trajectory selected allows the crew to reach Mars in 135 days, 125 days earlier than the arrival time for a Hohmann trajectory.

Minimum cost. The boosters for both the LLVM and WOPM vehicles are of the same design, and both return to Earth so that they may be reused in future missions. The dual flight design, with the WOPM and LLVM flying separately to Mars, allows reduction in the size and volume of the more complex, manned waverider. Regenerative life support systems reduce the amount of life-support supplies needed on the mission.

Feasibility in the time scale proposed. The mission has been planned as if it were the *first* Manned Mars Mission. A nuclear engine will be proven technology in the early 21st century. Composites will be sufficiently advanced and affordable for these types of missions.

Journey compatible with humans. The guiding principle behind the entire mission design is the safety and comfort of the crew. Sleeping, eating, resting, and working habits of the crew were considered carefully. The design focuses on the facts that this is a manned mission and that it is crucial that the crew return safely.

Stretching the technology envelope. Terrapin Technologies has proven that a waverider can be built, flown, and equipped for a crew and that solid reactor rockets can be used to explore the inner solar system. With these two technologies, the exploration of the planets lies within our grasp.