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MARS TRANSPORTATION SYSTEM

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Abstract

The University of Minnesota Advanced Space Design Program has developed a sample Mars exploration scenario. The purpose of the design project is to enhance NASA and university interaction, to provide fresh ideas to NASA, and to provide real world design problems to engineering students. The Mars Transportation System in this paper is designed to transport a crew of six astronauts to the Martian surface and return them to Low Earth Orbit (LEO) starting in the year 2016. The proposed vehicle features such advanced technologies as nuclear propulsion, nuclear power generation, and aerobraking. Three missions are planned. Orbital trajectories are of the conjunction class with an inbound Venus swingby providing a 60-day surface stay at Mars and an average total trip time of 520 days.

Introduction

The vehicle and mission profile in this report are the result of a joint study by the University of Minnesota, the Universities Space Research Association (USRA) and the NASA/Marshall Space Flight Center (MSFC). The goal of the Advanced Space Design Program is to provide NASA with fresh ideas and to provide engineering students with real world design problems. Each year schools involved with the program take on a new project and work with a mentor NASA center. This report is a summary of the conceptual design of a Mars Transportation System developed as part of the senior design curricula at the University of Minnesota.

The following mission requirements and assumptions were given to the design class.

Mission Requirements

1) Three missions to Mars will be planned starting in 2016.
2) The astronauts will remain on the surface for 30-100 days.
3) Landing sites will be selected for scientific interest and will include polar, volcanic, and canyon regions.
4) Artificial gravity will be provided for at least the outbound portion of the mission.
5) The above objectives will be accomplished in a cost effective manner with acceptable levels of safety.

Mission Assumptions

1) The surface of Mars has been accurately mapped.
2) A satellite system for navigation and communication is in place around Mars.
3) Nuclear propulsion and aerobraking are mature technologies.
4) A Heavy Lift Launch Vehicle (HLLV) system is operational.
5) Space Station Freedom is operational.
6) A minimal lunar base is operational.

Students were organized into ten disciplines: Systems Layout, Mission Operations, Structures, Aerodynamic Analysis, Crew Systems, Thermal Analysis, Orbital Mechanics, Avionics/Power, and Earth-to-Orbit (ETO)/Orbital Assembly. An iterative design process was used to define detailed design requirements, conduct trade studies, select a baseline configuration, and optimize the conceptual design. A student systems integrator conducted all interdisciplinary meetings and assigned/tracked action items. A Configuration Control Board (CCB) consisting of discipline group leaders selected the vehicle(s) configuration.

Mars Transportation System

The Mars Transportation System (MTS) is illustrated in Figure 1 and consists of eight major components: the Mars Transfer Vehicle Habitation Module (MTV HAB), the propulsion system and fuel tanks, the biconic lander, the Earth return aeroshell, the Mars ascent/descent vehicle, Mars aeroshell, a communication and navigation array, and a central truss which serves as a common mounting bus for all of the other sub-components. Masses of the major components are presented in Table 1.

Component	Mass(mT)
Truss	15.7
Biconic	143.4
Aeroshell(Earth)	12.5
MTV HAB	63.9
Ascent/descent vehicle	26.9
Engines, fuel tanks, and RCS	57.0
Aeroshell(Mars)	39.7
Total(dry)	359.1
Propellant	705.2
Total (with 15% contingency)	1118.2

Table 1 MTS Vehicle mass breakdown

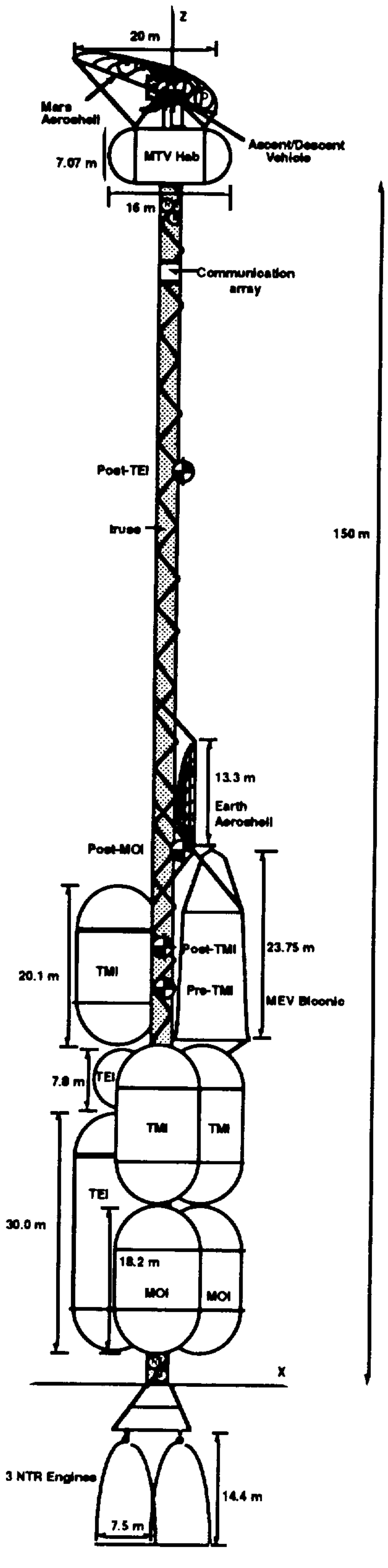


Fig. 1 Mars Transportation System

Each of these components will be discussed in detail in the following presentation.

Truss

The spine of the MTS system is the common mounting bus provided by a central truss and thrust structure. The truss is 150 meters long with a 3-meter equilateral triangle cross section. The truss members are constructed of boron-aluminum metal-matrix composite (MMC) and typically have outside diameters of 13 cm and wall thicknesses of 2 mm.

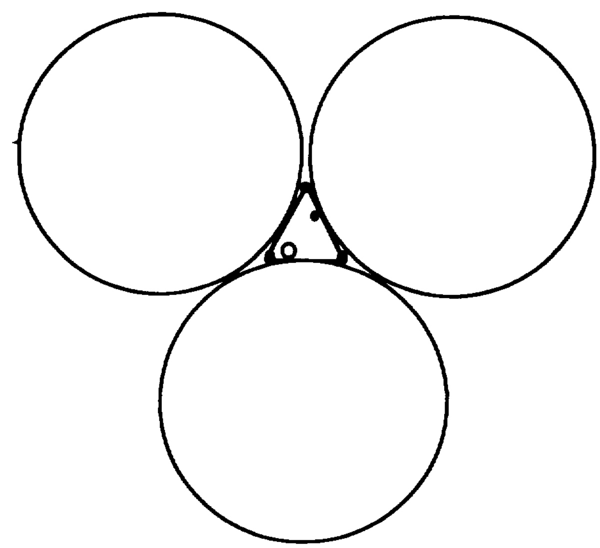


Fig. 2 Cross-section of truss with fuel tanks attached

The decision for selecting a central truss mounting structure was the result of the design requirement for artificial gravity. It was decided that the dynamics of tether systems are too unreliable, leaving the truss as the only practical option.

The truss also serves the secondary purpose of separating the habitation area from the radiation generated by the Nuclear Thermal Rockets (NTRs) and the Dynamic Isotope Power System (DIPS). In addition to the distance to reduce the radiation exposure, a blast shield is designed on the end of the truss to provide additional protection. A final line of defense to protect the crew from radiation generated by the NTR engines and DIPS power system is provided by positioning the fuel tanks along the truss between the radiation source and habitation module. Figure 2 is a cross-section of the MTV which shows how the fuel tanks are attached to the truss and the location of power trunks, communication/control lines, and fuel lines within the truss.

Finite element modeling of the truss has shown that it has excellent static and dynamic performance criteria. Under full thrust the truss should compress only 7 cm and when rotating at a rate sufficient to generate 1 g of simulated gravity on the Trans Mars Injection (TMI) coast, it should only stretch 25 cm. The safety factors for this design are 1.3 for tension and 65.5 in compression. To prevent harmonic resonances from shaking the truss apart, a series of accelerometers and Reaction Control System (RCS) pods are used to identify and counteract these resonance frequencies before their amplitude grows to a dangerous level.

The truss is constructed in Low Earth Orbit (LEO) by assembling 5 prefabricated bays of 30 meters length each.

MTV HAB

While in space the crew will reside in the MTV HAB. Dimensions of the module are presented in Figures 3 and 4. This single pressure vessel is designed to provide life support for a crew of six for 550 days. The habitat module consists of four main areas: living areas, science or work areas, a storm shelter, and an airlock. These areas are arranged so as to minimize the noise created by work, training, or exercise activities in the living areas.

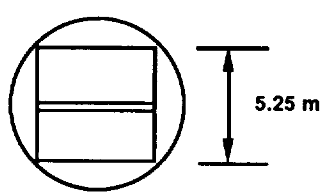


Fig. 3 Cross-section of MTV HAB

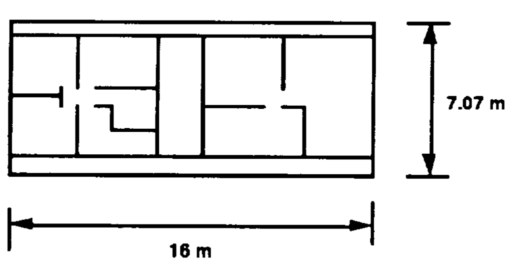


Fig. 4 Floorplan of top level in MTV HAB

After Mars Orbit Injection (MOI) the crew transfers from the MTV HAB into the descent module. Upon arrival on the Martian surface the crew lives in the habitat provided in the biconic lander. If at any time the surface habitat should become unable to support the crew members they will return to orbit and carry out studies from orbit within the MTV. Sufficient consumables and Environmental Control and Life Support System (ECLSS) redundancy allow the crew to spend the entire 520 days in the MTV HAB if necessary.

The proposed ECLSS system for the MTV HAB is a partially closed loop which reuses only non-potable water. This greatly increases the safety factor of the mission as the crew will not rely on the reuse of its primary water supply for life. A complete backup system is provided in the HAB in case of partial or total failure of the primary ECLSS system.

Biconic Mars Excursion Vehicle

Because the wake area behind the largest single element aeroshell is insufficient to contain all of the equipment that needs to go to the surface of Mars, an unmanned biconic lander is designed to carry the rovers, the Mars Habitation Module (MHM), and all other surface equipment. The external shape of the biconic lander is presented in Figure 5. The higher g-loadings and harder landing makes it an unacceptable vehicle for the crew transfer.

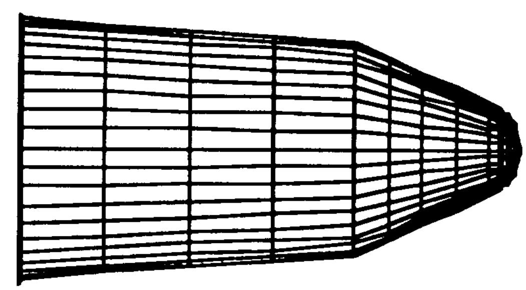


Fig. 5 45° Flared Biconic aerodynamic model

Once on the surface, the crew traverses across the Martian landscape to reach the biconic. A sophisticated navigation system should keep this distance very small, approximately 0.5 km.

On the surface, the crew resides in the MHM, significantly smaller than the MTV HAB, but able to provide all life support functions for a surface stay of 60 days. Figure 6 shows a vertical cross-section of the lander. Power is provided by a DIPS power system, which is deployed away from the MHM to reduce the crew's exposure to radiation, and which remains active after the crew departs to provide power for the rechargeable robotic rover and the transmitters onboard the biconic.

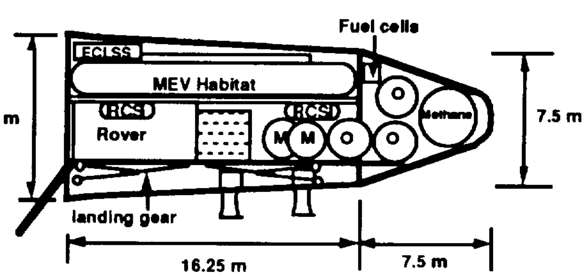


Fig. 6 Schematic of Biconic lander

The biconic lander features an advanced thermal protection system based on the one currently used by the space shuttle. A cross-section of the thermal protection system is shown in Figure 7. The most significant change is the addition of a ZrB_2 coating to the outer skin of the tile to provide increased heat resistance.

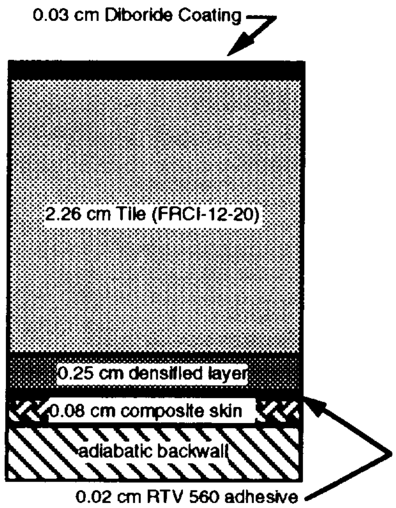


Fig. 7 Advance Thermal Protection System tile

Aeroshell-Assisted Mars Ascent/Descent Vehicle

The Aeroshell-Assisted Mars Ascent/Descent Vehicle is illustrated in Figures 8 and 9. This vehicle provides an accurate lander which transports the crew to and from the surface of Mars. The ascent vehicle is a secondary stage which is placed on top of the landing gear of the descent stage. Like the lunar excursion modules from the Apollo program, the descent stage remains on the surface to act as a launch platform for the ascent stage.

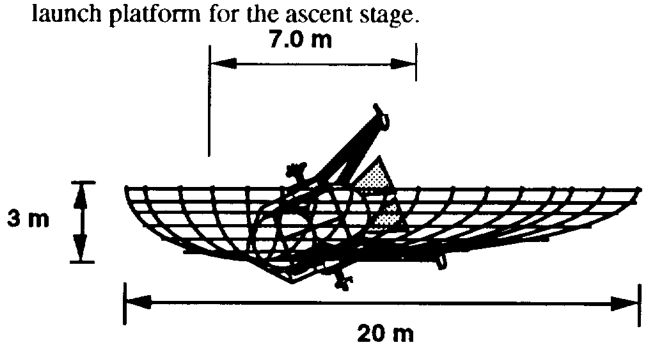


Fig. 8 Ascent /descent vehicle nested in Mars aeroshell

Once the ascent stage has returned the crew and the 2 mT of soil samples to low Martian orbit, it maneuvers the crew back to the MTV and docks with the airlock. This must be

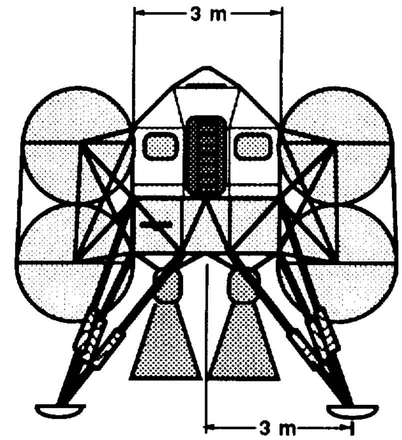


Fig. 9 a. Front view of ascent/descent vehicle

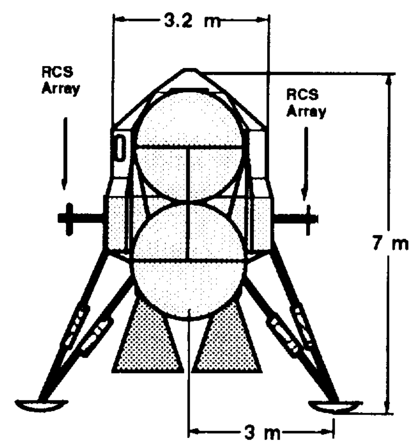


Fig. 9 b. Side view of ascent/descent vehicle

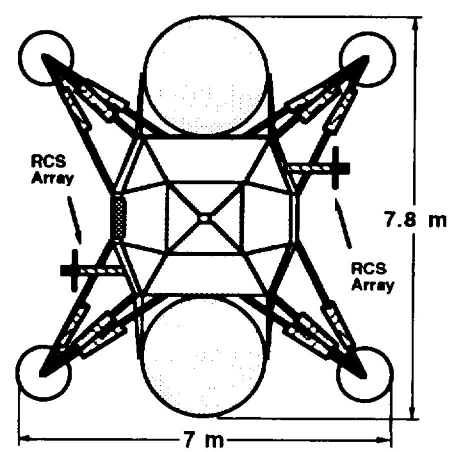


Fig. 9 c. Top view of ascent/descent vehicle carried out within 8 hours because there is no life support system onboard the ascent stage. The astronauts will rely on the personal life support systems on each of their Extra Vehicular Activity (EVA) suits until back aboard the MTV. While this may seem like a short time, it allows several opportunities for the ascent stage to dock with the MTV.

Propulsion System and Tanks

Perhaps the key technology which enables the mission scenario presented in this report is the Low Pressure Nuclear Thermal Rocket (LPNTR). This engine is a development from the standard solid core NTR but differs in that it does not need a complicated turbopump system since its combustion chamber pressure is very low (approximately 1 - 2 atmospheres). With such a low pressure in the combustion chamber, the pressure in the fuel tanks is enough to drive fuel into the engine. One drawback is that large nozzles are required to develop as much thrust as possible from the expanding exhaust gas. This is a small price to pay for the increased performance due to the LPNTR's higher operating temperature and reduced complexity of its design. The final engine system is a set of three independent engines mounted on gimbals that can swing ± 7° in any direction in order to compensate for single engine out situations and shifts in the center of gravity location.

The tanks for the Mars Transportation System (MTS) are designed so they may be easily manufactured and transported to LEO. All of the tanks have an outside diameter of 11.2 meters and hemispherical endcaps. The length of the tanks is all that needs to be changed for different tank volumes. The tanks are constructed of Kevlar 49 and E-glass and are covered with super-insulation to reduce the amount of liquid hydrogen which boils off.

Earth Capture Aeroshell

To return to Earth, the crew climbs back into the Mars Ascent Vehicle (MAV), taking the samples of Martian soil and the memory subprocessor unit from the MTV main computer with all of the mission information stored on it. As the crew nears Earth they stop rotation of the MTS, enter the MAV, and maneuver to the Earth aeroshell near the center of the vehicle. This maneuver will be performed about one day before the MTS arrives at Earth. As the MTS nears Earth, the docked MAV/Earth capture aeroshell package breaks away from the truss and aerocaptures into Earth obit while the truss coasts past Earth and enters into a heliocentric orbit. Sufficient ECLSS and consumables are aboard the MAV and Earth capture aeroshell to support the crew for 3 days, as well as enough fuel to achieve a propulsive Δv of 1 km/s.

Communication and Navigation Array

Essential to the success of this mission is an accurate navigation system and communication system which allow continuous communication with the Earth. These goals are met by an advanced integrated avionics package which is based on the existing Airplane Information Management System (AIMS).

Accurate navigation while in space is accomplished using a star tracker and an Inertial Measurement Unit (IMU). While either of these systems can be used independently, they are cross-checked in order to attain an even higher degree of accuracy. Navigation on the surface of Mars is accomplished through the use of radio beacons placed on the surface, two orbiting satellites, and the MTV. The pressurized rover has an additional 'dead-reckoning' system which acts as a backup in case of a communication's failure.

The communication needs for the mission are met by an advanced phased array antennae system onboard the MTV. This system is far more flexible than the dish-based systems currently in use. Not only will it enable communication with the Earth while the vehicle is rotating, but it also features fewer moving parts and much higher redundancy than a dish system with similar performance characteristics. The frequency of the proposed system lies in the Ka band and has a data transmission rate of nearly 100 Mbps, sufficient for television quality video.

While on the surface the crew's transmissions are relayed to the MTV and the two orbiting communication/navigation satellites and the MTV. They are then be amplified and directed to the Earth.

Landing Sites

Three different landing sites are chosen for the three missions to Mars. The sites are Olympus Mons, Valles Marineris, and Mangala Valles. These sites are chosen on the basis of geologic/scientific interest as well as ease of access.

Olympus Mons is located at 13° N latitude, and 139° W longitude. The Olympus Mons formation consists of large volcanoes and fissure vents. The mission to this area allows the crew to come close to a semi-active volcanic assemblage. The astronauts explore the surrounding territory to determine the age of these volcanoes, when they last erupted, and what types of ashen substances they have erupted in the past.

The second site, Valles Marineris, is located at 6° S latitude, and 78° W longitude. This site is composed of a sequence of thick plateau rocks, capped around their western region by ridged plains. At this site the crew explores the effects of volcanic tectonics as well as wind and water erosion on the formation of the canyons. The astronauts determine when the water that carried the ashen sediments was present and if its presence was due to migrating glaciers from the ice caps or lakes and streams.

Mangala Valles, the third site, is located at 7° S latitude, 147° W longitude. This site possesses numerous channels and possible underground wells. The astronauts determine the effects that volcanic tectonics played in the formation of the channels. The possibility of glaciers in the equatorial regions, which may have caused major glacial slides, is also investigated.

Crew Activities

On the surface of Mars, six astronauts explore the planet and perform experiments. The astronauts are divided into one group of four and one group of two.

The two-person crew spends half their mission time traveling in the pressurized rover and the other half of their time stopping to take samples and drill. Because the pressurized rover's oxygen capacity is twelve days the mission time is limited to ten days. In the event of treacherous terrain, or if the crew needs to spend more time at one site than another, extra time has been allotted for each trip.

The four-person crew uses the unpressurized rover along with the large coring drill on daily excursions. This crew obtains core samples at radial directions around the base camp and takes the samples back to the habitation module for testing. They set up and take down equipment at the beginning and end of each excursion. The four-person crew is also responsible for testing the samples brought back by the pressurized rover team. The crew works in shifts of two teams for ten hours on, ten hours off.

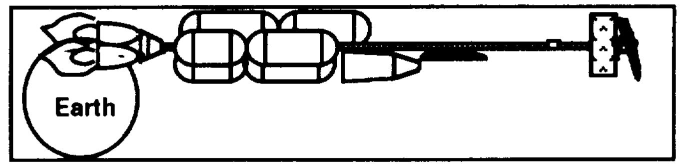
During the time in transit, all six astronauts will work in 8-hour shifts on interplanetary research and preparation for the excursion on Mars.

Mission Profile

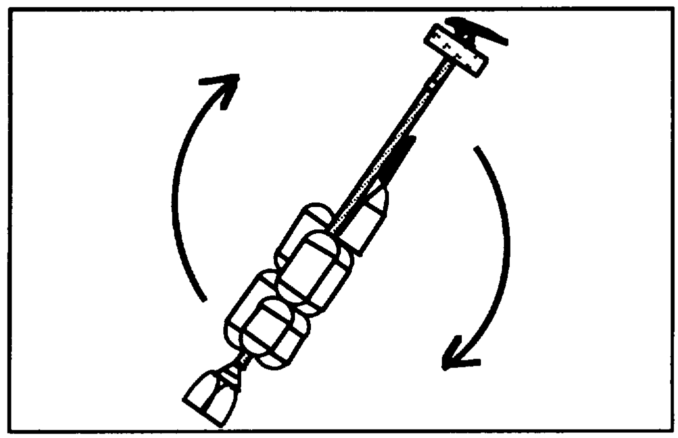
ETO and On-Orbit Construction

Two of the most important portions of the entire design project are the ETO and construction in LEO. Since launching a complete MTV directly from the Earth's surface is cost-prohibitive, all of the components are designed to be packaged and launched by projected launch vehicles. The vehicle chosen was the NLS-derived HLLV which features 4 LOX/RP boosters with a maximum payload of 224 metric tons. All components are designed to fit within the payload shroud and mass to LEO restrictions of this vehicle while minimizing the amount of orbital construction required.

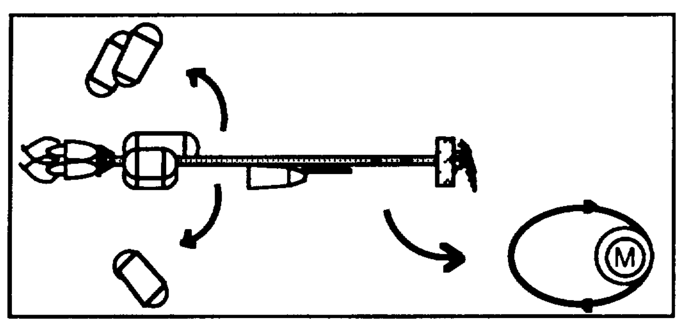
Graphic Mission Profile



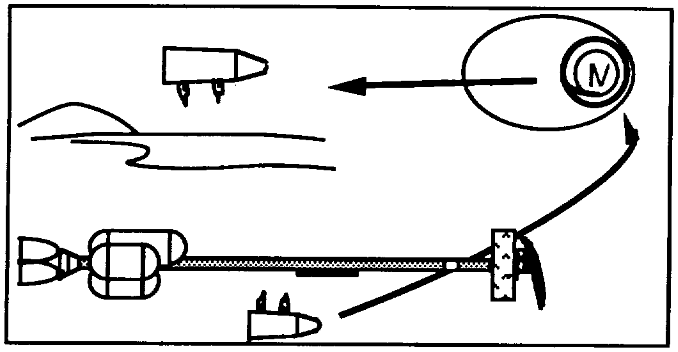
Phase 1. The NTR engines fire for the Trans-Mars Injection.



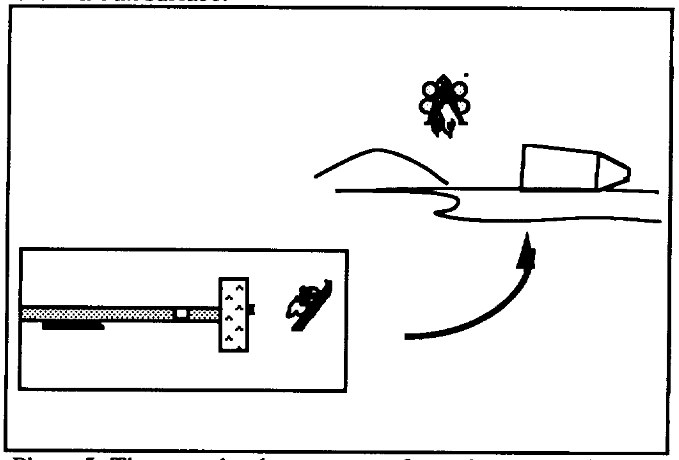
Phase 2. The rotation to generate artificial gravity is initiated and the MTS coasts to Mars. A mid-course correction and plane change requires stop and restart of rotation.



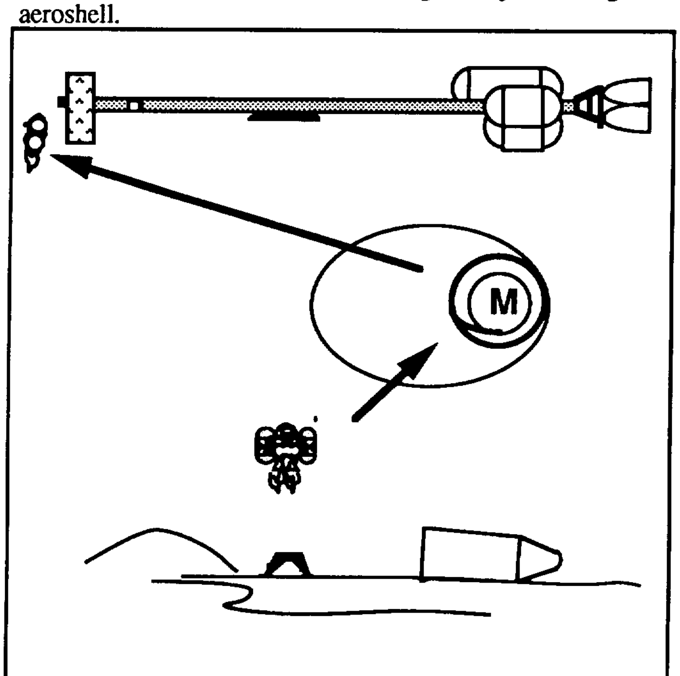
Phase 3. At Mars Orbit Injection the MTS stops rotating, jettisons empty fuel tanks, and propulsively brakes into an elliptical parking orbit around Mars.



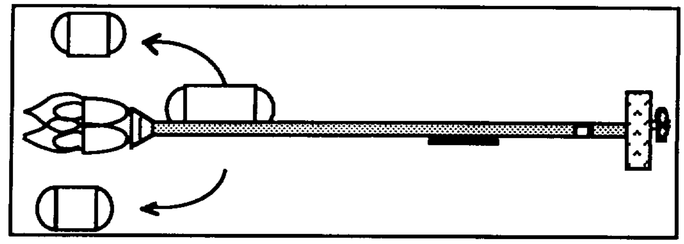
Phase 4. The biconic releases from the MTV, transfers to a circular parking orbit, performs a deorbit burn, and lands on the Martian surface.



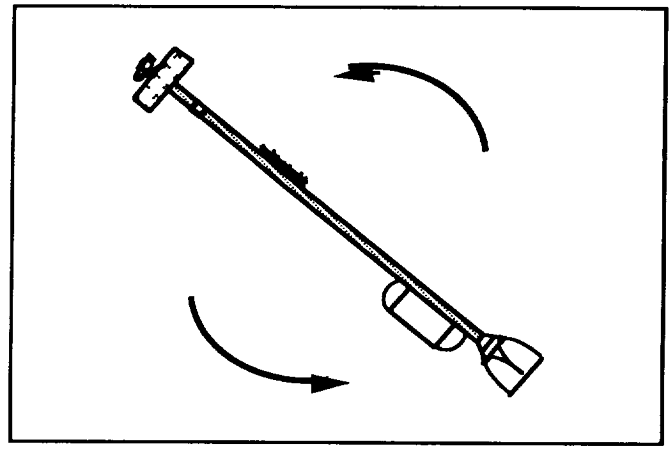
Phase 5. The crew lander separates from the MTV, changes orbits, and lands after aerobraking and jettisoning the aeroshell.



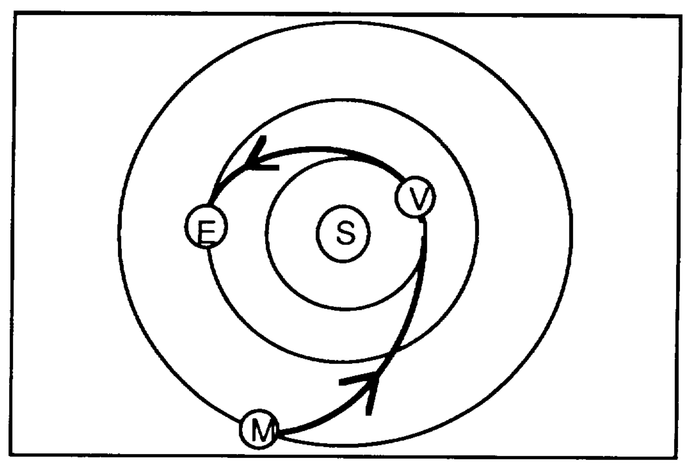
Phase 6. After completion of the stay on Mars, the crew returns to Martian orbit in the ascent module to rejoin the MTV.



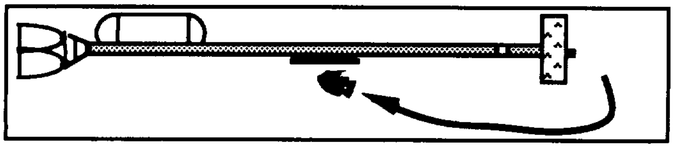
Phase 7. MTV jettisons the empty MOI tanks and performs Trans-Earth Injection burn.



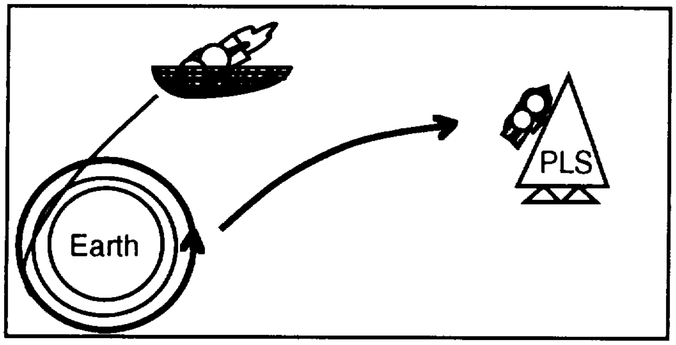
Phase 8. Artificial gravity is once again generated on the coast by rotating the ship. Due to reduced vehicle mass only 0.5 g is generated.



Phase 9. The MTS stops rotation for the Venus swingby maneuver. After the swingby, rotation is reinstated until one week before EOI.



Phase 10. The crew enters the Mars ascent vehicle, taking with them the soil samples and the memory units and maneuver to the MAV into the Earth Return Aeroshell.



Phase 11. Over a period of several days, the MAV and Earth Return Aeroshell aerobrake into a Low Earth Orbit. The crew rendezvous with the Space Station or Personnel Launch System vehicle. The MTV coasts past Earth and enters into a heliocentric orbit.

Outbound leg: Mission Phases 1-4

During this phase of the mission the crew completes its training and hones its skills to prepare for their arrival at Mars. Studies focus on research which cannot be conducted onboard a space station. These include effects of long-term exposure to simulated gravity on the human physiology, ECLSS demonstrations, and studies of micrometeoroid population and radiation fluxes in deep space.

Mars Surface Operations: Mission Phases 5-6

The 60 day surface stay does not offer much time for the extensive ground operations which are to be conducted. Five long-range pressurized rover trips and approximately 50 unpressurized trips are planned. Along with setting up the initial camp and surveying the area for interesting sites of intense study, the crew will unload and assemble the rovers. Surface studies focus on the geologic history of Mars and the possibility of past or existing life forms on the planet.

Inbound Leg: Mission Phases 7-11

Once the crew has completed the surface opertions, their next goal is to return to the MTV with the samples of Martian soil and initiate the TEI burn. On the return trip the artificial gravity will once again be initiated (Phase 8), and the crew continues scientific studies on the samples they collected.

Conclusion

Before this project becomes reality, several questions must be answered. First, the third launch window with the high chance of major solar flares raises the question whether the new technology of the year 2022 will be sufficient to ensure the safety of the crew. Second, a trip of this magnitude will have profound effects upon the crew's psychological makeup. The psychological and physiological effects on the crew are not well understood and therefore must be examined before a trip of this type is undertaken. Third, much of the technology used by the MTS remains in the conceptual stage. NTRs have not been developed much beyond laboratory designs and aerobraking remains a theoretical idea with very little hard data. This design relies heavily on these technologies.

Even with the assumptions made in it, this design represents a scenario which is very possible within the predicted timeframe. The two vehicle landers represent an optimal solution to the lander problem, which maximizes the payload to the surface while maximizing crew safety at the same time. The nuclear power sources for the surface operations are able to support robotic exploration long after the crew returns to Earth. The choice for three consecutive opposition class missions provides for a maximum amount of research without the prohibitive stay time associated with conjunction class missions. Finally, the rotating truss represents an excellent solution to the crew conditioning problem.