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PROJECT APEX: ADVANCED MANNED EXPLORATION OF THE MARTIAN MOON PHOBOS

University of Michigan
Department of Aerospace Engineering
Ann Arbor, Michigan

Professor Joe G. Eisley
Jim Akers, Teaching Assistant

Abstract

A preliminary design has been developed for a manned mission to the Martian moon Phobos. The spacecraft carries a crew of five and is launched from Low Earth Orbit in the year 2010. The outbound trajectory to Mars uses a gravitational assisted swingby of Venus and takes eight months to complete. The stay at Phobos is 60 days at which time the crew is busily engaged in setting up a prototype fuel processing facility. The vehicle will then return to Earth orbit after a total mission duration of 656 days. The spacecraft is powered by three nuclear thermal rockets which also provide the primary electrical power via dual mode operation. The overall spacecraft length is 110 m, and the total mass departing from Low Earth Orbit is 900 metric tons.

Introduction

Mars is the most like Earth of all the planets in the solar system. Understanding the evolution of the Martian climate will advance our understanding of the changes in the Earth's climate which will be of vital importance to the survival and enhancement of life here on Earth.

The manned exploration of Mars is a massive undertaking which requires careful consideration. A mission to the moon of Mars called Phobos as a prelude to manned landings on the Martian surface offers some advantages. One is that the energy requirement, in terms of delta V, is only slightly higher than going to the Moon's surface. Another is that Phobos is a potential source of water and carbon which could be extracted and processed for life support and chemical propellants for use in future missions; thus Phobos might serve as a base for extended Mars exploration or for exploration of the outer planets.

The design of a vehicle for such a mission is the subject of our Aerospace System Design course. The materials and equipment needed for the processing plant would be delivered to Phobos in a prior unmanned mission. This study focuses on what it would take to send a crew to Phobos, set up the processing plant for extraction and storage of water and hydrocarbons, conduct scientific experiments, and return safely to Earth. The size, configuration, and subsystems of the vehicle are described in some detail.

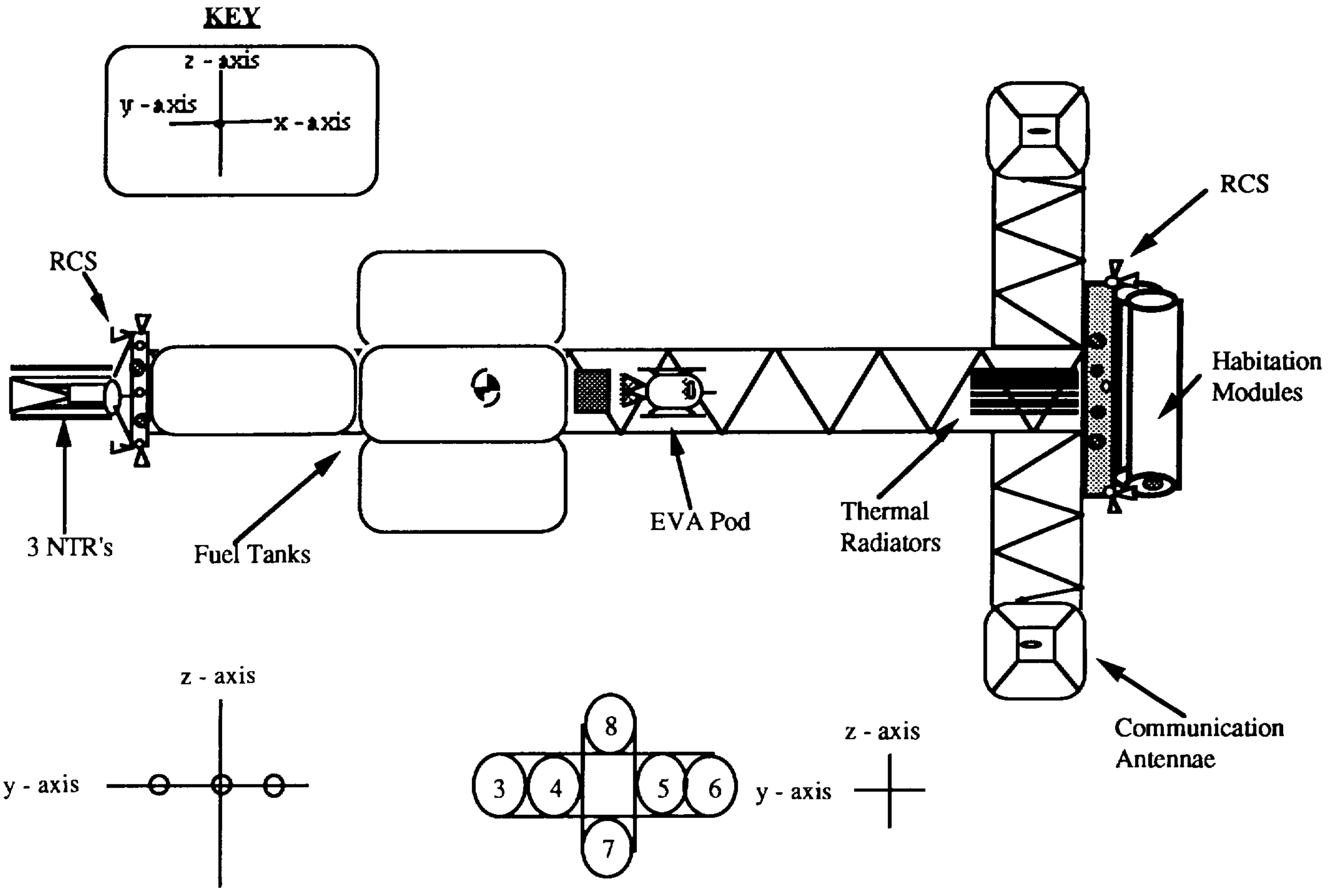
Objectives

1. Send a crew from Earth to the Martian moon Phobos.
2. Set up a prototype processing facility to extract water and hydrocarbons.
3. Conduct scientific experiments including an augmented robotic mission on the Martian surface.
4. Bring crew and Phobos samples back to Earth safely.

Fig. 1 Composite Picture of Phobos

Assumptions

1. Heavy lift launch vehicle with a minimum capability of 150 metric tons with designed growth to 250 metric tons is available to place the components of the spacecraft into Low Earth Orbit (LEO) for assembly.
2. Phobos is a carbonaceous chondrite asteroid containing water (20% by mass).



ENGINE CONFIGURATION

FUEL TANK CONFIGURATION

Fig. 2 Spacecraft Configuration - Top View

3. Unmanned precursor missions have determined a preliminary landing site, Stickney Crater, and delivered materials and equipment for the processing plant.

Phobos

Figure 1 shows Phobos, one of two moons of Mars (the other being Deimos). Phobos is 27 km long, 21.4 km wide, and 19.2 km high. Stickney Crater, which is on the end of Phobos facing Mars, is approximately 10 km in diameter. Phobos is in a low, almost circular orbit about Mars, with the semi-major axis equal to 9378 km and the eccentricity of the orbit only 0.015. Phobos orbits almost over the equator of Mars with an inclination of 1.02 degrees with a sidereal period of 7 hours 39 minutes 13.85 seconds.[1]

The gravity of Phobos is only .001g and the mass is estimated to be 9.8×10^{15} kg. Because of its low albedo of 0.05 and low density, Phobos is assumed to be an asteroid that was captured by Mars. Phobos' spectrum of reflectivity shows that it is similar in composition to a type 1 carbonaceous chondrite asteroid. Type 1 meteorites which have been analyzed on Earth show abundance of SiO_2 and H_2O in addition to other silicates (MgO, FeO) which are assumed to be present on Phobos.

Spacecraft Integration

The primary objectives in the design of the spacecraft were (1) to promote the safety of the crew by designing a stable ship that utilizes artificial gravity and (2) to provide shielding to the crew and ship components against all forms of radiation.

The spacecraft, shown in Figure 2, has an overall length of 110 m. Two habitation modules are attached at the front of the ship by the truss structure. Located behind the modules, two communication trusses extend 25 m each with counter-rotating platforms for antennae and navigation equipment. Eight fuel tanks are stacked around the main truss; two of which are feeder tanks. Each tank is 19.5 m long and has a diameter of 9 m. Three nuclear thermal rockets are stacked perpendicular to the truss in the y-direction. The total mass departing from LEO is 900 metric tons.

Artificial Gravity

Due to the long duration of this mission, the safety and comfort of the crew aboard the spacecraft were a high priority. After extended periods of time in a weightless environment, the human body begins to lose muscle mass due to minimal exertion of the muscles. Demineralization of bone tissue also begins, resulting in loss in strength and performance. To promote the health of the crew, artificial gravity was deemed necessary.

The optimal configuration for the mission was a tumbling scheme in which the spacecraft spins about the lateral body z-axis as shown in Figure 2. The spin rate was chosen to be in the range of 2.6-3.1 rpm, below the maximum allowable human rotation rate of 4 rpm. In addition, an artificial gravity in the range of 0.3g-0.5g was found to be the best compromise between maintaining crew health and minimizing system mass. A 0.01g lateral acceleration will be experienced by the crew during spin/despin operations.

The spacecraft will be tumbling during transit to Phobos and on return to Earth. No artificial gravity will be provided at Phobos, as the ship will be docked with the asteroid. The spacecraft will also need to despin for propulsive maneuvers and course corrections. In an emergency, despin can be achieved in five minutes.

Radiation

One of the primary hazards to the crew during the Mission to Phobos is radiation exposure. The four types of radiation encountered are Solar Flares, Galactic Cosmic Radiation (GCR), Solar Wind, and radiation from the propulsion nuclear reactors. The maximum total radiation exposure limit was set at 65 REM/yr and 33 REM/month per person. These levels of radiation will increase the chance of dying from cancer (the major effect of radiation) from 16% (the level on earth) to just under 18%. From these values, a radiation shielding configuration was developed.

A layer of tungsten and lithium hydride is placed between the nuclear reactors and the propellant tanks. This layer provides a "cone of safety" for the fuel tanks, habitation modules, and the communication platforms. For solar flare protection, the sleeping quarters are sheltered. Lithium hydride will be placed in the ceiling and walls of the sleeping quarters with water under the floor. The total radiation exposure is estimated to be 95 REM.

Propulsion and Power System

The APEX mission entails a duration significantly longer than any previous manned missions. The most important design trade-off is the choice of the primary propulsion system. This determines the overall characteristics of the design. Nuclear Thermal Rocket (NTR) engines were chosen to reduce the overall trip time, increase reliability, and increase efficiency.

Nuclear Thermal Rockets

The reactor design chosen for the mission is based on an improved version of a Rocketdyne, NERVA derivative, Carbide reactor.[2] Reactor mass is estimated to be seven metric tons with a thrust of 334,00 N (75,000 lb). The maximum Isp available must be improved to 1040 seconds or higher to ensure an effective Isp of 1000 seconds at full throttle during normal operation. The use of three NTR's provides a total thrust of 1,020,000 N with a maximum acceleration of 0.19g. The nuclear core will operate for up to 12 hours during full power propulsive maneuvers with a lifetime of three years. Three NTR engines will be used to escape LEO while only two engines will be needed for the rest of the mission.

Fuel and Tank Staging

Hydrogen has a significantly higher Isp than any other fuel which made it an attractive fuel choice. Since liquid hydrogen has a tendency to leak or boil away, the fuel tanks were designed with refrigeration. Refrigeration will reduce hydrogen boil off to zero.

A refrigerated fuel tank has a mass of 9100 kg. To reduce mass during the mission, the tanks will be dropped at various locations during the course of the mission. An intermediate tank staging scheme was selected to maintain ship symmetry, to reduce space clutter, and to provide reusability. One tank will be staged near Earth with six staged in orbit around Mars. The spacecraft will return with the final two feeder tanks.

NTR Operation for Propulsion

The reactor core of the NTR can be brought to full power within 60 seconds. The normal source flow through the tie tubes is the main propellant. The flow originates either directly from the tanks or from flow which has been previously routed through coolant loops in the thrust nozzle. This flow then proceeds via the tie tubes in the core to an outlet in the reactor. This heated propellant is routed to the turbines which power the propellant feed pumps. The flow is again rerouted and sent back through the core. This time the propellant proceeds directly through the flow channels in the fuel elements and is exhausted to space.

After a main burn is completed, the cooling process continues for up to six hours to remove heat from the reactor core.

Dual-Mode Operation for Power

For normal operation, the APEX spacecraft will require 175 kWe of electrical power. This power provides for life support, communications, experiments, and for cryogenic cooling of the fuel tanks. The power system must also be

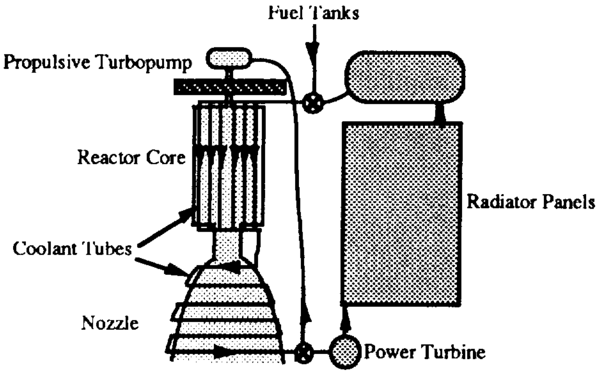


Fig. 3 Dual Mode Nuclear Thermal Rocket

capable of producing this power level for the duration of the two-year mission. For this purpose, a nuclear reactor is the best solution. To minimize shielding needs (and thus weight), the spacecraft will be using a Dual Mode Nuclear Thermal Rocket (DMNTR) which combines the power-producing nuclear reactor with the propulsion system.

An NTR must have a cooling system to keep the reactor and nozzle from melting. This is accomplished by running the propellant through cooling pipes in the reactor core and on the nozzle. The propellant is then fed through the reactor core again and is expelled out the nozzle. Power is produced by adding a turbo-brayton cycle to the coolant system. During electrical production, helium-xenon (He-Xe) is fed through the coolant system instead of the hydrogen used for the propulsive burns. The He-Xe passes through the reactor's cooling pipes and is routed to a turbine to produce power. From the turbine, the He-Xe passes through heat pipes to radiate the heat and traverses back into the reactor's coolant system. This differs from the propulsive burns in that the cycle is closed (see Figure 3).[3]

Project Apex will use three nuclear thermal rockets that are designed for dual mode capability. Only one reactor will be necessary for power production, the other two reactors will be used as backups. Each reactor will have its own coolant system with turbomachinery, but will share a common radiator. Individual radiator systems would be too heavy.

Back-up Power

The design of the DMNTR does not allow power production during a propulsive burn. The He-Xe working fluid to drive the power-producing turbines does not adequately remove the excess heat when the reactor is running at full power. This requires the use of a backup power source to provide electrical power during the propulsive burns. The maximum amount of time that power from the DMNTR would be unavailable for electrical power generation would be approximately 6 hours.[3] Power during these periods will be provided by a regenerative H-O fuel cell. The fuel cell will provide 20 kWe, enough for basic life support, communications, and computers for up to 24 hours.

Power Transmission

To deliver the power to the user, two independent transmission and distribution systems will be employed (See Figure 4). The power will be transmitted at 270 volts DC. DC power was chosen because of its extensive use in space, reliability, and simplification. For reliability and redundancy, only one distribution and transmission system will be necessary for normal operation with the second used as a backup. Voltage conversion to the user will be handled by small, low-powered, standardized, modular converters.

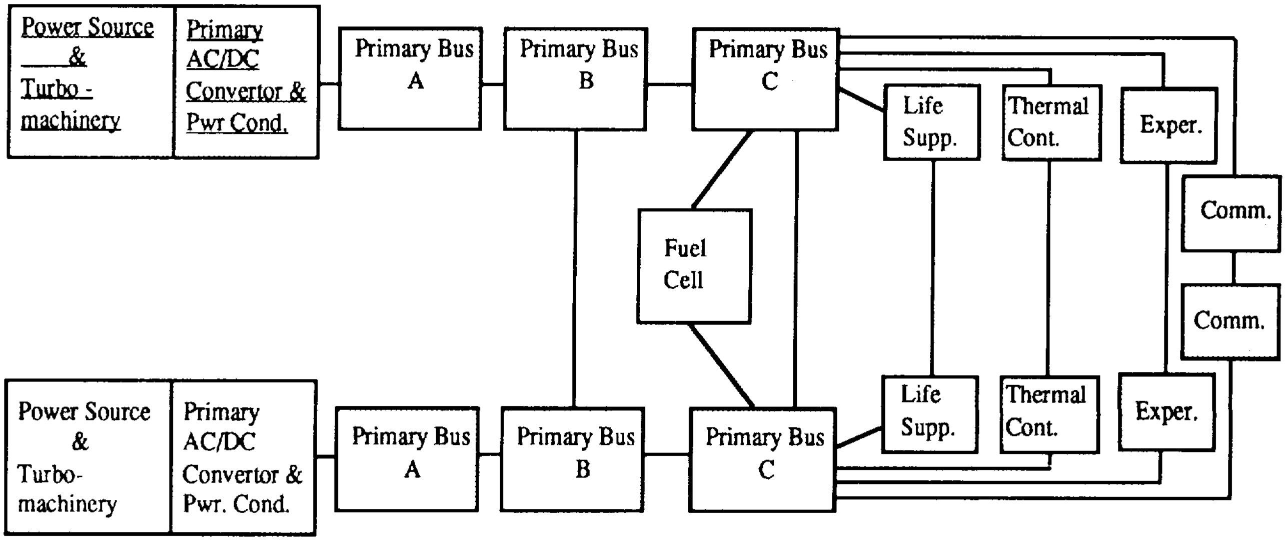


Fig. 4 Power Distribution Schematic

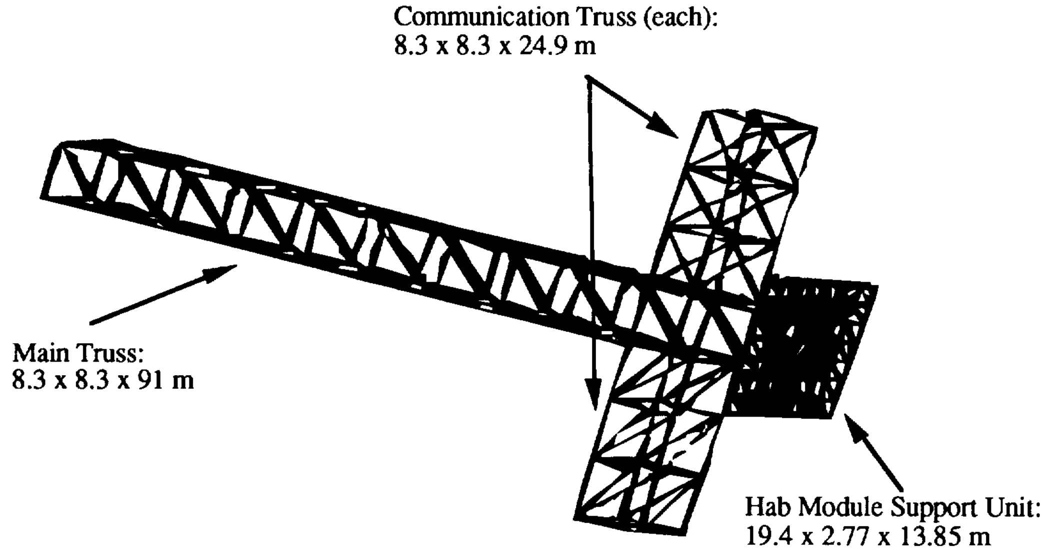


Fig. 5: Truss System

Thermal Control

Electricity produced and provided to the user generates large amounts of heat that must be rejected for the spacecraft to be habitable. Advanced systems such as Liquid Droplet Radiators and Curie Point Radiators are attractive solutions but are not compatible with the ship's rotation. Because of this, a standard heat-pipe radiator will be used. There are two sources of heat that must be dissipated: the nuclear reactors and the habitation modules. The habitation module radiators will use an internal two-phase water loop to transport the heat and an external two-phase ammonia loop to reject heat. Heat rejection at the nuclear reactors will be handled by a He-Xe mixture used for power production.

Structures

The structural components of the APEX spacecraft were designed to provide support for other subsystems. Emphasis was placed on strength, durability, and minimization of the total structural mass.

Truss System

The truss system is composed of three parts (Figure 5). The main truss extends from the nuclear thermal rockets to the habitation modules. The communications truss extends outward from the main truss so that communication equipment can have an unobstructed path from which to receive and transmit. The habitation module support unit provides support for the habitation module and the air locks.

Each part of the truss system was designed to be collapsible and self-deploying. This reduces the payload volume required to launch the trusses to LEO and greatly reduces onorbit assembly time. A collapsible box truss with precompressed joint springs was chosen. Graphite-epoxy was chosen as truss material for its high yield strength and low density.

A Finite Element (FE) analysis was performed on the proposed designs of the three trusses. The primary constraint for the main truss was a large enough moment of inertia to result in a minimum natural frequency of one hertz. The maximum acceleration experienced by the truss was 0.56g in compression. From the FE analysis, it was determined that the box truss was to have a cross-section of 8.3 m by 8.3 m with the dimensions of each member being .1575 m (outer diameter) and .1372 m (inner diameter). Each truss has a 1.4 factor of safety.

Habitation Modules

The two habitation modules are based on a NASA Space Station module with modifications (see Figure 6). The first layer is a meteorite shell of aluminum. Multi-Layer Insulation (MLI) follows the meteorite shell for thermal control. Standoffs acting as spacers between the first two layers prevent shifting and crushing of the MLI. Stringers running the length of the module control bending. Bulkheads encircling the cross-section prevent expansion in the radial direction.

The structural components were designed to withstand an internal pressure of 11 psi. The dimensions of the outer module shell are 4.7 m x 16.9 m. In addition, two airlocks, one on each module at opposite ends, were designed with the same structural configuration as the habitation modules.

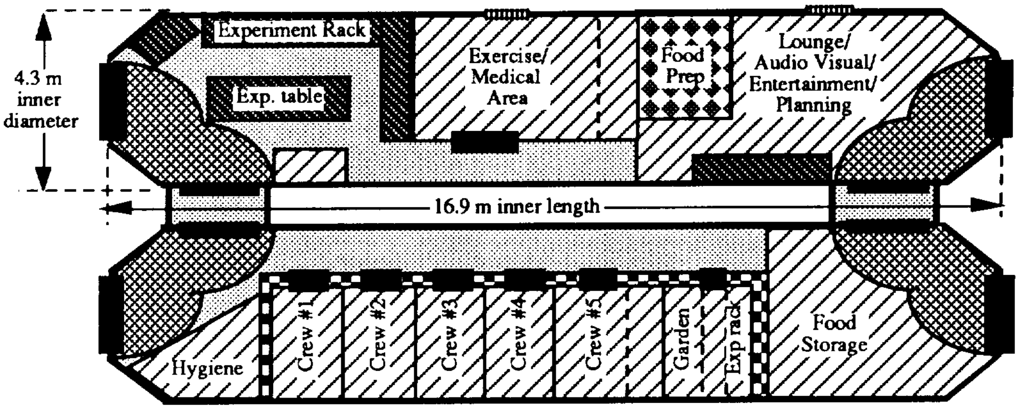


Fig. 7 Habitation Module Layout

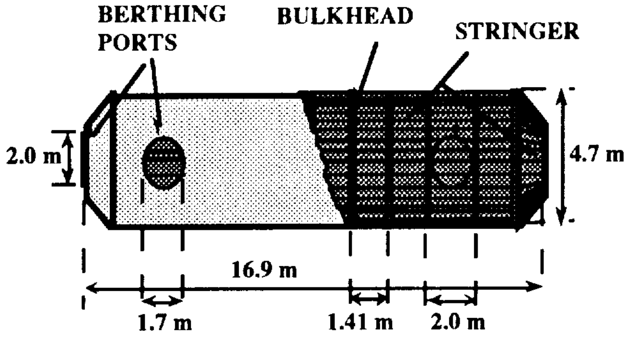


Fig. 6 Habitation Module Structural Support

Human Factors

Habitation Module Layout

There will be two cylindrical modules in which the crew will live during transit to and while on Phobos. The modules are designed to compensate for both microgravity and artificial gravity environments. Both modules have one floor with access between modules. The five crew quarters, hygiene facilities, galley, wardroom, medical facility, and laboratory are shown in Fig. 7. A command center is located in the crew quarters as well as in the laboratory for radiation protection.

Life Support System

A partially-closed environmental life support system was chosen for the spacecraft. The life support system consists of temperature and humidity control, atmosphere control, fire detection and suppression, waste management, air revitalization, and water recovery and management. Figures 8 and 9 show the air and water recycling processes. A 90% efficiency for air recycling and a 95% efficiency for water recycling are assumed; 1000 kg of oxygen and 5550 kg of water will be carried during the mission. Both amounts include 15% contingency supplies. In addition, 4720 kg of dried food will be provided for the crew. The Halon 1301 system was chosen for fire suppression as it leaves no corrosive or abrasive residues within the cabin and few ill effects for humans.

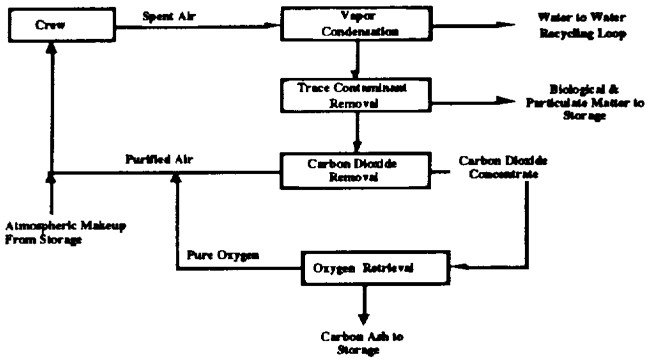


Fig. 8 Air Recycling Process

Communications

The communications system of Project APEX maintains a 50 Megabit per second (Mbps) full duplex connection from

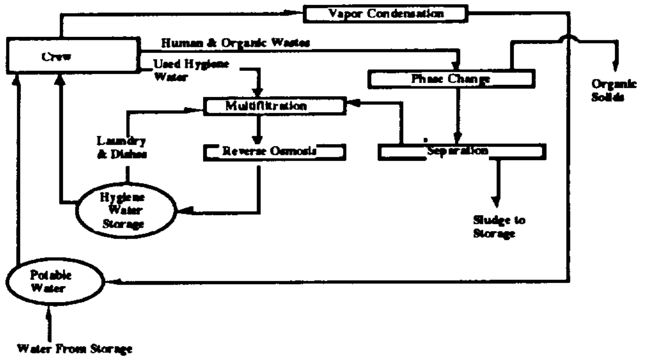


Fig. 9 Water Recycling Process

the spacecraft to Mission Control on Earth; this allows for the continuous transmittal of voice and video communications, experimental data and observations, and telemetry information. Seven major links are required in the design (see Figure 10):

1. Ground Terminal (GT): A 20-meter (diameter) antenna near Johnson Space Center (Mission Control), transmitting in the S-band to the Geosynchronous Relay Satellites (GRS).
2. Geosynchronous Relay Satellites (GRS): Three satellites in orbit about Earth with S-band downlinks to the GT and 24-meter antennas transmitting in the Ka-band to the Mars Piloted Vehicle (MPV), Mars Relay Satellites (MRS), and Phobos Relay Point (PRP).
3. Mars Piloted Vehicle (MPV), the spacecraft: Two 9-meter antennas mounted on both ends of the communications boom of the spacecraft, transmitting in the Ka-band to the GRS.
4. Transitional Relay Point (TRP): A 1-meter antenna mounted on top of the spacecraft, transmitting in the Ka-band to the MRS; the TRP will be used during the landing operations on Phobos.
5. Mars Relay Satellites (MRS): Two satellites in orbit about Mars with Ka-band downlinks to the PRP and 9-meter antennas transmitting in the Ka-band to the GRS.
6. Phobos Relay Point (PRP): A 2-meter antenna mounted on a 50-meter pole on the surface of Phobos, transmitting in the Ka-band to the MRS; the PRP will be used during the assembling operations on Phobos and will be left connected to the processing plant after the crew departs from Phobos.
7. Extra Vehicular Activity (EVA): Half-wave dipole antennas mounted in the astronauts' space suits, transmitting in the UHF-band to the MPV and PRP.

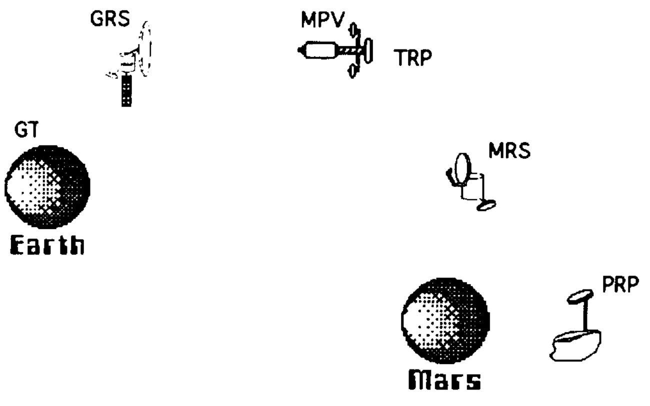


Fig. 10 Main Communication Links

Guidance, Navigation and Control

Guidance, Navigation, and Control (GN&C) of the spacecraft is achieved by the computer-managed interaction of the navigation, telemetry, and propulsion systems. The computer system consists of nine radiation-hardened, space-ready General Purpose Computers (GPC), each providing 16 MIPS of computing power. All computers will be linked in a FDDI-2 network. The navigation system consists of four star trackers to determine the spacecraft's attitude and position, an Optical Alignment System to recalibrate the star trackers, nine Inertial Measurement Units to sense linear rates of acceleration, and nine Ring Laser Gyroscopes to measure angular rates of acceleration. This system will also monitor the spinning motion of the spacecraft. The telemetry system consists of a long range, high gain radar and a short range landing radar. These radars will guide the spacecraft into the proper Phobos rendezvous position.

Mission Analysis

Several factors, including ΔV's, mission duration, stay time on Phobos, expected radiation dosage, and proposed launch date, went into the selection of an appropriate mission trajectory. To reduce radiation exposure, it was desirable to plan a mission around a solar minimum. An aggressive launch date was chosen allowing ten years for technological development.

Opposition Class

Project APEX will use an opposition class mission with a total mission time of 656 days. The proposed departure date from Earth will be November 19, 2010. The outbound trajectory includes a Venus swingby to conserve fuel. Once the ship reaches Phobos on October 3, 2011, the stay time for setting up the processing plant and conducting experiments will be sixty days. The ship will then arrive

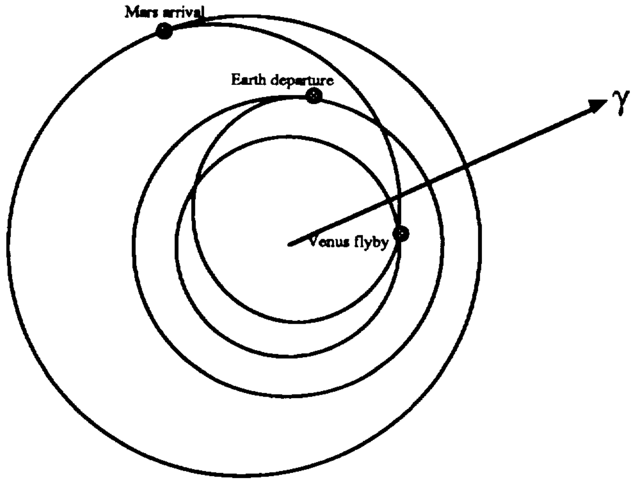


Fig. 11 Outbound Trajectory

back at Earth on September 5, 2012.

Earth Departure

The spacecraft will leave from LEO (see Figure 11). A single perigee kick will be used to break up the escape burn. The perigee kick was necessary to increase the ship's orbital energy without taking large losses due to G-Loss.[2] The first will put the spacecraft on an elliptical orbit with a period of two days. The second will give the spacecraft the required escape velocity to travel to Mars.

The main concern when doing perigee kicks is the radiation received while passing through the Van Allen radiation belts. These are two belts of high radiation surrounding the Earth. Using Apollo astronaut exposure levels, the astronauts will receive approximately 6 REM per passage. The total for the first 30 days of the mission will be approximately 28 REM, which is below the 33 REM per month limit.

Rendezvous with Phobos

When it reaches the Martian system, the spacecraft will insert itself into an orbit of 9400 km, which is 22 km higher than Phobos' orbit . Once the ship's position relative to the moon has been determined, a phasing burn will be performed placing the ship at 6 km from Stickney Crater.

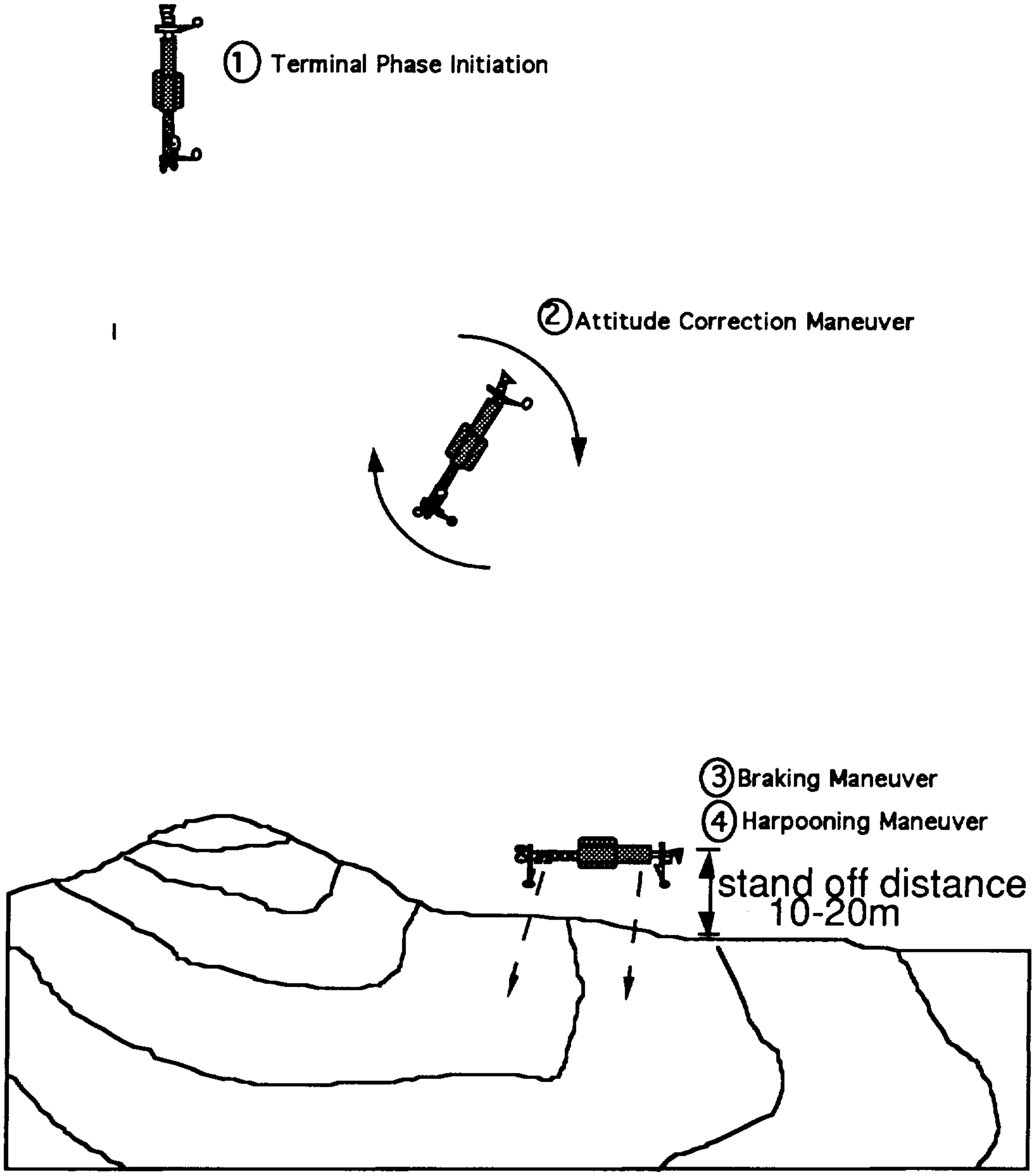


Fig. 12 Landing Maneuver

The spacecraft will land on Phobos near Stickney Crater. Since the gravity of Phobos is very low, the spacecraft will essentially "dock" with Phobos (see Figure 12). When the spacecraft is within twenty meters of Phobos, it will shoot harpoons into the surface and pull itself to the surface. After landing, the ship will remain tethered to the moon's surface because of the extremely low gravity.

Return to Earth

Once the mission at Phobos is finished, the RCS thrusters will be used to push the spacecraft away from Phobos (see Figure 13). After a safe distance is achieved, the main engines will be used to send the craft towards Earth. At Earth, a propulsive burn will be used to insert the spacecraft into high elliptical orbit. From there, the crew will be quickly removed by orbital transfer vehicles and the craft then slowly brought back to LEO.

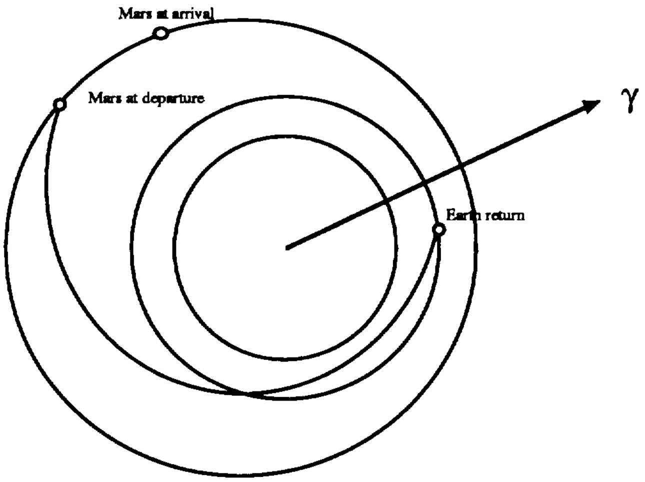


Fig. 13 Inbound Trajectory

Scientific Research

The scientific objectives for the Mission to Phobos consist of the following:

1. Assessment of the effects of long-duration space travel on human and plant physiology.
2. Assessment of possibilities for extraterrestrial fuel and metals production.
3. Assessment of use of extraterrestrial resources for manufacturing of construction products.
4. Determination of origin of Phobos.

Investigative categories include human life science, plant life science, materials science, manufacturing, Phobean and Mars soil analysis, and isolation/psychology. In addition, we propose to control a rover on the surface of Mars to acquire more information about Mars in order to facilitate a future manned Martian landing.

Phobos and Beyond

The utilization of space resources makes for effective exploration of the planets of the solar system. We propose to use materials that already exist on Phobos in an innovative approach to reduce the need, and thus the expense, of bringing everything from Earth. The economy of utilizing space resources is obvious and, the presence of Phobos is the key. The advantages and future use of Project APEX are described below.

A processing plant could be constructed on the Martian surface to create methane. Many current plans have the hydrogen needed for this reaction being shipped from Earth.[4] Extracting the hydrogen from Phobos could be accomplished at a fraction of the cost.

The majority of the fuel in a trip to the Martian system is used in the initial burn at Earth. Launching Phobos-processed fuel to Earth High Elliptical Orbit (HEO) for future mission use provides great cost savings.

Ultimately, Phobos could be used as a refueling station for descending to the Martian surface and for both manned and unmanned missions to the outer solar system.

Conclusions

The results presented in this report are the products of a preliminary design study of a Manned Exploration of the Mars moon, Phobos. We propose to use technology which may not exist at this time, but can be developed and tested within ten years. Additional areas of advanced research development are needed to support the overall mission success. These include the development of a heavy lift launch vehicle; automated rendezvous and docking capability; maneuverable extravehicular activity suits; telerobotic devices and telepresence robotics; and micro-gravity fuel transfer.

A preliminary estimation indicates that the development and production of the APEX spacecraft will cost $11.4 billion with an overall mission cost of $12.7 billion.

As this mission is concerned with making a mission to the Martian system economically feasible, it can be viewed as a precursory mission in a larger plan for much greater, permanent human involvement in space. The Space Exploration Initiative (SEI) is the present attempt by the United States to formulate this large scale plan; this mission can be considered as a small element of that overall, long-term mission.

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Fifty-four students participated in the design of Project APEX as part of AE 483: Space System Design. The project was conducted during the 1992 winter term.