1131-CR

253822

142P

A ROBOTICALLY CONSTRUCTED PRODUCTION AND SUPPLY BASE ON PHOBOS

A Design Presented by :

PHOBIA

Corp.

Presented to :

Dr. George W. Botbyl

Department of Aerospace Engineering

The University of Texas at Austin

and

NASA/USRA

```
(NASA-CR-186234)  A ROBOTICALLY CONSTRUCTED          N90-21872
PRODUCTION AND SUPPLY BASE ON PHOBOS
(Phobos Industrial Applications Corp.)
142 p                                  CSCL 13B      Unclas
                                              G3/31  0253822
```

4 May 1989

EXECUTIVE OVERVIEW

PHOBIA Corp. is involved with the design of a man-tenable robotically constructed, bootstrap base on Mars' Moon, Phobos. This base will be a "pit stop" for future manned missions to Mars and beyond and will be a control facility during the robotic construction of a Martian base.

This report begins with an introduction to the concepts and the ground rules followed during the design processs. Details of a base design and its location are given along with information about some of the sub-systems. Since a major purpose of this base is to supply fuel to space craft to limit thier fuel mass, mining and production systems are discussed. Also, other surface support activities such as docks, anchors, and surface transportation systems are detailed. Several power supplies for the base are investigated and inlcude fuel cells and a nuclear reactor.

A major factor in producing a base on Phobos will be the robotics which will be assigned to do most or all of the construction work. Tasks for the robots are defined in the robotics section along with descriptions of robots capable of completing the tasks. These robots are an important design component and are therefore reviewed in great detail.

Finally, failure modes for the entire PHOBIA Corp. design are presented along with an effects analysis and preventative recommendations. This section, along with the efforts in robotic research, are considered to be the major strengths of the design effort.

TABLE OF CONTENTS

page #

Appendicies

LIST OF FIGURES

LIST OF ACRONYMS

AAA	Autonomous Automated Assembly
AI	Artificial Intelligence
CA	Communication Antenna
CIMC	Central Information Management Control
DOF	Degree of Freedom
DTM	Desk Top Manufacturing
ET	External Tank
FCL	Freon Coolant Loop
FMEA	Failure Modes and Effects Analysis
GCR	Galactic Cosmic Radiation
HEE	Heat Exchanger Elements
HQ	Headquarters
ITV	Interplanetary Transport Vehicle
LAB	Laboratory
LEO	Low Earth Orbit
LH2	Liquid Hydrogen
LMO	Low Mars Orbit
LOX	Liquid Oxygen
LRT	Long Range Transit
NASA	National Aeronoautics and Space Administration
OMV	Orbital Manuevering Vehicle
OTV	Orbital Transfer Vehicle
PICON	Process Intelligent Control
RPS	Radiation Protection System
SEP	Surface Exploration of Phobos
SPE	Solar Particle Event
SRT	Short Range Transit
SR & QA	Saftey, Reliability and Quality Assurance
STN	Space Transportation Mode
WCL	Water Coolant Loop
WRHE	Water Reservoir Heat Exchanger

1. INTRODUCTION

The exploration of the solar system by humankind has already begun. Men and women have undertaken numerous excursions to space, and have made several trips to the Moon and back. Already, a semi-permanent human presence in space exists. Moreover, probes have been sent to all but the outermost planet of the solar system, and these will be followed in the approaching years by their human creators.

In order to reduce the cost of accomplishing these endeavors, utilization of extraterrestrial resources will have to be undertaken on a large scale. The price for boosting mass out of the Earth's gravity well is so great that extraterrestrial raw materials must be utilized. The solar system has many such resources in its moons and minor planets. Because of their small size, these bodies require less energy to escape their gravitational attractions than the Earth. Furthermore, many are believed to be rich in water and other minerals required for space exploration.

The Phobos Industrial Applications Corporation (PHOBIA Corp.) believes that these bodies can be developed to meet the needs of forward-looking societies, either in cooperation or individually. Using advanced automation techniques, the infrastructure required for human exploration of and expansion into the solar system can be safely and reliably assembled.

1.1 PHOBOS, THE INTERPLANETARY GAS STATION

For voyages from the Earth to the outer planets, one body stands out as a prime site for resource utilization: Phobos, the larger of Mars' two satellites. A small, craggy, oblong chunk of rock, this body bears little resemblance to Earth's moon. Its density indicates that the planetoid contains large quantities of water, probably locked up as water of hydration. Furthermore, its low mass means it has approximately one thousandth of the Earth's gravity. Finally, since Phobos is locked to the orbit of Mars, the outermost terrestrial planet, it provides the ideal gateway to the outer bodies.

Phobos' water could be mined, and processed into liquid hydrogen (LH2) and liquid oxygen (LOX), the prime fuels for chemical rockets. Past scenarios envisioned nuclear or solar propulsion for large-scale interplanetary voyages, due to the high cost of bringing chemical fuels up from Earth. However, the use of LOX mined on Earth's moon for outbound trips, and LOX and LH2 mined from Phobos for return trips and Mars exploration, would substantially reduce the cost of using chemical propellants. Since chemical rockets produce higher thrust than other types of engines, shorter flight times would result, thus reducing the exposure of crews and equipment to interplanetary radiation hazards.

Another major known resource on Phobos is regolith, a fine, powdery substance which is formed from the fragmentation of the surface of a planetoid by meteorite impacts over millions of years. This material can be used as a shield against cosmic and solar radiation. Although a meter or more of regolith is typically required to adequately shield a manrated spacecraft or habitation module, the material is virtually free compared to the cost of lifting equivalent shielding from the Earth's surface. Further, several studies have demonstrated the feasibility of using lunar regolith for making concrete [1-1, 1-2], and for constructing structural members [1-3]. The applicability of such methods to Phobian regolith seems plausible.

When the salvageable data from the failed Soviet mission to Phobos and planned U. S. missions (e.g. *Mars Explorer*) becomes available, they will verify the availability of water on the planetoid. In addition, these data may indicate the presence of other resources, such as methane or uranium, which could also be used as propellents in advanced spacecraft engines.

1.2 THE MANNED OUTPOST

Phobos can also serve as a stepping stone for manned exploration of Mars. Due to the moon's lack of atmosphere and low gravity, it is easier and cheaper to send astronauts to Phobos than to Mars. In addition, the cost of manned missions could be reduced even further by using propellent mined *in-situ* for the return voyage to Earth. On Phobos, manned crews could explore the Martian system from a natural space station, and also assist in the construction of a Martian base using telerobotics.

A manned mission to Phobos could be be accomplished sooner than a corresponding Mars mission, establishing early leadership in the exploration of the Martian system [1-4]. The milli-gravity, vacuum environment of the planetoid means that complicated, heavy re-entry and ascent vehicles do not have to be included in the mission, reducing the overall system weight and cost substantially. This manned mission could also be the first user of fuel mined on Phobos. Although it would not be prudent to send the first crew to Phobos without enough fuel for the return journey, their mission could serve as a proof-of-concept of Phobos' mining capabilities. Future missions could then depart the Earth system less mass than they would otherwise require, since no fuel for the return need be carried outward.

The establishment of a manned outpost on Phobos would provide a base for the first detailed exploration of an asteroid-type body. In addition, this outpost would serve as a base for the operation of telerobotic probes on Mars, Martian weather observations, and eventually telerobotic construction of a manned base on the surface of Mars itself. Once the Mars base is established, much of the equipment required for the Phobos base could be sent down to Mars, reducing the cost of constructing the planet-side base. At this stage, the Phobos outpost would become a man-tended facility, serving as both temporary habitat for crews sent up from the Mars base and as a safe-haven for passing spacecraft or the Mars base.

1.3 AUTONOMOUS AUTOMATED ASSEMBLY, THE KEY TO PHOBOS

To accomplish missions to the Martian system, a great deal of construction must be carried out far from Earth. Bases and facilities must be built in harsh environments, thus exposing astronauts to serious injuries. Although space exploration is known to be a risky endeavor, the death of an astronaut could bring the space program to a halt, as did the Challenger accident. However, as early as the 1980's, robotic technology is at a stage in which autonomous automated assembly (AAA) of space structures is close at hand. The use of robots for construction of the Phobos base will eliminate such a catastrophic risk.

The construction of space station *Freedom* in the 1990's will pioneer the technology of space-based robotic construction. If an evolutionary expansion approach into space [1-4] is implemented, the space station will be followed in the next century by a robotically-assembled base on the Moon. The construction of such a base will require that a great deal of autonomy be given to the robots, due to time lags on the order of several seconds for Earth-based monitoring and communications. Nevertheless, designers are optimistic that advances in artificial intelligence (AI) will make such robots practical within the next twenty-five years [1-5].

When the construction scenario is shifted to Phobos, however, fully autonomous robots are a necessity. Time lags on the order of forty minutes preclude any direct supervision and control from Earth. Little more than monitoring the construction *post facto*, and performing inspections and tests can be accomplished by the human mission controllers. Nevertheless, given the expected advances in AI and the experience gained through previous robotic construction missions, an AAA scenario for the Phobos base seems plausible.

1.4 *PHOBIA* CORPORATION'S DESIGN GOALS

The remainder of this document presents PHOBIA Corporation's preliminary design of a man-tenable, robotically-constructed outpost on Phobos. PHOBIA's design philosophy is based on several assumptions and groundrules which are derived from the preceding arguments, and which ensure that the design meets sensible standards of safety, environmental impact, and efficiency:

ASSUMPTIONS

- Time frame: 2020 - 2035
- International cooperation possible, but not ensured
- Moon base production of propellent for outbound trips
- Construction of components on Earth, assembly in Low Earth Orbit (LEO) at Space Transportation Node (STN)
- Autonomous robot construction techniques used for deployment on Phobos
- Evolutionary expansion strategy of solar system exploration

GROUNDRULES

- Human activities shall not affect the structural integrity nor the orbital motion of Phobos, and shall not substantially detract from its scientific or aesthetic value.
- The first manned expedition to Phobos will use fuel produced *in-situ* for its return trip, however, it will carry enough fuel in a backup capacity for a safe and timely return to Earth.
- Subsequent return trips from the Martian system and Martian space transportation systems will use Phobian fuel.
- Robotic construction activities are to be monitored by Earth stations.
- Human crews do not depart Earth until completion and checkout of habitation on Phobos.

The design also assumes an "upside" [1-6] social and political climate in which technology is driven to meet the requirements of the design.

The Phobos outpost will have three major functions:

1) providing a fuel station for spacecraft undertaking missions to the outer planets,

2) providing a base for the exploration of Phobos and Mars, and

3) serving as the command center for subsequent telerobotic construction of a bootstrap base on the surface of Mars.

The construction of the base is considered to occur approximately thirty to forty years from the present, in the neighborhood of 2020 to 2035. This time frame allows adequate time for the establishment of a lunar base, and an Earth-orbiting space transportation node, both of which are considered necessary for the development of a Phobos base. Figure 1-1 shows a schematic of the mission sequence.

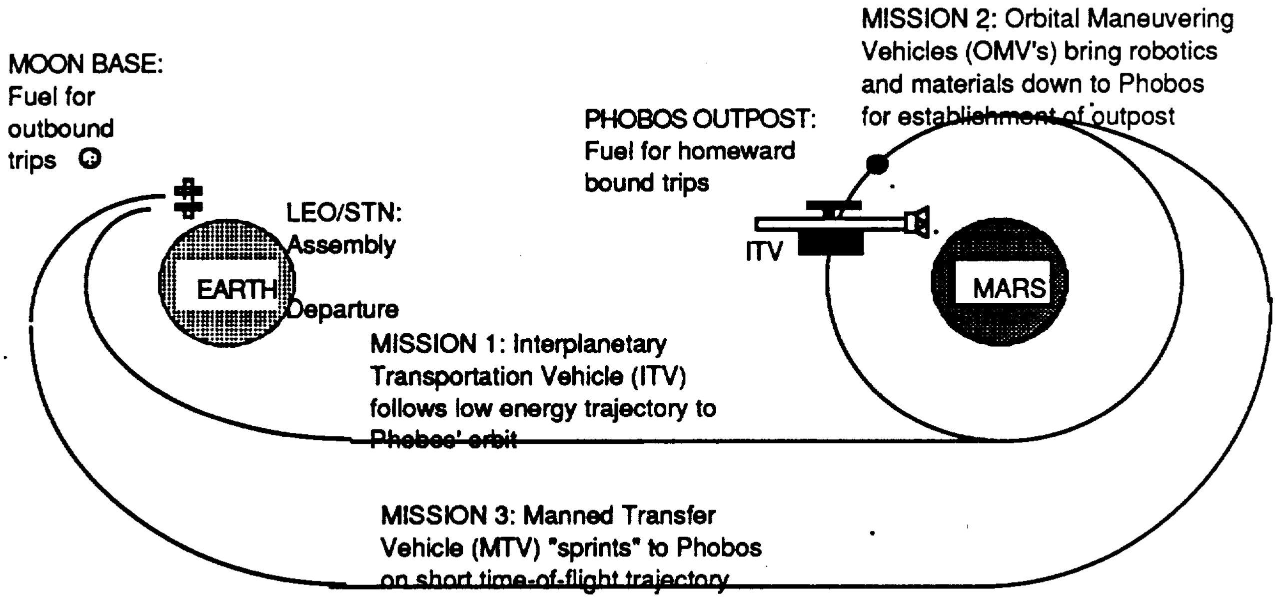


FIGURE 1-1: Mission Scenario for a Phobos Base

The design philosophy incorporates a concern for safety, reliability, and quality assurance (SR & QA). Since the base will be entirely constructed by autonomously acting robots, SR & QA takes on greater importance than ever before in space ventures. To ensure proper completion of each assembly sequence, all robotic construction activities are to be monitored and inspected by Earth stations. Reliability demands that numerous redundant systems be incorporated into the design, and also that modular, interchangeable systems be used whenever possible.

In addition, the design philosophy recognizes that human activities inevitably disturb pristine natural states. However, the base and its operations will not be allowed to affect the structural integrity nor the orbital motion of Phobos, and will not be permitted to substantially detract from the scientific or aesthetic value of the moon. Wherever possible, natural states will be preserved and/or protected, since the environments being disrupted hold the secrets of the history of the solar system.

Finally, the design is based on an evolutionary approach to solar system exploration [1-4]. Such an approach is methodical in nature, making slow, but consistent progress toward the eventual goal of establishing a permanent human presence throughout the solar system. The social and political climate favorable to an evolutionary exploration process may be termed upside, since it provides sufficient public interest and political/financial support to drive the necessary technologies to meet the needs of the design. Whether such a climate occurs through international cooperation, or through intense international competition is, in a pure sense, immaterial to the design. However, given the high costs of space exploration and the pressing problems besetting the Earth, cooperation seems the more realistic and ethical route.

2. SYSTEM OVERVIEW

PHOBIA Corporation's design for a Phobos outpost consists of integrated systems associated with the manned base, mining activities, surface operations, robotics, and power. Much of the technology required for these systems is projected to be available by the time frame considered for this mission (2020 - 2035). In addition to the design of these systems, PHOBIA engineers have prepared a preliminary mission plan for the deployment of the outpost.

Base Systems are related to the manned portion of the outpost and its associated subsystems. Mining Systems pertain to the design of the fuel production facility. Surface Operations comprise docking, exploration, and transportation. Robotics Systems are machines capable of performing jobs and tasks without the need for direct human supervision. Finally, Power Systems are the infrastructure responsible for providing energy to the manned base and the mining machinery. In addition to designing these systems, PHOBIA has also considered the modes in which various failures in these systems could occur, and the consequences of such failures on performance of the overall mission.

2.1 ENABLING TECHNOLOGIES

In preparing the designs for these systems, several assumptions were made concerning the technology which would be available in the time frame considered, 2020 to 2035. In the 1990's, space station *Freedom's* development and construction will yield advances in robotic construction techniques and artificial intelligence. Later, construction of a moon base will further develop these technologies to the point of limited autonomous construction capability. Much of this technology can thus be taken "off the shelf" for use by the Phobos mission. However, the technology will have to be driven in order to produce fully autonomous robotics.

This mission also requires assembly of many of its structures in advance at a low Earth orbit (LEO) Space Transportation Node (STN). The development of such a station will require cryogenic fuel management and automated docking procedures, which will also be required for the Phobos base. Thus, these technologies too can be taken "off the shelf." Finally, since breakdowns will be inevitable and spare parts far away on Earth, the base will need a system for parts manufacturing. Current work by the Desk Top Manufacturing (DTM) Corporation, in cooperation with the University of Texas at Austin, has demonstrated the feasibility of a laser sintering process for readily making prototypes [2-1]. Given twenty to thirty years time to mature, such technology could be extended to space and the production of spare parts at the Phobos base.

2.2 SEQUENCE OF EVENTS

Preliminary mission planning has resulted in a sequence of events for the assembly of the Phobos base. The components of the outpost will be deployed at the three sites, which are shown in Figure 2-1. This deployment will consist of five phases: preparation, three construction phases, one at each of the sites, and assembly of a surface transportation system.

2.2.1 Phase 1: Preparation

The first step in building the Phobos base is the construction the components of the base - the modules, nodes, power plant, docks, and mining facilities - on Earth. These components will then be launched to Low Earth Orbit (LEO). Assembly of the base - the connection and sealing of the modules to the nodes - will be completed at a Space Transportation Node (STN). The components will then be loaded onto an Interplanetary Transfer Vehicle (ITV) for transport to the Martian system. The ITV will insert into a co-orbit of Mars with Phobos, from which the packages will be sent. Three Surface Exploration Probes (SEP's) will be launched to Phobos: one to a smooth spot for mining and docking in Stickney crater, one to the power plant site, and one to the base site. These SEP's will serve as beacons for the launch packages and for the robots.

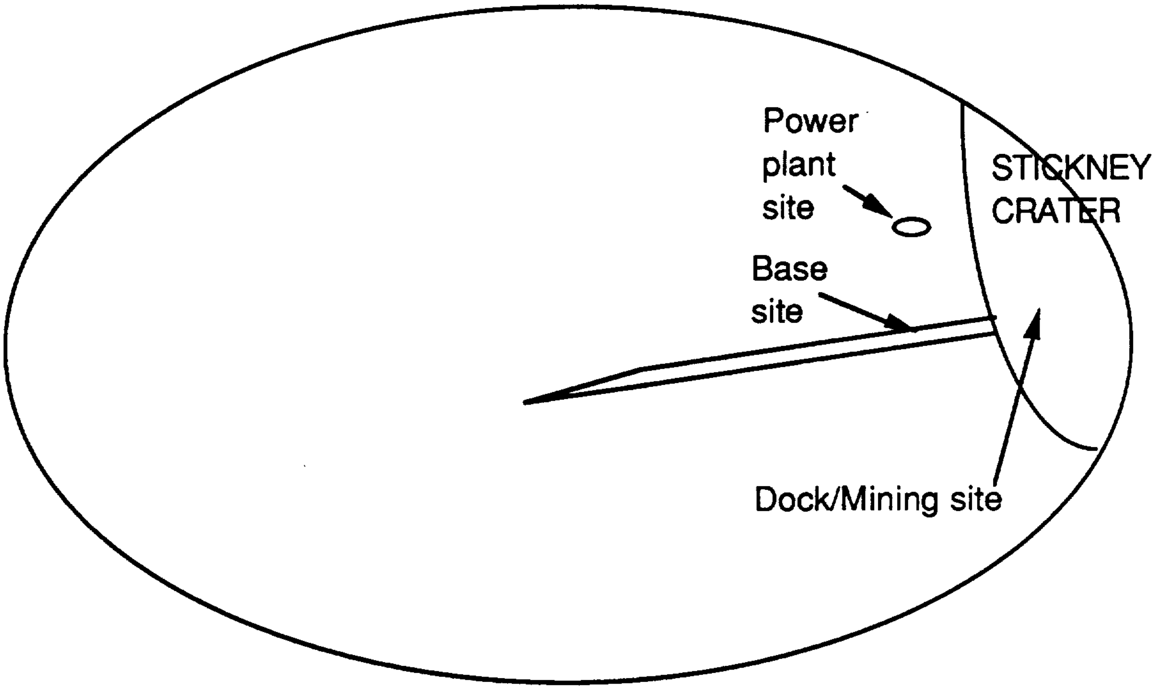


FIGURE 2-1: PRELIMINARY SITE LOCATIONS

2.2.2 Phase 2: Mining Site Construction

The first orbital maneuvering vehicle (OMV) deployed from the ITV will contain the mining equipment, refueling dock, construction robots, and approximately 70% of the surface transportation system. This package will be integrated with several of the ITV's fuel tanks and engines, so that these may be brought down to Phobos as well. The OMV will deliver the package to a smooth area of Stickney Crater indicated by the SEP. After delivering the package, the OMV will fly to the power plant beacon, laying cables along the way. These cables will transmit power to the mining system, and will serve as a path for the robots to follow to the power plant site.

Upon landing, the robots will receive a signal from the ITV to boot-up. They will climb out of the package, unload the foreman and the mining equipment, and will set up the mining site. Once the mining site is in working order (with the exception of power), the robots will follow the cable laid by the OMV to the power plant site.

2.2.3 Phase 3: Power plant site construction

The robots will prepare the power plant site by smoothing the site and removing any large rocks or other obstructions. The second OMV will deliver the power plant directly to the prepared site, then lay cable from the power plant to the base site beacon. This cable will provide power to the base, and will serve as a path for the robots to follow to the base site. The robots will make the power connection between the power plant and the mining site, and will initiate a checkout procedure of the power plant. They will then follow the cable to the base site.

2.2.4 Phase 4: Base site preparation

Upon arrival at the base site, the robots will smooth the area and remove any obstructions. When the site is ready, the third OMV will deliver the assembled base, the Radiation Protection System (RPS) components, and the remainder of the surface transportation system components. The robots will make the power connections between the base and the power plant, and will complete check-out of the base. Any problems found in the base systems will be repaired by the robots, or, if necessary, replacement parts will be brought from the ITV, or constructed using the laser sintering process. The robots will then assemble the RPS by assembling pre-constructed frames into a truss and filling it with Phobos regolith.

2.2.5 Phase 5: Surface transportation construction

The robots will then begin construction on the surface transportation system. Using the components sent in phase 3, the robots will construct the transportation leg between the base and the mining sites. At the mining site, they will use the components sent in phase 1 to construct the mining to power plant leg, and finally the power plant to base site leg.

3. BASE SYSTEMS

3.1 OVERVIEW

The base systems for the Phobos outpost includes all areas involving the manned interface. All systems have been designed to provide a habitable environment for a 6-man crew for 2-3 months. The operations to be supported include mining, fuel production, and Mars exploration and telerobotic base construction. The base systems are:

- Base location
- Base configuration
- Base interiors
- Radiation protection systems
- Life support and waste removal systems
- Emergency procedures
- Base structural integrety
- Construction sequence and robotic systems

The manned area of the base will be located on the side of Phobos facing Mars, in a trench near Stickney Crater. It is comprised of three main modules: Sick Bay, HQ/Laboratory, and Gally/ Recreation. The modules are connected by two storage nodes, with an airlock connected to one node. The crew quarters will be divided, two each, among the three modules. Radiation protection will be provided by regolith walls surrounding the base. The life support systems are partially closed, with the oxygen lost due to leakage being replaced by oxygen mined from Phobos. The thermal control system will consist of water and freon cooling loops. A fire suppression system, airlock, and the manned transfer vehicle provide for emergencies. The base will be made of aluminum shell to hold the pressure forces, with O-ring seals between modules and nodes. Autonomous robots will prepare the site, position the modules, construct the radiation protection system, and verify systems before the crew arrives on Phobos.

3.2 BASE LOCATION

The ideal base location on Phobos is on the side of Phobos facing Mars, inside a crater or trench. This location simplifies communications with a Martian base, while the trench walls provide radiation protection for portions of the Phobos base. A candidate site is shown in Figure 3-1 [3-1].

Figure 3-1 : Base Location on Phobos

The photo shows trenches originating at Stickney Crater and extending radially outward. These trenches are estimated to be 20 meters deep, extend 2-3 kilometers out of Stickney, and are approximately 100 meters wide [3-2]. The base will be placed in one of these trenches, and the power plant will be located approximately one kilometer away in a crater for crew safety.

The determination of which trench to use for the base will be determined from data provided by precursor probes to Phobos. These probes will seek a trench which is at lease 25 meters wide to allow for the base, the radiation protection, and space for expansion. The base site will be prepared by the construction robots, which will level the site and remove any obstructions.

3.3 BASE MODULES

The habitat for the Phobos mission will consist of three modules. Two of these modules, the Headquarter/Laboratory module and the Galley/Recreation module, will be standard size 15 ft. diameter and 21 ft. length versions. The third module, Sickbay, will be reduced in size to 9 ft. in diameter and 21 ft. in length. The habitat will be arranged in a triangular configuration along the longitudinal axis, with the two larger modules on the surface and the third module resting on top, as presented in Figure 3-2.

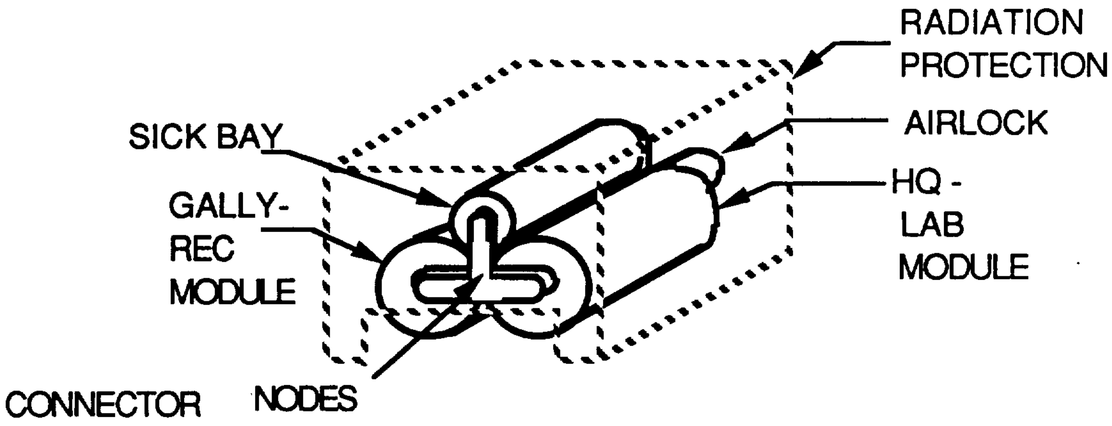


FIGURE 3-2 BASE CONFIGURATION:

3.3.1 Headquater/Laboratory Module

The Headquater (HQ) module will be the center of activity for the manned Phobos missions. All equipment for communication with Earth will be located in the HQ module. Also, several control and monitoring systems will be housed here. These systems will control explorer probes, rovers, and other EVA activities. They will also monitor the life support atmosphere, fire supression system, solar and meteorite activity, Martian weather and the Phobos mining processes. All of these systems will be linked to the Central Information Management Control System (CIMC), which will provide easy access to the stored data.

The Laboratory section of the module will provide an area to conduct experiments. Material research and sample analysis are possible uses for the laboratory (LAB).

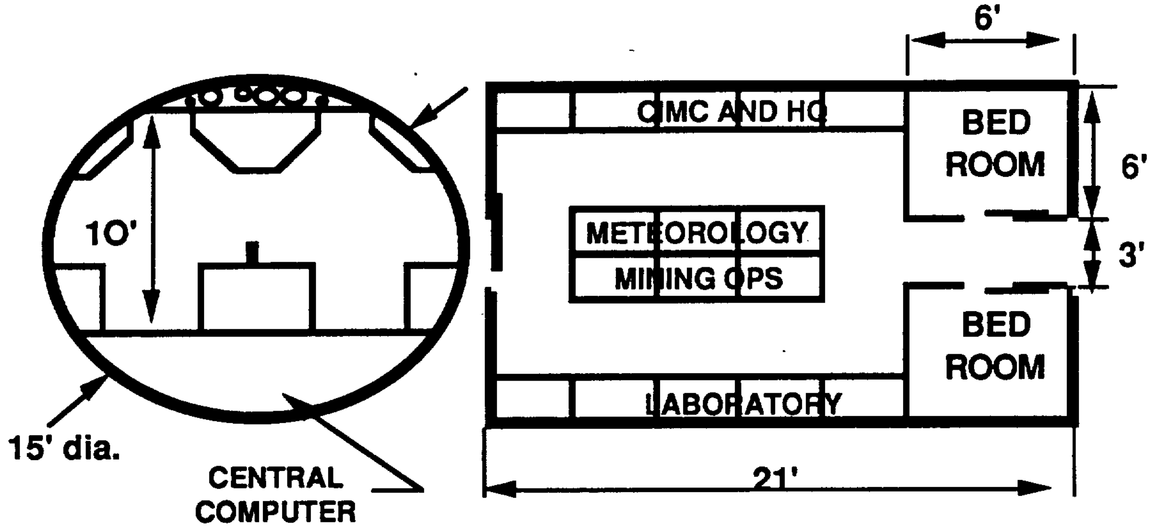


Figure 3-3 : Headquarters/Laboratory Module

Finally, the HQ/LAB module will contain bedrooms to house two crewmembers. A layout of the HQ/LAB module is presented in Figure 3-3.

3.3.2 Galley/Recreation Module

The Galley/Recreation module will be an area of relaxation for the crew, essential for their psychological well-being during long term space missions. Located here will be food storage, preparation, and dining facilities. A personal hygiene area will enclose a toilet, shower , and a small laundary.

An exercise area will be provided to maintain the fitness of the crew. Recreation equipment will be stored in the dining and exercise areas. Television will be broadcast from Earth as requested by the crew. Two bedrooms are also included in the Galley/Recreation Module. The configuration of this module is shown in Figure 3-4.

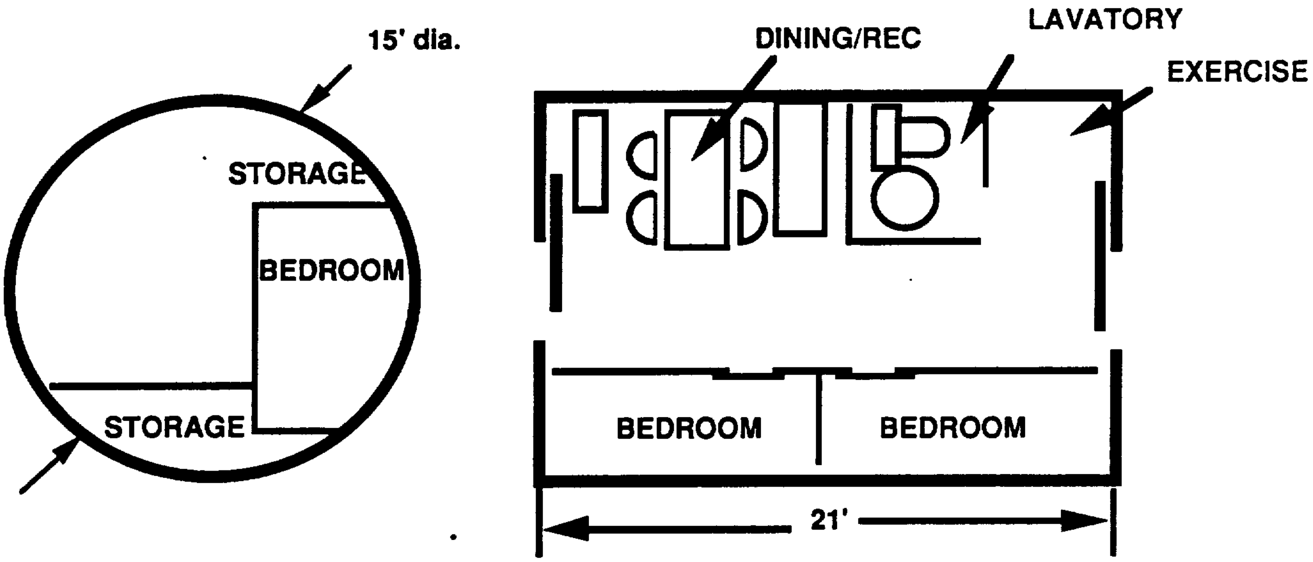


Figure 3-4 Galley/Recreation Module

3.3.2 Sickbay Module

The Sickbay module will serve the medical needs of the crew. Included will be a complete assortment of equipment and supplies needed to maintain the health of the crew in foreseeable situations. According to NASA's Jet Propulsion Lab (3-3), the following should be included:

- Diagnostic tools(x-ray,analysis of blood,urine,and tissue)
- General physical examination materials
- Respiratory support
- Cardiovascular support
- Complete pharmacopeia
- Limited dental and surgical equipment
- Computer-based medical library
- Communication for medical consultation with Earth.

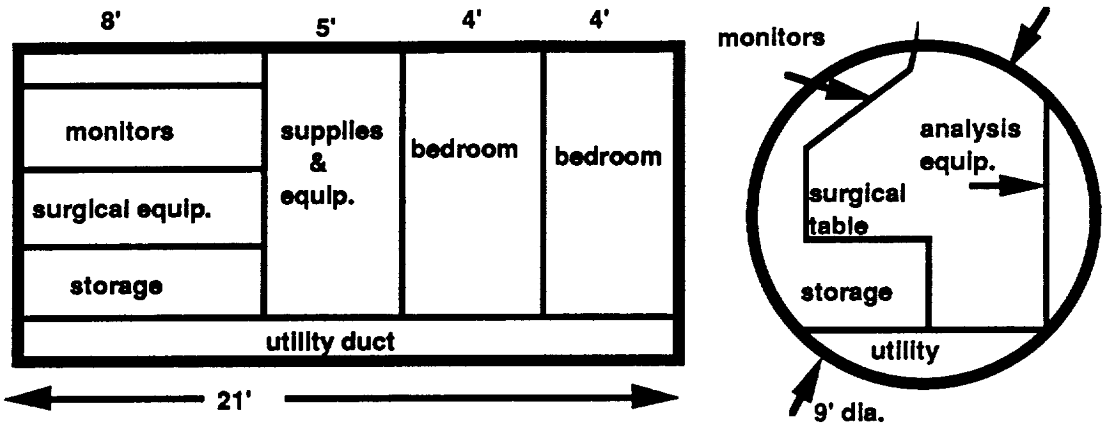


Figure 3-5 : Sick Bay Module

Also, included in the Sickbay module will be two bedrooms which will serve as recovery rooms when needed. A layout of the Sickbay module is provided in Figure 3-5.

3.3.4 Robotic Manipulation of the Modules

Once the base site has been prepared, the base assembly will be delivered by the OMV, and a checkout of the base systems will be performed by the robots. The robots will activate the monitoring systems aboard the modules, which will evaluate the condition of the base, pinpoint any problems, and transmit diagnostic data to Earth. If a problem is detected, the robot will be programmed to repair the system, or, if necessary, a replacement will be sent from the ITV.

3.4 RADIATION PROTECTION SYSTEM

An inherent danger in the achievement of the Phobos mission is exposure to solar and cosmic radiation. Prolonged exposure to this radiation is harmful to humans and equipment, thus radiation shielding is required.

3.4.1 Radiation Dangers

The workshop on Radiation Constraints for Exploration class missions [3-4] defined three sources of radiation necssary to consider in any long-term system design.

Van Allen Belt Radiation is a small amount of raidation trapped within the Van Allen Belts. It does not constitute a threat if transit time through the belts is short-term.

Solar Particle Events (SPE's) are the periodic flux of protons of helium, and other heavy ions due to solar flares. The effects of SPE radiation can be fatal to the crew if a craft encounters a burst without adequate protection.

Galactic Cosmic Radiation (GCR) is a predictable, continuous flux of high energy protons and heavy ions. The danger of GCR is due to the penetration power of the high energy particles, and the biological damage caused by the heavy nuclei. However, on planets and moons, the shielding of the planet surface reduces the flux from GCR by approximately half.

The workshop also determined that the maximum allowable dose equivalent of radiation to blood forming organs is 50 rem per year. In comparison, the highest measured exposure for a Shuttle mission in LEO is 0.56 rem per year, assuming the crewmember flies one mission per year.

3.5.2 Preliminary design

To provide radiation shielding for the crew and equipment inside the base, Phobia has designed a box-like retaining truss, which will surround the base on all sides with one meter of regolith (Figure 3-6). Phobia has determined that one meter will provide sufficient radiation shielding from both SPE's and GCR [3-5].

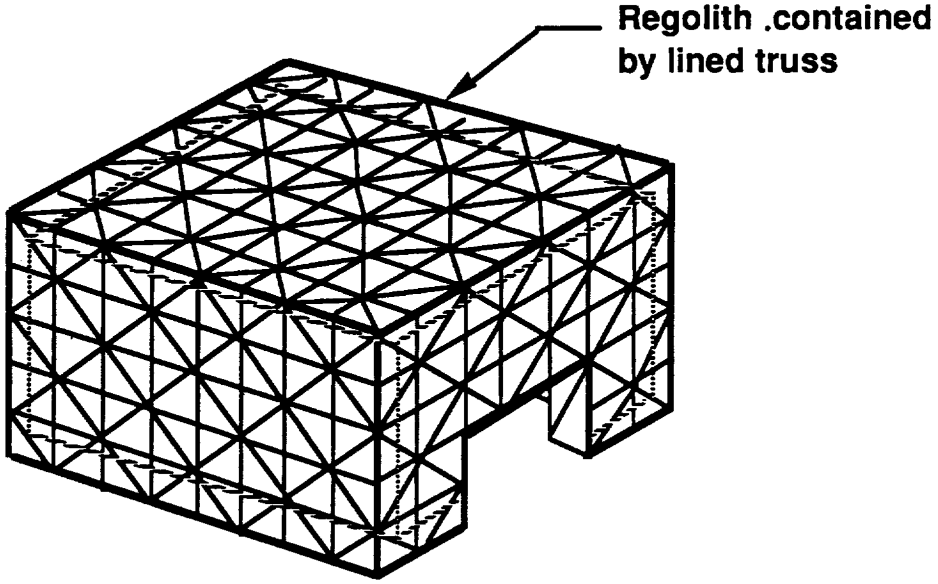


Figure 3-6 Radiation Protection System

The truss will be constructed of 5.08 cm diameter graphite-epoxy tubes, which are strong enough to support the mass of the regolith, but are light weight and cost effective. The box will have outside dimensions of 14.6 m long by 12.8 m wide by 9.14 m tall (48 x 42 x 30 feet). The inner dimensions are 12.8 m x 11.0 m by 8.2 m (42 x 36 x 27 feet). Each truss area will be six feet on a side, with a cross piece for structural integrity. The structure will have a mass of approximately 9000 kg.

The truss will be lined with a containment sheeting which will keep the regolith inside the truss. The sheeting must be flexible, to accomodate the shifting regolith without ripping,and must be able to adapt to the thermal elements on Phobos. Phobia has chosen to use Teflon sheeting for this purpose, because of its light weight and strong nature. The Teflon will also provide additional radiation protection. The loading on the sheeting would be similar to the loading on a swimming pool liner - with maximum stress at the bottom [3-6]. Approximately 1200 sq. meters of sheeting will be needed, which corresponds to a mass of 20,000 kg.

3.5 LIFE SUPPORT

Current work on the Phobos base life support system has been focused on the environmental control and life support system and the thermal control and heat management system. These systems are responsible for maintaining a breathable atmosphere and a comfortable climate for the crew.

3.5.1 Environmental Control

The environmental system will provide: a 20% oxygen, 80% nitrogen mixture regenerating 4.790 kg of Oxygen per day [3-7], a constant pressure of 14.7 psi, and an average 20% humidity level. The amount of oxygen is based on a 6 member crew.

A partially closed system was chosen on the basis of its being more efficient and than a partially open system. The partially open system would simply have discarded the astronauts' exhaled carbon dioxide and thus wasted the oxygen and carbon in those molecules.

The closed system chosen was developed for a lunar base by the Selene Engineering Company and is descibed in detail in Ref. 3-7. This system will first separate carbon dioxide from the atmosphere, then use a series of chemical reactions, sabatier, pyrolysis, and electrolysis, to separate it into oxygen and carbon. Oxygen will then be redistributed in the base, and the carbon, will be held in storage. The reaction equations for this process are:

1. Sabatier $CO_2 + 4\,H_2 \rightarrow CH_4 + 2\,H_2O$
2. Pyrolysis $CH_4 \rightarrow C + 2\,H_2$
3. Electrolysis $2\,H_2O \rightarrow 2\,H_2 + O_2$

Therefore, $CO_2 \rightarrow C + O_2$.

Due to the high effeciency of the module seals and the 99.87% air recovery ratio of the airlock pumps, oxygen and nitrogen leakage will be minimal [3-8]. Air leakage calculations in Appendix A show that approximately .0746 kg of nitrogen and .0186 kg of oxygen will be lost during a two and a half month period. Therefore, it will only be necessary to carry a small replenishing supply of nitrogen from Earth while excess oxygen will be mined on Phobos.

A ten day backup supply of oxygen will be mined on Phobos prior to the arrival of the crew.

3.5.2 Thermal Control and Heat Management

The system chosen for thermal control and heat management was taken from reference 3-7. The thermal system design for a lunar shack vehicle was highly compatible with the needs for the Phobos base. Criteria for development of the system were that it must be capable of:

- maintaining a comfortable and liveable cabin temperature
- collecting and transfering excess heat from crew and equipment
- dissipating heat.

The heat collection system consists of Heat-Exchange Elements (HEE) connected to a Water Coolant Loop (WCL) which feeds into a Freon Coolent Loop (FCL). The HEEs are dispersed throughout the cabin to collect heat through the airflow and transfer it to the WCL. The WCL consists of a network of pipes running through the cabin walls and carrying water heated by the HEEs to the FCL. Water for these pipes can be obtained on Phobos and injected into the system before the crew arrives. The FCL then absorbs heat from the water and returns it to the WCL. By the time the Phobos base is constructed, a more efficient and safer gas than freon will probably be in use, but for the purposes of this preliminary design, freon is an acceptaable material as long as the FCL is located on the outer surface of the base to avoid poisoning of the cabin atmosphere.

The heat reflection system uses Water Reservoir Heat-Exchangers (WRH-E) connected to the FCL as a sink, to dissipate heat into the Phobos environment, and as a source, to store heat for cabin heating purposes. Excess heat is dissipated through an internal coolant loop exposed to the environment while heat needed for warming the cabin in colder periods can be transferred back through the FCL. There are two WRH-E's for redundancy purposes which are located on the airlock.

More detailed information about all of the aforementioned systems can be found in reference 3-7.

3.6 SEALS

The seals used in this design can be divided into two types, those for the modal connection nodes and those for the airlock. It is desired to use similar seal types as for both purposes if possible.

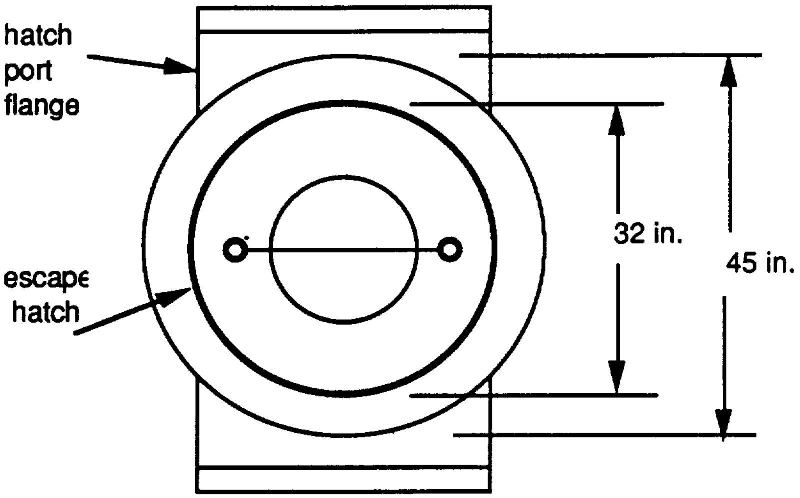
3.6.1 Modal Connections

Modules and airlocks will be mehcanically joined with the sealing system being used for the Space Station. Mechanical joining involves male/female joints held air tight by the force of the pressure in the airlocks and modules, and reinforced with O-ring seals. This method of joining was picked over adhesive bonding and welding for its compatibility with adding expansion modules and, in the case of sickbay, removing modules. Also, since oxygen can be mined in abundance on Phobos, the small amount of extra leakage that pressure seals have over welded seals is not of excessive importance.

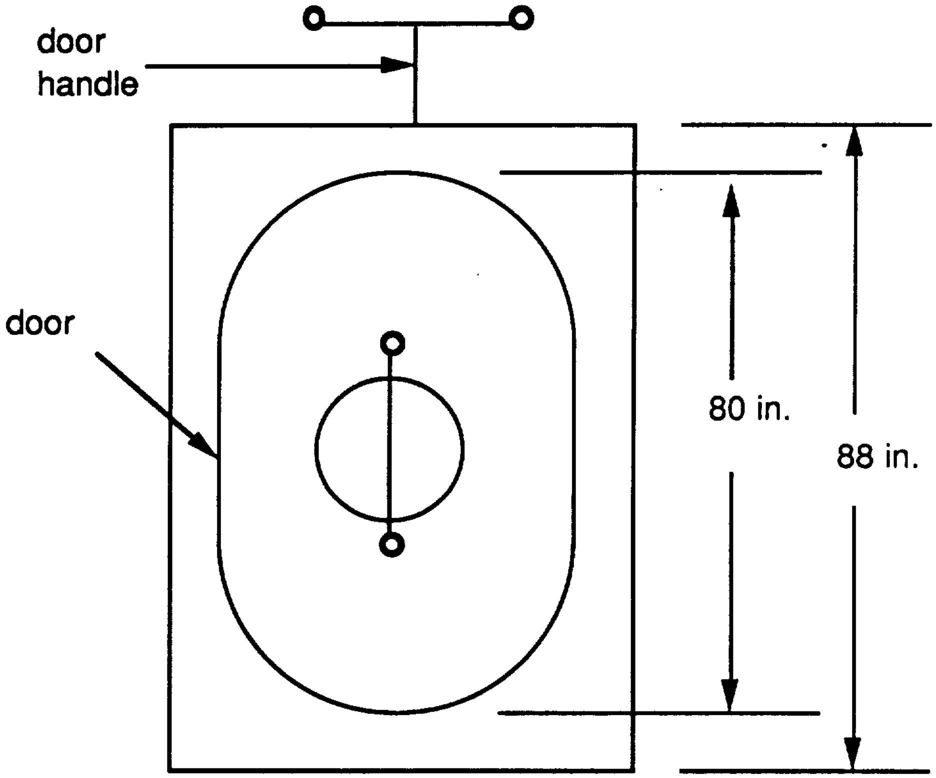
3.6.2 Airlocks

The airlock system chosen was designed for USRA by University of Texas at Austin Mechanical Engineering studens [3-8]. This airlock system was chosen for its minimal leakage, compatibility with the base design, redundancy with module seal design, and its safety features.

The airlock is cylindrical with two doors and an escape hatch, as shown in Fig. 3-7. Since the base will not be buried, the requirement for a third door leading to the surface of Phobos was eliminated. The door/module interface uses O-ring seals while a rotating seal is used for the locking system inside the door. A sliding vane pump is used for air removal and is capable of evacuating the airlock from atmospheric pressure to 1 torr in 55.7 seconds. Measurement devices and instrumentation are supplied for monitoring temperature, pressure, door status, and leakage. Thermocouples, strain gauges, and four magnetic proximity sensors are used for each of the first three functions respectively. Leakage will be determined using temperature



Top View



Front View

Figure 3-7 : Minimum Loss Airlock

and pressure status. Materials used for the airlock are: graphite reinforced plastic for the inner wall, an aluminum matrix composite for the outer wall, and fiberglass insulation between. A more detailed description of all the features of the airlock can be found in Reference 3-8.

3.7 FIRE SUPPRESSION SYSTEM

A fire suppression system in the Phobos base modules will be utilized in order to minimize possible damage from electrical and chemical fires. The system will be composed of detection and extinguishing subsystems.

The detection subsystem will be composed of several ionization detectors in each compartment, all linked to the central information management system. These detectors operate on the principle that smoke particles impede the mobility of air ions in a chamber, changing the current level to trigger an alarm [3-9]. The CIMC will monitor these detectors and alert the crew when necessary.

The extinguisher subsystem will consist of portable and fixed extinguishers. Two types of portable extinguishers will be employed. A water-based celulose foam extinguisher will be used to combat small open chemical fires. Secondly, a halogenated hydrocarbon (Halon) portable extinguisher will be used to combat small electrical fires. To facilitate the use of a Halon portable extinguisher, all instrument panels will have an attachment port for the extinguisher.

An extensive fire, which encompasses an entire module, will be combatted with a fixed Halon extinguisher. This system will be manually activated at the connection node, after the module has been evacuated and sealed. After the fire is extinguished , the module will be vented, repressurized and evaluated for safety.

In the event that an extinguisher is used, limited recharging capabilities will be available.

3.8 COMMUNICATIONS NETWORK

The assembly and operation of the Phobos outpost requires a continuous, reliable communications link. Instructions and other information will be exchanged by robots during deployment of the base elements, and periodic monitoring of these activities from Earth is required. Also, later manned missions will perform telerobotic activities, both on Phobos and Mars. Finally, development and operation of a Mars base will require a continuous link between Phobos and Mars.

3.8.1 The proposed initial system

Because of the unusual shape and rough surface of Phobos, line-of-sight communications are impossible in most scenarios. Furthermore, Phobos orbits Mars every 7.5 hours, preventing a direct, continuous link between the two. A network of communications satellites which overcomes both of these problems has been designed by the STAR TRUK Company [3-10].

A schematic of the initial communication system is shown in Figure 3-8. The system has three co-orbiting elements: the Phobos base, a dedicated communications satellite, or comsat, and the ITV. During deployment of the base systems, the ITV will be stationed at least 10 km off the leading side of Phobos, providing coverage to most of this portion of the moon's surface. In addition, the CIMC will have the capability to communicate with the robots from onboard the ITV, before its deployment, in case of a problem with the Foreman, or chief robot. Communications to or from the trailing side of Phobos will use the comsat, which trails Phobos by 120 degrees, to reflect signals back to the ITV. Communications with Earth will be provided by either the ITV or the comsat, whichever is in the Earth's line-of-site. A subsequent, redundant system, consisting of Mars-synchronous satellites, will be deployed when the Mars base becomes operational.

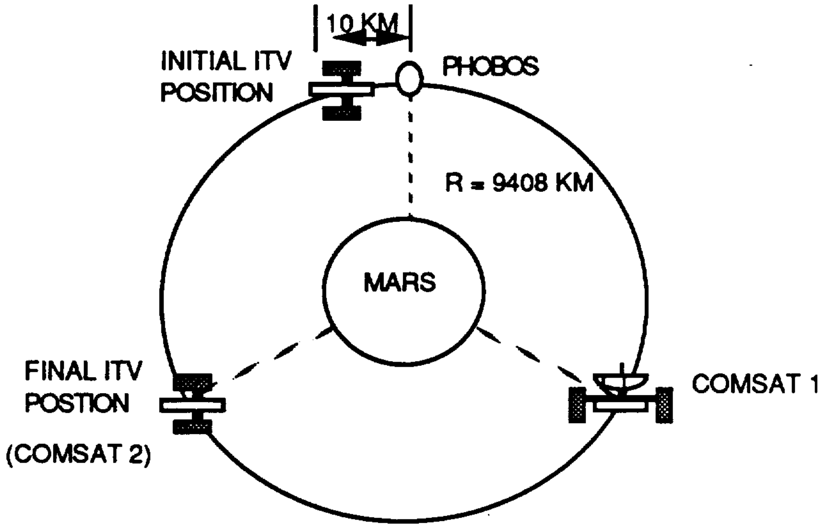


FIGURE 3-8: SCHEMATIC OF INITIAL COMMUNICATIONS SYSTEM

After assembly of the Phobos outpost, the ITV will move to a position 120 degrees ahead of Phobos. At this stage, the three main elements of the outpost on Phobos, the base, the mining/dock facility, and the power station, will be linked directly by cables. However, robotic operations will still require the communications network.

3.8.2 Antennas

Twin-gimballed dishes will be mounted to the base, the docking facility, and to each of the robots. While simpler, uni-directional antennas could be used for the base and the dock, such systems cannot be reoriented in case of a failure in the network. The antenna on the base will be nominally pointed to the ITV, and the dock antenna toward the comsat. Due to geographical constraints, these antennas cannot switch targets.

3.8.3 Operator

After full deployment of the base, communications can occur along several redundant routes, e.g. robot to robot; robot to comsat, comsat to ITV, base to dock, etc. It is likely that several links will be operating at any given time, as well. To efficently coordinate these transmissions, an operator is required. This requirement will be fulfilled by one of the expert systems aboard the CIMC. Redundant programs will reside in the Foreman and the ITV.

3.8.4 Navigation using the communications system

Although the robots will have advanced pattern recognition systems with which to navigate on Phobos, the possibility exists that they could become lost. In this event, the comsat and the ITV could be used by the robot to triangulate its position, assuming both were visible. In the event that only one is in sight, a method by which signals from the robot could be polarized by the comsat (or ITV) depending upon their incident angle could be developed. The robot would then measure the degree of polarization of the returning signal, and thus determine its postion with respect to the comsat. By measuring the time of travel for the signal, the robot would also know its distance from the comsat. Then, based on precise knowledge of the positions of the satellite and Phobos, the robot could determine its location on the moon.

4 MINING SYSTEMS

4.1 OVERVIEW

One of the primary uses for the Phobos base is as a fuel stop for interplanetary missions. Phobian regolith contains a significant quantity of water, and this water can be separated into liquid hydrogen(LH2) and oxygen(LOX) for use as rocket fuel. The regolith also contains various metals, which could be used to construct or repair the base and mining modules.

The mining process consists of four steps : collection, processing, storage, and transportation. In collection, the regolith is gathered and moved to the processing plant. In processing, the regolith must be crushed and separated into its various elements. The finished products are then sent to storage facilities. Finally, the LOX and LH2 must be transported to ships needing fuel.

Two options are being considered for the Phobos mining operation. In one scenario, the collection, processing, and storage of the regolith would all be done on the surface of Phobos. Alternately, tunnels could be bored into the regolith and the mining operations carried out underground.

Three possibilities have been considered as means of transporting the fuel to visiting ships. One possibility is to build a dock on the surface of Phobos and have the ships land there to be refueled. Alternately, an OTV carrying fuel could deliver the propellant to an orbiting dock located between Phobos and Mars. It would also be possible to build a vehicle capable of latching itself to a ship and fueling it in orbit around Mars.

4.1.1 Mining systems requirements

PHOBIA Corporation calculations estimate that 2017 metric tons of fuel will be required from the Phobos mining unit. This estimate assumes 621 tons are used in missions to the outer planets and 1396 tons are required for transport between Phobos and Mars [4-1]. The fuel calculations are given in Appendix B.

Since 250,000 kg. of regolith must be processed in order to obtain 15000 kg. of LOX, all mining designs must be capable of moving 33,620 tons of regolith per year, or 92 tons of regolith per day. As Phobian regolith has a mean density of 200 kg. per cubic meter, a quarry 460 cubic meters in volume will have to be excavated daily.

4.2 SURFACE MINING

Surface mining will be accomplished through the use of two tracked, roving vehicles, one of which will be a simple transport cart and the other an autonomous robot dedicated to mining tasks. The robot will be responsible for clearing paths from the processing plant to the mining area as well as programming the transport cart and digging. Sensors on the miner will be able to estimate the mining qualities of an area (density, content, accessibility) to determine the best sites. Candidate mining sites will be selected from a half-circular area on the side of the processing plant opposite the storage facilities. Figure 4-1 shows a general surface mining configuration.

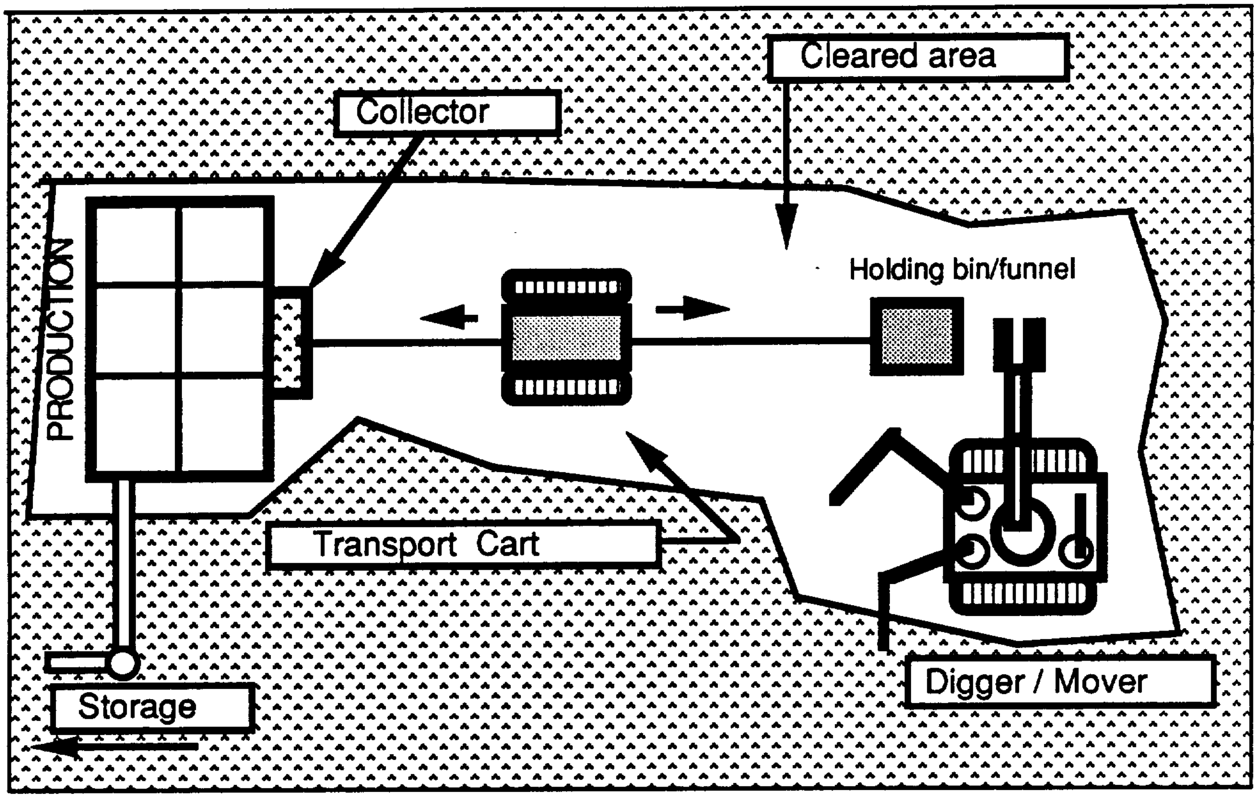


Figure 4-1 Surface Mining Layout

Since fuel production is not needed immediately and will eventually be a slow steady process, stockpiling of mined regolith will be possible. The regolith piles could be housed in structures similar to the one used for the base's radiation protection and would be placed close to the processing unit.

4.3 SUB-SURFACE MINING OPTION

This field of study focuses on the option of underground mining. This field is meant to be a long term expansion option only. Research and deliberation has illustrated that the surface mining method is both more feasible and less complicated. The tunnels created during the mining process could be used for future underground or base expansion.

4.3.1 Processing Plant Location

A candidate location for a sub-surface processing plant is inside Stickney Crater. This location limits the need for rigorous digging and avoids the safety risk associated with shaped explosives, which would be required to place the plant underground. The Stickney location also provides some protection from radiation and meteorites. Also, the plant will have direct access to the mining tunnels, below the surface, due to the depth of the crater.

4.3.2 Tunneling Device

Figure 4-2 shows one possible sub-surface tunneler that can be converted into a mining vehicle[4-2]. The tunneler and an excavation truck will be controlled by the on-board general purpose computers. Instead of locating the heating plates in the cutting head, the plates will be remounted adjacent to the cooling plates behind the drill head. This modification allows the tunneler to intake granular regolith instead of molten regolith, as in the previous design. In melting the regolith, the water trapped as water of hydration was dissipated away as steam. The new design allows the granular regolith to pursue the length of the pipe into the excavation truck while some of the flow is diverted to the heating and cooling plates in order to solidify the tunnel walls. The tunnel's new glass-like walls will prevent cave-ins and alleviate the need for heavy trussing structures. After the regolith is dumped into the excavation truck (Fig. 4-3) the regolith can then be easily transported.

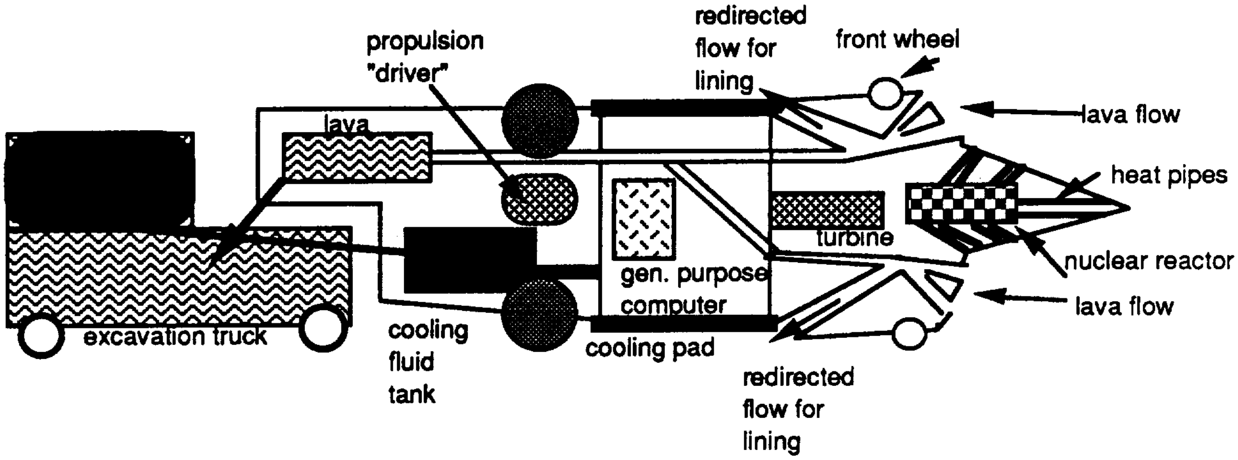
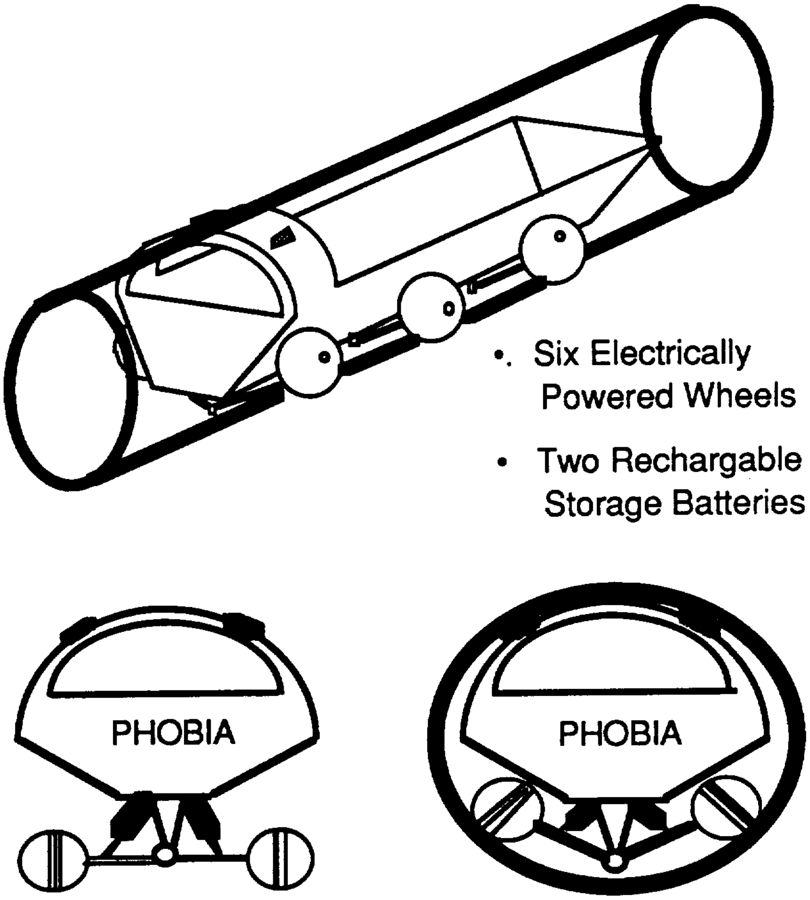


Figure 4-2 Sub-Surface Tunneler
Texas A&M Design [Ref. 4-2]

4.3.3 Further Research

One possible idea for future research includes pressurizing the tunnel by capping the open end of the tunnel with an airlock large enough to accomodate the excavation truck[4-2].



- Six Electrically Powered Wheels
- Two Rechargable Storage Batteries

On Flat Land

In Tunnel

Figure 4-3: Excavation Truck

4.4 REGOLITH PROCESSING

The regolith provided to the processing unit will undergo several treatments on its way to becoming fuel, water and breathable air. Most of the required steps will take place within the processing unit which will house individual sections for each process. The processing unit will be modular in design to allow for quick exchange of broken components by either the mining or construction robots. A breakdown of basic sections based on information from the IGS report [4-1] is shown in figure 4-4.

The processing plant to be used will be smaller than, but based on the one described in the IGS report. The first step in the process will be to accept the regolith into a receiving bay. From there, the material will be crushed to a manageable size and separated magnetically. This separation will sift out metals in the material which will be stored on the Phobian surface. The transport cart that delivers the regolith will be used to relocate this material. The next step is to bake the regolith to vaporize the water trapped within the material. This baking will produce a vapor, which will be condensed, and other waste material which will be saved as a possible source of ceramics in the future. The trapped vapor will contain several, possibly useful, gasses other than water which could be saved depending on storage space. A filter would then be needed to further purify the water before it is stored.

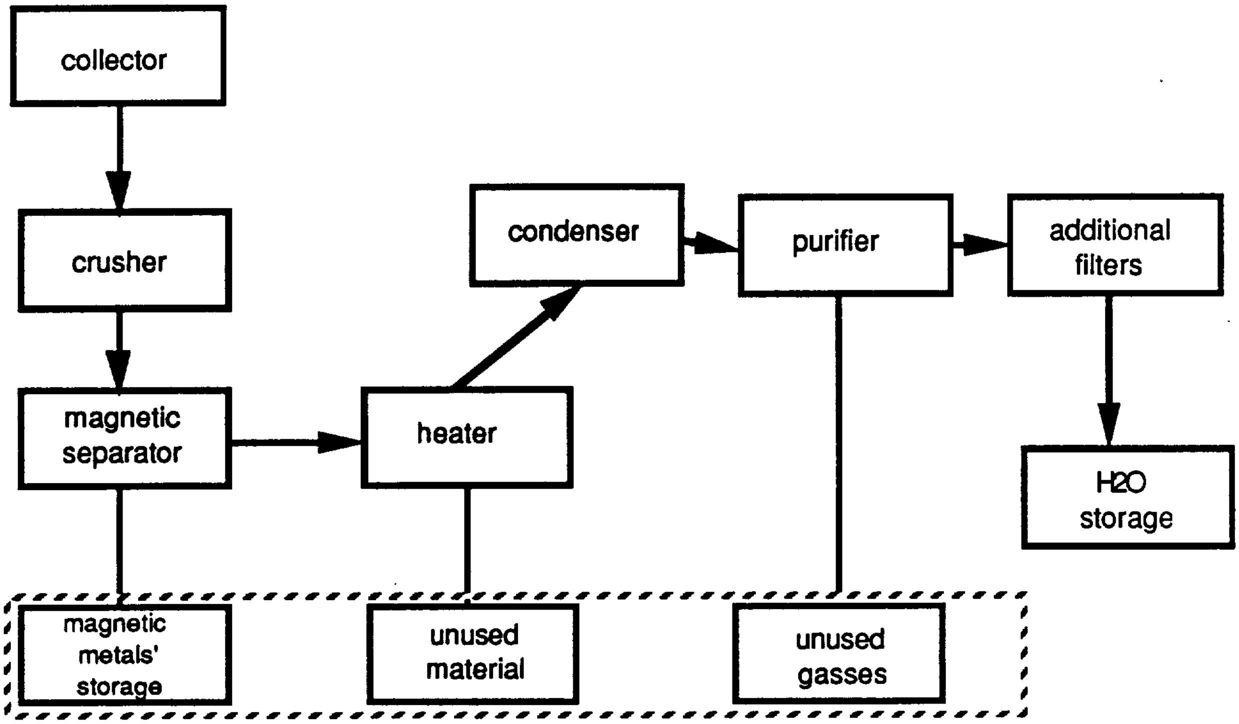


Figure 4-4 Water Production Sequence

The fuel production process will be completed through an electrolysis unit which will be separate from the main processing plant and situated near the LH2-LOX storage facilities to limit the transport of sensitive fuels.

4.5 FUEL STORAGE AND TRANSFER

4.5.1 Fuel storage

Primary storage will be used for water, as it is safer and easier to store than the eventual end products of liquid oxygen (LOX) and liquid hydrogen (LH2). These products will be produced on an as-needed basis to limit their storage requirements.

Two methods of water storage will be used. In the initial stages of fuel production, spent fuel tanks from the ITV will be used to store the water. As more space is needed, tanks may be manufactured from concrete or metals mined from Phobos.

Some storage must also be provided for the LOX and LH2. Fuel tanks may be scavenged from cargo ships. or manufactured expressly for the use of the mining facility on Phobos. All LOX-LH2 tanks must be carefully inspected before being delivered to Phobos due to the fact that they will be used to store highly combustible fuel.

4.5.2 Transfer of fuel to interplanetary vehicles

Three options have been considered as means to transport the LOX to spacecraft needing fuel. One way to transport the fuel would be to alter the cargo dock on Phobos so that spacecraft could land there to be refueled. This method would be very reliable, as the fuel lines and the damping mechanisms are the only components that would have to be maintained.

Alternately, a shuttle vehicle could supply all ships needing fuel. Two ideas using the fuel shuttle have been developed. One possibility would be to have the fuel shuttle capable of clamping itself to the interplanetary spacecraft and refueling the ship while in orbit around Mars. Another plan would have the fuel drop its fuel loads at the Mars transport node located in low Mars orbit. This orbiting cargo dock would then service each ship needing fuel. If the fuel shuttle concept were used, however, it would still be necessary to build the surface dock so that the shuttle could land on Phobos to pick up the fuel.

The decision matrix (Table 4-1) used to decide on a fuel transport system rates the various options on a scale of 1 to 3, with 1 being the highest rating. As shown, the surface dock ranks highest in nearly all categories. It is safest because low risk is involved with the proximity maneuvers required with the fuel shuttle, and it is most reliable because few components can malfunction. If the fuel shuttle concept were used, interplanetary vehicles would have to move towards Mars' gravity well in order to re-fuel, and thus would have to expend more energy escaping from the planet. Also, the fuel shuttles themselves would have to expend propellant in carrying their fuel loads to the dock. Therefore, the surface dock option is most efficient in the use of fuel.

TABLE 4-1
DECISION MATRIX - FUEL TRANSPORT SYSTEM

	A - SURFACE DOCK ONLY	B - LATCHED FUEL SHUTTLE	C - FUEL SHUTTLE WITH ORBITING DOCK
RELIABILITY	1	3	2
FUEL EFFICIENCY	1	2	3
EASE OF USE	2	3	1
SAFETY	1	3	2

The one disadvantage in using the surface dock alone is that orbital transfer and orbital maneuvering vehicles operating between Phobos and Mars would have to stop at the dock at every transfer they made (hence the rank of 2 under 'ease of use'). One way to eliminate this disadvantage would be to have an OTV, operating in conjunction with the orbiting dock, pick up just enough LOX for maneuvers between Phobos and Mars. Vehicles on their way to missions on the outer planets would dock at Phobos to refuel.

5. SURFACE OPERATIONS

5.1 OVERVIEW

The Surface Operations division of PHOBIA corporation is responsible for the design of the docking and transport facilities on Phobos, and for the exploration of the Phobos-Mars system. Surface Operations responsibilities have been divided into four categories : preliminary geological research, dock and anchor designs, Phobos exploration, and surface transportation.

The first step in establishing the Phobos base will be to build a dock to which cargo can be delivered. Later, once the base modules have been constructed, a dock for the manned lander will be built to accommodate the crew. When mining operations have been started, the cargo dock will be modified so it can be used to repair and refuel ships bound for missions to the outer planets.

Research has been done on the geology of Phobos so that PHOBIA designers can take into account the special problems and advantages of working on this moon. The information discussed in Section 5.2 was taken from the Mariner probes launched in 1971-1972, so some of the data may not be sufficiently accurate. When information from future missions becomes available, the data will be updated.

Even if better geological data becomes available in the future, it will almost certainly be necessary for the Phobos mission to do exploration of its own. Probes launched on Phobos will perform geological surveys, map the surface, and help in selecting the mining and base sites. Once the base is established, other probes will explore the Mars system.

A transportation system will also be needed, both to aid in exploration and to move crew and equipment. A short-range transport system will be used for crew transport around the base and mining sites, while a separate long-range system will be used to move bulky equipment over distances of several kilometers.

5.2 GEOLOGY

Phobos' geology was studied to aid in designing the base. Table 5-1 contains the orbital parameters and characteristics for Phobos [5-1,2,3,4]. The geological data in Table 5-1 was supplied by the Mariner 7 and Mariner 9 probes.

Table 5-1 : Geographical Data for Phobos

Distance from Mars at Mean Opposition = 9400.416 KM
Sidereal Period = 0.319 days
Inclination = 1.9 degs
Eccentricity = 0.019
Visual Magnitude at Opposition = 11.5
Dimensions = 27.0 x 24.1 x 19 KM
Assumed Density = 3.34 G/CM^2
Mass = 7.16 E+15 KG

Orbital Velocity	= 2.14 KM/S
Orbital Period	= 7.65 HR
Surface Gravity	= 0.745 CM/S^2
Escape Velocity	= 12 M/S
Average Temperature	= 300 K
J2	= 2.0 E-3
Rotation	= SYNCHRONOUS
Albedo	= 0.05
Average Depth of Craters	= 50 M
Estimated Depth of Trenches	= 20 M

Comparative analysis of this information was used to supply the most current data. As new findings become available, the PHOBIA data base will be updated. The element composition of Phobos was also investigated. Table 5-2 contains the element composition of the Type-1 Carbonaceous Chondrite, Phobos.

Table 5-2: Element Composition of Type-1 Carbonaceous Chondrite

ELEMENT	PERCENTAGE BY WEIGHT
SiO_2	23.08
H_2O	20.54
FeS	16.88
MgO	15.56
FeO	10.32

C	3.62
Al2O2	1.77
CaO	1.51
NiO	1.17
Na2O	0.76
Cr2O3	0.28
P2O5	0.27
MnO	0.19
Fe	0.11
TiO2	0.08
K2O	0.07
Ni	0.02

5.3 DOCKING AND ANCHORING FACILITIES

Two different dock designs will be used. One type will be needed for the vehicles transporting cargo and supplies to and from the Phobos base and another will be needed for the manned landing ship that will arrive to check out the base after the robotic construction has been completed.

5.3.1 Manned Lander dock

The dock built to accommodate the manned ship will be built into the airlock of the base modules. The dock will be designed in such a fashion that the crew can exit their ship directly from the nose cone into the airlock. After the crew exits the lander, the ship will remain attached to the dock to serve as extra storage space, living space, or an emergency escape vehicle.

5.3.2 Cargo dock

The cargo dock, shown in figure 5-1, will be contained in the first package delivered to Phobos. All vehicles delivering parts and supplies to Phobos will use this dock. Later, when LOX mining operations begin, ships needing to pick up fuel packages or re-fuel for interplanetary missions will land here. A small hangar for Phobos-Mars transports will be constructed next to the dock as soon as the robotics systems arrive.

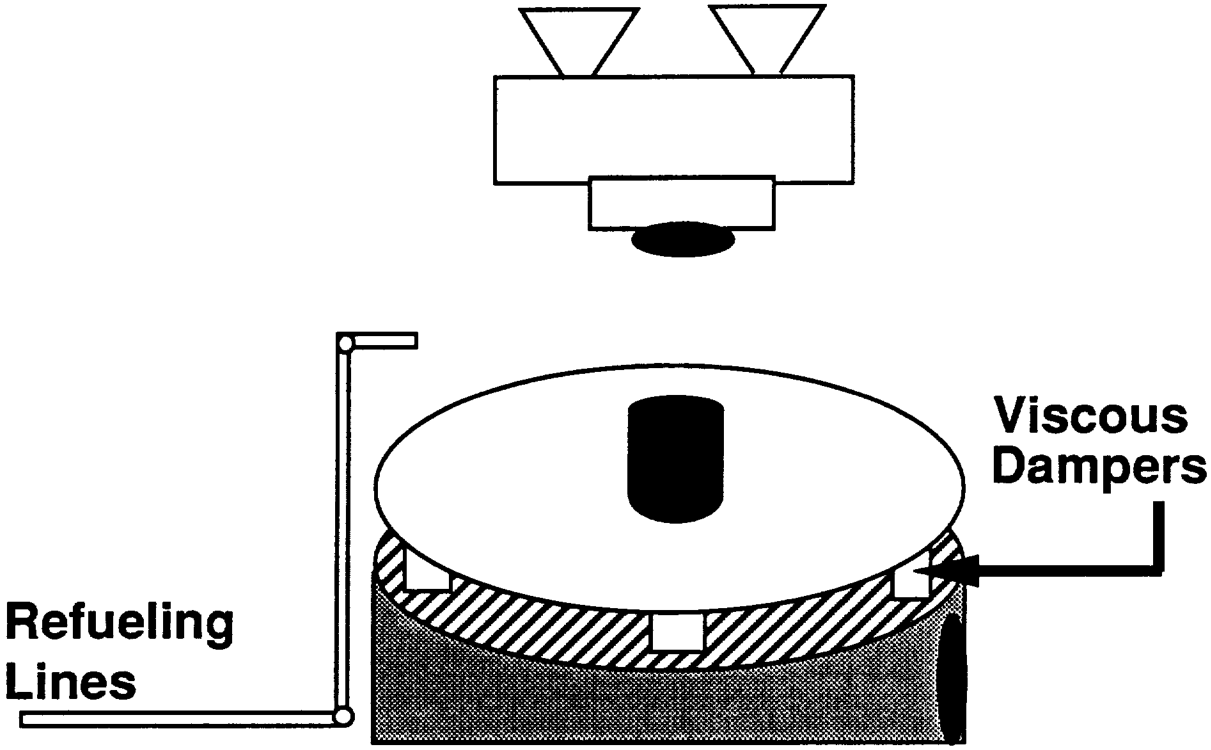


Figure 5-1 Refueling Dock

In order to prevent dust from damaging the rockets, all ships will land nose first into the dock. The latching mechanism, located in the center, will hold the ships in place. Fuel will be loaded into the craft by means of fuel lines leading from the fuel processing plant. Three viscous dampers will be built into the dock to reduce the vibration response of the ship.

5.3.3 Anchors

Because of the milli-gravity environment on Phobos, light equipment can be moved inadvertently by even small disturbances. Therefore, anchors must be used to hold a surface transportation system and lighter processors in place.

Two anchor designs have been considered, one for temporary and one for permanent anchoring. The temporary anchoring device is a diamond shaped screw that can drill either upwards or downwards. To set the anchor, the drill bores down into the surface of the regolith. When the anchor must be moved, it drills back up to the surface, and can be set again in a different location. For permanent anchoring, a reverse umbrella type anchor designed by IGS (5-1: p57) will be used. This type of anchor shoots into the ground and extends spines which hold the anchor in place. The two types of anchors are shown in Figure 5-2.

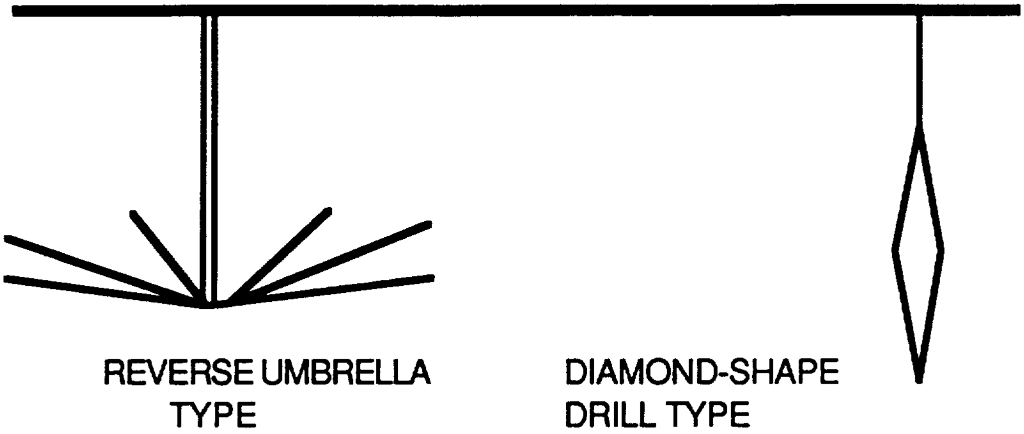


FIGURE 5-2 Anchoring Devices

5.4 EXPLORATION

Surface exploration of Phobos will be accomplished by expendable, unmanned spacecraft. Three surface exploration probes(shown in figure 5-2.1), or SEP's, will be deployed by the ITV just after it establishes an orbit a few kilometers ahead of Phobos. One SEP each will be sent to the proposed base, mining, and power plant sites. Before landing, each SEP will provide detailed mapping of the site. This information will be used by Earth-based controllers for final selection of the landing and mining sites and the base location. After landing at a position next to the chosen site, they will continue to provide geological data about each site and will act as navigation beacons for the OMV's.

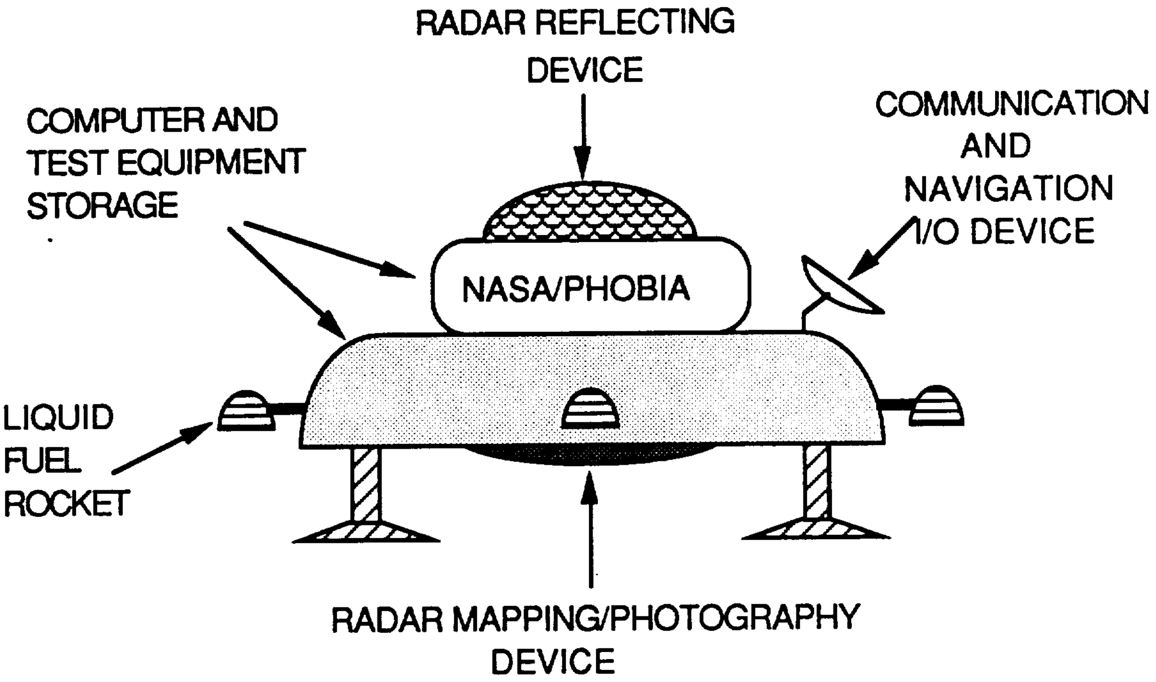


FIGURE 5-2.1 SEP Series

During the course of base development and production, additional SEP's will be sent to different locations on Phobos. All future probes will provide detailed mapping and photographs of the areas they fly over. Each SEP will perform a specific task after landing. Typical tasks would include obtaining seismic readings and soil samples.

The powered flight to each respective surface destination will be provided by small liquid fuel rockets. After landing, each probe will have sufficient battery power to complete its task. Each probe will operate on a separate frequency and will be equipped with a reflective shield which will bounce back emissions from the ITV in the event of battery failure. The size of the SEP series will be on the order of the Viking-1 probe or smaller and theit total mass will be 1500 kg.

5.5 TRANSPORTATION

The transportaion capabilities of the base will consist of short range transit (SRT) and long range transit (LRT). The SRT system will provide surface transportation around the Phobos base over distances less than one kilometer. The LRT system will provide surface transportation to future expansions of the base, on the order of several kilometers away.

5.5.1 Short Range Transit

A ski-lift design will be used for transporting the crew and cargo around the immediate area of the base, mining, and power plant sites (see Figure 5-3). As shown, a payload basket will be suspended on a cable line. Each payload basket will be able to support a payload of 1000 kg plus a crew of two astonauts. Power for the payload basket will be supplied by brushless, electric motors [5 - 5](see Appendix D).

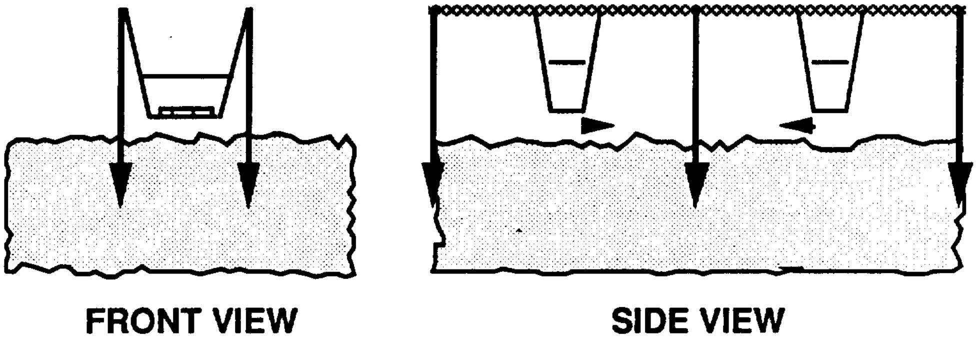


FIGURE 5-3 SRT System

The SRT system will be robotically constructed. Under the direction of the robot foreman, the robots will drill the holes for the suppports, place the supports in the holes, and secure them in place with umbrella anchors. An OMV will be used to string the cable along the supports. The robots will be capable of standing on each other in order to attach the cable to the supports. Once the ski-lift has been completed, the payload baskets will be mounted on the cable at the base, mining, and power plant sites.

5.5.2 Long Range Transit

A monorail design will be used for transporting the crew across the several kilometers separating the base, mining, and power plant sites (see Figure 5-4). Eventually, this monorail design will also be able to travel across the moon's surface to future bases. The shell of the monorail will be converted from an empty fuel tank of the ITV [5-5]. Power for the LRT system will be provided by brushless electric motors for efficiency. Motor size will depend on the mass of the fuel tank chosen for conversion(see Appendix D).

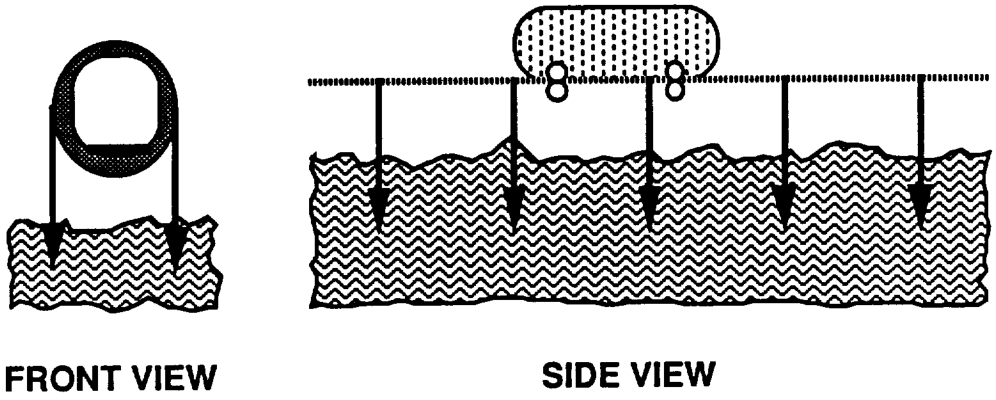


FIGURE 5-4 LRT System

The LRT system will be completely robotically constructed. Since the LRT system is not part of the preliminary base design, detailed robotic tasks are not given. However, some tasks will include the conversion of the fuel tank to a monorail shell, anchoring the supports, attachment of the motors, and connection of the shell to the rails.

6. ROBOTICS

6.1 OVERVIEW

The key to safely and efficiently developing the Phobos outpost is autonomous automated assembly. Bombarded by harsh solar and cosmic radiation, the planetoid is inhospitable to all but heavily protected humans. If the base were to be constructed under the supervision of on-site human controllers, these radiation hazards would require that a temporary shelter be brought along from Earth for their use. Furthermore, the astronauts would be subjected to the additional hazards associated with any construction task, and medical treatment would be several months away. By constructing the outpost using autonomous robots, the risk factor of the mission is thus substantially reduced, since astronauts would arrive at a completed, functioning base.

In order to accomplish the assembly of the outpost, the robots must be capable of manipulating and connecting large structural components, as well as detailed work such as drilling and soldering. These tasks can be accomplished with maximum flexibility through the use of modular effector packages, which attach to a legged chassis. Each effector package contains several modular end effectors to further increase the flexibility of the design. Each chassis will contain fuel cells which provide power for both the chassis and the effector package.

Control of the construction robots will be accomplished through a division of labor scheme. The chassis will contain the locomotion programs, and the effector packages will be programmed to accomplish their own tasks. All robotic tasks will be directed by a "foreman," which is a separate, immobile unit containing the bulk of the AI codes.

For mining operations, the major robotic activity will be digging and transporting the Phobian regolith, a fairly repetitious chore. Therefore, a more robust, but less flexible design is required. This robot will need approximately the intelligence of a cow, since its major function will be "grazing" for regolith. As with the construction robots, power will be provided by fuel cells.

6.2 ROBOTICS OPERATIONS

The purpose of this section is to describe the robotic activities involved in Phobia's design for a base on Phobos. PHOBIA has defined a robotics system in terms of two sub-areas: **jobs**, and **tasks**. **Jobs** are the major undertakings of the Phobos mission, such as the construction of the base RPS. Each job is composed of several **tasks**, such as the grasping of a frame element. The jobs and tasks of Phobia's robotic system are described in the following subsections.

6.2.1 JOBS

The following jobs comprise the robotic operations.

1. Boot-Up
2. Mapping
3. Site Preparation
2. Base Installation
3. RPS Installation

4. Power Plant Installation
5. Mining & Processing Plant Installation
6. Surface Exploration

6.2.1.1 Boot up. The construction robots will, from inside, open the delivery pallet and exit it. In the case of using the delivery pallet to provide structural support to the cargo, egress will involve both locomotion and disassembly tasks. If the pallet is a standardized pallet, with no active use of cargo, then egress will not involve disassembly.

6.2.1.2 Mapping. It is assumed that maps of Phobos will exist in sufficient detail to identify the areas where construction will take place. The first major task of the robotics system will be to make local maps of the areas selected from Earth. The paths connecting these areas and the landing site will also be mapped. The purpose of these local maps is to identify the best construction sites, to locate obstacles the robots must avoid, and to identify areas of scientific interest.

The construction robots will make detailed maps of the vicinity of the landing site, and the areas of the candidate sites for the base, the power plant, and the mining facility. The Phobian terrain may prevent line of sight communication; telescoping communication antennas (CA's) will be anchored in regolith to keep the construction robots in contact with the foreman.

Initially, the foreman will be positioned near the landing site; one antenna will be positioned here. Each chassis will have several CA's mounted on it. If a robot loses contact with the foreman, it will stop, install a CA, and reestablish communications with the foreman. The robot will then continue mapping.

6.2.1.3 Site preparation. The mining and construction robots will prepare the base site. Our plan for site preparation involves the removal of large rocks and excavation consistent with the RPS design. It has been proposed to use explosives for boulder removal on the moon [6-1]. Dust thrown by an explosion, however, takes much longer to settle on Phobos than on the moon. The robots could be hampered by this phenomenon, so PHOBIA is also considering a plan in which the boulders are unearthed by the mining robots, and carried off by the construction robots.

6.2.1.4 Base Installation. The base will be placed at or near its final position by an OMV which will greatly reduce the need for robotic manipulation of the modules. If required, three robots will lift the base and carry it to the final site. Study of the dynamics of this maneuver has revealed that each of the three robots will need to impart an upward force of 200 lbf. The base will be moved slowly in the horizontal direction, at a very low speed. Each robot will have to apply a horizontal force on the order of 100 lbf to accomplish this.

Installing the base in the site involves placement of the base which will have contact-actuated anchors on its underside, onto the surface.

6.2.1.5 RPS Installation. Construction and mining robots will be used to build the RPS. The truss components and the plastic film will be placed at the site. The construction robots will prepare the frame for the RPS and the mining robots will fill it with regolith.

6.2.1.6 Power Plant Installation.

The installation plan for the power plant follows the same form as that for the base installation. The site will be prepared, the power plant will be placed at the site, and an RPS will be constructed around it

6.2.2 TASKS

The **tasks** performed by the robots define the form that the robot takes. The tasks that the robots will do are the following.

1. Grasping
2. Manipulating
3. Structural Assembly
4. Electromechanical Assembly & Repair
5. Burying
6. Force Application

6.2.2.1 Grasping. The construction robots will be grasping objects of highly variable sizes, e. g., RPS frame elements, the assembled base, etc. The crux of the matter is that we need some number of grasping units, and that those units will have certain strengths, and that they will grasp things in a certain way. Phobia's design efforts have focussed upon the problems of RPS construction.

In considering the dynamics of robotic RPS construction, the following question presented itself: how many grasping arms will be required at any one time in order to connect the frame elements?

Figure 6-1 illustrates the situation of two bars being connected. Two gripping arms hold the bars in place while a connection end effector makes the joint. This solution appears viable provided that the "glue" which makes the connection can be "activated" by a single additional end effector, and, provided that the chassis provides stability for robot as well as frame elements.

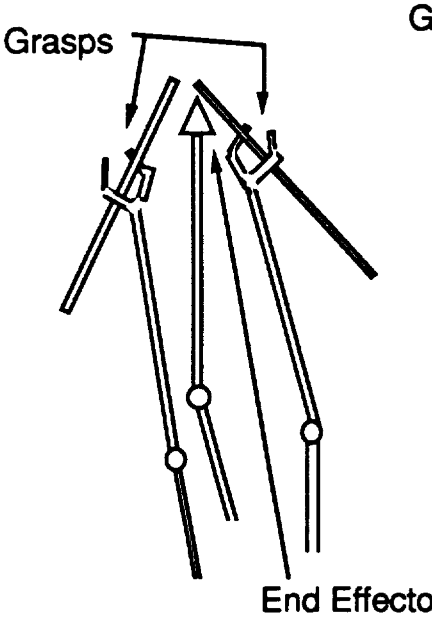


Figure 6-1: Grasping Bars

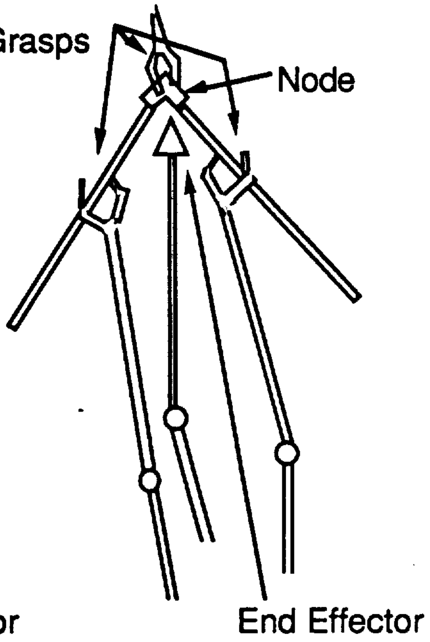


Figure 6-2: Bars & Node

Figure 6-2 illustrates a variation connection of frame elements. In this case, the connection is effected by a piece of node hardware. Three grasping arms would be needed to create this joint, and the chassis is again assumed to provide stability.

The Phobia Corporation's research included study of the ACCESS Space Flight Experiment [6-1]. The grasping of the truss elements was by connecting them to the Orbiter Payload Bay. In addition, each connection required two additional arms(provided by an astronaut,) to grasp the frame elements. No node hardware was used to connect the frame elements. Effectively, therefore, four grasping units were involved in the procedure, two of low dexterity(the tie-downs), and two of extremely high dexterity(the astronaut's arms.)

That four grasping units were required in the ACCESS experiment prompted Phobia designers to suspect the situations described in Figures 6-1 and 6-2 to be over-simplifications of the frame assembly problem. Phobia designers have thus decided to incorporate four grasping units into each construction robot.

6.2.2.2 Manipulation. As a specialized task, the domain of manipulation pertains to the delivery of end effectors to where they are to be applied. Manipulation is also the principle task involved in activating the anchors which connect objects to the surface of Phobos. Phobia's research has indicated that RPS construction, specifically truss/ frame assembly, is the driver of requirements for robotic manipulation.

6.2.2.3 Structural Assembly. Robotic truss assembly in space is a well researched subject; designs currently exist for robots which can perform this task using 4 and 5 DOF arms [6-2]. In the interest of redundancy, as many as nine degrees of freedom will be called for in assembling the RPS frame elements. Phobia's research indicates that it is likely that this technology will available [6-3].

6.2.2.4 Electromechanical assembly/ repairs. The ability for robots to make limited repairs on parts of the base system as well as on one another is the driver of the requirement that the robots be adept at fiddly [6-4, 6-5] motions. Manipulations on scales of milli- and centimeters will be required to close the power network, to perform system check-outs, and for the surface exploration of Phobos.

6.2.2.5 Burying. This task applies to the fuel pipelines of the mining operations system. Electrical cables, if used for power transmission, would be buried. In Phobos' gravity, little power is required to excavate regolith, but power will be required to replace it if dust is to be suppressed.

6.2.2.6 Force application. Due to the slow speeds at which large objects will be moved, the transportation of these objects owes more to the task of force application than to manipulation. An analysis of the transportation motions has shown that the construction robots will have to apply forces on the order of 200 lbf in order to transport the most massive system components.

Anchoring objects in the regolith, especially the RPS frame elements, will require construction robots to apply downward loads. Robot weight may not be cancel reaction forces. Further study is pending on whether this will be the case, and on how construction robots could cope with this situation.

6.3 CONSTRUCTION ROBOTS

6.3.1 Chassis

The construction robots will move via chassis units. Six legged, semi-autonomous, this half of the construction robot design carries the power source, and a full set of navigation sensors. This section is describes the current state of the chassis design in three sub areas:

1. mode of locomotion
2. size
3. relationship to other robots

6.3.1.1 Mode of locomotion. The environment of Phobos, and nature of the motions required of the chassis suggest the use of a walking robot. All but the largest of Phobos' surface features are unknown. By launch date geographic knowledge is assumed to have improved to the point where preliminary construction site selections may be made on Earth. Resolution of surface details to 1 m or better is not assumed to be possible within the assumed time frame.

Efforts begun in 1980 by DARPA, M. I. T., and Ohio State University to design a robot adaptable to highly irregular topography have recently yielded the Adaptive Suspension Vehicle [6-6], a legged vehicle. The Odetics Corporation [6-4] has developed a walking robot capable of radical changes in geometry and working in cramped, irregular environments with extreme dexterity. Phobia designers adopted this design philosophy after considering the problems that a treaded vehicle might have in delivering placing an effector package in its required position.

Phobia designers have considered the possibility that the Phobian regolith is deeply layered and unable to bear concentrated loads. An idea for the chassis to use snowshoe-type feet resulted.

6.3.1.2 Size was the prime consideration. It was found that the most demanding geometric configuration for the a robot on Phobos is that required to fix a tear in the inner ceiling of the RPS, which will be 25' above the ground. Construction robots with 15' reach ability are proposed in light of the face that due to the low gravity, the prospect of one robot lifting another up to do repairs is viable at this stage of the design. the chassis has been sized under th assumption that the proportions of the Odex-1 can be preserved in our design. The chassis is thus a legged cylinder with length of, 10' and diameter 4'.

6.3.1.3 Relationship to effector package. The chassis will be able to navigate and avoid obstacles independently of end effector package, provided it has instructions on where it wants to go, so that in case the effector package becomes unable to give instructions to its chassis, the chassis will be able to return the effector package and remove it, under instructions from the foreman robot.

6.3.2 Effector packages

While the chassis forms the bottom half of each construction robot, the top half will be a modular effector package. The design presented herein is a package specialized for general purpose construction activities. Due to the modularity of the design, however, the construction effector package could be removed at a later date and replaced with a package better suited to other activities, such as sample collection.

Figure 6-3 presents a schematic of the effector package. As the drawing shows, the unit will have six manipulation arms, and one arm devoted to its vision system. The manipulator arms will each have nine degrees of freedom (DOF's), providing greater flexibility and redundancy than the five or six DOF robots currently in use. Until recently, six DOF's was a limit of robotic solution algorithms, however, solutions to the problem of manipulation with seven or more DOF's have recently been found [6-3]. Since the vision system will not require the same degree of dexterity, only five DOF's are provided for its boom, reducing the complexity of the vision program.

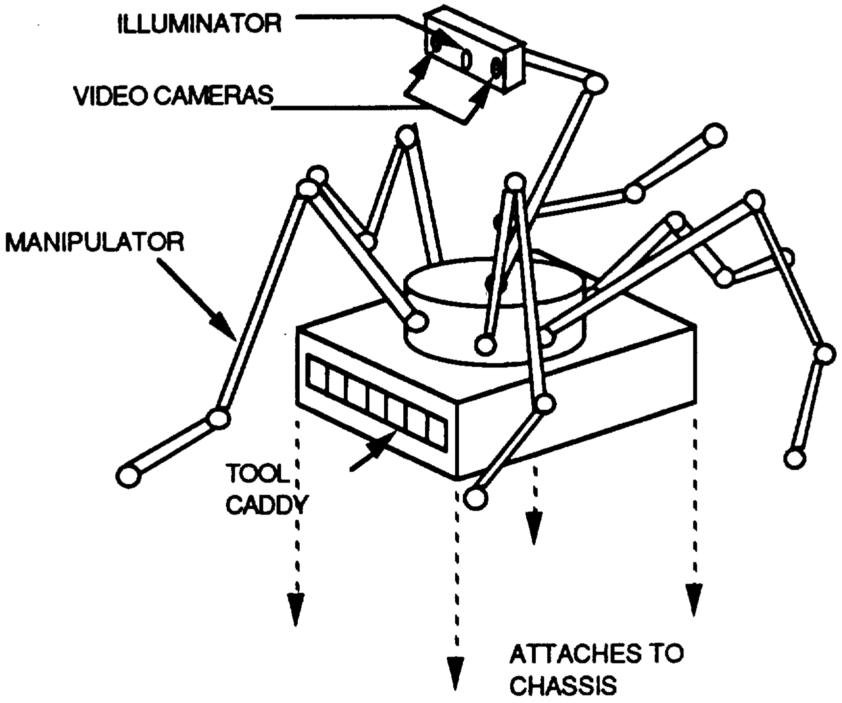


Figure 6-3: Construction Effector Package

This vision system will consist of two video cameras mounted in tandem and a centrally mounted illuminator. The use of two cameras provide the robot with depth perception through differential comparison of images, much the way a human sees. This eliminates the need for radar or other methods of distance determination. If the vision system becomes impaired, the effector package will have the capability for using the more limited cameras on the chassis unit.

The most important part of the effector package is the tool caddy. This collection of storage bins contains several types of end effectors and supplies required for grasping, drilling, excavating, and fine manipulations. When a particular operation is required, a manipulator arm merely reaches into the bin containing the proper tool for the application. The end effector then attaches to the arm with a latching mechanism. For coarse grasping tasks, such as carrying large structures, a three-fingered unit is employed. Such a unit provides strength, stability, and flexibility. Finer manipulations will be accomplished by a less bulky unit containing many specialized fingers, each serving as an individual tool, such as a set of pliers or a soldering iron. For drilling, a bit with a telescoping shaft similar to an automatic car antenna will be employed. Although the mining robot will perform most digging chores, a small entrenching tool will be provided in the tool caddy. In addition, shaped explosives packets may be included for performing larger excavations if further research demonstrates the risk to the robot of this concept is acceptable.

Since the effector package will not be used independently of a chassis unit, it will rely on the chassis for power and communications with the foreman.

6.3.3 Robotic construction management

The decision to design an autonomous system of construction robots, which was caused by the time lag between Phobos and Earth, led Phobia designers to plan the delegation tasks.

The construction activities on Phobos will have a manager, a computer program which delegates work to the three construction robots. The way in which this is done influences the amount of processing that takes place aboard each construction robot.

Phobia's designers developed two possible methods of accomplishing this:

1. Network Management
2. Foreman Management

The foreman management system, in which work is delegated among the three construction robots by a management unit, called the foreman. Descriptions of both systems, and the Phobia's reasons for choosing the foreman management system are given in the following subsections.

6.3.3.1 Network management. In this management scheme, each construction robot operates as part of a network which delegates work efficiently. The network is created by having 2 of the 3 robots supply radio inputs to a management program running aboard the 3rd. This 3-D robot will, in addition to processing its task and job programs, will run the management program which makes the delegation decisions. Delegation commands are returned, in situ to the robot aboard which decisions are made, and by radio to the other 2 robots.

6.3.3.2 Foreman Management. This foreman management system, each of the three construction robots multi-task into a management program, which runs aboard a separate unit, the foreman. Each construction robot will process task and job programs , and supply radio inputs to the foreman, which radios commands back. The foreman is a stationary unit, moved by a construction robot if necessary.

6.3.3.3 Management System Selection. The foreman management system was chosen because it does not expose the management program to dust and potential damage the work environment.

6.4 MINING ROBOTS

The mining and transportation of Phobian regolith will be an ongoing and tedious task more suited to machine-like robots rather than sophisticated "thinkers". Therefore these miners should be designed for maximum durability and less emphasis should be placed on intelligence. With this design philosophy in mind, two regolith movers have been conceptually developed for use in establishing and maintaining the fuel supply base on Phobos.

6.4.1 Regolith dump truck

The primary regolith transporter will be in the form of a tracked, dump truck style vehicle. It will not have any of the appendages of the other robots and it will have little or no intelligence capabilities. This regolith moving machine will simply wait for the mining robot to fill it and then proceed to a predetermined location. This location will be mapped by the mining robot beforehand and fed into the dump truck's memory.

The dump truck will be equipped with several features which will facilitate its specialized tasks. One such feature will be hinged doors which will close when the truck is full and will remain closed during transport. This feature was deemed necessary to reduce the problem of dust escaping due to rough terrain. Another aid to its mission will be a set of rubber-like rollers at the front and back of the truck which can be used to grip a rope to pull itself along. The rope can be threaded through the rollers when terrain conditions require extra traction, as determined by the mining robot. In this case, the miner would also secure both ends of the rope at the destinations. As a safety valve, the dump truck would possess a distress beacon which would be activated if its mission was interrupted or could not otherwise complete an assigned task.

Based on the numbers supplied in section 4.1 for production quotas, the payload capacity of the dump truck will have to be at least 4.275 m^3. This volume is based on an average of four round trips of the dump truck each hour. Since the entire mining and production facilities can be moved, the round trip distance, therefore time, need not exceed this limit. Sizing calculations can be found in Appendix C.

6.4.2 A dedicated mining robot

The core or brain of the mining robot will be the same as the construction robots to maximize compatibility. Also, if necessary, the miner will be capable of accepting the end packages of the other robots. If such circumstances were to arise, the miner would have to be reprogrammed to perform other tasks. Unlike the construction robots, the miner will be a tracked vehicle which will aid in its stability during digging and lifting.

The mining robot will have several tasks associated with its main goal of providing regolith to the production unit. Initially, it will be used to clear and level areas for the base, power plant, and processing unit. Also, it will act as the brain of the dump truck by clearing paths, determining when the towrope is needed, and downloading information to initiate tasks. The miner will require the ability to determine suitable mining locations around the processing plant and to avoid any adverse effects on other base systems.

As stated above, the mining robot will maneuver on tank-like tracks which, depending on the Phobian surface density, may prove less effective than the legs of its construction counterparts. This will be counteracted by providing the miner with three minor appendages in addition to its main digging arm which, when all used together, will serve as legs to lift and move the robot out of problem situations. These additional arms will also have other functions when not being used as legs. Such functions could include a jackhammer for reducing obstacles, a maintenance arm with several tools, and an anchor for balancing the robot during digging and lifting. The main arm of the miner will be a symmetric "clam shell" scoop which was chosen to minimize the torques, imposed during digging, on the chassis. Finally, to utilize the time while the dump truck delivers its cargo, a storage bin can be used by the miner to hold regolith so digging need not stop. This bin will be on stilts so the truck can park under it and be reloaded. It will also act as a funnel to minimize stray dust.

6.5 ROBOT POWER

The robots will be powered by hydrogen/oxygen fuel cells. While total power consumption of the robotics system has yet to be specified, Phobia designers do not expect them to require a continuous power output equal to that of lifting the 330,000 lbm base. Existing fuel cell technology has achieved a 40,000 hr, 12.5 kw power source which fits into the space of a 1 x 1 x 2 box [6-7]. In the time frame for this project, Phobia feels that this power source will be able to meet the power requirements of the robotic system.

6.6 ROBOT VISION

Industrial efforts have been directed towards constructing systems that allow a machine to understand its surroundings. PHOBIA has defined the term vision system to include the hardware and software necessary to perceive a scene and present a correct interpretation of it to a robot's controlling expert system. The requirements of an appropriate vision system for the Phobos mission were determined, and a search for such a system was made. It was found that development of PHOBIA's robotic system is contingent on advances made during the next few decades.

A vision system sufficient for the Phobos mission must have the following characteristics:

- Resolution
- Agility
- Real time operation
- Robustness

Resolution, agility, and intelligence are hardware issues satisfied by existing technology; feasability of PHOBIA's robots depends upon advances made in the areas of real time opertation and robustness.

6.6.1 Resolution

To resolve an image, in PHOBIA's terms, is to present it to a computer for analysis. In general, resolution is provided through integration of two components: a charge coupled device, such as a television camera, and an image digitizer. The image digitizer converts the image from the camera into an array of pixels and assigns to each pixel an intensity value and a hue value[6-8].

6.6.2 Agility

Agility is the capability of the vision components to be positioned properly with respect to objectives, light sources, and obstructions. The manipulator arm which carries the vision components will be similar to the other manipulator arms, and will require a substantial number of DOF. The reason for this is that the ability of a vision system to sucessfully recognize an object is highly sensitive to the angle from which it views an object. The manipulator arm must optimally position the vision components.

6.6.3 Real time operation

The dynamic construction environment necessitates real time processing of both geometric coordination algorithms and visual pattern recognition algorithms. This combination parallel processing has yet to be accomplished with the effeciency required by the Phobos mission.

A goal of current industrial research is the establishment of real time vision system processing that does not rely upon parallel processing of both pattern recognition and geometric coordination algorithmis.

The prohibitive amount of calculations involved in the vision process is the reason for these efforts.

A sensor-target scheme is being developed by Martin Marietta [6-9]. The system substitutes real time image recognition processing with "feature recogition"; instead of perceiving an object as a complete entity, this vision system recognises an object based on its distinctive geometric and textural features. Distinctive features are not extracted from an image but detected through analysis of the polarization of light reflected off of the object. The computational demands of this system are not as severe as those of a pattern recognition vision system.

Another approach to the computational efficiency problems associated with today's vision systems is the use of neural networks. Neural networks present the possibility of inherantly optimal computing and may be able to provide sufficient computer speed to allow the construction of pattern-recognizing vision systems[6-10] .

PHOBIA feels that the aerospace industry can and should develop either parallel or neural network processing technology, to a degree advanced enough for pattern recognition vision systems to be feasable. This is because the computational problems appear to be rooted in computer speed, and not in the physics of the vision process.

6.6.4 Robustness

Robustness will be required of PHOBIA's robotic vision system. Martin Marietta is testing an autonomous land vehicle at present. Its vision system has had diffuculties adapting to scene changes due to shadows, and irregular paths[6-8]. Acheivement of robust vision systems is assumed by PHOBIA'S designers.

6.7 ROBOTICS SOFTWARE

6.7.1 PHOBIA RESEARCH

Sequential programming will not be adequate for application to robotics on Phobos because it is not "intelligent" enough to allow for unexpected occurences[6-11]. In contrast to sequential programs, expert systems use rules to give the appropriate commands to the manipulators and end effectors. For the Phobos mission the controlling expert system of a construction robot will be interfaced with the manipulator and locomotor hardware in real time. For construction robots to succesfully negotiate the terrain of Phobos, which will not be mapped to high resolution before the mission, self programming software will be required. Phobia has researched the following areas of robotic software:

6.7.1.1 Current autonomous robots. The recent activities of the Center for Engineering systems Advanced Research have included the construction of an autonomous mobile robot, HERMES II. An expert system originally designed for industrial use was successfully adapted to give HERMES II the ability to navigate through an unfamiliar environment, and to avoid unexpected obsticles[6-11]. The expert system used aboard HERMES II is called PICON.

PICON(Process intelligent Control) has been proposed as a prototype real time control system for the Space Station[6-12]. PICON is a piece of software that constructs, alters, and initiates rules. Rules form the basis of any action or reaction of the system being controlled; e.g., assembly of a truss by a construction robot, etc.

PICON resonds to a question or problem by returning a suggestion for solution. It develops suggestions by applying the rules contained in its knowledge base.

6.7.1.2 The PARPLAN planning/delegation program. A currently existing AI code, PARPLAN, is designed to efficiently distribute tasks to the members of a multiarm robot[6-13]. This program is not an expert system, but a program written in Quintus Prolog. It monitors and controls the state vectors of a robotic manipulator system. The program gives primitive instructions, such as:

Hand #3 place gear #2 in slot #4 during the interval from T_1 to T_2.

Phobia Corporation feels that the PARPLAN program could be interfaced with an expert system for the purpose of providing task-level and primitive-level robotic control.

6.7.1.3 Current design philosophies. The Phobos mission will influence the design philosopies of robotics software suppliers in the area of autonomy. Space robotics research efforts in industry have produced conservative and ambitious approaches to the problem of controlling automated construction off the Earth. Consrvative philosophy in the design of robotics controll/planning software is that of the smart adaptive robot [6-14]. The smart adaptive approach restricts autonomy to motion primitives and retains human presence in the controll loop; humans operate the programs and/or expert systems driving the robot.

The approach involving smart adaptive robot allows for fast evolution of robotics systems because it simplifies failure mode planning greatly: human operators are available at all times. Design of fully autonomus systems is a slower, more difficult endeavor, but it is essential to the Phobos mission due to the remoteness of Phobos.

6.7.2 SOFTWARE SYSTEM DESIGN

PHOBIA Corporation adopted the philosopy that an autonomous robot is equivelent to an autonomous software entity. This section describes the software system design. A general overview is given, the autonomy and interdependence characteristics of the software are stated, and the subjob operating mode is introduced. The distribution of the various software species and their respective functions are described. The terms subjob, species and function were assigned definitons by PHOBIA Corporation, which are given in the following section.

6.7.2.1 Definition of terms. The construction robot **subjob** operation mode is similar to the job mode because it is initiated through a command from the foreman. Upon receipt of an ASSIST command, a construction robot first locates and approches the robot he is to assist. The robot establishes an RF link between its PICON istallation and that aboard the robot to be assisted.

The foreman then issues a job to the assisting robot--the same job that the overburdened robot is attempting to carry out. While in subjob mode, the assisting robot not only attempts to carry out a job, but it also processes the anomoly and error signals from the overburdened robot, thus having immediate knowledge of the diffuculties.

PHOBIA used subjob mode in designing a robotic assistance plan for two reasons. First, so that the the immobile foreman need not control the process in real time. In addition to this communication constraint the assistance problem requires that the assisting robot process the algorthims for the job in progress while not acting as an obstruction to the overburdoned robot. Hence, in the subjob mode, the assisting robot understands the job goal, but responds only to anomoly or error signals from the overburdoned robot.

The term **species** is used to identify a software item in name, and to denote the task controlled by the software. Species is not a program's commercial name. A more generic term, **function**, denotes an action taken by software in controlling a task. A species of software has more than one functon. A function is neither a task, nor a job. For example,consider a program that causes a construction robot to take the following actions. Locate, overtake, and follow the mining robot. Maintain a distance of 5 feet from it. The species is navigation, with three functions:

- Interface with vision system
- controll execution of locomotion task codes
- send status reports to foreman

6.7.2.2 General description. The foreman contains an installation of the expert system PICON which implements the mission jobs. The control interface RTIME will link the foreman's expert system to a PICON installation aboard the construction robots' effector packages. Similar expert system/interface parallelism exists between effector package and chassis, and between foreman and mining robot.

The effector packages use PARPLAN software to sequence the manipulation primitives. PARPLAN passes optimal state solutions to PICON, which interprets the output from PARPLAN using its knowledge base. PICON in turn drives the manipulators.

Jobs have meaning only to the PICON installations aboard the forman and effector packages. PICON essentally translates a job into a set tasks and presents the set to PARPLAN for translation into primitives and for optimization. The primitives are routed via RTIME to the manipulator actuators.

6.7.2.3 Autonomy, interdependence, software failure modes. The Phobos base can nominally be constructed without commands from Earth. The foreman will periodically check with ground control for changes in the mission plan, while the construction and mining robots will rely upon the foreman for instructions.

Should the foreman fail, the CIMC will take its place and direct the Phobos mission from aboard the ITV via the communication network. Subsequent failure of the CIMC will necessitate an unmanned delivery of a substite foreman to Phobos space from Earth. The option of teleoperation was eliminated due to the excessive time lags involved. Because the Mars base mission involved the use of operational hardware on PHobos, it was decided that computer components arriving with the Mars Base components do not present a viable substitute for the foreman.

Cooperation of construction robots will be accomplished through a **subjob operation mode**. The foreman initiates this mode by issuing an ASSIST command to a construction robot. The ASSIST command may originate from the foreman's PICON installation in response to request for help from an overburdened construction robot. It will also be possible for the forman to decide that a construction robot needs assistance.

6.7.2.4 Software species distribution. Software applications (species) are distributed within the robotic system as is shown in Figure 6-4. An important feature of this distribution is the assignment of navigation tasks processing the chassis. PHOBIA desisgners based the validity of applying PICON, RTIME, and PARPLAN to the Phobos mission on the high frequency with whch these systems have been incorporated into proposed Space Station and autonomous robotics applications [6-11,6-12,6-15].

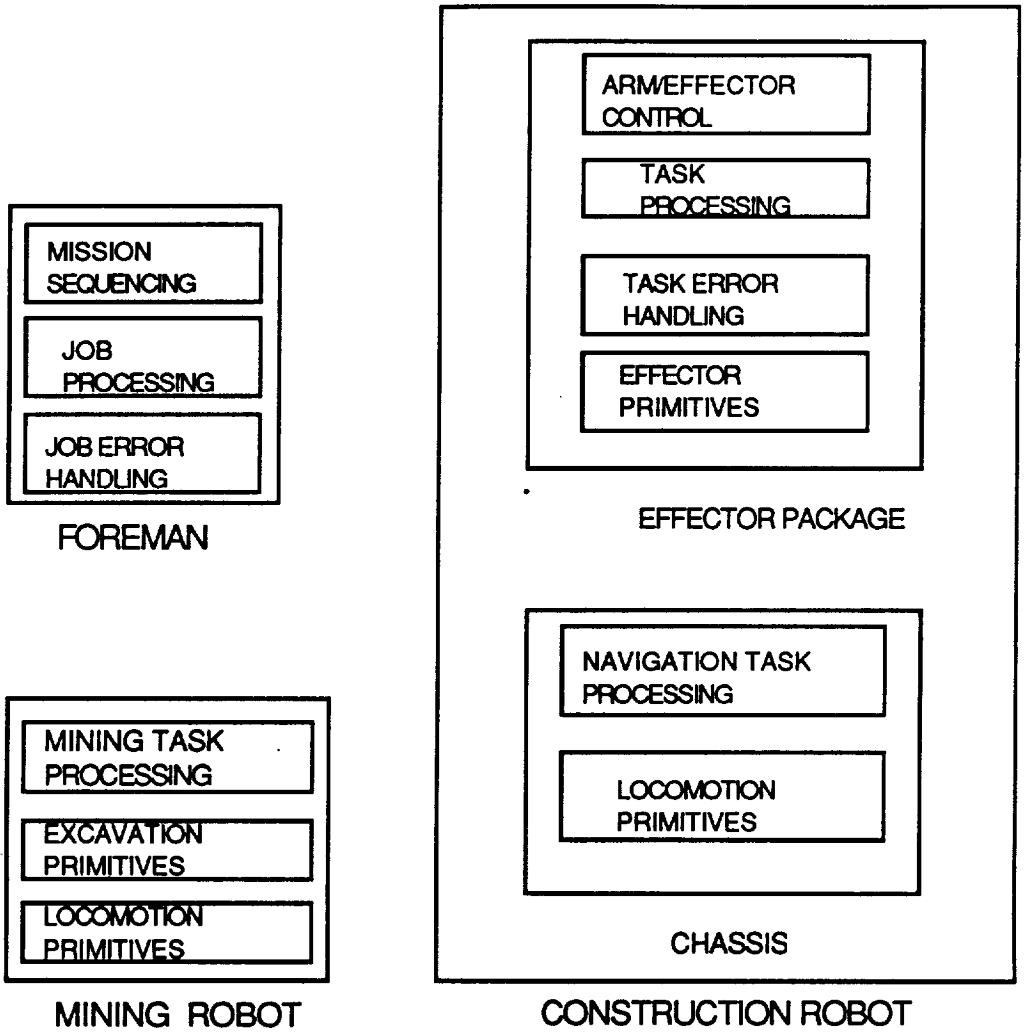


Figure 6-4 Software Speici Distribution

The question of how algorithms, which define the robotic tasks, should be implemented was addressed by Phobia. Each of PHOBIA'S construction robots will have an expert system aboard its effector package to provide control. The manipulator arms and end effectors will then rely upon smaller expert systems to suppy locomotion and sensory primitives.

The job, task, and primitive algorithms which will control the construction robots will be processed aboard the effector packages.

Aboard a construction robot, the results of job algorithm processing are supplied to a nested expert system which supplies the appropriate task commands to the software driving the actuators.

6.7.2.5 Software Species. Navigation software will be used by the construction robots. In travelling between the base, power plant, and mining sites during the construction phase of the mission, the robots will nominally be guided by the power cable layed by the OMV. Additional methods of site to site navigation will be available to the robots: comlink guidence via the foreman and the ITV, and landmark navigation made possible by the development of vision systems using pattern recognition.

Codes defining the navigation primitives are aboard the chassis. The chassis contributes substantially to the modularity of the robotic system because is has the ability to process navigation tasks (e.g., "go to the beacon at the base site and locate the disabled mining robot.") The mission as a whole will be controlled by programs running aboard the foreman.

6.7.2.5 Software distribution and interfacing. Figure 6-5 locates the interfaces between the various softwares. The distribution of actual programs is also expressd in this figure. RF links exist between the foreman and construction robots, and between the forman and the communication network. The network links the CIMC, which is the backup foreman, to the robots.

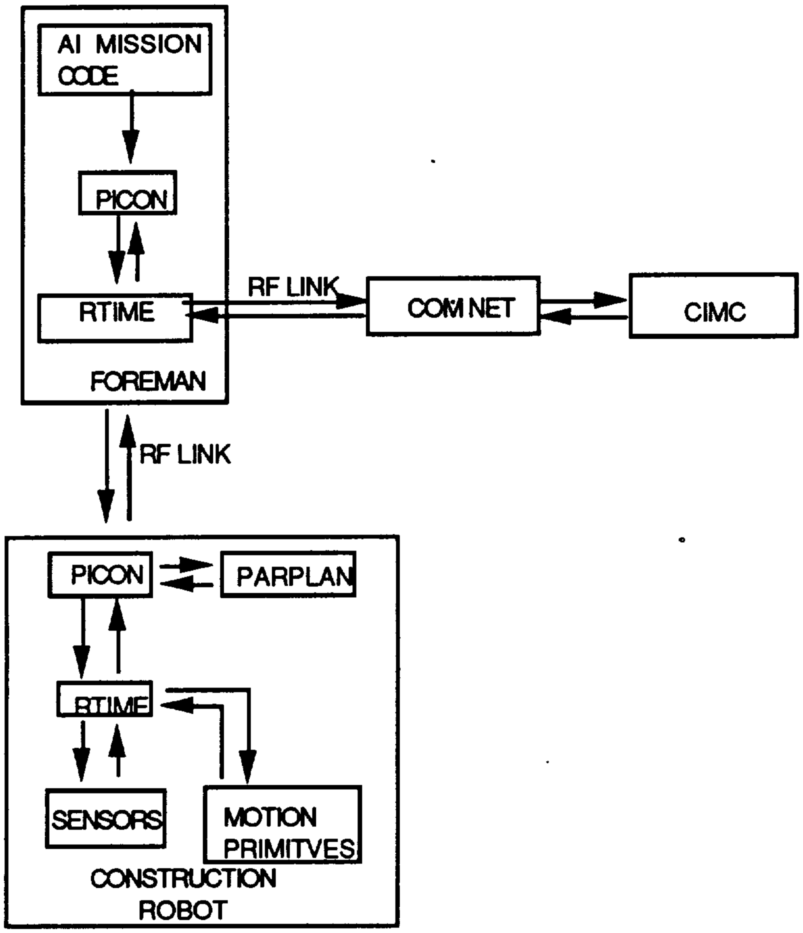


Figure 6-5 Software Interfaces

7 POWER SYSTEMS

7.1 OVERVIEW

The power systems for the Phobos base will have to support mining operations, fuel processing, life-support, habitation modules, and all electronics systems. A conservative estimate of the base power requirements is 1 MW [7-1].

Ideally, this power system would possess the following characteristics:

- Light Weight
- Constant Power Supply
- Long Working Life
- Durable
- Easily Transferable
- High Degree of Safety

7.2 POWER SYSTEM ALTERNATIVES

The power options reviewed for use on Phobos were nuclear power, both fission and fusion types, solar power, and fuel cells.

Nuclear Fission Power, Solar Power, and Fuel Cells are all currently technologically feasible as a power source for the base. A decision matrix comparing the three power options based on the aforementioned criteria is shown in Figure 7-1, with nuclear fission having the lowest total and thus being the most desirable power source for the base. A more detailed description of the power alternatives considered is discussed below.

	Fission	Solar	Fuel Cells
Lightweight	2	1	3
Constant Power	1	3	2
Long Working Life	1	2	3
Durable	1	3	2
Easily Transferable	1	3	2
Safe	3	1	2
Total	9*	13	16

Figure 7.1: Comparison of Power Alternatives
*** Lowest Total Indicating best option**

7.2.1 Nuclear Fission Power

A Nuclear Fission reactor is the most viable power option presently available. The fission power system being considered for use on Phobos is a 500 kW to 1 MW SP-100 nuclear reactor derivative. The system will have an approximate mass of 3000 to 4000 kg and can be housed within a 20m deep, 30m wide crater, as shown in Figure 7-2.

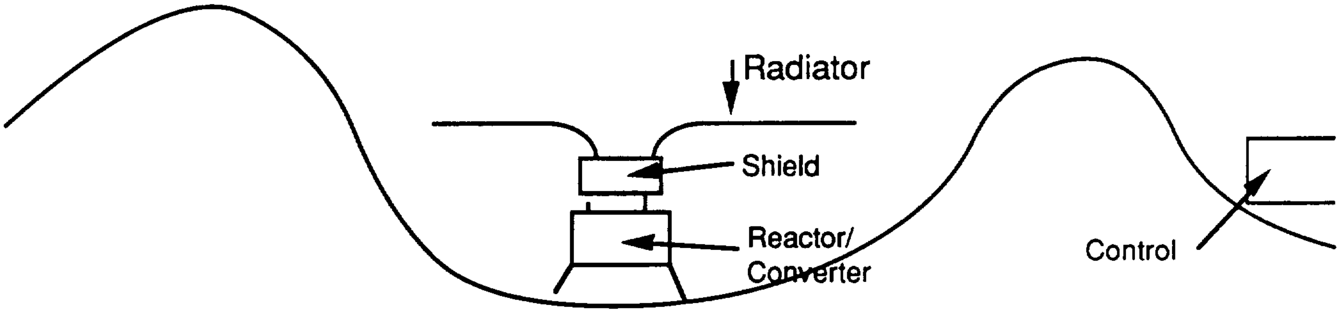


Figure 7-2 Nuclear Power Source Shielded in a Crater

The SP-100 system will be adapted for specific use on Phobos. By designing a system that will efficiently meet the specifications of the mission, the power to weight ratio of the reactor can be increased. An example of this is included in Figure 7-2. By using regolith to shield the reactor, 20000 kg of weight in radiation shielding will be conserved that otherwise would have to be transported from Earth [7-2]. Also shown in Figure 7-2, the controls are placed outside the crater. During construction of the base the controls will be monitored robotically, but when the base becomes man-tended, the controls will be transferred to CIMC control.

Two major problems to be dealt with are heat rejection and radiation protection.

7.2.1.1 Waste Heat Management

In order to reject enough heat, radiators will require a surface area on the order of hundreds of square meters, not to exceed 800 square meters [7-3]. The radiators may have difficulty in expelling enough heat if the surface of Phobos is as warm as estimated, or if the reactor experiences warming trends during periods when it is exposed to the sun. The average temperature of Phobos is 319K (7-4), but no information on the temperature fluctuations between daylight and darkness was found.

To help radiate the excess heat, the area around the reactor will be shaded [7-5]. Highly reflective, low solar absorptivity blankets could be placed around the vicinity of the radiators to reduce the surrounding lunar surface temperatures [7-6]. A more complicated system of heat dissipation may need to be employed, depending upon what surface conditions dictate.

Waste heat will also be used for additional electric power generation. The reactor will be designed so that a bottoming cycle will be included in the power generation process, in order that the thermal waste can be used to produce additional energy [7-7].

7.2.1.2 Radiation Shielding

Radiation protection is another major consideration when considering the use of a nuclear reactor. The power system will be located in a crater approximately 1 km from the base to protect it from any residual radiation from the reactor. The power controls and environment conditioning will be located approximately 150 m away from the power source and have its own radiation shielding [7-8].

To protect the power system itself, there will be shielding as indicated in Figure 7-2. The reactor will be dynamically controlled to compensate for back scatter radiation.

7.2.2 Nuclear Fusion Power

In the past, research in sustaining a nuclear fusion reaction has implemented the use of lasers or magnets to hold the reactor. The attempt to light the fusion fire takes place at extremely high temperatures and requires massive machinery. If fusion technology continues in this direction, the fusion reactors available in 40 to 50 years will be too large for practical space applications.

However, the recent studies of room temperature chemical nuclear fusion could change the direction of nuclear research. The viability of this option will depend upon verification of the results of an experiment conducted at the University of Utah. Currently, many institutions are trying to reproduce their results and confirm that the reaction is indeed fusion. According to a press release, 1 W of energy input yields 4 W of energy output during the reaction process. The reaction works with deuterium, which is contained in sea water. If these results are verified, 1 cubic foot of seawater could produce the same amount of energy produced by 10 tons of coal [7-9]. Such a system could prove to be very efficient and light weight, having significant impact on the Phobos base power system design.

7.2.3 Solar Power

Solar energy is another major power option. While it is safe and renewable, it does not provide constant power. Furthermore, the solar panels have a large surface area, and would require large storage facilities. This lack of reliability and the weight of the storage equipment are prohibitive factors for its use on Phobos. New technology may make solar power a more viable option in the future.

7.2.4 Fuel Cells

Regenerative H2-O2 fuel cells were ruled out for use as a major power source, but will be utilized as an emergency power source for the base. They are reliable and the reactants can both be mined from Phobos, thus saving transportation weight from earth [7-10]. Figure 7-3 shows a hydrogen-oxygen fuel cell system.

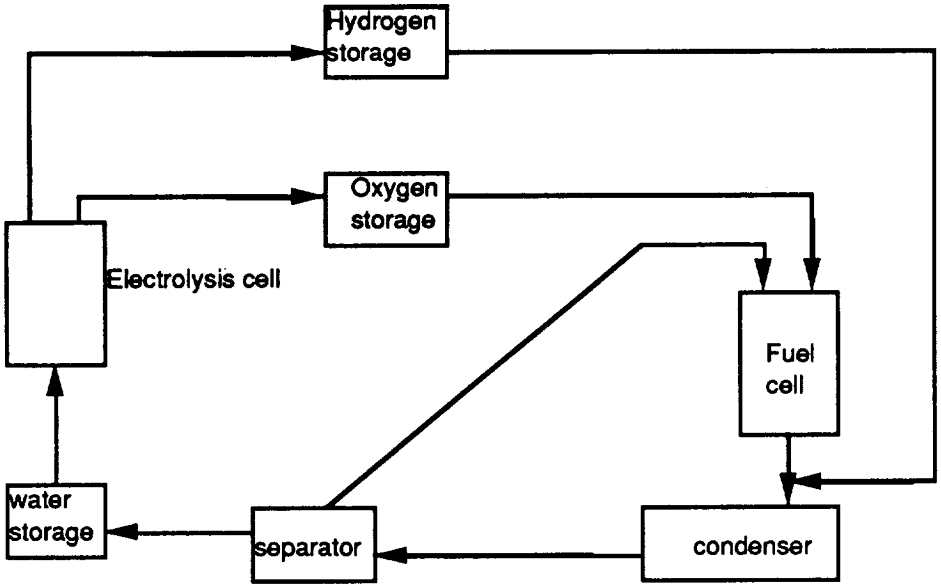


Figure 7-3 Regenerative H2-O2 Fuel Cell Configuration

7.3 WASTE DISPOSAL

Because nuclear fission will probably be used on Phobos, the question of how to dispose of the radioactive waste must be addressed. The end of the lifetime of the reactor will either cause permanent shutdown or refueling of the reactor. If the reactor is to be permanently shut down, the existing shielding and surrounding structure should be enough to safely contain the waste.

7.4 POWER TRANSMISSION

The power plant site will be located about 1 km from the site. To transmit the power, power cables will be used, buried in order to protect them from radiation. Using microwave transmissions to transmit the power from the reactor to the base is an alternative that may become technologically feasible within the time frame of the mission.

8. FAILURE MODES AND EFFECTS ANALYSIS

Failure modes and effects analysis (FMEA) is a qualitative method of exploring the possible modes by which components may fail and for determining the consequences of each mode of failure on the system as a whole.

The general characteristics of a failure mode and effect analysis are illustrated in the following table. In the left-hand column the major components or subsystems are listed; in the next column the physical modes by which each of the components may fail are given. This is followed, in the third column, by the possible causes of each of the failure modes. The fourth column lists the effects of the failure. Criticality, a ranking of the failure's importance is included to separate failure modes that are catastrophic from those that merely cause inconvenience or moderate economic loss. The final column is a list of possible remedies.

Failures are categorized by the following four levels denoting seriousness:

1. Negligible - loss of function that has no effect on the system.
2. Marginal - a fault that will degrade the system but will not cause the system to be unavailable.
3. Critical - a fault that will completely degrade system performance.
4. Catastrophic - a fault that will have severe consequences and perhaps cause injury, fatalities, or complete mission abort.

The emphasis of FMEA is to serve as a suitable starting point for understanding the failure mechanisms before proceeding to a more detailed safety analysis.

ITEM	FAILURE MODES	CAUSE OF FAILURE
<u>BASE OPERATIONS</u>		
Base Modules	Rupture	a. Poor workmanship b. Defective Materials c. Damage during transportation d. Overpressurization
Environment Control	a. Insufficient pressure b. Insufficient oxygen c. insufficient temperature control.	a. Leaks b. System failure
Seals	Leakage	a. Defective O-rings b. Loss of cabin pressure
Airlocks	Door malfunction	Locking mechanism failure
Thermal Control	Insufficient pressure in WCL	a. Leakage b. System malfunction
	Loss of FCL	a. Puncture of tank b. Pipe blockage
CIMC	ROM routines function improperly	a. Damage to ROM circuits b. faulty connections
	Data loss	a. Faulty storage media b. Faulty connections c. Damage to storage media

POSSIBLE EFFECTS	CRITICALITY	POSSIBLE ACTION TO REDUCE FAILURE RATE OR EFFECTS
a. Destruction of module b. Loss of crew c. Loss of module functions d. mission abort	Catastrophic	Close control of manufacturing process to ensure that workmanship meets prescribed standards. Rigid quality control of basic materials to eliminate defects. Inspection and pressure testing of completed modules. Provision for suitable packaging to protect modules during transportation. Close monitoring of pressure throughout module lifetime.
a. Crew illness b. Equipment failure c. Uncomfortable temperature	Critical	Close monitoring of environmental systems. Redundant control units. Personal breathing apparatus.
Loss of pressure and life support gases	Critical	Supply resealiong materials and equipment, such as gaskets and welding tools.
a. Loss of EVA capability b. Loss of docking capability c. Loss of crewmwmbers	Critical	Additional entrance/egress hatch. Pressure monitoring of airlocks. Periodic inspection and maintainance of locking mechanism.
Loss of temperature control	Marginal	Outlet pressure monitor informs of critical pressures.
Loss of temperature control	Marginal	Second FCL maintained independently of first.
a. Loss of control over subsystems b. Loss of data sharing and coordinating capabilities.	Marginal	Redundant control program on foreman directs robots to manually control systems wherever possible. Subsystems return data to Earth for coordination.
Loss of data sharing and coordinating capabilities	Marginal	Protect media from magnetic fields and temperature extremes. Subsystems return data to Earth for coordination.

ITEM	FAILURE MODES	CAUSE OF FAILURE
RPS	Radiation leakage	a. Miscalculation of reogolith requirement b. Poor workmanship c. defective materials
	Structural failure	a. poor workmanship b. defective materials
Foreman	Communications breakdown	a. radio failure b. physical damage to foreman structure
Com - net	Failure during construction	a. Electronic failure b. Satellite deployment failure
Com - net	Failure during crew occupation	a. Misuse by crew b. electronics failure
Com line between foreman and robots	Loss of communication between robots and foreman	a. electronics failure
Com - net	Failure with a crew on Mars, but no crew on Phobos	System failure

POSSIBLE EFFECTS	CRITICALITY	POSSIBLE ACTION TO REDUCE FAILURE RATE OR EFFECTS
a. Crew illness or death b. Equipment failure c. Mission abort	Critical	Close monitoring of radiation. Back - up procedure to expand RPS if needed.
a. Destruction of base b. Loss of crew c. Mission abort	Critical	Analysis of structure and materials on Earth. Procedure for removig crew if RPS collapses.
a. Loss of telemetry from robots b. Failure of foreman control of robots c. Failure of Earth control of robots	Critical	CIMC replaces Foreman.
Loss of robot navigation.	Marginal	Construction robots use surface referance navigation and return to foreman after task completion..
Loss of constant crew communication	Marginal	Periodic line of site communication with Earth.
Loss of foreman control of construction	Marginal	CIMC replaces foreman. Robots commanded to repair foreman if possible.
Loss of availability of fueling services	Critical	Repair by crew from Mars

ITEM	FAILURE MODES	CAUSE OF FAILURE
Anchors	a. anchors coming loose	a. poor workmanship b. miscalculation of loads
Lander Dock	a. latching mechanism failure	a. poor workmanship b. fatique
SEP Series	a. loss of communication/navigation abilities b. complete failure	a. battery failure b. crashes when landing c. hit by meteorite
SRT System	a. loss of locomotion b. structural failure	a. improper assembly b. electric motor damage c. fatique
LRT System	a. loss of locomotion b. structural failure c. complete destruction	a. improper assembly b. electric motor damage c. improper load calculations d. hit by meteorite
Nuclear Reactor	a. meltdown	a. coolant not controlled properly b. defect in reactor
Power Cables	a. cables severed	a. machining/robots digging in the area of the cables
Fuel Cells	a. inoperative	a. manufacture defect

POSSIBLE EFFECTS	CRITICALITY	POSSIBLE ACTION TO REDUCE FAILURE RATE OR EFFECTS
a. tracks shift out of place b. possible equipment damage/loss	Marginal	Adjust depth of anchors in regolith to account for problem.
a. manned lander could be damaged	Marginal	The robots will be able to perform preventive maintenance and routine inspections.
a. loss of navigation beacon b. delay in cargo landing on Phobos	Marginal	The SEP series will be equipped with a radar reflecting device which will bounce back signals to the ITV. Possible auxillary battery power installed.
a. loss of on-site transportation b. equipment damage/fatality c. time delay in mission	Critical to Catastrophic	Constructive robots will perform inspection and preventive maintenance on structures and motors. Back-up motors and safety lines be available.
a. loss of inter-site transportation b. equipment damage/fatality c. time delay in mission d. destruction of system	Critical to Catastrophic	Continued preventive maintenance performed by robots. Spare parts/motors available. Close control of construction to ensure safety factors are reached.
a. loss of main power source b. radiation exposure c. shut down mining since emergency power only operates base module d. possible mission abort	Critical	Close control/monitoring during operation. Possible shut down when base is not man-tended. Regenerative fuel cells to provide back-up power to base module.
a. mining operations shut down b. loss of main power	Critical	Alternate/extra cable available for robots to use to reconnect power supply.
a. loss of emergency power b. possible mission abort	Critical	Close control of manufacturing process to ensure quality. Possible testing of completed fuel cells.

ITEM	FAILURE MODES	CAUSE OF FAILURE
<u>SURFACE OPERATIONS</u>		
Production Unit	a. shut down (inoperative) b. component failure	a. improper assembly b. poor acclimatization to Phobos c. damage at installation d. wear due to constant use e. power supply interrupt
Mining Robot	a. loss of locomotion b. loss of power c. loss of communication d. complete destruction	a. damage due to terrain of Phobos b. defective software c. corrosive dust buildup d. hit by meteorite e. defective power supply
Mining Dump Truck	a. loss of locomotion, power, and communication b. complete destruction	a. damage from rough terrain b. corrosive dust buildup c. hit by meteorite d. defective power supply
Track/rope for Locomotion Assistance	a. discontinuity/break	a. defective material b. damage during installation c. applied forces too large
Tunneler	a. individual function malfunction	a. damage during transport b. defective materials
Excavation Truck	a. wheel fracture	a. unexpected terrain/obstruction
Tunnel	a. cave-in	a. loose/weak layers of regolith
Surface Dock	a. fuel line leak b. dampers damaged c. cracks in landing platform	a. fatigue b. poor workmanship

POSSIBLE EFFECTS	CRITICALITY	POSSIBLE ACTION TO REDUCE FAILURE RATE OR EFFECTS
a. discontinued fuel/oxygen production b. mission delay	Critical	Production unit will consist of sub-units which can be replaced by robots. Modular design of entire system to facilitate repairs. Derivative of lunar base production design to ensure reliability. Periodic inspection and preventive maintenance by robots.
a. discontinued fuel/oxygen production b. delay in base/power site preparation c. mission delay d. loss of mining robot	Marginal	Mining robot will be a modular design to facilitate repairs done by itself or by the construction robots. Back-up power to produce a distress signal in robot and its dump truck counterpart.
a. delay in fuel/oxygen production b. delay in site preparation c. loss of use of dump truck	Marginal	The mining robot will be capable of repairing the dump truck. Dump truck can be towed by other robots if necessary. Sturdy construction and preventative maintenance by mining robot.
a. delay in production b. delay in site preparation c. loss of effective dump truck locomotion	Marginal	Backup systems will be available to reduce long term effects. Use will be restricted to an as-necessary basis. Dump truck may be towed by other robots when needed.
a. temporary shut down of sub-surface tunneling b. decrease in production	Negligible	The excavation truck will be used as a tow truck for the tunneler. All functions of the tunneler will be housed in separate removable and replacable packages which one of the robots will replace.
a. temporary shut down of sub-surface tunneling b. decrease in production	Negligible	The tunneler will attach itself to the truck and escort it to the surface. The robots will remove the defective package and replace it.
a. time-inconvenience	Negligilbe	The tunneler will be able to adjust its programming and tunnel its way out of the cave-in. It will be able to seek out the excavation truck and retrieve it and then resume its original instructions.
a. damage to landing ships b. damage to dock landing pad c. difficulty in transportating fuel	Critical to Catastrophic	The robots will be able to perform routine preventive maintenance and monitoring of the manufacturing process. Extra parts and/or a back-up dock platform will be available.

ITEM	FAILURE MODES	CAUSE OF FAILURE
Anchors	a. anchors coming loose	a. poor workmanship b. miscalculation of loads
Lander Dock	a. latching mechanism failure	a. poor workmanship b. fatique
SEP Series	a. loss of communication/navigation abilities b. complete failure	a. battery failure b. crashes when landing c. hit by meteorite
SRT System	a. loss of locomotion b. structural failure	a. improper assembly b. electric motor damage c. fatique
LRT System	a. loss of locomotion b. structural failure c. complete destruction	a. improper assembly b. electric motor damage c. improper load calculations d. hit by meteorite
Nuclear Reactor	a. meltdown	a. coolant not controlled properly b. defect in reactor
Power Cables	a. cables severed	a. machining/robots digging in the area of the cables
Fuel Cells	a. inoperative	a. manufacture defect

POSSIBLE EFFECTS	CRITICALITY	POSSIBLE ACTION TO REDUCE FAILURE RATE OR EFFECTS
a. tracks shift out of place b. possible equipment damage/loss	Marginal	Adjust depth of anchors in regolith to account for problem.
a. manned lander could be damaged	Marginal	The robots will be able to perform preventive maintenance and routine inspections.
a. loss of navigation beacon b. delay in cargo landing on Phobos	Marginal	The SEP series will be equipped with a radar reflecting device which will bounce back signals to the ITV. Possible auxillary battery power installed.
a. loss of on-site transportation b. equipment damage/fatality c. time delay in mission	Critical to Catastrophic	Constructive robots will perform inspection and preventive maintenance on structures and motors. Back-up motors and safety lines be available.
a. loss of inter-site transportation b. equipment damage/fatality c. time delay in mission d. destruction of system	Critical to Catastrophic	Continued preventive maintenance performed by robots. Spare parts/motors available. Close control of construction to ensure safety factors are reached.
a. loss of main power source b. radiation exposure c. shut down mining since emergency power only operates base module d. possible mission abort	Critical	Close control/monitoring during operation. Possible shut down when base is not mantended. Regenerative fuel cells to provide back-up power to base module.
a. mining operations shut down b. loss of main power	Critical	Alternate/extra cable available for robots to use to reconnect power supply.
a. loss of emergency power b. possible mission abort	Critical	Close control of manufacturing process to ensure quality. Possible testing of completed fuel cells.

9. MANAGEMENT

9.1 MANAGEMENT

PHOBIA Corporation utilized the management structure which is depicted in figure 9-1 and shows the Program Manager as the single point of contact to the contract monitor. Technical details of the design were coordinated by the Chief Engineer who oversaw and organized the Technical Managers. The Technical Managers were assigned to broad areas of responsibility and were tasked with distributing the research work among their engineers.

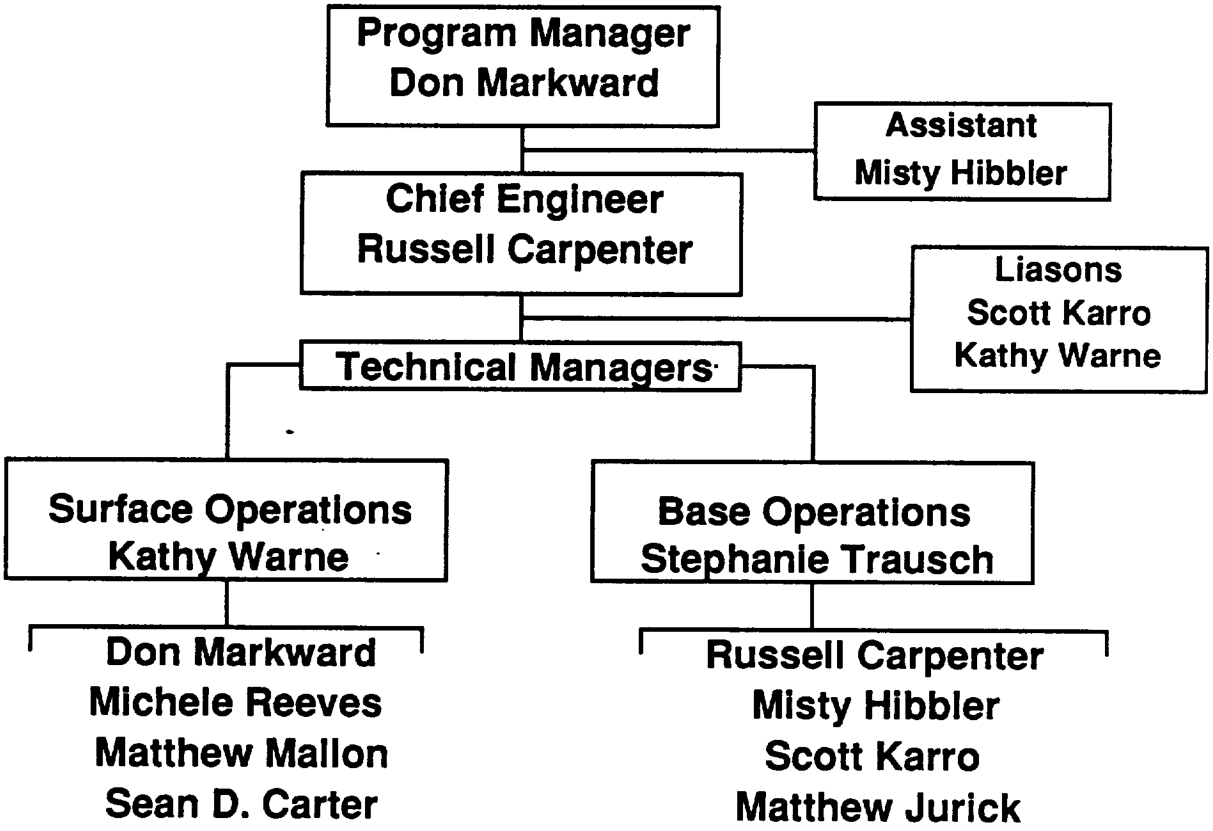


Figure 9-1 - Management Structure

The PHOBIA Corp. hierarchy provided an excellent format for the reporting of, and responding to, problems which occured during the design process. Each engineer encountering a difficulty reported to their Technical Manager who had the option of implimenting a solution or reporting to the Chief Engineer. If possible solutions had involved changes in the direction, scope or assumptions of the project, the Chief Engineer would have reported it to the Project Manager who would then inform the Contract Monitor of necessary changes. This process would simply be reversed for the implimentation of contract monitor ordered changes. Figure 9-2 shows the program schedule as compiled from reports from the Technical Managers.

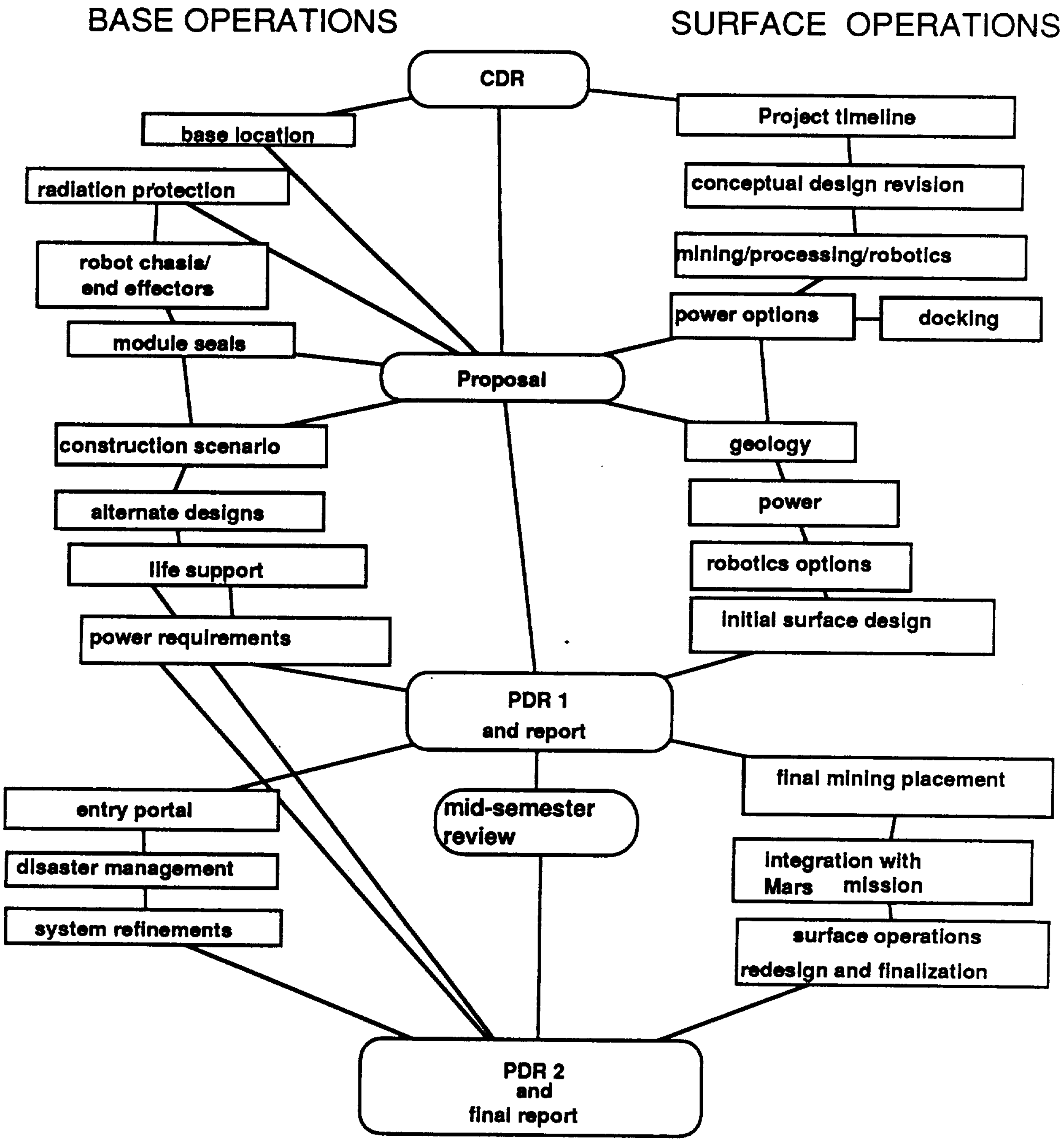


Figure 9-2. Task schedule for meeting milestones

9.2 Cost Analysis

Table 9-1 shows the reported workloads by week of all PHOBIA Corp. employees as of 1 May 1989. The total cost of salaries paid for these hours is computed to be $21,879.50 . Comparing this total to the predicted manpower costs given in the proposal of 27 February 1989, $24,544.00, it is seen that PHOBIA Corp. has managed to limit its salary expenses below those proposed.

Table 9-1
Workloads by week (in hours)

position\week	1	2	3	4	5	6*	7	sub.Tot.
Program Mngr.	8	5	15	7	3.5	0	3	41.5
Chief Engineer	12	5	26.5	3	5	0	7.5	59
Technical Mngrs.	17	18	20	11	15	0	23	104
Engineers	66.5	53.5	75	38	48	0	92	373

*Spring Break

position\week	8	9	10	11	12	13*	Totals
Program Mngr.	20	18.5	4	6	8		98
Chief Engineer	30	7.5	5.5	5.5	17		124.5
Technical Mngrs.	17	21	11.5	11	26.5		191
Engineers	115	94.5	52	82.5	120		837

* Not Available at Publication

REFERENCES

1. INTRODUCTION

1. Lin, T. D. "Concrete for Lunar Base Construction," Lunar Bases and Space Activities of the 21st Century, Mendel, W.W. ed.: Lunar & Planetary Inst., Houston, 1985, pp 381-390.

2. Young, J. Francis. "Concrete and other Cement-Based Composites for Lunar Base Construction," Ibid., pp 391-397.

3. Khalili, E. Nadorr. "Magma, Ceramic, and Fused Adobe Structures Generated In-site," Ibid., pp 399-403.

4. "Beyond Earh's Boundaries," 1988 Annual Report to the Administrator. NASA Office of Exploration, p. 9,14.

5. Parma, George. Personal Communication. Houston, Tx: NASA - JSC Structures and Mechanics Divisions, Feb. 19,1989.

6. "The Lunar Split," Project Report for the NASA/USRA Summer Graduate Design Program, Advanced Programs Office, NASA-JSC, May, 1988.

2. SYSTEM OVERVIEW

1. McClure, Paul F. Personal Communciation. Austin, Tx: The University of Texas at Austin. March 2, 1984.

3. BASE SYSTEMS

1. Thomas, P. and Veverka, J., "Grooves on Asteroids: A Prediction," Icarus, volume 30 Number 3, December 1979, p. 3 95.

2. Genrels, T., Physical Studies of Minor Planets, (Washington D. C.: NASA, 1971), p.400.

3. Welch, S. M., et al. The Case for Mars: Concept Development for a Mars Research Station. NASA-CR-179753, Jet Propoulsion Lab, April 15,1986.

4. Alred, John, "Preliminary Surface Shielding Options", presented to The Workshop on Radiation Constraints for Exploration Class Missions, Houston, Texas, May 27, 1988.

5. Roberts, Michael. Personal Communication. Houston, Texas: NASA-JSC Advanced Projects Division, April 21, 1989.

6. Heimann, Erich H. Do it Yourself with Plastics, New York: E.P. Dutton and Co. 1975.

7. "Final Design For a Lunar Construction Shack Vehicle," NASA/USRA Project, University of Texas at Austin, May, 1988.

8. "Design of a Minimum Loss Airlock For Use in Low Gravity, High Vacuum Space Environments," NASA/USRA Project, University of Texas at Austin, December, 1986.

9. Friedman, Roberty, Fire Safety Concerns in Space Operations. NASA-TM-89848, Cleveland: Lewis Research Center, 1987, p.4-5.

10. "Star Truk Final Report," NASA/USRA Project, University of Texas at Austin, May, 1989.

4. MINING SYSTEMS

1. "A Phobos Industrial Production and Supply Base," NASA/USRA Project, the University of Texas at Austin, December, 1986..

2. "Melting Head Tunneler Design," NASA/USRA Project, Texas A & M University, April 1988.

3. "Lunar Bore Project," Lunar Base Project, Texas A & M University, April 1988.

4. Fowler, Wallace T. Personal Communication. Austin, Tx: University of Texas Aerospace Engineering Department. March 29,1989.

5. SURFACE OPERATIONS SYSTEMS

1. Genrels, T., Physical Studies of Minor Planets, (Washington D.C.: NASA, 1971), p. 400.

2. Raton, Boca, CRC Handbook of Chemistry and Physics 60th Edition, (Florida: CRC Press, 1979), section F.

3. "Conceptual Design of a Mars Logistics Lander Connectible to a Rocket Hopper," Project Report for NASA/USRA Fall Graduate Design Program, Advanced Programs Office, NASA-JSC, Fall1988.

4. Pollack Etal, Mariner 9 Mission, NASA: Scientific and Technical Information Branch, Washington D. C., 1972.

5. "A Phobos Industrial Production and Supply Base," Project Report for NASA/USRA Fall Graduate Design Program, Advanced Programs Office, NASA-JSC, Fall 1986.

6. "Space Shuttle Fuel Tank Reclamation," NASA/USRA Project, GeorgiaInstitute of Technology, May 1985.

6. ROBOTICS SYSTEMS

1. John P. Wetzel, "Engineering, Construction & Planning in Space," in Proceedings of Space 88', ed. Stewart W. Johnson, (New York: American Society of Civil Engineers, 1989), p. 197, 490.

2. -----, The Space Station Assembly Phase: Flight Telerobotic Services Feasibility vol. 2, NASA CR 182690, Jet Propulsion Laboratory, 1988, p. 3-13.

3. Parma, George. Personal Communication, Houston, Tx: NASA-JSC Structures and Mechanics Division. February 19, 1989.

4. St Croix, Phillip de , ed., Robots, (New York: Crescent Books, (1985), p. 20, 75.

5. Cutosky, Mark R., Robotic Grasping and FIne Manipulation, Mass.: Kluwer Academic Publishers, 1985), p. 112.

6. Omni Magazine, (April 1989), p. 19.

7. "The Lunar Split Mission: A Robot Constructed Lunar Base Scenario," Davis, George, et all, The University of Texas, August 1988, p. 80.

8. E. J Lerner, Machines Sharpen Their Vision. Aerospace America, Nov. 1986, Vol 24, No. 11, pub: AIAA, pg. 36.

9. G. K. White, Passive Optically Controlled Transponder(POET): An Aquisition and Alignment Target for Autonomous Robotics. Space Automation II: Procedings of the SPIE Volume 729, Wun C. Chow, Sr., Editor, 1986.

10. R. Ricart, 2nd LT, Neural Network Based Architectures for Aerospace Applications, First /Annual Workshop on Space Operations Automation and Robotics(SOAR '87), NASA Publication 2491.

11. C. R. Weisbin, G. de Sausue, D. W. Kammer,A Real Time System for control of an Autonomous Mobile Robot Including Diagnosis of Unexpected Occurrences. Space Automation II: Procedings of the SPIE Volume 729, Wun C. Chow, Sr., Editor, Cambridge, Mass,1986.

12. D. Leinweber, J Perry, Controlling Real Time Processes on the Space Station. Space Automation II: Procedings of the SPIE, Vol. 729, Wun C. Chow, Sr., Editor, Cambridge, Mass,1986.
13 W. T. Park, Automatic Planning Research Applied to Orbital Construction, Space Automation II: Procedings of the SPIE, Vol. 729, Wun C. Chow, Sr., Editor, Cambridge, Mass,1986.

14. L. M. Jenkins, Telerobotic work System: Concept Development and Evolution. 21st Aerospace Mechanisms Symposium, April 29-May 1 1987, NASA Conference Publication 2470.

15. K. J. Shin, R. D. Throne, Y. K. Muthuswamy, Communication and Control in an Integrated Manufacturing System, First /Annual Workshop on Space Operations Automation and Robotics(SOAR '87), NASA Publication 2491.

7. POWER SYSTEMS

1. Duke, Michael B. and Alfred, John W., "A Lunar Base Scenario Emphasizing Early Self Sufficiency", NASA-JSC, Paper no. LBS-88-241.

2. Carlson, Lonald E., "Size and Mass Characteristics of Several Megawatt Space Nuclear Power Systems", Los Alamos National Laboratory, May 30, 1986.

3. Bents, David J. and Faymon, Karl A., "Space Power Systems Technology for the Manned Mars Mission, Part 2.," University of Michigan, February 10,1986.

4. "The Lunar Split Mission: A Robot Constructed Lunar Base Scenario," Davis, George. at all, The University of Texas, August 1988, p. 60-61.

5. Simonsen, Lisa C. etc., "Conceptual Design of a Lunar Base Thermal Control Ststem," April 5-7, 1988, Paper no. LBS-88-225, p. 8.

6. Mendell, W.W., "Lunar Bases and Space Activities of the 21st Century,"Lunar and Planetory Institute, 1985, p. 105.

7. Wall Street Journal, Southwest Edition, Dallas Texas. March 24, 1989, vol. LXXXIII no. 58, p. 1, A4.

8. Faymon, Karl A. and Kohout, Lisa L., "Space Power System Technology for the Manned Mars Mission, Part 1," University of Michigan, January 22, 1986.

8. FAILURE MODES AND EFFECTS ANALYSIS

1. Lewis, E.E., Introduction to Reliability Engineering. New York: Wiley,1987, pp. 336-338.

APPENDIX A
AIR LEAKAGE CALCULATIONS

FROM REF. 3.5 - 2

VOLUME OF AIR EVACUATED FROM AIRLOCK (V) = $1.998\ m^3$

AIRLOCK AIR EVACUATION TIME (t_2) = 55.7 sec

O-RING SEAL LEAKAGE RATE $(\dot{V}_1)$ = $1 \times 10^{-15}\ m^3/sec$

DOOR LOCK LEAKAGE RATE $(\dot{V}_2)$ = $2 \times 10^{-15}\ m^3/min$

AIRLOCK EVACUATION EFFICIENCY (ε) = 99.87%

$$M_T = M_1 + M_2 + M_3$$

WHERE:

M_T = TOTAL LEAKAGE

M_1 = O-RING SEAL LE

M_2 = DOOR LOCK LEAK.

M_3 = AIRLOCK EVACUA LEAKAGE

IDEAL GAS EQUATION:

$$\rho = \frac{P}{RT}$$

WHERE:

ρ = AIR DENSITY

R = AIR GAS CONSTAN

P = PRESSURE

T = TEMPERATURE

$$\rho = \frac{\left(1033.51\ \frac{kg}{m^2}\right)}{\left(287.074\ \frac{J}{kg\,°K}\right)\left(295.37\,°K\right)}\left(9.81\ \frac{m}{s^2}\right)$$

$$\rho = 1.1957\ \frac{kg}{m^3}$$

$$M_1 = \eta_1 \rho \dot{V}_1 t_1$$

WHERE:

t_1 = TIME OF MISSION

η_1 = NUMBER OF O-RIN

$$M_1 = (7)\left(1.1957\ \frac{kg}{m^3}\right)\left(1 \times 10^{-15}\ \frac{m^3}{sec}\right)\left(\frac{2.592 \times 10^6\ sec}{1\ MONTH}\right)(2.5\ MONTHS)$$

$$\underline{M_1} = \underline{5.42 \times 10^{-8}}\ kg$$

APPENDIX A

AIR LEAKAGE CALCULATIONS

$M_2 = \rho \dot{V}_2 t_1$

$M_2 = (1.1957 \frac{kg}{M^3})(2\times10^{-15} \frac{M^3}{MIN})(\frac{4.32\times10^{4} MIN}{1 MONTH})(2.5 MONTHS)$

$\underline{M_2 = 2.583\times10^{-10} kg}$

$M_3 = n_2 (1-e) \rho V$ WHERE: n_2 = ESTIMATED NUMBER OF TIMES AIRLOCK WILL BE USED

$M_3 = (30)(1-.9987)(1.1957 \frac{kg}{M^3})(1.998 M^3)$

$\underline{M_3 = .09317 kg}$

3.584 kg .7168 kg O_2
7.167 kg 1.433 kg O_2

∴ SINCE M_1 AND M_2 ARE << M_3, THEY WILL BE CONSIDERED NEGLIGIBLE. ⇒ $M_T \approx M_3$

SINCE O_2 AND N_2 ARE CLOSE IN SIZE AND MOLECULAR WIEGHT, O_2 AND N_2 CONCENTRATIONS WILL BE DIVIDED, FOR THE PURPOSE OF ESTIMATING EXCESS O_2 AND N_2 NEEDED, AS FOLLOWS:

COMPOSITION OF AIR: 80 % N_2
20 % O_2

$(.8)(.09317 kg) = 7.456\times10^{-2} kg$ N_2
$(.2)(.09317 kg) = 1.864\times10^{-2} kg$ O_2

FROM REF. 3.5-1:

6 CREW MEMBERS NEED 143.69 kg O_2 FOR 2.5 MONTHS

$\boxed{.01864 kg O_2 << 143.69 kg O_2}$

ASSUMING $e = .95$ $M_{O_2} = .7168$ kg
ASSUMING $e = .90$ $M_{O_2} = 1.433$ kg
} << 143.69 kg O_2

Appendix B

Fuel Requirements

The calculation for the amount of fuel needed for transportation between Phobos, Marsport, and Mars was supplied by the Startruk Corporation (Ref. 4-1.)

A program was written to determine the amount of fuel needed for interplanetary missions. This program yielded the following data :

Flyby Missions to the Outer Planets

	DELTA-V, (KM/S)	MASS OF FUEL, (KG)
JUPITER	4.591	18024.2
SATURN	6.148	39457.5
URANUS	7.261	77568.0
NEPTUNE	7.686	107469
PLUTO	7.873	126844

These calculations were made assuming the fuel had a specific impulse of 391 seconds and a payload weight of 6000 kg. A flyby mission was assumed for each mission. The patched-conic method was used to determine the delta-v's. A program listing follows.

Appendix C

Dump Truck Sizing Calculations

Assumptions -

- density of regolith - 200 kg/m^3
- Recoverable mass from 100 mtons of regolith

H_2 - 740 kg.

O_2 - 5932 kg.

- Water production - 50% efficient
- Electrolysis - 65% efficient

d - density of regolith

M_F - fuel mass

M_R - mass of mined regolith

V_{DT} - dump truck payload volume

N - number of round trips per hour of dumptruck

M_{O2}, M_{H2} - mass of fuel components

$$M_F = M_{H2} + M_{O2}$$

$$M_R = M_F / .0667$$

$$V_R = M_R / d$$

$V_{DT} = V_R / N$ where $N = 4$ for normal mining conditions

$M_F = 2017$ mt

$M_R = 30239$ mt(per yr.) $= 82.85$ mt(per dy)

$= 3.452$ mt(per hr.)

$V_R = 17.1\ m^3$

$V_{DT} = 4.275\ m^3$

So the dump truck bed, if a cube, would be about 1.6 meters on a side.

Appendix D

Brushless electric motors where chosen, primarily for their efficiency and ease of operation. Since their are no brushes, the only maintainence required of the robots would be lubrication of the rails, monorail shells, and payload baskets. The motor design would be simplified further since the motor will provide direct motion to the wheel.

The following graphs were prepared to aid in the designation of the motor size and wheel radius. These graphs were based on the vehicle mass, the desired vehicle velocity, the wheel radius, and the time required to reach the desired velocity.

The first set of graphs (#1- #8) were based on the equation for torque,

$$T = (M * V * R)/(DELTAT * 4),$$

where T is the required torque per motor, M is the vehicle mass, V is the vehicle velocity, R is the wheel radius, and DELTAT is the time to go from zero velocity to the final velocity. The multiple 4 is used in assuming there will be four motors.

Graphs 1- 4 illustrate the torque in Joules needed for a specified mass, a desired velocity, and a specified time to reach that velocity as the wheel radius is varied. For example, for a mass of 1150 kg (similar to the maximum payload of the SRT), a velocity of 8 m/s, a time of 60 seconds, and a wheel radius of 1.5 m, the necessary torque would be approximately 55 J. Graphs 5- 8 illustrate the torque needed for a specified mass, a desired velocity, and a specified wheel radius as the time to reach that velocity is varied. For example, for a mass of 31751.3 kg (approximately that of the ET of the Shuttle), a velocity of 5 m/s, a wheel radius of 1.5 m, and time equal to 150 seconds, the necessary torque would be approximately 410 J.

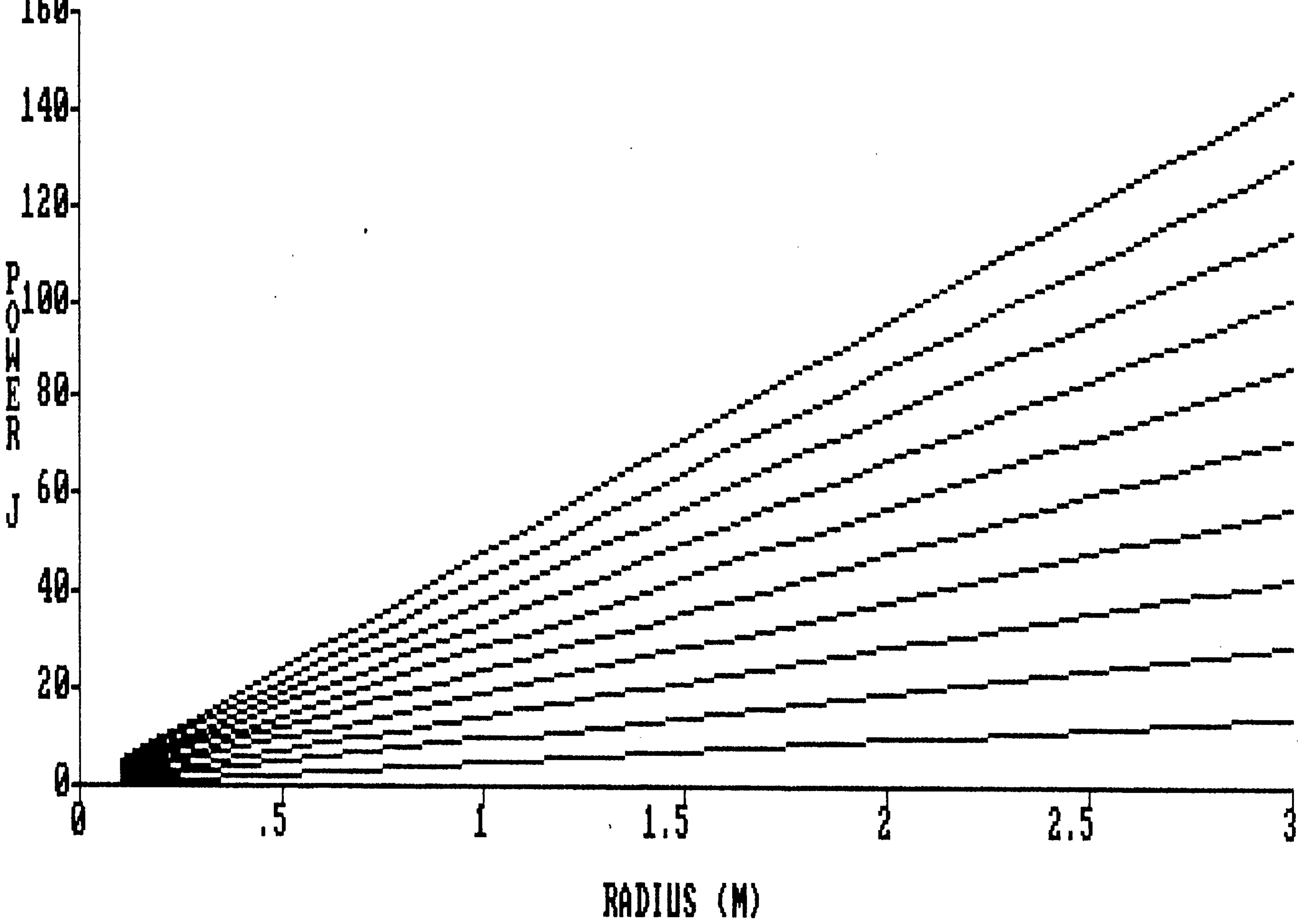
The second set of graphs (#9- #12) used the equation :

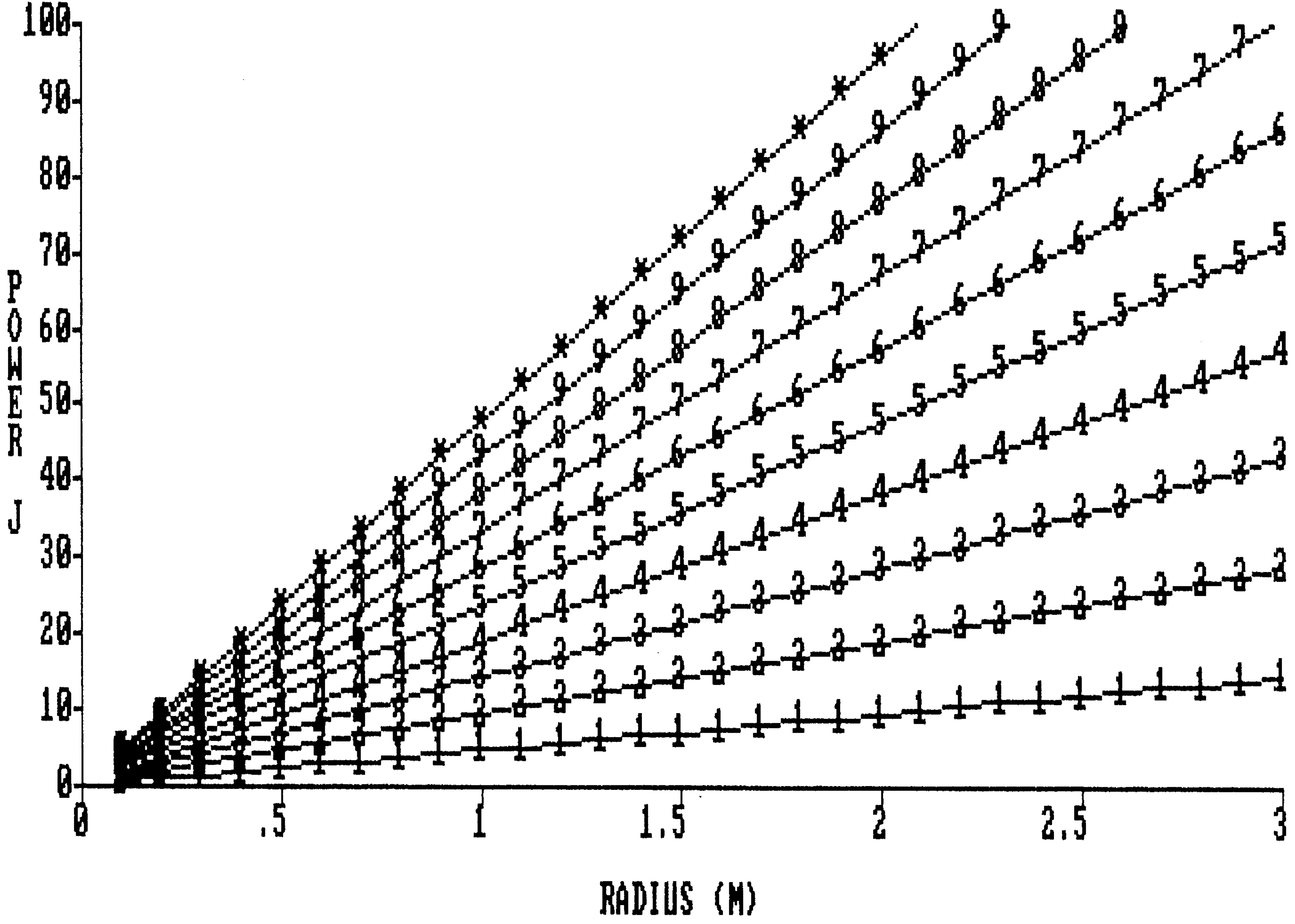
$$\mathrm{HP} = [(.5 * M * V^{\wedge}2)/\mathrm{DELTAT}] * 1.341\ \mathrm{E}\text{-}03$$

to obtain the necessary horse power. HP is the required horsepower, M is the vehicle mass, V is the vehicle velocity, DELTAT is the time required to reach that velocity, and the constant is a conversion factor.

Graphs 9- 12 illustrate the required horsepower needed for a specific mass and a desired velocity as the time required to reach that velocity is varied. For example, for a mass of 31751.3 kg to reach a velocity of 7 m/s in 150 secs, it would take approximately 7 hp.

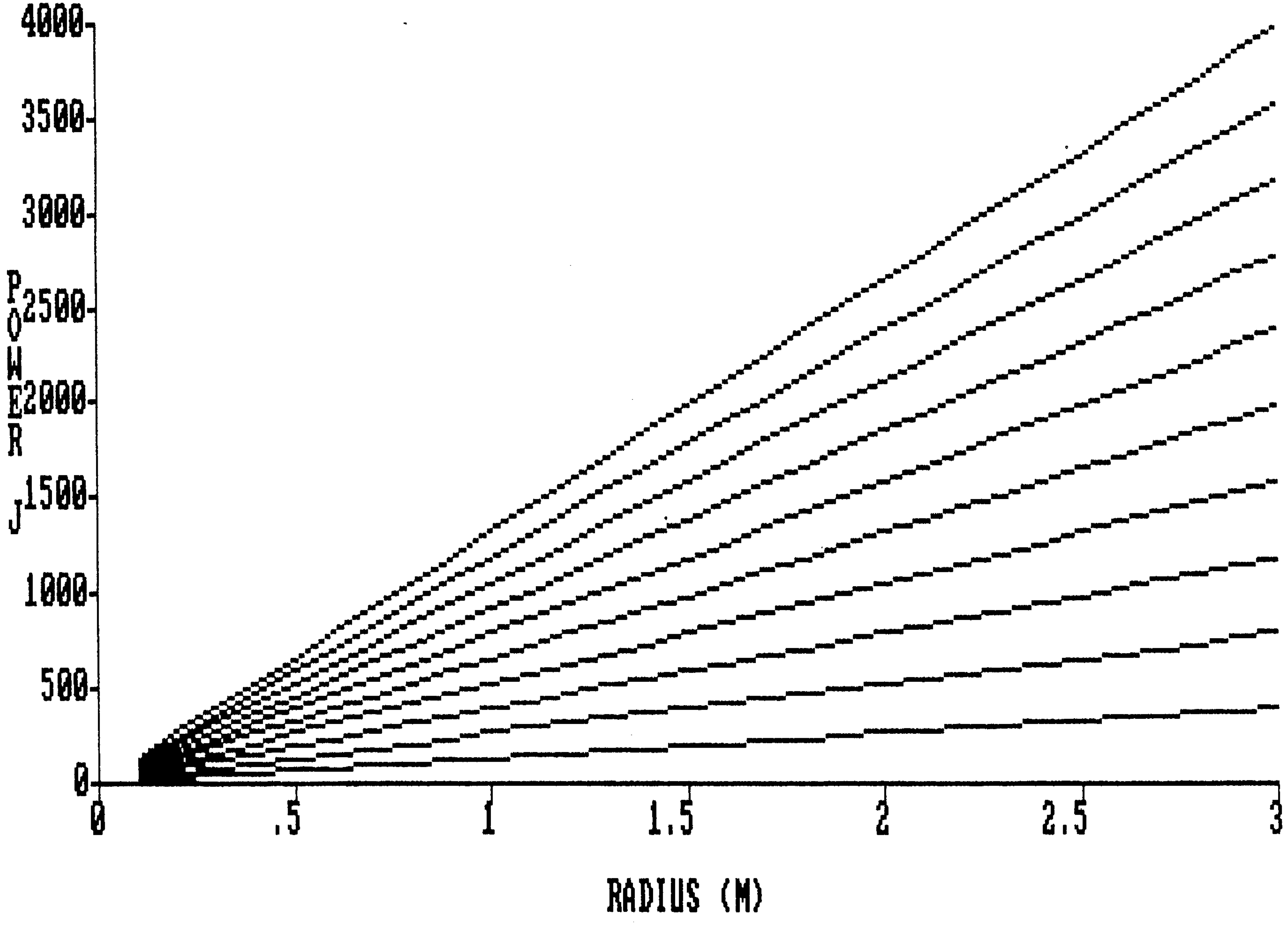
VELOCITY CURVES FOR DELTAT=60 SECS.

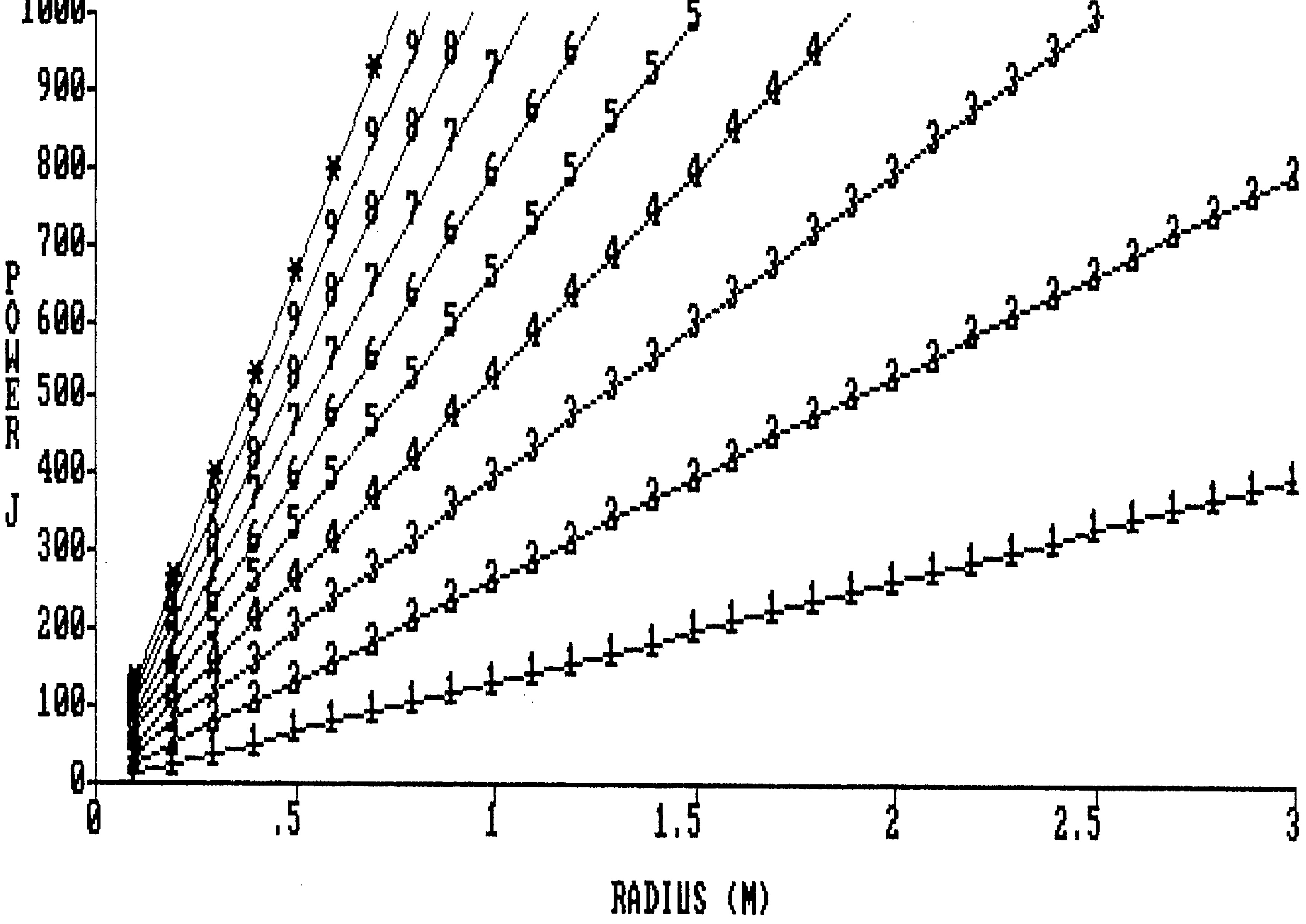




VELOCITY CURVES (M/S) FOR DELTAT=60 SECS.

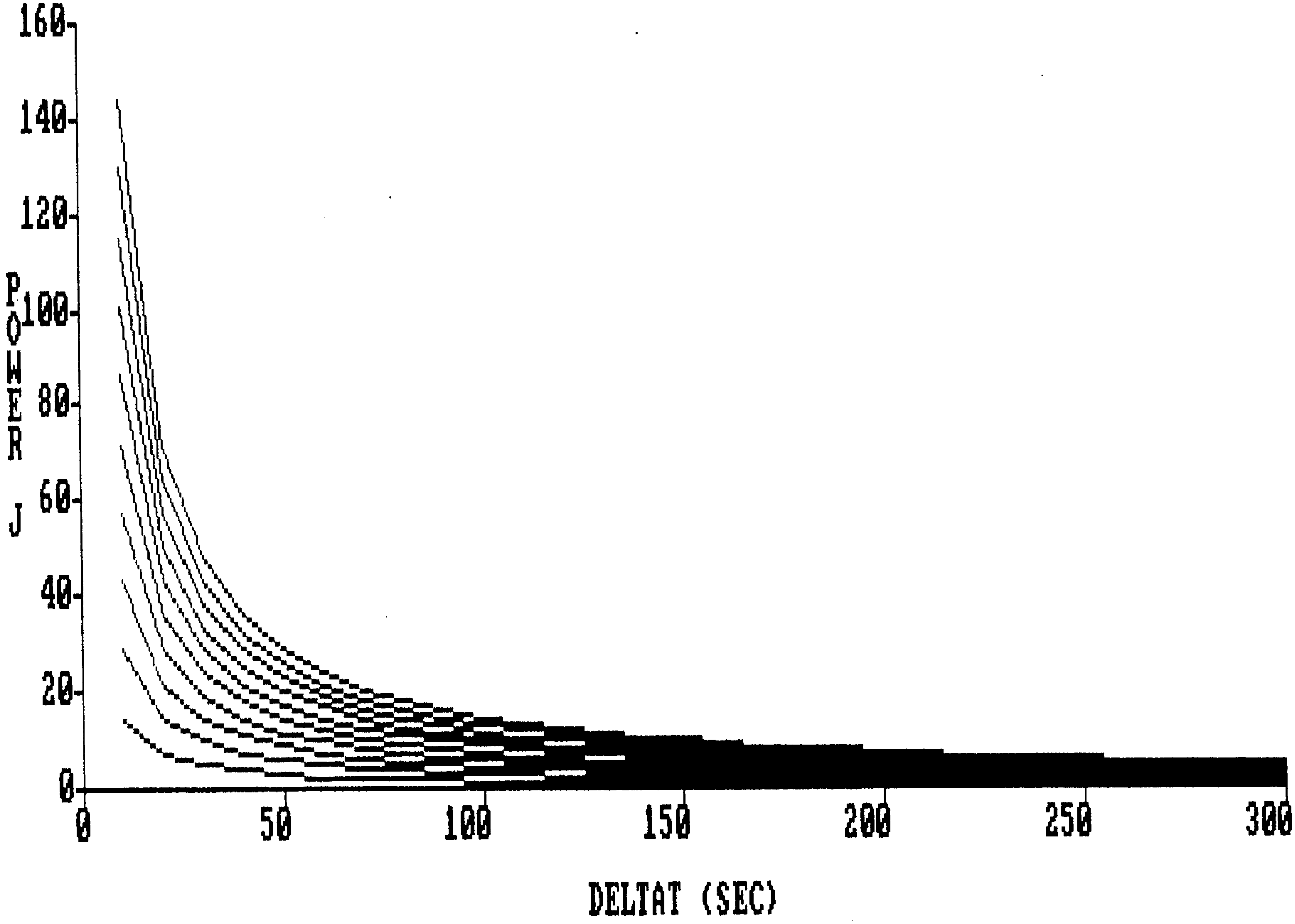
VELOCITY CURVES FOR DELTAT=60 SECS.



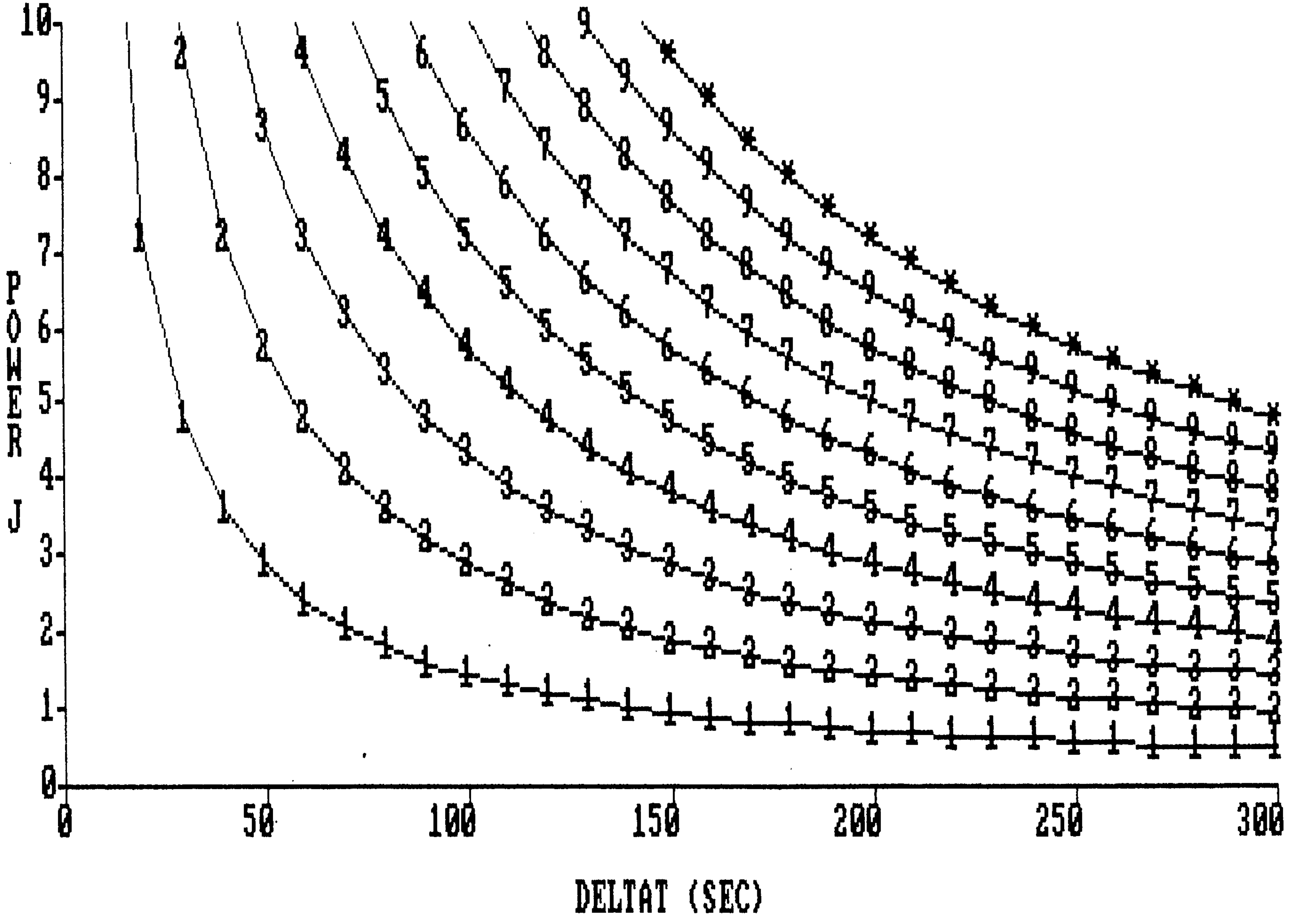


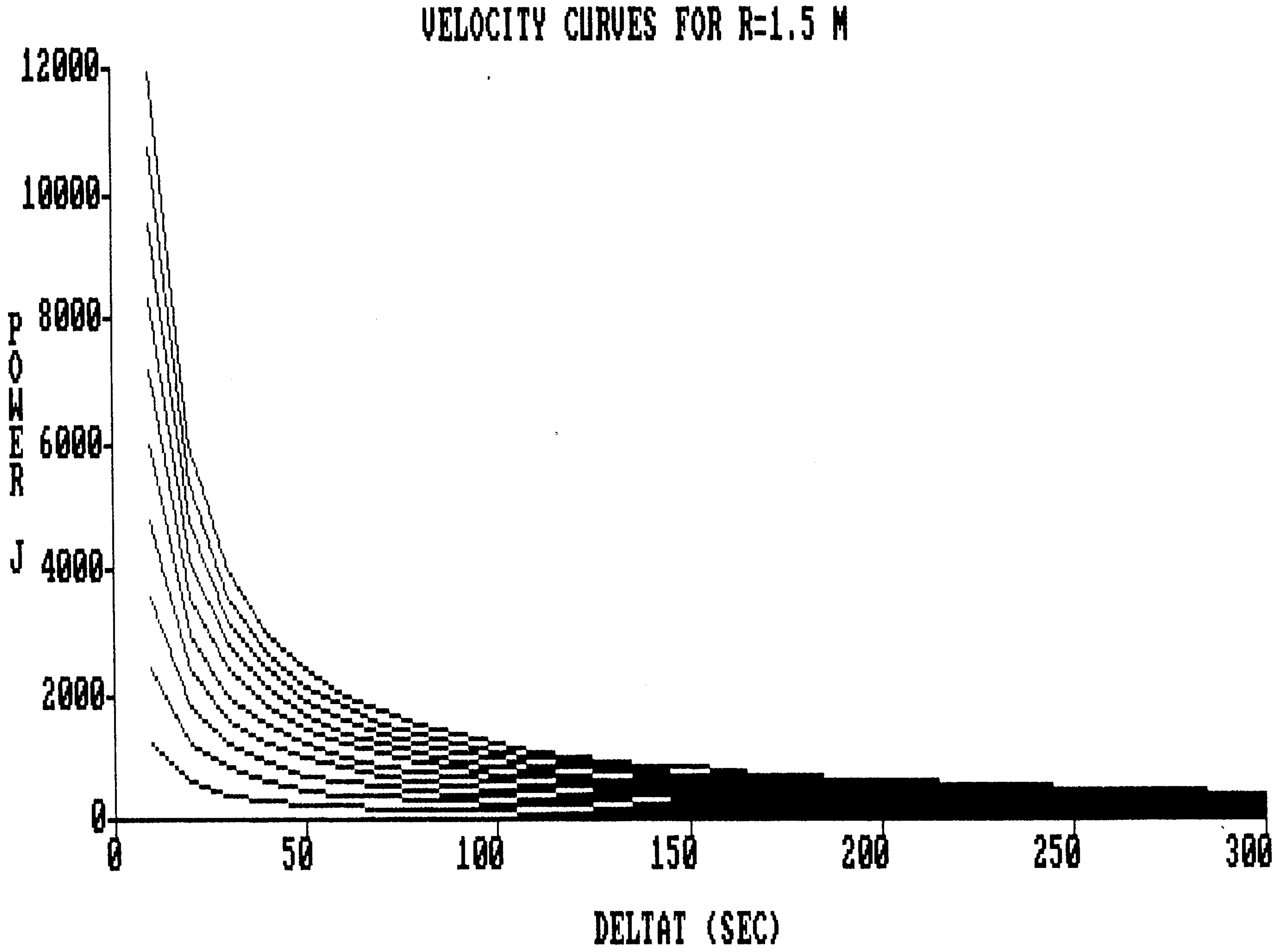
VELOCITY CURVES (M/S) FOR DELTAT=60 SECS.

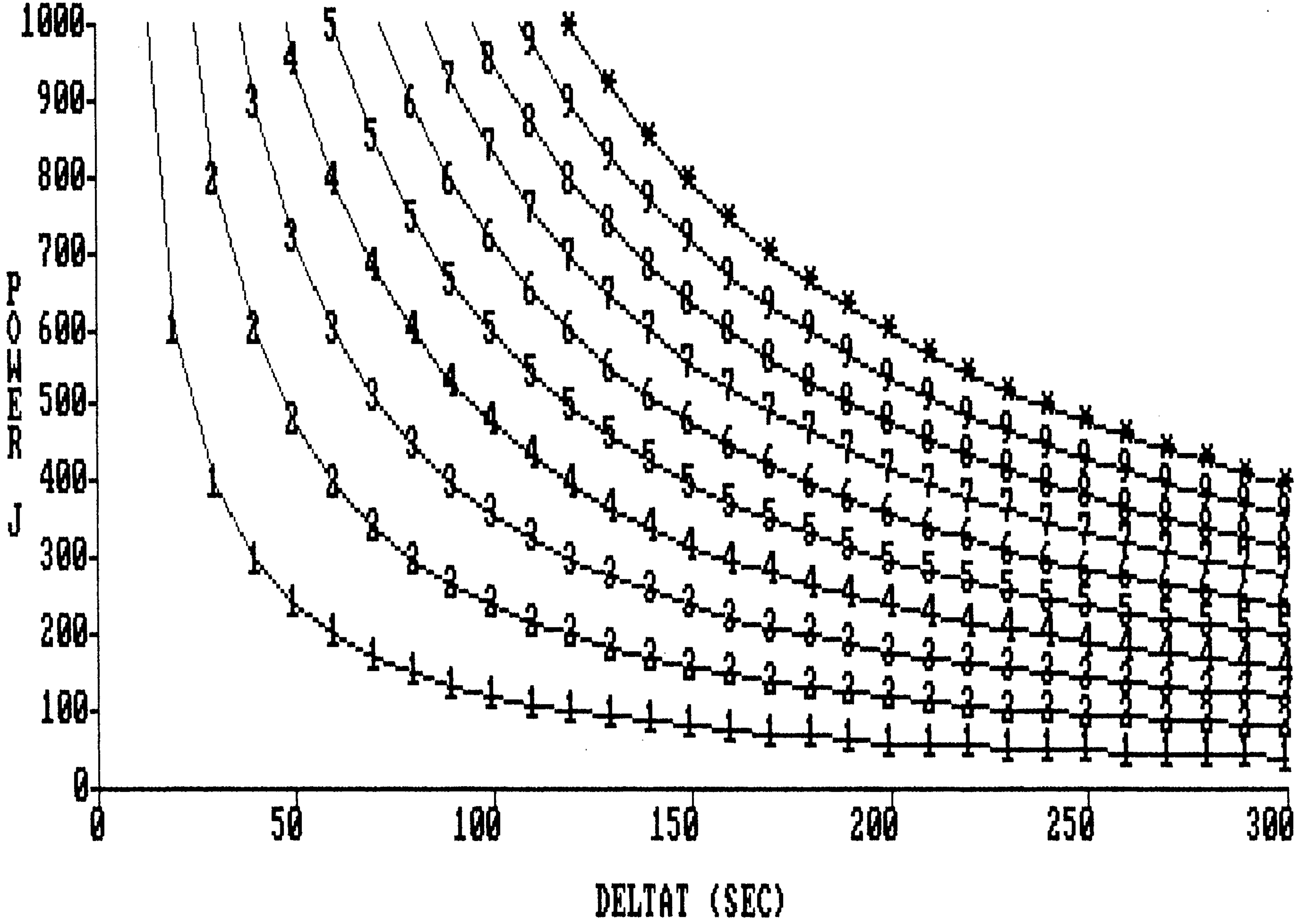
VELOCITY CURVES FOR R=.5 M



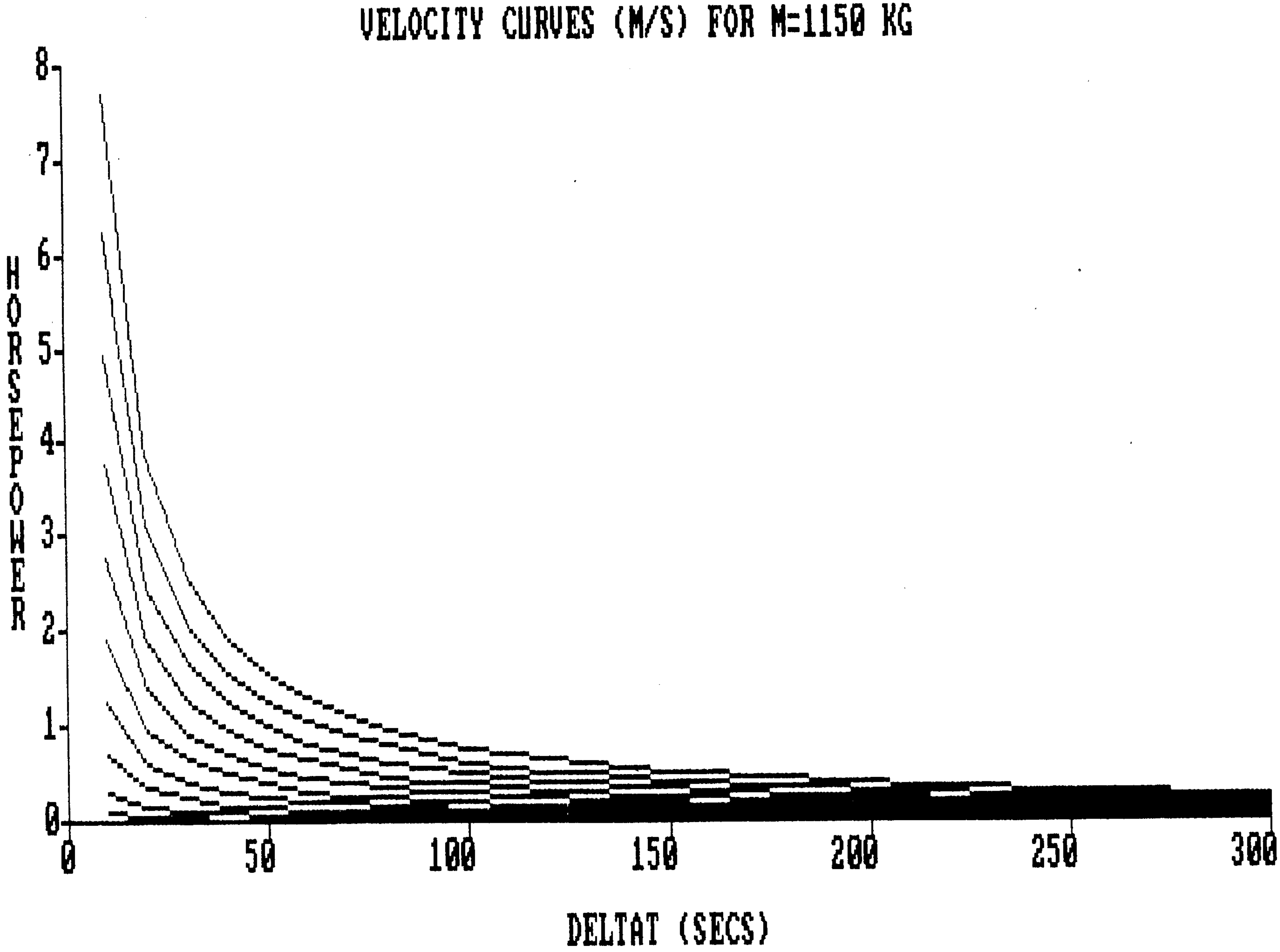
VELOCITY CURVES (M/S) FOR R=.5 M



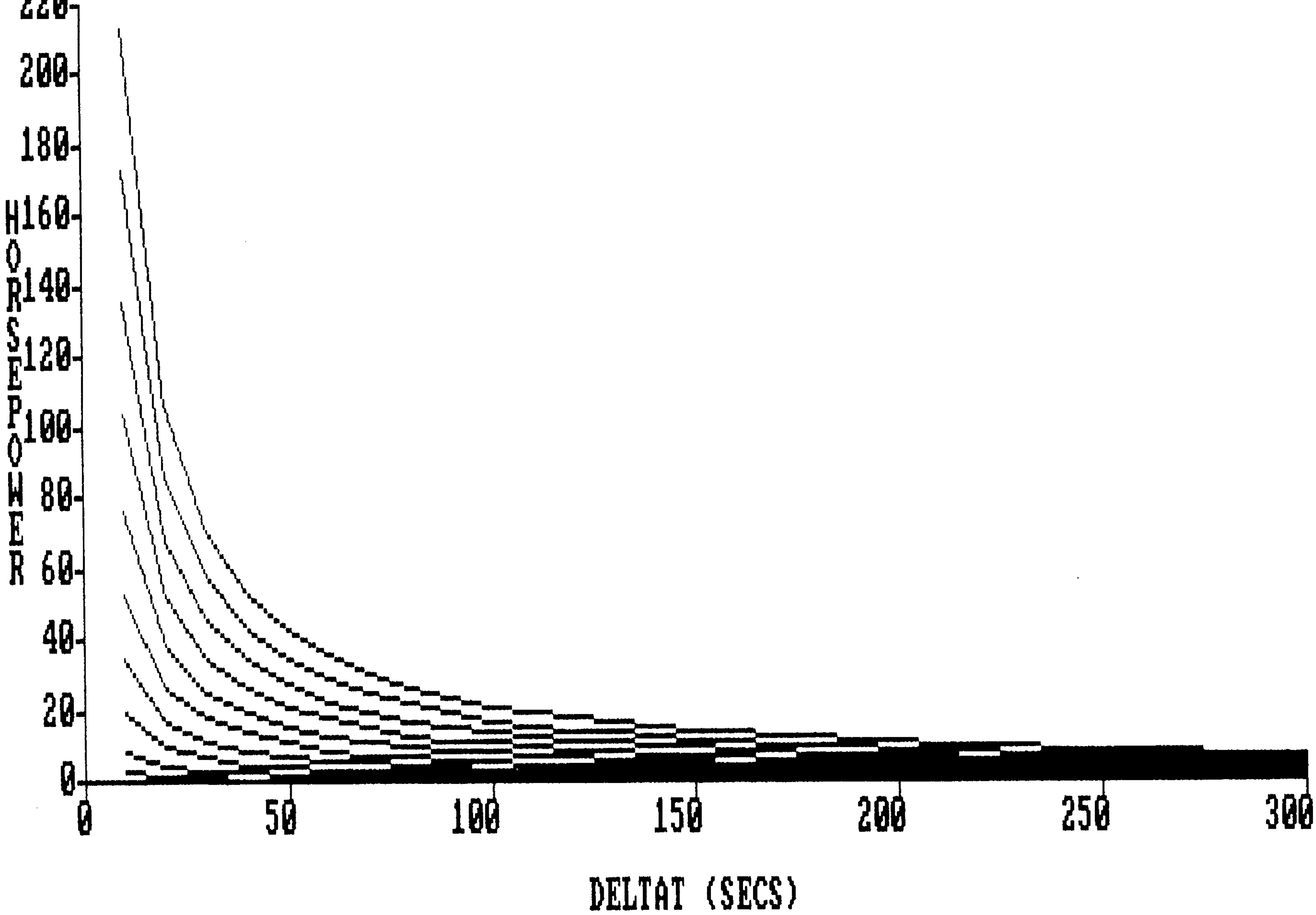

VELOCITY CURVES FOR R=1.5 M
POWER J
12000
10000
8000
6000
4000
2000
0
0
50
100
150
200
250
300
DELTAT (SEC)



VELOCITY CURVES (M/S) FOR R=1.5 M

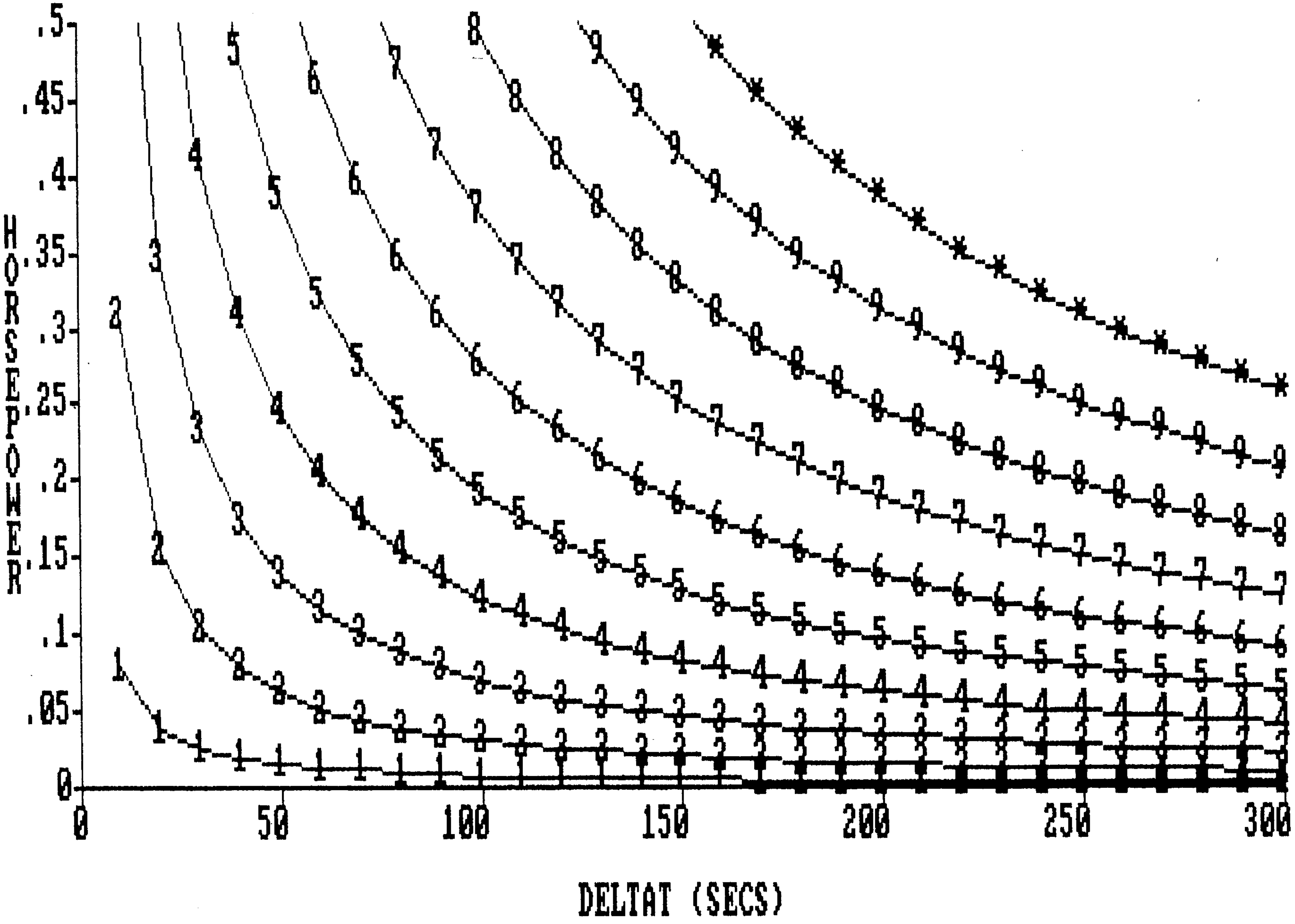


VELOCITY CURVES (M/S) FOR M=1150 KG



VELOCITY CURVES (M/S) FOR M=31751.3 kg

VELOCITY CURVES (M/S) FOR M=1150 KG



VELOCITY CURVES (M/S) FOR M=31751.3 kg