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University of Colorado
Cislunar Infrastructure
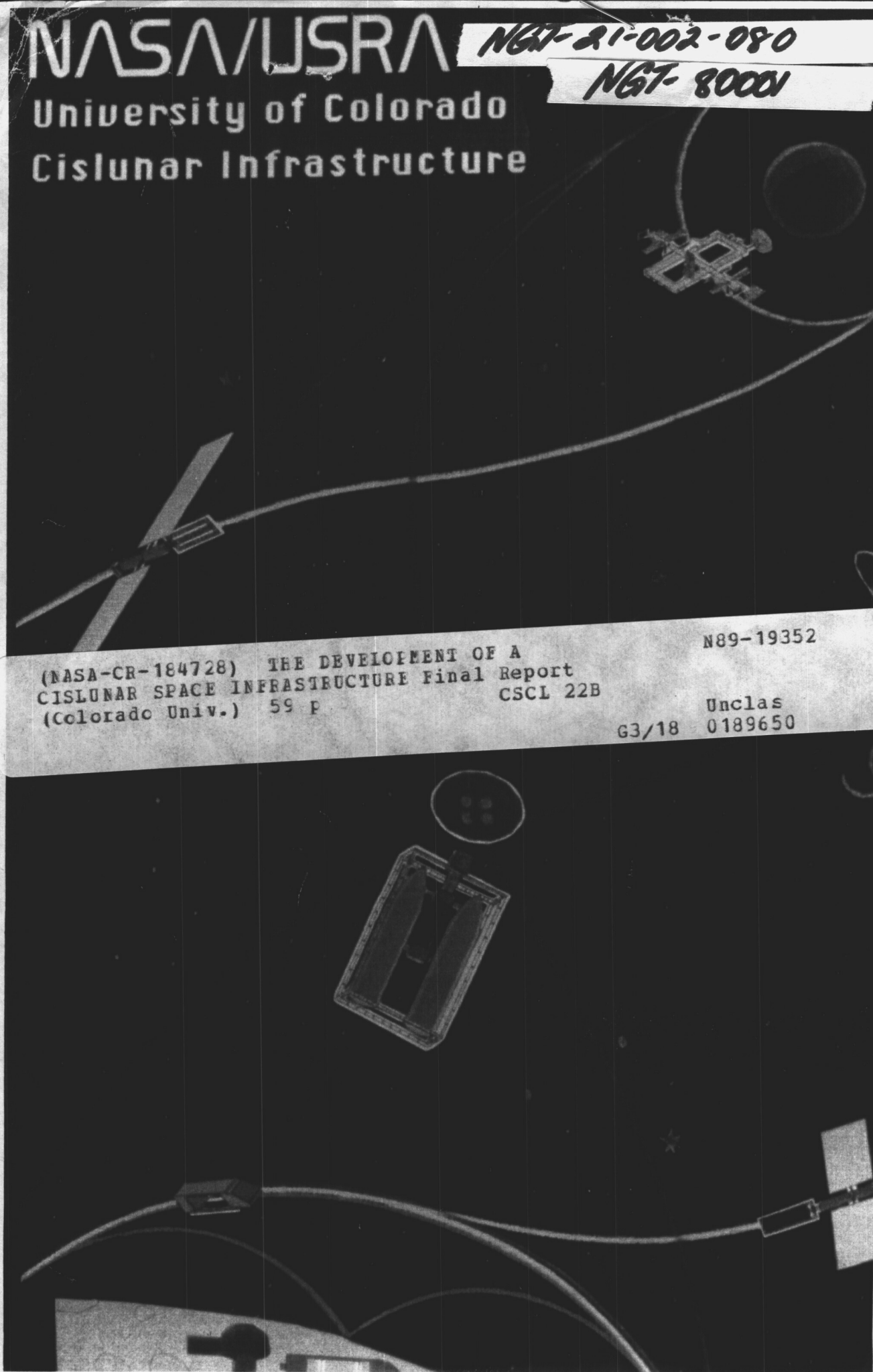
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THE DEVELOPMENT OF A CISLUNAR SPACE INFRASTRUCTURE

BY

C.A. Buck, A.S. Johnson, J.M. McGlinchey, and K.D. Ryan

Advisor: Marvin W. Luttges

University of Colorado, Boulder, Colorado 80309

ABSTRACT

The primary objective of the University of Colorado Advanced Mission Design Program is to define the general characteristics and phased evolution of a near-Earth space infrastructure. The envisioned foundation includes a permanently manned, self-sustaining base on the lunar surface, an L1 space station and a transportation system that anchors these elements to the LEO station. The implementation of this conceptual design was carried out with the idea that the infrastructure is an important step in a larger plan to expand man's capabilities in space science and technology. Such expansion depends on low cost, reliable and frequent access to space for those who wish to use the multiple benefits of this environment. The presence of a cislunar space infrastructure would greatly facilitate the staging of future planetary missions, as well as the full exploration of the lunar potential for science and industry. This paper will explore the rationale for, and propose a detailed scenario in support of, the cislunar space infrastructure.

LIST OF SYMBOLS

CELSS Controlled Ecological Life Support System
ECLSS Environmentally Controlled Life Support System
EPOTV Electric Propulsion Orbital Transfer Vehicle
ESA European Space Agency
EVA Extra-Vehicular Activity
FRG Federal Republic of Germany
GEO Geosynchronous Earth Orbit
GNP Gross National Product
HEO High Earth Orbit
HPV Human Powered Vehicle
L1 Libration Point between the Earth and Moon
LEO Low Earth Orbit
OMV Orbital Maneuvering Vehicle
OTV Orbital Transfer Vehicle

INTRODUCTION

Recently, the National Commission on Space report and Dr. Sally Ride's report to the NASA Administrator have advocated returning to the Moon. The University of Colorado Advanced Design class undertook an evaluation of how such a program might evolve. The goal was to define the evolution of a near-Earth space infrastructure having manned activities. The approach was to be a broad programmatic one that avoided Apollo-like, highly focused, technology demonstrations. The infrastructure design was based upon "enabling" as much access to space and the lunar surface as was feasible. It was conceived as a program that would allow U.S. science and technology an opportunity to flourish in uses of space.

A multi-phased program was developed by grouping mission activities within levels of increasing infrastructure support. The activities include those conducted in orbit, as well as those performed on the lunar surface. When defining mission scenarios, weighted consideration was given to the economic feasibility, flexibility, scientific interest, safety and required hardware of these missions. A preliminary design of key components and/or systems of the infrastructure is presented.

A clear rationale was attempted for each phase of the program, and a set of

metrics was developed to evaluate continued program growth. Predetermined breakpoints provided for systematic program evaluations and updates. Additionally, the impact of such a program and associated space infrastructure on the nation's economy is assessed.

INFRASTRUCTURE

An infrastructure is traditionally defined as "the basic facilities, equipment, services and installations needed for the growth and functioning of an organization" Examples of such an infrastructure are found in the highway system, the railway system, and the detailed network by which goods and services are distributed throughout this country. In today's society, the facilities, equipment and services are taken so much for granted, that the infrastructure has become virtually transparent. It is not until a disaster or a crisis occurs that the infrastructure becomes visible. Natural disasters such as floods, tornadoes and earthquakes often disrupt portions of our infrastructure and only then do infrastructure failures become newsworthy. The oil embargo of 1973 disrupted a major supply line that was a large part of the oil distribution infrastructure. Gas prices rose dramatically as the United States was forced to look elsewhere for oil. This example illustrates the resilience of an infrastructure. Certainly prices increased, but the oil distribution infrastructure was flexible enough to handle the crisis. The embargo did not result in a complete halt of the country's oil dependent activities. The infrastructure ensured a certain degree of programmatic safety. It allowed a parallel or alternative progression of events. This is in stark contrast to a situation where there is little infrastructure and where critical services are completely lost in times of natural disaster.

A space infrastructure provides a sort of "scaffolding" in anticipation of future program expansions. Development of a sound infrastructure for the space program will provide the foundation for the future development and exploration of space. It is necessary to build this infrastructure such that it may be the basis on which future space activities can flourish. It may be expanded upon and it may support creative and more technologically advanced work than we can presently imagine. Historically, it has been shown to be difficult to predict scientific breakthroughs or their implementations, but it has been possible to show that all of these things occur only when the infrastructure is capable of supporting them. Thus, a space program should be developed that will promote unexpected advances and that will directly benefit from them. The thesis developed herein highlights a space program founded on an infrastructure basis that will be strong, cost efficient, and most importantly, flexible.

Properly implemented, the proposed space infrastructure should provide services in a manner that those services are virtually taken for granted by the user. Not only basic services like life support, transportation and power must be provided. Diverse lab facilities must enable a wide range of investigations. In addition, the necessary support equipment must allow for logical and thorough investigations. This also implies facility availability in a realistic time frame, certainly months not years. For example, a scientist studying new superconductor materials might consider processing the material in microgravity to determine if a better crystalline form could result in better superconductive performance. In today's U.S. space program, this study would probably have to wait 4 years before flight. If the experiment failed and/or a follow on experiment were desired, another 2 years might be needed.

However, with proper facilities, the request could be made and within a year the investigator may have one or two months to conduct his investigation. The probability of an investigator actively pursuing space-based research will increase substantially if facilities are available in a timely manner, economically priced and comprehensively supplied. The space infrastructure must provide these qualities if the best talents in science and technology are to be attracted to the space arena.

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RATIONALE

The United States and the Soviet Union are no longer the only nations with strong commitments to space programs. Western Europe, Japan, China and India have all joined the space race. American successes such as Apollo, Titan, Saturn, Voyager, Skylab and Discovery are being overshadowed by names from other nations, such as Soyuz, Ariane, Energia, Vega, Mir and Hermes. Without the development of a near-Earth space infrastructure, the U.S. could soon lose the historic stature as a leader in space technology. Can we expect similar occurrences in other technological arenas? Will we soon be joining the ranks of the technologically handicapped third world countries? Will NASA's once sought after technology no longer be in demand?

A comparison of the U.S. space program and several competing programs is illustrated in Figure 1. During the 1970's, the U.S. was the undisputed leader in space technology, which was exemplified by repeated lunar missions and a large orbiting space station, Skylab. Skylab was only used for a short duration and eventually fell to Earth, the majority of time, virtually unused. Moon missions were abandoned. After more than 15 years, only the space shuttle represents the U.S. technological superiority in space. As the world enters the 1990's, the shuttle will have spent almost a third of the time since the first flight in an inoperable status. Current projections indicate that the Soviets' shuttle demonstration flight will occur as the U.S. shuttle returns to operation. A Soviet space shuttle coupled with the permanent presence of the Mir Space Station, which is smaller than Skylab, marks a potential shift in space faring capabilities.

The future holds many questions. Current long range plans of various space programs will place their technological level equal to, or greater than the U.S. program of the early 1980's. Will the U.S. stay 20 years ahead of the competition?

The international space programs of the year 2000 will be very competitive. Numerous countries will be able to provide launch services. Several newcomers to manned space programs will join the exclusive ranks of the U.S. and Soviet Union. The U.S.S.R. is appearing as if it is making the commitment to a manned Mars program. Failure of the U.S. to make a firm commitment to a well balanced program, could result in the U.S. becoming a second rate space faring nation. A cost effective, flexible infrastructure can provide the momentum for the U.S. space program to surge back toward a role of world leadership.

The University of Colorado Advanced Design Program proposes a near-Earth space infrastructure consisting of a lunar base, a manned L1 space station and a fleet of associated transportation vehicles. A near-Earth space infrastructure has the potential to generate great economic and scientific returns, as well as less tangible benefits such as increased nationalism and greater stature in world politics. It is expected that a near-Earth space infrastructure would be beneficial to the future of the United States by providing a degree of economic return similar to that attained by the Apollo program. A U.S. presence in Earth orbits would advance research in areas such as Earth studies, material processing and variable gravity experiments, as well as astronomy and solar studies. Although the direct benefits of a space initiative are difficult to assess, the United States must now make an investment in the technological future offered by space. The U.S. has exhausted many of the advantages gleaned from the infrastructure put into place by previous generations. It is time for us to build the infrastructure from which the U.S. of the 21st century will flourish. This investment will aid the U.S. in maintaining leads in science, technology and industry.

METHODOLOGY

The proposed evolution of a candidate infrastructure is illustrated in Figure 2. This preliminary scenario timeline consists of specific mission target dates that can accommodate changes depending on both funding and available technologies. The timeline is subject to any initial delays dependent on the date of program initiation. The infrastructure development program is checked periodically by

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NOW

	EXPENDABLE LAUNCHERS	SHUTTLE	SPACE STATION	LUNAR MISSION	MARS MISSION
USA	★	★	USED TO	USED TO	
USSR	★	?	★		
ESA	★				
JAPAN					

	EXPENDABLE LAUNCHERS	SHUTTLE	SPACE STATION	LUNAR MISSION	MARS MISSION
USA	★	★	★	?	?
USSR	★	★	★		★
ESA	★	★	★		
JAPAN	★	★	★		
OTHERS	?	?			

FUTURE ?
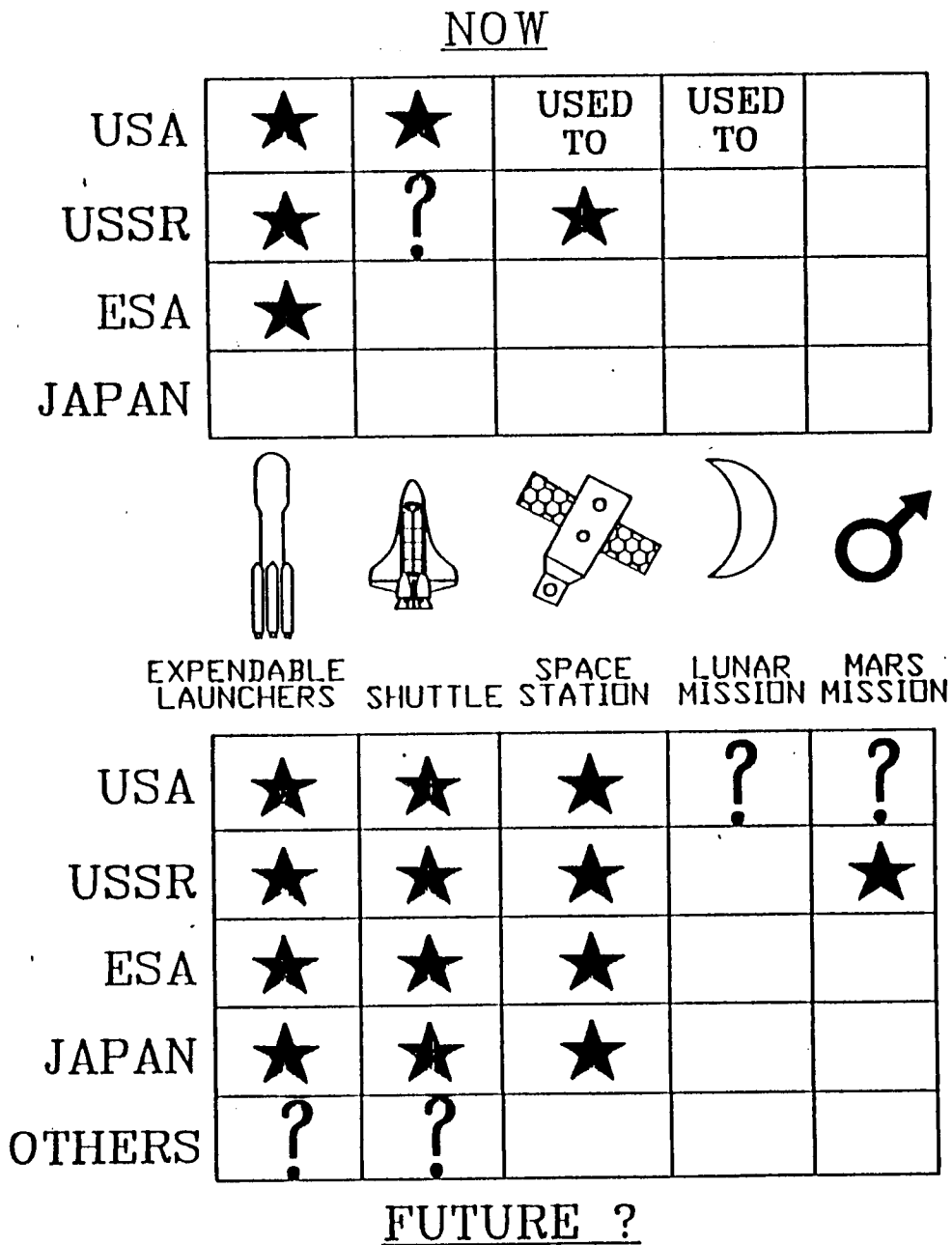
Figure 1 - Space Program Comparison

The U.S. space program is compared with several competing programs. The U.S. had a capable lunar exploration program and a large space station, Skylab, making it the undisputed space technology leader. Now, the soviet program capabilities are beginning to surpass the U.S. with the expected debut of its own space shuttle. Expected technology growth of these programs is expected to catch up with the U.S. space program. Soviets seem to be committing to a Mars program. Will the U.S. make the committment to stay ahead as a technological leader in space?

```
        LUNAR                    KEY
     POPULATION                EVENTS

     0  5  10 15 20
    ┌─────────────────────┬──────────────────────────────
1989│                     │
    │  ──── CONTINUOUS     │ 1990: PROGRAM ACCEPTED
1991│      HABITATION      │
    │                     │
1993│  ─ ─ TEMPORARY       │ 1993: ORBITAL MANEUVERING VEHICLE
    │      HABITATION      │ 1994: PHASE I — SITE SELECTION
1995│                     │
    │                     │
1997│                     │ 1997: ORBITAL TRANSFER VEHICLE
    │                     │       ECLSS LIFE SUPPORT
1999│                     │
    │                     │
2001│                     │ 2001: SMALL LUNAR LANDER, ECLSS
    │                     │       ELECTRIC PROPULSION OTV
2003│                     │ 2003: HIGH—EARTH ORBIT SPACEPORT
    │                     │
    │                     │ 2004: PHASE II — OUTPOST DEVELOPMENT
2005│                     │       LEVEL I AND II CELSS
    │                     │       COMPLETE TRANSPORTATION SYSTEM
2007│                     │
    │                     │
2009│                     │ 2010: PHASE III — PERMANENTLY MANNED
    │                     │             BASE WITH LEVEL III CELSS
2011│                     │
    │                     │
2013│                     │ 2013: FAR SIDE OBSERVATORY
    │                     │
2015│                     │
    │                     │
2017│                     │ 2017: PLANETARY STAGING
    │                     │
2019│                     │
    │                     │ 2020: ADVANCED L1 STATION — LEVEL III CELSS
2021│                     │ 2021: PHASE IV — SELF—SUSTAINING BASE
                                         LEVEL IV CELSS
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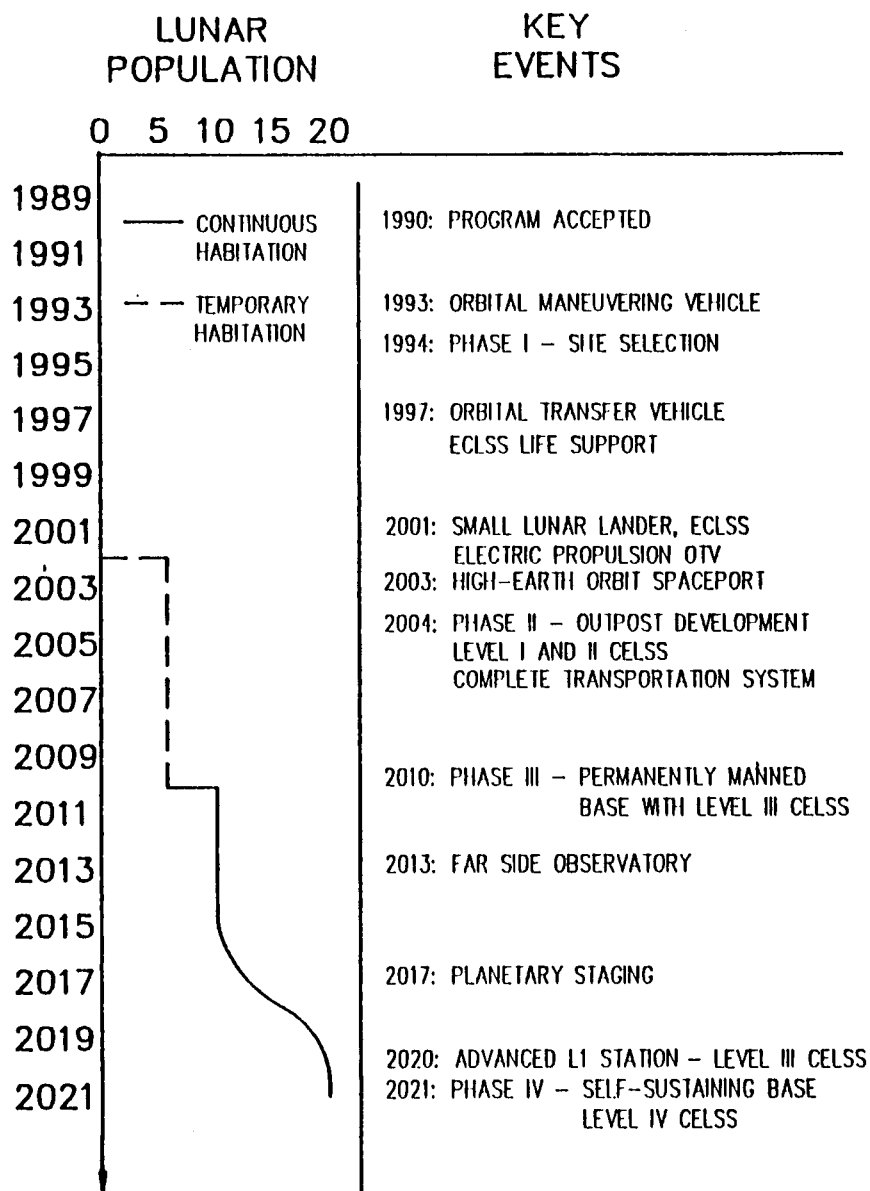
Figure 2 - Infrastructure Timeline

The growth of the cislunar infrastructure could grow along a schedule such as this. Early efforts are made to establish a viable transportation system and robotically survey the Moon for potential landing sites. Near the turn of the century, modest facilities will support a variety of scientific and research missions. As technology matures, economical utilization of lunar materials may become feasible, spurring more growth to a permanently manned phase. Further growth implies greater involvement in lunar activities and more sophisticated capabilities on the Moon. An advanced L1 station may become warranted. Eventually, the base may become virtually self-sustaining and contribute to the material support of advanced missions, such as a manned Mars mission.

means of breakpoints. These breakpoints are used to evaluate the progress and success of the program. Additionally, they will establish a series of driving questions that will have a bearing on the future of the program.

The evolution of the program is controlled by four goals. These goals relate to safety, costs, mission efficiency and program evaluation. The grouping of mission objectives into phases that require similar levels of infrastructure support is optimized using these goals and expected levels of available technology.

The first goal is to maximize human safety. This is addressed by minimizing transit times between destinations, by providing adequate radiation protection against solar flares, and by maximizing the use of automation and robotics to reduce risks 'to humans. Cargo will be transported without human crews. As the number of human missions increases, the infrastructure will enhance human safety by providing a safe haven and resupply depot in the lunar vicinity at an L1 space station.

The L1 station provides for greater flexibility within the transportation infrastructure. For example, emergencies on the Moon could receive assistance from the L1 station in approximately one day. Assistance from LEO would take almost four days.

Low cost is the second goal. Incorporation of previously designed space hardware, such as used on LEO space station, will help reduce program costs by eliminating additional research and development costs. Recycled hardware will also minimize costs. The L1 transportation node reduces overall transportation costs by providing a staging point near the Moon. This location was chosen to optimize overall delta-V expenditures. It also allows the consolidation of crews and cargoes in order to reduce overall transportation activities and costs. Electric propulsion cargo vehicles take advantage of low propellant usage to further reduce operating costs.

The development of the infrastructure was scheduled using a reasonable yet urgent and ambitious timeline. This provides realistic dates for breakpoints while minimizing cost overruns which occur when a contractor falls behind in development or production schedules. Funds will be committed on a phased basis. This reduces the financial investment for any given phase. Overall cost effectiveness should make follow-on program funding more attractive for congressional approval.

The infrastructure was designed in an open-ended manner. The inherent flexibility enables the continuance of a project should it experience a setback. Open-endedness means that a failure is merely a turning point and not a dead end. The most important characteristic of an open-ended design is that the goals of the design form the foundation for further expansion without specifying the direction the expansion must take. Single "final pathways" and bottle necks are, thus, avoided.

Mission efficiency demands the logical planning of both scientific experiments and mission objectives. Experiments for each phase are selected to take full advantage of the available support from the infrastructure. For example, early infrastructure support enables new scientific information and demonstrations of economical feasibility of using lunar materials for future expansion of the infrastructure. These mission objectives also infer what type of support is needed. For example, during the Outpost Phase, robotic vehicles are required to support various construction activities at the base. When no longer needed for construction, the simple change-over of modular components could convert a construction vehicle into an automated core sample return vehicle.

Finally, the fourth goal is that the missions must provide the means to evaluate further expansion of the infrastructure and continuation into the next phase of development. For example, if processing of lunar materials is not feasible then it is not probable that the program would continue into Phase III, Permanent Base, and power demands may not justify a nuclear power plant.

Evaluation of design performance at any particular stage of development is accomplished by a set of specific criteria and metrics. The evaluations take place at specified breakpoints and the design current status is compared logically to the predicted status for a given point on the overall timeline.

The methods by which the goals of the program will be achieved are dependent

upon the technologies available throughout the system evolution period. Some of the more important technologies which will enable the system are:

- Life Sciences and Life Support
- Transportation Systems
- Propellant Storage and Transfer
- Space Construction Techniques
- Automation/Robotics
- Power Generation
- Space Suits

Four assumptions were made in establishing the cislunar infrastructure scenario: 1) a reliable transportation system exists between Earth and low Earth orbit (LEO); 2) there is a functional LEO space station; 3) a heavy lift launch vehicle exists; and 4) on-orbit construction capabilities exist.

HEO ACTIVITIES

A high Earth orbit platform is needed to support the in-orbit activities and services that are necessary to promote safe and efficient planetary exploration. For safety, flexibility and cost efficiency, a platform will be placed in a halo orbit about Libration Point 1.

Space based operations provide several unique opportunities. Three major categories include 1) observational missions which look down on the Earth, 2) astronomical missions which look out into the universe and 3) microgravity science to study physical processes.

The first class of unique opportunity is Earth observational missions, and include a wide variety of applications. These include remote sensing missions which look down to the Earth's surface and atmosphere in order to better understand the forces at work on this planet and to provide a means to monitor and evaluate trends of Earth resources. Other applications include communications and navigation missions. By basing these platforms in space, a better perspective of the Earth is obtained. Those missions based in low Earth orbit cover wide areas on the Earth's surface due to the rotation of the Earth and the resulting progression of the the ground track of the satellite relative to the Earth's surface. Some of these missions are better enabled by geosynchronous satellites which monitor the Earth from a fixed perspective, such as some weather satellites.

Astronomy is another major class of unique opportunity; one which is significantly enabled by being done in space. Without atmospheric attenuation, space based astronomy can monitor the entire range of the electro-magnetic field. Infra-red, gamma ray and ultra-violet radiation are examples of electromagnetic radiation which are attenuated by the atmosphere of Earth. Only by collecting information on as many wavelengths as possible will man develop a clearer understanding of the universe.

All of these observational missions can be performed extremely effectively by unmanned observing platforms. Direct manned participation has been relatively limited to photographing the Earth from orbiting spacecraft and the very extensive solar studies from Skylab. The unmanned platforms are relatively inexpensive and are simply replaced at the end of the useful life of the satellite. However, trends toward the "great observatories" implies increased capital investment which cannot be simply discarded. These large observatories will ultimately require manned support in order to maximize the scientific benefits. Manned support is necessary to replace old sensor packages with newer technology sensor packages that have greater information gathering abilities. This transition is similar to that of ground based optical astronomy which has replaced photographic emulsions with charge-coupled devices that have greater light gathering power. Failure or maintenance of observatory systems also must be facilitated. Can a $2 billion dollar observatory be allowed to drift useless in space after 9 months because a piece of

orbital debris destroyed a key component or because a communications antenna pointing system failed? No, such a facility can not be allowed to become useless. Capabilities to effect repairs and to perform periodic maintenance tasks, such as refilling the cryogenic cooling system for infra-red observatories, is absolutely necessary to protect the investment made in such a facility. During the near future this can be only accomplished through manned activities. Future satellites, such as GEO communications satellites, also may be economically feasible to service and not merely replaced. This is particularly true when failures which occur prematurely, yet involve satellites that provide vital services, such as weather monitoring.

Although observational missions could be performed by unmanned platforms and serviced by manned missions, space operations provide another unique opportunity which can only be realized by a manned presence. Microgravity provides an opportunity to study the physics of a wide range of processes in which the dominant forces are different than those on Earth. Earth based processes are relatively well understood and are dominated by the force of gravity. In space, gravity is one thousandth (or less) of the value on Earth and becomes comparable (or less) in magnitude to surface tension forces and convection forces. Electrophoresis is better enabled because the electrostatic forces are not obscured by gravitational forces. The possibilities of microgravity based processes are still in their infancy. Certainly most of the expertise in materials processing lies in the Soviet Union and Western Europe, but access to space materials processing offers the U.S. an opportunity to develop new materials and new materials processing capabilities.

Space provides other opportunities. For example, the high quality of near infinite vacuum may prove beneficial to some processes. Solar radiation or geomagnetically trapped radiation may be exploited for research. There may be a wide range of other resources available for exploitation as well. However, without a viable infrastructure, the full potential of the space environment will never be fully realized ar even approached by some of our best talent.

Performance of microgravity experiments is better enabled by a human presence rather than an automated system. A free flying facility such as the Industrial Space Facility (or the Commercially Developed Space Facility) would provide a long term low gravity environment that is uncontaminated by accelerations induced due to humans moving about or the vibrations from the operation of life support and other systems. A manned space station could provide an environment suitable to explore a wide variety of processes in order to select promising experiments for the long term or the higher quality microgravity conditions found on free fliers. Although free fliers provide better microgravity conditions than a space station, provisions must be made to support humans nearby in order to exchange experiments and retrieve samples. Free fliers will be expensive to access if they are tended only from ground launch systems, such as the shuttle, rather than accessed from a space based facility (space station).

The infrastructure must provide economical support for these missions. In-orbit facilities are necessary to support a wide range of studies. A manned habitat is necessary to provide long term human presence in space. Laboratory facilities should include a wide range of instruments and supplies to allow for investigations to continue relatively unimpeded (for lack of space based resources and facilities). Current practices for space experimentation generally require long delays from experiment conception to performance in flight. Investigators, with follow on experiments, experience further delays to complete their experiments. Currently the total time of these delays is on the order of several years. A good idea may soon become obscure due to overriding new technologies or alternate solutions to the process being investigated; too many opportunities are lost. The envisioned infrastructure must enable investigators to proceed from one experiment to the next in a timely manner. Successes for these investigators translate into a healthy U.S. technology and a healthy U.S. Space Program.

As the infrastructure expands, another space station may become useful as a transportation node. The choice of location is based on several criteria; radiation

limits, line of sight to Earth, delta-V expenditures, and travel time to and from various locations (See Figure 3 for candidate orbits). Crew safety must come first. Because the GEO orbit would subject a crew to the trapped particle radiation in the Van Allen belts, it was immediately eliminated. Proximity to the moon is the second requirement, since the high earth orbit station will directly support lunar activities. Libration Point 3 is thus eliminated as well as the cycling orbits which are only in close proximity to the moon during part of their orbits. Because the high earth orbit station will initially serve as a transportation node for fuel storage and mission staging, the delta-V's between the station and the Earth and Moon are important. This criterion eliminates the Earth/Moon Libration Points 4 and 5.

Lunar orbit is eliminated by the probability that the platform will serve as a planetary staging base in the future. A base located in lunar orbit is only accessible to one inclination angle about the Moon. Therefore to reach different locations on the Moon, greater delta-V's may be encountered. Also to its' disadvantage, a lunar orbiting station will increase greatly the amount of station keeping required.

This narrows the choice to halo orbits around the first and second libration points. Using halo orbits, any lunar inclination can be accessed with no additional delta-V. Also, by utilizing a halo orbit, the station will remain in the vicinity of the libration point and only require small station keeping requirements (Farquhar, 1972). Libration Point 2 offers a 10 % delta-V savings over the Libration Point 1 with 150 % of the trip time for optimum transfers. However, for a four day trip time, the L1 point offers a 14 % savings in delta-V with respect to a shorter trip time (Johnson, 1988). Figure 4 compares the delta-V requirements for L1 and L2. Thus the L1 point was chosen as the location for the high Earth orbit spaceport. Figure 5 illustrates the delta-V's of an L1 based transportation node (ADL, 1987).

The manned L1 station will act as a staging point between LEO and the Moon. Several activities have been proposed for the L1 platform for the purpose of aiding and supporting the lunar base activities, as well as supporting the whole space infrastructure proposed in this paper. A sequence of operation is proposed in Figure 6.

Initially, the station will act as a refueling center by serving as a fuel and cargo depot. This will aid in establishing a more cost efficient transportation infrastructure. Resupply of propellants under low gravity conditions is a technology which is currently under development. The process is expected to become a routine operation in the future. Such a process would be required for space based vehicles such as the manned and unmanned orbital transfer vehicles. The primary obstacle to overcome involves the regulation of the fluids under low gravity conditions. The propellants must be situated in the tanks in such a manner as to allow their passage into and out of the supply lines. For this purpose, several systems have been developed, including the use of capillaries and "bladders" or skin friction devices (Kirkland, 1985).

Once refueling and storage become routine activities at the L1 station, L1 can concentrate its efforts on a transportation control center. With the increase in traffic in space due to the infrastructure developments, a "control-tower" will be needed to regulate traffic. This transportation control center will oversee all activity in the LEO to Moon vicinity.

Satellite servicing, as previously mentioned, is a necessary activity for the infrastructure. It is important to prevent an increase in space debris, which "presents a growing hazard of re-entering objects and in-space collisions", (National Commission on Space, 1986), and prolong the useful life of the satellite. The ability to replace the inoperable parts of a satellite allows the functional parts to be used to their maximum potential and provides an overall reduction in cost for the services the satellite provides. Examples of retrieval and repair of satellites already accomplished by space shuttle missions on an experimental basis include the Solar Maximum Mission spacecraft, and LEASAT 3 spacecraft. In addition, two communications satellites, Palapa and Westar, were retrieved and returned to Earth for repair. At the present time, satellite technology is improving very rapidly such that satellite servicing may not be economical at this time. For satellite servicing to
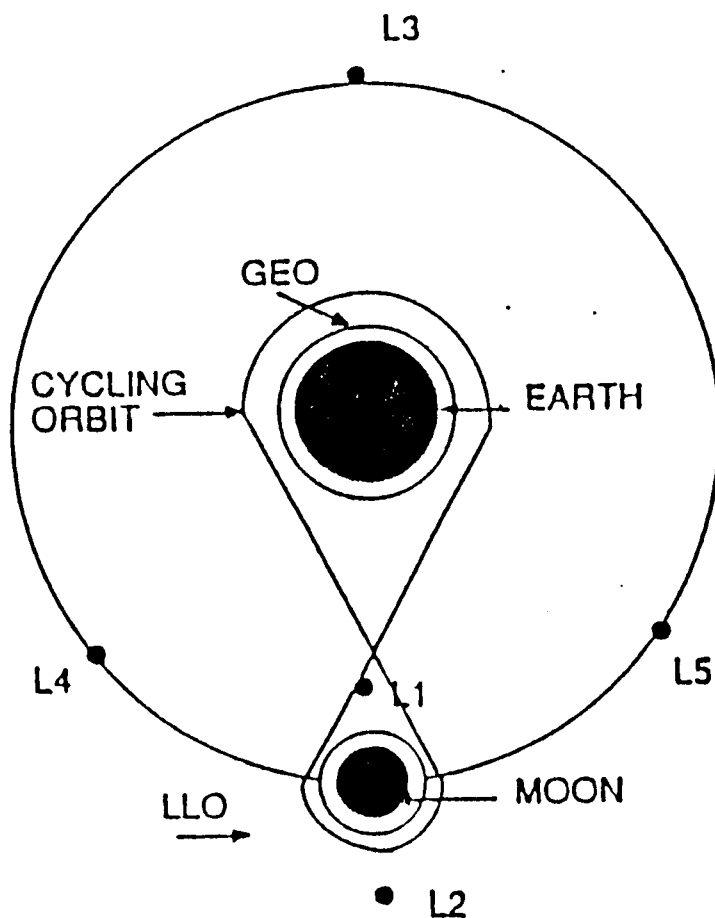
Figure 3 - Candidate Orbits for a High Earth Station

The schematic scene of candidate orbits for a high Earth orbit station include the five libration points, geosynchronous orbit, and lunar orbit.The choice of location is based on several factors, a few of which are radiation limits, line of sight to Earth, delta-V requirement and travel time to various locations.

L1 vs. L2

TO:	ΔV KM/SEC	TIME DAYS	EARTH	L1	MOON	L2
L1	3.8	4				
L1	3.7	6				
L2	4.4	4				
L2	3.4	9				
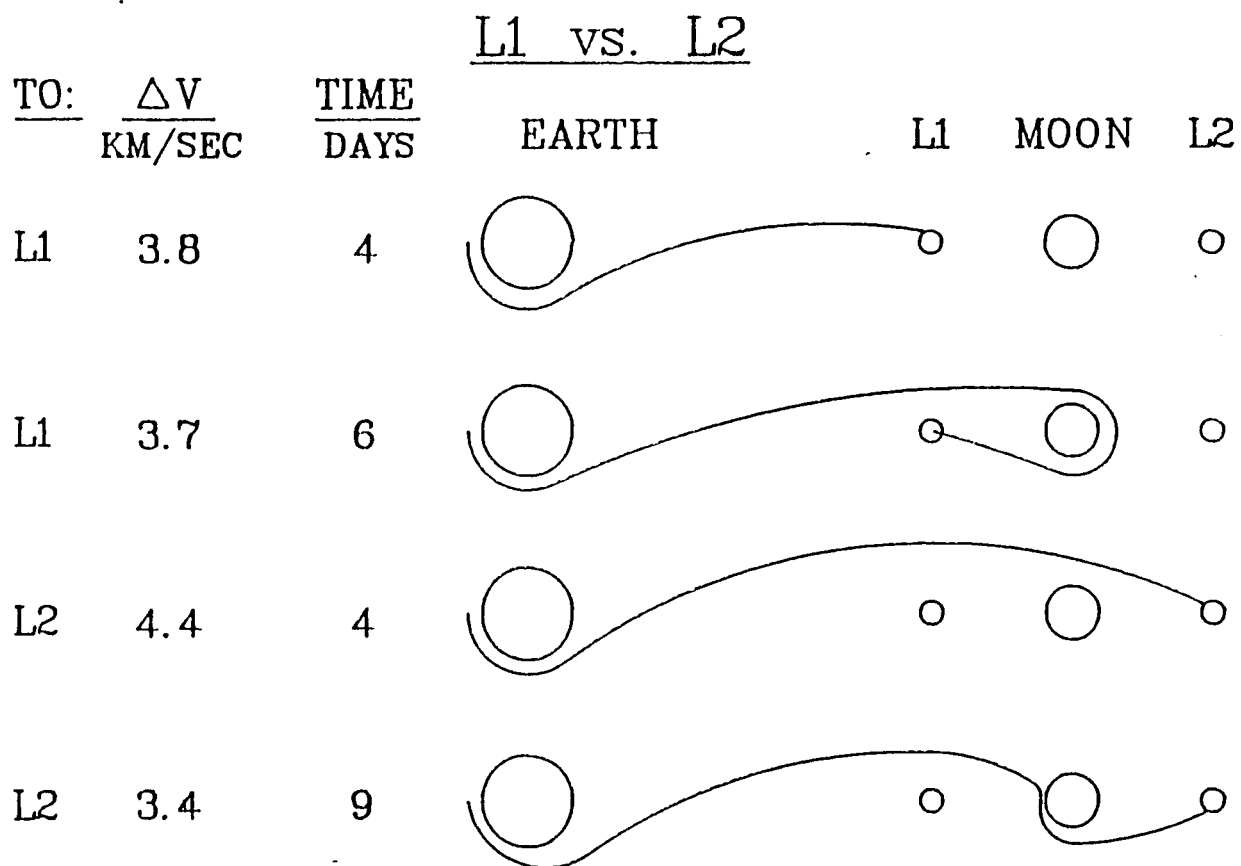
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Figure 4 - L1 vs. L2: Delta-V Comparison

A comparative analysis of delta-V's and travel time from the Earth to L1 to the Moon, and from the Earth to L2 to the Moon. The L1 point offers a savings in delta-V's with respect to a shorter trip time.

PRIMARY ROUTE DELTA–V's (KM/SEC)

FROM \ TO	LEO	GEO	L1	POLAR	LUNAR ORBIT	LUNAR SURFACE
LEO		4.2	3.8	4.3	4.1	**
GEO	2.0*		1.4	**	**	**
L1	0.8*	1.4		0.8*	0.6	2.5
POLAR	4.3	**	3.8		**	**
LUNAR ORBIT	1.3*	**	0.6	**		1.9
LUNAR SURFACE	**	**	2.5	**	1.9	

ADAPTED FROM ASTS STUDY, 1987
ARTHUR D. LITTLE, INC.

* — WITH AEROBRAKING

** — IMPROBABLE ROUTE

EP < LEO to LUNAR ORBIT – 8 KM/SEC
LEO to L1 – 6.75 KM/SEC + 0.5 KM/SEC CHEM BRAKE

Figure 5 - Delta-V's for Primary Routes

This chart describes the delta-V's required for various space travelled routes. Such space travel includes the locations of LEO, GEO, L1, polar orbit, lunar orbit, and the lunar surface.

ORBITAL TRANSFER VEHICLE OPERATIONAL

INITIAL L1, REFUELING, FUEL DEPOT

TRANSPORTATION CONTROL CENTER

SATELLITE SERVICING,
GEOSYNCHRONOUS CLEANUP

PERMANENTLY MANNED LUNAR BASE

PLANETARY STAGING
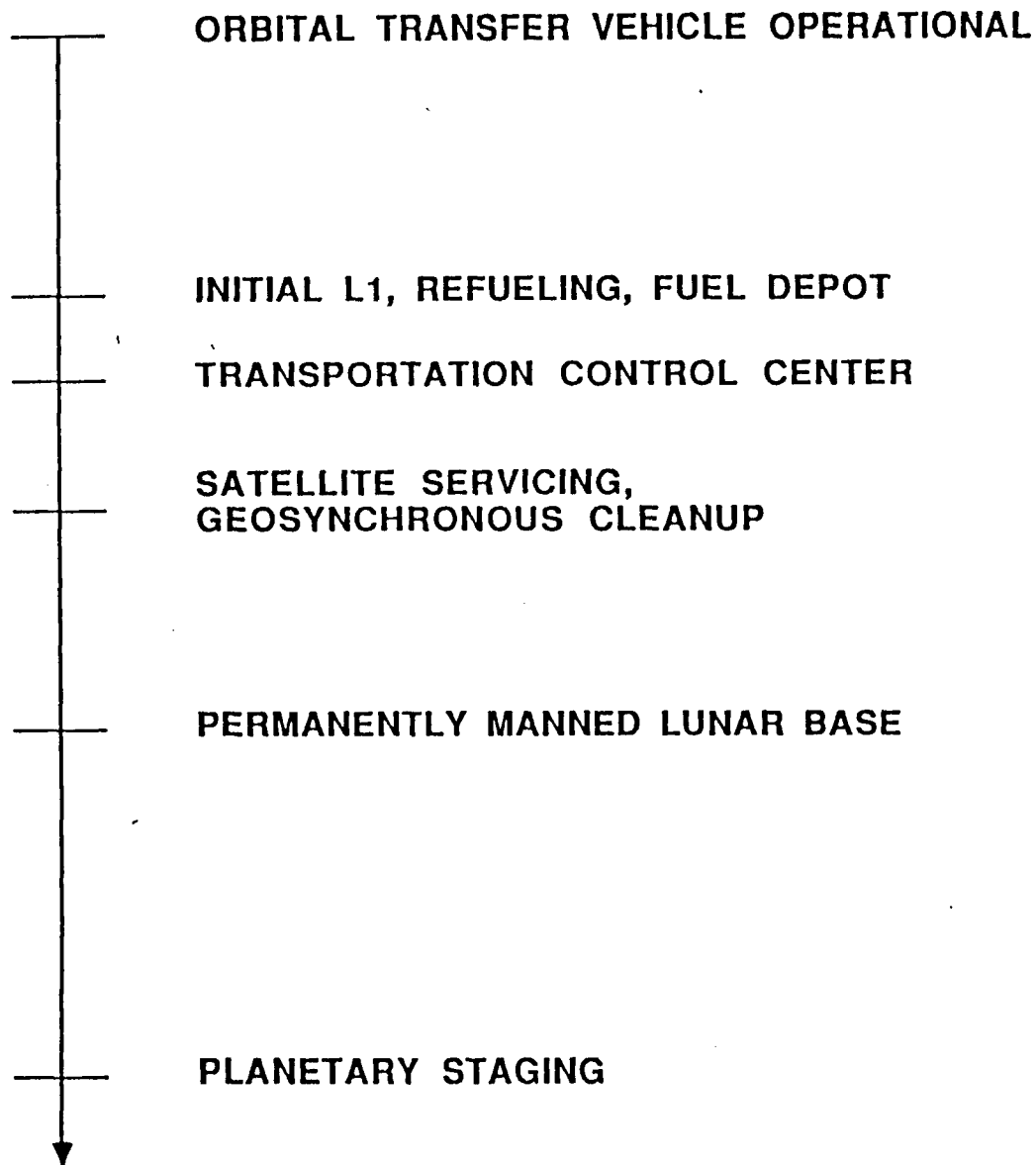
Figure 6 - High Earth Orbit Sequence of Activities

This high Earth orbit timeline details the activities and operations to be performed
at the L1 station. Activities and projects coinciding with the developments of the
L1 station are also shown, i.e., OTV operational and the presence of a lunar base.

become economical, gains in satellite technology must level off and cost efficient access to the satellites must be provided. This latter factor can be enabled by a space infrastructure.

Along with satellite servicing is GEO cleanup. As expired satellites drift through the geosynchronous region, a potential for collision with actively controlled satellites is created. Drifting is caused by the lack of station keeping in the expired satellite, as well as by the perturbing accelerations. Periodic variations in inclination ranging from 0 to 15 degrees are possible over a period of approximately 50 years. Future collisions between debris and satellites will generate even more debris. This phenomenon will further increase the potential for collisions. Therefore, it is evident that steps must be taken to clean up the GEO orbit. The L1 station is also an excellent location from which to base future planetary missions. A direct consequence of a spaceport located at L1 is planetary staging, in accordance with two of the initiatives presented in Dr. Sally Ride's report, Mission to Mars and Exploration of the Solar System, and the Pathfinder technologies for exploration of Mars. Interplanetary spacecraft may be assembled at the platform, and refueling may be accomplished without the added expense of missions to Earth, taking advantage of the gravitational pull at L1. Additional savings may be realized through the utilization of lunar resources.

Human safety is always a primary concern. The utilization of reusable spacecraft at L1 implies a greater margin of safety by providing a more flexible transportation system. "In space, refueling and refurbishing lead to a reusable vehicle that can be ready to refly in a time shorter than needed for a launch of expendable components from Earth... Staging at L1, which includes propellants, and possibly a spare lunar lander and an extra aerobraked OTV frame, can provide rapid assistance to Lunar missions compared to assistance staged from low Earth orbit" (Johnson,et al., 1988). The shortened reaction time required with such an infrastructure leads to enhanced crew safety and efficiency.

Prior to full HEO activities, the L1 site is a "parking orbit" for expended external tanks from shuttle, for obsolete GEO satellites and other space hardware on which the costs of transport to orbit have been paid. The role of this hardware in future missions is only partially predicted.

LUNAR BASE ACTIVITIES

The Moon will provide a focal point for advanced astronomy research, planetary studies and possible economic returns from processing of lunar resources. Advancements in sciences will be enabled through the use of lunar based observatories to study the universe while a better understanding of the solar system will be aided through geological studies conducted on the Moon. From these activities, added expertise in space science will evolve to support future and more remote planetary and lunar surface studies.

Advancing science is a general goal for astronomy. More specifically, astronomical research helps to answer questions about the formation of the stars, the planetary systems, and the areas beyond the edge of the universe. The National Commission on Space proposes that people undertake a unified and comprehensive effort in order to answer these questions. Radio astronomy is becoming increasingly more difficult to perform on Earth. A refuge is needed where the entire electromagnetic spectrum can be reserved for the purpose of pure astronomy, and the far side of the Moon provides an optimum location.

Astronomy is based upon the collection of faint electromagnetic radiation emitted by distant space objects. Highly sensitive telescopes which will pick up the various wavelengths are used. It also includes the study of cosmic ray particles and objects such as interstellar dust clouds (seen through radio and infrared techniques) and orbiting black holes in exploding galaxies (using x-ray and gamma ray telescopes).

The wavelengths of infrared sources, ultra-violet, x-ray, and gamma ray radiation from space objects do not penetrate the Earth's atmosphere, therefore, space based astronomy is needed to study these wavelengths. Optical and radio astronomy

is much improved in space, as opposed to what is available on the Earth's surface. Additionally, radio-interference from Earth can be shielded by the Moon, making radiotelescopes located on the far side lunar surface more effective. In space, atmospheric blurring is not present, and extremely long baselines for ultra-high angular resolution may be created. The sensitivity of observations is increased by increasing the area over which radiation is collected. The angular resolution is also sharpened through interferometry. Interferometry is the improvement of image sharpness by enlarging the physical dimensions of the observing system.

The positioning of an optical interferometer array on the lunar surface would improve the angular resolution to one micro-arcsecond at optical wavelengths (Burke, 1985). Angular resolution can never be better than the diffraction limit. This limit can be found by dividing the wavelength by the aperture diameter. The best angular resolution achieved on the Earth is 1/3 arcsecond. The Earth's atmosphere damages the phase coherence too severely at optical wavelengths for this type of interferometer array to be used on Earth. This Y-shaped array consists of 27 individual telescopes which weigh 250 kg each. Revolutionary new views of objects in the universe would be obtained if this system could be built in space. Lunar gravity will aid the interferometer array operations by seating bearings and by providing reference vectors for mechanical systems. The thermal qualities of the Moon will serve as shielding for the setup. The interferometer array will perform more effectively on the Moon than at LEO due to the obviation of thermal stresses that occur at LEO.

A radio telescope incorporating the Earth and Moon as one large system, the Moon-Earth Radio Interferometer (MERI), would offer optimum resolution. It would use the same principal as the Very Long Baseline Interferometry (VLBI) network on Earth with a different observational technique to synthesize the aperture. The celestial coordinate system could be improved using the unprecedented position accuracy of MERI, which in turn would improve celestial navigation and astronomical timekeeping. It may also be possible to search for black holes and neutron stars or even planets around radio stars using this interferometer technique (Burns, 1985).

By incorporating a Very Low Frequency (VLF) radio telescope in a large lunar observatory, an increased resolution and sensitivity in observations would be available. Discoveries can be made in the radio sky beyond a ten meter wavelength because the terrestrial ionosphere absorption is not a factor on the lunar surface. The lunar surface offers several advantages over free space. The lunar surface is a stable platform which is able to provide a large area (up to 200km) for multiple antenna setups, there is plenty of room for expansion, an additional structure is not needed to hold an antenna array in place (as would be the case in space), and the lunar far side is shielded from interference from the Earth. The initial array of this telescope would weigh less than 50 kg, and the computer data processing unit would weigh about 1200 kg. This system will have high priority for initial lunar scientific projects due to its simplicity and weight efficiency (Douglas and Smith, 1985).

Initially, structures for the lunar base, propellant for transfer vehicles, metabolic oxygen, food and water will have to be supplied by Earth resources. As the capabilities and size of the infrastructure increase, however, the utilization of lunar materials will be required for cost effectiveness and to reduce the lunar habitat's dependence on Earth-based supplies.

During the initial outpost phase which supports six crew members, the availability of oxygen and water will be of prime importance. Several methods of extracting oxygen from the lunar surface are available. Carbothermal reduction, hydrogen reduction, hydrogen sulfide reduction, fluorine exchange and electrolytic reduction are all possible processes. For the initial metabolic oxygen and water production, the hydrogen reduction process was deemed the most likely candidate due to its "clean" operation, simple chemistry, and the fact that hydrogen is the lightest weight reactant that can be transported from the Earth to the Moon. The major disadvantage of this process is that hydrogen is a good reducing agent for oxides of elements heavier than manganese on the periodic table. Only iron oxide and the iron portion of ilmenite are reducible. This constitutes only 15.8% by weight of the

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oxides present in the lunar fines. Approximately 40.5 lbs of lunar fines treated with 0.1 lbs of hydrogen will yield 1.1 lbs of water or 1.0 lbs of oxygen (Downs, 1971). The hydrogen reduction process will require 150 kw of electrical power and 500 kw of thermal power based on 20,000 lbs of oxygen produced per month. The plant itself could be setup and connected by a work force of three crew members. The operation of the plant will be computerized with operator attention being directed towards the solids handling operations.

This plant will be used for the production of water and metabolic oxygen. Oxygen production for use as a fuel, however, would probably not utilize this process because of the low efficiency of the system. Oxygen for propellant purposes would most likely utilize a carbothermal reduction process that would produce spun lunar fiberglass as a necessary by-product. This would provide production possibilities for various elements such as pipes and pressure vessels, as well as construction possibilities for facilities such as landing pads on the Moon and habitation volumes. This process would require only ten pounds of ilmenite for every pound of oxygen produced, and would require 2.16 Mw of power based on 1000 tons of oxygen produced per year (Downs, 1971).

In addition, mining and materials processing may provide the lunar base with raw materials to be used in future expansions of lunar activities, as well as space activities. The mining and processing of lunar materials for purposes other than oxygen or water production will appear at an advanced phase of lunar base development. Analysis of the lunar soil shows that there are many useful elements that could be used to produce a plethora of products, however, separation techniques are still emerging from a relatively embryonic art to a comprehensive technology grounded in the appropriate chemistry, physics and mathematics. It would, therefore, be more feasible to incorporate a direct utilization of lunar materials for the initial manufacturing on the Moon. The conglomerate of lunar materials (fines, microbrecias, and rocks) become a low viscosity fluid at about 1250 degrees Celsius and, upon cooling, form a glass-like monolithic substance. Under slow cooling conditions, the material becomes crystalline and can be classified as cast basalt when poured into molds. Cast basalt could be used in the production of furnace materials, tiles and bricks. The molten basalt could also be centrifugally cast to produce pipes and conduits. Sintered basalt could be used to manufacture small items such as tubing and light tools, while spun basalt could be used to produce acoustic and thermal insulation, packing material, and filters (NASA/ASEE, 1972).

A Controlled Ecological Life Support System (CELSS) will fulfill the requirements for long term human space missions by reducing the total mass required to be transported from Earth. The lunar CELSS will provide the "seed" to start up other life support systems, such as those needed for an advanced L1 station or a manned Mars mission and base.

In order to deliver lunar materials from the lunar surface to lunar orbit, some means of transportation is necessary. The mass driver, a device capable of launching raw materials from the lunar surface to lunar orbit, could become an integral part of the space infrastructure in one of its advanced phases. Once materials are received by a mass catcher out in space, they could either be processed at L1 or sent back to the Earth for processing. A concept such as this would save on the tremendous cost of transporting the raw materials by vehicle. There have been many preliminary design concepts for such a device, (cf. University of Washington, 1987) however they were not researched in depth for purposes of this report.

TRANSPORTATION

A significant component of the near-Earth space infrastructure will be the transportation system. This transportation system will move both cargo and personnel in space and on the lunar surface. This conceptual design of a transportation system is governed by means of a programmatic approach rather than the standard mission approach. This approach helps to determine an overall design methodology.

The methodology incorporates several design criteria into every part of the transportation system. The main criteria for a successful design are human safety, cost effectiveness and mission efficiency. These criteria relate specifically to the design of transportation vehicles through careful consideration of hardware systems, power systems, orbital dynamics, crew protection and modular characteristics.

In addition, the design of the transportation system should not be based solely on lunar mission scenarios. All near-Earth transportation nodes must be weighted for overall optimization of the transportation system. Low Earth orbit (LEO), geosynchronous orbit, Libration Point 1, lunar orbit and the lunar surface are all significant nodes. Efficient travel between any two nodes must be incorporated into the design.

The staging node at L1 is proposed, as was previously mentioned, in order to enable different types of missions. Tailoring of missions results in flexibility throughout the infrastructure. Transportation costs are reduced by providing an intermediate staging point easily accessible from LEO, GEO and lunar orbit (Johnson, Kliss, and Luttges, 1988). In addition, a halo orbit at L1 is advantageous because it provides cheap access to all Earth orbit inclinations and all lunar orbit inclinations.

The final design is based on several primary assumptions. The first assumption is that there exists a reliable and expedient system for transporting personnel and cargo between the Earth's surface and LEO. This system will most likely consist of Shuttle-like reusable vehicles (Shuttle, Shuttle-C, Hermes, etc.) and expendable launch vehicles such as Titan, Delta, Ariane, and a heavy lift launch vehicle with payload capabilities on the order of the Saturn V launch vehicle. This assumption is a realistic one since most of the desired capabilities currently exist and must only be expanded and upgraded to an acceptable level. The second assumption is that there will be a large scale LEO space station. This station will be capable of supporting on-orbit construction of large space structures and will also be capable of servicing and refueling each of the vehicles involved in the space transportation system. This assumption is also realistic but the time scale for the existence of this station is at present is somewhat nebulous. The transportation system which supports the infrastructure builds on these two basic assumptions and no further details related to these assumptions will be addressed.

Each of the vehicles which compose the transportation fleet share characteristics which are intrinsic to their designs. Modular components are used to reduce manufacturing and servicing costs, enhance system efficiency and provide the flexibility which must be inherent to any infrastructure. (See Figure 7.) Modular components include, but are not limited to, habitation modules, life support modules, fuel tanks, aerobrake shields and propulsion units as well as guidance, navigation and control hardware. Modularity enables one baseline vehicle to be used for either manned or unmanned or unmanned missions, depending upon the types of modules for which the vehicle is configured. A minimum number of propulsive units and a corresponding minimum mass of propellant are used to tailor the vehicle's propulsion system to the mission and thus maximize the vehicle's cost effectiveness. Additional habitation modules and life support modules provide for needed flexibility with respect to the number of crew members a given vehicle may transport on a single mission. Aerobrake shields are not transported unless the given mission includes the LEO node of near-Earth space. Thus, the benefits of modularity can be seen and these benefits justify the incorporation of modular components into the system design.

The fleet design provides the infrastructure with many options in regard to transport hardware and feasible transfer orbits. The vehicles fall into two main categories, manned vehicles and unmanned vehicles. The advantages of this mixed fleet become apparent as the mission requirements of the infrastructure are examined.

Since the infrastructure will enable repeated transport of personnel throughout cislunar space, safe manned vehicles are an important sector of the fleet. Safety is enhanced, through modularity and redundancy, when the system provides a number of options for recovery in the event of an emergency situation.

Examples of recovery options can be drawn from Apollo missions and current

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MODULAR COMPONENTS

LIFE SUPPORT

HABITATION

PROPELLANT
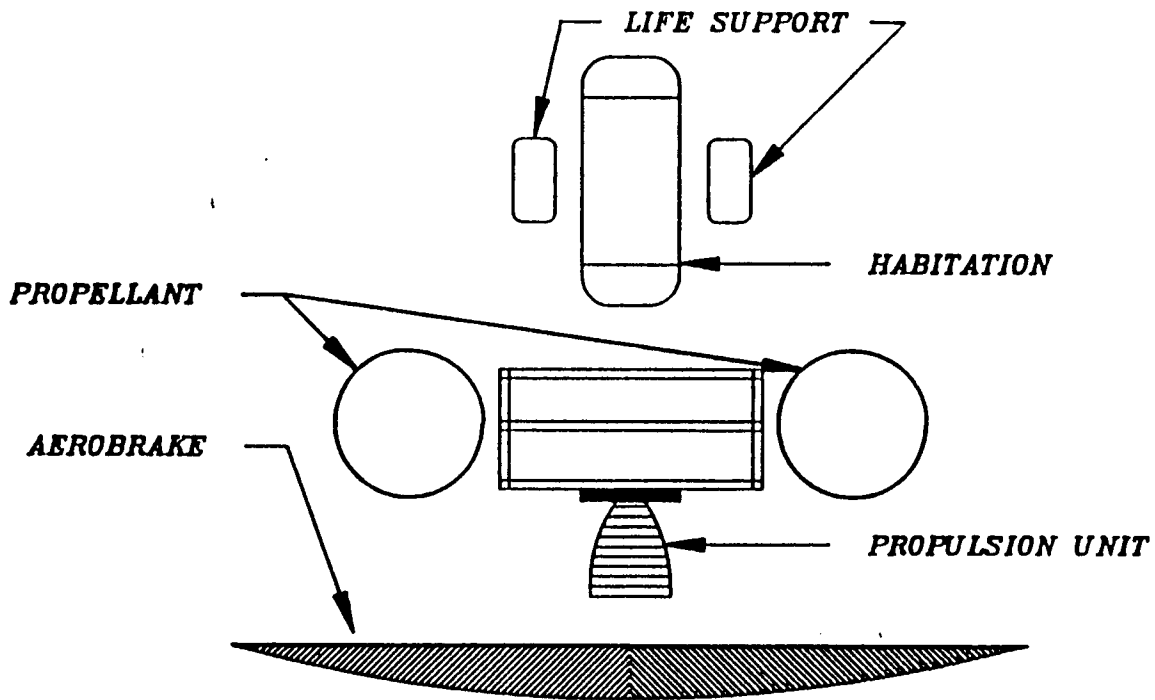
AEROBRAKE

PROPULSION UNIT

Figure 7 - Modular Vehicle Design

A modular approach to spacecraft design increases the flexibility, and hence safety, of the overall infrastructure. Shown is a possible configuration for a manned orbital transfer vehicle.

Space Shuttle mission scenarios. The Saturn V rocket used for the Apollo missions was a single-purpose, mission-oriented vehicle. In the event of an emergency, the three astronauts in the command module had but one location for safe haven in the entire cis-lunar space arena. In order to survive, the crew was required to return to LEO and effect a ballistic re-entry through the Earth's atmosphere.

An emergency situation occurred when the Apollo 13 mission experienced a catastrophic explosion of a liquid oxygen tank in the service module which supports the crew's command module. Nearly all of the command module's life support systems were rendered inoperable when the explosion occurred during the trans-lunar injection phase of the mission. Only because the lunar excursion module (LEM) was attached to the command module did the crew have the propulsion system and life support systems necessary to return safely to Earth. Had there existed an L1 station, a lunar base and additional flight-ready vehicles, the crew would have been guaranteed a higher margin of safety.

During the launch phase of a Shuttle mission the crew has numerous abort options. For example, should one of the Shuttle's main engines fail, the vehicle's capabilities give the crew several avenues by which to return safely to the surface of the Earth. The options include 1) an aerodynamic return of the vehicle to the launch site at Kennedy Space Center; 2) a ballistic trajectory across the Atlantic Ocean to Rota, Spain; 3) a single orbit around the Earth to land at Kennedy Space Center and 4) as a final contingency, an option for the the crew to leave the Shuttle and parachute to a land or sea recovery. This last option causes a loss of the vehicle but gives the crew a better chance for survival.

Once the Shuttle has reached an operational orbit, its crew, like the Apollo crew, has only one option should it become necessary to abort the mission. The Shuttle has to be flown to an acceptable landing strip during an opportune de-orbit time window. The availability of numerous landing sites increases the chances of successfully aborting the mission. The vehicle's flight systems must remain intact in order to do so. Because of the turnaround time needed, there is never a second Shuttle on the launch pad ready to recover a crew stranded in LEO. A transportation system which included several highly flexible and reusable vehicles, at least one of which would be able to depart for any node in cis-lunar space on a moments notice, would minimize the consequences of such a debilitating scenario. Not only does this modular flexibility put the vehicle in a position such that it can be matched to any mission need, it also reduces the likelihood of crew fatalities.

The transportation fleet is composed of several vehicle types. The flagship of the fleet is an aerobrake assisted orbital transfer vehicle (AOTV). This vehicle is shown in Figure 8. Capable of both manned and unmanned operations, this orbital transfer vehicle is propelled by a cryogenic chemical bipropellant system. The liquid hydrogen/liquid oxygen system provides both high thrust and high specific impulse (I_{sp}). This combination provides for a short duration transit between any two locations. The maximum total mass of propellants which the AOTV carries is 50 metric tons. The total payload mass is dependent upon the thrust available from the engines and the two nodes being considered. The designed dry mass of this vehicle is nine metric tons. This mass includes a mass of two and a half metric tons for an aerobrake shield.

The aerobrake is used to reduce the delta-V which the chemical propulsion system must provide upon return to LEO. The aerodynamic drag resulting from the shield's passage through an atmosphere of sufficient density reduces the thrust output from the engines needed to put the vehicle into a capture orbit about Earth.

For example, assume a given aerobrake shield could provide a delta-V of 2.8 kilometers per second upon passage through the Earth's atmosphere. This delta-V is almost one-quarter of the entire velocity change needed for a round trip from LEO to the lunar surface (12.1 km/sec). This results in a decrease in the required propellant mass or an increase in the vehicle's maximum payload mass. As long as the mass of the aerobrake is less than that of the propellant mass saved by use of the aerobrake, the aerobrake is justified. The aerobrake savings are valid only on a mission which involves the LEO transportation node. The aerobrake shield would be
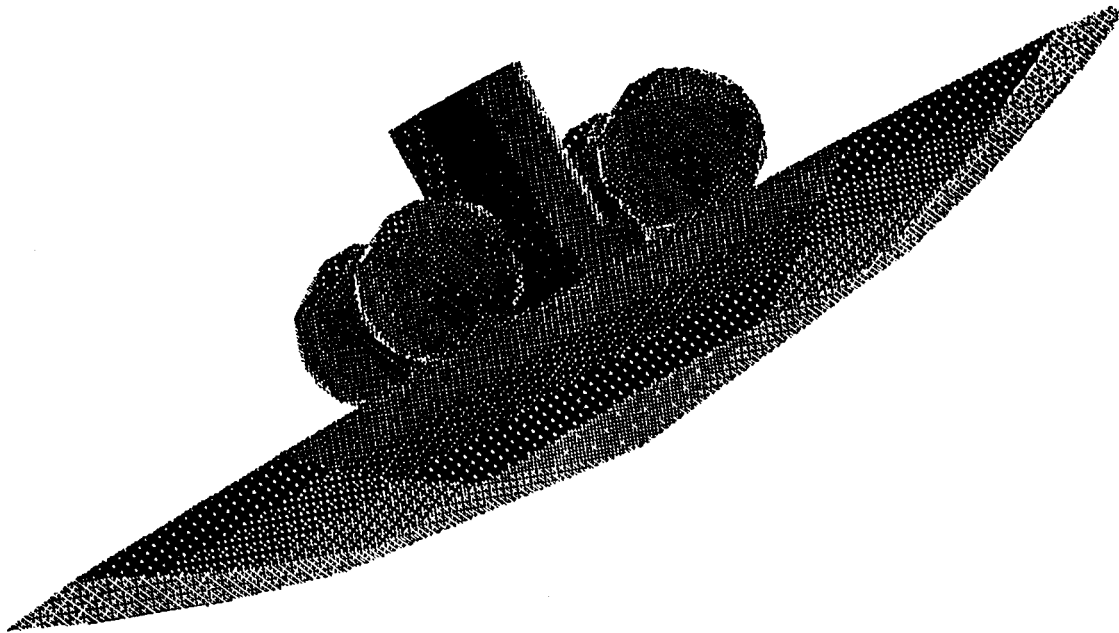
Figure 8- Aerobrake Assisted Orbital Maneuvering Vehicle (AOTV)

The AOTV is the most versatile vehicle of the entire fleet. Chemically propelled, the AOTV can operate either manned or unmanned. The vehicle is designed to carry up to six crew members and/or a large mass of cargo between any two locations in cislunar space. A detachable aerobrake shield is used when the mission includes a stop at low Earth orbit.

removed for the any other inapplicable mission scenario.

The second key vehicle in the fleet is a small lunar lander. A single stage vehicle, the small lunar lander is approximately twice the size of Apollo's Lunar Excursion Module (LEM) and has a dry weight of nine metric tons. This lander would be configured such that the vehicle would carry three crew members and various science payloads for exploration missions. As a lunar base became increasingly operational, the number of science payloads would decrease and the small lander would be reconfigured to transport as many as five crew members per flight. This lander is designed to travel between the L1 staging platform and the surface of the moon. At L1, the small lunar lander would be able to undergo minor repairs, refueling and reconditioning of life support equipment.

The third vehicle in the system is a cargo carrying lunar lander. Shown in Figure 9, this vehicle is substantially larger in size than the previously described lander, the cargo lunar lander also has much higher payload capabilities. The payload mass would be as great as 30 metric tons. In addition, this lander would be capable of shuttling six crew members (with the cargo) between a low lunar orbit and the lunar surface. The low lunar orbit restriction is due to the net mass of the vehicle and its cargo. The cargo lunar lander is not designed to reach lunar escape velocity and because of this, cargo destined for the lunar surface will be shipped directly from LEO to a low lunar orbit and loaded onto the cargo lunar lander.

The three previous manned vehicles are designed to take advantage of modular components. The two specific modular components available for use in manned vehicles are the habitation module and the life support module. The habitation module (or hab module) is a five-and-a-quarter metric ton aluminum pressure vessel designed to house up to three crew members. Some of the life support needs are provided by equipment housed in the hab module. However, the majority of the life support facilities are contained in the life support module. This module has a mass of 0.75 metric tons. Hydrogen/oxygen fuel cells provide both seven kilowatts of continuous power and 21 man-days of potable water. A regular crew of three would require two life support modules for a mission duration of two weeks. All of the wastes from the hab module would be stored in tanks in the life support module. This modularity allows for easy reconditioning of life support equipment at the LEO space station or at L1.

The AOTV and both classes of lunar landers are designed to use liquid hydrogen/liquid oxygen propellants. This design specification is brought about by the fact that manned missions are extremely time sensitive. Transit times must be minimized to reduce crew discomfort and minimize the mass associated with life support equipment. Certain inorganic cargoes are basically time insensitive as long as they arrive at their destination at a specified date. This concept brings about the fourth vehicle in the fleet.

The primary unmanned vehicle is an electric propulsion orbital transfer vehicle (EPOTV). A conceptual design for this vehicle is shown in Figure 10. Used only for unmanned transit between LEO and either L1 or low lunar orbit, an EPOTV would carry time insensitive cargo in a spiral transfer orbit. The transit time would be approximately 180 days from LEO to low lunar orbit. The power system would be comprised of a 300 kw solar-electric, xenon-ion engine array. The total array, consisting of twelve ion engines would have a specific impulse of 4000 seconds and a total thrust of 2.4 Newtons. The EPOTV could carry up to 20 metric tons for a total vehicle mass of 35 metric tons at launch. These figures correspond to a mass fraction of 0.57. (Aston, 1987).

In order for this design to be successful, there must be sufficient production of xenon propellant. In addition, the cost of the xenon must be low enough to reduce the overall cost of staging lunar landers and chemical propellants to the L1 node when compared to the cost of performing the identical mission with bipropellant transfer vehicles. The predicted savings is on the order of 20% - 30% of the cost associated with chemical propulsion.

The disadvantage of electric propulsive systems is the long transfer time. Proper timing and staging of equipment and propellants can overcome this disadvantage. As
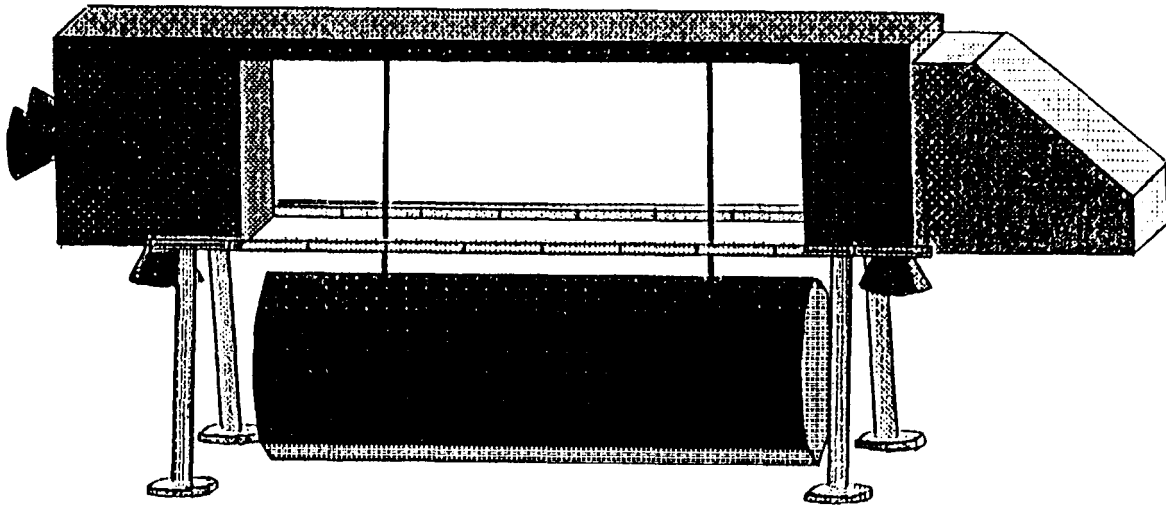
Figure 9 - Cargo Lunar Lander

The cargo lunar lander is designed specifically to transport large masses (up to 30 metric tons) between the lunar surface and a low lunar orbit. The cargo lunar lander would simultaneously be able to ferry up to six crew members in the control center located at the front of the vehicle.
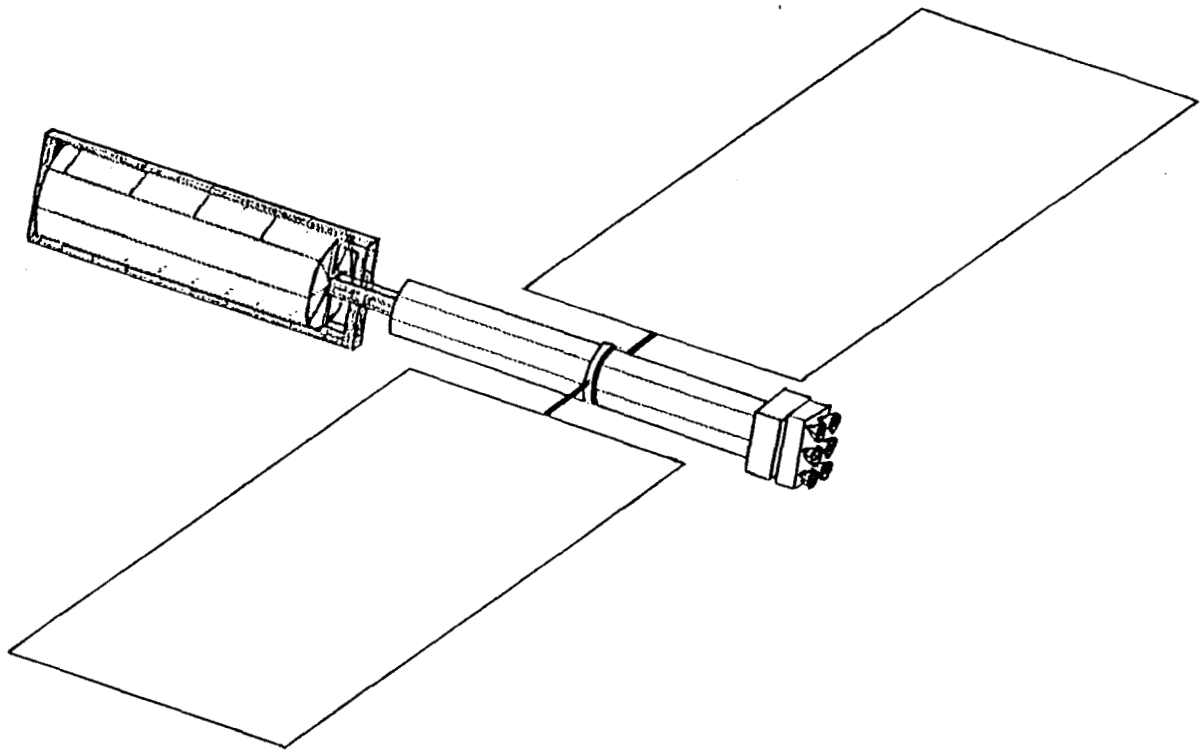
Figure 10 - Electric Propulsion Orbital Transfer Vehicle (EPOTV)

The EPOTV is a solar-electric xenon-ion powered vehicle designed only to carry time-insensitive cargos from low Earth orbit to either L1 or a low lunar orbit. The solar arrays provide 300 kilowatts of power to run a number of xenon-ion engines. Using engines with high I_{sp} and low thrust, the EPOTV transports up to 20 metric tons along a spiral orbit from LEO to low lunar orbit in 180 days. This vehicle will reduce the cost of staging propellant and make the infrastructure more cost effective.

power and propulsive technology progress, later versions would be nuclear powered at one megawatt or more, and may have increased cargo capabilities. Further into the future, such vehicles may be adapted to use a variety of propellants, some of which may be comprised of waste and various forms of space debris.

In addition to the EPOTV, another unmanned vehicle will be employed. This vehicle is known as an orbital maneuvering vehicles (OMV). The OMV will be a remotely operated spacecraft used to retrieve and transport GEO satellites, perform servicing operations and other tasks within the robotic capabilities of the OMV. Salvage and rescue missions are candidate operations that could be performed by such vehicles. The dry mass of each OMV would be approximately five metric tons. Since the candidate missions require only small delta-V expenditures, aerobrake assists will not be used and the mass of the OMV will be kept to a minimum. As the infrastructure matures, this small spacecraft could be used for robotic functions in lunar orbit, at the LEO space station or at the L1 spaceport.

Each of the vehicles in the fleet are reusable. The fact that a vehicle is reusable, and as such able to be refueled and refurbished quickly in space, is what makes several reusable vehicles safer and more economically feasible than a large fleet of expendable vehicles. In order to justify the use of reusable spacecraft, the concept of reusability must be further scrutinized.

One problem related to reusability is the refueling of spacecraft in a microgravity environment. The management of fluids in microgravity requires several major technologies. These technologies include the ability to acquire the fluid, pump the fluid and gauge fluid quantities within tanks (Johnson, Kliss and Luttges, 1988). The storage of cryogenic fuels for long durations in a space environment is also a technological challenge.

Fuel conservation and recovery becomes prevalent in a survey of reusability. Fuel tanks in general, and the Shuttle's external tanks in particular, are never completely emptied of their contents during a mission. If the Shuttle's external tanks were saved after each mission and the remaining propellants extracted, a significant savings would be realized. If an average of 3% of the volume of propellant in the external tank remains in the tank after insertion of the Shuttle orbiter into LEO, these remnants could be scavenged to benefit the entire transportation system. Over a period of ten years, with an average of ten Shuttle flights per year, the scavenging would result in over 2100 metric tons of fuel for future use (Johnson, Kliss and Luttges, 1988). These results would not occur without a significant financial investment in microgravity fluid management technologies. The future benefits from these technologies would greatly enhance the overall infrastructure.

Recycling of water after each mission also enhances vehicle reusability. The life support modules will contain full waste water tanks and empty fuel cell supply tanks at the conclusion of a mission. The waste water could be filtered and, through electrolysis, converted back into hydrogen and oxygen for use in the fuel cells on a subsequent mission. This process would take place at LEO and would reduce the mass of supplies which must be launched from Earth.

The component oriented transportation system design presented here is both efficient and safe. The use of a mixed fleet consisting of manned and unmanned vehicles provides vehicles which can be tailored to meet the needs of any given mission in cislunar space at the lowest possible cost. The vehicles' modularity promotes redundancy throughout the entire transportation system. In turn, redundancy promotes both adaptability for the vehicles and safety for crew members. The characteristics of this transportation system make possible a near-Earth space infrastructure which can enhance the United States' role in space.

INFRASTRUCTURE DEVELOPMENT

An integral part of the cislunar infrastructure will be the design and development of an operational manned lunar base and high Earth orbit station. The lunar base and L1 station configurations were designed considering maximum crew

safety, ease of construction, modularity, adaptability to different missions, durability, and cost. The driving factors in determining the size of the base were required habitation area, experimental and research activities, and the volume of the necessary advanced life support system. The size of the L1 station was determined by the initial activities to be performed at the L1 station, followed by the area needed for the crew , life support system, and power system.

The lunar base design was developed in incremental steps beginning from the remote sensing site selection and moving toward the ultimate goal of a self-sustaining lunar base. The development of the L1 station parallels the progress of the lunar base and the operations and support of these two facilities directly compliment each other. Thus, the design and developments of each have been placed in one multi-phased design program beginning in the year 1994. Infrastructure development occurs in four distinct phases. To develop a cohesive and sound infrastructure, each of the incremental phases must be of some technical and/or scientific merit on its own. This will ensure the utility and the credibility of the overall program despite any technical or economical setbacks that may be encountered along the way. The program must be capable of surviving a critical failure at any point in its development and still be of considerable worth.

Each of the four phases of program development are checked periodically by means of breakpoints. These breakpoints are used to evaluate the progress and success of the program. They will also bring forth a series of driving questions that will have a bearing upon the future of the program. Preliminary dates have been specified for each phase and breakpoint that occur along the developmental path, however, these dates are subject to change depending on levels of funding and technological advancement.

Phase I, Remote Sensing and Site Selection, will encompass a variety of remote sensing exploration missions, as well as manned missions to two sites. This phase will determine the location of an initial outpost. Phase I could begin as early as 1994 with the Lunar Geoscience Observer (LGO) mission currently proposed by NASA, but awaiting funding. Remote sensing of the topographical features of the lunar surface will aid in selecting a safe and promising site for the future lunar outpost. From the data obtained using this satellite, approximately ten of the most promising sites for a lunar outpost will be chosen.

Further evaluation of these sites will continue in 1998 with a series of ten missions. These missions will consist of a series of cluster spike probes that will land on the lunar surface (Figure 11). Each cluster will cover a predetermined exploration site of approximately 1000 square kilometers. The clusters will be launched from the Space Shuttle, and each will consist of two fully instrumented soft landers and ten smaller probes which penetrate the lunar surface. As the cluster nears the Moon, its individual parts will separate and land at predetermined locations on the lunar surface. Each of the smaller probes contains a spike that embeds itself in the lunar soil, several small retrothrusters to control entry velocity, electromagnetic and thermal sensors connected to the spike, a small panoramic camera, and other small durable instruments deemed necessary for such exploration activities. The small probes are designed to measure timing, strength, and frequency of electromagnetic pulses emitted into the lunar soil by the soft landers. The soft landers are fully instrumented and contain power enough to emit electromagnetic pulses into an electrode that drills into the ground. They also coordinate the data sent by the probes and relay it back to the Earth. By recording the timing, frequency, and strength of pulses emitted by the two soft landers, the structure of the lunar subsurface can be resolved. The cluster probe missions will allow the collection of basic data about the lunar subsurface over a large area and at a relatively low cost (Ander, 1985). This data will be used to select two sites for further evaluation by a manned mission. The Phase I missions are illustrated in Figure 12.

The first major program breakpoint will occur in the year 2001. At this time, the progress of the program as a whole will be evaluated, and the following question will be posed: *Should a lunar outpost be established?* The breakpoint decision will

CLUSTER SPIKE LANDERS

SOFT LANDER

INSTRUMENT AND FUEL PACKAGE

LUNAR SURFACE

DRILL

LUNAR SURFACE

INSTRUMENT PACKAGE

RETRO-THRUSTERS

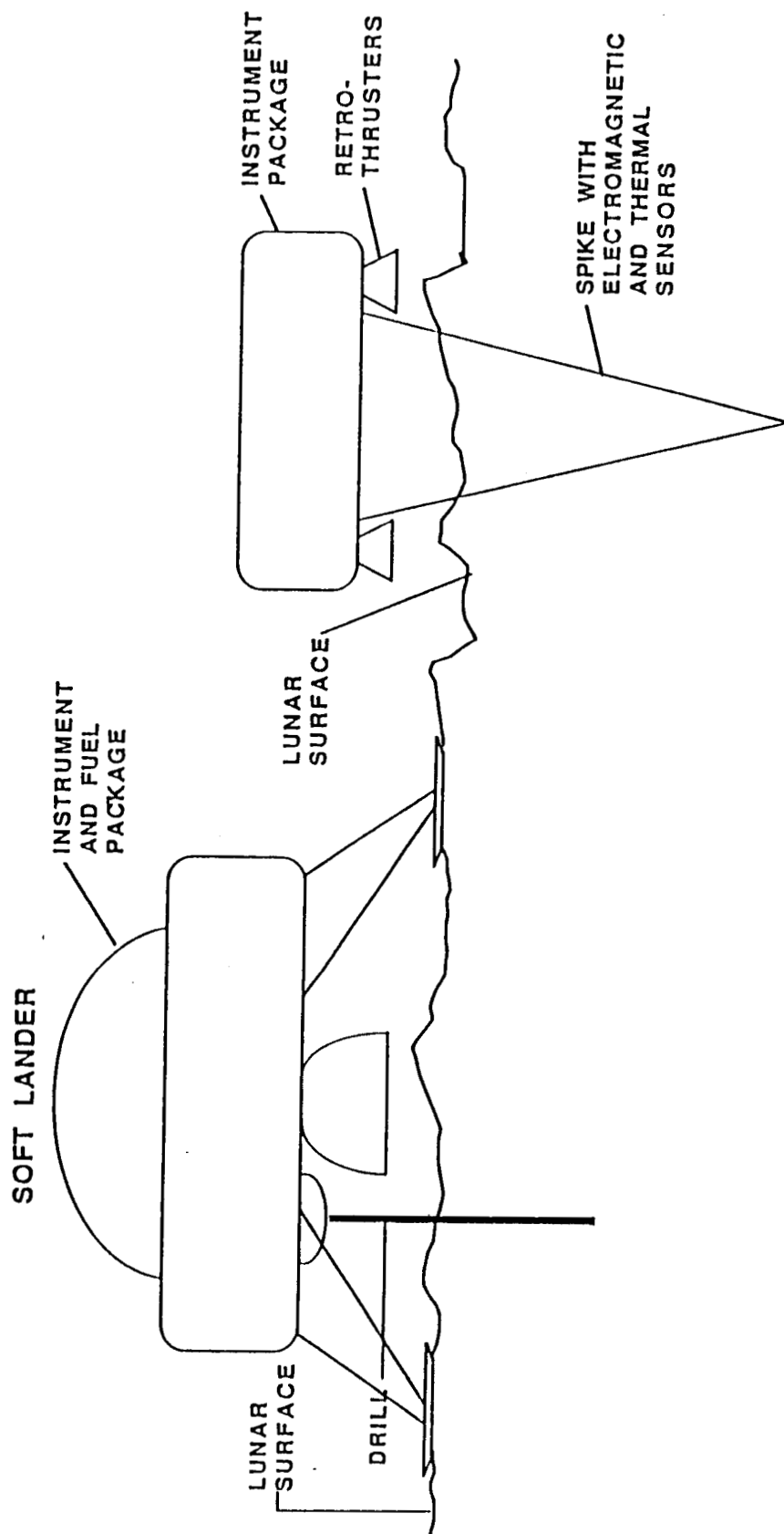SPIKE WITH ELECTROMAGNETIC AND THERMAL SENSORS

Figure 11 - Cluster Spike Probes

A series of cluster probe missions will aid in the remote sensing site selection of the initial lunar outpost. Each cluster consists of two fully instrumented soft landers and ten small probes which penetrate the lunar surface. Using electromagnetic and thermal sensors, the small probes are able to measure timing, strength and frequency of electromagnetic pulses emitted into the lunar soil by the soft landers. The soft landers then coordinate the data sent by the probes and relay it back to the Earth.

Phase I

Missions (1994-2002)

- Lunar Geoscience Orbiter
- Cluster Spikes/Soft Landers
- Manned Missions

LGO

Spike

Soft Lander
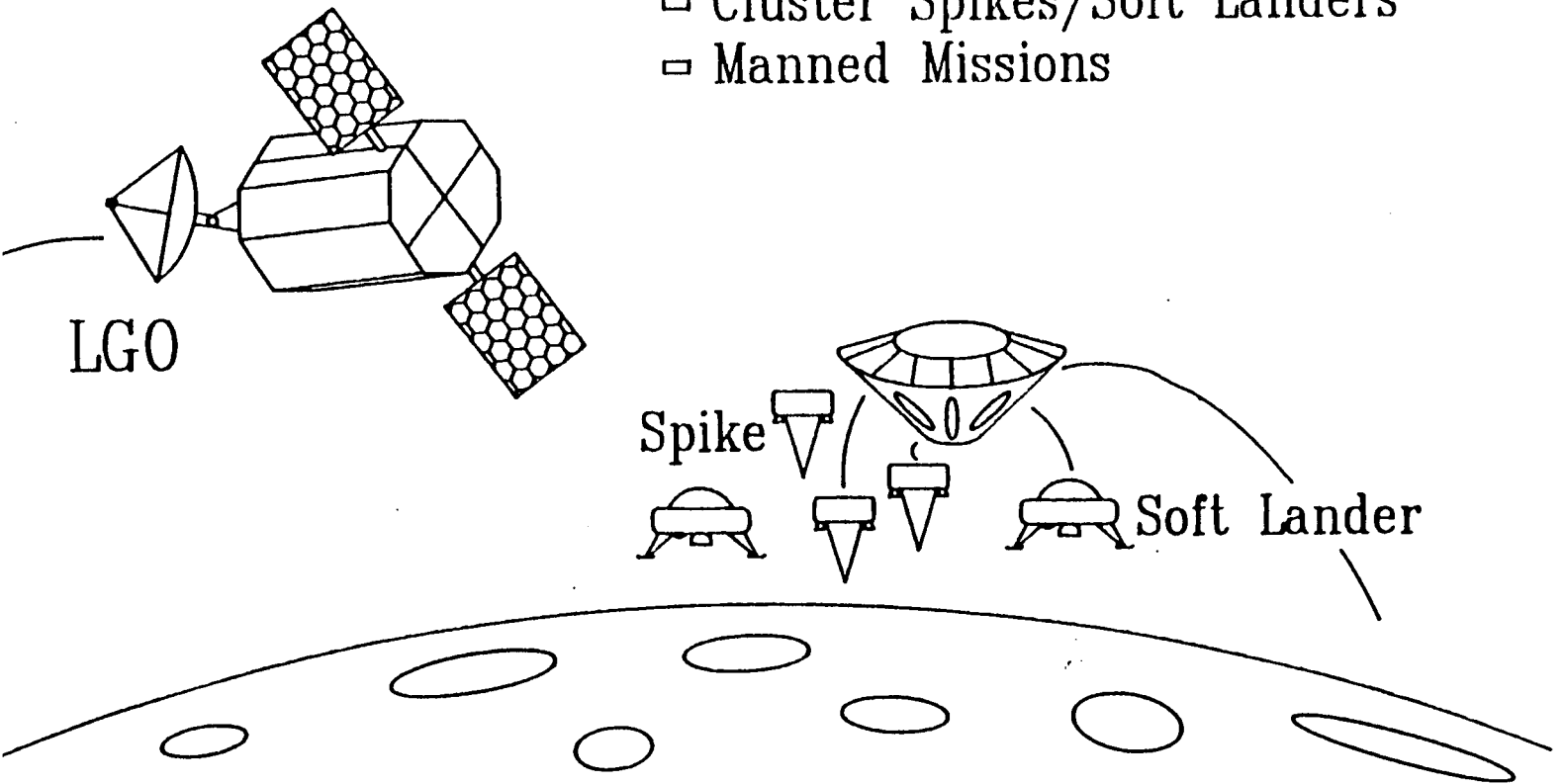
Figure 12 - Phase I

Phase I consists of a number of remote sensing exploration missions in order to determine an optimum location for the initial lunar outpost. Exploration will begin with the deployment of the Lunar Geoscience Observer (LGO), followed by a series of cluster probe missions. Further site evaluation will be made by manned missions.
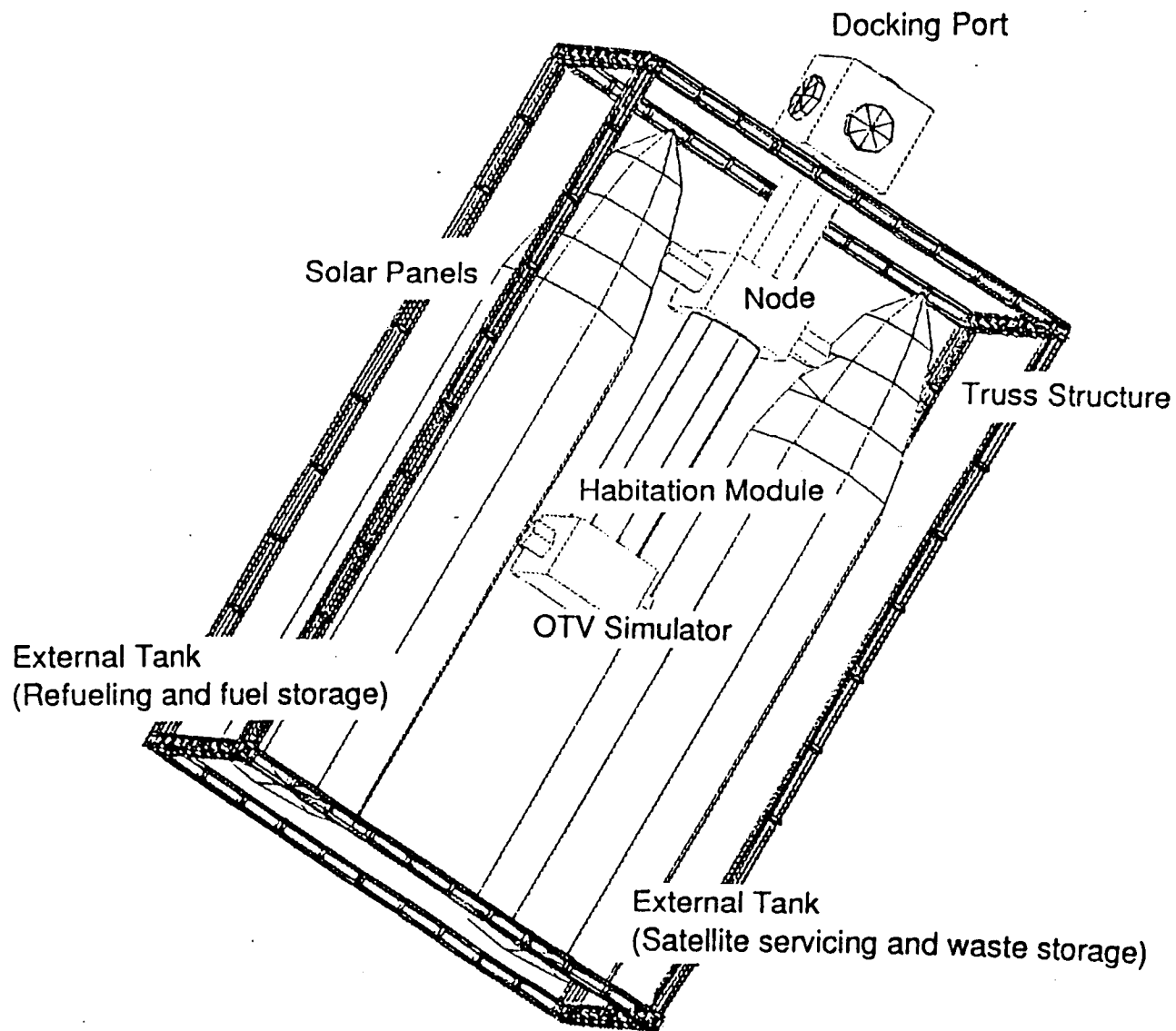
Figure 13 - Initial L1 Station

The design of the initial L1 station utilizes two external tanks, along with a space station habitation module and connecting nodes, all enclosed in a rectangular truss structure. Attached to the truss at the sun-synchronous section will be solar panels. The docking port is located on one of the adjoining sides of the truss structure. One external tank will serve as a refueling and fuel storage tank. The second external tank serves as a satellite servicing bay, as well as providing a waste storage area.

be based on results obtained by both the LGO and cluster probe missions. In addition, appropriate funds must be available, new technologies must be readied, and a transportation system capable of supporting the outpost phase must be in existence. In particular, the large lunar lander must be available. This breakpoint determines whether or not to proceed with the program based on the information received thus far.

If, for one or more reasons, the program is terminated, it will not have been a complete loss. Considerable amounts of data concerning the Moon's topographical features and subsurface composition will have been obtained. This kind of data may be used for future reference and for the development of a large lunar knowledge base, however, it is anticipated that expansion will continue into Phase II to allow for manned scientific studies on the lunar surface.

The final mission of Phase I, occurring in 2002, will be a manned exploration of the two most promising sites for a permanent manned facility. The two sites will be chosen from the ten sites explored by the cluster probes. The purpose of the mission is to thoroughly explore these sites, take core samples, and examine very specifically the topography of the candidate sites. Samples will be returned to the Earth for analysis.

The second of the program's major breakpoints will occur in 2003, after the return and analysis of data obtained on the manned missions. The preliminary outpost site will be selected from the two remaining candidate sites. Characteristics used in determining an optimal site will include the following: the presence of volatiles such as oxygen and hydrogen, readily available trace elements such as titanium, iron and aluminum, access to a radio-silent sky, and proximity to nearby craters (for a future nuclear reactor site).

During the proposed Phase I, the initial L1 station will be constructed both in LEO and at the Libration Point 1. At this point it can be assumed that the L1 station will be refurbished and attached at the LEO space station. Only final adjustments on the L1 station will be made at the libration point.

Several concepts were considered for the preliminary structural design. The projected activities indicated that initially the station would, at most be mantended. However, the cost of providing full life support capabilities initially is much less than addition of this mode later on. It was therefore decided that the platform would have manned capability. Other concepts considered for the design are modularity, staged growth, fail-operational design, and crew safety.

To achieve a quick, inexpensive, yet useful station, every attempt has been made in the overall configuration to utilize current technology. This will eliminate some development costs and satisfy the need for modularity.

Two external tanks, along with a habitation module and connecting nodes will be enclosed in a rectangular truss structure, see Figure 13. Flanked on the sun-synchronous section of the truss will be solar panels. And on one of the adjoining sides of the truss, a docking port will be located for orbital transfer vehicles. This docking port will be connected to a node, which in turn will be connected to a space station habitation module. Also, located at the opposite end of the habitation module will be an OTV simulator.

The two external tanks will be individually used for fuel storage, satellite servicing, and waste storage. The external tank to be used for fuel storage will simply contain O2/H2 propellant to be used for refueling spacecraft. The second external tank will be used as a satellite servicing bay. In the lower end of the tank, doors can be cut out in order to house the satellites and the service area. Also, contained in the second external tank is an area for waste storage, located in the upper portion of the tank.

The L1 platform requires shielding from micro-meteoroids and radiation. Micro-meteoroids are particles on the order of 1 micron in diameter that may reach speeds as high as 10^8 m/s. At such speeds micro-meteoroids have sufficient momentum to cause damage to the station. Shielding against micro-meteoroids may be implemented by using Kevlar and titanium bumper shields on critical areas of the platform. Adequate radiation protection from the sun has been obtained by

connecting the space station habitation module between the two external tanks. The solar panels, along with the propellant filled external tank, and the aluminum shielding of the tank will provide radiation protection from the sun for the crew members housed in the habitation module or satellite servicing bay.

Activities at the station will begin late in Phase I. In 2003, nearing the end of Phase I, the need for the refueling of major transportation system components will arise. By providing a base between LEO and the Moon, a tremendous cost savings can be attained, due to less travel time, and hence less delta-V's being encountered. Also, with developments in the containments of fluids in low gravity, the L1 station will be able to provide fuel and cargo storage, again promoting a financial savings in the proposed infrastructure design.

Phase II, Outpost Development, consists of establishing a man-tended outpost on the moon to provide for a series of 10 to 14 day missions. The purpose of these missions will be to perform science experiments and to research lunar processing capabilities. Concurrent with the lunar development is a modest space station located at L1 to serve as a transportation and staging node.

The Phase II outpost facilities will support six astronauts. For transportation purposes, each mission will correspond to a payload delivery size of approximately 25,000 kg. The deliveries will be made directly to the lunar surface by way of a lunar lander. The first Phase II mission will be to deploy a lunar construction vehicle with which to begin the lunar surface development. Other hardware staged during this phase will include a sandbagging device, a habitation module, and a series of solar arrays. The construction vehicle will be remotely operated from either Earth or the L1 station, and will begin its operations by excavating one side of a crater located at the chosen outpost site. Regolith from this excavation will be used in the sandbagging machine. This excavation mission will provide a ramp-like access to the crater floor. As soon as the habitation module has been landed and transported to the crater floor, it will be covered by a sandbagged regolith "tent" supported by a truss structure as illustrated in Figure 14 (Kaplicky and Nixon, 1985). The sandbagging device will be used to bag lunar regolith for this purpose. Like the construction vehicle, the sandbagging machine will also have the capability of being remotely operated from the L1 station, thus saving on any time delays presented under remote operations from the Earth. A water storage tank will be placed on top of the habitation module underneath the regolith "tent" to provide additional bulk shielding, as well as an efficient means of storage. The combination of a regolith "tent" and a water storage tank will provide radiation protection for the crew members during any anomalously large solar events. Toward the end of Phase II, additional modules may be brought to the lunar surface in order to expand experimental capabilities and living space. Such modules, as seen in Figure 15, will increase the access to research facilities on the Moon, thereby attracting a larger number of scientists and space entrepreneurs. These modules will be placed in close proximity to the crater such that in the event of an emergency, the crew would have a sufficient amount of time to don space suits and make the short traverse to the radiation bunker for protection. Although shielded by a two meter regolith "tent", the additional modules would not afford adequate protection to the crew during any severe solar flares.

An initial lunar outpost constructed in a crater will provide a safe environment in which to work, as well as substantial storage space around the habitation module underneath the regolith "tent". This space may be used for the storage of vehicles, oxygen and water.

In the beginning, Phase II power will be provided by a 30 kw solar array with fuel cells as a back-up system. The fuel cells could also provide metabolic oxygen and water in times of emergency. As the outpost evolves, this power may need to be stepped up to approximately 100 kw of available power by deploying additional solar arrays.

Throughout Phase II missions, lunar activities will vary widely. Geological studies of the Moon will be performed by studying core samples returned by robotic missions, as well as by studying mineralogical debris from craters. Unlike previous
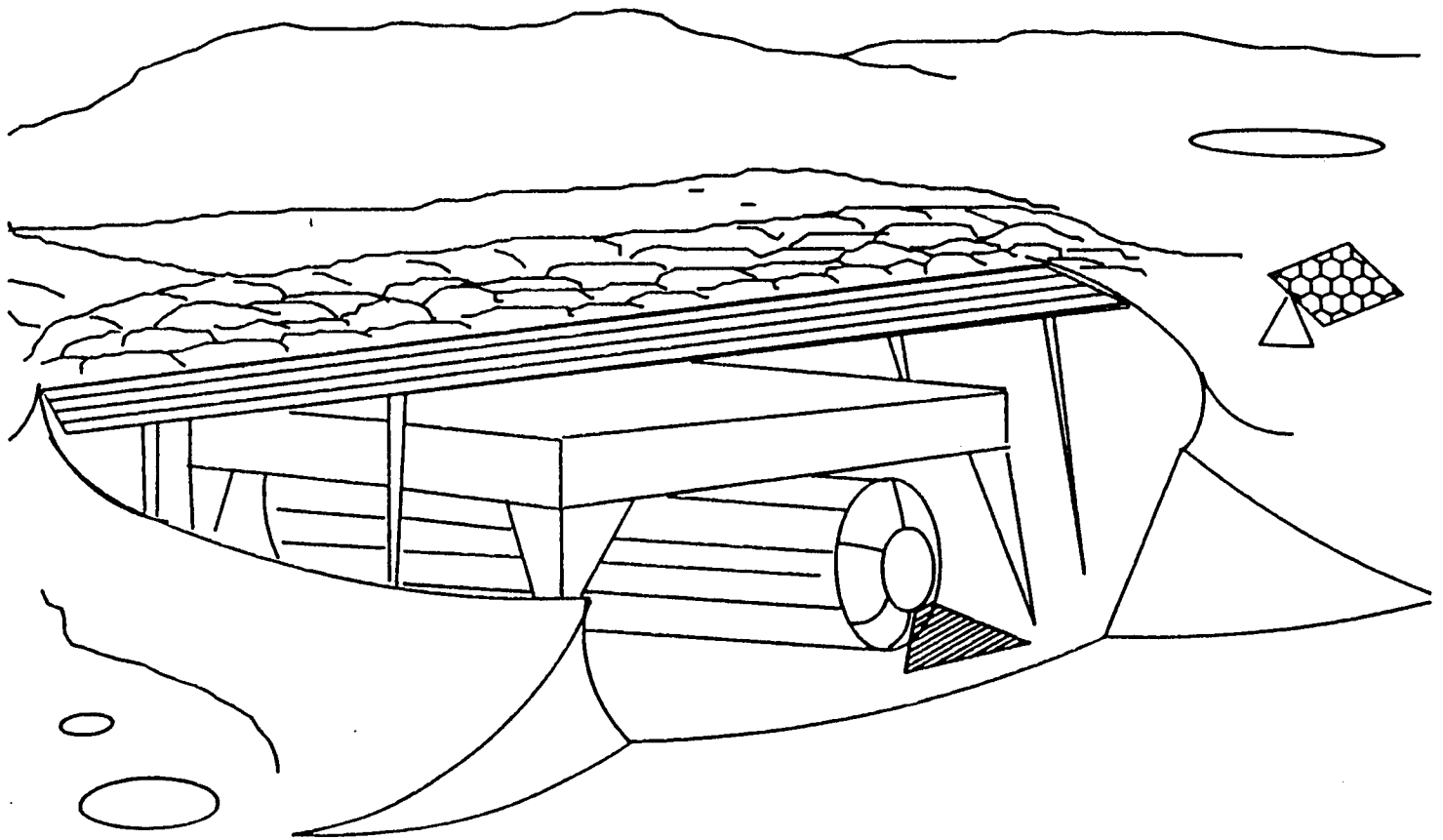
PHASE II

Figure 14 - Phase II

Phase II, Outpost Development, consists of establishing an initial lunar outpost which will provide for a series of 10-14 day missions. At this point, lunar activities will be varied. Geological and astronomical studies will be performed, candidate oxygen extraction techniques will be evaluated, and a first level CELSS will be tested.
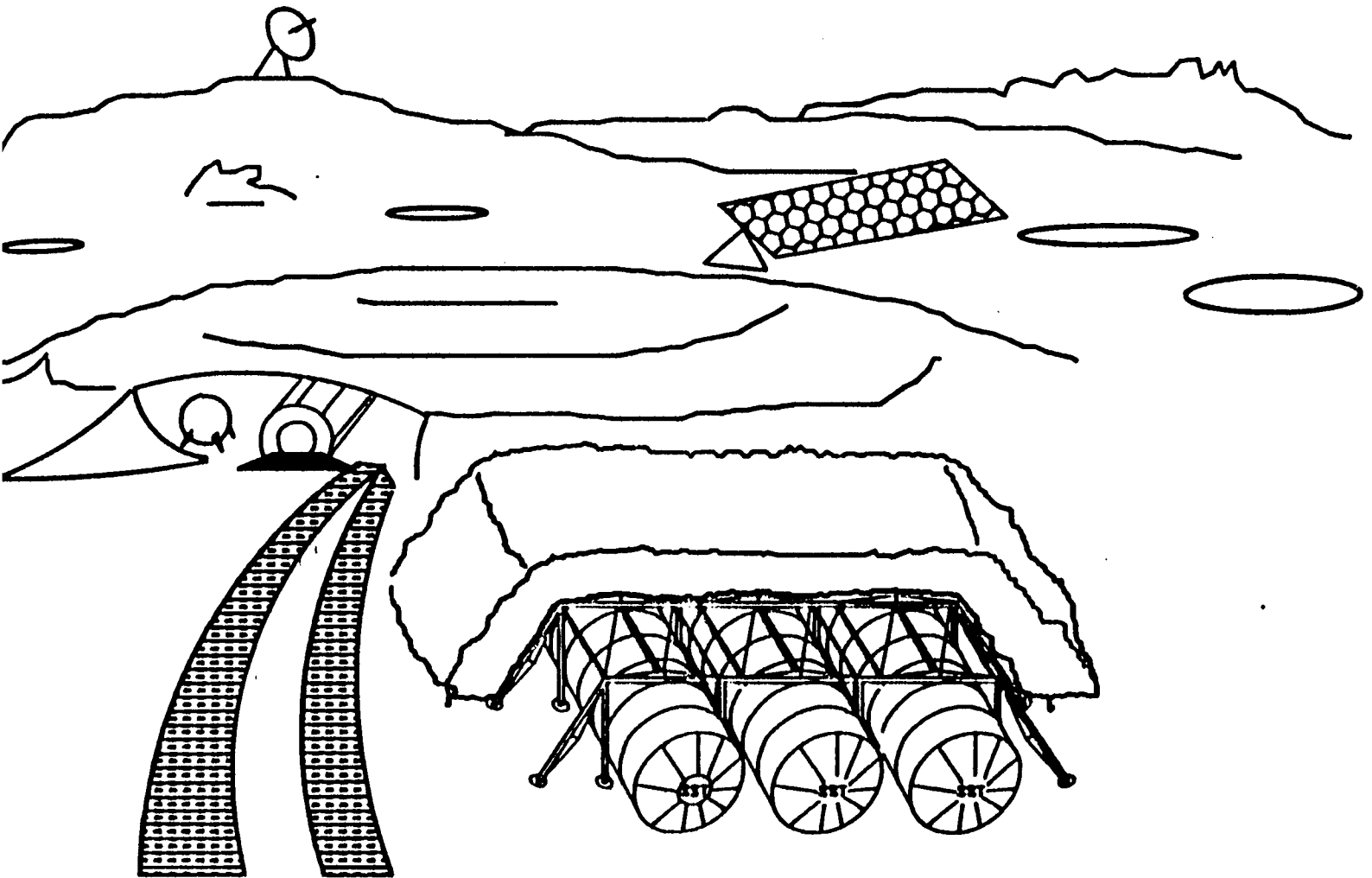
ADVANCED PHASE II

Figure 15 - Advanced Phase II

Additional modules brought to the lunar surface toward the end of Phase II will expand experimental capabilities. They will provide more readily available access to lunar research facilities, thereby attracting a greater number of scientists and space entrepreneurs.

sample return missions, these missions will return with large, substantial core samples from which to draw definitive conclusions about the lunar subsurface as well as the evolution of the Moon. New remote sensing packages will be carried by the lunar landers to look down during orbital phases of their missions. Further knowledge of the lunar subsurface at the outpost site will help in determining what, if any kinds of special hardware or subsystems will be necessary in order to perform most efficiently at the site. In addition, these samples may be used to perform initial material processing experiments in order to evaluate the potential for future full-scale mining and processing operations. Also important during these preliminary missions will be the implementation of a pilot oxygen plant. This pilot plant may come in the form of a habitation module configured as a laboratory, containing several candidate methods of oxygen extraction such as carbothermal reduction, electrolytic reduction and hydrogen reduction. Processes to obtain water from lunar regolith will be tested in a similar manner. Candidate volatile recovery processes will be assessed to determine the feasibility of simultaneous materials production, such as the production of fiberglass beams. Basic astronomy facilities may also be placed near the base during this time period.

The Outpost Phase will be a vital proof of concept for the controlled ecological life support system (CELSS). CELSS is an advanced life support system that utilizes both biological and physiochemical regenerative techniques to recycle wastes and to produce consumables. The development of such an advanced system will be crucial to the design and operation of advanced space missions (i.e. future manned Mars mission). The technological merits of a closed CELSS system could also be brought back down to Earth for use in third-world countries who suffer from severe drought and famine. For a lunar surface base, this life support system will provide consumables and will process wastes from the human crew. In addition, Phase II will provide a testing ground for 1/6-g physiological and biological experiments. These experiments will provide information concerning the efficiency and productivity of man while working in the low-g environment of the Moon. Such assessments will aid in developing better operational procedures in order to maximize the productivity and the psychological well-being of the crews. These evaluations will lead to a more efficiently designed permanently manned base, if one is to be built.

A transportation node at L1 provides a staging point for manned lunar missions and a more cost effective location from which to service GEO satellites. For example, two crews can be transported to L1. The crews will ready the lunar lander for one crew to use for a lunar mission while the second crew remains at the station to repair GEO satellites. Additionally, robotic lunar exploration is enhanced by control of such missions at the L1 station exploiting the lower transmission delay times. Constructing the station with external tanks and components developed for the LEO station reduces the cost of building such a station.

Breakpoint III will occur in 2008 after the full development of a lunar outpost. The success of Phase II activities will provide the means to assess the practicality of continued lunar development. At this point, the next logical decision in the lunar surface development program will be made. *Based on Phase II mission results, is a permanently manned base justifiable?* Key breakpoint considerations are the following: lunar oxygen production rates, CELSS efficiency, and demonstrated potential for further scientific and economic gains due to the success of the materials processing and astronomy experiments. These considerations will determine if a permanently manned base is justified. The pilot oxygen plant is important in order to demonstrate the possibilities of extracting oxygen form the lunar soil. This oxygen would be used for human metabolic consumption, propellant, and infrastructure resupply. The success of CELSS will be essential to the development of a permanently manned base since total resupply of consumables would be cost prohibitive. Thus, it is a crucial breakpoint consideration. The success of the material processing and astronomy experiments will be of importance, as they may have a direct influence upon anticipated future program gains, both scientific and economic.

Perhaps the construction of another outpost at a different location would be

needed to perform additional studies before committing to a permanently manned facility. Studies beyond the scope of these missions must be planned before further expansion of lunar facilities is warranted.

Also occurring during Phase II, in 2004, will be the advent of a transportation control center at L1. Since the L1 station is optimally located between LEO and the Moon, it can serve as a base to direct traffic. By controlling the space traffic, a safe and efficient space transportation system can be developed. Subsequent activities to promote safe and efficient space exploration include satellite servicing and GEO cleanup.

Phase III, Permanently Manned Base, will begin in 2010. This phase should lead to lower space program operational costs by beginning the development of large-scale processing activities to provide water, propellants and other materials from lunar resources. A nuclear power plant capable of providing 1-2 Mw of power will provide the energy required for the anticipated increased level of processing. Additional habitation modules, increased ECLSS and CELSS capability and closure, and a larger crew on the lunar surface are required to support the expanded lunar operations. A far side observatory will be constructed during this phase, if not already initiated. Phase III is illustrated in Figure 16.

This phase strives to establish economic uses of the moon. It would be hard to justify substantial investments if there is not a clear economic or technological return to the program. As more useful lunar derived products become available, the base will begin a shift toward self-sufficiency. Prime products will be lunar derived propellants, oxygen and water for life support, and materials for construction of larger habitat volumes. Phase III will continue through the year 2018 when the final breakpoint is reached.

Like all of the previous breakpoints, Breakpoint IV will examine the progress of the lunar surface development program. Results of all previous missions will be evaluated. Based on these evaluations, it will be determined whether or not a *self-sustaining* base will be initiated. This decision will be based primarily on the capabilities of technologies such as CELSS, oxygen production, and the possible return of lunar processed materials. All of these technologies are critical to the development of a self-sustaining base, and many will aid in the support of the overall infrastructure. For example, CELSS will be necessary for every vehicle, orbiting station, and outpost in the cislunar infrastructure. Utilizing CELSS to provide this life support is advantageous over resupply because the total launch mass needed for resupply exceeds the mass of the equipment needed for CELSS in the long run. However, the equipment for CELSS is extremely massive, in excess of 11,000 kg for ten persons. One scenario which would take advantage of the benefits of CELSS mass savings while limiting the equipment launched would be to use the lunar surface as a waste processing site and resupply point for the entire infrastructure. Having a centralized CELSS would be advantageous from the standpoint of management of the system. In this CELSS scenario, the decision for developing a self-sustaining base is at stake. If the CELSS technologies are available, and cost effective methods of implementing a CELSS are found, then developing a self-sustaining, fully complete CELSS to supply the entire cislunar infrastructure will be justified.

Materials processing is the other major driver in developing a self-sustaining base. If life support and materials processing technologies are developed, and the economic resources, both public and private, are available, then a self-sustaining base will begin evolving from the previous facility in 2021.

Coinciding with the development of the self-sustaining lunar base will be the expansion of the space infrastructure. In 2017, the L1 station, because of its ideal location, will serve as the staging point for planetary missions. An initial mission will likely be to the planet Mars. With the increase in activities being performed at L1, an expanded station may be needed to continue support for the infrastructure. With more advanced scenarios, for example, increases in lunar mining and materials processing, the L1 station will no doubt become a major operational control center in space. An advanced L1 station will rotate to generate artificial
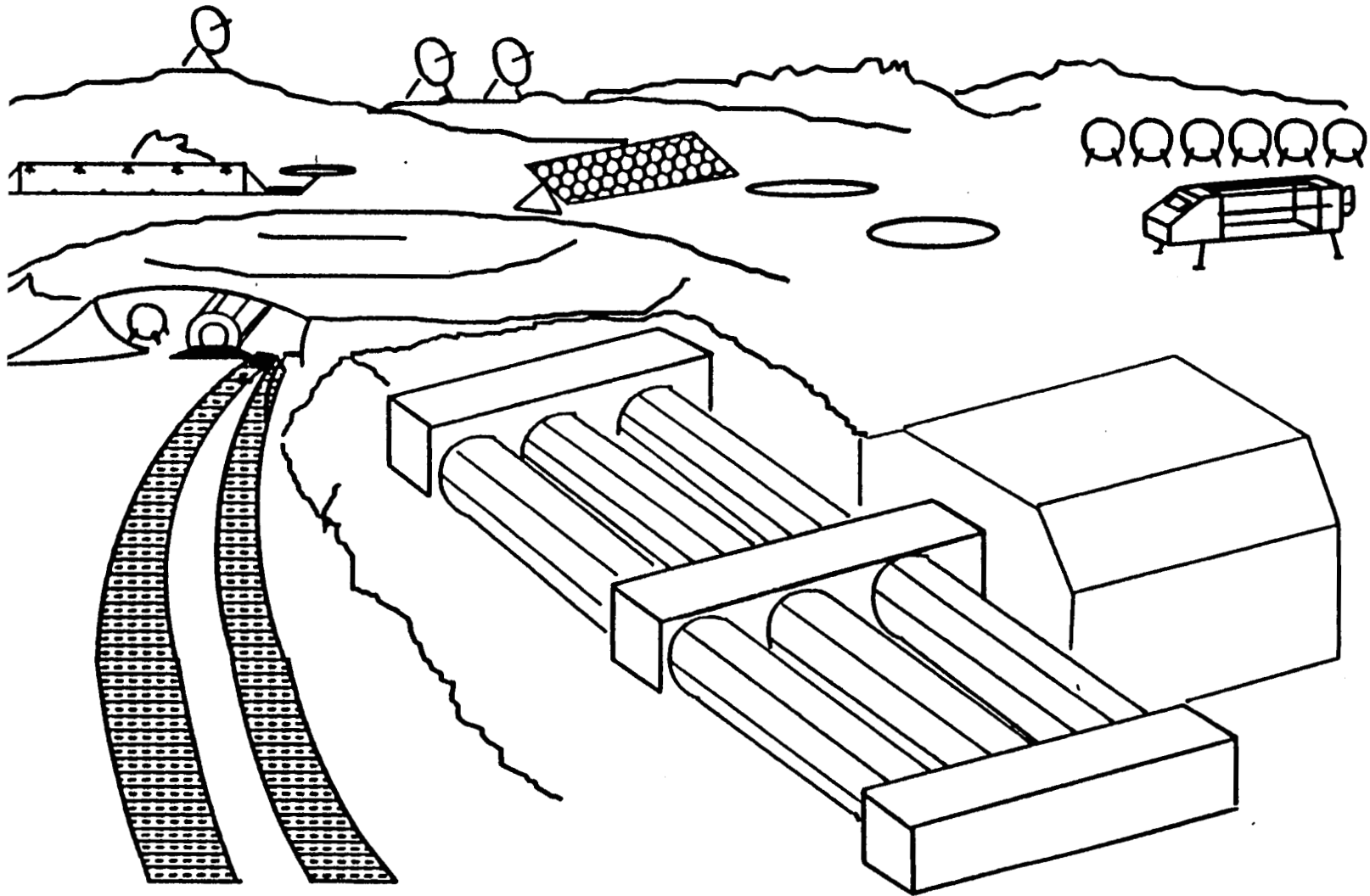
PHASE III

Figure 16 - Phase III

Phase III, Permanently Manned Base, will lead to lower space program operational costs by beginning the development of large-scale processing activities to provide water, propellants and other materials from lunar resources. Power will be supplied to the base by a nuclear reactor, and again, additional habitation and laboratory modules will be required to support the anticipated growth of lunar operations.

gravity and will use CELSS for most life support needs, see figure 17. Using artificial gravity at L1 will serve as an intermediate increase in gravity level for people returning from the Moon. Also, to assist in the maintenance of human health, artificial gravity will offset the long term effects of microgravity on the human body, i.e. loss of calcium in skeletal bones. A closed ecological life support system will allow the L1 station to become self sufficient and independent of any resupply.

Phase IV, Self-sustaining Base, results from the continued success of Phase III operations. Integrating more systems, new processes and better technologies (such as CELSS) into the base, promotes greater independence from Earth based supplies. These benefits will enhance operations within the entire infrastructure. Transportation costs will become lower due to the availability of lunar derived propellants and/or future reductions in Earth to orbit costs. Structural materials manufactured on the Moon may be used for base expansion, new outposts, space station expansion and materials to support the construction of equipment for manned Mars missions.

The implementation of a self-sustaining base will require greater power, life support, and materials mining and processing investments. Accordingly, base population will increase to approximately twenty inhabitants. As new systems are incorporated into the base, supply lines to the Earth will slowly be cut, and the base and the rest of the cislunar infrastructure will become self-supporting.

An advanced L1 station becomes justified as lunar activities and capabilities are expanded. The construction of an advanced L1 station is warranted as the permanently manned Phase III matures. An advanced L1 station will probably rotate to generate artificial gravity, will use CELSS for most life support needs and will serve as a staging site for manned Mars missions.

This multi-phased sequence represents an economically feasible expansion of space program activities. Each of the incremental advances is checked by a system of breakpoints. Four major breakpoints were incorporated in the infrastructure development program design in order to evaluate the progress of the program and to monitor the success of each of the phases. Each of the four phases was designed to be individually worthy such that in the event of a major setback or the termination of the program, the entire effort will not have been a catastrophic failure. By advancing logically and methodically, a firm base is established upon which a credible and successful program may be built.

Compression of this schedule can only be made with a firm commitment in resources and technology development. A more probable scenario is the lengthening of this schedule. Logically, the nation's capabilities must expand in a manner that provides a valid means to evaluate further growth. These evaluations should provide a clear rationale concerning what the next phase will provide both economically and scientifically. Perhaps the most important breakpoint is the one between the outpost and the permanently manned phases of operation. Additional outposts may be preferable to expanding one base, however, this can only be evaluated by well designed missions during the outpost phase.

A manned Mars mission is inevitable, but it is impossible to establish a specific time frame. Such a mission would have considerable impact on the proposed infrastructure program, and vice versa. Limited space program funding could make these programs competitors. Commitment to an early Mars mission (perhaps, including Soviet cooperation) would require stretching the timeline for development of the lunar infrastructure. An early Mars mission would most likely be staged from LEO with all Earth-derived materials. It would not realize the potential benefits of a mature cislunar infrastructure for staging. Fortunately, many of the technological challenges targeted for development in the infrastructure program are applicable to a manned Mars mission. A Mars mission staged at a later date may be a better choice. Long term operations in space will help establish and demonstrate the required system reliability needed for a manned Mars mission. In addition, the potential economic savings from the use of lunar-derived propellants and materials could provide a less expensive Mars spacecraft to depart from L1 rather than LEO. Finally, electric propulsion staging of fuel to Mars could take advantage of

SOLAR ARRAY

HABITATION MODULE

SHIELDING BOOM

MAGNETS

DESPUN DOCKING
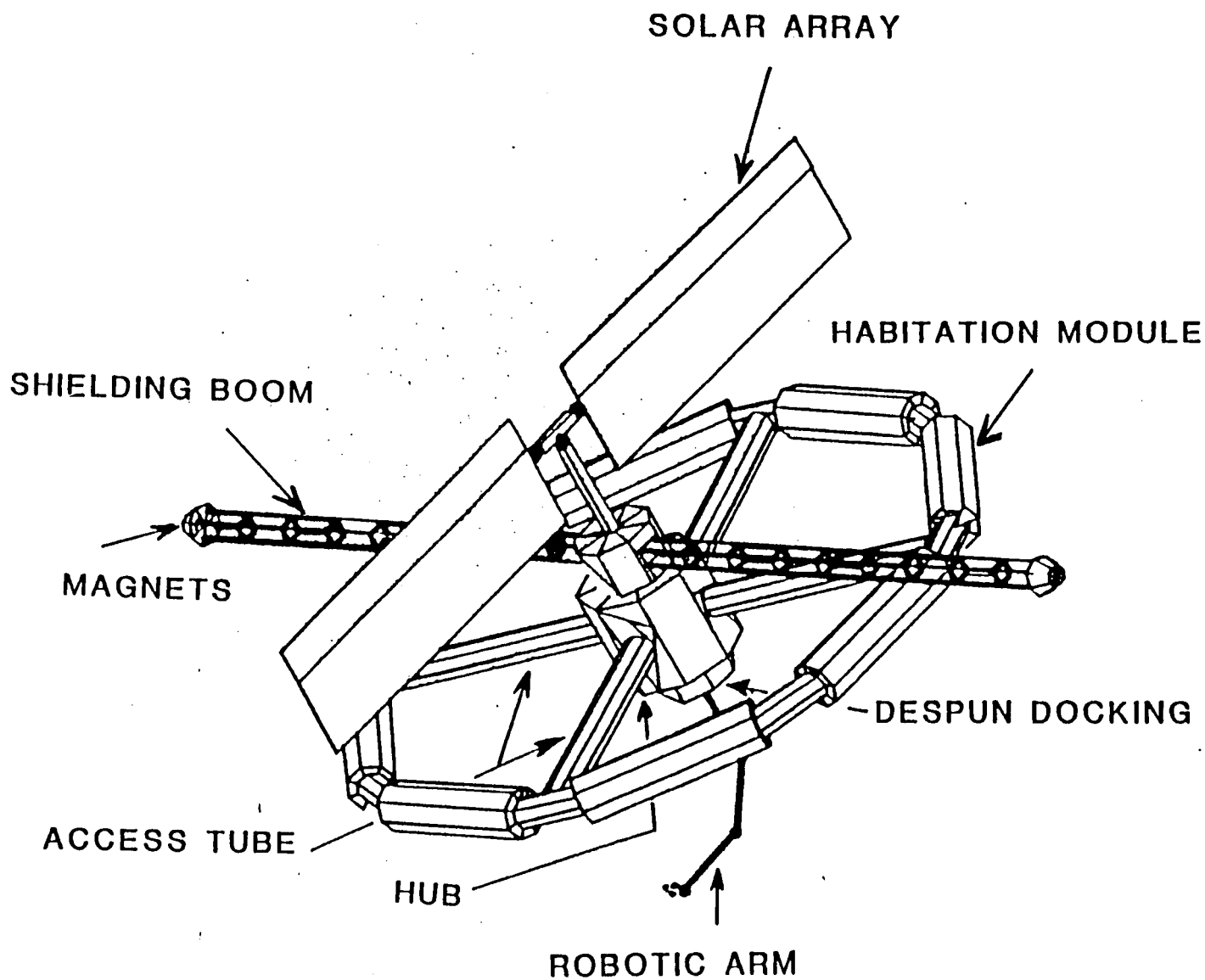
ACCESS TUBE

HUB

ROBOTIC ARM

Figure 17 - Advanced L1 Station

Schematic drawing of a highly evolved L1 station. The advanced L1 station will rotate to generate artificial gravity, and will become self-sufficient by incorporating a closed ecological life support system (CELSS).

similar technologies developed and proven in cislunar space.

SPECIAL FEATURES

Many elements of the infrastructure have been discussed, however there are several special design features that require additional description. These are the CELSS, training simulators, a human powered short range lunar vehicle and space suits. In addition, physiological responses to a microgravity environment are also discussed.

The first of these features, CELSS, is an advanced life support system utilizing regenerative techniques, both biological and physiochemical, to recycle wastes and to produce consumables. Currently such a system does not exist, however, the successful development of CELSS will be crucial to the design and operation of advanced space missions (i.e. a permanently manned lunar base or future manned missions to Mars). For a lunar surface base, this life support system will provide consumables and will process wastes from the human crew. Finally, the lunar surface may serve as a waste dump and resupply for the rest of the cislunar infrastructure, adding a demand equal to 10 people on the system.

Life support will be necessary for a variety of scenarios during the lunar surface development, that is, from a series of short stay missions to permanent habitation. CELSS development will reflect these varying degrees of life support requirements by embracing a phased growth approach. In order to develop the regenerative life support technologies that CELSS entails, it is necessary to provide a framework in which the various subsystems can be used as the technologies become available. A four phase development design has been proposed which will provide a regenerative life support system for all stages of the cislunar infrastructure development (Banks and Rose, 1988).

The major reasons for using a regenerative life support system over an open (resupply) system are: 1) It is the only way to fulfill the requirements for long-term missions involving humans; 2) It will reduce the cost of life support by minimizing the total mass launched over a long period; 3) The system will provide ecological simulation and protections required for an ever more challenged, polluted world environment.

In designing the lunar CELSS, there are several general design considerations. First, the system must balance processing and production rates while having a relatively small buffer space. Second the system will be operating in lunar conditions: one-sixth Earth gravity, a potentially high radiation environment, plus a cost of $13,000/kg to transport mass to the lunar surface (Duke, 1985). Third, lunar resources can be utilized, in particular, water and oxygen are obtainable from the lunar soil.

More specific considerations must also be taken into account. First, the system should be flexible enough to work in the variety of missions form short stays to permanent habitation. Second, it must overcome specific technical stumbling blocks: cellulose conversion, trace contaminant control, possible unknown effects of recycling whereby small amounts of mass build into ever larger unused mass. Third, the system must provide proper outputs in quantity and quality to provide for the crew. Specifically, these are outlined in Figure 18 (MacElroy, 1985, and NASA ECLSS TAP, 1985).
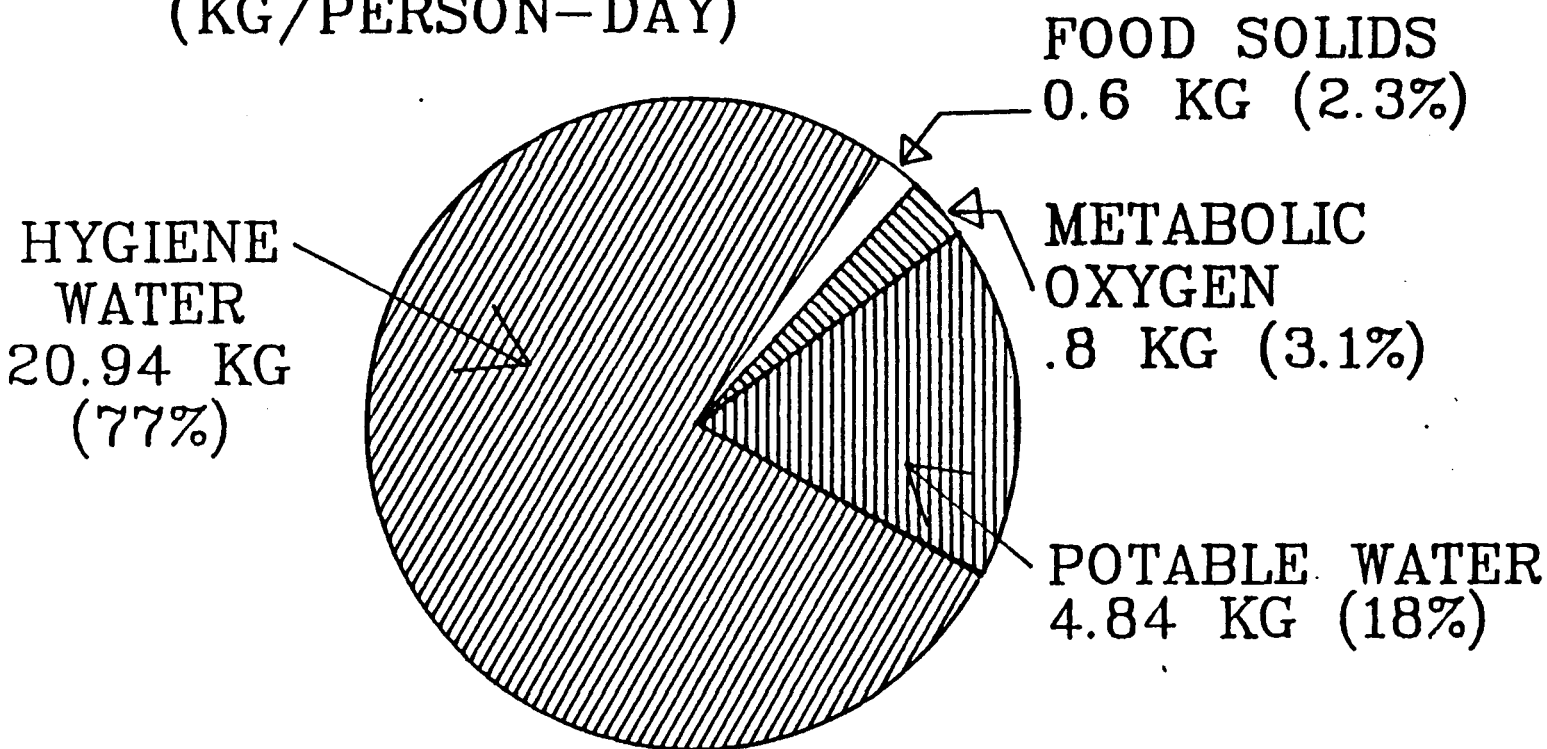
Currently a CELSS does not exist. In order to develop the regenerative life support technologies which CELSS entail, it is necessary to provide a framework in which the various subsystems can be used as the technologies become available. Hence, a four phase approach to evolving a CELSS is outlined here to provide a regenerative life support system for all stages of the cislunar infrastructure development.

LEVEL I CELSS - The first and most important step is to close the water loop. This is justified because the total mass devoted to water constitutes about 95% of all the consumable mass, as is shown in figure 18. Waste water represents about 89% of all human wastes. This consists of 20.94 kg/person-day of spent hygiene water, 1.85 kg/person-day of perspiration water, and 1.51 kg/person-day of urine and

INPUTS TO THE HUMAN BODY
(KG/PERSON-DAY)

FOOD SOLIDS
0.6 KG (2.3%)

HYGIENE
WATER
20.94 KG
(77%)

METABOLIC
OXYGEN
.8 KG (3.1%)

POTABLE WATER
4.84 KG (18%)

TOTAL: 27.24 KG/PERSON-DAY

Figure 18 - Inputs to the Human Body

The distribution of the mass of supplies to support humans is shown. The greatest mass used, 77%, is hygiene water. A Level I CELSS will attempt to allow all hygiene water to be recycled plus, recycling approximately 1/3 of the potable water by condensing the perspiration in the atmosphere. Level II CELSS will attempt to produce potable water from waste water. Oxygen needs may be met through an algae growth 'facility. Higher plants and aquaculture will add to supply the oxygen and solid food needs.

fecal matter.

The purity of hygiene water is not critical since it will not be ingested by the crew. Therefore, it may be easily filtered using filter setups (0.22 micron nitrocellulose) currently available commercially. This step alone will require very little power input - about 100 watts. Replacement of filters will be a routine and easy task to perform. Since these filters are made of cellulose acetate, they can easily be digested in the microbial bioreactor, as discussed below under Level II.

Perspiration water can easily be condensed and converted back to potable water using a Freon-21 coolant cycle, thus providing about one-third of the total potable water. Urine and fecal water are much more difficult to process into potable water, and will not be converted except with a Level II full-scale waste processing system.

LEVEL II - The second step in evolving CELSS is to process waste and purify and purify urine and fecal water to produce potable water. Here, the method is dependent on the length of the mission.

For a short stay mission of only two weeks, waste will be sterilized and converted back to water and carbon dioxide using a supercritical water oxidation (SCWO) system. SCWO is capable of destroying organic molecules rapidly at efficiencies exceeding 99.999% while producing purified water and carbon dioxide (Modell, 1986). The process is known to work on a small scale, as would be found with a 6 person short stay mission, but may not be adaptable on a large scale for more intensive missions as a permanent lunar base. SCWO occurs at 630 degrees Kelvin and 250 atmospheres and requires 5.36 kw of power (Olsen, 1986). The hardware occupies 1.2 cubic meters and weighs 691 kg. Despite this large mass commitment, problems of N_2 levels and gas separations, in general, remain.

For a permanently manned lunar base, waste processing will be done with a biological reactor, with SCWO done on a limited basis. The concept for the reactor is derived from Earth-based waste treatment facilities in which large volumes of waste are purified using a variety of physical and biological processes. In particular, the activated sludge process provides a large amount of processing in a relatively small volume. It is estimated, based on waste processing capabilities of activated sludge plants (Sundstrom, 1979), that a 200 liter reactor will process the waste for a 10 person crew with a turn around time of 6 hours. The yield form the biological waste treatment will be a nutrient-rich effluent which will serve as an excellent medium on which to grow algae and higher plants (Jones, 1982).

Another candidate waste processing system is a trickle filter composed of lunar soil or regolith. The trickle filter which will allow for greater recycling of waste products.

Once waste is processed with SCWO or a bioreactor, the effluent water will be purified in fuel cells. The specific system will be a Solid Polymer Electrolyte Water Electrolysis Subsystem (SPE-WES) (Quattrone, 1981). This system was selected over other phase-change purification systems (such as distillation) because much higher purity water can be made. Each fuel cell measures 20cm x 33 cm x 88 cm, weighs 91 kg, consumes 1.4 kw, and is capable of producing 52.5 kg of purified water per day (Rockwell International, 1984). In combination with the Freon-21 perspiration water recovery, the potable water supply for 10 people will be provided by one such fuel cell. This system will operate at approximately 3.2 volts at operating conditions of 180 F and a current density of 150 Amps per square foot. Special non-fouling thin film applied (in space) to the catalytic surfaces and electrolysis electrodes will diminish system service requirements and increase system useful life.

LEVEL III - This stage is characterized by the implementation of of an algal growth facility. This algae will feed on the nutrient-rich effluent water produced in Phase II and will serve as a means to convert carbon dioxide to oxygen. Algae is also a rich source of protein which will have potential as a food source for the crew. Since the effluent from the microbial bioreactor is a nutrient-rich effluent, an algal

growth facility feeding on this effluent is a logical addition to the CELSS. Algae will serve as oxygen producers since they consume carbon-dioxide and produce oxygen. Algae will be grown in a 400 liter swirl chamber illuminated by fiber optics during the day cycle and artificial lighting during the two week night.

Algae has been shown to be a possible source protein for a CELSS (Karel, 1985). Although algae may not at first appear the most attractive food source, it is a rich source of protein which is widely used in many Pacific countries and Hawaii (Steinkraus, 1982). Brown algae, in particular, is often boiled as a vegetable food component. Thus, minimum processing is necessary to make algae edible as a separate meal component or as a protein additive to other foods. Harvesting algae can be done by human crew without elaborate use of automation. Algal re-start conditions are easily satisfied by freeze-dried algae that require little volume and that are of little mass.

LEVEL IV - Level IV, the final phase in the CELSS development, will make a logical addition to Level Phase III by growing higher plants and supporting aquaculture. The growth of higher plants will not only increase the production of high quality food products, but will also increase oxygen production. Selection of plant species has been made based on the nutritional requirements of humans, the ease with which plant species can be grown, and the relative ease and flexibility of processing. Representative food species include soybeans, dry beans, potatoes and rice. For a 10 person crew, the higher plant subsystem is estimated to be very massive, occupying about 575 cubic meters, and is likely to be power intensive, requiring about 19 kw (Oleson, 1986). Thus, a fully complete CELSS is only warranted for a permanent base. Plant species cannot be harvested using extensively automated equipment, as this add a great deal of hardware and complexity to the system. Crew members will act as "gardeners," an activity which will provide relaxation and require little time.

Aquaculture will add variety and nutritional quality to the crew's diet. To harvest a sufficient quantity of aquaculture, a 1000 liter aquarium will be used. This system will be broken into subunits to isolate incompatible species and provide greater protection form infections spreading through the system. The aquaculture subsystem will be integrated into the algae subsystem, with algae serving as the major source for the aquaculture.

A CELSS cost analysis has been performed. Based on the initial hardware cost, launch and transportation costs, and ongoing resupply launch cost, each level of the scenario was examined. Initial results show that a fully complete Level IV CELSS will not pay off versus a Level III system until 23.5 years after system implementation, as shown in Figure 19. A microbial based Level III CELSS with algae is cost effective after only one year.

This phased approach to a CELSS development promotes logical advancements which will directly satisfy each portion of the infrastructure development. Life support needs are based on both mission length and crew size.

A second feature is development on on orbit and lunar surface high fidelity simulation facilities. Current training philosophy entails repetitive practice of required skills to ensure the necessary skill level is attained. Once on the moon, crews may spend greater times performing duties other than flying spacecraft. This implies a potential reduction in skill efficiency. A simulator will be required at the base to allow continuing practice of upcoming missions, emergency procedures and novel practice for emergency missions.

This could be enabled in one of two ways, or a combination of both. First, a portion of a habitation module could be dedicated to simulation. The second method would use a dual mode transportation vehicle. This vehicle could be used in a "simulation" mode to practice a mission or in an "operate" mode for actual mission performance. This dual mode vehicle would allow use of the actual controls and indicators onboard the lunar lander to simulate a mission. Thin visual display boards

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CUMULATIVE CELSS COST, LEVELS I-IV
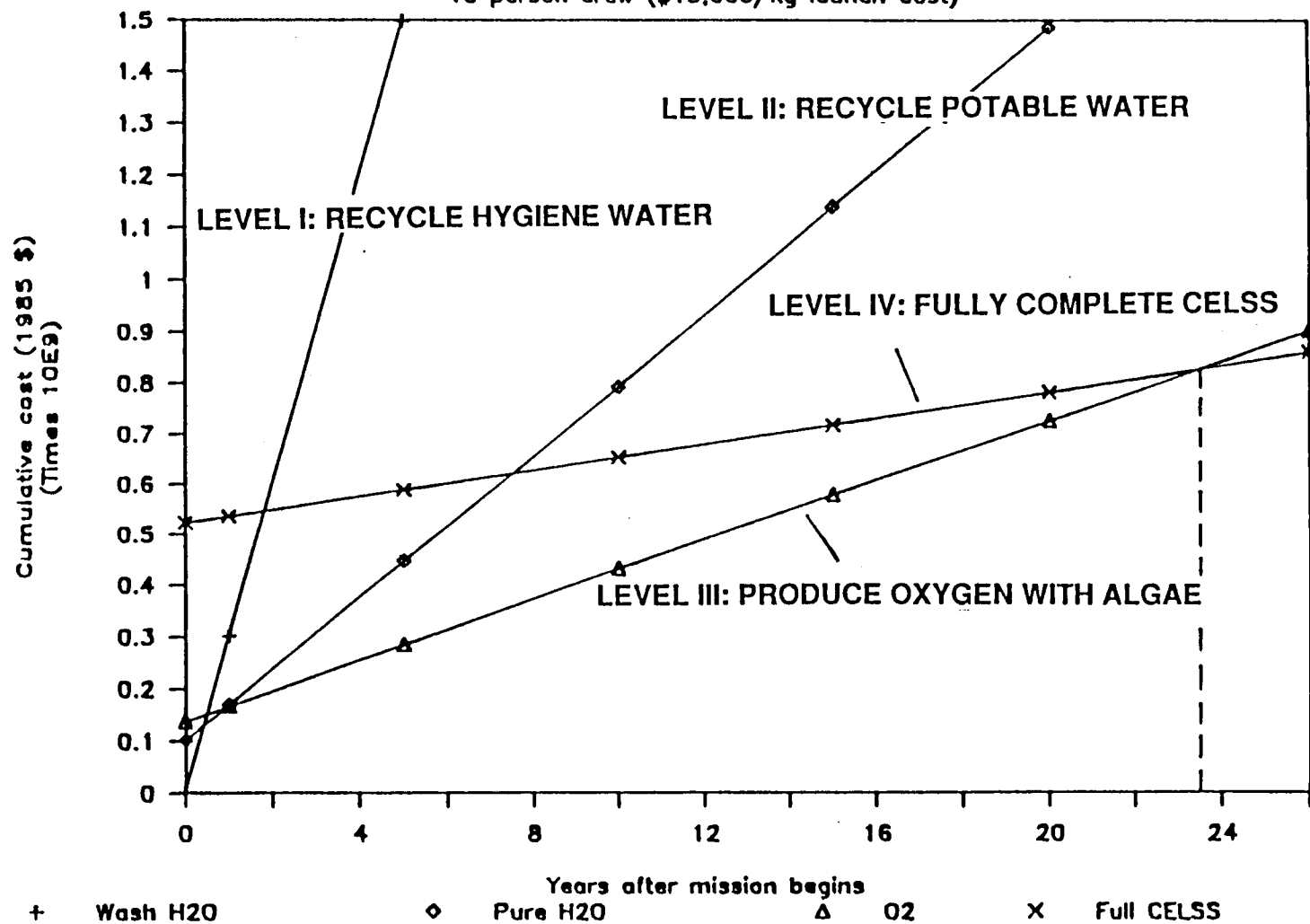
10 person crew ($13,000/kg launch cost)

Figure 19 - Cumulative CELSS Cost, Level I-IV

Based on the initial hardware cost, launch cost and on going resupply launch cost, each level of the scenario was examined. Initial results show that a fully complete Level IV CELSS will not be cost effective compared to a Level III system for 23.5 years after system implementation. After one year, the microbial based Level III CELSS is the most cost effective. This assumes all materials are of Earth origin.

would be placed over the window areas. Greater computer power also would be needed onboard.

The advantage of the dual mode transportation vehicle option would be that if multiple lunar sites were used a simulator would automatically be available at each site. Also the computer power to support simulation could be applied to performing rendezvous predictions or other orbital maneuvering calculations without ground, lunar base or space station support. The disadvantage is the increased weight of the displays, computers and dual mode circuitry all of which implies greater propellant consumption. A trade-off study of these options will be necessary to evaluate simulation technology levels at the time of final design. Another choice could be a hybrid of the above two, using transportation vehicle controls tied to lunar based computer support and utilities.

Additionally, an OTV simulator would become necessary. Crews in space for long duration may find the need to review emergency procedures, docking maneuvers or other operations. Such a simulator could be located in a space station node outfitted with a high fidelity simulator thus keeping OTV weight to a minimum.

A human powered vehicle (HPV) has been designed to fulfill the need for short range transportation on the lunar surface (Leech and Ryan, 1988). Such a need will undoubtedly arise with the advent of a lunar outpost and increased lunar activities. With its modest speed, 14km/hr, and 84 km range, the HPV can serve as a mode of transportation, an exploration vehicle, and also provide exercise and entertainment for the inhabitants on the moon. As the name implies, it will be powered by the astronauts themselves.

The design of the HPV, shown in Figure 20, is based upon the Earth-type recumbent and mountain bicycles, with special considerations given to the rugged lunar terrain and the maneuverability of the space suit. Since the space suit, a derivative of the Space Station Extravehicular Mobility Unit (EMU), is large and bulky, precise movements are difficult to achieve while wearing it, therefore to overcome these difficulties, minimum movement is desired. The recumbent position allows the rider to have something to push against and is able to develop a great deal more pedal pressure than would be possible when sitting in a traditional vertical position and relying on body weight alone. This configuration was chosen to allow for the easiest and minimum movement while in a space suit.

Also, instead of traditional rotary pedaling, the movement to drive the vehicle is a "push and pull" action done by both legs simultaneously. The mechanism that the astronaut's legs are powering is a simple crank-slider setup used in a reverse motion. Through a simple transmission, the crank rotation causes the back wheel to turn. Only small movements are needed with the HPV design, utilizing the strength of the astronauts' leg and back muscles, alleviating the suits' restrictive limits, and increasing the efficiency. A three wheel design was chosen to increase the stability and maneuverability over the traditional two wheel design while providing access to a greater variety of terrain than a four wheel design.

Along with this basic design, alterations (to the traditional bicycle) in material were made to account for the harshness of the lunar environment. A carbon composite frame was chosen for its lightweight and durable qualities. Kevlar tires with an open-chevron tread and chrome-moly steel studded tire grips provide lightweight and puncture resistant qualities, along with increased traction due to the studs. Hence, special design considerations have been given concerning space suit flexibility, durability, lunar surface terrain, and human safety.

In order for external lunar activities, such as an HPV mission, to be effective, a new space suit design modified for the lunar surface's harsh environment is warranted. These suits must be durable enough to withstand the abrasiveness of the lunar soil and prevent clinging of the soil to the suit. A high powered vacuum cleaner at the airlock could aid in the removal of the lunar soil. Additionally, the suit must be able to operate in a wide range of thermal environments, to be flexible, and to require zero prebreathe. The suit should allow considerable use between

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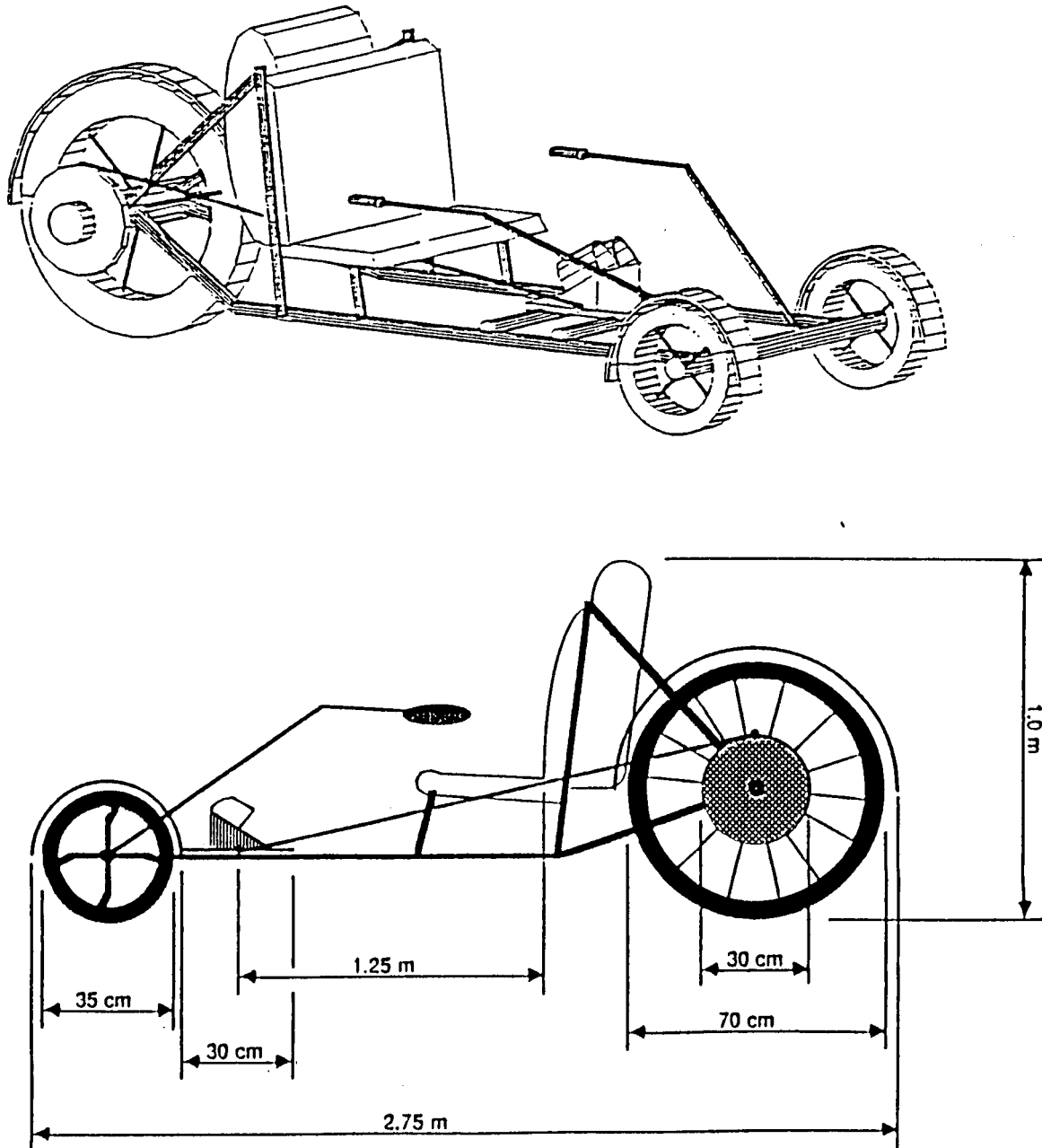# SHORT RANGE LUNAR TRANSPORTATION: A HUMAN POWERED VEHICLE

Figure 20 - Human Powered Vehicle

A human powered vehicle to be used for short range transportation on the lunar surface. The HPV is a three wheeled vehicle using a recumbent design and a backwards crank-slider mechanism. A carbon composite frame and studded Kevlar tires with an open chevron tread will be utilized to account for the harshnes of the lunar terrain.

maintenance periods and possibly automated rejuvenation of suit life support systems. On-orbit EVA space suits have similar requirements to satisfy space construction, transportation vehicle servicing, satellite servicing and other space activities (Buck, 1988). Current space suit design allows only limited use between servicing, is not flexible and requires prebreathe. Technological improvement of these suits is imperative in order to allow humans to efficiently operate outside their habitats or vehicles.

It is becoming increasingly more important to understand the physiological adaptations that occur in the different human subsystem when an astronaut is exposed to a microgravity environment, and to propose and provide adequate countermeasures which will lessen or counteract these physiological changes. Some of these physiological adaptations do not seem to harm the astronaut either immediately or on a long term basis, but a few of these responses may invoke a permanent change in the body's subsystems. Some of the less critical reactions experienced in microgravity are fluid shifts, red blood cell mass loss, and vestibular/sensory reorientation. For some more serious physiological adaptations, such as bone demineralization and muscle atrophy, countermeasures must be considered to assure that living in a microgravity environment for an extended period of time will not cause permanent modifications in these important body subsystems.

The upward redistribution and loss of body fluids occurs within the first 2-4 hours of microgravity adaptation. With the loss of the normal 1-g body force that "pulls" body fluids down to the lower extremities, the resultant upward shift of fluid raises the center of mass of the astronaut. The increased fluid volume in the upper half of the body sends a message to the brain that there is too much fluid in the body. This results in 2-3 liters being purged from the body through the excretory system. Some other effects of this fluid shift are noted in a 10% loss of vital lung capacity and the appearance of a puffy, bloated face. The former may hinder the astronaut's ability to exercise, while the latter might be an issue relevant to effective communication abilities (distorted facial features may be misinterpreted as an unintended facial expression). Upon return to a normal 1-g environment, the body fluids redistribute to a normal state almost immediately.

A major side effect of the fluid shift may be the subsequent reduction in red blood cell (RBC) mass. As much as 10-15% of the RBC's may be lost during the first two weeks of space flight. After about 60 days, a maintenance level of about 90% of the original RBC mass is reached. Other candidate causes for lowered RBC mass are: a shortened life span of the circulating RBC's, the direct effect of microgravity on bone marrow (causing reduced RBC production), or the negative calcium balance that occurs early in flight and continues throughout the flight. Blood plasma volume drops approximately 10% after prolonged stays in space. White blood cells are also affected by the lack of gravity. The mass of neutrophils increases, lymphocytes decrease and the total immune response is decreased. The loss in RBC mass an plasma when coupled with the deconditioning of the heart muscle (there is less resistance to pumping blood in a microgravity environment) may cause problems in the body's readaptation to gravity after prolonged micro gravity living.

The microgravity adaptation of the vestibular/sensory system occurs in must the same time frame as the body's fluid redistribution. Affecting 40-50% of the astronauts, this effect usually occurs only within the first week of spaceflight. Nausea, vomiting, pallor, and cold sweating are symptoms of Space Motion Sickness, or SMS, and are common manifestations of neuro-vestibular responses to microgravity. The response of many body systems to the normal 1-g force is aided by signals entering the brain from the vestibular apparatus. This sensory organ contains small, calcified granules, called otoliths, that rest on top of many excitable hair cell nerve endings. The weight of these otoliths upon the nerve endings causes a specific pattern of nerve signals for each position of the head with respect to the gravity vector. It is hypothesized that, following the brain's adaptation to weightlessness, otolith signals elicited by head tilts are reinterpreted by the brain as indicating translation. In microgravity environments, head tilts (roll and pitch) do not

produce change in otolith signals, but translation do cause the otoliths to signal. Therefore, the adapted brain learn to interpret all otolith signals as indicating translation. Movement reflexes and perception of self motion are altered according to this rearrangement of responses. SMS has the potential of impairing the productivity of astronauts during the first week in space, which is why it needs to become a better controlled response.

Muscle atrophy occurs in all astronauts during spaceflight, but it becomes more noticeable as the length of the flight increases. This involves the loss of muscle mass, strength, and tone in the red muscle fibers. Muscle atrophy affects the astronaut's muscle strength, coordination, and skeletal support. It does not seem to inhibit the astronaut's performance in the microgravity environment, but it does pose a problem when they need to readapt to the 1-g environment. Due to the fact that the muscles are remodeled to meet new functional requirements, atrophy occurs in the muscles the muscles of the lower extremities which are (in gravity) responsible for locomotion and body stabilization. This degradation is demonstrated by the increase in plasma and urinary concentration of several substances which would be consistent with the decrease in muscle mass and also by a loss in leg volume. The loss in leg volume cannot completely be attributed to the fluid shift phenomenon mentioned earlier. The muscle deterioration begins within the first day of the mission and continues throughout the flight. The recovery stage begins right after return to Earth, but it takes weeks to months, depending on the length of the mission, to recover the lost muscle strength.

There are several factors which are important to the maintenance of the body's skeletal system and bone integrity. One of the dominant maintenance factors is the force exerted by gravity on the skeletal system. The change in bone mineral metabolism caused by the absence of gravitational forces is one of the major concerns as far as physiological space hazards. A calcium balance upset is observed immediately, but the loss isn't noticeable in the bone matrix until approximately 10 days into the flight. A loss of 3-8% of the bone mineral composition has been observed in weight bearing bones over the course of various space flights. It would seem that the mineral composition would reach some type of a maintenance level, but this has not been documented. This should be one of the greatest concerns of the microgravity adaptation scenario. Recovery of these lost bone minerals begins immediately after a flight and the time required for recovery is proportional to the length the flight. If comparisons can be drawn between prolonged bed rest experimental adaptations and those that occur during spaceflight. For example, complete mineral recovery occurs 3-4 months after 2 weeks of total bed rest.

As a result of better understanding of the physiological effects of microgravity, certain measures may be developed to obviate some of the short term discomforts and/or long term disabilities that may otherwise result. Four types of countermeasures, if proven to be effective, may ultimately aid in reducing the adverse physiological adaptations: 1) pharmacological, 2) exercise, 3) magnetic or electric field application, and 4) physical hardware applications. Pharmacological treatments, such as dietary supplements and anti-motion sickness drugs, have been used in an attempt to alleviate aspects of bone demineralization, muscle atrophy, or SMS. These have had varied degrees of success in previous space flights and do not appear to have great potential for most long term effects. NASA is currently investigating the effect of exercise on physiological adaptations to microgravity. Specific exercise regimens may prove helpful in slowing the rate of, or perhaps preventing entirely, some aspects of bone demineralization, cardiac deconditioning, or muscle atrophy. Efforts at the University of Colorado, Boulder are being undertaken to examine the possibility of using magnetic or electric fields to stop or hinder the process of bone deossification. These fields might be used to simulate normal electrical impulses in the bone that are thought to be important in normal bone maintenance. Finally, some physiological effects may be obviated through the use of specially designed hardware. Soviets have attempted to reduce the muscle deterioration in microgravity by having cosmonauts wear a special suit to resist body movements. Preflight Adaptation Trainers (PATs) have been proposed as

potential devices to be used to help prevent the onset of SMS. The concept, being researched at Miami University, Wright-Patterson Air Force Base, and Johnson Space Flight Center, proposes that through training, visual-otolith responses may be systematically altered (as is microgravity) before actual space flight. Theoretically this would increase an astronaut's immunity to the neuro-vestibular discomforts in early flight. Figure 21 summarizes some of the important physiological effects of microgravity, their relative time scales, and some of the current work that may eventually serve to obviate these problems.

A timeline can also be assembled to summarize the postflight recovery rates exhibited by each of the microgravity adaptation responses, shown in Figure 22. All of these responses are ultimately a result of placing the body in a microgravity environment and must be considered to be interrelated. For example, the calcium balance, which is a major factor in bone demineralization, also plays a role in muscle atrophy. The calcium balance has an effect on the mechanisms for muscular contraction which is important in muscle conditioning. Correlations such as this are exemplary of the type of observations that need to be made when providing countermeasures to the problems encountered in living in microgravity.

ECONOMICS

Is it possible to commit large expenditures to such a program at a time when the economic climate of the government is one that is emphasizing budget reductions in order to balance the budget and to reduce the deficit? Perhaps a better question is whether the United States can afford not to pursue such activities. A space infrastructure can benefit the economy and reduce the budget deficit, it should not be viewed as a competitor for resources but rather as a producer of them. In order to stay competitive in world markets at the turn of the century, the answer is that the United States must make a commitment to technological research and development.

Next to the Soviet competition, Japan and the Federal Republic of Germany (FRG) are the closest competitors in technological arenas. Over the years 1983-1986, the gross national product (GNP) of the U.S. was almost three times that of Japan and over five times that of FRG. Research and development spending in all three countries is approximately 2.8% of their respective GNP's (Lederman, 1987). However, the distribution of such funds and the output of the respective economies vary. Figure 23 illustrates the strong American commitment to defense R&D, however, only 10% of this amount is devoted to research. Japan and FRG spend the majority of their R&D funds in non-defense activities.

Each economy provides different products to the world market. In order to measure the successful utilization of R&D expenditures, technology intensive exports were selected as the metric. The country with more state of the art technological products for world markets should have a greater share of export business. The left half of Figure 24, Relative Market Share, illustrates the ratio of technology-intensive exports for Japan and FRG relative to the U.S. export market. Japan's world export market is approximately 80% of the U.S. market. Although the U.S. has a larger share of the world market in absolute terms, it is not as effective as Japan and FRG per R&D dollar expended. The right half of Figure 24, R&D Weighted Market Effectiveness, weights the export markets of Japan and FRG to the amount of R&D funds expended. This weighted market share is normalized to the U.S. R&D weighted market share. Per R&D dollar, Japan is 2.3 times more effective and FRG is 4.4 times more effective in generating technology-intensive exports than is the United States.

Clearly, the United States is currently losing its technological edge in the commercial arena. Japan is becoming increasingly competitive in computer technology. The European Space Agency (ESA) is closing the technological gap between their space program and the U.S. space program. Already, ESA competes very well for Western launch services. In the next decade, ESA plans to have developed a small shuttle. Japan has similar designs to compete in the world market for launch services, manned spaceflight and possibly a space station. Where at one point
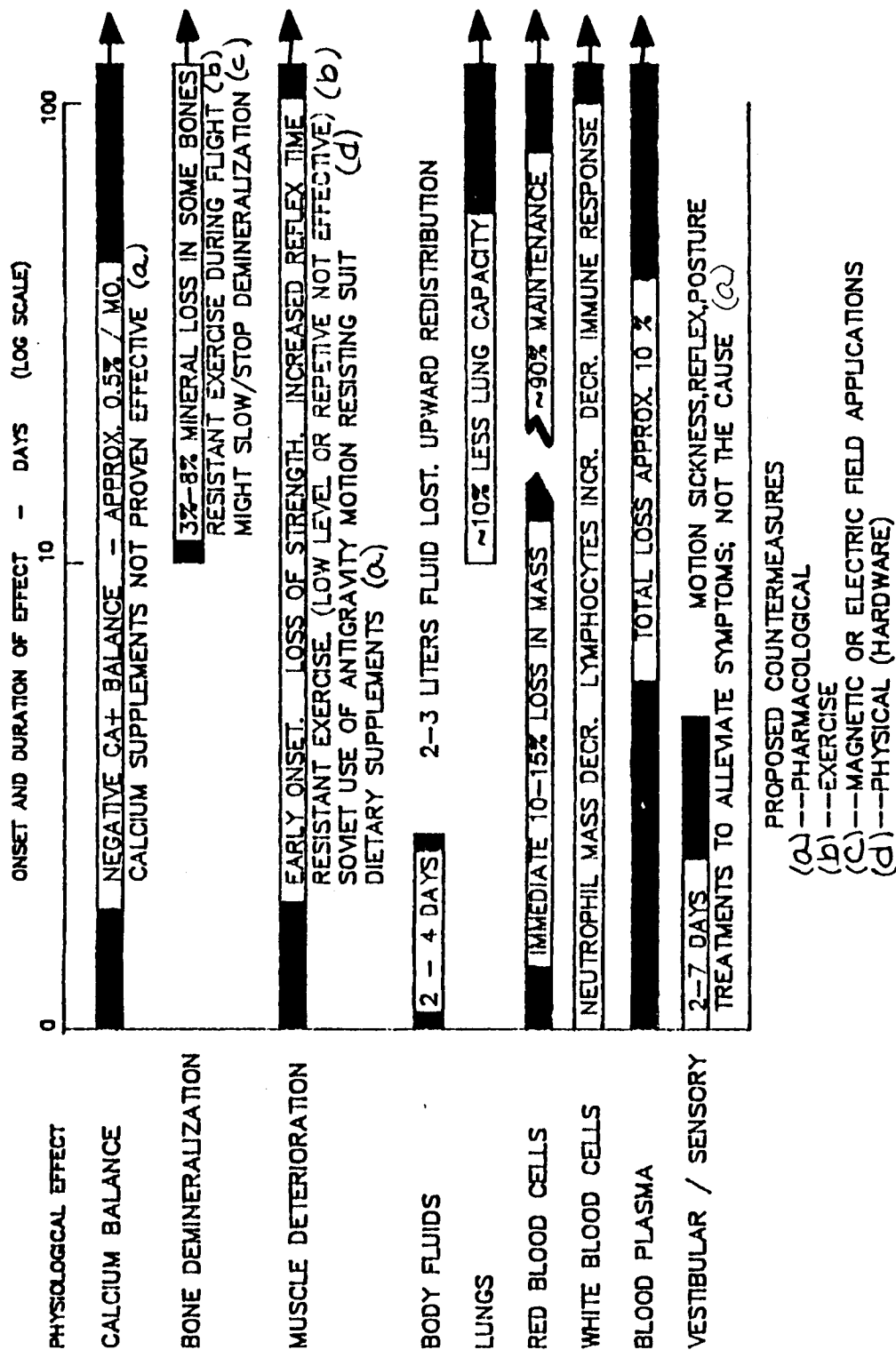
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Figure 21 - In Flight Physiological Timeline

Some of the important physiological effects of microgravity, their relative time scales, and some of the potential solutions to these problems are illustrated.

POSTFLIGHT RECOVERY TIMELINE

ONSET AND DURATION OF EFFECT — DAYS (LOG SCALE)
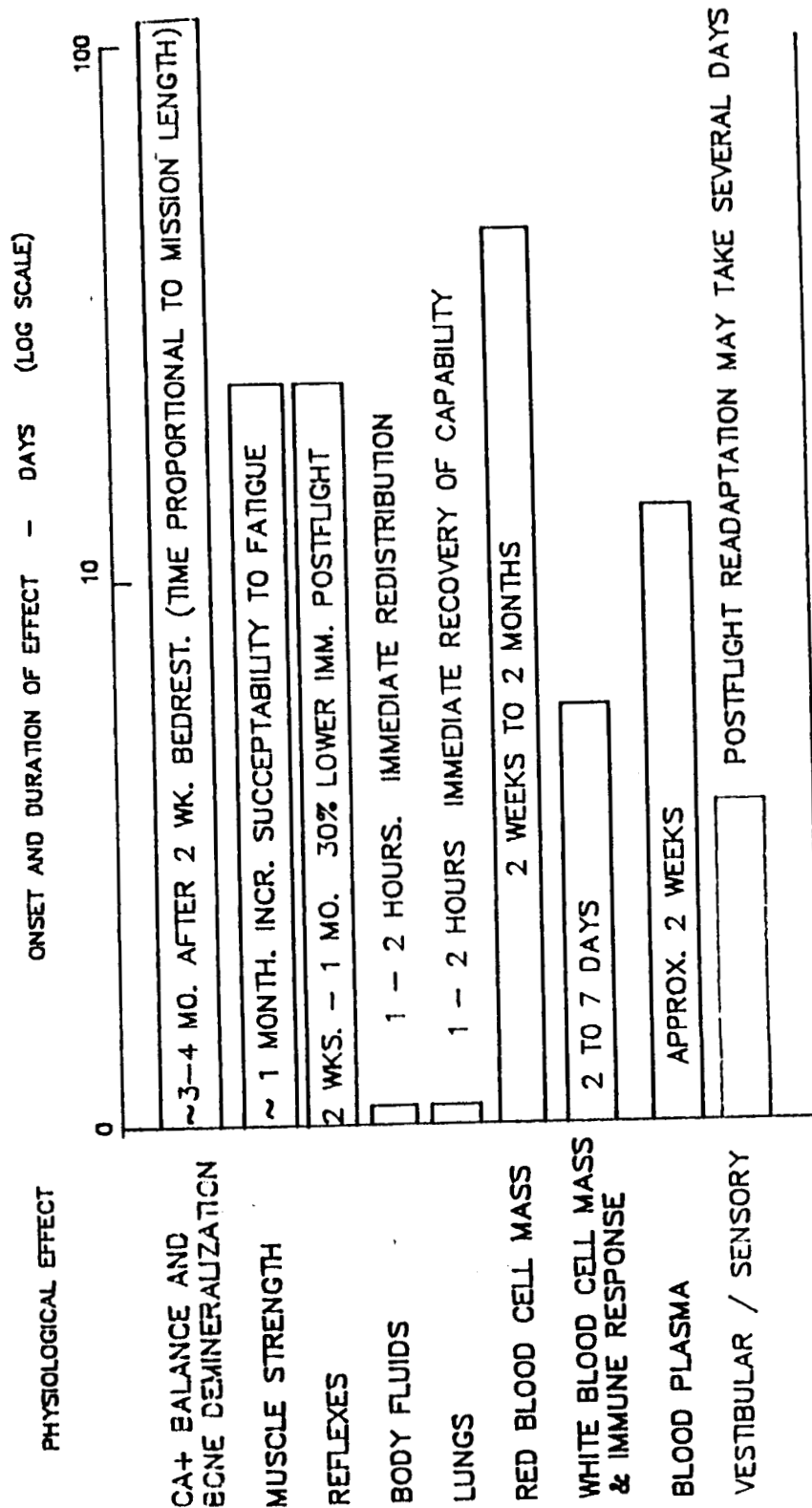
PHYSIOLOGICAL EFFECT	
CA+ BALANCE AND BONE DEMINERALIZATION	~3—4 MO. AFTER 2 WK. BEDREST. (TIME PROPORTIONAL TO MISSION LENGTH)
MUSCLE STRENGTH	~ 1 MONTH. INCR. SUCCEPTABILITY TO FATIGUE
REFLEXES	2 WKS. — 1 MO. 30% LOWER IMM. POSTFLIGHT
BODY FLUIDS	1 – 2 HOURS. IMMEDIATE REDISTRIBUTION
LUNGS	1 – 2 HOURS IMMEDIATE RECOVERY OF CAPABILITY
RED BLOOD CELL MASS	2 WEEKS TO 2 MONTHS
WHITE BLOOD CELL MASS & IMMUNE RESPONSE	2 TO 7 DAYS
BLOOD PLASMA	APPROX. 2 WEEKS
VESTIBULAR / SENSORY	POSTFLIGHT READAPTATION MAY TAKE SEVERAL DAYS

Figure 22 - Post Flight Recovery Timeline

Physiological effects of microgravity subside at different rates. Some effects, such as bone demineralization, have extremely long recovery times. Other changes, such as blood mass, recover within a few days of return to normal levels of gravity.

RELATIVE R & D EXPENDITURES
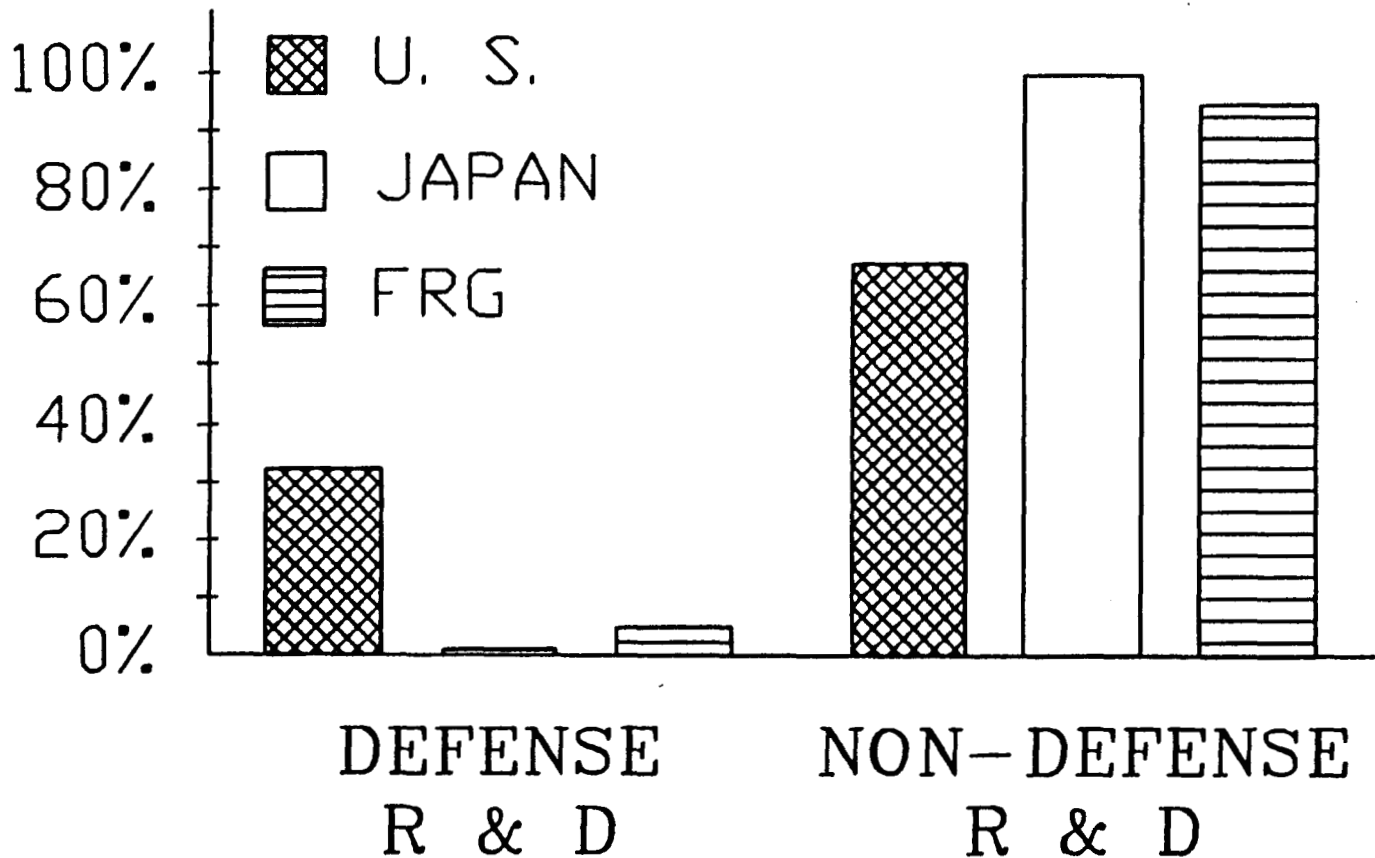
Figure 23 - Relative R & D Expenditures

Next to the Soviet competition, Japan and the Federal Republic of Germany (FRG) are the closest competitors in technological arenas. Over the years 1983-1986, the gross national product (GNP) of the U.S. was almost three times that of Japan and over five times that of FRG. Research and development spending in all three countries is approximately 2.8% of their respective GNP's (Lederman, 1987). However, the distribution of such funds and the output of the respective economies vary. This figure illustrates the strong American commitment to defense R&D, however, only 10% of this amount is devoted to research. Japan and FRG spend the majority of their R&D funds in non-defense activities.

RELATIVE SHARES OF TECHNOLOGY–INTENSIVE EXPORTS
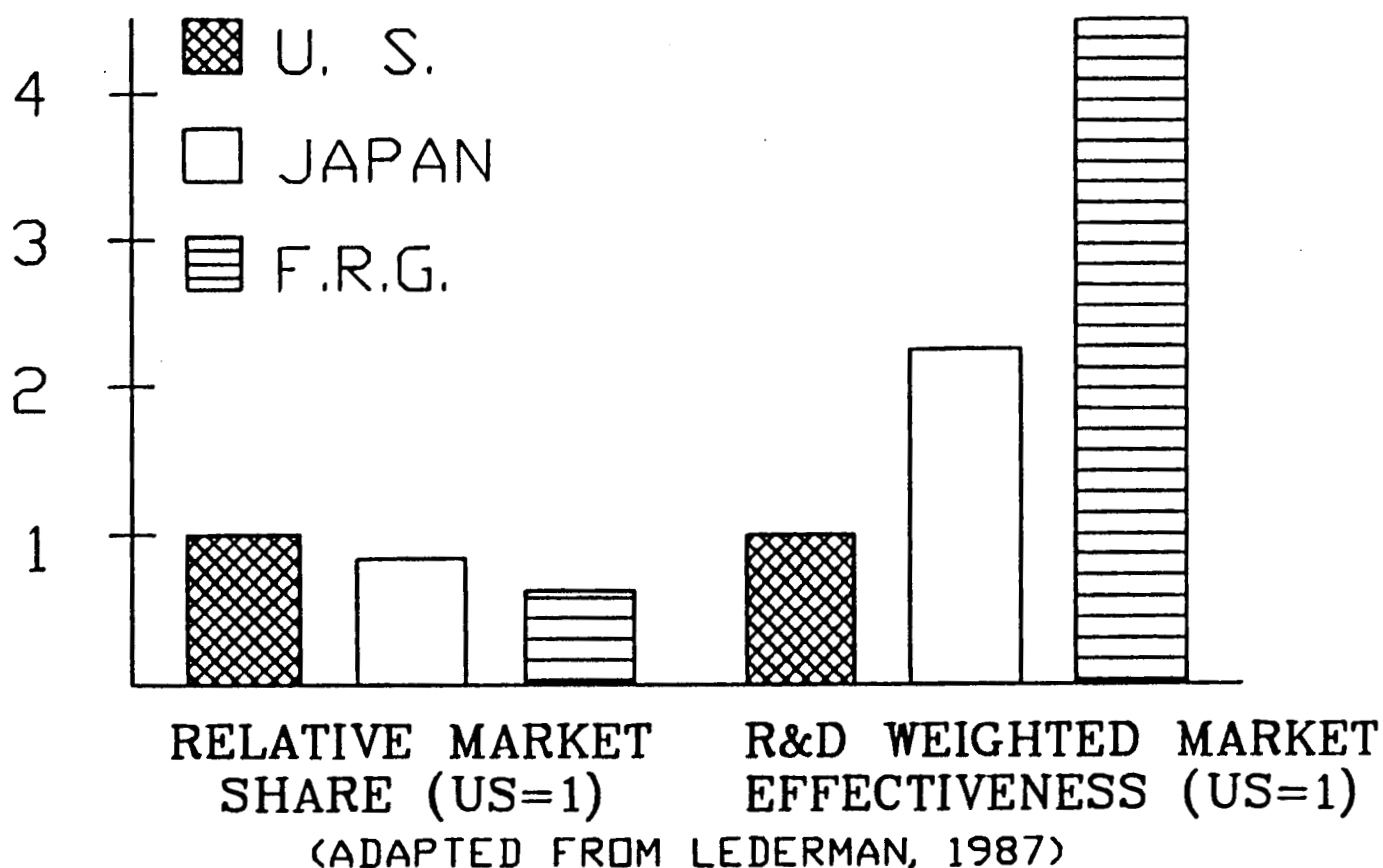
Figure 24 - Relative Shares of Technology

Each economy provides different products to the world market. In order to measure the successful utilization of R&D expenditures, technology intensive exports were selected as the metric. The country with more state of the art technological products for world markets should have a greater share of export business. The left half of this figure, Relative Market Share, illustrates the ratio of technology-intensive exports for Japan and FRG relative to the U.S. export market. Japan's world export market is approximately 80% of the U.S. market. Although the U.S. has a larger share of the world market in absolute terms, it is not as effective as Japan and FRG per R&D dollar expended. The right half of this figure, R&D Weighted Market Effectiveness, weights the export markets of Japan and FRG to the amount of R&D funds expended. This weighted market share is normalized to the U.S. R&D weighted market share. Per R&D dollar, Japan is 2.3 times more effective and FRG is 4.4 times more effective in generating technology-intensive exports than is the U.S.

the U.S. was the undisputed leader in space technology, the turn of the century could find the U.S. trailing behind Russia, ESA, and Japan, as well as various other countries trying to form space programs.

Failure to commit U.S. resources could result in further lagging of technological growth in this country. This would further reduce U.S. exports and weaken the country's economy. The proposed program to develop a cost efficient space infrastructure and to explore the moon could prevent this pessimistic scenario from occurring by increasing the nation's commitment to research and development.

Commitment to increased space program funding provides benefits throughout the nation's economy. Immediate effects are increased employment to support the development of these projects and concurrent growth in local support service economies to support the increased employment. Universities will find more money to support higher education and enhance graduate education. Other sectors of engineering and science may benefit from quality graduate education supported by funding of universities for space application studies. Space, thus, is a technological target that will embrace a broad advance in the U.S. competitiveness of the next century

Space technology is a multi-disciplinary effort. Therefore, funding supports a wide range of activities, thereby increasing the potential applications of new developments into other sectors of industry. Perhaps the greatest impact will be in the area of automation and robotics. This technology is vital to efficient space operations. However, this technology has enormous potential in industry to yield products less expensively and with greater quality than is currently possible. Robotics innovation will undoubtedly become more popular in world markets. Other areas of technological interest stimulated by the space program include artificial intelligence, medicine, new high-strength low-weight alloys, and computers.

The Apollo program was politically motivated; it was pursued in order to maintain the U.S. technological edge. Approximately 40 billion dollars were invested in this program, resulting in an estimated 200 billion dollars worth of benefits. Return on this investment is continuing today. The proposed space infrastructure should provide similar returns to the economy as a whole. Although not all of the specific products can be anticipated at this time, an investment in the future must be made to provide the framework for future innovation. Continued pursuit of products that show only a short term return on investment will not be in the interest of the U.S. economy as a long term world leader in technology. We must invest now. As tempting as it may be to consume all of the economic grain of our present harvest, we must put aside sufficient seeds for future harvests and economic well being. Space is fertile ground in which to plant these seeds for the future.

CONCLUSION

Thus, the University of Colorado Advanced Mission Design Program has defined the evolution of a cislunar space infrastructure and designed many of the infrastructure components. Technological advances, scientific gains, economic returns, greater political stature and national pride justify the development of such an infrastructure.

The economic health of the U.S. may depend upon a program such as this to assist in revitalizing the nation's technological leadership. Failure to invest in a diverse space program may lead to future economic pitfalls. Foreign launch services and satellites may be sought by U.S. corporations, further upsetting the U.S. trade balance by an area which has historically been a U.S. export service.

Such an infrastructure will enable diverse scientific research. In addition, the space infrastructure may enable commercial enterprise to take root in space. The infrastructure must be cost effective and flexible to encourage its use. A greater number of investigators would consider pursuing space based research if facilities were available in a timely manner, economically priced and comprehensively supplied. Extensive LEO Station laboratories could enable a wide variety of short term research projects. Reductions in the current time delays associated with access to

space-based laboratories is essential as is economical transportation. Extensive research may lead to the technologies for commercial exploitation.

As the infrastructure expands, cost efficiency and flexibility must be maintained. The high Earth orbit station is located at L1 to minimize propellant expenditures for the transportation system for the wide variety of expected missions. Lunar base facilities are expanded in a logical progression based upon need and opportunity. Like the LEO station, comprehensive laboratory facilities are desired throughout the infrastructure to enable diverse research activities.

Specific activities will take place through the use of an L1 space station, a lunar habitat and an extensive transportation system. The development and construction of the infrastructure are phased such that specific breakpoint criteria must be satisfied before the next phase can begin. By advancing logically and methodically, a solid foundation is established upon which a credible and successful program may be built.

Development of the infrastructure begins when the program is accepted. Around 1990, research and design of technologies, as well as hardware and programmatic considerations, will be accelerated. This scenario continues through 2021, when the lunar base becomes self-sufficient. At this point the open-ended nature of this design enables more aggressive projects, such as a manned Mars mission.

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Diane De Caix	Heidi Leech	

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