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MANNED SPACE HABITAT

NASA-USRA Advanced Space Mission Design Project

University of Colorado, Boulder

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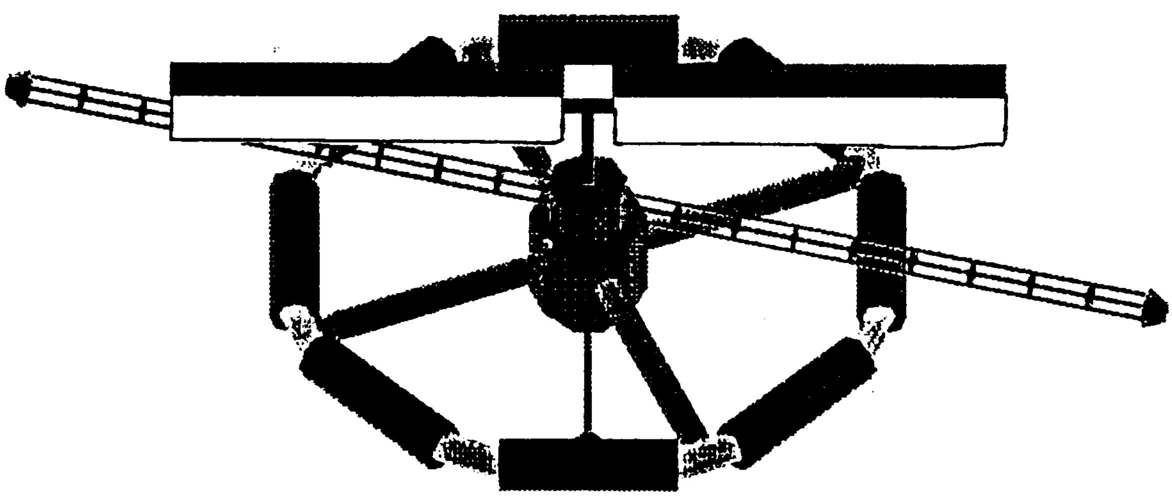

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The following students have participated in the Aerospace - 595 Space Habitation Design class that stems from the NASA-USRA University Advance Space Mission Design Project. We would like to thank members of previous classes as well for providing the foundation for our work.

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Gary Banks	Jud Cary	Craig Chapman
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Overview of NASA-USRA Activities at the University of Colorado

The design of a manned, rotating space station is the result of the NASA / University Advanced Space Mission Design Project at the University of Colorado, Boulder. The Universities Space Research Association manages the program and the University of Colorado has been involved for 7 semesters. The project is under the direction of Dr. Marvin Luttges and his Graduate Assistant Steve Johnson.

Several papers and presentations related to the project have been given during the last two years including:

Presentations: 1985 NASA-USRA Design Review at Kennedy Space Center 1986
NASA-USRA Design Review at Ames Flight Research Center
The National Commission On Space
Senator Harrison "Jack" Schmitt
Astronaut Marsha S. Ivans
NASA / Ames Sponsor Robert McElroy

1 C.U. representative went to NASA / Langley to research the NASA CAD Software.
3 C.U. Representatives went to NASA / Langley to present CAD usage in design efforts.
3 C.U. representatives went to the Architectural Concepts Review at NASA / Ames Research Center
7 AIAA papers were presented at the 1986 Region V student conference in Ames, Iowa.
1 AIAA paper was presented at the 1987 Region V student conference in St. Louis, Missouri
1 Paper was presented at the 1986 AAS Conference in Boulder, Colorado

Design reviews have been held with local university, industry and space society representatives. The turnout has been excellent and the response to the station design has been positive. Their input has been incorporated into the design of the station and this interface has proved productive for the university students.

Introduction

In the last few years the Low Earth Orbit (LEO) station has been discussed as the next logical step for the United States space program, a step that is today becoming a reality. A second generation station will also play a logical and vital role in the expansion of man into space. A second generation station will ensure that United States maintains the momentum and direction created by the LEO station.

The groundwork for this expansion has been laid. An overview is outlined in the report of the National Commission on Space. In this report second generation stations are discussed for an Earth-Moon libration point and in lunar orbit. The Solar System Exploration Committee of NASA's Advisory Council has given detailed reports on the scientific challenges, activities and economic benefits of planetary exploration, activities that a second generation station can promote. The National Academy of Sciences, which has often been involved in NASA's long range planning, has held symposiums on the possible benefits and technological requirements of Lunar development. A comprehensive groundwork has been laid for space exploration. A second generation space station located beyond LEO should be a focal point for this expansion.

The conceptual design of such a station is outlined in this report. The primary design criteria call for the station to complement other space activities in an active manner and, as the LEO station will do, assist in the development and implementation of long term space habitation technologies. This second generation station or Manned Space Habitat (MSH) should be operational by about 2010 to reduce the costs of future manned and unmanned space activities, specifically lunar operations, the exploration of Mars and the servicing of the Geosynchronous Earth Orbit (GEO).

To be operational in this time period dictates a technology cutoff between 2005-2010. This would allow for 15-20 years of technology growth beyond LEO station's 1980's technology. Systems and subsystems described in this report reflect anticipation of moderate technology growth. A few key technologies still in their infancy, but vital to the MSH, have been included.

The paper begins with a discussion of station activities. These activities dictate the location of the station. The justification for locating the station at the L1 Earth-Moon libration point follows that. Next some of the details regarding the crew of the MSH are outlined. Then we justify the use of artificial gravity on the MSH, followed by an overview of the structure of the station. The evolution of the L1 environment is then discussed. Several select subsystems are then outlined and the report concludes with the description of how the L1 MSH will complete some of its activities.

Station Activities

Past space endeavors have shown that space activities must be publicly justifiable. In fact public justification has been the major factor affecting space policies. In order that the MSH be seen in a positive political light, it must promote national pride, national and international interests, national security and economic development. In addition, to survive the bureaucratic horse trading that is part of any politically activity, the MSH should play a key role in the overall space program.

As outlined in "Pioneering The Space Frontier", future space activities must be mutually supportive in order for the space program as a whole to survive. The second generation station space station will serve other space program activities, such as advanced communication networks, Lunar exploration and colonization and planetary exploration, while advancing space habitation technologies. A second generation station must enable space activities otherwise not tenable using the Earth or the LEO station such as energy efficient satellite servicing and cost effective interplanetary mission staging.

The planned station must provide a return in three ways. First, the station should be somewhat self supporting, generating a positive economic return to offest the initial investment and continuing support costs, perhaps by processing lunar materials or servicing the GEO. Second, the station should reduce the costs of other space activities as compared to doing these activities from Earth or another space site. An example would be the reduced staging costs of a Mars mission from this station. Finally the station must provide technological support to the space program as well as to overall U.S. enterprises, by extending CELSS to other space missions or promoting advanced automation and robotics. Other scientific activities should complement LEO, GEO and Earth based astronomy, astrophysics and remote sensing of Earth phenomena.

The following four categories outline the basic activities that will take place on the MSH.

GEO Servicing - In GEO, satellite servicing, debris removal and satellite modification are needed. The station can provide an immediate economic return by performing GEO servicing. Two OTV's based at the station performing 20 satellite servicing missions per year would save over one billion dollars in satellite replacement costs. Station-based GEO servicing requires less propellant to be launched to LEO. A 4000 kg OTV with servicing equipment and equipped for aerobraking would require 129,000 kg of propellant be launched to LEO. This includes the 29,000 kg required for the servicing missions and the 100,000 kg required to move the OTV and propellant to GEO. Twenty such missions based in LEO would require a total of 328,000 Kg of propellant to be delivered to LEO. Missions originating at any of the Earth-Moon libration points would realize nearly identical savings since the energy required to transfer from one point in GEO to another is nearly identical to the energy required to reach GEO from the Earth-Moon libration points.

The MSH will provide a garage to service and resupply the vehicles that will go to GEO to perfom servicing work. The MSH will serve as a "parts store" for GEO satellite service. It will also serve as a repair shop for satellites that need repairs that cannot be done on site in GEO. The hardware in GEO can be collected and used again providing a component base for which the launch costs have already been paid. This component base may be used for other satellites and spacecraft, or as reaction mass in advanced station keeping systems. Satellite lifetimes can be extended, replacement costs will be reduced and vital orbit slots can be cleared of satellites no longer useful.

Scientific Technologies - The MSH must complement LEO and GEO science activities. It should develop space habitation technologies. It also should utilize non-terrestrial materials for as many uses as possible. All such activities fall into five different areas of technology need and development.

1. Life in Space Testing - Testing of the effects of artificial gravity on humans and plants will be a primary activity on the MSH. The testing, feasibility and use of Controlled Ecological Life Support System (CELSS) and Ecologically Controlled Life Support Systems (ECLSS) systems will also be a priority. Long-term human performance and adaptation questions can be seriously addressed.

2. Materials Processing - Earth resources are finite and currently all materials used in space are launched from Earth at high cost. To maximize these limited resources we must produce products that utilize all resources in a conservative manner, expending as little energy (hence dollars) as possible. Built-in reutilization schemes must be developed. The MSH will process and store materials from non-terrestrial sources such as the Moon and Earth crossing asteroids. The location of the MSH at either the L1 or L2 libration points provides an economically advantageous site for non-terrestrial material coordination since minimal energy needs to be expended to travel to LEO, GEO, the Moon and the other planets.

Space-obtained materials may be processed into metals, ceramics and glasses for the production of communication lines, solar cells, and structural elements. They can also be used as shielding, to make foams, and to yield into propellant. The lunar regolith contains O_2 (propellant), Si (solar cells); Al, Fe, Ti, (structure and electrical) Mg and Ca significant quantities. If water exists in the polar regions of the moon it could be used for life support, chemical processing and as propellant. Although little is known about the makeup of all asteroids two major types are of interest. The two types have been indicated by meteoroid strikes and are rich in iron and nickel (providing high-priced alloys) and carbonaceous compounds (providing volatiles that may not exist on the moon).

The majority of the mass of a LH_2/LO_2 rocket is oxygen. It is expected that 300 tons of oxygen will be required annually for space activities by the year 2000. Transporting this from the moon to L1 requires a delta-v of 2.4 km/sec compared with the delta-v of 12 km/sec from Earth to L1, similarly the delta v from the moon to LEO is 3.4 km/sec using aerobraking as opposed to a delta v of 8 km/sec from Earth to LEO. Although the production of lunar oxygen is not essential to the L1 MSH, it would vastly increase station potential to support future space program activities. Materials collection and processing from the asteroid belt and the Martian moons Phobos and Deimos could also be coordinated from the MSH. Processing could take place on the station as well as on a free flying materials, collection and processing facility.

3. Look Out - astrophysics and astronomy will both be performed on free flyers and will be controlled by the station so as to benefit from station servicing and equipment upgrades. A radio antenna at L1 combined with Earth based observatories would yield an order of magnitude improvement in angular resolution compared with baselines on Earth. Solar observatories could provide near continuous observations.

4. Look Down - L1 is an excellent location for studying Lunar effects on Earth. Complementing GEO and LEO based weather, geoddessy and Lunar observations, the MSH could provide excellent global monitoring.

5. Radiation Studies - The MSH offers an opportunity to study the GEO radiation environment with remote access and automated probes. On site experiments of the radiation would be possible through energy efficient access to GEO. Also the station environment should provide an excellent location to study a radiation environment that

is very similar to what man will endure during any space colonization or deep space exploration missions.

Lunar Support - Shuttles departing from an L1 or L2 station could land anywhere on the Lunar surface, pole to pole, without significant delta-v penalty. This advantage is not possible from a low lunar orbit. In addition the proximity of L1 or L2 MSH to the Moon (59,000 km) will enable near real-time communications with the Lunar surface. (Round trip communication time from L1 and L2 is 1/3sec, from Earth 2.5 sec) This would simplify remotely controlled Lunar operations. Lunar communication from L1 in conjunction with a communications satellite in a halo orbit about L2 would provide nearly continuous coverage of the entire lunar surface.

Planetary Staging - A staging base located at the station would yield significant energy savings over staging missions from LEO. The escape velocity from the Earth's equator is 11.2 km/sec. The economic benefits of a staging base at the top of the Earth's gravity well are illustrated by examining a sample Mars mission departing from L1. A Mars mission making a round trip from LEO would require a total delta-v of 6.50 Km/sec assuming co-planar Hohmann transfers and aerobraking at both the Earth and Mars. The same mission departing from L1 would require a total delta-v of 4.76 km/sec. The task of transporting the mission to L1 could be minimized by using reusable OTV's making several missions.

This benefit of staging from high Earth orbit (HEO) are truly realized if the Mars transfer vehicle is used more than once. Cycling space ships could use the L1 space station to refuel and resupply without going back down the gravity well. Crews could be transferred from the cycling space ships to and from the station. The MSH can extend it's CELSS to manned space ships so that an entire new system need not be launched from Earth. Space ships making sample return missions from the asteroids or from Jovian moons could utilize the station. The artificial gravity of the station will provide an intermediate step between microgravity environments (and Lunar environments) and the Earth's gravity. As a quarantine site, the MSH is essential. Table 1 shows a comparison of the delta v requirements for space missions originating in LEO and at L1. Table 2 illustrates the total energy savings for a multimission program. The overall savings are maximized if all the liquid oxygen is produced from lunar O2.

Velocity Change Required for Transfer

Destination	Departure site	
	LEO	L1
GEO	3.1 km/sec	1.5 km/sec
Moon	4.1 km/sec	2.4 km/sec
Mars	6.5 km/sec *	1.9 km/sec *
LEO	N/A	1.4 km/sec *
L1	39 km/sec	N/A

Table 1. Delta - V Comparison * = with aerobraking

Destination	Number of Missions by 2025	Delta V Savings by departing from L1 instead of LEO
Moon	25	42.5 km/sec
Mars	15	69.0 km/sec
GEO	100	1600 km/sec

Table 2. Long Term Energy Savings

The MSH can provide benefits in all of these activities. What the station can do best will depend upon the capabilities of the station and its crew.

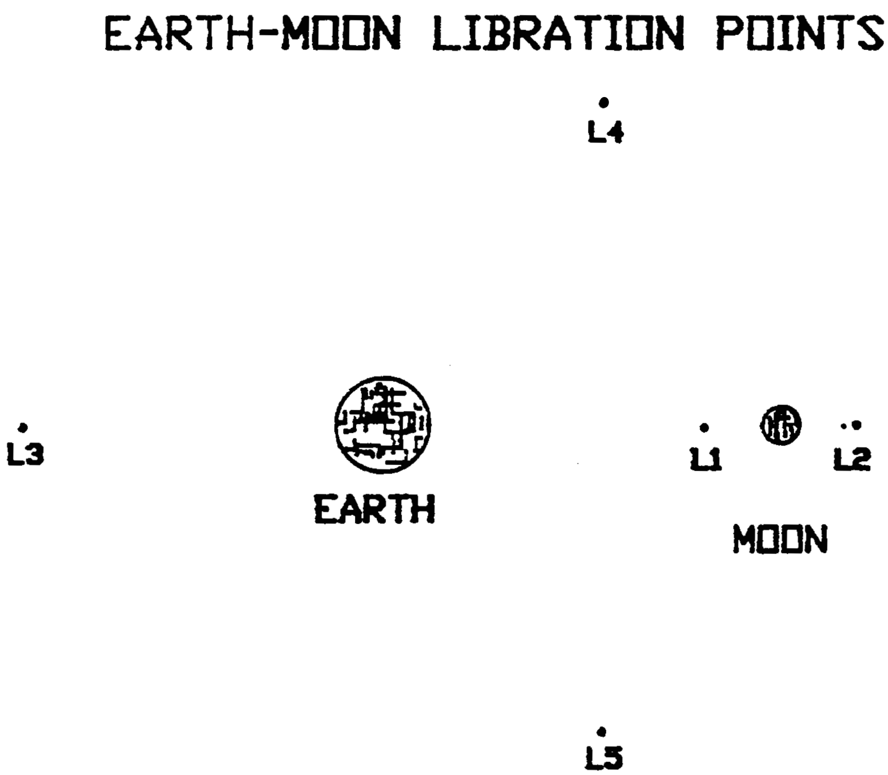
SITE SELECTION

A second generation station should be located in high earth orbit. Operations from such a station will minimize the cost of a long term program of colonization and exploration of the solar system, and minimize the cost of maintaining vital space resources such as the GEO. Delta-v is the velocity change required to do a mission. The larger the delta-v the more propellant required to implement the velocity change. The delta-v savings of a mission originating in high earth orbit is illustrated in the following example. A single servicing mission to a GEO satellite from LEO requires a total delta-v of 6.3 km/sec. Servicing the same satellite using a GEO based Orbital Transfer Vehicle (OTV) would require a delta-v of only 1.6 km/sec, nearly a six fold savings in energy expenditure. Servicing bases located in high Earth orbits such as GEO and the Earth Moon libration points provide this magnitude of energy savings. A location that minimizes the expense of many space program activities should be chosen, so GEO and other high Earth orbits were considered.

GEO was eliminated from consideration as the location for the MSH for two major reasons. The orbital altitude of geosynchronous satellites is 35,786 km. This lies in the heart of the trapped particle radiation belts that are a part of the Earth's magnetosphere. Radiation levels here reach an average of 5000 rads per year. A permanently manned space station at this location would require a shielding system that must operate around the clock in a failsafe manner. Only one operational example of such a system currently exists and that is a bulk shielding. In addition to the extremely high weight of such a system the possibility of harmful secondary radiation persists. Alternatives to such a system do not exist and may not exist by the time the station is scheduled to be operational. In addition, adding a station, free flyers and Omv's to GEO would further crowd and burden this dwindling resource. Because of these facts GEO was not considered an acceptable site for the MSH.

The five Earth-Moon libration points, L1 through L5, were also considered. A spacecraft can remain in a small circular obit or "halo" orbit around a libration point without spending a significant amount of propellant, 160 - 300 mps/year. Figure 1 shows the locations of these five libration points.

The L1 Earth Moon libration point was chosen as the location for the second generation station. Figure 2 gives a summary of the delta-v expenditures from L1 to several destinations. As noted earlier, station activities will determine the proper location for the MSH. The activities that location should permit are, in order of importance: servicing geosynchronous Earth orbit, supporting lunar operations and supporting solar system exploration and colonization. The L1 point best serves these activities as a whole. The analysis that leads to this conclusion follows.



R = Moon's Orbital Radius = 3.8E05 km

L1 - .85 R

L2 - 1.17 R

L3 - .99 R

L4 & L5 at Equilateral Triangles with the
Earth and Moon

Figure 1.

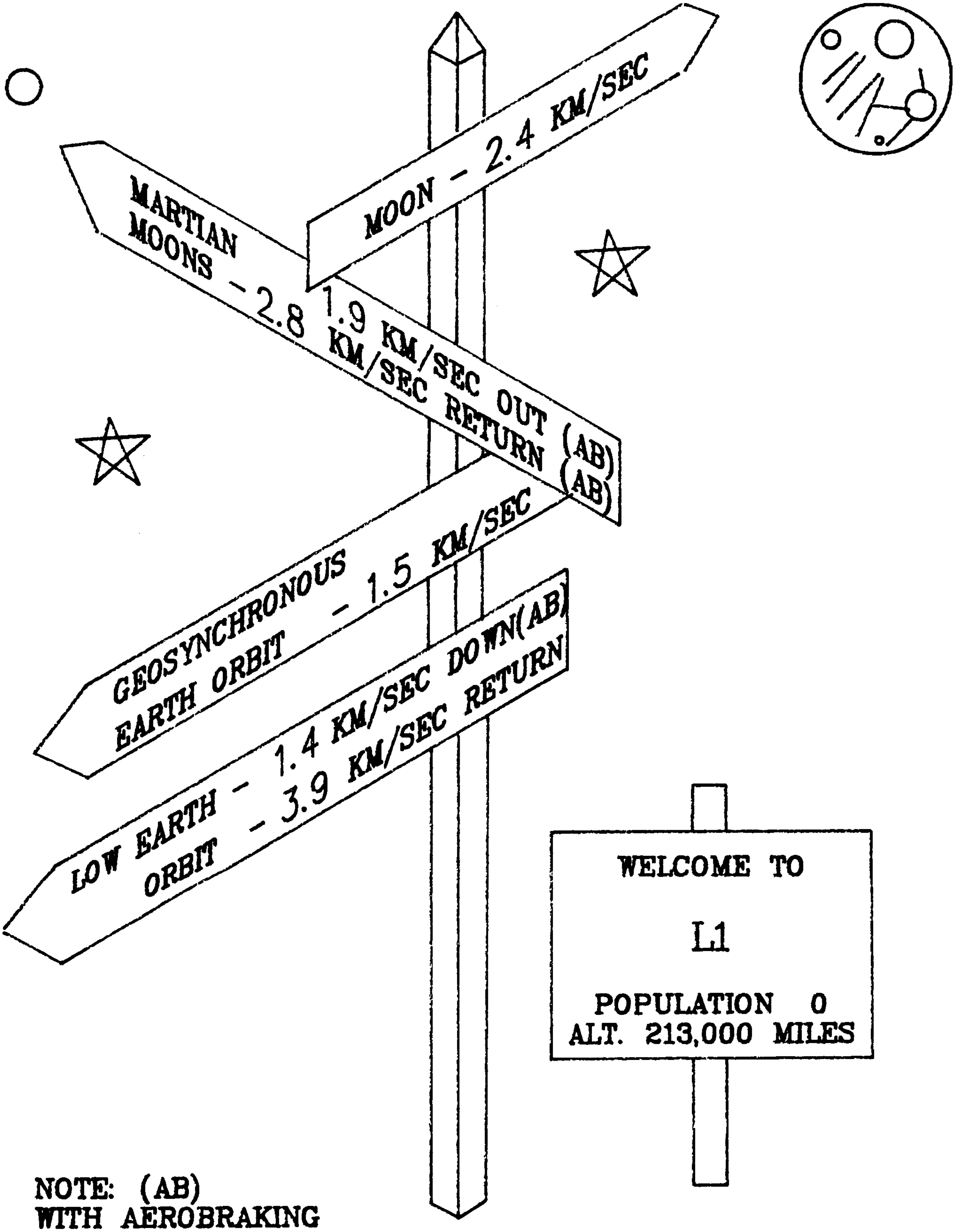

MOON - 2.4 KM/SEC
MARTIAN MOONS - 2.8 KM/SEC RETURN (AB)
1.9 KM/SEC OUT (AB)
GEOSYNCHRONOUS EARTH ORBIT - 1.5 KM/SEC
LOW EARTH ORBIT - 1.4 KM/SEC DOWN(AB)
- 3.9 KM/SEC RETURN
WELCOME TO
L1
POPULATION 0
ALT. 213,000 MILES
NOTE: (AB)
WITH AEROBRAKING

Figure 2.

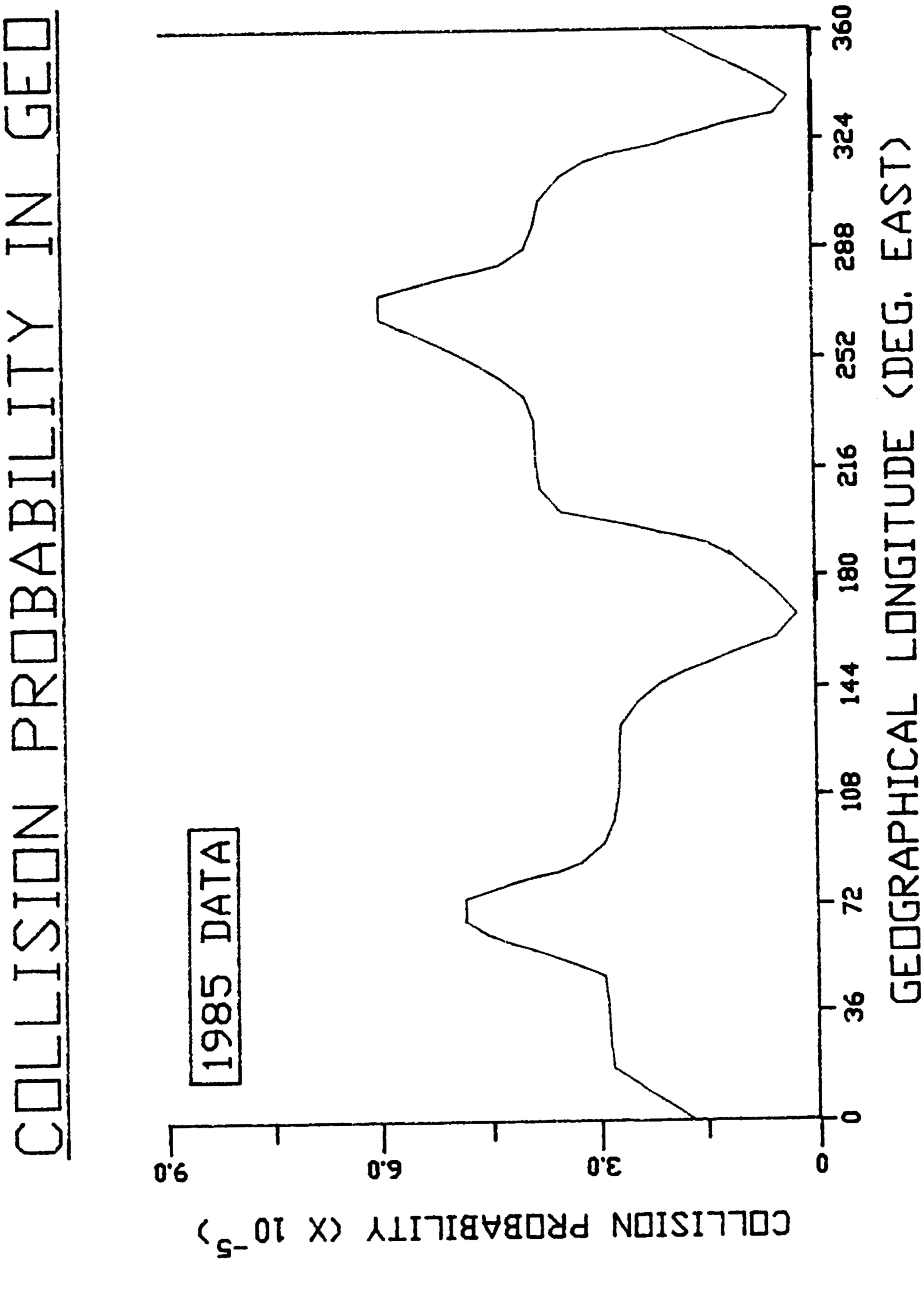

COLLISION PROBABILITY IN GEO
1985 DATA
0
36
72
108
144
180
216
252
288
324
360
GEOGRAPHICAL LONGITUDE (DEG. EAST)
0
3.0
6.0
9.0
COLLISION PROBABILITY (X 10^-5)

Figure 3.

Geosynchronous Earth Orbit (GEO) is the commercial success in space. However, intra-satellite frequency crowding and actual physical crowding at desirable locations (70 and 280 degrees longitude) are leading to a crisis at this vital resource. Figure 3 shows the distribution of satellites in GEO. In addition the possibility of collision is increasing, 0.00006 probability in 1985, 0.04 in 1992. If this problem is not addressed it may lead to a crippling of GEO operations. There are 190-200 satellites are currently in GEO and this number is expected to rise to 500 by the year 2000. These satellites, which have an average operational lifetime of ten years, are joined by spent upper stages and other large debris. Technological advances,such as better antennas, can alleviate the severity of some of these problems. Something more than these advances will be necessary to ensure the usefulness of GEO into the future. Satellite servicing is an excellent way of making the most of this limited resource. To help preserve this vital resource the station must enable satellite servicing.

The MSH can maximize the potential of the GEO if it is located to provide energy efficient access for multiple OTV missions to GEO for repair and refueling of satellites and removal of debris. A station located at any of the Earth-Moon Libration points or a high orbit outside the Earth's radiation belts satisfies the requirement of energy efficient access.

Twelve American astronauts have walked on the Moon. Since the return of Apollo 17 there has been talk of returning to the Moon. Analysis of samples returned by the Apollo astronauts have shown that the lunar surface has great potential for providing propellant and structural materials. For these and other reasons a Lunar base is part of the expansion plans for the space program and detailed studies of Lunar bases and technologies have already been done. The second generation station must complement Lunar activities to be an integral part of the space program. The station should serve the Lunar environment by providing the following: A location for the processing and distribution of Lunar materials for construction and propellant purposes, and a communications link for Earth-Moon and Moon-Moon transmissions. For these reasons the choice was narrowed to the L1 and L2 libration points. L3, L4 and L5 do not provide Lunar access as efficiently as L1 & L2. As noted previously a ship departing from an L1 or L2 station can land anywhere on the Moon, pole to pole, without significant delta-v penalty. L2 is slightly better than L1 for Lunar support activities.

There has been a great deal of talk recently about a comprehensive Mars exploration program that would involve many missions. The Soviets recently announced an elaborate Mars sample return program. The space race may begin anew with a "Race to Mars" or international cooperation may dominate a comprehensive Mars program. The latter alternative is certainly more economically attractive. Any program involving many missions beyond the Moon would benefit from a base in high Earth orbit. The libration points are co-planar with the solar system minimizing energy expense for planetary access. The station must assist in Solar system exploration and colonization by maximizing energy benefits of a high earth orbit. High earth orbit is ideal for serving cycling space ships, serving as a logistical node for refueling, resupplying and constructing spacecraft, serving as a production and distribution facility for materials from the Earth crossing asteroids and the Martian moons, providing a re-acclimatization environment for astronauts returning to Earth from the Moon and deep space missions. L1 is the better location for a base supporting planetary missions. It is more energy efficient than L2.

These three basic criteria - GEO servicing, Lunar support and planetary mission support are best served by locating the station at the L1 Earth Moon Libration point. L1 provides lower energy access to GEO than servicing from LEO. The L1 point is located only 59,000 km from the Moon (delta-v of 2.4 km/sec) so it can support lunar activities. L1 is an ideal location for starting planetary missions. Since it meets all three criteria well, L1 was chosen as the location for the station.

Crew Requirements and Activities

There are three possible levels of operation at L1: preprogrammed response or delayed response, telepresence, and physical human presence. The first option involves predetermination and definition of the entire mission and is far too rigid for productive staging and satellite servicing. The second option, telepresence - observing and controlling work in near real time using video and communications systems, offers expanded capabilities and will most certainly be employed in many space activities including operations at L1. However, it is still limited by the available level of robotics and sensor equipment. The third level is the most flexible and versatile level of operation. It will allow real time input and control.

Man will play a vital role in space at the L1 MSH. Despite the increased cost and complexity of a manned station it has greater flexibility and versatility, especially in the case of mechanical failures. Man is currently, and will continue to be, the best operator of one-of-a-kind tasks. Man's presence presents maximum advantages when unforeseen situations occur requiring immediate analysis and action - adaptation. Man improves data quality assurance by providing real time sampling and corrections for anomalies. Man can also screen data that is being sent to Earth for comprehensive analysis, this will reduce the large volume of information that will be transmitted.

Crew Size and Shifts - Initially astronauts will travel to L1 for short duration missions. At L1 they will perform satellite servicing that is to complex for automation and teleoperations.

The exact crew size and duration of stay at the completed MSH is still a big question. However the L1 MSH will begin operations with a skeleton crew (perhaps 5 astronauts). This group of astronauts will first concentrate on the final construction, integration and systems checks, then they will begin complex staging (1 or 2 people) and servicing activities (1 or 2) and materials processing (1). The number of astronauts at L1 and how they operate will be determined by the role of L1 MSH in space activities. A larger role means that more servicing, staging and materials processing will be done and additional astronauts will concentrate in these areas.

As the crew size increases, split shift operations will become the standard. The crew can be split into to two shifts each operating on twelve hour cycles. The station is designed to handle at least twenty astronauts and the life support systems can be upgraded to handle more for short periods of time. Initially, crew shifts will remain on the station for three months with a 1.5 month stagger (one shift leaving as the other enters the second half of their tour) for multiple shift crews to maintain continuity.

Crews will return to Earth for extensive physiological and psychological testing to see what artificial gravity affects are evident. If all is well based upon testing at the station and on the Earth, then the shifts will increase to six months in length with three month stagger. Nine to ten hours per day will be spent on station activities and physical exercise, and 14-15 hours per day will be spent on daily living tasks such as cooking, cleaning, eating and sleeping. Regardless of the exact crew size, several roles and duties can be discussed.

Station Commander - The chain of command is vital. There will be one person that is the senior astronaut, he or she will be called the station commander. If there is more than one duty shift, there will still be one station commander. The duties of the station commander (SC)are primarily the system maintenance of the L1 MSH. SCs will monitor the status of the station control systems (thermal, power, attitude, environment, stability, communications) analyze problems and make operational corrections. He will have direct control over decisions made on the station.

Station Operators - SO - The SO will be in charge of both the internal and external systems on the station. They can be likened to the mission specialists on the space shuttle, except upon the station these people will not be limited to one activity. Some of these disciplines include:

Communications- His/her job is to ensure that station personnel, ground based personnel and in flight astronauts all have access to the information they need. This SO will coordinate communication between different sites.

Medical Doctor - He/She will be in charge of both physical and psychological testing of the astronauts with an emphasis on determining the effects of artificial gravity on humans and the mental well being of those space bound for long periods of time. The MD will perform minor surgery, and practice general health.

Biologist - He/She will be responsible for the maintenance and health of the CELSS system. He/She will test different plants to study agricultural factors such as growth rate, strength and productivity and for study artificial gravity effects. This may well be a full time job.

Satellite Servicing Coordinator - One or two astronauts will coordinate satellite servicing by maintaining the OTV and its automated systems, finding the proper parts or fuel required from the stations stores and controlling the OTV and its systems during the flight and during the operations even if the entire operation is done using telepresence and teleoperations. They will maintain space suits for all EVA activity.

Materials Processing - One mission specialist will concentrate on the coordination and processing of non terrestrial materials including GEO refuse, lunar material and asteroid material.

Technicians will work with the automation and robotics systems, making repairs and adjustments. Some of their duties include running scientific experiments, coordinating free flyer and the information they generate, making mechanical repairs and building new S/C busses from old GEO satellites.

All station operators will be somewhat interdisciplinary. They will all act as logistics officers constantly recording what is used and what is left. They will work together on different tasks. For example the MD may assist the CELSS biologist during testing. Everyone may prepare food and help clean the station. On a station of this type missions specialists cannot be dedicated to single tasks as they are on the short duration shuttle missions. There will be a hierarchy of disciplines and roles with certain people in charge of one activity and others assigned to assist. A station operator who leads one project is likely to work under someone who was his subordinate on another task.

Justification for Artificial Gravity

Artificial gravity will be implemented on the MSH by spinning the torroidal structure. The reasons for implementing artificial gravity are:

1) Crew productivity gain over operating in microgravity;
2) Physiological problems in microgravity;
3) Operational problems in microgravity.

Productivity gains - In microgravity, approximately 30% of all waking hours must be spent exercising to maintain body conditioning, 25% are lost to human coordination problems and equipment handling problems, and 5% is wasted due to the lack of comfortable accommodations (Gardner, 1986). The purpose of the MSH is to provide a manned space station at L1. By implementing artificial gravity within the MSH, 60% of all waking hours, or 35,040 hours per year for a ten person crew, can be saved for productive mission-oriented work. Figure 4 illustrates the productivity benefits of artificial gravity.

Physiological problems - The known physiological problems caused by microgravity are many. Others remain to be discovered with longer space missions. Figure 5 lists some of the problems associated with zero gravity environments. Approximately one-half of all astronauts and cosmonauts have been found to suffer from space motion sickness, also known as space adaptation syndrome, caused by vestibular disorientation. This can lead to nausea, disorientation, vertigo, and in extreme cases vomiting. Since this malady usually lasts less than one week and no permanent effects are suffered, space motion sickness is insignificant compared to the many long-term side effects of microgravity. A high loss of bone calcium in microgravity causing an increase in calcium in other parts of the body is one such long-term effect. The microgravity environment also causes heart and skeletal muscle degredation, redistribution and loss of body fluids resulting in kidney malfunction, loss of muscle tone, and weakened cardiovascular and skeletal systems (Nicogossian, 1982). By creating an artificial gravity environment, it is believed that all of the physiological effects of the microgravity environment will be eliminated or reduced to insignificant levels.

Operational problems - Physical containment of the fluids in the CELSS system will be greatly simplified in artificial gravity. Also, physical systems such as showers, toilets, and livings spaces need no redesigning for artificial gravity. Most conventional earth based technology can be used on MSH. Everyday activities will be greatly simplified through use of artificial gravity.
In summary, a gravitational field of 0.8 g will be implemented on the MSH. It is believed that this level of gravity will eliminate the majority of microgravity problems and increase overall productivity aboard the MSH. Implementation of 0.8 g will be consistent with structure and dynamic considerations of MSH.

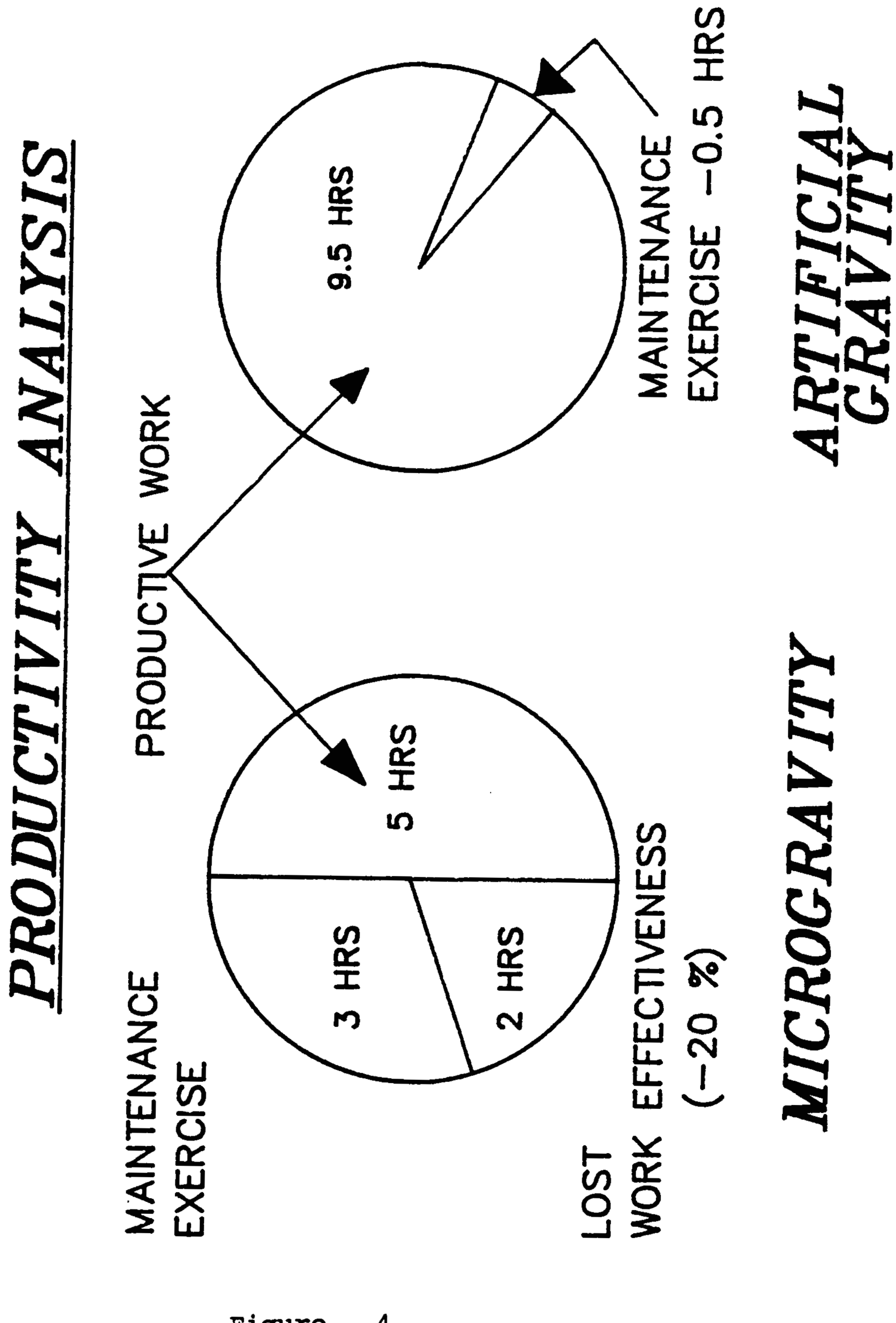

PRODUCTIVITY ANALYSIS
MAINTENANCE EXERCISE
3 HRS
2 HRS
5 HRS
PRODUCTIVE WORK
LOST WORK EFFECTIVENESS (−20 %)
MICROGRAVITY
9.5 HRS
MAINTENANCE EXERCISE −0.5 HRS
ARTIFICIAL GRAVITY

Figure 4.

PROBLEMS WITH MICROGRAVITY

PHYSIOLOGICAL

- O SPACE ADAPTATION SYNDROME
- O BONE DECALCIFICATION
- O MUSCLE ATROPHY
- O COORDINATION IMPAIRMENT
- O LOSS OF BODY FLUIDS
- O EXCESSIVE EXERCISE TIME REQUIRED

OPERATIONAL

- O CELSS MANAGEABILITY
- O MANAGEABILITY OF EVERYDAY ACTIVITIES

Figure 5.

STRUCTURES

To determine the optimum configuration and support for the Manned Space Habitat, the first step will be to determine the design criteria and then integrate them. Following this, other constraints can be applied and a final choice can be made. Once the choice for configuration has been made, some number crunching will be done and some specifications and subsystems can be developed.

The implementation of artificial gravity will require that the station be rotating. This means that the added factor of dynamic stability must be attended to in addition to the structural requirements associated with a non-spinning station. Satisfaction of the dynamic stability and the mission safety requirements are the two primary drivers in determining the optimal shape and support configuration. The Manned Space Habitat will have a torus configuration and spin about the axis perpendicular to the plane of the torus.

DESIGN CRITERIA - The list of criteria to ensure an efficient structural design must include the mission design requirements and crew safety considerations. They include: 1) Ensuring rotational stability and static integrity with respect to both shear and tensile loads. This is directly related to the safety and efficiency of the crew and mission. 2) Providing technical research facilities and accomodating satellite servicing. The satellite servicing is sure to be controled, to an extent, by telepresence or teleoperation and the onboard direction of the computers and associated crewmembers. The quick, accessability of these on-board systems to the astronauts will be mandatory throughout the mission. 3) Accomodating despun facilities, minimizing the overall station mass, and most importantly, providing a safe living environment for the entire mission by providing artificial gravity. The communications, radiation protection, power, and docking will all require despun sections due to the directional nature of these subsystems.

STABILITY - When designing a rotating structure, the first task is to determine a functional and efficient shape with stability being the predominant driver. To be stable, the spin axis of a rotating body must be coincident with the major axis of inertia. After calculating the moments of inertia about each axis, they can be applied to a stability format of equations to determine if the given configuration is within a "stability tolerance envelope." This procedure is outlined in figure A.

ACCESSIBILITY - Another key driver for configuration, is how effectively the chosen shape will enable duties to be performed inside the station. In the present case, this specifically refers to the accessibility of module(s) with respect to one another. This is directly related to how efficiently inter-module activities can be carried out during the mission.

THE OPTIONS - After examining several different shapes for the configuration and comparing their attributes, it was decided that the toroidal shape will best accomodate the design criteria. Through the stability analysis the torus satisfied all constraints better than other shapes like the "dumbell' and the triangle (tri-spoked). It also provided so-called "straight-line" access throughout the habitation modules, whereas, many other configurations would require that the crewmembers travel through the zero-g, center portion of the station.

FINAL CONFIGURATION - There are two plausible orientations of the modules on the torus system: perpendicular to the spin axis or parallel to the spin axis. Accessibility would be a more complex problem and the overall mass would increase (due to longer access tubes) in the parallel configuration, but the differential gravity gradient (created by rotation) would be minimized, and visa-versa for the perpendicular system. The key

STABILITY ANALYSIS:

Moments of Inertia by components for toroidal configuration:

TORUS TUBES:

Major Axis: $I_{zz} = 4\,[\,(1/12)\,m(3r^2 + h^2) + md^2\,] = 4.5456 \times 10^6$ kg•m^2

Minor Axis: $I_{xx} = 2\,[\,(1/2)mr^2] + 2\,[\,(1/12)m(3r^2 + h^2) + md^2\,] = 2.282 \times 10^6$ kg•m^2

$m = 15{,}600 \div 4 = 3900$ kg (ave.)
$r = 1.5$ meters
$d = 16.04$ meters
$h = 20.07$ meters

INTER MODULE ACCESS TUBES:

Major Axis: $I_{zz} = (1/12)m(3r^2 + h^2) + md^2 = 382{,}732$ kg•m^2

$I_{cc\ total} = 8 \times I_{cc} = 3{,}061{,}858$ kg•m^2

Minor Axis: $I_{xx\ total} = [\,4((1/12)m(3r^2 + h^2) + md_1{}^2)\,] + [\,4(((1/2)mr^2) + md_2{}^2\,)\,]$

$I_{BB\ total} = 1{,}532{,}088$ kg•m^2

$m = 475$ kg
$r = 2.5/2 = 1.25$ meters
$d = 30.57 - (4.5/2) = 28.32$ meters
$d_1 = 10.84$ meters
$d_2 = 26.16$ meters
$h = 6.33$ meters

CENTRAL HUB:

Major Axis: $I_{zz} = (1/2)mr^2 = 1{,}372{,}320$ kg•m^2

Minor Axis: $I_{xx\ total} = (1/12)m(3r^2 + h^2) = 1{,}321{,}493$ kg•m^2

$m = 76{,}240$ kg
$r = 6$ meters
$h = 10$ meters

Figure A

HABITATION MODULES:

Major Axis: $I_{zz\ total} = 8\ [\ (1/12)m(3r^2\ + h^2) + md_2{}^2\ ] = 149{,}451{,}845\ kg \cdot m^2$

Minor Axis: $I_{xx\ total} = 2\ [\ (1/12)m(3r^2\ + h^2)\ ] + 4\ [\ ((1/12)mr^2\ ) + md_1{}^2\ ]$
$+ 2\ [\ ((1/2)mr^2) + md_1{}^2\ ]$
$= 73{,}812{,}761\ kg \cdot m^2$

m = 22,500 kg
r = 2.25 meters
d_1 = 20.03 meters
d_2 = 28.32 meters
h = 18 meters

$I_{spin\ axis\ (zz)} = I_{major\ axis} = J = 1.5843 \times 10^8$

$I_{minor\ axis\ (xx)} = I = 7.8948 \times 10^7$

From previously mentioned equations:

$X = (\ J \div I\ ) = 1.00676$
$Y = (\ \omega_{spin} / \omega_{orbit}\ ) - 1$
where $\omega_{spin} = 0.5112$ rad/sec
and $\omega_{orbit} = 2.6 \times 10^{-6}$ rad/sec

Upon plugging X and Y into the 3 equations for stability criteria:

$F_1 = 1.6367 \times 10^{11} >>> 0$
$F_2 = 1.637 \times 10^{11} >>> 0$
$F_3 = 2.679 \times 10^{22} >>> 0$

****

Moments of inertia for configuration with modules parallel to spin axis:

(Same calculations as before except for the following:)

HABITATION MODULES:

Major Axis: $I_{cc\ total} = 8\ [\ (1/2)mr^2\ + h^2\ )\ ] = 1{,}444819 \times 10^8\ \ kg \cdot m^2$

Minor Axis: $I_{BB\ total} = 8\ [\ (1/12)m(3r^2 + h^2\ )] + 4(md_1{}^2\ ) + 2(md_2{}^2\ )$
$= 7.7294 \times 10^7\ kg \cdot m^2$

$m = 22{,}500$ kg
$r = 2.25$ meters
$d_1 = 20.032$ meters
$d_2 = 28.32$ meters

INTER MODULE ACCESS TUBES:

Major Axis: $I_{cc\ total} = 8\,[\,(1/12)m(3r^2 + h^2) + md_1^2\,] = 9.20206 \times 10^6$

Minor Axis: $I_{BB\ total} = 4[\,(3r^2 + h^2) + md_2^2\,] + 4m[\,d^2 + (3r^2 + h^2)\,]$
$= 4.7595 \times 10^6\ kg{\bullet}m^2$

where $X = 0.8672$
and $Y = 201{,}599$

$F_1 = 1.416 \times 10^{11} >>> 0$
$F_2 = 1.417 \times 10^{11} >>> 0$
$F_3 = 2.005 \times 10^{22} >>> 0$

MASS ESTIMATES FOR L1 MANNED SPACE HABITAT

HABITATION MODULES:

Shell including shielding (4900 kg /module)
Hardware (5000 kg/module)
CELSS (100,000 kg ÷ 8 modules)
Stabilization Jets (800 kg ÷ 8 modules)

TOTAL:
22,500 kg/module
(78 kg/m^3)

CENTRAL HUB:

Propellant and Hardware (600 kg)
Waste Heat Facility (13,900 kg)
30 day supply of food and water (15,040 kg)
Rotation rate stabilizers (32,000 kg)
Power storage from CELSS (2600 kg)
Power receiving antenna (50 kg)
Communication hardware (50 kg)
Storage facility (12,000 kg)

TOTAL:
76,240 kg
(78 kg/m^3)

TORUS TUBES:

2 Elevator systems (11,800 kg)
2 Ladder systems (3800 kg)

TOTAL:
15,600 kg

INTER-MODULE ACCESS TUBES:

3800 kg ÷ 8 modules @ 6.33 meters

TOTAL:
475 kg/tube

GRAND TOTAL:
275,640 kg

factor in either case becomes the stability of each set-up, and the difference is shown in the analysis in figure B. As it turns out, the toroidal configuration with the modules perpendicular to the spin axis satisfies the list of design criteria more adequately that any other choice.

ARTIFICIAL GRAVITY - In order to minimize adverse physiological effects, it is important to establish a magnitude of gravity in the habitation modules close to that magnitude found at the Earth's surface. Through a previous analysis, the magnitude of 0.8-g was selected, to be generated by placing the habitation modules 30 meters from the spin axis and rotating them at five revolutions per minute (1). The habitation modules will be in the 0.8-g range, but the magnitude quickly decreases as one travels towards the central hub. The range within the central hub alone is from 0-g to 0.15-g, form 0 to 10 meters, respectively.

STATION DESCRIPTION - Figure 6 shows the highlights of the L1 MSH structure.The station will first consist of the central hub, which will be the base of the station. It will have small despun facilities on either side to accomodate the power and communication subsystems as well as the docking facility which will be addressed later in the report. There will be four "spokes", which will contain elevator transport systems and counter-weights (two of each -- opposing). To support modularity, there will be eight habitation modules, all with the same dimensions. The habitation modules will be connected by inter-module access tubes which can take a lesson in modularity from the nodes developed for the LEO station. The "spokes" will connect to the central hub and to inter-module access tubes, connecting, in a sense, the outer ring to the inner circle.

DIMENSIONS - Dimensions of the major station components will be:

Habitation Modules
--18 meters long at a 4.5 meter diameter
--chosen as dimensions compatible with the expected size of the cargo bay of the Heavy Lift Launch Vehicle that will also provide adequate volume for crew and equipment.

Inter-module Access Tubes
--6.33 meters long at a 2.5 meter diameter
--chosen as the minimum size for support, access, and module interface.

Torus Tubes (Spokes)
--20.07 meters long at a 3 meter diameter
--chosen as best suitable size for transportation, strength of support, and interfaces.

Central Hub
--10 meters tall at a 12 meter diameter
--chosen as adequate size for storage, subsystem connection, microgravity projects, and docking interface.

MATERIAL - The material to be used for the bulk of each of these components is the Aluminum-Lithium 2090 alloy. Some of its specifications are listed in figure 4. The most recent mass estimates for the Manned Space Habitat are given in figure 3.

TETHERS - Tethers will be used to provide additional support and rigidity to the modules, as well as to secure the habitation modules to the central hub. It is important to maintain overall structural rigidity to ensure that most any moderate vibration introduced to the station will be damped out naturally. Very small vibrations should be damped by the inclusion of viscoelastic joint members. In case they are not, the attitude control system and its propulsion backup system will be required to artificially

Major Axis: $$I_{major} = I_{zz} = I_{spin\ axis} = \sum I_{components}$$

$$= J$$

Minor Axis: $$I_{minor} = I_{xx} = I_{yy} = \sum I_{components}$$

$$= I$$

Angular Velocities: ω_{spin} = spin angular velocity of the station

ω_{orbit} = orbital angular velocity of the station

Stability Parameters:

$$X = (J / I) - 1$$

$$Y = (\omega_{spin} / \omega_{orbit}) - 1$$

Stability Equations:

$$f_1(x,y) = 1 + 3x + [x + y(1+x)]^2 < 0$$

$$f_2(x,y) = [x + y(1+x)][4x + y(1+x)] < 0$$

$$f_3(x,y) = f_1^2 - 4 f_2 < 0$$

If any one of the above equations is satisfied, the rotating configuration is considered to be unstable.

Figure B

The Aluminum-Lithium 2090 alloy exhibits the following properties:

Yield Strength :	74 ksi
Tensile Strength (ultimate) :	82 ksi
Density :	0.093 lb / in^3
Temper :	T8
Elastic Modulus :	11×10^3 ksi
Cost :	~ $ 8 / lb.

damp them. These tethers will be made of Kevlar, which can have specifications as high as: 27 Msi tensile modulus and 510 Min. specific modulus.

ELEVATOR SYSTEM - The elevator system in the torus tubes will be required to transport both people and equipment between the zero-g central hub and the 0.8-g outer ring. The requirements will be: safety of the crew and station, minimum disturbance to the station's angular momentum, and minimal complexity and weight for initial assembly and maintenance. To avoid stability problems, the counter-weights must vary, according to the load placed in the elevators, the rate at which they travel through the opposing spokes. Several systems have been investigated, like the standard elevator, pneumatic lift, helical rail, belt and platform, and the electromagnetic rail. The electromagnetic rail system will be incorporated because it is very efficient, compact and light, will run without introducing the unwanted disturbances, and counter balancing can be controlled most effectively.

LESSONS FROM LEO - It will be very important to make effective use of technologies developed and investigated on the LEO station. Minimal redesign and efficient use of redesigned items such as tethers, elevators, habitation modules, and the modular interfaces can lead to significant time and monetary savings. The lessons learned at LEO will be wisdom at work on the MSH.

KEY TECHNOLOGIES - Throughout NASA's history there is evidence of of the effects of short-sighted planning. New policies are starting to straighten the planning process out. To augument this, there are a few topics related in the structures portion of this report which will need to be investigated right away in order to be developed for use in the time frame associated with the MSH. The despun sections need to be developed, although Galileo has one (and other GEO satellites do also), because they do not run without significant friction losses and they are not capable of efficient transmission of power nor communication. Structural loads on a spinning body and how to minimize the mass associated with holding them must be studied thouroughly. There are many opportunities for initial research in the thousands of amusement park rides that spin (which are not built to reduce mass, but must support loads nonetheless). The Japanese railway systems. New developments in superconductivity and the fact that a system of such large proportions must be condensed and adapted to a short distance will need to be investigated in order to provide the MSH with such a system. The ability to plan ahead and develop these and other technologies will be paramount to a successful structual design for the Manned Space Habitat.

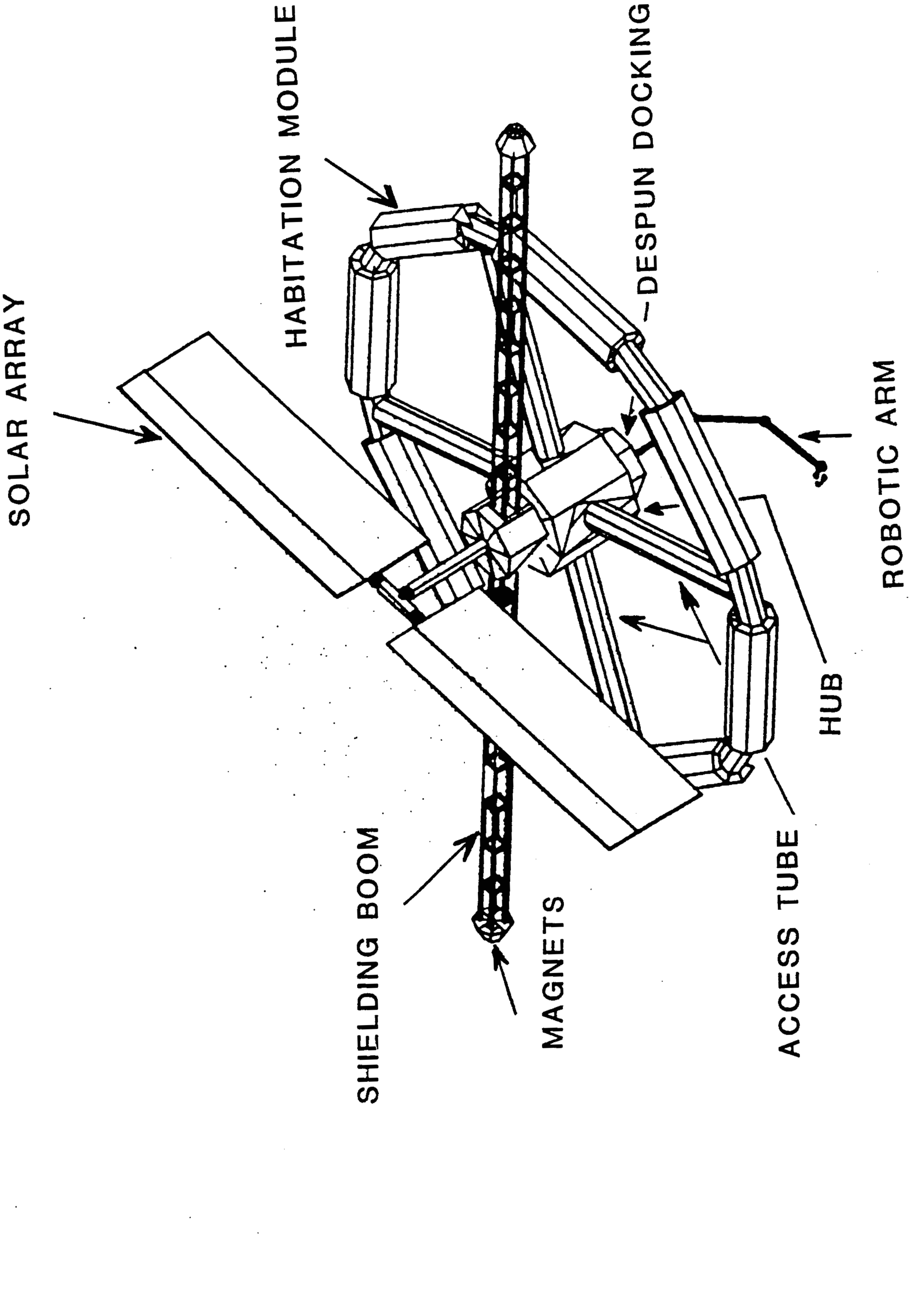

SOLAR ARRAY
HABITATION MODULE
DESPUN DOCKING
ROBOTIC ARM
HUB
ACCESS TUBE
MAGNETS
SHIELDING BOOM

Figure 6.

Station Evolution and Construction

It would be foolish to simply begin serving the L1 environment with a complex station. The pace and scope of future space program activities will determine the usefulness of various locations in the overall space program. The development scope that is followed in this report is generally based upon the timeline given in the Report of the National Commission on Space, "Pioneering The Space Frontier". Lunar and Mars operations are expected to grow significantly around 2005-2010. The L1 environment should initially be served by a small operational platform early in this growth period. Activities at this platform will demonstrate the usefulness of the L1 environment. When the L1 location proves out its potential then the platform will be expanded, first into a simple man tended platform around 2007-2010 and eventually into the a space station around 2010-2015. Growth at these times will complement growth of other space activities. Figure 7 represents this growth. This phased approach will also permit the incorporation of technological and scientific advances.

L1 Environment evolution - The L1 environment will initially be served by an automated platform. The staging of simple planetary spacecraft, fuel storage and the refueling and automated maintenance of a satellite servicing OTV will take place on this platform. Activities will be performed using teleprescence and teleoperations. As L1 becomes an increasingly important focal point for expansion into space, more complicated missions will be required of L1. The limitations of robotics and the time delay between Earth and L1 (about 1.5 sec) will create the need for the presence of man and the extended capabilities he brings. In addition to the increased possibilities man's presence permits, the humanistic reasons - the ideal of man exploring space, and the political reasons - the popular belief that man is best for the job, dictate that man work at L1. L1 will then be served by a man tended platform capable of more extensive missions. A multi port habitation module will be added to the platform. Finally as the potential of the L1 environment is fully realized the full time presence of man will be required. The free flying platform will continue to serve L1 during construction of the station. It's multi port module will evolve into a free flying docking facility for the station. Eventually the complete station will serve the space program from L1.

Launch of Station - launches in the 2005-2010 time period will use the heavy lift launch vehicle that is currently being developed by the Air Force and NASA. This vehicle will be at or nearing the end of it's operational lifetime and second generation HLLV will also be used if they are available. Several HLLVs payloads will be combined in LEO for single OTV flights to L1.

Moving the Station - Currently proposed orbital transfer vehicles will have a maximum capacity of 10,000 kg. The reliability and technical feasibility of these OTVs will lay the groundwork for the next generation of OTV's. Second generation OTV's with a 20-40,000 kg capacity will be used to transfer the components of the station to L1. Both electric powered and chemically powered OTV's are likely to be developed and both would be used for an L1 station. Many components of the station will not require fast transfer to L1 from LEO so electrically powered vehicles will be of great use.

Construction - Construction techniques learned from the assembly of the LEO station will assist in constructing the L1 MSH. Manipulator arms such as the Shuttle arm and the proposed arms for LEO station will play a large role in the construction and operations of the L1 station. An advanced MMU similar to the deep sea ALVIN may be necessary. The general construction sequence is: assemble central hub and erect power and communications tower, attach the four access tubes, attach intermodule

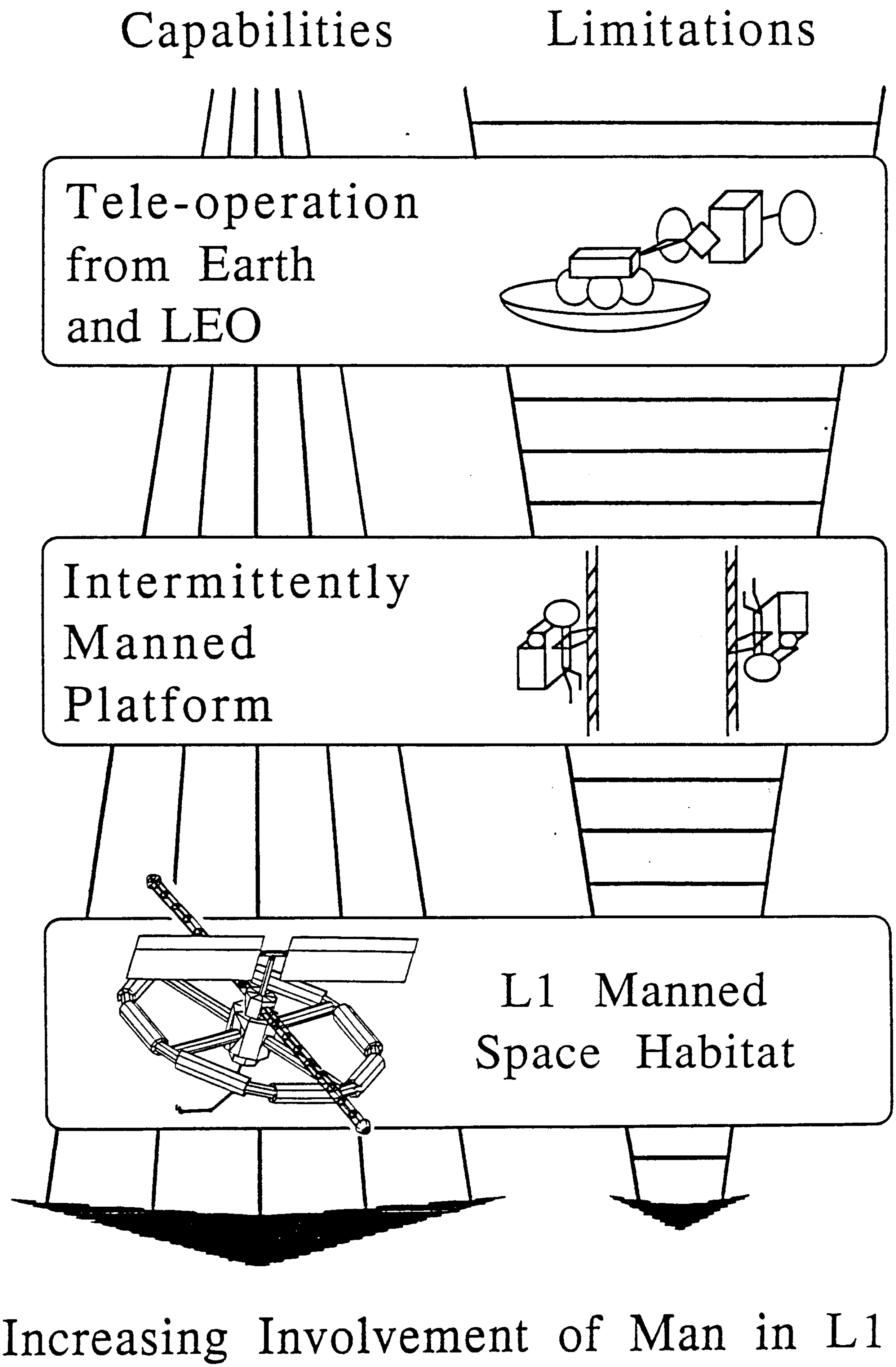

Capabilities
Limitations
Tele-operation from Earth and LEO
Intermittently Manned Platform
L1 Manned Space Habitat
Increasing Involvement of Man in L1

Figure 7.

nodes the four access tubes, attach the eight modules, the remaining intermodule nodes and the tethers. Science free-flyers will be deployed during the initial construction phases. The construction is projectde to take place over a two year period.

STATION SUBSYSTEMS

The following sections give an overview of the subsystems of the L1 MSH.

POWER SUBSYSTEM

Power Generation - The L1 station may be very power intensive. The power system is the cornerstone of the station. As in any environment, the more that is done on the station the more power required. The factors that dictated the choice of the power system in relative order of importance were:

1. Reliability - This is the most important factor. L1 cannot be reached from Earth in less than a day, assuming a vehicle would be ready. Therefore a comparison of failure modes is of prime importance and the power systems that are not susceptible to catastrophic failures are most desirable.
2. Weight and efficiency - For each system a maximum efficiency and likely weight was predicted and compared.
3. Safety - The chosen system should fail safe, it should be repairable with minimum risk to the repairman.
4. Expandability - The system should have the potential to grow with ease. Major redesign should not be required to accommodate higher demands or incorporate improved technology.

The three candidates for power generation were photovoltaics, solar dynamics, and nuclear. It was assumed that all three systems would provide power of the desired quality and the systems were sized to provide 250kw at the end of a ten year life.

The power generation system chosen for the L1 MSH was 100% photovoltaic. The system was chosen for the following reasons.

* The entire system is solid state so there is minimal possibility of catastrophic failure. (Most catastrophic failures are mechanical failures). If failures occur due to array degradation or broken wires the result is a small power loss (The exact amount of the loss depends on how many cells you have wired in each series setup, and this will depend upon the desired voltage levels.) Such failures are relatively simple to repair.
* The system is anticipated to have a 3% degradation per year resulting in an End of Life (EOL) value of 0.7 Beginning of Life (BOL). Therfore in order to provide 250 kw at the end of a ten year lifetime therefore the system was sized to provide 375 kw at the beginning of life. The load estimates for this sizing follow on the next page.
* The system will be mounted on station to eliminate large (50%) transmission losses of a microwave transmission system. This system will have slip ring or fluid contact losses and noise, but they will be minimal. Possible transmission fluids are Mercury and Gallium (good conductivity). Multiple rings will be used to ensure that some power will be available in the event of the failure of the primary ring.
* The system will be split into two equal size arrays each producing 50% of the power, each with independent steering systems.
* Multi-band gap (3 layer) solar cells (400nm-2000nm range) will be used. These cells have projected efficiency of at least 45%.
* 70% of the array area will incorporate Cassagranian concentrators (see figure 8) to focus sunlight a factor of 500 times upon the multiband gap cells. This yields a 5%

CASSAGRAINIAN CONCENTRATOR ELEMENT

SUBASSEMBLY MOUNTING

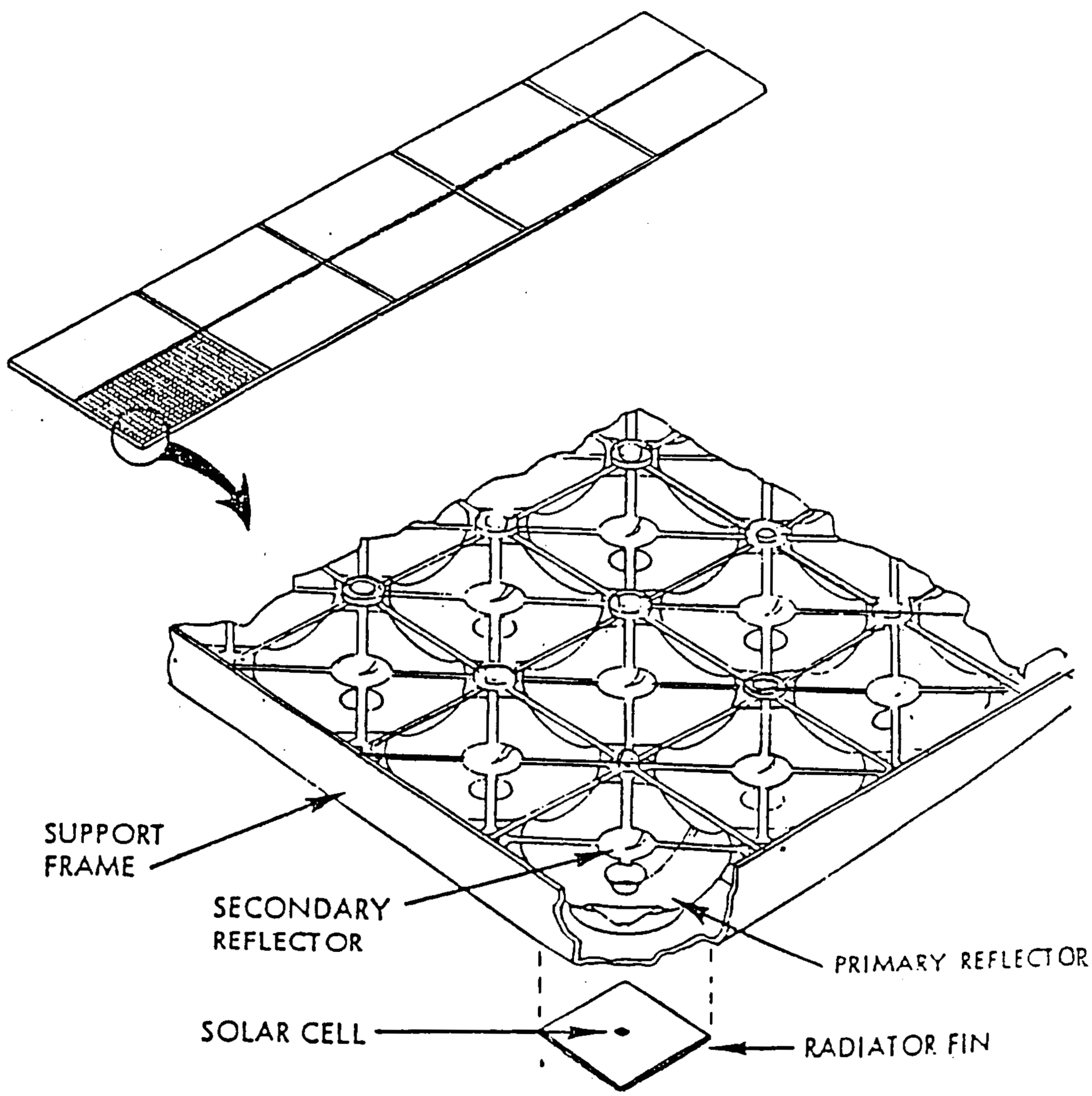


Figure 8.

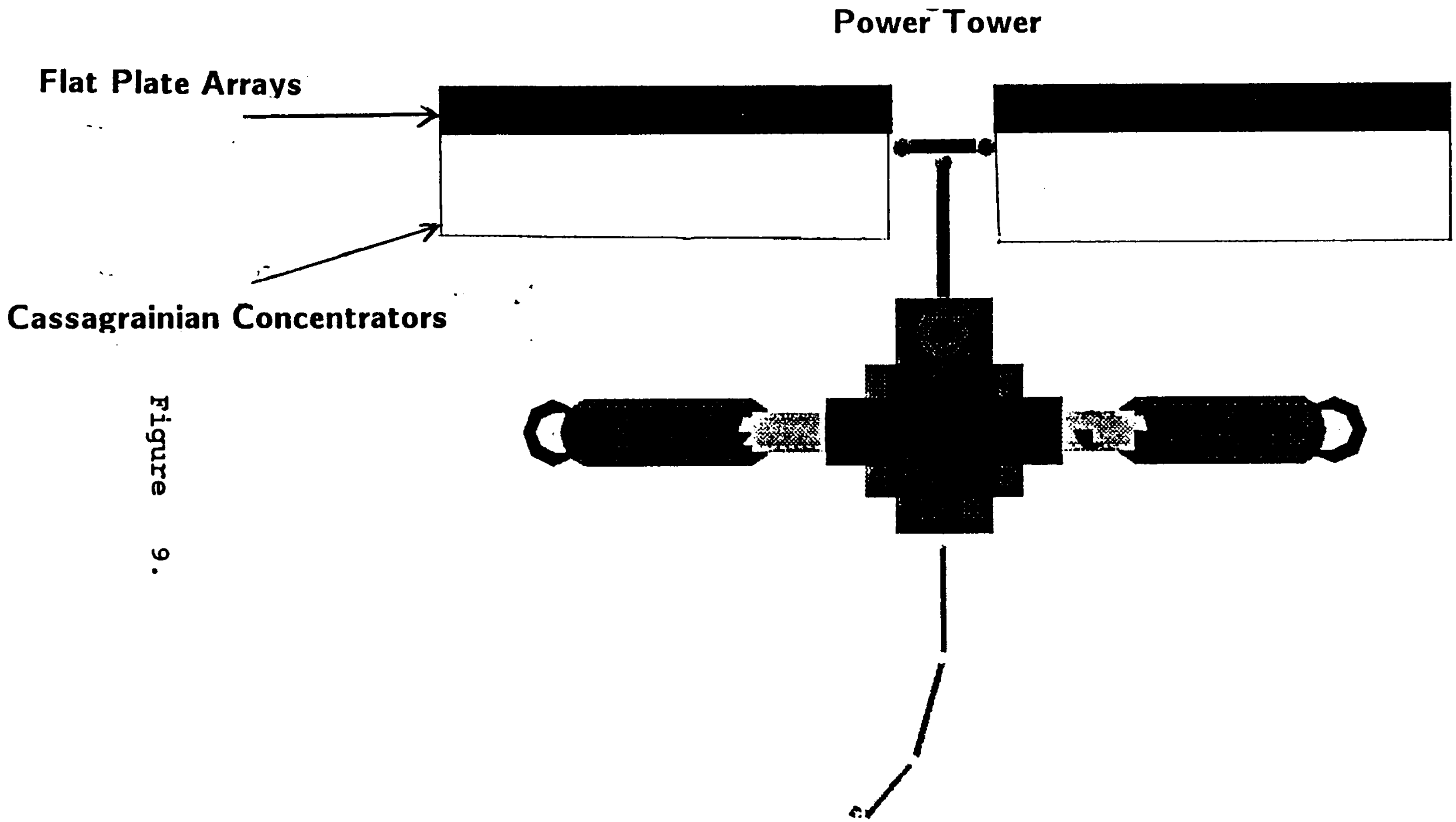

Power Tower
Flat Plate Arrays
Cassagrainian Concentrators

Figure 9.

efficiency increase. These concentrators have pointing requirements of 0.2 - 0.7 degrees. Concentrators can be adjusted during off peak time so that the cells last longer. Excess heat will be rejected through radiator plates on back of cells.

* 30% of the array area will be flat plate collectors that can provide immediate power without precision pointing requirements. This power can be utilized during the construction of the station and will provide power if the pointing system fails. Figure 9 shows the relative collector areas.
* Thermal radiators such as fins, louvers and heat pipes will be mounted upon the back of the solar substrate and the cell backs may be alluminized to enhance power and remove heat.

The following power generation options were rejected. These systems are currently undergoing development and it is likely that major advances will be made, hence these systems will be reconsidered from time to time.

A Nuclear system was rejected due to high radiation levels, the large amount of dead weight required for shielding and the possibility of catastrophic mechanical failure. Current space based system studies indicate that the entire reactor core must replaced every 10 years. Although the shielding may be used again. Benefits included no duty cycle, lack of pointing requirements and lower mass than photovoltaic system greater than 50kW. Maintenance may be difficult in space.

A Solar Dynamic system was rejected to complete dependence on pointing requirements, possibility of catastrophic mechanical failure, and current exclusion from LEO station. Benefits included lack of degradation over time, only working fluid needs to be replaced (not entire system). If solar dynamic technologies make large enough advances then a combination of solar dynamic and photovoltaic would be utilized.

Power Uses - The LEO station will have 50 -75 Kw initial power capability and will be expanded to around 200 kw by the turn of the century. For the man tended platform that will originally serve L1 this level may be sufficient, but as the L1 station becomes a reality more power will be required up to a level of 250 kw.

There are two classifications of loads in manned space stations, housekeeping loads and user loads. User loads include instruments and scientific equipment, EVA equipment and exterior lighting - all loads that are dedicated to serving specific missions or mission groups. Housekeeping loads are those dedicated to operating the facility. (Woodcock, 1986)

To estimate power loads for the L1 MSH the power budget for the LEO station (Woodcock, 1986) was used as a baseline. A thirty percent increase was assumed for module loads since L1 modules are about thirty percent larger resulting in a total of 10 kw per module for housekeeping loads which include fans, pumps, lights, eating equipment data and instrument electronics, internal communications and power management systems. Similar increases were made to estimate other loads as well. A design value of 250 Kw was chosen the system was designed to generate 150% of this value (or 375Kw) at beginning of life. A summary of the loads is shown in the following table.

MSH Power Use Budget

Housekeeping Loads -		
	8 Modules * 10 Kw	80 kw
	Heaters, External Lights,	24 kw
	Radiation Shielding	10 kw
	Reserve, Power Tools, Additional CELSS & Electric Propulsion - Stationkeeping	24 kw
User Loads -		
	Materials Processing Lab	30 kw
	Life Sciences Lab	15 kw
	OTV Housekeeping and Lights	10 kw
	Science Payloads - on station	10 kw
	Science Payloads - off station	10 kw
	External Communications	3 kw
	CELSS	34 kw
	TOTAL	250 kw

Power Management System - The power management system must accommodate changes in technology and demand. Some type of series bus regulator will be used to control the power, this will insure that batteries and critical systems are adequately supplied. Power will be transmitted through optical fibers and coaxial cable. LEO studies concentrated on 28v to 440v. High station power levels dictate higher distribution voltages however flight proven hardware exists for 28v systems and does not exist for 150v or higher levels which are more efficient. Off the shelf systems at 120VAC do exist, using this power level would reduce the cost of equipment. The willingness of NASA to fly different voltage levels on LEO will determine the levels to be used on L1 station. The primary distribution candidates for LEO are 20KHz (smaller transformers) for A.C., 400 Hz AC. Aircraft use 400HZ but no space hardware exists in this operational range. This is not considered a major problem. Either rotating machinery or solid state inverters will be used for power conversion. 20 KHz test systems have never been flown but have been tested and are considered extremely attractive.

Power Storage - The power storage system must provide minimal operational power for communication, attitude control, vital experiments and life support for both solar duty cycle (10.5 hrs.) and possible emergencies. In the event of an eclipse the system must provide approximately 40 kw of continuous power.

Both Regenerative fuel cells and Nickel Hydrogen Batteries are likely candidates storage system candidates. Both technologies are currently making significant strides and a choice between them cannot be made at this time. The final system will probably include both systems. Since a choice is not possible at this time we plan for both options. Ni-H batteries are more reliable than Fuel Cells and have high efficiency (70-80% eff.) and can handle depth of discharge up to 80%. Oxygen-Hydrogen regenerative fuel cells will also assist in water purification and provide a backup source of O2 is essential.

THERMAL MANAGEMENT SYSTEM

The thermal management system of the L1 MSH is responsible for heat transfer - the acquisition, transport and rejection of waste heat. The goal is to maintain the station temperature, for both man and machine, within prescribed limits. The internal heat inputs are the heat generated by the crew (135 Watts per person) and heat generated by the electrical equipment and wiring - total of 210 - 260 Kw of waste heat. External inputs are the sun's energy (the solar flux is 1390 Watts/m2), the Earth's radiant energy and the heat from the power generation system. Nearly 100% of the power that is generated by the arrays is ultimately converted into waste heat during transmission or use. The solar arrays will reject heat using an independent system. Precise thermal control work cannot be done until the operational limits of specific components have been defined, however we can discuss the overall system and the thermal control methods to be used.

Currently all space thermal control systems operate in a microgravity environment. The thermal control system of the L1 MSH will have the advantage of operating in gravity environment (although the station will operate for a small time before spin up). This fact will simplify the design of the system. Heat rejection during the initial operations will be implemented using thermal coatings since the input during this phase of operation will be primarily external. These coatings will not last for the entire station lifetime due to degradation but will the primary system will be implemented before this occurs and the heat rejection requirements are lower during the initial operations.

System Components - Both active (fluid) and passive systems will be used. In the habitation modules two thermal loops are used (Woodcock, 1986) one inside, using water, and one outside using freon or ammonia and employing radiators. Heat exchangers and evaporative cold plates will collect heat and transport it between thermal loops. Heat pipe arrays will be used for large area cooling. Gravity will simplify the use of single phase transport systems. Single phase systems are simpler than two phase systems. However two phase systems require lower circulation rates for high power system, this lowers the fluid volume requirements and the size of the circulating system but can complicate design. Regardless of which system is chosen the system will employ a multiple valve system. This will provide for better control of breaks, leakage and isolation of heat exchange problems. It will also reduce the required fluid reservoir size.

Rejection of heat will be completed by heat pipes, radiator fins and perhaps liquid droplet radiators. Liquid droplet radiators may not work well in the rotating, variable gravity environment of the station, however as they are space proven they will be given serious consideration. Both heat pipes and radiator fins do not degrade severely in a micrometeoroid environment as do completely pumped fluid systems. The interaction of the micrometeroid shielding and the heat rejection system will need to be studied.

CONTROL SYSTEMS

The MSH is an extremely complicated endeavor. The independently complex subsystems on the MSH are quite interrelated. The control mechanisms for these systems thus must not only monitor the functioning of each, but must also respond such that the systems are combined and coordinated for optimum operation. For example, the attitude control of the station obviously affects the docking systems. In addition, the use of the power system fuel cells for water purification (explained in the life support section of this paper) links the power system to the life support system. This sort of interconnection occurs elsewhere, throughout the MSH. The end result is the control for those systems must be linked as well for smooth, efficient, and safe operation of the MSH.

Requirements. In order for such efficient and safe operation to occur, we must have mechanisms that are highly fault tolerant, flexible, and transparent to technology. Fault tolerance will be the highest priority, for it most severely affects safety and mission performance. Control and operation of the most important and critical MSH systems must be maintained, even if at a reduced level, in the face of any single component or subsystem failure. This is known as fail-operational performance. For the less critical systems, some effort and cost can be saved by allowing operation of the system to cease, but in a way that does not endanger the station or the crew. This is fail-safe performance [Bekey]. Both of the above require methods of automatic failure detection, isolation, and recovery. In addition, the control systems must be flexible, to allow adding, modifying and even deleting mission and station operation systems without disturbing the overall framework. This flexibility is necessary to allow the station to fulfill its objective of efficiently supporting other varied space endeavors, and has the added benefit of allowing relatively easy recovery from original system design and implementation errors. Finally, the control hardware must be transparent to technology advances. Technology transparency will allow the station to incorporate expected advances in computing and communications technology through simple upgrading, keeping the station useful and competitive throughout its lifespan. These specifications will produce a versatile and multipurpose control system that will handle station operation well into the future.

Hierarchy. The best way to deal with the previously mentioned interconnection of the MSH control mechanisms is to place those mechanisms into a functional hierarchy [Albus, *et al*]. The various control functions (such as power systems control, radiation shielding control, life support control, station attitude control, and so on) will often make competing demands on the station resources. Some method of ensuring cooperation instead of harmful competition between the control functions must be used. A hierarchy of authority is necessary for such decision-making. See figure 10 for an example. The ultimate authority will be a system monitor function (implemented with both computer and human elements). The control functions will be placed under this master control function, and will be further broken up into their less general sub-functions, sub-sub-functions, and so on. Such a structured programming approach allows us to break the control problem into parts for which design and implementation is relatively straightforward, and that can then be integrated with ease.

The hardware, however, is not organized into a hierarchy. Doing so would adversely affect our fault tolerance, our flexibility, and our transparency to technology. The backups necessary to provide fail operational performance in such a system would be prohibitively expensive. Also, reconfiguring the system for new tasks would be expensive as well, most likely requiring the replacement of whole sections of the system hardware. Finally, upgrading the hardware, including backups, would be expensive and would cause interruptions in control operations. There is a better solution.

Network. While the necessity of a single authority for decision making requires a functional hierarchy for the control systems, there is no reason that this hierarchy must extend to the hardware as well. The control hardware will instead be organized into a network of communications links between standard nodes. The network will be flat, with all nodes of equal status. Standard input/output (I/O) modules will form these nodes. The I/O modules will be used to attach function specific sensors and actuators (such as a star scanner package or an attitude control thruster) to the

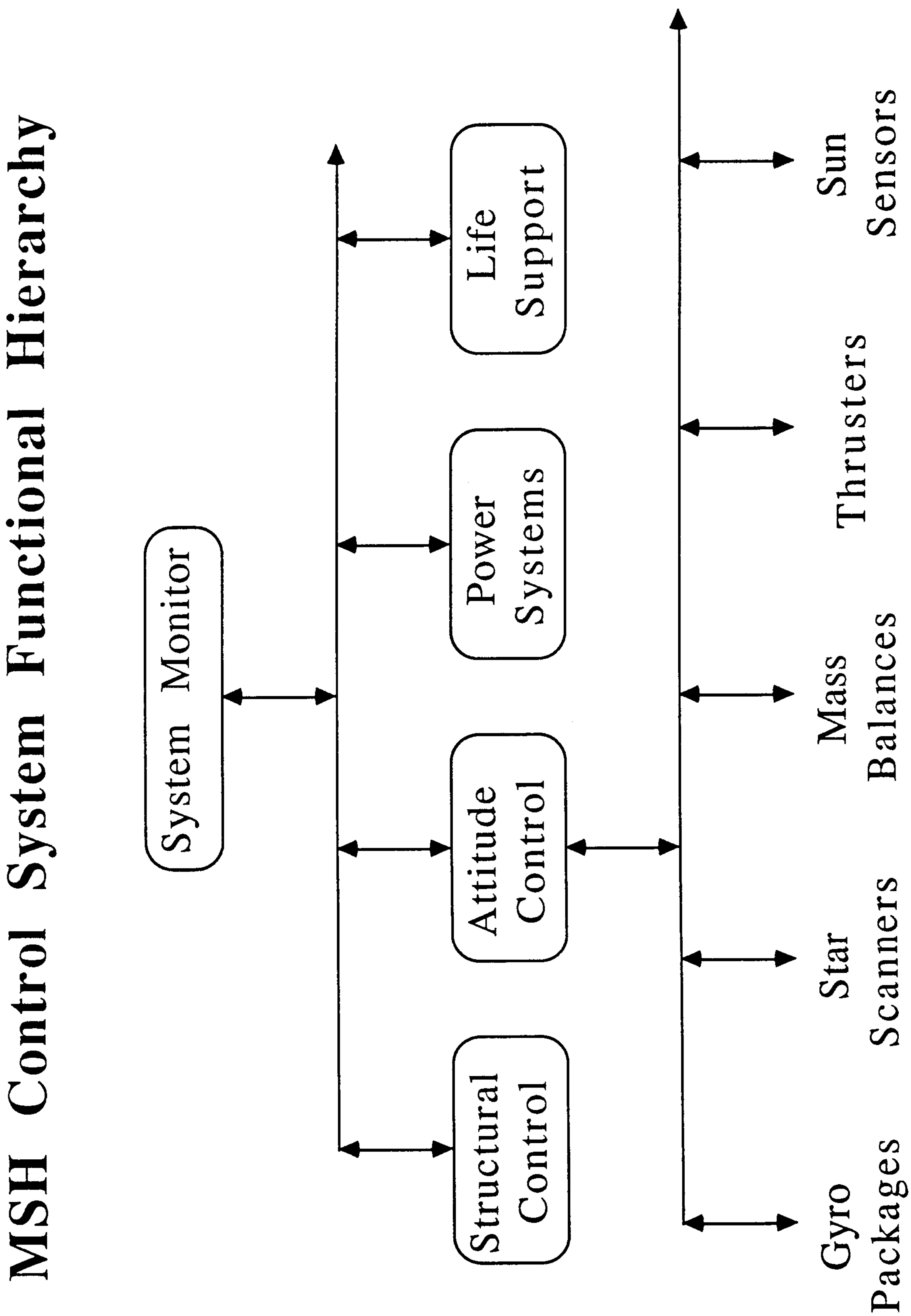

MSH Control System Functional Hierarchy
System Monitor
Structural Control
Attitude Control
Power Systems
Life Support
Gyro Packages
Star Scanners
Mass Balances
Thrusters
Sun Sensors

Figure 10.

Control System Network Example

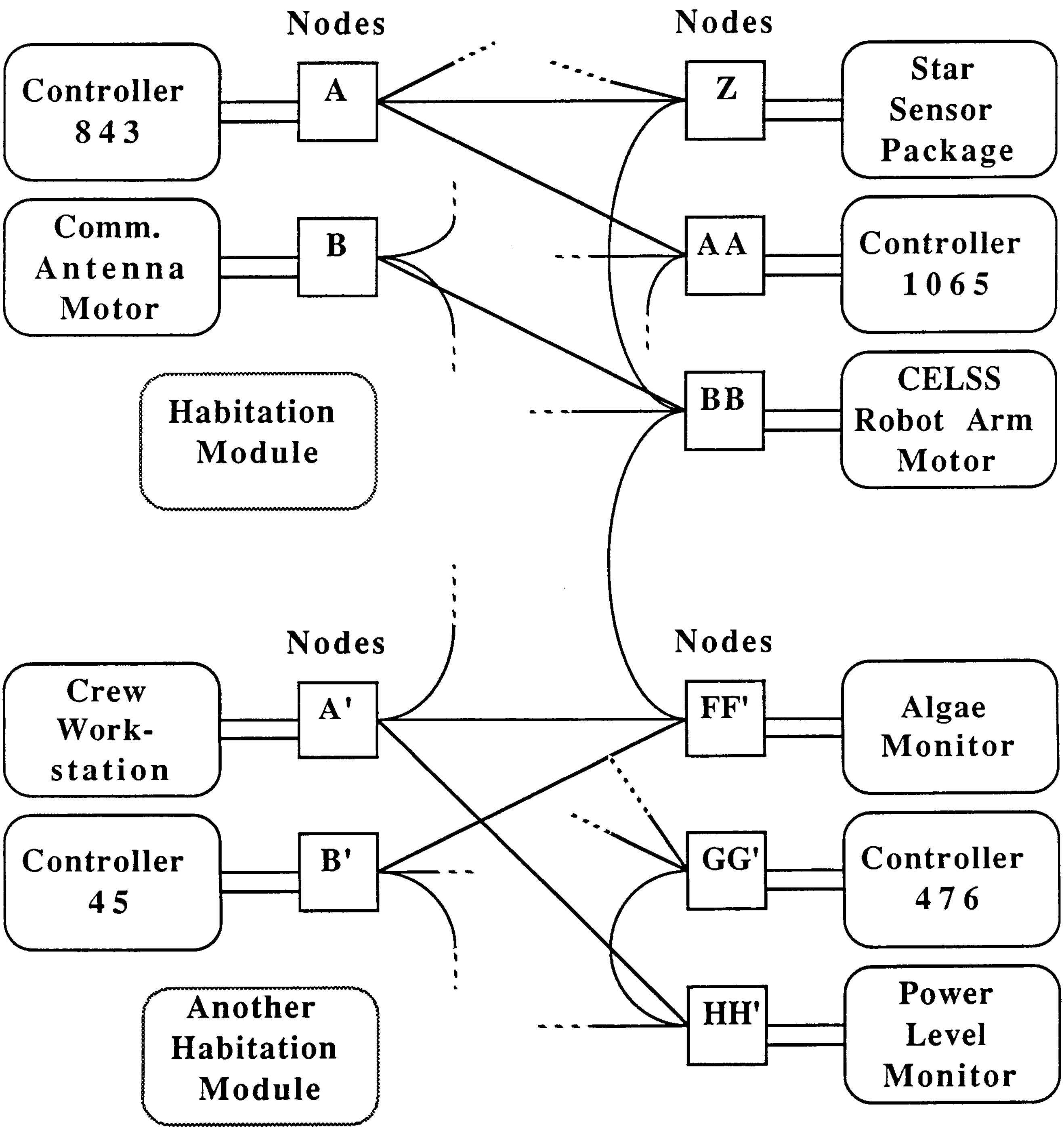


Figure 11.

network. The standardization of controllers and I/O modules is used to simplify operation of the system as well as simplify maintenance and upgrading.

The nodes will be connected so that no single failure in a node or link will break the network into two or more parts. The network will have a multiply connected topology within each habitation module and the hub, with additional connections between the modules. See figure 11 for one possible arrangement. This arrangement requires a much more complex protocol than other alternatives, such as a token passing ring (where only the node that currently has the bit string "token" is allowed to transmit). However, it also is easier to modify and can grow to handle a larger number of nodes [Woodcock]. This is essential if we are to satisfy our requirement of flexibility.

Operation. The hierarchy of control functions will then be programmed on this network. The crew will be an integral part of the system, communicating with the rest through general and specific purpose workstations. The control functions will be handled in software by a single controller or a group of controllers acting in concert. These functions will communicate with others over the network based on efficient routing and task assignment algorithms. Each level in functional hierarchy will issue directives to levels below and receive information and requests for resources in return.

Resource Envelopes. Those requests for resources provide a key to the efficient operation of the interconnected functions. As in a human organization, if all decisions must be made at the top level the chief executive is always overworked and the rest of the organization essentially sits idle. In order to reduce the workload on the higher level functions, and the communications traffic on the network, each function will have a defined space within which it is authorized to operate. This space will be represented as a resource envelope [Hansen]. Each function will have a set of resources at its disposal, and, unlike past representations of resource envelopes, a set that it must provide. The envelopes will be dynamic, changing as the constraints and objectives of overall system operation change. The resources included electrical power, crew time, station attitude, station configuration, atmospheric gasses, and so on. Any actions outside the envelope will require approval from a higher level function before they can be attempted. In other words, the outputs and possible inputs to the function are specified, and the transformation between the two is handled without bothering higher levels.

Performance. Most importantly, the integrated system above supports fail-operational performance. With the highly interconnected nodes, no single communications line or node failure need cause any system to break down completely. If a controller fails, another performing a nonessential duty can automatically take its place, or the failed controller's tasks can be parcelled out as a minor load increase on many other controllers. If a function specific piece of hardware fails, a minor interruption in the data flow is unavoidable unless a backup is on-line at the time. For critical, important systems this will undoubtedly be the case. If a communications line fails, its traffic will simply be re-routed. This ability to automatically reconfigure the system "on the fly" thus provides fail-operational performance.

As mentioned earlier, the effort and cost of setting up a fail-operational performance mode for a system will not always be necessary. For those cases, a fail-safe mode is easy to implement using similar controller reprogramming, or by locating programs to command a safe failure at distributed locations among the controllers.

Flexibility. The standard controllers, and the resultant ease of reprogramming the systems, also efficiently support our next most important requirement - flexibility. Any control node can be reprogrammed for new or changed operations functions to support new or changed subsystems. For example, resource boundaries can and will be changed as operations priorities change. In addition, the majority of the hardware is not function specific. This flexibility is thus inherent in the design - the only hardware, if any, that needs to be changed to support a new function are the special purpose sensors and actuators.

Technology Transparency. The modularity and standardization of the network components supports technology transparency. The communications lines, I/O nodes, and controllers can all be replaced piece by piece with little or no impact on the overall framework of the system. (This also helps with repairs.) Admittedly, upgrading the function specific sensors and actuators will require the use of backups if continuous operation throughout the switchover is desired, but the standard I/O interface to the network makes that replacement a simple matter.

The Control Functions on the MSH are divided into critical, semi-critical, and non-critical groups. The lists below are by no means exhaustive. Also, it is realized that many failures under just the wrong conditions in supposedly non- or semi- critical functions could result in catastrophe. Failure mode analysis will likely continue throughout the lifetime of the MSH, as it will in the case of the LEO station [CalSpace]. Regardless, it is still useful to have an idea of what systems will require fail-operational performance, which may require it, and which can most likely get by with fail-safe performance. Critical system are those where failures will generally be life threatening in a short time. Examples include:

a. Life support
b. Power systems
c. Radiation shielding

Semi-critical systems are those where failures are not generally life threatening in the short term. Examples of these include:

a. Attitude control
b. Structural control

Non-critical functions are those where failures are not generally life threatening:

a. Station keeping
b. Manufacturing
c. Satellite Servicing
d. Communications

The lists above by no means indicate the level of importance of the system in the operation of the MSH. The lists are instead solely based on the expected threat to crew safety in the event of a failure in the system.

What follows is the expected implementation of some of the major functions above, in order of increasing definition and detail. First comes the power control function. Power control is critical because the operation of so many other systems depends upon the availability of power. Next is the radiation shielding control. Finally we have our most detailed section of all, the attitude control function.

Power Control is essential to operation of the habitat. The power control function will first and foremost allocate power according to the output requirements of its resource envelope, which will be based on a priority list. It will also control the power generation and conditioning on board the MSH. Finally, it will maintain the power storage system, interacting with the life support water purification system as mentioned earlier.

Radiation Shielding Control. The Radiation Shielding Control Function is perhaps the most important from a crew health standpoint. Its primary responsibility is the operation of the solar radiation shielding system. This system, mentioned earlier, uses superconducting magnets mounted on a boom extended from the station to deflect solar flare radiation from the station. The shielding control function will be guaranteed of precise pointing of the boom by the attitude control function, and power levels to the magnets by the power control function. (Note that the boom pointing portion of the attitude control thus becomes a critical function.) The shielding control system will monitor the radiation levels in and around the MSH, as well as use predictions from space and ground based observatories, and adjust the protection system accordingly to reduce the exposure of the crew.

Attitude Control. Finally, we have the attitude control function. Attitude control can be broken up into two parts, attitude determination and attitude correction. Knowledge of the station attitude is composed of knowledge of the location of the center of gravity (CG), the spin rate, and the direction of the spin vector. If the attitude determined is not the one desired, the attitude control system must correct the attitude, possibly just waiting for passive systems to do their job or using thrusters and momentum wheels. For this function, unlike the previous ones, empirical knowledge of common attitude control implementations allowed the design to concentrate mainly on the sensors and actuators necessary.

Before starting on the sensors, however, it is helpful to learn how both internal and external forces affect the station attitude. The location of the center of gravity is affected by live loads (such as crew members moving around) and thermal and vibrational deflections of the station structure, all internal forces. The spin vector will be affected three ways by external torques placed on the habitat (solar radiation pressure, docking forces, etc.). The first result of these external torques is coning, rotation for which a geometrical axis is not parallel to the principal inertial axis (coordinate system misalignment). Nutation, rotational motion for which the instantaneous rotation axis is not aligned with a principal axis, is the second. Third, the external torques also affect the spin vector by causing precession, a change in direction of the angular momentum vector. Finally, the spin rate of the MSH will change with another example of internal forces, mass motion in and out of the hub.

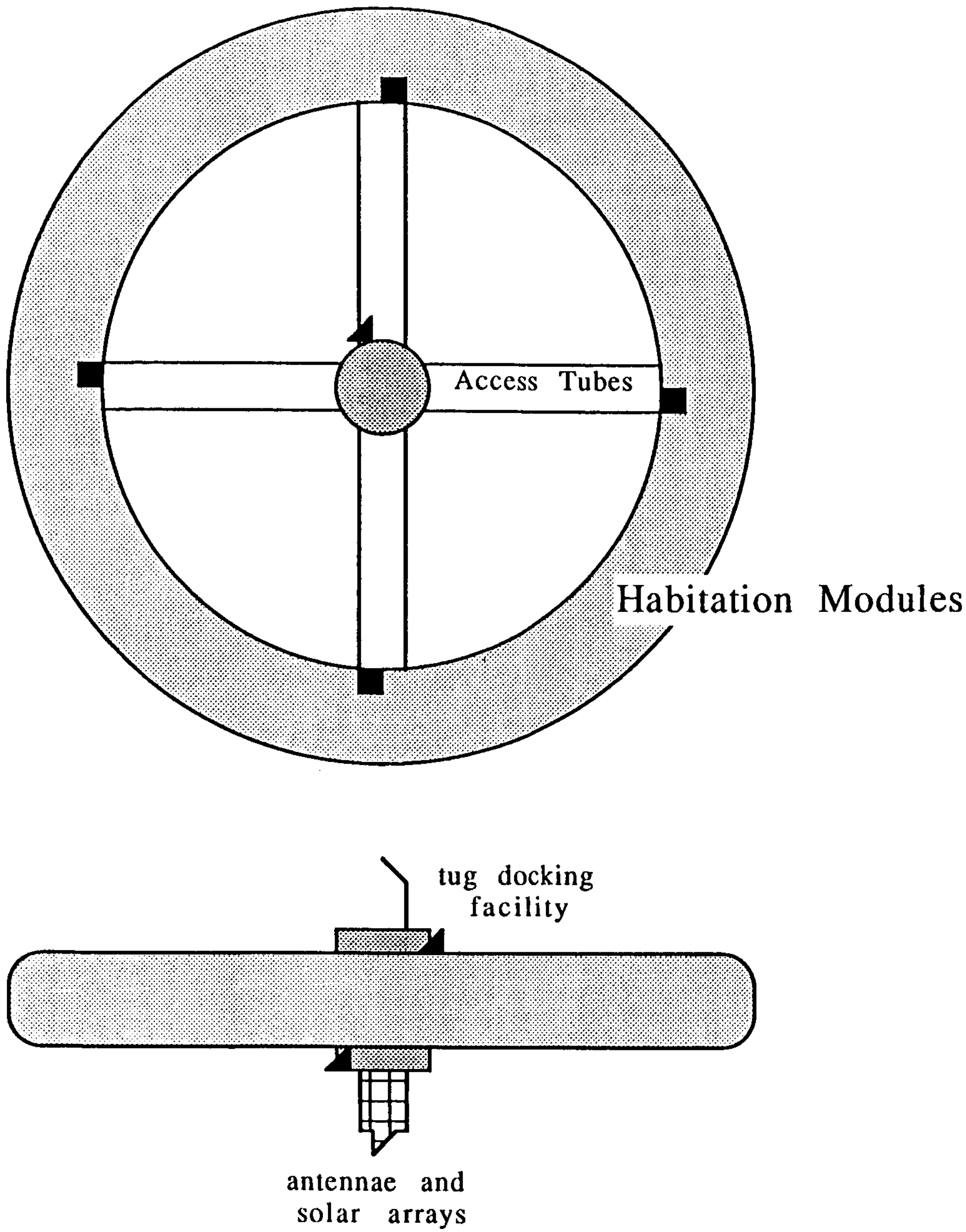
Attitude Sensors. The MSH attitude will be determined by both inertial attitude systems and external attitude references. The inertial systems will provide knowledge about the attitude and the structural vibration of the MSH. The external attitude references will be used to calibrate and check the inertial systems.

The inertial attitude sensors will be composed of rate and rate-integrating gyroscope packages distributed around the station. Rate gyros use a rotating wheel to establish an angular momentum vector. Rotation of the spacecraft about an axis transverse to this vector produces a torque that provides a measure of angular rate. A rate-integrating gyro also uses a rotating wheel, but directly measures the rotational displacement of the spacecraft with respect to the wheel's axis. [Fallon] Rate gyros are too imprecise to be sole source of inertial attitude knowledge, but they have a desirable large bandwidth, covering both low and high frequency motion. Rate integrating gyros, on the other hand, are too insensitive to low frequency motion to be sole source, but are more accurate than rate gyros. A number of packages containing one gyro of each type will thus be used to attain a high accuracy and large bandwidth. Proper blending of signals from the distributed gyro packages can suppress the contribution of structural vibration and expansion to the movement sensed by individual gyro packages.

The external attitude references will be provided by star scanners and sun sensors. Star scanners will be used as the main attitude reference for the station. Star scanners are lighter and less expensive than the next best alternative, star trackers. Also, star scanners are ideal for a rotating station since they must be rotating themselves. Star trackers on the other hand can not track stars moving faster than 0.5 to 1.0 degrees per second. Star scanners are thus the best choice for the main station's external attitude reference. The pointing of the solar arrays and radiation protection system, however, will be aided by the use of sun sensors. Sun sensors are photocells and associated circuitry used to determine the direction of a bright object. They can give accuracies of 0.1 arc second by using systems of offset photocells. See figure 12 for the location of the scanners and gyro packages on the main station. (The sun sensors will be located on solar arrays, not shown in the figure.) All this is actually possible with current technology. Future refinements, such as deep space asteroidal positioning and more advanced laser gyros, will make more accurate determination of the MSH attitude possible.

Attitude Correction. Attitude correction for the MSH will be handled by a combination of mass transfer, momentum wheel, and thruster systems. Momentum wheels, sharing the station's axis of rotation, and radial mass transfer mechanisms will be used to control the spin rate. As a mass moves outward from the station hub, the spin rate slows. As the mass moves inward, the reverse happens. This phenomenon is well known to watchers of spinning ice skaters. In order to correct for spin rate changes caused by crew and supply movement in and out of the hub, the system will move fluid or solid masses the other way. When these masses have all moved as far as they can, *ie.*, the system is saturated, the station propulsion system will be used to correct the spin rate as the masses are moved back. Momentum wheels located at the station's hub can also be used for this purpose. The spin of the station can effectively be stored and withdrawn from the

Attitude Determination Hardware



■ Gyro (rate & rate-integ.) Package

◢ Star Scanner Package

Figure 12.

momentum wheels by slowing them down and speeding them up. Fluid and solid mass transfer will also be used to correct mass imbalances around the circumference of the station. These imbalances are not expected to be more than 400 kg, close to the weight of five crew members. Solid masses will be moved when large corrections are necessary, while fluid transfer (mainly of the station water supply) will generally be used to make the finer adjustments. Partially filled ring dampers will be used to control the nutation induced by external torques [King, Woolley]. In general however, the external torques will be counteracted by the use of electromagnetic thrusters. These will take longer to produce large motions, but will require less reaction mass than the traditional gas jet or hydrazine thrusters. The use of momentum wheels, mass transfer systems, and thrusters will allow the MSH attitude control system to do its job.

In summary, the attitude control, power, and all the other functions are implemented in a functional hierarchy. This hierarchy is used to ensure that the functions cooperate instead of compete. This hierarchy does not extend to the hardware. The hardware is instead organized into a flat network of standardized controllers, I/O modules, and communications lines. Use of this sort of network enables technology transparency, flexibility, and most importantly, operation of systems after individual component failure. The functions programmed on the network were divided into critical, semi-critical, and non-critical areas to help determine which would require such fail-operational performance and which could settle for fail-safe performance. Representative functions were then examined in greater detail, finishing off with attitude control.

PROPULSION

A versatile and very reliable propulsion system will be an integral part of the Manned Space Habitat (MSH). Although low thrust orbit keeping will be the primary function, there are numerous other tasks that will require a broad range of thrusts. Subsequently, many tradeoff's will need to be made in order to develop a propulsion system that will be effective, minimize cost, and maximize the safety of the crew.

As mentioned above, orbit keeping will be the primary function of the system. The L1 point is gravitationally stable within the Earth-Moon system, but is dynamically unstable because the angular velocity of the L1 orbit must match that of the Moon, which requires holding the orbit velocity down. This means that small perturbations can lead to a rapid build-up of velocity which can quickly take the station out of its orbit. The propulsion system will be continually called upon to restore the station to its orbit.

Other duties of the system will include: spin-up and spin-down for both conventional and emergency situations, collision avoidance with respect to errant spacecraft or space debris, backup to the attitude control system, any precise maneuvering required, desaturation, moment cancellations, and extra-vehicular activity (EVA) safety. Each of these functions will place a unique demand on the propulsion system in the form of thrust level required and duration of thrusting.

SYSTEM REQUIREMENTS - Due to the large range of thrusts required and the small ranges available from various propulsion devices, it is convenient to divide the thrust level into three categories: low, moderate, and high thrust. A breakdown of the propulsion system functions and their specific thrust range is given in Table-1.

TABLE-1

Low(0.01 to 10lbf)	Moderate(10 to 100lbf)	High(>100lbf)
Orbit Keeping	Spin-up	Immediate Collision Avoidance
Precise Maneuvering	Spin-down	Emergency Spin-down
Desaturation	Docking Momentum Cancellation	Desaturation
Moment Cancellations	Collision Avoidance	Docking Momentum Cancellation
EVA Safety	Desaturation	

OPTIONS - With the requirements defined, it is now necessary to investigate the various options for completing the tasks. There are several devices available, both exotic and conventional. Some do not use any propellants (solar sails), some do not burn the propellant (electric), but all have unique characteristics. Due to complexity, thrust requirements, and the level of technology believed to be available only chemical and electric systems, such as electromagnetic arcjets and ion devices, will be investigated any further.

Chemical systems include cold gas thrusters, liquid monopropellant thrusters, and bipropellant thrusters. Liquid propellant thrusters are excluded from further investigation because the propellant are either unstable, hard to handle, or are incompatible with station subsystems.

COLD GAS THRUSTERS - Cold gas blowdown thrusters expand gas through a nozzle into the vacuum of space to produce thrust. They are very simple, reliable, and cost effective. They produce a small quality impulse bit at a very low specific impulse (usually less than 280s). A quality thrust is one that is accurate, repeatable, and will satisfy thrust performance requirements. Also, many of the propellant gases could be readily produced on the station (in conjuction with CELSS), but the propellant requirements are still very, very large and their lifetime is usually limited (on the order of 3000hr).

BIPROPELLANT SYSTEMS - The conventional bipropellant thruster also requires large amounts of propellant and has a low specific impulse (<480s). They will satisfy the high and larger moderate thrust requirements very well. The technology is advanced and the systems are fairly safe. They are complex, and therefore very expensive to operate and maintain. Bipropellant thrusters use an oxidizer/fuel combination to raise the chamber temperature, then in a similar manner to cold gas thrusters, the gas is expanded through a nozzle,producing a very high exhaust velocity.

Electrothermal/electromagnetic thrusters include many devices that are completely new technologies and are very promising for the future. Many of these systems were excluded because they are so relatively unknown. The thrusters considered are resistojets, arcjets, and pulsed electrothermal thrusters (PETs).

RESISTOJETS - Resistojets produce thrust by using electric resistance heaters to heat propellant as it flows into the chamber. The resistance heaters tend to wear out quickly creating a lifetime/maintenance problem. Resistojets do produce quality, low and moderate thrust, and are a proven technology. They are characterized by good specific impulse (up to 800s)and modest power requirements (approximately one half kilowatt per kilogram of propellant).

ARCJETS - Arcjets require about fifteen times as much power as the resistojets, but can achieve an excellent specific impulses (up to 2000s). By converting electrical energy to thermal energy through heat discharged from an arc to a propellant, then expanding the gas through a nozzle, the arcjet produces thrust. The current technologies are based on developments made in the late 1960's and have just recently begun advancing again. Thrust provided by arcjets is of a very high quality and covers the low range of thrusting, so the outlook is very positive.

PET's - Pulsed Electrothermal Thrusters (PET's) are very similar to arcjets in the fact that they use arcs to heat propellant, but instead of a constant arc a pulsed arc is used thereby alieviating the loss of ionizational energy. Their specific impulses are about the same as arcjets, but their efficiencies are higher. The technology is very new and it is not known whether the PET's will perform well over a long duration of time, and the power requirement is high (8 kw/kg).

ION PROPULSION - Electric propulsion is carried out by ion thrusters, which again produce a high quality low level thrust. Thrust is generated by electrostatically accelerating ions extracted from an electron bombardment ionization chamber. Ion devices are characterized by very high specific impulses (up to 20000s), high power draw (about 15 kw/kg), versatility, a contaminating exhaust plume (which can be avoided by using an inert gas), and a long lifetime (approx. 15000hr).

SELECTION CRTERIA - Realizing that there are a number of factors to take into

consideration when choosing a propulsion system, tradeoff's must be made in order to optimize the systems' ability to carry out its tasks in the most efficient, cost-effective, and safe manner. Criteria to measure this are: 1) Thrust performance. The device should carry out operations in one or more of the aforementioned thrust categories at a high quality level. 2) Specific impulse. This is a measure of how efficiently fuel is used, which translates directly into large mass savings when it is high, but also could mean more massive power supplies are necessary, therefore optimization is very important here. 3) Cost. 4) Simplicity and reliability. 5) Lifetime. Replacment needs to be avoided because it is time consuming and difficult in a space suit. 6) Power draw. An effective way to measure this is to determine how much power it takes to use one kilogram of fuel. 7) Propellant requirements. The less and the easier to store the better. 8) Pollution. Minimizing this is important because the contaimination poses a threat to not only the
station components and any EVA, but also to technologies like astronomy which count on an undisturbed environment. 9) Technology level. This is telling of the amount of research needed to make these systems operational on the MSH. Table-2 lists some of the data which shows where important tradeoff's can be easily recognized.

FINAL RECCOMENDATIONS - After reviewing the data it was decided that the orbit keeping task would be carried out by groups of ion propulsion devices called clusters. They have specific impulses of about an order of magnitude higher than all of the other devices. They produce quality low thrust, which is ideal for the task, and have the longest expected lifetime. The technology is expected to be advanced by the time of implementation, and the system is not overly complex. Ion thrusters do draw a lot of power, and require the power to be extensively conditioned, but lower thrust levels should minimize this drawback. Contamination can be avoided by using one of the inert gases, such as Argon or Xenon, as mentioned above. The moderate, on the low side, thrusts and some of the higher, low thrusts will be handled by resistojets. These are an already proven technology, and are only moderately complex. Resistojets have a relatively good specific impulse while not placing an undo strain on the power source. The resistive elements do tend to wear out, but they probably won't receive extended use like the ion devices, so they should last for a justifiable amount of time. Also, the propellant requirement is fairly high, but again this should not pose too much of a problem in their limited use. Hydrogen or Carbon-dioxide can be used as propellants, and they can be produced on the MSH by CELSS. Since the bipropellant thruster is the only alternative to carry out the higher moderate to high thrusts, the MSH will also employ its services. They would generally be used in emergency situations so an argument for the oxygen/hydrogen fuel combination can be made. These gases would be readily available, coming directly from CELSS. This is the ideal scenario for the "bugout" situation.

CONCLUSION - Once again, the various computer-monitored and implemented functions (station keeping, spin-up, collision avoidance, ...), and their subsequent thrust ranges will be accomodated by Argon or Xenon ion propulsion clusters, Hydrogen or Carbon-dioxide resistojets, and Oxygen/Hydrogen bipropellant thrusters.

COMMUNICATIONS SUBSYSTEM

The L1 MSH will need to communicate with platforms and the station in LEO orbit, satellites and platforms in GEO, the Earth, the Moon, Deep Space, and in the local environment. The system must provide voice channels, command and telemetry channels. Communications will include entertainment, personal, scientific and command information including secret information combinations of which may take place simultaneously. To accomplish this the L1 station will need several types of antennas. The overall system must be reliable, provide high signal quality (some bandwidths in excess of 50 GHz) and have high overall efficiency. High data transmission rates will be required to relay scientific information. A rate of 500Mbps is to be used. This will provide a signal reliability of at least 95%. Command information for teleoperations in GEO and on the Moon will pass through the station communication system and the time delays must be accounted for.

The station will use high gain, medium gain and omni-directional low gain antennas. These antennas will require a large field of view and will be mounted upon the power tower. Two primary types of system are under consideration, Millimeter Wave (MMW) and Optical.

MMW systems are well developed, have better lifetimes and involve lower cost and risk than optical systems. These systems are greatly affected by solar activity and suffer from atmospheric attenuation. MMW systems offer 98% accuracy, 60% efficiency, and 15 year system lifetimes. A large (21 m diameter) conical radio frequency antenna composed of eight triangular plates will be used. Each panel will have 36 - 10 cm dia. primary elements with phased array feeds and independent gimbal systems. Each panel will also have 78 - 5 cm diameter auxiliary elements. (Conley, 1986) This reflector is currently located on the free flying docking facility. If a set of smaller reflectors is used in place of the larger one then the system can be transferred back to the L1 MSH.

A Laser (optical) communications systems will also be used. It will serve as the primary system for most satellite to station and space to space local transmissions. These systems can also be used for security sensitive information. They are nearly 100% accurate and currently have 25% efficiency, and 10 year system lifetimes. Efficiencies are expected to rise to 50% in the near future. This system is light and compact, up to 15 times lighter than MMW, and it requires 80% less power for space to space communication than MMW does. A hoop of laser telescopes will provide the laser communication system.

SHIELDING

Introduction - Shielding the MSH crew from micrometeoroids and radiation are two necessary functions of the station. Micrometeoroids ranging from a few microns to a few kilometers in diameter can cause significant damage to the hull and subsystems of the MSH. It is estimated that a collision with a beach sand size particle (1-2 mm diameter) may occur two to three times per year. Collisions with smaller particles travelling at velocities as great as 170,000 km/sec may occur even more frequently, while a collision with a larger particle is less probable. Radiation shielding is necessary to maintain crew member's health onboard the MSH. Without proper radiation shielding, radiation sickness and more acute radiation related maladies can rend crew members inoperable.

First, the micrometeoroid bumper shielding will be examined after which the proposed method of radiation shielding will be discussed.

Micrometeoroid Bumper Shielding - Micrometeoroid shielding is necessary to prevent damage from particles as small as one micron diameter. It is not known how much natural debris is located at the first libration point, but currently L1 is relatively free of man-made debris. Still, micron particles travelling at 170,000 km/sec which may collide with MSH have as much momentum as a Volkswagen Bug travelling at 80 MPH. This is delivered to only a micron area of the shield. While only two or three impacts may occur per year, this could translate to significant damage in the 30 year life of the station.

Micrometeoroid bumper shielding on the MSH will be similar to that used on the Giotto spacecraft which rendezvoued with comet Halley in 1986, to that used on Skylab, and to that proposed for the LEO station. The outer layer (see figure 13) of the micrometeoroid shielding will be a 1 mm thick layer of titanium, which has an exceptionally high strength to weight ratio. This layer will be used to vaporize particles causing them to spread out and impact with 7 cm thick foam coated with kevlar aramid fiber composite. The kevlar aramid fiber, a 10 micron thick synthetic fiber, has an outstanding strength to weight ratio. It is five to six times stronger than steel per unit mass. Between the kevlar coated foam and the titanium layer will be a 23 cm gap held by titanium alloy spacers. The gap will allow the impacting particles to spread out and dissipate their energy over a large area. The foam layer will be attached directly to the hull of the MSH.

The bumper shielding must cover critical portions of the MSH as well as any freeflyers to protect them from micrometeoroid impact. The shielding system must be well integrated with the thermal control because the foam layer will tend to act as a blanket around the station.

Radiation Shielding - Another hostile environmental condition that the MSH must contend with is radiation. Radiation is the transfer of energy by particles or electomagnetic waves. This energy is measured in units of Roentgen Absorbed Dose, or RADs, equal to the deposition of 100 ergs of energy per gram of exposed matter. Different forms of radiation, however, damage biological tissues in different ways. The dose in RADs is thus corrected by a radiation quality factor (Q, also known as Relative Biological Effectiveness - RBE). The Q for electromagnetic forms is 1, while the Q for protons is dependent on their energy (Woodcock, 1986). The Q for cosmic rays is greater than 10. This correction (RAD * Q) yields units given the name Roentgen Effective Man, or REM for short.

Solar radiation consisting of photons, for which Q equals 10, will be the primary source of radiation on the MSH. On average, the sun emits an ordinary (OR) radiation

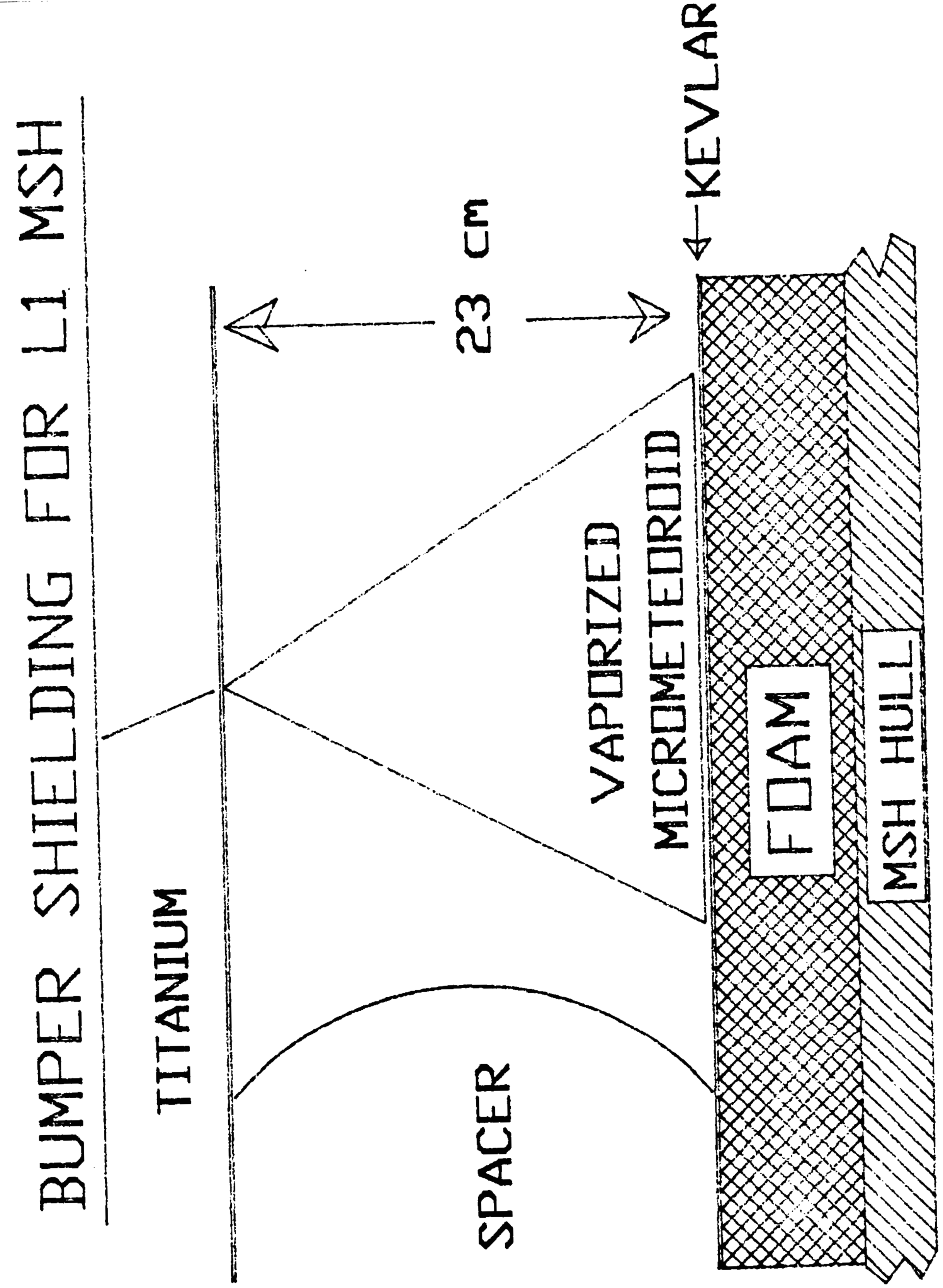

BUMPER SHIELDING FOR L1 MSH
TITANIUM
SPACER
23 cm
KEVLAR
VAPORIZED
MICROMETEOROID
FOAM
MSH HULL

Figure 13.

flux on the order of 100 REM / year. An anomalously large (AL) event, a solar flare lasting less that a week, produces radiation levels in the range of 5300 REM / event. AL flares, however, rarely occur even once per year.
Cosmic radiation, which is not aligned in a specific direction as the sun's radiation, produces on 4 REM / year and will be partially blocked by the bulk of the modules and equipment. However, at the same time this will cause Bremmstrahlung. When the cosmic rays impact a metal surface, they in turn cause emission of X-rays which are also hazardous to human health. It is thought that the Bremmstrahlung effect caused by cosmic radiation will not be severe enough to be a health hazard on MSH due to the low incidence and the limited time per mission spent by the crew.

Protection from radiation is necessary at all times since a lethal dose of radiation may be as low as 200 REM. The United States Federal Government has set radiation standards for radiation workers and persons not normally working with radiation. For radiation workers, the limit is 5.0 REM / year, while for non-radiation workers the standard is 0.5 REM / year. On the MSH it may be acceptable for the astonauts to be exposed to greater doses (3 REM / 3 months) since the typical mission duration will be only 3 months.

Radiation protection from the intense proton radiation will be accomplished with dual superconducting magnets on 100 meter collapsible trusses (see figures 14 & 14A). The magnets will deflect the protons at an angle of 18 degrees, producing a cone of reduced radiation in which the station will be placed. The shielding arms will be deployed continuously to deflect both AL and OR radiation. The shielding design proposed will reduce solar radiation to the acceptable level of 3 REM / 3 month mission.

Of several designs considered, the superconducting magnet design is currently the best solution for radiation shielding due to its simplicity, low power use, and light wight (4500 kg total). The power to operate the superconducting magnet will be approximately 10 kW including crygenic support for the magnets. The use of currently evolving superconducting materials, however, can reduce this power requirement by two orders of magnitude since cooling would not be needed.

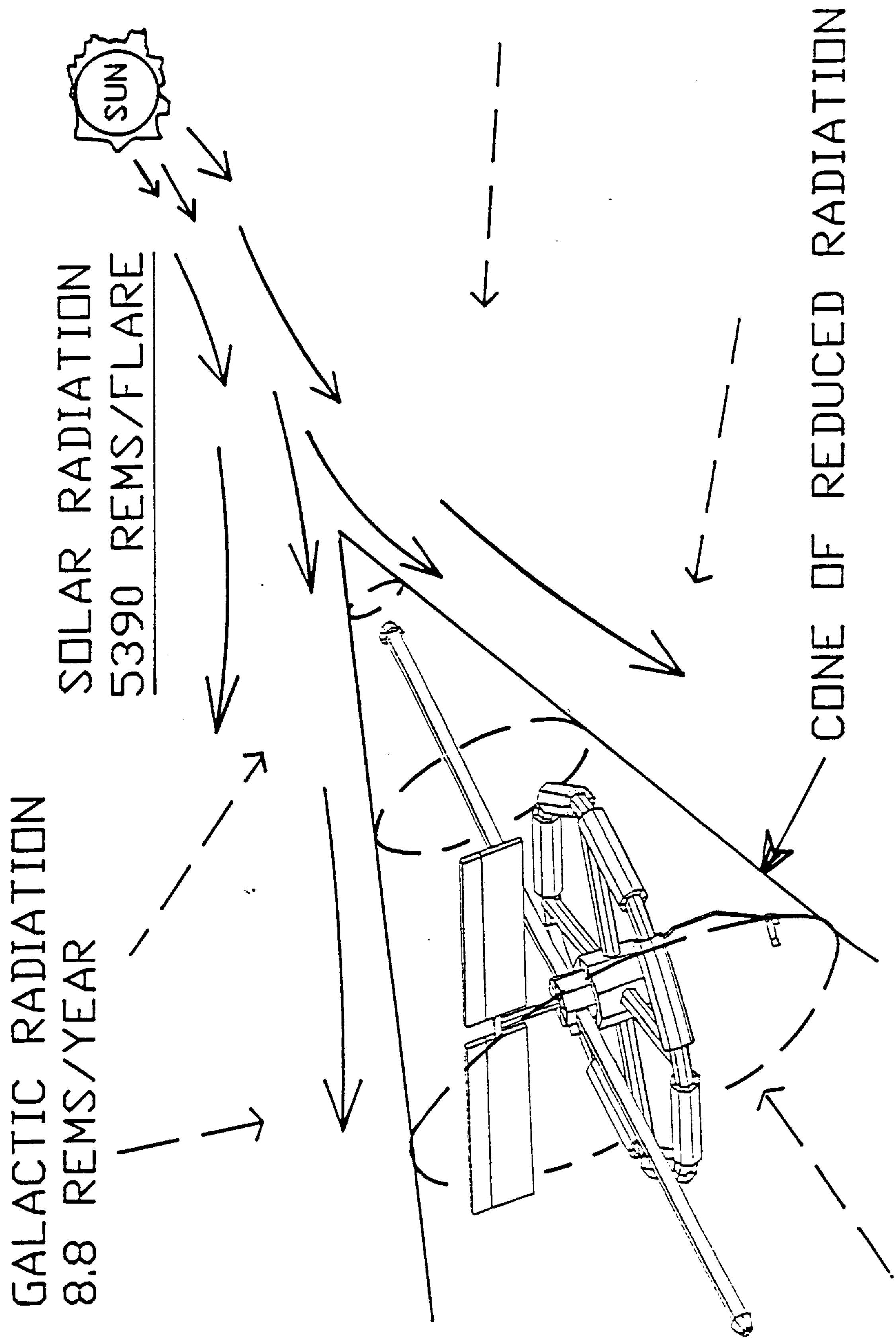

GALACTIC RADIATION
8.8 REMS/YEAR
SOLAR RADIATION
5390 REMS/FLARE
SUN
CONE OF REDUCED RADIATION

Figure 14.

ATTACHED MAGNETIC SHIELDING

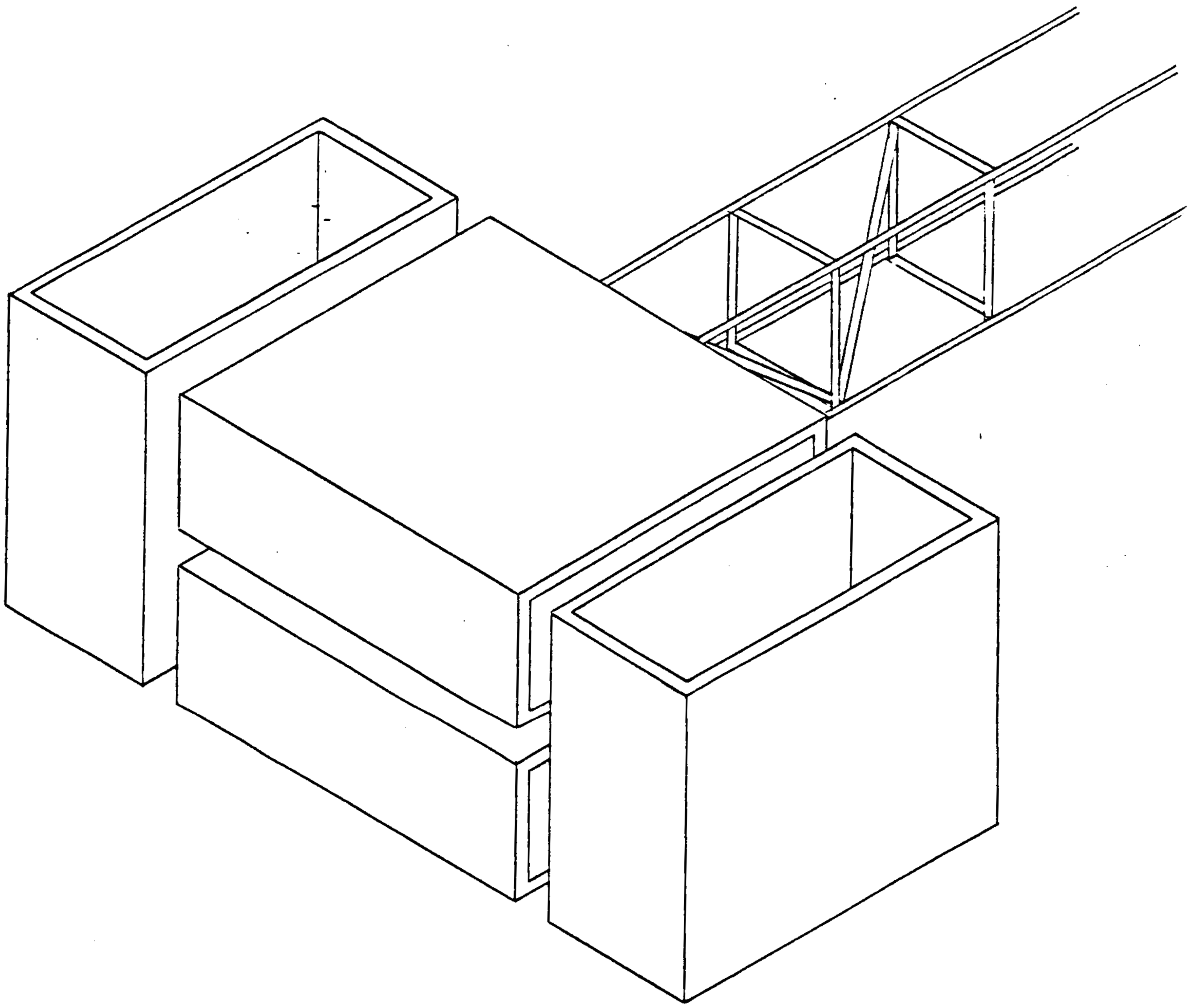


Figure 14A

DOCKING

Docking at the Manned Space Habitat must be done safely, and therefore with minimal disturbances introduced to the station. It must also enable transfer of people and goods from the various types of spacecraft to the station. Other onboard systems must not be inhibited by this process either.

REQUIREMENTS - Since the MSH will be rotating, the docking procedure will be inherently more complex. It will require the spin-up of the docking spacecraft to the exact angular momentum of the station. Obviously, this situation could lead to very significant disturbances introduced to the station. There is also concern for the well-being of the station environment, it is very important to minimize the amount of pollution from propellant exhaust. A safe place to handle the explosive and toxic propellant involved with satellite servicing is needed as well. In accordance with these problems a remote free-flyer, small shuttle, and a spin-up/spin-down robotic arm at the station have been theorized to accomodate docking.

PROCEDURE - The remote free-flyer will be outfitted with a multi-portal docking node, somewhat like the Soviet station Mir has. It will have five varieties of interfaces which should be adequate to accept the major types of spacecraft trying to dock there. By having this facility the chance of a catastrophic docking blunder is avoided, because large ships will not have to perform complex, minute maneuvers to dock at a spinning station. At this free-flyer there will be a quarantine and decontamination facility for astronauts, and a large hanger to perform large-scale satellite repair. (see figure 15) By having the spaceships dock away from the station an environment can be maitained that is almost free from their pollution. It will also be able to store dangerous propellants that should not be stored near the station.

From this free-flyer there will be a small shuttle, with about the same power and maneuverability, but a little bigger in size, as a Manned Maneuvering Unit, to carry personnel and equipment to the space station. (see figure 16) At this point a despun robotic arm, which may very well be the same arm that was used to construct the station, will capture the shuttle vehicle. This arm will be about 30 meters long and will have at least two degrees of freedom more than the shuttle arm. The arm will slowly bring the shuttle into the station where it will be attached to an interface on the despun section. Through momentum conservation devices in the central hub the shuttle will slowly be spun-up and the transfer of people and goods can be made.

OTHER FREE-FLYERS - In addition to the docking free-flyer it is expected that there will be at least two others for research activities. They will be a look-up/look-down technologies facility and a materials processing facility in zero-g and a variable gravity facility. Probably many others will be developed and/or requested through the duration of the mission, but for now there are just three members of the free-flyer "swarm".

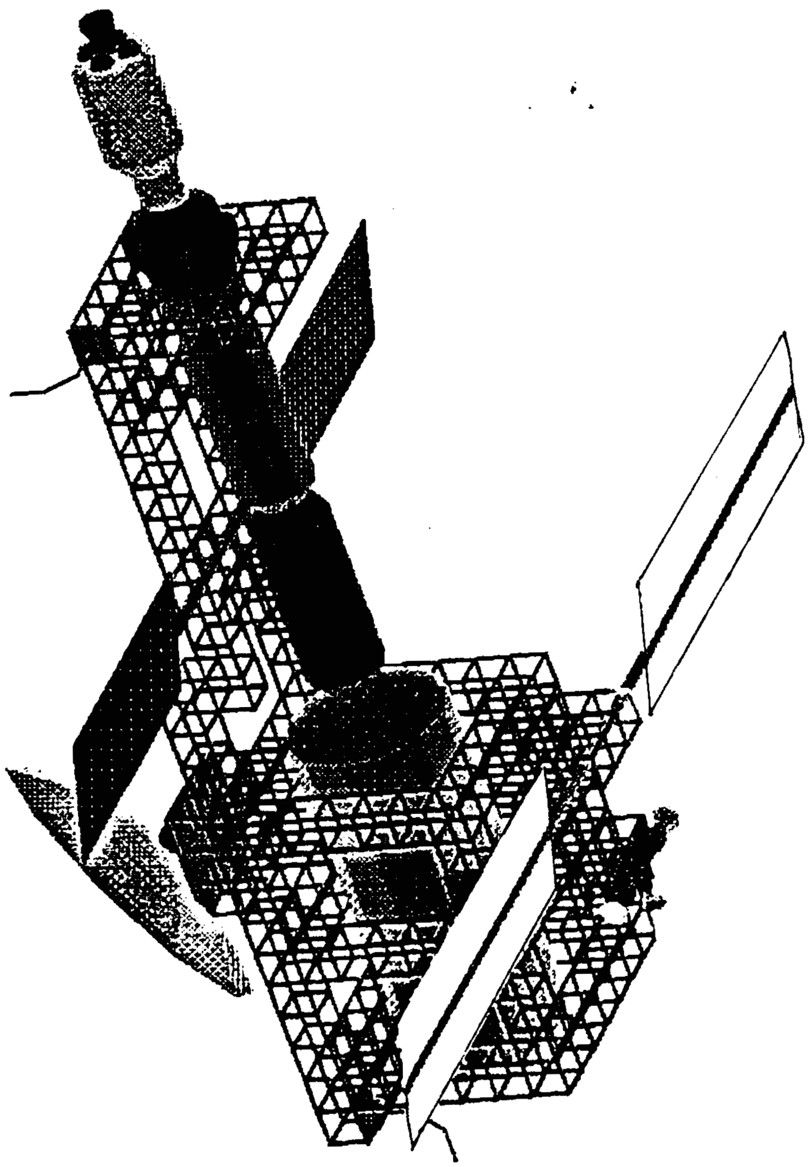


Figure 15.

ORIGINAL PAGE IS
OF POOR QUALITY

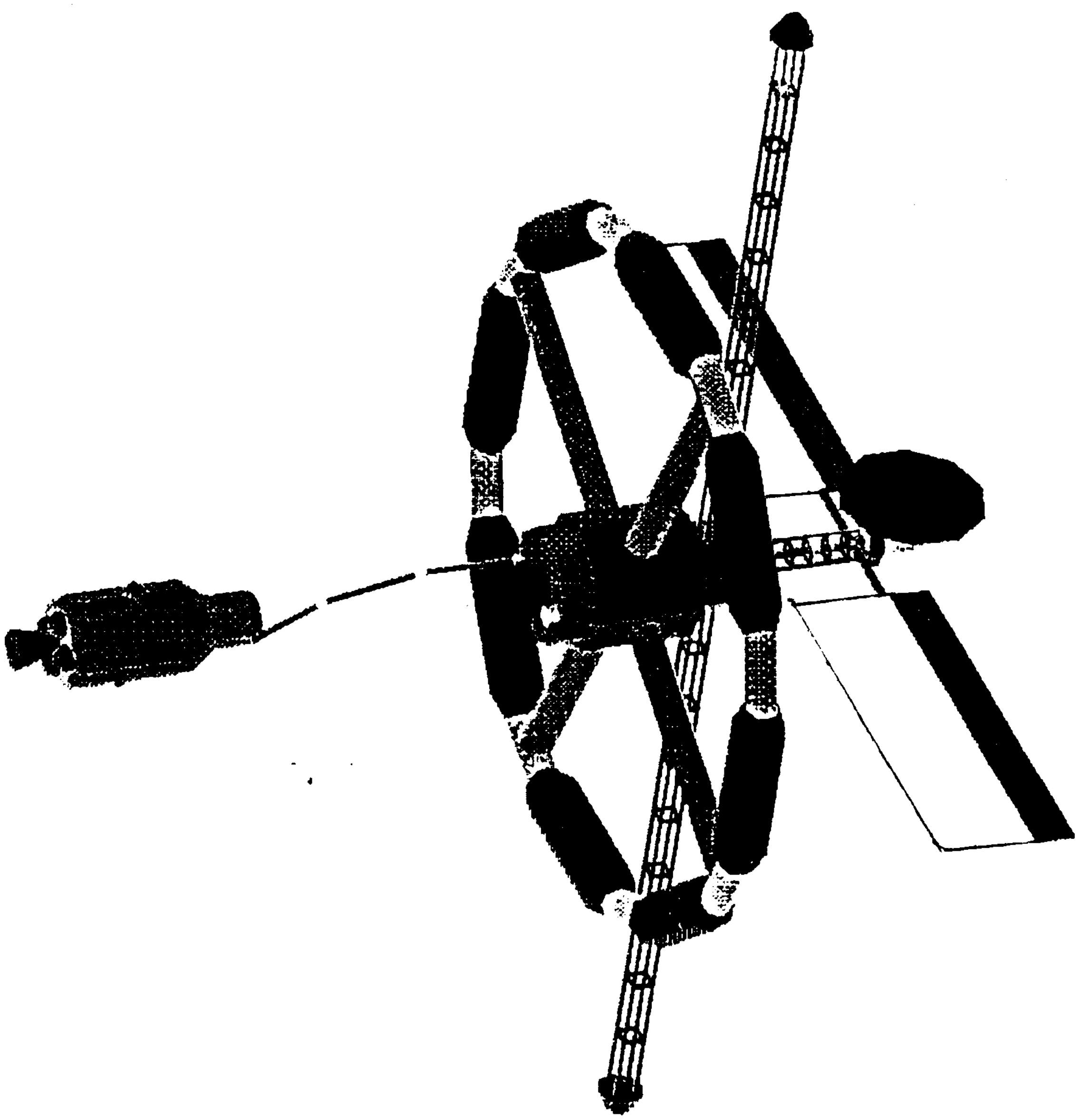


Figure 16.

Life Support Systems

Introduction - Life support is a broad term relating to those subsystems directly involved with supporting the crew both physiologically and psychologically. In developing the life support systems aboard the Manned Space Habitat, three goals have been singled out:

1) Maximize productivity while minimizing health and adaptation problems.
2) Minimize resupply from earth in the most cost effective way.
3) Maximize psychological well-being of crew.

These goals will be fulfilled through the following design choices.

1) In microgravity, many health and adaptation problems have been recorded, as discussed earlier. To reiterate, these range from short-term vestibular miscues causing space motion sickness to long term bone decalcification and cardiovascular problems. In addition, productivity losses have been estimated at 30% due to the microgravity environment. Thus, artificial gravity will be implemented on the station to maximize crew productivity and minimize health problems.

2) Consumables on the MSH will initially be provided by an ECLSS, or Environmentally Controlled Life Support System. An ECLSS is a realistic approach to life support, utilizing proven technology and minimal initial launch mass. Though an ECLSS is practical, it requires a large amount of resupply. Thus, the ECLSS will evolve into a CELSS, or Controlled Ecological Life Support System, during the first ten years of the MSH operation. A CELSS will require less resupply mass than an ECLSS, but it also will require a large amount of initial launch mass. Because CELSS technology is largely undeveloped and will require enormous research and development to become operational, it has been estimated that an operable CELSS will not be on line until 2010, or five years after initial launch of the MSH. Thus, the ECLSS will begin to incorporate new CELSS technology as it is developed. The MSH will serve as the initial space demonstration of CELSS operation, thus being a proving ground for using CELSS in future deep space missions.

3) Maximizing crew member's psychological well-being is desirable to increase crew productivity and to maximize the duration of a crew members' stay onboard the MSH. Many factors such as food quality and variety, personal space, and quality of artificial gravity contribute to the crew's mental health. Engineering to accomodate these human factors must begin in the planning stages. Human factors engineering will not be treated as a separate topic here, but will be integrated as part of the other life support systems.

Artificial Gravity - As mentioned previously, many adverse physiological side effects of microgravity have been documented. These, in conjunction with the loss of productive time in microgravity dictate the need for using artificial gravity in the MSH. The artificial gravity will eliminate nearly all physiological worries, and crew productivity will be raised through the gravity environment. Overall, there will be less time adapting to the MSH environment through use of artificial gravity.

Though a gravitational field will be present, the magnitude of the field will be only 0.8 times one earth gravity due to structural features of MSH. Despite the reduced magnitude of the field, most of the physiological and operational problems caused by microgravity will be eliminated.

Although artificial gravity will eliminate many problems, rotating the station may also create additional adverse side effects. To complete the effort of maximizing crew productivity and comfort by implementing artificial gravity, it is necessary to examine the field distortions causing these side effects and eleiminate them as much as possible. Specifically, the problems of gravity gradient, divergence from parallel of acceleration vectors, and Coriolis effect have been examined.

Gravity Gradient is the difference in the gravitational field felt from head to foot by a person standing in the rotating station. The gravity gradient is a function of both the angular velocity of the station and the radius of the station. Calculations have shown that the gradient is approximately 6.2% for a body length of 1.8 meters based on the station radius of 30 meters and angular velocity of 5 RPM. Although this is significant, it is felt that this is an acceptable operating range and that no adverse effects will result.

Divergence from parallel of acceleration vectors results from rotating the flat modules of the MSH. Because the artificial gravity field is radial in nature and the habitation modules are flat, an inconsistency exists between the two. To make the gravitational field perfect, it would be necessary to curve the module floors at 30 meters radius. However, doing this would create visual disorientation. While walking along the curved floor of the module, the vestibular system would signal that the floor was flat, while the visual system would indicate that the floor was curved. These conflicting signals would be disorienting to individuals walking along the floor.

Conversely, if a flat floor were used in the modules, the opposite effect would occur. It is interesting to note that while walking along such a flat module floor the gravity vector direction would indicate traversal of an incline, while the magnitude increase would indicate an ascent. At the same time, visual cues would indicate a flat surface. Such confilicting sensory cues may cause significant disorientation, and methods of reducing this effect must be found.

To comprimise the conflicting vestibular and visual cues, the module floors of the MSH will be divided into three 6 meter sections as shown in Figure 17. By sectioning the floors, the vestibular and visual cues will compromised, and the overall quality of the gravitational field will be improved.

Coriolis force is an effect created by the rotational movement of the station. The Coriolis force is increased as the angular velocity of the station is increased. Current studies by NASA indicate that the current rotation rate of the MSH, 5 RPM, may exceed the acceptable Coriolis level. In addition, 5 RPM may cause motion sickness. Should more evidence be found to support these studies, it may be necessary to reduce the rotation rate of the station from 5 RPM to less than 3 RPM to reduce the Coriolis force to an acceptable level.

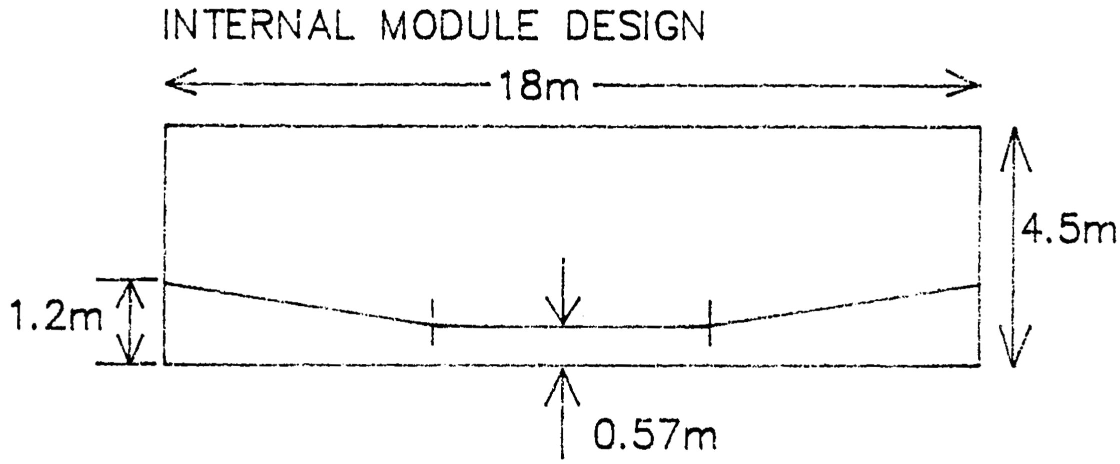
It is interesting to note that although a rotation rate of 5 RPM may initially cause motion sickness, the crew members may be able to adapt to this spin rate just as astronauts and cosmonauts adapt to microgravity.

In summary, artificial gravity will eliminate many physiological problems heretofore experienced in microgravity and will increase the productive time of the crew. To compensate for the imperfections in the artificial gravity field, the floors of the modules will be sectioned into three 6 meter sections. It may be necessary to reduce the rotational rate of the MSH at a later design phase to reduce the Coriolis effect at 5 RPM.

Controlled Ecological Life Support System (CELSS)

Terminology

ARTIFICIAL GRAVITY



DISTORTIONS AT 5 RPM, R = 30m

- O MAGNITUDE OF FIELD LESS THAN EARTH

  Ac = 0.8g

- O GRAVITY GRADIENT ACROSS THE BODY

  6.2% IN HABITATION MODULE

- O CHANGES IN FORCE VECTOR AS ONE MOVES FROM CENTER OF SECTION TO EDGE

  Ac MAGNITUDE CHANGE = +2%
  Ac DIRECTION SHIFT FROM PARALLEL = 5.7

Figure 17.

CELSS - A Controlled Ecological Life Support System utilizes biological treatment of human waste in conjunction with chemical and physical processes to produce edible biomass, oxygen, and purified drinking water. Currently, no such system exists. Developing a CELSS for the MSH will require approximately 20 years of research. The degree of closure such a system may achieve is unknown, but NASA has projected that it could not exceed 97%. This projected limit is based on current waste treatment processes in which 3% of all waste products cannot be converted to any useful biproduct. In general, as the level of closure of the CELSS increases, the initial hardware mass increases while the resupply mass decreases.

ECLSS - An Ecologically Controlled Life Support System differs from a CELSS by the degree of closure the system obtains. ECLSS utilizes largely proven technology; thus, the research input required is not as great as for CELSS. ECLSS system may reach up to 50-60% closure. The initial launch mass of ECLSS hardware is minimal compared to CELSS, while the ongoing resupply mass is greater.

Sludge - A mixture of human urine and feces, inedible plant portions, unused plant growth medium, and other organic waste products which are mixed together and combined with several strains of bacteria, chiefly E. Coli, to be used as a growth medium for algae and other plants.

Edible biomass - Any plant or animal parts which can be consumed by human beings. Most edible biomass is chosen for its high nutritional content and quality for use as a food source.

Algae - Any of various primitive, chiefly aquatic, one-celled or multicellular plants that lack true stems, roots, and leaves but usually contain cholorophyll. Grow symbiotically with bacteria to convert sludge to byproducts usable by humans.

Higher plant - An organism of the vegetable kingdom, characteristically having cellulose cell walls which has defined stems, roots, and leaves. Examples of higher plants used in the CELSS would typically include tomatoes, broccoli, and potatoes.

Aquaculture - Marine dwelling organisms including mollusks, fish, and shellfish.

Justification for CELSS - A life support system must provide four major components to its users:

- Atmosphere (oxygen);
- Edible biomass (food);
- Purified drinking water;
- Hygiene and industrial water.

Current life support systems used on the Space Shuttle and the Soviet Space Station Mir provide oxygen, some purified drinking water, and hygiene water through recycling, with the balance of these and edible biomass provided through resupply. Recycling, done with chemical scrubbing of atmosphere and filtering of water, has reached nearly 50% efficiency in current systems. For short term space flights, as in the Space Shuttle, such recycling methods are ideal.

For the 30 year life span of the L1 Manned Space Habitat, however, resupply becomes exceedingly costly and recycling becomes more cost effective. In this way, an increasingly closed life support system becomes increasingly cost effective for long term space habitation.

Three different scenarios of resupply and recycling methods have been analyzed for the MSH (see Figure 18). The first scenario involves 100% resupply. The second scenario utilizes conservative recyling methods (ECLSS) and resupply of dry food mass. The third scenario makes initial use of ECLSS technology moving toward 97% closure provided by a CELSS.

The first scenario, in which all consumables are resupplied, is used merely for a reference for the other two scenarios.

The second scenario, a conservative recycling method using water filtration and oxygen regeneration (the Sabtier method) has some advantages over a more closed system. Recycling would encompass distillation of waste water, condensation and filtration of water vapor, filtration of hygiene water, and 57% regeneration of oxygen. No biological recycling methods would be employed. The initial mass investment of such a system would be approximately 50,000 kg, and approximately 4000 kg of recycling would be needed per year.

In the third secenario, a Closed Ecological Life Support System, or CELSS, would involve nearly 80,000 kg initial weight investment while requiring less than 500 kg of resupply per year. Recycling would involve both biological and physical techniques to achieve nearly 97% maximum closure. Currently, 97% is thought to be the maximum closure a CELSS system may attain because 3% of human waste is untreatable by current sludge treatment processes. In the 30 year life span of the MSH, over 50,000 kg of total launch mass would be saved using a 97% closed CELSS. Thus, the third scenario will be the most mass effective over the life of the Manned Space Habitat.

In addition to the mass and launch cost savings of CELSS, the closed system is necessary to fulfill the mission objective of self-sufficiency. At L1, resupply is still possible, though costly. As mankind moves out further from Earth, as on a Lunar base or Mars colony, resupply becomes more costly and even unfeasible. Thus, for any extended mission away from the Earth-Moon system, a CELSS is required to achieve self sufficiency. The L1 MSH will serve as testing ground for the new technology needed for mankind's expansion into the rest of the solar system.

In summary, a CELSS is justified because of the launch mass saved by eliminating resupply mass and because of the requirement for self sufficiency of mankind in space.

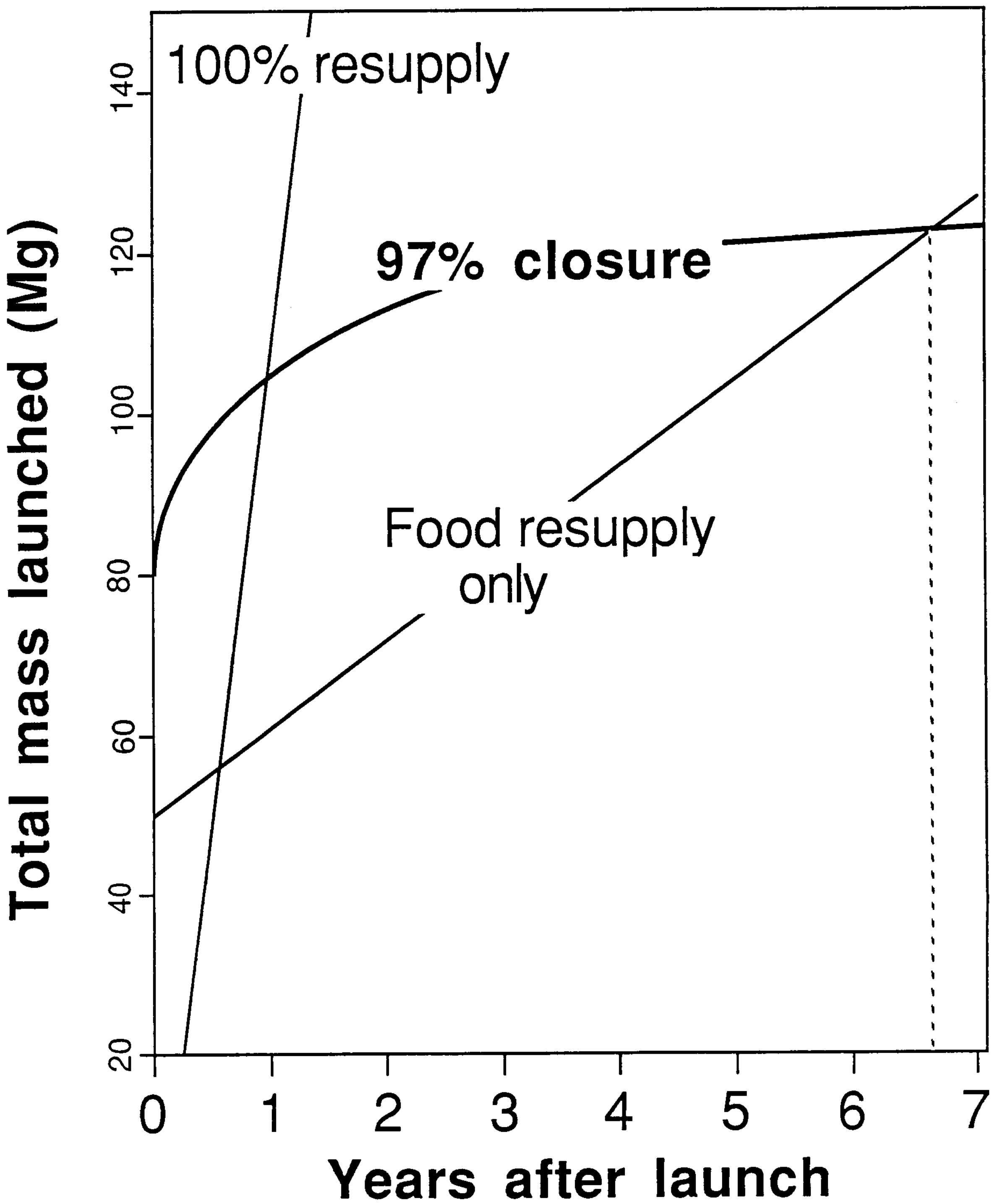
Overview of CELSS - CELSS utilizes the biological cycle between humans, bacteria, algae, plants, and marine life such as mollusks, fish, and shellfish (see Figure 19). This cycle is largely responsible for treating human waste, producing edible biomass, oxygen, and purified water for the crew, and fixing nitrogen in the life cycle. In addition, physical methods will be used to fine-tune the system. For example, water will be filtered and distilled in addition to being biologically treated. Also, atmospheric gas levels will be fine-tuned using gas absorbers and the Sabtier method to produce oxygen from absorbed carbon dioxide.

Table 1: CELSS demands on MSH subsystems
(Adapted from NASA estimates.)

Space requirement - 40 m3 / person. Fills approximately 1 module.- Used for plant and aquaculture growth chambers, storage, filtering and pumping units.

Servicing time - 30 min / day for a highly automated system;
- 4 hr / day for plant harvesting without automation.

Mass trade-offs: resupply vs. recycling



** Based on NASA ECLSS Technology Assessment Program, NASA LARC, 1985.

Figure 18.

- Includes tasks of planting, harvesting, and maintaining chambers and maintaining system.

Mass - 100,000 kg for 10 persons for hardware mass, organism mass, and consumables in system.

Power - 6.8 kW for a fiber optic lighting system which pipes sunlight directly to plants;

The CELSS system will have a large impact on other onboard subsystems, as highlighted in Table 1.

In general the major crew outputs consist of:

- Feces;
- Other solid organic waste (inedible food portions, etc.);
- Urine;
- Water vapor (exhaled water and perspiration);
- Spent hygiene, experimental, and industrial water;
- Carbon dioxide.

Solid organic wastes, feces and urine are treated in the same cycle using microorganisms and higher plants to yield drinking water, oxygen, and edible biomass. Water vapor, or atmospheric water, is condensed, purified, and added to the supply of drinking water. Carbon dioxide is stored in solid amine absorbers and released to the plant growth chambers where it is converted back to oxygen and stored as oxygen enriched gas for the crew. Spent hygiene and industrial water is purified in an isolated loop, and stored for reuse as hygiene water.

CELSS evolution - The Boeing Company has projected that it will take on the order of 20 years to design and manufacture a workable CELSS. Thus, during the initial manned phases of operation (between 2005 and 2010), a workable CELSS will probably still be in the design phase. Initially the life support will rely heavily on resupply, using approximately 50% recycling through ECLSS and requiring 50% resupply of consumables.

As CELSS technology becomes more developed, the physical recycling methods of ECLSS will be complemented by the biological recycling of CELSS. This creates the additional requirement on the ECLSS that it be transparent to the new CELSS technology as it is available. The MSH will serve as the initial space demonstration of CELSS technology fully integrated, autonomously, with crew needs.

CELSS as a Food Source - One main aspect of CELSS is that it serves as a food source for the crew members onboard the MSH. Thus, the organisms used in the biological cycle of the CELSS must be chosen for their functional use in the CELSS cycle and as a food source for crew members. As a food source, organisms will be chosen based on three attributes:

1) Nutritional content;
2) Potential yield of edible biomass;
3) Psychological benefits of flexibility and palatability.

A diet of higher plants has been chosen based on the above three selection criteria. The diet selected includes soybeans, dry beans, potatoes, carrots, broccoli, tomatoes, wheat, rice, strawberries, and sugar beets. Some higher plants, such as potatoes, broccoli, and tomatoes need minimal processing to become palatible. Others, such as grains, must be highly processed to produce flours, oils, and other staple food products.

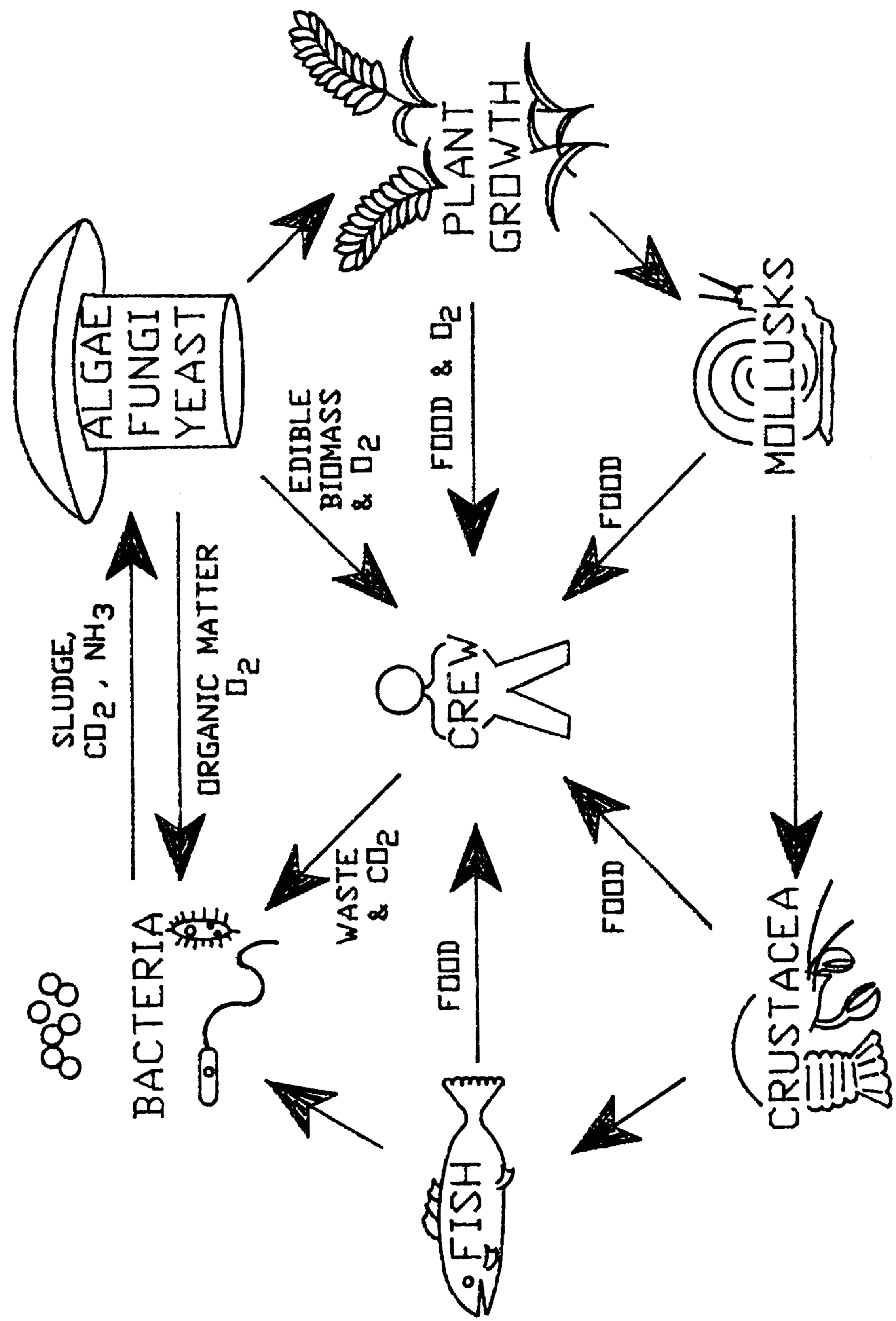

ALGAE
FUNGI
YEAST
PLANT
GROWTH
EDIBLE
BIOMASS
& O2
FOOD & O2
FOOD
MOLLUSKS
SLUDGE,
CO2 , NH3
ORGANIC MATTER
O2
CREW
WASTE
& CO2
FOOD
FOOD
BACTERIA
CRUSTACEA
FISH

Figure 19.

Algae will serve as a protein source after extensive processing. The algae cell bodies (single cell protein, or SCP) will be cooked, steamed, centrifuged, mixed, and extruded to produce dehydrated meat alalogs of ham, beef, chicken, or turkey. Also, it may be possible to use algae cells as an additive to many food products to increase the bulk of such products.

Large amounts of lower plants, for example mushrooms (fungus), yeasts, sprouts, etc. can be used directly by the crew without a large amount of processing.

The third major source of edible biomass will come from marine life, or aquaculture. Mollusks, shellfish, and fish require minimal processing, and will serve as a complete protein source as well as providing variety and flexibility in the crew's diet. These life forms, of course, can use algae directly.

Technical aspects of CELSS - The major processes involoved in the CELSS system have been identified. Figure 20 shows a mass flow diagram for the proposed CELSS system. The masses, in kg / day based on a ten person crew, refer to the total flow of a particular component the system must be capable of handling. In the following discussion, bold face words refer to specific processes in the flow diagram.

Sludge treatment - Solid organic wastes, feces and urine will be combined to form an organic sludge capable of supporting plant growth. This sludge cannot be utilized in its raw form; hence a preparatory step is needed to make the sludge usable to plant and bacterial life forms.

Sludge preparation will begin by grinding large particles (>10 mm diameter) by a physical process, something like a garbage disposal, to a size of approximately 1 mm diameter. The sludge will be thoroughly mixed and sonified using an ultrasound device operating at 20,000 Hz. Sonification is the application of high frequency sound waves used to produce particles of size less than 0.5 micron. At this size, sludge particles are readily availible to the system's sludge-digesting bacteria of average size 2-3 microns length and 0.5-1 micron width.

At this point in the sludge processing, flow feeds to two chambers, the **higher plant growth chamber** and the **algal growth chamber**. In these chambers, sludge will be converted by bacteria, algae, and higher plants to a form edible by human beings.

The process of growing plants, algae, and bacteria in harmony based on input from the crew does not consist simply growing those species which satisfy the crew's dietary needs. The process instead involves the complex interactions of the organism's interdependence to live in a consistant environment where no organisms are infected by other species or other species' biproducts, and no organisms suffer from a lack of dietary essentials.

This problem is similar to crop rotation. Farmers continuously rotate the location in which crops are grown. For instance, one year, a farmer may grow wheat on a certain plot of land. Wheat requires a specific set of nutrients from the soil. Over the course of the growing season, these nutrients are depleted from the soil. The next year, this plot of ground will be left dormant so that the nutrients essential to a wheat crop will be replenished by microorganisms in the soil. The following year, wheat can be grown on the same plot of land, thus continuing the cycle.

In the limited space of the CELSS system, growing area cannot be left "dormant." Hence, crop rotation will occur by varying the type and quantity of species in the growth chambers, thus keeping growth conditions supportive of all species in the growth

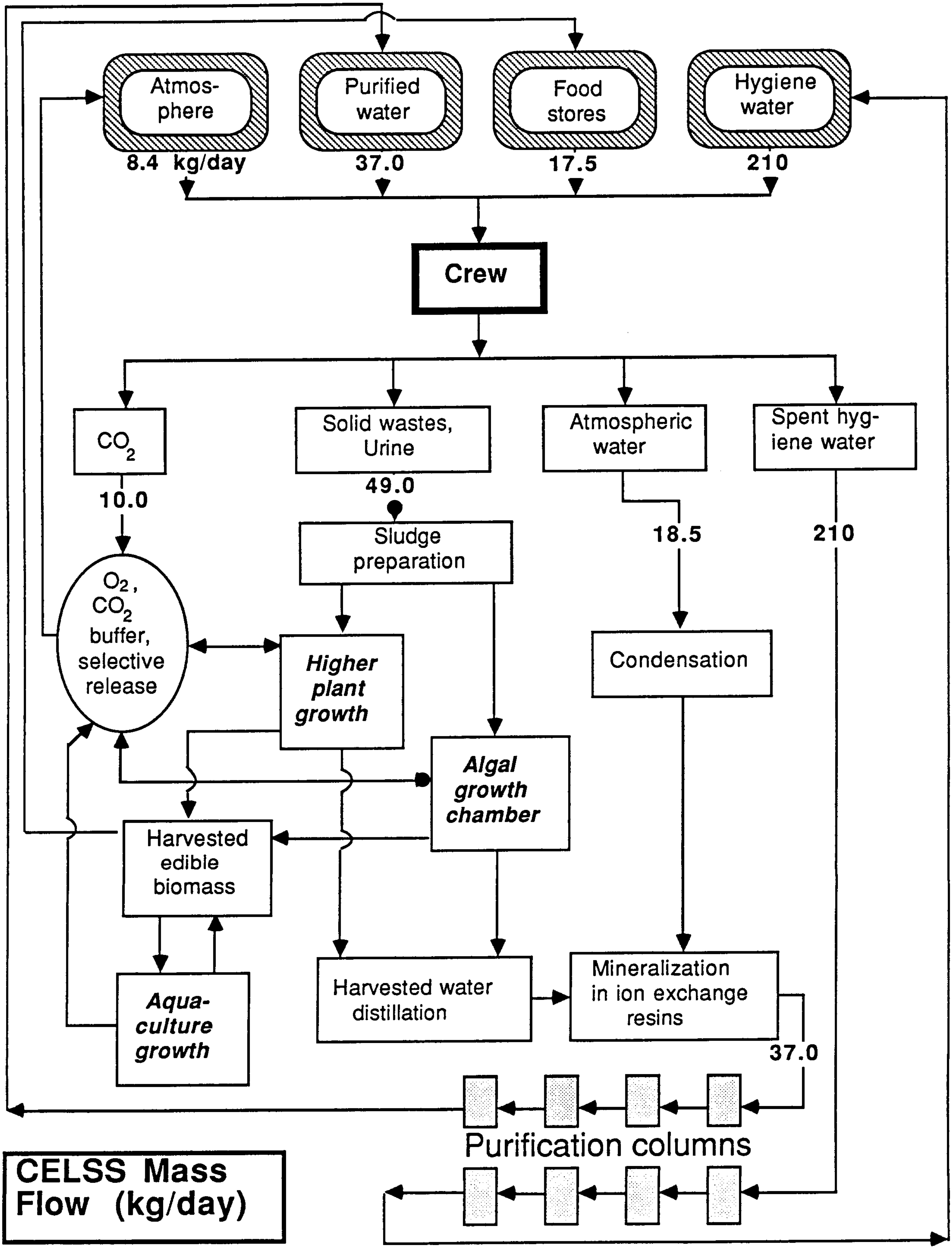

Atmos-
phere
Purified
water
Food
stores
Hygiene
water
8.4 kg/day
37.0
17.5
210
Crew
CO2
Solid wastes,
Urine
Atmospheric
water
Spent hyg-
iene water
10.0
49.0
18.5
210
Sludge
preparation
O2 ,
CO2
buffer,
selective
release
Higher
plant
growth
Condensation
Algal
growth
chamber
Harvested
edible
biomass
Aqua-
culture
growth
Harvested water
distillation
Mineralization
in ion exchange
resins
37.0
Purification columns
CELSS Mass
Flow (kg/day)

Figure 20.

chamber at a given time. Through consistent monitoring of inputs to, outputs from, and constituents in the growth chamber at any time, species will be selected for growth. This selection process will occur through the computer control system. Monitored results will be input to the control computer, where a data base will contain knowledge of what each species needs to thrive. These data will be comprimised between the dietary needs of the crew and the nutritional needs of the growing species. The best combination of organisms will be selected for the given monitored conditions.

Using these principles, an algal growth chamber has been designed. The chamber has been designed to fulfill four criteria:

1) Allow interaction between microorganism communities;
2) Make the chamber accessible for harvesting algal biomass;
3) Make the microorganism communities interchangeable;
4) Provide turbulent flow to ensure mixing of nutrients and no clumping of sludge particles.

The algal growth facility that will be used is a cone-shaped swirl chamber containing colonies of bacteria and algae. A dilute flow of sludge will be injected into the chamber where it will swirl on the inner surface of the chamber. Dialysis membranes will be used to contain colonies of bacteria and algae. As the flow swirls on the interior of the chamber, sludge particles will pass into the microorganism colonies. As the microorganisms digest sludge particles, they will produce biproducts which will be mixed in with the rest of the flow.

The algal growth facility will be highly automated, requiring no human contact under normal operation. (A scenario of algae harvesting has been outlined in the Operations section of this paper.)

Two of the outputs from the growth chambers will be **harvested edible biomass** and **harvested water.**

Harvested edible biomass consists of plants harvested in their raw form. Some of this material will be passed on to the **aquaculture growth chamber**, which lives readily on algae. Aquaculture is provided for variety and nutrition in the crew's diet, in addition to providing another life form to maintain the living balance of the CELSS system. Harvested aquaculture is added to the edible biomass supply, after which this supply is processed and distributed to the food stores, which feed the crew and provide an additional buffer supply in case of a major failure in the CELSS system.

Harvested water from the plant growth chambers can be converted to drinking water through filtering. On the Soviet space station, Mir, urine is directly filtered to provide backup drinking water for the crew. Although the water is uncontaminated, it is still "grey," and the psychological effects of drinking one's own waste as the only water source could be detrimental over a six month period. This has been documented by the Soviet cosmonauts, who preferred not to drink "grey water." Thus, water harvested from the plant growth chambers must be further purified by distillation before being ready for crew consumption.

Harvested water distillation will take place in the power system's fuel cells. Refering to Table 2, the fuel cells must distill 2.0 kg of water per day for each crew member, thus 24.0 kg for the entire crew. This distillation is in essence "free," since the fuel cells can be specifically designed to vaporize and recondense water as a method of power storage through electrolysis.

Table 2: Water exchanges (kg/man-day)

Source	Mass(kg/person-day)
Drinking water consumed	3.8
Exhaled water vapor	1.8
Urine/ waste water	2.0

Atmospheric water treatment

Atmospheric water vapor is present in large quantities from exhaled water vapor and perspiration. Hence, it is necessary to condense atmospheric water to maintain the humidity levels in the environment. At the same time, this water will be very pure, since it in essence has been distilled, thus making an excellent source of drinking water.

Atmospheric water will be **condensed** using a cooling and drying unit as on the Soviet Space Station Mir. After atmospheric water is condensed in the cooling and drying unit, it is passed with pumps into storage columns containing ion exchange resins and activated charcoal for purification. Here, the water distilled from the plant growth chambers is combined with condensed water vapor. Then the water is BmineralizedB with calcium, magnesium, bicarbonate, chloride, and sulfate to provide essential minerals to the crew. This constitutes the first stage of purification.

The second stage of purification contains four columns, each of 20 liter volume, for purifying the atmospheric water. These columns perform the following tasks:

1) Remove and purify organic and inorganic foreign bodies;
2) Decontamination;
3) Storage of drinking water;
4) Pump water to storage tanks throughout station.

The water will be stored and heated throughout the station to provide even mass distribution and easily accessible water to the crew.

Atmosospheric control - Atmospheric partial pressures will be maintained within critical tolerance levels, outlined in Table 3.

Table 3: Atmospheric composition for the crew

Atmospheric component	**Partial pressure (mm Hg)**
Nitrogen	300
Oxygen	160-240
Carbon dioxide	4
Water vapor	9
Total atmospheric pressure	700-760

Ideally, carbon dioxide and oxygen will be maintained in equilibrium using only the crew as a source of carbon dioxide and plants as a source of oxygen. However, due to size restrictions of the CELSS, this is probably not feasible. Thus, chemical treatment is required to maintain atmospheric control.

Solid amine absorbers will absorb excess carbon dioxide produced by the crew. This in turn will be released to the plant growth chambers and crew compartment. BSalcomine absorbersB will do the reverse and absorb oxygen from the plant chambers for release to the crew compartment.

In addition to gas absorption, the **Sabtier reaction** will be used to reduce carbon dioxide levels and recirculate oxygen to the crew. The Sabtier reation allows 57% of the oxygen treated to be reutilized by the crew, while the remaining 43% must be discarded as carbon dioxide with methane, which is flammable and toxic to human beings.

Monitoring of humidity, carbon dioxide, oxygen, and overall atmospheric pressure must be done continuously to assure a consistent and safe environment for crew members.

Hygiene water recycling - Hygiene and industrial water will be kept in a loop isolated from the drinking water. Since this water does not need to be extremely pure, simple filtration can be used to remove large molecules, and distillation is not required. In the MSH CELSS, hygiene water will be purified using an identical **purification column** setup as the drinking water and be purified with and ultrafiltration device to remove body salts and oils, soap, and other cleaning products. Hygiene water will never be combined with the pure drinking water for the crew as it will not be distilled or meet the purity requirements of drinking water. Storage and heating units will be provided throughout the station for hygiene and industial water, and adequate identification provided to keep hygiene water and drink water separated.

CELSS mass flow - Further characterization of a CELSS involves the complete mass flow involved within the system. Table 4 outlines approximate values for input and output masses from the crew.

From here, it is possible to construct a mass flow diagram characterizing the CELSS system, as in Figure . This is the initial step in defining hardware size, mass, power requirements, cost, automation requirements, control characteristics, and so on. Now that this initial mass flow characterization has been made, more specific hardware can be designed to fulfill the requirements for the mass flow and size of the system.

Table 4: Mass flow characterization (kg / person-day)
Compiled from NASA ECLSS technology assessment program.

Component	Mass
Inputs	
Drinking water	1.86
Food preparation water	1.85
Metabolic oxygen	0.84
Food solids	0.62
Food water	1.13
Hygiene water	18.20
Urine flush water	0.47
Experimental water	2.27
Outputs	
Fecal water	0.01
Fecal solids	0.03
Urine water	1.50
Urine solids	0.06
Sweat water	1.85
Sweat solids	0.02
Carbon dioxide	1.00
Spent hygiene water	18.20
Inedible biomass	3.20
Uneaten foods	0.06
Air lock loss	0.61

Summary - In summary, the CELSS system components must be largely isolated due to the size limitations of the Manned Space Habitat. The flow system of the CELSS was characterized and major subsystems defined. The mass flow rates in the CELSS system were defined, implying that now specific hardware can now be designed to handle the processes in the CELSS system.

OPERATIONAL SCENARIOS

Three operational scenarios are given here. They illustrate how the design of the L1 MSH assists and promotes station activities.

Automation Scenario of a CELSS Algal Growth Chamber

The higher plant growth chamber and algal growth chamber of the CELSS are obvious targets for automation. Recently, a complex scenario has been developed by The Boeing Company which fully automates growth and harvesting of the higher plants. Such a function would be desirable from the point of view that the crew is on the station to perform important tasks and not the mundane task of growing plants. However, the task of gardening is one which many people find enjoyable and relaxing. From a psychological point of view, allowing crew members to do their own gardening of higher plants is desirable. Thus, it has been decided to limit automation of the higher plant growth chamber and allow many gardening tasks to be done by the crew.

The algal growth chamber, on the other hand, is a target for automation as harvesting algae by hand certainly has little romantic or psychological appeal. Thus, four tasks have been assigned in automating the algal growth facility. These are:

1) Decision tasks ;
2) Monitoring of system;
3) Removal and addition of microorganism communities;
4) Harvesting of algal biomass.

Decision tasks - will be overseen by an expert computer system (see figure 21). The main duty of the expert system will be to integrate monitored data and distribute duties to the other components of the system. Part of the expert system will be a knowledge base, containing information about each of the organisms in the algal growth chamber and how those organisms interact. Recall that growth of algae is dependent on its interaction with different strains of bacteria. Thus, the swirl chamber for growing algae (see CELSS section for detatils) contains colonies of both bacteria and algae which are physically separated from each other by dialysis membranes but are free to interact with each other.

As an example, if bacteria 'Strain A' and algae 'Strain B' are known by the knowledge base to interact positively in the growth chamber then they will be grown together. However, if under a certain circumstance, say in the presence of large quantities of nitrites, Strain A and Strain B no longer interact positively but rather become infectious to each other, then the expert system will not allow 'A' and 'B' to be grown together under those circumstances. The knowledge base will contain data regarding all known interactions such as the example above illustrates. In this way, the interaction between bacteria and algae on which the algal growth depends will always be kept at a positive level, and the output of algal biomass will be at a maximum.

An artificial intelligence language such as LISP is readily able to handle such decisions as the expert system would require.

Automated monitoring will allow the expert system to know at all times the quantity of sludge particles in the growth medium, the density of the growth solution, gas levels, microorganism levels, turnover times, etc. in the growth chamber. This information will be used to determine what new microorganisms may be used in the swirl chamber to allow as many positive interactions as possible. Returning to the above example, the automated monitoring system would determine the nitrite levels in the growth medium at any time. This information would in turn be processed by the expert system to

Automation of the algal growth chamber

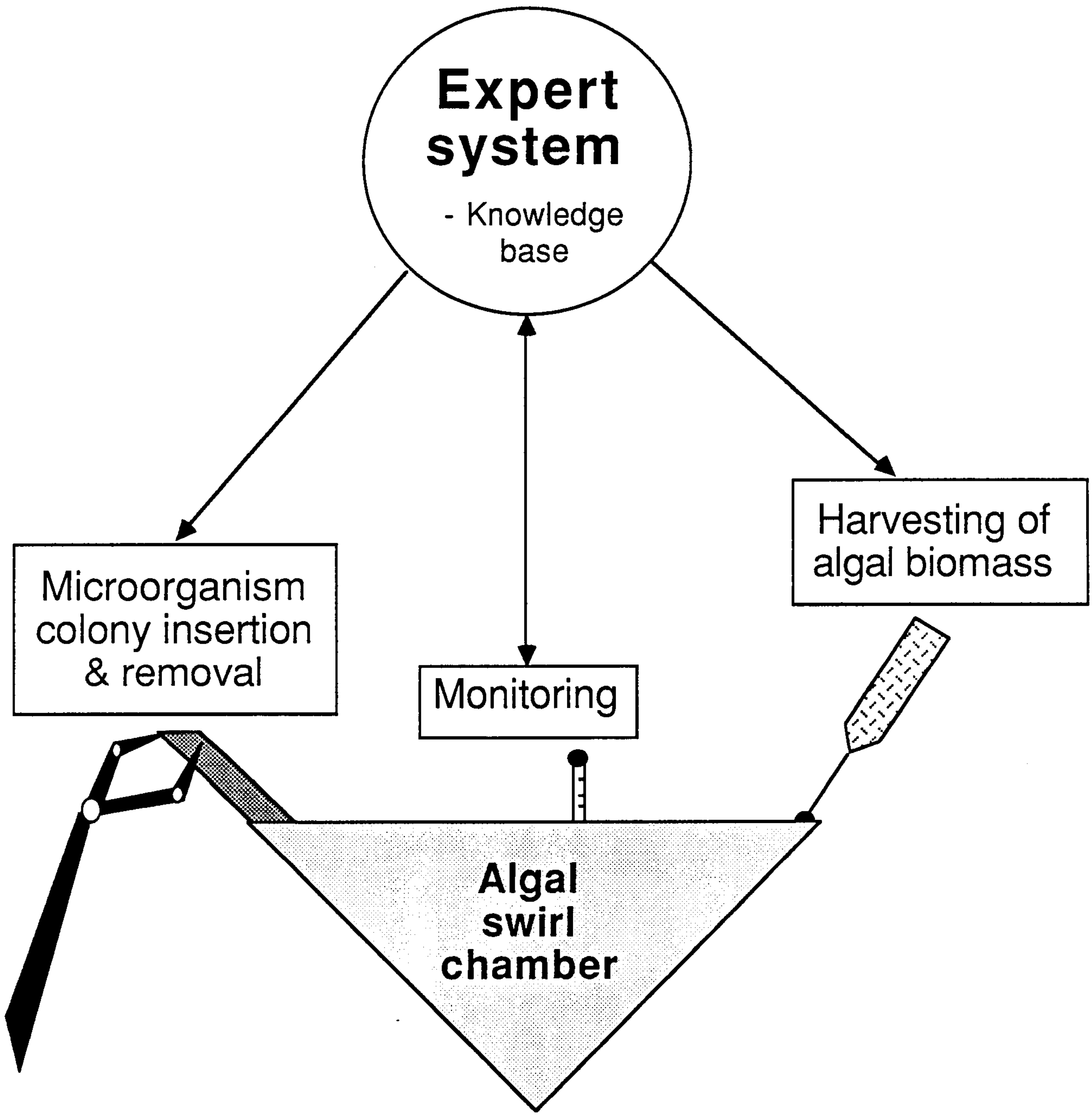


Figure 21.

determine what micoorganisms should be used in the chamber based on the given conditions.

Removal and addition of microorganisms will be done by an automated mechanism which lifts the microorganism colonies out of their slots in the chamber. If a new colony is needed as determined by the expert system, the old one is simply removed and discarded. A new colony is fabricated from freeze-dried microorganisms stored in labled containers. This colony is then inserted into the growth facility.

Harvesting of algal biomass is also automated. The algal growth space will be accessible through a number of septa -- rubber partitions through which a sterile hypodermic cannula can be inserted -- located on the upper horizontal surface of the swirl chamber. The expert system will determine when the algae is ready for harvesting based on information received through monitoring. To harvest algae, a hypodermic cannula will be inserted into the septum and a predetermined quantity of algal biomass removed. Once removed, the algal biomass will be sterilized and processed into meat analogs and food additives.

Satellite Servicing Scenario

The L1 MSH will be the logistics center for servicing of satellites in GEO. A teleoperated OMV based at L1 will make repair and refurbishment sorties to GEO, visiting many satellites during each trip. This same vehicle will transfer the supplies (propellant and repair parts) to GEO, and bring an occasional satellite back to L1 for more extensive repair. With this system, there will be no servicing platform in GEO (remember, it takes the same amount of propellant to transfer the servicing to L1 as it is to transfer it to another point on the GEO orbit).

This scenario involves a multiple visit mission. The operators of the MSH have been contracted for refueling of 4 GEO communications satellites, as well as repair of two more. One of those repair jobs is likely to be too complex for on-station work, so the satellite will have to be brought back to the "drydock" at the L1 MSH.

The OTV mission is designed by an expert system, and approved by the satellite servicing coordinator on the MSH. The mission design includes such things as the order of visiting of the satellites, chosing the capture mechanisms to take along, and so on. The OTV will save visiting the satellite it is to take back to L1 for last, to avoid having to drag its mass around for any longer than necessary.

The OMV is guided to each satellite automatically. After suitable analysis of the satellite motion, or waiting for the satellite to be de-spun by its operators if it has such a capability, the OMV captures or docks with the satellite. The capture or rendezvous plan was designed by an expert system, and approved by the OMV teleoperator on Earth or at the LEO station. The refueling or on-station repair operation is then be performed, under the guidance of that same teleoperator (see figures 22 and 23).

The last satellite visited is the one to be returned to L1 for more extensive repairs. It is captured and dragged off to L1 by the OMV. Once it arrives, it is placed in the repair hanger on the L1 MSH free-flying docking platform. The advanced teleoperated workstations in this hanger are used to remove a number of circuit cards with suspected faults and replace a section of the satellites solar array. The circuit board repair is beyond the capability of the workstation, so the boards are taken over to the station proper by the MSH docking tug. This allows the technician to work efficiently in his or her shirtsleeves in an artificial gravity environment. Once the repairs to the cards are finished, they are returned to the satellite. The bird is returned to its station in GEO by the OMV, as that vehicle heads down to do another set of repairs on still more satellites.

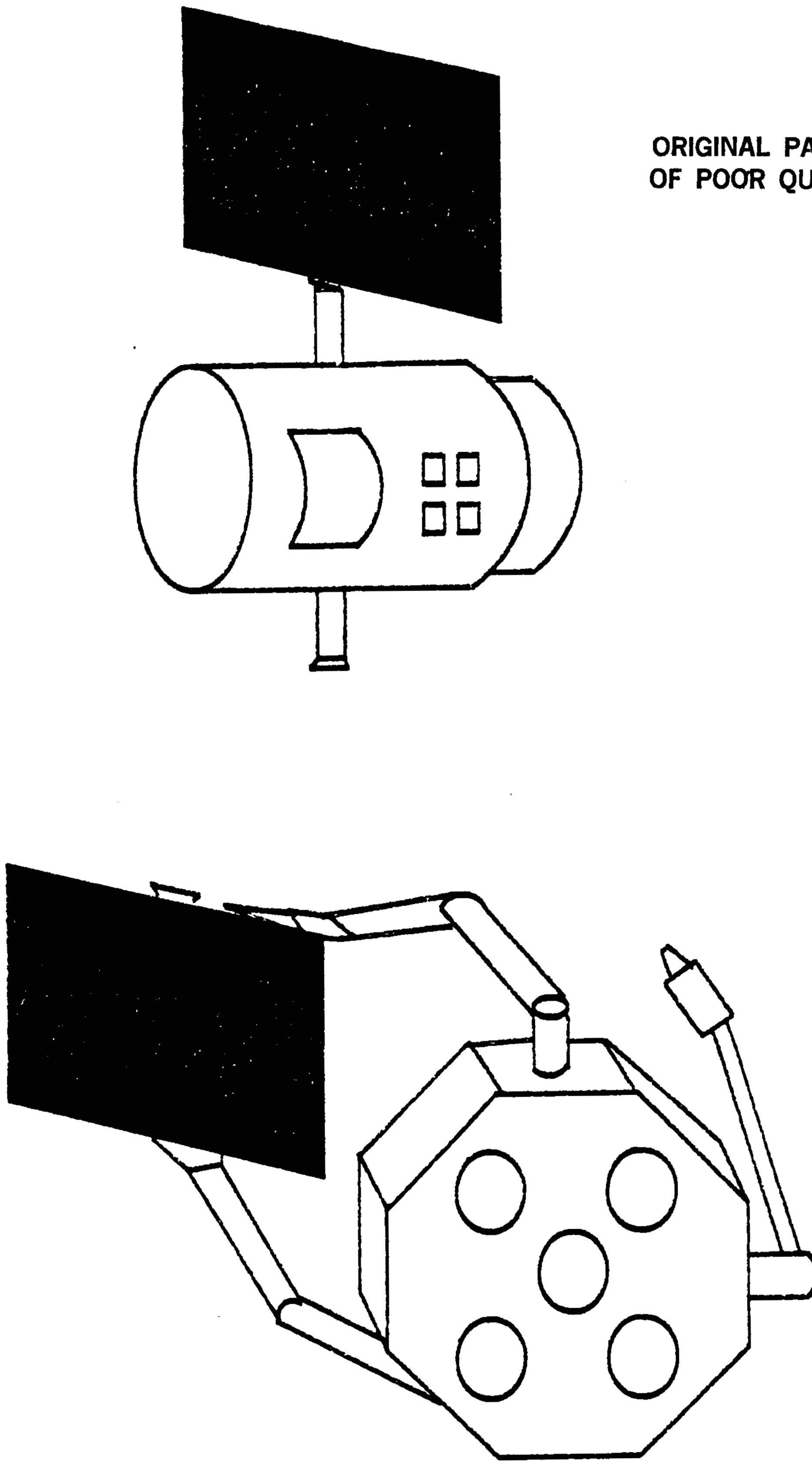


Figure 22.

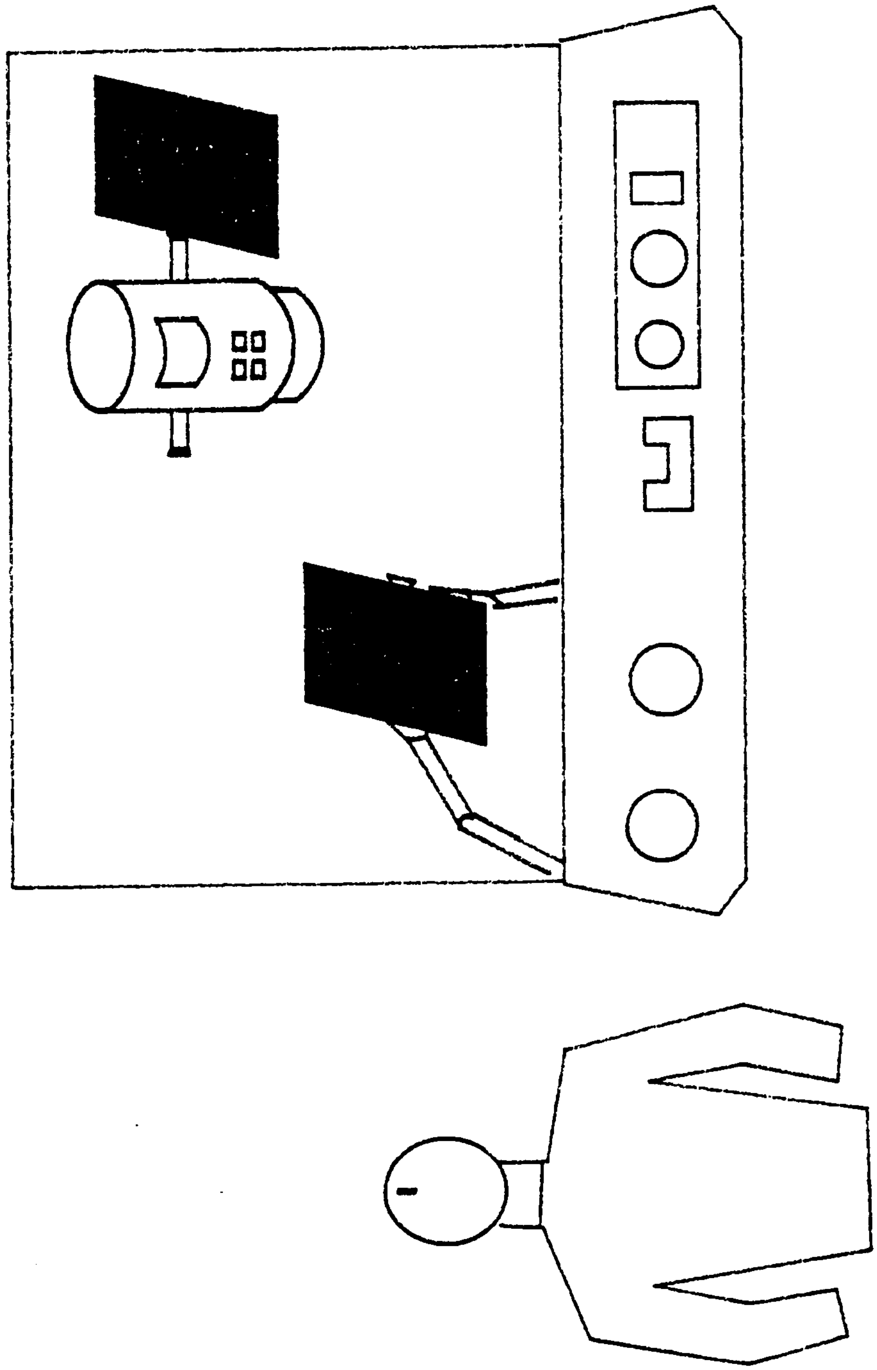


Figure 23.

Manned Mars Mission Staging Scenario

One of the main reasons for the existence of the MSH at L1 is to support planetary exploration missions. This scenario shows how such a mission might occur in 2015.

We begin with the Mars spacecraft modules. These are manufactured on Earth, because space based manufacturing is not yet capable of producing such intricate hardware. Like the station modules were, these modules are launched from Earth on heavy lift launch vehicles, and transported in partially assembled bundles from LEO to L1 by a reusable OTV. Certain items of intricate and advanced hardware (such as some antenna components, a "shell", and others) need not be hauled up from Earth - they're already present in the form of salvaged communications and research satellites. Since the L1 MSH has been the main logistics point for GEO repair and refurbishment missions for the past ten years, there are plenty of such spare parts available.

The spacecraft modules and structure are then assembled at L1 with crew and logistics support from manned space habitat. Extensive robotics and teleoperation techniques learned from the LEO station are used to assemble modules and tankage from Earth, along with structural members made at L1 MSH from lunar fiberglass, into the completed Mars spacecraft. The teleoperators are on Earth, except for a few select individuals who possess necessary skills and happen to be on the LEO station, the Moon, or even on the MSH. When problems arise that can't be handled via teleoperation, the MSH crew is available to handle them directly via an EVA. Spacecraft system integration is performed via teleoperation as well, with assistance from MSH crew members on the spot.

Once it is assembled, the Mars spacecraft life support system is seeded by CELSS carryover from the L1 MSH. Algae chambers on the spacecraft are seeded from MSH stocks instead of having stocks brought up from Earth. Higher plants, fish and mollusks are likewise provided from the MSH instead of Earth. This seeding from systems for which the gravity price has already been paid saves money.

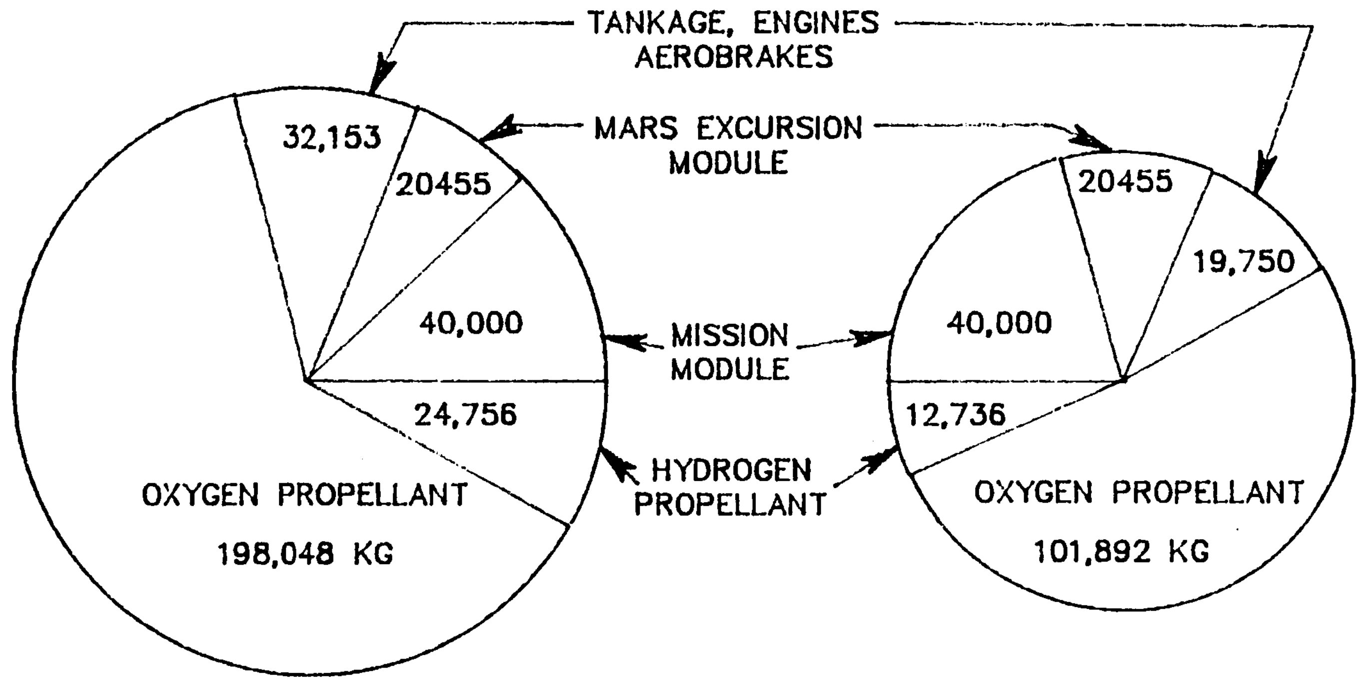
Once everything is ready, the spacecraft fuel tankage is filled from the L1 MSH "fuel depot". Oxygen obtained from Moon and stored here at L1 will be put to good use on the trip. Hydrogen from water ice deposits in permanently shadowed craters at the Lunar poles is also supplied. The availability of nearly free oxygen (once the refining equipment costs have been amortized) was the major point in favor of using H-O chemical propulsion instead of the more efficient ion systems. Figure 24 represents the energy savings of a Mars mission departing from L1.

Finally, the crew arrives and takes posession. After final checkout, the spacecraft is launched from L1 and is on its way. During the mission, the spacecraft crew will be engaged in a variety of science activities, including astronomical and solar studies. The L1 MSH will be used as an advanced portion of an expanded deep space tracking network. The antennae on the docking free flyer and the main station provide a communications relay point for mission operations and science data.

Upon the return of the mission to near-Earth space, the MSH and its associated platforms will act as a re-acclimatization and quarrantine facility for the Mars crew. The MSH crew will undoubtably enjoy the stories their guests can tell before the Mars explorers head back to the cradle of human civilization. The Mars spacecraft will then be refurbished, using stores from the MSH depot, for a second mission. This building upon permanent facilities is the real strength of the MSH.

MASS REQUIREMENTS FOR A MARS VEHICLE

(ISP = 450 SEC , λ_F =0.85 FOR AEROBRAKED STAGES
ALL MASSES IN KG, λ_F = 0.90 FOR NON-AEROBRAKED STAGES)



MARS VEHICLE DEPARTING LEO
INITIAL MASS = 315,412 KG

MARS VEHICLE DEPARTING L1
INITIAL MASS = 194,832 KG

Figure 24.

CONCLUSION

The L1 Manned Space Habitat will begin as an unmanned platform servicing Geosynchronous Earth Orbit in the 2005-2010 time period. As the demands on the L1 environment increase a habitation module will be added to the platform. Finally a rotating space station will be completed. Artificial gravity will be a vital part of the design yielding increased productivity. Throughout the evolution process, more crew members and additional capabilities will be added. This will make the station more habitable and more useful in the space operations it shall assume in the support of the overall space program. In its final design, MSH will consist of the main torroidal station, a docking, satellite servicing freeflyer (which served initially as the servicing platform), and a materials processing and astronomy freeflyer.

Several technologies need to be addressed soon for the L1 MSH, or any long term habitations, to be developed. These technologies include robotics, Controlled Ecological Life Support System (CELSS), artificial gravity implementation, despun technologies, materials processing, distributive computing, space construction techniques, and radiation shielding. Although much of this development can be accomplished through LEO and earth based studies, the MSH will serve as proving ground to many undeveloped and unproven technologies. If the United States space program is to succeed then action must be taken now in these areas, before these systems are in demand.

L1 was selected as the site for MSH because it can best support the many tasks for which the station will be used. The L1 MSH will serve as the focal point for U.S. expansion into the solar system, taking up where LEO station leaves off. The L1 MSH will act as a "service station." It will service GEO (providing a substantial economic return, offsetting operational costs), support lunar operations, and serve as a staging base for Mars and other planetary missions. Also, MSH will act as a space habitation proving ground, developing key habitation technologies such as artificial gravity, CELSS, and radiation shielding. Scientific tasks such as materials processing, look-out and look-down technologies, and Earth-Moon communications will be performed on MSH as well.

The L1 Manned Space Habitat will develop technologies vital to the entire space program. It will provide support to many space activities. It is not an end unto to itself, but rather the foundation for the integrated exploration and development of space.

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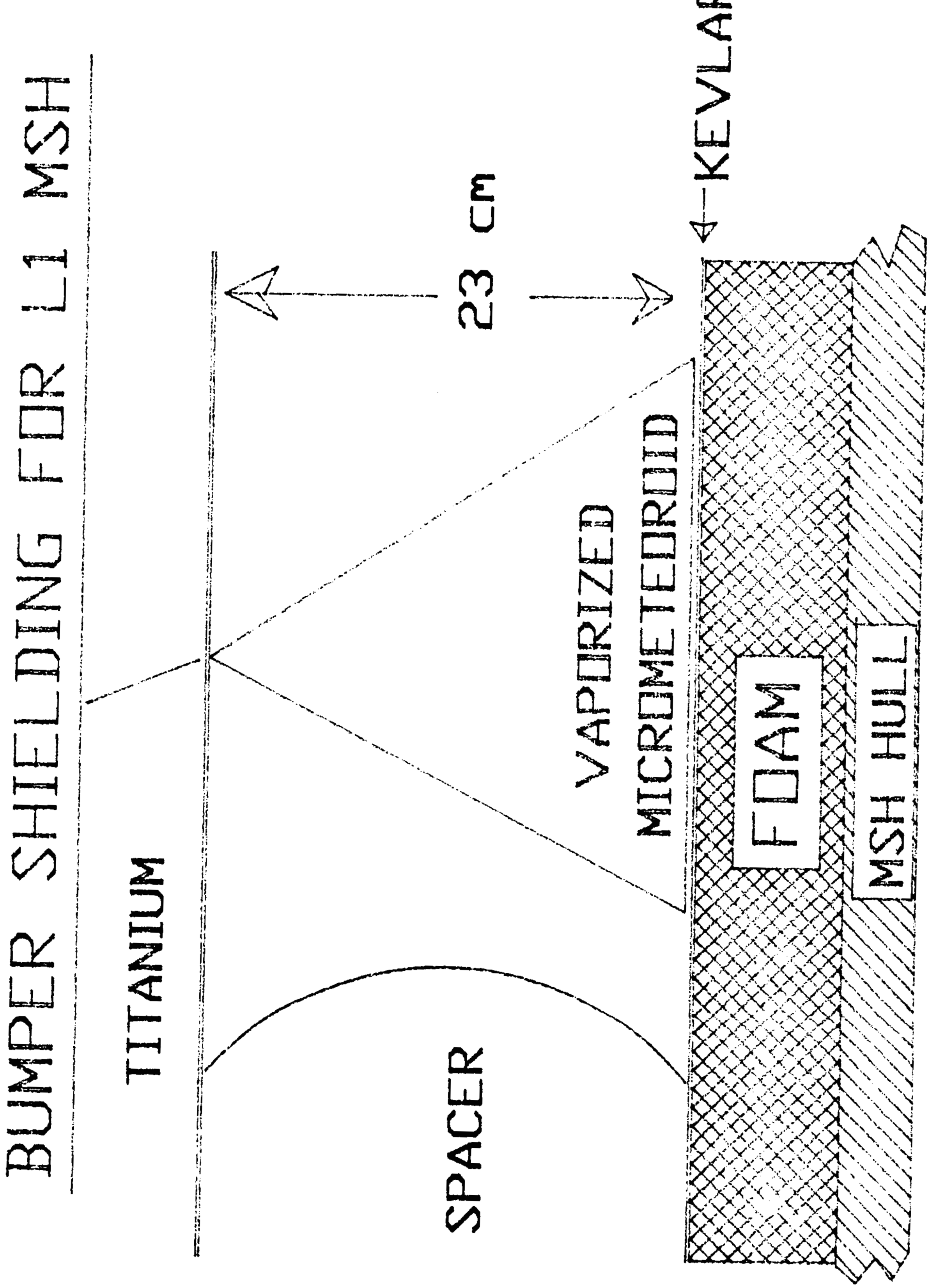
BUMPER SHIELDING FOR L1 MSH
TITANIUM
23 cm
KEVLAR
VAPORIZED
MICROMETEOROID
FOAM
MSH HULL
SPACER

Figure 13.