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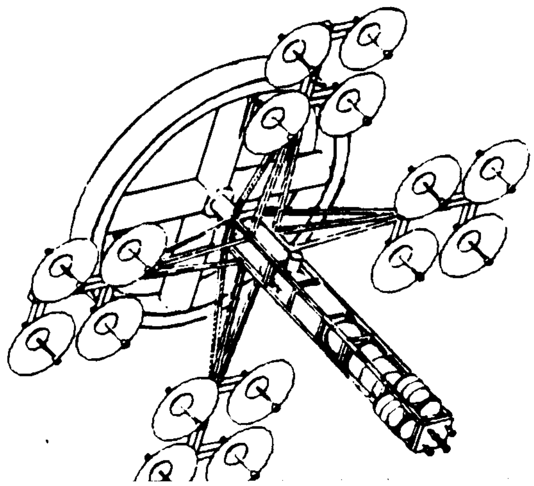
CAMELOT II



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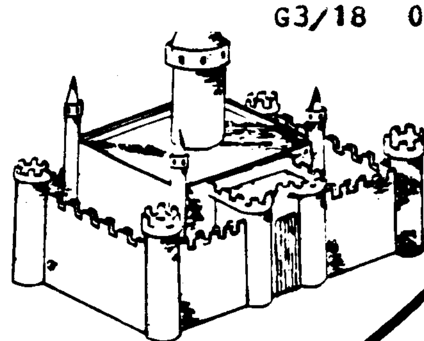

SPACE SYSTEMS DESIGN

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CAMELOT II

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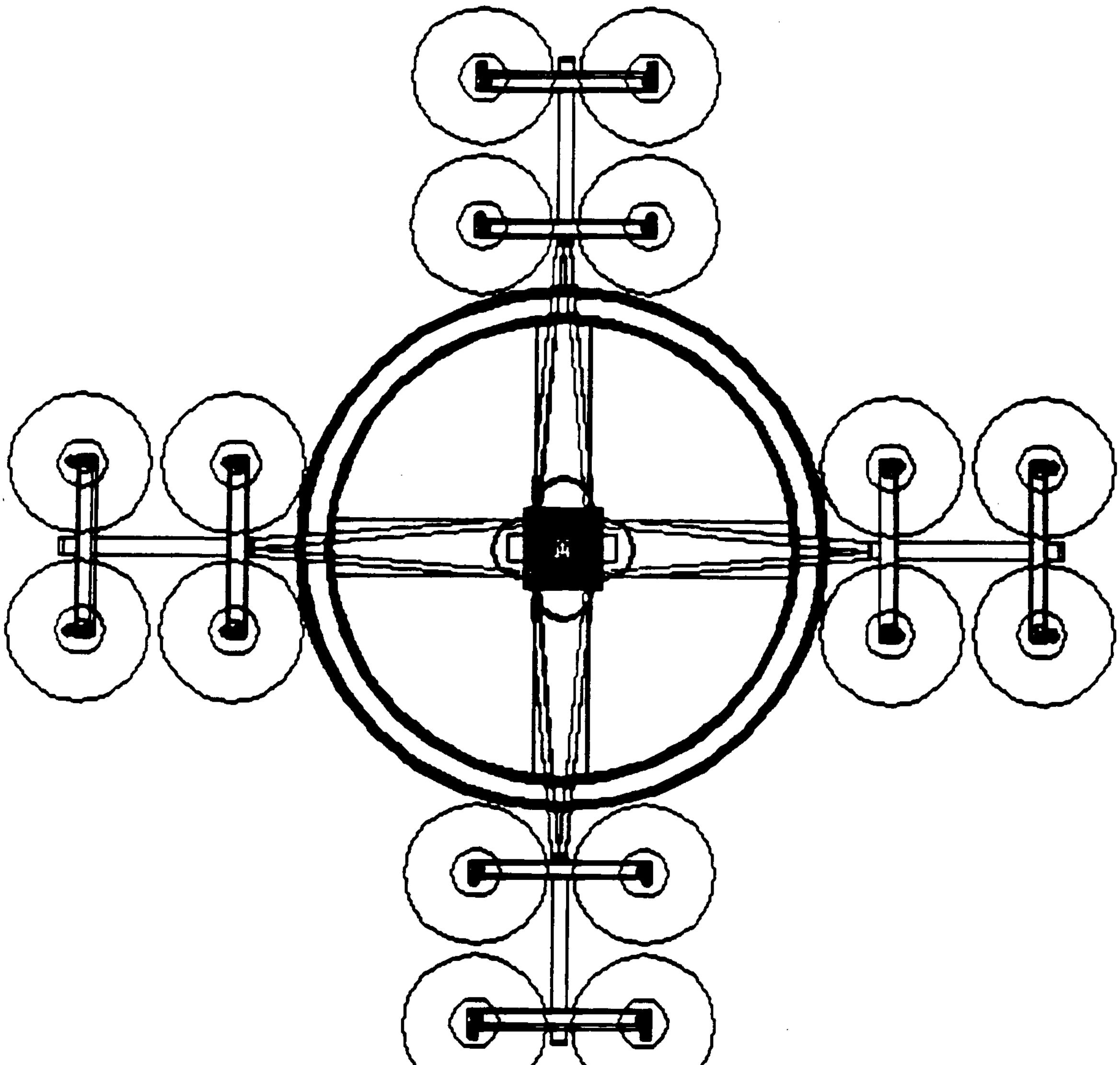

National Aeronautics and Space Administration
Universities Space Research Association

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University of Michigan CAMELOT II

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FOREWORD

Project CAMELOT II, the design of an Earth/Mars personnel transport, was completed by the students in Aerospace Engineering 484, "Computer Aided Design", as a team project in the Winter term 1988. It is a continuation and extension of project CAMELOT which was the design project in Aerospace Engineering 483, "Aerospace System Design" in the Winter term 1987. For this project, Aerospace Engineering 484 combined elements of the former computer aided design course format, that is, instruction in and use of CAD/CAE applications software, and the aerospace system design course format, that is, team organization and system design approach. The result was extensive use of geometric modeling and finite element analysis in the design of a spacecraft.

The project group consisted of 59 engineering students organized in 10 teams as identified in the report. Orientation and team organization began in the Fall term 1987 before the course started. All teams were able to begin work immediately at the start of the Winter term and provide a report on their activity at the end of the term. Several students from the course continued to work in the Spring term to do the composition and editing of the final project report.

We gratefully acknowledge the continued support from the National Aeronautics and Space Administration and the Universities Space Research Association in the Advanced Design Program. We especially wish to recognize Stanley R. Sadin, NASA Headquarters, Washington, D.C., and John R. Sevier and Carolynne Hopf, USRA, Houston Texas, for their general support of the program and Karl A. Faymon and Lisa Kohout, NASA Lewis Research Center, Cleveland, Ohio, for their technical support and encouragement throughout the project.

Joe G. Eisley
Professor of Aerospace Engineering
May 27, 1988

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Executive Summary

1. Introduction

Project CAMELOT is a study that was begun during the 1986-87 academic year at the University of Michigan under the sponsorship of the NASA/USRA Advanced Space Systems Design Program. The current study is a continuation and extension of the preliminary work that was reported in reference 1. This paper will summarize the work that was completed in the second phase of Project CAMELOT during the 1987 - 88 academic year. A complete design report will be available in several weeks.

The Project was inspired by two documents: Pioneering the Space Frontier: The report of the National Commission on Space (reference 2) and Elements of a Mars Transportation System, a paper by K. Nock and A. Friedlander (reference 3) both of which described the need for a permanently manned scientific station or base on Mars and the infrastructure necessary for safe and efficient transportation of personnel and cargo to and from such a base. One of the most important components of such an infrastructure would be a personnel transportation system that provided frequent and regular round-trip passage between Earth and Mars as a means of Mars base crew rotation. These spacecraft would travel on cycling trajectories that have the desired characteristic of minimizing the time of flight between the two planets by intercepting their orbits at regular and frequent intervals. Reference 3 has named these spacecraft CASTLE's - Cycling Astronautical Spaceships for Transplanetary Long-Duration Excursions.

The initial study examined the mission objectives, functions and requirements for a crew transportation system in support of a permanently manned scientific station on the planet Mars. Consideration of the trajectories required and the functions that the transportation system would perform led to an initial configuration whose main features were a large rotating torus, a non-rotating boom, two docking ports, a micro-gravity research facility, and three solar dynamic collection clusters. As a result of the requirements and subsequent design to meet these requirements, the initial design team coined the acronym CAMELOT - Circulating Autonomous Mars - Earth Luxury Orbital Transport (in the spirit of Nock and Friedlander's CASTLE).

The purpose of this report is to document the results of the current study, whose aim was to use the configuration generated by the initial efforts as a starting point and analyze and redesign several features of the configuration. No changes were made in the mission objectives or orbital mechanics of the mission, but several key changes have been made in the spacecraft systems and layout.

1.2 Orbital Mechanics

Figure 1.3 is a schematic of the Up-Escalator orbit which was chosen as the baseline or nominal trajectory on which calculations in the second phase of the study would be based. The nominal trajectory was calculated using several standard simplifications, namely:

1. Earth and Mars are in concentric, co-planar, circular orbits around the sun
2. Gravity effects of Mars are ignored.
3. The synodic period of Earth and Mars is 2.135 years

These assumptions result in an up-escelator orbit that has a period of 2.135 years, exactly equal to the synodic period, with a short leg transfer time between Earth and Mars of only 4.5 months and a long leg transfer time between Mars and Earth, of 21 months. By equating the period of the escalator orbit with the synodic period of the two planets, the CASTLE should encounter Earth and Mars in the same relative positions each orbit. The issue is complicated, however, by the fact that the Earth-Mars alignment , while repeating every synodic period relative to each other, does not repeat itself in an inertial reference frame. The Earth-Mars alignment occurs 48.7 degrees further around the Sun each orbital period. This advance in the positions of the planets requires that the semi-major axis of the escalator orbit also be rotated by 48.7 degrees in order for the encounters to occur on a regular basis.

The rotation of the semi-major axis is effected in two ways (in the nominal trajectory). A large portion of the angular change can be achieved using gravitational assist at Earth, and the remainder can be achieved by a small propulsive burn near the aphelion of the orbit. In theory, the full 48.7 degree rotation could be achieved at Earth if a flyby close enough to the center of the Earth could be negotiated . However, calculations show that the required altitude for such a large rotation angle would in fact be below the surface of the Earth. A more realistic approach assumes a flyby altitude of 1000 km from the surface and results in a rotation of 43.7 degrees. This is almost the entire rotation required and a small burn (ΔV) near aphelion provides the remaining 5 degrees of rotation. Figure 1.3 shows where the ΔV is made.

Mission Overview

The CASTLE will move along the Escalator trajectory without stopping at either Earth of Mars. Taxis provide the means of crew transfer to the CASTLE at Earth and Mars flybys. The CASTLE will be inserted into its escalator trajectory soon after assembly and spin up of the torus are completed. This initial insertion is the only time the CASTLE has to be "launched". On all other orbits besides the first one, the CASTLE will be enroute to Mars with two Taxis attached. When approximately five days away from Mars, both Taxis will separate and perform maneuvers to attain an orbit around Phobos, one of the moons of Mars.

At the same time Two taxis will depart the Phobos spaceport for eventual rendezvous with the CASTLE. The Taxis will be required to complete propulsive burns that will allow each Taxi to escape planetary gravity along hyperbolic trajectories that will intercept the CASTLE Escalator trajectory. These two Taxis will remain with the CASTLE until the next planetary encounter. Earth encounter and Taxi transfer will occur in a similar manner. The Earth Taxi base will most likely be stationed in a low Earth orbit (LEO), possibly as a space station.

2. Propulsion

In order for the orbital maneuvers to be effected correctly, various propulsion and attitude control systems had to be designed. These include thrusters to spin up and maintain the spin rate of the torus, engines for initial orbital insertion, engines for the propulsive ΔV to rotate the orbit, and attitude control thrusters for solar alignment.

For the spin of the torus four pairs of thrusters are placed on the torus with their fuel. The actual spin up takes about 4 hours. Orbital insertion from LEO is accomplished with nine liquid hydrogen/liquid oxygen rocket engines which generate about 70000 Newtons of thrust each. The burn time for insertion is approximately 8 hours.

The insertion burn is made with the end of the spacecraft boom and solar collectors facing almost 90 degrees away from the sun. Immediately after insertion a moment is applied to rotate the vessel. This is accomplished by placing three engines near the end of the boom. Each generates from 2500-4400 Newtons of thrust. The entire maneuver takes approximately 1 hour. During this time electrical power must be provided by fuel cells, as the solar collectors will not be in their optimum position.

The fuel required for these burns is tremendous. Large fuel tanks mounted outside the truss of the boom stores the fuel for the insertion maneuver.

Once the solar collectors are oriented towards the sun, a continuous moment of approximately 55 Newtons is provided by nine hydrogen resistojets, each producing about 0.1 Newtons of thrust, mounted at the end of the boom near the main engines in order to keep the collectors pointed at the sun.

The torus must maintain a relatively constant rotation for its artificial gravity to work. As it spins, there will be some frictional forces in the interface which will induce boom rotation. This is undesirable from the purpose of the boom's micro-gravity lab, the resistojets firing to maintain solar orientation and for docking purposes. To prevent boom rotation small thrusters (each can produce about 450 Newtons of thrust) will be mounted along the length of the boom and on the trusses which support the solar collectors.

Due to the nature of the optimized(versus the nominal) up-escalator orbit and its interaction with the orbits of the Earth and Mars, no corrective orbital burn will be required until the third, fourth and fifth orbits. The corrective orbital burns require no additional rotation, as they are to be perpendicular to the plane of motion; a delta V away from the sun. The delta V required can be accomplished by five main engines firing at full power, over a period of approximately 1 hour at the aphelion of the orbit.

Other considerations are engine lifetime and fuel storage. Because the initial insertion uses 80% of the effective lifetime of the nine main engines (10 hour lifetime) and they are not needed again until the third aphelion, they will be removed when the CASTLE reaches the Earth for the first time. At that time a pod with only five engines of the same type will be attached, to be used for the orbital corrections. Additional fuel tanks for LH_2 and LOX will be included in this pod. As the total time required for orbital corrections is less than 4 hours, the maintenance required for these five engines should be minimal.

During the course of the mission the LH_2 and LOX will suffer from a certain amount of boil-off due to solar radiation. To minimize boil-off the main engines are shielded from their fuel tanks by a thermal insulator. The shape, insulation and paint of the tanks are also designed to minimize boil-off. A small amount of extra fuel will be carried in each tank as a safety factor. Because the temperature of LOX is higher than that of LH_2 it is less vulnerable to radiation induced boil-off. As such the LOX tanks will be placed sunward of the LH_2 tanks and provide further shielding for them.

3. Docking

The primary goal of the CASTLE is to transfer personnel and equipment between Earth and Mars. As described in the introduction, the CASTLE travels on a cycling trajectory. After its initial insertion into this trajectory it never stops moving. It is therefore necessary for the passengers to rendezvous with the spacecraft as it flies by the planets and to disembark as it approaches the planets. This necessitates that a location and facility to which the orbital transfer vehicles (or "Taxis") can dock, and from which they can depart, be include on the spacecraft.

A two module docking facility has been designed with significant changes over the earlier study. The two modules are the Docking and Operations Capsule (DOC), and the Cargo Acquisition Bay (CAB).

The DOC contains all the operations and control for:

Berthing of Aeroassisted Manned Transfer Vehicles (Taxis)
Mobile Remote Manipulator System (MRMS)
Cargo Acquisition Bay (CAB)
Extra Vehicular Activity (EVA)

It contains the two berthing ports where the Taxis mate with the CASTLE. The berthing is done using a system of two arms for each port that attach to the taxis after they have achieved rendezvous, and berth them to the CASTLE. The DOC also contains an airlock chamber that is used for transfer of large cargo between the CAB and the rest of the CASTLE. This airlock is the interface to the unpressurized CAB and serves as an EVA staging area. In addition, the airlock has a contingency exit leading directly to the outside and can be used as a hyperbaric chamber in case of an emergency.

The Cargo Acquisition Bay (CAB) was designed to be a multi-purpose port for transfer of all non-manned cargo and also to serve as a multi-purpose space platform for a number of uses seen and unforseen. The CAB uses two MRMS to transfer the cargo which is brought up on the supply ships. These MRMS are mounted on tracks, allowing them to traverse the entire non - rotating structure of the CASTLE. In addition, the CAB is also used for:

Platform for repair and maintenance of the CASTLE
Taxi maintenance
Space based manufacturing
Long duration exposure experiments

4. Power Systems.

The CASTLE power requirements are fundamental to the design of its power system. Three important power levels (Minimum Life support, Normal Operations, Minimum Power Available) have been detailed in the original CAMELOT report. Power allotments for each of these levels have been revised due to changes implemented in the design of the CASTLE by Project CAMELOT II. The revised figures are:

Minimum Life Support	: 200 kW
Normal Operations	: 350 kW
Minimum Power Available	: 400 kW

The system has been designed for the Minimum Power Available level as this will allow a 15% safety factor while maintaining Normal Operations power as well as providing extra power for experimentation.

Based on the above power allotments, as well as other considerations, it was determined that a solar dynamic power system would be used as the Primary Power system for the CASTLE. A solar dynamic power system consists of an Energy Source subsystem, a Power Conversion subsystem, and a Radiator subsystem. The Energy Source subsystem is made up of a solar concentrator which focuses energy from the sun into a receiver. The Power Conversion subsystem consists of a heat engine which converts thermal energy into electricity by using an alternator. The Radiator subsystem rejects the waste heat from the heat engine.

The CASTLE solar dynamic system has sixteen solar dynamic units. At the ends of each of four booms, which are spaced evenly and extend out from the main truss, are four solar dynamic units. Each of the sixteen concentrators will be of the Newtonian parabolic type. The sixteen heat engines are free piston Stirling engines with linear alternators and the radiators of the Curie Point Radiator (CPR) design.

The Reserve Power system, which provides at least Minimum Life Support power when the solar dynamic system is not in operation, consists of hydrogen-oxygen regenerative fuel cells.

Conditioning and regulation of all power generated on the CASTLE is done by a Power Management and Distribution system (PMAD) of 20 kHz, 440 volts, AC power relying upon expert systems.

The integration of the three systems (Primary, Reserve, and PMAD) meets all the criteria necessary for the design of a reliable, low mass, long lifetime, autonomous spaceborn power system.

5. Interface

One of the major design requirements for the CASTLE is the 0.4g living environment for the crew, provided by the rotating torus. However, the systems which are required by the torus in its operation, specifically electricity, communications, docking operations, and orbital insertion, require a section of the CASTLE which is non-rotating. This non-rotating section houses the solar dynamic power units, orbital insertion engines, and communications systems, all of which require careful control and precise orientation throughout the mission. Other important operations undertaken in the non-rotating section are the docking of taxis and micro-gravity research. All of these systems are included in the non-rotating boom of the CASTLE design. The integration of the boom with the torus, the non-rotating with the rotating, presents unique problems to the design and operation of the CASTLE as there must be a section of the ship which is able to rotate and remain stationary simultaneously. This section of the CASTLE is called the interface.

A system has been devised to maintain a zero relative rotation between the torus and the boom, and this system is at the heart of the interface design. In order to join the torus and boom of the CASTLE, each section will be connected to a rotating or non-rotating section of the interface, respectively.

These sections of the interface are arranged, roughly speaking, as concentric cylinders. The outer cylinder is the rotating portion of the interface and is connected to the hub of the torus. The inner cylinder is the non-rotating portion of the interface and is connected to the truss structure of the boom and the micro-gravity lab. Bridging the cylinders are two sets of bearing races. The angular contact bearings which are contained in these races allow the torus to rotate while the boom remains stationary. The major problem which arises is friction in the bearings. This will cause the boom to 'bleed' energy from the torus, thus decreasing the rotation rate of the torus and increasing rotation of the boom. While much of the friction problem may be dealt with by proper choices in bearing and race materials and lubricants, even the best materials solution would still be subject to friction, and any friction will cause boom rotation. Therefore, another solution is necessary to overcome the friction remaining after anti-friction materials are incorporated into the design. The solution is a combination of a drive gear around the circumference of the interface with four electric drive motors, called the Torque Compensation System.

The Torque Compensation System uses thrusters on the solar array booms, four 1/4 hp (137.5 W) feedback controlled, AC induction motors, and a gearing system in the hub. When the torus slows down due to friction (i.e.,. the nonrotating boom begins to rotate), thrusters on the solar arrays will be fired to cancel out the angular momentum of the non-rotating boom. Simultaneously, the AC motors will kick in to bring the angular velocity of the torus back up to 3.2 rpm.

Load Transfer

The interface also serves as the means of transferring thrust loads from the boom to the torus. These forces will be greatest during insertion and other correction burns. The boom truss structure carries the loads to the interface through the load transfer cone, which connects the end of the boom to the inner cylinder of the interface. The angular contact ball bearing system then transfers the forces to the outer cylinder of the interface which is connected to the hub of the torus. The material selection for these components was dictated by the maximum forces exerted on the interface during insertion, while the structural integrity of the interface components was determined by a finite element analysis.

Personnel and Crew Transfer

A third concentric cylinder located within the inner, non-rotating portion of the interface, called the egress tube, serves as a hallway through which personnel and equipment are transferred in a shirtsleeves environment. The egress tube is pressurized from the micro-gravity lab section of the boom, and at the hub end of the egress tube, there is a hydraulically extendable connection which then mates with the elevator to form a pressurized hallway.

Power and Data Transfer

Since electricity is generated in the solar arrays positioned on the nonrotating boom, the majority of the power generated will have to cross the interface to get to the torus. Power transfer is completed by utilization of up to six electrical conducting rollers located between the two surfaces. This method has a 99% efficiency and offers a very small frictional contribution.

Continuous communications flow through the interface is also essential. Data transfer and communication is accomplished through two sets of six laser transmitters, one on either side of the gap, paired with two sets of optical collectors found directly opposite.

6. Elevator

As described in the docking and interface chapters, personnel and supplies board the spacecraft via the docking ports located in the non-rotating boom. In order to reach the torus, which is the main living and working area of the CASTLE, they must travel through the interface where they enter an elevator car and travel out to the torus. Conversely, to disembark at Earth and Mars, or to work in the micro-gravity module, or to perform EVA or repairs in the CAB, they are required to travel in toward the interface. In order to facilitate this movement back and forth, an elevator has been designed that not only moves "up" and "down" the shafts, but also rotates to compensate for and eliminate disorienting and uncomfortable effects due to coupling of the various velocities of the spacecraft, the elevator and the rotating torus (know as the Coriolis effect).

The elevator subsystem consists of an elevator cabin that rides in a cradle inside the shaft. The cradle consists of two circular tracks separated from the outside of the cabin by two rings of ball bearings which allow the cabin to rotate within the tracks to compensate for the coriolis force. Four rails attach to the circular tracks and orient the cabin within the shaft and allow it to move up and down the shaft. An electric motor uses a pulley system to drive the cabins motion from the torus to the hub, but gains potential energy in doing so. This potential energy is then used to power motion in the opposite direction, thus minimizing power requirements.

The shaft is unpressurized and therefore the pressurized cabin must mate perfectly with the interface entrance and with the torus entrance in order to avoid pressure losses. This is accomplished by use of telescoping airlocks at the interface and torus that move towards the cabin (which is stationary at the hub and spinning with equal velocity at the torus) and lock onto the doorway, thus creating a pressurized passage.

Only tow of the four shafts have been designed to house elevator cabins, These two are 180 degrees opposed so as to minimize walking distances within the torus. The cabins move with a 2 m/s radial velocity thus covering the 35 m spoke in 17.5 seconds. Actual travel time, including acceleration and deceleration as well as interface and habitat matching, is thus 50 - 70 seconds per trip.

7. Radiation Protection and Torus Structural Analysis.

One of the most significant changes to the original configuration of the CASTLE concerns the form of protection from solar radiation, most specifically charged particles produced by large solar flares. Radiation shielding is a problem inherent with long term space travel away from the protective atmosphere and magnetic field of Earth. During an Earth-Mars mission several intense solar flares are likely to be encountered and any craft expected to deliver its crew alive must overcome these solar events. Adding material to the spacecraft will work but requires so much extra mass that fuel requirements and mission constraints become excessive. For that reason the possibility of using superconducting cables to generate a magnetic field about the torus and thereby deflect virtually all of the impinging radiation away from the habitat area was investigated. It is estimated that the magnetic field scheme of protection requires about half as much mass as does the passive method described in CAMELOT I. Based on early research by NASA and the DoD, and recent major developments in high temperature superconductivity, it was decided to replace the passive radiation shielding system of CAMELOT I (5 to 25 cm. thick aluminum walls) with an electromagnetic shield.

Recent advances in superconductor technology now allow the superconductivity to occur at temperatures as high as 120K. By the twenty-first century, many scientists believe that the critical temperature may be as high as 300K. In its simplest form a superconducting magnet consists of a spool of superconducting wire, an insulated container with provisions for maintaining the operating temperature below the critical limit, and a power source for starting ("charging") the magnet. The superconducting material (which consists of brittle ceramic fibers embedded in a metallic, often copper, medium for ductility) has the unique property of exhibiting zero resistance to the flow of direct current when operating below its critical temperature and critical current density. The material which appears to have the greatest potential for development as a high critical temperature superconductor is yttrium-barium copper oxide ($YBa_2Cu_3O_{7+d}$).

To protect the interior of the torus it was determined that a magnetic (so called B) field of 0.43 Tesla is required. Four superconducting cables, each of 2.4 inches outer diameter, are required to obtain the necessary field. Two cables are positioned along the inner radius of the torus while the other two cables are positioned along the outer radius of the torus. The cables are placed between the inner wall (which acts as a pressure vessel to maintain suitable air pressure within the habitat) and the outer hull of the ship (which acts to protect the ship from damaging collisions with particles drifting in space). By positioning the cables this way the cables are protected from colliding with space particles and the hull serves as additional insulation to help Having four separate cables is a safety feature. If any cable happens to fail, the other cables serve as adequate backup while repairs are made.

The operating principal is relatively simple. A low voltage (70 volts), high current supply is needed. Once the magnet is energized the power supply is removed. The current within the cables will continue to circulate and maintain the field as long as the cable is kept below the critical temperature. The beauty of the superconducting system is that while a conventional magnetic system would require megawatts of continuous power the superconducting system would require relatively little power for only a short while.

Methods were devised that minimize losses in power as well as maintain the temperature of the coils below the critical temperature and control temperature gradients between the "light" and "dark" sides of the torus.

Structural Requirements

As expected, the four superconducting cables will have tremendous forces acting on one another when they are fully charged. The force is expected to be on the order of 2 meganewtons per meter. In addition, forces due to propulsive burns, torus rotation, thermal stresses and internal pressure all contribute to the overall structural loads. Finite element methods were used to ensure that the structure will withstand these loads. The current design is probably overly conservative and can be optimized further.

8. Internal Habitat Design

One of the primary objectives of Project CAMELOT was to provide a "Luxurious" environment for the passengers (compared with previous spacecraft) and to do it affordably. The chief component of this comfort is the rotating torus which provides a 0.4 g gravity field in order to counteract the negative physiological and psychological effects of microgravity. This level of gravity poses its own set of problems, especially as related to positioning of furniture and equipment and distribution of rooms and facilities.

In order to optimize the benefits of the low gravity field and minimize the discomfort due to the rapid rotation rate required to produce this artificial gravity, a detailed study of all the rooms and their contents was performed. In addition, launch vehicle constraints require that the torus be broken up into eleven modules of varying sizes, each separated by airlock-type doors. Each of these modules is integrated into the overall ventilation, water supply, waste disposal, and electrical systems. In addition, an innovative mass balancing system has been designed which utilizes water tanks beneath the torus floor to compensate for movement of people and objects within the torus.

Detailed floor plans were developed indicating location, usage, utilities, lighting, floor space and all other variables required to optimally design and locate a room. Crew comfort and safety remain the chief driving factors of the design and are responsible for most decisions made.

9. Truss Design

Most of the components of the CASTLE are very sensative to vibration and shocks and require adequate protection from loads that would cause these effects. The propulsive burns for orbital insertion and axis rotation described earlier are such sources of such loads. Other sources include attitude control thrusters and taxi docking maneuvers.

In order to protect the spacecraft, a truss structure was designed that carries most of the loads away from the various modules which are housed within the truss. The main component of the truss structure is the main boom which houses the propulsion system, the taxi - docking ports and cargo acquisition bay, the solar dynamic trusses, the micro-gravity facility and the interface. The solar dynamic trusses make up the remainder of the truss work.

All the sources of impulsive and large, constant loads were determined and the trusses were designed based on maximum loading and location of the loads. The main boom is of the single bay, single laced four element design, with a 1 meter square cross-section per corner element. A single bay thus has an 8 meter cross section which allows for the containment of all the modules within the boom. The modules are connected to the corners of the truss with viscous dampers that dampen out any loads travelling along the boom.

The solar booms are made up of the same truss elements arranged in a slightly different pattern. The use of the same design allows for redundancy and interchangeability of elements and nodes used to connect the elements. The solar booms are 35 meters tall and hold the solar collectors beyond the range of the docked taxis.

All elements of the trusses are made of graphite-epoxy composite clad by aluminum. This material is considerably stronger and lighter than traditional aluminum and withstands radiation and temperatures encountered in space.

Finite element analysis of entire spacecraft, held together by the trusses, verified that the maximum stresses in the truss did not exceed yield. In addition, deflections are seen to be very small and optimization should lead to considerable weight savings. Natural modes and rigid body dynamics of the CASTLE were also studied using finite element methods and yield similar positive results.

10. Assembly

As indicated in earlier chapters, the CASTLE will be assembled in a Low Earth Orbit. The orbit chosen has an altitude of 1113.6 km and is inclined to the equator at an angle of 28.5 degrees. This orbit was selected to minimize cost of launching the components, final insertion into cycling trajectory, and radiation hazards to the assembly crew.

In order for the assembly sequence to proceed as outlined, it is assumed that a Heavy Lift Launch Vehicle (HLLV) capable of transporting the maximum load of 209,824 Kg to the construction site will have been developed. Such an HLLV would be similar to the one described in NASA TM 86520 with a few minor modifications. In addition, development of several key technologies is assumed. These include robotics and artificial intelligence, telerobotics and remote manipulator technologies. In addition, it is assumed that the LEO Space Station will be in place, along with a manned Lunar Base.

Several techniques and tools have been designed that allow for a small crew, inhabiting two Space-Station like modules, to easily and efficiently complete the assembly. Specially designed devices allow for the orientation and mating of the eleven torus modules, the four radial elevator spokes, the hub and interface assemblies, the numerous trusses and the solar boom and main boom assemblies. Some of these devices are modifications of current designs, others are original and very innovative.

A detailed HLLV launch and assembly sequence has been devised that calls for assembly to take from four to twelve months, with a further six month period devoted to system verification and startup. Contents of each HLLV or Shuttle II launch are described and crew activities are mapped out for he entire sequence.

A cost analysis including all development, terrestrial manufacture and orbital assembly costs (but excluding development of the global infrastructure such as Space Station, Shuttle II, HLLV, Lunar base and various technologies) was performed and indicates that the total cost from initiation of development to insertion into cycling trajectory will be on the order of $ 150 Billion in 1988 dollars.

11. Conclusion

A Cycling Spacecraft for regular, frequent transit between Earth and a Mars base has been analyzed and developed beyond the initial configuration study. Analysis has led to numerous design modifications and improvements, as well as providing more detailed system definition. Major components of the second phase study include a breakthrough detailed design of an interface between a rotating portion of a spacecraft to a non-rotating portion, an elevator system that changes orientation to eliminate coriolis forces, an electromagnetic radiation shield that significantly reduces the mass of the spacecraft and a detailed assembly sequence and cost analysis. In addition modifications to the propulsion and the power generation subsystems, taxi docking facilities and internal layout design have led to a more efficient, significantly more reliable and more comfortable vehicle. Finite element stress and overall dynamic analysis has verified much of the system and indicates the validity of the design. Computer simulation of many moving components, including torus rotation, elevator and interface operation, and attitude control mechanisms further validate and support the design.

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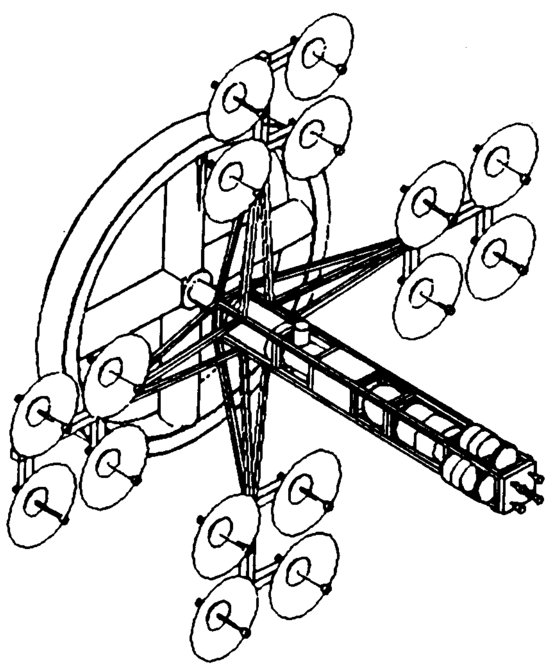
Special thanks to Jeff Farmer and Paul Garn at the NASA Langley Research Center for their assistance.

Chapter One

Introduction



1.1 Introduction

Project CAMELOT is a study that was begun during the 1986-87 academic year at the University of Michigan under the sponsorship of the NASA/USRA Advanced Space Systems Design Program. The current study is a continuation and extention of the preliminary work that was detailed in the Project CAMELOT report (reference 1).

The Project was inspired by two documents: Pioneering the Space Frontier: The report of the National Commision on Space (reference 2) and Elements of a Mars Transportation System, a paper by K. Nock and A. Friedlander (reference 3), both of which describe the need for a permanently manned scientific station or base on Mars and the infrastructure necessary for safe and efficient transportation of personnel and cargo to and from such a base. The recent "Ride Report" also called for development of a Mars base as a long term NASA goal.

One of the most important components of such an infrastructure would be a personnel transportation system which provides frequent and regular round-trip passage between Earth and Mars as a means of Mars base crew rotation. These spacecraft would travel on cycling trajectories that have the desired characteristic of minimizing the flight time between the two planets by intercepting their orbits at regular and frequent intervals. Reference 3 has named these spacecraft CASTLE's - Cycling Astronautical Spaceships for Transplanetary Long-Duration Excursions.

The initial CAMELOT study examined the mission objectives, functions, and requirements for a personnel transportation system in support of a permanently manned scientific station on the planet Mars. Consideration of the required trajectories and the necessary functions that such a transportation system led to an initial configuration whose main features were a large rotating torus, a non-rotating boom, two docking ports, a micro-gravity research facility, and three solar dynamic collection clusters. As a result of the mission requirements and subsequent design to meet these requirements, the initial design team coined the acronym CAMELOT - Circulating Autonomous Mars- Earth Luxury Orbital Transport .

The purpose of this report is to document the results of the current study, whose aim was to use the configuration generated by the initial efforts as a starting point to analyze and redesign several features of the configuration. No changes have been made in the mission objectives or orbital mechanics of the mission, but several key changes have been made in the spacecraft systems and layout. Some of the important changes are:

1. The propulsion system has been modified considerably to better effect the orbital maneuvers.
2. The solar dynamic power system has been modified and augmented.
3. The elevator system design has been significantly enhanced and defined.
4. An interface between the rotating and the non-rotating portions of the spacecraft has been designed.
5. The interior layout of the spacecraft has been modified and improved.
6. An electromagnetic sheilding system has replaced the passive radiation sheilding system.
7. Berthing ports have been designed and analyzed.

This report will provide details of the analysis that led to these design changes. In order to better understand the details of this report, the executive summary of the initial configuration report (reference 1) is attached as appendix A. In the remainder of this report, the current study will be referred to as CAMELOT II and the previous work will be referred to as CAMELOT I. What follows is a brief description of the configuration of the spacecraft as designed in the earlier study, and discussions of the mission and cycling trajectory of Project CAMELOT.

1.2 Project CAMELOT and the US Space Program

Immediately following the tragic loss of the Space Shuttle Challenger in January 1986, NASA, the federal government and numerous scientific and civilian agencies began to re-evaluate and study the role of man in space and the long term goals of the US Space Program. A number of reports have since been published, each calling for essentially the same long term goals including development of a LEO Space Station, returning to and developing the moon, manned and unmanned missions to mars, and eventually a permenantly manned base on Mars.

Project CAMELOT assumes that all of these goals will be achieved in the near future. Based on a hope that funding and support will be forthcoming from the appropriate agencies and industry, we have developed a scenario which has every possibility of being realized. The scenario includes the following timelines: We envision a fully operational LEO Space Station by 1996, finally placing the US in space on a permenant basis; a return to the moon by 2003, and a permanent lunar base and mining facility by 2007; a first manned Mars mission (perhaps done in peaceful cooperation with the Soviet Union) by 2010; a manned Mars base by 2020, and a Mars/Phobos mining facility by 2025. Within this scenario Project CAMELOT would become operational before the year 2035, transporting up to twenty engineers, scientists, and support personnel to and from Mars on a regular and frequent schedule. By this time operations on Mars and Phobos will be well underway. Production of propellants and mining of minerals will be financially self-supporting. Export of space-based products to Earth will have created an industry capable of sustaining itself. Plans will have begun to mover further out into the solar system, perhaps to Saturn and Jupiter.

We believe that the next Administration, along with NASA and the Aerospace community as a whole, must take it upon themselves to publicly and financially back the Space Program, thereby laying the foundations for increased and more consistent expansion of the technologies required to develop the space infrastructure that is necessary to support projects the size and scope of CAMELOT. With such backing untold benefits can be reaped from both the technologies that will be developed on Earth, and the products and processes that will undoubtedly spring from industrialization and experimentation in space. Without such backing the future of mankind in space will undoubtedly be as fitfull, sporadic and dangerous as it has been these first twenty years.

Most of the students who participated in both phases of the CAMELOT study have graduated and are working in various Aerospace related fields. The work we are presenting here is the culmination of our entire undergraduate engineering training and is our contribution to the ever growing databank of ideas that may very well be implemented within our life time. We feel that this report identifies several key technology issues that require immediate attention if succesful implementation is to occur, and that could contribute significantly to numerous other projects that are bound to be studied in the next half century.

Project CAMELOT, as presented in this and the previous report, is a logical extension of the long term NASA goals, just as the LEO Space Station is the logical extension of the current capabilities and programs. The two reports describe a system which is based on current or attainable technology and could be implemented by or before the year 2035. All that is required for this system to be useful and operational is for the support infrastructure to be developed, the long range goals set in stone and striven for and supported on all federal and private levels, and for students, educators, private industry, and federal administrators to work together and ensure that the United States remains at the forefront of technology and scientific exploration.

1.3 Initial Configuration

1.3.1 Introduction

The mission objective for the CASTLE is to provide comfortable and regular transportation for a crew of 20 people between Earth and Mars. The emphasis on comfort and reliability necessitated considerable effort toward the design of the living and working sections of the spacecraft. In addition, all the support systems required to ensure crew comfort and safety had to be designed. These systems include the power generation system, the propulsion system, the docking bay, the radiation and micrometeoroid shielding systems, the truss structures for support of the various componenents, and the communications system. Each of these systems is described below and shown in figure 1.1.

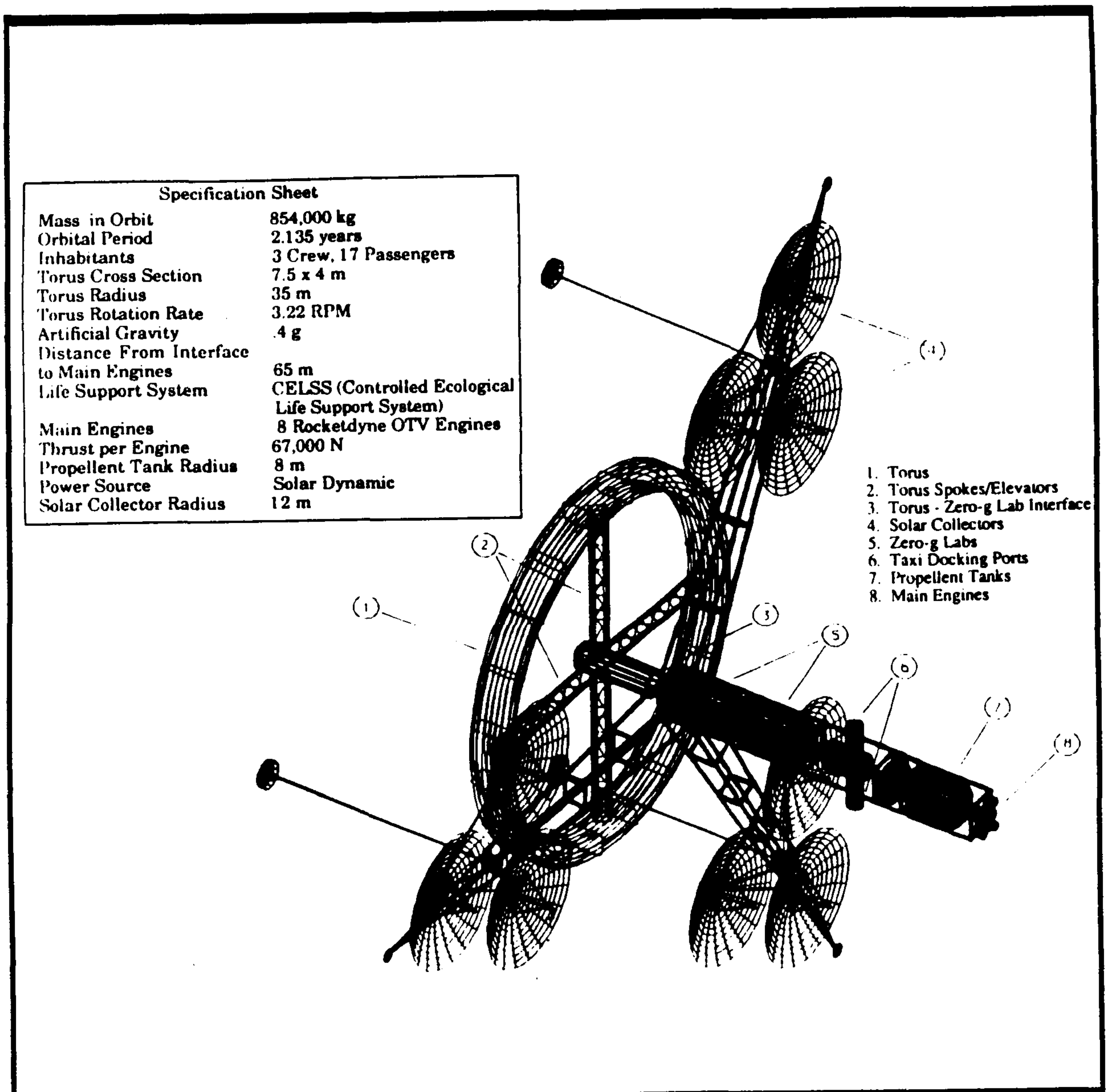


Fig. 1.1 CAMELOT I configuration

1.3.2 Torus

The rotating torus contains the living quarters and much of the working area of the CASTLE. It consists of 20 sections that fit together to form a 35 meter radius toroidal configuration. The cross section is rectangular with a 7.5 meter width and a 4.0 meter height. The torus rotates about the central hub at an angular rate of 3.22 rpm thus producing an artificial gravitational force of 0.4 g's at the outer surface (the floor) which is very similar to the gravity on Mars.

1.3.3 Micrometeoroid Sheilding

A honeycomb structure, 0.05 meters thick (5cm), serves as a passive shield against micrometeoroid strikes in deep space. This sheild was designed based on the numerical probabilities of encountering variously sized particles and is considered adequate protection against dust sized particles which are most likely to pose a threat to the CASTLE. Larger particles are less numerous and thus less likely to strike the spacecraft.

1.3.4 Radiation Sheilding

The CASTLE is lightly shielded using the 5 cm of honeycomb aluminum structure mentioned above as protection against Class 1 solar flares (up to 500 rad) and has several Safe Havens that are heavily sheilded to stop Class 2 and 3 solar flare radiation. The effectiveness of this system requires functional early warning systems that can predict solar flare activity and allow sufficient time for crew and personnel to move themselves and vital animal and plant life into the safe havens. Each safe haven has only 5 square meters of floor space and yet add considerable mass to the spacecraft because the walls are 25 cm thick aluminum.

1.3.5 Truss Structures

There are several truss structures that have been designed to provide structural and dynamic integrity to the CASTLE. These include the three solar-dynamic collector supports, the main non-rotating boom, and the elevator shaft supporting truss. The main boom truss consists of three members in a triangular pattern located at each of the four corners of a square that surrounds the main boom components. A unit section of this truss consists of a 1.5 meter cube. The other trusses are similar in design.

1.3.4 Power System

The main sources of electrical power for the CASTLE are the nine solar dynamic collection dishes grouped in three clusters of three dishes and located 58 meters from the main boom on large support trusses. The nine 25 meter diameter dishes provide a nominal power supply of 400 kW at aphelion, the furthest distance from the sun, and thus have the capability to provide significantly more power when closer to the sun.

1.3.5 Communications System.

Three communications towers are located at the end of the trusses supporting the solar collection equipment. The communications dishes are able to rotate 180 degrees and extend 10 m above the truss, allowing for continuous incoming and outgoing transfer of information between the CASTLE and Earth, Mars, and other vehicles such as incoming Taxi's.

1.3.6 Micro-gravity Research Facility

Two modules, each 15 meters long, are located in the non-rotating main boom, so as take advantage of the micro-gravity environment for various research and maintenance activities. They are located 10 meters behind the interface and are designed to provide laboratories for scientific experiments, recreation facilities, and maintenance and repair facilities.

1.3.7 Taxi-Docking Ports

Two docking ports are located at the end of a 15 meter module that links the docking area with the micro-g section, and are configured 180 degrees opposed to each other. A 3 meter diameter egress tube runs the length of the module and ends in a 5 x 5 meter storage room. Personnel and cargo move from the taxi into the storage room and then through the pressurized egress tube into the mcro-g section. From there they enter the interface and are then moved out to the torus via the elevator.

1.3.8 Propulsion System.

The propulsion system is located 65 meters away from the torus on the main boom. Two tanks contain the propellant for the eight main engines which are located at the very end of the boom. A large tank (11.08 meters long and 8 meters in diameter) contains liquid hydrogen and a smaller tank (4.7 meters long and 8 meters in diameter) contains liquid oxygen. Both tanks are located within the boom trusswork and are designed to be removed rather than refueled.

1.3.9 CELLS: Closed Ecological Life Support System.

The Life Support Systems for the spacecraft are self contained and make up a closed ecological cycle. Almost all food, both plant and animal, are grown onboard in appropriate locations. In addition, all water, air and waste purification and treatment are performed via the plants and other mechanisms. Minimal resupply of foods and water are required every orbit.

1.4 Orbital Mechanics

1.4.1 Introduction

As described in the introduction, the mission of Project CAMELOT is to provide comfortable and frequent means of transportation between Earth and Mars in support of a permanently manned scientific base on Mars. There are several means of providing such transportation, one of which is the concept known as a circulating trajectory. The idea of using such a trajectory was first studied in detail by the astronaut Edward Aldrin. He began his work in 1984 and has developed his ideas to the point where the "escalator-orbit" was endorsed by the National Commision on Space in their final report published in 1986 (ref. 2). Other noted astrodynamicists have continued the work begun by Aldrin and have tried to optimize the orbital maneuvers required by the spacecraft, thus minimizing the necessary fuel and the time of flight while maximizing the frequency of orbit repetition.

CAMELOT I includes a detailed description of an optimized cycling trajectory between Earth and Mars, based on a paper by J. Nock and A Freidlander (ref. 3). CAMELOT II did not attempt to modify the orbital mechanics that are laid out in reference 1, thus all calculations in CAMELOT II are based on the "Nominal Trajectory" and the "Optimized Trajectory" that was discussed in the CAMELOT I report . A brief description of the nominal trajectory is given here.

1.4.2 Nominal Trajectory

Escalator Orbits

The orbits of Earth and Mars lend themselves very well to the use of Circulating Trajectories for transportation between the two planets. As the name suggests, the circulating trajectory is a heliocentric (centered about the Sun) orbit that repeats itself indefinately. Several kinds of circulating trajectories have been studied, including VISIT orbits (ref. 4), Conjunction transfer orbits, and Escalator orbits.

The Escalator class trajectory consists of two orbits known as the Up and the Down Escalators. The two orbits have similair orbital parameters except that the Up Escalator has its short transit time of 4.5 months between Earth and Mars and a 21 month transit from Mars back to Earth, whereas the Down Escalator has its long transit time of 21 months between Earth and Mars and the shorter leg on the return from Mars to Earth.

In an ideal situation both the Up and the Down Escalator orbits would be used to minimize the length of travel time for any passengers, be the going to or coming from Mars. However, in the interest of financial savings, the transportation system must be able to function with only one of the two options available. For this reason Project CAMELOT has chosen the Up Escalator as the nominal trajectory upon which to base the design of the spacecraft.

Orbital Parameters

Figure 1.3 is a schematic of the Up-Escalator orbit which was chosen as the baseline, or nominal, trajectory on which calculations in the second phase of the study would be based. The nominal trajectory was calculated using several standard simplifications, namely:

1. Earth and Mars are in concentric, co-planar, circular orbits around the sun
2. Gravity effects of Mars are ignored
3. The synodic period of Earth and Mars is 2.135 years

These assumptions result in an up-escalator orbit that has a period of 2.135 years, with a short leg transfer time between Earth and Mars of only 4.5 months and a long leg transfer time between Mars and Earth of 21 months. By equating the period of the escalator orbit with the synodic period of the two planets, the CASTLE should encounter Earth and Mars in the same relative positions on each orbit. The issue is complicated, however, by the fact that the Earth-Mars alignment, while repeating every synodic period relative to each other, does not repeat itself in an inertial reference frame as shown in figure 1.2. The Earth-Mars alignment occurs 48.7 degrees further around the Sun each orbital period. This advance in the positions of the planets requires that the semi-major axis of the escalator orbit also be rotated by 48.7 degrees in order for the encounters to occur on a regular basis.

The rotation of the semi-major axis is effected in two ways (in the nominal trajectory). A large portion of the angular change can be achieved using gravitational assist at Earth, and the remainder can be achieved through a small propulsive burn near the aphelion of the orbit. In theory, the full 48.7 degree rotation could be achieved at Earth if a flyby close enough to the center of the Earth could be negotiated . However, calculations show that the required altitude for such a large rotation angle would in fact be below the surface of the Earth. A more realistic approach assumes a flyby altitude of 1000 km from the surface and results in a rotation of 43.7 degrees at Earth. This is almost the entire rotation required and a small burn (ΔV) near aphelion provides the remaining 5 degrees of rotation. Figure 1.2 shows where the ΔV is made near aphelion.

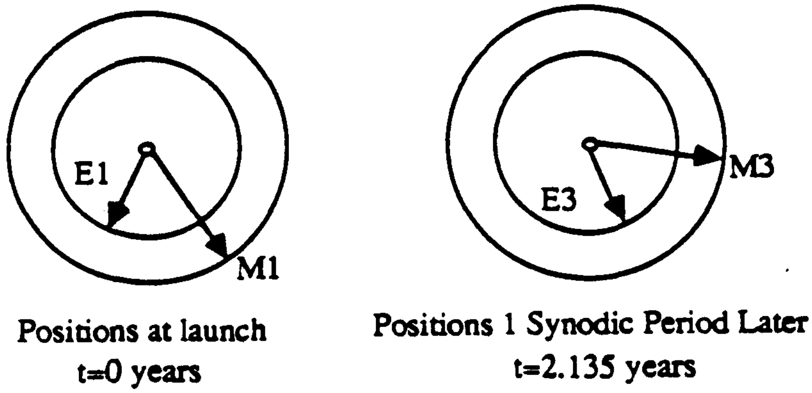


Fig. 1.2 Constellation Rotation Per Synodic Period

In figure 1.2 Earth and Mars are shown at their relative positions at the time the CASTLE leaves Earth for the first time. In the next frame they are shown one synodic period later when the CASTLE is again passing by Earth. Earth and Mars are in the same positions relative to each other, but this constellation has rotated by 48.7 degrees relative to the initial positions.

Optimized Trajectory

Given the initial orbital parameters an optimized Up Escalator trajectory was then calculated in order to minimize the ΔV required at aphelion. This optimization is still based on a circular, coplanar model and uses the flyby altitudes at Earth and Mars, along with the ΔV, as the variables. The Optimized orbital parameters are shown in table 1.1.

Data for Optimized Up Escalator Orbit

Time of Flight from Earth to Mars	4 months 28 days
Time of Flight from Mars to ΔV	10 months 28 days
Time of Flight from ΔV to Earth	9 months 23 days
Transfer Angle Between Earth and Mars	132.8 degrees
Closest Approach to Earth	1,000 km
Closest Approach to Mars	16,300 km
ΔV Required near Aphelion	220 m/s

Table 1.1 Optimized Orbit Data

Figure 1.3 shows one cycle of the nominal (not optimized) Escalator trajectory with E1 and M1, E2 and M2, E3 and M3 indicating the positions of Earth and Mars at Earth flyby, Mars flyby and second Earth encounter, respectively. The numbers on the figure are all time intervals in months.

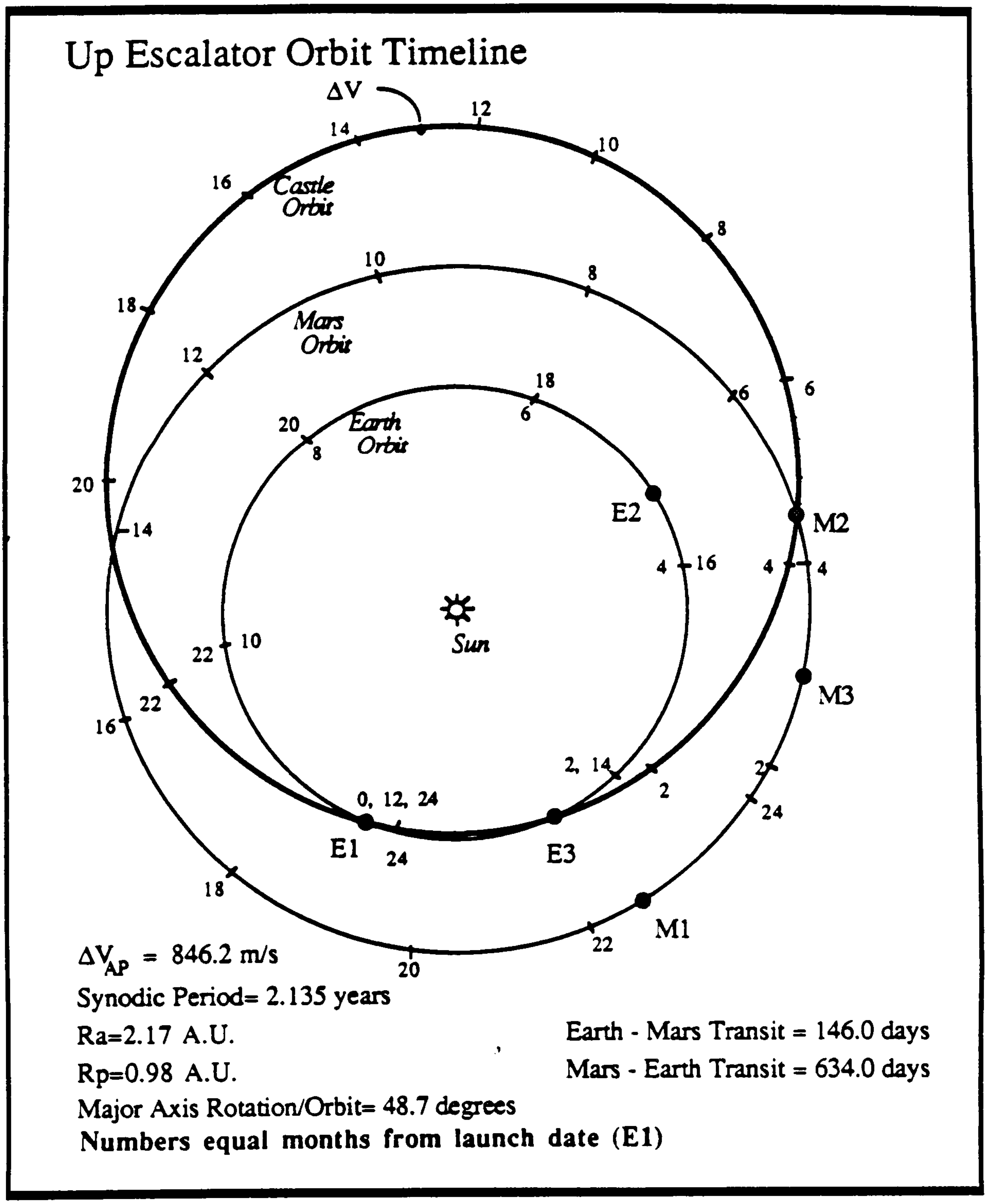


Fig. 1.3 Up Escalator Orbit Timeline

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1. Space Systems Design Class, " A Cycling Transportation System in Support of a Manned Mars Base", Project CAMELOT, Department of Aerospace Engineering, The University of Michigan, 1987.

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Special thanks to Jeff Farmer and Paul Garn at the NASA Langley Research Center for their assistance.

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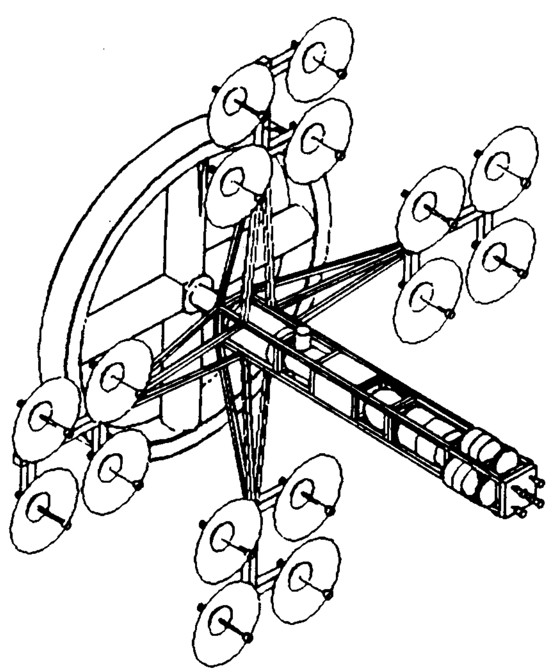
Chapter Two

Propulsion



2.1 Introduction

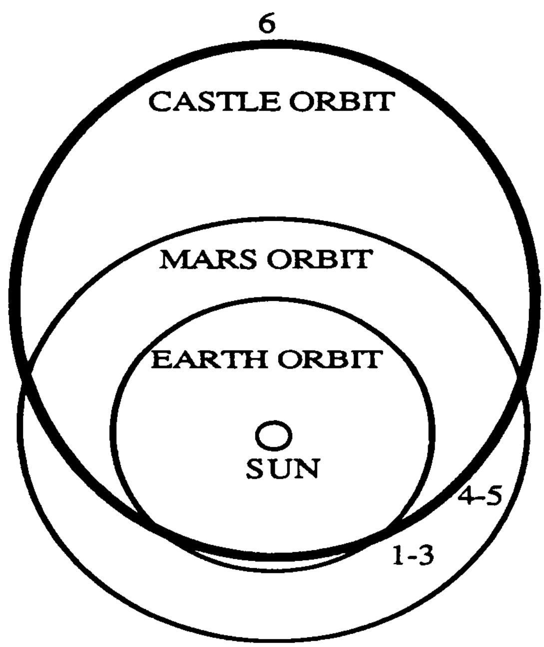
In order for the CASTLE to successfully traverse its designated orbit between Earth and Mars, it must have a propulsion system designed to meet the specific needs of the spacecraft. These specific needs of the CASTLE are a function of the spacecraft mass and geometry as well as a function of the propulsive manuevers required for the CASTLE. Two needs of the CASTLE in particular greatly influenced the design of the propulsion systems: the need for the spacecraft to have a constant solar orientation and the need of the spacecraft to maintain a rotataing torus and nonrotating main boom. A listing of the specific needs of the CASTLE propulsion systems is given in figure 2.1

Once the specific needs of the CASTLE propulsion systems were determined, along with the actual geometry of the spacecraft, specific thrust and burn time requirements were formulated. With this knowledge, the propulsion systems were designed. The primary design objectives for the propulsion systems were to minimize fuel masses, burn times, and maintenance requirements. These design objectives were constained, however, by the requirement of not overstressing the physical structure of the vessel with too large an impulsive burn.

What follows in this chapter is an analysis of the propulsive requirements for the CAMELOT mission. The summary will present an overview of the solutions to the CASTLE's requirements as formulated in the CAMELOT II study. This summary is followed by a more thorough examination of the spacecraft's needs and the CAMELOT II solutions to those needs.

<u>Propulsion System Demands</u>

1. propulsion necessary to initially spin the torus.
2. insertion of the spacecraft from low Earth orbit (LEO) into its up-escalator orbit
3. a rotation of the spacecraft to orient its solar collectors towards the sun.
4. maintenance of constant solar orientation throughout the orbit.
5. efficient use of fuel tanks and boom space
6. attitude control for both small maneuvers and to prevent fricitonally induced boom rotation.
7. efficient use of engines through the use of a cruise configuration, removing useless mass
8. propulsion to maintain Earth/Mars flyby; orbital maintainence.
9. fuel storage and refueling



1.) Torus Spinup
2.) Orbital Insertion
3.) Initial Sun Alignment Maneuver
4.) Continuous Sun Alignment
5.) Attitude Control
6.) Aphelion Orbital Correction

Fig. 2.1 Propulsive Maneuvers

2.2 Propulsion Systems Summary

Primary considerations for this group were mass constraints, thrust requirements for maneuvers, thrust capabilties and efficiencies of various propulsion systems, space constraints for fuel tanks and for shuttle taxis on the spacecraft boom, as well as fuel consumption and storage for the spacecraft. Once the maximum dry mass of the spacecraft was set at 2.1 million kilograms it was possible to determine the thrust required for the mission's various orbital corrections.

The best way to examine the propulsion systems for the CAMELOT mission is to break the mission up into different orbital maneuvers that occur as the spacecraft travels between the Earth and Mars. There are a variety of propulsion systems on the spacecraft, as well as a variety of fuel storage systems which will supply power for the engines. The basic mission breakdown which the propulsion group addressed in its design efforts are outlined above in figure 2.1.

For the spin of the torus four pairs of AJ46-1 hydrazine thrusters are located on the torus with their fuel. The actual spin-up takes about 4 hours. Fuel and engine lifetime would remain for a de-spin and another spin-up.

Orbital insertion from LEO is accomplished with nine liquid hydrogen/liquid oxygen (LH_2/LOX) rocket engines, currently manufactured by the Rocketdyne corp. Each engine generates about 70000 Newtons of thrust. The burn time for insertion is approximately 8 hours.

The insertion burn is made with the end of the spacecraft boom and solar collectors facing almost 90 degrees away from the sun. Immediately after insertion a 240,000 Newton-meter moment must be applied to rotate the vessel. This is accomplished by the firing of three AJ10-199 LH_2/LOX rocket engines which are located near the end of the boom to maximize the moment arm at about 45 meters. Each of these engines generates from 2500-4400 Newtons of thrust. While these engines fire, three identical engines fire in the opposite direction to prevent distortion of the vessel's orbit. These engines are located on the boom closer to the vessel's center of mass, so as to minimize their opposition to the moment which we need. The entire maneuver takes approximately 1 hour. During this time, electrical power must be provided by fuel cells, as the solar dynamic units are not in an operable alignment with the sun during this manuever.

The amount of fuel required for these burns is tremendous. Large fuel tanks mounted outside the truss of the boom store the fuel for the insertion maneuver. Upon completion of the rotation burn the tanks are detached from the boom and tethered to make room for the shuttle taxis, and to reduce spacecraft mass. Upon reaching Phobos the tether is disconnected, allowing the fuel tanks to be used there for various tasks.

Once the solar dynamic units are oriented towards the sun, a continuous moment of approximately 55 Newton meters is required to rotate the vessel during the orbit so that solar orientation remains constant. Because the moment required is continuous, and the thrust required is low, electrical rockets are ideal. For this reason, nine hydrogen resistojets, each producing about 0.1 Newtons of thrust, are mounted at the end of the boom near the main engines. Similar to the configuration of engines for the initial rotation manuever described above, nine identical resistojets are mounted in opposition to the others, closer to the center of mass of the vessel, in order to prevent distortion of the spacecraft orbit. Such a configuration allows the orbital path to be maintained while rotation is achieved. All of these resistojet engines are fueled by the Hydrogen fuel tank mounted inside the truss of the spacecraft boom.

Since the projected mission length of the CASTLE is about 15 years (1.31×10^5 hours), engine endurance factors are important for such an application where the engines are continuously in use. The critical component of the resistojet engine, in terms of engine endurance, is the heating element. Current resistojets have been demonstrated to have lifetimes on the order of 10^4 hours. Within fifty years, however, it is anticipated that lifetimes on the order of 10^5 hours will be possible. In any case, resistojets are the best choice for this propulsive application since their lifetimes are much larger than those for any form of chemical rocket engine, and also since other types of electrical propulsion devices are not capable of meeting the thrust requirements of this application (references 1 and 2).

The torus must rotate at a relatively constant rate in order for it to provide a stable artificial gravity environment. As the torus spins, there will be some frictional forces in the interface which will induce boom rotation. Such a rotation of the main boom is undesirable for three reasons: it would destroy the micro-gravity environment of the micro-gravity lab, it would conflict with the firing of the resistojets to maintain solar orientation, and it would make docking nearly impossible. To prevent this boom rotation, small AJ10-197 LH_2/LOX thrusters (each capable of producing about 450 Newtons of thrust) are mounted along the length of the boom and on the trusses which support the solar dynaimc units. These thrusters are fired periodically to oppose the torus rotation. Fuel for these thrusters comes from the tanks located in the main boom. These thrusters will anchor the boom, so that an electric motor in the interface will be able to overcome the frictional slowing of the torus rotation, thus maintaining the relative rotation of the torus to the main boom.

Due to the nature of the up-escalator orbit and its interaction with the orbits of Earth and Mars, no corrective orbital burn will be required until the third orbit of the CASTLE. Succesive corrective orbital burns are required for the fourth and fifth orbits of the CASTLE. The corrective orbital burns will not result in any rotation of the spacecraft, as these burns are to be perpendicular to the direction of motion of the CASTLE; a delta V away from the sun. The required delta V of the corrective burns is accomplished by the firing of five main engines at full power, over a period of approximately 1 hour, at the aphelion of the CASTLE orbit.

Because the initial insertion manuever uses 80% of the effective lifetime of the nine main engines (10 hour lifetime) and because the main engines are not needed again until the corrective orbital burn at the third apehelion, the nine main engines will be removed from the CASTLE when it reaches Earth for the first time. At that time a pod with only five engines of the same type will be attached, to be used for the orbital corrections. Additional fuel tanks containing LH_2 and LOX are included in this pod. Because the total burn time required for the orbital corrections is less than 4 hours, the maintenance required for these five engines should be minimal.

During the course of the mission a certain amount of boil-off of LH_2 and LOX will occur from the fuel tanks. To minimize this boil-off, the fuel tanks are shielded from the main engines by a thermal insulator. For the tanks, the thermal conductivity of their material was considered, along with its structural strength. The shape, insulation and paint of the tanks are designed to minimize boil-off. A small amount of extra fuel will be carried in each tank as a safety factor. Because the temperature of LOX is higher than that of LH_2 it is less vulnerable to radiation induced boil-off. As such the LOX tanks are located sunward of the LH_2 tanks to provide further shielding for them.

2.3 Mission Analysis

2.3.1 Torus Spin-Up

In order to maintain comfortable living conditions for the passengers and crew, artificial gravity must be maintained. To simulate the conditions on Mars, a gravitational force of 0.4 g's should be present in the CASTLE's torus. Since the torus has a radius of 35 meters, this means that the torus should be rotating at a rate of 3.22 revolutions per minute.

At approximately 7.5 months before insertion, four thrusters located on the torus will fire to start the torus spin-up. The thrusters are Aerojet AJ46-1 thrusters, with a thrust level of 444 N. Using these thrusters, a complete spin-up (or de-spin) could be completed in approximately 3.15 hours. There are a total of 8 thrusters, configured in opposed thruster pairs at four positions on the outer face of the torus, so that there is a capability for an initial spin-up and an emergency de-spin and respin. Table 2.1 describes the AJ46-1 rocket engine and figure 2.2 shows a side view of an AJ46-1 rocket engine.

Table 2.1 Aerojet Corp. AJ46-1 parameters

Thrust (N):	300
Propellant:	N_2H_4 (hydrazine)
Chamber Pressure(MPa):	1.38
Isp(sec):	237
Lifetime(hrs/pulses):	600 / 4000

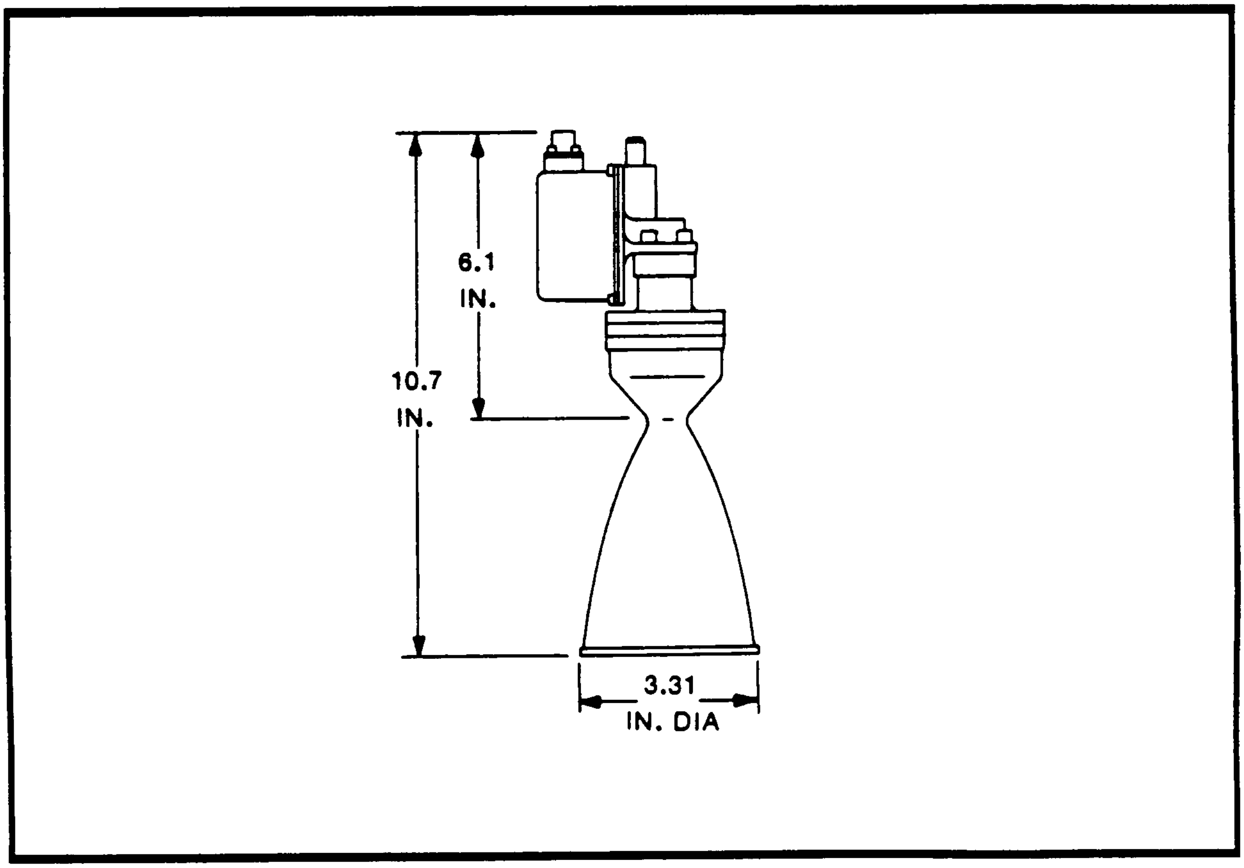


Figure 2.2: AJ46-1 rocket engine (reference 3)

Due to the difficulty of transferring propellants across the interface, the thruster packages on the torus have to be completely independent of the systems on the main boom. Since these thruster packages must be independent, a simple, yet effective thruster system was sought. The Aerojet AJ46-1 thrusters use monopropellant hydrazine, N_2H_4, and have an Isp of 280 sec. Hydrazine was chosen as the propellant because it is a highly energetic fuel and because it is easy to store. The engine and fuel packages are located directly in line with the torus spokes, on the outer face of the torus. Shielding is not a problem with these tanks due to hydrazine's high boiling point. Since the freezing point of hydrazine is around 35^o F, these fuel tanks must be kept warm. For this purpose, each fuel package has heating coils. In addition to having heating coils, each fuel package is located on the sunward side of the outer face of the torus with the thruster pairs in their shadows. With this configuration, the fuel package receives both the heat from the Sun's radiation and the heat from the thruster exhaust (when the thrusters are firing).

In the event of an emergency, the torus may have to be despun. If this need occurs, the torus can be de-spun in the same amount of time (approximately 3.15 hours) as it takes to spin-up. This de-spin is accomplished using the thrusters opposite the initial spin-up thrusters in the thruster pairs on the outer face of the torus.

2.3.2 Orbital Insertion

The orbital insertion of the CASTLE will be accomplished using the nine CASTLE main engines. These main engines are Orbital Transfer Vehicle (OTV) Engines designed and built by Rocketdyne Corp. Table 2.2 lists the performance parameters for these engines. Figure 2.3 shows a side view of one of the engines.

The insertion maneuver requires a tremendous amount of fuel (3.5 million Kg.). To accomodate this much fuel given the geometric constraints of the vessel, four sets of LH2 / LOX fuel tanks are mounted on the exterior of the main boom in addition to the fuel tank set mounted inside the truss network. The dry mass of the CASTLE is about 2.1 million kilograms. With all of its fuel in its insertion configuration the spacecraft has a mass of almost 5.5 million kilograms. Most of this fuel will be burned up during the eight hour insertion burn. A side view of the aft section of the main boom in its insertion configuration is shown in figure 2.4.

Table 2.2: Rocketdyne Corp. OTV engine parameters

Thrust (N)	6700-67000
Propellant	LH_2/LOX
Chamber Pressure(MPa)	10.34
Isp(sec)	482.0
Mixture(O2/H2)	6:1
Life(hrs/pulses)	10/300

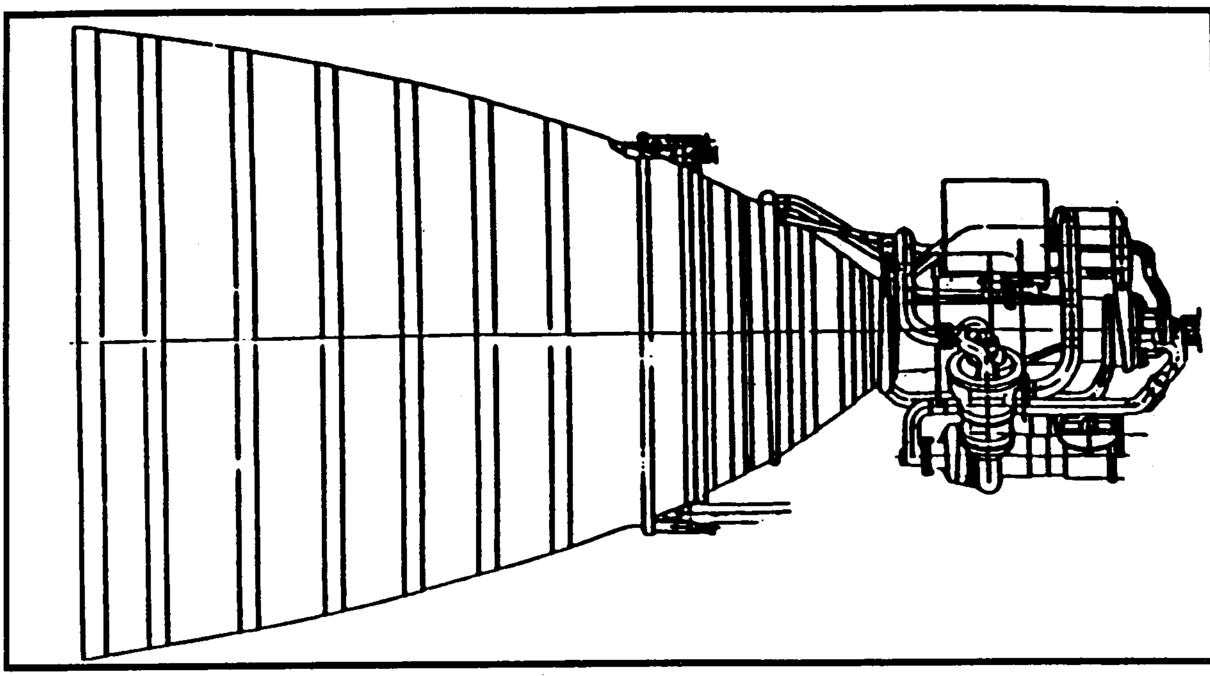


Figure 2.3 CASTLE main engine (reference 3)

Because the delta V for the initial insertion maneuver is rather large (4650 m/sec) the time required for insertion would range from 70 hours with only one engine firing at full power, to 7.8 hours with all nine engines firing. Given the limiting factor of the engine lifetime, no fewer than seven of the nine engines would need to fire for the insertion to succeed. This is one reason why the spacecraft will have nine engines. The nine engines are arranged in a symmetric three by three matrix for the purpose of redundancy. If one should fail it would be simple to shut down another and go with a symmetric configuration of seven. The chances of two failing are slim, yet if this should happen, seven could complete the insertion and the AJ10-199 rockets could aid in the attitude control necessary due to the slightly off centerline thrust vector. Each nozzle is also gimbaled to have approximately 13 degrees of play.

To deal with the concern that impulsive accelerations would cause severe structural damage at the outset of the insertion burn, an engine startup plan was devised. The main engines of the CASTLE are fully throttleable. To initiate firing all nine would be started in groups of three at ten second intervals. Their throttle setting would be at 10% of maximum idle after a minute had passed. During the next ten minutes all nine engines would be gradually brought up to 100% thrust settings. This plan maximizes safety while minimizing wasted fuel due to prolonged low thrust settings.

The insertion pod consists of 9 Castle Main engines and 9 resistojet engines. Each main engine has a mass of 209.5 kg while the resistojets each have a mass of 10 kg. The structure of the mounting plate for the engines is a 1 x 2 x 8 m truss work designed to transmit the loads of the nine main engines equally to the four corners of the main boom truss. This structure has a mass of 4500 kg. No fuel storage or other trusswork is included in the insertion pod. The shroud has a mass of 500 kg. The total mass of the insertion pod is 7150 kg. Figure 2.4 shows a side view of the aft portion of the main boom as it is configured for initial orbital insertion.

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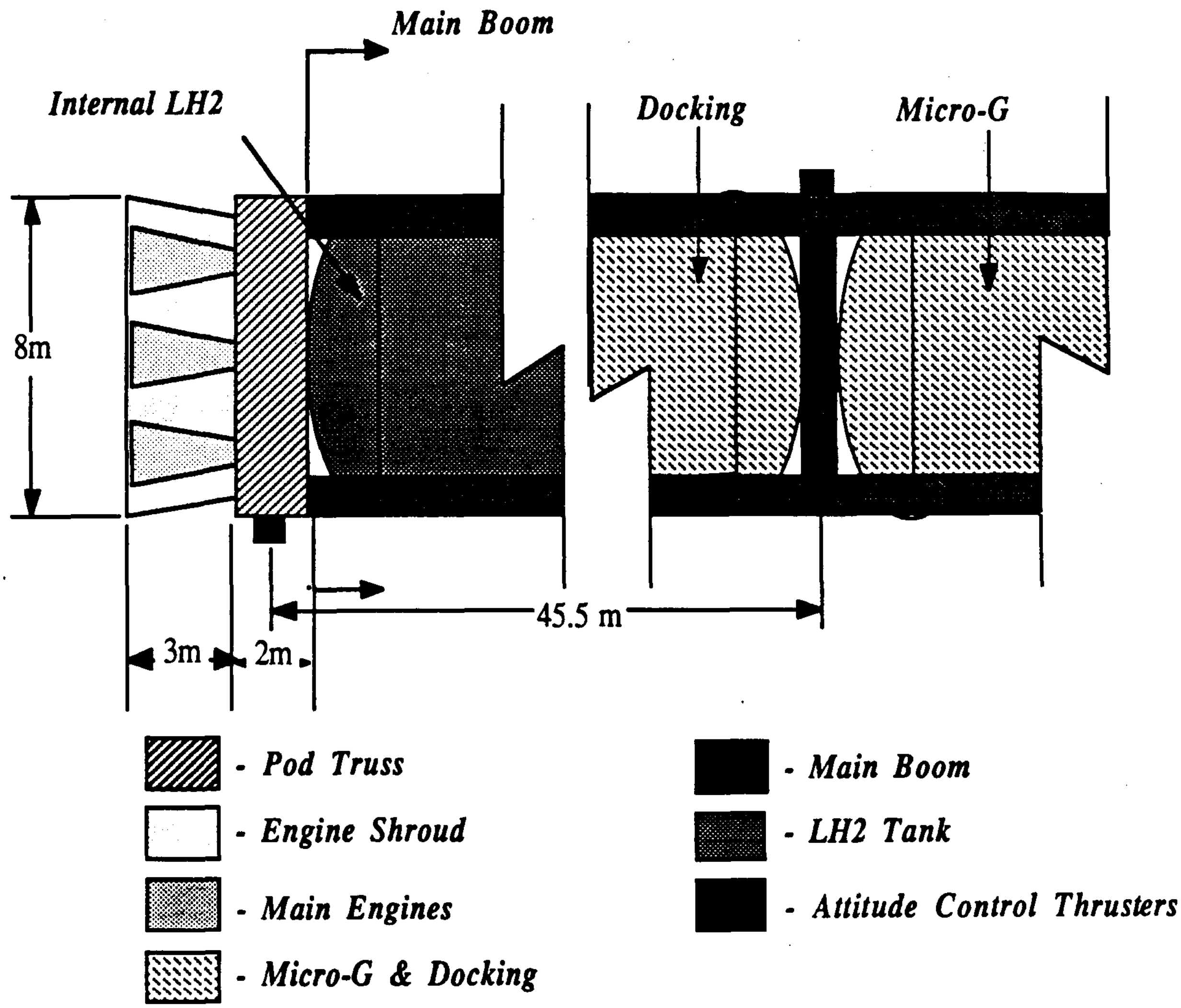

Figure 2.4 - Initial Insertion Configuration

2.3.3 Initial Solar Alignment Maneuver

After the CASTLE insertion maneuver has been completed, the boom axis of the spacecraft will be parallel to the direction of motion of the CASTLE in its trajectory around the sun. The operation of the solar dynamic collectors requires that the aft boom be pointed directly toward the sun. To accomplish this, a ninety-degree rotation Initial Sun-Alignment maneuver is performed. To perform this manuever, a coupled moment thrust is required rotate the CASTLE while keeping its trajectory in the correct orbital plane. The required moment-time is 239,700 Nm-hr based on a 1.5 million kg torus. This correction maneuver will be performed immediately after the completion of the insertion burn.

Thruster Characteristics

The engines to be used for this maneuver are Liquid Oxygen/Liquid Hydrogen Aerojet AJ10-199 thrusters with the following characteristics :

Table 2.3:Initial Sun-Alignment Thrusters (ISAT) AJ10-199

Thrust (N):	2780
Propellants:	LOX/LH2
Mixture Ratio (O2/H2):	2.5
Chamber Pressure (MPa):	1.724
Isp (Vacuum Steady State, sec):	427
Propellant Flow Rate(kg/sec):	664
Engine Mass (kg):	14

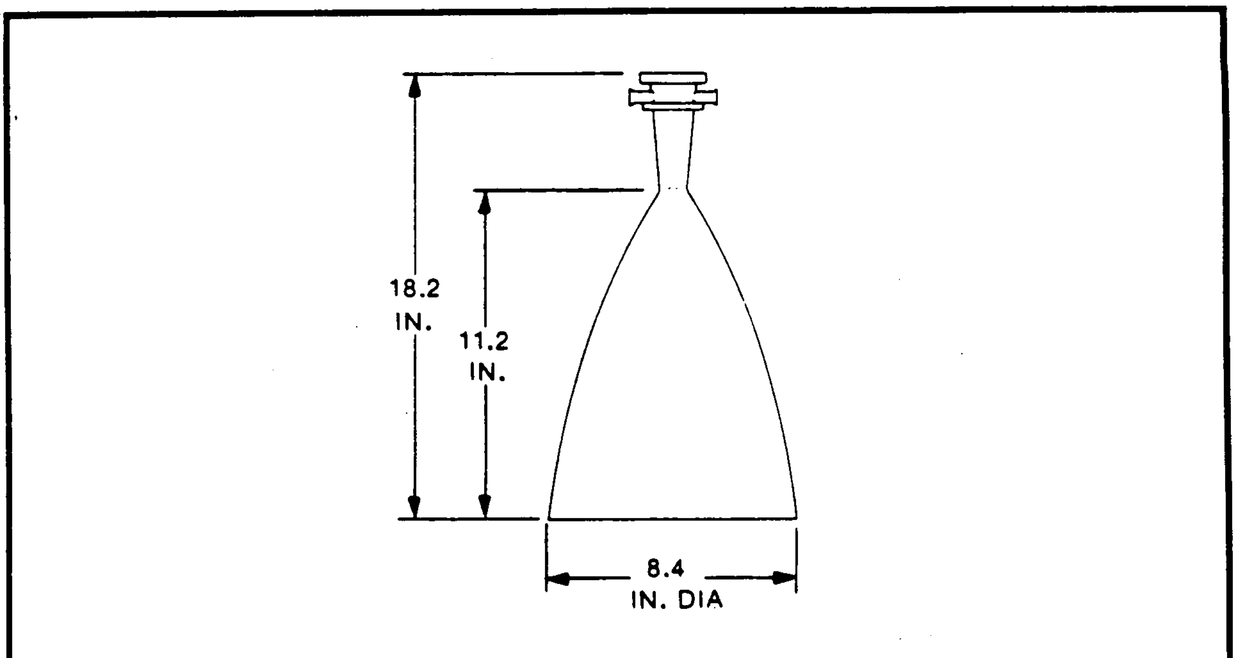

Figure 2.5 side view of AJ10-199 rocket (reference 3, p78)

Thruster Placement

Two ISAT (Initial Sun-Alignment Thrusters) are located just aft of the micro-gravity module. The two ISAT which complete the moment couple are located just forward of the CASTLE main engines. This placement corresponds to a distance of 45 meters between the two pairs of thrusters. This is the largest distance feasible to minimize the thrust required to perform the 90 degree rotation of the spacecraft.

Maneuver Characteristics

The Initial Sun-Alignment Maneuver will take place just after the insertion of the CASTLE into its cyclic Earth-Mars orbit. During this manuever, all four of the ISAT will burn together for slightly less than one hour after which time the solar dynamic units may be operated. The manuever will use fuel and oxidizer from the large insertion propellant tanks. These tanks will be jettisoned after this maneuver to allow adequate space for Taxi docking.

The characteristics of the Initial Sun-Alignment Maneuver have been summarized in the following table:

Table 2.4: Initial Sun-Alignment Maneuver Characteristics

Thrust (each location)	5560 N	7530 kg	LOX
Burn Time	1 hour	1670 kg	LH2
Total # Engines	4 ISAT (AJ10-199)	9200 kg	

Although this particular type of maneuver should only be needed once, the thrusters will still have available lifetime and may be used for a similar maneuver if necessary or for additional attitude control in exceptional circumstances.

2.3.4 Continuous Solar Orientation Thrusting

Once the Initial Sun-Alignment Maneuver aligns the aft portion of the main boom with the sun, a continuous moment will be needed to maintain this orientation. To accomplish this, two packs of nine hydrogen gas resistojets, mounted next to the AJ10-199 thrusters used above, are used. The resistojet is an electrically powered rocket engine currently under development at NASA Lewis Research Center. Table 2.5 describes some important performance parameters of a hydrogen gas resistojet. All data given is from tests within the past two years. Figure 2.5 shows a cutaway side view of one of the engines.

Table 2.5 Hydrogen gas resistojet engine parameters

Thrust (N)	Propellant	Chamber Pressure(MPa)	Isp(sec)	Lifetime(hrs)
up to 0.3	hydrogen gas	13.3	300	10^4 (projected 10^5)

The same need for a couple (as with the Initial Sun-Alignment Manuever) applies to this maneuver. Thrusters can be fired with equal thrust in opposite directions and as long as they are not the same distance from the center of mass of the vessel, it will rotate. The required moment for this maneuver is quite small; a moment of only 65 Newton - meters. A continuous thrust of 1.36 Newtons applied at the end of the spacecraft boom would provide the moment necessary for a constant solar orientation given an additional 1.36 Newtons applied in the opposite direction closer to the center of rotation. A conventional hydrogen resistojet produces thrusts ranging from 0.1 to 0.3 Newtons.

The resistojet was chosen for this application for the several reasons. First, since resistojets produce such low thrusts, they should not impinge upon the spacecraft's structural stability. However, since their thrust is higher by a factor of about ten than a typically more efficient Ion rocket engine. The required moment would need far too many Ion engines for them to fit on the spacecraft, and maintenance with so many engines would be prohibitively complicated. Given that one orbit of the spacecraft takes over 19200 hours and that current chemical rockets have lifetimes on the order of 10^1 hours, the entire class of chemical rockets is ruled out. The resistojet today has been demonstrated to have a potential lifetime on the order of 10^4 hours. The element that fails first is the heating element, and research indicates that the lifetime of the heating element could be realistically extended, within the next fifty years, to as much as 10^5 hours. This implies that the entire spacecraft mission could be carried out without the necessity of replacing the resistojet engines.

The amount of thrust put out by a conventional hydrogen resistojet varies with the combustion chamber pressure. Generally at higher pressure you get more thrust, but use more fuel. At lower pressures the engine is more efficient with fuel, but requires more electrical power. The most fuel efficient system would employ twenty resistojets and would require 52000 kg of hydrogen per orbit. This fuel would come from the fuel tanks mounted inside the main boom and in the cruise configuration pod. Again, it would be replenished when necessary by a refueling vessel at Phobos.

Electrical power requirements for the resistojet engines would be about 6.6 kilowatts. This demand is an insignificant portion of the 200 extra kilowatts available to the spacecraft after life support power demands have been met. Another safety factor would be that the resistojet can be operated without the use of the heating element, without using any power. In this mode more fuel is required to produce the necessary thrust, but in an emergency the engines could continue to meet mission requirements. Note also that the resistojets could make use of boiled off LH_2, but might require a small amount of electricity to boil the LH_2 designated for their consumption if a passive solar system would not suffice.

2.3.5 Insertion Fuel Tank Detachment

After the 8 hour burn for initial orbital insertion, the four sets of fuel tanks mounted on the main boom over the docking bays will be emptied. For two reasons, these fuel tanks will have to be removed from the vessel. The first reason is that these fuel tanks block the shuttlecraft berths. These shuttlecraft berths must be clear immediately after insertion since, immediately after insertion, there will be two taxi shuttlecraft joining with the CASTLE. These shuttlecraft are necessary since, as the CASTLE is in a circulating orbit, it never ceases in its motion and therefore it relies upon the shuttlecraft for transfer of cargo and personnel.

Below is a scaled computer image of the aft portion of the boom with the insertion tanks still mounted (fig. 2.6)

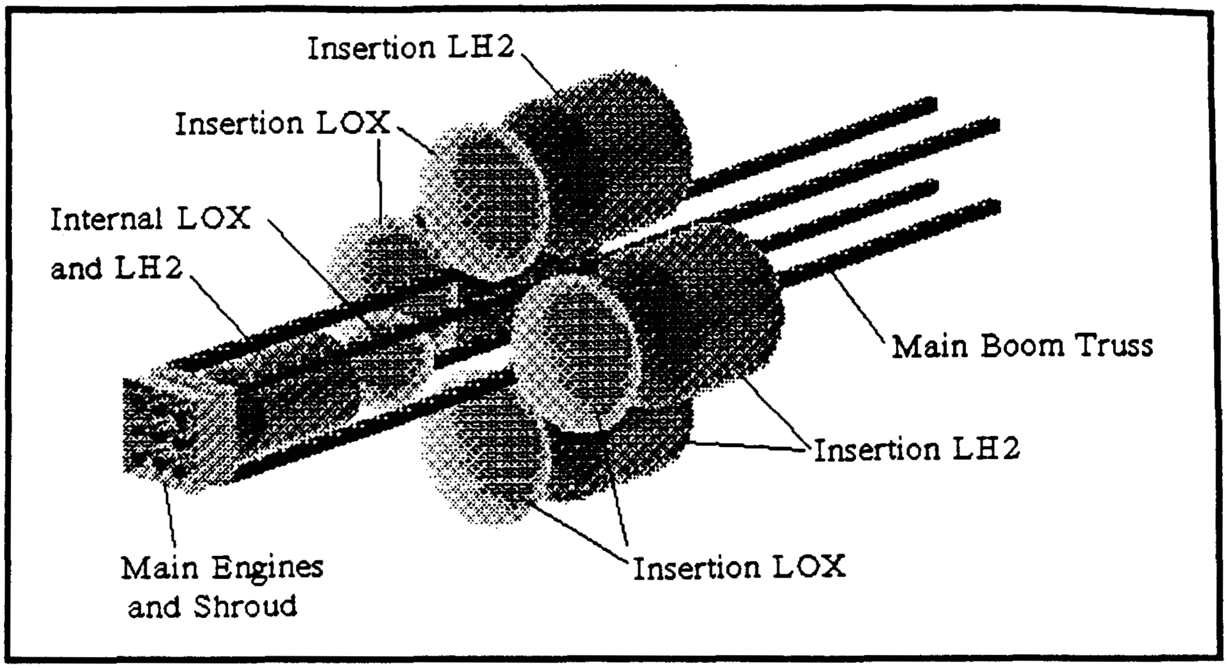

Fig. 2.6: insertion configuration

The second reason for removing these fuel tanks is due to their large mass. Specifically, the fuel tanks have an empty mass of about 65,000 kg. There is simply no need for the vessel to burden itself with this extra useless mass for any longer than it must. Rather than jettisoning the empty tanks into interplanetary space, the tanks will be detached from the boom, and brought with the CASTLE to Phobos by means of a series of tethers. This will allow the shuttlecraft to berth with the CASTLE without having to waste the fuel tanks.

The fuel tanks will be detached from the CASTLE by the mechanical arms mounted on tracks near the docking area of the main boom. The tanks would then drift away from the CASTLE while remaining tethered to the spacecraft's boom. The tanks will also have a radio beacon mounted upon them to facilitate finding them. Upon arrival at Phobos, the tethers will be disconnected by the same mechanical arms near the docking area. These tanks could then be retrieved by orbital transfer vehicles and utilized by the miners on Phobos or by the scientists on the Martian surface, thereby minimizing waste.

2.3.6 Torus Spin Maintenance and Attitude Control

The rate of torus spin will be monitored by an electric motor in the interface which will keep the rate of rotation constant with respect to the non-rotating boom. Because of the frictional forces present in the interface, the boom will not remain non-rotating. To keep the boom still and thus, maintain the rate of rotation of the torus, there are small chemical thrusters located on the solar booms to create a moment that will counteract the boom's tendency to rotate. These thrusters are Aerojet AJ10-197 LH2, LOX chemical thrusters. They are located on the solar booms such that the moment-arm is as large as possible thus minimizing the magnitude of the force needed. These thrusters will be fired as needed as determined by the torus control system. The fuel for these thrusters will be fed directly from the internal tanks at the rear of the boom.

In addition to those thrusters located on the solar booms, additional attitude control thrusters are needed to compensate for any perturbations in the planned trajectory of the CASTLE. For this purpose, LOX/LH2 Aerojet AJ10-197 thrusters will be used also. Each of these thrusters provides a thrust of 111.2 N at an Isp of 348 sec for pulsing thrust. The characteristics of these thrusters are included in 2.6 and shown in fig. 2.7.

Table 2.6: Attitude Control Thrusters AJ10-197

Thrust (N):	111.2
Propellants:	LOX/LH2
Mixture Ratio (O2/H2):	3.0
Chamber Pressure (MPa):	1.03
Isp (Vacuum Steady State, sec):	400
Isp (Pulsing, sec):	348
Propellant Flow Rate(kg/sec):	0.0326
Engine Mass (kg):	2.0
Lifetime (hrs):	6.2

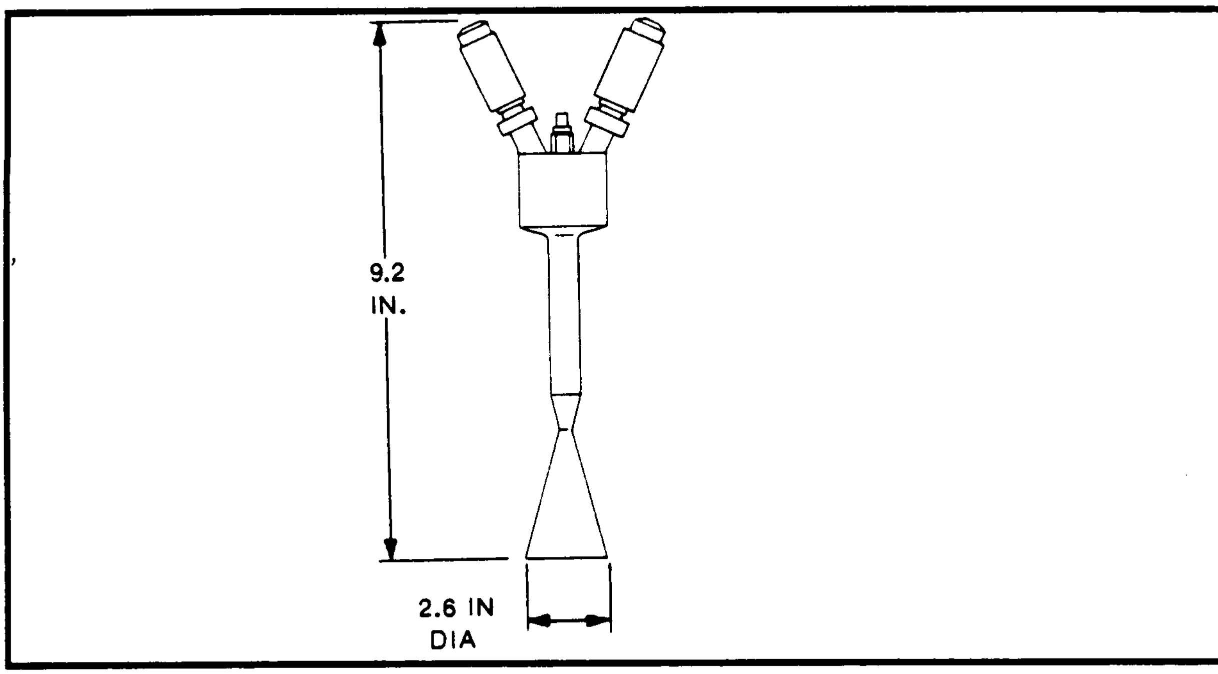

Figure 2.7: side view of an AJ10-197 (reference 3, p78)

Thruster Placement

The attitude control thruster units are arranged in two configurations: quads and pairs. A quad consists of four thrusters oriented at 90-degree angles. The four nozzles are positioned in the +x, -x, +y, and -y directions. A thruster pair consists of two thrusters oriented at 180-degree angles. To make the minor corrections in attitude and to oppose the friction at the interface, 12 sets of thruster pairs will be placed along the truss and 2 sets of thruster quads will be located on each of the four solar dynamic booms.

This gives a total of 20 thruster units and 56 individual engines which will allow adequate attitude control with sufficient redundancy. All of these thrusters will draw their propellant from the CASTLE's internal propellant tanks in the truss. The mass of propellant required for the attitude control system is about 20,000 kg.

The network of AJ10-197 thrusters on the nonrotating section of the CASTLE is coordinated by computer to provide instantaneous attitude adjustment at precise locations. This is done in such a way as not to create acceleration problems for the micro-gravity module and interface, or dynamic problems for the solar dynamic units. These types of problems should in fact be of little concern, since, for these thrusters, the thrust level is relatively low and the burn times are short.

2.3.7 Insertion Engine Replacement and Attachment of Cruise Pod

After their use in the orbital insertion manuever, the 9 engines at the end of the boom will have, for all practical purposes, used up their entire lifetime. Because of this, these engines cannot be used for the orbital correction burns. This means it is necessary for the CASTLE to either carry extra engines for the orbital correction burns or to have a replacement scheme for the existing nine main engines. It was decided that replacing the main engines would be more advantageous in terms of cost and mission parameters. Also, since the insertion tanks are to be jettisoned at Phobos and used for fuel storage on the surface of Phobos, it will be necessary to add more fuel storage to the CASTLE in order to complete the necessary orbital correction burns. To facilitate this engine replacement and fuel tank addition, a pod system was designed for the orbital correction burns. This replacement pod, which shall be referred to as the orbital correction/cruise pod, houses 5 Rocketdyne OTV engines and 9 resistojet attitude control engines. These resistojet engines are for use in maintaining the solar orientation of the spacecraft.

Since the first orbital correction burn is not needed until the third orbit of the CASTLE, there will be two orbits' time in which to replace the burned out engines with the new engine and fuel pod (orbital correction/cruise pod). After its installation, the new pod will be used for the rest of the spacecraft's lifetime. If for some reason the pod cannot be installed even by the second Earth flyby, there is still enough lifetime left in the insertion engines to complete one correction burn so that the CASTLE will be able to encounter Earth after its third orbit. The pod is to be connected to the CASTLE in the same manner in which the modules of the main boom are connected during initial assembly. Accordingly, the truss of the pod and the truss of the main boom will connect at a total of sixteen points, four connection points at each of the four corners of the pod. An added advantage of the pod system is that it allows an easier transfer of fuel to the resistojet attitude control thrusters. For the pod system, it is only necessary to transfer fuel from the internal tanks of the spacecraft to the pod in order to fuel the resistojet thrusters. Since the pod fuel tanks only contain enough fuel for one orbital correction, these tanks must be refueled at each Phobos encounter during the fourth, fifth, and sixth orbits.

The orbital correction/cruise pod consists of 5 Castle Main engines (209.5 kg), 9 resistojet engines (250 kg), a shroud (500 kg), and a mounting plate. This pod also consists of a trusswork (8,200 kg) identical to that of the main boom in design. The total mass of the correction pod is 10,000 kg. It contains two bays, one 8 m long and the other 15 m long. The LOX tank is located in the 8 m bay and the LH2 is located in the 15 m bay. The LOX is located on the end of the pod, nearest the engines and the sun, to shield the LH2 tank from the sun and the heat of the engines. A shroud is also located around the engines on this pod to control plume impedance on the solar arrays and the communications dishes. Below is a computer drawing of the aft section of the boom in with its cruise pod attached, and a side view of the same portion of the boom (fig. 2.8)

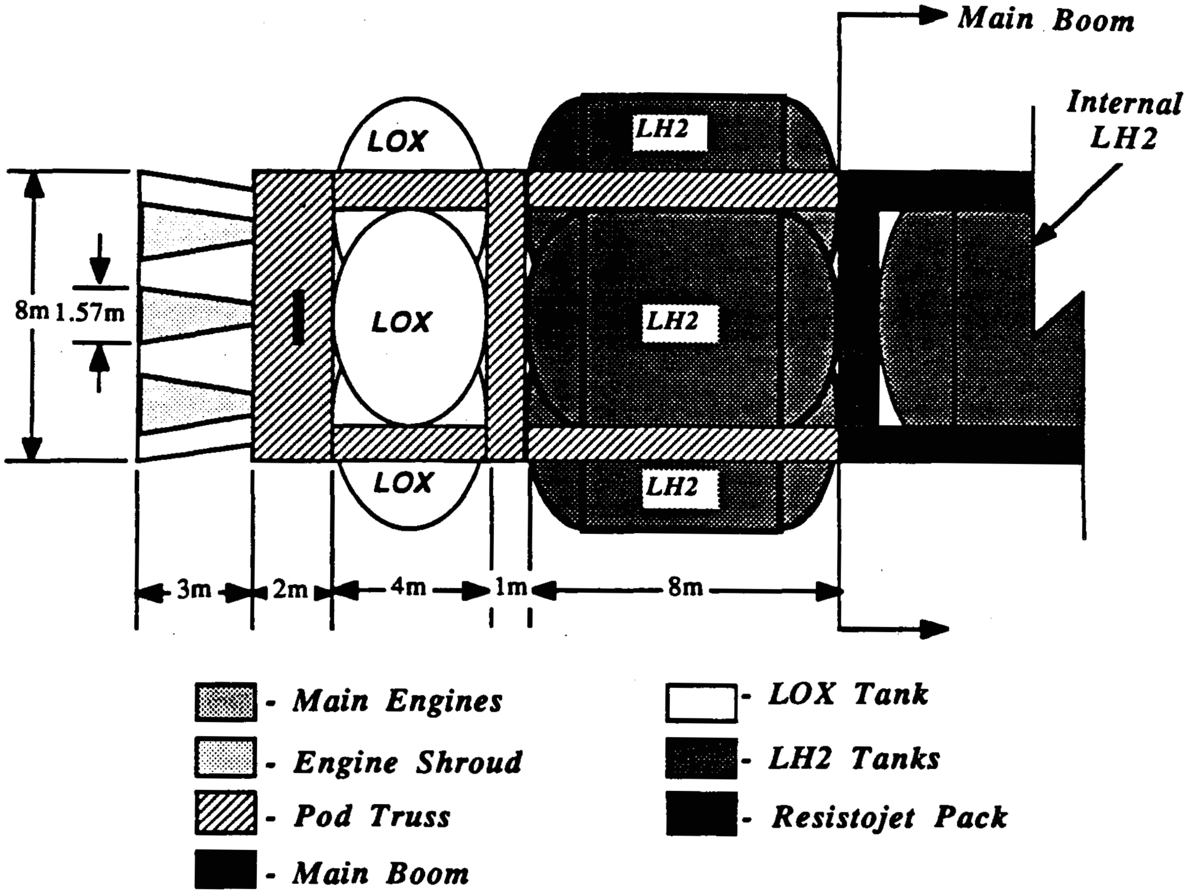

Fig. 2.8: Orbital Correction/Cruise Configuration

2.3.8 Orbital Correction Burns

The CASTLE up-escalator orbit is a heliocentric orbit used to transport personnel between Earth and Mars. The CASTLE, in its orbit, takes only four months to travel from Earth to Mars and twenty one months to go from Mars back to Earth. The total period of the orbit is equal to the synodic period of the orbits of Earth and Mars. That is, every 2.135 years Earth and Mars are the same distance apart, but shifted 48.7 degrees.

Unfortunately, the two orbits are not exactly in the same plane of rotation, and this slight difference requires a periodic correctional thrust for the CASTLE. Therefore, to ensure fly-by of Earth and Mars on each pass, the orbit must be rotated 48.7 degrees. Most of this rotation is accomplished using the Earth's gravitational field. But of the first seven orbits, on orbits three, four, and five, the rotation imparted by the Earth is not sufficient to keep the ship's trajectory near enough to Earth and Mars. For this reason, during these orbits, the CASTLE's main engines will fire to rotate the orbit further. This is done with a radial burn at aphelion (since this is where the required delta V is a minimum).

With five engines firing at full thrust, the required delta V can be achieved in about one hour. The required delta V values are different for each of the three out of seven orbits which do require such a burn. In no case does the average acceleration of the vessel exceed 0.15 m/s^2. This means that the maximum average acceleration during this manuever is less than the average acceleration value during initial insertion (0.166 m/s) which persists over a period of almost eight hours. Never, during the orbital correction burns, will the level of strain on the spacecraft approach the level of strain on the spacecraft during initial insertion. Therefore, since the spacecraft is designed to withstand the stresses of orbital insertion, these orbital correction burns should not pose a threat of structural damage to the CASTLE.

Below is tabulated the data for the three orbital corrections required during the course of the first seven orbits. A dry mass of 2.1 million kg is assumed.

Table 2.7: Orbital Correction Data for 5 Engine Burn

Orbit #	DV (m/sec)	Initial Mass(kg)	Fuel Mass Used(kg)	Thrust(N)	DT(hr)	Avg.acc.(m/s^2)
3	540	2410922.0	258922.0	333750	1.024	0.146
4	740	2514537.2	362537.2	333750	1.434	0.143
5	450	2365701.7	213701.7	333750	0.845	0.148

Given five engines, each with a ten hour lifetime, the crew of the CASTLE will have a good deal of flexibility when it comes to choosing engine thrust settings and the number of engines to use.

During the orbital correction manuever, the electrical power for the CASTLE will not be supplied by the primary power system (solar dynamic units). Instead, as during the initial insertion manuever, the electrical power for the spacecraft will be supplied by the reserve power system (regenerative fuel cells).

2.3.9 Fuel Storage

The CAMELOT I study advocated the use of chemical thrusters on the CASTLE for the torus spin-up manuever. In the redesign of the CASTLE according to the CAMELOT II study, these chemical thrusters used for torus spin-up have been replaced by monopropellant thrusters. This was done for the purpose of meeting the increased thrust demands of the new CASTLE design and for the purpose of simplifying the storage of propellants. The new thrusters have an increased thrust, thus reducing the number required to perform the spin-up maneuver and greatly increasing the lifetime of the thrusters. The long duration storage of hydrazine for these thrusters is also much easier than the long duration storage of cryogenic propellants for the chemical thrusters.

The auxiliary fuel cells located on the torus will have cryogenic storage of LH2 and LOX. These fuels will be located on the shaded side of the torus to minimize the boil-off of the cryogens.

The basis for propellant storage inside the main boom comes from the CAMELOT I report. In that report, the tanks were designed to contain the liquid oxygen and liquid hydrogen for the orbital correction burn near aphelion and for attitude control of the non-rotating section of the spacecraft. These tanks were designed to also carry a small amount of excess fuel which the docked taxis would be able to access in the case of an emergency. Passive cooling techniques were employed to minimize boil-off of the cryogenic propellants. Also the total volume and mass of the tanks were determined by a number of factors. Those factors included: the propellant volume, the temperature and pressure at which the propellant is to be maintained, the material used for the tank walls, the shape of the tank, the boil-off rate of the propellant, and various external design constraints (reference 4).

In the CAMELOT I report, it was proposed that all of the propellant required during an orbit would be contained in two tanks located on the interior of the trusswork. The additional propellant required for insertion would be stored in tanks that would be attached to the trusswork alongside the interior tanks. The interior tanks had to meet the constraints imposed by the trusswork, namely it had to have a diameter of 8 meters and have ellipsodial end caps to minimize the unused space on the interior of the trusswork. These internal tanks were to be replaced, at Phobos, for each orbit.

The CAMELOT I report also specified several details of the interior tank design. According to the report, each tank would be at a pressure of 0.2 atm but would be designed to withstand a pressure of 3 atmospheres. The tank wall would be constructed from the aluminum alloy 6066-T6 with a thickness of 0.0055m in order withstand the pressure forces at the required temperatures. Each tank would be surrounded by 0.02 m of fiberglass and have a stand off deployable shield coated with a reflective paint such as TRW's S13-G-LO, which reflects 80% of the incoming radiation, on the sunward side of the CASTLE.

For the CAMELOT I study, the volume of propellants needed was based on the assumption of a 1 million kg dry mass of the CASTLE. The data supplied by the CAMELOT I report is shown in table 2.2.8.

Table 2.8: Based on CAMELOT I for the propellant required, tanks, and masses

		propellant volume(m^3)	propellant mass(kg)	tank dry mass(kg)
Torus spin-up				
	LH2	1.42	100	negligible
	LOX	0.27	300	"
Initial insertion				
	LH2	3,500	246,000	23,200
	LOX	1,314	1,470,000	17,400
Orbital Correction burns (using internal tanks)				
orbit 1	none			
orbit 2	none			
orbit 3	LH2	245.9	17,285.7	
	LOX	92.7	103,712.3	
orbit 4	LH2	343.4	24,142.9	
	LOX	129.5	144,857.1	
orbit 5	LH2	202	14,200	
	LOX	76.2	85,200	
orbit 6	none			
orbit 7	none			
Attitude control (stored in main internal tanks with the rest of the propellants)				
per orbit	LH2	20.3	1428.6	
	LOX	7.66	8571.4	
the size of the internal tanks were as follows				
	LH2	490	30,337	4873
	LOX	170	174,524	2405

The dry mass of the CASTLE according to the CAMELOT II study is about 2.1 million kg. This increase in the dry mass of the CASTLE to 2.1 million kg has dramatically increased the amount of propellant required. In addition, the LH2 required for the continuous burning of the resistojet thrusters was never accounted for in the CAMELOT I design. With the increase in the amount of propellants due to these two factors, it is now prohibitive to have all of the propellant that would be needed for an orbit requiring a correctional burn to be stored in the LH2 and LOX tanks mounted inside the main boom. For this reason, a fuel pod was designed for the CASTLE to house the increased propellant. This fuel pod will be attached to the end of the main boom before the third orbit.

The present values for the mass and volume of LH2 and LOX are shown in table 2.9 below.

Table 2.9: Present propellant requirements based on a dry mass for the CASTLE of 2.1 million kg.

		insertion mode		cruise mode
	LH2	567629 kg		101560 kg
	LOX	3708168 kg		634540 kg
Orbital Correction				
orbit 1	none			
orbit 2	none			
orbit 3	LH2	36990 kg	LOX	221935 kg
orbit 4	LH2	51791 kg	LOX	310746 kg
orbit 5	LH2	30530 kg	LOX	183175 kg
orbit 6	none			
orbit 7	none			
Continuous Resistojet thruster per orbit	LH2	40000 kg		
Other attitude control per orbit	LH2	1300 kg		

Other miscellaneous consumption (including an estimated 5% loss of cryogens per orbit)

LH2	5078 kg
LOX	31730 kg

The size of the internal tanks are as follows

	propellant volume(m^3)	propellant mass(kg)	tank volume(m^3)
LH2	656.8	46,500	722.5
LOX	268.1	300,253	292.9

In hopes of trying to help to minimize the mass of the propellant, a more detailed study of the cryogenic storage tanks was undertaken.

The preliminary design for the CAMELOT I's cryogenic storage tanks is discussed in section 2.2.2 of that report and is illustrated by figure 2.7 in the CAMELOT I report. The basic design of these tanks is described in the fifth paragraph of this section (2.3.9 Fuel Storage). This design of the cryogenic storage tanks was based on the assumption that the only heat flux to the tanks is due to the solar radiation.

The thermal energy balance for the tanks is given by the following equation (reference 7):

$$Q_{ab} + Q_{gen} = Q_{rad} + Q_{st}$$

where Q_{ab} = is the rate at which energy is absorbed by the object
Q_{gen} = is the internal energy generation rate
Q_{rad} = is the rate at which energy is radiated by the object
Q_{st} = is the rate at which energy is stored by the object

The tank (object) is assumed to be isothermal thus:

$$Q_{rad} = \acute{O} F T^4$$

where F = radiation factor,
T = temperature in absolute units, and
Ó = Stefan-Boltzmann constant.

$$Q_{st} = W\, dT/dt = 0$$

where W = the thermal capacity and
t = the time.
Q_{gen} = negligible = 0

$$Q_{ab} = Q_s + Q_a + Q_e$$

where Q_s = direct solar energy,
Q_a = albedo (reflected solar energy from planets) energy = negligible = 0,
Q_e = emission from other objects (such as Earth & Mars) = negligible = 0.

The thermal balance equation is now reduced to the following:

$$Q_s = Q_{rad}$$

Our primary concern is therefore with the heat flux into the tank, Q_s.

To determine the heat flux into the tank due to the solar flux was a major focus. In this determination the conditions found at 0.98 times Earths orbital radiuswill be used since every other point of the orbit will have a lower value of solar flux and thus a lower heat flux into the tank. For example, the value for solar flux at Earth is 422 Btu/hr. ft^2 (1393 W/m^2) while at Mars orbit the value of the solar flux is approximately 200 Btu/hr. ft^2 (540 W/m^2).

The coating for the tanks was one of the major differences between the CAMELOT I design and the design proposed in CAMELOT II. In the CAMELOT II design, instead of just using the TRW S13-G-LO coating, a second surface mirror coating (fused silica, silvered on back) will be used to increase the amount of solar flux that will be reflected. The absorptivity of the

TRW's S13-G-LO is 0.2 while the absorptivity of a second surface mirror coating is 0.07 (reference 5).

The effect of this change is most evident in the determination of the surface temperature. The equation to determine the surface temperature is as follows (reference 6):

$$(Q_s)(\text{alpha}) = (\acute{O})(\text{epsilon})(T^4)$$

where alpha is the absorptivity of the coating, epsilon is the emissivity of the coating, and T is the surface temperature. The CAMELOT I coating produces a surface temperature of 273K on the shield and an estimated tank surface temperature of nearly 5K while the mirror coating produces a surface temperature of 217K. This temperature was then assumed to be the temperature on the exterior side of the insulation by neglecting the thermal resistance of the paint layer.

In the previous design the shield would be deployed on the sunward side, however this significantly increases the complexity of the assembly and propellant distribution from the tanks. This shield also would require the CASTLE to be oriented towards the sun in LEO and would be useless during orbital insertion and also in the case that the CASTLE orientation could not be maintained toward the sun. For these reasons, the concept of using a deployable shield was dropped thus reducing the mass associated with the sheilding of the tanks.

Having calculated the surface temperature of the tank and, having assumed that this is the temperature on the exterior side of the insulation, the temperature on the interior side of the insulation was needed. Since the tank wall is made of only 0.0055 m aluminum, its thermal resistance is several orders of magnitude less than that of the insulation. Because of this fact, the thermal resistance of the tank wall was neglected. By neglecting the thermal resistance of the tank wall, the interior side of the insulation in effect becomes the interior side of the tank for these calculations. Therefore the interior side of the insulation was approximated to be at the normal boiling point of the cryogens(20K for LH2 and 78K for LOX).

With this approximation of the temperature on the interior side of the insulation, the thermal energy balance equation could be simplified to be a one dimensional conduction equation (reference 7). This equation is :

$$q'' = q/A = (k/L)(T_h - T_l)(\text{S. F.})$$

where q"= heat transfer rate,
q = heat,
A = surface area,
k = thermal conductivity,
L = thickness,
Th = high temp.,
Tl = low temp.,
S. F. = a safety factor of 1.5 to ensure that this is a conservative estimate.

From this equation, it became apparent that the ideal insulation would have an extremely low thermal conductivity and would be very lightweight. The insulation which was chosen, according to these criteria, is a multilayer insulation (MLI).

The insulation considered in the CAMELOT I report was fiberglass, which had a wide range of values for both its conductivity and density. A comparison was made of an evacuated fiberglass insulation and a multilayer insulation(MLI). Table 2.10 shows the physical characteristics of these insulations.

Table 2.10

Evacuated fiberglass with boundary temperatures of 300K and 77.4K.

Density (kg/m^3)	Thermal Conductivity (W/mK)
50	0.0017

Multilayer Insulation--Aluminum foil spaced by glass fiber paper with boundary temperatures of 300K and 20K.

Paper Thickness	Sample Thickness	Layers/cm	Density (kg/m3)	Thermal Conductivity (W/mK)
0.0002m	0.025m	20	140	0.00006

Due to the tremendously low thermal conductivity properties of the MLI, it was chosen over the fiberglass insulation. For the fiberglass insulation the heat transfer rate would be 22.4 W/m^2 while for the MLI the heat transfer rate is only 0.9 W/m^2 (both heat transfer rates are for the LH2 tank).

Since, with the MLI, the heat transfer into the tank is so small through the insulation, it was assumed that it would be negligible compared to the heat leak into the tank form the supports and piping. This heat leak will be briefly discussed in the next section. Ideally, a more in depth study would try to optimize the insulation so that the boil-off rate nearly matches the requirement for gaseous hydrogen (resistojets, fuel cells) and oxygen (fuel cells, life support). Such detail is beyond the scope of this class.

Mechanical - supports and piping

Having determined that the heat transfer through the insulation is very slight, it became apparent that the major portion of the heat leak into the tank is from the supports and piping. This, in fact, was one of the major conclusions from a thermal analysis of long-duration cyrogenic tanks for lunar storage performed by the Boeing Company (reference 8). In this study, the heat flux into the tank was determined to be approximately 60% through the supports. The piping contributed about 4% of the total heat leak.

Several materials for the tank supports were considered in an effort to minimize the heat leaks from the supports. For example aluminum was considered, but, since the thermal conductivity of aluminum is quite high (64W/mK), it was deemed unsuitable as a material for the supports. Several other common materials used for tanks supports were considered, including stainless steel and titanium among others. New advances in composite materials will perhaps produce a material that has a thermal conductivity so low that heat leaks for the supports will be negligible. Below is a short table (2.11) listing several possible materials that exist presently.

Table 2.11 Support Characteristics:

Material	stress(1000psi)	Thermal Conductivity(W/mK)
Stainless Steel	150 (drawn 210000psi)	2.8
Titanium alloy (4Al-4Mn)	145	1.86
titanium, pure	85	11.2

Perhaps of even more importance than the selection of the material, is the design of the actual supports (reference 9). To minimize the heat transfer even further, the supports are made as long as possible to increase the distance of the heat path. Often these supports are tangent to the surface of the tank at the point of attachment. As much of the support as possible is insulated to further reduce the heat transfer. The configuration of a typical support structure is shown below (fig. 2.9).

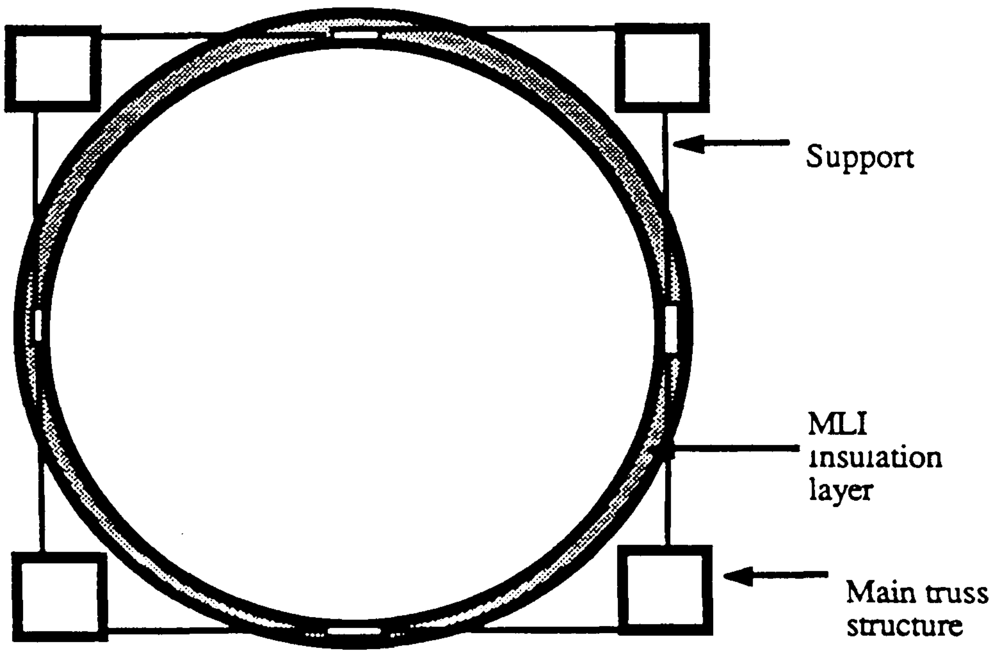

Figure 2.9: Typical support structure. View from the aft end of the boom towards the hub.

Ullage space

Ullage literally means empty space. Quoting from Barron's *Cryogenic Systems* "Cryogenic-fluid storage vessels are not designed to be completely filled for several reasons. First, heat inleak to the product container is always present; therefore, the vessel pressure would rise quite rapidly if no vapor space were allowed. Second, inadequate cool-down of the inner vessel during a rapid filling operation would result in additional boil-off, and the liquid would be percolated through the vent tube if no ullage space were provided. A 10 percent ullage volume is commonly used for large storage vessels." (Reference 4). For these reasons, a 10 percent increase in the volume of the propellant tanks was accounted for in the dimensioning of the tanks.

Meteorite impact--self-sealing tanks

Meteorite impact and subsequent leakage was one of the many safety concerns considered by the propulsion team of CAMELOT II. Several statistical studies have been made, based on experimental data gathered by satellites, which have shown that as the size of the meteorite increases the possibility of being struck decreases dramatically (Reference 10). Meteorites that will have the highest probability of impacting with the tanks are micro-meteorites, which are on the order of a grain of sand in size. These objects are hazardous because of their extremely high velocities.

Two approaches can be taken to eliminate this hazard; either prevent meteorite penetration by increasing the shielding or allow the penetration and seal the puncture. Increasing the shielding is too costly an alternative due to mass considerations. Another set of detailed studies has shown that when liquid propellants are exposed to pressures below their triple points, solidification occurs. This solidification can be utilized for sealing meteorite punctures (Reference 11). Because of these studies, a mesh like layer has been included in the design of the insulation blanket in hopes that it will help promote the solidification of the propellant at the point of penetration, thus sealing the penetration.

2.3.10 Refueling

The liquid hydrogen and liquid oxygen in the insertion tanks and the initial fuel in the internal tanks would come from mining operations on the Moon. The much lower escape velocity of the Moon, compared to that of the Earth, would reduce the cost of bringing the tremendous amounts of fuel required for insertion into the high LEO in which the CASTLE is assembled.

On every flyby of Mars, the CASTLE will receive an allotment of fuel for the internal tanks for attitude control. The orbital correction/cruise pod tanks will also be supplied with fuel on the third, fourth, and fifth orbits for the radial aphelion burn. The fuel that the ship receives on its encounters with Mars will come from mining operations on Mars' moon Phobos, where a gravitational acceleration of only 0.5 m/s^2 will greatly reduce the cost of fuel transportation.

Fuel from the moon and Phobos will be transported to the CASTLE by large nuclear-electric cargo ships. These ships will already have been used for the establishment of bases on the Moon, Mars, and Phobos; therefore they will not have to be built specifically for this mission (Reference 12).

Although the feasibility of transferring liquid propellants from one vehicle to another in microgravity has not yet been demonstrated, a series of tests has been proposed to do so. They would lead up to the construction of a test vehicle that would be carried into orbit by the space shuttle. The vehicle would perform liquid propellant transfers in the cargo bay of the shuttle to verify the possibility of refueling a spacecraft under such conditions (Reference 13).

The nuclear reactor of the cargo ship will be detachable from the rest of the spacecraft. This would allow it to separate from its reactor at a great distance from the CASTLE and approach under chemical propulsion. Once the cargo ship maneuvered alongside the CASTLE it would take only a few hours to transfer the required fuel and supplies. But, the initial fueling while the CASTLE is still in LEO would take a considerably longer time due to the large quanties to be transferred. In addition, it would be more difficult to keep the reactor away from the CASTLE. This could be accomplished by inserting the cargo ship into the same orbit as the CASTLE, but a certain angle away from it. Then the reactor could be detached and the cargo ship could increase its altitute, allowing the CASTLE to catch up to it, or the cargo ship could decrease its altitude and catch up to the CASTLE (references 13).

2.4 Supplemental Data

2.4.1 Engine Maintenance Schedule

Service on the engines will be required periodically. A short diagnostic test will be given to each engine after each burn to test if maintenance is necessary. This test will take about five and one half hours to complete, and will include what is mentioned in table 2.12. As seen, these tests will require no EVA. Table 2.12 also gives IVA and EVA times for periodic engine maintenance, engine replacement, and unscheduled maintenance. The scheduled EVA engine maintenance is only necessary for the CASTLE main engines after every ten burns, and with a successful mission should never be necessary aboard the CASTLE because the engines are not scheduled to burn more than ten times during the spacecraft's lifetime. Because of the redundancy built into the propulsion system, it will not be necessary to immediately repair any minor damage to an engine, so long as the existing damage does not endanger the rest of the propulsion system. With a major failure in the pod, it will be possible to replace the system at the next earth encounter, using the same method as was used to mount the orbital correction pod from on the third earth encounter.

Operation	Facilities	Tools	Delta Time	Castle Man Hours IVA	Castle Man Hours EVA	Castle Man Hours Total
Engine-Turnaround Maint.			3.4 hr	5.4	---	5.4
- Analysis of flight data	Castle Computer	Engine Software	2 days	2	---	2
- Lock up pressure decay	Castle Computer Refuel	Engine Software	0.5 hr	0.5	---	0.5
- Engine valve op check	Castle Computer Refuel	Engine Software	0.6	0.6	---	0.6
- Nozzle visual inspect.	Castle Computer Refuel	RMS - CCTV	0.2	0.2	---	0.2
- Nozzle extension check	Castle Computer Refuel	RMS - CCTV	0.2	0.2	---	0.2
- Gimbal actuator check	Castle Computer Refuel	RMS - CCTV	0.2	0.2	---	0.2
- Turbopump torque check	Castle Computer	Engine Software	0.3	0.3	---	0.3
- Ignition system check	Castle Computer	Engine Software	0.5	0.5	---	0.5
- Instrumentation c/o	Castle Computer	Engine Software	0.3	0.3	---	0.3
- Solenoid c/o	Castle Computer	Engine Software	0.2	0.2	---	0.2
Engine - Periodic Maintenance			4.0	4.0	6.0	10.0
- Setup Operation		Engine Tools LRU ASE	0.5	0.5	1.0	1.5
- Turbopump boroscope	Power, Lights	Boroscope	1.0	0.5	1.0	1.5
- Thrust chamber inspec.	CCTV Monitor	RMS, CCTV	1.0	1.0	---	1.0
- Engine LRU replacement	Power, Lights EMU, HPA	Engine Tools LRU ASE	2.0	1.5	3.0	4.5
- Tool stowage		Engine Tools LRU ASE	0.5	0.5	1.0	1.5
Engine - Castle Engine Remove And Replace	RMS, EMU, Foot Restraint Lighting	Engine Fixture Eng. Dis. Tool Protective Covers	5.0	3.8	6.0	9.8
- Setup tools			0.5	0.5	1.0	1.5
- Attach engine fixture			0.5	0.5	1.0	1.5
- Disconnect engine			0.5	0.5	1.0	1.5
- Move engine to storage			0.2	0.2	0.4	0.6
- Pickup replacement			0.1	0.1	0.2	0.3
- Align and attach			0.7	0.7	1.4	2.1
- Check/verify QD's			2.0	0.8	0.5	1.3
- Store tools		LRU ASE	0.5	0.5	0.5	1.0

Table 2.12: A maintenance schedule for the CASTLE main engines (Reference 14)

The main concern regarding the main engines would be for the initial insertion maneuver. That is, the larger liquid fueled engines as designed today are rarely expected to perform a burn as long as the 7.8 hours required for insertion: the largest delta T is for complete overhaul and that is only 5 hours. Maintenance during insertion would be nearly impossible. This question would be best answered by further testing and development over the next 50 years.

Attitude control thruster units and all fuel lines are monitored for potential valve failure. The smaller thrusters have much redundancy built into their sheer numbers, and could also be replaced from storage if absolutely necessary. As mentioned earlier in section 2.3.4 the resistojet's simplicity allows for virtually maintenance free operation. The critical resistojet element is the heating resistance coil. If current projections of extending the lifetime of the coil to 10^5 hours do not prove true, a stock of said elements could be stored as cargo for use in periodic replacement . Given the mobility of the solar collectors, the use of the resistojets could be modified to accommodate a shorter heating element lifetime.

2.4.2 Total Spacecraft Mass Variation During the Mission

Table 2.3.2 gives a good approximation of the initial mass of the spacecraft. The mass of the vessel will be relatively constant throughout the mission except during major orbital correction burns and the arrivals and departures of the shuttle taxis. Because the taxis are berthing rather than docking the change in mass should not effect the trajectory of the spacecraft tremendously. Also, while the overall mass will noticeably change, all of the mass inside and including the torus section (the most massive portion of the CASTLE) will not change much at all.

Table 2.13 Initial Spacecraft mass summary (kg):

Propulsion System		
Main Engines	9 @ 210 kg	1890
Engine Shroud		500
Engine Mount Structure		4500
Insertion Tanks		
LH2	4 @ 11,000 kg	44,000
LOX	4 @ 5000 kg	20,000
Internal Tanks		
LH2		6000
LOX		3500
Internal Propellants		348600
Attitude Control Engines		
Resistojet	18 @ 10 kg	180
Aerojet AJ10-199	4 @ 14 kg	60
Aerojet AJ10-197	56 @ 2 kg	120
Torus System		
Propellants		22,400
Aerojet AJ46-1	8 @ 2.2 kg	20
Pipes, Pumps, etc.		7500
		459300 kg
Docking		
DOC		33,000
CAB		30,000
Misc.	——	17,000
		80,000 kg
Solar Dynamic Power System		
concentrators, receivers, engines, and radiators	16 @ 1600 kg	25,600
Trusswork	4 @ 3340 kg	13,400
Rotary Joints	20 @ 160 kg	3,200
PMAD & cables		2 [illegible]00
		4[illegible],000 kg

Regenerative Fuel Cell System		**10,000 kg**
Trusswork & Connectors		**80,000 kg**
Micro-G Laboratory		**110,000 kg**

Interface I		
Torus Connection		15,000
micro-gravity Connection		143,000
Inner Hub		5,000
Bearings	4 @ 1,160 kg	5,000
Interface II (power & data transmission)		20,000
		188,000 kg
Elevator		
Elevators	2 @ 4,000 kg	8,000
Driving Units	4 @ 1,500 kg	6,000
Misc.		2,000
		16,000 kg
Torus		
Structure		638,000
Sub floor		3,900
Sub Ceiling		4,000
End Caps		800
Sub Walls		3,900
Partitions		2,800
Misc.		42,000
CELSS		329,600
		1,025,000 kg
Torus Spokes	4 @ 30,200 kg	**121,000 kg**
TOTAL(ALL SYSTEMS)		**2,134,000 kg**

The dry mass of the cruise pod configuration would be significantly different from the mass given above. The dry mass of the propulsion systems in their insertion configuration would be 85490 kg, whereas the dry mass of the cruise pod configuration would be only 35500 kg. Additionally, the mass of the docking section would be increased by 254000 kg with the two shuttle taxis attached. The total mass difference including propellants would be even more pronounced. Again, the propulsion systems are the only systems with a 'dry' and 'wet' mass.

The total or 'wet' mass varies greatly between the insertion configuration and the cruise configuration. Table 2.14 gives the total mass summaries for the propulsion systems.

Table 2.14 Insertion and Cruise Configuration Propulsion System Mass Summary:

Insertion Configuration

Main Engines	9 @ 210 kg	1890 kg
Main Engine Shroud		500
Engine Mount Structure		4500
Insertion Tanks		
LH2	4 @ 11000 kg	44,000
LOX	4 @ 5000 kg	20,000
Insertion Propellants		3,542,500
Internal Tanks		
LH2		6000
LOX		3500
Internal Propellants		
LH2		46,200
LOX		302,400
Attitude Control Engines		
Resistojet	18 @ 10 kg	180
Aerojet AJ10-199	4 @ 14 kg	60
Aerojet AJ10-197	56 @ 2 kg	120
Torus		
Propellants		22,400
Aerojet AJ46-1	8 @ 2.2 kg	20
Pipes, Pumps, etc.		7500
		4,001,770 kg

Main Engines	5 @ 210 kg	1050 kg
Main Engine Shroud		500
Engine Mount Structure		4500
Trusswork		8200
Pod Propellants		
LH2		55,360
LOX		332,140
Pod Tanks		
LH2	4 @ 2500 kg	10,000
LOX	4 @ 1300 kg	5200
Internal Tanks		
LH2		6000
LOX		3500
Internal Propellants		
LH2		46,200
LOX		302,400
Attitude Control Engines		
Resistojets 18 @ 10 kg		180
Aerojet AJ10-197	56 @ 2 kg	120
Torus		
Propellant		15,600
Aerojet AJ46-1	8 @ 2.2 kg	20
Pipes, Pumps, etc.		7500
		798,470 kg

The overall mass of the CASTLE is significantly decreased in the cruise configuration. To complete this summary of spacecraft mass, table 2.14 followed by figure 2.10 which describes this variation of the total CASTLE mass throughout the duration of the mission has been included.

Table 2.15 Overall CASTLE Mass Change Summary:

Activity	Time	Mass	
1. Assembly completed in Low Earth Orbit	T = -7.5 months	1,721,400	kg
2. Thrusters on torus fire to start torus spin-up (3.15 hrs.)	T = -7.5 months	1,714,600	kg
3. Insertion tanks brought from lunar base	T = -1.0 weeks	5,669,700	kg
2. Main engines fire and burn for insertion	T = 8.0 hours		
5. After insertion is complete chemical thrusters fire for initial rotation		2,127,200	kg
6. After rotation is complete			
a. chemical thrusters shut off,	T = 9.0 hours		
b. insertion tanks moved, and			
c. resistojets fire	T = 9.5 hours	2,127,200	kg
7. Taxis dock	T = 9.75 hours	2,381,200	kg
8. First Mars fly-by	Day 146	2,321,600	kg
a. passenger exchange,			
b. insertion tanks collected, and		2,257,600	kg
c. internal tanks refueled (from Phobos)		2,317,200	kg
9. First aphelion -- no maneuver required	Day 390	2,219,900	kg
10. First Earth fly-by	Day 780	2,063,000	kg
a. passenger exchange			
b. main engines removed			
c. orbital correction pod attached		2,148,300	kg
11. Second Mars fly-by	Day 926	2,088,700	kg
a. passenger exchange			
b. internal tanks refueled (from Phobos)		2,402,400	kg
12. Second aphelion -- no maneuver required	Day 1170	2,305,200	kg
13. Second Earth fly-by	Day 1560	2,148,300	kg
12. Third Mars fly-by	Day 1706	2,088,700	kg
a. passengers exchange			
b. internal and pod tanks fueled (Phobos)		2,789,900	kg

15. Third aphelion	Day 1950		
a. before maneuver		2,692,600	kg
b. after maneuver (approx. 1 hr.)		2,415,300	kg
16. Third Earth fly-by -- passenger exchange	Day 2340	2,258,400	kg
17. Fourth Mars fly-by	Day 2486		
a. before refuel		2,198,800	kg
b. after refuel		2,789,900	kg
18. Fourth aphelion	Day 2730		
a. before maneuver		2,692,600	kg
b. after maneuver		2,304,300	kg
19. Fourth Earth fly-by -- passenger exchange	Day 3120	2,147,400	kg
20. Fifth Mars fly-by	Day 3266		
a. before refuel		2,087,800	kg
b. after refuel		2,789,900	kg
21. Fifth aphelion	Day 3510		
a. before maneuver		2,692,600	kg
b. after maneuver		2,463,700	kg
22. Fifth Earth fly-by -- passenger exchange	Day 3900	2,306,800	kg
23. Sixth Mars fly-by	Day 4046		
a. before refuel		2,247,200	kg
b. after refuel		2,402,400	kg
22. Sixth aphelion -- no maneuver	Day 4290	2,305,100	kg
25. Sixth Earth fly-by -- passenger exchange	Day 4680	2,148,200	kg
26. Seventh Mars fly-by	Day 4826		
a. before refuel		2,247,200	kg
b. after refuel		2,402,400	kg
27. Seventh aphelion -- no maneuver	Day 5070	2,305,100	kg
28. Seventh Earth fly-by -- passenger exchange	Day 5460	2,148,200	kg

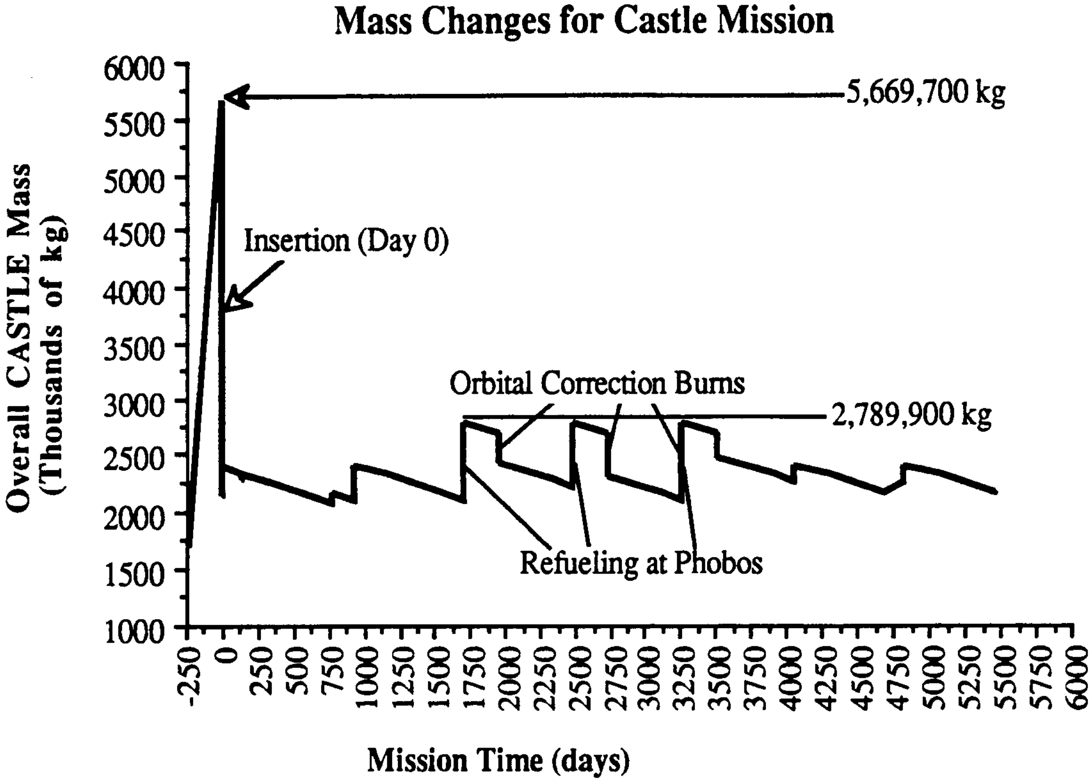

Fig. 2.11 Mass Change Summary Throughout Mission

2.4.3 Electrical Power Requirements for Propulsion System

The electrical power demands of the CASTLE propulsion system can be divided into the following parts: power needed for valve control, power needed for engine ignition, power needed for the fuel pumps, and power needed for heating the hydrazine fuel on the torus and the hydrazine fuel for the resistojets. These estimates are lower than initially anticipated as the main engines run on a turbo pump system, and as such would require little electrical power while in operation. Table 2.15 summarizes potential maximum consumption rates of electrical power by the propulsion systems of the CASTLE.

Table 2.16: Estimated Electrical Demand of Propulsion Systems:

Event	Power Required		Duration of Demand
Torus spin-up (or down)	10	kw	3.15 hours
Orbital Insertion	45	kw	ignition only
Orbital Correction	25	kw	ignition only
Solar Orientation maintenance	7	kw	continuous
Torus Spin Maintenance	2	kw	impulsive monthly

2.5 Conclusions

2.5.1 Recommendations for Further Analysis

There were some design aspects of these propulsion systems which were not able to be investigated in the CAMELOT II study. Those design aspects which should be studied further are detailed below.

In conjunction with the entire spacecraft, there is a general need to perform an even more detailed structural analysis of the entire truss support structure with the objective of minimizing the mass. The spacecraft, as it stands, is over designed in certain areas and there are a range of safety factors. A good amount of fuel could be eliminated, and more flexibility imparted to the propulsion systems were the mass of the spacecraft to decrease.

A basic analysis of the vibrational modes produced during the extended burns would be useful to designers concerned with structural failure due to these vibrations. A general assumption was made in this effort that the vibrations would be of such frequencies so as to not harm such a massive and relatively flexible body as the CASTLE. Still, detail would be useful.

A good thermal analysis could be performed, using a CAD program, on the rocket engines and the shielding around them. This would be relatively straightforward and would be necessary to determine the required shielding in hot spots. The analysis made on the fuel tanks and the fuel storage could be extended with CAD as well. This would determine optimum locations for fuel tank mounting and could save some fuel mass from boil off. Additionally, as indicated in section 2.3.9, the rate of boil off might be controlled with insulation to exactly match the demands for Hydrogen and Oxygen in other CASTLE systems (including the resistojets).

The dynamics of the tethering of the empty insertion fuel tanks, and of exchanging the old engines for a new orbital correction/cruise pod should be looked into. These proceedures may be more complicated than they seem at this time. It may be necessary to make the insertion fuel tanks mobile to avoid possible collisions with the CASTLE.

The initial design report, CAMELOT I, called for a second CASTLE to be constructed and placed in a down-escalator orbit, at the same time as the initial spacecraft would be traversing its up-escalator trajectory. This would allow for a shorter turnaround time for passengers to and from Mars. For a schedule of planetary encounters for the down-escalator orbit, refer to the CAMELOT I report. That schedule is proportionally accurate, yet its listed launch date of the mission is too early by about 40 years. The down-escalator trajectory would also utilize correction burns on the third, fourth and fifth orbits (out of a projected seven) which would be 270, 1110 and 660 meters/second respectively. The second delta V would require a burn of almost two hours long with five main engines. While the up-escalator voyage would take an initial 2.8 months to reach Mars, a previously launched CASTLE on a down-escalator trajectory would arrive in about 21 months. Time to Earth for the up-escalator vessel would be about 21 months from Mars, but only 2.8 for the down-escalator vessel. In general, this concept provides greater flexibility for crew and passenger exchange and should be considered in the future.

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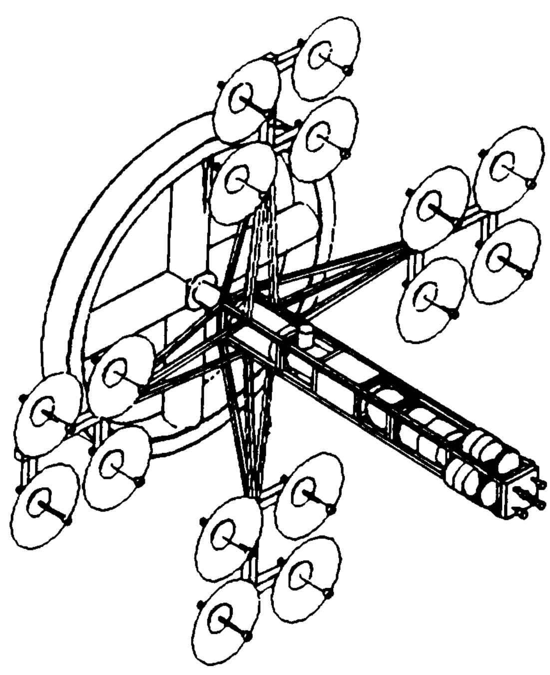
Chapter Three

Docking



3.1 Introduction

The docking group's objective was to create a design that would facilitate the transfer of personnel and cargo between external vehicles and the CASTLE. Due to the highly elliptical orbit of the CASTLE, there will be a limited time period when the transfer ships from Earth can deliver the supplies and personnel to the CASTLE. Because of this time constraint, it was decided that transfer of personnel and transfer of cargo be separate operations, facilitated by the use of two modules, the Docking and Operations Capsule (DOC) and the Cargo Acquisition Bay (CAB).

The DOC contains all the operations and controls for:

Berthing of Aeroassisted Manned Transfer Vehicles (Taxis)
Mobile Remote Manipulator System (MRMS)
Cargo Acquisition Bay (CAB)
Extra Vehicular Activity (EVA)

The Taxis mate with the CASTLE at two berthing ports located on the DOC. Berthing is achieved using a system of two remote arms for each port which berth the taxis after they have achieved rendezvous. The DOC also contains an airlock chamber that transfers large cargo from the CAB to the interior of the CASTLE. This airlock is the interface to the unpressurized CAB that serves as an EVA staging area, and is equipped with a contingency exit leading directly to the outside. This airlock is also capable of being used as a hyperbaric chamber in case of an emergency.

The Cargo Acquisition Bay (CAB) is designed to be a port for transfer of all non-manned cargo and also to serve as a multi-purpose space platform for a number of uses. The CAB uses two MRMS to transfer the cargo which is brought up on the supply ships. These MRMS will be mounted on tracks, allowing them to traverse the entire non - rotating structure of the CASTLE. In addition, the CAB is also used as a platform for:

Repair and maintenance of the CASTLE
Taxi maintenance
Space based manufacturing
Long duration exposure experiments

The berthing process was chosen over docking or tethering since berthing allows a controlled collision that generates energies which are small enough to be considered negligible.

Berthing is defined as the joining of two spacecraft using a manipulator or other interface mechanism. In this case, it involves Orbital Flight Operations and Berthing Arms Operations which grasp the approaching Taxi and slowly attach it to the docking port. There will be two berthing arms attached to each docking port which use a laser guidance system to assist in connecting the Taxi to the berthing mechanism. Once the Taxi is attached to the docking module, special latching mechanisms are activated to secure the Taxi in place.

The Taxis are officially called Aeroassisted Manned Transfer Vehicles, and were designed by Virginia Polytechnic Institute & State University (see reference 3.1). Alterations of their design are necessary to make it more compatible with the CASTLE, since the projects were developed independently. The Taxi's primary purpose is to transfer crew and cargo to and from a LEO space station, and the Phobos spaceport, to the CASTLE. The Taxi is equipped with a large heat shield capable of withstanding high temperatures which occur during Aerobraking through the atmospheres of Earth and Mars. Since the Taxi travels from heliocentric orbits as it nears the planets, it must aerodynamically decelerate to establish a low planetary orbit. This represents a savings in energy in that no extra fuel must be brought along for deceleration, although it introduces other technical and safety concerns. The Taxi is a side firing type vehicle as shown in figures 3.1 and 3.2 below.

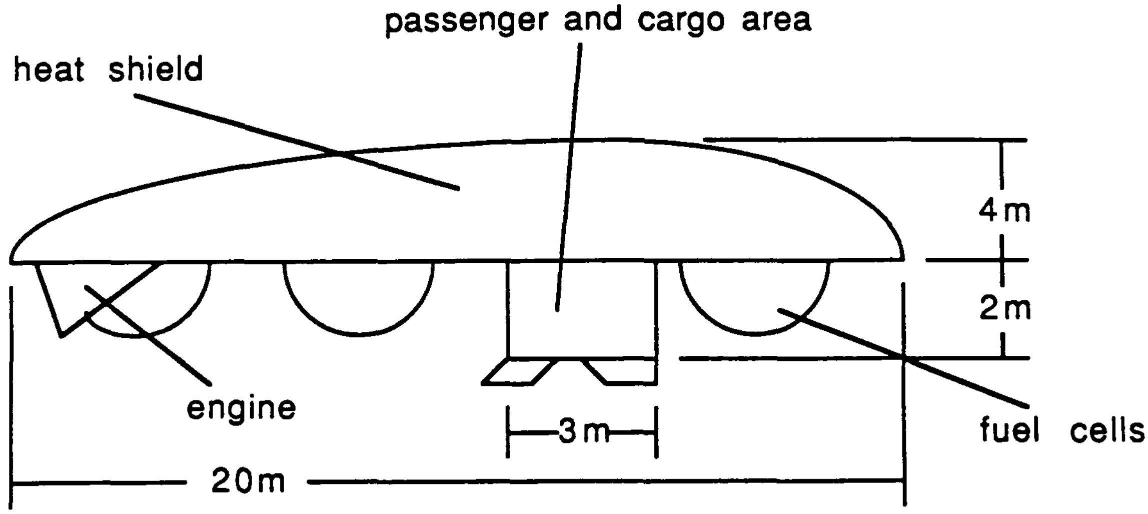


Figure 3.1 Side firing Taxi (side view)

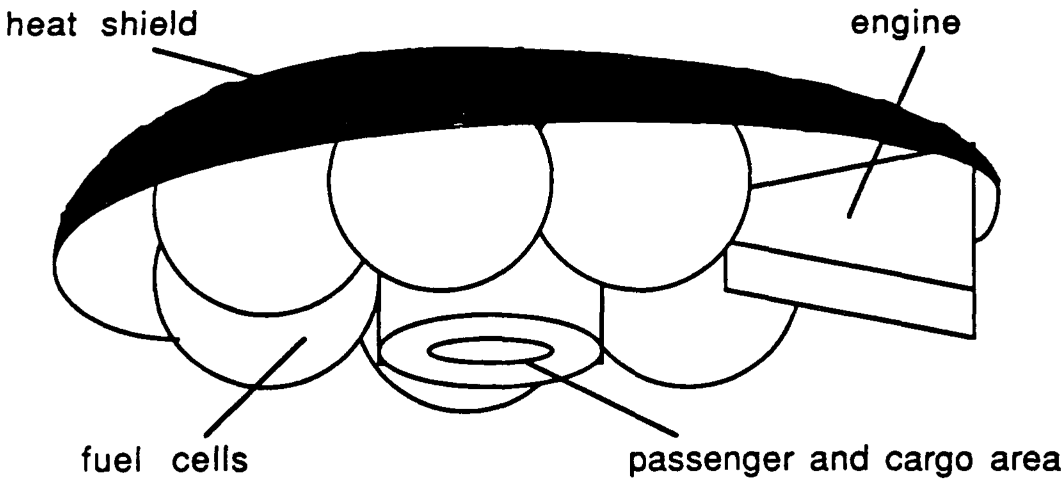


Figure 3.2 Side firing Taxi (oblique view)

The CASTLE is designed to carry a three person crew and seventeen passengers. The Taxi's are therefore designed to carry a crew of nine with a maximum capacity of eleven. Transfer time from LEO and Phobos to the CASTLE is normally one to five days, with seven days being the maximum. As a safety precaution, the Taxis have the capability of returning to LEO and Phobos in the event of an abort. The main design parameters of the Taxis are listed below.

Heat shield diameter	20 m
Dry mass	24,000 Kg
Propellant mass	104,000 Kg
ΔV Range, Prop	4.90 - 7.27 Km/s
ΔV Range, Aero	1.80 - 3.50 Km/s
Thrust 890,000 Newtons	

The taxis rendezvous with the CASTLE after the insertion burn. They then join the CASTLE to berth as shown in figures 3.3 and 3.4.

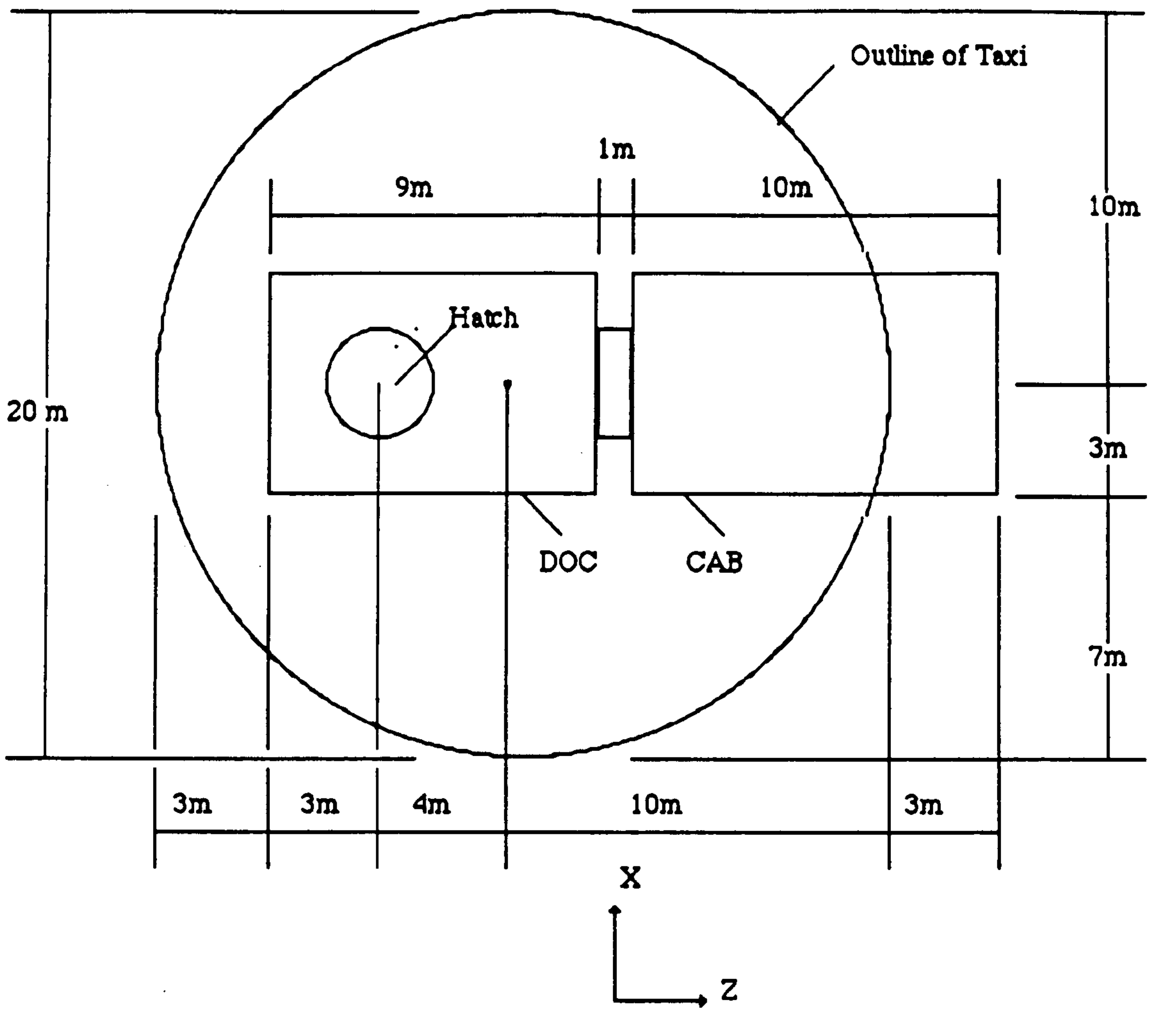


Fig. 3.3 Berthed Taxi (overhead view)

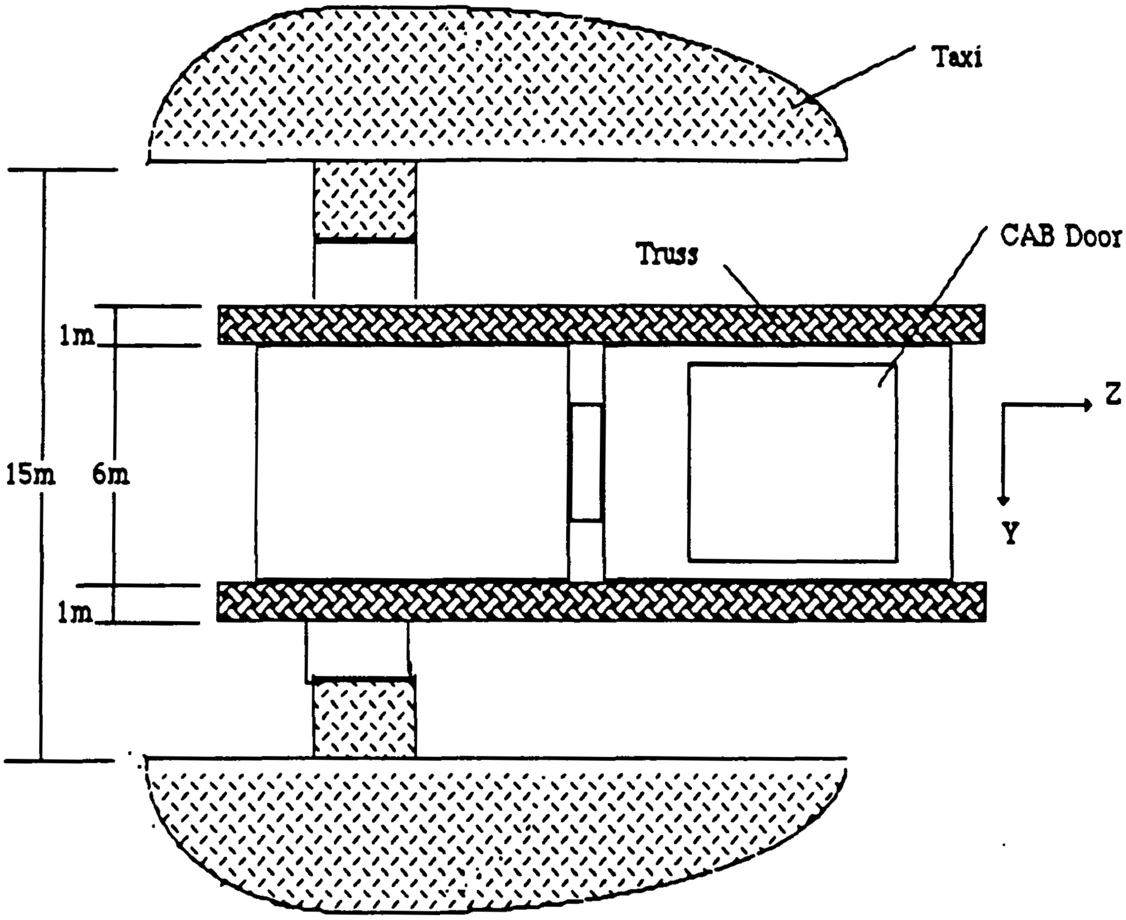


Fig. 3.4 Berthed Taxis (side view)

This configuration provides a 15 m clearance for CAB operations while the Taxis are berthed on the station.

3.2 Berthing

In the Mars mission, the CASTLE will be enroute to Mars with two Taxis attached. When approximately five days away from Mars, both Taxis will separate and initiate small delta V's on the order of 50 m/s to change the minimum approach distance to planetary atmospheric graze. At graze, an Aero-braking procedure will be initiated to burn off the energy of the hyperbolic trajectory. Concurrently, two Taxis will be departing from the Phobos spaceport for eventual rendezvous with the CASTLE. All separations and attachments of the Taxis with the CASTLE require consideration of the berthing process.

Berthing is defined as the joining of two spacecraft using a manipulator or other interface mechanism. In our case, it involves Orbital Flight Operations and Berthing Arms Operations which grasp the approaching Taxi and slowly attach it to the docking port, assisted by a laser guidance system. There are two berthing arms attached to each docking port to assist in connecting the Taxi to the berthing mechanism. Once the Taxi is attached to the docking module, special latching mechanisms will be activated to secure the Taxi in place.

A berthing process was chosen over docking or tethering, since berthing allows a controlled collision that generates smaller collision energies. These energies are so small that they are considered negligible. Therefore, no additional energy absorbing mechanisms are needed.

In controlling its approach to the CASTLE, the Taxi must use its Reaction Control System (RCS) engines for translation and attitude control. The Taxis RCS firings produce contaminations and a pressure flow fields, both of which can have adverse effects on the CASTLE. External contamination limits for the CASTLE are much more stringent than for any previous manned spacecraft. The RCS flow field must not affect the CASTLE's structure and control systems or components such as solar reflectors, radiators, or the torus interface. In order to minimize these effects, the two berthing arms finish the final stage of the berthing process, thus making RCS firing near the CASTLE unnecessary.

3.2.1 Rendezvous and Berthing Process

The rendezvous and berthing process occurs in three distinct spatial zones about the CASTLE as indicated in figure 3.5 below.

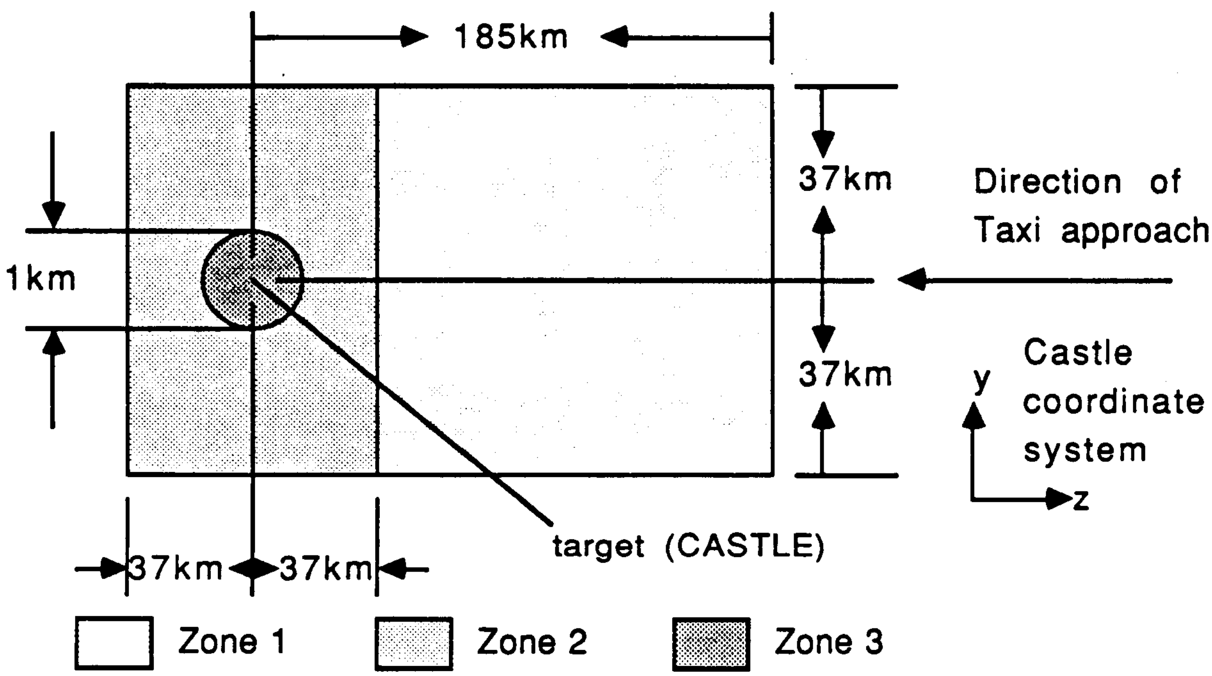


Figure 3.5 Taxi Operations Zones

In the above figure, Zone 1 is the Rendezvous Zone, Zone 2 is the Control Zone, and Zone 3 is the Proximity Operations Zone.

Rendezvous Zone

This is the first zone the arriving Taxi enters. It begins 185 km in the z direction behind the target (CASTLE docking port) and ends 37 km behind the target. In the vertical direction (y-direction), the zone is defined by a 37 km distance above and below the target. This zone location and size are designated to be consistent with the standard Stable Orbit Rendezvous Technique. With this technique, the Taxi arrives at an offset point some distance behind the target from which it may perform its closing maneuvers.

Control Zone

The second zone begins 37 km behind the target and ends 37 km ahead of the target. It also, as above, encompasses the area 37 km above and below the target. The Taxi's position and velocity are tracked by the laser guidance system on the CASTLE, which calculates attitude corrections to be executed by the Taxi. Execution of attitude corrections at this distance prevents RCS flow fields from affecting the spacecraft. These operations require no participation from the CASTLE or Taxi crews, but can be manually overridden if necessary.

Proximity Operations Zone

This area is defined by a 1 km diameter sphere, centered at the target. Final adjustments to the attitude, consistent with those required by the berthing system, are implemented. When the Taxi is within 7 m of the berthing port, the berthing arms reach out to grasp it. After the berthing arms attach to the Taxi, the rest of berthing process is completely monitored from within the DOC. Monitoring includes communication, tracking, and back-up targeting for the Taxi. These activities impose requirements on the DOC for various hardware and software systems.

3.2.2 Separation from the CASTLE

A typical separation scenario for the Taxi berthed to the CASTLE begins with the separation of the Taxi from the CASTLE using the two berthing arms. With a small separation rate provided by the MRMS, the Taxi will move away from the port. A minor intermediate maneuver may be required to ensure a favorable geometry for the separation of the Taxi and CASTLE. After coasting for approximately 15 minutes, the Taxi performs a larger separation maneuver of approximately 0.9 m/s. This ensures a separation of approximately 18.5 km at the orbital transfer maneuver ignition. This range is needed so that the CASTLE will be at a safe distance should the Taxi suffer a catastrophic failure, such as an explosion. It is at this point that the separation has been completed.

3.2.3 Berthing Control System

The berthing control system has to overcome misalignments caused by three factors. First, errors can occur due to orbital mechanics if the Taxi center of mass is not at the same altitude or in the same orbital plane. Second, Taxi's RCS jet cross-coupling effects may occur due to the fact that the RCS jets are not mounted orthogonally with respect to the Taxi body axis coordinate system. Third, plume-induced target motion may also occur from the RCS jets. When the Taxi RCS jets fire, the exhaust plumes will blow against on the CASTLE, causing it to move. The direction and rate of this motion depends on the separation distance, the number and type of jet firings, the plume-CASTLE contact area, and the CASTLE's control system capabilities.

For the berthing process, it is essential that every step be carefully monitored. If even one small error occurs, it could prove fatal. In order to insure safe docking, four cameras are placed on each berthing arm. These cameras monitor each step of the berthing process. The television monitors, along with the other berthing arms controls, are located in the DOC. A sufficient lighting system is installed outside the docking system to aid in supervision of the berthing process.

In addition to the cameras, Attitude Control System (ACS), Local Vertical-Local Horizontal (LVLH), Laser PROX OPS Sensor (POS), and electromechanical attenuators are used. The CASTLE Attitude Control System has perfect inertial attitude sensors and Local Vertical-Local

Horizontal attitude hold, usually maintaining zero degree with respect to LVLH with ± 1.0 deg. and 0.1 deg./sec. deadbands. The Laser PROX OPS Sensor provides perfect data (range, range rate, azimuth and elevation angles, and azimuth and elevation angular rates) between berthing port and the Taxi. Further, four pairs of electromechanical attenuators are included in the berthing controls. The attenuators control the position of the docking interface relative to the base ring.

3.2.4 Berthing Mechanism

The berthing mechanism is used as the interface for the Taxi and the CASTLE during the berthing process. It can also disperse the concentrated berthing forces on the port gently, through the attenuation mechanism. However, certain requirements for the proper operation of this mechanism are necessary:

1) Significant forces must be along the x-axis only
2) Taxi must initially have zero angular rate
3) Taxi closing speed at 0.030 m/sec. along the berthing axis
4) Constant force must be maintained on the berthing mechanism
5) The displacement of the berthing mechanism must be below 0.15 m

In accordance with current studies in the Space Station Reference Configuration, the berthing disturbance is modelled as a 3870 N force acting along the berthing axis for a period of 1 second.

3.2.5 Berthing Dynamics Analysis Results

Berthing Dynamics Analysis is concentrated on assuring the abilities of the berthing arms to berth the Taxi to the CASTLE. The analysis primarily covers the areas of post-capture and berthing dynamics. The following conclusions have been reached, based on the capture and berthing studies to date:

1) The relative velocity at capture cannot exceed 4.2693 cm/s
2) Using berthing arm 'joint runaway' (i.e.,. maximum allowance) as a design/performance driver, the following set of berthing interface mechanism sizing parameters have been defined.

	'Runaway'	Nominal
closing velocity (cm./s)	4.2693	1.5247
lateral velocity (cm./s)	±2.7445	N/A
angular velocity (degrees/s)		
roll-	±0.0200	N/A
lateral -	±0.2200	N/A
lateral misalignment (cm.)	±10.1650	6.0990
angular misalignment (degrees)		
roll -	±2.0000	0.2700
lateral -	±2.0000	0.7000

By assuming the control system is sufficient to fulfill these berthing dynamics requirements, the collision energies are so small that they can be considered negligible. This is proved by structural analysis.

3.3 Structural Analysis of the Docking Module

Because the berthing process actually involves a collision between the Taxi and the docking module, it is necessary to analyze the structural performance of the module to be certain that it can perform under the maximum applied forces. This is accomplished by creating a finite element model to determine the stresses and displacements of the structure and the reactions of the mounting supports under maximum loading conditions.

The berthing guidelines specified by NASA for use in the future space station are followed. NASA recommends a berthing velocity of 0.1 ft/sec(.03048 m/sec) acting along the berthing axis. The time of impact is not to exceed 1 second. With a Taxi mass of 127,000 kilograms, an impulsive berthing force of 3870 Newtons is developed along the berthing axis (see figure 3.6).

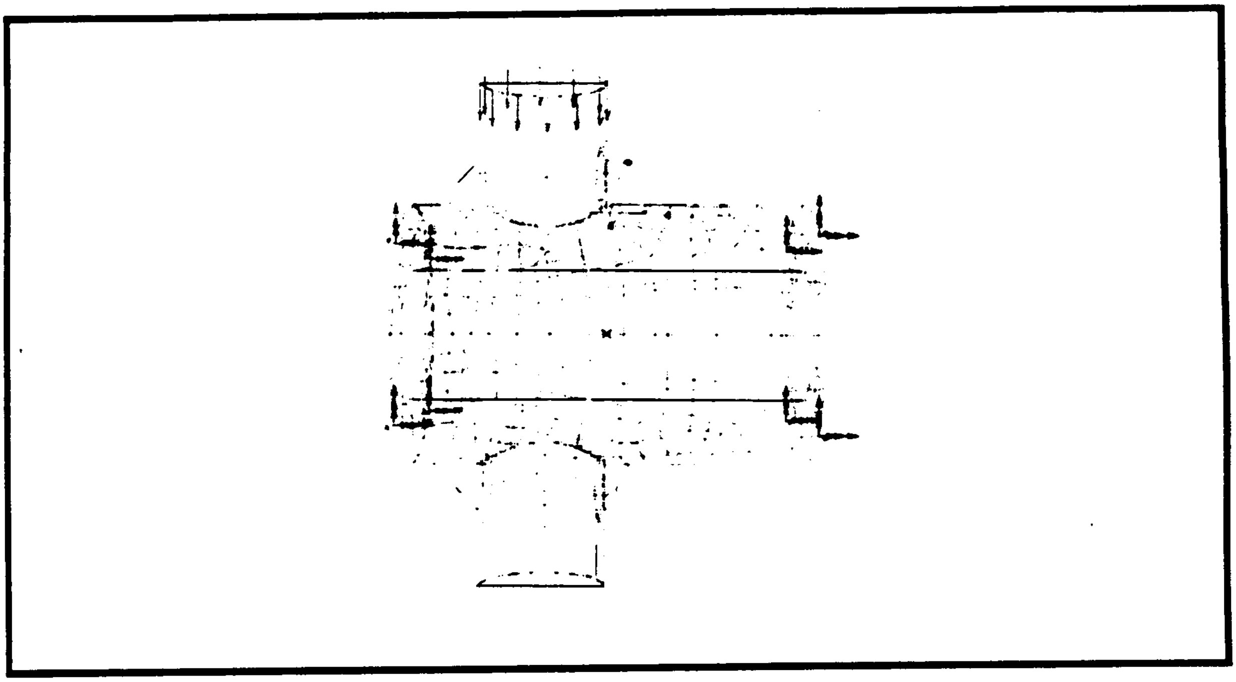


Fig. 3.6 Loads and Constraints

As previously mentioned, a berthing speed control system has been devised which can easily achieve this 0.1 ft/sec(.03048 m/sec) berthing velocity. However, to assure structural integrity in the event of a control system malfunction, the structure is analyzed with berthing velocities of up to 1 m/sec(.3048 m/sec), providing an acceptable safety margin.

All berthing loads are transferred directly into the docking module. The module is restrained by four beams on either end which connect it to the boom truss structure. These beams are pin-jointed, and therefore carry all loads in either tension or compression.

The material selected for the structure is 2219-T851 aluminum alloy. It has the following mechanical properties:

Yield Strength = 317 MPa
Elastic Modulus = 68950 MPa
Poisson's Ratio = 0.33

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It should be pointed out that the structure is extremely strong. A large wall thickness of 0.03 m was chosen not due to strength considerations, but rather to provide radiation protection. As a result, the structure is very lightly stressed, even when tested with excessive berthing velocities. The accompanying finite element stress analysis confirms this.

Finite element analysis provides the following results:

1) The maximum stress occurs at the intersection of the berthing tube and the main docking module cylinder(see stress contour plot, figure 3.7). A Von Mises stress of 3.024 MPa results at this point, well below the material's yield point.
2) The largest displacement is a very small 0.4 millimeters. The displacement at the berthing site is 0.25 millimeters along the berthing axis.

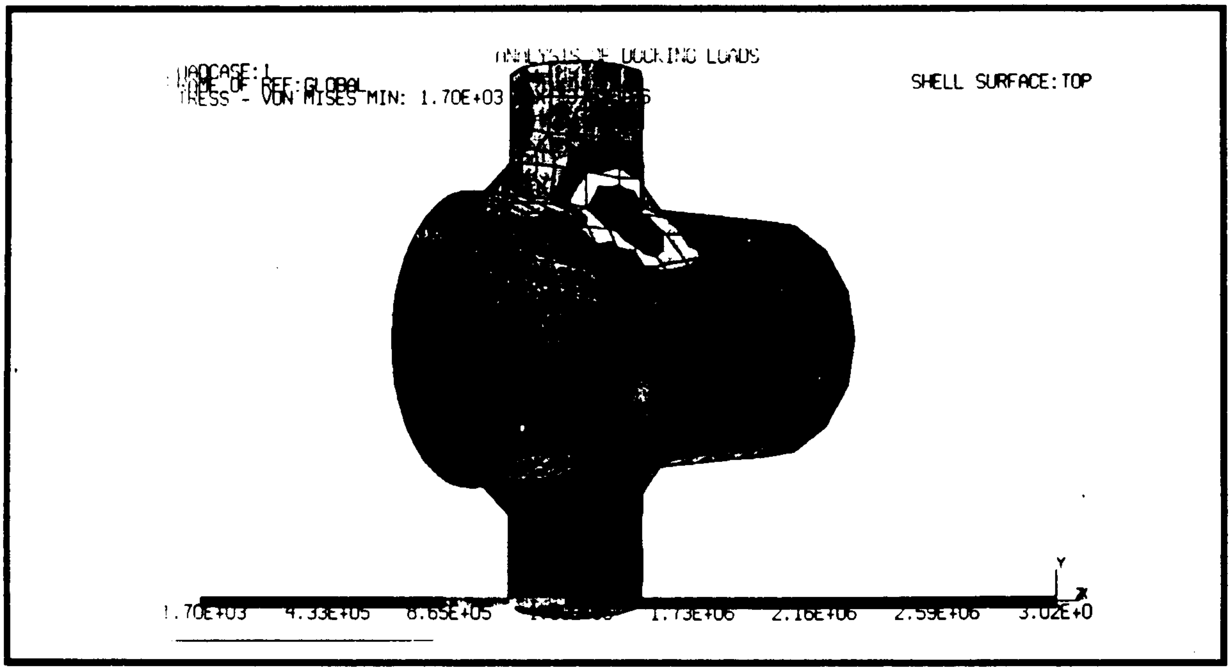


Fig. 3.7 Von Mises Stress Contour Plot

As the results show, stress and displacements are both very low due to large wall thicknesses and the relatively low berthing velocities .

3.4 Docking and Operations Capsule (DOC)

The DOC is a cylinder, 6 meters in diameter and 9 meters in length. This volume provides ample space for the placement of systems and controls which are essential for docking and maintenance operations. These systems and controls are presented in the following sections.

3.4.1 Airlock Controls

The airlock control system is comprised of two airlocks (one of which may function as the hyperbaric chamber), the vacuum pump system, air storage tanks, and the control panel. The first airlock, or the "secondary airlock," will be used to transfer large volumes of cargo from the unpressurized Cargo Acquisition Bay, or CAB, to the DOC. Due to the extreme size of the secondary airlock, it is generally reserved for the transfer of large pieces of cargo. The secondary airlock is located at the far end of the DOC.

The primary airlock, located in the CAB, is used for all EVA staging activities. This includes maintenance, experimentation monitoring, and basic space manufacturing. Because of the small dimensions of the primary airlock, it is easier to evacuate and more efficient than the secondary airlock for most EVA or cargo handling tasks.

3.4.2 Life Support Control System

The life support control system consists of a pressurized air-line network which draws air from the main ECLSS unit, located in the Micro-G Laboratory module. This network circulates the air, keeping a constant partial pressure mixture of nitrogen and oxygen. The control panel, located above the secondary airlock chamber, monitors the flow and composition of the air, and increases or decreases the partial pressures as needed. The humidity and temperature controls for both the Micro-G lab and the DOC are located in the Micro-G section.

In the event of an emergency, the DOC has been designed to be sealed off from the Mirco-G lab. The Contingency (emergency) ECLSS system consists of storage tanks for pressurized oxygen and a vacuum sealed container of lithium hydroxide. The stored oxygen allows personnel to survive in the DOC and boom for anywhere from one to three weeks, depending on the number of crew members in the DOC. This time period should be sufficient for any problem to be solved and for necessary repairs to be made. Once the repairs have been made the CASTLE may return to normal life support operations.

3.4.3 MRMS Control Systems

The MRMS control system consists of two identical stations. Each unit is capable of working in conjunction with another, or as separate units. Station One is responsible for the operation of one MRMS, while Station Two is responsible for the operation of the other MRMS. These stations are located above the airlock chamber, and each station has 6 monitor screens, one mock-up arm (inside the DOC-for movement simulation), and one computerized control system board.

It is important that all tasks performed by the MRMS be carefully monitored. In procedures such as cargo transfer, a crew member must observe and control the entire process. There are many MRMS functions which require manual operation. Such things as the size and shape of the object being moved are important in deciding how fast to move it, where to place it, and if both arms will be necessary. As a result, there are two separate systems necessary in the MRMS control system. These are a television camera / monitor observation system, and a laser tracking system. In case either a television camera or monitor fails, a window is placed to provide visual sightings for manual operation.

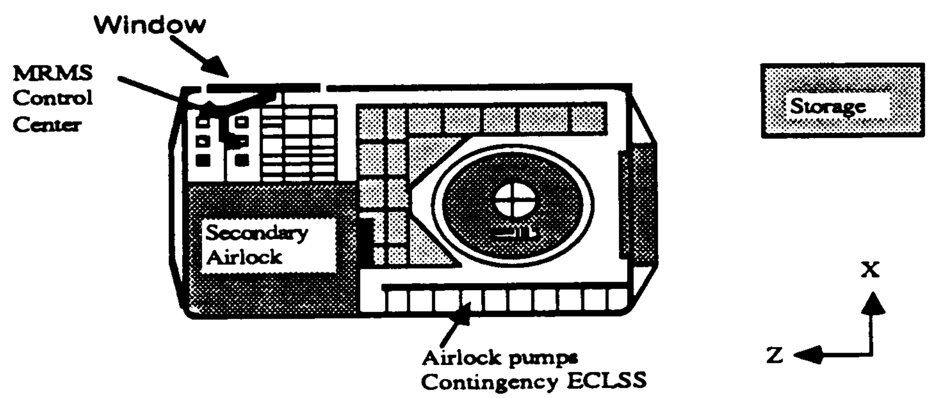


Figure 3.8 Cross-section of DOC

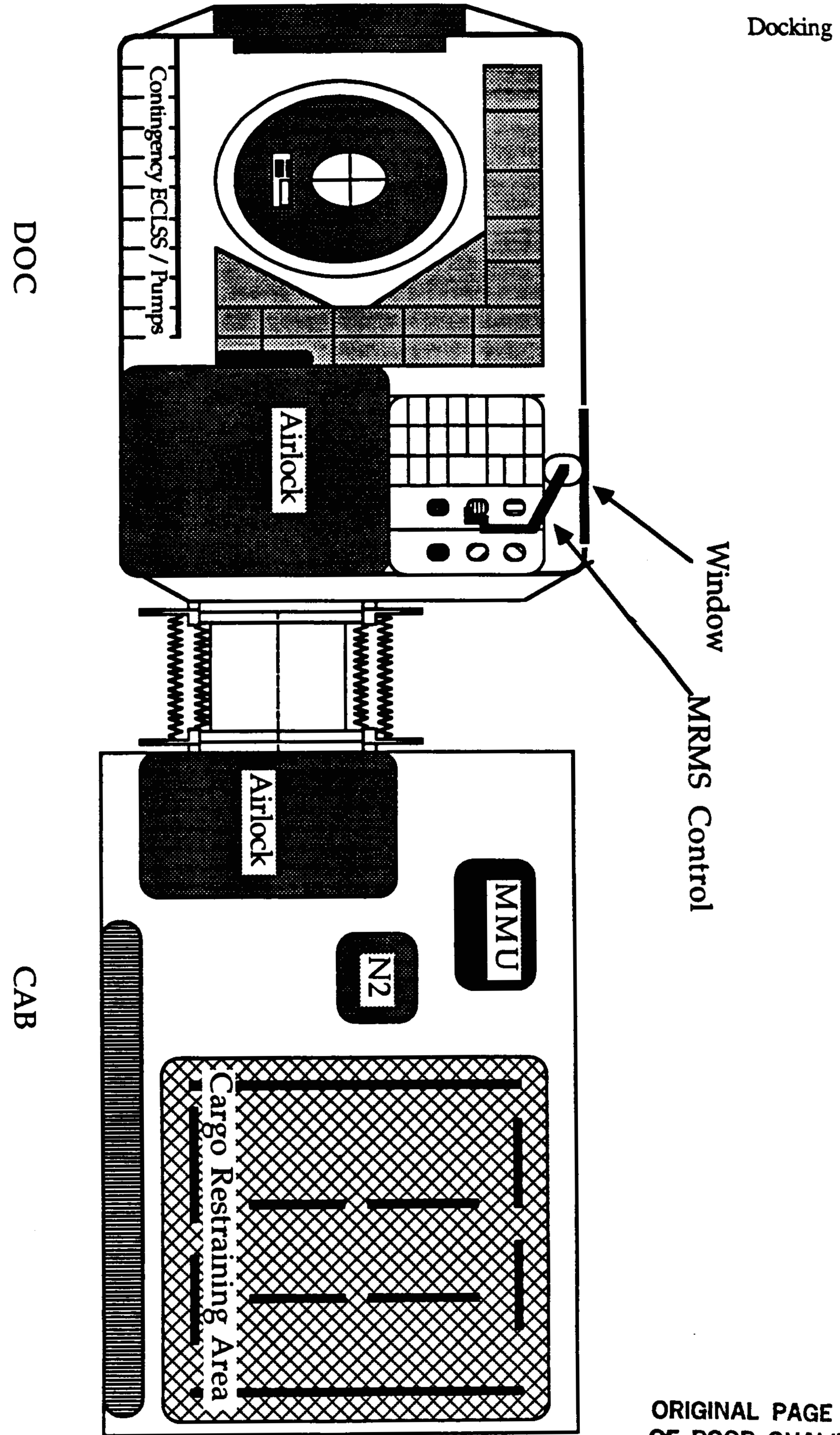
Similar to the berthing arms, the MRMS arms have four cameras to monitor operations, strategically placed to observe the arms from any angle during use. One is placed at the base of the arm, one at the elbow joint, one at the wrist joint, and one at the tip of the RMS. The monitors for each camera and the main controls for the MRMS are located in the DOC.

From inside the DOC, a crew member can observe and control the MRMS actions. There is one television monitor for each camera on each arm. The activities of the MRMS may be observed at different angles or positions with these monitors, thus aiding the controller in properly performing the necessary task. The controller manipulates the robot arm with a control similar to a joystick. Separate controls extend the arm, contract the arm, control the speed, etc. Another feature of the MRMS control system is the ability to choose between using both arms or just one arm. Those operations which require the use of both arms must be more carefully controlled, since they must do everything simultaneously. For example, when the propulsion section needs the engines replaced after orbital insertion, the arms have to work in conjunction with each other. To do this there are special features in the control system which allow for either a program to be loaded that operates the arms in the prescribed manner or for Station One to control both of the arms and have them work simultaneously.

A laser tracking system supplements the cameras, providing additional information necessary for the MRMS tasks. This system gives the controller information regarding the relative positions of the cargo and the speeds at which they are being moved. This information is displayed on a CRT next to the control panel.

DOC data	Dimensions (m)	Volume (m^3)	Mass (kg)	Power (W)
Docking Shell	l = 9.0 d = 6.0	254.5	17,000	--------
Docking Tubes	l = 2.5 d = 3.0	35.3	3,918	--------
Airlock	3.5 x 3.5 x 3.5	43.0	3,052	--------
ECLSS	4.0 x 5.0 x 1.3	21.9	5,614	7,060
Lighting	--------	--------	24	240
MRMS	l = 15.0 d = 0.3	--------	3,000	500
Berthing Arms	l = 8.0 d = 0.3	--------	400	300
DOC (totals)	--------	304.0	33,000	8,100

Table 3.1 DOC Design Data



Configuration of the Docking section

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3.5 Cargo Acquisition Bay (CAB)

The Cargo Acquisition Bay, or CAB, is an unpressurized module that acts as the loading dock for the CASTLE. All cargo is transferred through or stored in the CAB by means of the mobile remote manipulator system, or MRMS. The types of cargo being transferred are food, medical supplies, other consumables, new equipment, spare parts, instruments, replacements of working fluids and coolants, replacements for life support, and emergency propellents for the Taxis. There is also material that will have to be taken off the CASTLE , such as waste products and used experimental equipment. The cargo is transferred form large and efficient cargo vehicles that are available for hauling heavy loads between the planets. Several of these cargo ships are used, rendezvousing with the CASTLE for only a few hours while fuel and other goods are exchanged via MRMS. The frequency of trips is dictated by the need for fuel, with fuel replenishment occurring just weeks before every major course correction to minimize boiloff.

3.5.1 Multipurpose Platform / Maintenance Center.

The CAB also acts as a multipurpose platform, as it is also a base for staging all EVA which will handle repair and maintenance of the CASTLE and the Taxis. The CASTLE is designed to require a minimum amount of maintenance, as all main systems have redundancy built into them, and they contain advanced systems of automation and artificial intelligence to monitor themselves for failure. The systems are designed to automatically diagnose a problem, alert the crew, and isolate the failure without degradation of required performance. With all of these precautions, a system failure will not disable the ship unless it is of catastrophic proportions.

The three permanent crew members, as well as several others of the transient personnel, are trained to perform extravehicular activities, and to make repairs on the outer parts of the ship such as the truss, the solar collectors, and the engines. Repairs are made, with the help of the MRMS, in or near the CAB when possible. This reduces the danger that accompanies any EVA. All tools for repair are contained in the CAB, including the battery operated tools that are stored in service compartments. The tools can be attached to the MMU's by the use of velcro.

The CASTLE is designed to be fairly easily maintained, and to be well protected against emergencies, both of which are major concerns when dealing with manned spaceflight. The ship is fitted with extensive detection systems to detect such problems as fire and pressure loss as quickly as possible. Crew members are trained in basic emergency procedures concerning these problems. This ship should be able to withstand successfully any problems encountered during its journey.

3.5.2 Manufacturing and Experimentation

Room in the CAB is provided for space based manufacturing and long duration exposure experiments. This includes material processing furnaces at the end of the CAB for metal alloys and crystal growth. In space, substances can be purified 10 to 15 times better than on earth, with productivity being 100 times higher. Exposure experiments will show how materials react to radiation and whether or not there is any degradation of the materials over time. The CAB is equipped with materials to construct reusable platforms that will aid in exposure experiments. Depending on the duration of the experiment, the platforms can either be held by one of the MRMS units or attached to the truss. In case an exposure experiment is combined with a zero gravity experiment, the platform can be deployed by an arm, letting the experiment float along with the CASTLE. This will have to be done carefully and monitored to make sure the platform does not change position and run into part of the CASTLE, or away from it into space. In the event that this does occur, an arm will be nearby to retrieve the platform.

3.5.3 Design Requirements

The dimensions of the CAB are 6 m x 6 m x 10 m and it has an interior volume of 312 m^3. The cargo bay door is 5 m x 6 m and is .03 m thick, and retracts behind one of the cargo restraining areas (see figure 3.9). All cargo should clear the cargo bay door by .09 m and should not be more than 20,000 kg. The wall design is .03 m of aluminum over .051 m of insulation with a shielding of .0011 m of aluminum. This protects the CAB from radiation and meteorites . Radiation and meteorite protection determined the design of the CAB wall, as this is an overdesign based on structural considerations. Radiation is a serious problem for space travel, especially during periods of intense radiation levels (i.e.,. solar flares and Van Allen Belt). In order to protect the crew from radiation, the wall has to be thicker than if the only worry was structural failure due to forces from orbital correction or pressurization.

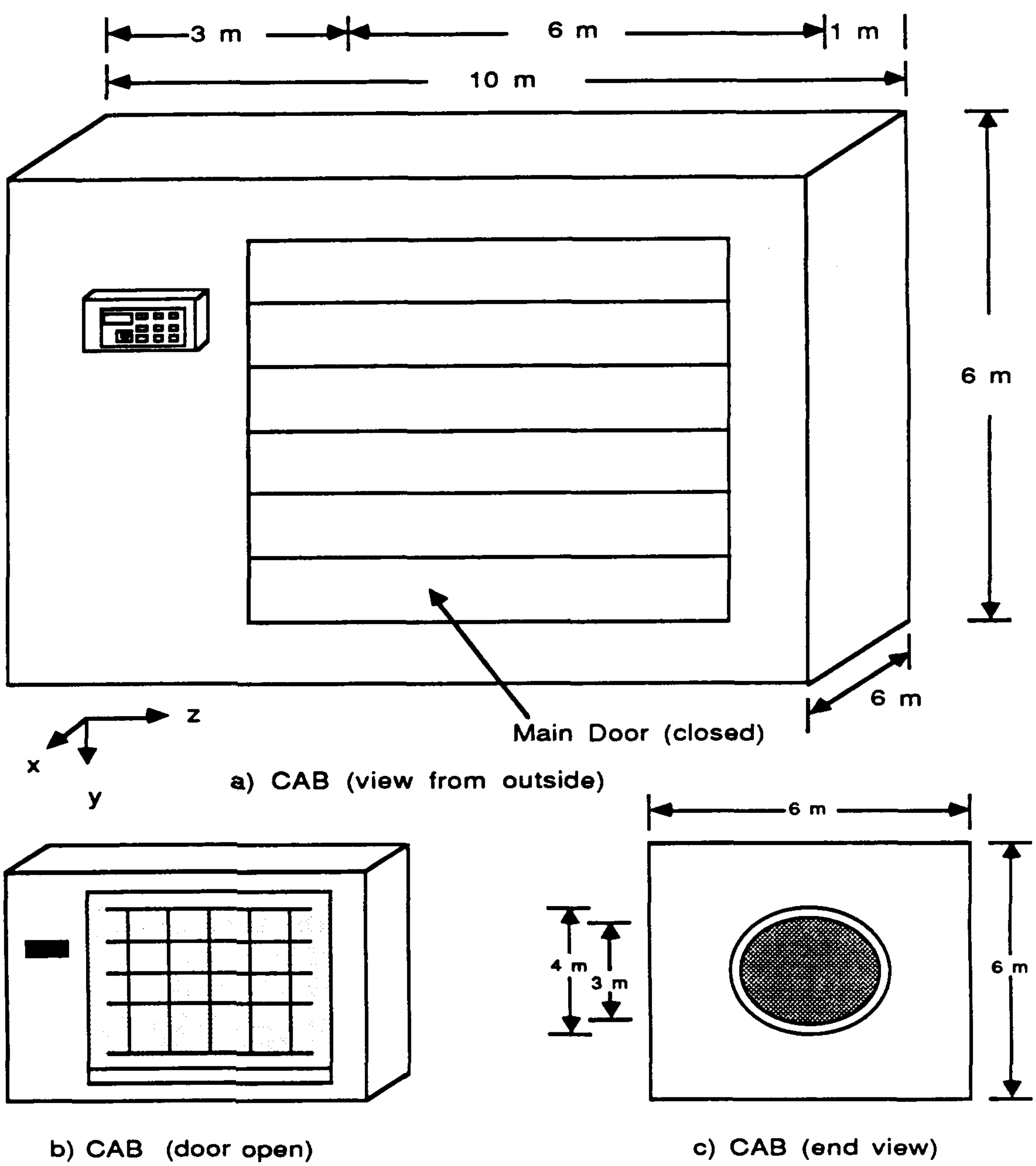

Figure 3.9 Cargo Acquisition Bay (multiple views)

The purpose of the insulation and outer wall is for protection of the crew from meteorites and also to act as a heat shield. Without the insulation, the side of the CAB facing the sun tends to get very hot, becoming dangerous to the crew. Also, while the CASTLE should not run into any large meteorites, it does need protection from smaller particles which sometime travel at extremely high velocities. The outer wall and insulation act as a buffer zone so that fast traveling particles will not puncture the inner hull.

3.5.4 Interior

The primary airlock is located in the CAB, and serves the crew in all EVA activity, while the secondary airlock in the DOC is used for transfer of cargo to the interior of the ship. The primary airlock in the CAB is able to house two astronauts at a time. This airlock is used so that a smaller volume can be pressurized and depressurized.

There are three Manned Maneuvering Units to assist the astronauts in EVA. These are located in the CAB near the airlock to the DOC, along with their service stands and fuel tanks. The MMU thruster jets run on nitrogen gas, while the computer system runs on batteries that are charged by the service stand. Interior lighting in the CAB, along with exterior lighting on the truss and on the MRMS help the personnel with cargo transfer and EVA activity.

Besides the MMU's, the CAB has areas available for the placement of bulk cargo storage. This area is used, when the CASTLE performs Earth and Mars flybys, to provide quick and easy transfer and storage of needed supplies. The area consists of a mesh on the inside of the CAB to which the cargo will be strapped down until there is sufficient time for removal to other parts of the CASTLE. A computer system monitors the center of gravity at all times so that cargo may be positioned to minimize the change in ship's the center of gravity. Also, there are numerous wall storage areas, used to store spare parts for the MMU's and tools for the repair and maintenance of the Taxis and CASTLE. In addition, materials to build re-usable platforms for experiments are also stored in separate compartments.

Controls to open the CAB door are located on the inside and outside of the CAB while the main controls are in the DOC. The inside of the CAB also contains controls for the airlocks, the MMU service stand, and recharging units for battery operated tools.

See figure 3.10 for interior views of the CAB, and table 3.2 for CAB design data.

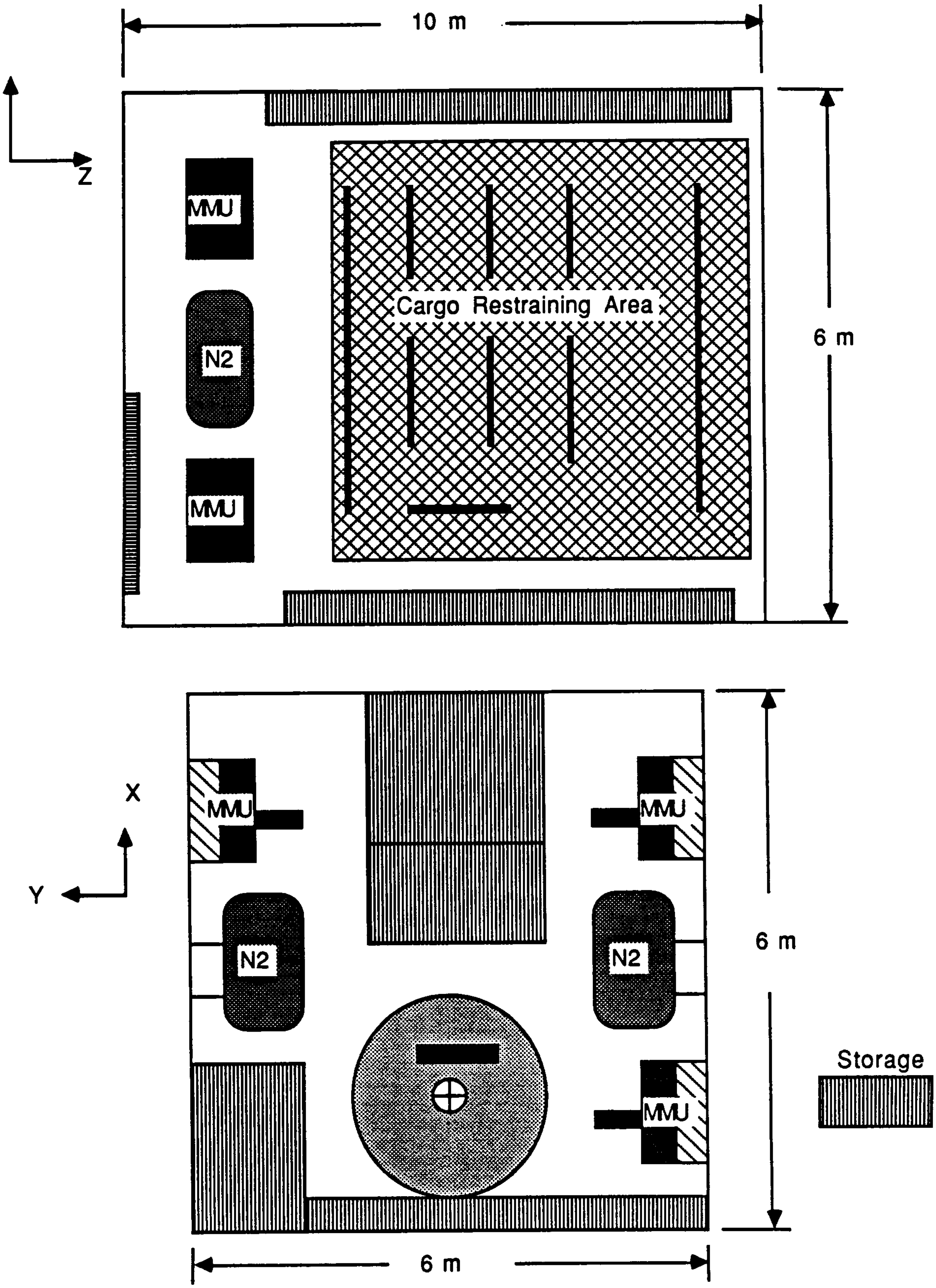

Figure 3.10 CAB (interior views)

CAB data	Dimensions (m)	Volume (m^3)	Mass (kg)	Power (W)
Shell	6.0 x 6.0 x 10.0	360.0	25,986	--------
Door	5.0 x 6.0 x 0.03	0.8	2,100	--------
EVA Airlock	2.5 x 2.5 x 3.0	17.5	1,657	--------
MMU (2)	1.0 x 1.5 x 1.0	1.5	205	--------
Service stand	--------	--------	1,330	500
Lighting	--------	--------	12	240
CAB (totals)	--------	360.0	30,000	740

Table 3.2 CAB Design Data

3.6 The Mobile Remote Manipulator System (MRMS)

In addition to the Remote Manipulator System (RMS) arms used for berthing, there are two RMS arms mounted on a moving platform. These arms are capable of traversing along the entire length of the CASTLE and will serve many purposes. The primary purpose of these arms is to provide a simple method for the transfer of personnel and cargo. They are also needed for various construction activities, such as positioning astronauts for Extra Vehicular Activities (EVA) functions, transportation of modules and payloads from the cargo bay, and positioning these modules for attachment to the truss structure. Other uses include maintenance and repair of the CASTLE.

The MRMS arms move along the length of the CASTLE on a track mounted to the truss structure. The tracks are attached in such a way that they do not interfere with the berthing ports. They are mounted on the same side as the CAB door to allow for easy transfer of cargo into the CAB. The tracks are tubular in shape, 10 centimeters in diameter and 1 centimeter in thickness. They are hollow with control wires running through them. There are two sets of two parallel tracks running along the truss, one on each side of the CAB door. On the track is a mobile platform on which the MRMS is mounted (See figure 3.11).

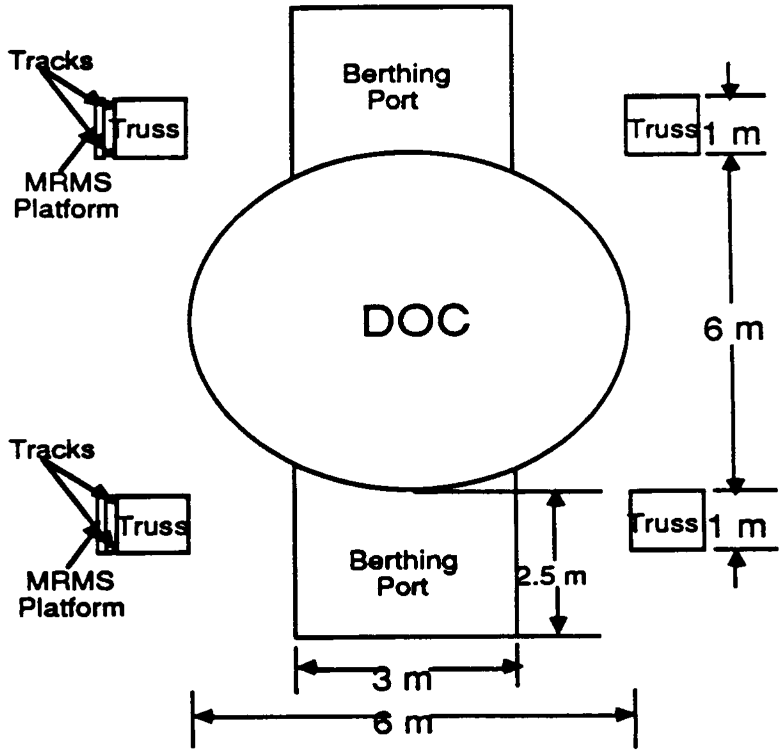

Figure 3.11 MRMS tracks and platform (side view)

The MRMS platform is a 1 meter square with a thickness of 10 centimeters. On each corner, three wheels are mounted to the bottom. Also attached to the bottom of the platform is a small generator which provides power to the top wheel (See figure 3.12). It is this wheel which allows the platform to move along the tracks. It is shaped so that it follows the contour of the track. The other two wheels are necessary to provide stability to the platform. Each of the three wheels has a diameter of 5 centimeters and a thickness of 2 centimeters. The RMS is mounted to the center of this platform.

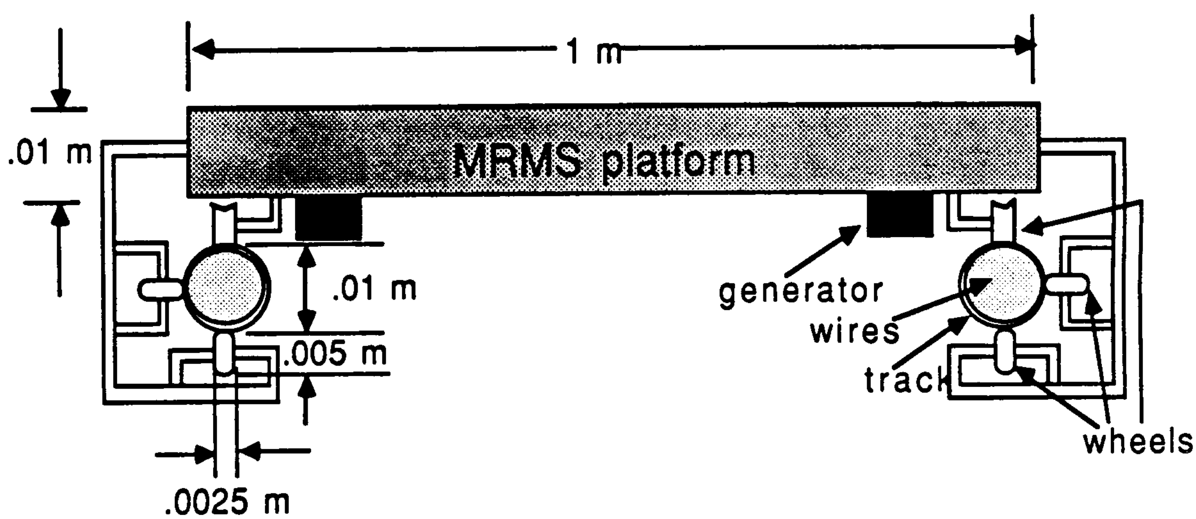

Figure 3.12 MRMS platform

The RMS arm has a total length of 15 meters, 7 meters to the elbow joint, 7 meters to the wrist joint, and 1 meter to the end. The RMS is capable of lifting cargo or other objects weighing up to 20,000 kg. While they are not in use, especially during insertion and any orbital correction procedures, the MRMS arms are secured to the truss.

3.7 Capsules Structural Design

3.7.1 Structural Material

A requirement for maintaining the CASTLE's service life of 20 years or more is the selection of structural materials which do not suffer erosion from the space environment, which provide sufficient strength to endure multiple repetitions of pressure and thermal cycling, and which maintain an internal pressure of 101,350 N per square meter without leaking. Since it would be difficult to maintain an acceptable leak rate for a module made with conventional riveted and mechanically fastened skinned construction, it is proposed that the module be constructed with all welded, integrally machined, skinned panels of 2219-T851 aluminum plate. This material has good strength (Yield Strength: 46 KSI), high fracture toughness, good resistance to stress corrosion, good weldability, and good machinability. Therefore it conforms to all of the above criteria.

3.7.2 Meteoroid/Debris Protection

The meteoroid/debris protection criterion for the DOC and CAB has been established as 95 percent probability of not having a penetration of the modules pressure skin for a 20 year life in the space environment. The concept chosen for this design is the double wall bumper which has one 1.1 millimeter thick aluminum bumper located .051 m away from the module pressure skin (fig. 3.13). The .051 m gap is filled with a multilayer insulation to provide thermal insulation and meteoroid/debris protection. Since there is a requirement to prevent crushing of the multilayer insulation, thermally nonconductive stand-offs between the two aluminum sheets that keep the bumper from deflecting into the insulation and thereby degrading its thermal characteristics. The particular material for the insulation has not been selected since new advanced materials are expected for the future.

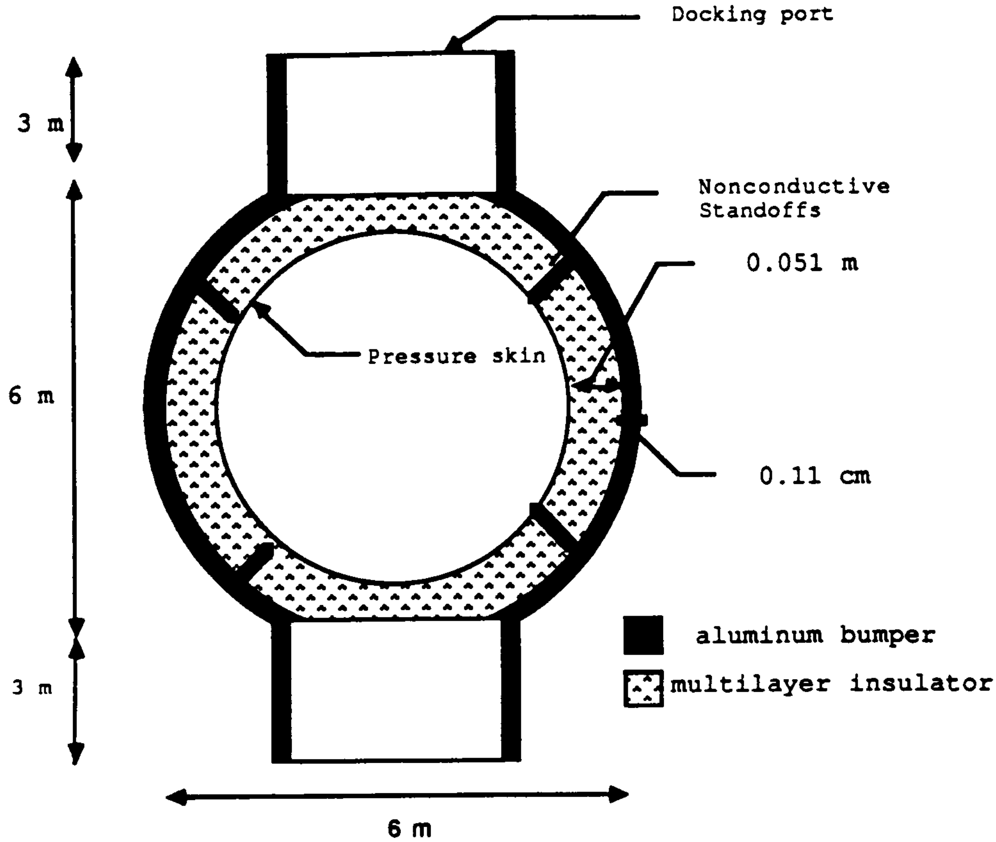

Fig 3.13 Meteoroid/Debris Protection Design in DOC

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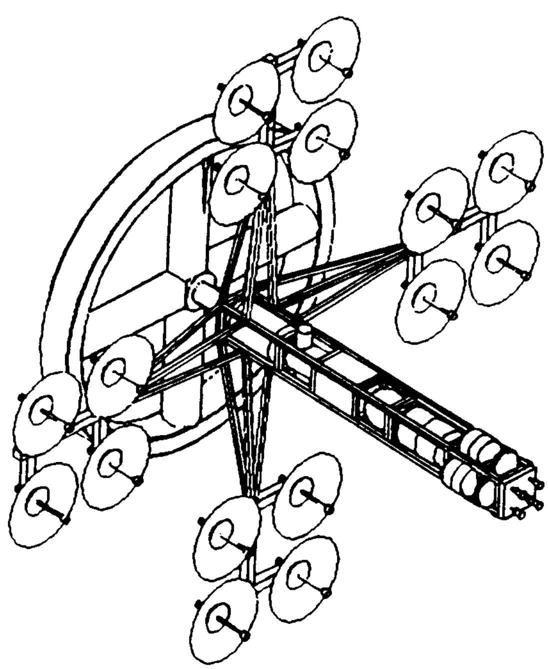
Chapter Four

Power Systems



4.1 Power Systems Introduction

In order to operate all of the neccessary systems on board a spacecraft, a self-contained spaceborn power system is required. For long duration space missions, the power system must be a highly reliable, lightweight system which can operate for long periods of time with very little maintenance. Large spacecraft need a power system with a modular design that can be easily assembled in space. Also, for manned space missions, emergency life-support power must be provided in the event that the main power system fails or is shut down. In this chapter, the Project CAMELOT II design of a power system which satisfies the above criteria is presented.

As outlined in Project CAMELOT, a spacecraft power system consists of three major parts. These are the Primary Power system, the Reserve Power system, and the Power Management and Distribution (PMAD) system. Each of these systems, as designed and analyized by Project CAMELOT II, is addressed in this chapter.

The CASTLE power requirements are fundamental to the design of its power system. Three important power levels (Minimum Life support, Normal Operations, Minimum Power Available) have been detailed in the original Project CAMELOT. Power requirements for each of these levels have been revised due to changes implemented in the design of the CASTLE by Project CAMELOT II. The revised figures are:

Minimum Life Support	: 200 kWe
Normal Operations	: 350 kWe
Minimum Power Available	: 400 kWe

The Minimum Power Available level is the minimum amount of power which the Primary Power system can generate under normal operation during the CASTLE orbit. This is the condition for which the Primary Power system was designed. The Minimum Power Available level was set to 400 kWe in order to provide a 15% margin of safety above Normal Operations power. This margin of safety was set to accomodate a possible failure of part of the Primary Power system as well as to accomodate special peak power requirements.

The Primary Power system is responsible for meeting the power needs of the CASTLE for the majority of the CAMELOT mission. The Primary Power system that has been designed for the CASTLE is a solar dynamic power system. A solar dynamic power system consists of an Energy Source subsystem, a Power Conversion subsystem, and a Radiator subsystem. The Energy Source subsystem is made up of a solar concentrator which focuses energy from the sun into a receiver. The Power Conversion subsystem consists of a heat engine which converts thermal energy into electricity by using an alternator. The Radiator subsystem rejects the waste heat from the heat engine. Shown in Figure 4.1 is a single solar dynamic unit.

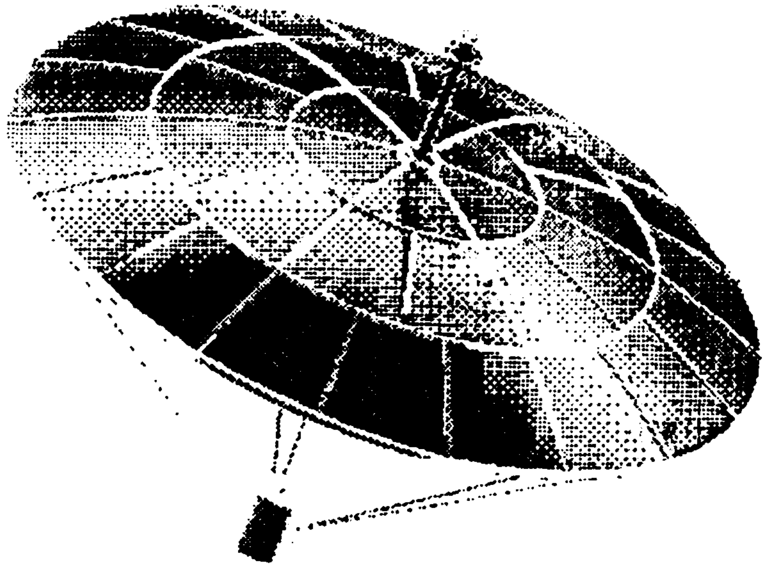


Fig 4.1 Single Solar dynamic Unit

CAMELOT II has designed the CASTLE solar dynamic system such that it has sixteen solar dynamic units. At the ends of each of four booms, which are spaced evenly and extend out from the main truss, are four solar dynamic units. A picture of one boom with the four solar dynamic units on it is shown in Figure 4.2. This configuration differs from that originally proposed in CAMELOT. Their proposal was for "a set of three clusters each containing three Cassagranian reflectors." The decision to instead have four booms with a total of sixteen collectors was made for three primary reasons. First, having four booms spaced evenly around the CASTLE instead of three gives better structural stability. Second, having sixteen reflectors instead of nine gives greater system redundancy, thus reducing the consequences for failure of a single unit. Third, arranging the solar dynamic units in multiples of two instead of three, allows an easier scheme to be designed for orienting the solar dynamic units such that they are pointed at the sun.

Our design specifies sixteen solar dynamic units, each consisting of one concentrator, receiver, heat engine, and radiator. Each of the sixteen concentrators will be of the Newtonian parabolic type. The sixteen heat engines have been selected to be free piston Stirling engines with linear alternators. Each of the sixteen radiators will be of the Curie Point Radiator (CPR) design. The advantages and analysis of these design decisions are addressed in the following pages.

The Reserve Power system is responsible for providing Normal Operations power during the major propulsive manuevers of the spacecraft. It is also responsible for providing at least Minimum Life Support power in the case of a Primary Power system failure or other emergency which would require the shutdown of the Primary Power system. The Reserve Power system that has been designed for the CASTLE is a regenerative fuel cell system. This system will consist of hydrogen-oxygen fuel cells and electrolysis cells.

The Power Management and Distribution system (PMAD) is responsible for conditioning and regulating all of the power generated on the CASTLE. The PMAD system that has been designed for the CASTLE will condition power to 20 kHz 440 volts AC and will rely on the use of expert systems to distribute power and monitor the operation of the power systems.

The design of the three power systems (Primary, Reserve, and PMAD) meets all the criteria neccessary for the design of a reliable, low mass, long lifetime, autonomous spaceborn power system.

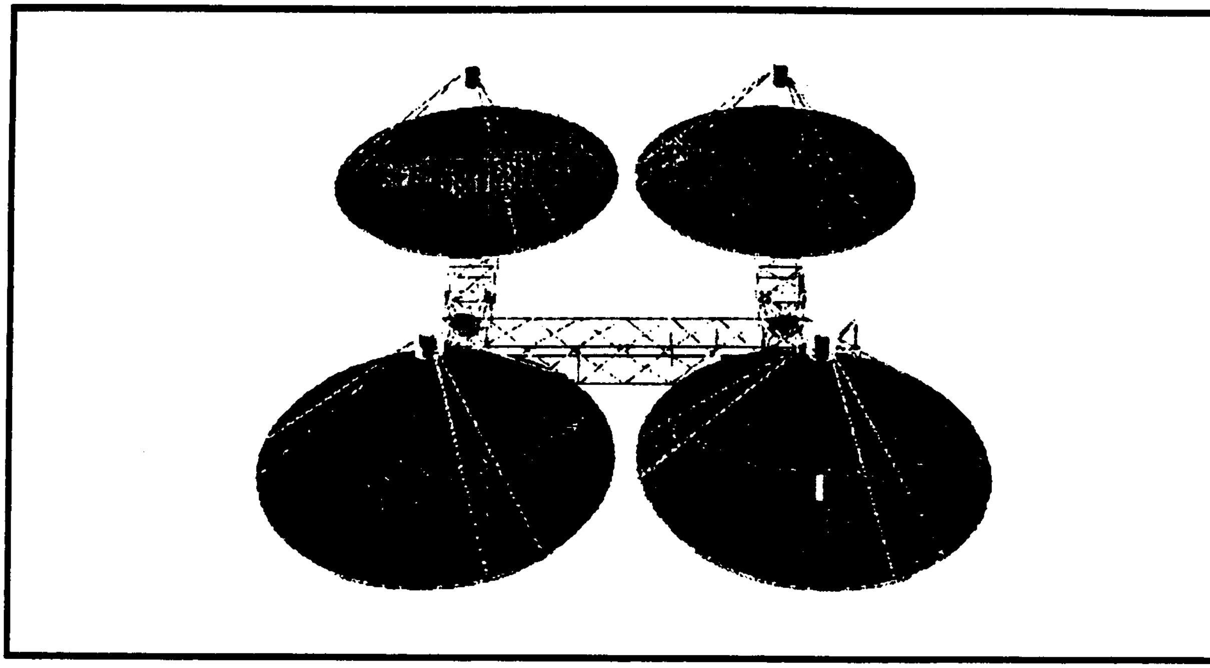


Fig. 4.2 Four Collectors on truss

4.2 Primary Power System

The Primary Power system consists of an Energy Source subsystem, a Power Conversion subsystem, and a Radiator subsystem. For the CASTLE, a solar dynamic power system, consisting of 16 independent solar dynamic units, has been chosen. This solar dynamic power system has been designed for the Minimum Power Available condition. Accordingly, each solar dynamic unit has been designed to provide 25 kWe of useable power at its design point. This 25 kWe of useable power corresponds to 27 kWe of engine output power when power transmission losses are accounted for. Since the Minimum Power Available level is the power level for which the Primary Power system was designed, this power level will be referred to as the nominal power level.

The text in the following sections details the design of the Primary Power system in terms of its various subsystems.

4.2.1 Energy Source Subsystem

The purpose of the Energy Source subsystem is to supply a useable form of energy to the Power Conversion subsystem. The Energy Source subsystem must consist of an energy source and a means of converting the energy from the source into the useable energy which is then supplied to the Power Conversion subsystem.

Choice of Energy Source

For large space-based power systems, only two energy sources are practical: nuclear and solar. The option of using a nuclear source for the CASTLE was studied in CAMELOT I and was determined to be unacceptable. The primary reason that nuclear power is unacceptable for the CASTLE is that a nuclear system would need to have extremely massive shields in order to prevent the deadly radiation from escaping the nuclear reactor. Also, even with appropriate shielding, a nuclear power system poses serious crew and space enviromental risks in the event of a power system failure. Since the option of using a nuclear source was ruled out, the sun was chosen as the energy source for the CASTLE.

Choice of Energy Source Subsystem Configuration

Solar energy can be converted into electrical energy using one of two methods. In the first method, solar energy is converted first into thermal energy and then, by means of a Power Conversion subsystem, is converted into electrical energy. This is done by solar dynamic systems. In the second method, solar energy is converted directly into electrical energy. This is done by photovoltaic systems (solar cells). In this case there is obviously no need for a Power Conversion subsystem. Since solar dynamic systems are smaller and less massive than photovoltaic systems of equivalent power generation capability, solar dynamic power systems are more attractive for large space-based power systems. For this reason, a solar dynamic power system was chosen as the primary power generation system for the CASTLE.

As mentioned above, the Energy Source subsystem must consist of an energy source and a means of converting the energy from the source into the useable energy which is supplied to the Power Conversion subsystem. For the solar dynamic system, the energy source is the sun, and the form of energy that is supplied to the Power Conversion subsystem is thermal energy. Since the solar dynamic system uses a natural energy source, the only function of the Energy Source subsystem is to collect the energy from the sun and convert it into thermal energy. The two components of a single solar dynamic unit which accomplish this task are the concentrator and the receiver.

Concentrator Description and Design Specifications

In terms of size, the concentrator is the largest component of the solar dynamic unit. Its purpose is to reflect the sun's energy, focusing it into a small region inside the cavity of the receiver. Inside the receiver, the solar energy is absorbed and converted into the thermal energy of the absorber material.

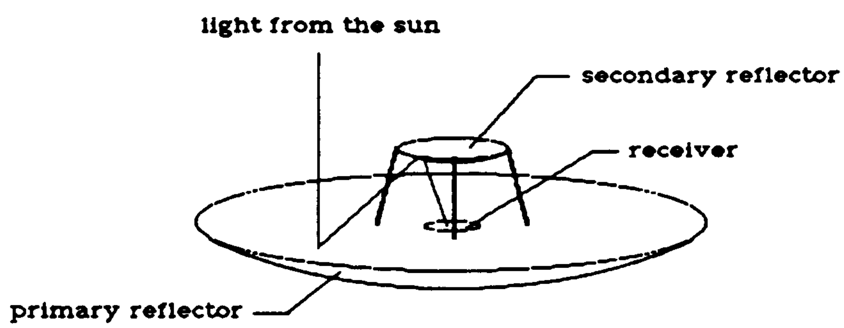
At a particular location in space, the amount of solar energy that the concentrator can reflect depends on the solar energy flux, which is a function of the distance of the concentrator from the sun. At Earth the solar energy flux is about 1,370 Watts per square meter. As one moves away from the sun, the solar energy flux drops off as the square of the distance. In order for the power system to always be able to provide the nominal amount of power required to the CASTLE, the power system must be designed for the condition of minimum solar energy flux. This condition occurrs at the apnelion of the CASTLE orbit where the solar energy flux is only 291 Watts per square meter.

In designing the concentrator one of the most important considerations is to minimize its mass. In the case of the concentrator, trying to minimize its mass results in first trying to minimize its size. Since the size of the concentrator is determined by the amount of solar energy it has to reflect into the receiver, the size of the concentrator can be reduced by increasing its efficiency as well as the efficiencies of the other components of the power system. With this goal of minimizing mass in mind, the solar dynamic power units were designed.

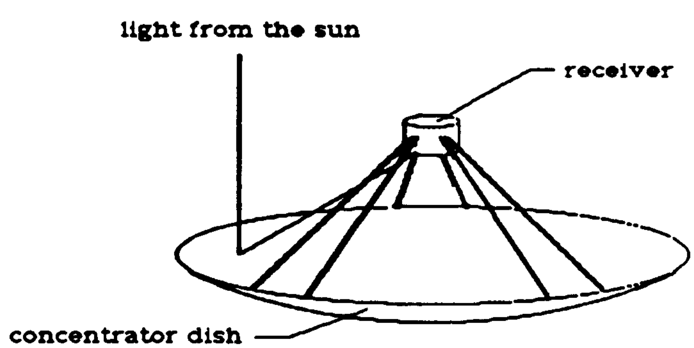
Concentrator Configuration

For a given Power Conversion subsystem design, the size of the concentrator can be minimized by maximizing the efficiency of the Energy Source subsystem (the concentrator/ receiver pair) . The concentrator design which will allow for the highest Energy Source subsystem efficiency is the design which has the least reflective losses and the highest concentration ratio. The concentrator configuration which best fits this description can be described as a Newtonian parabolic concentrator. This was the type of concentrator which was selected for the CASTLE.

The Newtonian parabolic concentrator, shown in Figure 4.3, is a concave reflective dish which is in the form of a paraboloid of revolution. For this configuration, the incident solar energy is reflected directly from the concentrator dish into the receiver which is located at the focal point of the paraboloid.



Cassegranian concentrator



Newtonian parabolic concentrator

Fig. 4.3 Cassagranian and Newtonian Concentrator Configurations

Before specifying that the CASTLE concentrators would be of the Newtonian paraboloid configuration, several other types of reflecting-type concentrator configurations were considered. In the final analysis, the Newtonian was chosen because it is the ideal reflecting surface, and therefore is capable of providing the highest concentration ratios and highest efficiencies.

Other configurations that were considered were the Cassegranian configuration (specified by CAMELOT I) , the offset paraboloid configuration, and various configurations which used surfaces designed to approximate a paraboloid. The offset paraboloid configuration and the parabolic approximation configurations were not chosen because they are not capable of concentration ratios as high as those for the true parabolic configuration. The offset configuration was also disqualified due to the fact that current reasearch has uncovered problems associated with the offset concentrator's ability to provide even solar energy flux distributions within the receiver's cavity.

The Cassegranian configuration, also shown in figure 4.3, consists of a primary reflector and a secondary reflector. In this configuration, the primary reflector first reflects the incident solar energy onto the secondary reflector which in turn reflects the energy into the receiver cavity. The main advantage of this configuration is that it allows the receiver to be mounted on the back of the concentrator. This increases the stability of the solar dynamic unit, reduces the stress on the concentrator, and reduces the unit's moment of inertia about the support struss onto which the concentrator is mounted. In spite of these factors, the Cassegranian configuration was not chosen because it also possesses some major disadvantages.

The first major disadvantage of the Cassegranian configuration is that it is not capable of having effeciencies or concentration ratios as high as that for the Newtonian configuration. This lower efficiency of the Cassegranian configuration is primarily due to the losses associated with having a secondary reflecting surface. The reduced concentration ratio is due to the increased spreading of the solar image which occurs at the secondary reflecting surface. Along the same lines, because the solar energy must undergo two reflections with the Cassegranian configuration, the Cassegranian configuration is more sensitive to pointing and surface slope errors.

The second major disadvantage of the Cassegranian configuration is that the surface of the secondary reflector must be designed to withstand high temperatures. This is due to the high concentration ratio onto the secondary reflector and also due to radiation exchange between the receiver and the secondary reflector.

As mentioned previously, one of the primary goals used in designing the concentrator was to minimize its mass. The first step in doing this was to choose the concentrator configuration which would provide the highest Energy Source subsystem efficiency. The next step was to optimize the concentrator system in terms of those remaining design parameters which will effect the concentrator mass. This was done in the design process of the two major parts of the concentrator, the reflecting surface and the support structure. Each part is important in terms of optimizing the design of the concentrator.

Concentrator Reflecting Surface

The primary design consideration for the reflecting surface of the concentator is that it reflect as much of the solar energy that is incident upon it into as small an area as possible. This corresponds to maximizing the efficiency of the concentrator and maximizing the concentration ratio.

It should be noted here that maximizing the concentration ratio is important because the larger the concentration ratio, the smaller the solar image, and the smaller one can make the receiver aperture. Reducing the size of the receiver aperture in turn reduces reradiation losses from the receiver cavity. Correspondingly, if less energy is lost from the receiver, then less energy needs to be concentrated into the receiver; therefore, the concentrator need not be so large.

The reflecting surface which was chosen for the CASTLE is divided into sections called gore segments. The segmenting pattern is shown in Figure 4.4. The reflecting surface was subdivided into these gore segments for two main reasons. First, these gore segments are neccessary because it would not be practical to fabricate the reflecting surface as one piece. Second, it would not be possible to transport into space such a large stucture as the concentrator if it were not in several pieces. The segmenting pattern of Figure 4.4 shows that there are three rows of segments. The number of segments in each row, moving out radially from the origin, are 6, 12, and 18. This configuration was chosen based on the criteria that the gores be between three and three -and-a-half meters long on a side. Although the largest gores that are being fabricated now are only one meter on an edge, it is reasonable to assume that gores that are 3.5 meters on an edge will be able to be fabricated in the future.

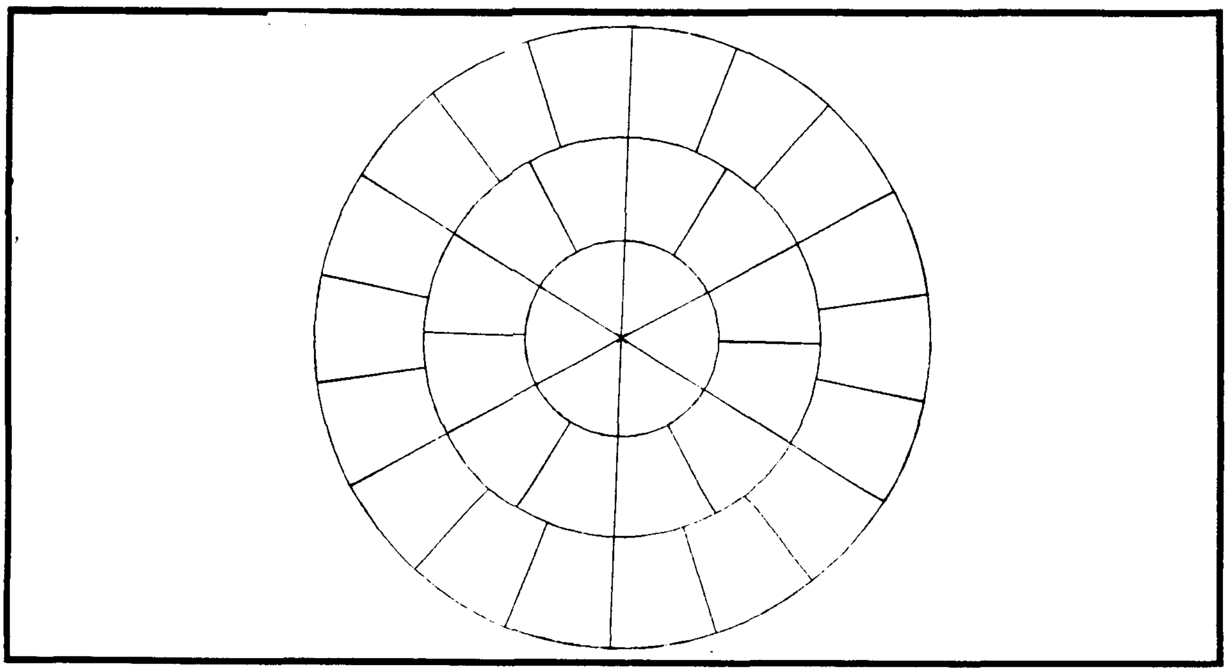


Fig. 4.4 Gore Pattern

A representation of a typical gore segment's appearance is shown in Figure 4.5. This cross-section view shows the multilayer composition of each gore. The stiffness of the gore segment is provided by the aluminum honeycomb core which is sandwiched between two layers of a graphite/epoxy material. On top of this sandwich is the reflective material (aluminum on glass) . This is then covered with a thin layer of protective material such as MgF_2 which protects the reflective surface from atomic oxygen degradation.

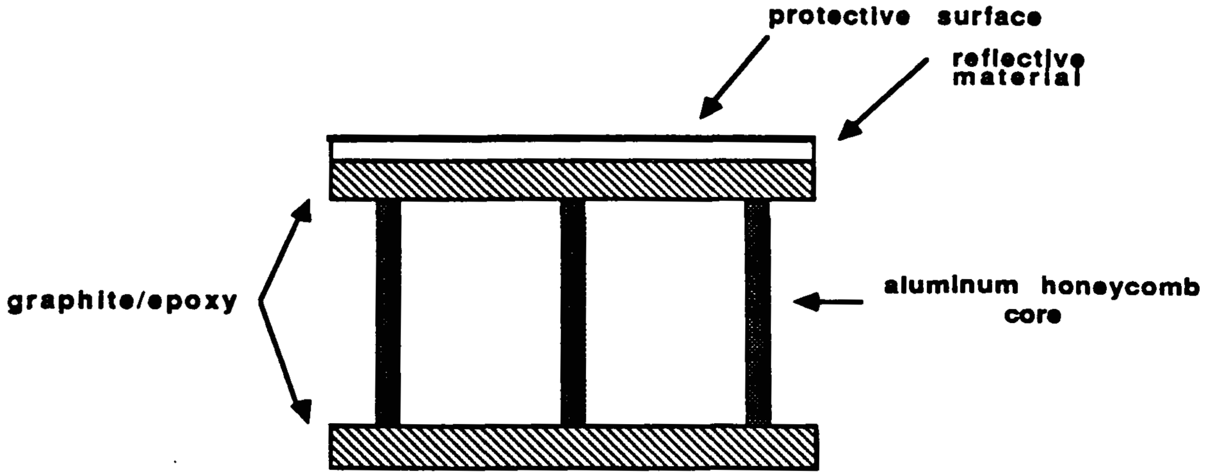


Fig. 4.5 Cross Section of a Typical Gore Segment

Typical gore segments of today have specific masses between 2.25 and 6 kilograms per square meter of surface area. Projections for the year 2000 place the specific mass of the entire concentrator (reflecting surface and support structure) at values of less than 1 kg per square meter. Because of this projection, a specific mass of 1 Kg per square meter was specified for the gore segments of the CASTLE concentrators.

Other specifications regarding the gore segments are that they must have a total hemispherical reflectivity of at least 0.9 and they must be machineable to 0.5 mrad surface slope error. These two parameters have a very significant effect on the efficiency of the concentrator/receiver pair.

The total hemispherical reflectivity is a measure of the percentage of the solar energy which will be reflected by the concentrator surface. An increase in the total hemispherical reflectivity of the concentrator surface will allow a direct reduction in concentrator size.

The surface slope error provides a measure of how much the actual reflective surface of the concentrator deviates on the average from its specified shape (a paraboloid of revolution). This error is typically a result of the machining process of the gore segment. The surface slope error is significant in that it directly affects the concentration ratio of the concentrator. An increase in the average surface slope error will decrease the concentration ratio of the concentrator. As explained previously, decreasing the concentration ratio of the concentrator requires an increase in the size of the concentrator.

The specification that the gores have a total hemispherical reflectivity of 0.9 is reasonable. Gore segments of today are capable of this. The specification that the gore segments be machineable to 0.5 mrad surface slope error is much more demanding of technological advances, especially given the larger size of gore segments to be used. Such a fabrication process should be feasible, however, given that surface slope errors less than 1 mrad are obtainable under present technology. This specification that the gore segments be machineable to 0.5 mrad surface slope error is neccessary in order to keep the size and mass of the concentrators at a minimum. As a reference, a doubling of the average surface slope error would necessitate an increase in concentrator area by a factor of 1.07

Concentrator Support Structure

The primary design specification for the support structure is that it be lightweight, yet strong enough to withstand the impulsive forces transferred to it from the rest of the spacecraft. It is important that the support structure be designed such that these forces do not result in natural mode vibrations of the concentrator. The primary forces that will be transferred to the concentrator are those due to propulsive manuevers of the spacecraft and those due to the rotation of the solar dynamic units.

There are several types of support structures that would meet the needs of the CASTLE concentrators. There are two, however, which have the potential to be the least massive. The first of these is known as a deep-truss structure. This structure would consist of about 100 truss units, interconnected, and contoured to the shape of the concentrator. These 100 truss units, when connected to each other, would form a parabolic surface onto which the gore segments could be attatched. The main advantages of this type of structure are that it is very rigid and it is easily deployable.

The other type of support structure that would meet the needs of the CASTLE concentrators is a web-like frame structure constructed of lightweight box beams. Since this type of structure is less complex than the deep-truss structure, it was chosen for the CASTLE for the purpose of modeling the concentrators.

Figure 4.6 shows the concentrator with the box-beam support structure. The structure consists of six primary beams, an inner support ring, an outer support ring, two intermediate stiffening rings, and several intermediate radial beams. The inner ring provides the connection from the concentrator to the truss. The outer ring defines the outer edge of the paraboloid. The six primary beams move out radially along the contour of the paraboloid from the inner support ring to the outer support ring. The two intermediate rings provide added stiffness to the structure while providing a mounting surface for the gore segments. The other radial beam segments are primarily designed to provide a mounting surface for the gores. This concentrator support structure would be assembled piecewise in space, and then the gore segments would be fastened to it.

In order to test the application of the box-beam support structure for the CASTLE concentrators, a feasability study was conducted. This study consisted of a finite element analysis of the structure. The purpose of this analysis was to determine the required dimensions of the various beams such that the structure would remain rigid under a typical loading scheme. The material that was used in modeling the concentrator is a high-modulus graphite/epoxy. Using this material, the finite element analysis was conducted to find a working support structure. The solution that was obtained was by no means an optimum one due to the time constraints of the project. The solution that was obtained, however, did provide a mass estimate of a workable support structure. Based on the above analysis, the mass of the concentrator support structure is approximately 300 Kg.

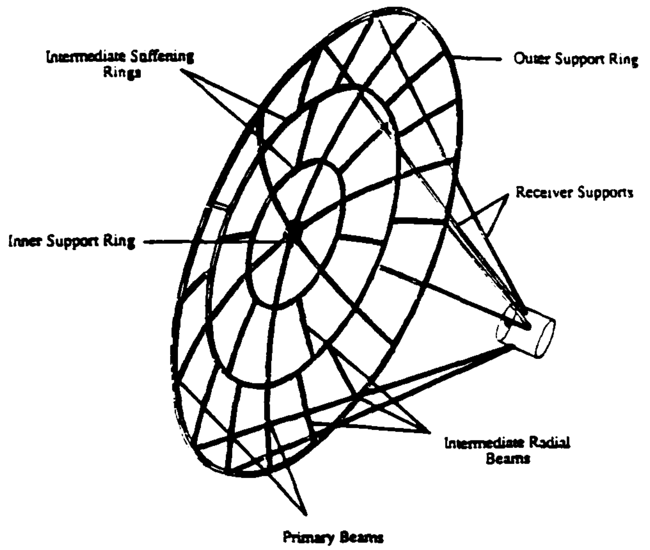


Fig. 4.6 Concentrator Supports

Besides providing a rigid surface onto which to mount the gore segments, the concentrator must also support the receiver and engine. This will be accomplished through the use of three pairs of struts (see Figure 4.6) . Each pair of struts moves from a point on the sidewall of the receiver to two points on the rim of the concentrator. The main problem with the design of these struts is that they must interface with the wall material of the receiver (Silicon Carbide) and must be able to withstand temperatures of about 1000 K at the receiver end. Although a material such as Tungsten would work, it should be avoided if possible due to its high density. There are, however, special types of graphite/epoxy composites which should also work and have considerably lower densities. These are known as PT graphites. For the CASTLE, a PT graphite material is recommended because of its lower mass; however, further study of the feasibility of using this material is recommended.

Other Design Aspects

Another design specification that has been incorporated into the design of the concentrators is a method of providing a reduced solar energy flux to the receiver. As mentioned before, the power system was designed to provide nominal power at aphelion. Since the solar energy flux increases as the CASTLE moves toward the sun, a method of reducing the solar energy concentrated into the receiver must be available. If such a system was not available, more energy would be supplied to the receiver than the engines could use, and as a result of this, the receiver would burn up.

One method of reducing the amount of energy focused into the receiver would be to off-point the concentrators slightly so that less of the solar image would make it through the receiver aperture. Unfortunately, there is one major problem with this. By offsetting the concentrators, the distribution of the concentrated solar image with respect to the receiver would be altered. Not only would the size of the image be increased, but it would also be distributed asymetrically about the receiver aperture plane. Because of the larger size of the solar image, less of the energy would make it through the receiver aperture. That amount of energy which would not make it through the aperture would be incident upon the outside of the receiver. This would create localized hot spots around the receiver aperture with possible temperatures above the receiver material limits. An asymetrically distributed solar image would also be hazardous, since the energy that would pass into the receiver would create localized hot spots inside the receiver cavity. These hot spots would induce thermal stresses, which, over a period of time, would lead to fatigue of the receiver structure.

Since off-pointing the collectors is an unacceptable solution to the problem of reducing the amount of energy focused into the receiver, another solution is necessary. The solution that has been designed for the CASTLE uses a method of reducing the collection area of the concentrator as the CASTLE moves from the aphelion to the perihelion of its orbit. This decreasing collection area will offset the increasing solar flux as the CASTLE moves toward the sun and will therefore keep the amount of energy focused into the receiver relatively constant.

To allow the collection area of the concentrator to be reduced, actuators will be placed underneath the gore segments of the middle and outer rings of the concentrator. Each set of actuators will allow the gore segments to be individually dispalced such that the incident solar energy will be reflected harmlessly back at the sun. This is shown in Figure 4.7.

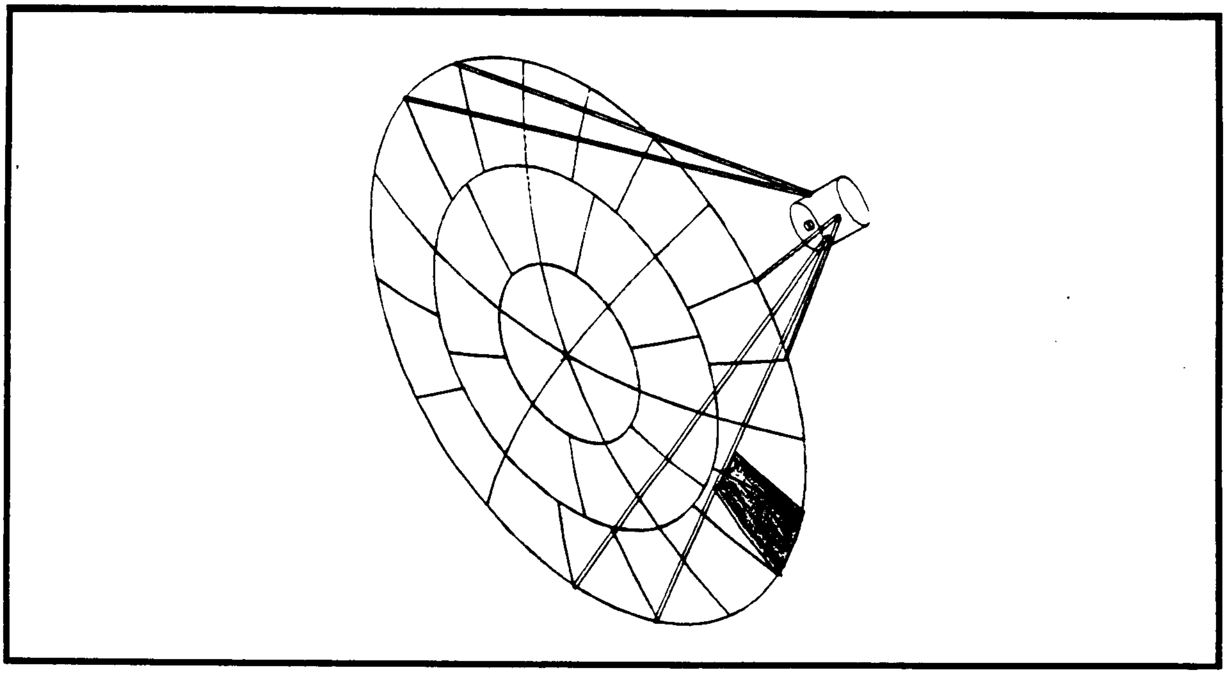


Fig. 4.7 Off-pointed Gore

Although the gore segment off-pointing concept has a mass penalty associated with it, it would avoid the hazards of off-pointing the concentrators while providing a means for the PMAD system to regulate power generation. Initially, when the CASTLE leaves Earth, only the six gore segments of the inner ring and four of the twelve segments of the middle ring will be needed for each solar dynamic unit to produce 25 kWe of useable power. As the CASTLE moves towards aphelion, the number of needed gore segments will increase until all gore segments are needed to produce 25 kWe at aphelion. The other benefit of this gore segment off-pointing concept is that it allows each solar dynamic unit to generate power at various levels at a given distance from the sun. For instance, at aphelion, two of the outer gore segments of a concentrator could be displaced allowing that solar dynamic unit to produce only 21 kWe. Since each concentrator will be individually controlled, the solar dynamic power system will be able to accomodate a wide range of power requirements. The only limitations will be those due to the Power Conversion subsystem (the maximum and minimum power generation capability of each heat engine), and those due to the size of the gore segment (the finite size of the power step associated with off-pointing a single gore segment).

Receiver Description and Design Specifications

In terms of mass, the receiver is usually the largest component of the solar dynamic unit. Its purpose is to convert into thermal energy the concentrated solar energy which is reflected into the receiver cavity by the concentrator. The receiver must also provide a means of transferring this thermal energy to the Power Conversion subsystem.

In a typical receiver, the solar energy is converted into thermal energy when it strikes the surface of an absorber. In most cases, the absorber is merely a lining inside the receiver cavity which is made of a material having a high absorptance. The thermal energy of the absorber is then transferred to the working fluid of the engine (Power Conversion subsystem) by means of a conduction and/or convection scheme. Some of the thermal energy of the absorber, instead of being transferred to the Power Conversion Subsystem, is transferred to a thermal energy storage material. The thermal energy which is stored in this material is used to provide thermal energy to the Power Conversion subsystem when there is no solar energy being concentrated into the receiver cavity. Such a situation occurs when the concentrators are in shadow (ie: the occult phase of a planetary orbit).

As with the concentrators, the primary goal used in designing the receivers for the CASTLE was to minimize mass. The method of minimizing the mass of the receiver is not as straight-forward as the method of minimizing the concentrator mass. This is because the mass of the receiver is not just a function of size, but also a function of the process by which the thermal energy of the absorber is transferred to both the Power Conversion Subsystem and the thermal energy storage material. Minimizing the mass of the receiver is acheived by optimizing these energy transfer processes.

Receiver Configuration

Minimizing the receiver mass can be accomplished by optimizing the processes by which the thermal energy of the absorber is transferred to both the Power Conversion subsystem and the thermal energy storage material. This optimization process is a function of the type of Power Conversion subsystem being used (Brayton or Stirling engine). Since Stirling engines are being used for the CASTLE, this optimization process must be done for a Stirling engine configuration.

Such an optimization process, because of its length and complexity, was not practical for the CAMELOT II study. Fortunately, however, such an optimization study was conducted by Sanders Corporation under contract for N.A.S.A. Lewis Research Center. The purpose of the study was to find several Stirling receiver configurations which would have much lower masses than previous Stirling receiver concepts. The study was conducted under the specification that the receivers were to be designed for a 7 kWe solar dynamic unit for use in LEO.

The results of the Sanders study, published in March of 1987, specified four different low mass receiver configurations. Of these four configurations, one was singled out as being the most promising configuration for future space applications. This configuration is known as the Domed Cavity Heat Pipe Stirling Receiver. It was this configuration which was chosen as the basis for the design of the CASTLE receivers.

A drawing of the Domed Cavity Heat Pipe Stirling Receiver as portrayed in the Sanders report is shown in Figure 4.8. This design has three main parts: the absorber surface, the heat pipe, and the thermal energy storage section. The absorber surface is the hemispherically shaped dome above the receiver aperture. The heat pipe is the inner cavity of the receiver which encompasses the region between the absorber surface and the Stirling engine heater head tubes. The thermal energy storage section is an outer cylinder which encapsulates the heat pipe.

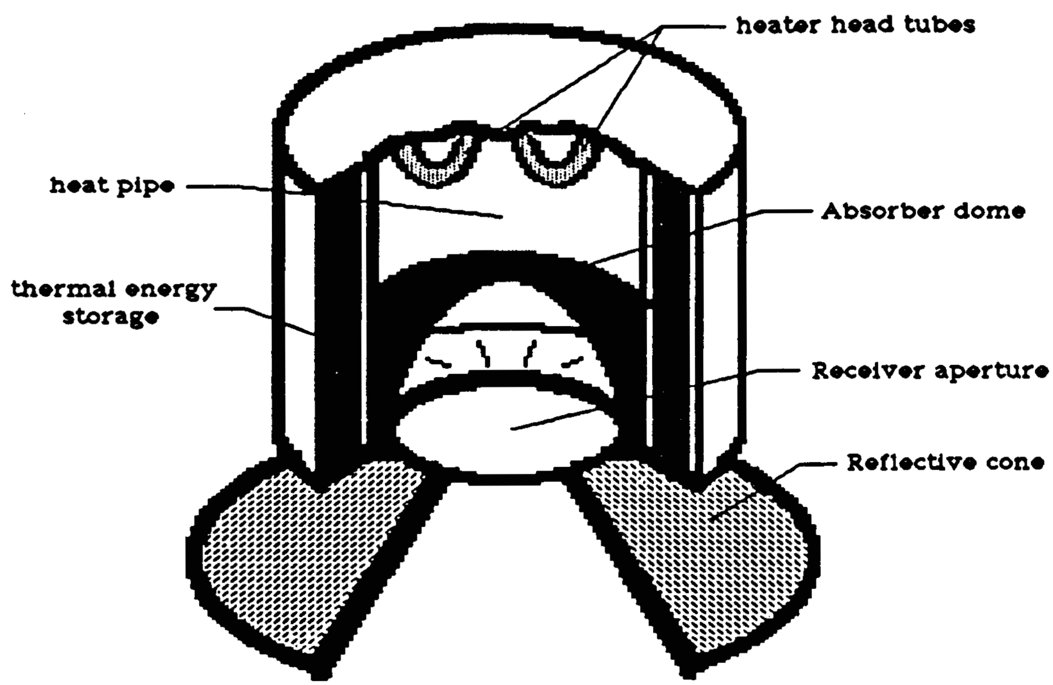


Fig. 4.8 Domed Cavity Heat Pipe Stirling Reciever

For this receiver design, the concentrated solar energy enters through the receiver aperture and is absorbed at the hemispherical absorber surface. The thermal energy of the absorber is transferred to a layer of liquid Sodium which lies on the back side of the absorber surface. The back side of the absorber surface serves as the evaporation end of the heat pipe. For this reason, the absorber surface is also referred to as the evaporation dome. As the liquid Sodium evaporates off the surface of the dome, it moves to the condenser end of the heat pipe. At the condenser end of the heat pipe, the Sodium vapor condenses on the heater head tubes of the Stirling engine. This serves to heat the working fluid of the engine. The condensed Sodium is then returned to the evaporation dome by a wicking structure which lines the heater head tubes, the walls of the heat pipe, and the evaporation dome. As the liquid Sodium moves through the wicking structure, it passes over the side walls of the receiver cavity. As it passes over the side walls, the liquid Sodium trnsfers heat to the thermal energy storage material which lies underneath.

Since the design requirements for the CASTLE receivers are somewhat different than those used by Sanders in designing the Domed Cavity Heat Pipe Stirling Receiver, the Sanders design was only used as the basis for the design of the CASTLE receivers.

The ways in which the design requirements of the CASTLE receivers differ from the Sanders design are the following. First, the CASTLE receivers will operate at a temperature of 1500 K. This is considerably higher than the 1039 K operating temperature specified for the Sanders design. Second, the CASTLE receivers will be designed for a 27 kWe solar dynamic unit for use in orbit between Earth and Mars. Third, the CASTLE receivers require no thermal energy storage. The impact of each of these design requirement differences will be discussed in the following sections.

Impact of Operating Temperature on Receiver Design

Because the CASTLE receivers will operate at a much higher temperature than that for the Sanders design, the CASTLE receivers must be built of different materials which can withstand the elevated temperatures. The Sanders design advocated the use of refractory metals in the construction of the receivers. Although a refractory metal such as Tungsten would be able to withstand the 1500 K temperature of the CASTLE receivers, it was not chosen for the CASTLE receivers because of its high density.

The material that was chosen for the CASTLE receivers is Silicon Carbide. There were several reasons underlying its selection. First, relative to Tungsten, Silicon Carbide is equally capable of withstanding the receiver temperature of 1500 K. Second, Silicon Carbide has a strength to weight ratio which is about five times greater than that for Tungsten. Third, since the heater head tubes of the CASTLE Stirling engines will be made of Silicon Carbide, using Silicon Carbide for the receiver will reduce receiver/engine interface problems.

The elevated temperature of the CASTLE receivers has other effects on the receiver design. The elevated temperature affects the dimensions of the heat pipe, the choice of the wicking material, the wicking configuration, and the choice of thermal energy storage material. Since the CASTLE receivers will have no thermal energy storage material, this last effect can be ignored. The other three temperature effects, although significant, were not addressed by the CAMELOT II study because of time constraints. It should be noted, however, that these elevated temperature effects should not limit the application of the Domed Cavity Heat Pipe design to the CASTLE receivers.

Impact of Power Level and Orbit on Receiver Design

Since the CASTLE receivers are part of a solar dynamic unit that generates more power than that specified for the Sanders design, the CASTLE receivers must be designed to withstand a larger solar energy input. In order to withstand this larger energy input, the CASTLE receivers must have more absorber surface area (an absorber dome of larger radius). Generally, the design should be such that the average solar flux on the absorber surface is no greater than 10 Watts per square centimeter. This larger dome size will affect the dimensions of the heat pipe cavity.

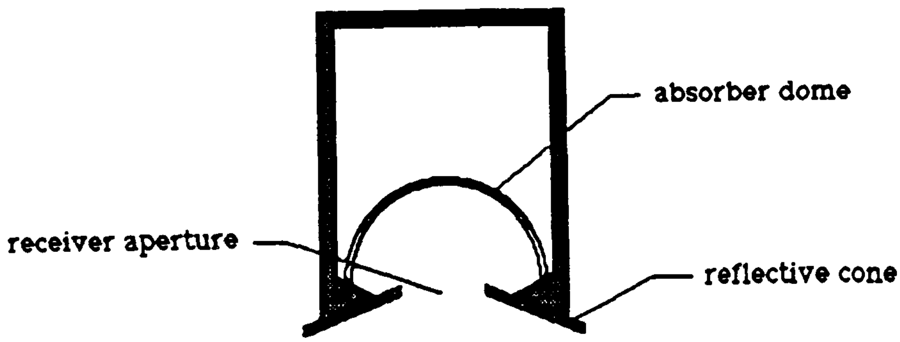
Since the CASTLE receivers are in an orbit in which the distance from the sun varies dramatically during the orbit, the CASTLE receivers must also be designed to accomodate the changing size of the solar image with changing distance from the sun. Although one generally thinks of the sun as a point source of energy because it is so far away, it actually is not a point source. In actuality, the sun subtends a measurable solid angle at distances from the sun as far away as the aphelion of the CASTLE orbit. The value of this solid angle at the point of CASTLE aphelion is about 0.0043 radians. As the CASTLE moves toward Earth, this angle increases to a value of about 0.0095 radians at the peihelion of the CASTLE orbit. Since the size of the solid angle of the sun increases, so will the size of the solar image at the focal plane increase.

In order to account for the change in size of the solar image at the focal plane, the receiver aperture must be sized in order to accomodate the largest solar image. The largest solar image is defined by a reflected ray from the outer edge of the concentator at the perihelion of the CASTLE orbit. Since, at perihelion, the outer ring of the concentrator gore segments will not be used, the outer edge of the concentrator is defined as the outer edge of the middle ring of gore segments for the purpose of calculating the largest solar image. Based on the size of the solid angle of the sun, the location of the outer edge of the concentrator reflective surface, and an estimated total concentrator error of 1 mrad, the largest aperture radius that is required is 0.23 meters. This is in contrast to the minimum aperture radius of 0.13 meters which is required at aphelion.

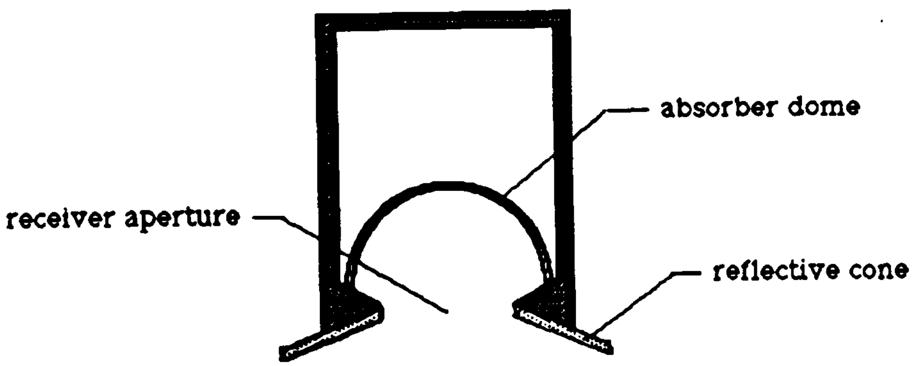
Rather than specifying that the receiver aperture radius be set to the maiximum value of 0.23 meters, it was determined that a method of varying the size of the receiver aperture should be developed for the CASTLE receivers. This decision was based on the mass penalty associated with using the maximum aperture radius.

At aphelion, the required aperture radius is merely 0.13 meters. With this aperture size, reradiation losses from the receiver cavity are about 16% of the energy concentrated into the receiver. If, by contrast, the maximum receiver aperture radius of 0.23 meters were to be used, the reradiation losses from the receiver cavity at aphelion would be about 37% of the energy concentated into the receiver. Since more energy would be lost from the receiver cavity using this design, more energy would have to be concentrated into the cavity in order for the solar dynamic unit to produce the required 25 kWe of useable power. This corresponds to requiring that the diameter of the concentrator be increased by 3.1 meters. Such an increase in concentrator diameter would result in a mass increase of 150 Kg.

If a method of varying the receiver aperture was specified for the CASTLE receivers, rather than specifying a constant maximum aperture radius for the receiver, much of the associated mass penalty would be saved. A possible scheme for allowing the receiver aperture size to vary would be to allow the movement of the reflective cone-shaped surface whose top cross-sectional area is defined by the minimum receiver aperture size. This cone-shaped surface would be divided into three segments. Each of these segments would have a motor driven actuator attatched to it, with the actuator motors being attatched to the receiver support structure. These motor driven actuators would be used to displace the cone-shaped segments and thus vary the aperture size. This displacement of the reflective cone segments is shown in Figure 4.9.



Minimum aperture size



Maximum aperture size

Fig. 4.9 Variable Reciever Aperture Concept

This method of varying the size of the receiver aperture is merely a conceptual design used to demonstrate the feasibility of having a variable receiver aperture. By the year 2030, perhaps a better method of varying the size of the receiver aperture will be devised. In any case, such a system would have to have a low enough mass to make its application worthwhile. Since the mass penalty associated with not having a variable aperture size is about 150 Kg, a system designed to vary the aperture size should not have a mass greater than 50 Kg. This means that the mass savings associated with such a variable aperture area system should be no less than 100Kg.

Impact of No Thermal Energy Storage on Receiver Design

No thermal energy storage system will be included in the CASTLE receivers because such a system is not worth its associated mass penalty. As mentioned in the *Receiver Description and Design Specifications subsection*, the purpose of a thermal energy storage system is to provide thermal energy to the Power Conversion subsystem when there is no solar energy being concentrated into the receiver cavity. Such a situation usually occurs when the concentrators are shadowed from the sun. A thermal energy storage system is worthwhile for planetary orbiting spacecraft since the concentators frequently cycle in and out of the occult phase of the orbit. For the CASTLE, such a thermal energy storage system is not worthwhile.

There are several reasons why a thermal energy storage system is not worthwhile for the CASTLE. The first reason is due to the fact that the CASTLE is designed to operate in an orbit around Earth and Mars. In this orbit, the amount of time during which the concentrators are shadowed by Earth and Mars is relatively minimal.

The second reason why a thermal energy storage system is not worthwhile is that the CASTLE will be equipped with a regenerative fuel cell system which can fulfill the same function as a thermal energy storage system. This regenerative fuel cell system is necessary to provide power to the CASTLE during the initial insertion of the CASTLE into its orbit. The fuel cell system is also needed in order to supply power to the CASTLE during a failure in the primary power system (solar dynamic system). Since the fuel cell system can supply power to the CASTLE while the solar dynamic units are not operating, it can fulfill the same function as the thermal energy storage system of the receivers. On the other hand, a thermal energy storage system could not fulfill all the functions of the regenerative fuel cell system.

The third reason why a thermal energy storage system is not worthwhile is that a thermal energy storage system is very massive. Such a system typically accounts for more than half the mass of a receiver. For the CASTLE receivers, such a thermal energy storage system would add about 600 Kg to the mass of each receiver.

Because a thermal energy storage system is not necessary and because such a system is very massive, it should not be included in the design of the CASTLE receivers. Because of this decision, the size of the receivers can be reduced and the mass of the receivers can be greatly reduced. In addition, not including a thermal energy storage system in the receivers should not affect the normal operation of the receivers.

Design of Energy Source Subsystem

Based on the CAMELOT II study, using many of the design specifications and requirements listed in the preceeding pages, a design of the Energy Source subsystem was formulated. The system was designed such that, at aphelion, it met the requirements of the Power Conversion subsytem to provide nominal power to the CASTLE.

In order to provide nominal power to the CASTLE, each Power Conversion subsystem (Stirling engine) must generate 25 kWe of useable power. Accounting for losses in the PMAD system and for losses across the various rotating interfaces of the CASTLE (losses were estimated to be 7.5% of the generated power), each Power Conversion subsystem must generate 27 kWe. Based on its own design, in order to generate this amount of electrical power, the Power Conversion subsystem requires a thermal energy input of 65.9 kW.

In order to provide this thermal energy input to the Power Conversion subsystem, the Energy Source subsystem would need to have the following design specifications listed in Table 4.1.

Table 4.1: Energy Source Subsystem Design Specifications

Concentrator Specifications

Concentrator Diameter:	19.82 m
Number of Gore Segments:	36
Total Concentrator Mass:	780 Kg
Support Structure Mass:	300 Kg
Reflective Surface Mass:	330 Kg
Actuator Mass:	150 Kg

Receiver Specifications

Receiver Diameter:	0.9 m
Receiver Height:	1.2 m
Receiver Minimum Aperature Diameter:	0.26 m
Receiver Maximum Aperature Diameter:	0.46 m
Absorber Dome Radius:	0.39 m
Total Receiver Mass:	600 Kg

Design Assumptions

The design process of the Energy Source Subsystem was based on the following assumptions listed in Table 4.2.

Table 4.2: Energy Source Subsystem Design Assumptions

Concentrator Focal Length to Diameter Ratio:	0.5
Total Hemispherical Reflectivity of Concentrator Surface:	0.9
Combined Concentrator Errors:	1 mrad
Absorptance of Absorber Dome:	0.85
Receiver Insulation Losses:	1%

In designing the concentrators, a focal length to diameter ratio of 0.5 was chosen. This was done in order to simplify the geometry of the concentrator receiver pair, and thus ease the calculations involved in the design process. Such an f/D ratio lies in the range of typical values specified for current concentrators under development.

A total hemispherical reflectivity of 0.9 was chosen for the reflective surface of the concentrator. As mentioned in *Concentrator Reflecting Surface* subsection, this is the minimum value of the total hemispherical reflectivity that should be used for the reflective surface of the CASTLE concentrators.

A combined concentrator error of 1 mrad was selected for the modelling of the Energy Source subsystem. This combined error is the sum of the individual errors due to the mounting of the gore segments, the surface slope error of the segments, and the pointing of the concentrator. As also mentioned in the *Concentrator Reflective Surface* subsection, the surface slope error of the gore segments should be less than .5 mrad. In accordance with this specification, the pointing error should also be less than .5 mrad and the mounting error should be negligible.

The absorptance of the absorber dome of the receiver was assumed to be 0.85. This is the absorptance of Silicon Carbide which is the material recommended for use in the construction of the receivers.

The insulation losses of the receiver were assumed to be 1% of the energy supplied to the Power Conversion Subsystem. Since insulation material is relatively lightweight, keeping the insulation losses at 1% is worth the mass penalty of the insulation material.

Design Proceedure

The design proceedure that was used in designing the Energy Source subsystem involved an iterative proceedure of estimating the concentrator size and then calculating the energy losses from the receiver for that concentrator size. The primary reason that such an iterative process was necessary is that since the receiver aperature size varies with the size of the concentrator, and since the amount of energy lost from the receiver varies with the size of the receiver aperture, the amount of energy lost from the receiver then varies with the size of the concentrator.

In order for the Energy Source subsystem to supply, at aphelion, the 65.9 kW of thermal energy necessary for the Power Conversion subsystem to generate 25 kWe of useable power, the concentrators must be 19.82 meters in diameter. At aphelion, a concentrator of this size will supply 80 kW of solar energy to the receiver. This is based on the solar constant of 0.291 kW per square meter at aphelion.

For a concentrator of this size, the receiver will have the following characteristics. The minimum receiver aperture must be 26 cm in diameter in order to accomodate the solar image at aphelion. The maximum aperture must be 46 cm in diameter in order to accomodate the solar image at perihelion. The absorber hemisphere must have a radius of 39 cm in order to maintain an average solar flux of less than 10 Watts per square centimeter on the absorber surface. Based on these receiver dimensions, the amount of energy lost from the receiver cavity at aphelion, due to reradiation and re-reflection of the incident solar energy, is about 16% of the incident solar energy. The remaining receiver dimensions were scaled according to the dimensions of a version of the Sanders Domed Cavity Heat Pipe Stirling Receiver design. Using this scaling proceedure, the overall diameter of the receiver was estimated to be 0.9 meters (this does not include the insulation material). Also using the scaling proceedure, the height of the receiver was estimated to be 1.2 meters.

The mass of the concentrator was estimated in three parts. First, the mass of the reflective surface was estimated using a specific mass of 1 Kg per square meter of surface area for the gore segment. Second, the mass of the support structure was estimated based on the volume of graphite epoxy that would be used in the required support structure. Third, the mass of the actuators was estimated assuming a mass of 5 Kg for each actuator assembly (one assembly per gore in the outer and middle rings). Based on these three parts, the total mass of the concentrator is 780 Kg.

The mass of the receiver was estimated in four parts. First, the mass of the containment structure and the evaporation dome was estimated assuming that these components would be made of Silicon Carbide. For estimating the volume of Silicon Carbide needed, a receiver wall thickness of 3 cm and an absorber dome thickness of 1 cm was assumed. Second, the mass of the wicking structure was assumed to be 50 Kg. Third, the mass of the insulation was estimated to be 20 Kg. Fourth, the mass of the variable aperature system was assumed to be 50 Kg. Based on these parts, the total mass of the receiver is 600 Kg.

Energy Source Subsystem Conclusion

In conclusion, the Energy Source subsystem which has been chosen for the CASTLE was designed to meet the unique needs of the CASTLE. Many of these unique needs are based on the fact that the distance of the CASTLE from the sun will vary appreciably during the course of the CASTLE orbit. The primary need of the CASTLE, however, is that the mass of the CASTLE be minimized. The Energy Source subsystem was designed to meet this primary need without sacrificing the reliability of the system.

4.2.2 Power Conversion Subsystem

Introduction to the System

The purpose of the power conversion system is to transform the thermal energy provided by the Energy Source subsystem into electrical energy. The Power Conversion subsystem consists of two main elements: the heat engine and the alternator. The heat engine converts the thermal energy from the Energy Source subsystem into mechanical energy. The alternator converts this mechanical energy into electrical energy.

A heat engine/alternator configuration which fulfills the following criteria must be selected for use on the CASTLE solar dynamic power system. The selected conversion system will

(1) Reliably produce power.
(2) Offer a long life expectancy.
(3) Exhibit high efficiency.
(4) Have minimal mass.
(5) Exhibit minimal vibration.

All of the above criteria are very important, but it is critical that the system be able to produce power reliably over a long lifetime. The high efficiency is also particularly important because it influences the overall solar dynamic system efficiency and therefore the overall solar dynamic system mass. For example, a low efficiency engine will mandate a much larger and correspondingly more massive Energy Source subsystem than a high efficiency engine.

The Power Conversion subsystem configuration that was selected for the CASTLE is a two-opposed free piston Stirling engine / linear alternator configuration. The Stirling engine offers the potentially highest operating efficiency of any applicable heat engine/alternator configuration. (The Stirling cycle is the most efficient thermodynamic cycle that exists.) Indeed, the only "competititve" heat engine for space power production is the Brayton engine. Analysis of the Stirling and Brayton engines has shown that the Stirling engine offers lower mass and higher efficiency (Reference 10). On the other hand, Brayton engines have been developed and tested to a greater extent than Stirling engines. However, by the year 2030, Stirling engines should be thoroughly demonstrated in a wide range of applications. The necessary technology and understanding of Stirling engines is being developed today, and it appears likely that Stirling engines eventually will be used in dynamic power systems on the Space Station and on many other spacecraft of the year 2000 and beyond.

Further benefits arise from the use of the free piston/linear alternator system. The system minimizes frictional dissipation and offers the potential for reliable, long-term power conversion. Since there are only two moving parts per engine--the displacer piston and the power piston/alternator plunger--a simple configuration is realized with minimal friction. Free piston Stirling engines don't require mechanical linkages and rod seals (which involve frictional losses and wear). Gas springs are used which minimize frictional losses and engine wear, but they do allow some thermodynamic losses. The simplistic configuration, and the minimal wear of components, offer the potential for a long lifetime with high reliability.

Additionally, since a two-opposed configuration has been adopted for our design, vibrations are quite negligible. The configuration involves two engines which are dynamically opposed (sharing a common axis of oscillation) such that their vibrations virtually cancel each other (Reference 10). The linear alternator efficiently and reliably converts the power piston's mechanical energy into electrical energy. The power piston essentially acts as a magnet which moves through electrically conductive coils (around the cylinder). Electrical power is directly derived from this configuration without the addition of mechanical linkages--and without frictional losses. Consequently, the two-opposed free piston Stirling engine meets all of the criteria for implementation to the CASTLE's solar dynamic power system.

The remainder of this section is divided into subsections which address (1) how a free piston Stirling engine generates electrical power, (2) the developmental Stirling engines which we partly based our design upon, (3) the specifications of our Stirling engine design, and (4) a justification for our engine operating conditions and specifications.

Description of a Free Piston Stirling Engine's Operation

The operating principle of the free piston Stirling engine is rather simple. The engine consists of three main components: the displacer piston, the power piston, and the heat exchangers. The engine operates by transfering gas back and forth between compression and expansion spaces due to displacer piston motion. This gas transfer involves cyclical pressure changes which move the power piston back and forth. See Figure 4.10 for an illustration of the engine.

SIMPLIFIED ILLUSTRATION OF A FREE PISTON STIRLING ENGINE

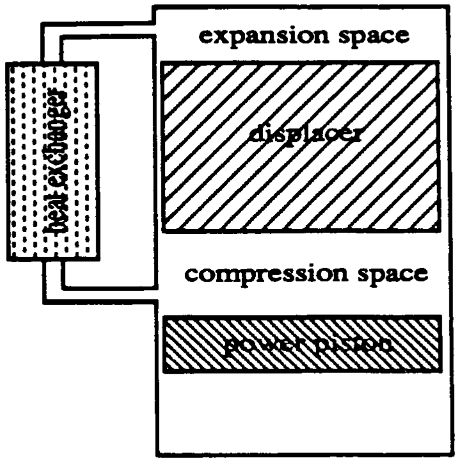


Fig. 4.10 Free Piston Stirling Engine

There is a fixed amount of gas maintained in the engine, distributed between the compression space, the expansion space, and the heat exchanger space. The piston movements transfer gas between the (hot) expansion space and the (cold) compression space. When more gas is within the hot expansion space, the pressure is high, and the power piston is forced outward (downward in Figure 4.10). Gas is concurrently transferred through the heat exchangers and into the cold compression space. The pressure drops due to the reduction in gas temperature. As a result, the power piston reverses its stroke, compressing the gas within the compression space. The displacer piston concurrently moves (upward in Figure 4.10) so that most of the gas is now contained within the cold compression space. After the compression stroke, the displacer returns (downward in Figure 4.10) to the other end of the cylinder such that the gas is transferred back to the hot expansion space. The pressure within the engine increases again, because of the substantial rise in gas temperature, and the cycle continues (Reference 11). An illustration of the pistons' motion is given in Figure 4.11. Smooth, relatively sinusoidal piston motion is maintaned during engine operation.

SIMPLIFIED ILLUSTRATION OF STIRLING ENGINE PISTON MOTION

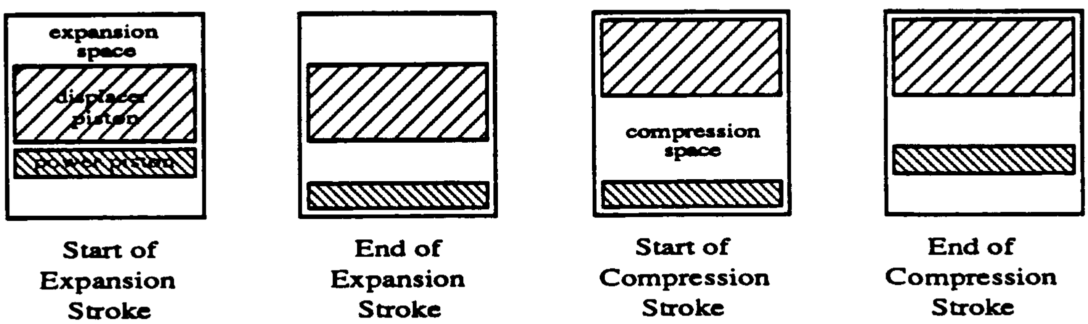


Fig 4.11 Stirling Engine Piston Motion

For each cycle, the gas must be transferred through the heat exchangers so that the temperature differential between compression and expansion spaces is maintained. The heat exchangers consist of a heater, a cooler, and a regenerator (not shown in Figure 4.10). The heater serves to increase the gas temperature to that of the expansion space. The regenerator exchanges and stores heat. (The regenerator consists of a series of screen mesh which store gas heat during part of the cycle and transfer heat back to the gas during another part of the cycle.) The cooler serves to decrease the gas temperature to that of the compression space. When hot gas is transfered to the cold space, it passes through the regenerator where much of its heat is stored, and to the cooler where additional heat is rejected. When the cold gas is transferred back to the hot space, it passes through the regenerator, regaining its stored heat, and through the heater, gaining additional heat (Reference 11). Consequently, the regenerator significantly increases the engine efficiency. An effective regenerator minimizes the amount of heat which must be supplied by the heater and rejected by the cooler.

In order to maintain the smooth cyclical displacer piston and power piston motion, gas springs are used. The gas springs are sealed internal gas volumes which oppose piston motion, but do not involve frictional dissipation or side forces as mechanical springs do. The gas springs, however, do involve some thermodynamic losses (Reference 10). One gas spring opposes the displacer piston's motion, and another gas spring opposes the power piston's motion.

In order to force the gas to pass through the heat exchangers, tight seals on the displacer piston are necessary. Additionally, tight seals on the power piston (and on all other components) are necessary to prevent gas leakage (which would decrease system efficiency). Gas bearings are utilized to allow smooth, nearly frictionless piston oscillation while minimizing the amount of gas which passes by the pistons, along the cylinder walls.

Electrical power is obtained through linking the power piston to an alternator plunger. The magnetic plunger follows the oscillation of the power piston, and passes through a conductive coil. The changing magnetic field, caused by the oscillating plunger, produces an alternating electrical current.

Description of Some Advanced Stirling Engine Designs and Technology

While Stirling engines have not been demonstrated nearly as extensively as many other engines (such as Brayton engines), many Stirling engines have been developed. C.D. West describes twenty three developed Stirling engines. Our design of the CASTLE Stirling engine was based upon several Stirling engines: a current demonstrator engine and some conceptually designed engines of the future. A free piston Stirling engine linear alternator (FPSE/LA) system--named the Space Power Demonstrator Engine--has been developed to prove the feasibility of such an engine's implementation for space power production. Its performance has been tested at NASA Lewis Research Center (Reference 10). A more advanced conceptual design of a space power FPSE/LA system--called the Stirling Space Engine--has been completed (managed by NASA Lewis R.C.) (Reference 10). Automotive Stirling engines have also been designed. Both General Electric Company and Mechanical Technology Incorporated completed conceptual designs for advanced, highly efficient Stirling engines for automotive application--named CASE I and CASE II (References 13, 14). The design of the CASTLE Stirling engines utilized the best features of these engines in order to obtain a highly efficient space power Stirling engine. This sub-section will highlight some features of each of these engines.

Space Power Demonstrator Engine

The Space Power Demonstrator Engine (SPDE) extended Free Piston Stirling Engine (FPSE) technology. Some of the accomlplishments within this program demonstrated many of the capabilities and attributes of FPSE's. The configuration of the SPDE involves two opposed engines, and has shown to be extremely dynamically balanced--one of its major accomplishments. However, the engine's performance was very limited in design. It also fell short of its design goal of 25 kWe and 25 % efficiency, primarily due to alternator inefficiency. The engine used materials with magnetic properties, and some engine components were identified as magnetically interfering with the alternator operation. A power output of 17 kWe and an overall engine/alternator efficiency of about 15 % was observed (Reference 10).

Even with an efficient alternator, the achievable engine efficiency was very limited by engine temperatures and thermodynamic losses. A maximum operating temperature of 650 K(377 °C) was exhibited with a temperature ratio of 2 (hot end temperature divided by cold end temperature) (Reference 10). This relatively low temperature ratio limits the achievable engine efficiency to 50 % (without any losses). Various thermodynamic losses were exhibited which reduced the engine efficiency substantially below 50 %. (See Appendix B2 for the SPDE thermodynamic loss breakdown--R.C. Tew, "Overview of Heat Transfer...") Most of the losses did occur as a result of heat conduction and/or transfer. The engine's gas bearings and springs minimized frictional losses, but allowed thermodynamic losses. It should be noted that the SPDE used only one gas bearing seal--on the cold side of the displacer-- which allowed thermodynamic losses in the region between the displacer wall and the cylinder wall. Also, the gas springs allowed thermodynamic losses due to heat transfer between the piston/cylinder walls and the gas. Some of the other losses involved heat conduction and/or transfer along the engine component walls due to thermally conductive materials. Still, other losses were observed and are specified in Appendix B2 (Reference 12).

Stirling Space Engine

The conceptual design of the Stirling Space Engine (SSE) promises to extend the capabilities of a space power Stirling engine beyond that exhibited by the SPDE. Advanced materials (super alloys) will be used to construct the engine components, allowing much higher temperatures than the SPDE. A heater temperature of 1050 K (777 °C) with a temperature ratio of 2 has been specified. However, the temperature ratio again limits the achievable efficiency to 50 % (without losses). A power output of 25 kWe and an engine efficiency greater than 25 % is expected. Additionally, a minimal specific mass of less than 6 kg/kWe is anticipated--far lighter than the SPDE. The SSE also uses concepts and components applicable for 1350 °K (1077 °C) refractory metal applications (Reference 10).

Advanced Designs of Automotive Stirling Engines

A Ceramic Automotive Stirling Engine (CASE) Study was performed by General Electric (G.E.) and Mechanical Technology Incorporated (MTI) (Reference 13, 14). While the configuration for such an automotive Stirling engine is different than the FPSE design chosen for the CASTLE, it was felt that the two engine configurations are sufficiently similar in most areas to allow comparison. The primary reason for analyzing the CASE designs was for their design of ceramic engine components. A major motivation for a ceramic Stirling engine was to improve the obtainable efficiency of a Stirling engine by extending its maximum operating temperature. Ceramic materials can allow much higher operating temperatures than conventional metals. Additionally, ceramic materials offer thermal conductivities outside the range of metals (Reference 14). Consequently, ceramics offer the potential for reducing many thermodynamic losses.

G.E. and MTI arrived at very similar decisions in materials and engine operating temperatures. The G.E. report, however, exhibited a more detailed analysis of engine losses and a justification for improving the losses through ceramic applications and engine reconfigurations.

G.E.'s report included the design for CASE II which is based on the year 2000 ceramic technology, featuring a radically reconfigured engine. A heater head temperature of 1100 °C (1373 K) with a temperature ratio of 4.25 was selected. Selected materials for the hot engine components include: Mullite for the displacer, cylinder housings, and regenerator housings; Silicon Carbide for the cylinder head, heater tubes, mantel, and cylinder liner; and Alumina-Boro-Silicate Fiber for the regenerator matrix. The anticipated net engine efficiency is 50 % at 60 kW net power (compared to 34.2 % at 60.1 kW net power for the very similar metal Automotive Stirling Reference Engine). (S. Musikant, et al)

Specifications of the CASTLE Stirling Engine / Linear Alternator Design

A total of sixteen Stirling engines on the CASTLE will be used to provide 432 kW of electrical power. (This will supply a net 400 kW of electricity to the CASTLE's loads.) Each CASTLE Stirling engine (CSE) has been designed to provide 27 kWe. A two-opposed FPSE/LA configuration has been selected, and each half engine produces 13.5 kWe.

The engine efficiency is 44%, and the overall system (engine plus alternator) efficiency is 41%. The maximum engine temperature is 1500 K (1227 °C), and the temperature ratio is 3.75. Also worth noting is that ceramic materials have been chosen for many engine components, mostly high temperature engine components. The specifications for the Castle Stirling engines are listed in Table 4.3.

TABLE 4.3
CASTLE STIRLING ENGINE SPECIFICATIONS

Engine Type:	Free Piston (Two-opposed configuration)	
Net Power Output:	27 kW electricity	
Net Efficiency:		
Engine	44 %	
Alternator	93 %	
Engine + Altern.	41%	
Mass:	~ 160 kg per engine (assuming ~ 6 kg/kWe)	
Temperatures:	Hot end: T_H = 1500 K (= 1227 °C)	
	Cold end: T_K = 400 K (= 127 °C)	
	Temperature Ratio: T_H / T_K = 3.75	
Mean Pressure:	15 MPa	
Phase Angle:	65 ° (Displacer-Piston)	
Working Space Volumes:		
	Mid-Stroke Volume:	2360 cm^3
	Piston Swept Volume:	264 cm^3
	Displacer Swept Volume:	89.0 cm^3
	Heat Exchanger Volumes:	894 cm^3
Working Fluid:	Helium	
Materials for Components:		
	SiC	*cylinder head, cylinder liner heater tubes*

Mullite	*cylinder housings, displacer, power piston, regenerator housing*
Alumina-Boro-Silicate Fiber	*regenerator matrix*

Another feature of the CASTLE Stirling engne design is the use of additional sets of seals / gas bearings and the reconfigured displacer piston. Seals have been added near the hot end of the displacer, and a large appendix gap (the space between the displacer and cylinder walls) has been designed. Please note the CSE configuration, shown in Figure 4.12. (Note that this is a representation of the engine and does not accurately exhibit the true shape of future Stirling engines.)

CONFIGURATION OF CASTLE STIRLING ENGINE
One Half of 27 kWe engine
(showing major components)

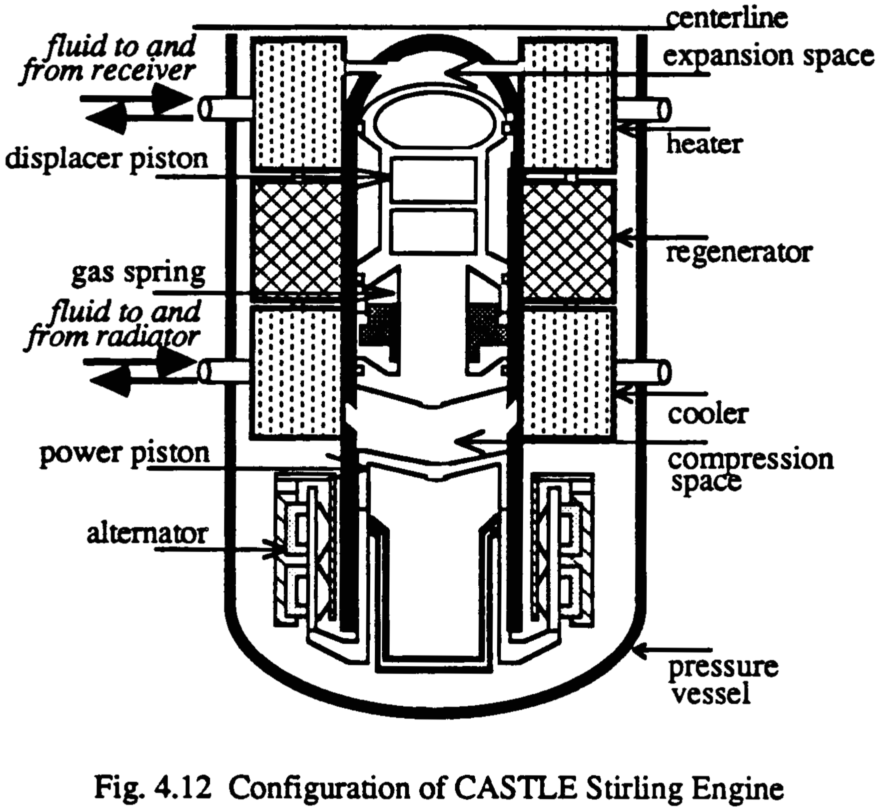


Fig. 4.12 Configuration of CASTLE Stirling Engine

Justification of the CASTLE Stirling Engine Specifications and Operating Conditions

The design of each CASTLE Stirling engine (CSE) has been physically modeled after the SPDE in many ways, but it also exhibits the specific mass of the SSE and the operating temperatures and engine component materials of the CASE II. Since a two-opposed FPSE/LA system was selected to operate at a power output comparable to the SPDE design, the same working space volumes, mean pressure, and phase angle (between displacer and piston) were selected (Reference 12). The alternator efficiency of 93% was selected since this was the unobtained design goal of the SPDE. Our application of ceramics would eliminate the magnetic interference of the linear alternator which occurred in the SPDE. Also as in the SPDE and SSE, Helium was selected instead of Hydrogen to serve as the working fluid since it offers fewer permeability and corrosion problems. The specific mass of the CSE was assumed to be comparable to the anticipated specific mass of the SSE (6 kg/kWe)--a very small specific mass indeed. Differences in engine materials and efficiency between the CSE and the SSE will probably yield differences in specific mass, however.

The other engine specifications were rather radical in comparison to the SPDE. A very high maximum temperature and temperature ratio was selected, and a very high efficiency is anticipated. The CSE hot end temperature was specified to be slightly greater than the heater head temperature of the CASE II. Specifically, a hot end temperature of 1500 K (1227 °C) was selected since advancements in ceramics beyond the 2000 will likely allow such temperatures. A low end temperature of 400 K was selected to maximize the feasible temperature ratio while staying within the realistic limits of the Currie Point radiator. The extreme temperature ratio does not pose the same system weight problems exhibited in conventional radiators. The Currie Point radiator's mass stays relatively constant for a wide range of heat rejection rates and temperatures. Also, the large temperature gradients resulting from the large temperature ratio are not as extreme as the CASE II design which specifies a temperature ratio of 4.25.

The reconfigured displacer includes seals (hydrodynamic) to be placed near the hot end of the displacer. Hot end seals have not been possible in the past due to the extreme temperatures. Indeed, the CSE will have even much higher temperaures, but the adoption of ceramic materials would allow such a configuration. The General Electric report anticipated that a hot end ceramic seal would be possible by the year 2000, and we are assuming that the advancement of technology will certainly allow this configuration by the year 2030. The adoption of the hot end seal has many advantages in itself, particularly the reduction of some thermodynamic losses. It also allows for a large appendix gap between the hot and cold displacer seals. This large appendix gap will further reduce thermodynamic power losses.

Calculation of the engine efficiency was based upon a thermodynamic analysis which considered thermodynamic losses (and the alternator efficiency). The SPDE's observed thermodynamic losses were "extrapolated" for the CSE and then added to the CSE's specified mechanical power. This sum was equated to the product of the engine's Carnot efficiency and the rate of heat input to the engine. This equation allowed the calculation of the necessary rate of heat input so that efficiency terms could be calculated. Please see Appendix B1 for a detailed description of the computation. This analysis was felt to be quite reasonable as a first approximation to the engine's efficiency and necessary specifications (certainly much better than most simplified equations used for first order analysis).

The analysis uses extrapolations of the SPDE's thermodynamic losses. The percent change of thermodynamic losses in the CASE II compared to its similar metal automotive Stirling engine was determined (from G.E.'s report). The percent changes in applicable thermodynamic losses were first applied to the SPDE losses and then extrapolated. This extrapolation obtained the anticipated thermodynamic losses of the CSE. The anticipated improvements in SPDE losses are justified through the redesigned CSE. The application of ceramic materials which offer very desirable characteristics should reduce many of the losses observed in the SPDE. The seals in the modified displacer configuration will significantly reduce the thermodynamic losses within the appendix gap (the space between the displacer wall and the cylinder wall). Additionally, the displacer will have a larger appendix gap (than the SPDE) between the two seals so that other thermodynamic losses are minimized. The application of mullite to the cylinder and regenerator housings, the displacer, and the power piston will minimize conduction losses due to the extremely low thermal conductivity of mullite (2.8 W/m°C). (S. Musikant, et al) Additionally, a reduction in regenerator matrix filament size (by using Alumina-Boro-Silicate Fiber) should reduce the regenerator pumping loss due to reduced flow resistance. Also, a mild reduction in regenerator reheat loss should occur due to reduced thermal conductivity along the regenerator axial direction and increased thermal conductivity along the regenerator radial direction. Please see Appendix S2 for a breakdown of the thermodynamic losses in both the SPDE and the CSE.

Since hysteresis losses did not concern CASE II, a rough estimate was made for these losses. It was thought that low thermally conductive ceramics would reduce hysterisis losses since the CSE should be a much more adiabatic engine than the SPDE. The magnitude of change was estimated from the conduction loss improvement for the CASE II, since hysterisis loss is related to thermal conduction. The CASE II was designed to improve the conduction loss by 85 %, and a conservative improvement of 70 % was assumed. Again, please see Appendix B2 for the loss breakdown.

A major concern in adopting ceramic materials for engine design is their brittle properties. The validity of a ceramic Stirling engine does rely upon the advancement of ceramic technology. Since the CASE Study anticipated appropriate feasible technology by the year 2000, ceramic space power Stirling engines for the CASTLE in the year 2030 is reasonable.

Power Conversion Subsystem Conclusion

In conclusion, our design for the CSE seems to meet all the necessary criteria, including a very high efficiency. Technological advancements in Stirling engines within the next forty years should demonstrate that highly efficient ceramic Stirling engines for space power application are entirely feasible. Indeed, advancements may yield Stirling engines of even better characteristics than that of our anticipated CSE.

4.2.3 Radiator Subsystem

Radiator Subsystem Introduction

For the solar dynamic power system of a spacecraft, a radiator is necessary to reject waste heat from the Power Conversion subsystem. For space-based power systems, waste heat must ultimately be radiated to space. Radiation is the only cooling method available to space-based power systems, since conduction and convection require contact between an object and its environment. In the vacuum of space, there is no such contact available.

As the power level of a space-based power system increases, the heat rejection radiator of coventional technology becomes the dominant mass and volume contributor to the power system. The optimal design and development of future power systems, such as solar dynamic power systems, will requre advanced heat rejection concepts utilizing innovative approaches to overall system mass and size, while increasing thermodynamic performance and system efficiency. Advanced heat rejection systems will be required to withstand the detrimental effects of meteoroid and space debris impact, as well as addressing such pertinent requirements as reliability and maintainability.

The liquid droplet radiator (LDR) configuration was chosen in the CAMELOT I project. In this configuration, waste heat is rejected to tiny liquid droplets which are ejected into space in a fine sheet and recovered some distance away by a collector assembly which gathers the droplets and pumps the fluid back to the power converter. While in space transit, the droplets radiate heat, thus lowering their temperature. Conceptually, this heat rejection system has very low mass because the mass of the droplets per unit area is very small in comparison with conventional radiators. Unfortunately, the mass of the droplet generator and collector are not small.

In addition, there are other limitations which make the liquid droplet radiator unattractive for the CASTLE. The most severe limitation of the LDR is that imposed by evaporation losses of the droplets while they are in transit. The LDR of CAMELOT I was sized to be 50 m long. The fluid losses involved in this distance are quite significant. There are other fluid losses due to limitations on the aiming accuracy of the droplet generator and the efficiency of the droplet collector. For long term continous missions, such as those planned for the CASTLE, extensive radiator fluid resupply would be necessary due to the fluid losses. Another limitation is the structural instability associated with having a 50 m long apparatus extending outward from the back of the concentrator.

An attractive feature of the LDR is that the droplets are not contained. This renders the radiator virtually immune to meteoroid damage. However, this feature results in an additional problem for the spacecraft in that the radiator cannot be properly operated during accellerated maneuvering. Because of these limitations, a new radiator configuration was adopted by CAMELOT II.

This new radiator system is the Curie point radiator (CPR). As invented by M.D. Carelli and associates at the Westinghouse Advanced Energy Systems Division, the CPR system is based on the same operating principle as the LDR. It retains many of the benefits of the LDR, such as very low mass and near immunity to meteoroid damge, while reducing or altogether eliminating many of the limitations associated with the LDR, such as significant fluid losses and the inability to operate during maneuvering.

In the CPR, waste heat is transferred to small solid ferromagnetic particles which are heated above their Curie point to a nonmagnetic state and released into a magnetic field in space. As the particles radiate heat, their temperature drops below their Curie point, and they become ferromagnetic again. At this point, the particles are subject to the magnetic force and driven to a collector for recycle. See Figure 4.13 for an illustration of the operation principle of the CPR.

Advantages of CPR

There are two significant advantages to using small particles (of the order of 1mm) as the radiating element. First, the mass requirement is minimized because of the large surface to volume ratio, and second, the area requiring micro-meteoroid protection is greatly reduced. This results in an overall mass reduction. The mass of the radiating elements is a minor fraction (10 to 20%) of the total radiator system mass.

The operational benefits of using a magnetic field to guide and collect particles are unique to the CPR system. Particle inventory can be actively controlled and the loss of particles can be effectively reduced to zero by increasing the field strength. The system can be designed for maneuvering capability by adjusting the magnetic field to mission requirements. No particle losses result from mis-aiming, splashing, etc.. One disadvantage, however, is that the magnetic field may cause perturbations in other magnetic components of the spacecraft.

The use of solid particles instead of liquid droplets has several key advantages. Losses due to vapor pressure are completely eliminated. The solid particles, unlike droplets, can be coated, which will increase their emissivity in addition to preventing sublimation loss. With solid particles, there is no need for strict temperature control. When specifying the range of operation of liquid droplets, an adequate margin must be provided in order to avoid being too close to the freezing point or a temperature where vapor pressure produces significant inventory losses. This limits the choice of available materials and causes restrictions on the discharge temperature of the Power Conversion subsystem (in this case the Stirling engine). With the CPR, there is virtually no temperature limitation. Magnetic materials can be found with Curie points as low as 300 K and as high as 1500 K. This allows the selection of a CPR material which is best suited for the Power Conversion subsystem charateristics, and makes the optimization of the entire system possible.

OPERATING PRINCIPLES OF CURIE POINT RADIATOR

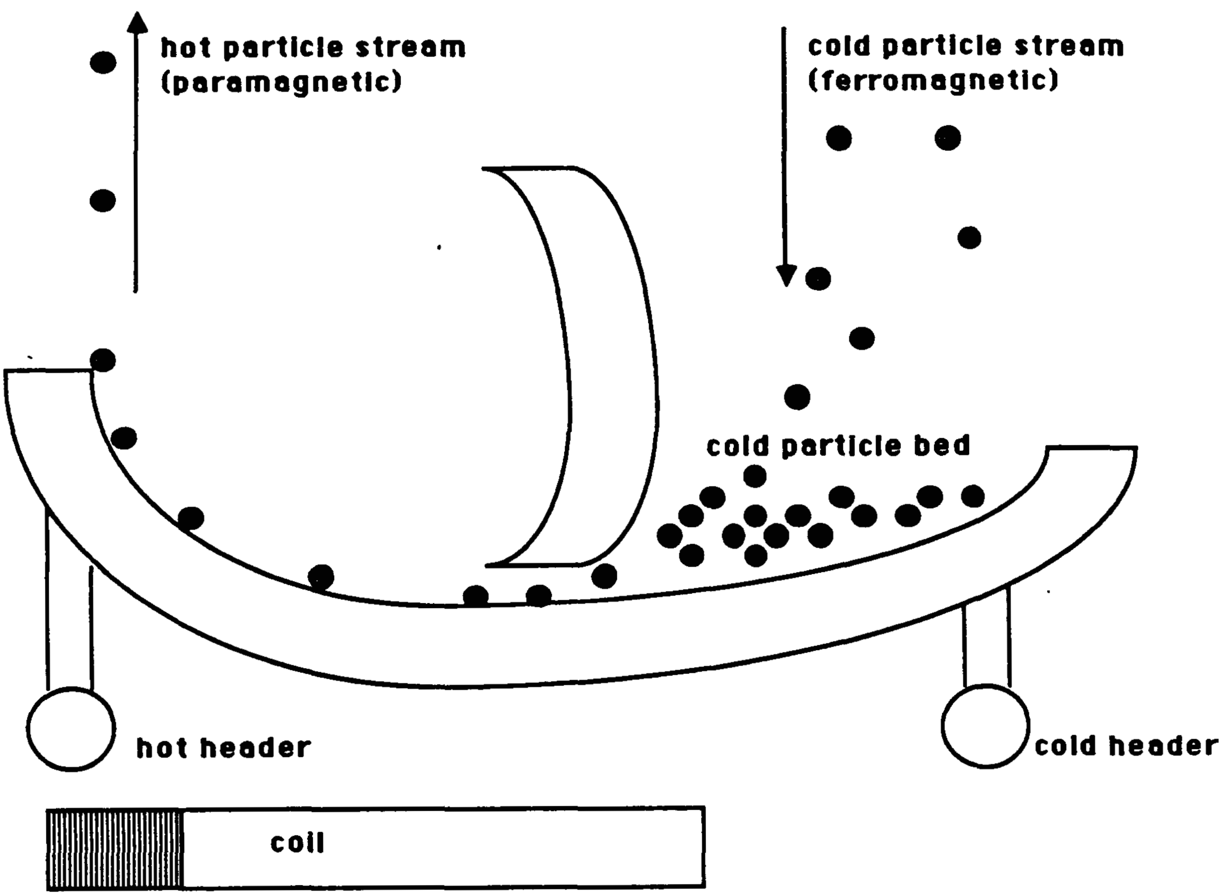


Fig. 4.13 Curie Point Radiator Operating Principal

CPR Configuration

The CPR configuration chosen has been designed as an almost completely passive system with very few moving parts except for the particles. This design provides extremely high reliability while allowing significant mass reduction and parts minimization.

The CPR system consists of six key components outlined in Table 4.4.

Table 4. 4 - CPR Components

Component	Function	Design Objectives
Particles	Reject waste heat to space	Minimum mass per unit power Minimum inventory loss
Heat Exchanger	Transfer heat from working fluid to particles	Minimum area and mass per transferred power
Magnet	Provide magnetic field to guide and collect particles	Control particle inventory with minimum mass
Collector	Collect particles	Minimum area Conserve inventory Maximum reliability
Injector	Feed particles to heat exchanger	Maximum reliability
Ejector	Remove particles form heat exchanger and eject into space	Maximum reliability Conserve inventory

The CPR configuration selected is a magnetically pumped design, conceptually illustrated in Figure 4.14. It consists of a cup with a complex arrangement of finned channels which are internally heated by an exhaust fluid. These finned channels are located on top of a magnet. The cup contains a "pile" of particles. While the temperature of the particles is below their Curie point temperature, a magnetic force is exerted by the magnet on the particles. As the particles near the cup walls, they are heated and become paramagnetic. Since these particles are now paramagnetic, there is no longer a force holding them against the cup wall and they are "squeezed out" by the cold ferromagnetic particles (a tangential component is generated by the inclination of the cup wall). The cold particles then come in contact with the cup wall and replace the departing hot particles. Once cooled, the particles are again attracted towards the cup by the magnet. They are collected, re-heated and the process continues. The edge of the cup is contoured in such a way that it provides an angular component to the hot released particles. Combined with the magnetic field, this will cause the cooled particles to land in the collecting of the cup and replenish the particle pile.

Simplicity is the most significant feature of the configuration shown in Figure 4.14. One single component, the cup, satisfies the functions of heat exchanger, collector, injector, and ejector. This offers the potential for high mass reduction. This is important because the ancillary (non-particles) systems account for most of the radiator system mass.

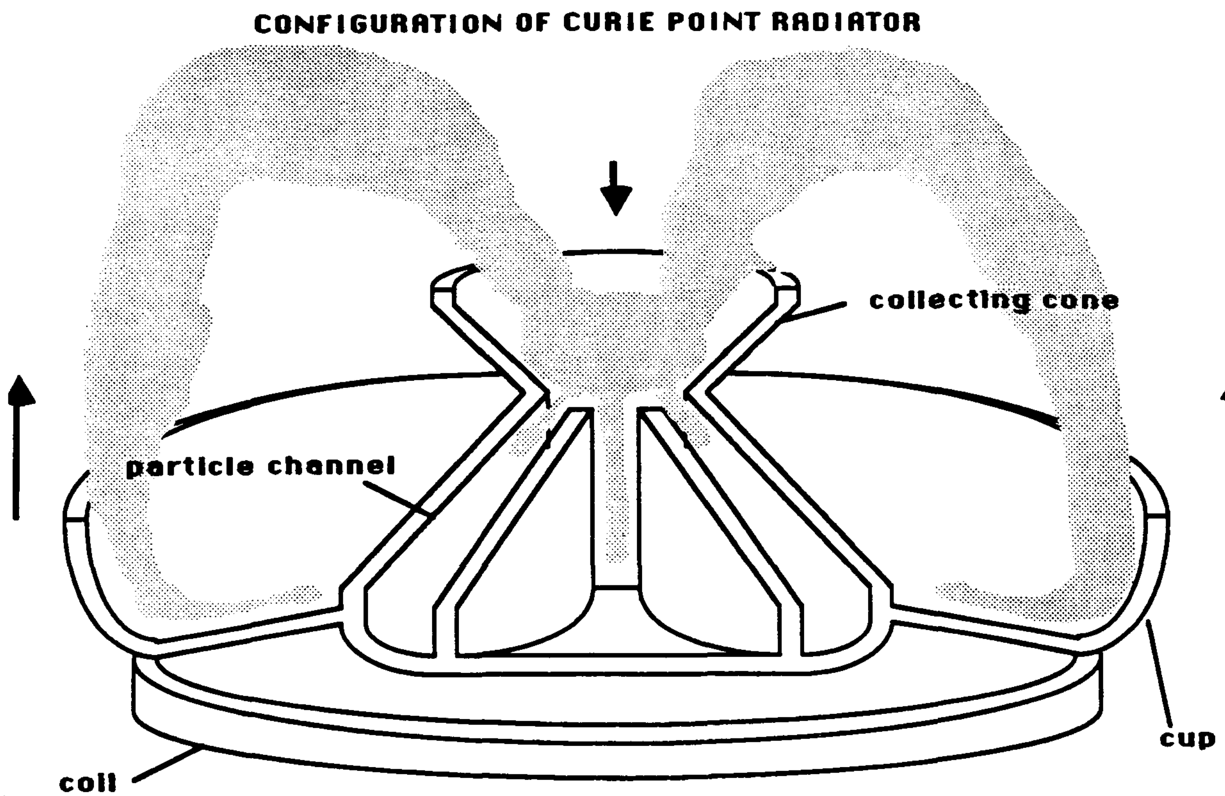


Fig. 4.14 Curie Point Radiator Configuration

System Parameters

The following system parameters were derived from the design of the CASTLE Stirling engines.

Hot Temperature of Engine	1500 K
Cold Temperature of Engine	400 K
Particle Ejection Temperature	450 K
Total Power Radiated	590 kW

Discussion of Components and Materials Selection

The first material optimization was to select the material for the radiating particles. Properties required were high magnetic permeability with low residual magnetism, structural and chemical stability, good thermal characteristics (high thermal conductivity and emissivity), low density, and low cost. With the mean temperature of the engine working fluid being 900 K, a particle ejection temperature of 450 K was established. The material chosen for the particles is $Ba_2Zn_2Fe_{12}O_{22}$ which has a Curie point temperature of 403 K The emissivity of this material can be significantly improved by coating it with SiC which has an emissivity of 0.9. A spherical particle geometry was chosen because it is much less prone to jamming during the injection / ejection phases than parallelipiped or cylindrical geometries.

The magnet is the most massive component of the CPR. It is reasonable to conclude that a superconducting magnet would meet the design objective of minimizing mass while maintaining a sufficient control of particle inventory. The state-of-the-art in lightweight air-born superconducting coils is epoxy potted Nb_3Sn superconducting wire that has Cu_2S wire strand insulation and layer to layer combined S-glass fiber reinforcement and electrical insulation. These magnets are intrinsically stable and very reliable. The superconducting magnet would be responsible for supplying a field strength of .325 T during normal operation. This figure is higher than would normally be neccessary due to the competition for the particles from the magnetic field involved with the radiation protection of the torus. The field strength and direction could be varied according to mission maneuvering requirements.

Low mass and low area per power transferred are the design objectives for the cup, which serves as a heat exchanger. The CPR heat exchanger is designed to function as a counter flow heat exchanger. Hot gas enters the fin arrangement of the heat exchanger at the outer radius and cools as it flows towards the center. At the same time, cold particles entering the fin channels at the center are heated as they travel outward. Heat transfer in the channels is achieved by conduction and radiation from the walls to the particles. The chief properties desired of the cup are high thermal conductivity, high magnetic permeability with low residual magnetism, and high strength while retaining low density. The cup must also be shielded against meteoroid and space debris impacts.

Design Summary

Number of Radiators	16
Size of Particles	1.0 mm diameter spheres
Initial Particle Velocity	80 - 120 mm/sec
Mass Flow Rate	0.250 kg/s
Cloud Extension	<1.0 m
Cup (Heat Exchanger) Diameter	1.0 m
Magnetic Field Strength	0.325 T
System Specific Mass	1.20 kg/kW
Mass of Each Radiator	44.2 kg
Total System Mass	710 kg

Summary and Justification

The choice of the CPR system is based on retaining the advantages of the LDR while improving on and virtually eliminating its limitations. While the LDR provides the reduced mass and required high invulnerability to meteoroid damage, it faces the severe problem of inventory loss due to vaporization, aiming inaccuracies, and splashing on the collector. Inventory loss of a high degree on a long missiion such as that proposed for the CASTLE would be disastrously inefficient. Another limitation of the LDR is that it is not suited for missions that require extensive maneuvering while in full power operation. The CPR has the low mass potential and high meteor invulnerability of the LDR, while achieving virtually no inventory loss and offering high optimization for any power conversion system.

Although the CPR is an innovative and relatively untested radiator system, preliminary experimentation by Westinghouse Advanced Energy Systems Division shows that the CPR is a feasible confiquration for future space applications. Future consideration might be given to reducing the number of radiators, as the Curie point radiator is designed for multi-megawatt space system capabilities. The main reason CAMELOT II did not pursue this was concern for system redundancy.

4.3 Reserve Power System

As reasearched by CAMELOT I, the purpose of the Reserve Power system is to provide a backup source of power. Since the solar dynamic power system can not be operated during major propulsive maneuvers, such as initial insertion and orbital correction, stored energy is needed for these times. Also, in case of failure of the Primary Power system, stored energy will be needed to allow time for repairs. The CASTLE Reserve Power System needs to supply the nominal 400 kWe of power for use during propulsive manuevers and a two week reserve at 200 kWe (Minimum Life Support Power) for use during an emergency. Without power, the CASTLE will be incapable of supporting life, thus it is essential to provide a reserve system.

The Reserve Power system that has been designed for the CASTLE is a regenerative fuel cell system (RFC). This system will consist of hydrogen-oxygen fuel cells and electrolysis cells. They fuel cells will be used to provide power to the CASTLE during normal solar dynamic shut down and emergency situations. These fuel cells generate power by converting hydrogen and oxygen (the reactants) into water in the presence of an electrolyte. The electrolysis cells will be used to convert the water produced by the fuel cells back into the reactants. The electrolysis cells use electricity in combiniation with water to perform the reverse reaction of the fuel cells. After the fuel cells have been used to generate power, the electrolysis process will convert the water produced by the fuel cells back into hydrogen and oxygen, provided that the Primary Power system is capable of providing excess power for the electrolysis process.

The regenerative fuel cell system of the CASTLE is broken up into eight sections. Each of these sections is capable of generating 50 kWe. Each fuel cell section consists of eight independent fuel cell units, each capable of generating 6.25 kWe, and two electrolysis units. Two electrolysis units per section should be sufficient to reconvert the water into reactants since the time during which the fuel cells are in use is minimal relative to the amount of time the electrolysis cells have in which to replenish the reactant supply. The fuel cell units will be set up in a parallel cofiguration such that any combination of fuel cell units may be supplied from the hydrogen and oxygen tanks. Of the eight fuel cell sections, four are located on the torus. Each of the remaining fuel cell sections is located inside the base of one of the solar booms (where the solar booms are joined to the main boom).

For this regenerative fuel cell system, based on current specific power densities (.42 kg/kW-hr) for hydrogen-oxygen fuel cells, the mass of reactants needed for two weeks of Minimum Life Support power is about 30,000 kg.

As an overall backup system, H_2-O_2 RFC integrates well with the rest of the spacecraft. Hydrogen and oxygen intended for the fuel cells can be diverted to the CASTLE rocket engines to serve as an emergency source of propellant. Similarly, hydrogen and oxygen from the propellant tanks may be transferred to the fuel cells if power becomes the priority concern. The stored reactants can also help in the event of a life-support emergency. The oxygen may be used as a backup for the atmosphere of the CASTLE, and the fuel cells can produce water if a shortage develops. The RFC provides a comfortable two week grace period to effect repairs on the solar dynamic system when neccessary, as well as providing power during times of shadow or orbital correction.

4.4 Power Management and Distribution System

4.4.1 Introduction

Since the power that is generated by the Stirling engines is neither in the right place or at the right frequency, it becomes necessary to transfer the power to its needed location in a usable form for the CASTLE's loads. It therefore becomes necessary to have some control system that will perform this function. The power management and distribution (PMAD) system is responsible for the all of the transmission, distribution, and conditioning of electrical power between the energy source and the user loads. In most Earth based power stations human controllers decide how much power will go to what loads. In a long duration space based mission, a highly autonomous controller is desirable. Since safety, reliability ,and minimization of crew involvement are the key objectives in designing the CAMELOT II's PMAD system, artificial intelligence and expert systems seem to offer the best alternative for the PMAD to meet it's objectives and responsibilities.

4.4.2 Artificial Intelligence

Artificial intelligence (AI) is a discipline devoted to developing and applying computational approaches to intelligent behavior. A branch of AI called expert systems uses knowledge and reasoning techniques contained in a computer program for problems that would normally require human expertise to solve. Using this type of technology in the CASTLE's PMAD would practically eliminate the ground support and crew involvement that is needed in a large scale space power system today. It would also increase the factor of safety for the crew since it would reduce the need for astronauts to perform repairs or replacement procedures in space through EVA maneuvers. This system would also be more reliable since it would minimze the risk of human error and would make more consistent decisions when dispatching power. It would also eliminate valuable crew time that might otherwise be spent at tasks such as system monitoring and other housekeeping chores. The main problem with AI in spacecraft power systems is that we currently have little to no practical experience with this type of large power system. By the year 2030, when the CASTLE is operational, we should have detailed knowledge of space station power plants and will be able to develop complex expert systems that can deal with any problems that might arise.

4.4.3 PMAD Subsystems

The PMAD system computer will be housed in a section of the micro-gravity laboratory module. The system will be subdivided into the main control system and four subsystems: power generation, allocation, health status, and fault management. The main control system would link the four subsystems together and provide the interface through which the crew could interact and input information. The tasks of the four subsystems are described below.

Power Generation Subsystem

The Power Generation subsystem would be primarily concerned with maintaining and monitoring the generation of power. It would be responsible for keeping the solar dynamic dishes within their proscribed pointing accuracy by controlling the rotation of the rotary joint. The need to perform this operation will be based upon power output data from the Stirling engine. When the actual power output is lower than neccessary, the power generation subsystem will move the rotary joint in order to attain maximum power output.

This subsystem will also monitor and control the concentrators, Stirling engines, and Curie point radiators. At a certain point in the CASTLE's orbit, the solar collectors will supply more power than is needed. The PMAD will use the actuators of the concentrator to offset as many gore segments as neccessary to meet the power requirement. The PMAD could also change the working pressure or the piston stroke of the Stirling engines to supply the needed amount of power. The Power Generation subsystem will also insure that each Curie point radiator's heat rejection temperature is sychronized with that of its Stirling engine.

This subsystem will be primarily made up of a database containing knowledge as to the limits and operating states of the power generation equipment. This will require an AI system that is able to discriminate between the various operating states and be able to act accordingly based on this knowledge.

Allocation Subsystem

The Allocation subsystem is responsible for the transmission, distribution, conditioning and management of the electrical power. Transmission concerns taking the unconditioned power from the Stirling engines and transferring it to the conditioning elements. Since part of the transmission process takes place across the alpha rotary joint it will be necessary for this subsystem to monitor the power transfer module located in the rotary joint.

Since the Stirling engines generate power at a frequency and voltage that will not be usable in the CASTLE systems it is necessary to condition the power into a usable form. CAMELOT II has specified that the systems of the CASTLE will use 20 kHZ, 440 Volts AC power. Since NASA's proposed space station is using a 20 kHz power system many of the high frequency distribution problems will have been solved before the CASTLE is built. By using this high frequency we also gain proportionally lower transformer and inductor weights, some reduction of semiconductor switching losses, and a higher harmonic for light weight filters to remove electro-magnetic interference.

After the power is conditioned it must be distributed to the user loads. This will require a complex AI management system that will be able to schedule users loads based on such factors as power availability and mission objectives (cargo transfer, micro-g experiments, propulsive maneuvers, etc...). It will also have to monitor the system components to make sure they are operating within the proscribed limits and make discriminative decisions based on the knowledge contained in the expert system.

Health Status Subsystem

The Health Status subsystem will be tied into the control system that monitors the power system components. In a complex power system like that proposed by CAMELOT II, it will become necessary not only to cope with component failures, but to also predict the failures before they occur. The function of the health status subsystem is to take the data gained from monitoring the components and categorize it based on the performance of the component. The PMAD system has four states into which it categorizes power system elements.

(1) Normal: The data received by the health status system is within the normal operating limits of this component. No further action is necessary.

(2) Degraded: A component's efficiency has fallen below acceptable limits. An AI expert system will monitor the components' performance over a period of time. If the performance is less than the ideal performance the component may be classified as degraded.

(3) Emergency: A sudden loss of performance is categorized as an emergency state. This state differs from the degraded state since the failure is detected without

prior warning. The health status subsystem will alert the fault management subsystem so that procedures can be initiated to correct the problem.

(4) Corrective: After an emergency state has been reached and when repair procedures have been intiated a corrective state is declared. This mode specifies the state of the component durind repair. When the corrective measures are completed and the component is operating as it should, the corrective state is aborted and a normal state resumes.

Fault Management Subsystem

The Fault Management subsystem is concerned with determining, isolating, diagnosing and correcting problems with the CASTLE power system. When an abnormality is detected in any of the other subsystems, fault management is alerted. This subsystem will have the most advanced AI software since it will have to take the given data and classify it based on the contained knowledge of the power system operation. It diagnoses the problem and uses some sort of problem solving knowledge to initiate repair operations. In some cases the fault management system will initiate repairs on it's own (if possible). This may included simple operations such as tripping a circuit breaker or diverting power from one load to another. In more serious and complex problems, such as sudden component failure, the fault management subsystem will shut down components and alert the crew to the problem. If necessary it will start up the regenerative fuel cells for secondary power. When crew intervention is neccessary, the fault management system will direct them through the repair operation by using its store of diagnostic, discriminative, and problem-solving knowledge. This high degree of autonomy eliminates the need to have a power systems expert on board since the PMAD system is the expert. All that is required is that the crew have a small amount of technical expertise.

4.5 Other Design Specifications-Rotary Joint

Since the CASTLE will not always be in perfect alignment with the sun, it is necessary to develop a system that will allow the solar dynamic unit to be pointed at the sun to insure maximum power generation. Such a system requires a rotary joint that can provide structural stability to the support truss, rotate the truss to the proper alignment, and allow for power and data tranfer across the joint. CAMELOT II has specified the use of five rotary joints per solar boom; one to control rotation of the upper end of each main solar boom and four to control the rotation of each of the four arm booms. This will allow the solar dynamic units to be rotated about two perpendicular axes; therefore, the concentrators will be able to be pointed at the sun for almost any orientation of the spacecraft.

One of the most promising rotary joints is the Alpha Joint Bearing currently being developed by AEC-Able Engineering Company of Goleta California. This system is being designed for the NASA dual keeled space station. With future advancements in materials technology we feel that a version of the Alpha Rotary Joint will be acceptable for the purposes of the CASTLE.

The Alpha Rotary Joint is made up of two large identical circular structures and eight small roller bearing packages. The circular structures make up the rotating and non-rotating parts of the joint. The non-rotating section is the part that serves as the mount for the bearing packages. They are identically made to save cost, provide redundancy, and to provide matching thermal expansion properties of the two structures.

The roller bearing packages are composed of three roller bearings in a preload arm, yoke, and dovetail mount. Eight of these packages will be mounted uniformly along the non-rotating strucutre to provide rotation. Currently one of the main problems with this joint is the thermal expansion that is caused by the face of the joint that faces the sun. This side heats up faster than the other side and causes the material to expand. Given current technology, the Alpha Joint also may have problems maintaining the pointing accuracy for the CASTLE because of stiffness requirements. Material advancements should eliminate these problems, however, and provide the CASTLE with a viable rotary joint.

4.6 Power Systems Conclusion

The efforts of the CAMELOT and CAMELOT II studies have resulted in the design of a power system which meets the unique needs of the CASTLE. The design of this power system was optimized in terms of spacecraft mass without sacrificing the reliability of the system. Since a rescue mission could not be effected for the CASTLE at most stages of its orbit, the passengers of the CASTLE would not be able to survive without power if a catastrophic failure in the power system occured. For this reason, a great deal of redundancy has been built into the power system. The unique needs of a vehicle such as the CASTLE has posed several new and interesting design problems. For many of these problems, the CAMELOT studies have provided unique solutions. Many of these solutions require technoligical advances in definite areas. It is our hope that by having addressed these required technological advances we will have helped to define the path of future technological advances so that missions such as the CAMELOT mission will become a reality.

POWER SYSTEMS APPENDIX 1

CALCULATION OF STIRLING PARAMETERS

Specified (fixed) Parameters:

Power Output	$P_{out} = 27$ kW (13.5 kW per half engine)
Temperatures	$T_H = 1500$K $T_K = 400$ K
Alternator Efficiency	$h_{alt} = 93\%$
Thermo. Power Loss	$P_{thermo} = 19.2$ kW (9.6 kW per half engine)

Definition of Variables:

Rate of Heat Input to Engine:	Q_{in}	Net Overall Efficiency:	h
Mechanical (brake) Power:	P_{mech}	Net Engine Efficiency:	h_{eng}
Thermo. Power Loss:	P_{thermo}	Net Alternator Efficiency:	h_{alt}
Other Power Losses:	P_{loss}	Carnot Efficiency:	h_{car}
Electrical Power Output:	P_{out}	Rate of Heat Rejection:	Q_{rej}
Heater Head Temperature:	T_H	Cold End Temperature:	T_K

Thermodynamic Analysis: (Based on one half of engine. $P_{out} = 13.5$ kW)

The First Law of Thermodynamics requires the following relationship:

$$Q_{in} = P_{mech} + P_{thermo} + P_{loss}$$

--But the Engine's Carnot Efficiency dictates the Mechanical Power and the Thermo. Power Loss:

$$(h_{car})\,(Q_{in}) = P_{mech} + P_{thermo}$$

--The Carnot Efficiency is governed by the ratio of Cold End Temp. to Hot End Temp.:

$$h_{car} = 1 - (T_K / T_H)$$
$$= 1 - (400 / 1500)$$

The Carnot Efficiency is defined: $h_{car} = 73.3\%$

--The Mechanical Power is defined by the specified power output and the alternator efficiency:

$$h_{alt} = (P_{out}) / (P_{mech})$$
$$P_{mech} = (P_{out}) / (h_{alt})$$
$$= (13.5 \text{ kW}) / (.93)$$

Hence, the Mechanical Power is defined: $P_{mech} = 14.5$ kW (for one helf engine).

--The Thermodynamic Power Loss has been defined: $P_{thermo} = 9.6$ kW (for one half engine). (The results from the "Thermodynamic Loss Breakdown for One Half Engine" were linearly scaled to yield an expected loss of 9.6 kW.)

--Cosequently, the Rate of Heat Input is given:

$$Q_{in} = (P_{mech} + P_{thermo}) / (h_{car})$$
$$= (14.5 \text{ kW} + 9.6 \text{ kW}) / (.733)$$

The receiver must transfer Heat at the rate $Q_{in} = 32.9$ kW (per half engine).

APPENDIX 1 (continued)

--The Rate of Heat Rejection (required by the radiator) is:

$$Q_{rej} = P_{thermo} + P_{loss}$$
$$= Q_{in} - P_{mech}$$
$$= 32.9\ kW - 14.5\ kW$$

The Radiator must reject heat at the rate Q_{rej} = 18.4 kW (per half engine).

--The Net Engine Efficiency is defined as:

$$h_{eng} = (P_{mech}) / (Q_{in})$$
$$= (14.5\ kW) / (32.9\ kW)$$

The Net Engine Efficiency is h_{eng} = 44%.

--The Net Overall Efficiency is defined as:

$$h = (P_{out}) / (Q_{in})$$
$$= (13.5\ kW) / (32.9\ kW)$$

The net efficiency of the engine including the alternator is h = 41%.

Power Systems Appendix 2

THERMODYNAMIC LOSS BREAKDOWN FOR ONE HALF ENGINE

(25 kWe engine)

THERMODYNAMIC LOSS	SPDE	% CHANGE	CASTLE ENGINE **	REASON FOR CHANGE
Appendix Gap Loss	1.33 kW	- 93	.09 kW	Hot and cold seals on displacer; large appendix gap.
Conduction Loss	1.86	- 85	.28	Very low thermal conductivity of displacer, cylinder, regenerator housing.
Regenerator Reheat	3.83	- 2.0	3.75	Reduction in regenerator matrix filament size
Working Fluid Pumping Loss				
• Heater	.67	0	.67	Reduction in regenerator matrix filament size.
• Regenerator	.96	- 35	.63	
• Cooler	.29	0	.29	
• Connecting ducts	.19	0	.19	
Hysterisis Loss	1.62	- 70 *	.49	Very low thermal conductivity of displacer, cylinder, regenerator housing
Gas Spring Hysterisis	.73	- 70 *	.22	Very low thermal conductivity of displacer, cylinder
Other (leakage, porting)	.69	0	.69	
Leakage Loss	.36	0	.36	
Heater & Cooler Gas-to-Wall Temperature Difference	1.19	0	1.19	
Total Losses	13.72 kW		8.85 kW	

* These percent changes were estimated through a comparison of conduction loss improvements. As a rough estimate, the improvement in hysterisis loss was assumed to be comparable to the improvement in conduction loss expected in the CASE II design.
(70% improvement was a "conservative estimate" compared to the 85% change for conduction.)

** This thermodynamic analysis assumes a 25 kWe CASTLE engine. Linear scaling is used to size the results for the 27 kWe CASTLE engine. The expected loss for half of the 27 kWe engine is 9.6 kW.

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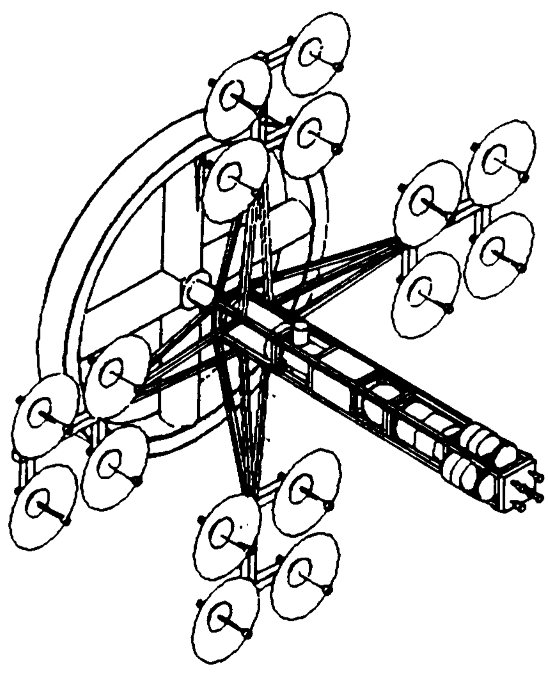
Chapter Five

Interface Design

5.1 Introduction
5.2 Rotational Maintenance
5.3 Transfer of Loads
5.4 Personnel and Equipment Transfer
5.5 Power and Data Transfer
5.6 Conclusion



5.1 INTRODUCTION

5.1.1 Purpose

Several studies have been conducted over the years concerning the use of artificial gravity in large space stations. One of the most recent and most complete such studies is An Advanced Technology Space Station For the Year 2025, a study conducted through the NASA Langley Research Center. This study, and all others before it have recognized that one of the most important aspects of long-duration space flight is the detrimental physiological and psychological effects of micro-gravity. In addition, they have noted that probably the best and the most difficult means of preventing these effects is by creating an artificial gravity field by rotating a portion of the spacecraft.

While admitting that this is the way to proceed, none of these reports have studied in any detail, the technology and the spacecraft components required to maintaina rotation of one portion of a spacecraft, while ensuring no rotation in other sections as is required for numerous tasks. The CASTLE is a perfect example of a spacecraft with a rotating section (the torus) and a non-rotating section (the main boom). It was decided that a large emphasis would be placed on designing an interface between these two sections that would then stand as a benchmark design that could be used or improved upon by subsequent studies of rotating spacecraft.

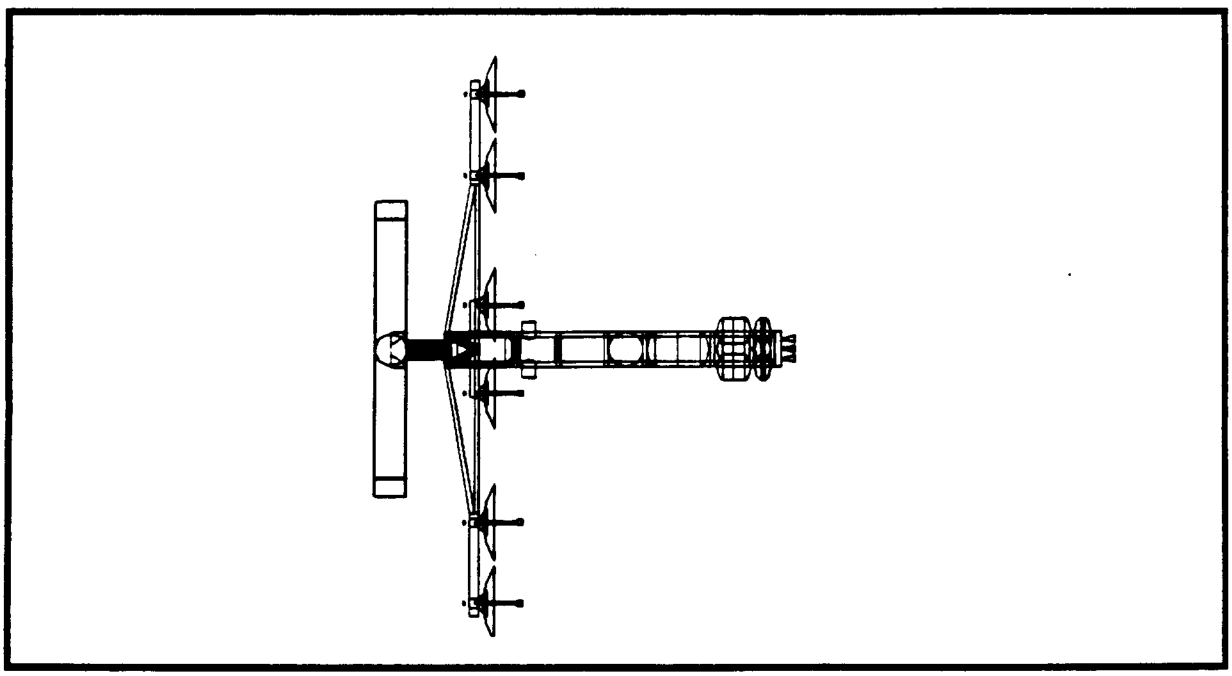


Fig. 5.1 Highlighted portion indicates interface

Unlike any previous spacecraft design, the CASTLE is composed of a large rotating torus and a large non-rotating boom. By definition, the interface joining these components must be a complex system that strikes a balance among several competing constraints. Such constraints include minimizing friction, maintaining relative velocities and orientations, transferring large propulsive forces, providing cargo/personnel transport and linking communications and electrical facilities.

Major design constraints for the interface were:

1) Maintain stationary orientation of the boom while insuring the torus rotates at a constant rate.
2) Transfer acceleration forces from the boom to the torus during insertion and correction burns.
3) Transfer power, communications, personnel, and equipment between the boom and the hub of the torus.

The design problems encountered in meeting these contraints required unique ideas and specialized systems. This chapter details the resulting design of such an interface and it is hoped that the resulting interface will be used as a reference in future design work and studies.

5.1.2 Rotation at Interface

As indicated above, the rotation rate of the torus is a major factor in the proper operation of the CASTLE. However, the zero rotation rate of the boom is equally important as the systems housed on it require precise orientation. Predictably, then, the heart of the interface is a system designed to maintain this rotational relationship.

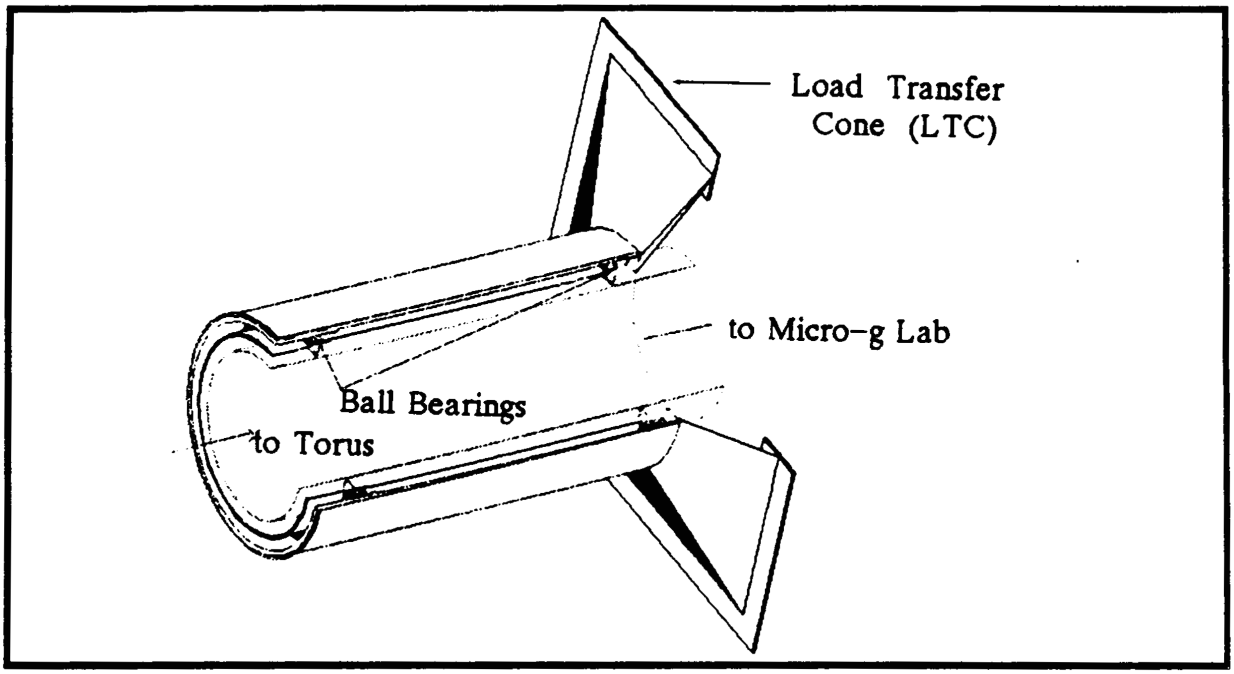


Fig. 5.2 Assembled interface showing main components

The main sections of the interface are arranged, roughly speaking, as concentric cylinders. The outer cylinder is the rotating portion of the interface and is connected to the hub of the torus. The inner cylinder is the non-rotating portion of the interface and is connected to the boom's truss structure and micro-g lab.

Bridging the cylinders are two sets of bearing races. The angular contact bearings contained in these races allow the torus to rotate while the boom remains stationary.

A significant problem in this design, however, is friction in the bearings. Friction retards the momentum of the torus while it tends to induce rotation in the boom. While much friction may be eliminated in choosing proper bearing and race materials and lubricants, its complete elimination is impossible. The designed solution to this problem is the Torque Compensation System (TCS).

The TCS includes thrusters on the solar array booms, four 1/4 hp (137.5 W) feedback-controlled AC induction motors, and a gearing system in the hub. As the boom begins rotating, thrusters on the solar booms are ignited to eliminate the induced angular velocity. Simultaneously, the AC motors are activated to restore the torus' 3.2 rpm angular velocity. In actuality, the TCS motors run continuously. They idle when the boom is stationary and increase in power as needed. The net result is a non-rotating boom attached to the hub of a constantly-rotating torus.

5.1.3 Load Transfer

The interface also transfers force from the boom to the torus. This force is greatest during insertion and correction burns. During such a burn, the boom's truss structure carries the load to the interface's Load Transfer Cone (LTC). The LTC connects the end of the boom to the inner cylinder of the interface. The angular contact ball bearing system on the inner cylinder subsequently transfers the force to the outer cylinder of the interface. The outer cylinder is conveniently connected to the hub of the torus.

The material selection for these components was governed by the maximum forces expected on the interface (during insertion), while the structural integrity of the interface components was determined by finite element analysis.

5.1.4 Personnel and Equipment Transfer

Egress Tube

The interface design specifications called for a pressurized hallway linking the micro-g module of the boom and the elevator. Furthermore, a "shirtsleeve" environment was to be provided throughout this area.

For a two-cylinder interface to be pressurized, a rotating pressure seal is necessary between the rotating outer cylinder and the non-rotating inner cylinder. However, since a rotating pressure seal is subject to much surface contact, this seal would significantly increase friction between the torus and boom and create the possibility of a catastrophic situation should it fail.

To avoid such a seal, a pressurized interface requires an egress tube. The CASTLE's egress tube is a 3.0 m diameter concentric cylinder located within the inner, non-rotating portion of the interface. The tube narrows to a 2.2 m diameter as it approaches the elevator. Its hollow interior provides the "shirtsleeve" environment suitable for personnel and equipment transport.

Telescopic Hallway

Because the torus spokes are not pressurized, it was necessary to devise an airtight elevator/interface connecting system. The resulting system operates in the following manner.

As the pressurized elevator cab enters the hub, it rotates at rate equal and opposite to that of the torus. Thus, the cab's rotational velocity is effectively zero with respect to the CASTLE's boom. During interface/elevator connection, a hydraulically-extendable sleeve on the end of the egress tube moves outward and mates with the cab. The sleeve completes a pressurized hallway from the cab to the micro-g section of the boom. The extension tube design allows the interface to connect directly to the elevator without the unacceptable safety risks of pressure seals.

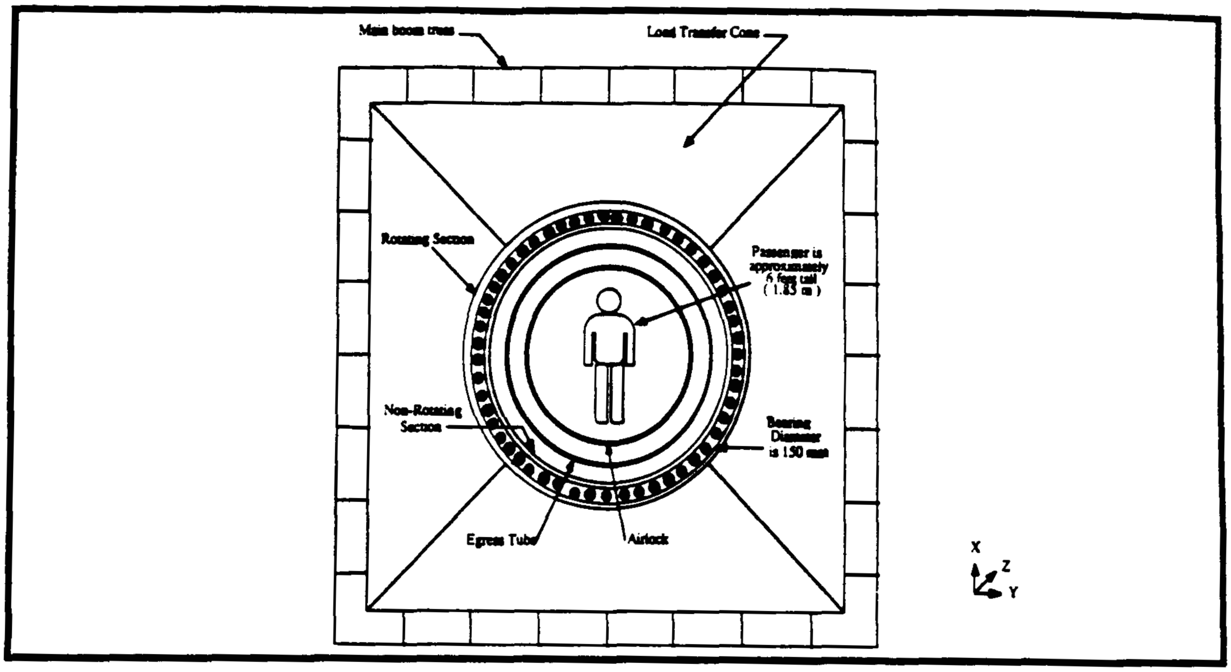


Fig. 5.3 Torus end view of interface

5.1.5 Power and Data Transfer

For a power and data transfer system, the most efficient means of moving electricity and communications over the gap between the rotating and nonrotating cylinders was sought. Since electricity is generated in the solar arrays on the non-rotating boom, power must cross the interface to get to the torus. Power transfer is handled by up to six electrical conducting rollers located between the two surfaces. This method has a 99% efficiency rate yet contributes very little friction.

Continuous communications transmission through the interface is also essential. Data transfer and communication is accomplished through two sets of six laser transmitters, one on either side of the gap, paired with two sets of optical collectors found directly opposite them.

5.2 Rotational Maintenance

5.2.1 Angular Contact Ball Bearing System

System Structure

In choosing a bearing system for the interface, several design constraints were observed. First, the system must withstand a large thrust load during the eight-hour-long insertion burn. Second, it must maintain 100% structural integrity for the entire 175,000-hour projected lifetime of the CASTLE since a component failure would be virtually irreparable. Finally, the system should have minimal friction so as not to impede the spin of the torus.

A bearing system meeting the above constraints and producing the least amount of friction was chosen. The system incorporates angular-contact ball bearings. Ball bearings were chosen after three other types, radial, thrust and tapered-roller bearings, were eliminated from consideration. Radial bearings do not perform well under a thrust load while thrust bearings do not perform well under a radial load. Tapered roller bearings contribute higher friction due to the large amount of surface area in contact with the bearing race.

Angular-contact ball bearings, however, are designed to sustain both thrust and radial loads. In addition, their coefficients of friction are very low, normally on the order of 0.002 and below.

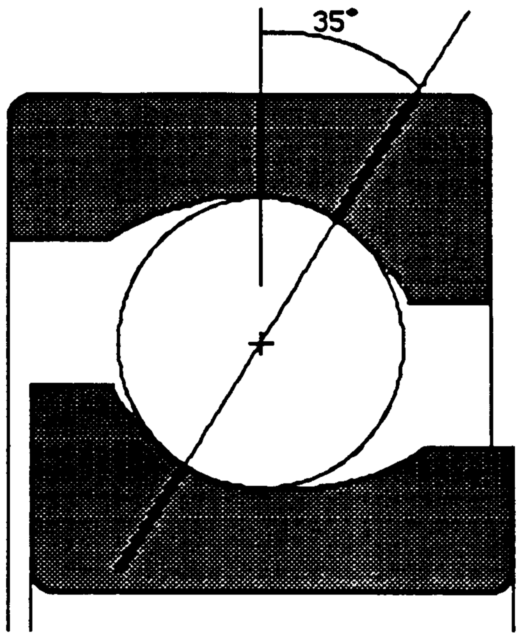


Fig. 5.4 Ball Bearing showing races and angular contact

The only fixed design parameter on the interface was the 3-meter diameter cross-section of the egress tube. Thus, the outer rotating cylinder's diameter could range from just over 3 meters to 8 meters and still be supported by the truss. While minimizing mass was of paramount importance, a small cross-sectioned interface might not sufficiently withstand the forces of insertion. Therefore, the outer cylinder, optimized for highest reliability under maximum stress with minimum mass, was designed with an outer diameter of 4.26 meters. The inner diameter varies to allow for the bearing races and the power, data, and communication transfer mechanisms, but gradually increases with distance from the hub. A variable cross-section permits the outer cylinder to be as thick as possible at the hub where it must transfer the entire torus load.

The inner non-rotating cylinder was optimally designed to have an inner diameter of 3.54 m. While its outer diameter varies similarly to outer cylinder's diameter, it is thicker at the opposite end of the interface to handle loads being transferred from the LTC to the bearing system. There is a 10 millimeter gap between the rotating and non-rotating cylinders to allow for the displacement of the non-rotating cylinder during insertion.

In designing the ball bearings, the general rule is the greater the load expected on the system, the larger the bearing diameter and contact angle should be. Given the cylinder sizes and maximum forces expected, bearings with a diameter of 150 mm and contact angle of 35 degrees were chosen. To provide greater reliability and system redundancy, the number of bearing races was doubled from two to four. Two pairs of tandem angular-contact bearing races, one located 0.45 meters from the LTC and with a diameter of 4 meters and one positioned 0.95 meters from the hub and with a diameter of 3.89 meters, complete the bearing system. The races are packed at 70% of capacity as the larger races near the LTC each have 58 bearings while the smaller races each have 56. There are a total of 228 ball bearings.

Materials

Because the interface is in the extreme environment of space, the bearings must be machined from a material that not only handles loads but which minimizes chances of failure due to environmental stresses. Therefore, silicon nitride (Si_3N_4) was chosen for both ball bearings and races.

Silicon nitride, a ceramic, provides a number of benefits as a bearing material. First, with an elastic modulus of about 300 GPa, it is as strong and hard as many hard metals. Nevertheless, it has a density of just 3.2g/cm^3, much lower than most metals of equal strength. Silicon nitride also has a very low coefficient of thermal expansion -- a property important in space where temperatures range widely. Moreover, silicon nitride has high thermal shock resistance. Both low thermal expansion and high shock resistance help minimize the chance of bearing failure due to severe temperature changes.

One problem with silicon nitride, as with most ceramics, is its inherently low ductility. However, this brittleness is greatly affected by how the material is processed since most flaws are introduced during processing. Since the CASTLE is to be built in the future, it is reasonable to hypothesize that materials processing will have advanced sufficiently to reduce some of the processing flaws present in the ceramics of today. It should also be noted that this brittle nature is much less dramatic when the materials are under compression, as are the bearings in the interface, and thus should not present a problem in the CASTLE. Silicon nitride's high strength, hardness, and thermal shock resistance coupled with its low density and thermal expansion make it an optimal material for the ball bearings and races of the interface.

Lubrication

Though lubricants for the bearings only slightly improve friction coefficients, it is believed that such lubricants reduce wear of the bearings and help cushion against shock, thus minimizing maintenance needs.

Molybdenum disulfide (MoS_2) was chosen as the bearing lubricant. Molybdenum disulfide is a solid lubricant with many applications in the aerospace industry. Unlike liquid lubricants, molybdenum disulfide does not require any sort of pumping to insure proper distribution of the lubricant. The solid lubricant actually clings to the surface it is lubricating. This behavior is extremely effective in a ball bearing assembly. Unlike most lubricants, molybdenum disulfide is effective even in the vacuum of space where solid lubricants, such as graphite, actually become abrasive. Moreover, molybdenum disulfide retains its lubricating properties under high pressure loads such as those present on the bearings of the interface.

Analysis

The ball bearing system, due to its angled design, not only transfers the loads from the non-rotating cylinder to the rotating cylinder, but also serves to keep the boom and the torus joined. This is consistent with the primary design consideration of allowing a rotating torus with the CASTLE remaining an integral whole.

The ball bearing system is designed to withstand the maximum load of orbital insertion in addition to loads encountered during correction burns. During insertion, a force of 300 kN is placed on the interface. This corresponds to a 2.6 kN force per bearing for those in races nearest the LTC. Using established equations relating ball diameter, number of balls, angle of contact, race diameter and force on the system, a life expectancy (in revolutions) before 10% of the bearings fail may be obtained. Owing to its large race and ball diameters and large angle of contact, the CASTLE bearing system has a calculated lifetime of approximately 3,000,000,000 revolutions or 1900 years. Assuming the CASTLE is in service for 20 years and the torus spins constantly at 3.2 rpm, the bearings need survive just 33,664,000 revolutions. While these figures may reflect an overly conservative design, it is consistent with the 100% reliability required of the interface to insure the success of the CASTLE's mission.

5.2.2 Torque Compensation System (TCS)

Specifications

The Torque Compensation System meets several specifications. First, the torus rotates at 3.2 rpm continuously to provide a 0.4 g environment for habitat. Second, the boom must remain stationary. Third, a frictional force of 541 Newtons occurs tangentially to the interface bearings during insertion period. To overcome this force, 363 watts (~1/2 horsepower) of power must be supplied. Finally, the system must perform flawlessly for more than 20 years.

Alternative Designs

Three alternative designs were considered for the TCS: a propulsion system, a motorized system, and a magnetic system.

The propulsion system utilizes thrusters attached to the external wall of the non-rotating interface cylinder to counteract the frictional torque encountered by the support bearings.

The motorized system uses motors and a gear mechanism to spin the non-rotating cylinder against the rotating cylinder. Thus, if the boom spins with respect to the rotating torus at the same angular speed (3.2 rpm) but in an opposite direction, the boom remains stationary in a Newtonian reference frame. This is analogous to a mouse running inside an exercise wheel: the mouse moves forward with respect to the wheel but remains stationary with respect to the ground.

The magnetic system is designed according to the same principle. Instead of motors and gears, however, a magnetic mechanism is used to rotate the "non-rotating" boom. A magnetic core is on the non-rotating cylinder facing the rotating cylinder, while coiled electrical wire facing the magnetic core is on the rotating cylinder. In applying an electric current to both the core and the wire, a torsional force is generated between the rotating and non-rotating cylinders. The result is the same manner as for motorized system.

After careful consideration of response time, economics, reliability and simplicity, it was decided that the motorized system is best suited to the CASTLE.

Gear System Configuration and Specifications

According to the motorized TCS design, a ring gear is attached to the rotating cylinder, while four motors with four pinion gears are on the end of the non-rotating cylinder. The specifications of the gears are listed in Table 5.1.

Table 5.1 Gear Specifications

STEEL SPUR GEAR	PINION GEAR	RING GEAR
pitch:	3	3
teeth:	18	430
pitch diameter:	0.1524m	3.7253m
width(face):	0.0762m	0.0762m
addendum:	0.008467m	0.008467m
dedendum:	0.010583m	0.010583m
base diameter:	0.1432m	3.9644m
angular speed:	78.222rpm	3.2rpm
pressure angle:	20 degrees	20 degrees

Considering the 20-year life-expectancy of the CASTLE, AC induction motors are most desirable since they have no brushes or rings which could fail. Therefore, four 1/4 hp, single phase, AC induction motors (General Electric catalog #C563) and four 20-degree pressure angle steel spur gears (Boston Gear, Royall, Inc. catalog# N018B) are utilized. The maximum power required for the TCS is one-half horsepower during insertion. Note that this system supplies twice the required power. Thus, even if two motors fail during insertion, the torque compensation mechanism will still operate normally.

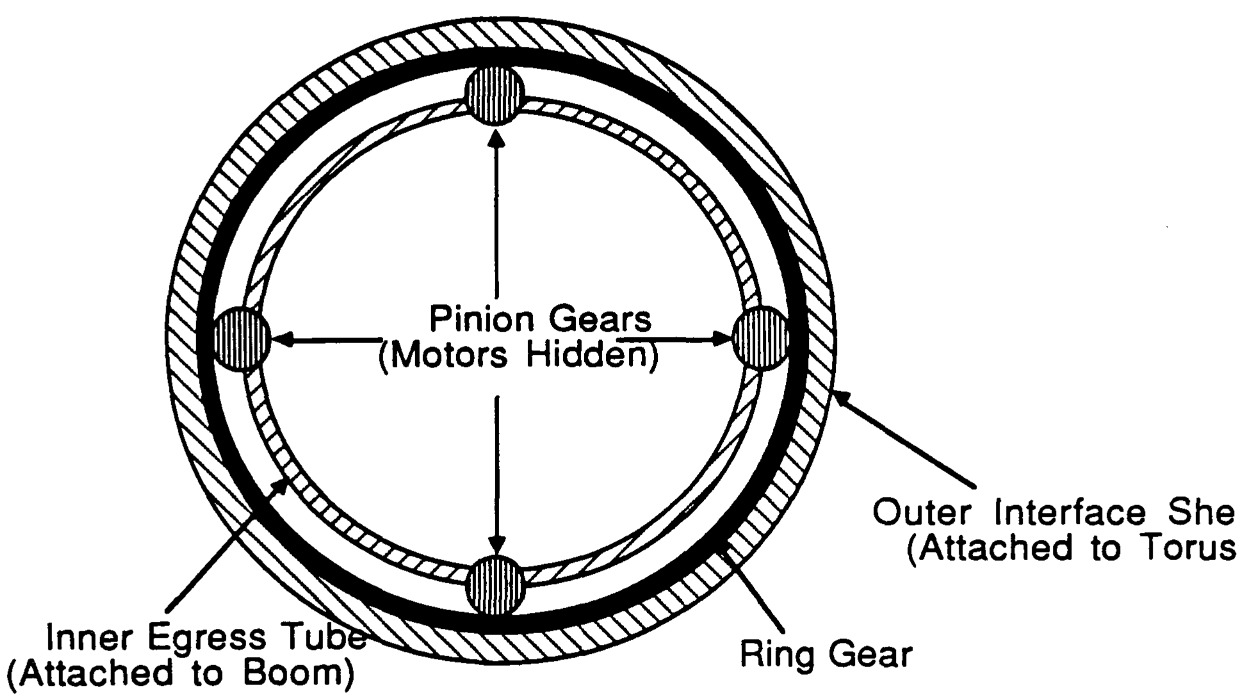


Fig. 5.5 Torque Compensation Motor Configuration (Axial View)

Motor Configuration and Specifications

The price of each motor is $330 if purchased directly from General Electric. For increased applicability, the motors can be modified to operate in an ambient temperature range of 40- to 90 ^{o}C. This modification results in a $74 cost increase per motor. The pinion gears are available at retail for $77.50 each.

Stress Analysis

The maximum force transmitted by the gear is 541 N. The frictional losses in the spur gear are nominal such that the gear is considered to be 100% efficient.

Using the Lewis Equation, the stress of the spur gear tooth was calculated to be 2.16 N/m^2. This is significanly less than the maximum allowable stress of 23.74 N/m^2. In addition, the dynamic tooth load was calculated to be 2120 N. This force does not exceed the wear tooth maximum of 6283 N. From these calculations it is obvious that the gears are suitable for the application.

Automatic Control System

Two speedometers are used in the control system to measure the relative speed between the rotating and non-rotating cylinders. A PID controller accepts the error signal (the difference between the reference angular velocity, 3.2 rpm, and the measured speed of the stationary boom from the speedometer) as input and transmits a signal to a semiconductor power drive. After receiving the signal from the controller, the semiconductor power drive regulates the frequency of the electric current from the power supply. This controls the angular velocity of the motors.

Errors are minimized in this system as there is no steady-state error or overshoot with the PID controller. The block diagram of the control system is shown in Figure 5.6.

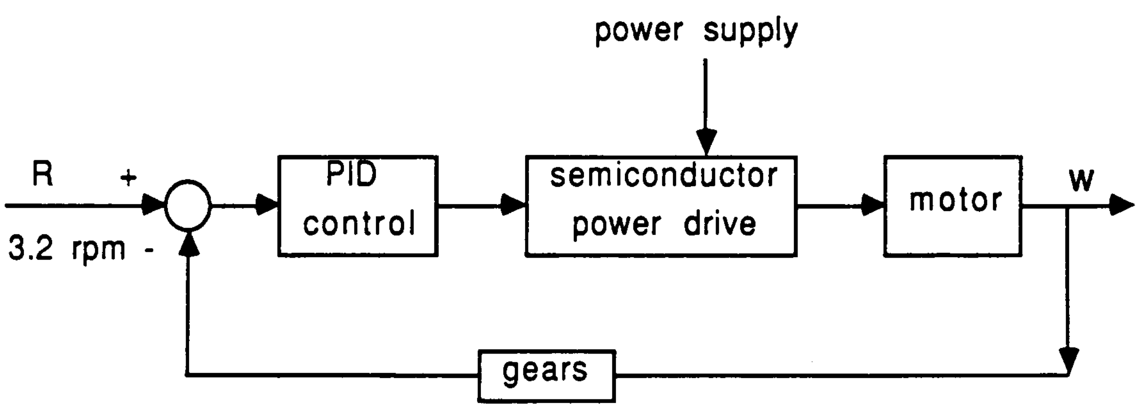


Fig 5.6 Block Diagram of Control System

5.3 Transfer of Loads

5.3.1 Load Transfer Cone (LTC)/ Inner Cylinder

Structure

The Load Transfer Cone (LTC) is the load bearing member which connects the boom's truss structure to the inner cylinder of the interface. The LTC has an 8m x 8m square base and a 4.26 m diameter circular top (refer to Fig. 5.7). The height of the LTC is 1.25 m and the thickness varies from 50mm at the base to 360mm at the top where it joins with the inner cylinder. The inner cylinder of the interface transfers the loads through the angular contact bearing sets to the outer cylinder and hence hub of the torus. The inner cylinder is approximately 8.75m in length and 3.54m in diameter.

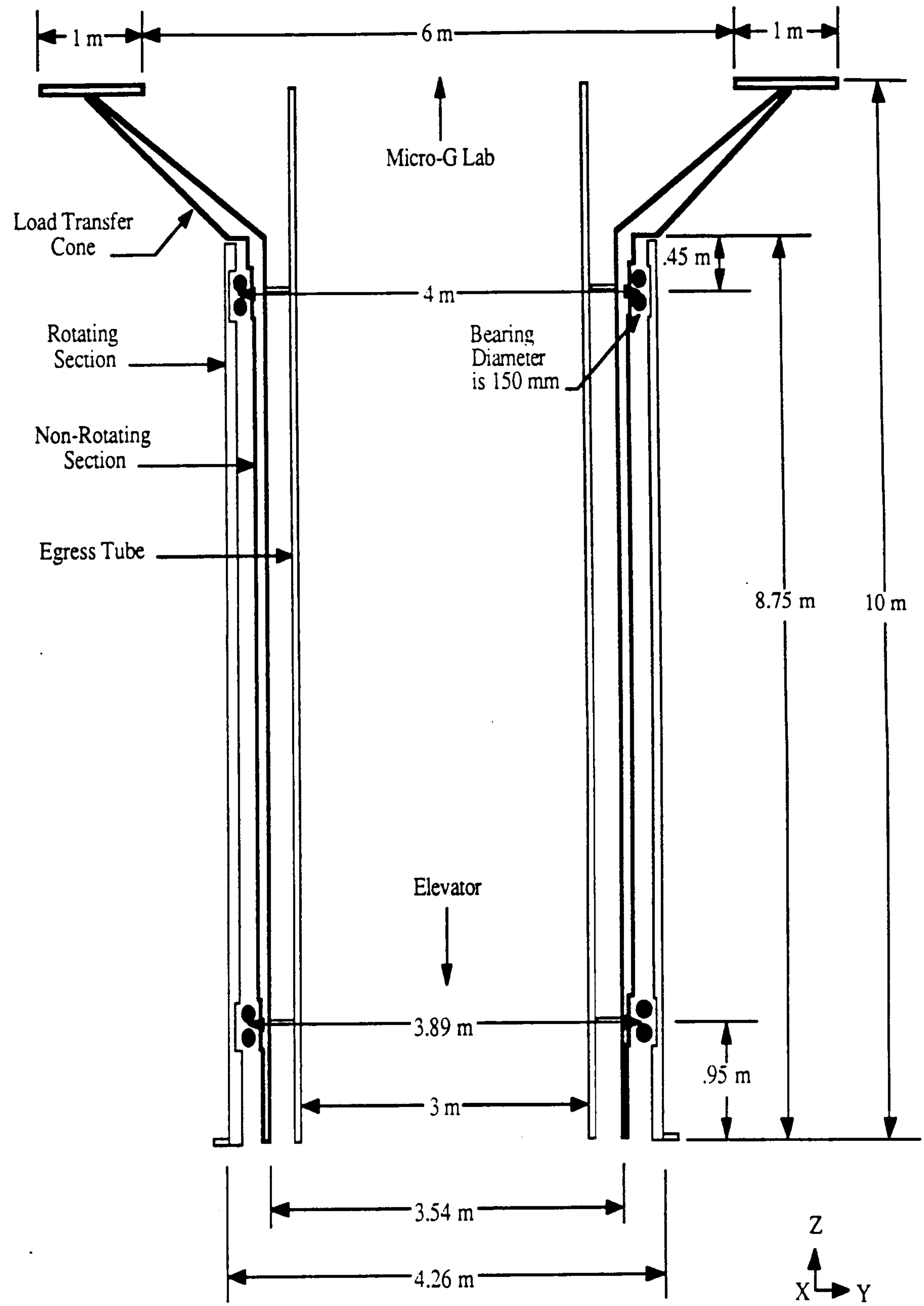


Fig. 5.7 Cross-Sectional View of the Interface

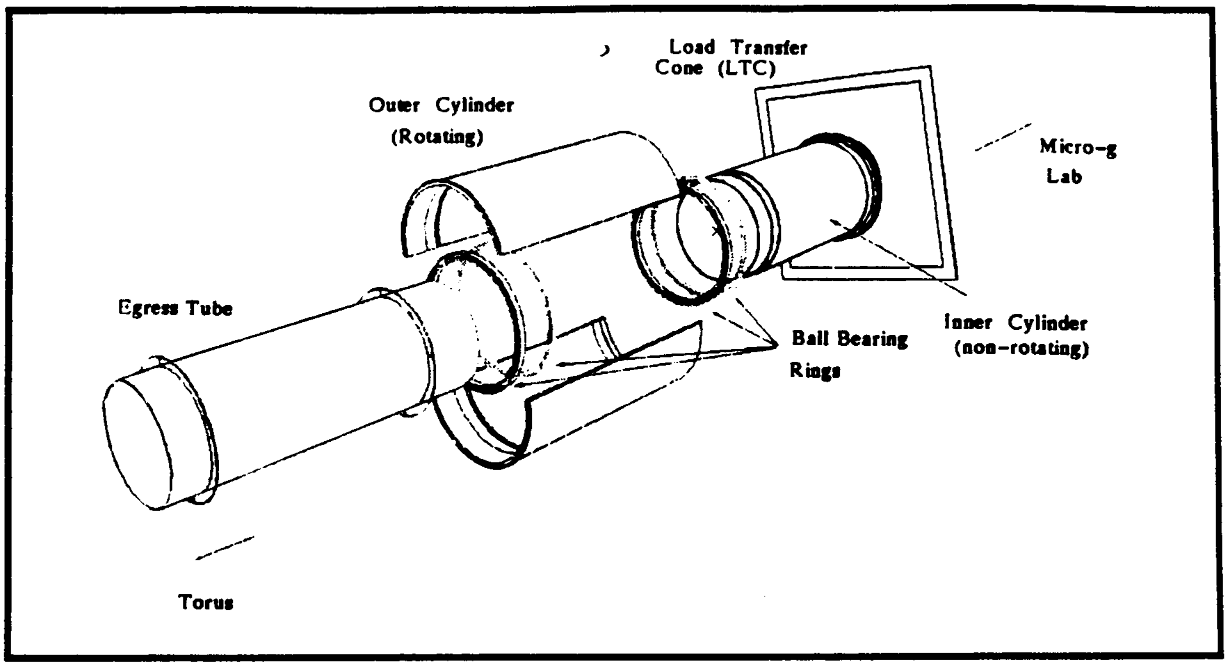


Fig. 5.8 Exploded view of interface

Material

The LTC and the inner cylinder are made of aluminum, a light weight material which allows the components to maintain their structural integrity.

Analysis

A finite element analysis was performed to examine the effects of the maximum force, 300,000 N/m^2 during insertion, applied to the LTC. The load was distributed around the edge of the base. To model actual conditions, the LTC was restrained at the top where it joins with the inner cylinder of the interface. The LTC was analyzed in both maximum displacement mode and maximum stress mode.

The maximum displacement was found to be 11.4 mm. This displacement occurred at four points, each midway between the base corners of the LTC. The maximum principle stress during maximum displacement was 1.81×10^7 N/m^2, which corresponds to just 3.5% of the yield strength of aluminum (see Fig. 5.9). Maximum shear stress was 8.35×10^6 N/m^2 and maximum Von Mises stress was 1.45×10^7 N/m^2.

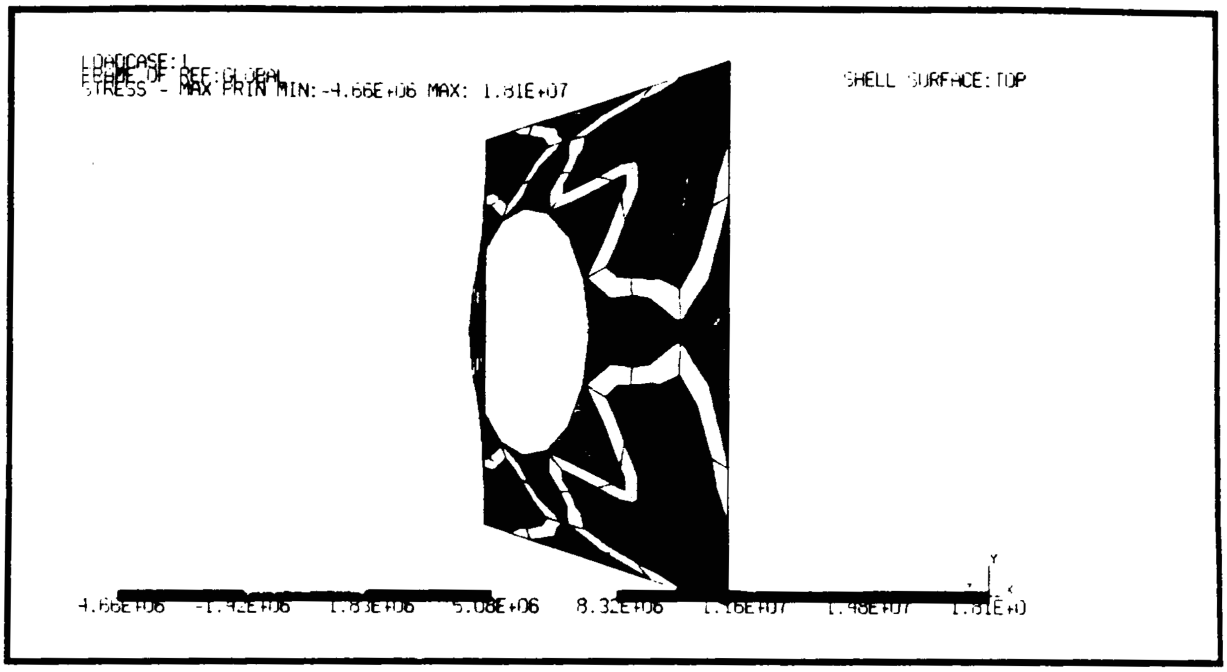


Fig. 5.9 LTC maximum principle stress contour plot

5.3.2 Outer Cylinder

Structure

The outer cylinder of the interface is connected to the hub of the torus. All loads transferred from the boom to the torus are applied to the outer cylinder by the pair of bearing rings closest to the boom. These bearing rings, in combination with the those on the torus end of the interface, keep the outer and inner cylinders joined.

The outer cylinder is 7.5 m long with an outer diameter of 4.26 m. The inner diameter changes due to the varying thicknesses of the interface wall. Wall thicknesses range from 0.03 m to 0.105 m and create structural supports for the bearing rings. Preliminary design analysis showed these values are satisfactory to support loads incurred during insertion.

The shell is relatively thick to provide sufficient support for the bearing rings and enough bulk to connect the cylinder to the torus hub. Moreover, it provides additional radiation protection for personnel, equipment and mechanisms in the interface.

The outer cylinder is made as two axially-split half cylinders. This allows for greater ease of assembly. Indeed, due to the contour of the inner cylinder wall, this method is essential as the inner and outer cylinders will not slide together over the bearing rings. Once the four bearing rings are secured on the inner cylinder, the two halves of the outer cylinder are joined around it to form the complete outer shell.

Materials

The outer cylinder, like the inner cylinder and LTC, is fabricated from aluminum. Aluminum is relatively light yet strong enough to support the loads exerted on the outer cylinder.

Analysis

As stated above, the outer cylinder of the interface transfers loads from the hub to the bearings nearest the boom. Note the calculated forces on the bearings closest to the hub are minimal loading during orbital insertion. The finite element analysis of the outer cylinder was conducted for a maximum load in which all orbital insertion engines are fired at once. The analysis therefore represents the maximum possible forces the interface might incur. Obviously, this load exceeds that expected during actual insertion.

The outer cylinder, due to the angular contact bearings, receives both an axial compression load of 1,142,000 N/m^2 as well as a radial expansion load of 39,800 N/m^2. For a complete analysis, the outer cylinder was examined in two modes, a maximum displacement mode and a maximum stress mode.

For maximum displacement analysis, the interface shell was restrained only near the torus end such that the boom end could displace axially. In addition, it was assumed that the inner cylinder of the interface did not restrain radial contraction. Finite element analysis showed a maximum axial contraction of 2.06 mm at the boom end. The maximum radial displacement was less then 1.00 mm. Maximum rotational displacements were equally small.

The maximum principle stress present during maximum displacement was approximately 5.0×10^6 N/m^2 (see Fig. 6.10). This is well within the range of elastic deformation and is just 1.2% of the yield strength of the structural material. Maximum shear stress was $1.22 \times 10^7 N/m^2$ and maximum Von Mises stress was $2.34 \times 10^7 N/m^2$. All of these values allow a considerable safety factor.

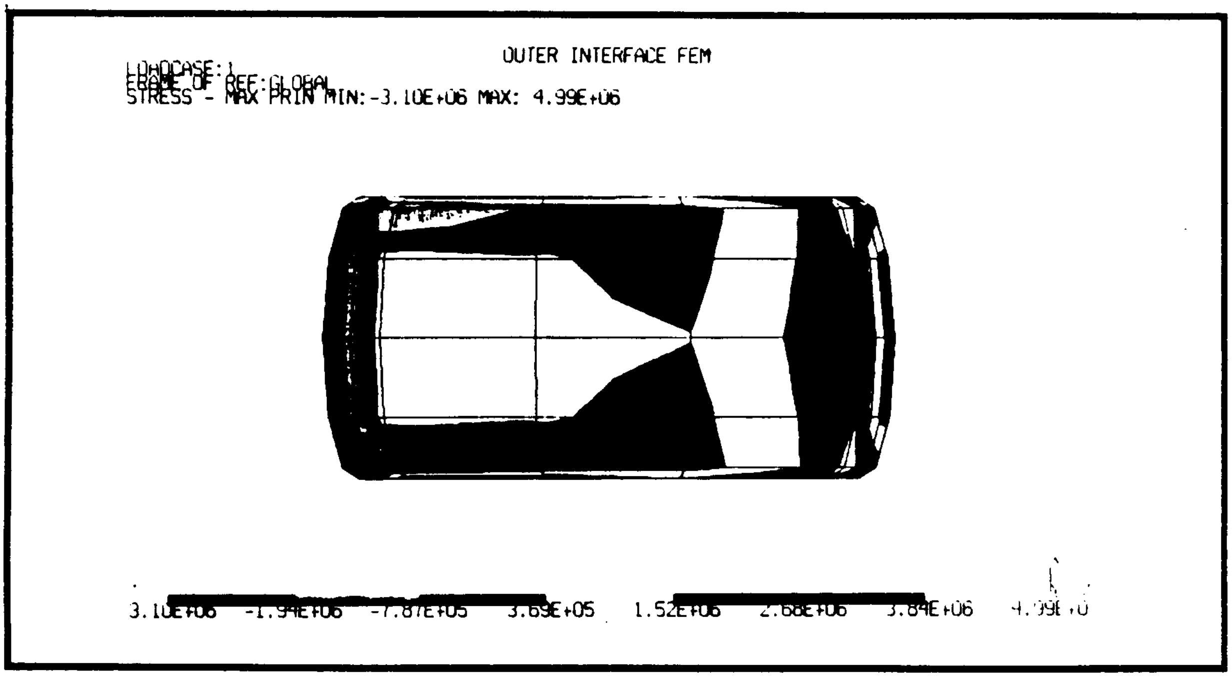


Fig. 5.10 Maximum principle stress contour plot
(Maximum displacement case)

For the maximum stress analysis, it was assumed that the contraction of the outer cylinder is completely restrained by the inner cylinder bearings near the boom end. Therefore, maximum stress is exerted on the cylinder sections supporting these bearings. In addition, the torus end of the cylinder was restrained.

The maximum radial displacement was less than 1.00 mm, while the maximum radial and rotational displacements was equally small. The maximum principle stress encountered was $4.29 \times 10^7 N/m^2$, just 10% of aluminum's yield strength (see Fig. 5.11). Maximum shear stress attained $2.1 \times 10^7 N/m^2$, while Van Mises stress peaked at $3.8 \times 10^7 N/m^2$. Once again, these values are well within acceptable safety limits.

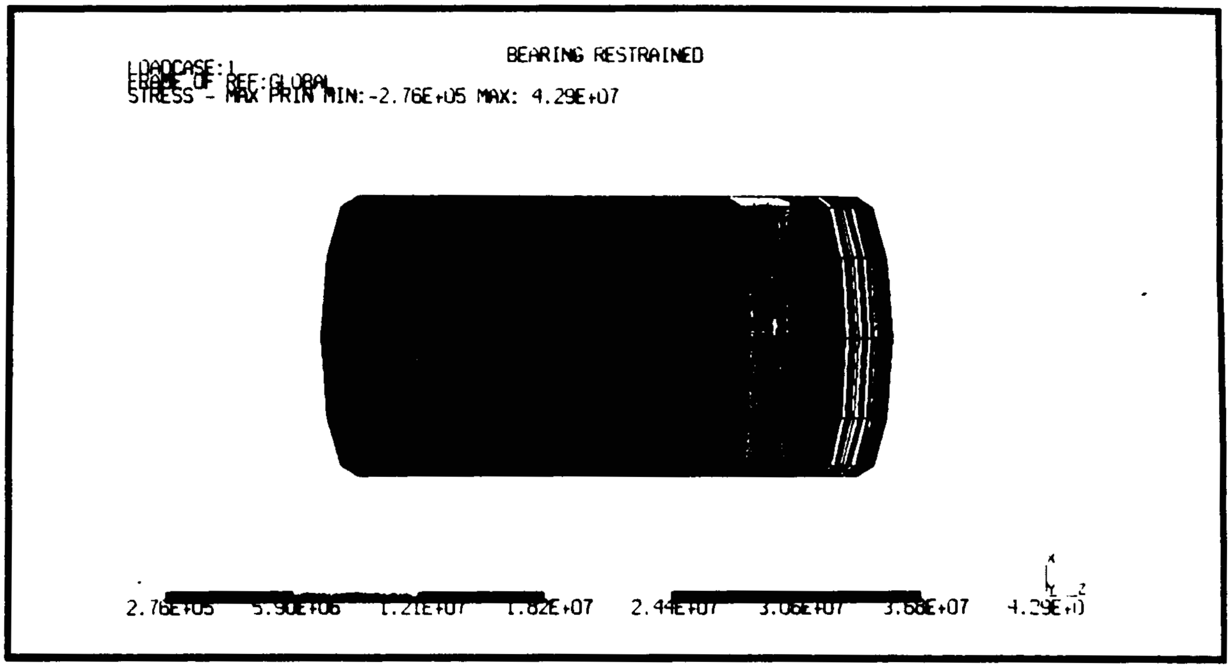


Fig. 5.11 Maximum principle stress contour plot
(Maximum stress case)

Both finite element analyses indicate that maximum loading conditions do not effect the integrity of the interface and that the current interface design will guarantee sufficient safety and reliability.

5.4 PERSONNEL AND EQUIPMENT TRANSFER

5.4.1 Elevator Mating

As the elevator enters the hub, it begins spinning in a direction opposite to that of the torus. Seen from the interface, the elevator appears to be decelerating until finally it becomes stationary. At that point, a telescopic hallway on the egress tube extends approximately 1.5 m from the interface and connects with the elevator cab. Once the pressure-tight connection is made, the hatches to the elevator and the interface are opened allowing personnel and cargo access. (see Fig. 5.12)

The design of the mating/locking mechanism between the interface and elevator was borrowed from hydraulics. The mechanism is a modified "quick disconnect"-type coupling used to couple pressure hoses. With this design, the elevator and the interface can be connected and separated by simply pushing the parts together and pulling them apart, respectively. The telescopic hallway acts as the male fitting. When extended, it presses into the female fitting of the elevator to form an air-tight connection. When retracted, it permits the elevator cab to transverse the spoke without obstruction.

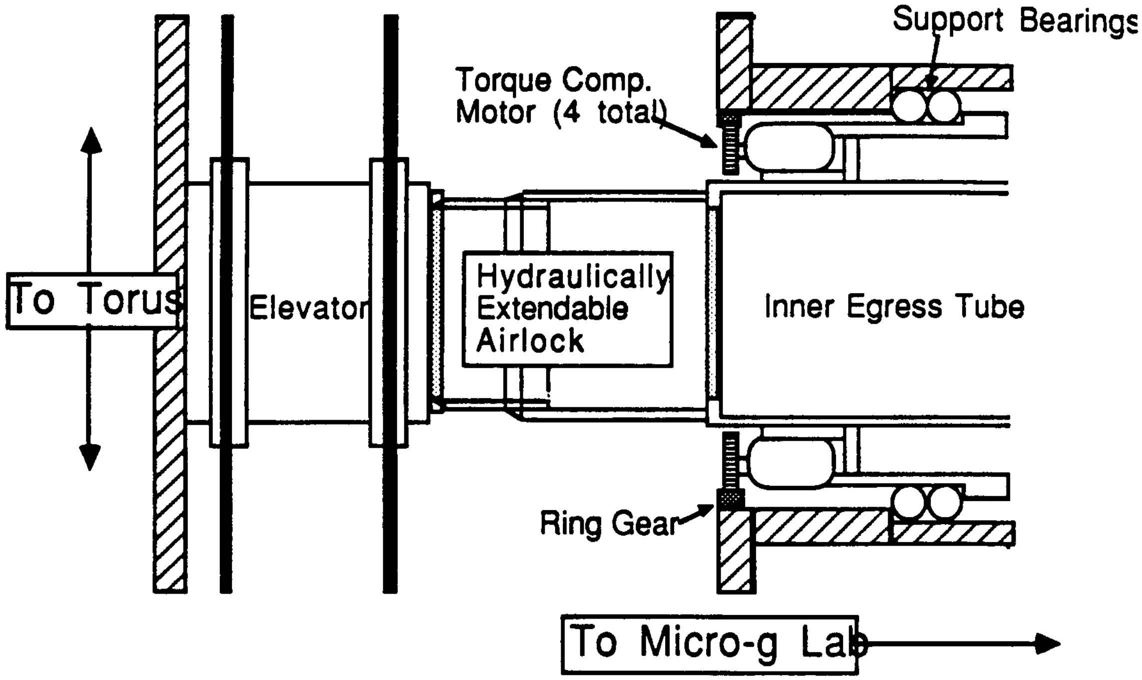


Fig 5.12 Cross Section of Hub

5.4.2 Telescopic Hallway

The telescopic hallway connecting the egress tube with the elevator consists of two stainless steel tubes, one located within the other.

The design looks and behaves much like a hydraulic cylinder. There is a torus-shaped pneumatic chamber, approximately 0.1 m wide and of varying length (depending on the position of the hallway, extended or retracted), located between the two cylinders. Air was chosen as the actuating fluid to prevent greasy surfaces and leakage problems associated with standard hydraulic fluids. Palmetto-G ring seals, shown in Fig. 5.13, are recommended for a pressure-tight seal. These seals result in very low friction at low pressures and, due to their design, have no extrusion problems.

To retract the hallway, high pressure air (5.5 - 6.0 atm or 550,000 - 608,000 N/m^2) is pumped into the pneumatic chamber from the interior of the egress tube. This process takes approximately 30 seconds and uses 995 W of power. To extend the hallway, the actuating chamber is simply vented to the interior. The actuating chamber pressure will decrease to atmospheric and the pressure forces on the end of the hallway will cause it to extend.

Since there is no appreciable air loss through the seals (on the order of 6×10^{-14} m^3/sec or 37.6 cc in 20 years), the mass of the air in the entire system is conserved. Moreover, no discomfort to personnel from pressure changes during hallway movement is foreseen.

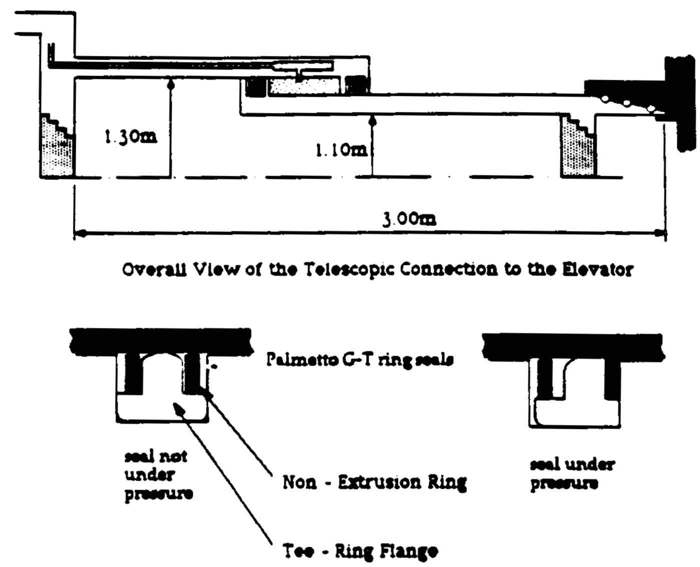


Fig 5.13 Closeup of Airlock Extension Mechanism

5.4.3 Airlocks and Airloss

The airlocks in the interface are circular with an inner diameter of 2.1 m and an outer diameter of 2.2 m. There are two airlocks between the egress tube and the elevator. Actually, just one is required. However, if an elevator problem arises, the dual airlocks can be used as an EVA-type chamber from which repair operations inside the spokes can initiate. In addition, it is good practice to have built-in redundancy as a safety precaution.

The first airlock is located at the end of the telescopic hallway while the second is located where the hallway meets the egress tube (3 m distance). The former is at the extreme end of the telescopic hallway to minimize air loss during elevator connection. Obviously, there must be a small gap between the elevator door and the airlock. The air trapped in this area during connection will be lost each time the elevator leaves the hub. Air losses are estimated to be on the order of 1 m^3 per day. This is equivalent to one phone booth full of air being lost every other day. It is expected, however, that this air is replaceable by the CELSS system.

Several features facilitate airlock usage. First, as shown by Fig 5.14, the handles of the airlocks rotate in opposite directions such that a person attempting to open these rather massive doors need not brace himself to do so. Second, there is a mechanism to initiate door movement. Specifically, when the handles are turned, a spring loaded bolt releases into the door and provides some opening force. When the door is shut, this same mechanism seals the door and recocks the bolt. This is similar in design to a car door. Finally, the hatches open inward so that if decompression of the telescopic hallway occurs, the air flow will tend to pull the doors shut and help avoid a disastrous decompression of the entire micro-g area.

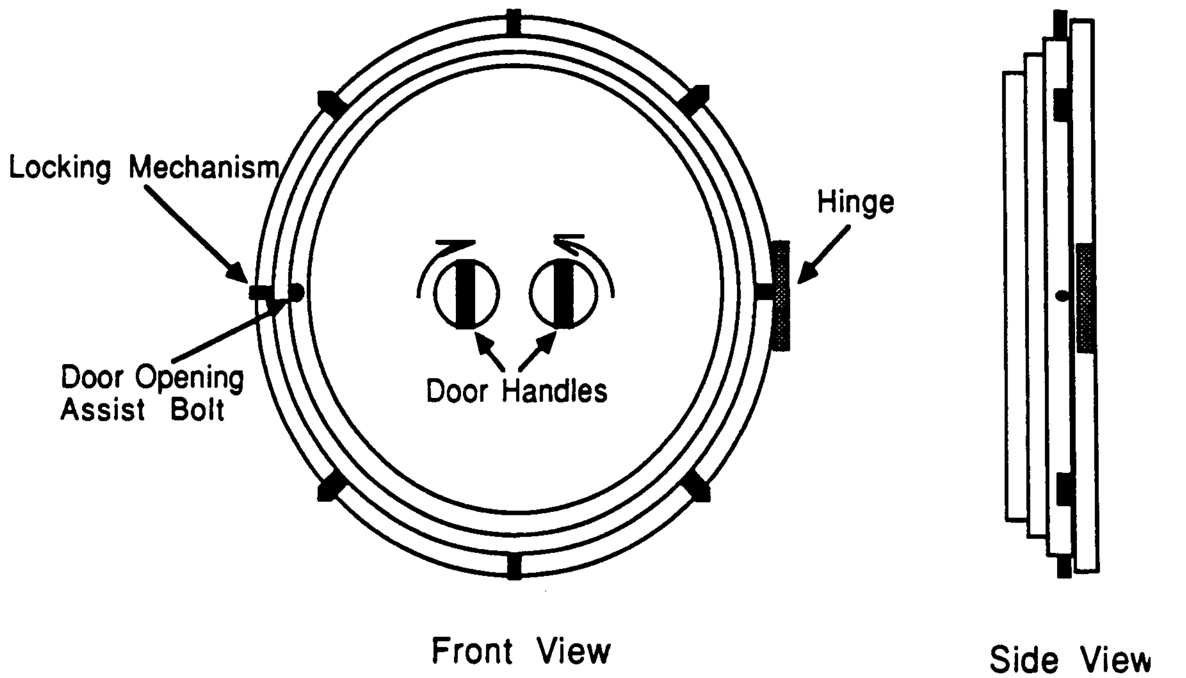


Fig 5.14 Two View Drawing of Airlock Hatch

5.5 POWER AND DATA TRANSFER

5.5.1 Laser Optics Communication

Data transfer through the interface is accomplished via a system of lasers. The lasers use pulse-induced modulation to transfer data to a ring of collectors inside the main boom. Two separate rings are used to complete the process. Each ring consists of two separate parts, one part having six lasers spaced 60 degrees apart, the other part acting as a collection ring. This system allows data transfer rates of approximately 1 gigabit per second with an error of just 1 bit per second per laser.

Configuration

The rings are designed such that the lasers always face the collectors. As the laser ring spins, alternate sets of three lasers (120 degrees apart) activate on both sides of the ring. The lasers alternate so that the they are always sending data to the approximate center of a collector. If the lasers are not aimed toward the center of each collector, imperfections in the edges of the collectors would increase error rates dramatically. Three lasers are used simultaneously because, as stated above, up to one bit per second per laser may be in error. A "best two out of three" processor is used to resolve discrepencies. The odds of two bits being incorrect at the same time is 1 in 10^{18}, but the system is prepared for even this contingency.

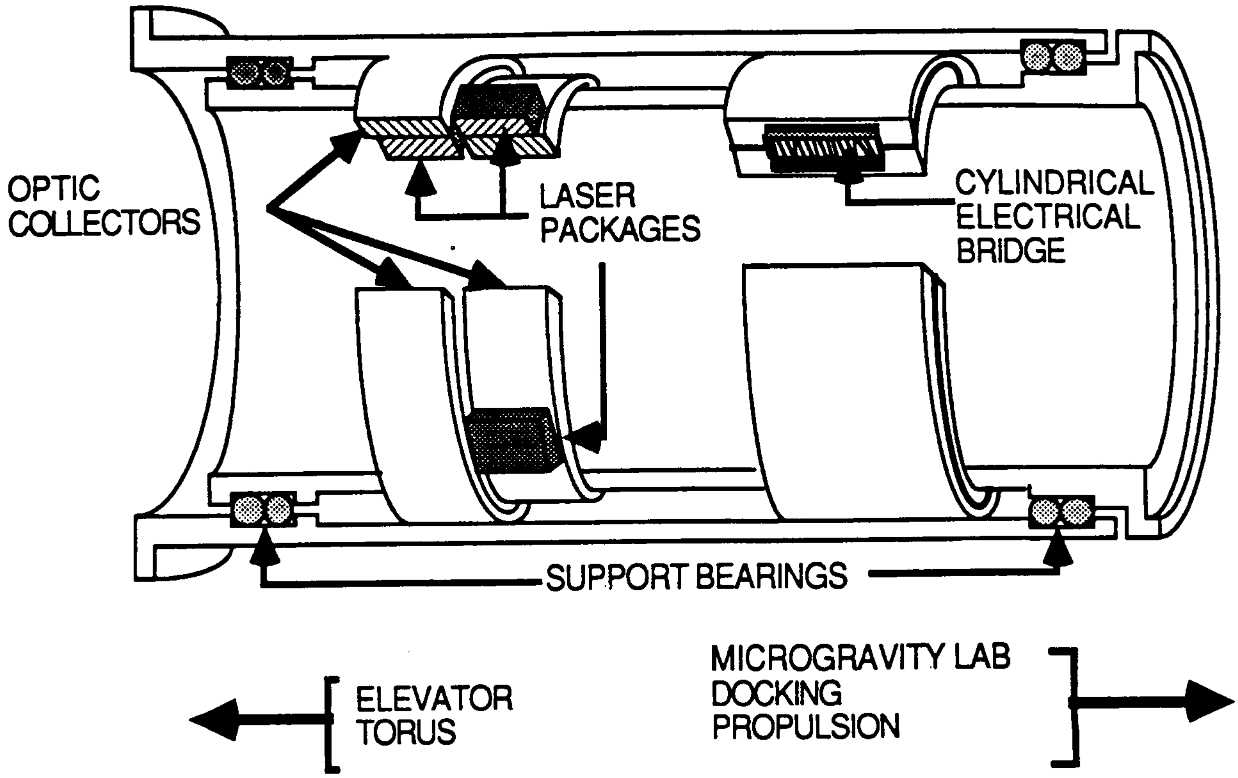


Fig. 5.15 Schematic of Data and Power Transfer Configuration

Power Consumption

Data transfer takes by far the most power to operate. Below is a breakdown of how the required power is allocated.

Laser Unit:	**Power Consumption**
Laser and Control Mechanism	273.1 W
Modulator/Driver	70.5 W
Electronic Processing	149.4 W
Total	**493.0 W per laser**
Average Power Consumption: 6 lasers X 493 W/laser	2958.0 W
Maximum Power Consumption: 12 lasers X 493 W/laser	5916.0 W

5.5.2 Rolling Conductors

Power is transferred through the interface by up to six electric conducting, non-stressed, roller bearings. These drums have a composite center and an outer shell of conducting sterling silver

(~100 mm thick). The rails on which they roll are also silver. Sterling silver is used because it has high electrical conductivity and a low coefficient of thermal expansion. Obviously, these drums result in some friction. This friction generates heat in addition to that generated by electrical resistivity. However, in using a material with such conductivity and expansion properties, heat generation is minimized.

If a material with a high coefficient of thermal expansion were used, the drums would expand, producing even more friction thus exacerbating the problem. If a material with a high electrical resistivity were utilized, the same would result.

As a solution to this expansion problem, the races on which the conducting rollers lie will be bonded to a compressible base. This base, made of an elastic, polymeric material, yields when the rollers undergo thermal expansion. (see Fig. 5.15)

One problem in this design is that the rolling conductors will generate an internal magnetic field from which the rest of the interface must be shielded. Protection is accomplished by surrounding the bearings with a grounded metallic shield. The induced currents will simply drain away, causing no further problems.

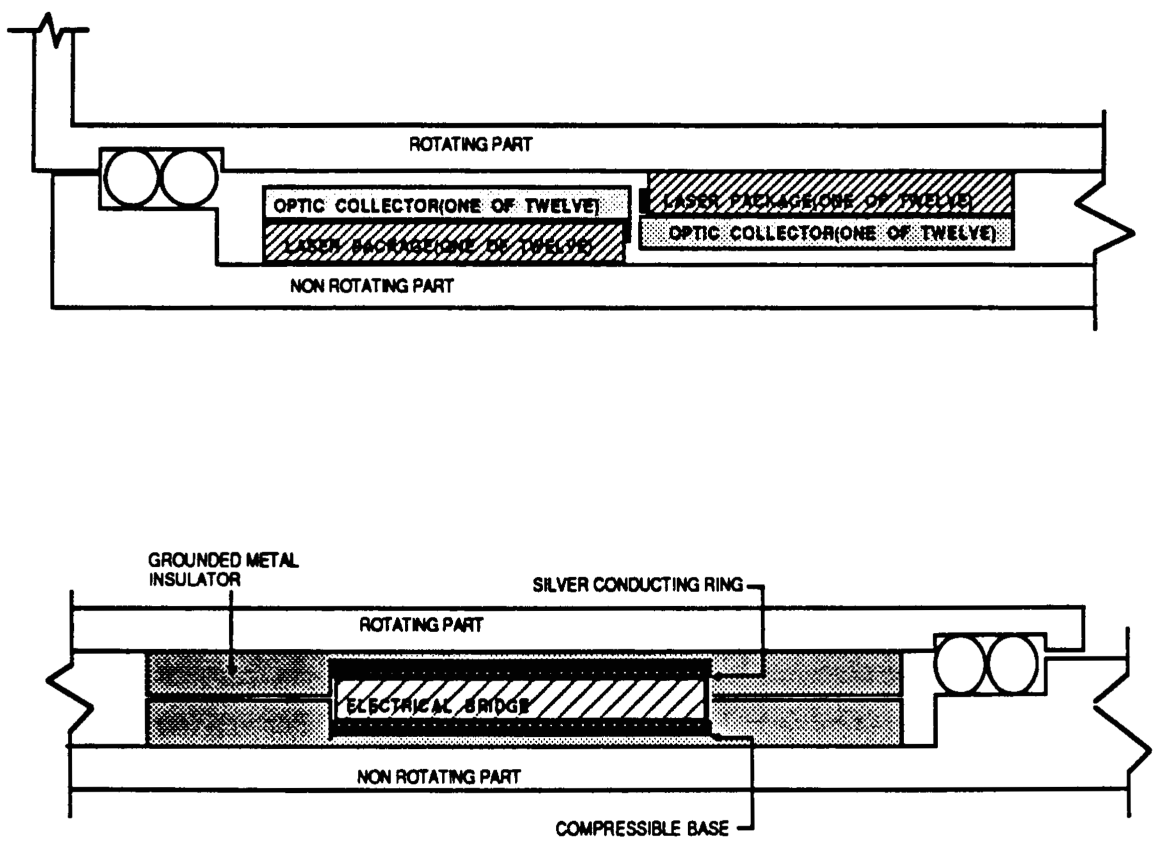


Fig. 5.15 Closeup of Data and Power Transfer Mechanism

5.6 Conclusion

The interface is reliable, durable, and energy efficient. It is designed to maintain the stationary orientation of the boom while allowing constant rotation of the torus. It is also designed to transfer forces from insertion and orbital corrections from the boom to the torus while providing continuous passage of passengers, equipment, electricity, data, and communications between these sections of the spacecraft.

In order to meet the design constraints, the interface incorporates anti-friction materials in the bearing assembly and low-density, high strength materials in all of the load-bearing components. Analysis of the structural components indicated that under maximum loading conditions, the interface would maintain its structural integrity and continue to operate within the design peramenters. The mass of the interface is 160,000 kg. While this is considerable, it is relative to the masses of other CASTLE components.

It should be noted that the interface is presently over-designed. Therefore, while it performs its necessary functions adequately, further iterations of the design process are necessary to produce an optimum design which incorporates low mass and efficient, reliable operation. (see Table 5.2).

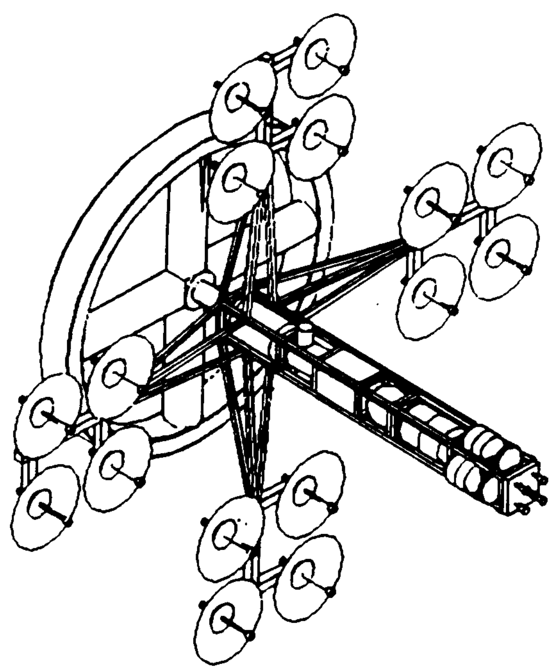
Finally, the complete interface will require up to 8.716 kW of power as outlined in the table below.

Interface System	**Average** (kW)	**Maximum** (kW)
Personnel/Equipment Transfer	0.995	1.250
Data/Power Transfer	2.958	5.916
Torque Compensation	0.275	0.550
Miscellaneous	1.000	1.000
Total	**5.228**	**8.716**

Table 5.2 Power Requirements of the Interface

Chapter Six

Elevator Design



6.1 Introduction

As described in the previous two chapters, passengers board and leave the CASTLE via the docking ports on the main, non-rotating boom of the spacecraft. In addition, micro-gravity research facilities as well as maintenance operations facilities are located in the main boom. It is therefore necessary to design a means by which crew and passengers can move easily and comfortably between the torus, which houses the habitation and operations areas of the CASTLE, to the main boom. The design of this system is complicated by the fact that the torus is rotating, while the hub of the main boom is not. In addition, the variation in the level of gravitational force between the torus and the hub neccesitates an innovative drive mechanism for the elevator since it cannot rely on gravity as do elevators here on Earth.

The elevators are housed within the radial spokes that connect the torus and the hub. Unlike the CAMELOT I study which called for four elevators, it was decided to use only two of the torus spokes for transportation. Under this condition, the longest distance a passenger has to travel between the elevator and any other point inside the torus is 55 meters. The other two spokes are left intact for structural integrity.

Once the basic configuration and purpose were identified, five major design requirements were decided upon. These five requirements would govern the final design of the elevator system:

1) Crew Comfort - The passengers aboard the CASTLE are not trained astronauts, and therefore are not able to withstand the stresses and discomforts which astronauts are trained to tolerate.

2) Interface Matching - The elevator must match the design requirement for a non-pressurized rotating/non rotating interface.

3) Cargo Sizes - The elevator not only accommodates passengers, but also cargo with a maximum dimension of 1.5 m (as limited by the torus hallways).

4) Weight Minimization - The elevator design must be constructed of materials which minimizes the elevator's weight, but yet adequately protects its passengers from the levels of radiation encountered in space.

5) Power Minimization - Due to the energy production limitations aboard the CASTLE, the energy used to drive the elevator must be minimized.

6.2 Elevator System

6.2.1 Elevator Unit

Exterior

The entire exterior of the elevator is made out of aluminum which is light weight and strong. The elevator cabin is a hollow tube with an outside diameter of 3 m and a thickness of 10 mm. The ends of the tube are capped with circular plates that also have a diameter of 3 m and a thickness of 10 mm. This thickness proved to be structurally sufficient as well as an adequate protection from radiation. Since the elevators are contained within spokes that offer partial radiation protection, the two thicknesses together are sufficient to block the amount of radiation specified by NASA. The floor of the elevator is also 10 mm thick and has dimensions of 2.18 x 4.00 m. The largest distance between floor and ceiling is, therefore, 2.55 m, offering ample room to stand and maneuver cargo.

The exterior of the cabin is surrounded by two rings of ball bearings located one meter in front and one meter behind the center of the elevator. These ball bearings are encased in a circular track with an inner diameter of 3.0 m and an outer diameter of 3.5 m. The width of this track is also 0.5 m. The specifics of the ball bearing rings will be described in section 6.2.2.

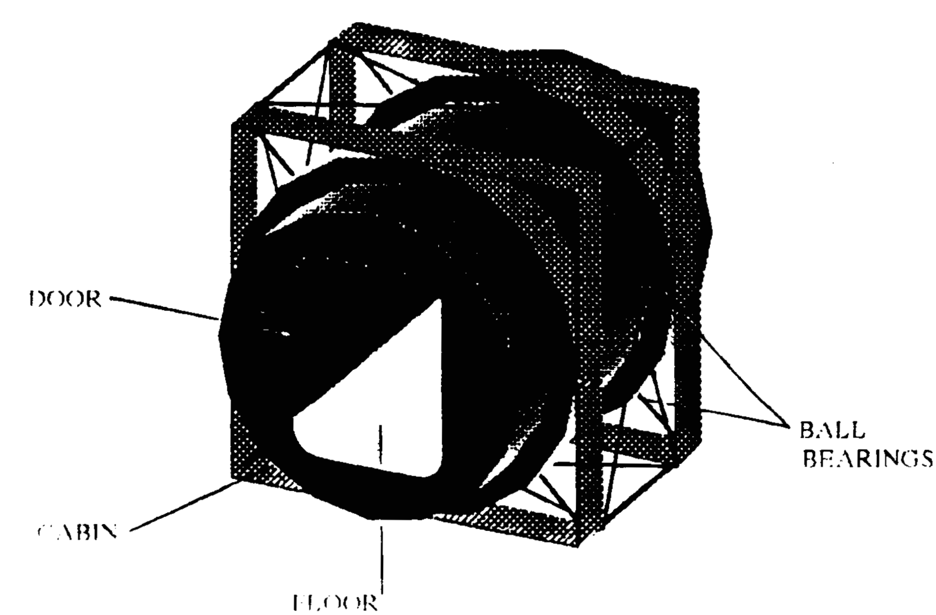


Fig. 6.1 Isometric View of Elevator Unit

The two rings of ball bearings allow the elevator cabin to rotate freely inside the circular tracks. These tracks, along with the truss structure, make up the elevator cradle. There are two purposes for these ball bearing rings. First, they help to compensate for coriolis acceleration (see 6.3.1). Second, they allow the elevator to remain stationary when matched with the interface (see 6.2.5).

The cradle, at all times, remains aligned with the spoke as the elevator traverses between the hub and the torus of the CASTLE. When compensating for the coriolis acceleration, the floor of the elevator, however, will not remain perpendicular to the sides of the cradle as shown in the figure above. Rather, its orientation constantly changes throughout the trip as the resultant force acting on the elevator changes. Because of this elevator orientation, the passengers only feel a force directly through the floor as they would in an elevator on earth (see 6.3.2).

When matched with the interface, these ball bearing rings allow the cabin to remain stationary with respect to the boom while the cradle rotates around it with the angular velocity of the torus. A more detailed discussion of this will be given in section 6.2.5.

The truss structure, which connects the two circular tracks containing the ball bearings rings, was added to give additional strength by taking some of the load off of the ball bearings. The truss members are aluminum rods with a diameter of 20 mm.

Door

In designing the door to the elevator, a number of design constraints were considered. First, it was decided that the door should open inward for two reasons. One, so that the door will not interfere with the airlocks at the torus or at the hub. Two, so that the pressure from inside the cabin will help seal the door due to the pressure differential existing between the pressurized cabin and the non-pressurized spoke. Further, so that the door interferes as little as possible with our interior space, it was designed to be hinged at the top and in the middle. To open the door, the passenger simply pulls inward and the door swings in and up. Various positions of the door can be seen in figure 6.2.

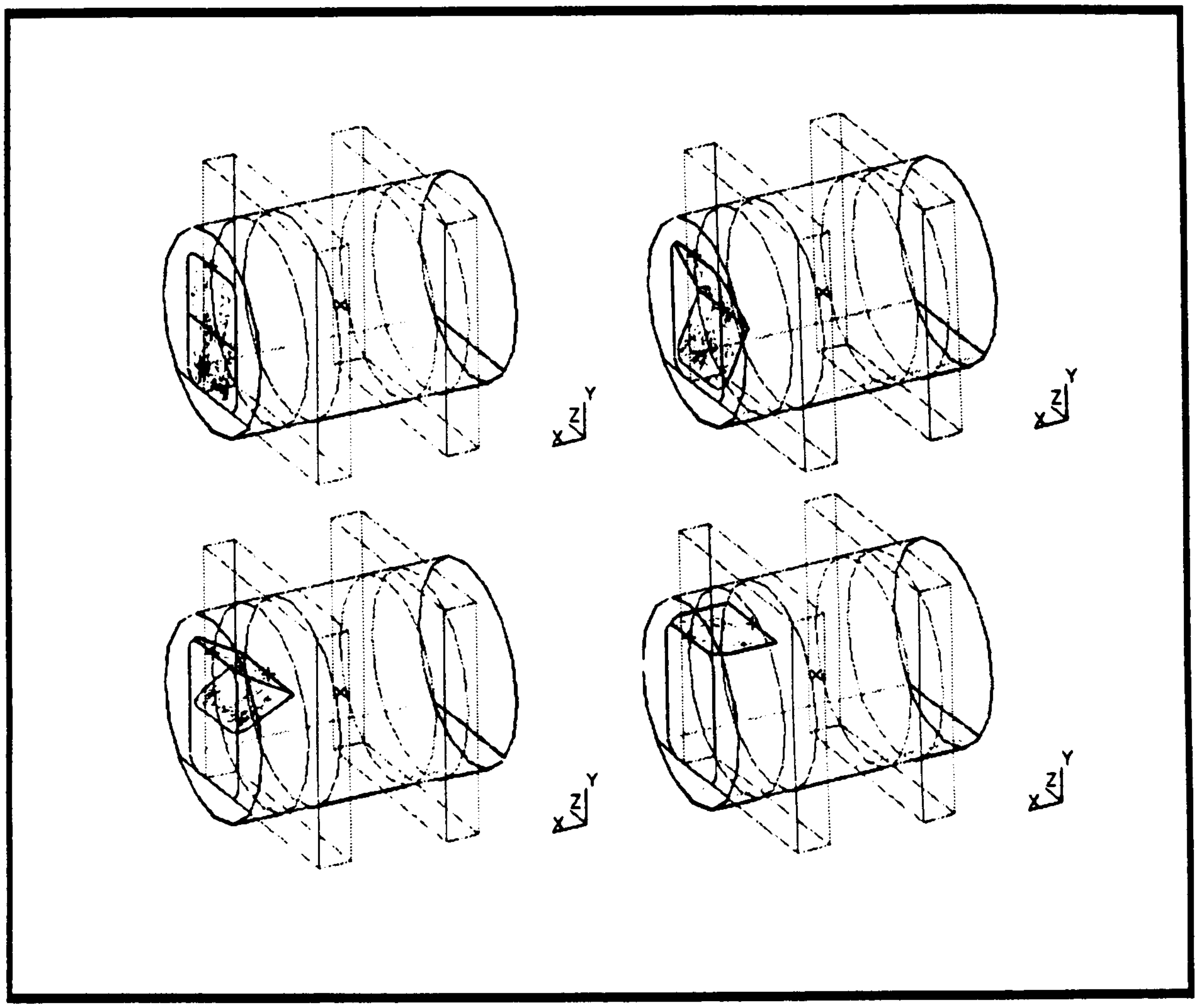


Fig. 6.2 Elevator Door at Various Positions

The bottom of the door is attached to tracks on either side of the door frame so that it remains in the plane of the door. The door is also designed to seal airtight so that the elevator can hold its own atmosphere during the journey. The door is 1.5 m wide by 2.0 m high. It is located directly in the center of the 3.0 m diameter end plate of the cabin. Corner fillets of radius 0.25 m were added to create a better air-tight seal and to reduce the stress at these critical points in the structure.

Interior

The inner section of the elevator which carries the passengers and cargo is called the cabin. The cabin has seating for six passengers and the total space available for crew and cargo is twenty cubic meters. The cabin also contains necessary emergency equipment and control systems.

Cargo Area

The interior of the cabin is tubular with the floor situated 0.45 m above the outer edge of the tube. The surface area of the floor is 8.7 square meters. The passenger seats and cargo space occupy 6.6 square meters. The remaining space is reserved for clearance of the elevator door and the control systems. Cargo will be anchored with straps to prevent it from sliding inside the cabin when the elevator is experiencing little or no artificial gravity or in case of a failure of the rotating mechanism. There is also a limited amount of cargo space under the floor. Emergency supplies, such as oxygen tanks, are stored below the floor.

Passenger Seats

Six passenger seats are provided for crew comfort and safety. The seats are positioned along the tubular walls of the elevator such that the passenger is facing the same direction as the spin of the cabin, rather than perpendicular to it. This minimizes the physiological effects of the cabin rotation on the passengers. As a safety precaution, the passengers are required to wear waist and shoulder belts similar to those in an automobile.

Onboard Equipment

The elevator will carry certain necessary equipment at all times. First and foremost are emergency supplies such as oxygen. Oxygen masks are accessible directly beneath each seat. Also onboard the elevator is a communication system which allows the passengers to converse with the crew members in the hub and the torus in case of an emergency. In addition, the elevator houses the control systems for the elevator drive motor and the cabin rotation motor (See section 6.2.3).

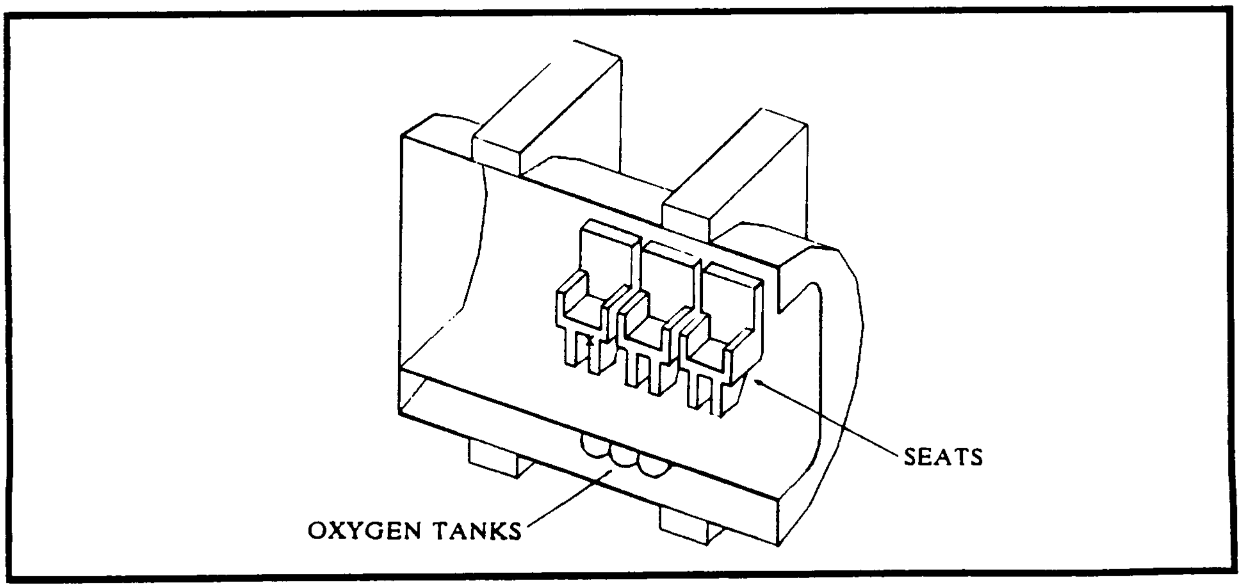


Fig. 6.3 Interior View of Elevator Cabin

6.2.2 Traversing Mechanism

Tracks

The two CASTLE elevators travel through the spokes on four rails, roughly 0.40 x 0.36 m in cross section, extending the full 70 m diameter of the torus. There are four 3.5 m guide pins per elevator. These guide pins are attached to each of the four corners of the non-rotating elevator cradles and fit into the asymmetrical gap in the rail.

As the elevator is capable of continuous rotation, it was necessary to develop a scheme to power the unit and still allow it to rotate freely. This was done by equiping one track with a pair of conductive strips running the entire length of the track. The pin traveling through this track is equiped with two electrical bushings, one positive and one negative, that are always in contact with the conducting strips. A similar arrangement exists in the forward ball bearing ring surrounding the elevator cabin. There is a complete electrical circuit for the full range of the cradle and cabin movement. The elevator therefore has power, at all times, for lights, climate control, rotation motors and control systems.

Since the tracks are continuous, an elevator could traverse the entire diameter of the torus. In this configuration, however, there are two elevators on the same set of tracks. Therefore, the elevators are allowed to traverse only half the diameter (from torus to hub). Only in the hub, where spin or de-spin occurs, do the elevator paths overlap. Therefore, only one elevator can occupy this space at any time.

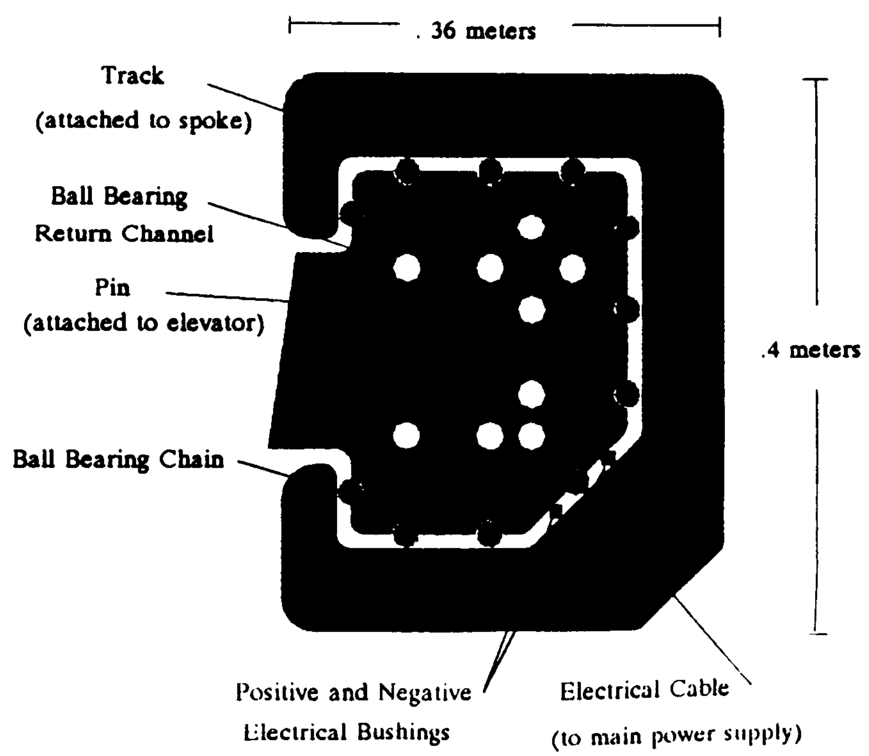


Fig. 6.4 Cross-Sectional View of Track and Pin

Ball Bearings

Since the energy supply of the CASTLE is very limited , it is necessary to reduce frictional losses in the tracks as much as possible. This low friction was accomplished by using a series of ball bearings between the stationary track and the moving guide pin. Around any cross section of the guide pin are eleven ball bearings, each twenty millimeters in diameter, through which the load of the elevator and cradle is transferred to the tracks. Each of these ball bearings is, in turn, attached to the one above and below it in a chain link fashion, with a 5 mm spacing between each ball.

The chain links are designed so that they are allowed to move freely between the track and pin. Each of the eleven ball bearing chains travels the full length of the guide pin along the outside (between the track and the pin) and then back through the pin, thus completing a loop. Therefore, each ball bearing chain is slightly more than twice the length of the pin; i.e.,. 7.0 m.

A similar system is used for the low friction interface between the elevator cabin and cradle. Because the tracks in this case are circular and thus continuous, there is no need for the ball bearing chain to complete the loop by going through a guide pin. The chain completes the loop on the outside of the guide pin instead and the design is simplified slightly over the track bearings.

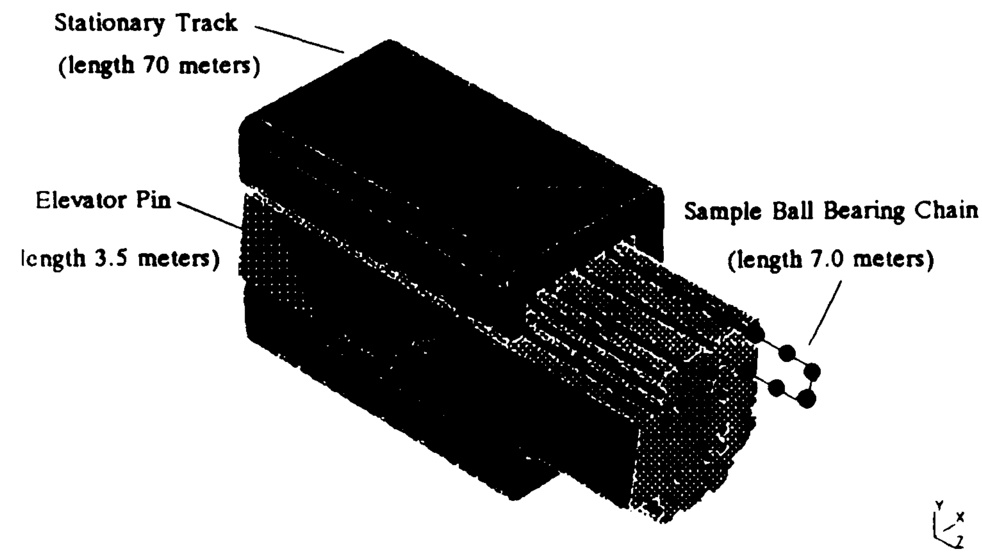


Fig. 6.5 3-D View of Track and Pin with Ball Bearing Chain

Pulleys

Electric drive motors move the elevators by using a system of pulleys. Unlike a normal elevator in which gravity is always exerting a constant force on the mass in the downward direction thus requiring a drive motor to pull the mass in only one direction (against gravity and up); the motor driving the CASTLE elevator has to pull the elevator in both the "up" and "down" directions. It must pull the elevator in the down direction (with gravity) only at the very start of the trip; because when the elevator is at the hub it has no preference as to which spoke it wants to traverse. The artificial gravity has no effect on the elevator at this point. Therefore, the motor has to start the elevator in the desired direction. This is accomplished with a closed loop pulley system. The cable is attached to the elevator through the guide pins and the guide pins then become part of the cable loop. The portion of the cable attached to the guide pin is, therefore, inside the rail and is safe from entanglement.

Because the paths of the elevators overlap in the hub, the cable is attached to only two of the four guide pins on each elevator. By choosing diagonal pairs, one elevator can enter the hub without interfering with the cable and pulleys of the other elevator. The second elevator then occupies the remaining spaces.

Each cable runs from the hub to the torus and back forming two continuous loops. It is attached to the elevator at the two previously mentioned points, such that these portions of the cable are moving in the same direction. The two remaining portions of the cable move in the opposite direction but are not attached to the elevator. A rotation of the loop (with the drive motor) in one direction translates the elevator up the spoke, while a rotation of the loop in the other direction moves the elevator in the opposite direction, or down the spoke.

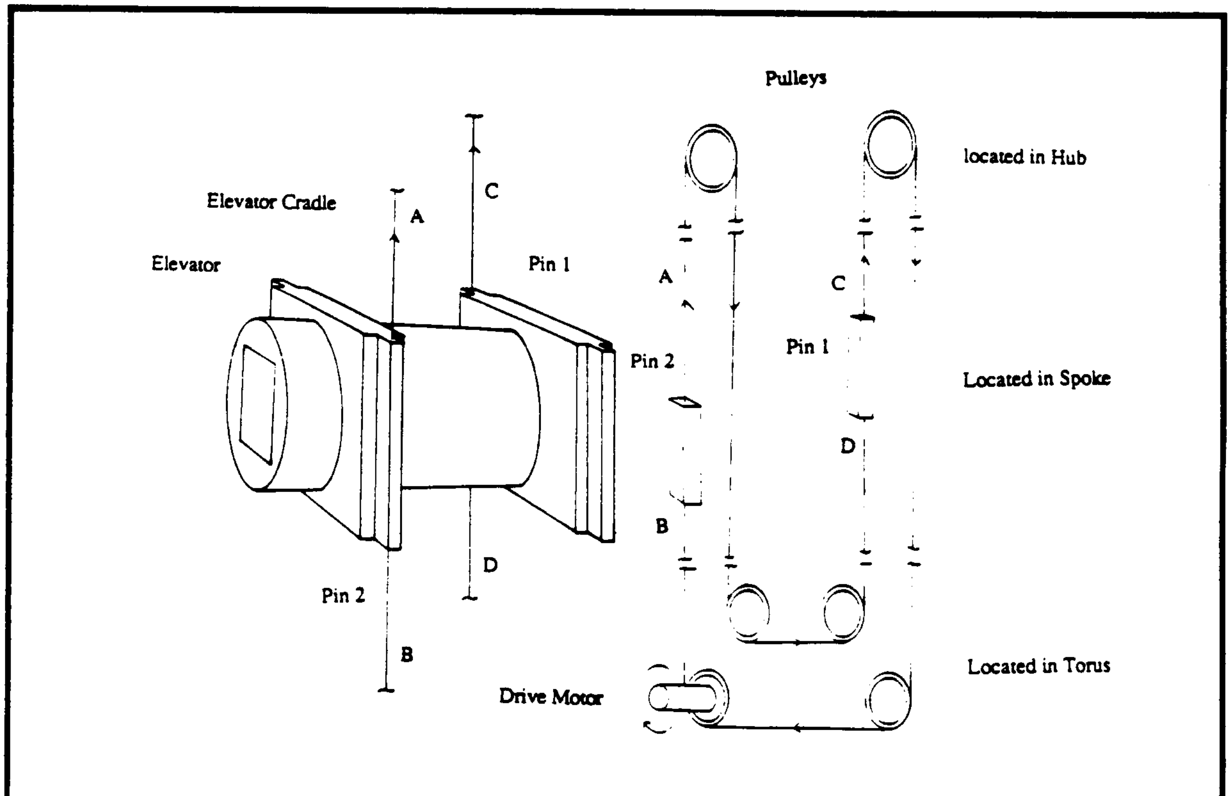


Fig. 6.6 Pulley Loop and Elevator Attachment Points

6.2.3 Drive Mechanism

Description of Equipment

It was decided that the driving unit should act as both a motor and a generator in order to reduce the power requirements. Since the elevator works against gravity during its trip from the torus to the hub, the drive unit must draw power from its generated storage supply and from the spacecraft's solar units. However, on the trip from the hub to the torus, the elevator begins with a large potential energy. A vast amount of this potential energy is stored during the trip from the hub to the torus. Although much power can be stored, the elevator still depletes its storage cells during a trip from the torus to the hub. This occurs because: 1) the generator is not 100% efficient, 2) some of the potential energy is used to prevent the elevator from free falling and 3) power is required to light the cabin and run the elevator's drive computers.

Location of Drive Units

It was decided to have the main drive units detached from the elevator for two reasons. The first is to decrease the weight of the equipment which must traverse through the spokes. The direct result of this reduction of weight is a decrease in the amount of power required. The second reason is to protect the motor. Since the spoke of the spacecraft is neither pressurized nor protected from the harsh environment, a motor that is attached to the elevator would have a very short life due to the extreme environmental conditions encountered in space. By placing the drive unit inside of a climate controlled elevator room located in the torus, the motor is not subjected to these extremes, thus prolonging its life. In addition, the motor can be more easily serviced by eliminating the need to work in a non-pressurized environment.

The cabin rotation motor that is used to compensate for coriolis acceleration is located on the elevator cradle and is attached to one of the ball bearing tracks. Parallel to the ball bearing ring is a circular gear also surrounding the elevator cabin. The gear from the rotation motor can therefore turn the cabin by turning the gear surrounding the cabin. This motor is controlled by an accelerometer that detects the direction of the acceleration experienced by the unit and aligns the elevator accordingly.

6.2.4 Power Requirements

Even with the integration of the energy storage system, the system is not 100% efficient. As mentioned in section 6.2.3, additional power is required on the elevator trip from the torus to the hub when the motor must perform work against the artificial gravity. However, taking into account a worst case scenario, the maximum amount of additional power required, given the minimum amount of stored energy available, would be 10 kw. This case would occur when the energy stored is minimum due to empty elevator trips from the hub and the energy required is maximum due to a full elevator trip to the hub. In addition to this maximum amount of required power, it should also be noted that such power requirements are required at random intervals. Also, there are noticeable peak periods of heavy elevator and power use throughout the day.

6.2.5 System Characteristics

Travel Time

The average traversing velocity of the elevator is approximately 2 m/s. Covering a distance of 35 m along the spoke takes 17.5 seconds; the actual travel time is then 20 seconds, including initial acceleration and final deceleration. The time spent in the elevator is about 50-70 seconds giving ample time to adjust the rotational speed of the elevator cabin for interface matching.

Interface Matching

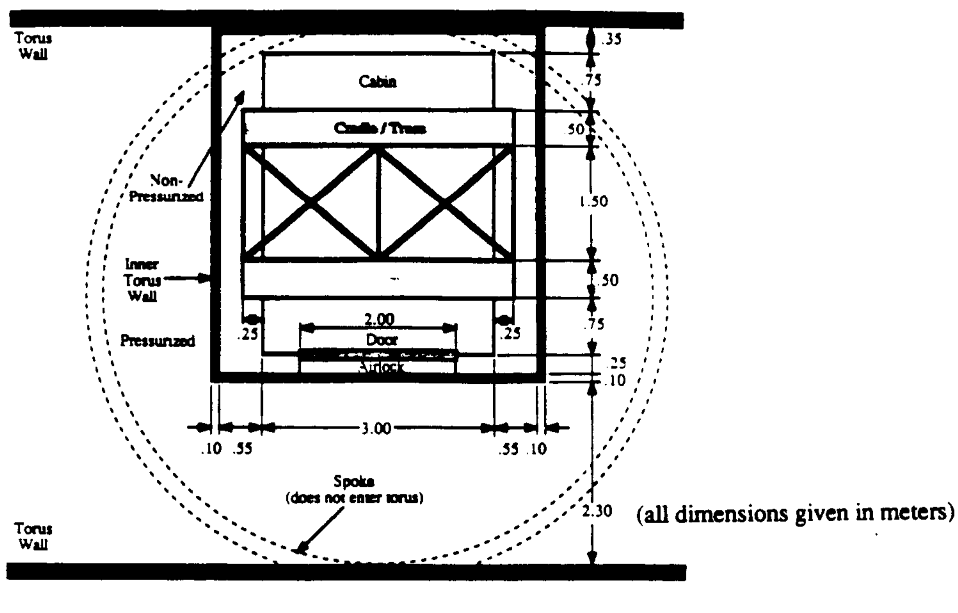
As mentioned in the introduction, the elevator was designed to match the rotating/nonrotating interface at the hub. This required that the elevator door be, in effect, the interface. This placed two new limitations on the elevator design. First, when in the hub, the elevator door must be positioned in the exact center so that the elevator cabin can be airlocked with the interface tunnel. Second, the elevator cradle must rotate freely about the z-axis of the ship while the cabin remains stationary with respect to the interface tunnel. This allows the crew and cargo to pass safely between the elevator and the interface tunnel.

The first requirement imposed the restriction that only one elevator can occupy the hub at any time. This prompted the reduction of elevators from four to two since the opportunity to use more than two elevators at a time is limited. The second requirement imposed that the elevator has to be a self-contained environment allowing for free rotation. With these requirements, the elevator was designed as a pressure-tight unit while travelling through a non-pressurized spoke. Therefore, there are pressure locks at the interface and at the torus. Furthermore, the elevator unit consists of two components: the cradle and the cabin (see section 6.2.1). The cabin can rotate freely about the z-axis with respect to the cradle and vice versa, as they are interfaced with two ball bearing rings.

When the elevator reaches the hub, the cabin is connected to the interface tunnel by means of an airlock. Brake shoes gradually decrease the rotational speed of the cabin until the tube is non-rotating with respect to the interface tunnel. Passengers can then exit the elevator. The cradle, however, remains rotating at the same angular velocity as the torus.

Habitat Matching

Habitat matching involves matching the design for linking the torus and the spokes, as well as matching the design for the hallway inside the torus. It was decided to position the elevator off-center in the spoke so that there would be ample space for a hallway in the torus for the



TOP VIEW OF ELEVATOR LOBBY

Fig. 6.7 Top View of Elevator Position in Torus/Spoke Cross Section passage of cargo and personnel. Had the elevator been positioned at the very center of the torus cross section, two very narrow hallways would have been formed on either side of the elevator. In the final design, there is a 2.3 m allowance for the torus hallway (see figure 6.7). The elevator enters a non-pressurized chamber that is open to the spoke and extends into the torus. Here, airlocking procedures are performed thus allowing the crew and cargo safe passage between the elevator and the habitat area.

6.2.6 Emergency Procedures

It was deemed necessary to plan emergency procedures in the event that the elevator breaks down with passengers aboard. Since the spokes are unpressurized, without proper consideration a malfunction of the elevator could be fatal. Consider a worst case scenario where the elevator becomes stuck in the middle of the spoke. The passengers have no means of travelling through the unpressurized spoke to either the torus or the hub. Hence, a warning system would alert the crew in the torus to the problem and the elevator would be manually lowered to the torus by engaging a manual braking system and disengaging the motor. The elevator would then drop slowly down the spoke at a controlled speed with the aid of the manual breaking system as well as the artificial gravity pulling it downward. Pressure suits were not considered feasible due to their large volume and weight which would have to be stored inside the cabin.

6.3 Analysis

6.3.1 Coriolis Effect

Description

Crew comfort was considered a very important design consideration because some of the crew aboard the spacecraft are not astronauts and have not been through a rigorous training program. The main obstacle that must be eliminated to maximize crew comfort is the coriolis effect. This coriolis effect stems from the combination of the elevator's radial movement and the torus' angular rotation. These motions cause a coriolis acceleration (i.e.,. force) which acts perpendicular to the radial artificial gravity force.

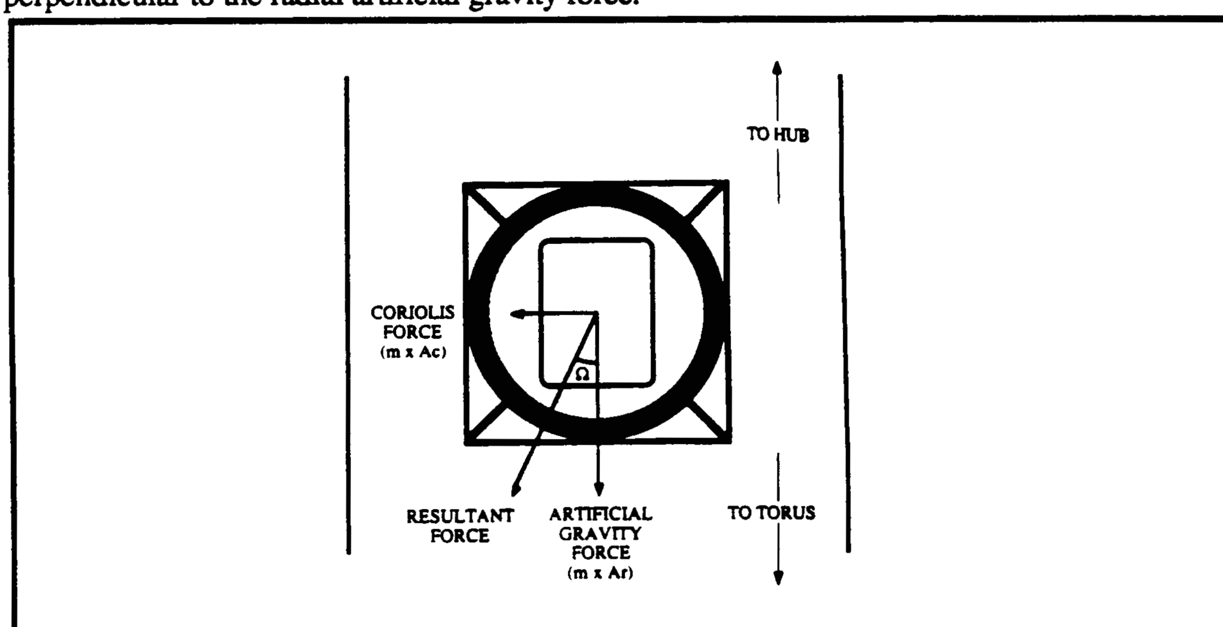


Fig. 6.8 Force Resulting from Artificial Gravity and CoriolisAcceleration

The tangential coriolis force (mA_c) is a function of the radial velocity and the angular velocity (see below). The coriolis force, therefore, remains essentially constant since these two parameters are essentially constant. It is the change in the radial artificial gravity force (mA_r) acting on the elevator that causes the resultant force to change. The artificial gravity force is a function of the radial distance (r) of the elevator from the hub (see below). The resultant of these two forces is shown in figure 6.8 and representative numbers are shown in Table 1.

In an uncompensated elevator travelling through the spoke, a passenger would feel as though s/he were falling either forward or backward. This coriolis effect, in addition to the lack of visual orientation, causes severe motion sickness in the elevator passengers.

Artificial Gravity Force = mA_r

where m = mass of elevator plus occupants and cargo
A_r = radial acceleration
$= rw^2$

where r = radial distance from hub
w = angular velocity of torus

Coriolis Force = mA_c

where m = mass of elevator plus occupants and cargo
A_c = coriolis acceleration
$= 2wu$

where w = angular velocity of torus
u = radial velocity of the elevator

TABLE 6.1 Representative Values of Resultant Acceleration at a Given Radius

r (m)	A_r (m/s^2)	A_c (m/s^2)	**Resultant accel** (m/s^2)	**W** (degrees)
0	0.0	1.349	1.349	90.00
5	0.569	1.349	1.464	67.15
10	1.137	1.349	1.764	49.87
15	1.706	1.349	2.175	36.33
20	2.274	1.349	2.644	30.68
25	2.843	1.349	3.147	25.38
30	3.411	1.349	3.668	21.58
35	3.980	1.349	4.202	16.72

Elimination of Coriolis Effects

In order to eliminate the sickness which stems from the coriolis effect, it was decided to continuously align the elevator such that the resultant force (see figure 6.8) acts directly through the centerline of the passengers. This is another reason for the design of the rotating elevator cabin. During the passage of the elevator through the spoke, the computer controlled motor (described in section 6.2.3) aligns the elevator interior at the necessary angle. Thus, by aligning the resultant force through the centerline of the passengers body, the coriolis effect is eliminated and the passengers only notice an increased body weight. An example of the passenger alignment at various positions in the spoke is shown in figure 6.9.

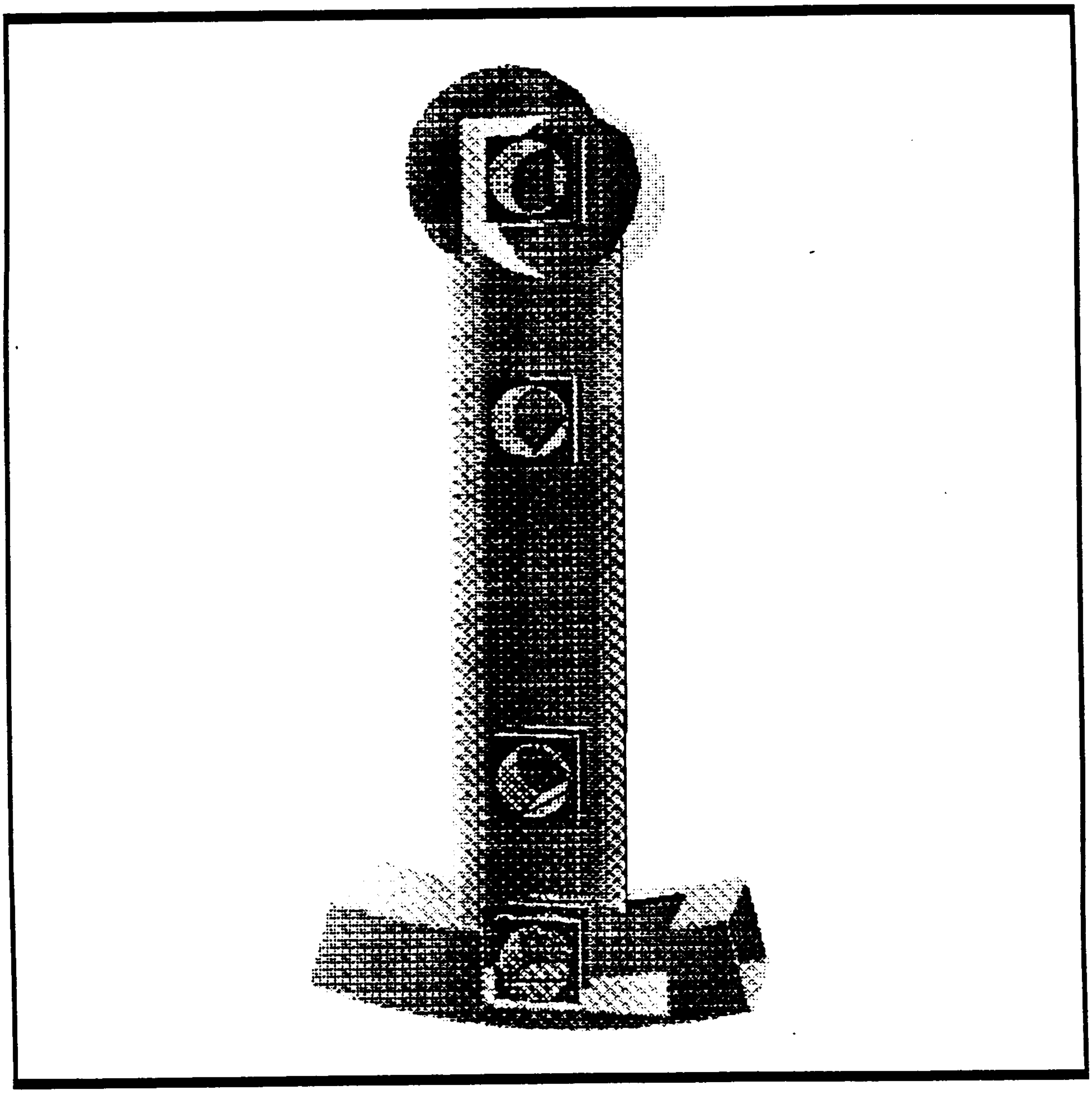


Fig. 6.9 Elevator at Various Positions in Cutaway Spoke

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6.3.2 Stress Analysis

A model of the elevator cabin was created for finite element analysis. Since the pressurized elevator cabins are positioned in non-pressurized spokes, an elevator cabin was modeled to investigate the forces and stresses corresponding to this situation. The model is similar to a pressurized cylinder such as a soda can filled with soda. The two bearing rings help maintain the shape of the cylinder much like the barrel straps on a wooden barrel. One other characteristic is the door in one of the end plates of the cylinder. There is a rim around the edge of the door that helps form an airtight seal when the elevator travels between the torus and the hub. The elevator should be inspected regularly at those places where the finite element analysis has shown the stress concentrations to be the highest (See figure 6.10 below).

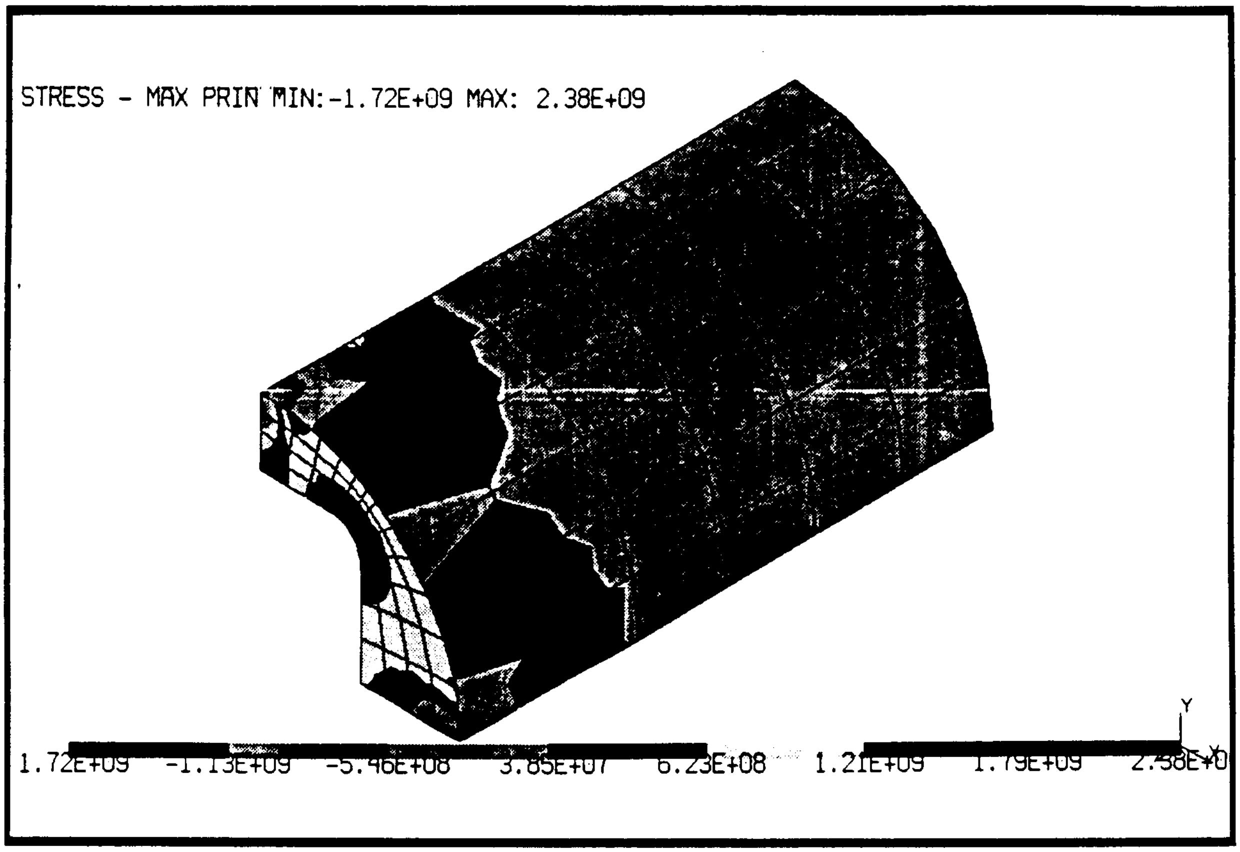
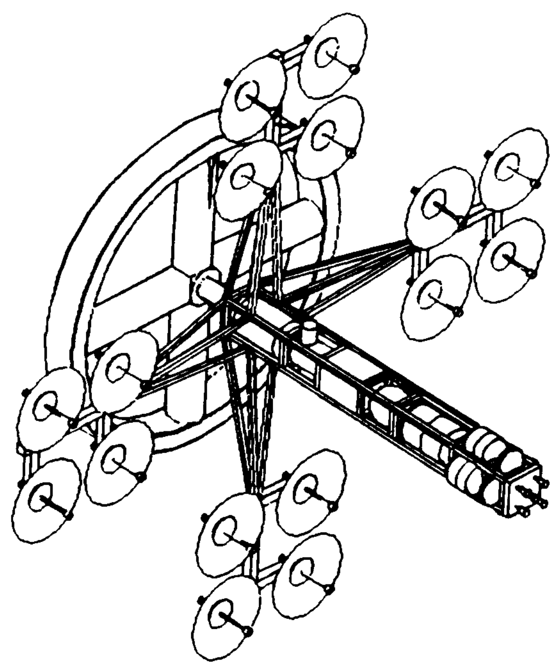


Fig. 6.10 Finite Element Stress Contour

Chapter Seven

Radiation Protection



7.1 Introduction

Perhaps the most difficult and least understood problem associated with sustaining life during long term space travel is the problem of protecting life from the harmful radiation found in the space environment. Radiation consists primarily of charged particles having high levels of momentum. When these particles impinge on living cells damage ensues which, in sufficient quantity, leads to death. Most radiation encountered during an earth-Mars mission emanates from the sun although a significant amount is also due to the more generalized cosmic radiation. The graph below (ref 7.1) shows the types and quantities of radiation found between Earth and Mars.

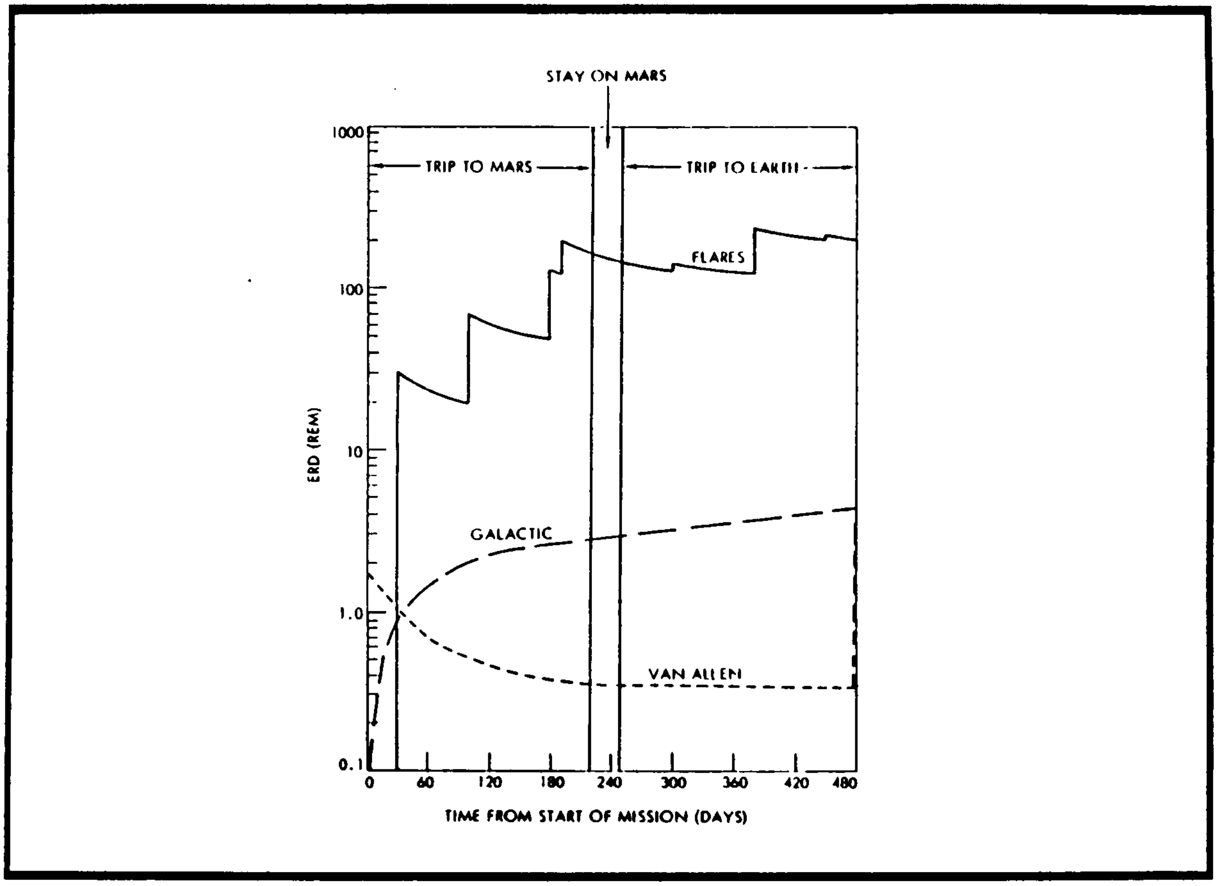


Fig. 7.1

As indicated by the graph above, the problem of radiation protection is most severe during solar flares which periodically (although not entirely predictably) erupt on the sun's surface sending enormous quantities of intense radiation into space. The graph shown on the next page (ref 7.1) indicates that the frequency of these solar events is such that several will be encountered during the mission.

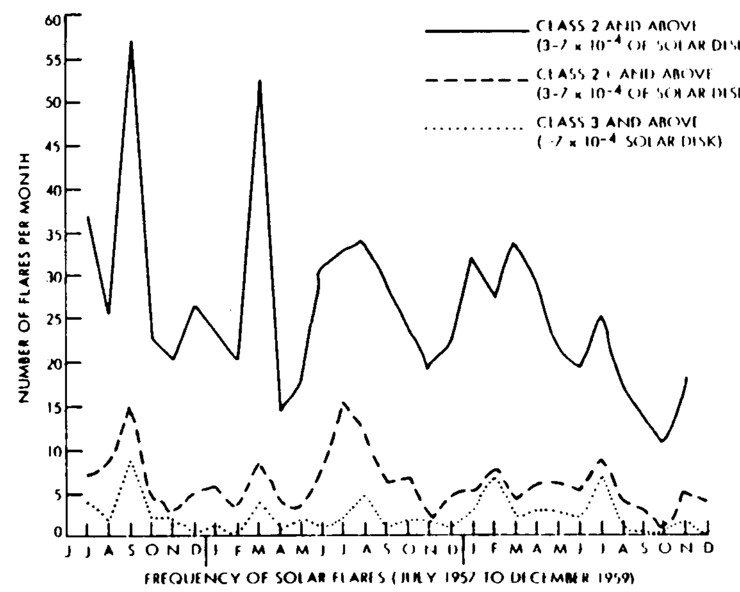


Fig. 7.2

In the following sections of this chapter the problems associated with the design of a satisfactory shielding system are discussed.

7.2 Methods of Protection

The simplest and most obvious means of shielding against radiation is to erect a barrier between the radiation source and the items to be protected. Indeed, this is the most reliable method and the earth's atmosphere fulfills that objective for life on earth. However, for spacecraft, minimizing mass is of primary importance and to provide sufficient material shielding for long term radiation protection would account for well over half of the total ship mass and would consequently be prohibitive. As a compromise, the concept of a "safe haven" was developed during the CAMELOT I phase of this project. According to this plan, the hull of the ship would be designed to protect against the so called cosmic radiation while certain areas of the ship (two rooms called safe havens) would have extremely thick walls to protect against the more intense and less frequent solar events. When a solar flare becomes imminent, all personnel and other living organisms (plants and animals from the CELSS units) would be evacuated for the duration of the "storm" to either or both of the safe havens. While the safe haven approach to the radiation problem certainly reduces the mass of the ship when compared to trying to shield the entire ship, it is a very cumbersome design because of the inherent redundancy which must be built into the safe havens to protect life for days at a time without needing to use other parts of the ship. Sanitation, food, ship controls, medical facilities, work, etc. must all be available in the safe havens. Moreover, the safe havens proposed by CAMELOT I were necessarily small and were not actually suitable for occupancy by both the crew and their accompanying plants and animals. In fact, no provisions were made for transporting all of the plants and animals to the safe havens in an emergency situation. To overcome these problems, other techniques were investigated for radiation shielding and a solution, presented later, was arrived at.

As mentioned earlier, the earth's life forms are protected from harmful radiation by the shielding effect of the atmosphere. More than this, however, the earth also has a magnetic field of 4 x 10^{-5} Tesla which serves to deflect significant amounts of radiation. In fact, because of the earth's magnetic field, astronauts in earth orbit are adequately protected for long periods without excessively bulky vessels. For this reason CAMELOT II is proposing that the safe haven concept be removed from the overall CAMELOT design and in its place a form of lightweight magnetic shielding be employed. Not only would such a scheme reduce the mass of the ship by approximately half (ref 7.2) but also it is in keeping with the "luxury liner" concept of the CAMELOT mission in that it increases the effective volume of the ship (by eliminating the safe havens) and it gives full use of the entire ship all of the time (rather than only during periods of minimal solar activity). Designing a suitable magnetic field generation system, however, is complicated and hindered with its own set of drawbacks. In the following sections superconducting cables are proposed as a means to generate a magnetic field around the torus of the CASTLE.

7.3 Design of a Magnetic Radiation Deflection System Using Superconducting Material

7.3.1 Introduction

In the mid-1960's NASA and DoD sponsored many research projects to evaluate the possibilities for applying the relatively new science of high-field superconductivity to problems related to space flight. At that time, however, superconductors were not very advanced and temperatures near absolute zero were required for good performance. Fortunately, recent advances in superconductor technology now allow the phenomenon to occur at temperatures as high as 120K. Many scientists believe that by the twenty-first century the critical temperature may be as high as 300K. In its simplest form, a superconducting magnet consists of a spool of superconducting wire, an insulated container with provisions for maintaining the operating temperature below the critical limit and a power source for starting ("charging") the magnet. The superconducting material (which consists of brittle ceramic fibers embedded in a metallic, often copper, medium for ductility) has the unique property of exhibiting zero resistance to the flow of direct current when operating below its critical temperature and critical current density. The material which appears to have the greatest potential for development as a high critical temperature superconductor is yttrium-barium copper oxide ($YBa_2Cu_3O_{7+d}$).

7.3.2 Proposed Design for CAMELOT II

To protect the interior of the torus it was determined that a magnetic (so called B) field of 0.43 Tesla is required (supporting calculations are found at the end of this chapter). As shown in figure 7.3, four superconducting cables, each of 57.6 mm outer diameter, are required to obtain the necessary field. Two cables are positioned along the inner radius of the torus while the other two cables are positioned along the outer radius of the torus. The cables are placed between the inner wall (which acts as a pressure vessel to maintain suitable air pressure within the habitat) and the outer hull of the ship (which acts to protect the ship from damaging collisions with particles drifting in space). By positioning the cables this way, they are protected from colliding with space particles and the hull serves as additional insulation to help keep the superconductors cool. Moreover, this positioning of the cables forces the magnetic field to be cancelled within the habitat area.

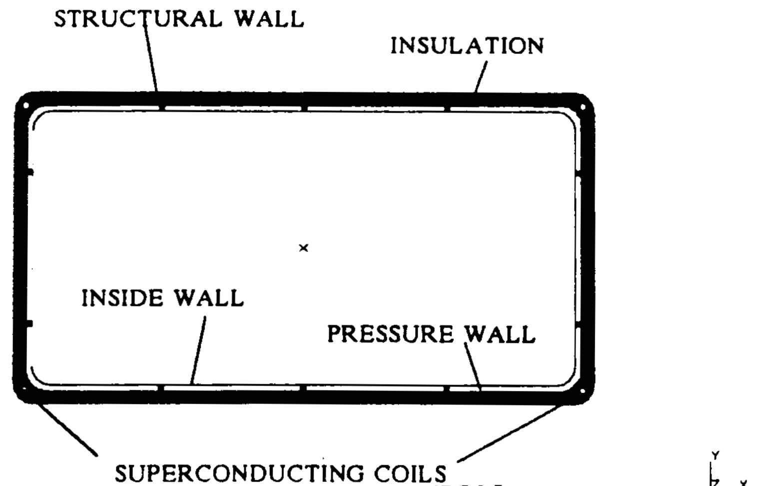


Fig. 7.3

Ideally, to reduce power requirements, the superconducting cables would be wrapped around the torus to form a giant solenoid. Unfortunately, such a scheme does not lend itself to easy construction. Also, having four separate cables is a safety feature. If any cable happens to fail, the other cables serve as adequate backup while repairs are made.

7.3.3 Electrical Requirements

Although the actual design of the electrical system required to operate the superconducting shield is beyond the scope of this investigation, the basic concept can be easily explained. A low voltage (70 volts), high current supply is needed. Once the magnet is energized, a superconducting short, called a persistence switch, is made across the leads and the power supply removed. The current within the cables will continue to circulate and maintain the field as long as the cable is kept below the critical temperature. The beauty of the superconducting system is that while a conventional magnetic system would require megawatts of continuous power, the superconducting system would require relatively little power for only a short while. As shown in the calculations given at the end of this chapter, 4×10^9 J are required for initial charging. This amounts to 100 kW for 11 hours. Prior to charging, however, the cables and cryogenic system must be operating below the critical temperature of the superconductor.

Over time, the cables will lose some of their charge due to losses at the interfaces of the cable sections which are required for construction purposes. An automatic control system monitors the charge on each of the cables and make adjustments as needed. With proper mission planning, these power requirements can be satisfied during times of low overall power demand. Other controls are needed to monitor the cryogenic system, the proper operation of each cable and the effectiveness of the radiation protection as well as to alert the crew of solar events so that extra attention is given to assure efficient operation of the system.

7.3.4 Thermal Considerations

Due to the tremendous thermal gradients and the rather stringent temperature requirements dictated by the use of superconducting coils, a thorough quantitative heat transfer study was deemed beyond the scope of this report. Instead, by way of addressing the problem, a number of heat management devices and methods were incorporated into the design of the torus, through which (with proper sizing etc.) the demanding temperature control requirements could conceivably be achieved.

There are three concerns that must be addressed regarding heat management in the torus. First, a critical temperature of 92K must not be exceeded in the superconducting coil at any time. Even a momentary deviation above this temperature would cause a drastic increase in the resistance of the coil. This increased resistance perpetuates further heat rise until the initial charge is dissipated rendering the coil inoperable. In order to prevent such an occurrence, it is proposed that each superconducting coil be cooled independently with of a liquid nitrogen cooling loop running through the core of each cable. The nitrogen would absorb heat as it flows through the cable and subsequently dissipate the acquired heat through radiative condensers located on the dark side of the CASTLE. Figure 7.4 on the next page shows a schematic of a typical condenser. To further safeguard against heat rise in the cable, each cable is wrapped in several layers of aluminized mylar which has a minimum thermal conductivity of 2.4×10^{-5} Btu/hr-ft-R therefore rendering it an excellent insulating material.

A second consideration in heat management is that of the thermal stresses created by the tremendous temperature differences between the sun facing and dark sides of the torus. The torus experiences a worst case heat flux of 1392 kW (ref 7.3). This occurs just after the ship leaves the earth and is due not only to the proximity of the sun, but also to the radiative heat transfer reflected from the earth. This constant heat flux can drive the temperature of the solar side of the spacecraft in excess of 340K while the ambient temperature of space on the dark side of CASTLE remains near 4K. The thermal stresses produced by such an arrangement cannot be dismissed. It is therefore suggested that heat pipes (see figure 7.5 and explanation) be employed to transfer heat from the solar facing side to the dark side of the torus. These devices could be located between the inner and outer wall of the torus. They are ideally suited for spacecraft applications because fluid motion is driven by a capillary wick structure which allows heat transfer to occur in the absence of, or against the force of, gravity. The wall temperatures thus equilibrated would also ease the difficulty of maintaining a comfortable and constant temperature within the living areas of the torus.

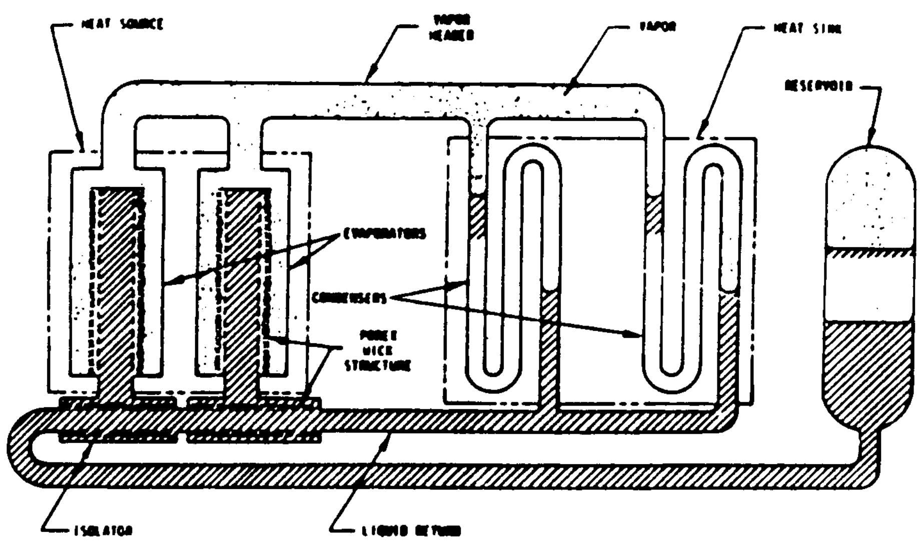


Fig. 7.4: Schematic of Radiative Condenser (ref 7.3)

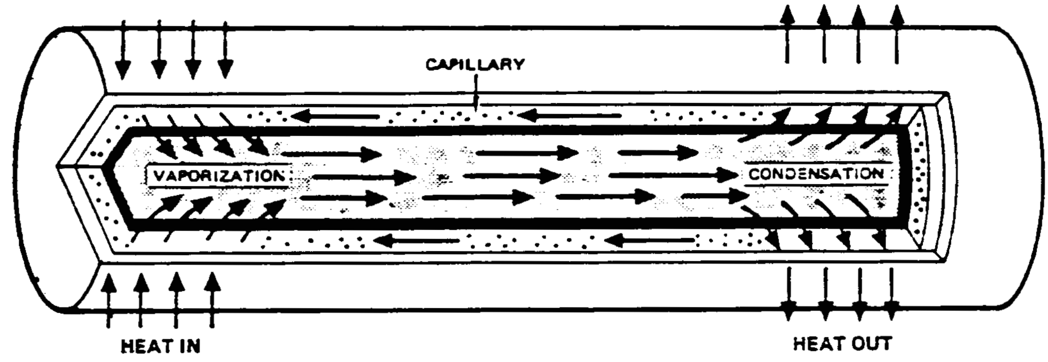


Fig. 7.5: Schematic of a Heat Pipe

The basic heat pipe is a passive, hermetically sealed, closed container which contains a capillary-wick structure and a small amount of vaporizable fluid. This device employs a vaporization-condensation cycle with the capillary wick pumping the condensate to the evaporator. Since the vapor pressure drop between the evaporator and condenser is very small, the cycle is essentially an isothermal process. With proper design, the heat pipe can transfer large amounts of heat with minimal temperature losses. (From Hughes Aircraft)

Finally, in the interest of passenger comfort, maintaining a comfortable temperature within the torus itself must be assured. As mentioned above, heat pipes represent the first step towards the attainment of such a goal. They are not, however, a sufficient measure. Further steps must be taken to insulate the living area from the temperature extremes experienced by the outer walls of the torus. The two means of heat transfer which must be considered are conduction through the torus truss structure and radiation between the inner and outer walls. The problem of radiation can again be minimized with the use of aluminized mylar insulation placed on both the inner side of the outer wall and the outer side of the inner wall. This would significantly reduce the rate of radiative heat transfer between these two surfaces.

The problem of conduction is not so easily solved. Since there are mechanical connections between the inner and outer walls of the torus, there are paths along which conductive heat transfer takes place. The problem, therefore, reduces to selecting a material of sufficient strength so as not to compromise the rigidity of the truss structure, but yet possessing a low enough thermal conductivity to prevent excessive conductive heat transfer. The material that best meets these requirements is a composite called Kevlar. Kevlar has a strength to density ratio ten times that of aluminum while its thermal conductivity is about half that of aluminum.

7.3.5 Structural Requirements

As expected, the four superconducting cables have tremendous forces acting on one another when fully charged. As calculated at the end of this chapter, the force is expected to be on the order of 2 MN/m. Finite element methods have been used to determine how much reinforcement is required to withstand forces of this magnitude. The best design appears to be to secure the cables to a truss structure which holds the torus together. Figure 7.6 shows a finite element analysis stress distribution plot of the torus. This stress distribution results from applying the load due to the magnetic force to the walls of the torus. After making initial assumptions regarding the necessary wall thicknesses the finite element model was applied to determine if failure would occur by the Von Mises yield criterion. By iteration, the optimal wall thicknesses could be determined for any given factor of safety. Unfortunately, sufficient time was not available to fully execute the necessary iterations. A more complete analysis would also incorporate a torus truss structure which would serve to make the torus more rigid as well as absorb some of the magnetic force. Note that while the interior wall serves as a pressure vessel to contain the atmosphere in the habitat area, the outer wall protects the ship from collisions with particles drifting in space and protects the torus from collapsing due to the high loads exerted upon it.

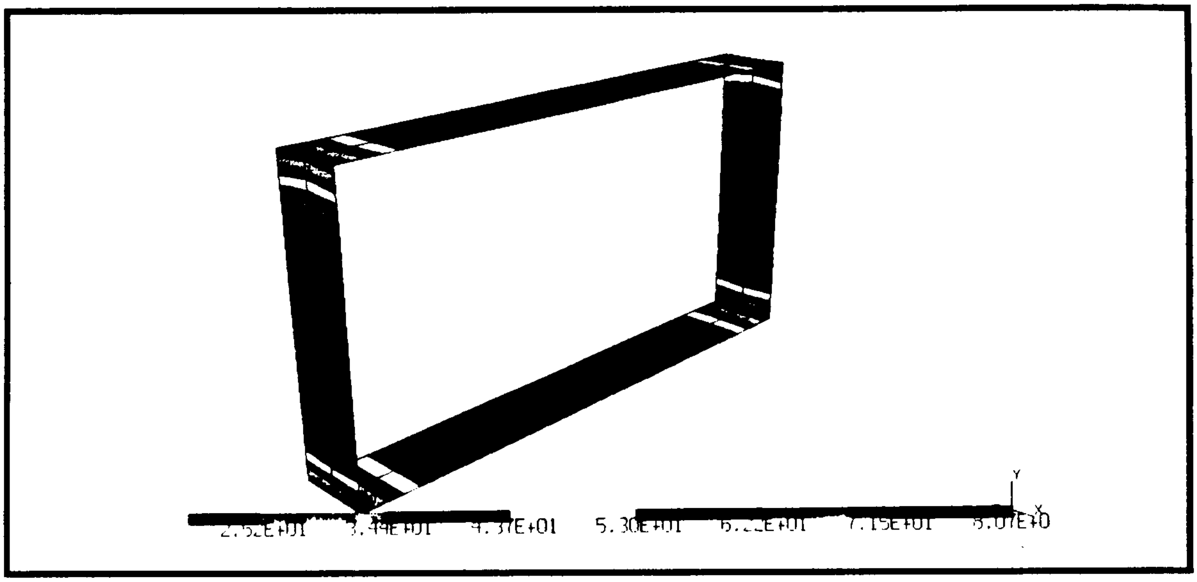


Fig. 7.6

Although the stresses due to the magnetic interaction of the superconducting cables are the most significant, many other stresses also act on the ship's structure and need to be accounted for before the structure can be considered safe. Stresses due to acceleration, for example, contribute an additional 6000 N across the torus cross-section during insertion (with a specific impulse of 400 seconds). In addition, the interior of the torus is pressurized. This is actually beneficial, however, since the outward pressurization stress would tend to offset the inward magnetic stresses. Lastly, thermal stresses due to the temperature gradient caused by the hot and cold sides of the torus exterior may not be negligible. To determine these stresses requires knowledge of the temperature distribution in the torus structure. This is complicated by the competing rates of radiative heat transfer input and output (which in turn are dependent upon relative position to the sun and planets) as well as conduction within the structure. After developing the governing nonlinear equations, a numerical method would have to be used to obtain meaningful results. The resulting worst case temperature distribution could then be used in a finite element analysis to determine the resulting stresses. Finally, all of the stresses acting on the structure would have to be combined and a final set of iterations performed to determine the optimal wall thicknesses. The wall thickness specifications are believed to be very conservative.

The most critical area of the torus in terms of structural considerations is where the elevator shafts connect with the torus. During periods of acceleration these joints experience the greatest stress because of their position relative to where the acceleration force is applied. Although the acceleration may be small, the joints must absorb the reaction forces due to the large mass of the torus. As a first approximation it can be assumed that one-fourth of the torus mass is lumped at the end of each of the elevator shafts. Bending, torsion and shear stresses act along each shaft and increase with distance from the hub, therefore becoming maximum at the joint with the torus. In addition, the spinning motion of the torus causes a radial load and resulting normal stress at each joint. Given more time, a finite element analysis of this situation would be performed to confirm that these loads would not interfere with the structural integrity of the torus.

7.3.6 Construction

The cables must be manufactured in sections and installed on each module of the torus while still on earth. Once in space the sections will only have to be joined and sealed. When the torus is nearly complete the cryogenic system can be started and the system checked for leaks.

7.3.7 Potential Problems

As mentioned earlier in this chapter, use of a superconducting magnetic field is not without its problems. Although the design indicates that the net magnetic field inside the torus is zero, the possibility exists that one or more cables will either partially or completely fail, thus losing the balance. The effects on humans of magnetic fields of an intensity other than that found on the earth's surface are not known and recently even the effects of terrestrial magnetic fields have been under speculation as a cancer causing agent. Some work has been done by NASA, DoD and USSR scientists to determine the hazards but as yet no conclusion has been made (ref 7.4). Also, the effect of stray magnetic fields on spacecraft instrumentation and guidance systems is a major concern. Passive shielding of sensitive equipment may be possible but could require a significant mass increase. More research is required in these areas to reach definitive conclusions.

7.4 Conclusions

Radiation shielding is a problem inherent with long term space travel away from the protective atmosphere and magnetic field of earth. During an earth-Mars mission, several intense solar flares are likely to be encountered and any craft expected to deliver its crew alive must overcome these solar events. Adding material to the spacecraft works but requires so much extra mass that fuel requirements and mission constraints become excessive. For that reason, the possibility of using superconducting cables to generate a magnetic field about the torus and thereby deflect virtually all of the impinging radiation away from the habitat area was investigated. It is estimated that the magnetic field scheme of protection requires about half as much mass as does the passive shielding scheme. Although the magnetic scheme has no absolute backup, it does have a redundancy factor of four. No machine can have an absolute guarantee against failure. Of course, the system relies upon the ship's electrical system, but if the electrical system fails completely no absolute backup exists either. In the long run, it is believed that more research will lead to sufficiently advanced technology to make superconducting magnetic radiation shielding a viable and practical alternative to passive shielding.

7.5 Calculations

7.5.1 Magnetic Field

B_o=2E/(Zcr_o(lnl))

E=600x10^6 eV (1 eV=1.6x10^{-19} J)

Z=1.6x10^{-19} C

c=3x10^8 m/s

lnl=ln(8r_t/r_o)-2=2.17

r_t=torus radius=34.4 m

r_o=radius of protected habitat=4.25 m

B_o=0.4337 Tesla

7.5.2 Inductance

L=$m_o r_t$(lnl)

m_o=1.26x10^{-6} Henry/m

r_t=34.4 m

lnl=2.17 (calculated above)

L=7.4x10^{-5} Henry

7.5.3 Current

I=2p$B_o r_o$/m_o

B_o=0.4337 Tesla (calculated above)

r_o=4.25 m

m_o=1.26x10^{-6} Henry/m

I=7.19x10^6 Amps

7.5.4 Energy

$W=0.5LI^2$

$L=7.4x10^{-5}$ Henry

$I=7.19x10^6$ Amps (calculated above)

$W=3.97x10^9$ J

7.5.5 Mass of Superconductor

$M_{sc}=(r_{sc}/J)(2pr_t)(2p/m_o)(B_o r_o)$

$r_{sc}=4000$ kg/m^3

$J=1x10^9$ Amp/m^2

$r_t=34.4$

$m_o=1.26x10^{-6}$ Henry/m

$r_o=4.25$ m

$M_{sc}=7947$ kg

7.5.6 Syructural Force Due to Magnetic Interaction of Cables

$F/l=(m_o II')/(2pr)$

F/l=N/m

$m_o=1.26x10^{-6}$ Henry/m

I=current in first cable (Amps)

I'=current in second cable (Amps)

r=distance between cables

Force on 1 due to 4 = $42.2x10^5$ N/m

Force on 1 due to 3 = $17.9x10^5$ N/m

Force on 1 due to 2 = 22.5 N/m

The forces on each cable are identical due to symmetry.

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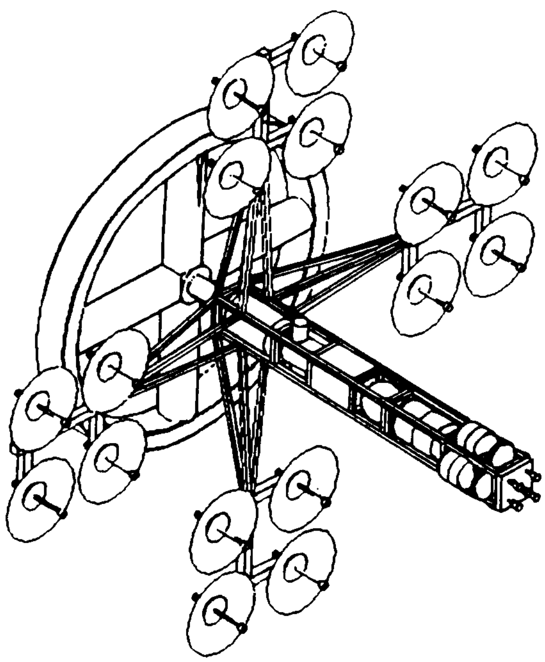
Chapter Eight

Internal Habitat Design



8.1 Introduction

Sometime in the not too distant future it is likely that man will journey to other planets to visit, to learn and perhaps eventually to stay. There are vast resources on other planets that we may some day be able to tap and bring back home to earth. War or environmental decay may force man to seek a new home on another planet. With no more frontiers left on earth to conquer, it could be the spirit of adventure that leads man to seek out new worlds on distant planets. For one reason or another, it is inevitable that man will take new steps to new worlds, and among those new worlds is our nearest neighbor, Mars.

Looking at man's current exploits in space it becomes obvious, except for a few instances, that we would like to limit the time man spends in space as much as possible. The space missions we have are always geared toward astronauts with years of training who can rough it in the hostile environment of space. It is important to remember that space is a hostile environment, and therefore little attention can be paid to comforts. It is with this reasoning in mind that astronauts deal with the numerous inconveniences imposed upon them such as waste disposal and muscular atrophy.

In light of this, how can man even fathom a trip to our neighboring planet. It is not very likely that man is about to violate the laws of physics and travel at, or anywhere near, the speed of light. This means that trips to Mars, by virtue of trajectory, will be lengthy endeavors. To ask astronauts to deal with the rigors of space for several days or even weeks is a reasonable request, bearing in mind their sense of duty. However, to ask them to deal with these same inconveniences over a period of two years, approximately the time a typical round trip to Mars would take, would be unreasonable. To ask civilians, who at best have had some space training and more than likely have had none, to undertake a two year odyssey with these inconveniences would be unthinkable. What we, the designers, have to do is to eliminate the deleterious effects of space travel by creating a more friendly and accommodating environment, one which would not be unendurable for the anticipated length of time.

Project CAMELOT II's mission is shuttling personnel back and forth between Earth and Mars. This voyage occurs on the shuttle vehicle called the CASTLE. Unlike other space missions, an artificial gravity of 0.4g is provided, the same gravity which occurs on Mars. To simulate this gravity a torus shaped structure is used for our habitat. This torus rotates so that the centripetal acceleration creates 0.4g. If the torus are cut and unrolled, it would essentially be a long skinny building. The objective in designing this habitat was to eliminate, as much as possible, the inconveniences of modern space travel. Comfort and stress reduction are the key considerations during the design process. The previous proposals of the room layout and design are examined and consequential changes are made. Some things that are considered are the materials to be used, how to handle noise, whether it was feasible to put windows in all the rooms, how to evenly distribute the mass, and many more to follow.

This section of the CAMELOT II report will take you on tour of the torus and will include a discussion of many things including the torus shape, the artificial gravity provided by the torus, the structures holding the torus together and in place, the utilities provided on board, the mass distribution system, a description of each room on the torus with corresponding diagrams, and a discussion of how people will spend their time during the long trip between Earth and Mars.

8.2 Torus Description

8.2.1 Torus Shape

The primary living and working area for the passengers and crew of the CASTLE is the torus. The torus is a rotating doughnut shaped structure with a rectangular cross-section. The torus radius to the outer surface is 35.0m. The circumference of the torus at the floor is 217m, the interior width is 7.0m, and average floor to ceiling height is 2.85m.

The outer shell of the torus is composed of aluminum and is filleted to ensure a constant thickness of 180mm. As shown in the diagram, the outer dimensions are 7.5m x 4.0m. More detail on the shell can be found in the Radiation Shielding section.

8.2.2 Artificial Gravity

The torus rotates at 3.22 revolutions per minute. It is designed to provide a 0.4g gravitational acceleration comparable to that of Mars, allowing one to become acclimated to Martian gravity before arrival.

8.2.3 Modularization

The torus is divided into 11 modules of various lengths. In order to fit into the launch vehicle, each module could be no longer than 25m (measured at floor length). A key factor in determining module length and room allocation was the placement of airlocks. Airlocks are required between every module in case of a rupture in the shell. By activating the airlocks, the modules on either side of the damaged one could be protected. Each module is also designed to group similar/complementary rooms with each other (e.g., Freezer, Kitchen, and Dining/Conference Room in the same module). Furthermore, an entire room needed to be in one module, not split between two with an airlock in the middle. The modules are pressurized prior to lift-off, so an assembly crew need only fit them together once in orbit.

8.2.4 Structures

The inner structure of the torus is supported by the outer shell. Connection points are located along the torus circumference at even metered intervals for ease of assembly. These inner structural walls are made of aluminum honeycomb, which is lightweight yet structurally sound. The space between the inner structure and shell is the utilities/tankage/storage area.

8.2.5 Utilities

As with any living area, the torus will need extensive support systems in the form of utilities. Most important among these will be fresh/waste water, ventilation, solid waste disposal and electrical systems. In addition, a complete emergency management system is also integrated into the overall design.

Unlike most Earth based utility systems, the one aboard the CASTLE is self sufficient. This is made possible by reliance on solar dynamic power and environmental regeneration through biological reclamation of waste products in the CELSS. This greatly reduces the amount of food, water, air and fuel that needs to be placed into the ship. All organic waste generated by the crew will be circulated back into the CELSS and broken down to be used as fertilizer by the plants.

Fresh / Waste Water System

The fresh/waste water system is composed of interlocking tanks underneath the floor of the living area in the torus. Placement of the tanks under the floor was done for structural reasons (it requires less supporting struts and therefore less mass to place them directly against the hull) and for safety reasons (in the event of a tank rupture, water will remain under the floor instead of raining down on the living area possibly causing damage). As water is used, it is pumped into either a reclaimed water storage tank or a waste water storage tanks and remains there until the CELSS units can process it. The difference between reclaimed water and waste water is their source. Reclaimed water comes from the sinks and showers and is therefore not very dirty and requires minimal purification before it can be placed back into the fresh water storage tanks. Waste water, on the other hand, is strictly sewage and requires extensive purification before it can be returned to the fresh water storage tanks. After processing, the fresh water is then pumped into fresh water tanks are it remains until needed. To ensure the highest level of safety, only biodegradable cleaning products will be used in the ship to prevent a build up of potentially harmful chemicals in the water system. This water system is also used as a mass balancing system which is fully explained in section 8.2.6.

Solid Waste Disposal System

Solid waste which is non-organic in nature must be stored somewhere in the ship until it can be transferred to the resupply ship at either Earth or Mars. It is important that waste is not just thrown into space because once it is out there, it remains there virtually forever. Over time it would build up and eventually could cause damage to any ship that came in contact with it. Hence the need for a solid waste disposal system. The system designed for the CASTLE consists of a compactor unit which decreases the size of the waste as much as possible, and a storage canister located inside the empty spokes. As waste is generated, it is temporarily stored in the torus section until enough accumulates to require that it be placed into the storage cannister. At that time it is compacted and sealed into plastic bags which are then placed into a small airlock connected to the evacuated storage cannister. A simple conveyer system places the waste into bins in the cannister where it remains until a resupply ship can take it back to Earth or Mars for permanent disposal.

Ventilation System

The ventilation system aboard the CASTLE is located above the ceiling of the living space in the torus. Because the ship is a closed environment, it is critical to maintain constant recirculation of the air. This is done by placing both input and output vents in every room. The air sucked out of each room is returned to the CELSS units where carbon dioxide is removed and oxygen is added. The Environmental Supercomputer System in the CELSS, utilizing sensors in every room of the torus, monitors the atmosphere around the clock and responds to any changes in a room's environment by increasing or decreasing the airflow into and out of that room. In addition to the CELSS' ability to regenerate the air in the torus, the constituent gasses of air are stored in tanks below the floor to account for losses due to leakage as well as provide an emergency supply of air in the event of a hull rupture or CELSS failure. In extreme circumstances, living could be confined to one or more modules and the air in the other vacant modules could be removed and supplied to the smaller living area enabling the atmosphere to maintain the minimum quantity of oxygen required for life.

Electrical System

The electrical system in the torus is located above the ceiling and behind the walls of the living area. Power supplied by the solar dynamic system is routed through the hub, down the spokes and into the torus. Cables running in easy access ducts above the ceiling deliver power to all rooms and systems throughout the torus.

8.2.6 Mass Balancing System

The function of the mass balancing system is to provide a mass balance 180 degrees from every point on the torus. Such a balance is crucial to insure a smooth and stable rotation. In the habitat design there are areas such as the laboratories and computing centers that are much heavier than others such as the lounge and chapel. The living configuration would be awkward and unnatural if designed with the heavy rooms opposite from one another. Accordingly, the habitat is designed to provide the optimum configuration for acoustics, lighting, and convenience. Considerations such as these would necessarily fall to the wayside if the configuration are designed for mass balance alone. In short, the habitat would be an unpleasant place to live. Even a habitat which optimized mass balance in its configuration would require some sort of system for balancing the movement of heavy items. Simply put, the habitat configuration optimizes comfort, causing a balance problem, and the mass balance system fully compensates the imbalance.

Initially, the mass balance system was to be designed also to compensate for changes in angular momentum; however, calculations showed that such changes are negligible. The worst case considered is if all twenty passengers, carrying 30 kg each, ran from one side of the torus 108.5 m around the other side, i.e., 2200 kg traveling 4.44 m/s. Such mass action would increase or decrease the angular momentum (depending on the direction traveled) only 0.00757%, a negligible amount.

Figure 8.1 shows the torus ring with floor loading in kg/m for each room. The floor loading are the estimated average mass of the room divided by the torus length of the room. For example, the chapel is shown with a floor loading of 440 kg/m. The chapel is 4 m long by 5.5 m wide. The total floor loading of the chapel is (440kg/m)x(4m) = 1760 kg. Note that the number 440 kg/m is not a true pressure; it is a load per torus length. Figure 8.1 also shows the number system used for the mass balance system. The torus is 217 m long (around). The numbering system gives, in meters, the torus length starting from the Freezer and moving clockwise. Accordingly, the left wall of the Freezer is 0.0 m.

The system was designed to balance the present configuration with the capacity to allow 2200 kg per 5 meter space (440kg/m) to move anywhere in the torus. For example, if a 2200 kg fish tank 7 m (the width of the cross section) by 5 m in size are moved from one side of CELSS to the other, the torus would remain stable. Also if 440 kg/m additional mass, originally not on the torus, are brought into the habitat area from the main boom, the torus would remain stable.

To accommodate this, each tank is large enough to hold the quantity of water necessary to balance the present loading configuration, with additional space equal to (440 kg/m)X(tank length (m)). For example, the first entry of Table 8.1 lists a 0.2 cubic meter tank. The area from 0.0 to 0.5 m is heavier than its counterpart at 108.5 to 109.0 m, therefore it needs no water underneath its floor. (The water balance is on the opposite side of the torus.) However, the tank can accommodate (0.5m)x(440kg/m)= 220 kg of extra mass, or 0.2 cubic meters of water. Thus, 220 kg of mass may be placed opposite this location, and water will flow into the tank, balancing the torus. The other tank sizes are calculated similarly. If distribution changes are made beyond the capacity of the water balancing system, a warning signal will be activated. For example, if a passenger decides to move a chair from the lounge to his cabin, and the water tank is already full beneath the room on the other side of the torus from his cabin, a red light will start blinking in the hallway, and the passenger will know to put the chair back into the lounge.

One of the most important qualities of the system is its ability to balance the elevators. The tanks under the elevators are large enough to allow 15,000 kg of mass at both elevator locations. This amount includes the mass of the elevator, 10,000 kg, plus 5,000 kg of mass that may be transported through the elevators. Because of the balancing system, the elevators can be anywhere on their spokes and the torus will remain in balance.

The system consists of water, tanks, pipes, and pumps to be controlled by the supercomputers in the computing center. A portion of the mass balance will be achieved by placing the tanks of reclaimed water and waste water beneath rooms which are exceptionally light compared to their counterparts across the torus. The rest of the water used in the mass balancing system will be the fresh water supply, incorporated with the plumbing and with the CELSS Water Management System. The materials required are listed below. The pipe material most likely will be a composite material whose properties are unknown at this time. As the head and power required of the pumps cannot be calculated without the friction coefficients and other characteristics of the pipes that will actually be used, the number and sizes of pumps are not included. However, the pumps will not be large, on the order of 7 kW, fitting easily between the floor and the tanks. The tanks will be supported by the torus shell, with the piping network above the tanks and below the floor. The pipe inner diameter was calculated using the worst case considered above, i.e., 2200 kg moving 4.44 m/s. It is assumed, safely, that items will never travel faster than the passenger carrying them (there will be no other means of transport).

WATER: 89.69 cubic meters of fresh water
TANKS: 44 of various sizes between 0.2 and 15.6 cubic meters
PIPES: inner diameter = 80 mm

The mass balancing system is designed to balance the floor loading only. It is assumed that the structural masses (walls, floors, piping, electrical equipment) are essentially constant throughout the torus. The floor loading listed are estimates of the average loading in the entire room. For example, in the location 0.0 to 0.5 m, there is an average floor loading of 857 kg/m, or 428.5 kg on the entire 0.5 by 7.0 square meter area.

The tanks used are spread across the width of the cross section and across the length specified in the table. This is necessary because a heavy mass may be placed anywhere in the torus, so water must be able to flow anywhere in the torus. However, although there will virtually be water everywhere under the floors, it will be contained in 44 tanks, with the piping either above or below the tanks, depending on space available. If the water are not contained in such a manner, any leakage would be catastrophic. The reclaimed water tank and waste water tank will be placed underneath the areas requiring the most mass. The reclaimed water tank will be located under CELSS at 77.5 to 87.0 m. The waste water tank will be located under CELSS at 196.0 to 217.0 m.

In the event of a computer breakdown, the mass balancing system would close all pipes so that the water distribution would remain the same as it was before the breakdown. Thus, the torus would be stable while the computers are down, provided the mass distribution remained the same. In such an event, the crew would notify the passengers to remain where they are until the computers are running again.

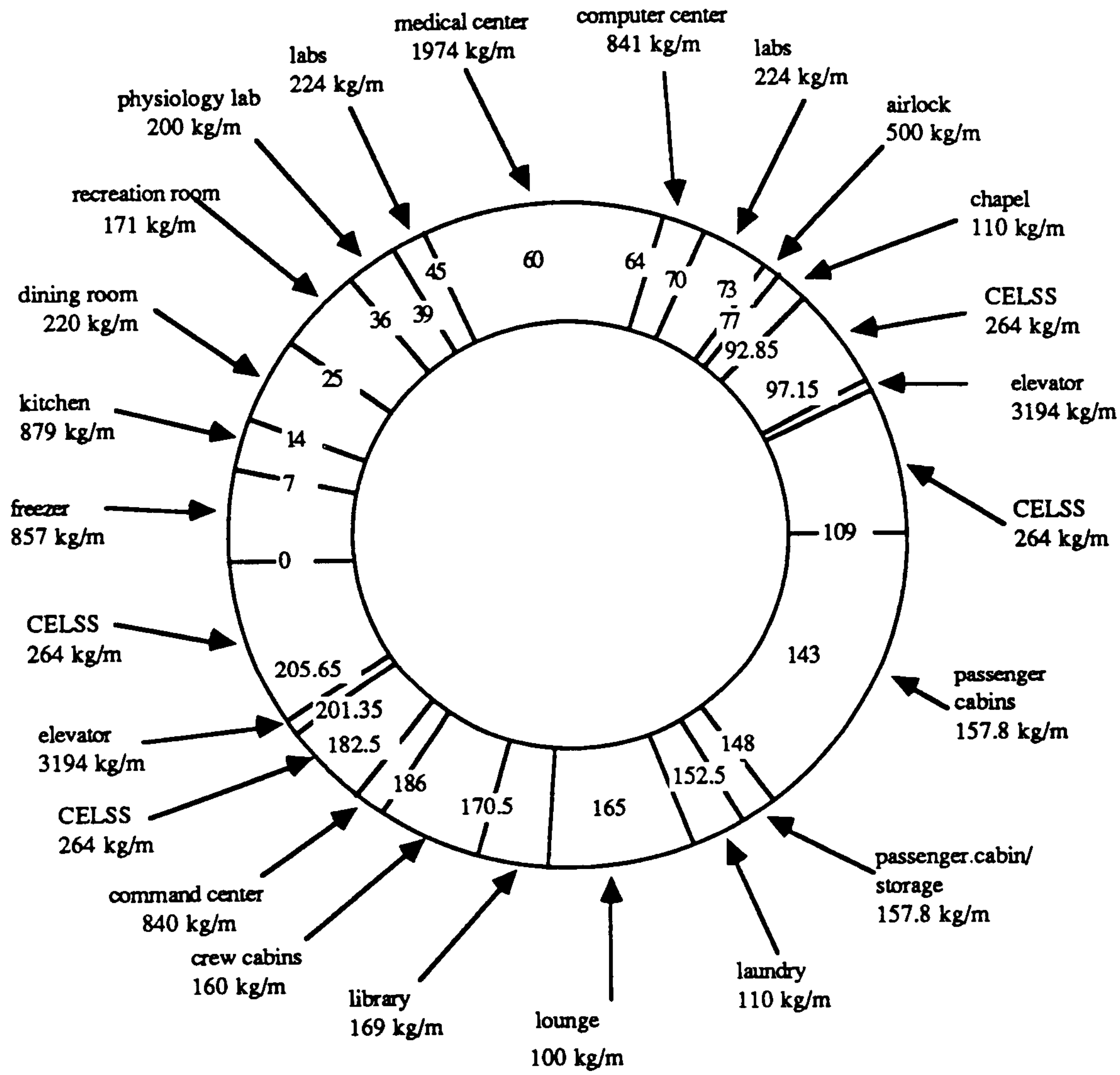

medical center
1974 kg/m
computer center
841 kg/m
labs
224 kg/m
labs
224 kg/m
physiology lab
200 kg/m
airlock
500 kg/m
recreation room
171 kg/m
chapel
110 kg/m
dining room
220 kg/m
CELSS
264 kg/m
kitchen
879 kg/m
elevator
3194 kg/m
freezer
857 kg/m
CELSS
264 kg/m
CELSS
264 kg/m
passenger
cabins
157.8 kg/m
elevator
3194 kg/m
CELSS
264 kg/m
passenger.cabin/
storage
157.8 kg/m
command center
840 kg/m
crew cabins
160 kg/m
library
169 kg/m
lounge
100 kg/m
laundry
110 kg/m
0
7
14
25
36
39
45
60
64
70
73
77
92.85
97.15
109
143
148
152.5
165
170.5
186
182.5
201.35
205.65

Figure 8.1

Table 8.1

LOCATION (m)	MODULE	ROOM	FLOOR LOADING (kg/m)	TANK (cubic meters)
0.0-0.5	K	Freezer	857.0	0.2
0.5-7.0	K	Freezer	875.0	2.9
7.0-14.0	K	Kitchen	879.0	3.9
14.0-25.0	K	Dining	220.0	4.8
25.0-36.0	J	Rec.	171.0	4.8
36.0-39.0	J	Phys.	200.0	1.3
39.0-44.0	J	Labs	224.0	2.2
44.0-45.0	J	Labs	224.0	0.4
45.0-56.5	I	Med.	1974.5	5.1
56.5-60.0	I	Med.	1974.5	1.5
60.0-62.0	I	Comp.	841.0	0.9
62.0-64.0	I	Comp.	841.0	0.9
64.0-70.0	I	Labs	224.0	2.6
70.0-73.0	H	Airlock	500.0	1.3
73.0-74.0	H	Chapel	18.0	0.5
74.0-77.0	H	Chapel	18.0	3.5
77.0-77.5	H	CELSS	264.0	0.5
77.5-87.0	H	CELSS	264.0	4.2*
87.0-92.85	G	CELSS	264.0	3.8
92.85-97.15	G	Elevator	3194 (maximum)	15.6
97.15-109.0	G	CELSS	264.0	8.0
108.5-109.0	G	CELSS	264.0	0.5
109.0-115.5	F	P. cabins	157.8	7.4
115.5-122.5	F	P.cabins	157.8	8.2
122.5-133.5	E	P. cabins	157.8	5.5
133.5-143.0	E	P. cabins	157.8	4.3
143.0-144.5	D	P. cabin/stor	157.8	0.7
144.5-147.5	D	P. cabin/stor	157.8	1.5
147.5-148.0	D	P. cabin/stor	157.8	0.3
148.0-152.5	D	Laundry	100.0	2.5
152.5-153.5	D	Lounge	100.0	8.6
153.5-165.0	D	Lounge	100.0	16.6
165.0-168.5	C	Library	169.0	7.9
168.5-170.5	C	Library	169.0	2.2
170.0-172.5	C	C. cabins	160.0	2.2
172.5-178.5	C	C. cabins	160.0	3.0
178.5-181.5	C	C. cabins	160.0	2.3
181.5-182.5	C	C. cabins	160.0	0.4
182.5-185.5	C	Command	840.0	1.3
185.5-186.0	C	Command	840.0	0.2
186.0-196.0	B	CELSS	264.0	4.4
196.0-201.35	A	CELSS	264.0	3.8
201.35-205.65	A	Elevator	3194.0 (maximum)	15.6
205.65-217.0	A	CELSS	264.0	8.0**

* The 4500 kg reclaimed water tank is located here.
**The 5000 kg waste water tank is located here.

8.2.7 Layout

The habitat region of the torus is divided into 11 modules of various lengths. These in turn are subdivided into a total of 38 rooms. The placement and design of these rooms was a crucial factor in the "livability" of the habitat area. Factors weighing heavily in the decision of layout are: noise, physical limitations, diversity and convenience.

Noise

In the closed torus, noise travels well and becomes a problem unless measures are taken to minimize its effects. Placement of certain noisy rooms such as the lounge, recreation room and dining room is done to separate them from the cabins which require a quiet atmosphere. In addition, the elevators are placed within the CELSS module to further isolate noise from the cabins. Acoustic materials are also used extensively throughout the living area on walls, ceilings and floors to dampen as much sound as possible.

Physical Limitations

The torus is divided into 11 modules so that the launch vehicle can carry them into Earth orbit. The maximum allowable length which fits into the rocket was 25m of span. This was taken into account when the rooms are placed around the torus due to the fact that between each section there exists a mandatory airlock which separate the modules from one another and hence would separate any room with a wall down the middle if we tried to place it in two adjoining modules. This required a great deal of arranging and rearranging to fit rooms into the modules in an acceptable order. Some large rooms like the lounge, recreation room and dining/conference room took up the majority of available space leaving small areas for rooms which needed to be located near them in the same module.

The reason for having airlocks between every module is that in space there exists a great deal of debris, primarily small pieces of rock, which can impact the hull of the CASTLE and cause a breach through which all the atmospheric gasses in a module would escape. If there are airlocks, the breach will still occur, but now the pressure doors in every module automatically close and only one module loses its atmosphere instead of the entire ship. Located in each module is also a pressure suit to be used in the event of a hull breach to go into the depressurized area and make the necessary inspection and repairs if possible.

Diversity and Convenience

The final considerations taken into account in the layout and design of the rooms in the torus are diversity and convenience. In the uniform cross section of the torus, monotony is the probable outcome unless steps are taken to avoid it. Diverse architecture and layout are the answers to this problem. By mixing up the layout, spaces are created which are not uniform throughout the torus. Features such as hallways which are placed at different heights and locations in the torus (sometimes down the center, other times at the side) and ceilings which are not always made flat (hallways have arched ceilings, many rooms have peaked ceilings, and the chapel has a domed ceiling) are used to add diversity. Lighting is also integrated into the designs by extensive use of indirect lighting effects. By projecting light onto the ceiling in the hallways and many of the rooms, the illusion of open space above is created. The cycle of night and day is also achieved by changing the color and intensity of the projected light in the corridors to simulate sunshine in the day and moonlight in the evening.

Convenience affected the layout by mandating that certain rooms be near one another and by requiring that amenities be provided. The laundry is placed next to the cabins for reasons of convenience, namely that the passengers would find it annoying to have to walk to the other side of the torus every time they did their wash. Likewise, the crew cabins are placed next to the command center where they can react quickly to any situation which arises that requires their immediate attention. The amenities placed throughout the ship are things like intercoms, computer workstations, bathrooms, and drinking fountains, to name a few. These are incorporated into the layout and design to maximize their usefulness and accessibility.

8.3 Torus Configuration

The torus section of the CASTLE is divided into 11 modules, each containing various rooms. The modules are of different lengths to accommodate the mix of rooms contained in each them and therefore have unequal floorspace. Below are listed all 11 modules starting with module A and proceeding around the torus, in order, to module K which connects back to A completing the full circle. Following each description is the floorplan for that module.

8.3.1 Module A

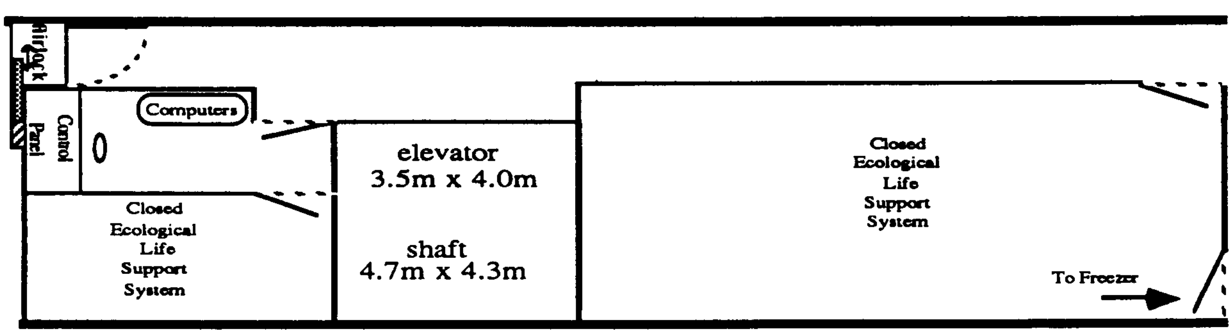
CELSS

CELSS, Controlled Ecological Life Support System, is intended to provide a closed ecological system aboard the CASTLE. CELSS is composed of an extensive variety of living organisms and supporting mechanical equipment. It supplies a continuing growth of food supplies, eliminates carbon dioxide, produces oxygen, and decomposes and converts waste products into useable substances. This eliminates the need for large stores of food and oxygen and will reduce the need for waste storage facilities. The CELSS system is subdivided into four subsystems--Food Management System, Water Management System, Waste Management System, and Air Revitalization System. By nature, these four systems are interactive with each other and promote regeneration of the bulk of the waste items produced on the ship. CELSS technology integrates all four systems in an attempt to provide a completely closed system. The Environmental Supercomputer System is housed inside Module A's CELSS. CELSS units are also housed in Modules B, G, and H. A complete description of CELSS and how it functions is contained in the CAMELOT I report.

Elevator

One of the two elevator stations is located within this module. Placement of the elevators in the CELLS module was done to facilitate resupply of the biological units as well as to group two of the noisier systems together thereby leaving the rest of the ship much quieter.

Module A - 21.0m



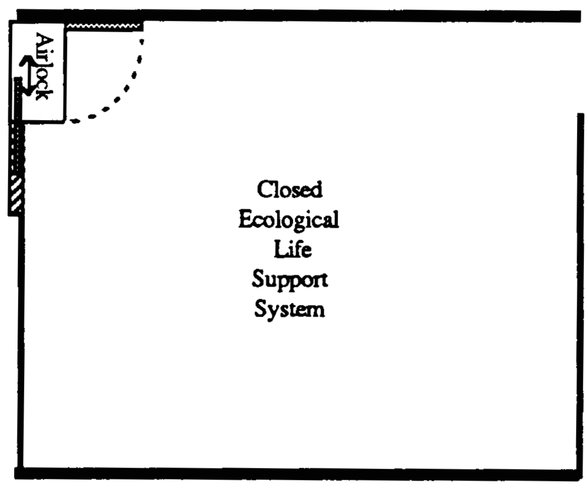
CELSS
21m x 7.0m

8.3.2 Module B

CELSS

Refer to section 8.3.1 for a description of CELSS.

Module B - 10.0 m



CELSS

10m x 7.0m

8.3.3 Module C

Library

The library is a room for which the passengers and crew can go to relax. There is a diverse selection of reading material including computers containing current periodicals from Earth. These computers have diskettes with periodicals sent through the communication system from Earth and a large variety of readings that are originally stored on diskettes. Earth transmits current articles and magazines monthly to keep the passengers informed of current events. The passengers are able to request additional readings from Earth. The library has two lounge chairs, a couch, coffee tables, three computer terminals, and a large selection of reading material on paperbacks and diskettes.

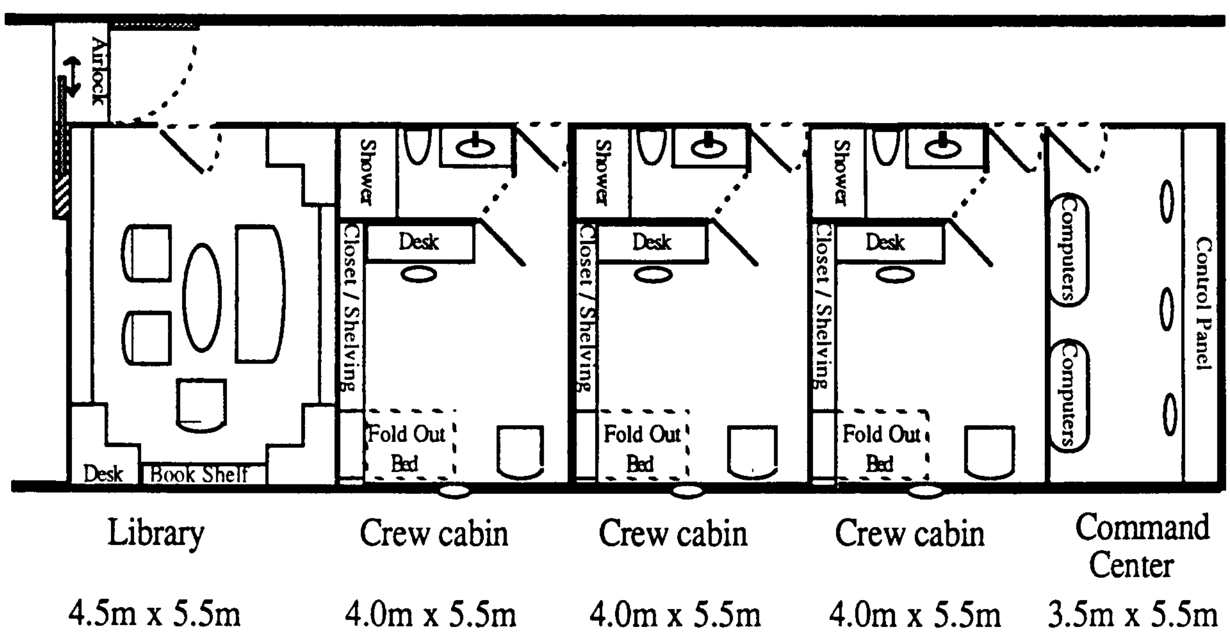
Crew Cabins

The crew cabins are made spacious because the crew will remain on board the CASTLE for the entire 2.135 year orbit. In addition to making these rooms spacious, the crew cabins are equipped with their own bathrooms, providing comfort and privacy over the extended period. The crew is allowed to bring 100 kgs of personal belongings from Earth. Although the crew cabins are made large, relative to the amount of space available on the spacecraft, the space is still rather limited. Therefore, to make the rooms appear more spacious, each cabin is well lighted, light colored, equipped with a bed that folds into the wall, and a window. All of these features gives the crew cabins a greater sense of spaciousness and comfort. The crew cabins are also placed next to the Command Center so that the crew will have easy access to the controls of the spacecraft in the event of an emergency.

Command Center

The Command Center is the room from which the crew operates the ship. This room has a Supercomputer which monitors all ship functions (including the mass balancing system). This room is the primary location for all controls to the ship. If anything needs to be done to or by the ship, this is the best location to send the command; the reason being that this room has direct access to the Supercomputer. The ship can be controlled from any of the other computer workstations on board the CASTLE, however, an access code must first be administered, thereby delaying the process. As a safety precaution, only the crew has access to the Command Center and the access code. Although it is highly unlikely, a passenger may not be able to cope with the environment, and may try to sabotage the spacecraft, so limiting the access to the Command Center was deemed a necessary precaution. In the event a problem arises in the spacecraft, the computer system in the Command Center can detect it and warn the crew. The degree of the warning will depend on the level of danger. If the problem is minor the crew will be notified of the problem, but the computer system will implement all necessary corrections. This allows small corrections to be administered in the event the crew is not in the Command Center. If the problem is greater, the computer system will notify the crew by triggering their beepers (if they are not in the Command Center). The crew will then go to the Command Center, examine the problem, and decide on the optimum solution. The computer system will then check this decision against other possible solutions, and if it decides that another approach should be taken, it will inform the crew. The crew will then have the final decision as to which solution to administer.

Module C - 21.0m



8.3.4 Module D

Passenger Cabin

Refer to section 8.3.5 for a description of the passenger cabin.

Maintenance Room

This room contains an industrial style sink for routine cleaning of the torus as well as all the necessary cleaning supplies. In addition, it contains a lightweight vacuum cleaner. Tools for routine small scale repairs are located in cabinets along one wall and a workbench with stools lies along another.

Laundry

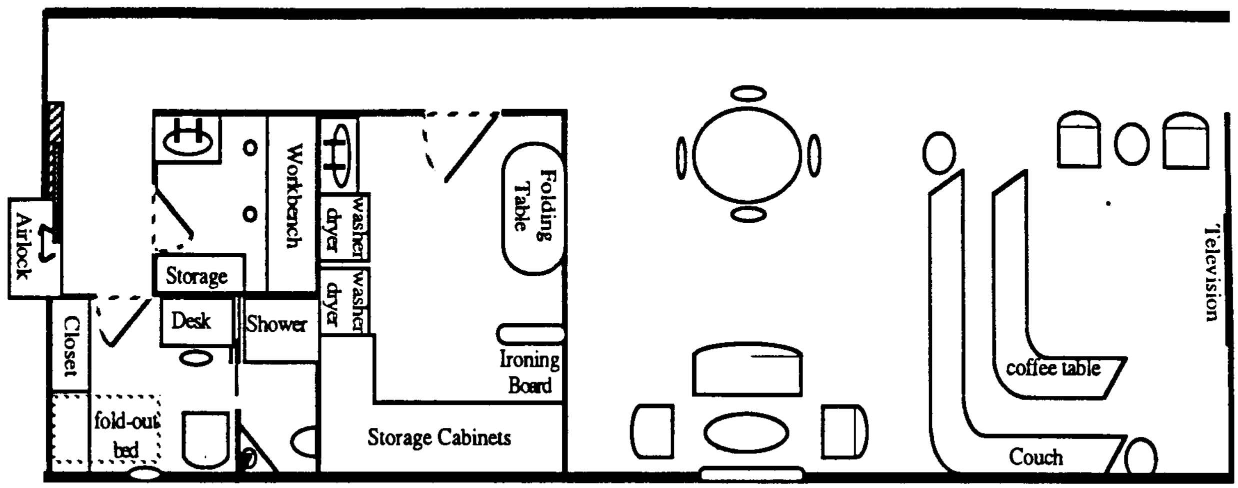
The laundry has all the facilities to clean clothing and linen. There are two stacked washer and dryer sets, an ironing board, and all the necessary supplies. This facility stores enough cleaning supplies to last more than an entire round trip, and will be replenished by Earth at every Earth passing. The crew and passengers clean their own clothing, but will alternate the duty of cleaning communal items such as tablecloths and napkins.

Lounge

The lounge was designed to be spacious and luxurious. The space itself is relatively large, 12.5 m x 7.0 m, but is made to appear even larger with the proper decor. This effect is done by using only light colors, because lighter colors tend to make a room seem larger than darker colors do. Other techniques used are indirect lighting, curved ceilings, and a large spherical window for wide angle viewing. This window is similar to the portals of the crew and passenger cabins in that it is electronically polarized, and the amount of polarization can be adjusted by the viewer. All these techniques make the limited space seem larger than with conventional lighting, ceilings, and dark colors. In addition to making the rooms spacious, however, they must also be uncluttered. The amount of furniture is limited because even when all the above techniques are used the rooms are not spacious if too much is placed in them. There is enough room for everyone to sit comfortably, but there is not any excess furniture. The furniture is also very luxurious and comfortable. It is very important that the passengers and crew are all in a soothing ambience, because they are on the spacecraft for a long period of time.

The lounge is separated into three meeting areas. The first area has a couch and two chairs that surround a flat screened television. This area is used for viewing movies that have been taken on board and documentaries and various other films that are sent from Earth. The second area has a couch and two chairs that surround the large bubbled window. This area allows people to gaze out into the stars and socialize with some of the others on board. The third area is a game table. This area allows people to play card games and board games. The lounge has areas that will satisfy everyone's tastes.

Module D - 22.0m



Passenger Cabin 5.0m x 5.5m | Laundry 4.5m x 5.5m | Lounge 12.5m x 7.0m

8.3.5 Module E

Passenger Cabins

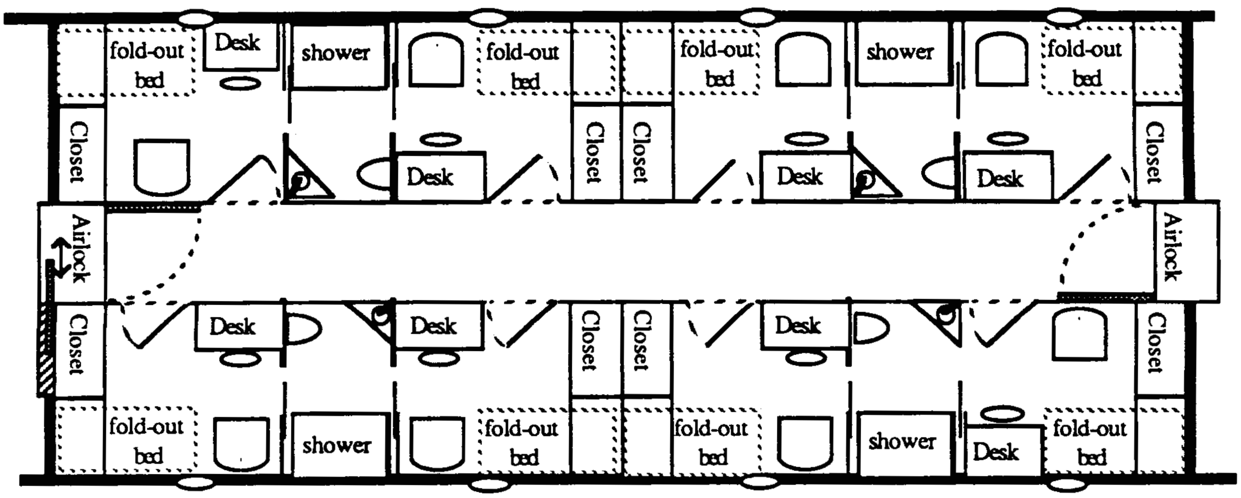
There are a total of 17 passenger cabins in the CASTLE. Every passenger will have a private room and share a bathroom with one other passenger. Because there are an odd number of rooms, one cabin will have a private bathroom. Cabins with a common bathroom will have occupants of either the same sex or married couples. If the numbers do not work out evenly, the extra member of either sex can take the room with the private bathroom.

The private cabins are equipped with a fold out bed, closet, window, desk with a computer workstation, entertainment center and lounge chair. In addition, each passenger will be allowed to bring 50 kg of personal belongings. Having a foldout bed frees up needed space during the day when it is not being used. The beds are also placed along the width of the torus due to a determination by NASA that this was the most comfortable and healthy orientation to sleep in. The window in each room helps to break the confinement experienced in such a closed in space as well as creates a more Earth like environment lessening the sense of alienation. Should the occupant wish to shade the window in the cabin, an electrically polarizable plastic film is sandwiched within the window and all that is required to dim or completely block the window is a turn of the knob. The computer workstation in each room is connected to all three supercomputer systems allowing the passengers to do any computer work from their cabins. All communications can also be done either through the computer system or on the intercom system which can transmit audio and visual. The intercom transmits any visual image over the communication network and displays it on the flat screen monitor mounted over the desk. This monitor acts as an intercom, computer screen and television which is also connected with the main television in the lounge such that movies being shown in the lounge can be viewed in every cabin. The entertainment center is connected to the flat screen monitor for viewing television and movies and incorporates speakers specifically designed for the interior of the cabin which are mounted in the ceiling.

The bathroom between each cabin contains a shower, toilette, sink and storage cabinet. Though small by Earth standards, the layout of the bathroom is such that an individual can move about with relative freedom.

As with all rooms, light colors and indirect lighting are used to create the illusion of space. Ceilings are also peaked at the center to further enhance spaciousness as well as add diversity to the cabins.

Module E-17.0m



Passenger Cabins

3.5m x 2.75m

Bathrooms

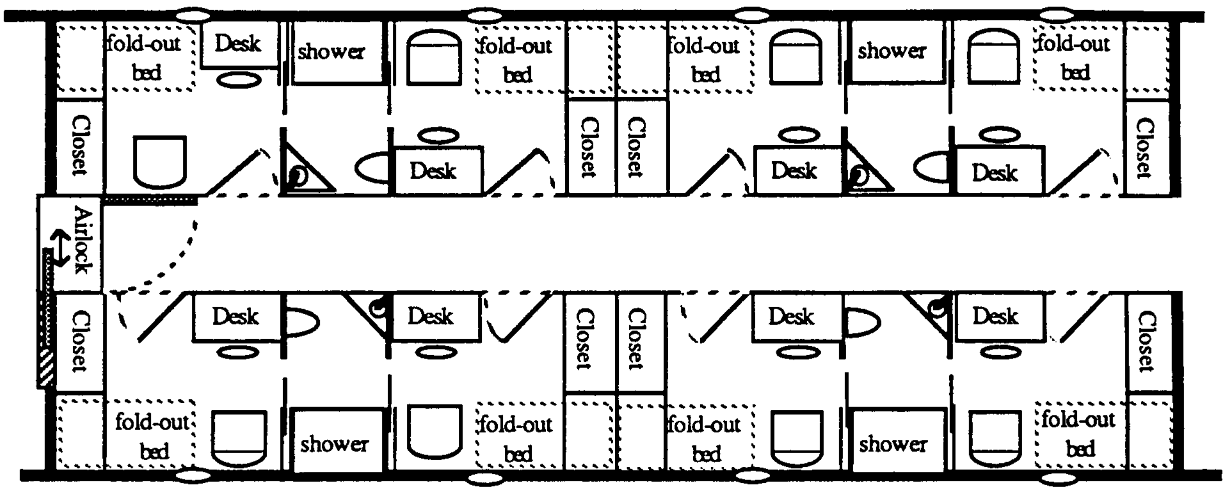
1.5m x 2.75m

8.3.6 Module F

Passenger Cabins

Refer to section 8.3.5 for a description of the passenger cabins.

Module F-17.0m



Passenger Cabins

3.5m x 2.75m

Bathrooms

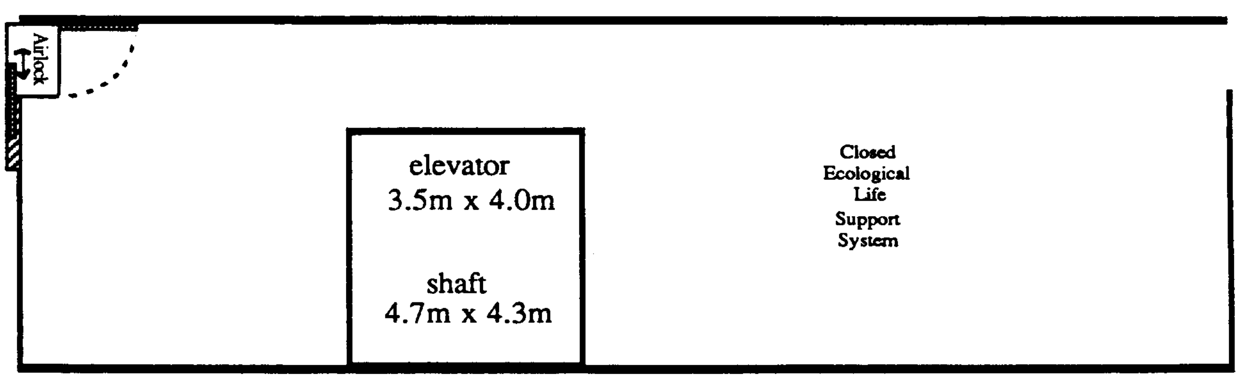
1.5m x 2.75m

8.3.7 Module G

CELSS
Elevator

Refer to section 8.3.1 for a description of CELSS and the elevator.

Module G - 21 m



CELSS
22m x 7.0m

8.3.8 Module H

Airlock

The airlock is an addition to the previous design. It was initially added for the use of the astronauts who assemble the CASTLE in low Earth orbit. It is also used in the event that a problem develops that necessitates Extra Vehicular Activity (EVA) directly from the torus. The airlock will provide access through the "ceiling" of the torus. The centrifugal force created by the rotation of the torus will help to hold the astronaut onto the outer shell of the torus as he moves in and out of the airlock. EVA equipment, including Manned Maneuvering Units (MMUs), is stored here in addition to the Micro G section of the CASTLE.

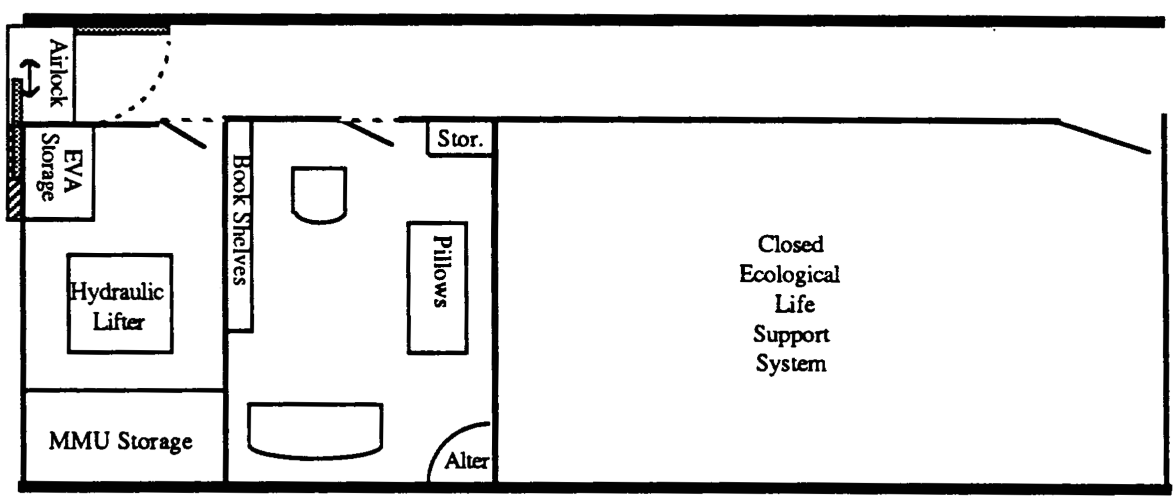
Chapel

The chapel is intended to be a quiet room where passengers may go for prayer or silent meditation. Inside are chairs and pillows for the passengers to sit on and a small altar in one corner. Due to the multitude of differing religions, no religious articles are permanently fixed in the room. It is likely that each passenger would bring his own religious articles among his personal effects, however, there is a cabinet with religious materials on hand. There is also a bookshelf on one wall containing numerous religious writings.

CELSS

Refer to section 8.3.1 for a description of CELSS.

Module H - 17.0m



Airlock 5.5m x 3.0m

Chapel 5.5m x 4.0m

CELSS 10.0m x 7.0m

8.3.9 Module I

Medical Center

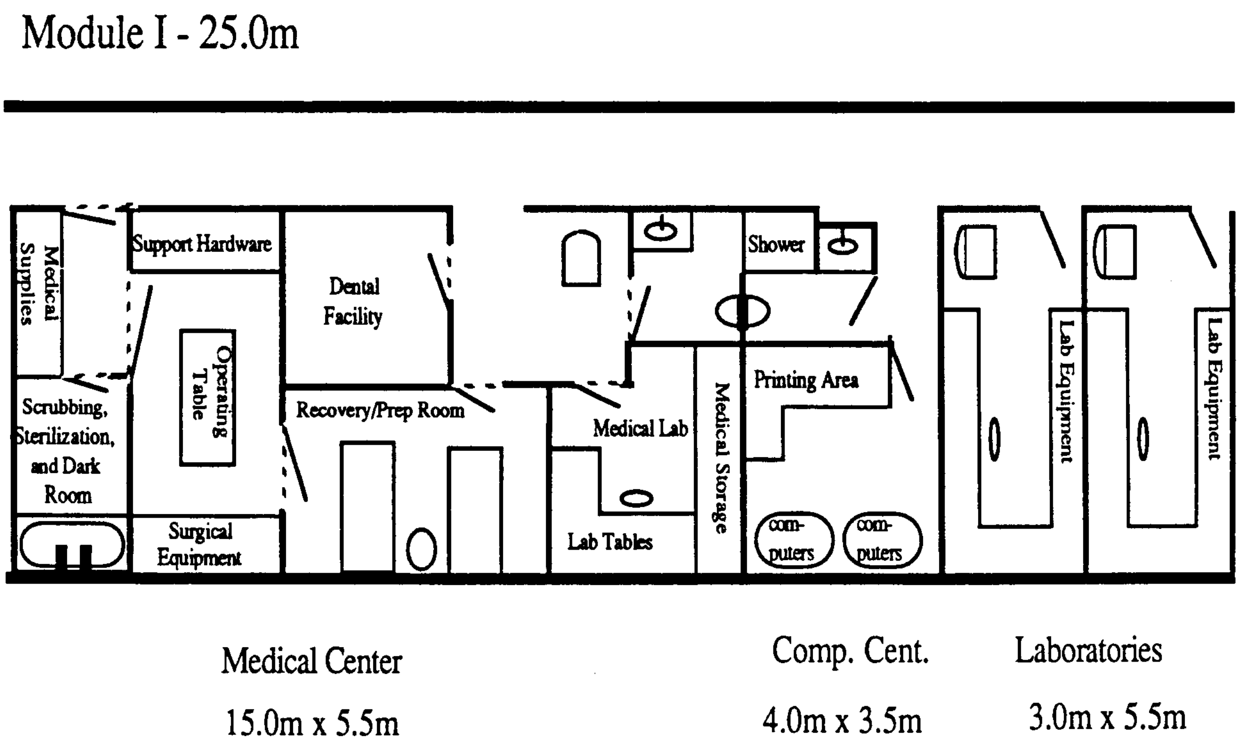
The Habitat is designed with safety in mind; therefore it will be most imprudent not to prepare for injury or at least illness. In anticipation of this, there has been placed on board the torus a rather large medical facility prepared to counter all but the worst possible ailments. The medical center will serve both physiological and psychological needs, providing remedies for routine ailments as well as providing an intangible sense of support by its mere presence. Included in the medical center are surgical, dental, health maintenance and psychological facilities along with all the necessary supplies required for the treatment of any illnesses which could occur during the long voyage between planets. For a detailed description of the medical center, please refer to chapter five of The CAMELOT I report.

Labs

Refer to section 8.3.11 for a description of the Labs.

Computer Center

The computer center is the location for the supercomputers used in the research labs. Each lab, and most of the other rooms as well, has a computer work station linked to the ship's supercomputers. All functions can be done from any of these workstations eliminating the need to go to a centralized "computer lab". The computer center is used primarily for obtaining hardcopy printouts which are not be available at most of the work stations due to weight considerations.



8.3.10 Module J

Recreation Room

From data obtained through both American and Soviet space flight, it has been shown that astronauts must exercise to inhibit muscle atrophy. Calcium loss as evidenced by pre-osteoporitic bones upon astronauts' arrival back at Earth has been a problem even with extended exercise in space. However, this bone loss occurred in a zero gravity environment. The 0.4g environment of our CASTLE provides some stress upon the body against which it must work. It is hoped, but remains to be seen, whether this induced gravity will be sufficient to maintain physical condition.

The Recreation Room includes machines designed to prevent atrophy and bone loss as well as maintain cardiovascular strength by incorporating hydraulic resistance machines, bikes, rowing machines, and aerobic exercise classes. The passengers and crew have to "work out" on a regular basis, including both a strength and conditioning portion as well as an aerobic portion. They will generally have the freedom to choose the time they want to work out and the type of excersise they wish to do. A mirrored wall, mats, music, and a TV are also available in the Recreation Room.

The strength and conditioning portion of a workout is conducted using the hydraulic resistance machines. They are chosen because they are very lightweight compared to free weights, Universal, or Nautilus equipment. Each station works a specific muscle group, and people may have to go through a circuit several times in order to sufficiently maintain their fitness level. The use of resistance machines is an integral and necessary portion of the passengers' activities. They not only prevent muscle atrophy, but stress the tendons and ligaments which in turn strengthen bones.

One can use the Lifestyle bikes (which simulate riding up hills by increasing/decreasing resistance), the rowing machines, or attend an aerobics session for the aerobic portion of one's workout. This excersizes the heart, and a strong heart is needed upon return to Earth, because it will initially be harder for one to pump blood after spending extended periods of time in a 0.4g environment.

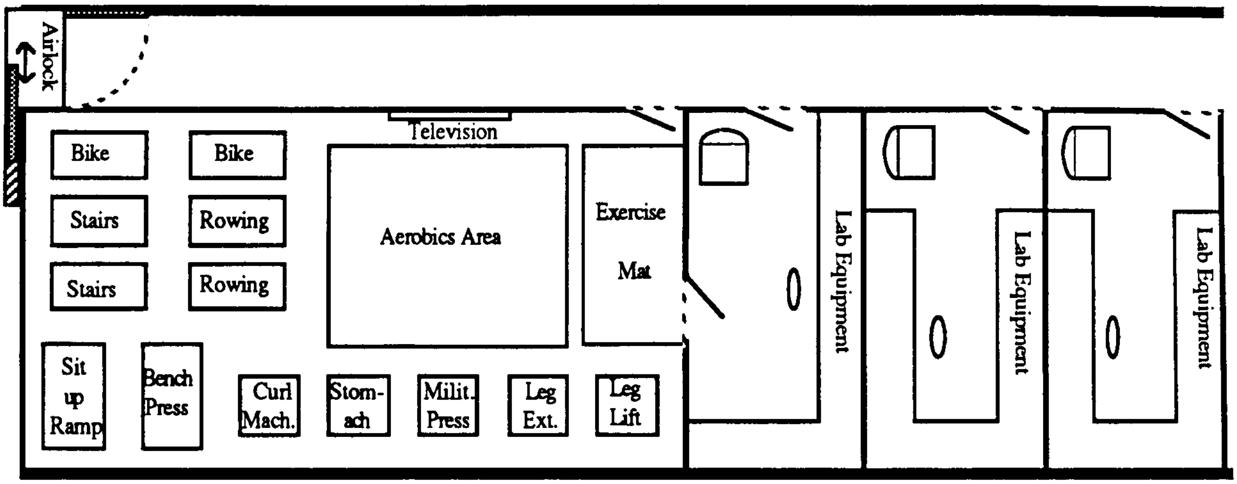
Physiology Lab

Prior to take-off, extensive and rigorous testing are done on the astronauts to determine body composition and fitness level. While in flight, such tests are repeated throughout the trip, providing the first information database on humans in long duration, low-gravity missions. The Physiology Lab, in combination with the Medical Center, is able to perform strength and bone loss tests. Metabolic rates, heart rates, blood pressure levels, etc. can also be determined. These tests will be conducted on a regular basis to monitor improvements, decreases, etc., and recommendations will be given if one needs to alter his/her activities to prevent or reverse a condition.

Labs

Two general science labs are located in this module. Typical work which will be done in these labs is chemistry, biology, physics and materials research.

Module J - 20.0m



Recreation Room 11.0m x 5.5m | Physiology Lab 3.0m x 5.5m | Laboratories 3.0m x 5.5m

8.3.11 Module K

Freezer

The refrigerator is quite large, but there needs to be enough food to feed twenty people for two years, assuming a worst case scenario. No refrigerator can possibly meet these needs, so the large majority of food is frozen and can be defrosted when it is needed. This is done with a huge walk in freezer. The freezer itself takes up as much room as the entire kitchen. There is an easy access door directly into the kitchen which must be kept closed at all times. To maintain food for the long duration, the freezer temperature is kept at or below -32 degrees Celsius. This properly slows down enzyme actions in the meat, and is in compliance with department of health standards.

Kitchen

The kitchen is designed to conform as efficiently as possible to its function. First of all, since it is used on a daily basis to cook for twenty people, it is allotted a large amount of space, seven meters by five and a half meters. It has three entrances/exits, one to the dining room, another to the corridor and a third to the freezer. In the center of the kitchen is an island on which food preparation can be done. The island has a sink as well as a hot plate/food warming capability.

Conservation of space is a primary concern. To make the best use of the space, the function of particular items was consedered. For instance, counter space would be at a premium around meal time so it was decided to suspend a radar range, among other things, from the wall above instead of resting it on a counter. Another consideration was dynamics. How people move around and into or out of the kitchen. Since a great deal of food is coming out of the freezer into the refrigerator, a door was put straight into the freezer from the kitchen instead of forcing someone to go through the corridor.

It was decided to have two basic modes in which the kitchen is used, those being snack mode and main meal mode. For the main meals, there is a rotating duty roster to mandate who is cooking on any particular day. The sink, food prep counter and stoves/ovens are all located in close proximity to limit movement in the kitchen. Food is easily removed from the oven or stove and placed on the food warmer directly behind it.

There is also times when the kitchen is in the snack mode. For instance, breakfast is a meal that people usually eat alone or in small groups. Lunch is the same way, and then there are always people who snack between meals. For these people we have included two main features, a snack bar and a microwave oven. The snack bar enables people to have a quick bite to eat without having to use the dining area. The microwave offers a quick method of warming previously prepared food or doing some quick cooking on your own.

The dry storage area is separated into two areas, one for poisons/cleansers and one for food. This is in accordance with department of health regulations. There is direct lighting in the kitchen because bright lights are necessary for safety. Also for safety, all lights are equipped with light shields to prevent injury from shattered light bulbs.

In addition to the items already discussed above, there are a few other items which are worth mentioning. There is a dishwasher to handle all the dirty dishes produced by meals. This is run daily. There are separate disposal areas for dry and wet refuse. Another very important item is a hand wash sink. This item is often overlooked but is probably the most important item, considering that it is a closed ecological life support system. Every time someone goes to the bathroom, blows their nose or even just wipes their face and then proceeds to handle food which will be eaten by others, they run the risk of transmitting pathological bacteria. This problem is remedied rather well by frequent trips to a handwash sink

Dining/Conference Room

The dining/conference room has two functions. It is used several times daily as the dining room and as a conference room when needed during the trip. To serve these purposes, this room is designed for both uses rather than having a seperate dining room and coference room.

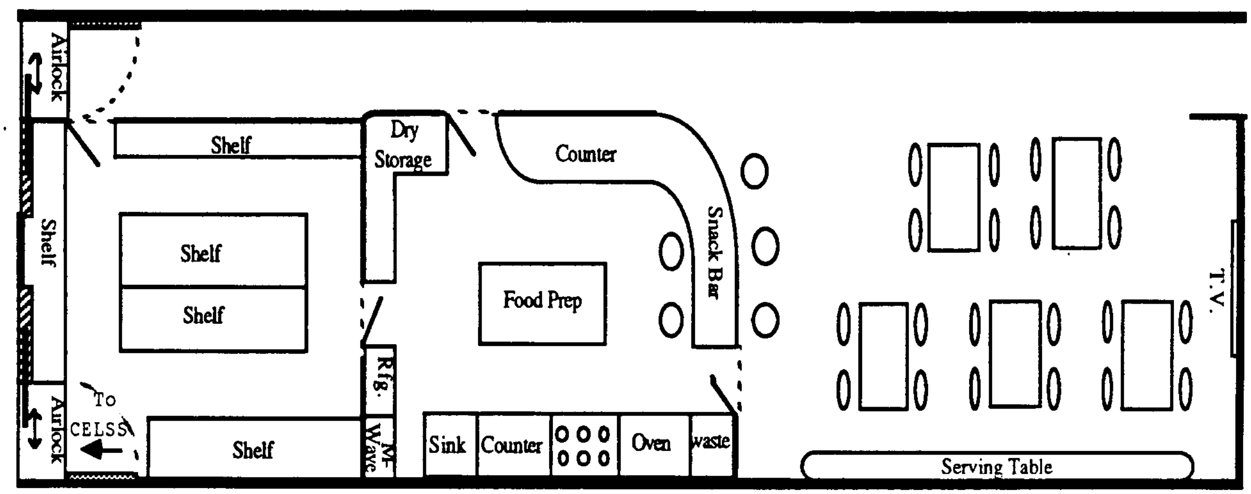
During meals, it is important to be in a comfortable, relaxing and social environment. The dining room has such features. The chairs are cushioned and swivel to provide comfort and ease in getting up or sitting down and are positioned such that when eating, the occupant sits with or against the spin. This is based on research indicating such a need. There is a serving table in the dining room to cut down on traffic into and out of the kitchen. There are hot plates on this table to keep food warm. The food is laid out by whoever has kitchen duty on any particular day. The tables are small, each one accommodating four passengers at a time. This allows people to mingle in small groups. The tables are secured to the floor and but can be moved to accommodate larger parties.

Another important aspect of this dining room is the illusion of space. It is designed to appear bigger than it actually is. This perceived space is a very important aspect from an environmental psychologist's standpoint. Most of the modules have a corridor running through them, either through the center, as with the passenger cabins or along one wall of the torus, as with the crew cabins. In the dining/conference room, however, there is no corridor. This gives the passengers the entire seven meter torus width to dine in. To enhance this spaciousness, there is no wall between the kitchen and the dining room. This allows the passengers to gaze deep into the next room. Also increasing the spaciousness of the dining room is the curved outer wall of the kitchen. Sharp corners delineate space but the gentle curve of the kitchen wall allows a person to literally see around corners and therefore the closed in space is less adequately defined.

Perception is important here also. Bright, glaring lights produce a hostile environment. Soft, gentle lights produce an inviting atmosphere. Indirect lighting is employed here by bouncing the lights off the ceiling and allowing it to reflect to the tables and floor below. The use of mirrors and paintings on the walls also stimulate a lighthearted atmosphere to help battle the fatigues of space travel.

As mentioned earlier, the tables are secured to the floor but can be moved. This serves as a social expansion joint and, more importantly, as a means of converting the dining room into a conference room. Should anyone deem it necessary, all the tables can be moved to form one big conference table. The chairs can swivel so they can all face in one direction. The wall opposite the kitchen (see diagram of module K) has a TV screen which is used to view transmissions from earth, or other news worthy events. Above it is an overhead projector screen which is used for visual aid. Design considerations for the conference room are: ease of configuration, viewing, and sound projection.

Module K - 25.0m



Freezer 7.0m x 5.5m

Kitchen 7.0m x 5.5m

Dining/Conference Room 11.0m x 7.0m

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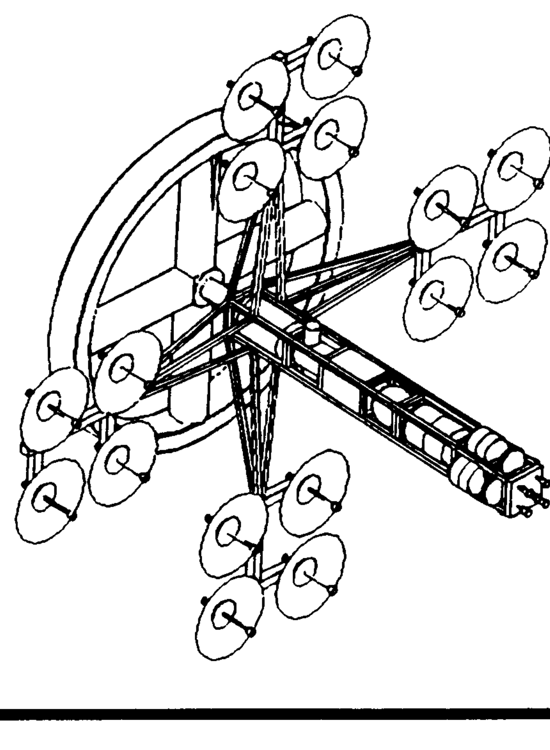
Chapter Nine

Truss Structure Design



9.1 Truss Design

The CASTLE is an extremely complicated spacecraft incorporating a large number of new technologies. As is the case with most state-of-the-art electronics, the systems aboard the CASTLE are extremely sensitive to vibrations and shocks. To protect these systems, a complicated structure is needed. This structure must be able to absorb the intensive compressive loads encountered during insertion into orbit and the moments encountered during orientation towards the Sun without transferring any of the load to the hulls of the modules placed within the structure.

In order to protect the internal systems best, it was decided that the spacecraft should consist of a number of modules loosely connected to each other and held together by a rigid truss structure. This design allows the truss structure to absorb all the loads encountered while the modules within are safely protected by a series of viscous dampers (i.e. shock absorbers).

The criteria established for the design of the truss are:

(1) High stiffness in bending, compression and torsion

(2) Low mass

(3) Easy assembly in LEO

(4) Locations for MRMS tracks.

The design of the solar booms and finite element analysis on the CASTLE were also completed. To arrive at the current designs, the following have been investigated:

(1) The loads applied to the spacecraft

(2) Possible truss structure configurations

(3) Possible solar boom configurations

(4) Material the truss structure is to be constructed from

(5) Design of the individual elements

(6) Finite element analysis on CASTLE

9.2 Loads Applied to the Spacecraft

Once inserted into orbit and oriented towards the Sun, the CASTLE will be free of all propulsive loads except occasional burns to correct the orbit and will, therefore, be safe from damage. While insertion and orientation are taking place, the spacecraft will be subjected to severe compressive loads and bending moments. The most extreme of these forces will be those caused by the engines during initial insertion.

9.2.1 Loads During Insertion

In order to minimize the travel time between earth and Mars, the CASTLE will be placed in a heliocentric orbit that will carry it out of the planetary ecliptic plane. To reach the desired orbit at its present mass of 2.0 million kilograms, the CASTLE must undergo a propulsive load of

603,000 Newtons for 8 hours. The maximum acceleration encountered by the CASTLE will be on average 0.154g. This force was treated as an axially applied static force.

9.2.2 Loads During Orientation

Once inserted into orbit around the Sun, the spacecraft must be oriented with the solar dynamic system facing towards the Sun. To carry out this maneuver, thrusters have been placed on top of the tail end of the spacecraft. Thrusters that generate equal force are placed just in front of the center of mass of the spacecraft but acting in the opposite direction (refer to chapter on propulsion). These thrusters work in a lever and fulcrum manner to force the ship to orient towards the Sun. Similar thrusters are used to stop the rotation of the spacecraft. The thrusters produce 2500 Newtons each and create a bending moment of approximately 100,000 Newton-meters about the center of mass.

9.3 Truss Structure Design

There are several classical truss designs available that are capable of withstanding these types of loads (compressive and bending), but few are suitable for use with loads of these magnitudes. The most suitable geometric shape for the truss design of the CASTLE is a rectangle. This shape allows for the containment of the cylindrical modules in the most effective manner. For the purposes of this investigation, the possible designs have been broken into two subsets: single element designs and four element designs.

9.3.1 Single Element Designs

Single element designs consist of long members on the edges of the rectangle connected by shorter members at periodic intervals. There are three types of single element trusses: single bay-single laced, single bay-double laced and double bay-double laced (figure 9.1). The configuration tested for the main boom used 4 m long, single, solid members along the corners of the boom and used diagonal cross-bracing for support as in the single bay-single laced configuration. Advantages for this setup include low weight, simplicity and a high stiffness. However, difficulties arose when members were removed to open space for the docking tubes and cargo bay because this substantially reduced the strength of the truss. In addition, the structure contained several unrestrained degrees of freedom. Another problem was encountered with buckling in the 9 m long cross-braces. The buckling load was found to be only 6000 N, which is lower than the expected force in these members. Also, a structure was needed for the Mobile Remote Manipulator System (MRMS), which the single member truss could not provide. For these reasons, the single member truss design was not chosen.

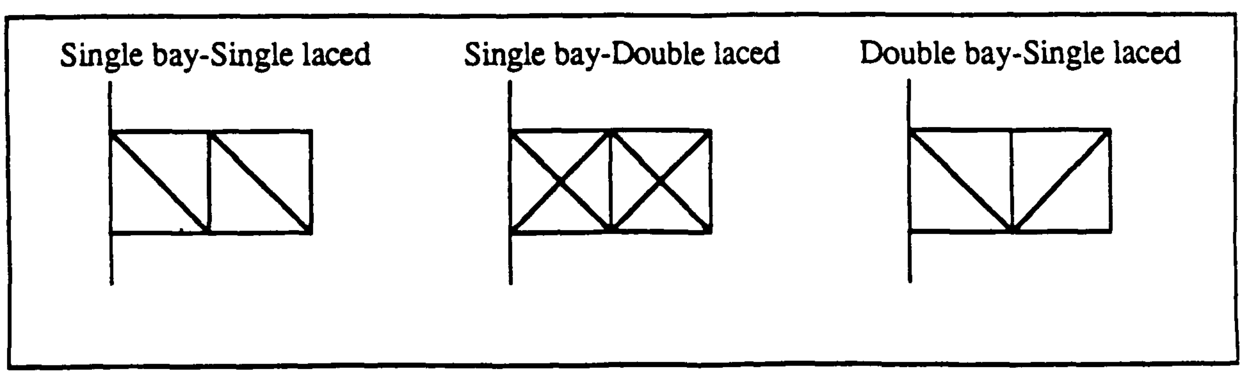


Fig. 9.1 Single Element Truss Structures

9.3.2 Four Element Designs

Since it was apparent that single element designs were insufficiently strong to withstand the forces encountered by the CASTLE, a different type of truss had to be studied. The most useful choice for a rectangular truss is the four element design. The four element design consists of four single element trusses, one along each edge, connected by single element trusses at various places along the length of the truss. Although these trusses are quite heavy, they are several orders of magnitude stronger than single element trusses in compression, bending and torsion. In addition, the rigid edges of the four element trusses provide far better vibrational damping characteristics than single element trusses. Finally, the four element truss structure provides the locations needed for the track that the MRMS move along. The combination of these factors led to the decision to use a four element truss for the CASTLE.

Once the decision was made to use a four element truss, it became necessary to decide what type of structure to use for the edges. Single bay-single lace, single bay-double lace, double bay-single lace square trusses and a single bay-single laced triangular truss were all modeled on the computer and tested for various loads and bending moments. The triangular truss had an unsatisfactorily large deformation when subjected to the bending moments the CASTLE will experience. The single bay-double laced truss deformed least under all the loads but has an increase of mass of nearly 40% over the single laced trusses. The double bay-single laced truss and the single bay-single laced truss were equally strong under compressive loads, but the single bay-single laced truss withstood a bending moment greater than that withstood by the double bay-single laced structure without requiring any increase in the mass of the truss. For this reason, the single bay-single laced, four element truss design was selected for the CASTLE spacecraft (figure 9.2).

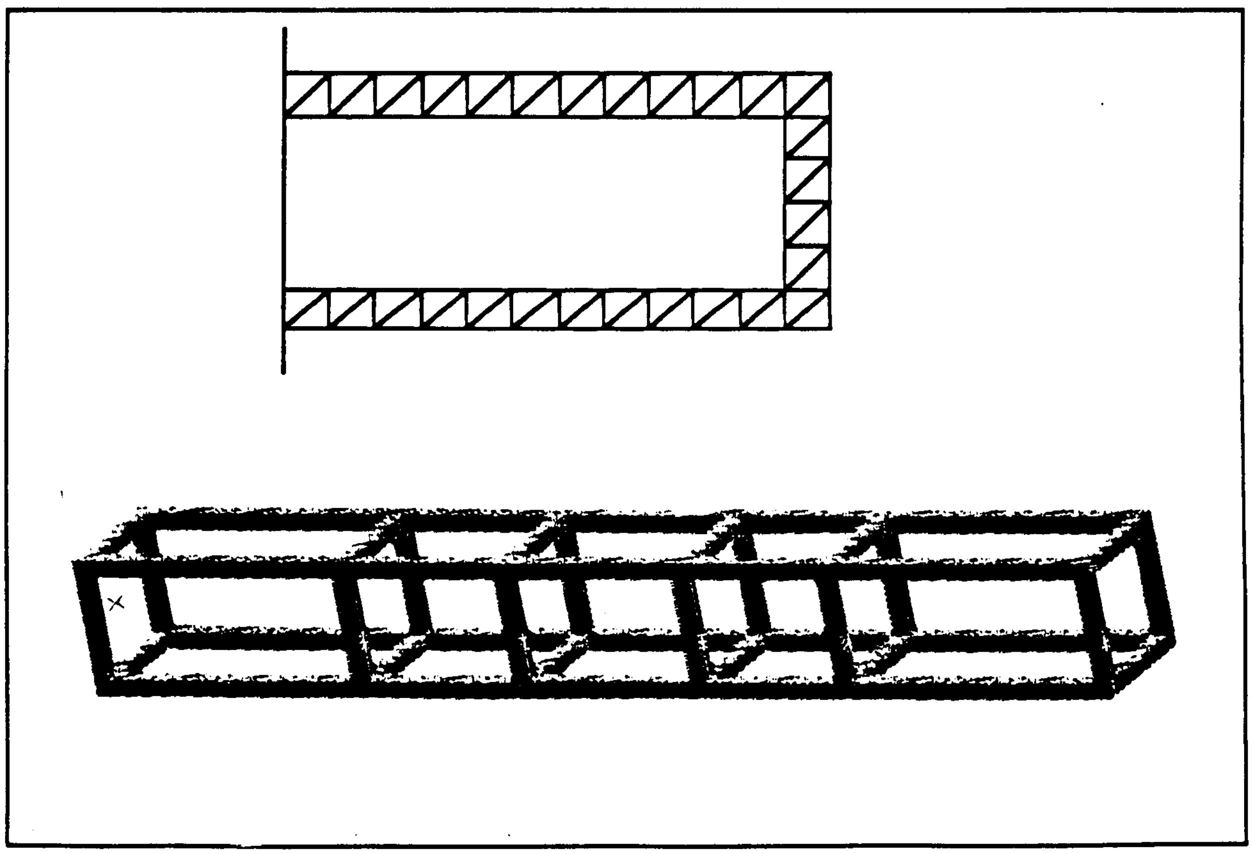


Fig. 9.2 Single Bay, Double-Laced, Four Element Design

It was decided to make each corner truss 1 m square in cross section. These corner trusses are connected at various points along the length of the CASTLE by similar trusses. Connected, the entire truss network has an 8 m square cross section (figure 9.4). This 8 m cross section allows for the containment of the various modules and fuel tanks that comprises the CASTLE's non-rotating section. The modules are connected to the truss at the corners. The connecting elements are viscous dampers that act much in the same way as ordinary shock absorbers. These dampers protect the modules from any perturbations imparted on the truss by the propulsive systems, berthing of the taxies or meteor impacts (figure 9.3).

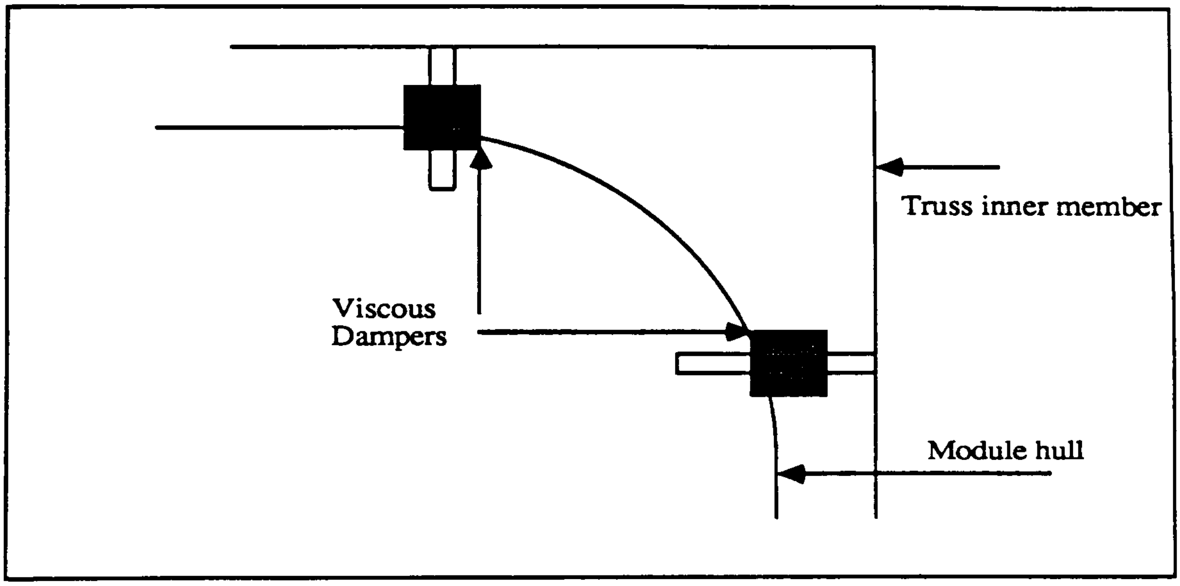


Fig. 9.3 Truss/ Module Connection

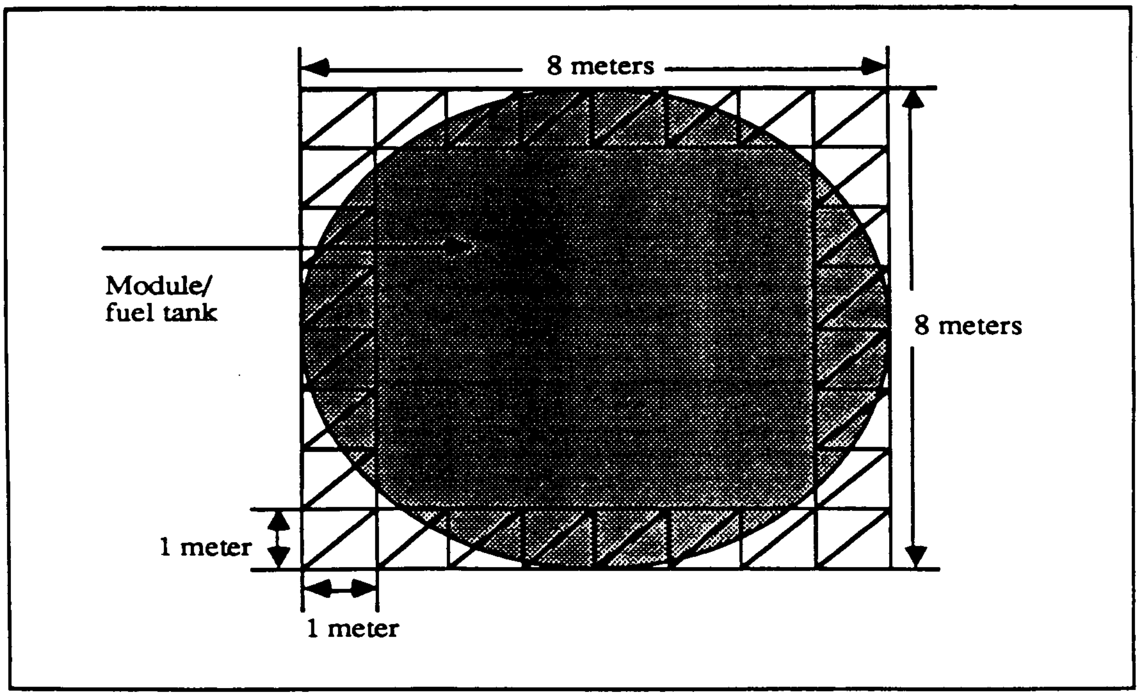


Fig. 9.4 Main Truss Section

9.4 Solar Boom Design

The solar boom truss configuration is similar in design to that of the main truss. Once again, the single bay-single laced, four element truss configuration was employed and successfully stood up under finite element analysis.

Each of the four solar booms consists of four single bay-single laced 1 m trusses identical to those used for the main boom. Using this type of construction, the majority of the elements and nodes throughout the truss are interchangeable. This facilitates truss construction and repair. The only non-standard nodes and elements are those used to connect the solar booms to the main boom and to connect the solar dynamic units to the solar booms.

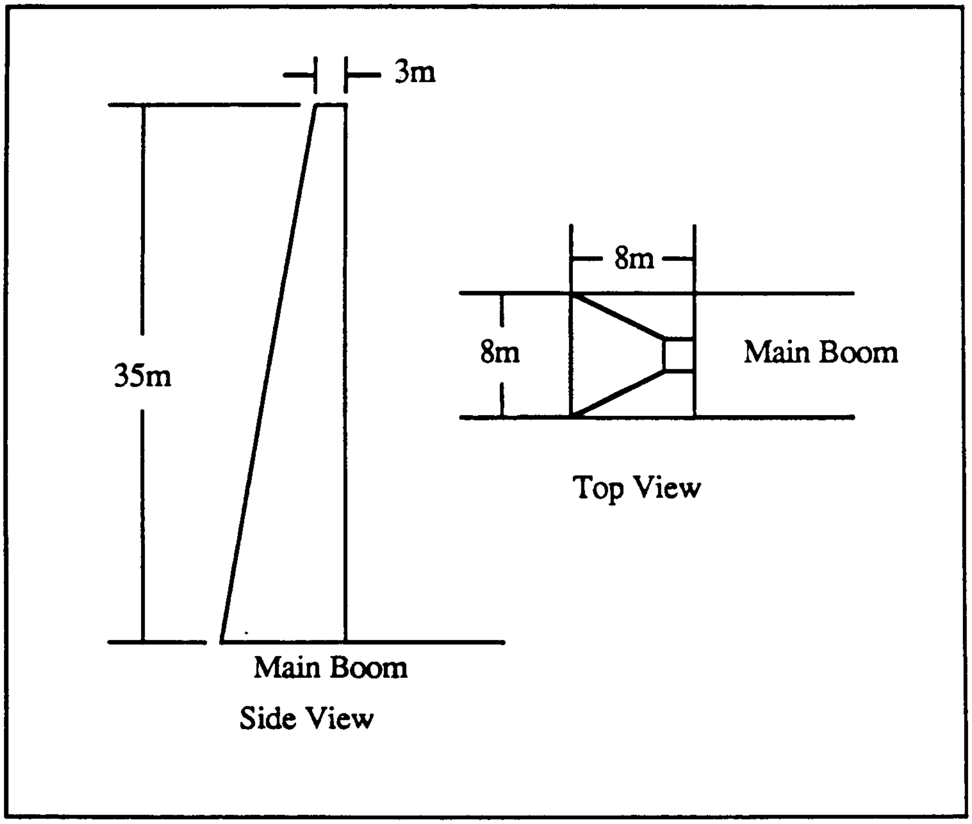


Fig. 9.5 Solar Boom Configuration

The configuration of the solar booms is intended to:

1) Maximize the distance between the solar dynamic units and the torus (to allow the solar dynamic units to rotate).

2) Maximize the distance between the solar dynamic units and the taxies (to allow room for docking operations).

3) Minimize the length of the booms while taking solar dynamic unit shading into account.

Based on these requirements, the solar booms where placed at the interface end of the main boom with the side of the solar boom facing the sun perpendicular to the main boom. The optimal distance from the CASTLE z axis to the solar dynamic unit interface was determined to be 39 m. The resulting solar boom assembly is a 35 m high pyramid with an 8 m x 8 m base and a 3 m x 3 m peak (figure 9.5).

9.5 Construction Materials

Space is one of the harshest environments known to man. Objects in space are subject to extreme cold or heat, intense thermal and ultraviolet radiation and a nearly absolute vacuum. Because of these factors, anything sent into space must be extremely durable. It must have a coefficient of thermal expansion that is nearly zero to prevent expansion or contraction with changes in temperature. It must not become brittle when irradiated and it must be able to withstand very low pressures. For years, aluminum has been the primary building material in space but recent advances in composites have yielded several materials suitable for use in space. Composites can be manufactured today that have several times the strength of aluminum but only a fraction of the weight. The limiting factor faced by manufactures of composites is the cost involved in the manufacturing and molding processes.

Since the proposed mass of the CASTLE is nearly 2.0 million kg, an obvious criterion for truss material selection was low mass. It was also important that the material selected be producible in large quantities at relatively low costs. Research done by the Lockheed Corporation in Burbank, CA suggests that the best way to produce a strong material cheaply is to use a very strong, very thin core layer of composite material clad by a common metal. This creates a material that is strong and light but relatively inexpensive because a large part of it is a common metal.

For the CASTLE, a graphite-epoxy composite clad by aluminum was chosen. This material possesses four times the strength of ordinary aluminum in compression and bending while weighing only slightly more than half. This material has been tested under various types of radiation and has been shown to suffer no degradation in hardness. In thermal tests, the material was found to have a very low coefficient of thermal expansion (figure 9.6).

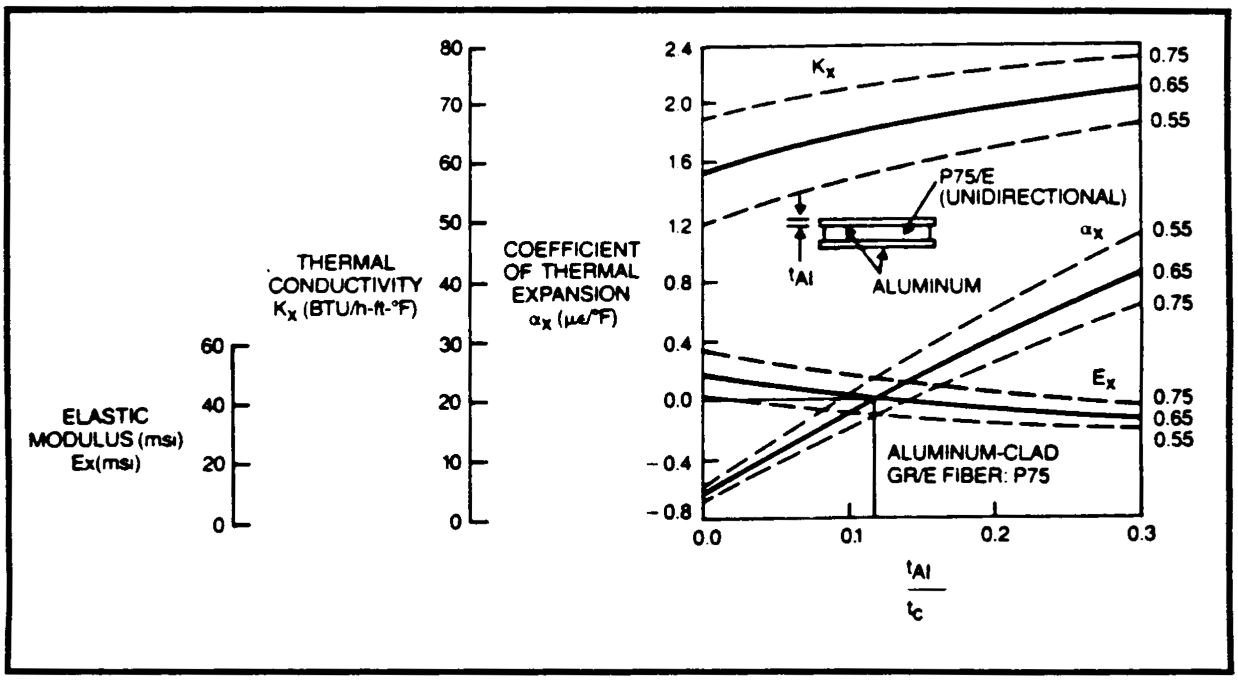


Fig. 9.6 Aluluminum Clad Graphite-Epoxy Composite Characterisitics

9.6 Design of Individual Members

Besides being designed for strength, the individual members of the trusses had to be designed to be handled by the astronauts who will be assembling the CASTLE in low Earth orbit. With this in mind, the individual members of the trusses are 1 m in length and circular in cross section. The outer diameter of the cross section is 50 mm and the inner diameter is 36 mm (figure 9.7). This design allows the members to exceed the strength required in bending, compression and torsion and remain small enough to be handled easily by the astronauts. The outer diameter of 50 mm was selected because it is the diameter of the relaxed hand placed in the glove of a space suit. This further facilitates the construction of the truss in space because it helps reduce the fatigue encountered by the astronauts assembling the truss.

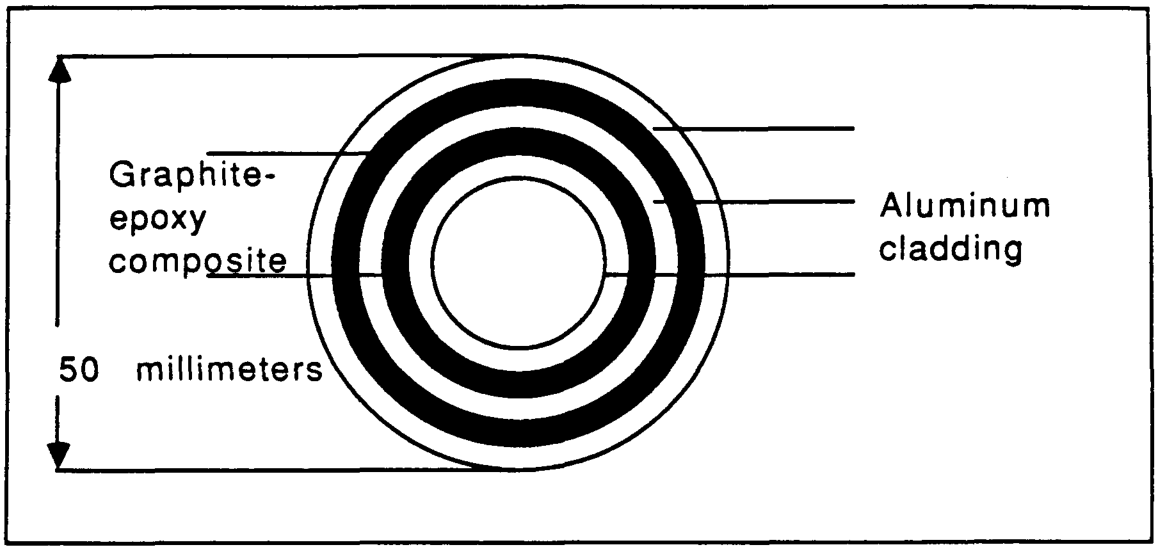


Fig. 9.7 Individual Member Cross Section

9.7 Finite Element Analysis on the CASTLE

In order to verify the structural integrity of the CASTLE and to examine its natural modes, a finite element model of the entire spacecraft was constructed. The model consisted of 467 nodes and 653 elements. The single bay-single laced truss used in the frame was modeled as a beam element with the equivalent properties of the truss. A breakdown of the FE model is given in table 9.1. The model used in the analysis is shown in figure 9.8

The greatest acceleration the spacecraft should encounter is 0.154 m/sec^2. A linear static analysis of the castle under a loading of 0.25 m/sec^2 was performed. Even at this maximum loading, the stresses in the frame were below the yield stress of the aluminum-clad graphite-epoxy. The finite element model that was developed was also used to study the natural modes and dynamic response of the CASTLE.

Table 9.1

Part of CASTLE	Number of elements used	Type of element	Note
Truss structure including solar booms	171	linear beam	equivalent beams approximating the 1 m truss
Torus	108	thin shell	
Spokes	128	thin shell / rectangular	
Hub and Interface	68	thin shell	
Connectors	148	linear beam	connects lumped masses to truss
Solar Collectors	16	lumped mass	2937.5 kg each
Micro-G lab	1	lumped mass	120000 kg
DOC	1	lumped mass	40000 kg
CAB	1	lumped mass	40000 kg
LO_2 tank	1	lumped mass	305900 kg
LH_2 tank	1	lumped mass	52200 kg
Pod LO_2 tanks	4	lumped mass	1400 kg each
Pod LH_2 tanks	4	lumped mass	2500 kg each
Main engines	1	lumped mass	6050 kg

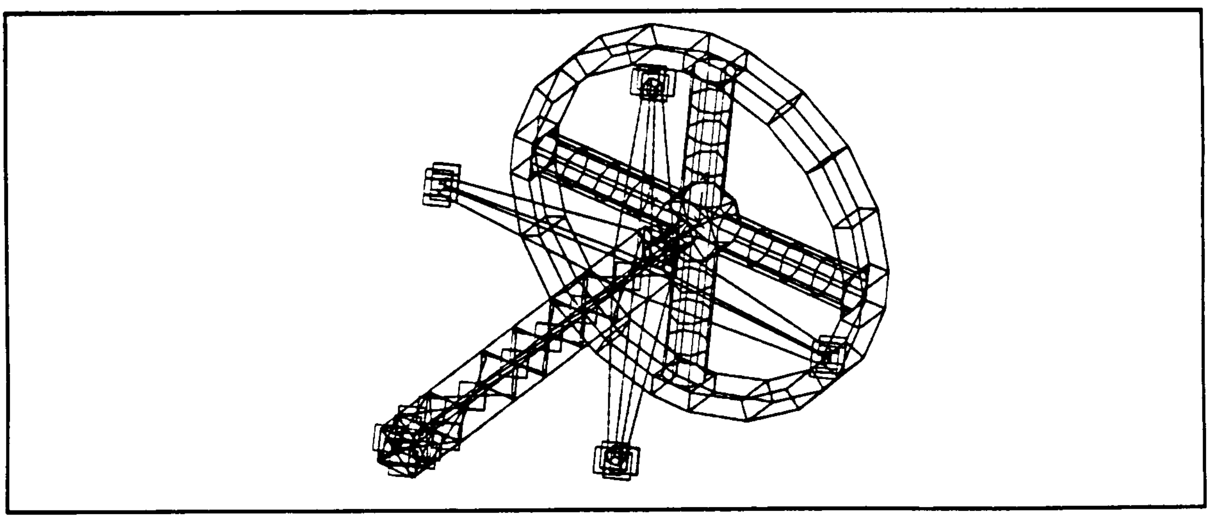


Fig. 9.8 CASTLE Finite Element Model

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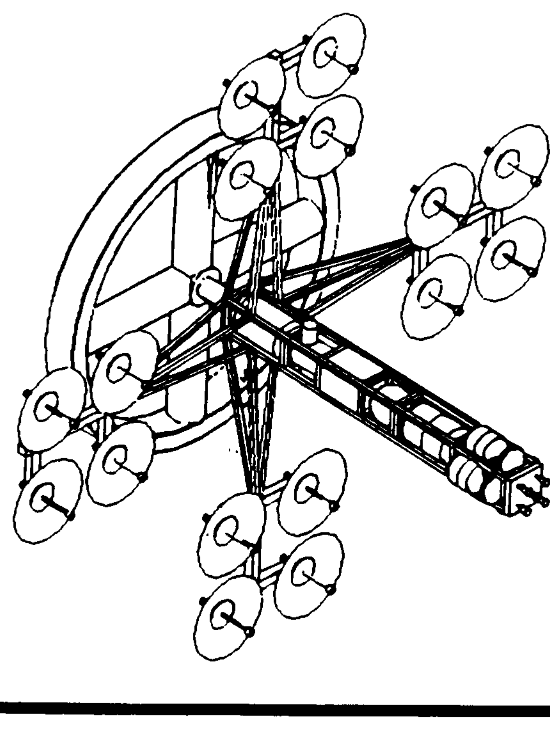
Chapter Ten

Orbital Assembly



10.1 Introduction

As the previous chapters of this report discussed the components that comprise the CASTLE, it is fitting that this final chapter address the task of assembling the CASTLE in space. The Assembly group studied this task. Following CAMELOT I's determination of an assembly site, the CAMELOT II Assembly group's objectives were three-fold: design connections and equipment for the CASTLE's assembly, determination of a component launch schedule, and a cost analysis on the CASTLE.

This chapter discusses these objectives in order following a brief discussion of the assembly site information from the CAMELOT I report.

10.2 Assumptions Necessary to Complete CASTLE Assembly

This report makes certain assumptions regarding the state of technology at the time of the mission. Some assumptions are also made regarding our position in space exploration. The report assumes:

1. The existence of a Heavy Lift Launch Vehicle (HLLV) as described in NASA Memo 86520 (ref 10.1). The HLLV accepts a cylindrical payload up to 50 m in length by 15 m in diameter and has a maximum cargo weight of 209,824 kg. It is capable of boosting this payload to the assembly site in upper Low Earth Orbit (LEO). A large number of these HLLV's are needed, and the existence and use of these vehicles is imperative for the mission to proceed to the orbital construction phase.

2. Robotics and artificial intelligence have developed to the point of acceptable reliability and accuracy. Robotics are used extensively during construction for tasks such as maneuvering large components and making standardized connections. Artificial intelligence plays an important role in controlling these processes.

3. The existence of a lunar base. This base includes a refinery to provide the fuel and oxidizer used by the CASTLE's engines during insertion. This method of providing fuel is preferable to launching it from earth due to the large amounts required, and the high cost of lifting payloads from earth to LEO.

4. The existence of a permanent manned space station. The space station serves as a storage sight, and supplies the construction crew with any perishable items, such as food and water. It also serves as a safe haven in the case of any emergencies that could arise during construction.

10.3 The Construction Orbit

The assembly site is in low earth orbit at an altitude of 1113.6 km and inclination angle of 28.5 degrees to the equator. This orbit was selected after due consideration of the following factors.

10.3.1 Insertion Burn

One of the most important considerations in choosing a construction orbit is the escape velocity, Δv, required for the completed CASTLE to escape from its present orbit. It is desirable that Δv be minimized, keeping in mind all other considerations. At this altitude, a satisfactory value for Δv of 4.65 km/sec is obtained. For further information on the insertion maneuver or the Δv, please refer to the Camelot I Report, or appropriate sections of this report.

10.3.2 Radiation Hazards

Radiation at the construction site is another concern, particularly radiation from two sources: the Van Allan Belts and the sun. Since the radiation shielding that would be provided by the magnetic field from the super conductors is inoperable until the completion of the Castle, some other form of radiation protection would be needed to protect the construction crew. A passive form of shielding would be too costly in terms of weight, and would be redundant after the super conductors were operative. Based on this it was decided that peculiarities in the Earth's own magnetic field would be employed as a type of radiation shielding, rather than providing a shielding of our own.

The Van Allan Belts are regions around the earth where the earth's magnetic field has trapped high levels of radiation. The intensity of the Van Allan Belts, however, varies with both altitude and latitude within the earth's magnetosphere (Figure 10.1). Therefore, if an appropriate altitude is chosen, intolerably high radiation levels can be avoided. The construction orbit is out of the areas of the highest concentration of high energy particles.

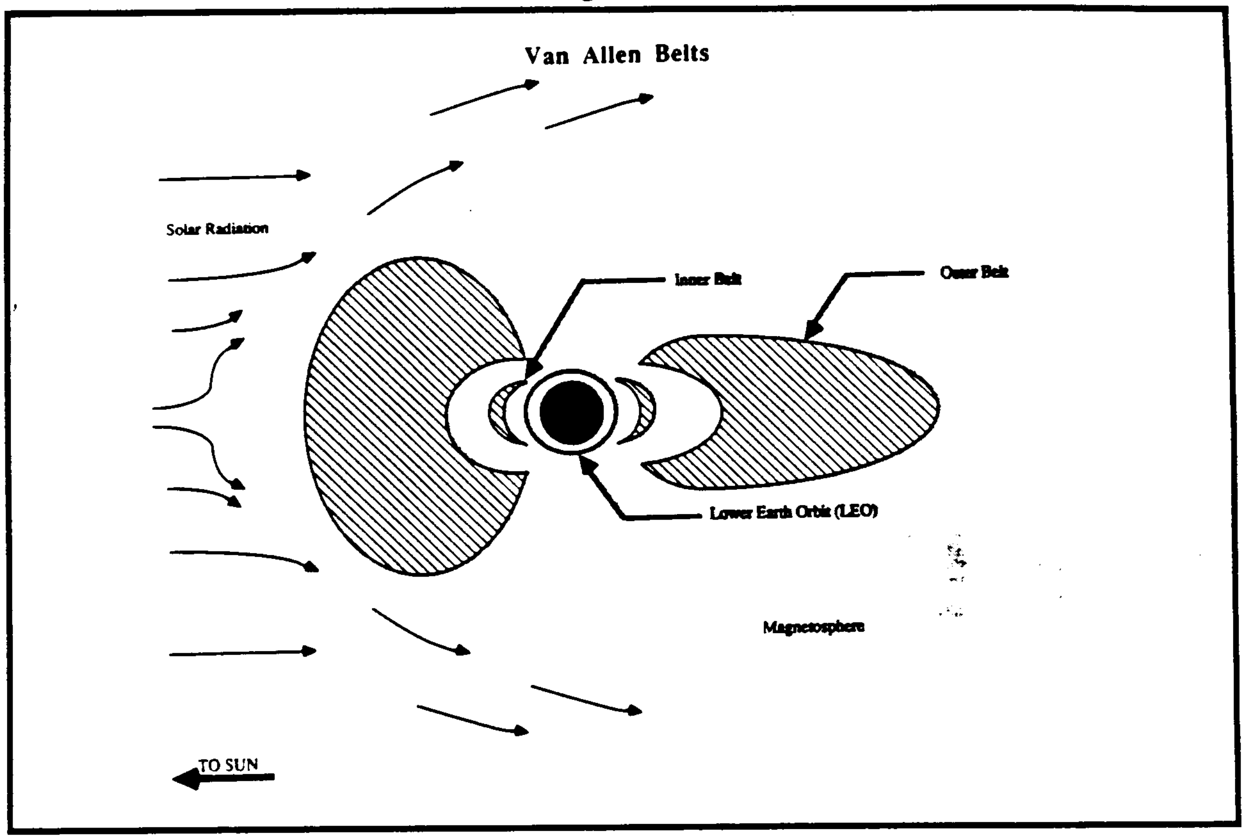


Figure 10.1: The Van Allen Belts and the Earth's Magnetosphere

The radiation from the sun is also avoided by choosing a suitable orbit. Generally, most of the sun's radiation is of low enough energy that the protection of a spacesuit is enough. However, solar flares are an exception to this. Again, the earth's magnetic field provides a solution. At low inclination angles, the radiation from solar flares is deflected away from the earth, and thereby prevents the crew from being exposed to this radiation (Figure 10.2). An inclination angle of less than 60 degrees is sufficient, so that no additional protection is required.

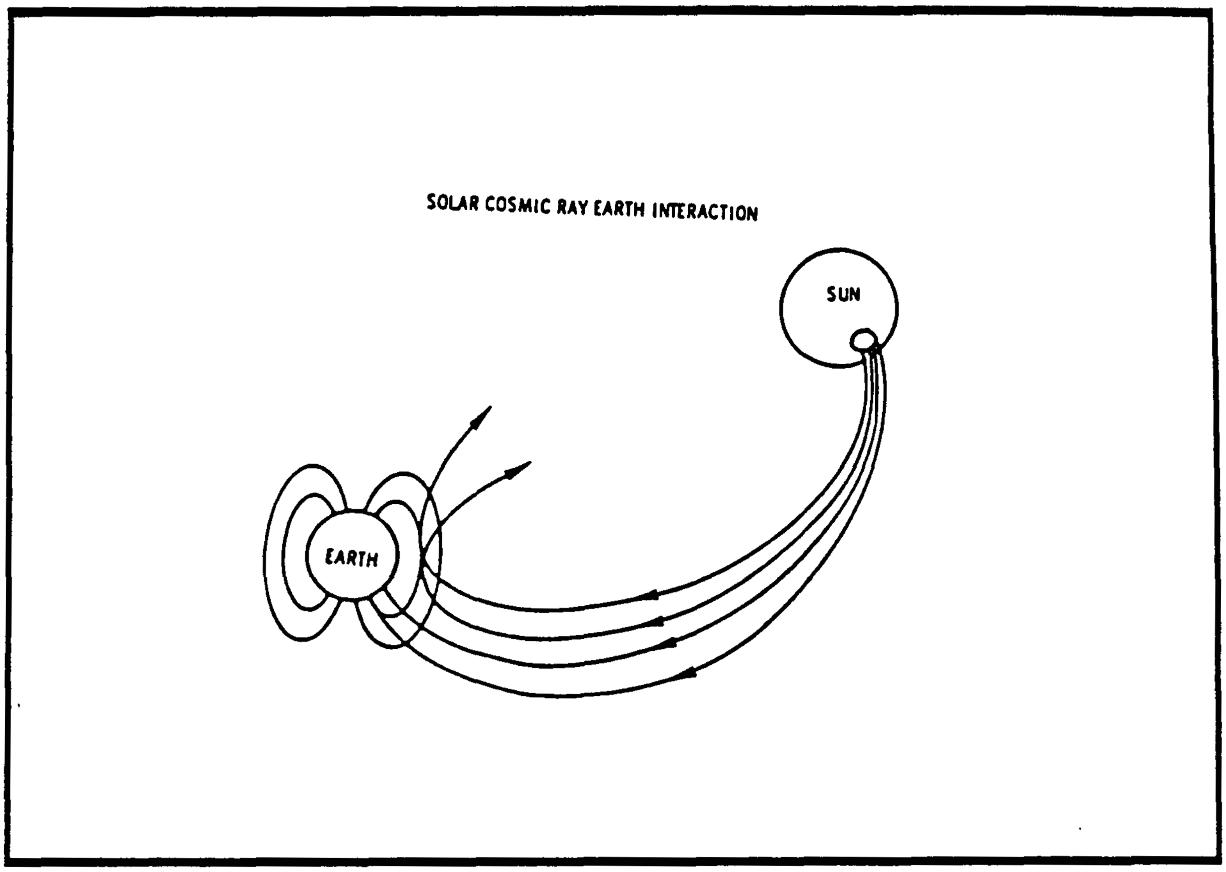


Figure 10.2: Solar Flare Radiation and Low Inclination Angles

10.3.3 Orbital Decay

Since a partial atmosphere extends far above the earth's surface, the CASTLE will experience some aerodynamic drag during its 1.5 year assembly period. Drag should obviously be kept to a minimum so as not to interfere with the CASTLE's orbit. Thus, higher orbits are preferable since they encounter less atmosphere and correspondingly less drag.

10.3.4 Cost of launching

Finally, launch costs were also considered in determining a suitable site. Simply stated, the higher the orbit, the greater the cost of lifting the components to the site (Figure 10.3). In addition, physical constraints imposed by the HLLV limited the altitude to which large components could be sent.

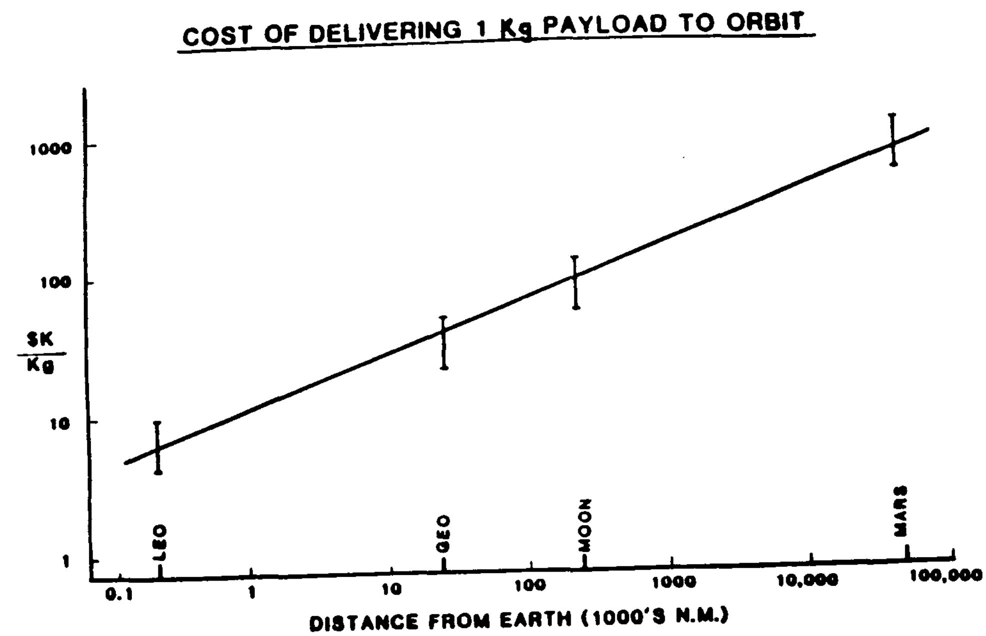


Figure10.3: Launching costs versus altitude

10.3.5 Summary

The assembly site chosen optimizes the above factors. At an altitude of 1113.6 km and inclination angle of 28.5 degrees, the site is a safe distance from the Van Allen Belts yet it remains tucked inside the magnetosphere's solar shielding. Moreover, the escape velocity necessary for the 2.38 million kg craft to escape LEO during insertion will be minimized.

10.4 Heavy Lift Launch Vehicle and Other Construction Equipment

10.4.1 The Heavy Lift Launch Vehicle

The Heavy Lift Launch Vehicle (HLLV) that is used to lift the components of the CASTLE to the construction orbit is outlined in reference 10.1, and illustrated in Figure 10.4. The maximum dimensions of the payload are as shown, essentially a cylinder of 51.21 m in length and 15 m in diameter (Figure 10.5). The maximum weight of the payload that may be lifted to the construction orbit is 209,824 kg, with engines operating at 133%. During the launch, the payload encounters a maximum acceleration of 4.816 g's.

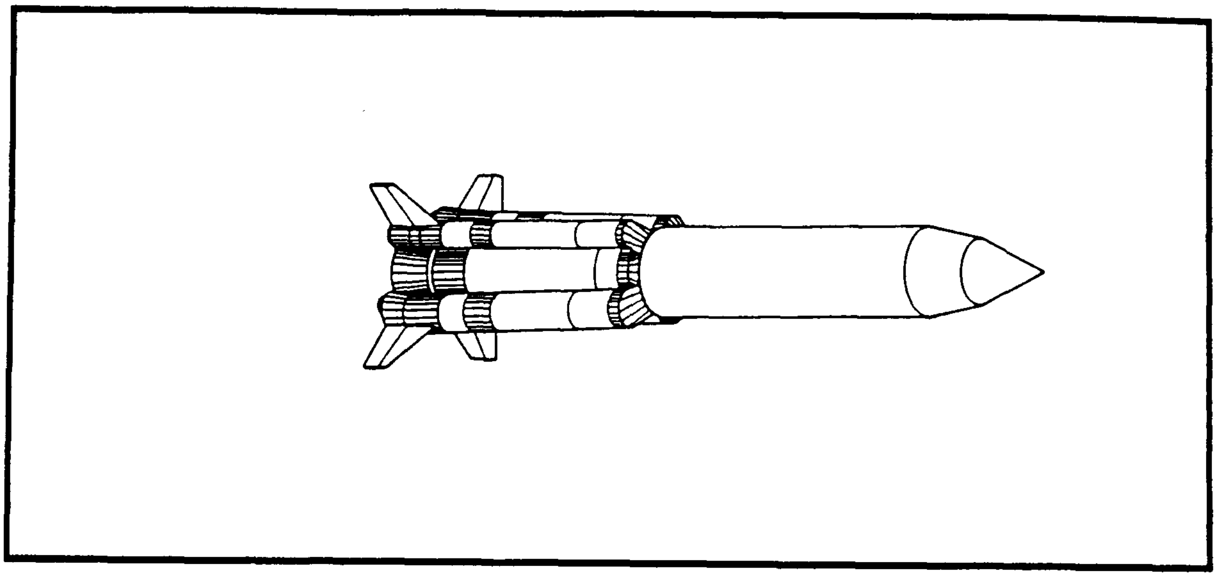


Figure 10.4:The proposed Heavy Lift Launch Vehicle used to lift the CASTLE components to the construction orbit.

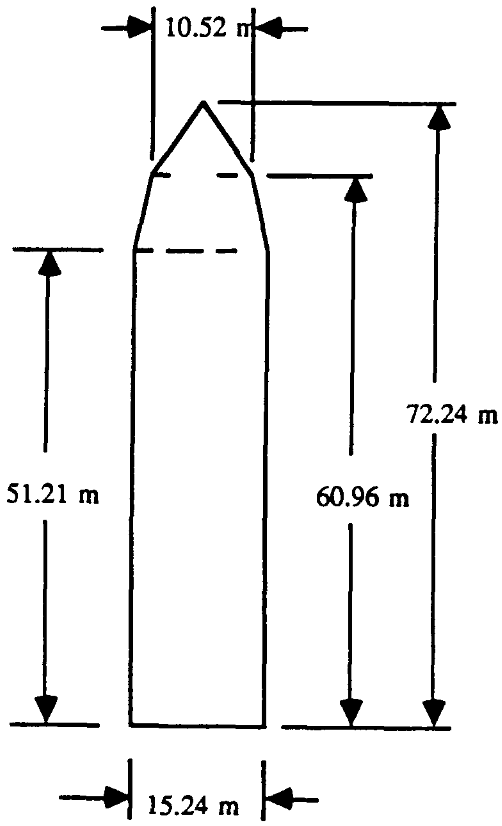


Figure 10.5a: Payload dimensions

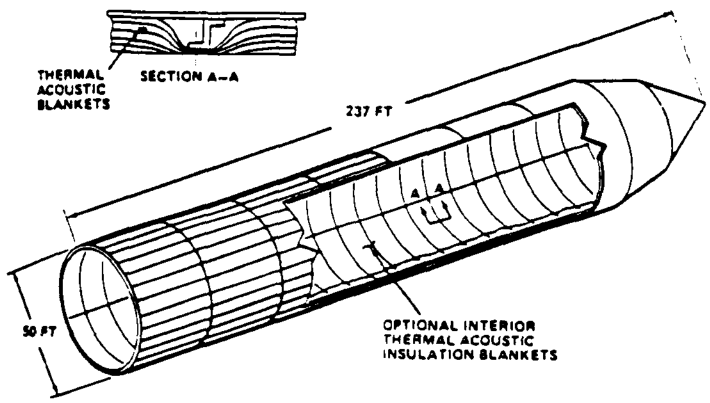


Figure 10.5b: Payload fairing details

There are, however, some modifications to this memo in order to adapt the HLLV to better suit the CASTLE's needs. The HLLV as specified in the memo can obtain a maximum altitude of only 1000 km. In order to deliver the payload to the construction orbit of 1113.6 km, some additional fuel will have to be placed inside the payload area of the HLLV. This fuel will then be used to attain the additional 113.6 km in altitude. The amount of additional fuel is approximately 13600 kg. If still more fuel is required, there is a 15% contingency mass built into the center core stage of the HLLV itself. This would amount to another 7300 kg available for fuel and tanks. This additional fuel would be sufficient to lift 209,824 kg to 1113.6 km.

The launch sequence has also been changed in order to minimize the amount of additional fuel that is required. In accordance with reference 10.1, the HLLV is launched from the Florida peninsula, Point A (Figure 10.6). However, instead of cutting the engines for injection into a 185.5 km x 1000 km orbit, the extra fuel is used to boost the HLLV into a 185.5 km x 1113.6 km orbit, as seen by Point 1. The center core stage engines are then used to inject the HLLV into this 185.5 km X 1113.6 km elliptical orbit. The center core stage engines, along with the P/A module, are then released at Point 2 and the payload will orbit the earth until Point 3, where the kickstage will inject the payload into a 1113.6 km by 1113.6 km construction orbit.

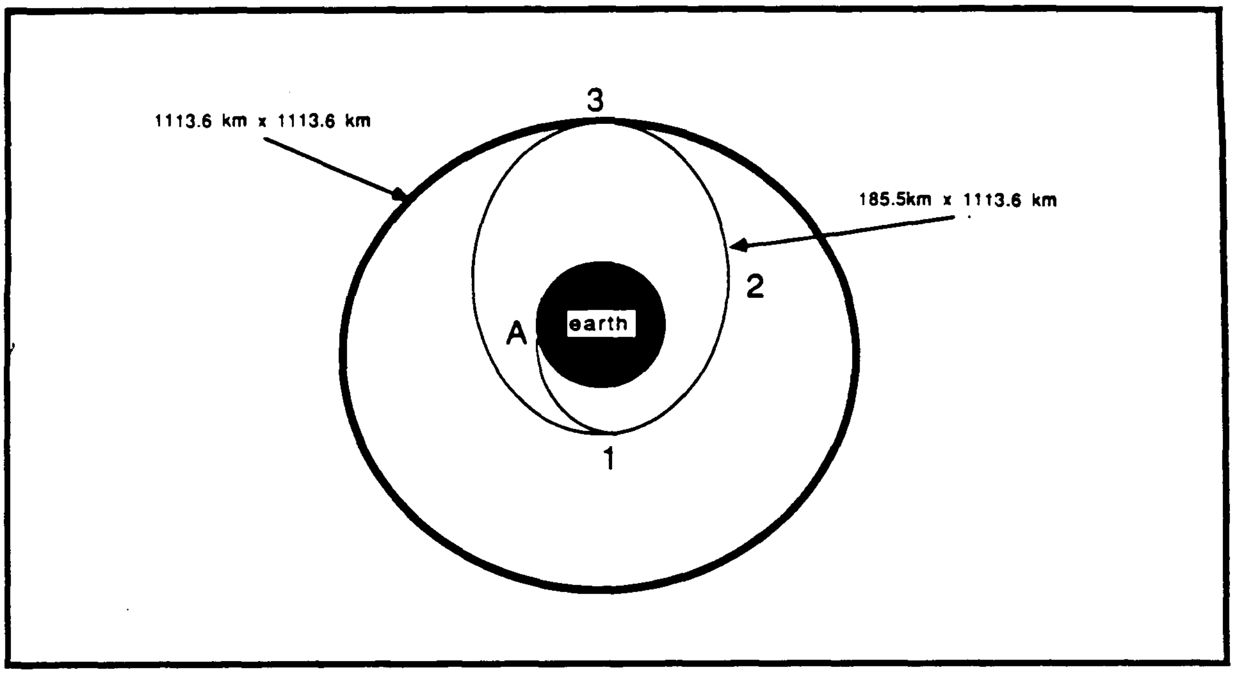


Figure 10.6: Modified HLLV orbit
A launch from Florida
1 inject at 185.5 km x 1113.6 km
2 payload separation - loss of P/A module
3 kick stage ignites, injecting to 1113.6 km x 1113. km

10.4.2 Construction Cranes

One of the most important types of construction equipment required for the CASTLE's assembly is a large crane (Figure 10.7). Two cranes have such varied duties as moving CASTLE segments into position, removing the HLLV payload from the vehicle (Figure 10.8), and clamping and securing components.

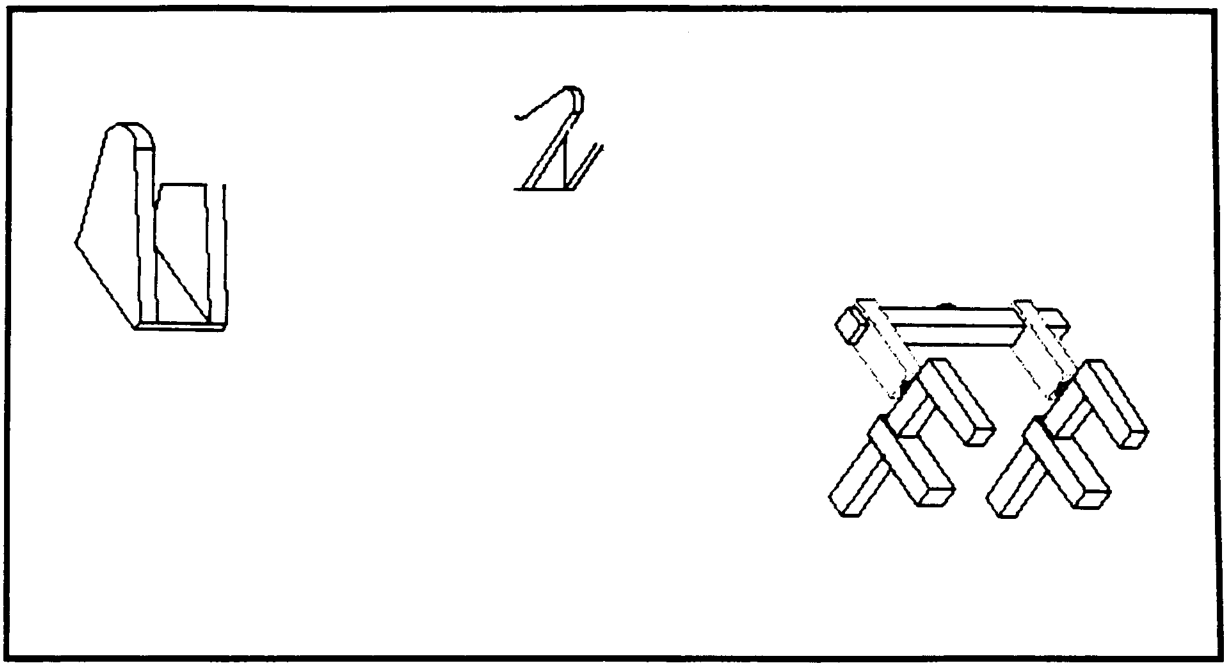


Figure 10.7: The crane used in the CASTLE assembly. It aids in many functions, including grabbing and moving CASTLE components.

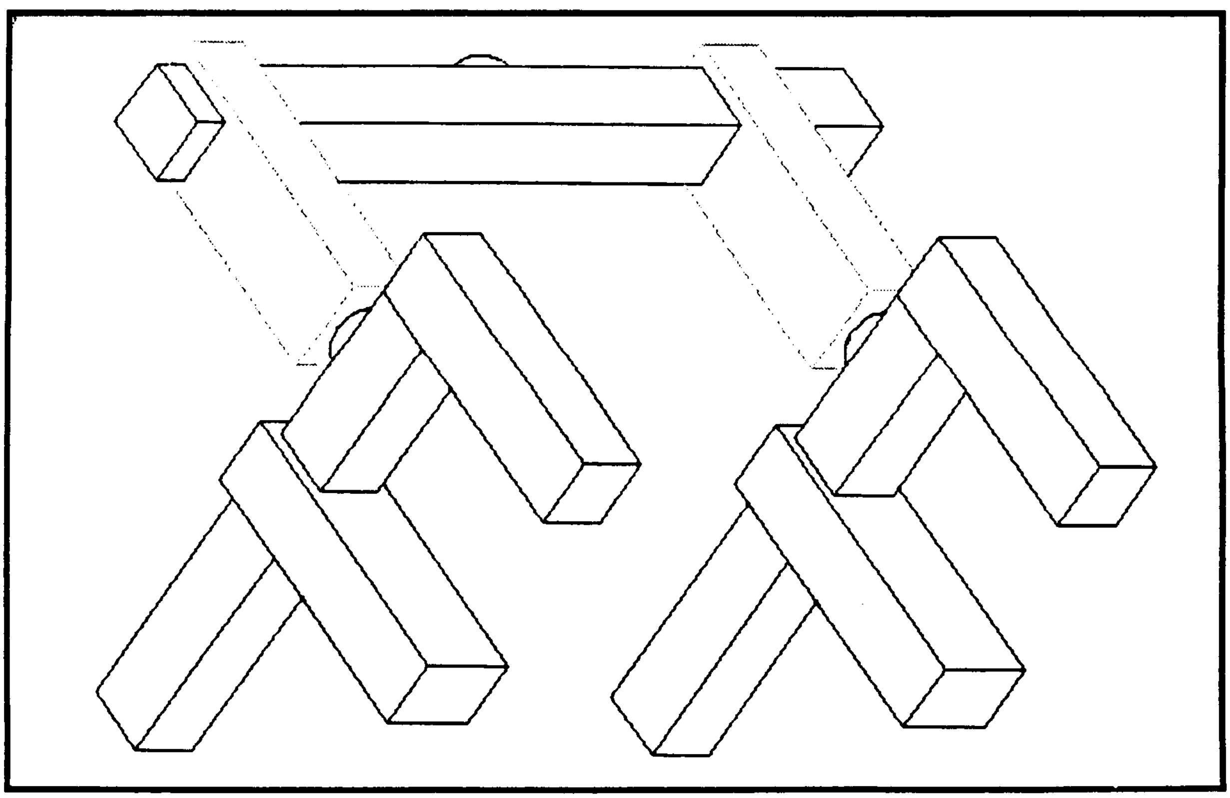


Figure 10.8: The manipulator. It is used to grab onto the CASTLE components and place them into position.

The cranes are very similar to cranes used here on earth. They are hydraulically operated as they must apply large forces. The hydraulic pumps are run by electric motors, powered by the solar dynamic units during sunlit periods, powered by batteries during shaded periods. The cranes move on a track located along the CASTLE, and thus are able to assist in any required location.

10.4.3 Orbital Maneuvering Vehicle

Orbital Maneuvering Vehicle's (OMV's) are used during construction to assist in moving and aligning the CASTLE components (Figure 10.9).

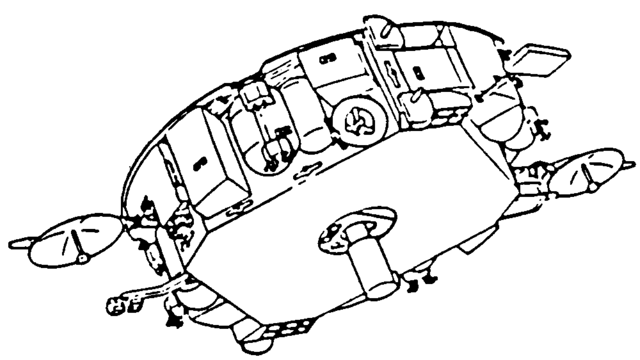


Figure 10.9: The Orbital Maneuvering Vehicle (OMV) used to aid in the CASTLE assembly

10.4.4 Crew Habitat Modules

Two space station habitat modules will be delivered to the construction orbit via the space shuttle and serve as the crew quarters and command center until the Castle is nearly complete (Figure 10.10). Only when the torus ring is nearly completed can the crew move into the Castle.

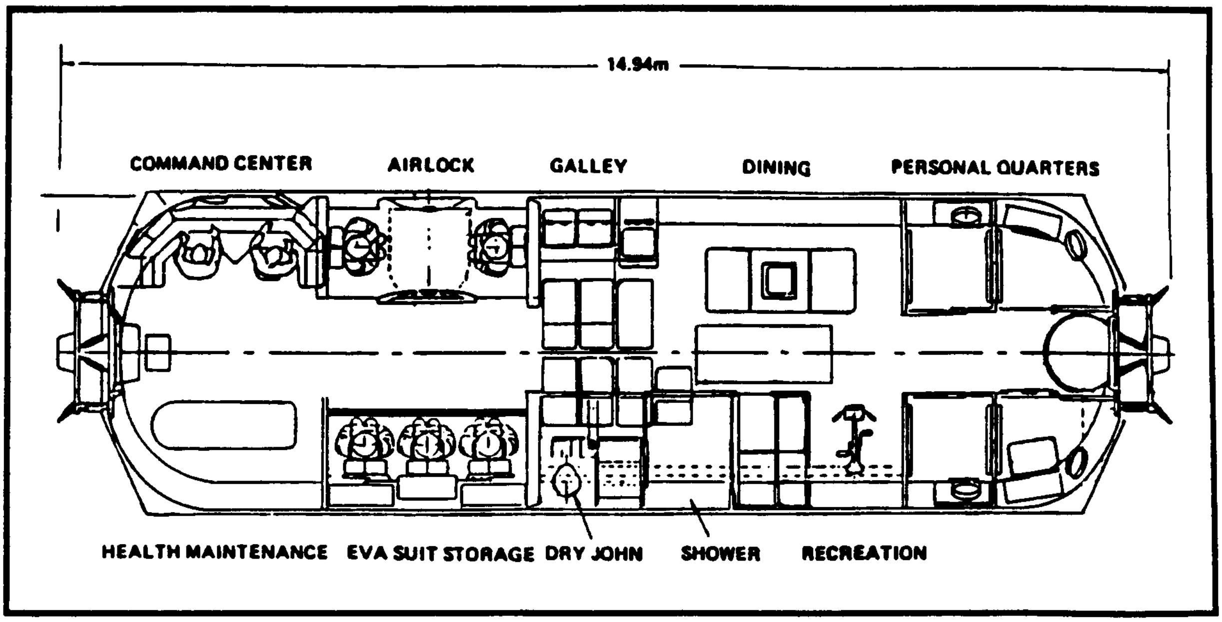


Figure 10.10:The habitat module (designed by Boeing) used to house the assembly crew during the construction of the CASTLE.

The habitat modules used have been designed by Boeing for use in the space station. They are basically a self contained home and work area for up to three people. Each habitat module contains personal quarters for three, a lavatory, a command center, an airlock, etc. There is also storage for three EVA suits. Access to the habitat module is through a module-to-module berthing interface, (Figure 10.11). This interface is used to join the modules to each other, as well as to the hub of the torus.

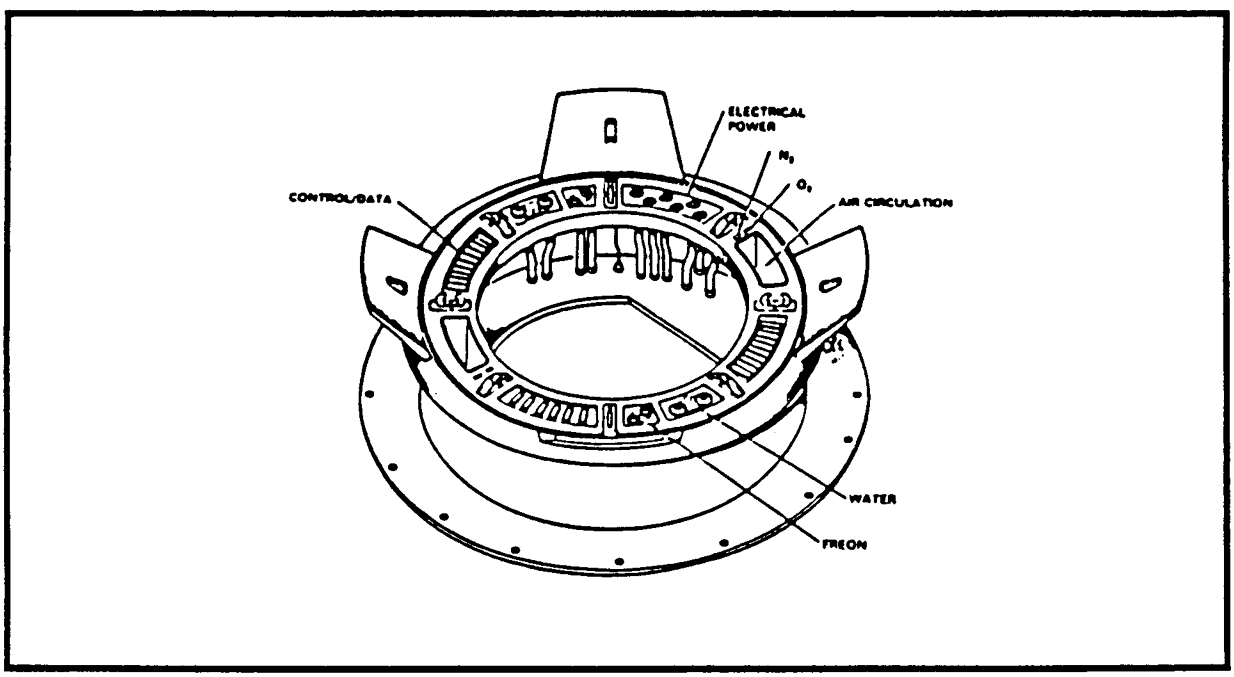


Figure 10.11: The Berthing Interface connecting the habitat modules together, as well as to the hub.

The use of these habitat modules is a matter of convenience. The crew could either stay in these modules, or in a section of the torus. If they stay in the torus, a torus section must be one of the first pieces that is brought to the construction orbit. This piece would have to be severely modified, however, if it were indeed to be used as the crew quarters. This is because no single torus section has everything required by the crew. If the section has three rooms for the crew to sleep in, then it does not have a command center. If the section has a command center, it has no airlock, and so forth. The habitat modules are specifically designed to be self contained and are ideal for our purposes.

The habitat modules also provide a very convenient location from which all EVA will originate. Each module contains both an airlock and EVA suits. Later on, once the docking module is installed, EVA may proceed from this location also. No other airlocks will be operational during the construction phase, simply because they are not needed.

10.5 Construction Procedure

Due to the mass and volume constraints of the HLLV, the CASTLE must be assembled from smaller, connectable components. Depending upon the component, different attachment techniques are used to secure the connections. These attachments include torus section to torus section connections, spoke to torus connections, spoke to hub connections, truss connections, and solar boom connections. The various connections are detailed in the following sections.

10.5.1 Torus Assembly

The 11 modules of the torus fit together in a chain-like fashion, one piece on the end of another (each of the 11 modules has been given a letter to identify it - see Figure 10.12). In order that the last module is able to slide in place, the torus is cut into pieces along a meridional plane (Figure 10.13). This plane is defined by the axis of rotation of the torus and a line radially outward from this axis. This allows the last piece to be slid in to complete the ring without any interference from other modules.

Each module is connected to the next through the use of a sliding sleeve on the outside and locking rods within the walls. Spring loaded pawls in the outer wall move up into notches on the underside of the ring to secure the connection. The rods originally serve to keep the modules perfectly aligned, but then lock to help secure the joint. The crane is used extensively on torus assembly both to position the torus modules and to complete the locking process.

A torus connection proceeds as follows. The crane positions itself at the edge of the assembled portion of the torus and, using its clamps, grabs the new module by its lock blocks. At this time, the module's sleeve is in the retracted position as are the four rods on the partial torus. The crane, with the aid of an OMV, then draws the new module to the end of the partially completed torus. The new module is laser-aligned into position, and the rods are remotely inserted into four alignment holes in the new module. At this time, the new module may only move directly toward the partial torus - lateral motion is prevented by the four rods.

The crane then releases the new module, since it can no longer drift away, and grabs the sleeve. The sleeve is then pulled over the connection until its rear contacts a stop on the new module (Figure 10.14). The sleeve continues to move with respect to the rest of the torus, however, and the new module moves with the sleeve. Upon additional force from the crane, the new module compresses a gasket on its end which begins sealing the joint. With further compression, the spring-loaded pawls embedded in the torus module pop up into catches in the sleeve. Upon locking the four rods remotely, the sleeve is now firmly anchored to both modules and the joint is complete (Figure 10.15).

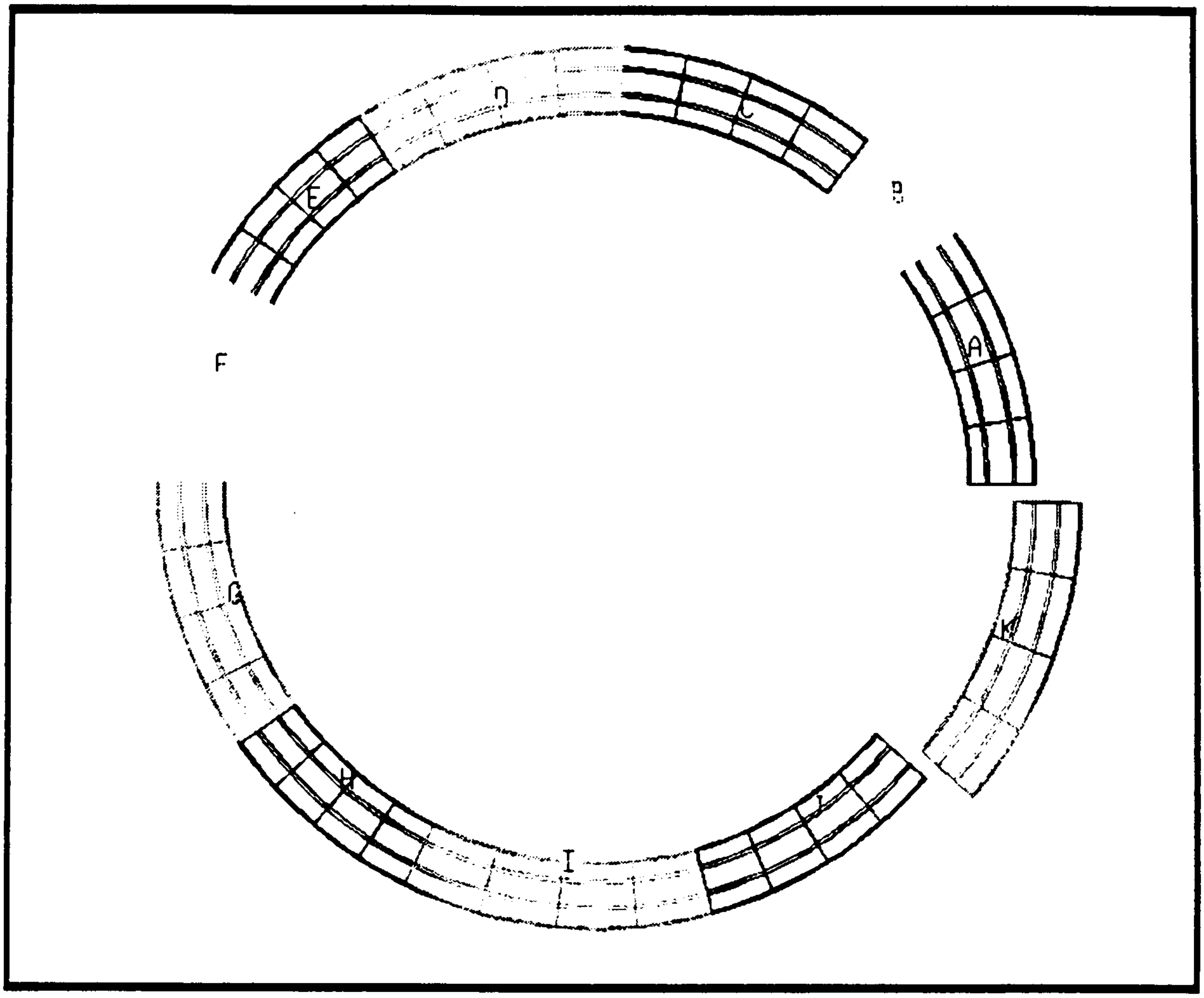


Figure 10.12: The torus

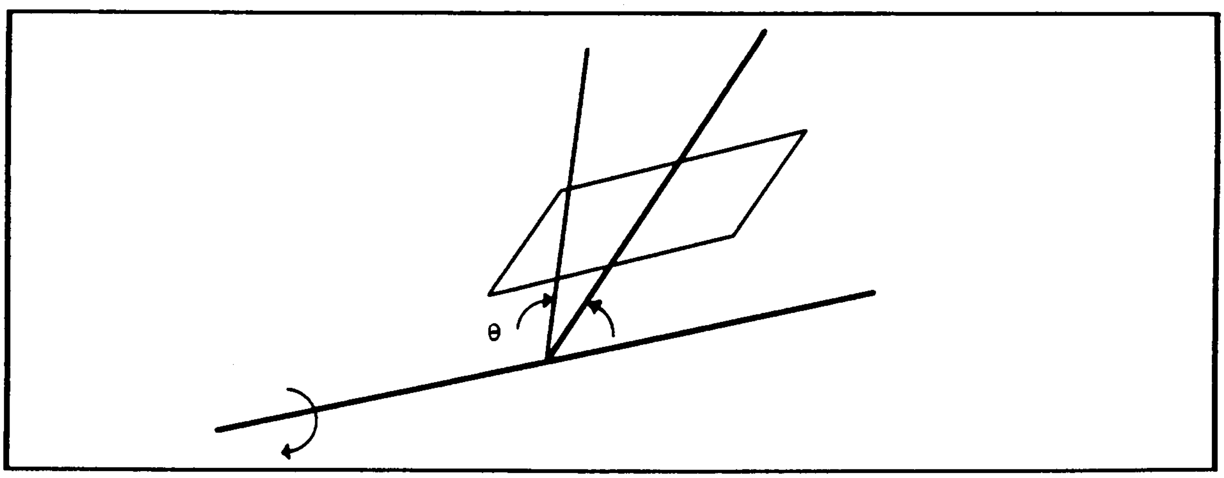


Figure 10.13: Meridional plane used to define the torus cut

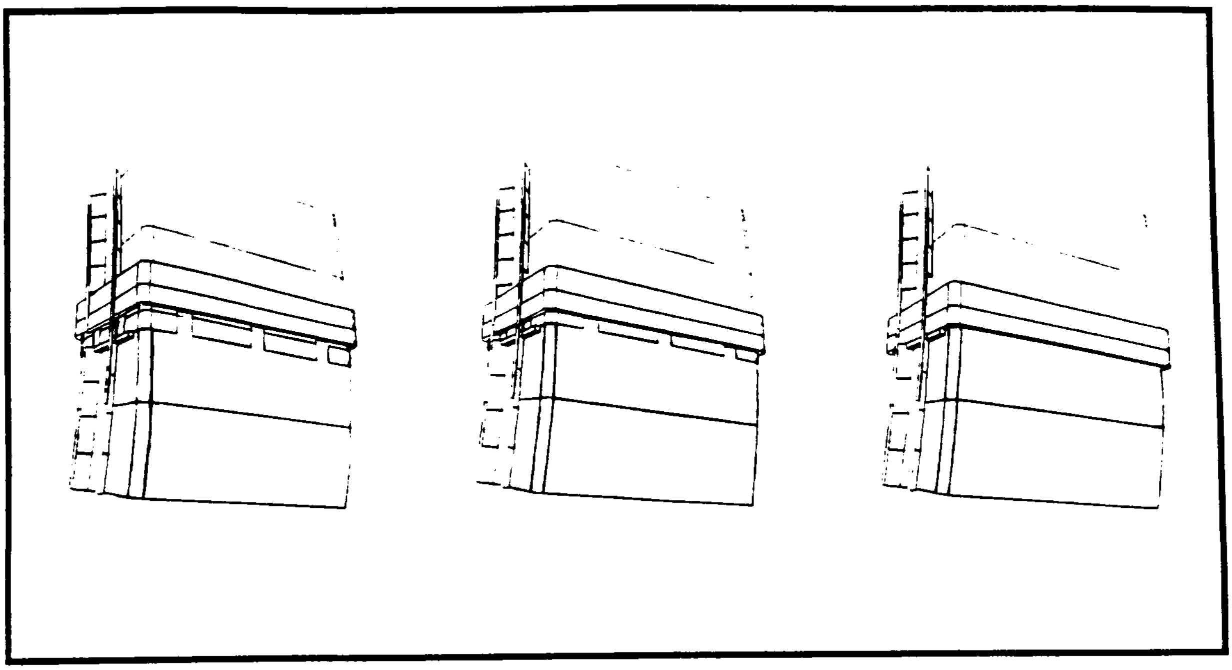


Figure 10.14a: A typical torus connection, with the sleeve in the retracted position. Note the crane track on the side of the torus.

Figure 10.14b: The sleeve has been partially slid to the closed position.

Figure 10.14c: The sleeve is in its closed postition, and the joint is complete.

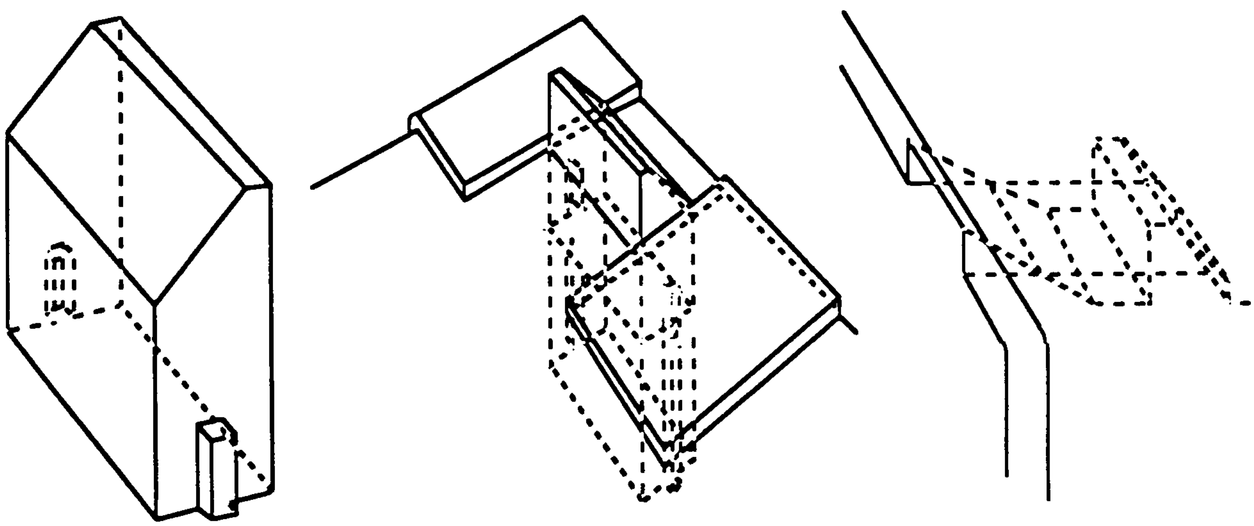


Figure 10.15a: The lock block.

Figure 10.15b: The lock block in the torus section.

Figure 10.15c: The block slot in the sleeve.

To help visualize this process, an analogy is appropriate. Consider a normal room door and its jamb. The above sleeve models the jamb, and the module is the door. As the door is swung shut, the spring-loaded latch is forced back into the door due to the angle at which the latch hits the jamb. When the door is closed all the way, the latch springs back into a catch in the jamb, and the door cannot be opened. The same happens with the torus connection. As the sleeve slides over the module, it pushes the lock blocks back into the torus until the blocks can spring back out into catchs in the sleeve. The only difference here is that the modules must be pressed tightly together before the lock blocks can spring out.

Electrical and other connections within the torus are now completed from inside the torus, either above the ceiling, or below the floor. Many of the connections can be of the type that are completed simply by joining the torus modules together. Metallic pads on the end of the modules cross the gap, and carry the voltage to the next module.

10.5.2 Spoke and Elevator Shaft Assembly

The elevators are contained within two of the four spokes. Before launch, the elevator is secured inside the spoke and end caps are placed over the ends of the spoke. The end caps serve to protect the elevator components from damage by flying objects, such as ice particles and micro-meteors.

The entire assembly, spoke and elevator, is launched as one unit. Once at the assembly site, the spoke is joined to the hub before the appropriate torus segment is connected onto the end of the spoke. Minor electrical connections at both ends of the spoke conclude its assembly.

The actual connection of a spoke, however, requires some detail as it serves a number of important functions. The design of the spokes is driven by three major requirements. First, a spoke with a circular cross section is desired to maximize its shear strength and resistance to bending yet minimize its mass. However, since the rectangular elevator shaft is to be located along the wall of the torus, the spoke required a square cross section near the torus. Lastly, the connection of the spokes to both the torus and the hub must be easily accomplished, yet be very strong and durable.

The final spoke design meets all of the above criteria (Figure 10.16). To optimize strength, a circular cross section of 7.5 meters - the width of the torus - is utilized for most of the length of the spoke. At a distance of 1 m from both hub and torus, the spoke cross section transforms to a 7.14 m x 7.14 m x 0.10 m thick square (Figure 10.17). The spoke ends then fit snugly inside similar square sockets (7.50 m x 7.50 m x 0.18 m thick) mounted on the inside of the torus ring and on the outside of the hub. The sockets contain the fastening mechanisms to secure the connections. A smaller rectangular cross section offset from center extends into the torus. This 4.3 m x 4.7 m x 0.1 m thick extension serves as an elevator shaft, and contains the elevator rails and an air-tight doorway which exits to the habitat hallway.

The fastening mechanism in the square cross-sections is designed to allow simple, quick, reliable connections. It consists of eight spring-driven pawls - two on each side - secured to the inside walls of the square sockets. Matching notches on the outer walls of the rectangular sections of the spoke accommodate the pawls.

The assembly scenario is as follows. First, the spoke is connected to the hub. Next, a crane positions the torus module near the end of the spoke. Following removal of the socket cover plate, the crane places the square socket over the end of the spoke and continues inserting the spoke until all eight pawls have locked into their appropriate notches. At this time, the spoke/torus connection is permanently fastened and the crane may begin securing the module to the rest of the torus via pulling the ring over the torus connection. Upon securing both ends of the segment, the elevator may safely traverse the spoke and enter the torus.

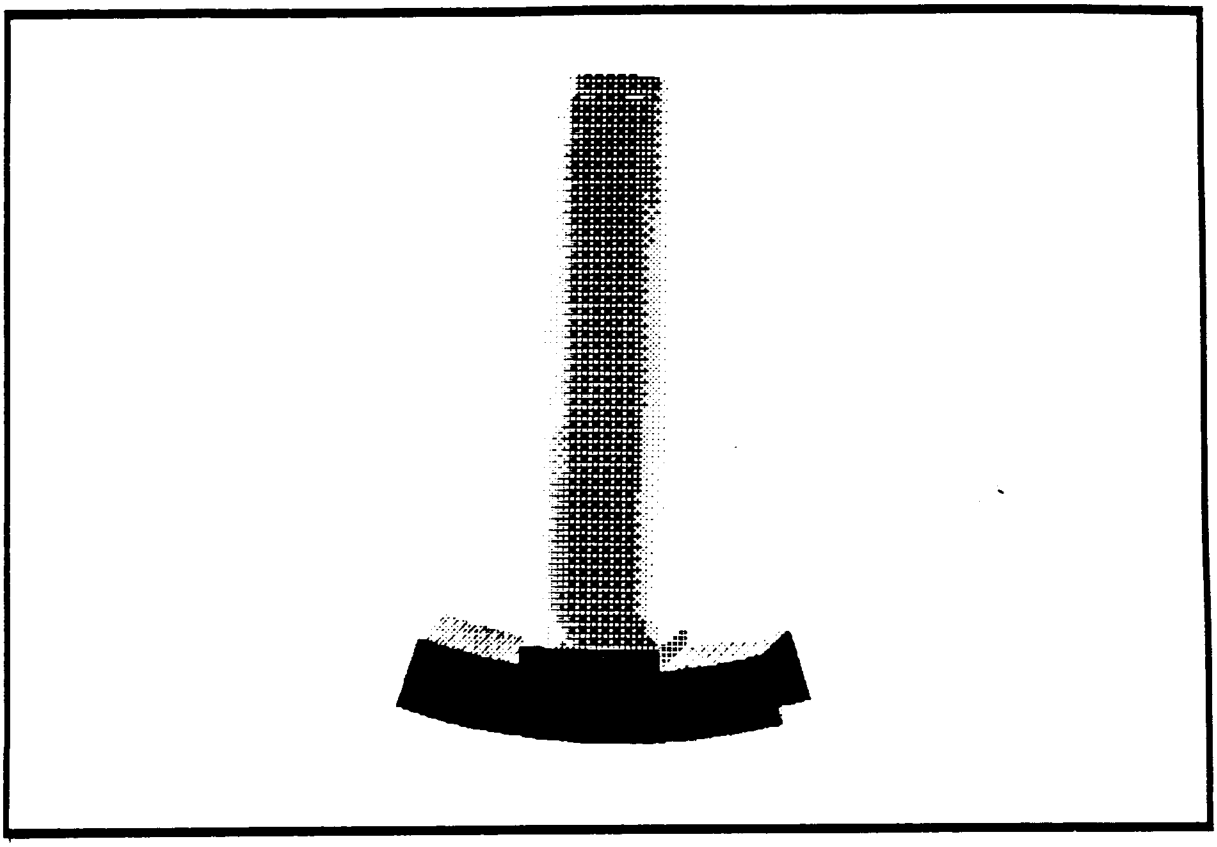


Figure 10.16: The spoke

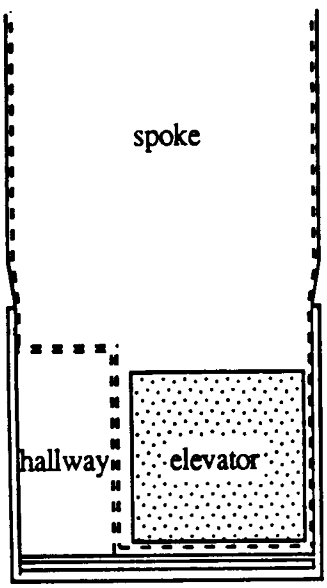


Figure 10.17a: The top view of the spoke.

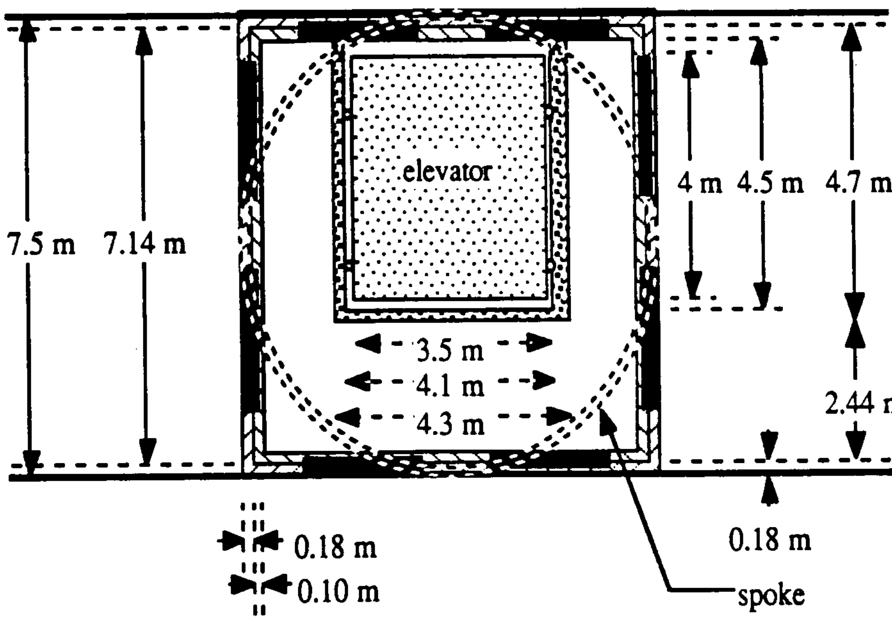


Figure 10.17b: The side view of the spoke.

During the compressing procedure, gaskets on the top of the torus create an air and pressure-tight seal. Note, however, that the segment must be pressurized before it can accommodate human beings.

The spoke/torus interface incurs maximum stresses during the CASTLE's insertion into heliocentric orbit. At that time, the hub tries to "push" its way through the center of the torus ring and thus create significant transverse and moment forces on the connection. These forces are borne by both the square cross-sectional portion on top of the torus and the end of the spoke anchored to the floor of the torus.

The two spokes without elevator facilities connect to the torus in a similar fashion. The only exception to this is that the elevator shaft does not penetrate the torus. Instead, the spoke stops when it meets the torus surface. The only drawback to this is that the square socket must bear the entire load during insertion. For this reason, the socket and spike end may need to be formed form a stronger material than the rest of the parts of the elevator spokes.

10.5.3 Hub Assembly

The hub serves the purpose of connecting the interface to the rotating torus. It is simply an attachment point for the interface and four spokes As such, it contains four fastening mechanisms similar to the ones used between the spoke and torus. That is, the spokes are slid into appropriately fitted sockets in the hub. The interface attaches to the hub using nodes, that are described in the following section.

10.5.4 Truss Section Assembly

The truss structure is launched in a total of 8 components, consisting of the interface, the micro-gravity lab, the docking area and CAB, the engine pod and fuel tanks, and four solar booms. Each of these components have attached to them the part of the truss structure that surrounds them. Where two pieces join, a node is placed such that it holds the two pieces of the truss together.

This node has been specifically designed for this purpose, and has been stress tested to determine that indeed it is capable of withstanding the forces involved. Conceived by Massachusetts Institute of Technology and the Lockheed Corporation, this node is designed to be very versatile and easily installed. It works in the following manner. One half of the connector, the male end, is attached to a hexagonal element (Figure 10.18). This allows the connectors to be placed at increments of 45 degrees from each other. If a standard truss beam is made up of 1 m x 1 m x 1 m segments, 45 degrees between beams is the exact angle required for all cross bracing. The female end of the connector is cut to accept the male connector and hold it in place. A locking sleeve is then slid over the male connector such that the joint is permanent (Figure 10.19). To the other end of the female connector is attached the beams. These beams are simply threaded into the female connector. A combination of male and female connectors, along with one hexagonal element make up a single node.

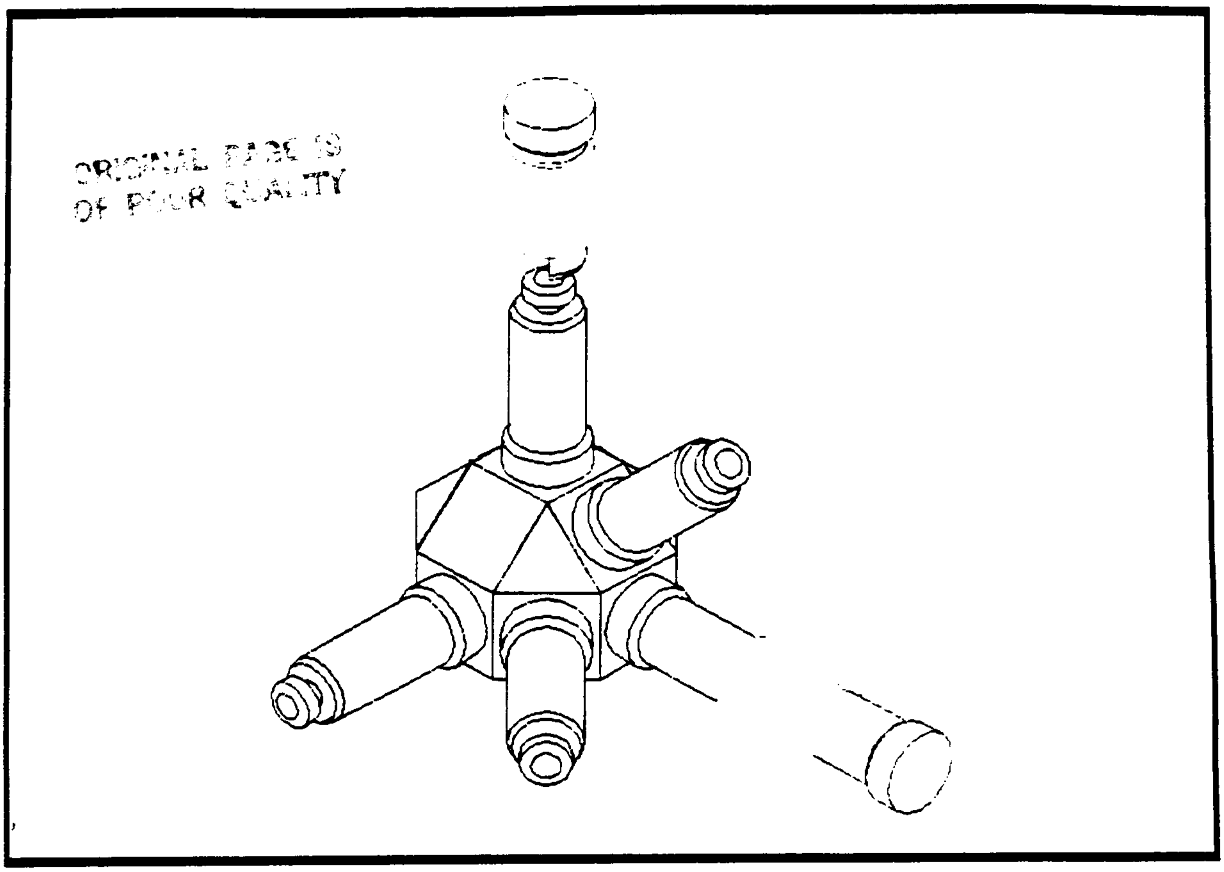


Figure 10.18: A truss node (designed by MIT and Lockheed).

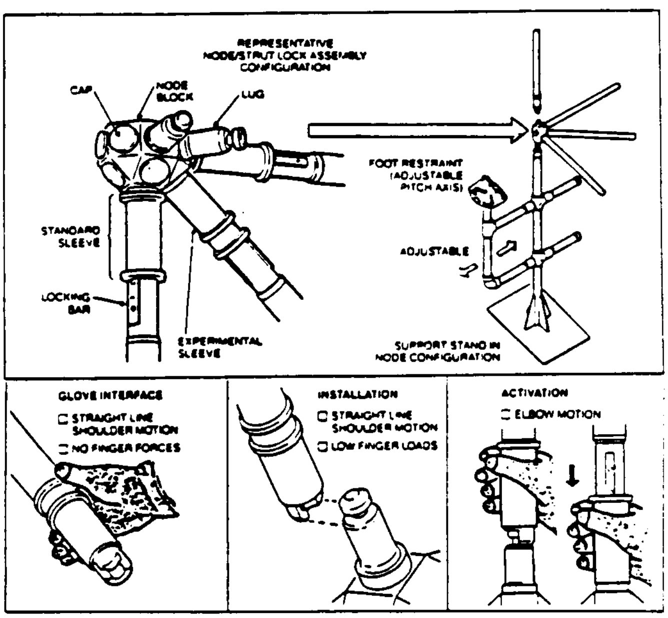


Figure 10.19: How a joint is completed at the truss node.

This node is suitable for both human and automated deployment; however, special considerations for human deployment have been incorporated into the design. For instance, the diameter of the male and female connectors is 0.06 m. This is the most comfortable diameter for the astronaut, since this is the natural distance between the thumb and finger of a pressure suit. Thus, little finger movement is required in order to firmly grip the node. In addition, the movements required to secure the connection are simple for either astronaut or machine.

10.5.5 The Flexible Couplings

The Flexible couplings are one meter tubes which connect all modules along the main boom. The flexible couplings serve two main purposes:

1. They minimize the transmission of the docking forces incurred at the docking module, to the remaining spacecraft.

2. Without a degree of inter-module flexibility, main truss deflections would induce a bending moment into these modules. Since the flexible couplings are incapable of carrying a bending moment, they isolate the modules form this effect.

The flexible connectors were designed to provide a standard size and mounting configuration, lending themselves to use between any of the various spacecraft modules. Each connector consists of a flexible, corrugated aluminum, inner and outer bellows, located between two mounting flanges. (Figure 10.20) The mounting flanges are bolted to the spacecraft modules, and an airtight seal is maintained by providing a rubber O-ring seal at this interface. A clearance is provided between the inner and outer bellows to allow for the space necessary to run inter-module communication and power supply wiring. Finally, a polyethylene inner liner is inserted to provide a more habitable inner surface.

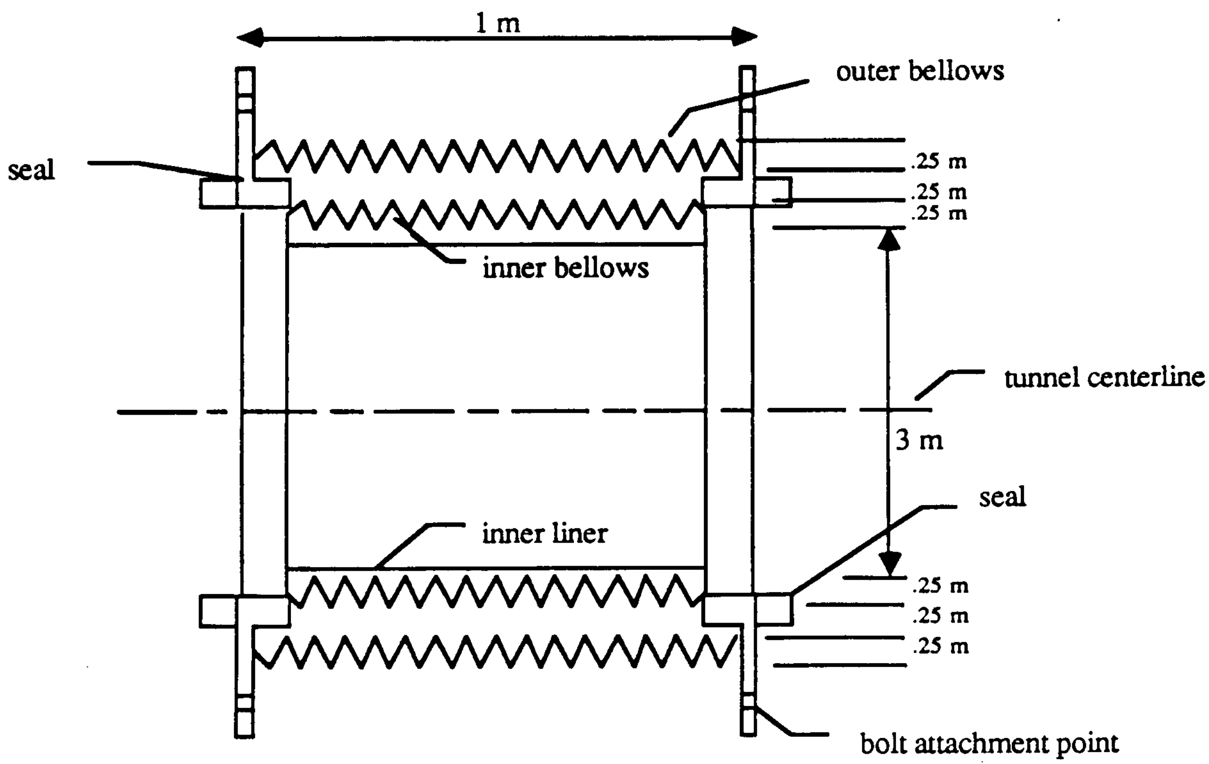


Figure 10.20: The flexible coupling (designed by the docking group)

10.5.6 Solar Boom Assembly

The solar booms are attached to the main truss structure with the truss nodes described above. The standard 1 m x 1 m x 1 m truss segments are utilized on the solar booms to maintain uniformity and consistency about the entire truss structure.

10.5.7 Electrical and Other Attachments

For the most part, electrical connections on the truss utilize quick connectors which lock into place automatically. However, each electrical connection is located where it may be easily reached for inspection and replacement.

10.6 Launch and Construction Schedule

The construction sequence has been carefully devised to minimize wasted movements and to maximize the potential use of all the construction equipment available. It is estimated that 1.5 years is the amount of time required to complete construction of the CASTLE. This includes the actual construction time, systems checking time, and the time required to get CELSS fully functional. The actual construction time is very short, on the order of four months, due mainly to the design of the connections. 12 months are allowed for a complete check of the entire craft. The CELSS will be started approximately two months after the CASTLE is completed.
Since the construction time is so short, it was decided that the construction crew would remain on the CASTLE until it is complete. There are no crew changeovers until the entire ship is built. Then the construction crew can be replaced by a new crew that is trained to test the ship, and trouble-shoot any problems that may arise. The trouble-shooting crew might not stay the entire 12 months devoted to testing the ship, depending on how long the testing takes.

The first step is to place two habitat modules into the construction orbit (Figure 10.21). This is done using two space shuttle-type transports, since these modules are in earth orbit already. They merely have to be transported from the space station. They are placed into the construction orbit, and await the next step

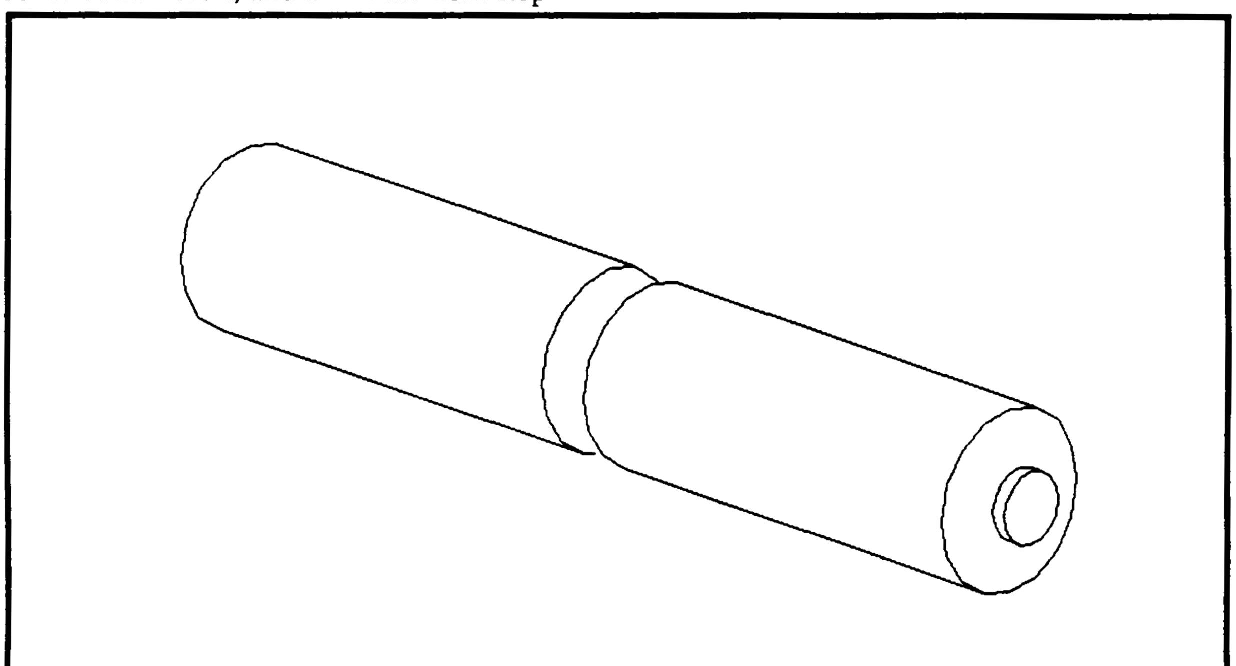


Figure 10.21: The habitat modules.

A third space shuttle docks with the two habitat modules, and transports its cargo into the habitat modules. This cargo includes food and water for the crew, construction tools, an OMV, and the construction crew itself. Construction is now ready to begin.

The first HLLV arrives with its cargo of the CASTLE hub, the two cranes, and a solar boom. The solar boom is temporarily mounted on one of the two habitat modules (Figure 10.22). It provides the power the crew will need to begin construction, as well as that required to operate the habitat modules. The two cranes are then mounted on a small section of track, again on one of the habitat modules. They stay there only until more sections of track arrive.

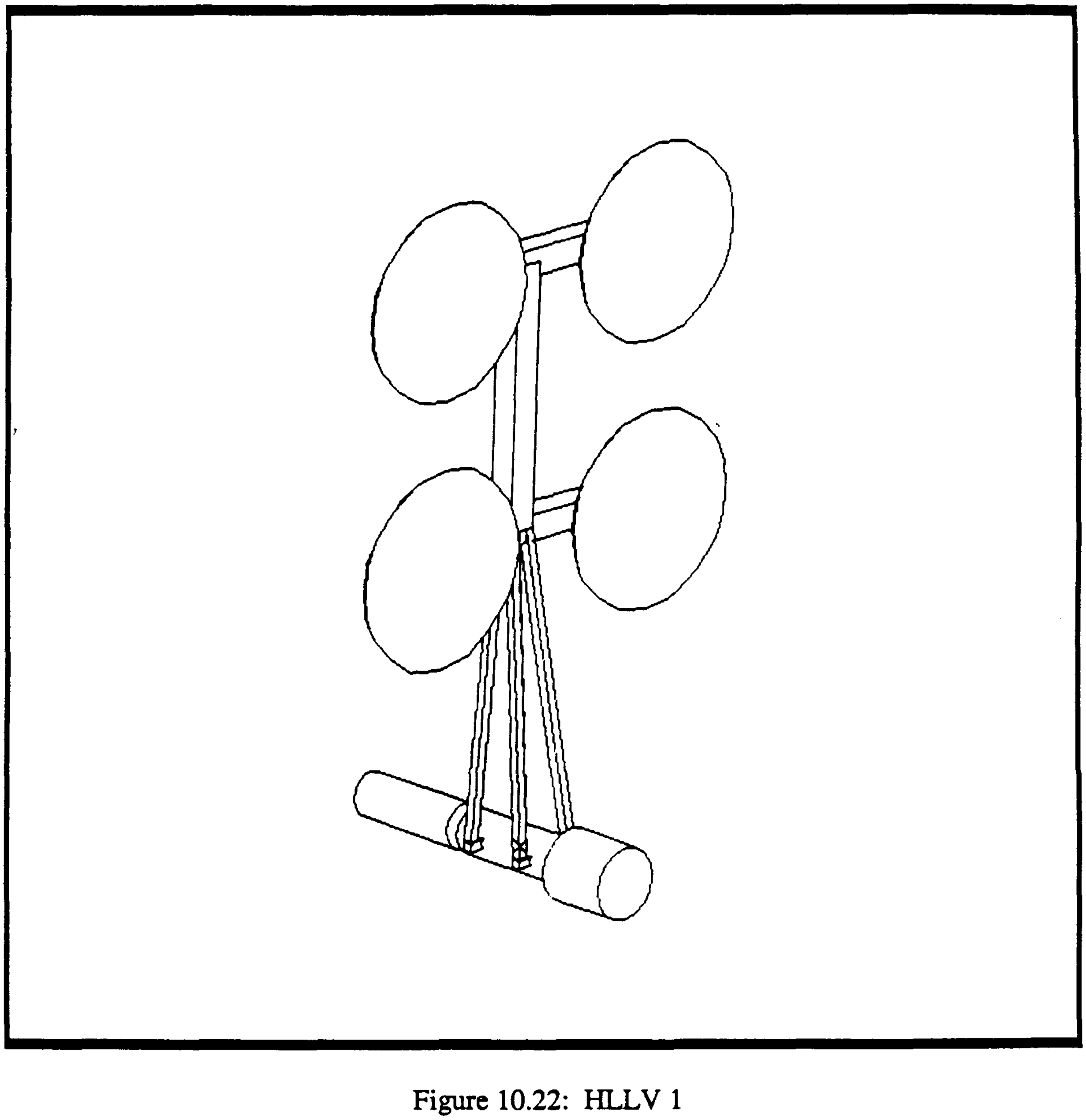


Figure 10.22: HLLV 1

The hub is then attached to an end of a habitat module. It is manipulated in place using the cranes. Once it is in place, access to the hub may be gained from the habitat module, as the hub is launched with an internal pressure of 1 atm.

The next HLLV arrives with the interface (Figure 10.23). Using the cranes, the interface is moved into position next to the hub and permanently attached. Once all necessary electrical and other utility connections are made, the interface connection is complete. Access to the interface interior can be gained through the hub. The interface is also launched with a pressure of 1 atm. At this point, the two cranes mount themselves onto the railing of the interface.

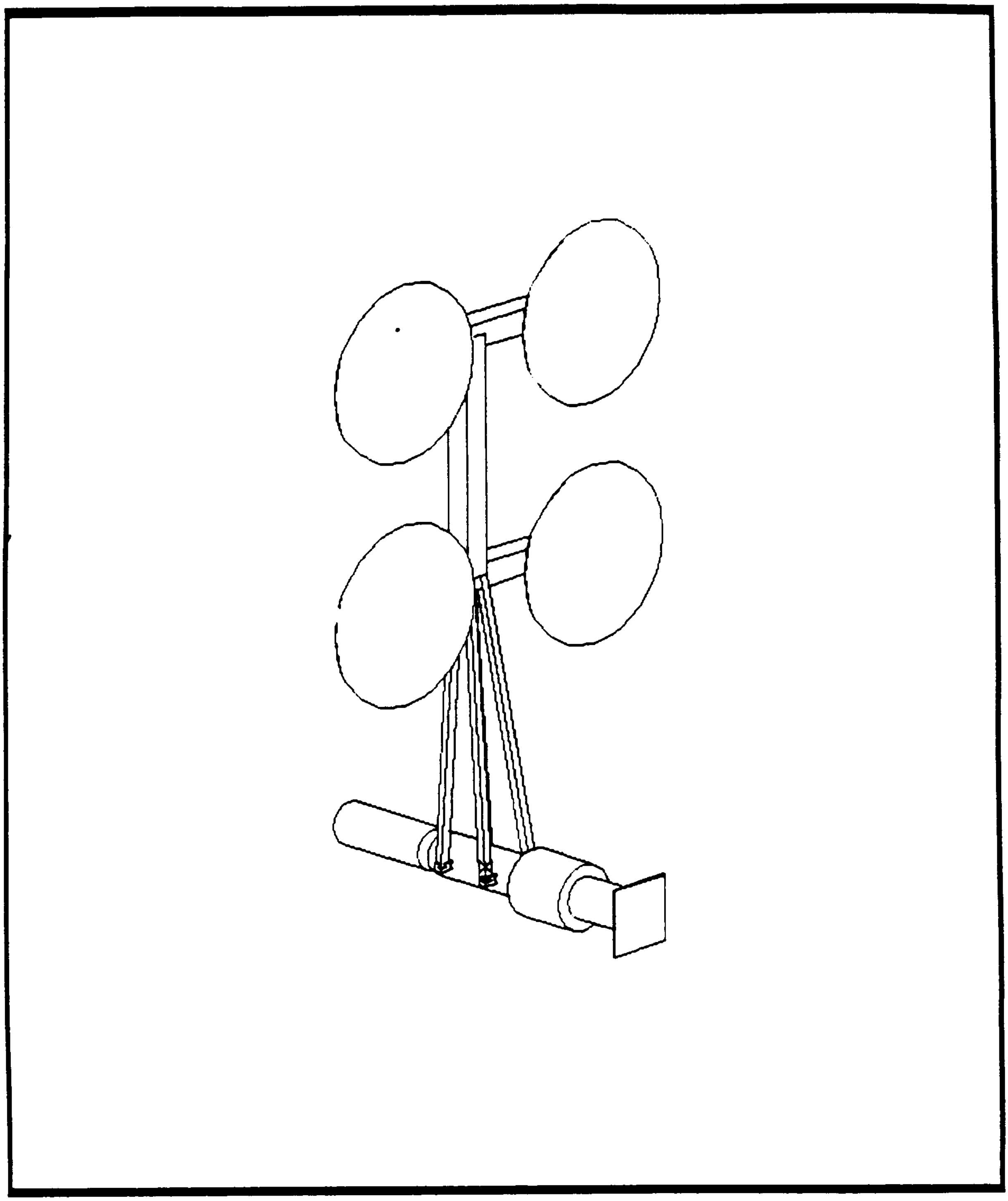


Figure 10.23: HLLV 2

HLLV 3 brings the micro-g section of the truss as well as another solar boom (Figure 10.24). Again, the cranes move the micro-g lab into position next to the interface, and it is attached at the ends of the truss with the aforementioned nodes. The micro-g is launched into orbit pressurized. The solar unit is mounted in its permanent position on the non-rotating part of the interface. Again the cranes are used to place the solar boom into position. This second solar boom fulfills the additional power requirements as the CASTLE grows larger.

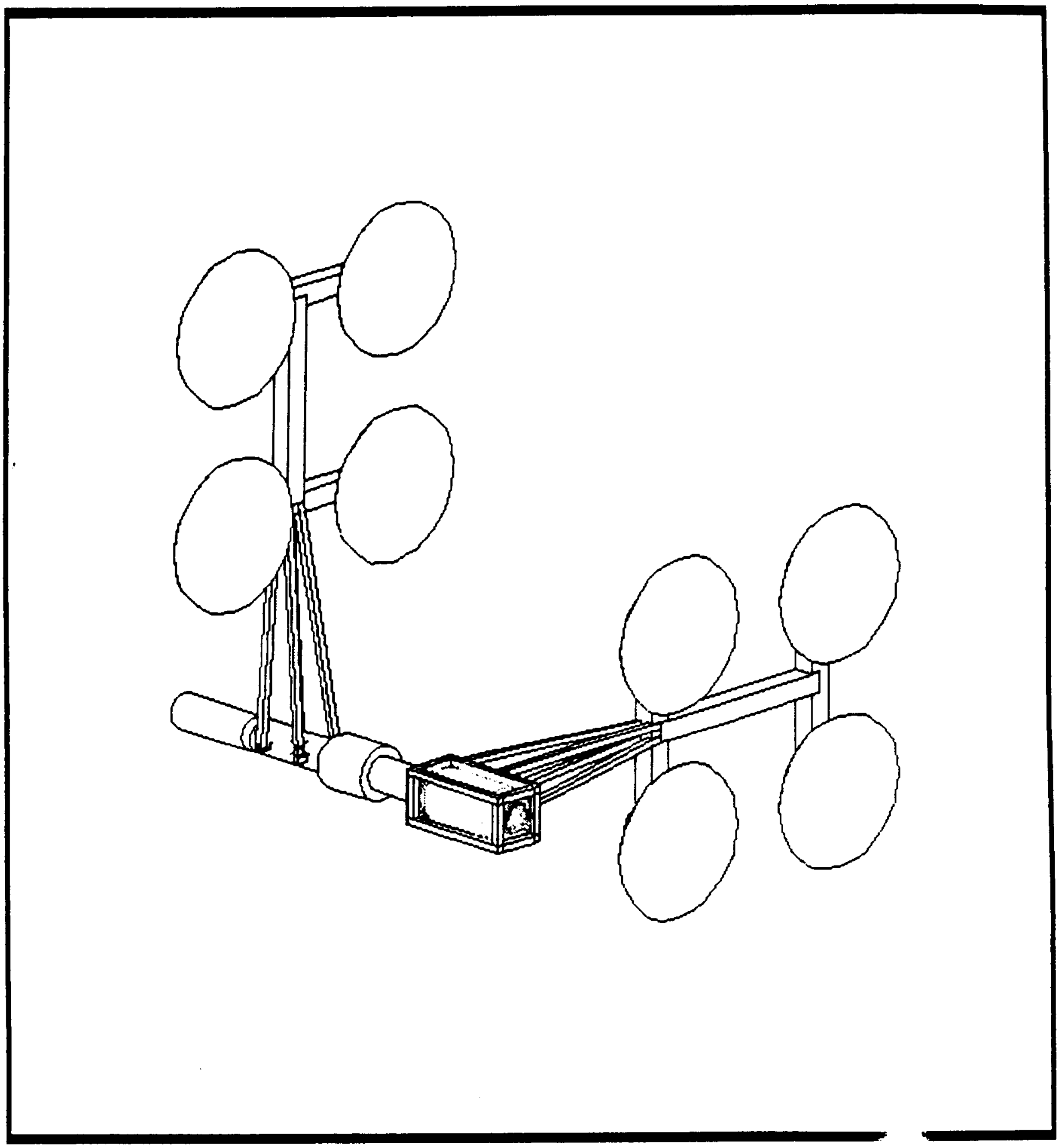


Figure 10.24: HLLV 3

HLLV 4 delivers the docking section of the truss as well as the first spoke (Figure 10.25). The docking section is attached to the end of the micro-g section of the truss using the truss nodes. Once the docking module is attached, there are two points on the CASTLE where access to space is possible. One is back at the habitat modules, the other is from the CAB on the docking module. The CAB can also be used to store equipment and can act as a working platform for any EVA. Also, the docking berths are made fully functional, so that supplies, such as food and water can now easily be transferred to the CASTLE. The spoke is attached to the hub using the cranes as described previously.

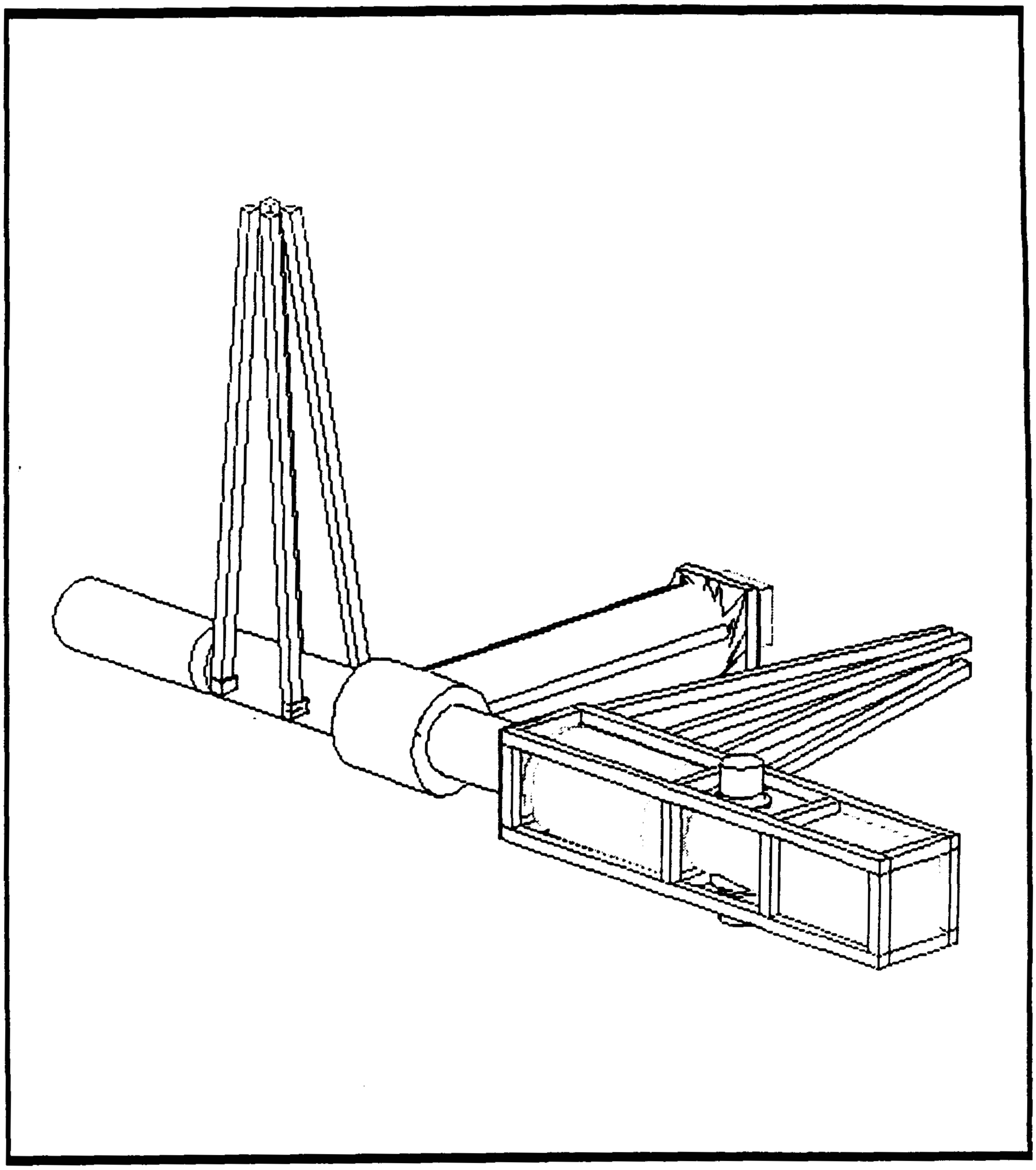


Figure 10.25: HLLV 4

HLLV 5 brings up the insertion engines and their fuel tanks (Figure 10.26). The tanks are launched empty as fuel will be brought from the moon rather than the earth. The nine insertion engines are brought up attached to the engine deck. All that is required to attach the engines and fuel tanks is to position them, using the cranes, next to the docking module and to firmly lock them in place using the truss nodes.

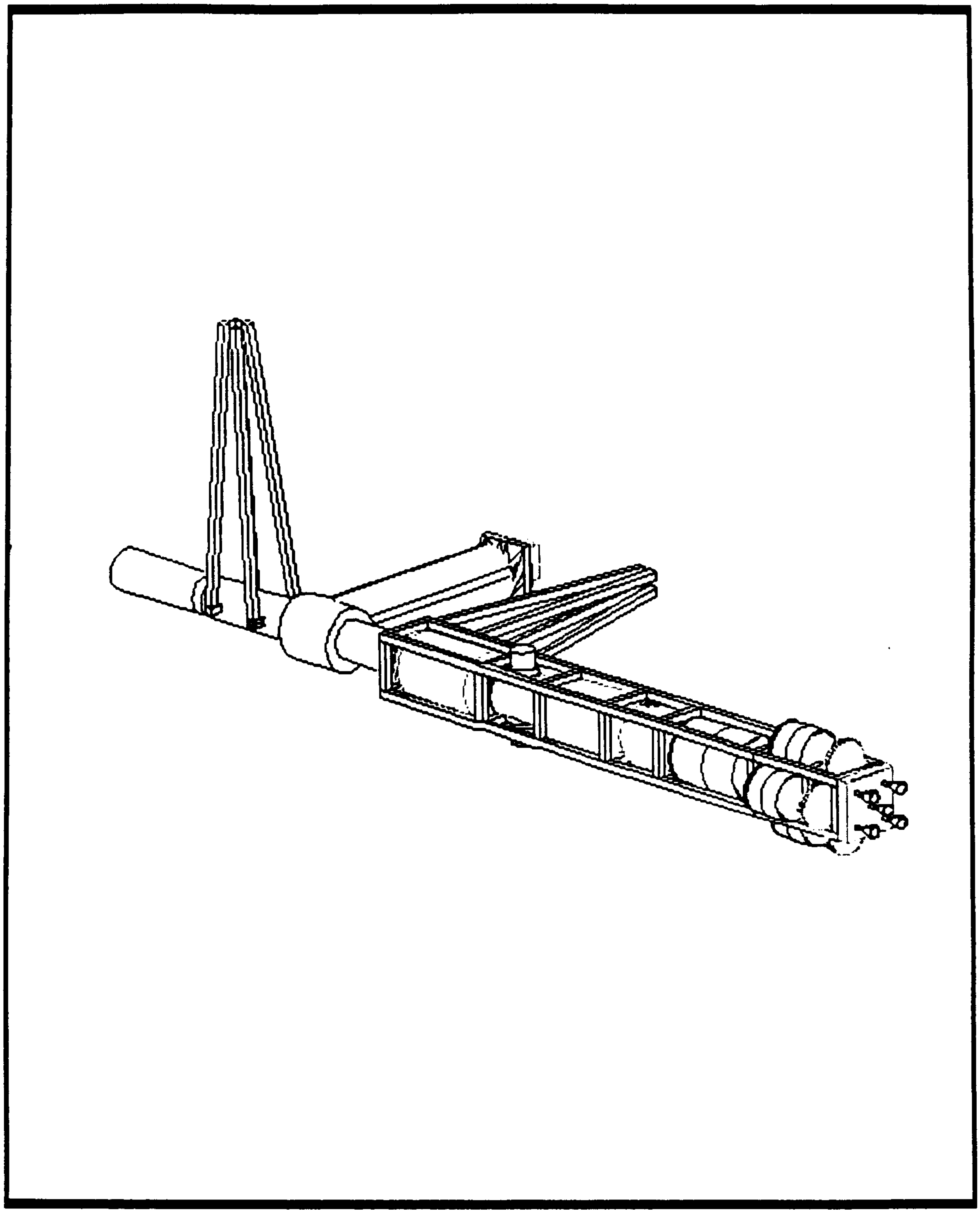


Figure 10.26: HLLV 5

The last two solar booms and another spoke are then brought up on HLLV 6 (Figure 10.27). The two solar booms are placed in their correct locations and attached with the nodes. Also, at this point, the solar boom attached to the habitat module is moved to its permanent location. All four booms are now in their final position. The second spoke is place in its position on the hub, again using the cranes.

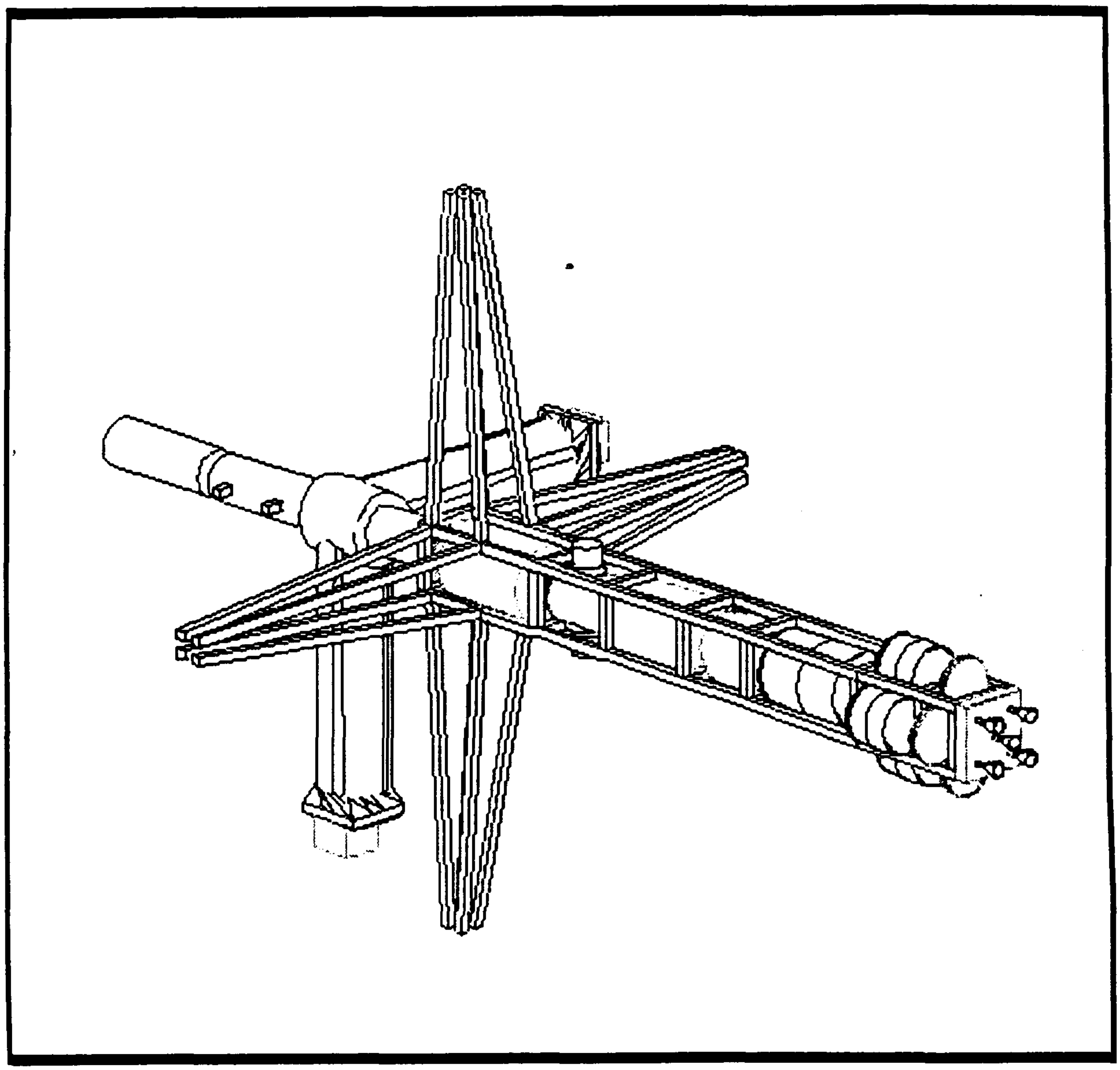


Figure 10.27: HLLV 6

HLLV 7 brings up the final two spokes (Figure 10.28). They are simply placed in their positions on the hub.

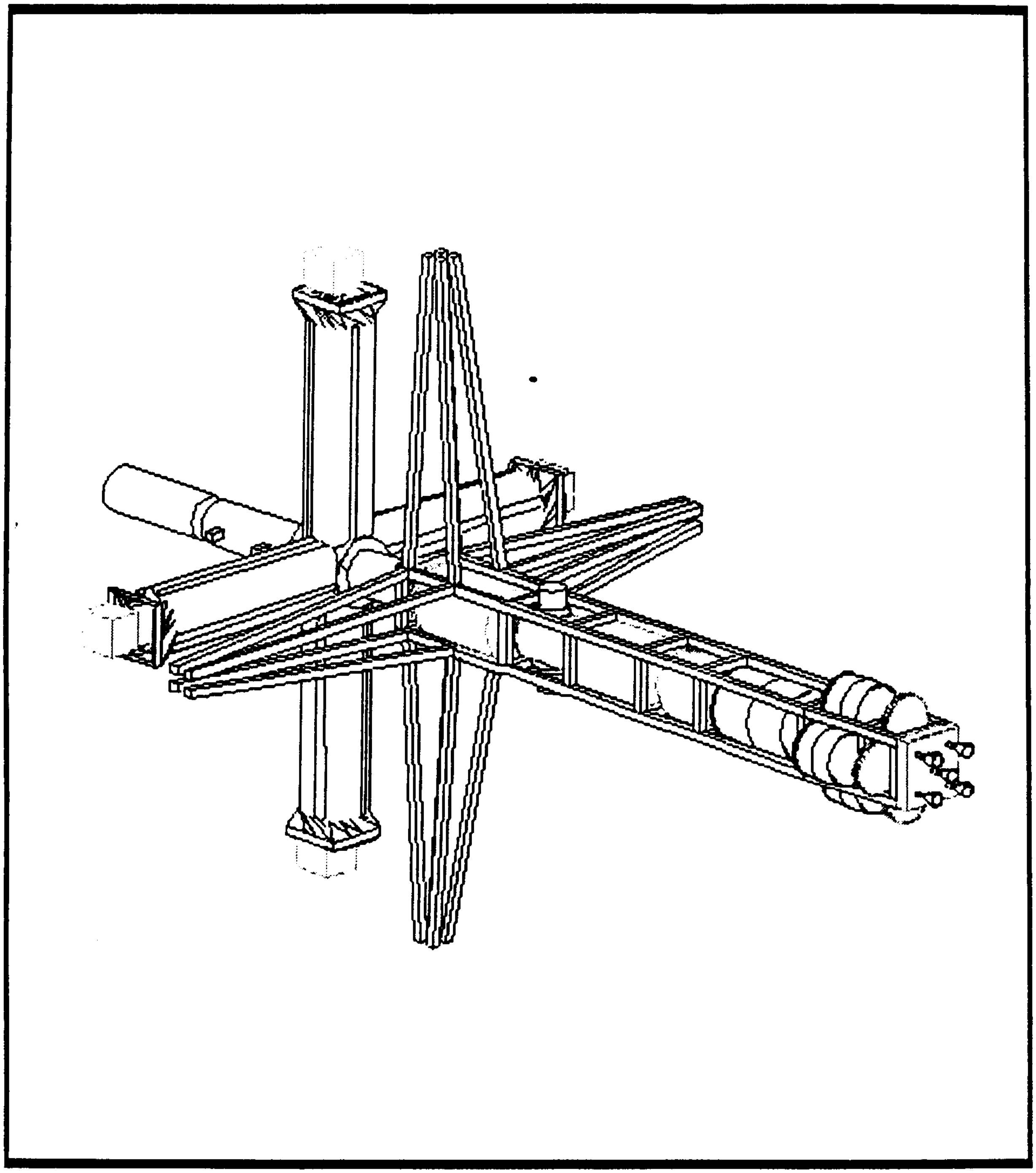


Figure 10.28: HLLV 7

The last 6 HLLV's bring up the eleven segments of the torus (Figure 10.29). HLLV 8 brings up sections G and F. Section G attaches to a spoke containing an elevator. The elevator within this spoke is then made operational. All the torus modules except A and G are launched with 1 atm. of pressure, so that the crew may work in the torus without the use of space suits. Once modules A and G are in place, they too are pressurized to 1 atm.

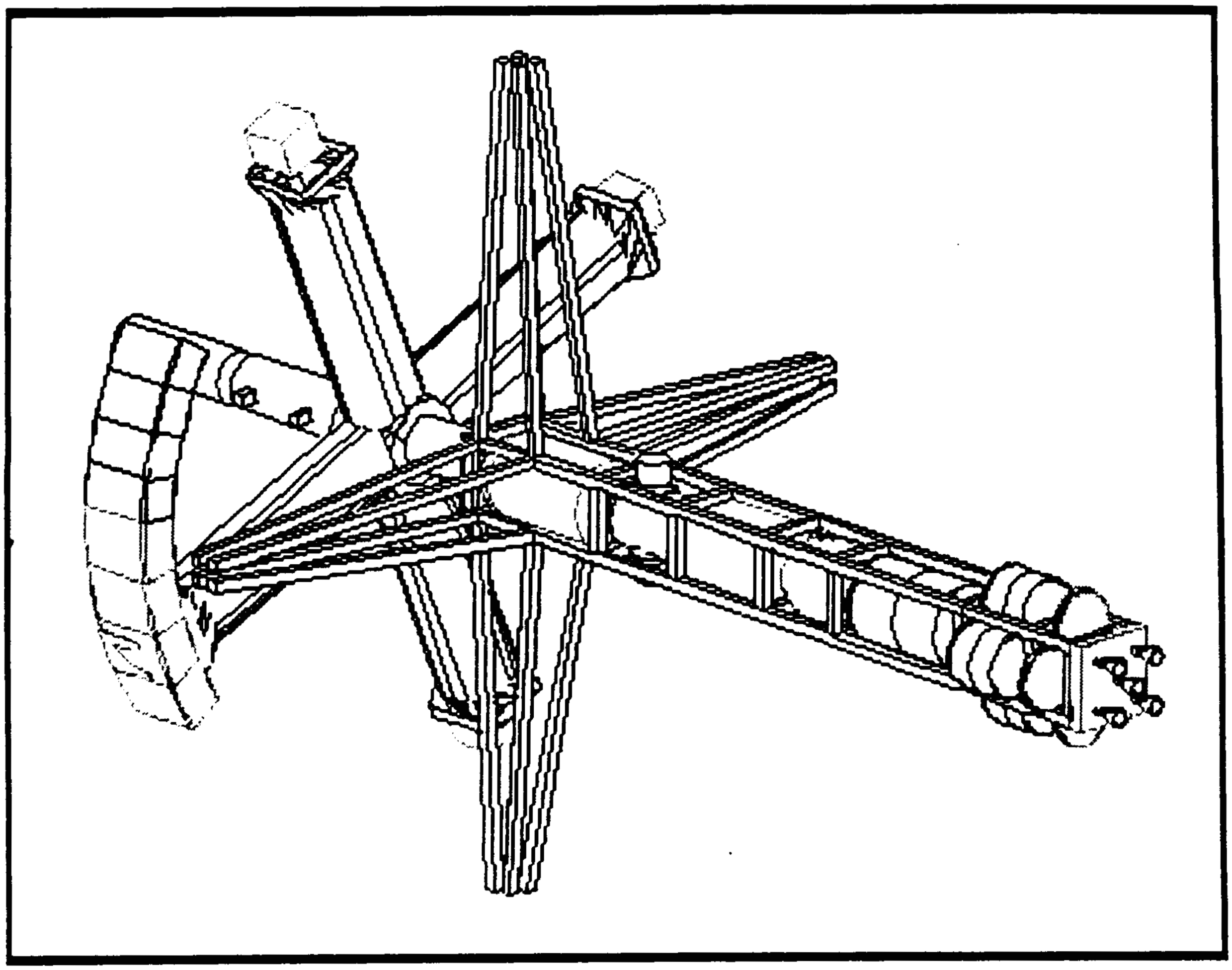


Figure 10.29a: HLLV 8

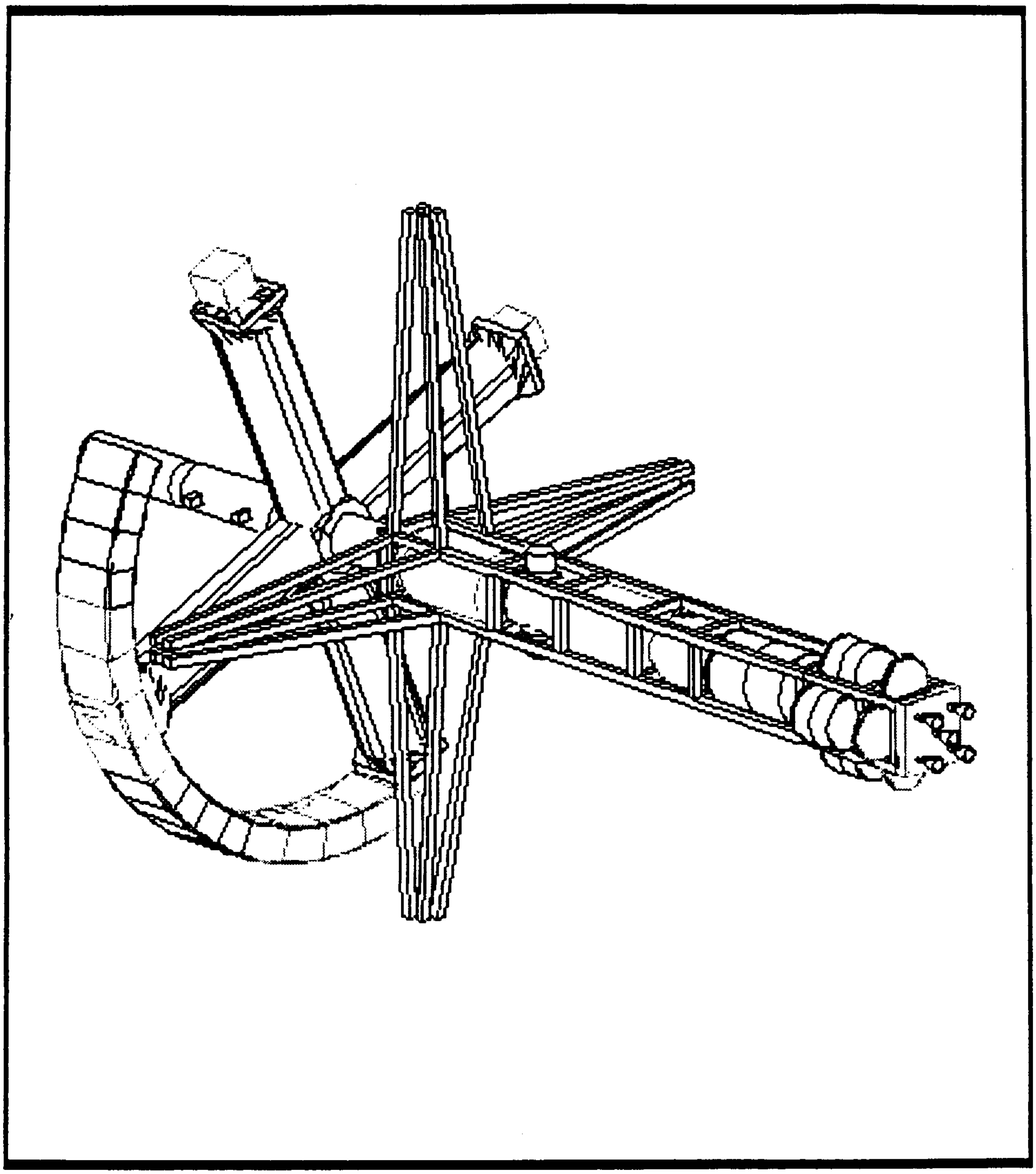


Figure 10.29b: HLLV 9

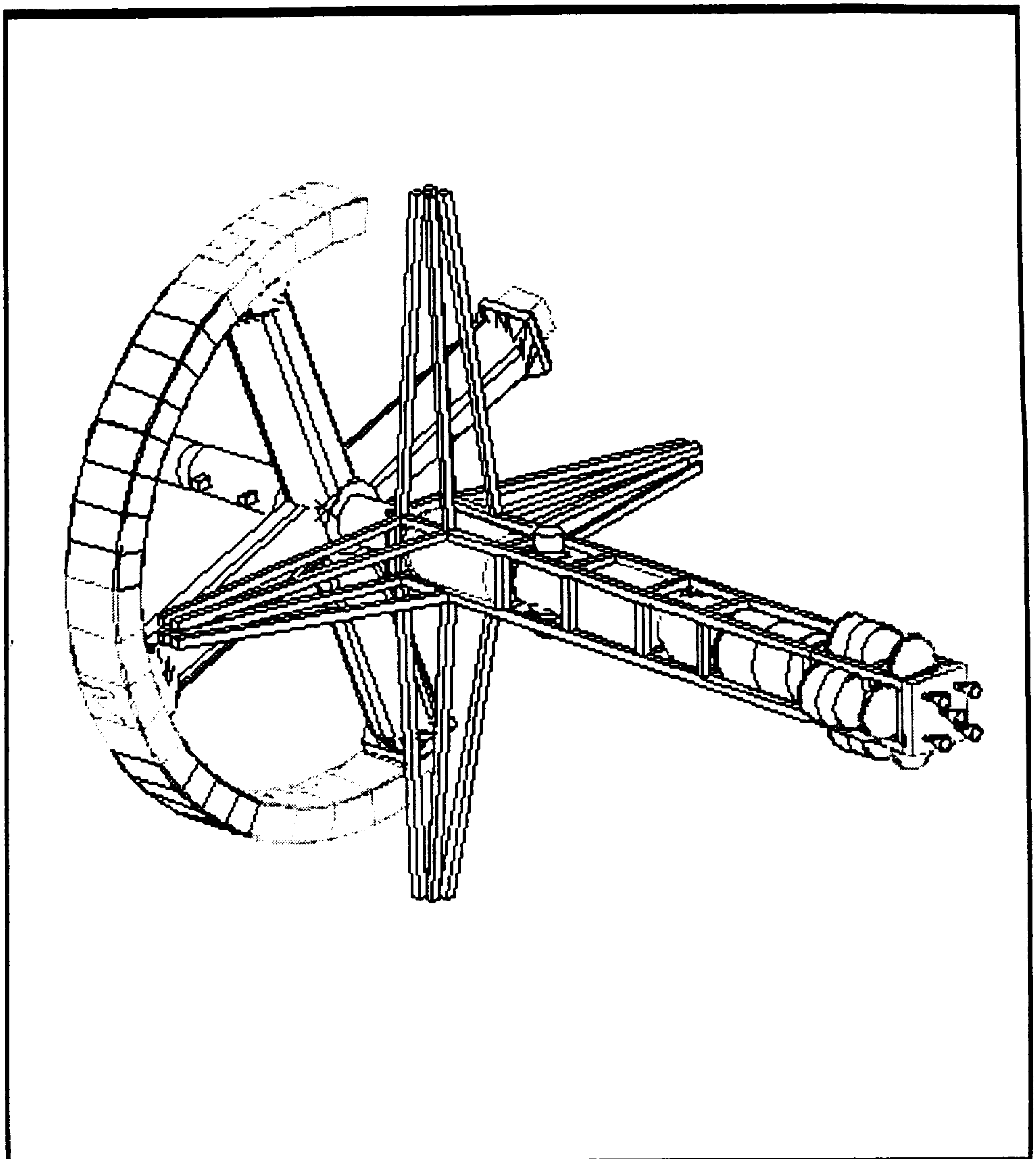


Figure 10.29c: HLLV 10

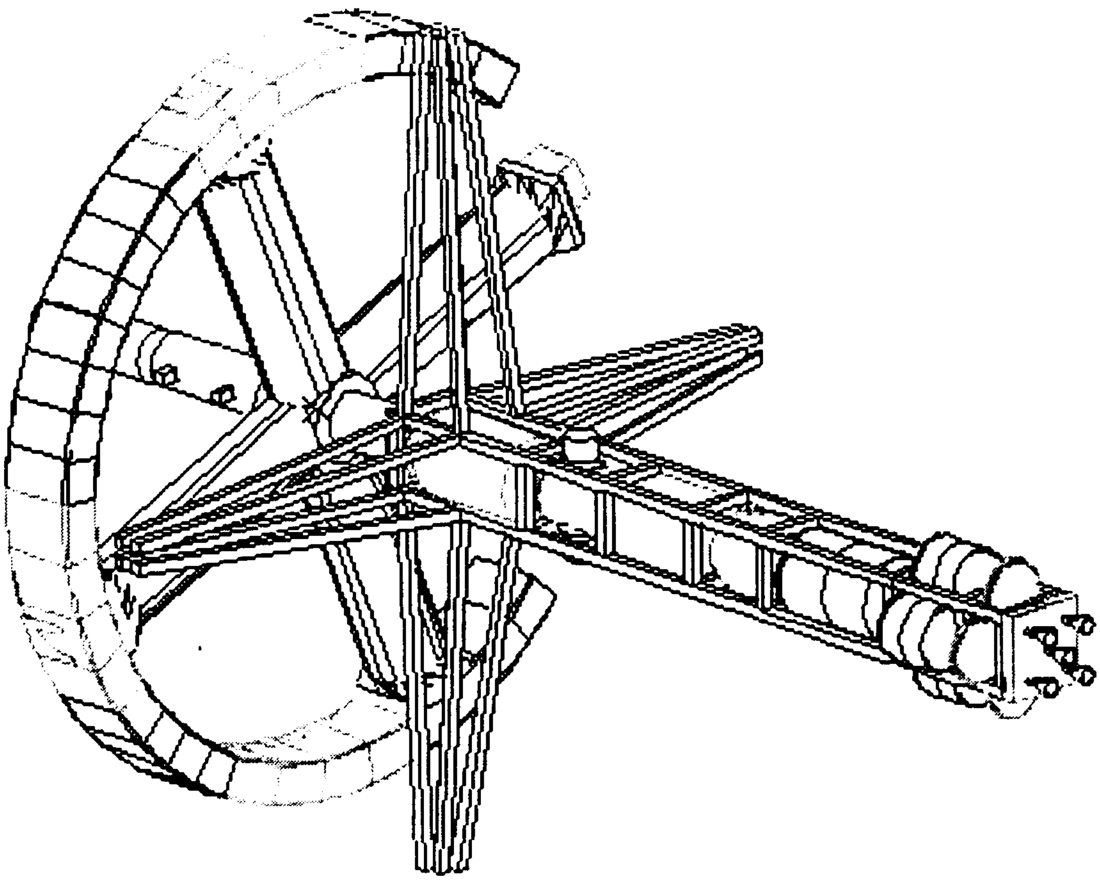


Figure 10.29d: HLLV 11

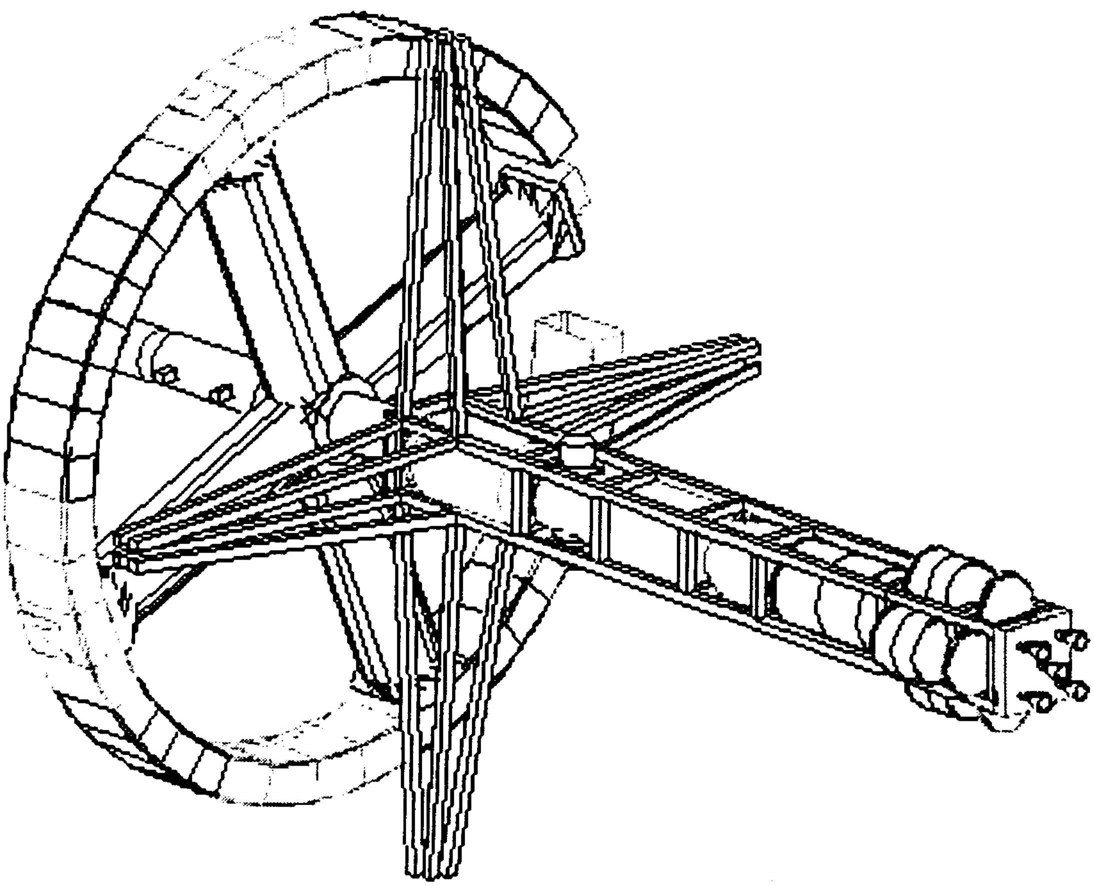


Figure 10.29e: HLLV 12

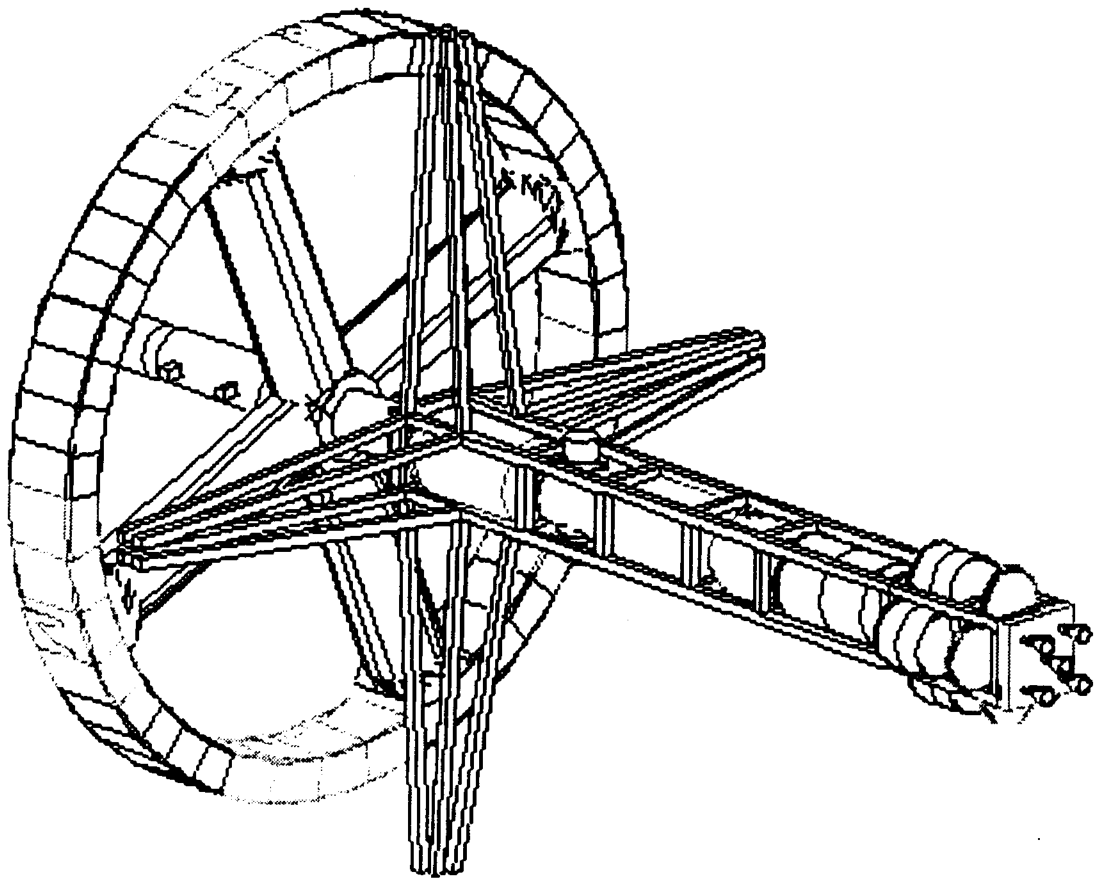
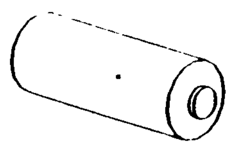
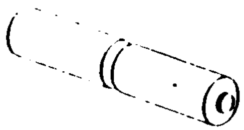
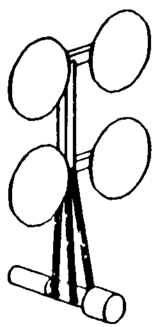


Figure 10.29f: HLLV 13

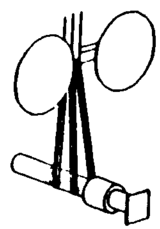
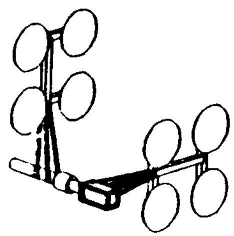
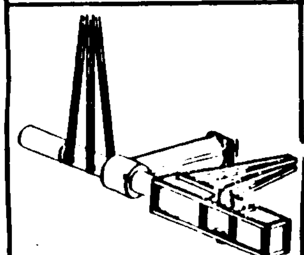
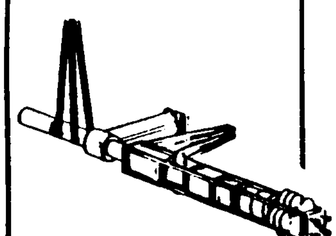
HLLV 9 contains modules H and I, HLLV 10 contains modules E and D, HLLV 11 contains modules C and J. HLLV 12 has modules B and K, and HLLV 13 has module A. HLLV 13 also has any final supplies that might be needed to complete the construction of the CASTLE. Modules D and J connect to the two spokes without elevators, and module A connects to the second elevator spoke.

All final connections, including electrical and plumbing are then finished, and the CASTLE is complete.

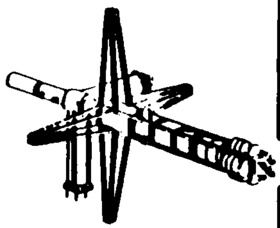
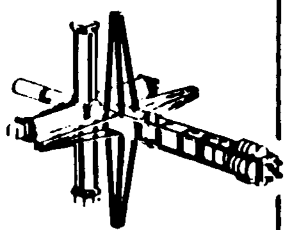
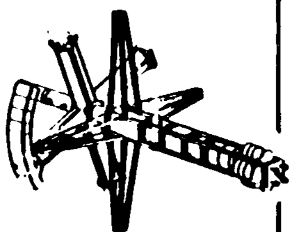
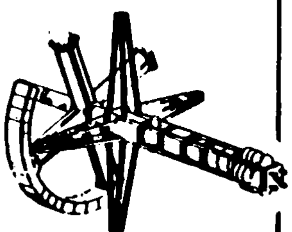
CASTLE Assembly Sequence

Assembly Sequence	HLLV	Shuttle	Payload Description	Payload Mass	Ship Cumulative Mass	Requirements
		1	Habitat Module	13500 kg	---	none
		1	Habitat Module	13500 kg	---	none
		1	Crew OMV Food and Water	6 Crew Members OMV Food and Water	---	none
	1		Hub 1 Solar Array 2 Cranes	110×10^3 Kg + 2 cranes	$.110 \times 10^6$ Kg	2 Cranes - one is usable from payload OMV

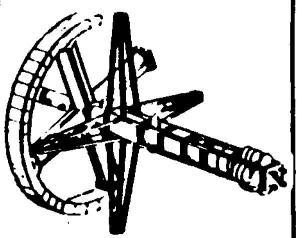
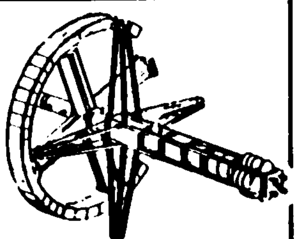
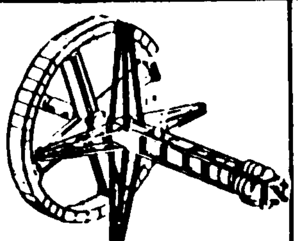
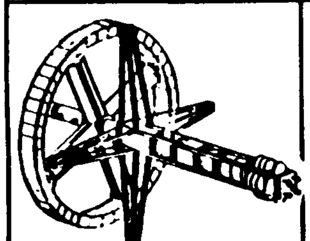
CASTLE Assembly Sequence

Assembly Sequence	HLLV	Shuttle	Payload Description	Payload Mass	Ship Cumulative Mass	Requirements
	1		Interface	200.0×10^3 Kg	$.310 \times 10^6$ Kg	2 Cranes OMV Limited EVA
	1		Micro G section	137.0×10^3 Kg	$.447 \times 10^6$ Kg	2 Cranes OMV Limited EVA-node deployment
	1		Docking 1 Spoke	200.0×10^3 Kg	$.647 \times 10^6$ Kg	2 Cranes OMV Limited EVA-node deployment
	1		Fuel Tanks Engines	65.0×10^3 Kg	$.712 \times 10^6$ Kg	2 Cranes OMV Limited EVA-node deployment

CASTLE Assembly Sequence

Assembly Sequence	HLLV	Shuttle	Payload Description	Payload Mass	Ship Cumulative Mass	Requirements
	1		2 Solar Arrays 1 Spoke	200.0×10^3 Kg	$.912 \times 10^6$ Kg	2 Cranes OMV Extensive EVA- solar node deployment
	1		2 Spokes	200.0×10^3 Kg	1.112×10^6 Kg	2 Cranes OMV Limited EVA
	1		2 Habitat Modules G, F	187.0×10^3 Kg	1.299×10^6 Kg	2 Cranes OMV Limited EVA
	1		2 Habitat Modules H, I	202.0×10^3 Kg	1.501×10^6 Kg	2 Cranes OMV Limited EVA

CASTLE Assembly Sequence

Assembly Sequence	HLLV	Shuttle	Payload Description	Payload Mass	Ship Cumulative Mass	Requirements
	1		2 Habitat Modules E, D	187.0×10^3 Kg	1.688×10^6 Kg	2 Cranes OMV Limited EVA
	1		2 Habitat Modules C, J	196.0×10^3 Kg	1.884×10^6 Kg	2 Cranes OMV Limited EVA
	1		2 Habitat Modules B, K	168.0×10^3 Kg	2.052×10^6 Kg	2 Cranes OMV Limited EVA
	1		2 Habitat Modules A	100.0×10^3 Kg +supplies	2.152×10^6 Kg	2 Cranes OMV EVA

10.7 Cost of Assembly

As no project design is considered complete without a price tag, a cost analysis was conducted for CAMELOT II. Before actual cost estimates are given, however, an explanation of the scope of the analysis is in order.

First, the CAMELOT orbiter is supported by several facilities that will boast hefty costs themselves. Most importantly, a fuel production facility on Phobos and a satellite of Mars is not included in the cost study. Other extra costs, such as those required for maintenance, provisions, and transport costs between the planets and the CASTLE have been ignored.

Secondly, many assumptions have been made throughout this report as to the state of technology in the 21st century. Thus, in considering costs of CASTLE components utilizing future technology, educated approximations are made. Please note, however, that this adds a significantly increased probability of error, and final costs should by no means be considered firm.

Finally, despite these assumptions and the 2025 launch date, cost estimates are based on 1988 U.S. dollars. In evaluating the figures at a later date, one need only obtain a conversion factor for the price of the dollar.

Given these preliminary considerations, the table below is constructed from total cost estimates for the CASTLE subsystems. These values include costs incurred in the design, testing, and manufacture of the specific components. The final cost estimate for the CASTLE is just below $150 billion, a figure in line with current NASA estimates.

Note that the cost of assembly includes developing the machinery used in assembly, launching the various components to the Low Earth Orbit assembly site, and the man-hour support cost over the approximate year and a half assembly period. The chart below indicates the approximate cost of launching a one-ton payload to various altitudes, and serves as a guide in determining the cost of launching the CASTLE.

Table 10.2: The cost analysis summary.

Group	Cost Estimate (billions of dollars)
Interface I & II	2.00
Habitat I	1.70
Habitat II	8.50
Solar	20.00
Docking	2.40
Spacecraft	20.00
Elevator	0.34
Propulsion	1.70
Assembly	84.80
	141.44

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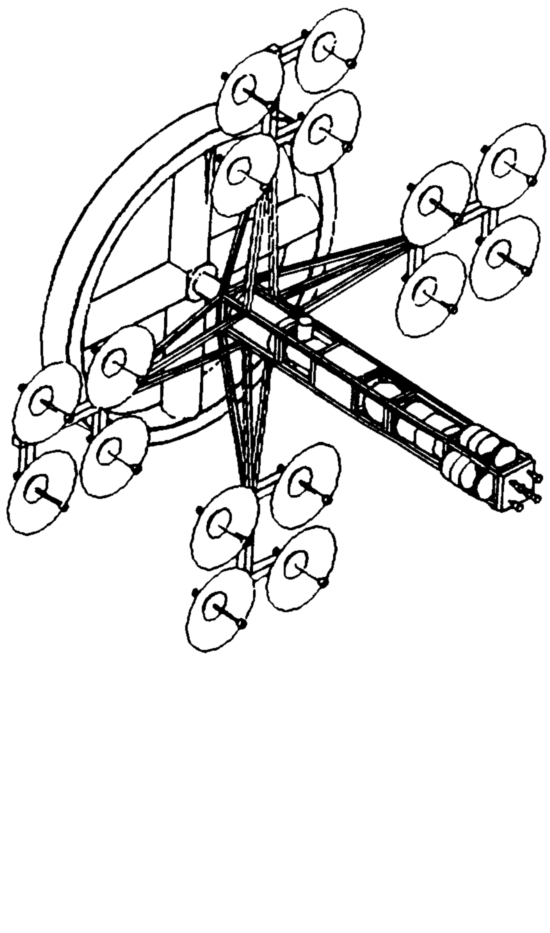
Appendix

CAMELOT I Executive Summary



Chapter 1: Introduction to Project CAMELOT

Section 1.2: Introduction

Space offers tremendous opportunities for the future. No other endeavor known to man offers as great a chance to expand the scope of human activity. The twenty-first century will bring about a new era in space. Not only will astronauts be living and working in space, but everyone will become eligible for space work in the next century.

In order to ensure sustained growth in our space program, we need to set long-range goals. The enthusiasm died after the Apollo program because we had nothing planned for after going to the moon. Hence, we lost much of the support of the American public. We need to recapture the enthusiasm and spirit of the Apollo Program to recapture the public's support. The public plays the important role of influencing congress to support our project. The National Commission on Space has played a major role in setting goals and objectives for the future in the exploration of space.

In Chapter 1, a time table of events leading to Project CAMELOT is discussed. This time table is based upon a logical progression of technological developments. The enabling technology that will open our doorway to the future will be the development and implementation of the space station. This system will open up the space frontier and will give us the ability to carry out our long-range goals in order to maintain an on-going space program. The scenario that is presented is bold and challenging and to some, may seem impossible. However, the idea that man would one day be able to set foot on the moon was also once thought of as being impossible. Having faith in the challenge presented before us helped us achieve this great goal. A bold space program motivates and unites the most creative minds in the world. We go to Mars not because of our technology, but because of our imagination and creativity.

Section 1.3: Project Timeline

The following list of major events is a possible scenario for the next decades leading up to Project CAMELOT.

1994 Space Station operational

1995 First Heavy Lift Launch Vehicle (HLLV) flight

2009 First Aerospace Plane flight

2010 Moon base permanently manned

2015 Torus Habitat established at first Earth-Moon libration point as a spaceport

2019 First manned Mars landing

2035 Mars base and CASTLE system fully operational

Chapter 2: Trajectory

Section 2.1: Orbital Correction

A permanent Mars space station or planetary base would require regular, relatively frequent visits by a supply and personnel transfer vehicle from Earth. The mission of Project CAMELOT is based on the assumption that regular flybys of Earth and Mars will be feasible. The most advantageous method of accomplishing these flybys is to place a space station (CASTLE) into a heliocentric (sun centered) orbit that encounters Earth and Mars at regular intervals. This space station should require little or no propellant and should encounter Earth and Mars on a regular basis. The encounters would ideally involve the same approach characteristics at Earth and Mars time after time as found in circulating type trajectories.

The concept of circulating trajectories focuses about a round trip method to get between Earth and Mars on a regular basis. Cyclic trajectory advantages include relatively frequent schedule of encounters at the planets and close approach distances. Project CAMELOT optimizes these advantages with an Escalator type trajectory.

The Escalator trajectory has an orbital period around the sun of 2.135 years with a short leg transfer from Earth to Mars of only 4.5 months. The long leg of the transfer from Mars back to Earth takes 21 months. The Earth/Mars alignment around the sun has a period of repetition, the synodic period, equal to 2.135 years. The Earth/Mars alignment does not repeat itself in inertial space however. The relative locations repeat, but at an angle of 48.7 degrees further around the sun. In order to have a repeatable Escalator orbit, the CASTLE must complete its trajectory with a period equal to the synodic period while at the same time keeping up with the angular rotation of 48.7 degrees per cycle. The Escalator class trajectory fulfills these requirements and consists of two variations, labeled the Up and Down Escalators. The two orbits have similar orbital parameters except that the Up Escalator has its short leg from Earth to Mars and the Down Escalator has its short leg from Mars to Earth.

To rotate the Escalator orbit by the required 48.7 degrees gravitational assist at Earth can theoretically be used if a flyby close enough to the center of the Earth can be negotiated. However, in order to obtain the necessary 48.7 degree rotation, a flyby altitude which is less than zero is required. It is therefore necessary to limit the Earth flyby to a positive altitude and make up the rest of the orbital rotation by some other method. To minimize atmospheric drag while maximizing gravitational effects, a flyby altitude of 1,000 km was chosen. The angular shift obtained at Earth from this flyby altitude is about 43.7 degrees. The remaining five degree shift has to be made up with a propulsive burn near the aphelion (furthest distance from the sun) of the Escalator orbit. The Up Escalator trajectory was chosen as the starting nominal trajectory because of the benefit of refueling at Mars, only a few months prior to the required propulsive burn at aphelion.

To calculate the nominal trajectory it was assumed that the Earth and Mars were in co-planar, circular orbits about the sun. Neglecting the gravitational effects of Mars, with an Earth flyby altitude of 1,000 km, it was calculated that a propulsive change in velocity (ΔV) of 846 m/s was needed to rotate the major axis of the orbit the extra 5 degrees needed to achieve the complete 48.7 degree shift. The CASTLE will be near the aphelion of its orbit when the ΔV is affected, about 2.17 AU (1 AU = 14,599,000 km) from the sun. The perihelion (closest distance to the sun) of the Escalator orbit is 0.98 AU. The flight time of the Up Escalator from Earth to Mars is 145.9 days. The flight time of the remaining leg of the trajectory (from Mars to Earth) is approximately 636 days. The approach velocity of the CASTLE with respect to the Earth is 6.0 km/s, while the approach velocity at Mars is 9.3 km/s. Following the establishment of the initial nominal trajectory it was decided to attempt to lower the propulsive ΔV required.

This orbit can be optimized without significantly changing the basic dynamic mission parameters. The optimal ΔV required was found by setting the flight time from Earth to Mars, the angle covered by going from Earth to Mars, and by adjusting the Mars flyby altitude. From this, the ΔV required was reduced to an approximate value of 220 m/s with a Mars flyby altitude of approximately 16,300 km. Although the scope of Project CAMELOT makes it necessary to design along the circular, co-planar assumption, the real world analysis shows that only minor propulsive modifications would be necessary to expand the CASTLE into the "real world" realm.

Section 2.2: Orbital Correction Propulsion

In order to maintain the CASTLE's cyclic orbit, a propulsive maneuver is required. The orbital correction maneuver rotates the semi-major axis of the CASTLE's elliptic orbit, therefore ensuring rendezvous with Earth and Mars on every orbit. In order to perform this orbital correction, the propulsive system must change the velocity of the CASTLE. The total change in velocity required, or ΔV, determines the amount of propellant required and length of burn time for the rocket engines. The correction maneuver occurs at aphelion, the point in the orbit farthest from the sun. The nominal trajectory is the basis for the system design.

The maneuver for the nominal trajectory involves a ΔV of 847 m/s and must occur every orbit. It will be accomplished with chemical rocket engines using liquid oxygen (LOX) - liquid hydrogen (LH2) propellants. All calculations are based on currently available technology. Present state-of-the-art technology in chemical rocket engines is represented by the Rocketdyne Orbital Transfer Vehicle (OTV) rocket engines. The thrust of a single engine is 66,750 N with a lifetime of ten hours. Using four engines, located at the rear of the CASTLE, the orbital correction can be accomplished with a power-on time of one hour.

The propellant tanks required to complete the orbital correction are also large enough to contain the attitude control propellants of the non-rotating section of the ship. The LOX tank carries 174,524 kg of oxidizer and has a volume of 170 m^3. The LH2 tank contains 30,337 kg of fuel and has a volume of 490 m^3. The tanks are stored within the truss of the CASTLE, and each has a diameter of eight meters. Ellipsoidal endcaps to both tanks have been chosen to minimize unused space within the truss. The total length of the LOX and LH2 tanks is 4.71 m and 11.08 m, respectively. These two tanks can be placed inside the truss, one in front of the other, by a rendezvousing tanker at Phobos.

The tanks are insulated to protect against propellant boil-off due to radiation from the sun. A temperature-resistant aluminum alloy contains the propellants, and a sheet of 0.02 m fiberglass insulation externally surrounds the tanks. The aluminum alloy is 0.0055 m thick. In addition, a deployable shield coated with a reflective paint is fastened in front of the tanks on the sunward side of the CASTLE. The shield is unattached to the tanks. The mass of the LOX tank, LH2 tank, and protective shield is 2,405 kg, 4873 kg, and 50 kg, respectively.

Section 2.3: Initial Insertion

Following the establishment of the nominal trajectory the orbital altitude for CASTLE construction had to be determined. The altitude chosen had to provide the easiest conditions for this construction combined with the most efficient use of propellant. The absolute minimum ΔV required to escape from a circular orbit and enter the circulating escalator trajectory on the ecliptic plane is ΔV equal to 4.26 km/s, made at an altitude of 15,580 km. However, this altitude is not acceptable for construction because of the high amounts of radiation exposure due to the Van Allen Belt. At a circular low earth orbit (LEO) of 1113.5 km the required ΔV to inject the CASTLE into its orbit is 4.65 km/s, also slightly higher than the optimal injection altitude but still well within reason. LEO was chosen for CASTLE construction.

Once construction of the CASTLE is completed the problem of insertion into the Escalator orbit had to be considered. The cyclic Escalator orbit lies in the ecliptic plane, the plane containing the Sun and the orbit of the Earth. As a consequence, to inject into circulating orbit from Earth, one must pay attention to the position of the ecliptic plane relative to the CASTLE construction plane. The ecliptic plane inclination from the equator is 23.5 degrees. Since it was decided that the CASTLE would be constructed in the high LEO orbit of 1113.6 km inclined 28.5 degrees from the equator, the CASTLE insertion procedure must therefore involve a five degree plane change as well as the posigrade velocity change of 4.65 km/s for hyperbolic boost.

The insertion from the circular low earth orbit into the cyclic trajectory in the ecliptic plane of the solar system requires an impulsive propulsive maneuver to achieve the proper hyperbolic velocity. This maneuver can be done in many ways. One possibility is the direct tangential burn into cycling orbit. Another is a two step process in which the CASTLE first does a retrograde Hohmann Transfer elliptical orbit around Earth, producing high perigee velocities that make hyperbolic injection velocity changes smaller. Whatever the method, the point of insertion along the Earth orbit is very specifically chosen.

Section 2.4: Initial Insertion Propulsion

Once the CASTLE is constructed in a low earth orbit (LEO), it must be boosted to a heliocentric orbit around Mars. This is a one-time-only boost, and is completed using the on-board Rocketdyne OTV engines. The orbital insertion requires a ΔV of 4.74 km/s, and eight OTV engines can accomplish the maneuver in 4.4 hours.

The initial boost requires 1.71 million kg of propellant. The propellant, which includes enough for initial attitude control maneuvers, is transported from earth to LEO in conveniently storable tanks. The LOX is stored in six spherical tanks, each containing 245,000 kg of oxidizer and with a radius of 3.74 m. These tanks are stored in the truss of the CASTLE. The LH2 is stored in two larger, spherical tanks of radius 7.47 m. Each tank can hold 123,000 kg of fuel and is attached to the outside of the truss during the insertion.

The initial insertion propellant tanks consist of a 0.0055 m-thick aluminum alloy wall and an external 0.05 m-thick wall of fiberglass insulation. The LOX tanks each have a mass of 2900 kg, and each LH2 tank has a mass of 11,600 kg. Upon reaching Phobos, the tanks are jettisoned and the propellant tanks for orbital correction and attitude control are loaded onto the CASTLE.

Section 2.5: Rendezvous

The subject of rendezvous is important to Project CAMELOT because of the nature of the Escalator trajectories. The CASTLE moves along the Escalator trajectory without stopping at either Earth or Mars. Flyby velocities are relatively high as compared to planetary orbital speeds. It is therefore necessary to provide a means for crew and cargo to be transferred to the CASTLE at Earth and Mars flybys. In order to do this, an Orbital Transfer Vehicle, or Taxi, must be used to provide the link between Earth and Mars Spaceports and the CASTLE.

The planetary encounters and hyperbolic rendezvous will occur as follows. The CASTLE is enroute to Mars with two Taxis attached. When approximately five days away from Mars, both Taxis will separate and initiate small ΔV's on the order of 20 m/s to change minimum approach distance to planetary atmospheric graze. At graze, an Aero-braking procedure will be initiated to burn off the energy of hyperbolic trajectory. The Aerocapture will slow each Taxi down into a planetary, highly elliptic orbit where three ΔV's will be made to allow the Taxi to rendezvous with Phobos. Concurrently, two Taxis will be departing the Phobos spaceport for eventual rendezvous with the CASTLE. The Taxis will be required to complete propulsive burns that will change altitude at periapsis to a minimum orbital distance. When the Taxi is at the furthest point from Mars a ΔV will be made to change the orbital plane and place the Taxi back on the ecliptic plane, thereby allowing rendezvous with the CASTLE. Rendezvous is close to a straight line travel due to the relatively small distance traversed along the heliocentric orbit. These two Taxi's will remain with the CASTLE until the next planetary encounter. Earth encounter and Taxi transfer occurs in much the same way.

Section 2.6: Mining on Phobos

Phobos is Mars' innermost moon and is an excellent source of propellant. Phobos has a mass of 9.9×10^{15} kg, and is made up of 20% bound water by weight. This water can be transformed into liquid oxygen (LOX) and liquid hydrogen (LH2) propellants. To obtain the propellant needed for each cycle of the CASTLE, 258, 750 kg of water must be mined during each ship cycle (about 2.14 years). To obtain this much water, 1,293,750 kg of Phobos' material must be mined. A chemical plant will extract the water from the rock and split it by electrolysis into gaseous oxygen and hydrogen, which are then cooled to form LOX and LH2. Approximately 2,000 kg of rock will be mined and then processed daily to meet the refueling requirements.

Section 2.7: CASTLE Replenishment

Some items used aboard the CASTLE will need to be replaced occasionally, such as propellant, some types of food, working fluids, lab equipment and other ship system parts. Large nuclear electric cargo vehicles will be used to haul heavy cargo and propellant up to the CASTLE orbit, where they will rendezvous with the ship and unload their cargo. One replenishment will occur during every ship cycle.

Chapter 3: Crew

Section 3.1: Crew Rotation

The Mars base is manned by 34 people. Each CASTLE carries 20 people, including 17 passengers and 3 crew members. For a single CASTLE scenario, there will be 20 people aboard at all times, with 17 people leaving the ship at Mars to remain at the Mars base, and 17 people leaving the Mars base and boarding the ship to return to Earth. In the dual CASTLE scenario, with both an up- and down- CASTLE, both ships will carry the full load of 20 people for only the short part of the journey (4.5 months), and will carry only the 3 crew members for the long part of the journey (1.75 years). The up-CASTLE will bring 20 people from Earth to Mars, and the down-CASTLE will be used to carry people from Mars to Earth. For detailed diagrams of this rotation, see sec.3.1.4.

Section 3.2: Crew Selection

In Project CAMELOT, a new type of space scenario is presented. People are going to live in the CASTLE for at least four months. Further, their tour of duty on their entire Mars excursion will last for years. If they run out of food or require emergency medical attention, they will not be able to turn the CASTLE around and come back home. Life support, medical, and human factors must all take into account this fact and provide for as much as possible along the way.

Chapter 4: Human Factors

Section 4.1: Introduction to Life Requirements

The aspect of long duration, manned spaceflight brings about new challenges in the field of human factors. So far, space missions in general have been either very short or within the reach of an emergency rescue flight. Thus, life support has been based solely on providing enough open storage of food, water, and air to last for the length of the mission. Astronauts who have experienced medical problems in space have simply waited to return to Earth to be treated. The thought of waste management has been that of providing a trash receptical large enough, and very little has been done as far as providing a comfortable lifestyle for space travellers.

Section 4.2: Life Support and Environmental Control

In life support, a system based soley on stored foods, water, and air is no longer practical. A new system is now available which will manufacture food, clean and reprocess water, and recirculate air continuously. It is called a Controlled Ecological Life Support System (CELSS) and is indeed, a closed ecosystem in which waste products from humans or materials usage is put back into the system to recycle the nutrients therein. The system, in a nutshell, consists of an agricultural component (plants), an aquacultural component (fresh and salt water marine life), selected small animals and their habitat (chicken coop), and both organic and mechanical water and waste processing systems. The diet on board the CASTLE will be supplemented with selected stored foods every cycle to enhance the quality of meals, but still, there is a great overall savings in mass and volume using CELSS over a storage system (not to mention providing freshly grown foods). Thus, CELSS alone will take care of the four main considerations in life support: (1) Food management; (2) Water reclamation; (3) Waste management; and (4) Air revitalization.

Section 4.3: Required Health Maintenance and Medical Provisions

Although there is no way to fit an entire hospital into the CASTLE, a quality, versatile health maintenance facility must be provided along with a well-rounded doctor and nurse. The facility should have an adequate pharmacy to provide for day to day discomforts, most illnesses, and emergency. Further, the doctor, nurse and facility must be capable of performing minor surgery such as appendectomies or tonsilectomies, etc., and treating injuries from accidents that occur during the journey to Mars.

Section 4.4: Adaptation to Artificial Gravity

The artificial gravity induced in the living section of the CASTLE poses special problems. The effect of a gravitational gradient is an important factor which must be considered in the design of a system as large as Project CAMELOT.

Section 4.5: Human Factors

Finally, the human factors such as the psychological stresses of living in an isolated and hostile environment must be provided for. These are considerations ranging from the color schemes of the walls to the activities available on board the CASTLE. Useful work, as well as recreation and exercise, must be distributed to all passengers to fight off boredom and depression. Further, exercise is important in keeping the muscles in shape while living in less than one half of the Earth's gravity. A psychiatrist is highly recommended to be on board and act as a counselor, therapist, and "cruise director" in order to keep up the morale of the passengers and crew.

There are a great many things to consider when planning to enclose people in a hostile environment for long periods of time. Over the course of this project, only the major problems were considered. Yet, as complex as the human mind and body are on the Earth, they are compounded in space, and it is of the utmost importance that human factors considerations be put above mass and cost considerations in a project such as CAMELOT.

Chapter 5: Habitat Design

Section 5.1: Introduction

The design of the habitat for the CASTLE is unique due to the need for artificial gravity, the inhabitant's living requirements and certain mass and dimension constraints. In addition, the design required a cooperative blend of Architecture and Aerospace Engineering ; acollaboration necessary for man's extended presence in space.

Section 5.2: The Torus

The habitat of the CASTLE consists of micro-g section and a torus which rotates to produce artificial gravity. The artificial gravity (0.4g) is induced by rotating the 35m radius torus at a rate of 3.2 revolutions per minute. The circumference of the torus at the floor is 218.6m and its width (interior) is 7.0m. It is made up of 20 modules, each 11m long. The maximum number of inhabitants for the habitat is 21.

Due to the unique shape of the habitat and because of its enclosed environment, the following aspects had to be modified from Earth standards and included in the design. They are: acoustics, lighting, ventilation, plumbing, volumetric layout, corridors and airlocks. Furthermore, the habitat has to act as a physically isolated, mini-community, and therefore, contains the facilities necessary for the comfort and health (both physical and mental) of its inhabitants. The rooms on board the torus were categorized by their anticipated noise levels and are as follow.

CELSS'	Laboratories'	*Noisy areas
Chapel^	Lounge/Library^	^Quiet areas
Command Center/Safe Haven'	Medical Center^	'Buffer areas
Crew Cabins^	Passenger Cabins^	
Dining/Conference Room*	Recreation Room*	
Galley (Kitchen)	Safe Havens'	

Section 5.3: Rotating to Non-rotating

Travel between the rotating torus and the non-rotating micro-g section is accomplished by travelling in one of the four slow-moving elevators housed in each of the torus' spokes and also entering the rotating/non-rotating interface (RNI). The RNI is basically an elevator lobby which can rotate up to the hub rotation or down to the zero rotation of the micro-g section.

Section 5.4: Micro-g Section

The micro-g section is a cylinder which is 8m in diameter and 15m long. The facilities located in the micro-g section are an observatory, a recreation room, laboratories, an EVA preparation room, an airlock/decompression chamber and a Safe Haven.

Chapter 6: Support Systems

Section 6.1: Power

The Power Systems group has focused its attention on providing the CASTLE with the electrical power that it requires, and controlling this power. This task was divided into five separate areas: Energy Source, Power Conversion, Heat Rejection, Power Management and Distribution, and Reserve Power. These smaller tasks were given to individual group members to tackle, and each component was integrated with the others as each was designed, in order to create a workable, self-consistent power system.

The design parameters are broad. The requisite amount of power must be delivered reliably. The system is required to be lightweight. A high degree of autonomy is desired, in order to avoid the need for humans to constantly monitor the system, lessening the demands made on crew and passenger time. The design of the system must be modular for easy assembly in space. Modularity is also desired because it supplies a level of redundancy to the power system, for if a component of one module fails, it is certainly more desirable than having the whole system fail.

The Energy Source chosen for CASTLE is known as solar dynamic. This involves using dish-shaped mirrors to concentrate the sun's rays onto a small area, the absorber. The heat generated in the absorber is used to drive a mechanical engine which creates useful electricity. There are nine such collectors on the CASTLE, divided into three clusters of three. This type of system is a departure from the normal use of solar power in space. Past space missions have used solar photovoltaics, which convert solar radiation directly into electricity, but at low efficiency. An additional drawback to photovoltaics is that they degrade noticeably with time. This is unacceptable for a long duration mission such as that undertaken by Project CAMELOT.

Choosing the Power Conversion System involved choosing a specific heat engine to convert the heat to electricity, the working fluid of the engine, and the operating temperatures and pressures. The choice made is the free piston Stirling engine. Such an engine is hermetically sealed (welded shut) to avoid the need for high pressure valves and seals. There are two pistons, a displacer and a power piston. The displacer shuttles the working fluid (helium) back and forth from a hot side to a cold side. The hot side was chosen to be at 1500K, and the cold side at 700K, which yields an ideal efficiency of 53%. The expansions and contractions resulting from this fluid shift cause the power piston to oscillate. A linear alternator wrapped around the engine derives AC current from the power piston oscillation. The actual efficiency of such a Stirling engine in the year 2035 was taken to be 45%

The Heat Rejection system is necessary due to the inherent inefficiencies in any power converter. Not all of the heat from the sun can be successfully converted to electricity; some must be rejected as waste heat. The system chosen to carry out this function is the Liquid Droplet Radiator (LDR). The LDR is a new technology, the goal of which is to avoid the large masses of traditional radiators. Heat is rejected in this system by spraying millions of tiny droplets of liquid tin at 700K into space and recollecting them after they have cooled to 600K. The mass of an LDR is small due to the fact that for a very small droplet, the surface area to mass ratio is very large. The mass can be as low a one-sixth that of a conventional heat-pipe radiator. There are three Liquid Droplet Radiators on the CASTLE, one serving each cluster of three Stirling engines.

The Power Management and Distribution (PMAD) system is responsible for making the electric power generated by the Stirling engines available in a useful form to the CASTLE and controlling the entire power system to insure harmonious operation. The power is transmitted from the engines at 20kHZ and 440 Volts AC. At the receiving end, this power is transformed into whatever voltage and frequency is needed for a particular application. The entire system is controlled by a master computer, which directs a secondary level of computers, each of which controls a specific subsystem.

The Reserve Power system is necessary in case of a shutdown or failure of the primary system. Enough reserve power must be provided to support life for a reasonable period of time to affect repairs. The system chosen is a set of Hydrogen-Oxygen Regenerative Fuel Cells. This system involves tanks of hydrogen and oxygen which react in the fuel cells to produce water and electricity. It is a regenerative system in that the water produced can be diverted back to an electrolysis stack and converted back to hydrogen and oxygen, if enough surplus power is available. A further virtue of the fuel cells is their versatility. If loss of atmosphere is a priority problem, the oxygen can be used as a backup. Also, emergency water can also be provided.
The power system described is a reliable, autonomous, low maintenance system that meets the power needs of the CASTLE.

Section 6.2: Communication

The communications system features luxuries that enhance people's psychological health.

Several luxuries were designed into the system with one exception. The speed of electromagnetic propagation through free space limits our speed of transmission. This constant speed is near the speed of light, which is 300 million meters per second. Because of the great distance that the CASTLE will travel, transmission times are usually several minutes long. A timetable in Section 6.2 shows the time delay between message and response to be more than 20 minutes for about half of the journey. Design for the luxury of immediate response is not possible.

However, a convenient and easily used system was designed by appropriately coordinating the means and forms of communication. The means by which a person communicates features easy use of many functions. The forms permit communication with many places.

The means of communication are performed at a Communications Station, or CS. The CS's are located conveniently throughout the ship. Thus, no person has to travel far or wait in line to use the CS. Each CS performs many functions. A person can write, speak, and visually present information. To do this, each CS features a video screen, video disc recorder, or VDR, keyboard, intercom, desk and chair. Each CS also can communicate with many places. A person can communicate with another onboard, the Taxi support vehicle, Earth, or the Mars colony.

The CS's are also terminals of a powerful mainframe computer. The mainframe acts as the switching network for the various communication forms. For example, the terminal operator requests a channel opened to Earth so that he can begin a correspondence with his family. Very soon after the request, the computer will open a channel. The terminal operator can now transmit his message to Earth. The CS as a mainframe terminal also has access to tremendous computing power and vast memory storage.

Section 6.3: Torus Rotation and Attitude Control

Attitude Control

In order to maintain the desired ship orientation at all times during the mission, it must be possible to provide small, intermittent thrusts at various points on the CASTLE whenever necessary. In particular, the attitude of the CASTLE must be continually adjusted so as to maintain an orientation that is radially away from the sun for most of the mission. The thrust levels required for such control are on the order of 100 newtons for a period of about five seconds. The attitude control maneuvers are made with the current state-of-the-art LOX/LH2 control thrusters. A suitable thruster is the Aerojet AJ10-167. The thrust of a single thruster is 111.2 N, and it has a lifetime of 6.2 hrs. On the non-rotating section of the CASTLE, pairs of thrusters are located on each wall of the section at six positions along the axial direction of the truss. A thruster pair consists of two thrusters, each firing in diametrically opposite directions to one another perpendicular to the truss. On each solar collector boom there are three equally-spaced thruster quads. A quad consists of four thrusters, with one nozzle pointed in each of the +x,-x, +y, and -y directions of the thruster's coordinate frame. One of the axes is directed along the boom.

The attitude control thrusters are fed from the main engine propellant tanks, which are located within the truss section. The mass of the LOX is 7,500 kg, and the LH2 mass is 2,500 kg.

Torus Rotation

The torus section of the CASTLE must rotate at a constant angular velocity in order to provide artificial gravity for the habitat modules. The torus is initially spun up to its steady state rotation of 3.2 rpm. The Aerojet AJ10-167 control thruster is suitable to accomplish the spin-up, as well as any additional rotation maintenance that may be required for the torus. Four thruster quads are located on the outer circumference of the torus, each quad at a point midway between an intersection of the torus and an elevator spoke. In addition, eight thruster pairs spaced evenly around the torus complement the thruster quads. The quads have one thruster axis directed tangentially along the torus, and the thruster pairs are directed tangentially as well.

The propellant tanks for the torus thrusters are located on the front side of the CASTLE, along the wall of the torus that is constantly directed away from the sun. Four packages of LOX/LH2 tanks provide propellant for the thrusters, with a package located at each of the torus/elevator intersections. Each LOX tank contains 900 kg of oxidizer and has a volume of 0.85 m^3. Each LH2 tank contains 300 kg of fuel and has a volume of 4.30 m^3. The LH2 tanks are spherical with a radius of 1.0 m, and the LOX tanks are ellipsoidal, with a major axis of 1.0 m and a minor axis of 0.2 m.

Since the tanks are located in the shaded portion of the torus, very little insulation is required to protect against boil-off. The tank material consists of a 0.0055 m-thick, temperature-resistant, aluminum alloy on the internal wall and a 0.02 m-thick fiberglass insulation on the exterior. Because the tanks are so small, their mass is negligible.

Section 6.4: Mechanical Support Systems

Three mechanical systems were developed to fit the special needs of the design of the CASTLE. These systems are: the Taxi docking configuration, necessary for the transfer of passengers between the Taxi and the CASTLE; the rotating/non-rotating interface, necessary to transfer passengers, air, power, and communications between the living and working quarters in the torus and the work areas in the micro-g section; and the torus elevator system, necessary to move passengers from the hub of the rotating section in minimal gravity to the perimeter of the torus at a gravity of .4 g.

The Taxi docking interface configuration has been designed by VPI. Entry into the crew module is done via the outer hatch into the airlock space. The outer hatch is then closed and the airlock is pressurized The inner hatch can then be opened to allow access to the interior of the crew module.

The rotating/non-rotating interface incorporates oversized ethylene-propylene o-ring seals seated in angled channels about a primary core, with the entire unit being shielded from radiation. Heat sinking and lubrication reservoirs are also incorporated. Beyond pressurization, power and data transfer has also been considered. The basic power interface incorporates a circumferential channel in which power transfer " drums " are seated. The rotating drum acts as a power bridge. Data transfer occurs via an interference insulated circumferential male-female channel. The interference insulation is a Teflon-Aluminum grounded " sandwich " which surrounds the communications interface.

The torus elevator design incorporates two ideas to solve the problems presented by the rotating torus. A coil-spring potential energy storage system is utilized to store the energy lost by the elevator as it moves radially outward along the spoke, later using this energy to provide much of the acceleration required to bring the elevator back to the hub. Columns of ball bearings, nested in an aluminum casing, act as smooth guiderails for rods mounted on the sides of the elevator to solve the problem of stability.

Chapter 7: Overall Configuration

Section 7.1: Introduction

This chapter describes and explains the configuration and placement of the main components of the CASTLE. The components are discussed starting at the torus end, or bow, then moving along the main axis toward the propulsion system, or stern. The components examined are the torus, truss structure, solar collectors, communication dishes, micro-g modules, the Taxi docking interface, and the propulsion system. A large portion of this chapter is devoted to the development of the torus since it is the most important component of the ship and many of the other components needed to be designed around it.

Section 7.2: Torus

The mission objective for the CASTLE is to provide a comfortable transportation system for a crew of 20 between Earth and Mars. This necessitated an emphasis on the design of the living and working section of the ship. To insure that a crew of 20 arrive in good health and spirits at Mars, and also remain that way on the journeys to and from the planet, many factors had to be considered. Along with the design specifications from life sciences regarding contents of the habitat, protection against meteors and radiation, and the need for artificial gravity had to be designed into the CASTLE habitat. The torus is the result of those considerations.

7.2.1 Micrometeoroid Shielding

The subject of protecting the CASTLE against micrometeoriod strikes in deep space was examined and it was determined, based on the obtainable data, that protection against encounters with dust sized micrometeoroids was indeed possible using an inner and outer wall construction with a honeycomb interface. However, hypervelocity encounters (10-70 km/s) with more massive particles presented a far more serious design problem. In this case, no practical solution could be found.

7.2.2 Space Radiation Shield

Space radiation presents a serious hazard to the crew of the CASTLE. Its habitable areas must therefore be shielded to ensure the safety of the crew for the duration of the mission. To design this shield, the two types of deep space radiation, solar flares and galactic radiation, were examined. Solar flares are periodic outbursts of alpha particles, protons, and gamma rays given off from the sun. Galactic radiation is a constant source of radiation, consisting of a low flux (4 particles/cm^2-s) of energetic bare nuclei which appear to fill the galaxy isotropically. It was determined that the CASTLE needs protection only against the radiation caused by solar flares.

Solar flares are classified according to the amount of output radiation. For this reason, two types of shielding is used on this mission. The CASTLE is lightly shielded to stop Class 1 solar flares (up to 500 rad) and has several "Safe Havens" that are heavily shielded to stop Class 2 and 3 solar flare radiation (500 rad and above). Thus, there must be equipment on Earth and Mars (and possibly on board) that can predict solar flares, in order to insure ample time for crew retreat to the Safe Havens. In the event of a solar flare, all crewmembers will retreat to heavily shielded areas for the duration of the flare. Each Safe Haven has 5 m^2 of floor space and thus, 45.78 m^2 of total surface area. These Safe Havens house the command module, medical facility, temporary crew quarters, and various storing compartments (used for food, water, spare electronics, etc.).

7.2.3 Artificial Gravity Producing Configurations

Another consideration in the design of the habitat was the inclusion of artificial gravity. It was determined by life sciences that the amount of muscle and blood tissue breakdown due to a gravity free environment was great enough to necessitate this inclusion. As the torus is designed, the artificial gravity is produced by the rotating of the torus about the central axis of the CASTLE. The torus is spun up at the beginning of the mission to create the necessary centripetal acceleration needed to cause artificial gravity. The torus need not be despun during nominal operation, thereby giving the advantage of fuel savings over several alternate gravity producing configurations. These configurations are described in detail in Chapter 7.

Section 7.3: Truss Structure

The truss chosen for the boom triangular in cross section, and 1.5 m on a side (Figure 7.8). Four of these triangle trusses will be arranged parallel to each other at the corners of a rectangle 6.3 m on a side to accommodate the micro-g modules and fuel tanks.

Section 7.4: Power System

The main source of electrical power for the CASTLE is the solar collectors and Stirling engines, located an average of 58 m from the main truss, radially outward. Nine collectors are arranged in three sets of three 25 m diameter dishes.

Section 7.5: Communication System

Three communications towers are located the end of the truss supporting the solar collection equipment. The communication dishes have the capability to rotate 180 degrees and extend 10 m from this truss.

Section 7.6: Micro-gravity Section

Two micro-g modules are 15 m long and have 8 m diameters. They are located 10 m from the torus. These modules are placed inside the main axis structure.

Section 7.7: Taxi Docking Ports

A 3 m diameter pressurized tube, 15 m in length, connects the micro-g module with the Taxi vehicle docking area. A 5 m by 5 m storage room is located at the end of this tube. This room may be used as the main staging area for EVAs. Two 3 m diameter, 1 m long tubes connect this compartment with the Taxi docking ports. The Taxi docking ports are 180 degrees apart.

Section 7.8: Propuslsion System

The propulsion system is located 65 m from the torus. Two tanks contain the propellant for the CASTLE. Both tanks are 8 m in diameter. The smaller tank (4.7 m long) contains liquid oxygen and the larger tank (11.08 m long) contains liquid hydrogen. Eight main engines are located at the stern of the CASTLE. The engines are housed in a 3 m by 2 m framework.

Section 7.9: Ship Assembly

The CASTLE is being assembled in low Earth orbit (LEO) at an altitude of about 1,000 km. Assembly will begin about 15 months before insertion of the CASTLE into its final launch orbit. Assembly materials and propellants will be lifted from Earth by a Heavy Lift Launch

Vehicle (HLLV), (see NASA technical memorandum TM-86520 for HLLV details). The HLLV has a payload of 200,000 kg and area of 15m diameter and 60m height. To lift all the parts needed for the CASTLE, 12 HLLV launches will be needed: 5 launches for the ship itself and 7 launches for the propellant. The first HLLV launch will bring up several habitat modules and one cluster of 3 solardynamics units. The modules will be connected and the power system set up to establish a space station to house the assembly crew. The next four launches bring up the rest of the ship. The following seven HLLV launches bring up the propellant. Two Taxi vehicles will dock with the completed ship about two weeks before insertion.

Chapter 8: Safety and Maintenance

Section 8.1: Safety

The crew aboard the CASTLE has to deal with emergencies such as radiation from a solar flare, pressure loss, and fire. In the case of radiation, the ship's monitors are able to predict when a solar flare will arrive and provide ample warning for the crew to take shelter. Once a solar flare has been detected, the most important step is to move all crewmembers to an area shielded against the excess radiation (i.e., Safe Havens). People will remain in the Safe Havens until the radiation monitors indicate that the flare has passed.

To detect pressure losses, there are pressure sensors located throughout the ship that alert the crew when the pressure in a section drops below a certain level; they also measure the rate of pressure loss to deterine the severity of the emergency. For a slow pressure loss, the crew in the affected area will locate the hole and seal it with a "blister patch". Rapid pressure losses will cause the airlocks in the affected area to close and seal off the depressurizing region. A repair crew in pressurized suits will then enter through the airlock to repair the damage.

To detect a fire, there are conventional smoke detectors and infrared sensors located throughout the ship. There are Halon 1301 extinguishers and deionized water foams located frequently and conspicuously through the ship. All crew members are trained in basic fire-fighting procedures. One crew member is appointed Fire Marshall and is in charge of fighting all fires. Small fires will be fought with extinguishers and water foams. Large, uncontrollable fires may require venting of the affected section's atmosphere, which will extinguish the fire automatically.

Section 8.2: Maintenance

The CASTLE systems all have redundancy built into them. They are designed to automatically recognize a failure, alert the crew, and isolate the failure without degradation of required performance. All crew members are trained in basic repair procedures. Many ship components can be replaced by removing few surrounding components and by having the crew perform a small number of common routines. The three permanent crew members are trained to perform extavehicular activities to make repairs to the outer parts of the ship.

Chapter 9: Cost Analysis/Justification

Section 9.1: Cost Analysis

In Chapter 9, a cost analysis is performed to give you an ideal of what the cost of Project CAMELOT would be if we did it today. The breakdown of the cost is listed in Table 1. The primary source for this cost estimate is *The Cost Estimation Model for Advanced Planetary Programs*, which is a NASA publication. The system cost is in terms of development labor hours. The subsystem cost is in terms of both development and production labor hours. The estimation of the cost for the ecological system, fuel, and launch costs, listed in the *other* column in Table 1, require different approaches because they are not covered in the model. These approaches are discussed in Chapter 9.

Initially, only one CASTLE will be produced, with the hope of another joining it after a few years. For this reason, both the total cost of one CASTLE system and the total cost for a two CASTLE system are shown in Table 1. With an additional cost of only 5.4 billion dollars, a second CASTLE is feasible, cost effective, and desirable.

Table 9.1

Project CAMELOT (Billions of 1987 Dollars)

	One CASTLE System	Two CASTLE System
Subsystem	12.00	16.39
System	4.40	4.40
Other	2.01	3.01
Total	18.41	23.80

The total cost of Project CAMELOT is 18.41 billion dollars. With a 1987 United States population of 240 million, the cost per capita would be only $76.71 for the one CASTLE system. If you extended this cost over a period of twenty-five years, the cost of Project CAMELOT would only be $3.07 per year per person. We spend a great deal more on defense, recreation, and medicare per year. Cost should not be a pertinent factor in delaying the start of our project.

Section 9.2: Cost Justification

Project CAMELOT will provide a cost-effective Mars transportation system through low maintenance costs, availablity of space materials, international cooperation, and product spin-off. The CASTLES are designed to last fifteen years without major overhaul. Hence, this reduces the cost of having to perform major maintenance frequently. Minor servicings will be done on board during regular orbits. Mining on Phobos will provide us with propellant which will lower the cost of shipping this propellant up from Earth. The implementation of extraterrestrial resources, along with mining on Phobos and the moon, provides new products to be utilized on Earth and in outer space along with the decreased cost of shipping them up from Earth. International Cooperation will not only reduce the cost of Project CAMELOT, but it will also help to reduce political tensions on Earth. Project CAMELOT will be an international project to the extent of subcontracting out subsystems. Product spin-off alone will outweigh the cost of Project CAMELOT. Advancements in technology will take place. One of the major technological advances that will come from Project CAMELOT will be the development of the self-contained ecological system. Not only will this ecological system be used in space, but it may have many applications for use on Earth. These advancements serve to make us become more efficient which will lead to future success. Most importantly, education will advance. A bold, imaginative space program will inspire young people to go into the fields of science and technology. The education of our youth will ensure growth. These benefits will outweigh the cost of Project CAMELOT and will increase the wealth of the nation.

Today, applications and spin-offs of space technology are making life better for people throughout the world. The Apollo Program added many new products that are now a part of everyday life. The chief undefined benefit of the Apollo Program was the elevation of national pride. This program brought out creativity and inspired us to achieve. We can accomplish great things when we are challenged to do so. Space offers us a tremendous chance to grow, achieve, and develop. In this spirit, Project CAMELOT will advance the creativity and imagination necessary to carry the United States and all nations of the world through the 21st century.