Space Station Based Microacceleration Experiment Platform

Final Report

Submitted to
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Spacecraft and Mission Design

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Executive Overview

In the spring semester of 1990, the μg Group of the University of Texas at Austin accepted the task of studying microgravity experiments and Space Station's microgravity environment, as well as designing a Space Station Based Microacceleration Experiment Platform (MEP) for experiments with more sensitive requirements than Station will be able provide. The statement of work called for a teleoperated free flyer in Space Station's orbit , either leading or trailing it. However, the atmosphere at typical Space Station orbital altitudes is sufficiently dense to decay orbits over a period of months. Unfortunately, this decay occurs at different rates for bodies with with different drag characteristics. Since an objective in the design of a microgravity experiment platform is to minimize its incident drag forces rather than match them with Space Station's, the concept of a leading or trailing orbit was discarded. Taking this into consideration, the MEP was designed to perform orbital transfers for either boosting to a higher altitude to eliminate drag forces, or to transfer back to Station after their orbits have drifted apart.. The MEP was also designed to be a modular platform, with pieces launched either by the space shuttle or expendable launch vehicles, composed of modules which fit into a truss. Modularity was chosen to maximize the types of missions which can be performed. An optional mode of operation, highly recommended for appropriate experiments, is to eliminate drag by "levitating" experiments inside a module. Thrusters on the vehicle would fire to prevent the module and experiment from colliding. The MEP is composed of specific subsystems, tailored to meet microgravity environment requirements, including the structure, power, communications, utility connections, guidance, navigation, and control, propulsion, and thermal control. The MEP can carry individual experiments up to 1000 kg for durations of up to 2 years. Recommendations for future design work have been included in this report.

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1. General Summary

Normal Space Station Freedom activities, such as docking, astronauts' movement, equipment vibrations, and space station reboosts, exert forces on the structure, resulting in static or transient accelerations greater than many microgravity experiments can tolerate. A solution to this problem is to isolate experiments on a separate platform free from such disturbances. This document describes the Space Station Based Microacceleration Experiment Platform, a proposed solution to the Space Station microgravity experiment problem. It is modular in design and can be telerobotically assembled and operated. The MEP consists of a minimum configuration platform to which power, propulsion, propellant, and experiment modules are added. The platform's layout is designed to take maximum advantage of the microgravity field structure in orbit.

2. System Overview

2.1. Problem Description

2.1.1. Space Station Microgravity Limitations

NASA has studied a number of Space Station configurations to assess the quality of its microgravity environment for microgravity experiments[1]. Of the current configurations under consideration, only one contained as much as 65% of the experiment lab in the 1 μg envelope. Of the alternate configurations proposed to specifically improve the microgravity environment, one achieved 95%, but crew activities which cannot be isolated proved to be too detrimental sensitive experiments. The third recommendation of the **Space Station Freedom Microgravity Environment Definition** requests the following action:

> "Evaluate the Program options for free-flying critical microgravity experiments that require disturbance levels below those that can be provided on a permanently manned facility."

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[1] Space Station Freedom Program Office, **Space Station Freedom Microgravity Environment Definition**.

2.1.2. Experimental Requirements

The primary design objective of the Microacceleration Experiment Platform is to provide an environment suitable for as wide a variety of microgravity experiments as possible. A current list of all proposed microgravity experiments was studied to determine required microgravity levels, power requirements, heat rejection needs, experiment durations, masses, and volumes[2]. Typical experiments include crystal growth, materials processing, biological effects, and fluid behavior. Since future microgravity experiments may have more stringent requirements than exist at present, the design parameters were chosen as either the worst case requested or to match the Request for Proposal. Table 2.1.1 contains a list of the most restricting design parameters for a microgravity experiment platform.

Table 2.1.1. MEP Design Parameters

Microgravity Level, μg	0.1
Power, kW	5
Temperature, °C	4-2200
Duration, years	2
Mass, kg	1000
Volume, m^3	48

The listed microgravity level of 0.1 μg is actually a time-average value. Figure 2.1.1 is a composite of worst case microgravity tolerances for various experiments, shown as a function of the frequency of an induced vibration. As frequency increases, the tolerance improves. Any vibrations inherent in the structure must be checked to make sure they fall below this curve.

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[2] From Fraser, W. (Space Industries), "Report of the Committee on a Commercially Developed Space Facility."

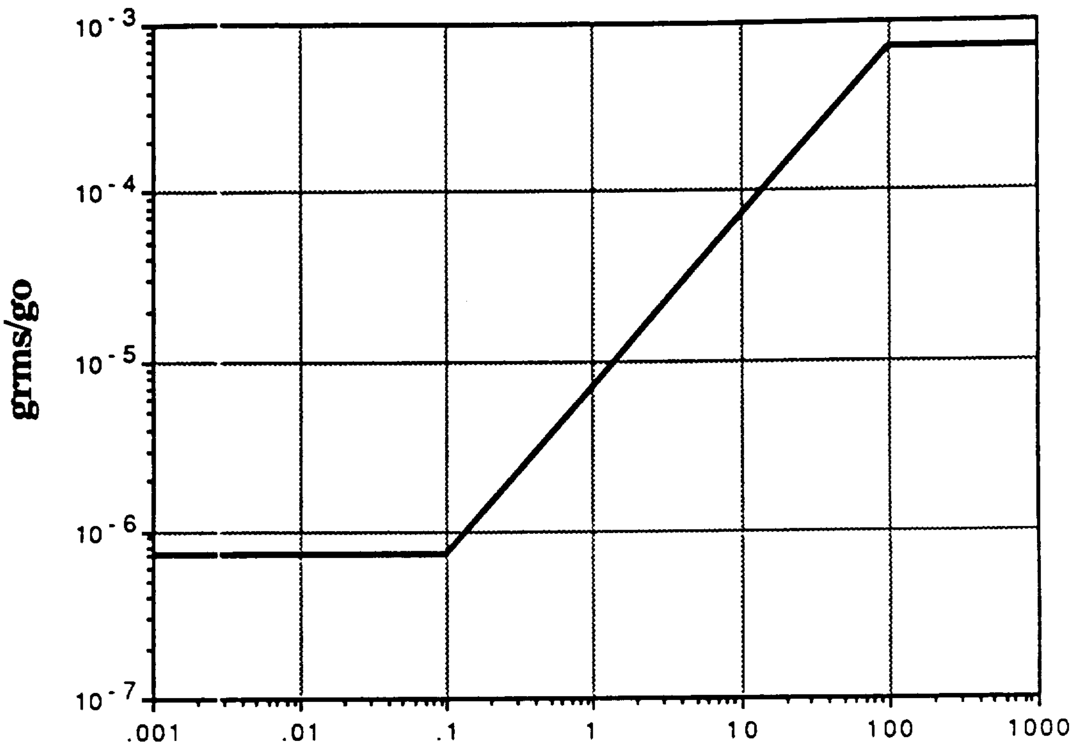

Figure 2.1.1. RMS Acceleration Requirements for Transient Oscillating Disturbances

2.1.3. Atmospheric Drag

A major obstacle in providing a microgravity environment is the presence of atmospheric drag. For a typical space vehicle at the nominal space station orbital altitude of 190 nautical miles (n.mi.), atmospheric drag is a time-varient force which induces an average acceleration of[3] 0.3 µg. This is greater than the minimum tolerance of many experiments. Drag is proportional to density, which decreases increasing altitude. An orbital altitude of about 300 n.mi. is required to effectively eliminate the effect of drag.

Another aspect of the atmospheric drag problem is that Space Station Freedom will perform a reboost approximately every 90 days. If the MEP were to fly in formation with Space Station, it would also have to reboost, a maneuver

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[3] Lindenmoyer, A., Presentation Notes, **Summary of Space Station Freedom Microgravity Environment Definition Report.**

which is currently expected to induce an acceleration of about[4] 0.6 μg. This would also contaminate the microgravity environment.

2.1.4. Keplerian Effects

Keplerian effects refer to the acceleration of any point in a rigid body due to its distance from the center of mass of the body. Every point in an orbiting rigid body, taken as a point mass, wants to travel in a slightly different orbit. Structural rigidity prevents this from occuring, resulting in a contamination of the microgravity environment. Constant acceleration surfaces are elliptical tubes aligned along the body s velocity vector as shown in Figure 2.1.3. Figure 2.1.4 shows the gravity gradient structure, where the body's velocity vector is perpendicular to the page. These figures show that an orbiting body has a "sweet line" of microgravity which passes through the center of mass in the direction of the body's velocity vector.

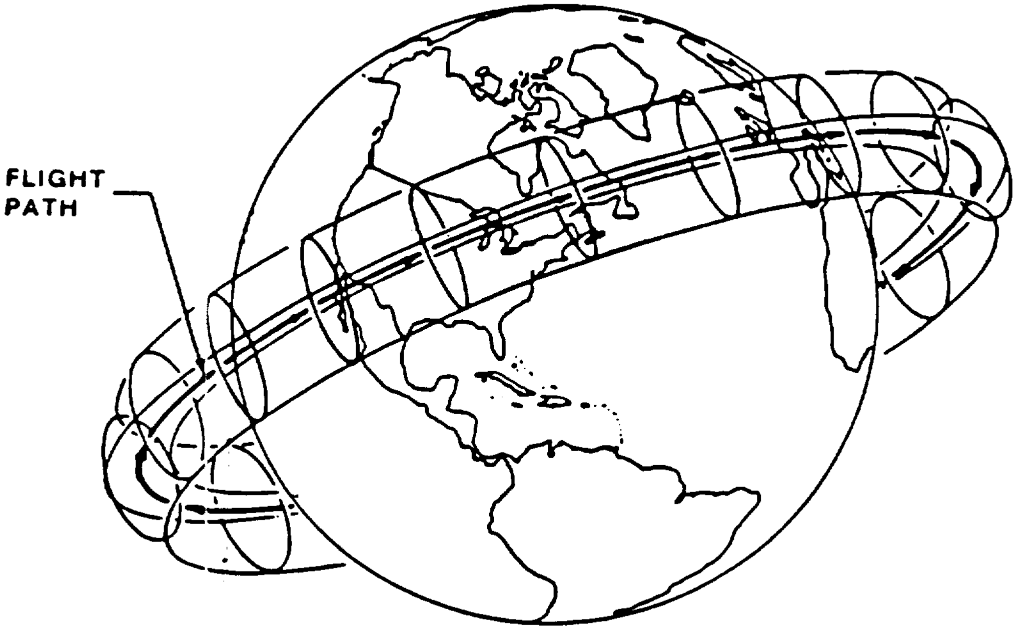

Figure 2.1.3. Micro-G Envelope[5]

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[4] Space Station Projects Office, **Space Station Projects Requirements Document.**, p. 3-2.

[5] Demel, K.J., Presentation Notes, **Space Station Microgravity Considerations and Materials Processing for Commercial Development**.

THE COMPOSITE STRUCTURE OF THE GRADIENT FIELD OVER EXTENDED VOLUMES IS INDICATED HERE. R_0, R_1, & R_2 ARE THE RADII OF THE OUTER MIDDLE & INNER CIRCLES RESPECTIVELY WHERE

$$R_0 = 2^1 R_1 = 2^2 R_2$$

FOR ACCELERATIONS A_R & A_{CP}

FOR R_0, R_1 & R_2 USE TABLE BELOW.

DISTANCE FROM CG (M)	ACCELERATION ($10^{-6}G_0$)	
	RADIAL	CROSS PLANE
R	A_R	A_{CP}
1	0.375	0.125
2.	0.75	0.25
4	1.50	0.50
8	3.00	1.00
16	6.00	2.00
32	12.00	4.00
64	24.00	8.00

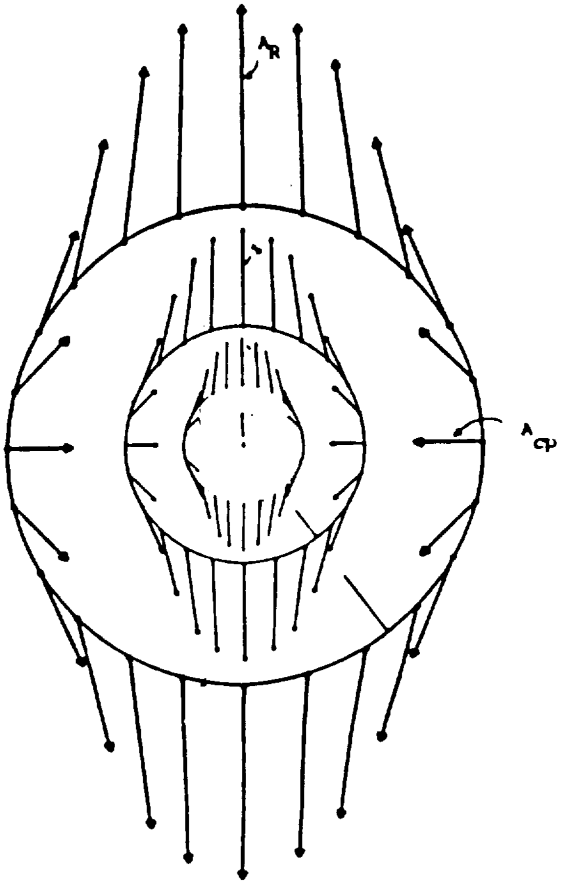

Figure 2.1.4. Gravity Gradient Structure[6]

2.1.5. Mechanical Vibrations

Structural vibrations induced by mechanisms such as pumps or gyros present a serious threat to microgravity experiments. Treadmill use by astronauts is enough to prevent many microgravity experiments from being performed on Space Station Freedom. Therefore, every subsystem considered for the MEP was closely examined in terms of the amount of structural vibration it produced.

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[6] ibid.

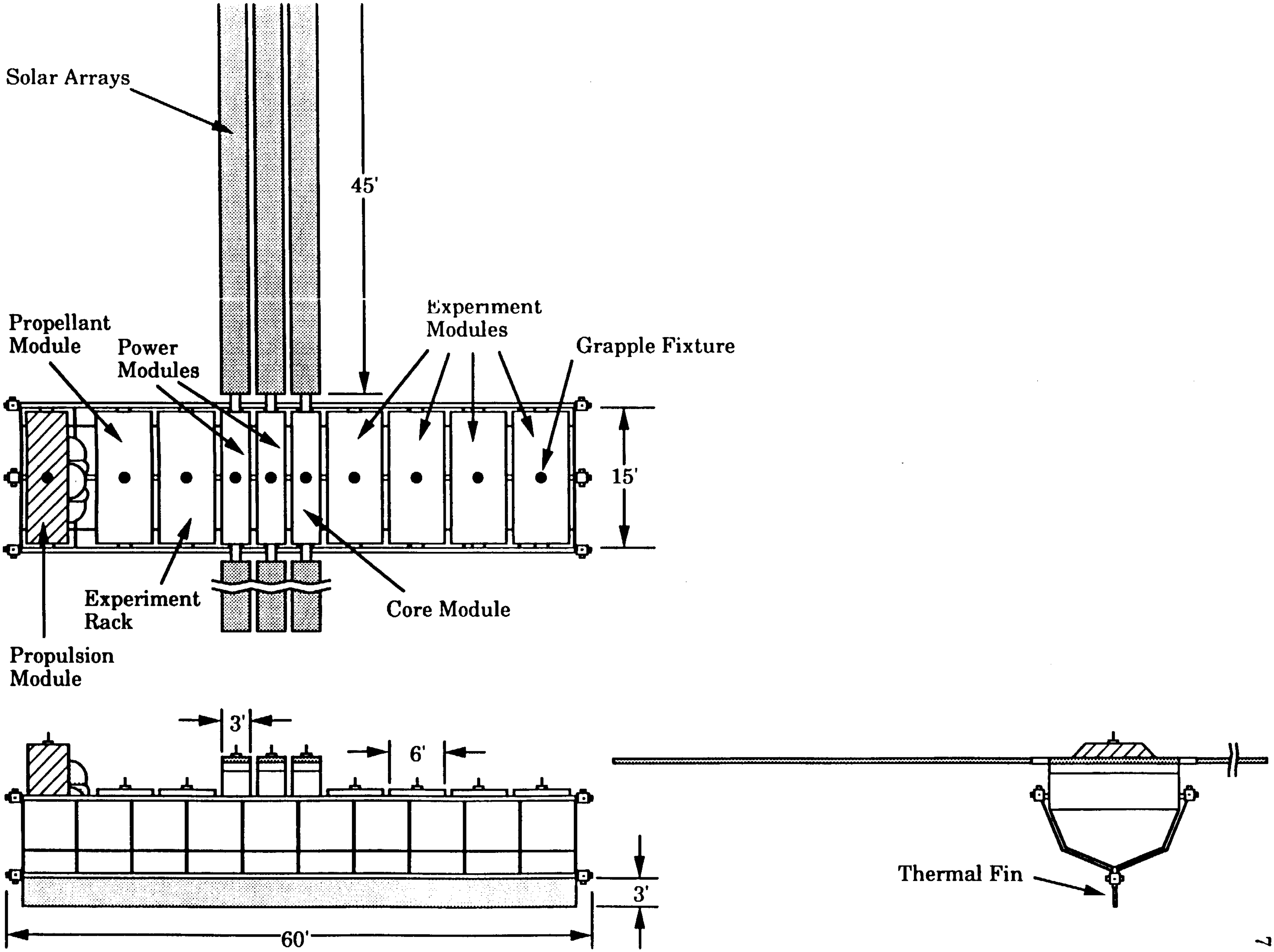
2.2. Vehicle Configuration

The proposed MEP is shown in Figure 2.2.1. Its layout is based primarily on the considerations presented in Section 2.1. It is modular in design, providing ease of use for many types of experiments and mission profiles. The vehicle's longest axis is along its velocity vector, to minimize adverse Keplerian effects. In the center is the Core Module and two Power Modules, which provide systems necessary to all experiment missions: power, computer, data retrieval system, television equipment, thermal control, and communications. Shown in this configuration are four Experiment Modules and one Experiment Rack Module. Each module is 15' wide, 6' long, fits inside the space shuttle cargo bay, and is equipped with standard shuttle keel trunnions, which also secure it to the MEP truss. Also shown on each module is a grapple fixture, to provide a means of removing the modules from the shuttle's cargo bay and placing them in the MEP, using either the Shuttle's Remote Manipulator System (RMS) or Space Station's Teleoperated Manipulator System (TMS).

Also shown in Figure 2.2.1 is the Propulsion Module, which will be used for those missions in which it is deemed necessary to boost to a higher altitude to eliminate atmospheric drag. Beside it is the Propellant Module, which provides fuel for the Propulsion Module as well as the reaction control system (RCS). The extra Power Modules with solar arrays are depicted in this configuration for those missions with experiments which require more power than the Core Module can supply.

All modules sit in a truss structure, which provides the majority of the structural stiffness for the MEP. It is composed of three main utility beams (shown as rectangular in cross-section) and two smaller structural beams which run the length of the MEP. Connecting these beams are ten rows of four 6' x 5'9" shear panels separated by ten U-shaped beams.

The three utility beams provide utility lines and connections so that each module can plug into the Core Module's power supply, computer, television systems, data retrieval system, and thermal control system. Fuel lines for the RCS are also located in the middle utility beam.


Solar Arrays
45'
Propellant Module
Power Modules
Experiment Modules
Grapple Fixture
15'
Experiment Rack
Core Module
Propulsion Module
3'
6'
3'
60'
Thermal Fin

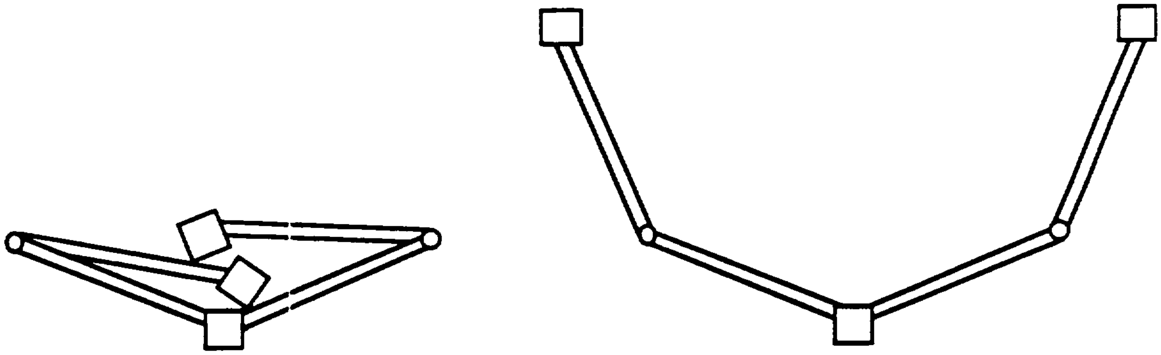
2.3. Mission Profiles

Two distinct mission profiles must be considered for the MEP. First is the launch and construction of the MEP and its major components. Second is deployment, execution, and return of microgravity experiments. The execution of the experiments is further divided into different modes, which will be chosen depending upon the specific microgravity requirements, duration, and budget for a given mission.

2.3.1. Launch and Construction

The MEP will be launched, in stages, by the Space Shuttle. These pieces will be collected and stored at the Space Station until enough are present to justify an experiment mission.

The first component to be launched will be the truss structure. During operation, the truss essentially acts as a mock-up of the shuttle cargo bay and must therefore be larger than the payload bay. It has therefore been design to fold up as shown in Figure 2.3.1 for launch. Upon arrival at Space Station, it will be unfolded and locked into operational position. A subsequent shuttle launch or launches will bring the Core Module, and if necessary for the first experiments chosen to fly, the Propulsion Module, Propellant Module, and Power Modules.



Launch Configuration

Operational Configuration

Figure 2.3.1. MEP Truss

2.3.2. Experiment Missions

Experiment Modules can be launched via the shuttle or expendable launch vehicles, according to the needs, budget, and schedule of the experimenter. The expendable launch vehicle option is especially advantageous for smaller experiments, which do not require an entire module and can be collected and inserted into a multi-purpose Experiment Rack. After an experiment has been completed, the module or package can be returned to earth via the shuttle, either to be studied or to refurbish the module. It is assumed that availability of cargo space on the shuttle will not be a problem for return voyages.

2.3.3. Experiment Modes

When enough similar experiments have been collected for a mission, the MEP can be released from the Space Station to execute the experiment phase. The nature of the experiment phase, or the "experiment mode," will be determined by the microgravity requirements, mission duration and allowable cost for the mission. These modes are described below.

2.3.3.1. LEO Station Keeping Mode

The simplest mode of operation, in terms of communication with Space Station, is the low earth orbit (LEO) station-keeping mode. The idea is to fly in the same orbit as the Space Station, either leading or trailing it.

The first problem inherent with station-keeping is that Space Station reboosts, which occur approximately every 90 days, complicate the plan of flying in formation. As mentioned before, boosting with the Space Station would impart an acceleration of approximately 0.6 μg, which is an unacceptable acceleration level. Therefore, station keeping is not an option for any mission over 90 days.

Another problem with station-keeping, however, is that drag degrades a body according to its ballistic coefficient , B_C, which is defined by[7]

$$B_C = \frac{W}{C_D\,A} ,$$

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[7] Bate, Mueller, White, **Fundamentals of Astrodynamics**, p. 424.

where C_D is the drag coefficient, A is the cross-sectional area, and W is the weight of the body. Space Station Freedom is expected to have a ballistic coefficient of about[8] 9 - 12 lb_f/ft^2. Assuming a supersonic blunt-body C_D of 0.2 and a wide range of experiment masses, the MEP ballistic coefficient will be from 300 - 600 lb_f/ft^2. This is such a substantial difference that LEO Station-Keeping Mode is not feasible.

2.3.3.2. LEO Solo Mode

A variation of the station-keeping mode is to let the MEP fly solo, with no attempt to prevent its orbit from drifting away from Space Station's. After the experiments are completed, the MEP would perform an orbital transfer to rendezvous with Space Station. Or, similarly, the MEP could be placed in an orbit such that the two vehicles rendezvous when Space Station reboosts. The first option, however, is more flexible in that it could accommodate an unforeseen problem which would extend the experiment mission duration.

The disadvantages of LEO solo mode are that atmospheric drag is still a significant factor, and the propulsive maneuver is expensive. Also, starting at Space Station's highest orbital altitude, a LEO solo mission could still only last approximately 90 days before re-entry into the atmosphere becomes a problem.

2.3.3.3. Experiment Levitation Mode

One solution to the atmospheric drag problem is to "levitate" the experiments inside a module. The MEP, including the module containing the experiments, would be subject to atmospheric drag, while the experiment would fly freely inside the outer shell of the module. Naturally, the vehicle would fly in an orbit degraded by the atmosphere, while the experiment package would fly drag-free. This results in the experiment drifting towards the module wall. Sensors would be placed to detect when the experiment package came too close to a wall, and then thrusters on the vehicle would be fired to offset the relative motion. The net result would be that the MEP would be "flown around" the experiment, and the experiment would experience no atmospheric drag.

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[8] **Space Station Freedom Microgravity Environment Definition.**

One drawback of the Levitation Mode is that only one experiment package can be flown at a time. The proposed way to handle this is to store a number of packages in the module, and deploy and retrieve them one at a time with a robotic arm located inside the module. Section 3.7.3 details the Levitation Module design.

Another disadvantage of the Levitation Mode is the fuel cost for attitude adjustment. Presently, the exact frequency and magnitude of required attitude adjustments is not known and should be studied. However, computing a first approximation by taking 0.3 μg as a typical average drag acceleration and multiplying it by the mission duration yields a total ΔV of 75 ft/s required by a 90 day mission and 609 ft/s required by a 2 year mission.

Also, not all experiments are suited for levitation mode. Power, thermal control, and data transfer can all present problems for a free floating experiment package. Size, however, is the most limiting factor. Not only do experiments have to fit inside and share the levitation module with other experiments, but there must be adequate space remaining for drifting.

2.3.3.4. Drag Elimination Boost Mode

A final mode of operation is to transfer the MEP to an altitude high enough to where atmospheric drag does not present a significant problem and the MEP's orbit would not decay. This corresponds to an orbital altitude of approximately 300 n.mi[9].

2.3.4. Comparison of Experiment Modes

Table 2.3.1 gives approximate ΔV requirements for each of the aforementioned modes for both a 90 day and a 2 year mission. LEO station keeping mode is listed even though it has been eliminated as an option. LEO solo mode is the cheapest of the remaining modes, but only for missions which can be completed without a reboost, a duration of about 90 days.

For missions longer than 90 days, levitation and drag elimination boost are the only options. Levitation is more economical in terms of ΔV for shorter missions and is only slightly more expensive than drag elimination boost mode for longer missions. It also provides a better microgravity environment, and is

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[9] **Loftus, J.R., Orbital Debris from Upper Stage Breakup.**

therefore usually recommended. However, for those experiments which are suitable to be flown in levitation mode, the drag elimination boost is the only option.

Table 2.3.1. Comparison of ΔV Requirements for Experiment Modes

Operational Mode	Propulsive Maneuvers	ΔV for 90 Day Mission, ft/s	ΔV for 2 Year Mission, ft/s
LEO Station Keeping	Deploy	2	N/A
	Retrieval	2	
	Total	4	
LEO Solo	Deploy	2	N/A
	Orbital Transfer	514	
	Retrieval	2	
	Total	518	518
Levitation	Deploy	2	2
	Attitude Adjustment	75	609
	Orbital Transfer	514	514
	Retrieval	2	2
	Total	589	1127
Drag Elimination Boost	Deploy	2	2
	Orbital Transfers	1028	1028
	Retrieval	2	2
	Total	1032	1032

2.4. Space-Station Facilities

The station-side facilities required for the MEP are a platform berthing attachment, a module storage tray, and a teleoperated manipulator system.

2.4.1. Platform Berthing Attachment

The platform berthing attachment provides an attachment point on the space station for the MEP while the MEP is being outfitted for a mission. The attachment is shown in Figure 2.4.1.

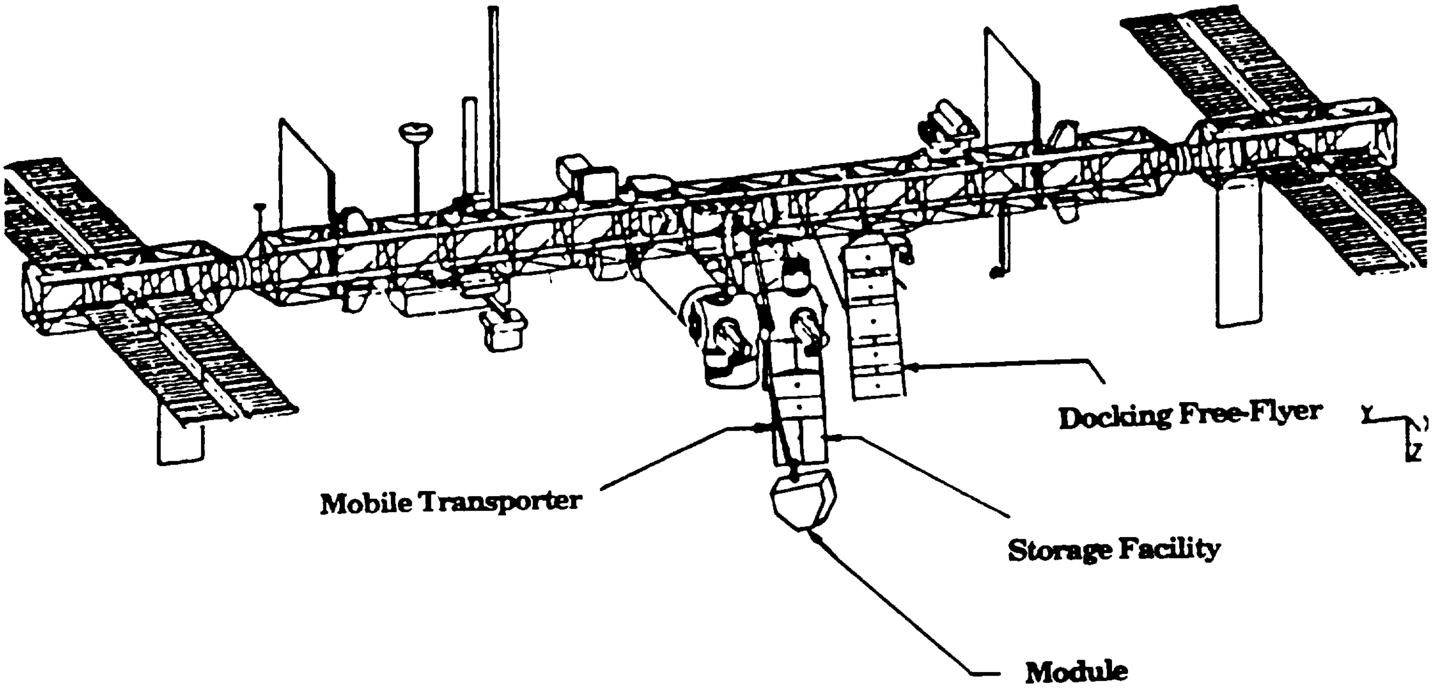

Figure 2.4.1. MEP Refurbishment at Space Station Freedom

2.4.2. Module Storage Tray

Modules not currently in use on the MEP are stored in the module storage tray on the space station. This tray is within the reach of the teleoperated manipulator system during outfitting operations. The tray is also pictured in Figure 2.4.1.

2.4.3. Teleoperated Manipulator System

The assembly of the MEP will require a teleoperated manipulator system. The remote manipulator system shown in Figure 2.4.2 and Figure 2.4.3 on board the space shuttle is such a system and will be sufficient for the MEP's requirements. However, the extended reach and payload capacity of the mobile transporter planned for use on the space station would allow greater assembly flexibility. The mobile transporter on the space station is shown in Figure 2.4.1.

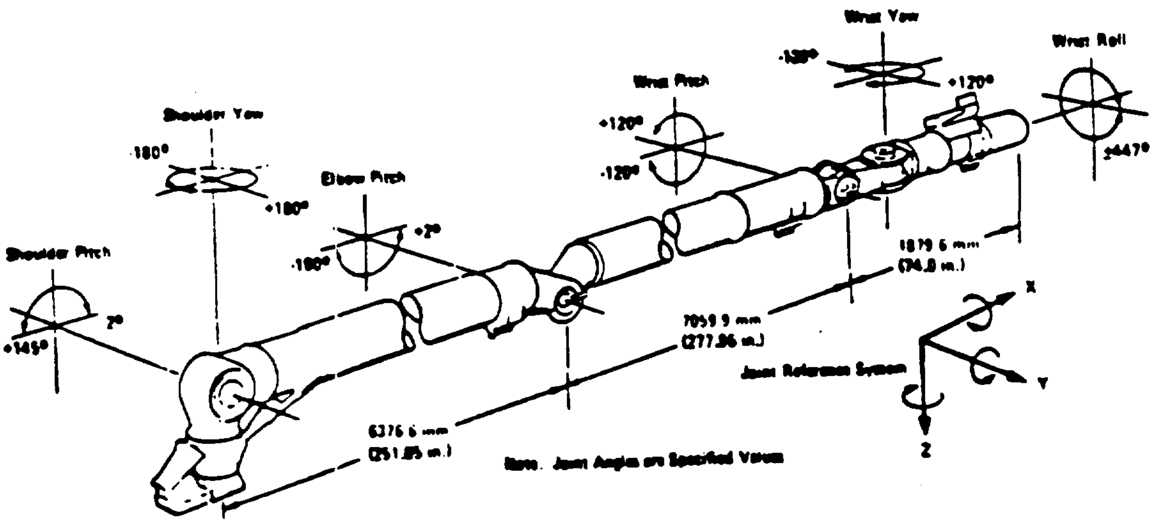

Figure 2.4.2. Remote Manipulator System Movement Configuration[10]

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[10] From Rockwell International: **Space Shuttle Transportation System.**

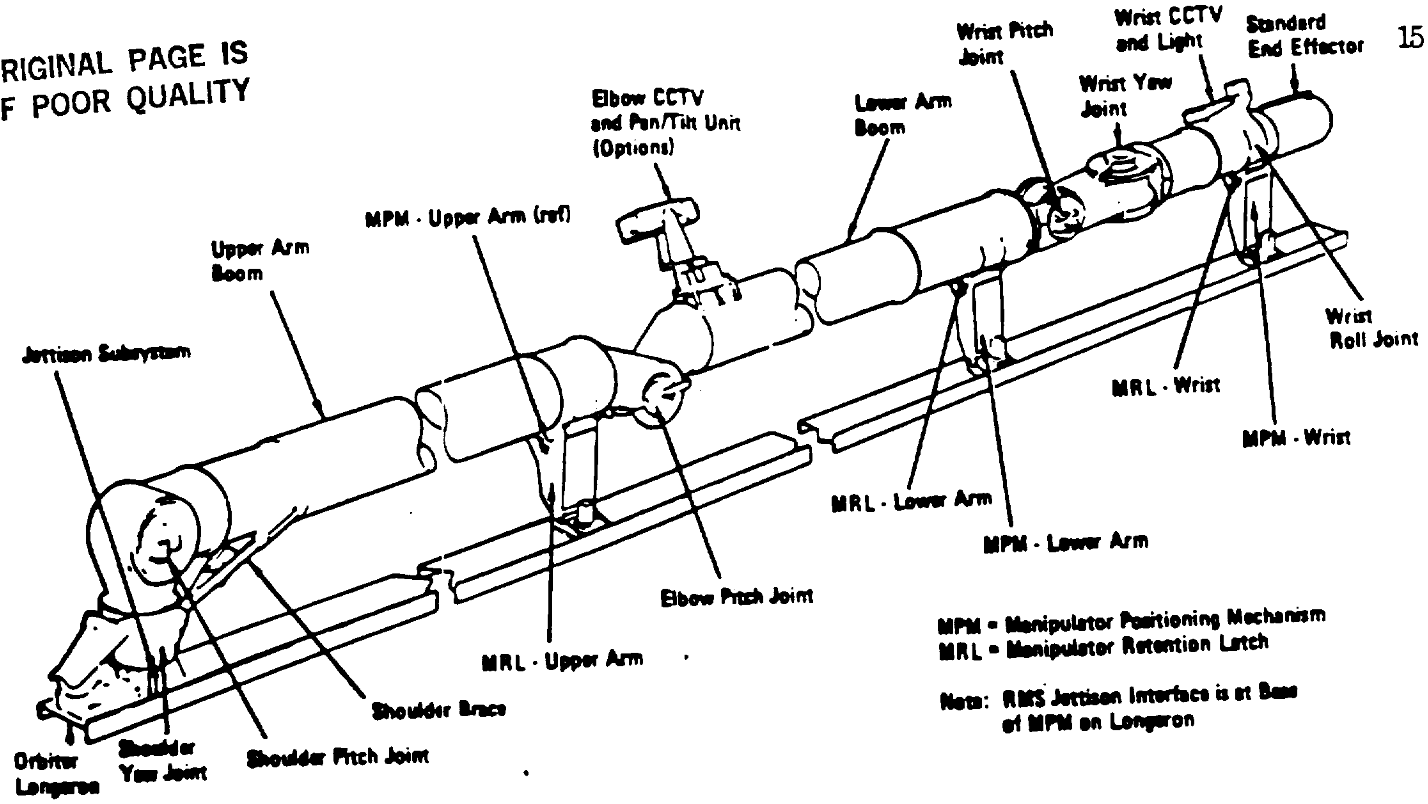

Figure 2.4.3. Remote Manipulator System General Arrangement[11]

3. Subsystem Descriptions

3.1. Structural Subsystem

The major concerns involved in the design of the MEP structural subsystem were to

1) Maximize the size of the microgravity envelope available to the experiments onboard the MEP.
2) Design the structure to withstand the static loads imparted on the structure.
3) Provide adequate support to the experiments onboard the MEP
4) Preserve the microacceleration environment of the MEP

3.1.1. Microacceleration Envelope

The structure of the MEP was designed to lie primarily along the local horizontal. This provided each experiment exposure to the center of the elliptical

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[11] ibid.

microacceleration tubes. Unfortunately, this also eliminated the possibility of using gravity gradient stabilization.

3.1.2. Static Loads

The static loads encountered by the MEP structure include launch loads, docking loads, attitude control maneuver loads, and contingency landing loads. Since the MEP is launched in the Shuttle folded and without any experiments, launch loads are minimal. Docking, attitude control maneuver, and contingency landing loads are all small enough to allow the dynamic requirements of the structure to drive the size of the structural members.

3.1.3. Experimental Support

Experimental support is provided in the same way payloads attach to Space Shuttle. Keel and longeron fittings are available every four inches along the utility beams of the structure.

3.1.4. Preservation of Microacceleration Environment

While the MEP is in an experiment mode, the platform must maintain a quality microacceleration environment. During this mode, the attitude of the MEP is controlled by the control moment gyros (CMGs) onboard. These gyros are the source of the largest forcing function applied to the MEP structure. The oscillations induced by the gyros on the structure must not ruin the microacceleration environment of the experiments onboard. To ensure this, an initial dynamic model of the MEP was created to perform dynamic analysis on the MEP structure.

Starting with the general equation for the dynamic response of a structure after encountering a disturbance:

$$d(t) = \sum_{n=1}^{\infty} D_n \sin(\omega_n t + \alpha_n) \quad , \tag{3.1}$$

where d(t) is the displacement of a point on the structure, n is the mode number, D_n is the modal amplitude at that point in the structure, ω_n is the natural frequency of the nth mode, t is the time, and α_n is the phase angle of the $n^{\underline{th}}$ mode. From this, the acceleration of a point on the structure can be obtained by finding the 2nd derivative of equation 3.1 with respect to time:

$$a(t) = -\sum_{n=1}^{\infty} D_n\,\omega_n{}^2 \sin(\omega_n t + \alpha_n). \tag{3.2}$$

Equation 3.2 can be thought of as a superposition of n acceleration functions applied at different frequencies with the $n^{\underline{th}}$ acceleration function given by

$$a_n(t) = -D_n\,\omega_n{}^2 \sin(\omega_n t + \alpha_n). \tag{3.3}$$

The root mean square (RMS) acceleration of a specific mode is thus given by

$$a_{rms}(\omega_n) = \frac{1}{\sqrt{2}} D_n\,\omega_n{}^2\,. \tag{3.4}$$

Finally, the RMS displacement of a point on the structure is given by

$$D_n = \sqrt{2}\,\frac{a_{rms}(\omega_n)}{\omega_n{}^2}. \tag{3.5}$$

If a_{rms} in equation 3.5 is replaced by the allowable acceleration function given in Figure 2.1.1, then D_n represents the allowable RMS displacement function given in Figure 3.1.1. This function gives the maximum allowable RMS displacement for any point on the structure or in an experiment.

An initial dynamic model of the MEP structure was created to perform transient analysis on the structure. This model was created using NASTRAN and the first four normal modes were found to provide an example calculation of maximum modal displacements. The first four mode shapes and their corresponding frequencies are given in Figure 3.1.2.

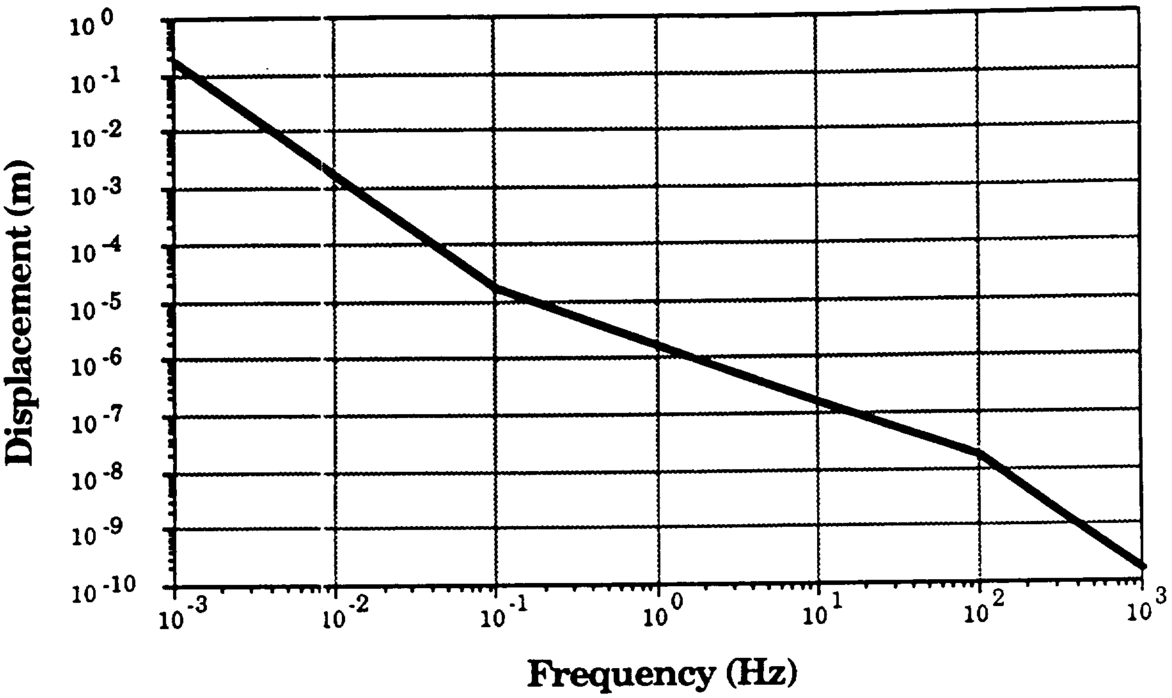

Figure 3.1.1. Allowable RMS Displacement Function

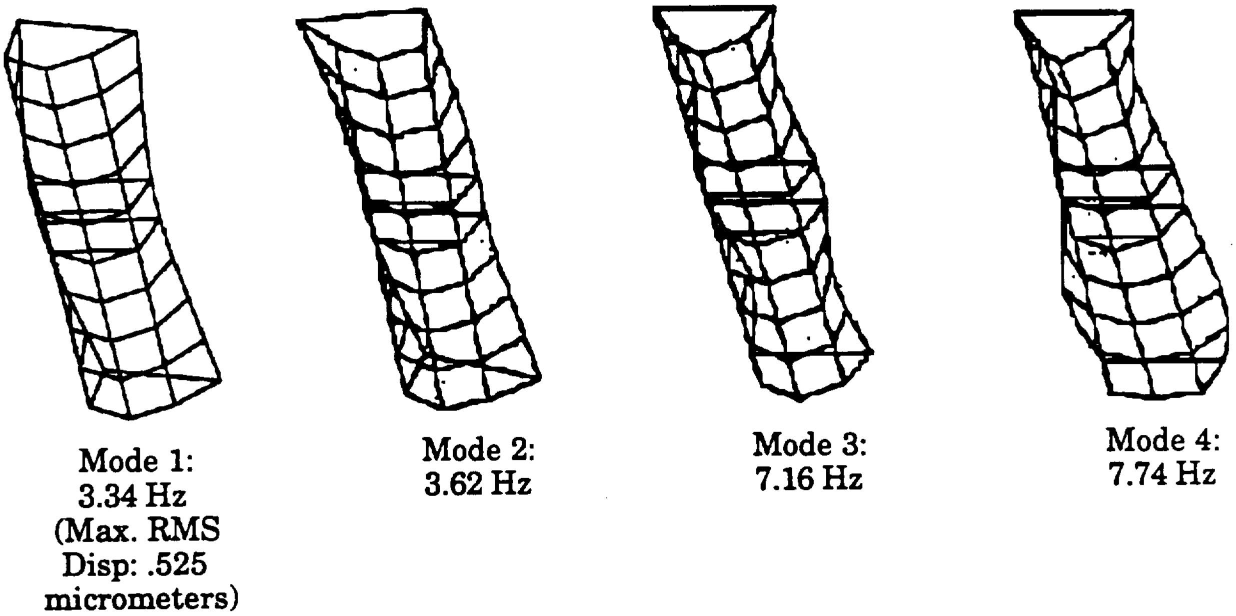

Figure 3.1.2. MEP Normal Modes 1-4

As shown in Figure 3.1.2, the maximum allowable displacement for an experiment due to the first mode of the MEP structure is .525 micrometers; a stringent constraint.

The dynamic model is not complete in that the masses of the experiments are not included in the analysis. Inclusion of the experiment masses would probably reduce the natural frequency but increase the allowable displacement. Thus, a tradeoff is found in the dynamic design of the MEP structure. The results of this design tradeoff would result in the determination of the largest control moment the CMGs would be allowed to exert on the MEP.

3.2. Utility Subsystem

The vehicle will have three utility beams. The beams will serve as structural supports as well as housing various utility lines. A schematic representation of the utility beams are shown in Figure 3.2.1.

There are two side beams; one will house the fuel and electrical lines and the other will hold data and oxidizer lines. The data and electrical lines were placed in separate side beams so that there will be no electromagnetic interference due to the electrical current flow. In addition, the fuel and oxidizer are also placed in separate beams to avoid any accidental ignitions due to fuel leakage. A schematic of the propellant plumbing is shown in Figure 3.2.2. Oxidizer and fuel lines are isolated from each other for safety and have redundant pipes. The lower utility beam will only house the thermal control heat pipes.

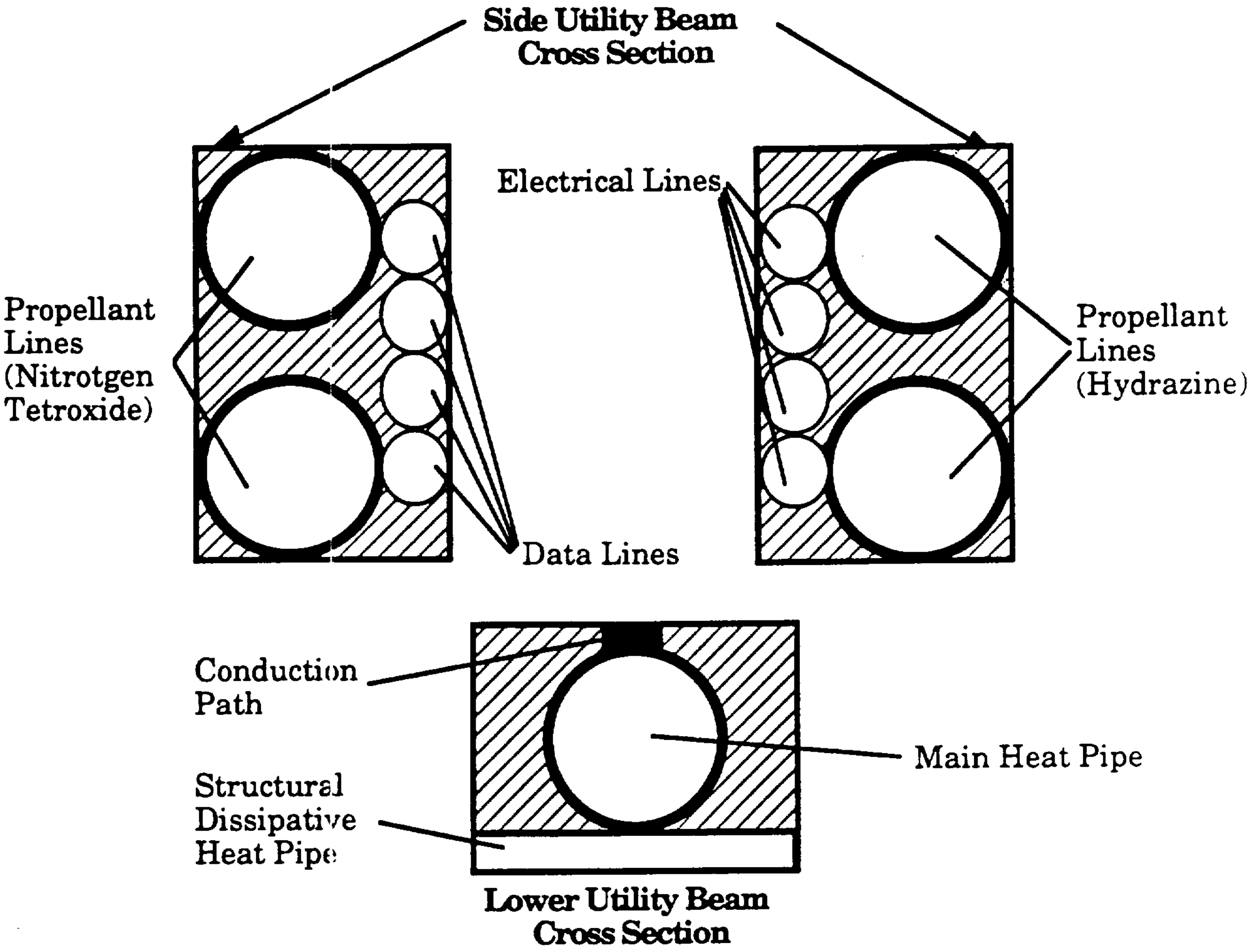

Figure 3.2.1. Utility Beam Cross-Section

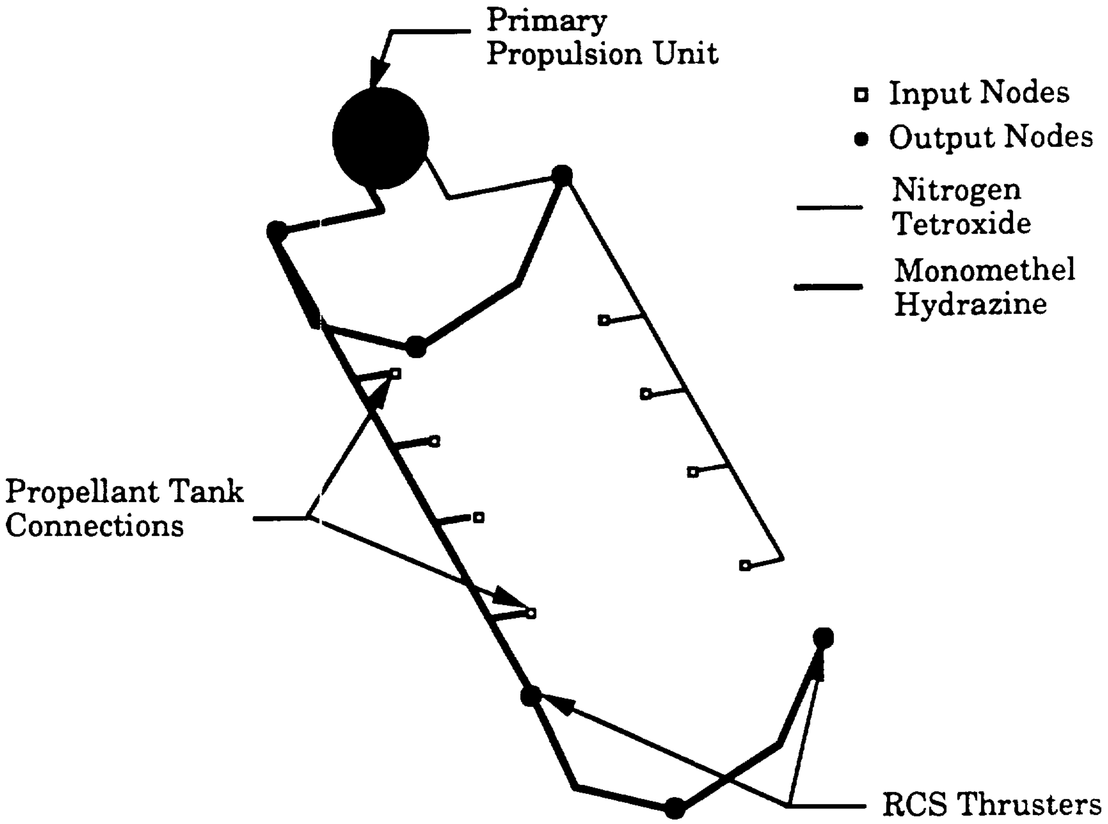

Figure 3.2.2. Propellant Plumbing Schematic

3.3. Power Subsystem

The function of the power system of the MEP is to provide the experiments and its own systems with the required power long enough to completely perform their functions. The power required by some of the proposed experiments and their duration were plotted in order to make the first power requirements estimation. Figure 3.3.1 shows power versus duration for currently proposed experiments[12]. Most of the experiments will require about 1 to 1.5 kW of power for about 10 days. However there must be an option of providing power up to two years.

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[12] Fraser.

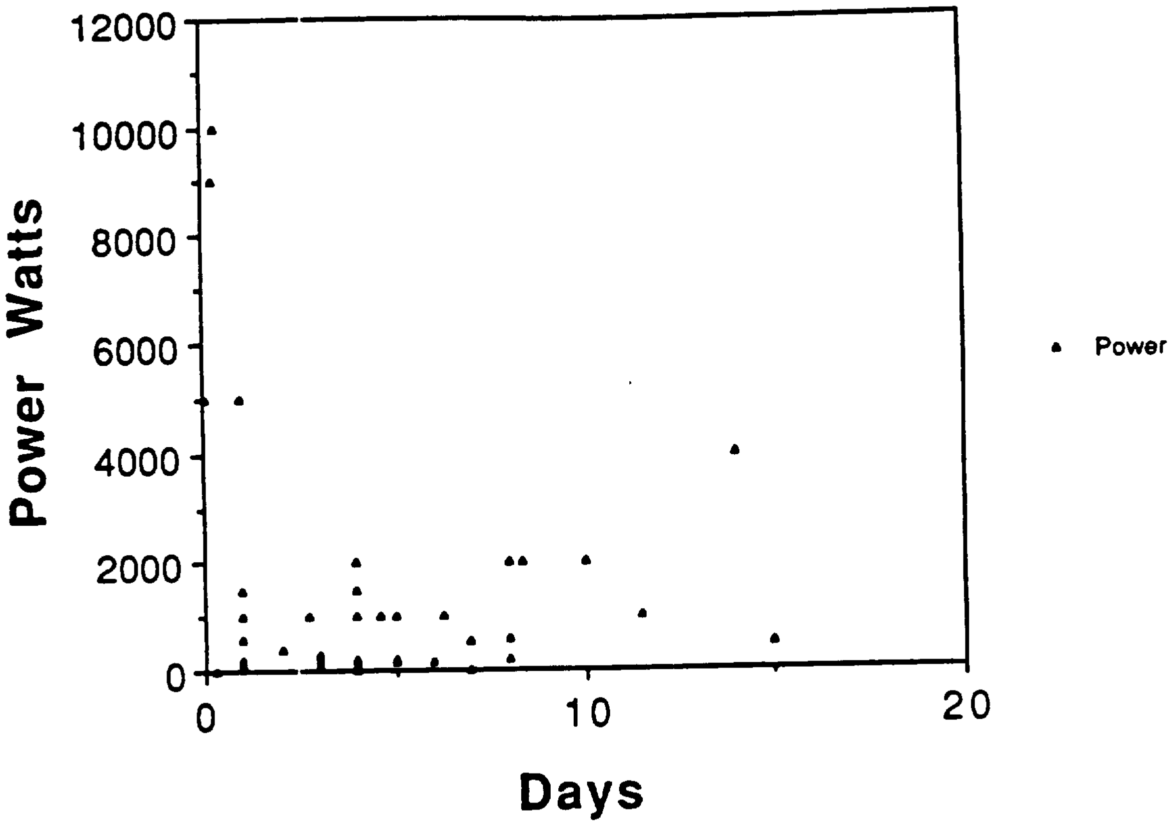

Figure 3.3.1. Power Requirements of the Experiments

3.3.1. Comparison of Power Systems

Several different power systems were considered: nuclear generators including Radioisotope Thermal Generator (RTG), fuel cells, solar cells and power transfer from Space Station via microwave. Table 3.3.1 is a comparison of these systems.

Nuclear generators are not suitable for the MEP, since there is no need for such great power, and the complexity of the system is going to present problems. RTG's are mainly used for deep space probes, where sun radiation is too small to consider solar arrays; also, they are inefficient and can cause interference and heat problems if they are placed close to the MEP. Power transfer via microwave is a futuristic design, and is doubtful if it is going to be developed sufficiently to be used when the MEP operates.

Solar cells will be able to provide the required power for the required duration, since solar radiation is the energy source. There are several problems associated with solar arrays but a well designed system will compensate with no further difficulties. Solar cells are used by the majority of the earth satellites.

Table 3.3.1. Comparison of Power Systems

Power System	Advantages	Disadvantages
Nuclear Generator	High Power >.5-1 MW	Massive, Dangerous, Inefficient for Low Power, Complicated in Design and Operation
Radioisotope Thermal Generator	Used When Solar Radiation is Small	Heavy, inefficient, produce heat and radiation
Fuel Cells	Efficient	Storage and Cycling of Liquids, Short Storage Time
Power Transfer via Microwave	Little equipment on Free Flyer	Futuristic Design
Solar Cells	Unlimited Source of Energy (Sun), Good for Low to Medium Power (kW)	Low Efficiency, Temperature Dependant, Degrading of Material (Radiation Effect), Batteries Required

3.3.2. Solar Arrays

Solar cells can be made out of different materials. The most important and practical are Silicon (Si) and Galium Arsenide (Ga-As) cells. Table 3.3.2 shows the advantages and disadvantages of using Ga-As over Si. Also Figure 3.3.2 shows the dependency of the efficiency of Si and Ga-As solar cells on temperature[13]. Finally, it was decided that the advantages of using Ga-As cells are well worth their higher price and density.

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[13] Chetty, P.R.K., Satellite Technology and its Applications.

Table 3.3.2. Comparison of Ga-As Over Si Solar Cells.

Advantages	Disadvantages
Greater Efficiency (15.7% vs 7.7% @ 120°C)	Higher Density (2.2 x Si)
Greater Open Circuit Voltage	Higher Cost (4 x Si)
Less Temperature Dependent	

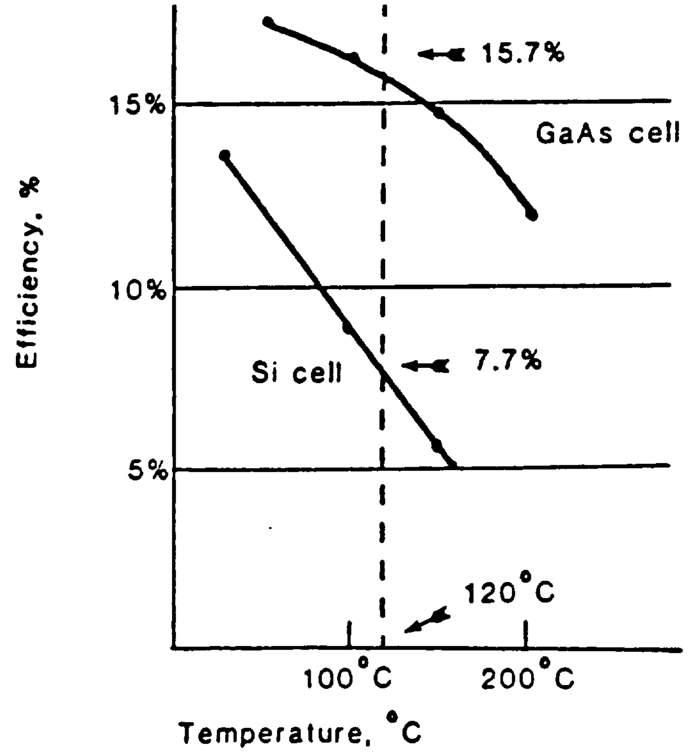

Figure 3.3.2. Efficiencies of Si and Ga-As Solar Cells

3.3.3. Batteries

Solar cells require the use of batteries. Because the system will be charging and draining the batteries about 15 times in 24 hrs, one of the main requirements is high cycle life. Table 3.3.3 shows the different batteries that are currently in use and their specifications[14]. Ni-H_2 batteries combine longer lifetime, reduced weight, unlimited overcharge capability, and do not build up pressure. Although

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[14] ibid.

this technology has not fully been fully demonstrated yet, development should be finished by the time the MEP flies.

Table 3.3.3. Specifications of Different Batteries

Type of Cells	Electrolyte	Nominal Voltage/ Cell (Volts)	Energy Density (WHr/kg)	Temperature (Deg C)	Cycle Life at Different Depth of Discharge Levels			Whether Space Qualified
					25%	50%	75%	
Ni-Cd	Diluted Potassium Hydroxide (KOH) solution	1.25	25-30	-10 -40	21000	3000	800	Yes
$Ni\text{-}H_2$	KOH solution	1.30	50-80	-10 -40	>15000	>10000	>4000	Yes*
Ag-Cd	KOH solution	1.10	60-70	0 - 40	3500	750	100	Yes
Ag-Zn	KOH solution	1.50	120-130	10 - 40	2000	400	75	Yes
$Ag\text{-}H_2$	KOH solution	1.15	80-100	10 - 40	>18000	—	—	No
Pb-Acid	Diluted sulfuric acid	2.10	30-35	10 - 40	1000	700	250	—

*$Ni\text{-}H_2$ cells are employed on-board the Navigational Technology Satellite (NTS-2) and other geosynchronous satellites. However, these cells have not been used on any low earth orbit satellites.

3.3.4. Design Description

The primary power system will be housed in the core module and there will be power modules of about 1 kW each, which can be placed on the MEP in case of increased power requirements. Inside the core module or the power module, there will be a power control unit. The unit will be connected to the solar arrays, the batteries and the loads. When the spacecraft is in sunlight, the solar arrays will send the energy produced to the power control unit. The power control unit will send the electric energy provided by the solar arrays to the loads and to the batteries to charge them. When the spacecraft is in shadow the solar arrays will not produce any power and the control unit will take the power necessary to supply the loads from the batteries. In LEO, this cycle will be repeated about 8 times in 24 hours. Figure 3.3.3 shows the general arrangement of the power system. Figure 3.3.4 shows the power system contained with in the power module.

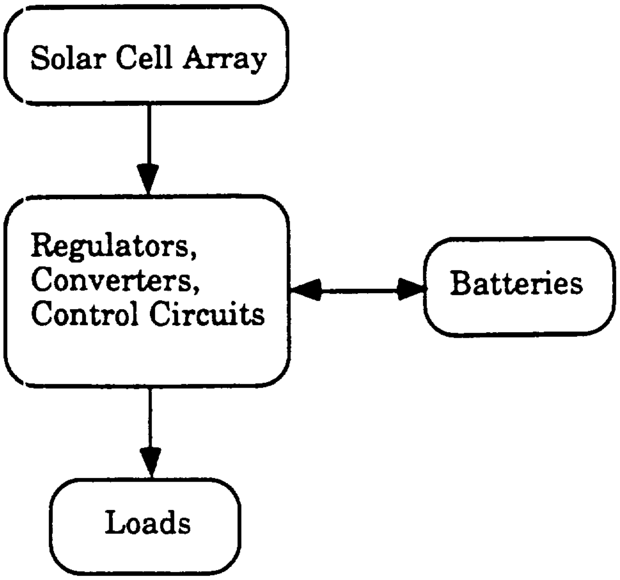

Figure 3.3.3. Power Distribution Schematic

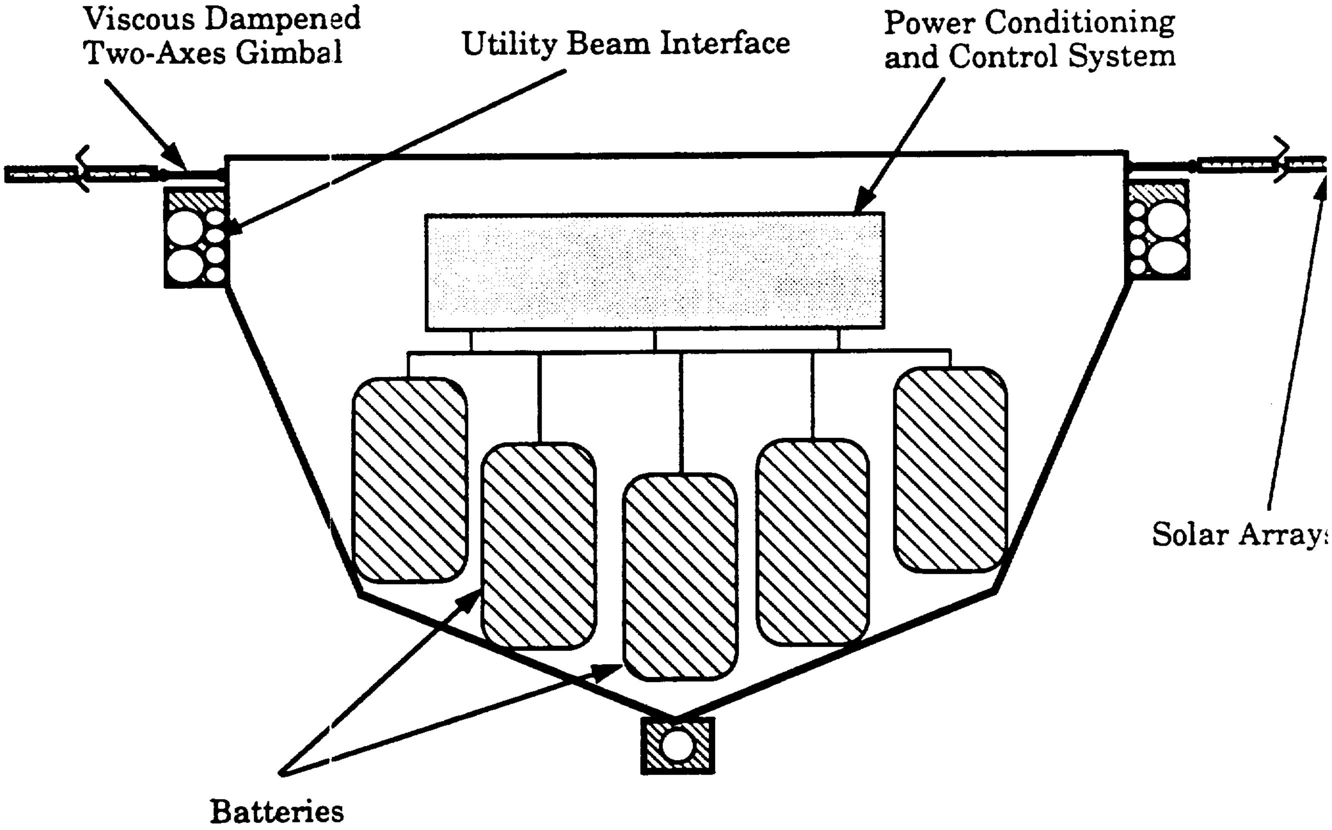

Figure 3.3.4. Power Module Cross Section

To size the main components of the power system, a requirement of 1 kW was assumed plus an additional overhead of 500 W. The voltage requirement for the power distribution to the loads was set at 28 V since this is an aviation and space system standard. To accomplish this, the Ga-As array must provide 7000 W of power. This will be able to run the MEP systems and experiments and charge the Ni-H_2 batteries in half a typical orbital period. The array output voltage will be 35 V so it will have a potential required to charge the batteries. The batteries will be composed of 28 cells in series to provide the 28 Volts to the loads. This results battery in a battery with a capacity of 3.5 kW-hr and a weight of 175 lbs.

3.4. Communications Subsystem

The main function of a communication system is to provide a reliable exchange of information from the MEP to an outside station. There are three categories of information that can be exchanged: tracking, telemetry, and command. Tracking information is used for finding position and velocity vectors from a known location such as a ground station or a moving spacecraft. Telemetry data are the conditioned outputs of sensors on the MEP. These sensors maybe temperature couplers connected to an engine part to monitor proper operation, radiation sensors located on top of an experimental arrangement for recording changes in the radiation emittance patterns with respect to varying parameters or video images from a certain experiment. The last category is command information; these activate or deactivate different systems of the MEP, for example, turn an experiment on, direct the control system of the MEP to perform a certain maneuver, or reorient the antennas of the MEP. Generally, the MEP is expected to transceive all of the above categories of information, but due to its design purpose telemetry information is expected to be transceived more frequently than other

3.4.1. Design Considerations

One of the main design requirements of the communications system is the ability to maintain constant communication between the MEP and any selected station. Due to the nature of electromagnetic waves, the MEP and the communication station must be within line of sight of each other. Therefore, the

MEP will not be able to communicate directly with either the space station, the orbiter, or any ground tracking stations at all times due to its orbital characteristics. The solution employs the TDRSS satellites, currently in use by many spacecraft, for the relay of information between the MEP and ground stations and spacecraft. TDRSS is a communication system composed of several relay satellites at geosynchronous orbit, and it operates on specific bands.

3.4.2. Design Description

The MEP communication system will operate on two different bands. The V-band (50-54 GHz) has been allocated for direct communication among spacecraft. It is going to be used whenever the MEP is in the line of sight of the orbiting transceiving stations such as the Space Shuttle, Space Station or the OMV. This mode also simplifies the communication link since no relay satellites are necessary.

The second band that will be used is the Ku Band (13-15 GHz) which is the most "efficient" (for time rate of information exchange and other) that the TDRSS satellite is using. Using this band a link can be establish between the MEP, Space Shuttle, Space Station and other stations, via TDRSS satellites. This link can be used at the times where direct communication is impossible. Figure 3.4.1 shows graphically the communication links. The use of the above method establishes communication links constantly, eliminating any problems that may arise from inability to communicate at a specific time.

The communication system is, mainly, going to transceive data in digital form. Since the Ku Band will be employed, modulation and signal transferring techniques will be very similar to the ones used by the Space Shuttle. These techniques will employ Unbalanced Quadrature Phase Shift Keying technique to modulate a subcarrier signal; the data transmission rate is of the order of 50 Mbps without substantial error.

Besides digital data, images may have to be transmitted from the MEP and therefore the communications system must have such capability. For TV images, a Frequency Modulation technique can be used to modulate the carrier signal. Additionally, Spread Spectrum technique maybe useful to be employed in transceiving both digital and analog information since there are some distinct advantages from its use.

Because of the different number of experiments that will take place on the MEP, simultaneous operation of different channels containing information of different forms is necessary. Therefore, the detailed system design must provide for this capability. Also, for the sake of simplicity in the design, the V-band data transmission system will be similar to the Ku Band system, the only difference being the frequency of the carrier and the equipment that is designed around the carrier, like the antenna. However, since there can be a greater data transmission rate capability at the V-band, there is the option of developing an altogether different communication system for the V-band, which will take full advantage of such capability.

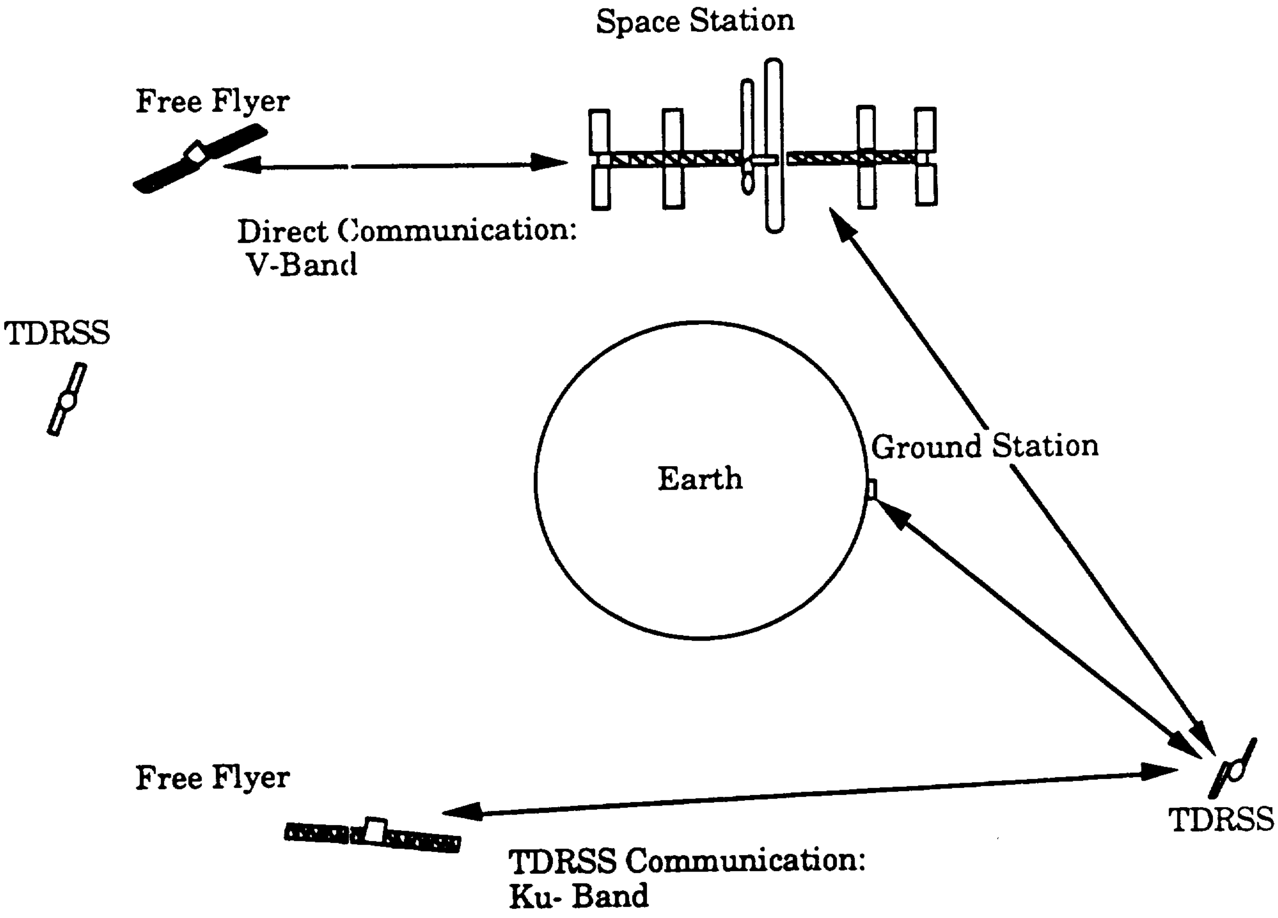

Figure 3.4.1. Communication Links Between MEP and Transceiving Stations

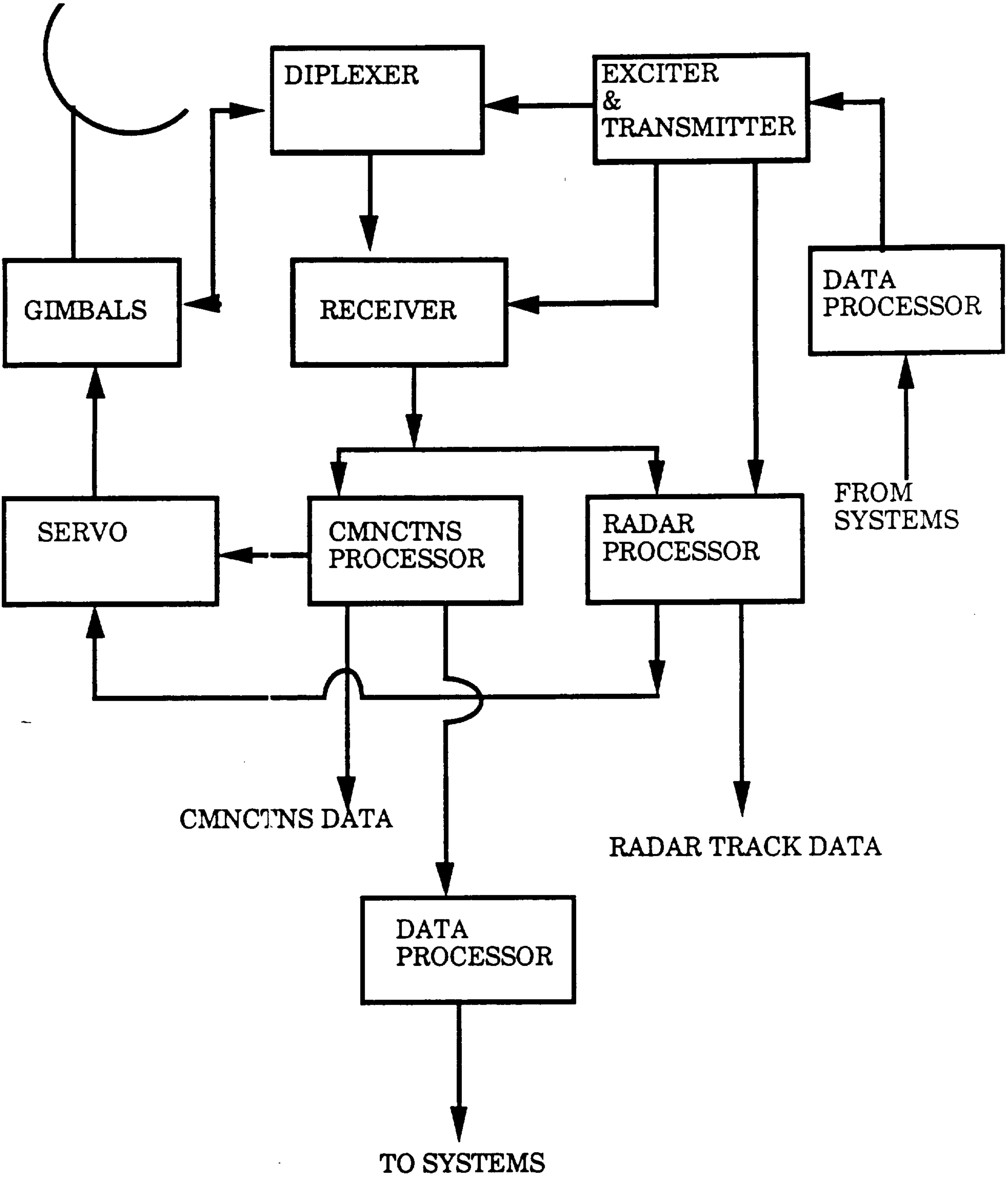

Figure 3.4.2. Detail of the Space Shuttle Communication System

The Ku Band transponder will have an output of 80 watts, fed to a 40 dB antenna. The Traveling Wave Tube should be about 0.1 ft.cu. and weigh 6 pounds. The antenna will be a 36 inch parabolic reflector. The above system described is one currently in use by the Space Shuttle; it satisfies the communication requirement of the MEP. Figure 3.4.2 shows a general schematic of the Shuttle's communication system, similar to the one presented on the NASA technical paper by Griffin, Kelly, Steiner and Vang[15].

The use of the above communication band and equipment, especially antennas, present a difficulty with finding the direction that the antennas have to point at. Due to the narrowness of the electromagnetic waves at the Ku and V-bands, the receiving and transmitting antennas on the two spacecraft or ground station, must very closely aligned in order to ensure sufficient strength in signal reception. The close alignment is hard to achieve with narrow electromagnetic waves at a distance, and therefore employing a tracking method is necessary. Since the data transceived contain information about the signal, the data will be analyzed by radar equipment and get fed to a tracking network. Again, due to the narrowness of the signal this not as effective. Figure 3.4.2 shows how the information received will be shared by both the radar and communication processor of the purpose of tracking.

An S-Band transceiver will be employed for the only purpose of tracking antennas from the MEP. The wider electromagnetic wave indicates better the general area of the emmited signal and therefore the transmitting antenna. The signal transmitted on the S-Band does not have to be modulated, therefore a Continuous Wave signal will be sufficient. The Shuttle uses an 140 Watt transmitter for data communication; the MEP transmitter's power will not be as high since no data is communicated.

3.5. Guidance, Navigation and Control Subsystem

The purpose of the guidance, navigation, and control (GNC) subsystem is to maintain the MEP's velocity vector along its longitudinal axis and counteract external torques (from atmospheric drag or gravity gradients) without inducing accelerations which would destroy the experiments' microgravity environment.

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[15] Griffin, Kelly, Steiner, Vang and Zrubek, **Shuttle Ku Band Communications/Radar Technical Concepts**.

3.5.1. Stabilization

Table 3.5.1 gives a comparison of different types of stabilization techniques currently in use. The MEP will use three-axis stabilization because it provides the required fine pointing capabilities.

Table 3.5.1. Stabilization Techniques

Type	Comments
Three Axis Stabilization	Active method, requires attitude actuators, fine pointing control is possible, fast and flexible, uses consumables, expensive
Spin Stabilization	Simple, used for some scientific satellites, destroys μg environment
Gravity Gradient Stabilization	Stable with respect to main central body, requires long booms, control limited to about one degree, minor axis must point towards earth
Solar Radiation Stabilization	Used in high altitude or interplanetary orbits, passive method
Magnetic Stabilization	Can be used close to earth, coarse control, slow

The specifications for the control moment gyro chosen for the MEP are given in Table 3.5.2. This technique will require one body axis to point towards earth as well as an attitude measurement system.

3.5.2. Attitude Measurement

Four types of attitude measurement techniques were considered for the MEP. These techniques include the Global Positioning Satellites (GPS), earth horizon sensors, sun sensors, and star sensors, and are compared in table 3.5.3. Although GPS is the most massive and power consuming option, it provides the accuracy required by the MEP. A backup system of combined earth and star sensors is also included in the final design.

Table 3.5.2. Double Gimballed Momentum Wheel Specifications for 3-Axis Attitude Control

Size, mm	380 D x 355 H
Power, W	8 at Steady State 80 at Maximum Torque
Mass, kg	22.4
Wheel Angular Momentum, N ms	50
Wheel Speed, rpm	4600
Wheel Reaction Torque, N m	0.1

Table 3.5.3. Comparison of Attitude Measurement Devices

System	Power, W	Mass, kg	Size, cm
GPS	90	65	21.1 x 44.4 x 27.9
Earth (horizon) Sensors	8	2.5	10.2 x 7.62 D
Sun Sensors	7.6	2.2	10.6 x 7.6 D
Star Sensors	18	7.7	16.8 x 18.0 x 31.0

3.5.3. Desaturation

A momentum wheel is used to stabilize a spacecraft about a particular axis by providing variable-momentum storage capabilities. This rigidity is achieved by aligning the momentum wheel to this axis and operating it at a particular speed. On the MEP, magnetic torquer bars will be used to react or counteract the earth's magnetic field effect which will result in an absorption of momentum by the momentum wheel in order to maintain the spacecraft in its specified orientation. This process results in an increase in the speed of the momentum wheel until it reaches its designed highest speed. This state is known as saturation. Therefore, the momentum wheel speed must be reduced in order to avoid damage to the wheel. This can be accomplished with thrusters.

3.6. Propulsion Subsystem

The propulsion subsystem can be divided into two separate parts; the propulsion module, which is added to the MEP for high energy missions, and the Reaction Control System (RCS), which is present on all MEP configurations. Also

detailed is the optional propellant module.The experiment platform propulsion system is required to perform many different tasks. The primary system will boost the MEP to higher altitude orbits. The secondary system is responsible for station keeping, minor orbit adjustments, and attitude control. Several propulsion systems were considered; nuclear thermal, ion, solid propellant, and liquid propellant. The MEP requires a system that has the following characteristics:

1) restart capabilities
2) reusable engines
3) long term storage
4) space station technological time frame
5) simplicity
6) minimal additional power requirements.

3.6.1. Propulsion Module

The purpose of the propulsion module is to provide the capability to perform orbital transfers, typically a change from about 150 n.mi. to 300 n.mi. and back. Several types of propulsion systems were considered. These are compared in Table 3.6.1.

Nuclear thermal has many advantages such as long term storage and multiple start capability. However, the MEP will be docking with space station thus the safety hazards were much too great. This option was eliminated.

Electrostatic ion engines have many of the same advantages of nuclear thermal engines. The main draw back to this concept is that it requires a great deal of external power. Since power is a very limited resource this concept was no longer under consideration.

Solid propellant provide many advantages over the previously discussed concepts. The technology has been proven through many flight hours. Solid propellant systems are very simple easily stored for extended periods. However, the lack of multiple starts was a major drawback. In addition, this system is not very flexible to the MEP's changing propulsive requirements.

Table 3.6.1. Comparison of Propulsion Systems

System	Advantages	Disadvantages
Nuclear Thermal	High Isp 850-1500 sec Flight-Ready System 1972 Restart Capabilities Long Term Storage	Safety Hazard High Mass of Reactor Lacks Political Support Large External Power
Electrostatic Ion	Long Term Storage High Isp Restart Capabilities	High External Power Unproven Technology
Solid Propellant	Simplicity Long Term Storability Proven Technology No Need for Refueling	Lacks Restart Capability Difficult to Customize Not Reusable Wasted Structure Mass
Liquid Propellant	Existing Hardware Restart Capabilities Proven Technology Easily Adaptable	Cryogenics, Poor Storage Complex Hardware Propellant Dangerous

Liquid propellants have all the required capabilities. The disadvantages can be avoided by making proper selection of propellants. There are some propellants, cryogenics such as liquid hydrogen and oxygen, that cannot be stored for long periods. However, Monomethel Hydrazine and Nitrogen Tetroxide are adequate substitutes. The complexity of the hardware can be avoided by using pressurized gas to move the propellant as appose to a turbo pump.

A very similar propulsion system is proposed for NASA's Orbital Maneuvering Vehicle (OMV)[16]. The OMV's primary propulsion system is a detachable module. With some modifications the same module could be adapted for the MEP. There are four engines on this module requiring Monomethel Hydrazine as the fuel and Nitrogen Tetroxide as the oxidizer. The oxidizer to fuel ratio is 1.64. They provide 13-130 lbf each with a specific impulse of 280-300 seconds. This particular system was chosen because its propellant had long term storage capabilities. The engines are reusable thus the system will be less

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[16] NASA, **User's Guide for the Orbital Maneuvering Vehicle**,.

expensive in the long run. This system also had multiple start abilities and best fit the desired characteristic of the required propulsion subsystem for the MEP.

3.6.2. Reaction Control System

The secondary propulsion system provides the MEP with attitude control, station keeping, and orbit trim. Several liquid propellant systems were considered; 1) cold gas, 2) bipropellant, and 3)monopropellant.

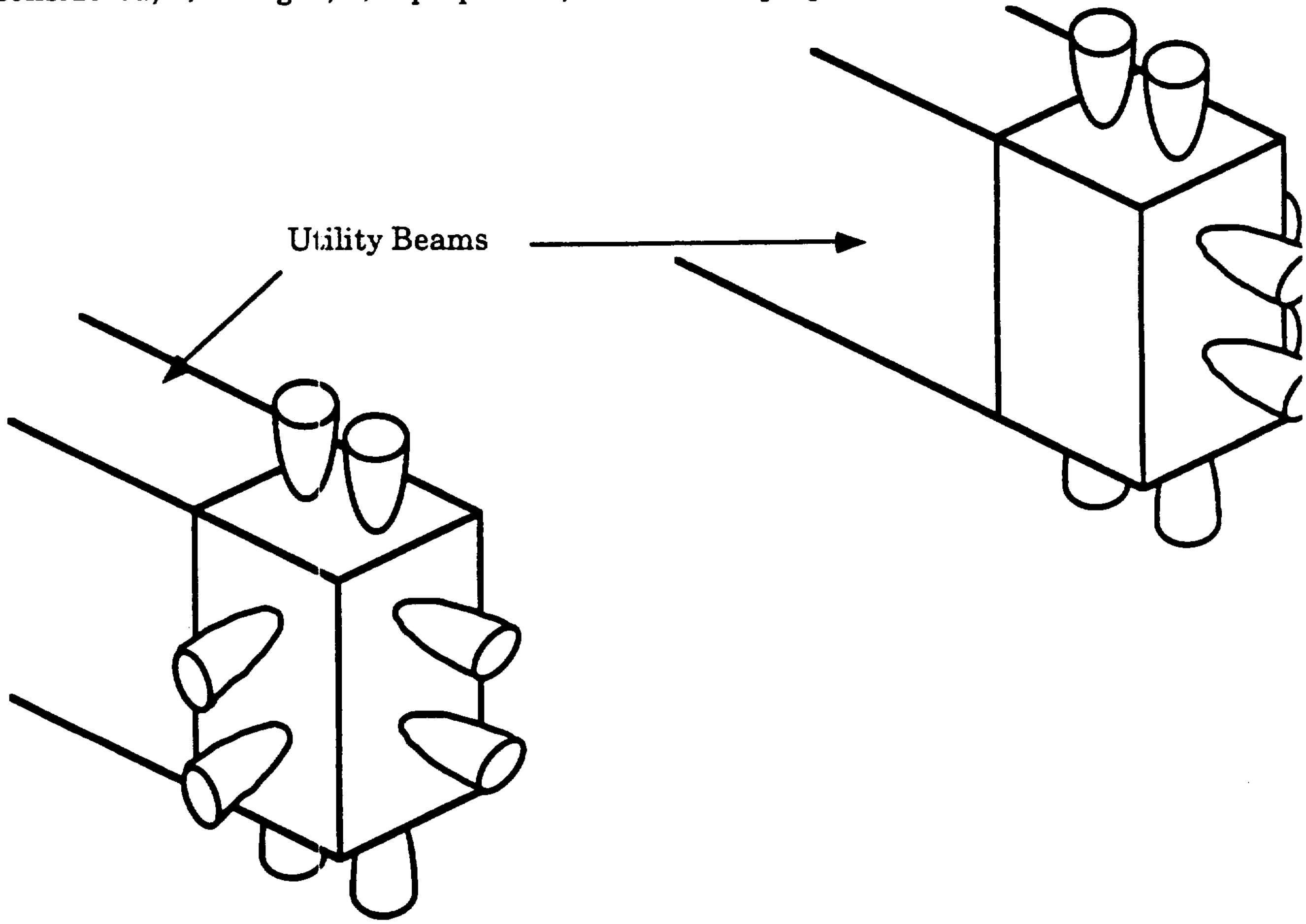

Figure 3.6.1. Reaction Control System (RCS)

The cold gas system is very simple, but the Isp of the fuel was much too low. With such a low Isp accommodating for large propellant mass may be a problem. In addition, using the cold gas system will introduce a new and unnecessary element into the propulsion system. A monopropellant unit has all the advantages of a cold gas system plus a higher Isp. With the monopropellant

system monomethel hydrazine, from the primary propulsion system, could be used as a fuel.

The bipropellant system is more complex since the system has to handle two propellants. The secondary propulsion system does not require the high performance of a bipropellant system.

A monopropellant system was chosen for simplicity and performance. Hydrazine will be used as the fuel since all the propellant already exists from the primary propulsion subsystem. The monopropellant provided about 15 lbf maximum of thrust at a specific impulse at about 220 seconds.

Figure 3.6.1 shows the reaction control system and its location at the end of the utility beams.

3.6.3. Propellant Module

Due to variations in experiment masses and mission requirements, the MEP can add additional propellant modules containing monomethel hydrazine, nitrogen tetroxide, and nitrogen for propulsive maneuvers. Tables 3.6.2 and 3.6.3 detail the sizing of the propellant tanks. The resulting propellant module design is shown in Figure 3.6.3.

Table 3.6.2. Propellant Mass Distribution

Assumed Vehicle Mass, lb_m	20,000
ΔV 150 to 300 nmi, including return, ft/s	1600
Amount of Fuel and Oxidizer Required, lb_m	3887
added 25% for contingencies, lb_m	4860
Total Oxidizer Mass, lb_m	3020
Amount of Fuel (1.64 Mix ratio), lb_m	1840
Fuel Required for 200 ft/s of ΔV using RSC, lb_m	560
Total Fuel Mass, lb_m	2400

Table 3.6.3. Preliminary Propellant Tank Sizing

Total Fuel Mass, lbf	2400
Total Oxidizer Mass, lbf	3020
Fuel Density, kg/m3	870
Oxidizer Density, kg/m3	1430
Fuel Tank Diameter, ft	6.08
Oxidizer Tank Diameter, ft	3.61

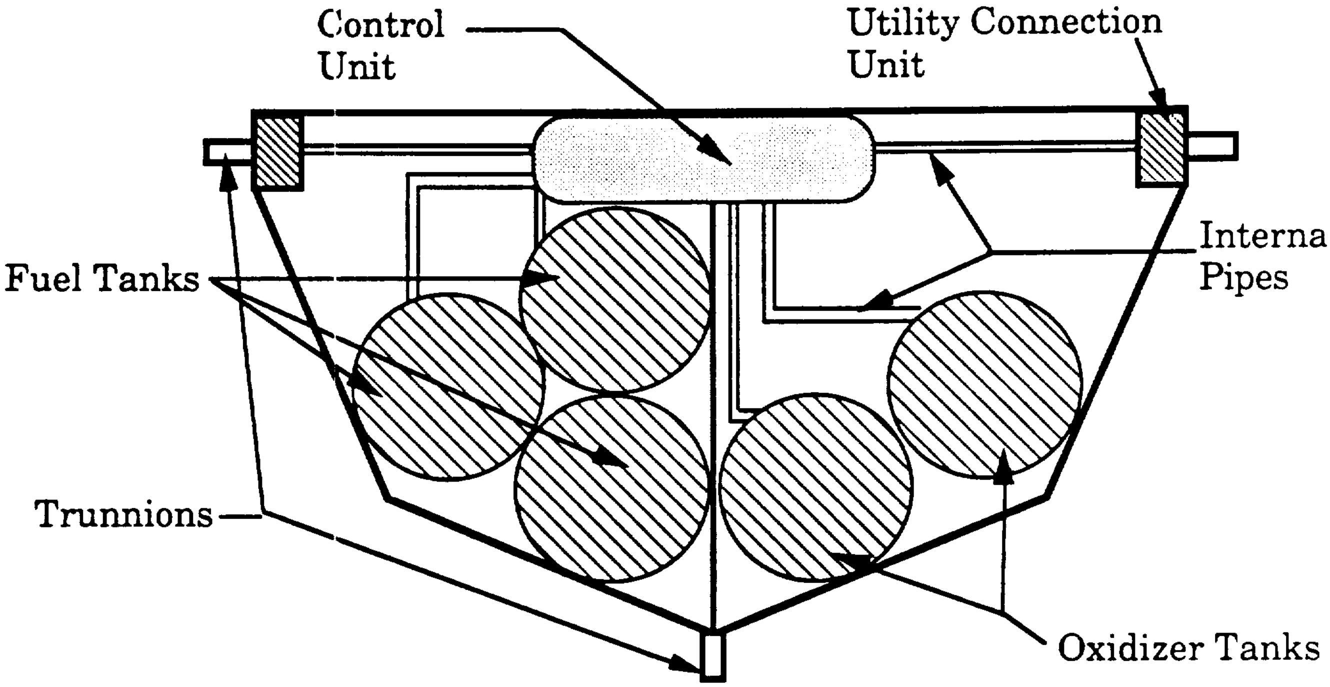

Figure 3.6.3. Propellant Module Cross Section

3.7. Thermal Control Subsystem

The thermal control system must provide for complete thermal control of the MEP. This includes thermal rejection of incident radiation and rejection of heat generated by the MEP's systems and experiments.

3.7.1. Microacceleration Design Constraints

The microacceleration mission of the MEP requires that the thermal control system maintain not only the thermal environment of the MEP, but also, like all systems on the MEP, the microacceleration environment.

3.7.1.1. Thermal Flexing

Uneven solar heating of the MEP in orbit will cause the MEP to deform due to thermal expansion of the platform's structure. Since the MEP's orbit causes periodic changes in the magnitude and direction of the incident radiation, thermal flexing will occur. This periodic disturbance will be detrimental to the microacceleration environment. Therefore, the thermal control system should provide for reduction or elimination of thermal flexing effects.

3.7.1.1. Thermal Control System Oscillations

Conventional thermal control systems on spacecraft such as the Space Shuttle rely on fluids to transport the heat from spacecraft systems. The systems use pumps to propel the working fluid through heat input and output points as well as connecting pipe networks. If such a system was used on the MEP, the vibration caused by these pumps would have an adverse effect on the microacceleration experiments onboard the platform. Therefore, such a system was ruled out. The system designed for the MEP uses a combination of heat pipes and radiator panels.

3.7.2. Heat Pipe Theory

A heat pipe is a closed tube, like that shown in Figure 3.7.1, which has its inner surfaces lined with a porous capillary wick. The wick is saturated with the liquid phase of a working fluid and the remaining volume of the tube contains the vapor phase. Heat applied at the evaporator by an external source vaporizes the working fluid in that section. The resulting difference in pressure drives vapor from the evaporator to the condenser where it condenses releasing the latent heat of vaporization to a heat sink in that section of the pipe. Depletion of liquid by evaporation causes the liquid-vapor interface in the evaporator to enter into the

wick surface and a capillary pressure is developed there. This capillary pressure pumps the condensed liquid back to the evaporator for re-evaporation[17].

Heat pipes are several orders of magnitude more efficient than other convective heat transfer systems and are nearly isothermal. Heat pipes can be modified to provide variable heat rejection rates, isothermal conditions, and on/off operation.

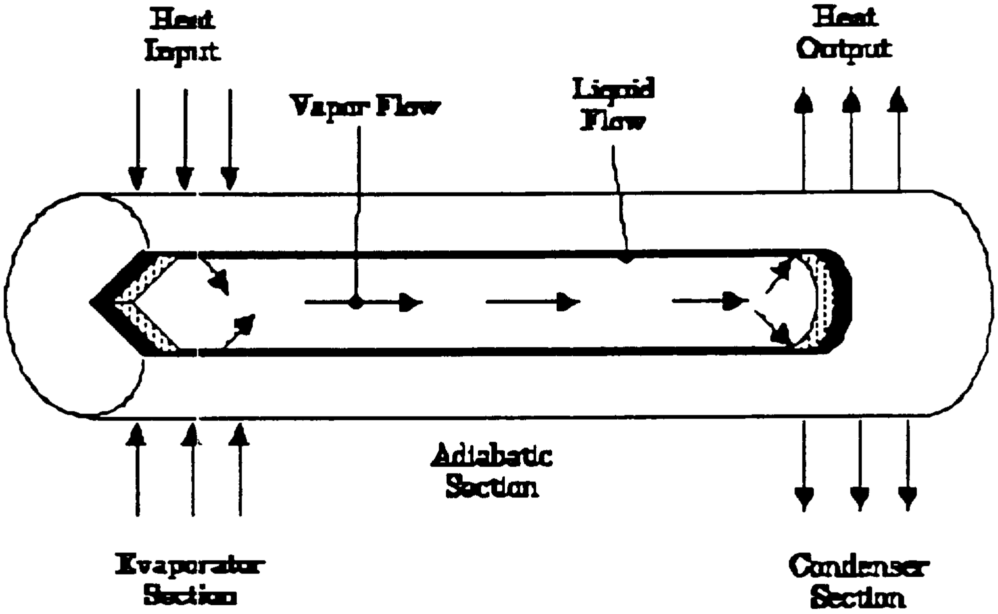

Figure 3.7.1. Heat Pipe Operating Principle[18]

3.7.3. Thermal Control Subsystem Design

The thermal control subsystem is divided into two component systems; the incident radiation dissipation system and the generated heat dissipation system.

3.7.2.1. Incident Radiation Dissipation System

The Incident Radiation Dissipation System is shown in Figure 3.7.2. The Figure shows a section of the MEP structure composed of utility beams and hinge

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[17] S.W. Chi, **Heat Pipe Theory and Practice: A Sourcebook**.
[18] ibid.

beams connected by shear panels. Heat pipes are affixed to the inner surface of these shear panels. These heat pipes have the effect of equalizing the temperature of the MEP structure and thus putting the structure in an isothermal state; thereby eliminating thermal flexing. As one side of the MEP is heated by incident radiation, the heat pipes rapidly transfer the heat to the unexposed, or less exposed side of the MEP where it is dissipated by radiation through the shear panels. Since the shear panels double as radiator panels, their outer surface will have tailored absorptive and emissive characteristics.

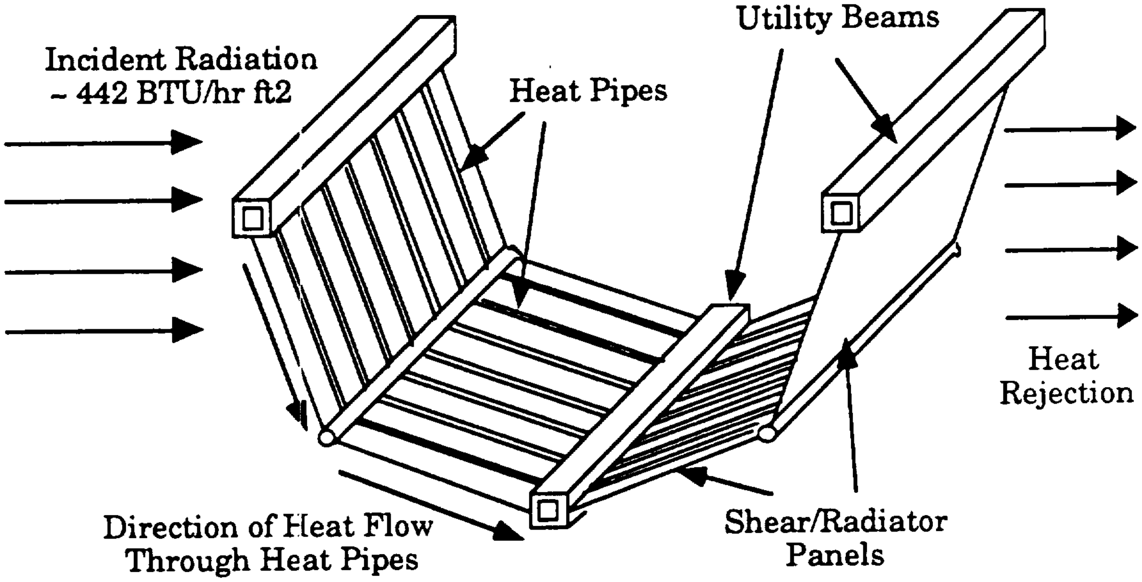

Figure 3.7.2. Incident Radiation Dissipation System

3.7.2.2. Generated Heat Dissipation System

The Generated Heat Dissipation System is responsible for rejecting the heat generated by the MEP systems and experiments. The system consists of a heat pipe, a radiator fin, and a number of conduction paths. Figure 3.7.3 depicts the system which resides in the keel utility beam. A heat pipe runs the length of the utility beam and has a conduction path to a radiator fin and conduction paths to all experiments and systems which require cooling. The heat pipe transports heat from the experiment/system conduction inputs to the radiator fin. The heat pipe distributes the heat evenly over the length of the 60' x 3' radiator fin. The fin has an estimated total rejection capability of 2 kW and is mounted on a viscous joint to reduce the effects of fin oscillations.

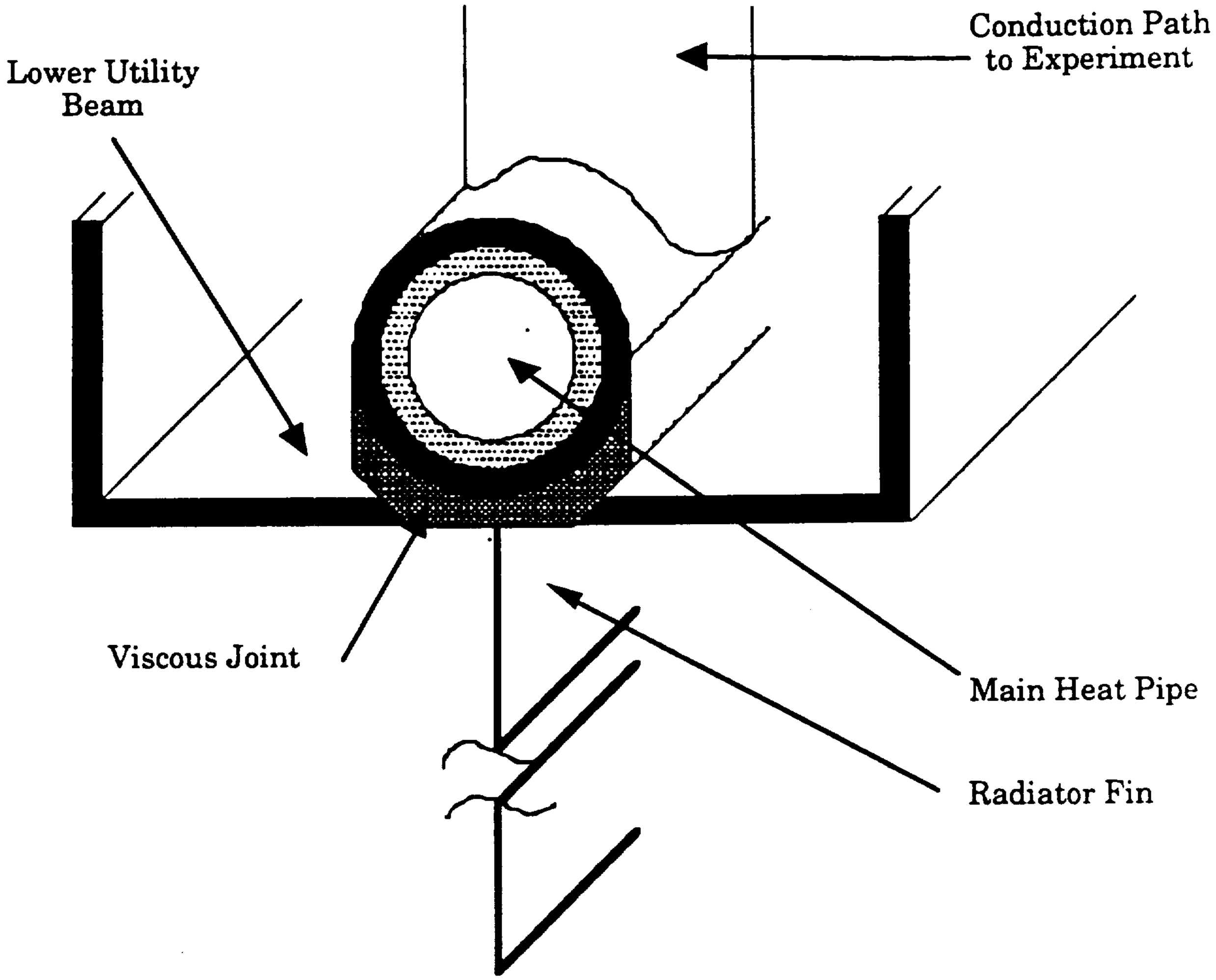

Figure 3.7.3. Generated Heat Dissipation System

3.8. Experiment Modules

Experiment modules can either be designed by the user with compatible connections to the MEP, or experiments can be flow in either the Experiment Rack Module or the Levitation Module.

3.8.1. Typical Experiment Modules

A typical experiment module is shown in Figure 3.8.1. It is 15' wide and typically 6' long, and will fit in the shuttle cargo bay. The three trunnions shown perform the dual task of fastening the module to the shuttle bay during launch and the MEP truss during operation. Also common to each experiment module are power, data, communications, television, and thermal control connections, which plug into outlets on the three utility beams. Each module should have thermal insulation to protect against incident radiation, and micrometeorite shielding is also recommended for long duration experiments.

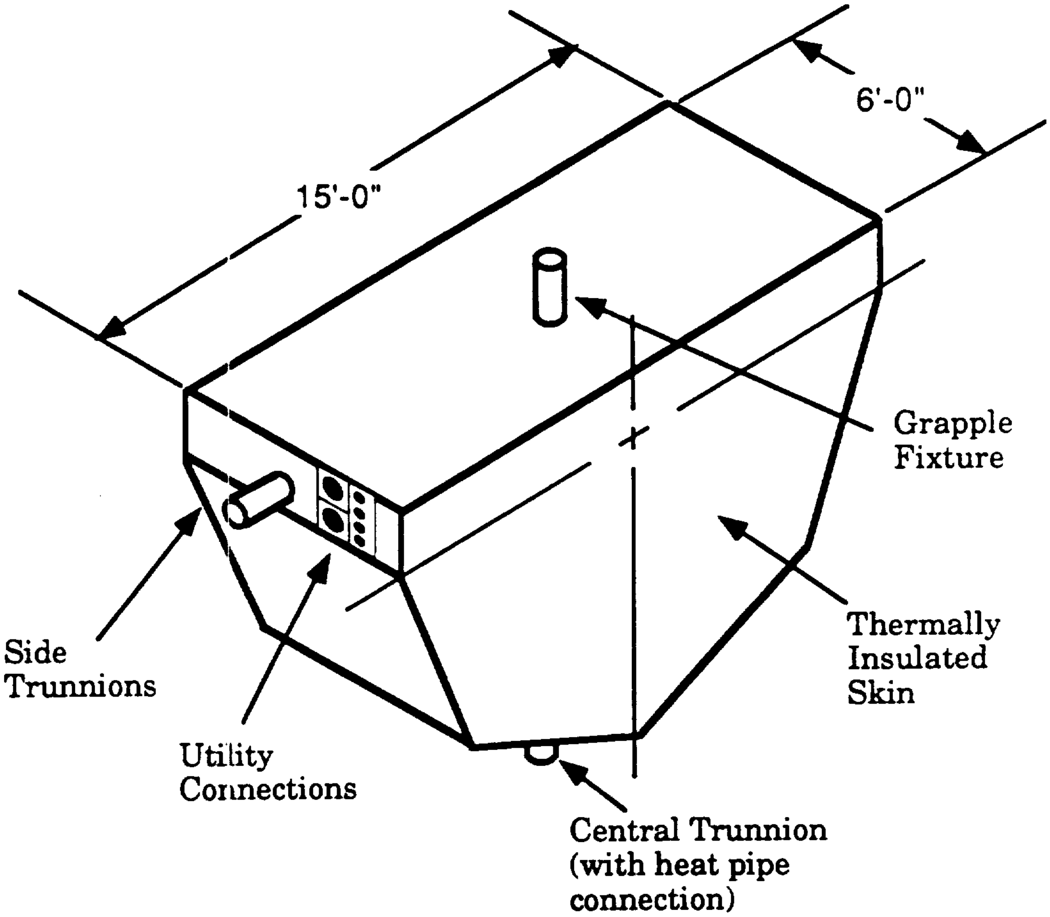

Figure 3.8.1. Typical Experiment Module

3.8.2. Experiment Rack

Figure 3.8.2 depicts the Experiment Rack Module. Its purpose is to provide an inexpensive interface between the MEP and smaller experiments which do not require an entire dedicated module. These experiment packages will arrive at the Space Station/MEP outfitting location, either by shuttle or expendable vehicle launch, and then be inserted into the rack. Each rack location provides utility connections.

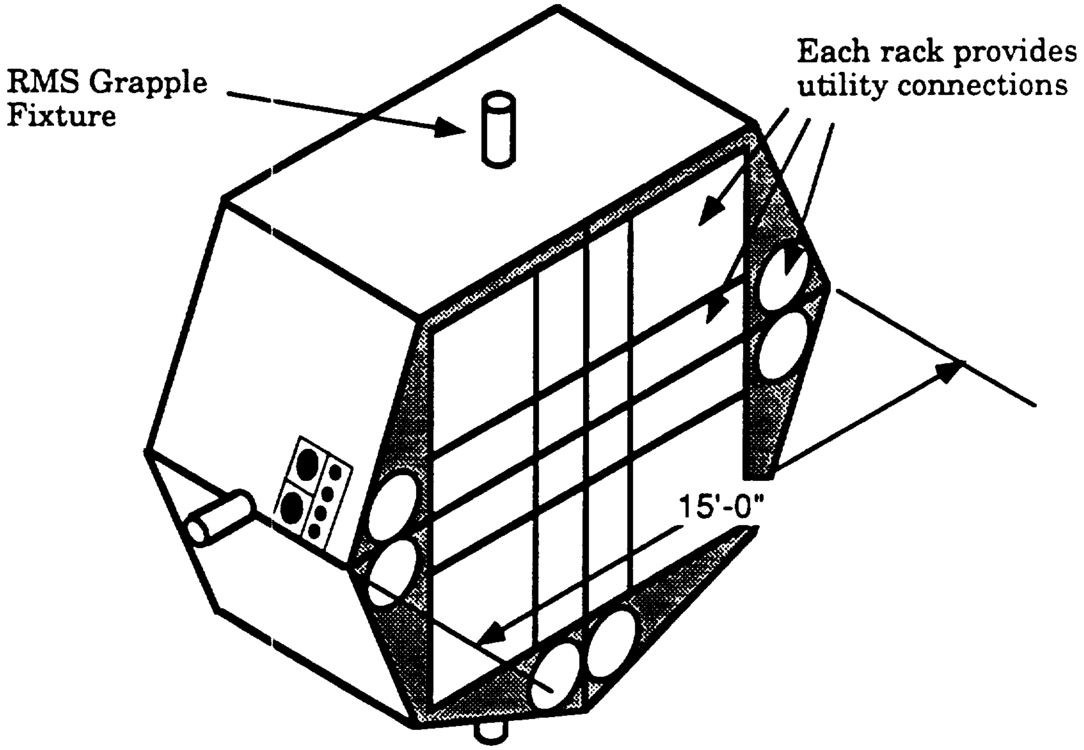

Figure 3.8.2. Experiment Rack Module

3.8.3. Levitation Module

The Flotation Module is a special purpose experiment module that will fly on missions entirely dedicated to "Levitation" Mode (See Section 2.3.3.3). Pictured in Figure 3.8.3, it is 25' long as apposed to typical lengths of 6'. This provides an extra margin of safety as the experiment package begins to drift with respect to the rest of the vehicle.

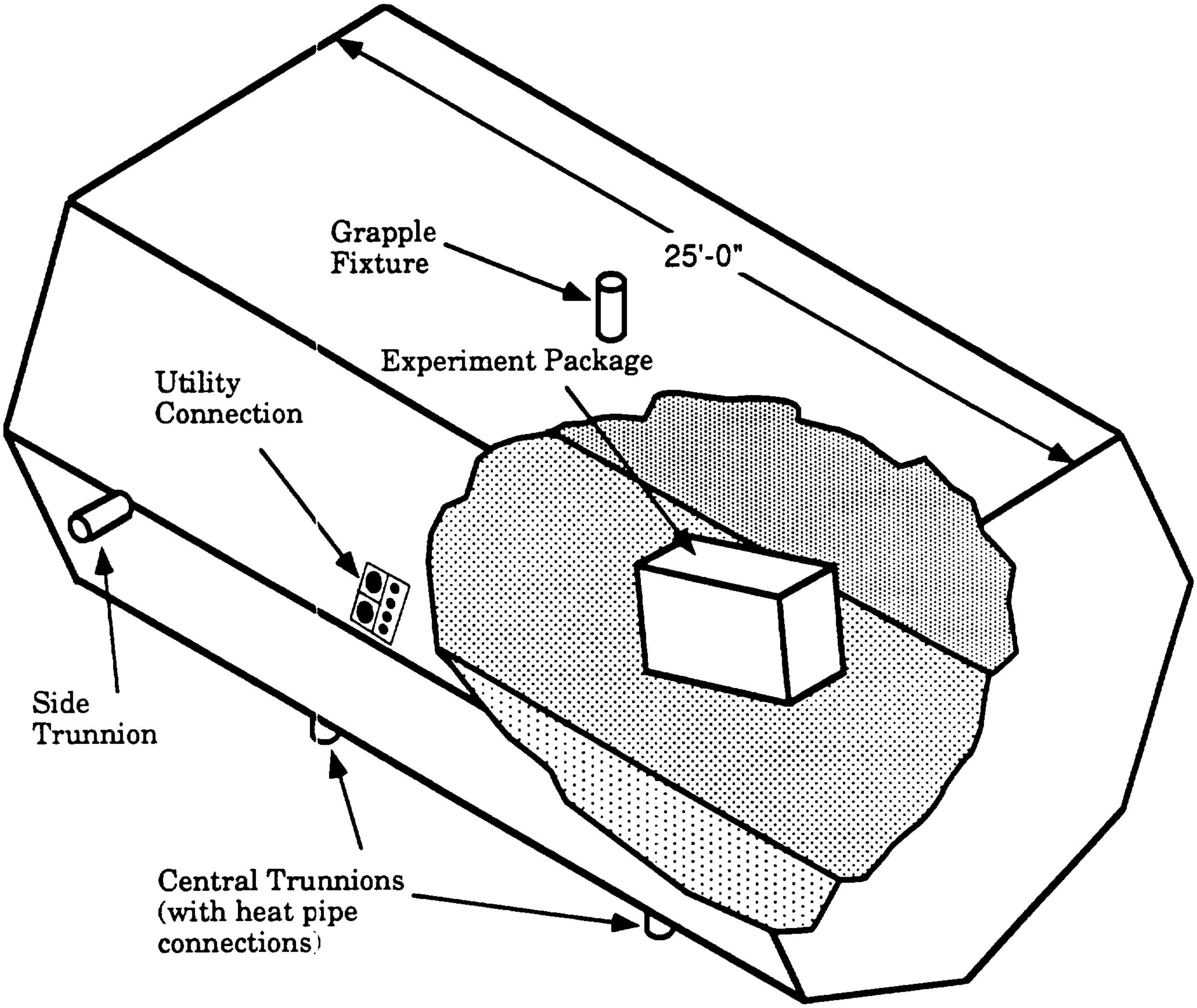

Figure 3.8.3. Experiment Levitation Module

4. Summary of Recommendations

The following is a summary of recommendations for future design work on the MEP.

4.1. Orbital Mechanics

A detailed orbital mechanics model which computes atmospheric drag effects on Space Station and the MEP is needed. This could be used to determine

relative orbital drift between the two vehicles, as well as a precise mission duration limitation for the LEO solo mode.

4.2. Levitation Mode

An accurate study of attitude adjustments required by the levitation mode for a given mission duration is needed. The required control algorithm also requires study.

4.3. Structural Subsystem

4.3.1. Damping

Frictional or viscous forces designed into the joints of the truss structure could provide damping which would allow greater control over the microgravity environment. Such effects should be studied.

4.3.2. Cross-Sections

The NASTRAN model used to do modal analysis on the truss assumed 1/16" thick shear panels, 1.6" diameter truss elements with 1/8" thick walls, and 6" diameter utility beams with 1/4" thick walls. These parameters are not optimized in terms of stiffness to mass ratios. For example, in one NASTRAN run, the shear panel thickness was doubled, and the lowest natural frequency decreased. What is the optimum shear panel thickness? What is the best thickness and diameter of truss elements in terms of higher natural frequencies? These questions need to be answered.

4.3.3. Material

The NASTRAN model also assumed aluminum was the structural material. Would composites have better characteristics? Which composite would be best? Would it be worth the increased cost?

4.4. Communications

The MEP will use moving antennas for communication. Antenna rotation effects on the microgravity environment should be studied. Can rotating another antenna in the opposite direction solve the problem? What about a viscous joint?

4.5. Guidance, Navigation, and Control

The momentum wheel's effects on the microgravity environment should be studied more closely.

4.6. Thermal Control

Sizing of the thermal control system still needs to be done. What is the required diameter of the heat pipes? What fluid should be used? What wick material would be most effective? Is a thermal fin necessary, or are shear panels sufficient?

5. Management Report

The group structure is listed in the proposal (Appendix A). There have been no changes to the group structure and it has provided adequate flexibility as the project progressed. Table 5.1 shows the total manhour distribution so far. The total manhours accumulated is approximately 1674 hours. The contractual accumulated manhour is 1404 hours. The project was 270 manhours over the contractual maximum. An updated project schedule is shown in Figure 5.1.

Table 5.1. Total Manhour Distribution

Personnel	Total Hours
K. Barber	152
T. Economopoulos	203
E. Evenson	256
R. Gonzalez	185
S. Henson	232
E. Parada	196
R. Robinson	222
M. Scott	173
B. Spotz	223
Total	1674

Teleoperated Experiment Free-Flyer for Micro-g Experiments Operated from Space Station Freedom

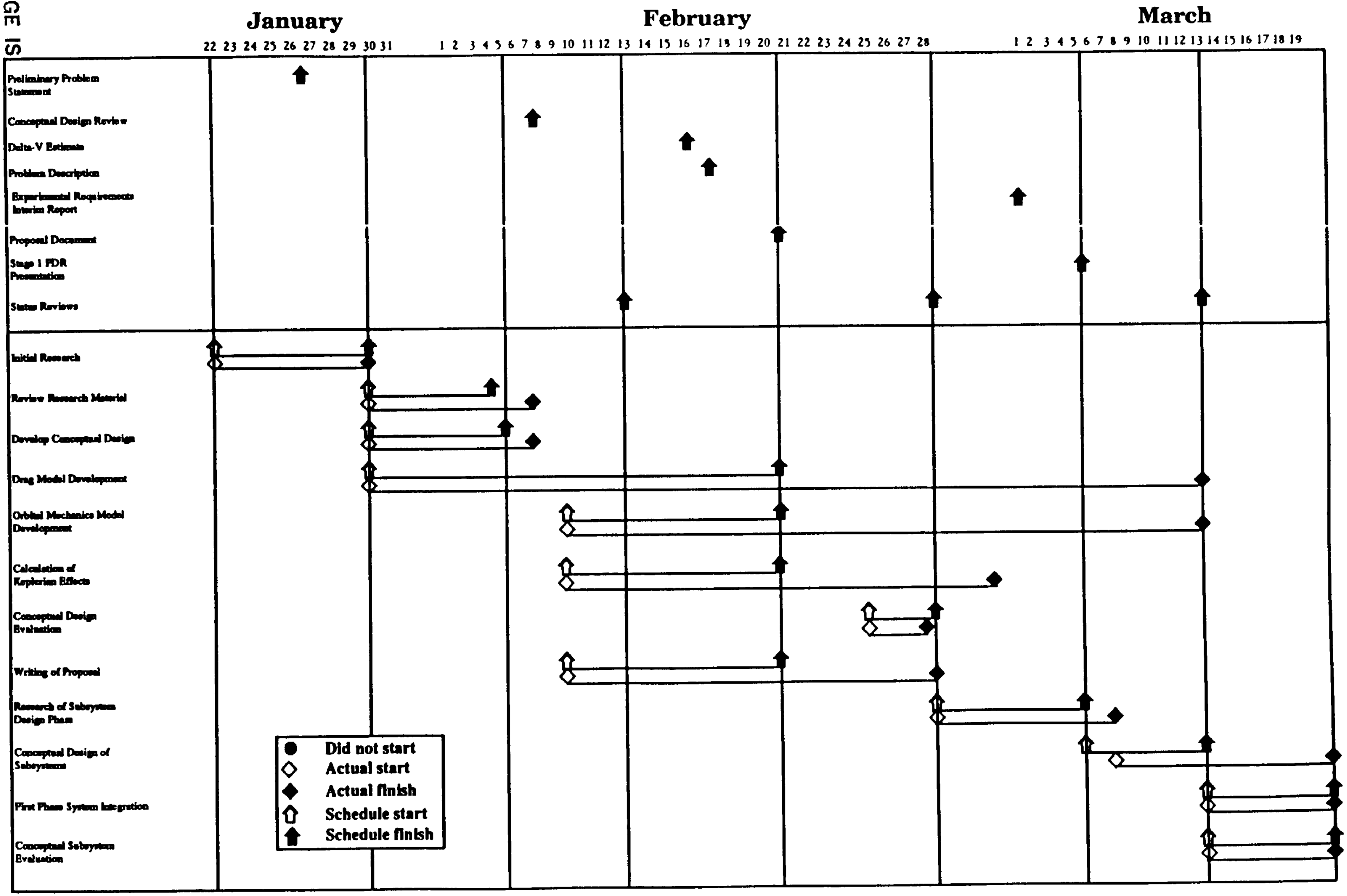

Figure 5.1 Project Timeline

Teleoperated Experiment Free-Flyer for Micro-g Experiments
Operated from Space Station Freedom

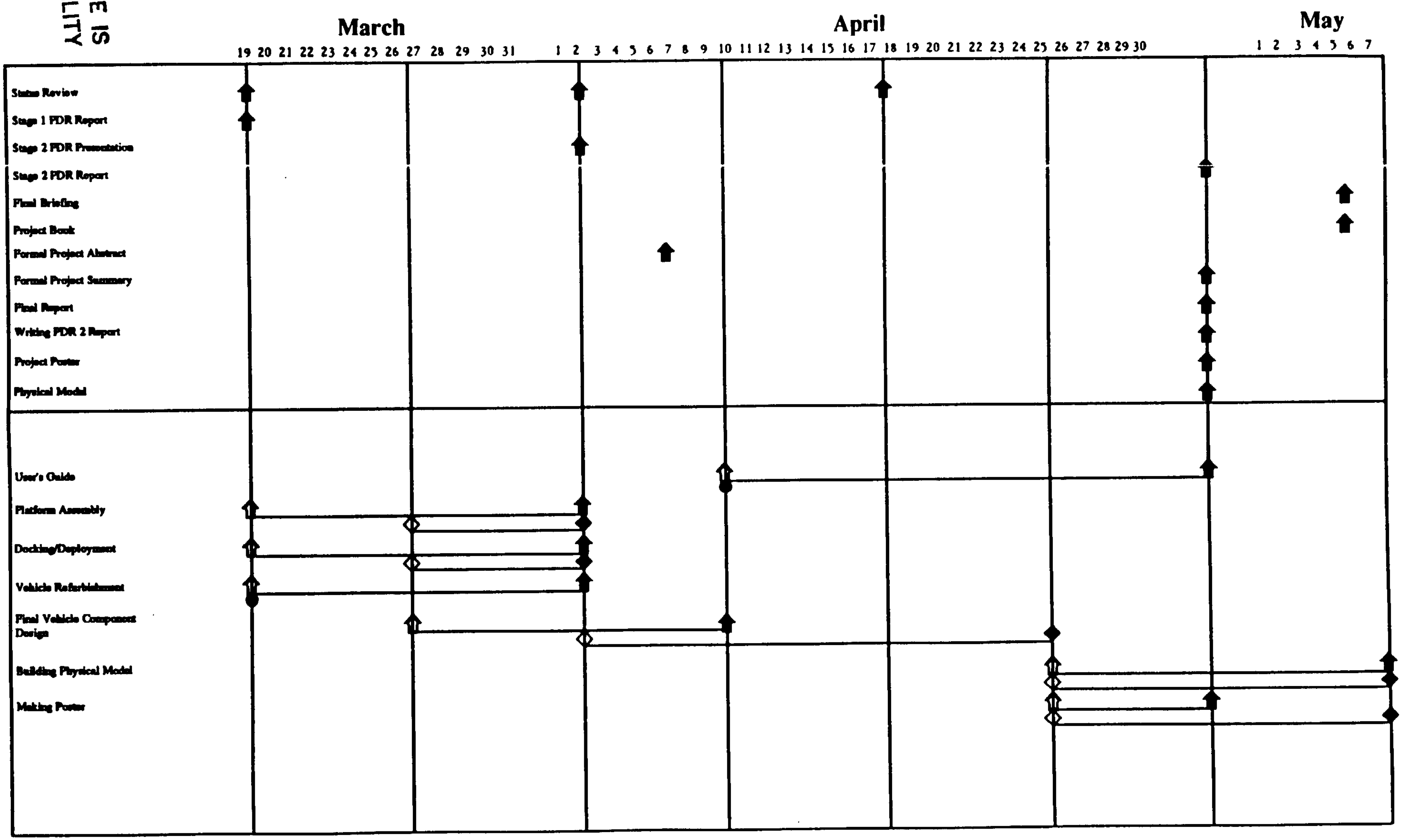

Figure 5.1: (continue)

6. Cost Report

The cost breakdown is shown in Table 6.1. Manhour cost is based on a group average earning of $16.39 per hour. A total of 1674 hours translates to about $27,437. Travel cost accumulated is about $240: two students on one visit to NASA. Sixteen hours of consultation have been required up to date. At a rate of $75 per hour this translates to $1200. There were about twenty NASTRAN modal analysis were done, the total cost is about $1200. Therefore, the total cost accumulated is $30,077. See Appendix A for the cost derivation.

Table 6.1. Project Cost Breakdown

Manhours	$27,437
Travel	$240
Consultation	$1200
Computer Time (NASTRAN) -	$1200
Total Cost	$30,077

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Appendix A. Project Proposal

Project Proposal for a

Teleoperated Space Station Microgravity Experiment Platform

Submitted to

Dr. Wallace Fowler

Professor for ASE 274L/174M
Spacecraft Design

Department of Aerospace Engineering
and Engineering Mechanics
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by

Steve Henson Rick Robinson
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Erik E. Evenson

February 1990

Executive Overview

Space Station Freedom environment experiences disturbances such as vibrations and microaccelerations due to movement of astronauts, shuttle docking and undocking. Therefore, Freedom is not suitable for a group of experiments which require high quality microgravity conditions. One solution is to deploy platforms with these sensitive experiments away from the Space Station. These platforms, Free Flyers, will be assembled and controlled from the station. Their orbits will be determined by several parameters including the duration of the experiment and quality of microgravity field. Therefore, the orbits could be similar to the orbit of Freedom or higher than that. A numbers of design are being investigated, most of these being of modular arrangement. The system will include enough pieces to assemble a wide variety to experiment platforms. The complete project, from initial research through the final design phase will be met within 14 weeks. Total manhours required to complete this project is estimated at 1966 hours. The estimated cost of the project will be 41,748 dollars which includes the salaries and expenses of the nine engineers members of the designing group.

Table of Contents

List of Illustrations

1.0 General Summary

Experiments which require a high quality microgravity environment will not be possible on Space Station Freedom due to normal activities which occur on the station. Such activities include docking, astronauts' movement, equipment vibrations, and Freedom reboost. The Microgravity Experiment Platform Project involves the design of a free-flyer which will reduce these disturbances by being removed from the space station. The proposed free-flyer will deploy, adjust, and retrieve itself, accommodating experiment masses up to 1000 kg and durations up to two years.

The project will involve four phases of development, two of which are completed. In the Research Phase, general information on free-flyers and microgravity requirements was obtained from various sources. The Conceptual Design Phase generated various free-flyer concepts. The Design Evaluation Phase will compare the proposed designs based on various criteria. The Detailed Design Phase will begin once the conceptual designs have been evaluated. Solutions for subsystem requirements such as propulsion, power, guidance, navigation and control, layout, communication, and automation will be evaluated.

The project management structure and project scheduling are describe in the Management Proposal. Cost information is presented in the Cost Proposal.

At the conclusion of the Microgravity Experiment Platform Project, the government will receive several end-deliverables. These include a formal project summary, a formal design report, scale models and a poster of the proposed system.

2.0 Technical Proposal

2.1 Research Phase

The preliminary research phase involved collecting information encompassing all aspects of the system and its mission including information on microgravity experiments and their requirements. Sources of information included personal contacts and documents from the NASA - Johnson Space Center (JSC). Mr. Kenneth Demel , Commercial Advocacy Customer Integration and Microgravity Program Director spoke to project team members about system requirements on all experiments and Mr. Steve Trumasle of the Avionics Division discussed an upper atmosphere model. Mr. Gregg Edeen and Mr. Edgar Castro of the Structures and Mechanics Division provided information on orbital debris and Space Station Freedom.

Mr. William Fraser of Space Industries, Inc. contributed general information on free-flying vehicles and problems which should be addressed during this project. Additional sources of information were obtained from the University of Texas Engineering Library. Other areas of research included the micrometeorite environment, space station reboost, vibroacoustics, and solar and thermal effects. Structural limitations to microgravity regions called Keplerian effects

(see Appendix A), atmospheric drag and drag modelling, and Freedom interfaces were also researched.

2.2 Conceptual Design Phase

The basic conceptual design of the proposed free-flying vehicle consists of a family of vehicles made up of common modular components. Each module has a particular function: propulsion, power, navigation and control. This configuration allows for versatility in meeting specific mission requirements. Refurbishment before and after each mission will be performed telerobotically from Freedom. Experiment data could be stored, relayed back to Freedom, or relayed back to Earth via a Tracking and Data Relay Satellite System (TDRSS) link.

Currently, seven proposed conceptual designs are being considered. The Modular Microgravity Experiment Platform design provides a framework for experiments and necessary support modules (see Figure 1). By matching the ballistic coefficient of the platform with that of Freedom, the free-flyer will be able to remain in Freedom's orbit , either leading or trailing it. At this orbit the platform will be subjected to atmospheric drag and Keplerian effects. The Platform may also be used for higher altitude orbits in order to eliminate drag and reduce Keplerian effects. The platform concept is the foundation for the concepts that follow. Because of the wide variety of requirements (see Appendix B), this design would provide the flexibility to accommodate most experiments.

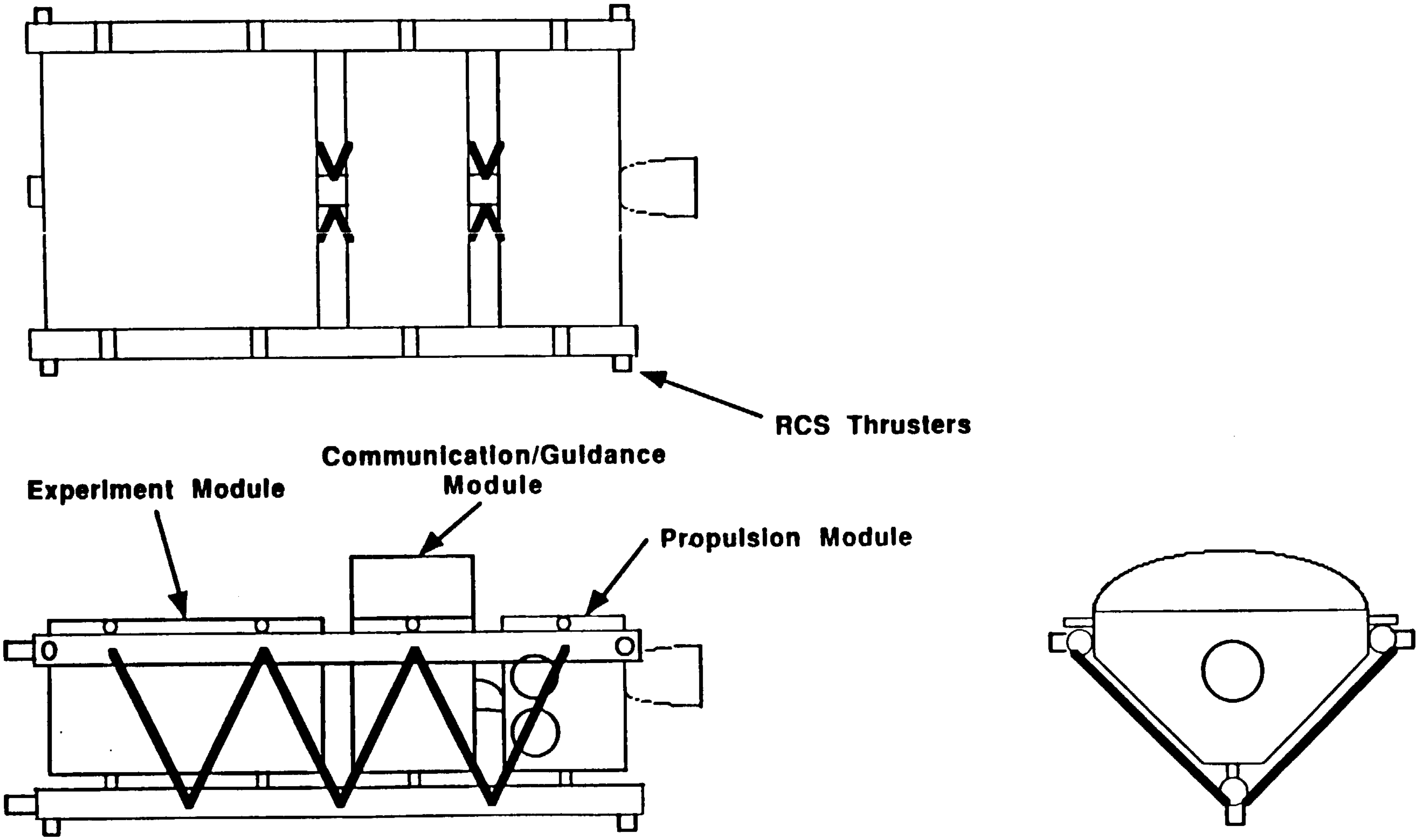

Figure 1: Modular Microgravity Experiment Platform: Conceptual Design

The High Altitude Boost/Drag Elimination Mode consists of boosting the free-flyer to an altitude high enough to reduce atmospheric drag, resulting in an improved microgravity environment. Problems arising as a result of boosting to a higher orbit including higher fuel requirements and leaving the proximity of Freedom resulting in limited use of its communication systems.

The purpose of the High Altitude Boost/Keplerian Effect Reduction Mode is to boost the free-flyer high enough to cause an increase in the size of the microgravity envelope (a reduction of Keplerian effects).

High altitude provides a larger region in which microgravity levels will remain constant and atmospheric drag will be completely eliminated.

A Floating Experiment Module will eliminate drag effects by flying the experiments within a shell (see Figure 2). The shell will experience atmospheric drag, while the experiment module levitates inside. Special care must be taken to ensure that the experiment module never comes in contact with the shell. The result is that atmospheric drag effects on the experiments will be eliminated, although a complex control system will be required.

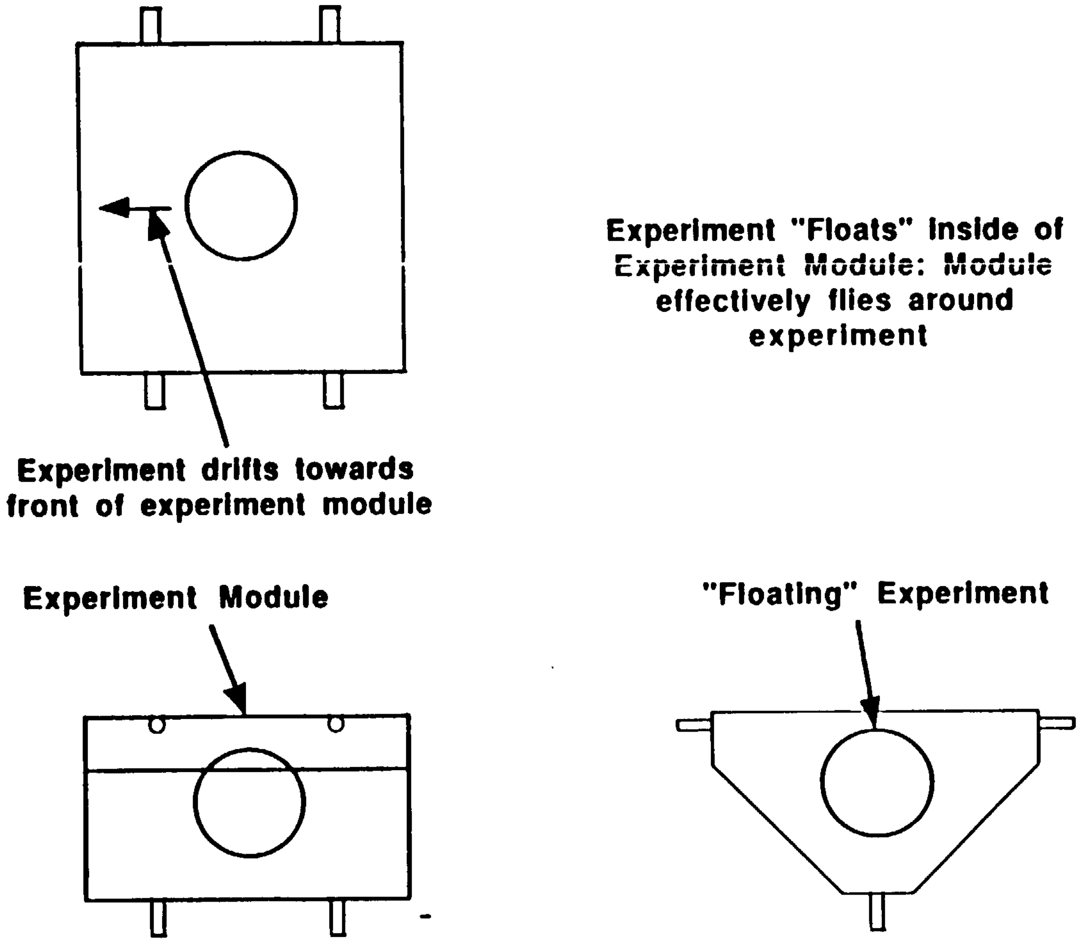

Figure 2: "Floating" Experiment Module: Conceptual Design

The Drafting Free-Flyer is similar to the Floating concept. It will involve placing the experiment modules behind a shield which will reduce atmospheric drag effects . One limitation of this concept is that remaining in proximity to Freedom will not be possible, so full time utilization of Freedom's communication system may not be possible. Also, reaction control jets may interfere with the experiment module, as shown in Figure 3.

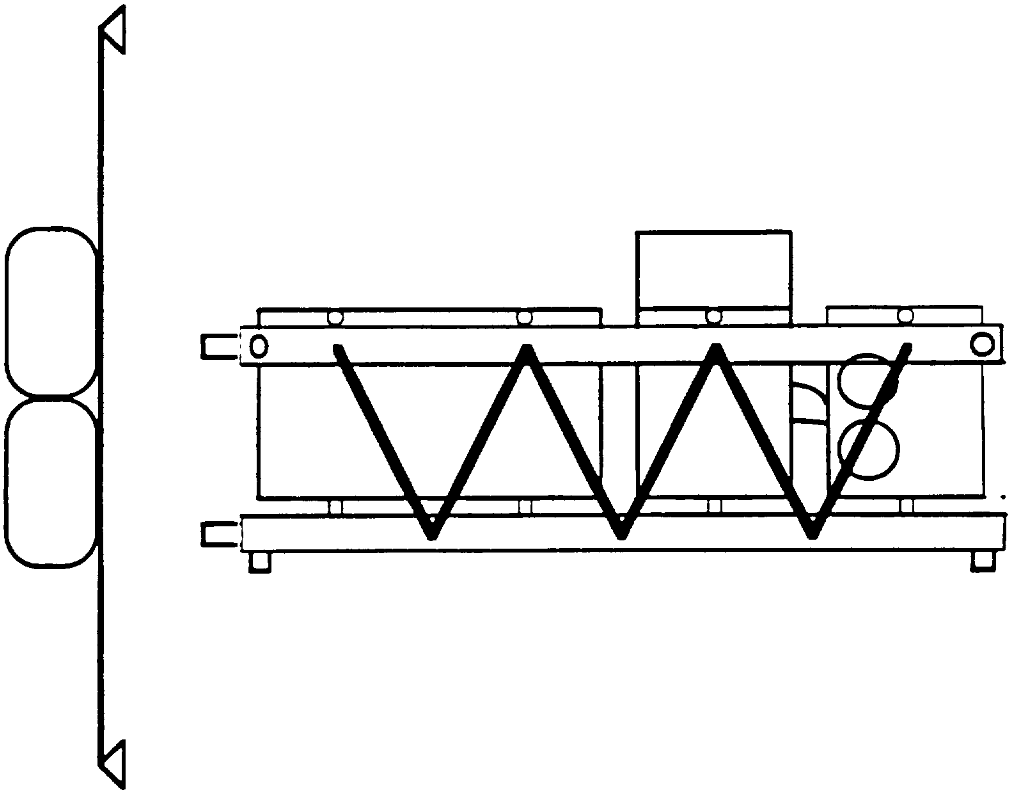

Figure 3: Wake Shield for Drafting Free-Flyer

The External Tank Free-Flyer would use space shuttle external tanks as a framework to contain experiments and necessary support modules. During nominal shuttle missions the external tank reaches 98% of required orbital velocity. By supplying the extra thrust required to reach orbital velocity the external tank would provide a large volume for future experiments. Refurbishment of the external tank to suit specified mission requirements would be performed on-orbit. A major advantage of using such a configuration is the large volume— lending itself to support production scale facilities as shown in Table 1.

Table 1: Space Shuttle External Tank Dimensions

Length	154.2 ft
Diameter	27.5 ft
Inert Weight	66,000 lb

A Tethered Free-Flyer was proposed in order to minimize delta-v requirements for docking and deploying maneuvers with Freedom, especially when considering short duration experiments. Upon further research this concept was rejected because of the adverse effects of a taut tether.

2.3 Design Evaluation Phase

The design evaluation phase involves a comparison of the conceptual designs based on atmospheric drag, propulsion requirements,

microgravity environment quality, microgravity envelope size, and other considerations.

2.3.1 Atmospheric Drag

Atmospheric drag is one of the primary causes of accelerations on spacecraft in low-earth orbits. A computer model of atmospheric drag has been obtained and is currently being modified to make appropriate calculations. From this model, free-flyer accelerations will be calculated, as well as orbital decay. This is necessary to estimate the quality of the microgravity environment and the distance the free-flyer will drift from Freedom.

2.3.2 Propulsion Requirements

A major evaluation criterion for each design is its cost in terms of required delta-V. Deployment and docking, orbit changes, attitude adjustment, and the strategy for dealing with Freedom reboost contribute to the propulsion requirements. Initial calculations are based on a Hohmann transfer for orbit changes and the C.W. equations for proximity operations. More sophisticated mathematical models will be required later.

2.3.3 Microgravity Environment Quality

An approximate estimation will be made to determine the quality of the microgravity environment of the free flyer. Three factors which may affect the quality of the environment include quasi-steady, oscillatory, and transient accelerations.

2.3.3.1 Quasi-Steady Acceleration

Quasi-Steady acceleration is mainly a result of the vehicle's interaction with the Earth's atmosphere. Many experiments are effected by the magnitude and direction of these types of acceleration. Acceptable magnitudes range from less than 1μg for materials processing to about 17 μg for biotechnology experiments. For directional solidification crystal growth, experiments are at least 10 times more sensitive to accelerations applied perpendicular, as opposed to parallel to the crystal growth direction [Ref 2].

2.3.3.2 Oscillatory Accelerations

Oscillatory accelerations are inherent to most space structures. Sources within the structure such as rotating and reciprocating machinery, modal oscillation of trusses, and low frequency pitch drift error must be considered when evaluating the quality of the microgravity environment. Table 2 provides a range of frequencies and their corresponding acceleration amplitudes. According to Reference 2, commonly used components of space structures such as centrifuges, control moment gyros, and fans should not produce unacceptable accelerations.

Table 2: Permissible Microgravity Acceleration Levels

Frequency Range	Amplitude
$f < 0.1$ hz	< 1 μg
$0.1 < f < 100$ hz	f x 10 μg
$f > 100$ hz	< 1000 μg

2.3.3.3 Transient Accelerations

Many experiments are sensitive to impulses of micro-accelerations known as g-jitters. The effects of these pulses are dependent on the amplitude, duration, and duration between each pulse. To obtain the required 1% non-uniformity [Reference 2], the integrated impulses must be on the order of "10's" of μg-sec.

2.3.4 Size of Microgravity Envelope

The microgravity levels of a rigid body in orbit change as a function of position relative to the center of mass of the body due to the gravity gradient field. The size of the ellipse determines the region in which the experiments can be performed and is proportional to the cube of the ratio of orbit altitude to the radius of the earth. Differences in acceleration seen by a particular particle and that seen at the center of gravity are known as Keplerian effects. A curve connecting points of equal Keplerian accelerations take on the shape of an ellipse. Figure 4 outlines this ellipse based on a 1 μg Keplerian acceleration at a 270 nmi altitude. A detailed discussion of the Keplerian effect is listed in Appendix A.

2.3.5 Other Considerations

Other factors which will determine the system configuration include volume, mass, and power requirements. Additional evaluation criteria are experiment durations, contamination level, and

STRUCTURE OF GRAVITY GRADIENT FIELD

FOR A CIRCULAR ORBIT, THE ACCELERATION DUE TO GRAVITY GRADIENT EFFECTS ON A POINT R METERS FROM THE FLIGHT PATH OF THE CG IS:

DISTANCE FROM CG (M)	ACCELERATION ($10^{-6}G_0$)	
	RADIAL	CROSS PLANE
R	A_R	A_{CP}
1	0.375	0.125
2	0.75	0.25
4	1.50	0.50
8	3.00	1.00
16	6.00	2.00
32	12.00	4.00
64	24.00	8.00

ORBIT ALTITUDE: 270NM, 500KM

Z AXIS RADIAL FROM EARTH

Y AXIS CROSS PLANE

X AXIS VELOCITY VECTOR (⊥ TO CHART)

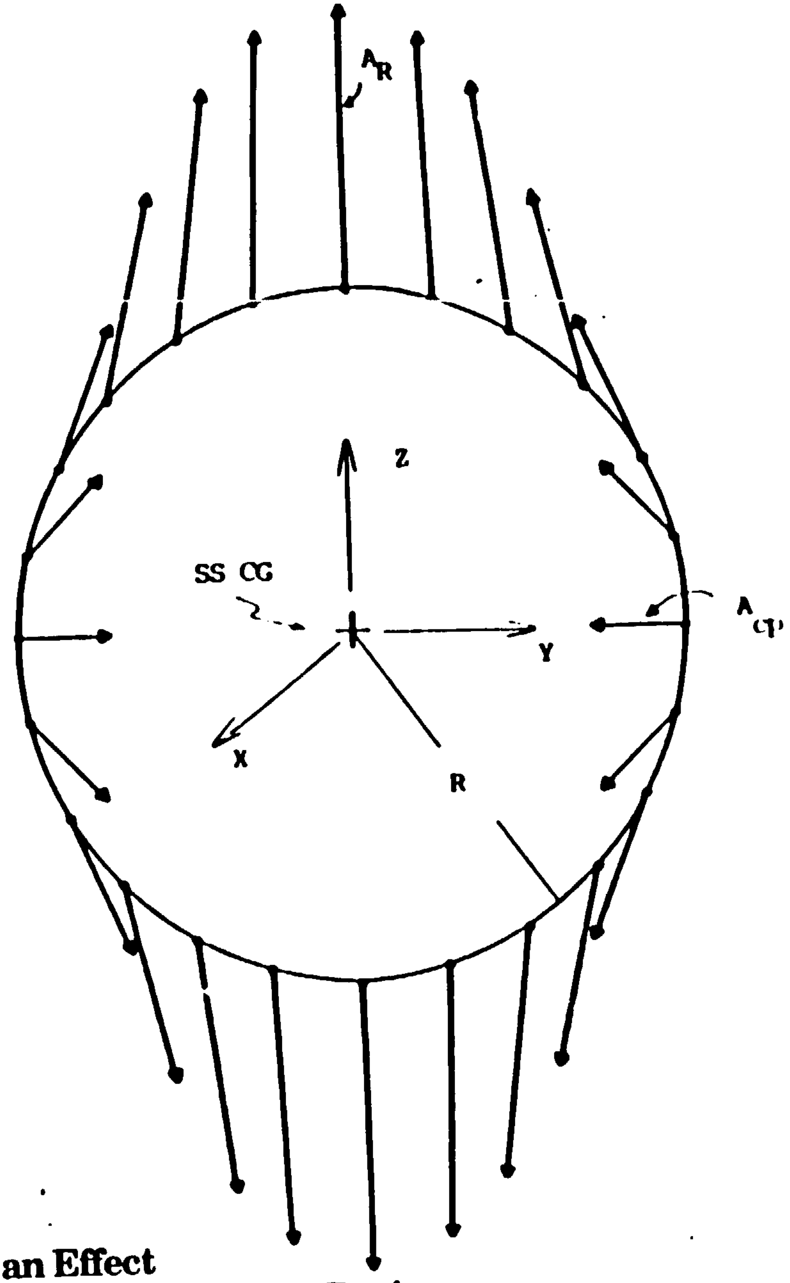

Figure 4: Keplarian Effect

temperature. Table 3 provides the system requirements based on a worst case scenario.

Table 3. Extreme Experimental Requirements

μ-g tolerance	0.1
Volume	1.36 m^3
Mass	1000kg
Power	5 kW
Duration	2 yrs

2.4 Detailed Design Phase

In the detailed design phase we will consider subsystems which will be required on the free-flyer. Examples of these subsystems are layout, propulsion, power, guidance and control, communication, and automation.

2.4.1 Layout

The Modular Microgravity Experiment Platform design is based on a modular layout. Once the power and propulsion requirements have been determined, the optimal layout can be determined. Optimal layout will depend on an analysis of possible experiments, their durations, microgravity tolerances, and power requirements.

2.4.2 Propulsion

The primary requirement for the propulsion system is the delta-V required by the vehicle. Other considerations include the mass of the free-flyer, the maximum thrust level at any point of the mission,

required attitude control and the ability of the propulsion system to be resupplied. Safety and Freedom interface will also be addressed.

2.4.3 Power

Overall system power requirements on the proposed free-flyer will be composed of the requirements of each experiment as well as overall system requirements. If an experiment requires additional power above that delivered by the baseline configuration, power modules could be added. Possible power systems include solar arrays, nuclear generators, batteries, and microwave power transmission from Freedom.

2.4.4 Guidance and Control

The guidance and control subsystem will depend on the mission profile which takes into consideration factors such as mission duration, space station reboost strategy, and propulsion system selection.

2.4.5 Communication

Communications subsystems will be used for transfer of experimental data, experiment control, and free-flyer control systems. Potential options include periodic data transfers to Freedom and continuous transfer to Earth via a TDRSS link.

2.4.6 Automation

Automation systems will be required for the purpose of self-deployment/docking, retrieval, and remote activation of experiments.

3.0 Management Proposal

3.1 Organizational Structure

The company organizational structure consists of four levels: the program manager, technical director, senior engineers, and engineers. The program manager is responsible for the majority of the managerial duties and acts as a single point of contact for the group. This includes cost tracking, task assignments, and any other duties that would allow the group to function efficiently. The technical director serves as the technical liason between the contractor and the government and coordinates the technical efforts of all engineers.

The Microgravity Experiment Platform design group is composed of nine student engineers. The organization is divided into three subgroups which are under the supervision of the senior engineers. Under each subgroup there are other engineers who are each responsible for a specific area. Since there is a limited number of engineers, each engineer will be responsible for more than one area. Manpower will be shifted to different areas as required. The detailed organizational chart is shown in Figure 5.

The orbital environment subgroup will be responsible for the orbital mechanics and external disturbances of the experiment platform. The

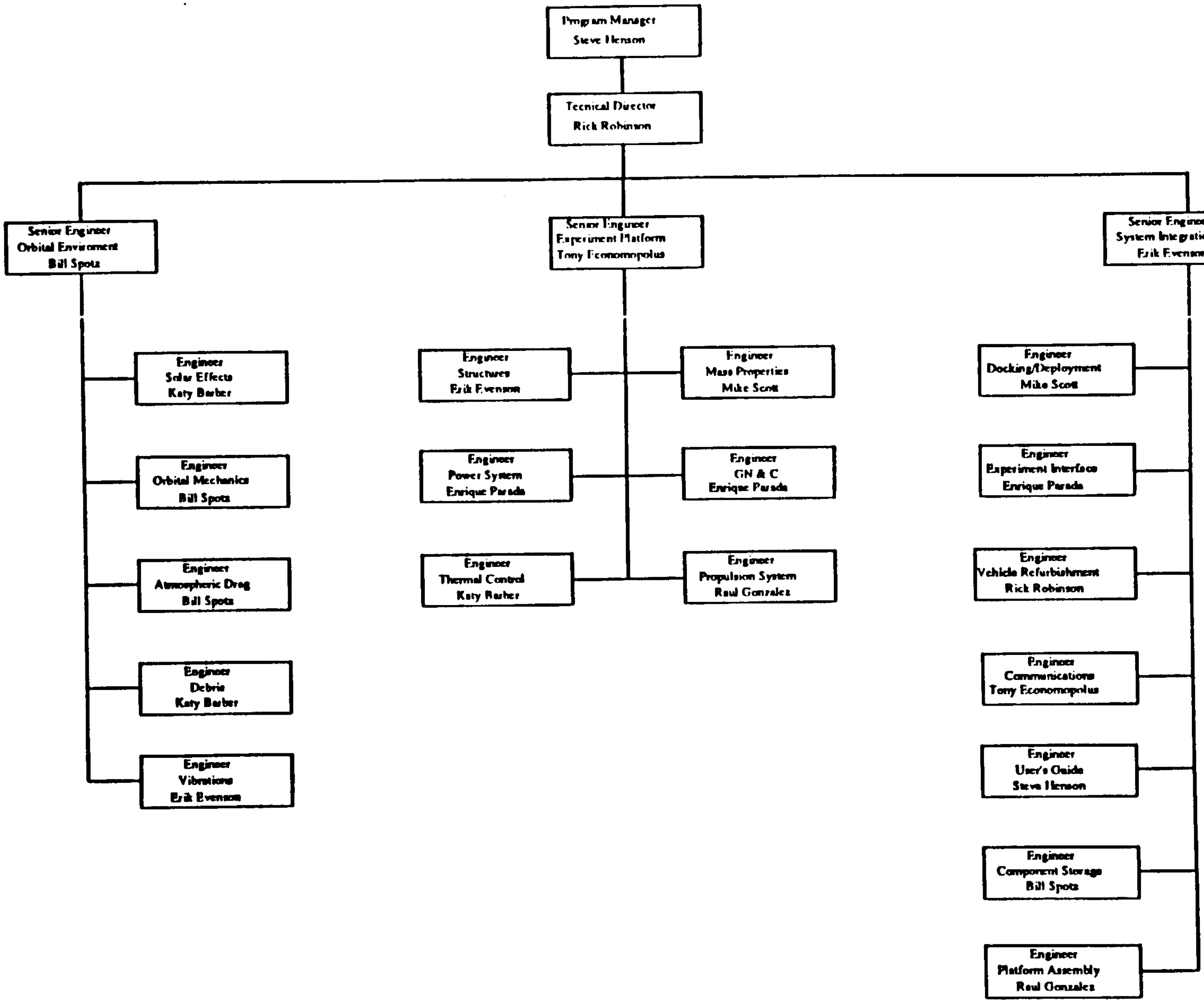

Figure 5: Organizational Chart

experiment platform subgroup is going to design the experiment platform and its subsystems. The system integration subgroup will work on the system integration that will be needed for proper communication and fitting between the space station and the free flyers. Each of these subgroups are divided into several, more specific areas. Appendix C describes in detail the description of each specific area. As action items are required the program manager will assign these task to the appropriate member.

This organizational structure provides flexibility that will be required for this project. As the project progresses, changes are possible not only among the specific areas that are being studied, but also among the engineers who study them. Because of the nature of the project, additional research and design in other areas may be required, or research on a current area may prove to be trivial. This may lead to a reassignment of engineering manpower. However, the basics of the current structure will be maintained in order to have an organization which will provide optimum communication and interaction among engineers.

3.2 Project Scheduling

The project scheduling is based on the experience gained from the phase prior to the proposal. The initial research gathering and analysis process usually takes about two weeks. Then the conceptual design phase follows; this is normally a ten day process. The design evaluation process then follows. During this phase rough analysis are done to differentiates on concept from another. This phase is

expected to require about three weeks, depending on the complexity of the analysis. This general process will be followed to design the subsytems of the free-flyers. Figure 6 shows the day to day progress of each design phase.

After the proposal there will be further research on some aspects of the project and then the group will begin the conceptual design of the systems and subsystems on the free flyer and on the space station. These systems include the propulsion of free flyer, structures, communications, payload, etc. It is expected that an iterative process will be required for the completion of an optimum design within the given timeframe. Finally, the last stage will be the generation of a final report and the construction of the model and poster. Figure 7 illustrates the steps design process of the subsystems.

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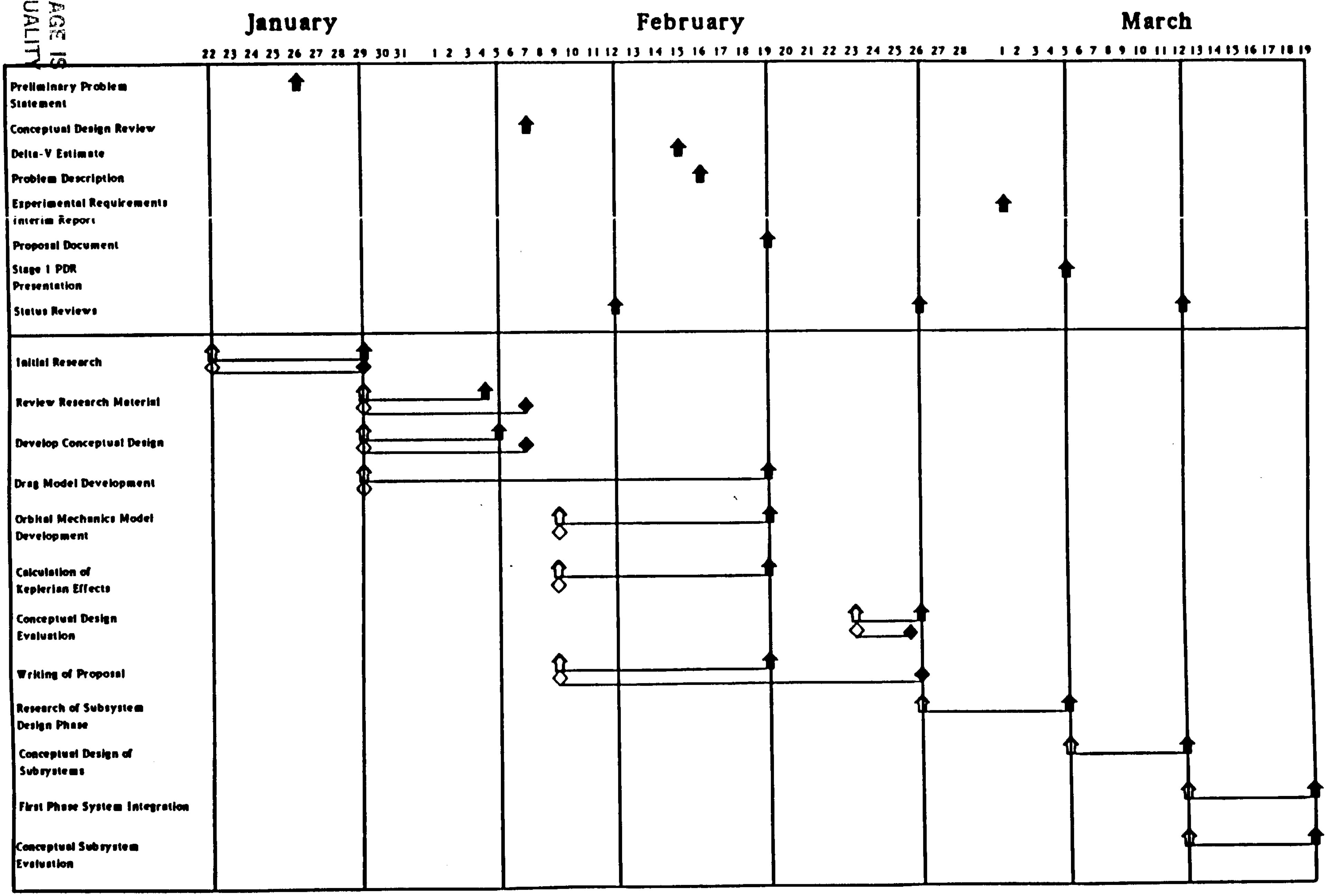
Teleoperated Experiment Free-Flyer for Micro-g Experiments Operated from Space Station Freedom



Teleoperated Experiment Free-Flyer for Micro-g Experiments
Operated from Space Station Freedom

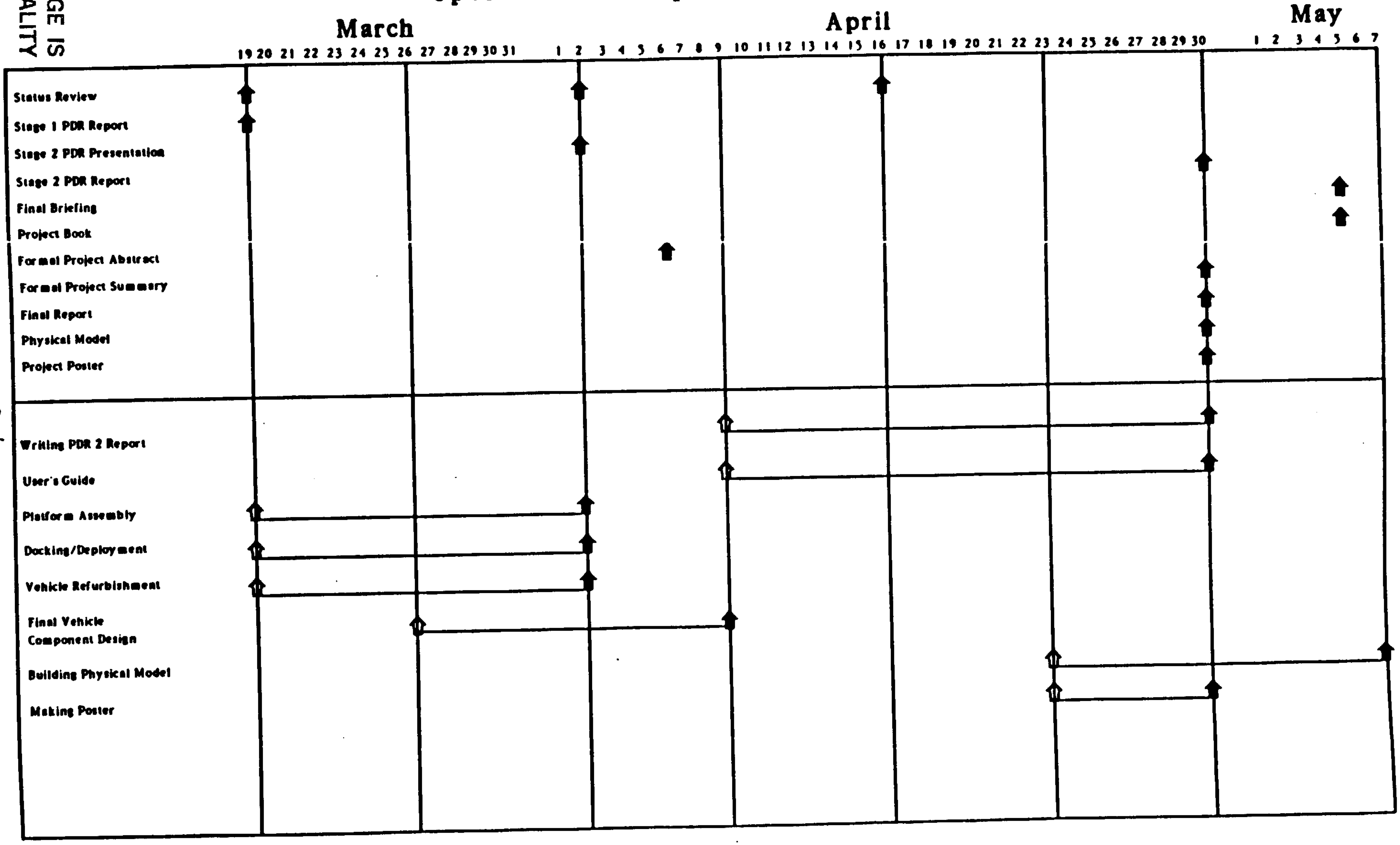


Figure 6: (continue)

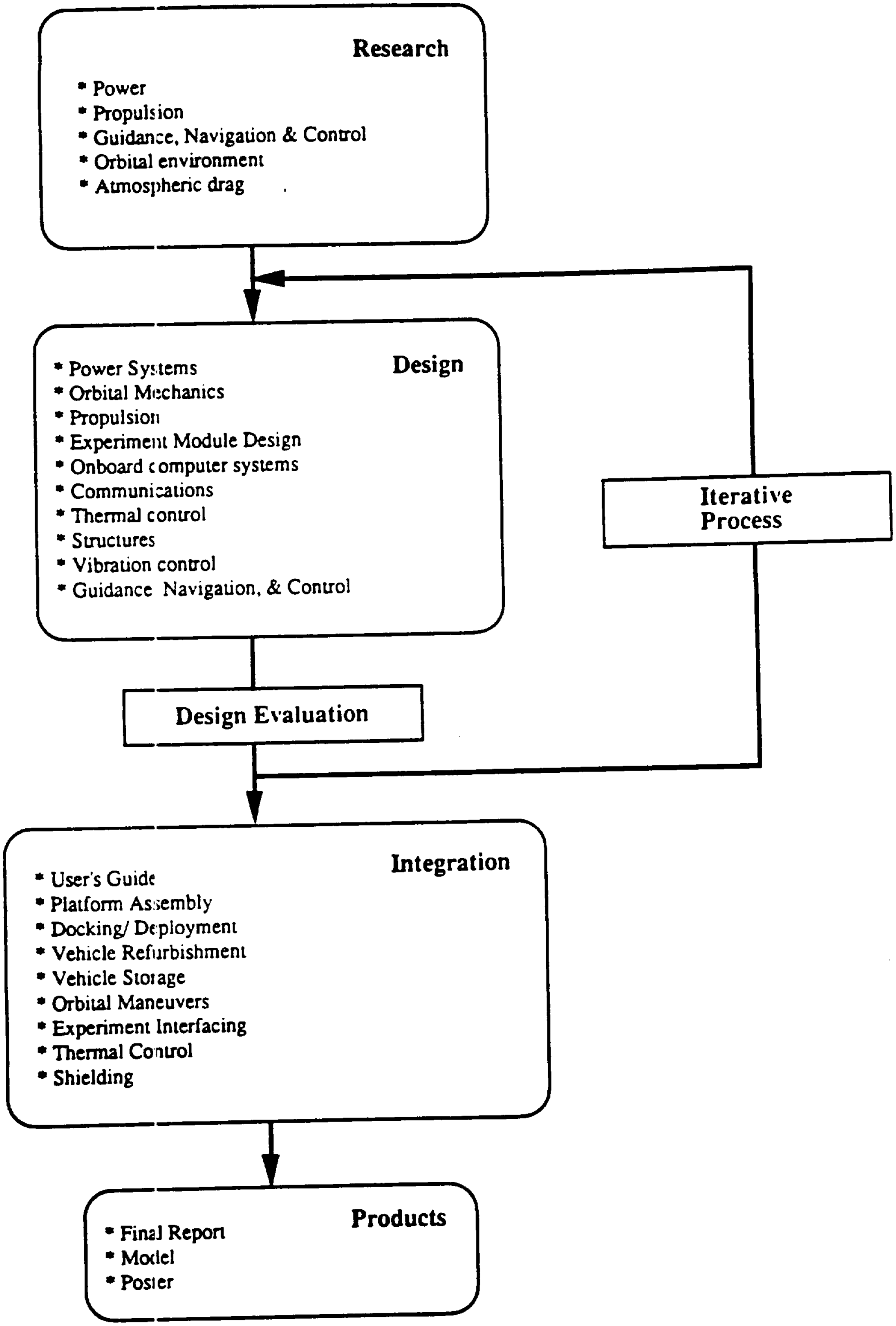


Figure 7: System Design Process

4.0 Cost Proposal

4.1 Personnel Cost

The personnel cost is based on the University of Texas guidelines for classes. It is expected that a student spends three hours outside of class for every hour in class. Therefore, this design project requires twelve hours per week per student. That translates into 108 hours per week for the entire group. The project will last a total of fourteen working weeks. Thus, the estimated manhour required for this design study is 1512 hours. During the week of the CDR the group experienced a dramatic jump in manhour input. A thirty percent error should account for any such fluctuations in the future.

Therefore, the total amount of manhours required for this project is estimated at 1966 hours.

There are twenty three positions in the organization; one program manager, one technical director, three senior engineers, and eighteen engineers. The program manager earns $52,000 per annum while the technical manager earns $45,760 per year. The senior engineers and the engineers earn $41,600 and $31,200 per year, respectively. Therefore the group averages payscale for the group is about $34,094 per year or $16.39 per hour. At this rate the groups total manhour cost for this project is estimated at about $32,222. The formulation of the projected cost is shown in Table 3.

July 24, 1990:

Pages 24, 25, and 26 removed because of funding information.

Philip N. French
PHILIP N. FRENCH
Document Evaluator

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Appendix A : Keplerian Effects

For most applications the assumption of resultant gravity force acting on the center of gravity of an object is made. However, because gravity actually acts on each particle within an object, slight differences in acceleration between the resultant gravity force acting on the center of gravity and the gravity felt by an individual particle exist. These accelerations are known as Keplerian Effects. A curve surrounding the center of gravity connecting points of equal Keplerian acceleration takes on the shape of an ellipse known as an Iso-gravity ellipse. The shape of this ellipse remains constant; the eccentricity remains the same. However, its size is dependant upon the altitude of the center of gravity of the body above the earth and the magnitude of the particular Keplerian acceleration in question. Equations describing Keplerian accelerations include the following:

$$A_{cp} = \frac{3\Delta Y R^2 g_o}{(R + h)^3}$$

$$A_r = \frac{\Delta Z R^2 g_o}{(R + h)^3}$$

where ΔY: distance cross plane from the center of gravity,

ΔZ: distance radially from the center of gravity,

R: mean equatorial radius from the center center of gravity,

h: altitude of the center of gravity of the body above the Earth,

g_o: the acceleration due to gravity.

Note: ΔY, ΔZ are coordinate measured in a body-fixed coordinate system with the x-axis along the velocity vector of the body, the z-axis acting radially between the centers of gravity of the Earth and body, and the y-axis completing the orthogonal set.

Appendix B: Experimental Requirements

(from W. Fraser/SII:"Report of the Committee on a Commercially Develope Space Facility)

Appendix C: Task Descriptions

- assembly:

  Determine how the free-flyer will be assembled on orbit. Generate a procedure for optimizing the free-flyer configuration (optimizing resource usage) and for assembling the free-flyer with all experiments.

- atmospheric drag:

  Investigate how the atmosphere causes the free-flyer orbit to decay. Also, see what accelerations result from drag. Determine the force on the vehicle due to drag and the delta V necessary to counteract it. Analyze using a computer model.

- communications:

  Research Freedom communications systems. Determine the communication needs of the free-flyer and whether Freedom's communication system can be used. Do background research on TDRSS (as a possible ground-link).

- computer models:

  Create computer graphics of the free-flyer (with animation, if possible).

- data acquisition:

  Determine data acquisition requirements for each experiment. Design the data acquisition system for the free-flyer, integrating it with onboard computer and communications systems.

- debris:

  Determine the debris environment for proposed free-flyer orbits.

- docking/ deployment:

  Research systems currently in use. Develop an autonomous system for the free-flyer.

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- experiment interfacing:

  Determine how to interface experiment modules to the free-flyer. Include all systems: power, communication, data acquisition, etc.

- experiment module design:

  Design experiment modules incorporating interfaces for power, communications, and consumables. Determine experiment volume and mass.

- guidance, navigation, and control:

  Develop systems for controlling attitude, docking/deployment, station-keeping, and continuously thrusting against drag.

- mass properties:

  Create a database with the mass of all free-flyer components and a total for each configuration.

- onboard computer systems:

  Determine all requirements driving the onboard computer system design— docking/ deployment, communication, guidance, navigation, and control, and data acquisition.

- orbital mechanics:

  Look at the orbital mechanics for all mission profiles; include proximity operations (C.W. equations), orbit change (Hohmann transfer, as a first approximation), decay, and continuous thrust against drag.

- physical models:

  Construct physical models of the free-flyer in various configurations. Modular models would be best.

- power systems:

  Determine maximum and minimum power requirements for each possible experiment and for the complete free-flyer.

Decide which power options are best— batteries, solar, nuclear generators, microwave power beamed from Freedom, etc.

- propulsion:

  Determine all required Delta V's. Determine best candidate engines (and associated Isp's) along with possible propellants (with densities).

- shielding (radiation/ thermal/ micrometeorite):

  Determine shielding requirements for radiation, thermal, and micrometeorite (determined from debris model) protection.

- solar effects:

  Investigate the effect of direct sunlight on the free-flyer. Determine if solar radiation pressure is negligible or not.

- structures:

  Design vehicle layout, then develop a baseline structure and determine structural mass. Consider rigid vs. flexible structures and how this affects the micro-gravity environment.

- thermal control:

  Design an internal thermal control system (to take care of heat generated by experiments, electronics, etc.) and an external thermal control (shielding, blankets, etc.).

- user's guide:

  Generate a user's manual which describes the free-flyer, its mission, and how to utilize it. This should be a complete guide for the user.

- vehicle refurbishment:

  Determine the method for change-out of experiments and refurbishing fuel, power (batteries?), and other consumables. Determine the method for storing free-flyer supplies on Freedom.

- vehicle storage:

  Determine the method and location for storing (and attaching) the free-flyer on Freedom with all its associated components.

- vibrations:

  Investigate all systems that might cause vibrations or accelerations on the free-flyer. Create a table showing these systems and resultant disturbances.

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MICROGRAVITY SCIENCE AND APPLICATIONS DIVISION HARDWARE

9-Jan-89

	LOCATION	SIZE (cu ft)	MASS (lbs)	PEAK POWER (kW)	GRAVITY LEVEL* (micro-g)	RUN TIME (hours)	RUN FREQUENCY (#runs/flight)	CREW INVOLVEMENT	COMMIT DATE
BIOTECHNOLOGY									
Bioreactor (BIO)	Middeck	6	110	<1	<10	1-3 weeks	1-2/flight	Medium	L-10 months
Protein Crystal Growth (PCG)	Middeck	4	110	<1	<1	6-26 days	1	Minimal	L-1 month
CONTAINED PROCESSING									
Adv. Auto. Directional Solidification Furnace (AADSF)	MSL	11	925	1	<10	150	1	Minimal	L-4 months
Crystal Growth Furnace (CGF)	Spacelab	48	444	2	1	200	6	Minimal	L-10 months
Metals and Alloys Solidification Apparatus (MASA)	Spacelab	48	450	2	<10	240	6	Medium	L-10 months
Gallium Arsenide Crystal Growth (GaAs)	Get Away Spec.	9	400	0	<10	20	2	Minimal	L-2 months
MEPHISTO	USMP	8	330	<1	<10, 0-100Hz	110	1	Minimal	L-4 months
CONTAINERLESS PROCESSING									
Acoustic Levitation Furnace (ALF)	Spacelab	41	440	<3	<10	4hrs/cart**	6-8/cartridge**	Minimal	L-12 months
Drop Physics Module (DPM)	Spacelab	41	993	<2	<1	2	28	High	L-12 months
High-temperature Acoustic Levitator (HAL)	Spacelab	TBD (Definition Phase)		<5	<10	1	30	Minimal	Space Station
Modular Electromagnetic Levitator (MEL)	Spacelab	TBD (Definition Phase)		<3	<10	<2	20	Minimal	Space Station
FLUIDS/COMBUSTION									
Fluids Experiment System (FES)	Spacelab	41	1085	2	<10	8 days	11	Medium	L-12 months
Vapor Crystal Growth System (VCGS)	Spacelab	18	163	<1	<10	8 days	2	Medium	L-12 months
Pool Boiling Experiment (PBE)	Get Away Spec.	9	430	0	<10	TBD	9	Minimal	L-2 months
Surface Tension Driven Convection Exp. (STDCE)	Spacelab	30	<500	<1	<10, 0-40Hz	10	10	Minimal	L-12 months
Advanced Fluids Module		TBD							Space Station
Droplet Combustion Experiment (DCE)	Middeck	6	152	<1	<10	6	25	Minimal	L-10 months
Solid Surface Combustion Experiment (SSCE)	Middeck	6	130	0	<10	20 min	3	Minimal	L-2 months
Advanced Combustion Module		TBD							Space Station
FUNDAMENTAL PHENOMENA									
Lambda Point Experiment (LPE)	MSL/USMP	41	1400	<1	<100	120	1	Minimal	L-6 months
Isothermal Dendritic Growth Experiment (IDGE)	USMP	32	700	<1	<10	65	25	Minimal	L-4 months
Critical Fluid Light Scattering Experiment (CFLSE)	USMP	20	<300	<1	<10, 40Hz	76-276 hrs	-	Minimal	L-6 months
Critical Fluid Viscosity Measurement Exp. (CFVME)	USMP	20	<300	<1	<10, 0-40Hz	>9 days	-	Minimal	L-6 months

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* Micro-g = 1.0E-06 g at frequencies below 0.1 Hz unless specified otherwise.

** The number of cartridges carried per flight is constrained only by manifesting and total mission time.

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MICROGRAVITY SCIENCE AND APPLICATIONS DIVISION HARDWARE

SPACE STATION FACILITIES		SIZE (cu ft)	MASS (lbs)	PEAK POWER (kW)	GRAVITY LEVEL* (1.0E-06g)	RUN TIME (hours)	RUN FREQUENCY (#runs/48 days)	CREW INVOLVEMENT	COMMIT DATE
Advanced Protein Crystal Growth Facility	APCG	71	551	1	<1	24 continuous	2	Minimal	Not Applicable
Biotechnology Facility	BTF	108	2315	5	<10	24 continuous	1 to 5	Medium	Not Applicable
Fluid Physics/Dynamics Facilities	FP/DF	71	2428	10	<1	8	135	Medium	Not Applicable
Modular Containerless Processing Facility	MCPF	71	1784	4	<1	336	3	Medium	Not Applicable
Modular Combustion Facility	MCF	71	1543	9	<1	6	180	Medium	Not Applicable
Space Station Furnace Facility	SSFF	177	5954	37	<1	24	45	Minimal	Not Applicable

* Microgravity level at frequencies below 0.1 Hz.

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CCDS FLIGHT EXPERIMENT REQUIREMENTS

Experiment	Hardware Status	Size (FEOs)	Mass (kg)	Temp (C) (max)	μ g (time range)	g Level (min)	Peak Power (watts)	Commit Date	Crew Time/Activity
Zeolite #1	To Be Designed & Built	0.5 1.7	TBD	175	> 72 Hours	10^{-4}	300	Spring 1992	4 Hours, Mix Materials, Monitor
Zeolite #2	Modified MLR	1.0	70	90	72 Hours	10^{-4}	200	Early 1990	On/Off
CdTe Crystal Growth	Modified Grumman Furnace, Modified Boeing Furnace, Modified FEA, All Possible	0.5 1.7	TBD	900 (1200 C insert)	4 Days (multiple runs)	10^{-5}	1000	1993	Periodic Crew Assistance
Polymer Membranes	Module To Be Designed, Could Use Basic FEA Package	0.3	22 to 45	130	Several Hours	10^{-4}	200	1991	On/Off, Activate Relay
Doped Linear Optic Substrates	FEA (modified insert)	0.3	22 to 45	130	Several Hours	10^{-4}	200	1992	On/Off
Polymer Composites	FEA Ideal	0.3	22 to 45	100	8 Hours	10^{-4}	150	1990	Shake, On/Off
Directional Sol #1 Metal Alloys	MASA (to be built)	TBD	TBD	1400	4 Days	10^{-3}	1000	1992	2 Hours
Directional Sol #2 Metal Alloys	To Be Designed & Built	TBD	TBD	1700	4 Days	10^{-3}	1000	1993	2 Hours
Ceramic Composites	FEA Modification	TBD	TBD	Ambient	8 Hours	10^{-4}	200	1990	Minimal On/Off
Containerless Process #1 Metals	Metal and Alloys Levitation Furnace (to be designed & built)	TBD	TBD	2200	3 to 4 Days	10^{-3}	2000	1994	TBD
Containerless Process #2 Metals	Metals and Alloys Levitation Furnace (to be designed & built)	TBD	TBD	2300	3 to 4 Days	10^{-3}	2000	1994	TBD
LEMZ of Indium	Modified FEA	0.6	80	150	1 Day	10^{-3}	110	12/89	6 Hours, Hands On
Zeolite Crystal Growth	Ready	0.5	90	150	4 Days	10^{-3}	None	Now	1 Hour, On/Off
Zeolite Crystal Growth	To Be Designed & Built	0.7	200	150	5 Days	10^{-3}	200	3/91	10 Hours, Mix, Load Samples
CVTE of CdTe (Boeing)	Designed & Built	1.7	~400	1000	4 Days	10^{-3}	200	12/91	10 Hours, Extensive Interaction
CVTE of Hg2Cl2	Designed, Not Built	1.7	~400	800	5 Days	10^{-4}	150	12/91	10 Hours, Extensive Interaction
NLO/TGS Growth	To Be Designed	1.0	150	200	6 Days	10^{-4}	150	6/92	4 Hours, On/Off, Check
DS of CdTe	CG For Grumman Furnace	1.0	200	1200	8 Days	10^{-4}	~600	12/91	6 Hours, On/Off, Check
LEMZ of GaAs	To Be Designed	1.5	300	1250	4 Days	10^{-5}	~1500	12/91	8 Hours, Real Time, Remote Monitoring

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CCDS FLIGHT EXPERIMENT REQUIREMENTS (Continued)

Experiment	Hardware Status	Size (FEOs)	Mass (kg)	Temp (C) (max)	μ g (time range)	g Level (min)	Peak Power (watts)	Commit Date	Crew Time/Activity
Atomic Oxygen	Under Development	TBD	TBD	TBD	N/A	N/A	None	3/91	Automated Expt (Cargo Bay)
Cosmic Ray Project	GAS	*	13	40	N/A	N/A	None	3/90	On/Off
Polymer Demixing	GAS	See Above	9	25	10 Hours	NA	Neg	3/90	On/Off
Polymer Processing	GAS	See Above	9	200	10 Hours	NA	10	3/90	On/Off
Electrodeposition	GAS	See Above	11	25	8 Hours	NA	20	3/90	On/Off
NLO Films	GAS	See Above	7	80	4 Days	NA	15	3/90	On/Off
Organic Crystals	GAS	See Above	7	140	4 Days	NA	15	3/90	Periodic Crew Assistance
PVT of ZnSe	Boeing Furnace	NA	NA	NA	NA	NA	NA	TBD	Periodic Crew Assistance
GaAs Thin Film	24 Mos. to Completion**	8 ft Payload Bay Cross Bay Carrier	1100	N/A	N/A	N/A	N/A	7/91	24 Hours on RMS. Shuttle attitude important, no garbage dump
AlGaAs Superlattice Growth	↓	↓	↓	↓	↓	↓	↓	3/92	↓
CBE Growth of InP	↓	↓	↓	↓	↓	↓	↓	11/92	↓
Thin Film High Temperature S/C Growth	↓	↓	↓	↓	↓	↓	↓	6/93	↓
Plant Cell Growth Dynamics	Design Reactor Need Sq. Version	0.3 to 0.5	50	< 90	5 to 20 days	10^{-4}	500	1991	8 to 10 Hours
μ g Actuator System Test	TBD	0.3 to 0.5	50	<90	1 day	10^{-3}	1000	1991	Activate/Off
Bio Reactor Design Test	TBD	1	200	<90	5 to 20 days	10^{-4}	500	1993	8 to 10 Hours
Vapor Diffusion Protein Crystal Growth	Built & Flown	0.3	50	35	4 Days	10^{-4}	100	Now	4 Hours, Mix & Monitor
Advanced Protein Crystal Growth	To Be Designed & Built	0.6	80	40	4 Days	10^{-4}	200	1991	5 Hours, Mix & Monitor

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CCDS FLIGHT EXPERIMENT REQUIREMENTS (Continued)

Experiment	Hardware Status	Size (FEOs)	Mass (kg)	Temp (C) (max)	μg (time range)	g Level (min)	Peak Power (watts)	Commit Date	Crew Time/Activity
Fuel Cell	Under Design (GAS)	0.5	50	NA	1 Day	10^{-3}	100	1993	On/Off
Battery	Under Design (GAS)	0.5	50	NA	3 Days	10^{-3}	100	1993	On/Off
Heat Pipe/Two-Phase Flow	Under Design (GAS)	0.5	50	NA	1 Day	10^{-3}	1000	1992	On/Off
Rankine Cycle	Under Design	Unknown	50	NA	1 Day	10^{-3}	100	1993	On/Off
Microwave Power Transmission Demo/Phase I	Under Design	TBD	TBD	Ambient	NA	NA	1000	1992	TBD
Microwave Power Transmission Demo/Phase II	Under Design	TBD	TBD	Ambient	NA	NA	1000	1993	TBD
Bone #1	Animal Enclosure Module (AEM)	0.3	40	Ambient	4 to 7 Days	10^{-3}	20	1989	None
Bone #2	AEM	0.3	40	Ambient	4 to 7 Days	10^{-3}	20	Summer 1990	None
Granule	CFES	4.0	810	4	2 Days	10^{-3}	360	1991	Periodic Intervention
Densitometry	DPA Flight Approval Req'd	1.0	200	Ambient	4 to 7 Days	10^{-3}	550	1991	Periodic Intervention
Biomaterials									
(1) Collagen	Modified FEA	0.3	40	60	TBD	$\leq 10^{-3}$	200	1990	Periodic Sample Change Out
(2) Synthetic	Synthesis Apparatus	0.3	50	200	TBD	$\leq 10^{-4}$	200	1991	Real Time Photo ** 1 Hour Total
(3) Virus Biologics	Generic Bioprocessor (to be built)	0.6	80	60	TBD	$\sim 10^{-3}$	200	1992	Sample Changes
Biomed. Isomorphisms	Modified Star Enter. Apparatus	0.3	40	40	TBD	$\sim 10^{-3}$	200	1991	Periodic Monitoring
Micro-Organisms Reactor	Modified KC135 Hardware	0.6	40	40	TBD	10^{-3}	200	1991	Sample Changes & Stabilization
Higher Plants	Modified Plant Growth Rack	1.0	75	40	TBD	10^{-3}	2000 (Peak)	1991	Plant Handling (1 hr Daily)
Centrifugal Fluid Management	Modified NBS Swirl Device	0.3	50	60	TBD	10^{-3}	500	1992	Loading & Photo Documentation (15 min/12 hrs)
Biofluid Rheology	Modified Rheo Apparatus	0.6	40	100	TBD	10^{-3}	500	1992	Sample Changes Every 2 Days

CCDS FLIGHT EXPERIMENT REQUIREMENTS (Continued)

Experiment	Hardware Status	Size (f E Os)	Mass (kg)	Temp (C) (max)	μg (time range)	g Level (min)	Peak Power (watts)	Commit Date	Crew Time/Activity
Capillary Movement of Water	To Be Designed & Built	0.3	TBD (~20)	30	8 Days	10-3	50	Spring 1992	On/Off, Activate
Robotic Manipulator	To Be Designed & Built	TBD	TBD	100	1 Day	NA	600	1992	4 Hours, Hands On
Fuel Cell	To be Designed & Built	0.5	100	300	Several Days	10^{-4}	300	1990 91	On/Off
Power Converter	To be Designed & Built	0.5-1.0	50	300	8 to 16 Hours	10^{-3}	1500	1990 91	On/Off

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TBD = To Be Determined
NA = Not Available
N/A = Not Applicable
* = Experiments to be combined and flown in GAS can
** = Experiments to utilize wakeshield