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A Study of Concept Options for the Evolution of Space Station Freedom

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PREFACE

Space Station *Freedom* will be a versatile, multifunctional facility that will provide for continuous human presence in low Earth orbit. *Freedom* will be capable of evolving over its extended operational lifetime to be responsive to changing user needs and long-term national goals. The Evolutionary Definition Office (EDO) at the Langley Research Center (LaRC) has the responsibility for the definition of evolution paths/options beyond the baseline system to meet future needs. In addition, the EDO is responsible for defining requirements on the baseline station design, e.g., hooks and scars, to assure viable growth options.

Studies have been conducted to assess the impact of future missions on the station configuration, systems, and operations. These studies have considered two major growth options (paths). One option emphasized the development of a multidiscipline research and development (R&D) facility to accommodate growth in science, technology, and commercial missions. The second option emphasized the role of the station as a transportation node to support the proposed solar system exploration missions. This option also allows enhancement of research accommodations and provides the means to add functions, such as assembly, servicing, and repair of space transfer vehicles and satellites.

This document presents descriptions for each configuration option and provides details of the analyses performed to assess the viability of each. Much of the work described in this document will be included in the Space Station *Freedom* Evolution Reference Databook. The reference configuration is a combination of station growth paths for SEI support and R&D emphasis.

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1.0 INTRODUCTION

1.1 PHASED PROGRAM

Space Station *Freedom* will evolve from the baseline or Assembly Complete (AC) configuration to an enhanced capability configuration as determined by user needs and U.S. Space Policy. This evolution will take place over several years in incremental steps. The Langley Space Station *Freedom* Office is responsible for the process of defining the long-term requirements, the establishment of evolutionary configuration concepts that meet future national goals, and the identification of hooks and scars to the baseline station that will assure that these goals can be met.

1.2 PURPOSE OF THE STUDY

The evolution configurations described in this document served as a starting point for the further development of an evolution reference configuration to guide the "design for evolution" process within the Space Station *Freedom* Program. In addition, this document contains a system-by-system description of the features which currently exist in the baseline design.

This study provides a database for evolution configuration concepts. Functional and physical characteristics, as well as supporting analyses, are provided for two manned-base configurations, a Research and Development (R&D) configuration and a Transportation Node configuration. The Transportation Node configuration is comprised of a further break-down into a lunar operations configuration for near-term exploration missions to the moon and a lunar/Mars configuration for far-term missions to the moon and Mars. This document provides reference material for the evaluation of the baseline station's ability to accommodate growth. It is intended to assist in the assessment of evolution options and to facilitate definition and evaluation of software hooks and hardware scars required in the baseline station. The analyses presented here are unique to the configuration for which they were performed. The data are intended solely for reference and evaluation purposes.

Section 1 provides an overview of this document and describes the analyses that were performed. Sections 2 and 3 provide the station characteristics, including mass, center of gravity, moments of inertia, and ballistic coefficient, as well as analysis results, for the R&D station and the Transportation Node, respectively.

Section 4.0 provides, for each element and distributed system in the growth categories, a functional description and an enumeration of physical characteristics such as dimensions, mass, and volume.

Section 5.0 provides a detailed explanation of the analyses performed, the assumptions used, and the results for the growth R&D and Transportation Node configurations.

1.3 BASELINE CONFIGURATION

The baseline space station configuration is illustrated in Figure 1.3-1, and its physical characteristics are summarized in Table 1.3-1. The baseline configuration will consist of a truss assembly, called the transverse boom, on which elements, such as the laboratory (lab) and habitation (hab) modules, and distributed systems, e.g., electrical

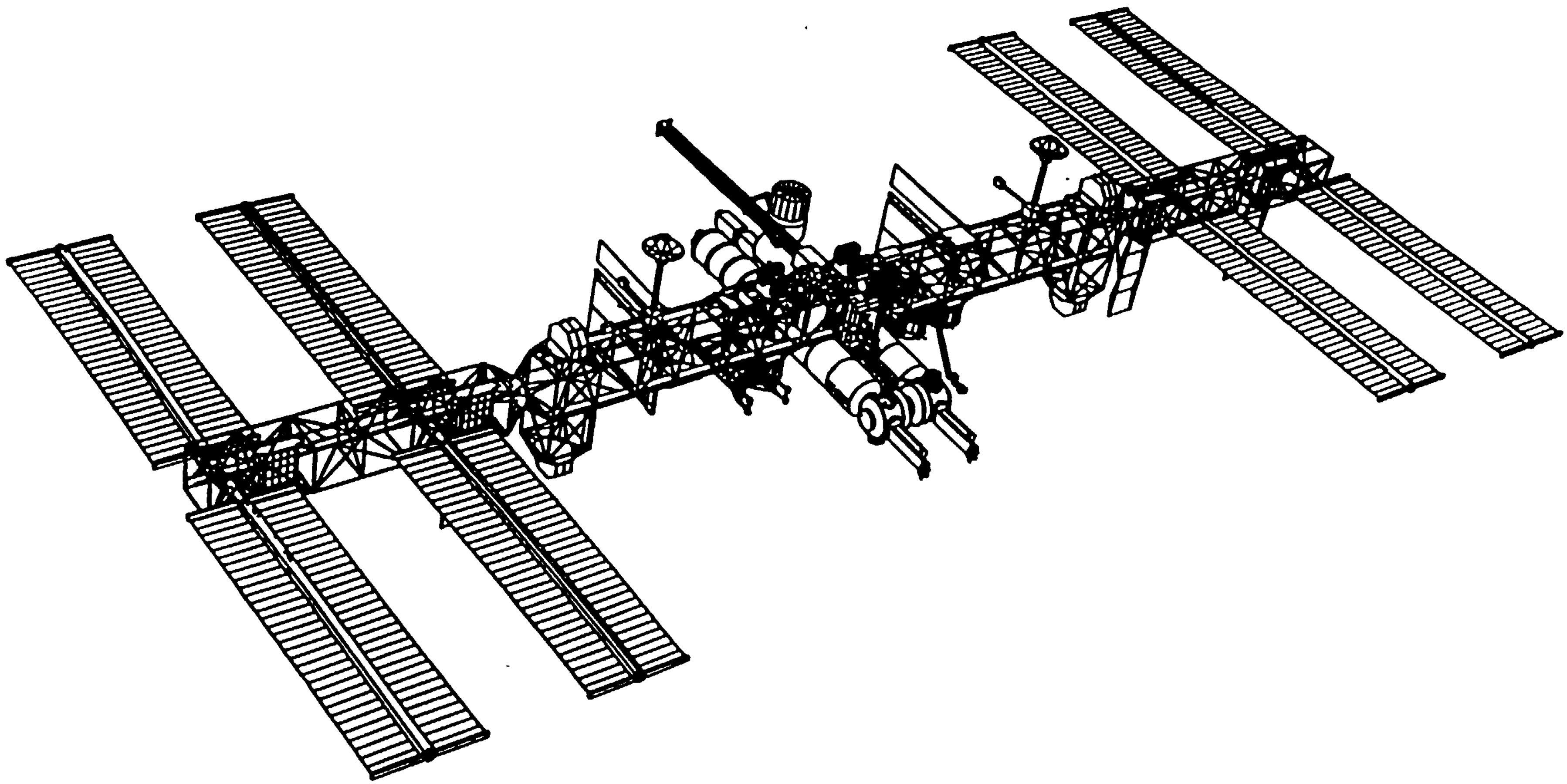


Figure 1.3-1 : Baseline Space Station Freedom Configuration

Characteristics	Value
Mass (kg)	266,000
Average drag area (m^2)	2,310
Average ballistic coefficient (kg/m^2)	50.2
Inertias ($kg \cdot m^2$) with respect to the center of mass	IXX = 1.6E8 IYY = 2.2E7 IZZ = 1.7E8 IXY = 5.7E5 IXZ = -1.6E6 IYZ = -9.3E8
Center of mass (m) from center of transverse boom	X = -1.27 Y = 0.21 Z = 3.51
Maximum lengths (m)	X = 60.0 Y =155.0 Z = 80.0
Average flight attitude (degrees) from LVLH	Roll (X) = 0.34 Pitch (Y) = - 8.00 to -11.62 Yaw (Z) = 0.25
Attitude control momentum (N•m•s)	4,000

Table 1.3-1: Summary of baseline configuration physical characteristics

power system, will be attached. The truss will be built up in 5 m (16.4 ft) cubes or bays using 5.08 cm (2 in) diameter truss tubes. A utility tray that runs through the length of the truss provides cabling and plumbing for resource distribution.

The baseline station will have four pressurized modules. Three of these modules, one each from the U.S., Europe, and Japan, will be dedicated laboratories. The fourth pressurized module (hab module) will provide an area for rest, recreation, and health services for eight crew members. The pressurized modules will be interconnected by four resource nodes which also serve as the control centers for space station command, control, and operations. Two of the resource nodes will have an NSTS docking mast and a cupola for direct viewing of proximity operations. The baseline station will also have a hyperbaric airlock and attached pressurized logistics carriers.

External to the pressurized volume will be the Mobile Servicing Center (MSC), a telerobotic servicing platform that can traverse up and down the truss structure using the Mobile Transporter, and the MSC Maintenance Depot (MMD). Also attached to the transverse boom are attached payload accommodation equipment (APAE), pallets, unpressurized logistics carriers, and an NSTS docking ring.

Attached to the transverse boom will be four photovoltaic modules that provide the station with 75 kW of power. Also attached to the truss will be four thruster modules, a resistojet module, and thermal radiators.

1.4 EVOLUTION CONFIGURATION CONCEPTS

Space Station *Freedom* must be capable of evolving over its extended operational lifetime in order to respond to changing user needs and U.S. space policy. Evolution is defined as the process of increasing the capacity and capability of *Freedom* after the completion of the approved baseline program. While the pace and direction of evolution beyond the baseline is impossible to predict with any certainty, advanced studies have been conducted in the program to assess the impact of future missions on station configuration, systems, and operations. The general approach has been to develop design requirements for *Freedom* which will insure that viable evolution options remain open for the future.

Two evolution configuration options were studied. The first is a research and development (R&D) oriented station that can provide extended laboratory and servicing capabilities for science and technology experimentation. The R&D configuration concept is shown in Figure 1.4-1. It is a platform from which astronomical and Earth observations can be made and an on-orbit research and development facility on which life sciences, microgravity, and on-orbit manufacturing can be pursued. It is capable of performing on-orbit servicing of free-flyers as well as station attached payloads.

The second configuration concept, shown in Figure 1.4-2, is a lunar/Mars Transportation Node designed to support the manned Space Exploration Initiative (SEI). The Transportation Node for the near term is a Lunar Operations Transportation Node (shown in Figure 1.4-3). This configuration is required for lunar missions and to support life science research and technology demonstrations for manned Mars missions. It differs from the lunar/Mars Transportation Node concept only by the later addition of a facility for assembly, checkout, and refurbishment of Mars transfer vehicles.

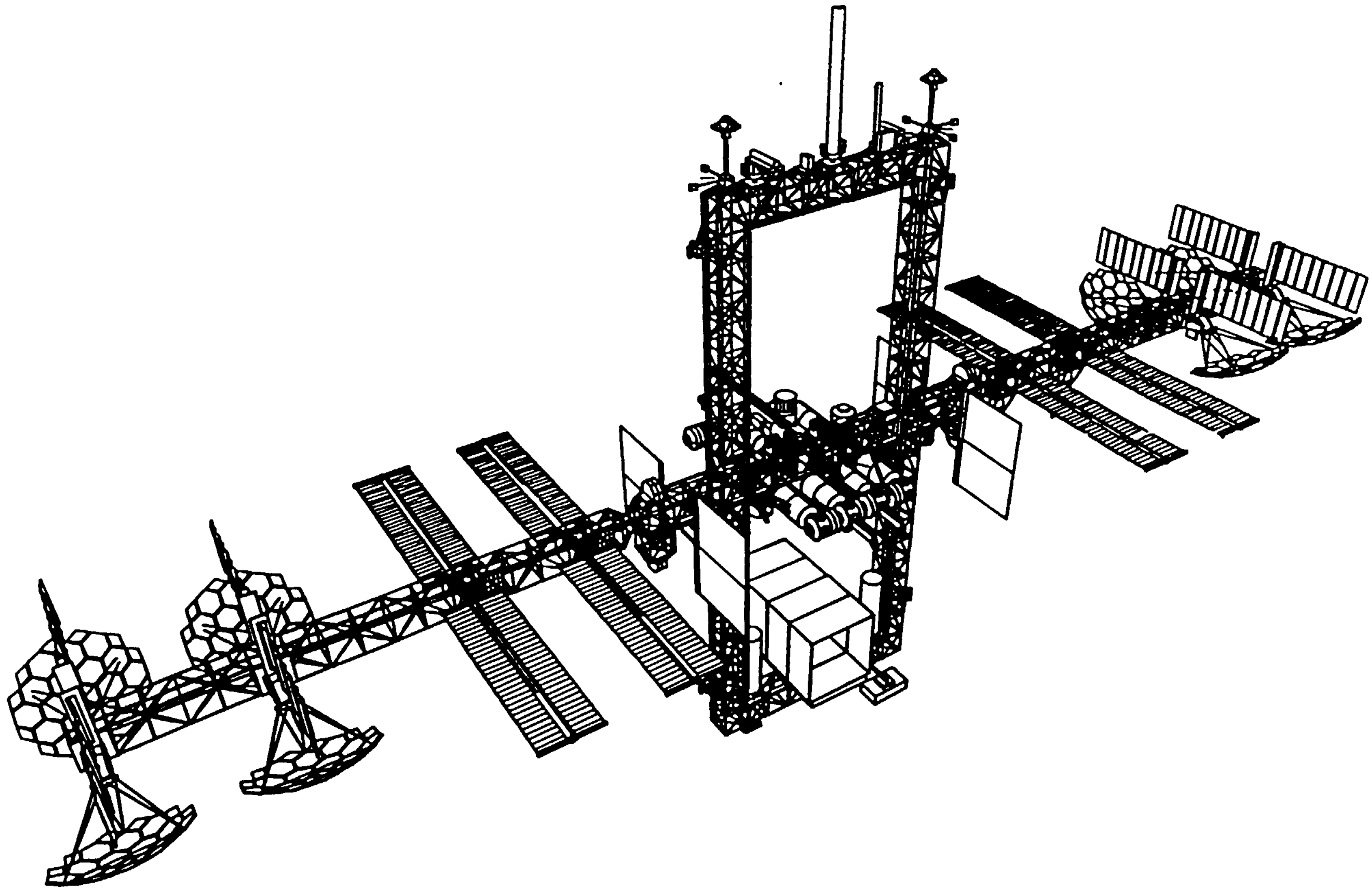


Figure 1.4-1 : R&D Configuration Concept

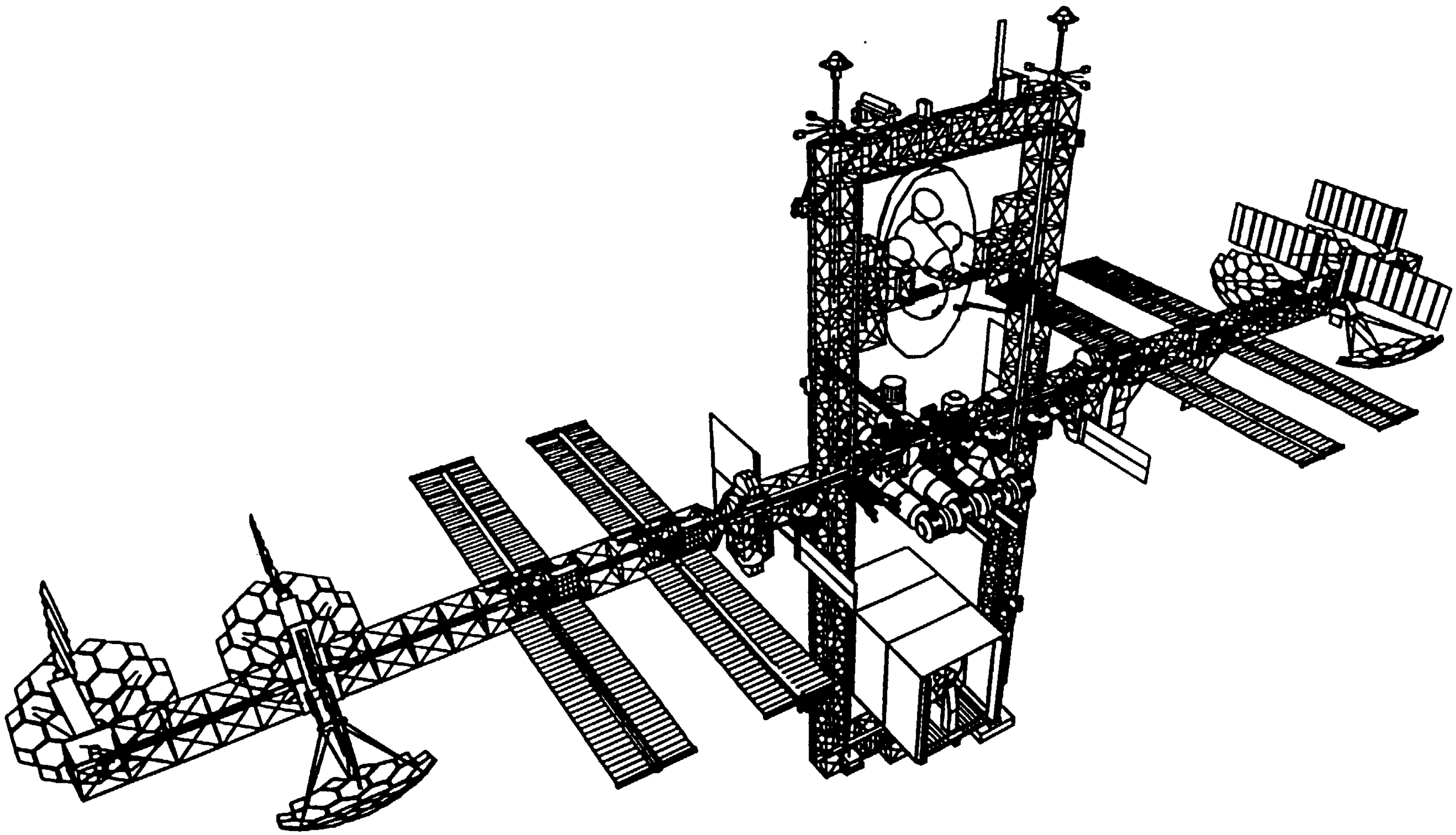


Figure 1.4-2 : Transportation Node Configuration

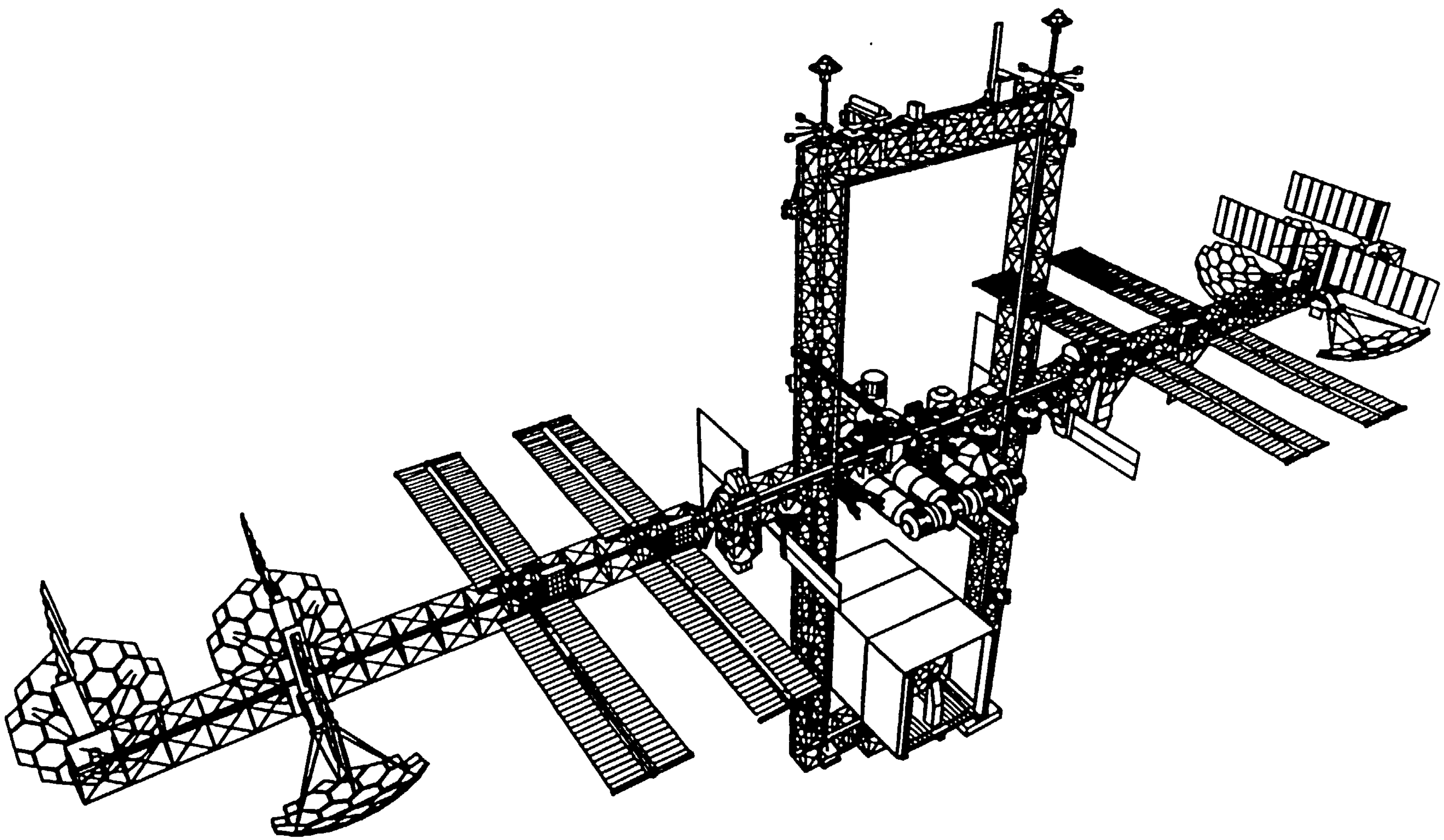


Figure 1.4-3 : Lunar Operations Transportation Node Configuration

Both the R&D and the Transportation Node configuration concepts include the addition of dual keels, solar dynamic power modules, pressurized modules, and resource nodes to the baseline station. Each concept represents a specialized response to perceived long-range national space program goals. Further physical descriptions of the R&D and the Transportation Node configurations are provided in sections 2.2 and 3.2, respectively.

This document contains both functional and physical descriptions of the elements for each configuration. There are two categories of elements: baseline replicated elements and growth elements. The growth elements can be further divided into those common to both concepts and those that are unique to a particular concept. Replicated elements are those that are identical to baseline elements and will be duplicated in the evolution station. Examples include structural components and lab and hab modules. Elements common to both evolution configurations, but not to the baseline station, include extended resource nodes, solar dynamic power modules, and pocket labs. Examples of configuration-unique elements include exploration vehicle assembly and servicing facilities.

1.5 DESCRIPTION OF ANALYSES

Most of the analyses presented here were performed using the IDEAS^2 integrated space station analysis software. This software package contains the multidisciplinary analysis capabilities required for system-level space station evaluations. These include:

- rigid-body controls analyses and flight mode characterization
- evaluation of microgravity environments
- orbital lifetime and reboost analyses
- determination of payload viewing envelopes
- structural dynamics analyses

An important feature of the IDEAS^2 software is that a single geometric model forms the basis for many of the various analysis functions, thus promoting consistency and eliminating duplication of effort in generating separate models for the analyses. IDEAS^2 Space Station *Freedom* models were created for each growth delta (shown in section 5.0) using an enhanced version of the GEOMOD solids modeling program. The geometric data was then processed by MODGEN which creates analytical models compatible with the analysis modules.

The analysis programs in IDEAS^2 are integrated through a project relational database which contains both input and output program data. Utilities are available for reviewing and modifying input data stored in the database and for generating plots of analysis results.

Detailed definitions of the analyses and the assumptions used in performing them are provided in Section 5.0. The results from the analyses for the R&D and the Transportation Node configuration concepts are provided in Sections 2.3 and 3.3, respectively.

2.0 R&D FACILITY CONFIGURATION CONCEPT

The baseline station could be enhanced to provide greater research and development capabilities. For the R&D configuration, these enhancements consist of extended facilities for such research as earth and astronomical observation, life science, microgravity, materials research, technologies demonstrations, and satellite servicing. To provide these capabilities, the crew, power, pressurized volume, and external attach points are increased. Additional functions, such as Space Transfer Vehicle (STV) and satellite servicing, are also implemented. The R&D configuration analyzed in this report emphasizes microgravity research and materials production, although differences in resource or pressurized volume requirements for other research emphases are noted.

2.1 FUNCTIONAL REQUIREMENTS

A comprehensive analysis of the growth of the Space Station *Freedom* as a multidiscipline R&D facility has been conducted and the results are presented in "Growth Requirements for Multidiscipline Research and Development on the Evolution Space Station" (NASA TM 101497). A summary of this analysis is presented below and was the basis for the functional requirements discussed in this section.

Facility and resource requirements for a multidiscipline space station are driven primarily by the types of research and development being conducted and the level of Earth-to-orbit transportation available. In the referenced study, mission sets were developed for four specific utilization emphases on the station: microgravity research, microgravity research and materials production, life sciences research, and observational science. Multiple growth scenarios were then postulated from the combination of each emphasis with three mixed-fleet transportation models (conservative to aggressive lift capability). The analysis process generated growth requirements for the resources: electrical power, crew, pressurized volume, attach points, truss structure, and logistics. As an example, the growth power requirement varied from a minimum of 125 kW for scenarios constrained to the conservative lift capability to 325 kW for the microgravity and materials production with aggressive transportation support.

The R&D configuration presented in this report best suited the microgravity and materials production emphasis. The growth resource requirements for this configuration are summarized in Table 2.1-1.

Power requirements for the R&D configuration will be accommodated by the addition of solar dynamic units attached to the transverse boom. The additional pressurized volume necessary to support the experiments and crew will be provided through the addition of common modules, pocket laboratories, and extended resource nodes. Additional payload attach points and servicing facilities will be accommodated by the addition of booms and keels.

A detailed description, including the physical characteristics, of the growth elements and the distributed systems is contained in Section 4.0.

Table 2.1-1: **MULTIDISCIPLINARY R&D GROWTH REQUIREMENTS**

	Baseline	R&D Configuration
Average Power	75 kW	275 kW
Crew	8	24
Pressurized Modules		
US Habitation	1	3
US Laboratory	1	3
ESA Laboratory	1	1
JEM Laboratory	1	1
Pocket Laboratory*	N/A	3
Structures		
Space Transfer Vehicle Servicing Facility	N/A	1
APAE	2	18
Airlocks	1	2

*Alternately referred to as "User Supplied Pressurized Modules"

2.2 CONFIGURATION DESCRIPTION

Figure 2.2-1 shows front and side views of the overall R&D reference configuration. Attached to the lengthened transverse boom will be two full-size lab modules (in addition to the three lab modules of the baseline configuration) and three pocket labs. A pocket lab is a short, single-ended module attached to a resource node port. The front view (Figure 2.2-1) shows the pocket labs attached to extended resource nodes, which are standard station nodes with an extra cylindrical rack section to extend their length. The pocket labs will provide space for experiments requiring pressurized volume. To accommodate the additional crew, the single hab module of the baseline configuration will be supplemented by two additional hab modules. Figure 2.2-2 illustrates the top view of the module pattern. The additional lab and hab modules will be connected to the existing modules by the extended resource nodes.

Vertical keels and upper and lower booms will be added to provide additional locations for attached payloads and to accommodate the STV Servicing Facility. Four sets of solar arrays and eight solar dynamic units, located on the transverse boom outside the alpha joints, will provide up to 275 kW of power. As shown in Figure 2.2-1,

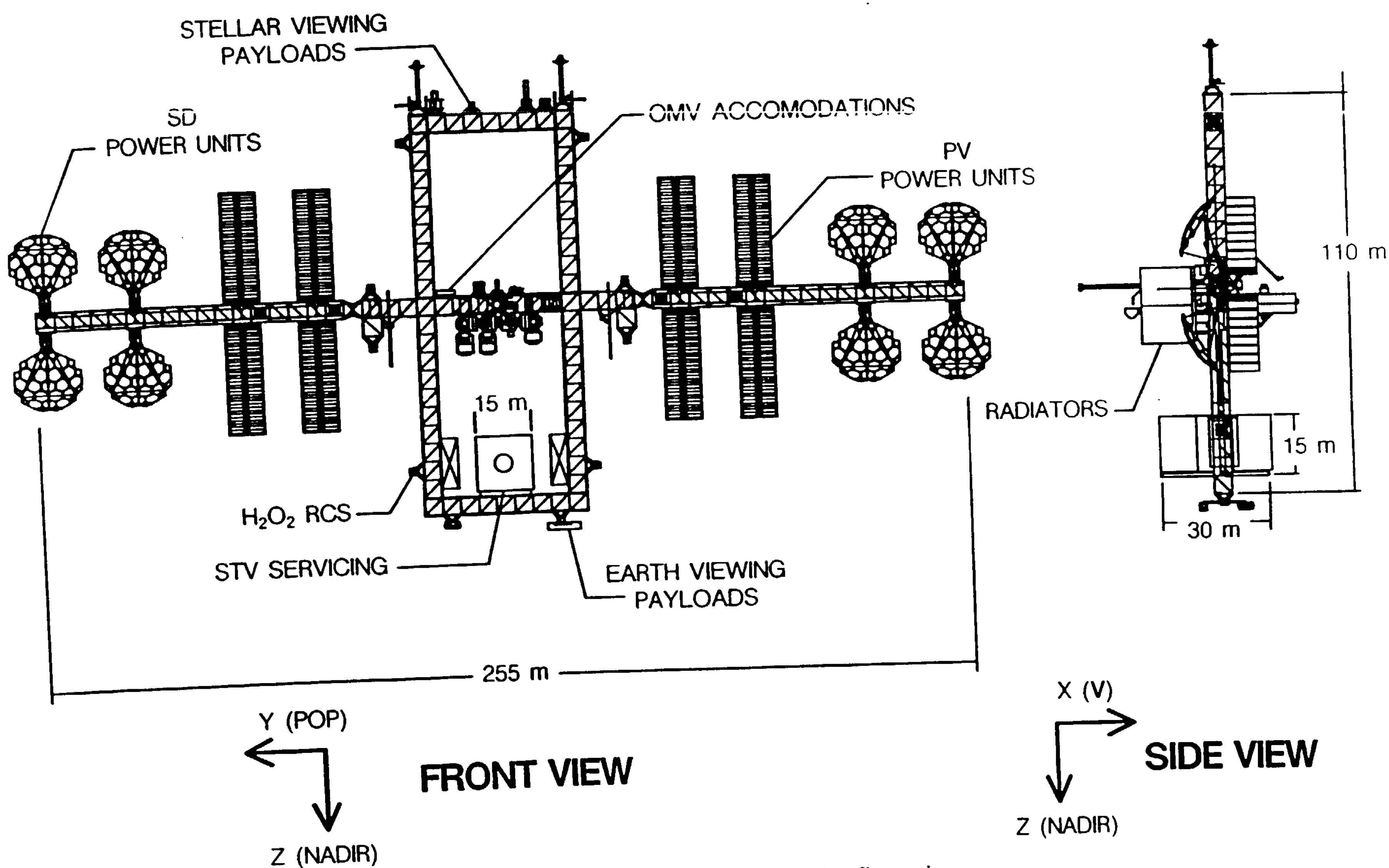


Figure 2.2-1 : Front and Side Views of R&D Configuration

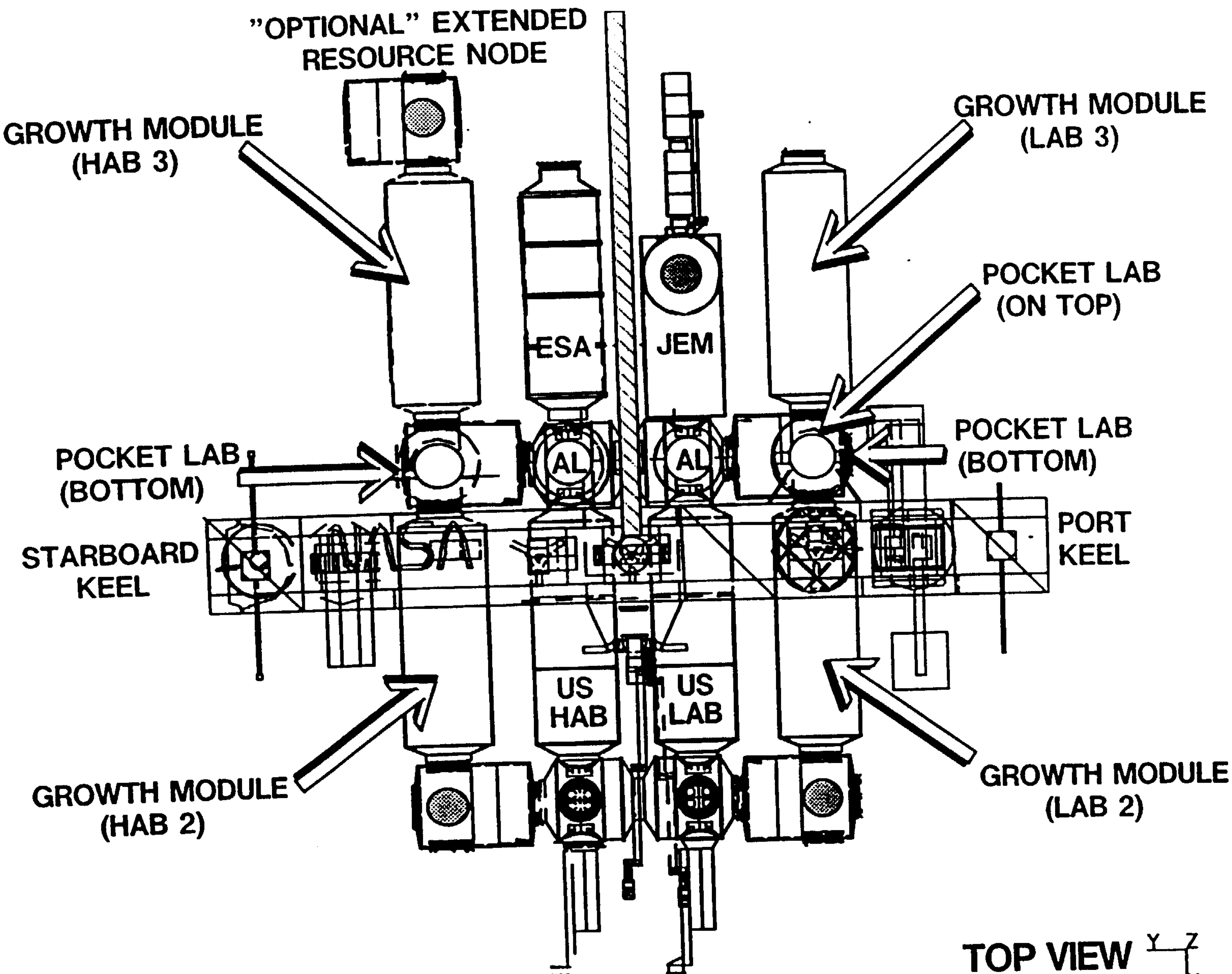


Figure 2.2-2 : R&D Configuration Module Pattern

the STV hangar for orbital transfer (geosynchronous) and vehicle storage and maintenance will be located on the lower boom.

2.3 R&D CONFIGURATION CONCEPT ANALYSES

The results of the analyses performed for the R&D configuration concept are summarized in this section. Analyses and supporting data for the intermediate configurations are given in section 5.0.

2.3.1 Mass Properties

Analyses were performed on several cases of the R&D configuration to assess the impacts resulting from changes in fuel storage and vehicle accommodations. Table 2.3.1-1 shows the mass properties for three R&D configuration cases involving potential STV and shuttle arrangements. The origin of the geometrical coordinate system, shown in Figure 2.2-1, is located in the middle of the center truss bay of the transverse boom. The first row in Table 2.3.1-1 reflects the configuration at its steady state heaviest with full STV tank farms and an STV in the servicing hangar. The second row contains the mass properties of the configuration assuming no fuel in the STV tank farms and no STV in the hangar. The third row reflects the same configuration as the first row with the addition of a berthed shuttle.

The center of gravity varies from 1.5 meters above the module pattern to two or three meters below, indicating that good steady-state microgravity can be achieved. The inertias yield gravity-gradient stability in pitch (IXX>IZZ) and small body-to-principal axis rotations, i.e., flight attitudes will be near the local vertical/local horizontal (LVLH).

2.3.2 Attitude Control Analysis

Steady-state attitude flight mode characterization and control system sizing were performed using Attitude Predict (ATTPRED) of IDEAS[2]. The control momentum gyroscope (CMG) controls analysis performed assumes only steady-state environmental disturbances, such as aerodynamic and gravity-gradient torques. Large dynamic disturbances, such as orbiter berthing or STV deployment, and the corresponding interactions between the CMGs, reaction control system (RCS), and station attitude will be evaluated in future studies.

Table 2.3.2-1 summarizes the microgravity, flight mode, and CMG control characteristics of the R&D reference configuration for various combinations of atmospheres, vehicle and fuel accommodations, and control system assumptions. Maximum solar cycle equates to a worst-case (year 2001, flux=243, geomagnetic index=19.6), two-sigma atmosphere at an orbital altitude of 407 kilometers (220 nmi). Minimum solar cycle equates to a best case (year 2007, flux=86.4, geomagnetic index=16.0), nominal atmosphere at the same altitude. The gains chosen for the CMG controller were optimized to provide minimal deviations in pitch attitude ("pinched pitch" method), except for certain cases where the gains were adjusted to emphasize pitch momentum reduction at the cost of increased pitch deviations ("relaxed pitch" method). All configurations studied yielded average flight attitudes within three degrees of LVLH for roll, pitch, and yaw. Deviations over one orbit from the average

Space Station Configuration	Mass (kg)	Center of Mass (m)			Inertias (kg•m•m)					
		X	Y	Z	IXX	IYY	IZZ	IXY	IXZ	IYZ
Wet Tank Farm and STV	687,000	-2.3	-0.2	7.0	1.22+E9	3.94+E8	9.21+E8	2.16+E5	-9.02+E6	-3.77+E6
Dry tank farm, no STV	631,000	-2.3	-0.2	3.8	1.12+E9	3.11+E8	9.10+E8	2.10+E5	-9.61+E6	-4.29+E6
Wet tank farm and STV, NSTS docked	795,000	0.8	0.2	8.2	1.24+E9	4.59+E8	9.69+E8	7.41+E8	8.77+E6	-1.01+E6

Table 2.3.1-1 : Mass Properties for R&D Configurations

Space Station Configuration	Micro-G at Lab Center	Average Flight Altitude (degrees)			Attitude Drift Pitch (Y) per Orbit (degrees)	Peak Momentum (N•m•s)
		Yaw (Z)	Pitch (Y)	Roll (X)		
Wet Tank Farm and STV, with max solar cycle	1.2	< 0.1	2.4	0.4	< 0.1	10,000
Wet tank farm and STV, with max solar cycle, relaxed pitch	1.2	< 0.1	2.4	0.4	1.4	4,000
Wet tank farm and STV, with min solar cycle	0.9	< 0.1	1.8	0.4	< 0.10	8,000
Dry tank farm, no STV, with max solar cycle	1.1	-0.2	2.8	0.4	0.2	9,000
Dry tank farm and STV, with max solar cycle, relaxed pitch	1.1	-0.2	2.8	0.4	1.5	4,000
Wet tank farm and STV, STS attached, with max solar cycle,	1.5	0.3	-1.0	0.1	0.2	10,000
Wet tank farm and STV, STS attached, with max solar cycle and relaxed pitch	1.5	0.3	-1.0	0.1	1.2	5,000

Table 2.3.2-1 : Micro-G and Control Properties for R&D Configurations

flight attitude were less than +/- 0.1 degrees in roll and yaw and less than +/- 0.2 degrees in pitch for the pinched pitch control gains and less than +/- 1.5 degrees in pitch for the relaxed pitch control gains. Attitude error rates for all configurations and all assumptions were below 0.005 degrees/second. The CMG peak momentum control requirements for maintaining attitude were all below 10,000 Newton-meter-seconds (Nms) for the pinched pitch method and below 5,000 Nms for the relaxed pitch method. All momentum requirements are well within the capability available from the six 4750 Nms CMGs on the baseline configuration. Figure 2.3.2-1 represents the flight attitude history over five orbits for the R&D configuration with wet tank farms and an STV for: 1) a maximum solar cycle, pinched pitch case, 2) a minimum solar cycle, pinched pitch case, and 3) a maximum solar cycle, relaxed pitch case. Figure 2.3.2-2 represents the corresponding momentum control requirements over the same five orbit period. The roll and yaw values shown on the figures are nearly identical for all cases with the only differences noticeable in the pitch channel.

2.3.3 Microgravity Environment Determination

The steady-state microgravity profile shifts as the center of mass changes on the station. This change in mass properties is primarily due to the presence or absence of the STV and the amount of propellant in the STV tank farms. Figures 2.3.3-1 and 2.3.3-2 show the steady-state on and two micro-g regions for the dry R&D configuration (no STV, with empty STV tank farms) and the wet R&D configuration (STV, with full STV tank farms) in a worst-case 2-sigma atmosphere (flux = 243, geomagnetic index = 19.6) at an altitude of 220 nmi. The highest center of mass location is obtained in the dry R&D configuration, which provides the U.S. lab module a portion of the one micro-g region. In this case, less than two micro-g's are sensed in the entire module pattern, as seen in Figure 2.3.3-2. The size of these regions will increase if a less severe atmosphere exists or a higher altitude is obtained. The lowest center of mass location is found in the wet R&D configuration. This case shifts the one micro-g ellipse to the lower portion of the U.S. lab module and maintains a less than two micro-g region for the entire module pattern. During normal operations of the R&D station, the center of mass will pass through the center of the module pattern as the STV tank farms go from dry to wet and the STV goes on and off the station. Since the microgravity environment is optimal at the station center of mass, it can be assumed that on average the sensed microgravity environment in the modules will be better than shown in both Figures 2.3.3-1 and 2.3.3-2.

2.3.4 Orbit Lifetime and Reboost Analysis

Table 2.3.4-1 shows the reboost/orbit lifetime characteristics of the R&D configuration. The two cases examined, with STV and fuel and without STV and fuel, represent the potential maximum and minimum masses associated with the configuration. Although one case is more massive than the other, there is no significant difference in fuel requirements, because the more massive case has a higher ballistic coefficient. However, almost an order of magnitude more fuel is required for altitude maintenance during the solar cycle maximum, as compared to the solar cycle minimum for the same altitude.

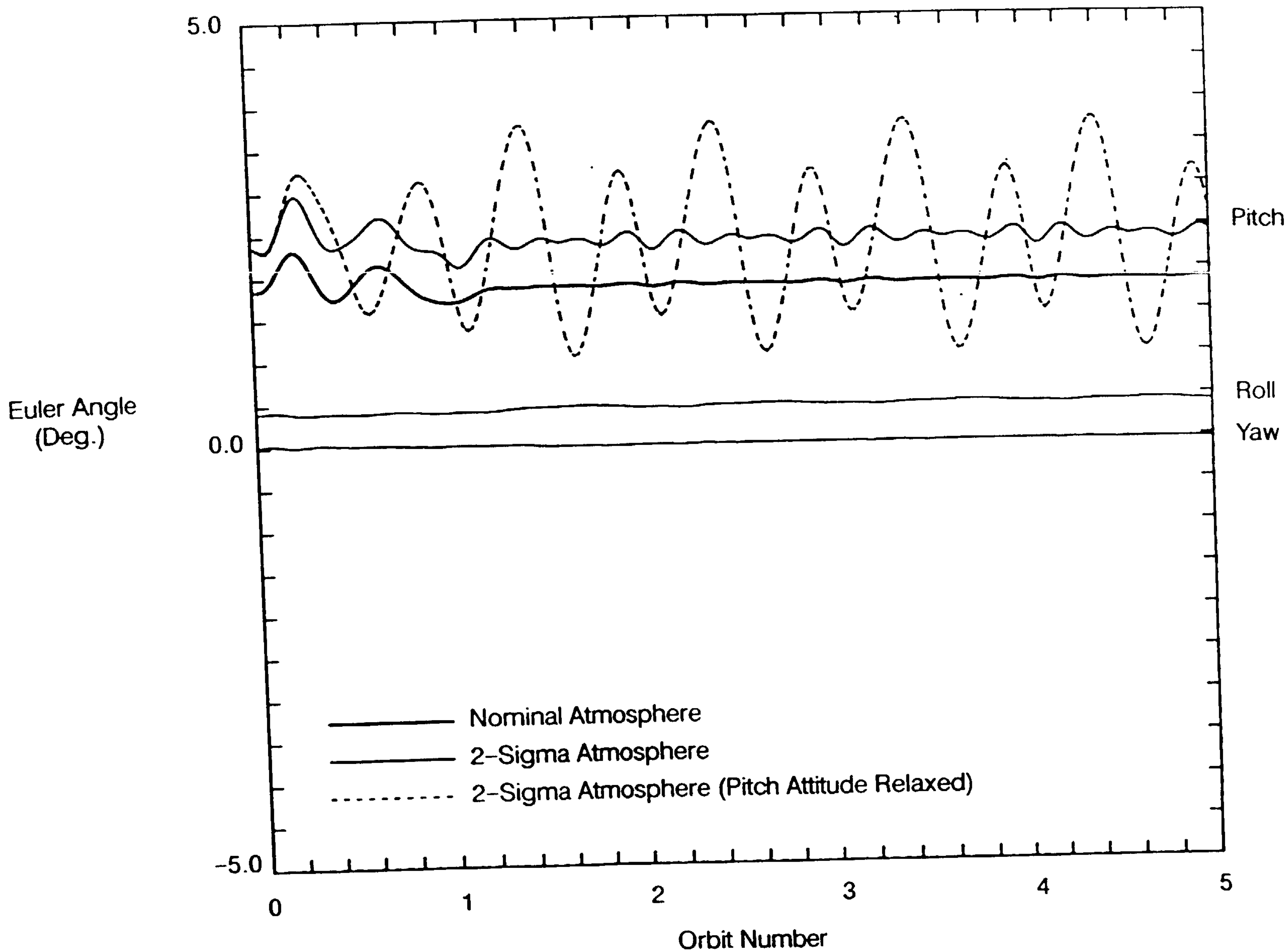


Figure 2.3.2-1 : R&D Configuration Attitude History Comparison
(Assumes Wet Tank Farms and Fueled STV)

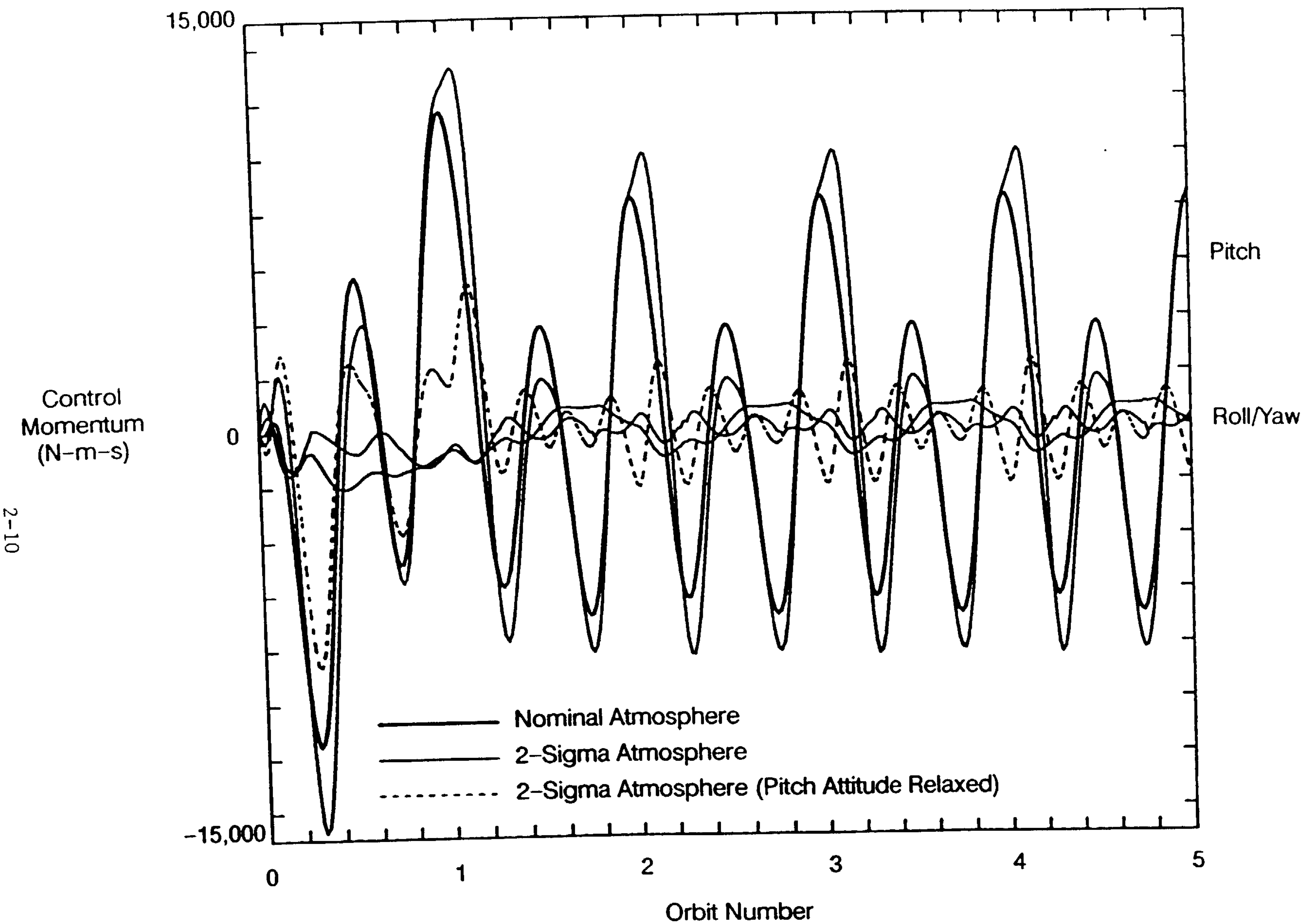
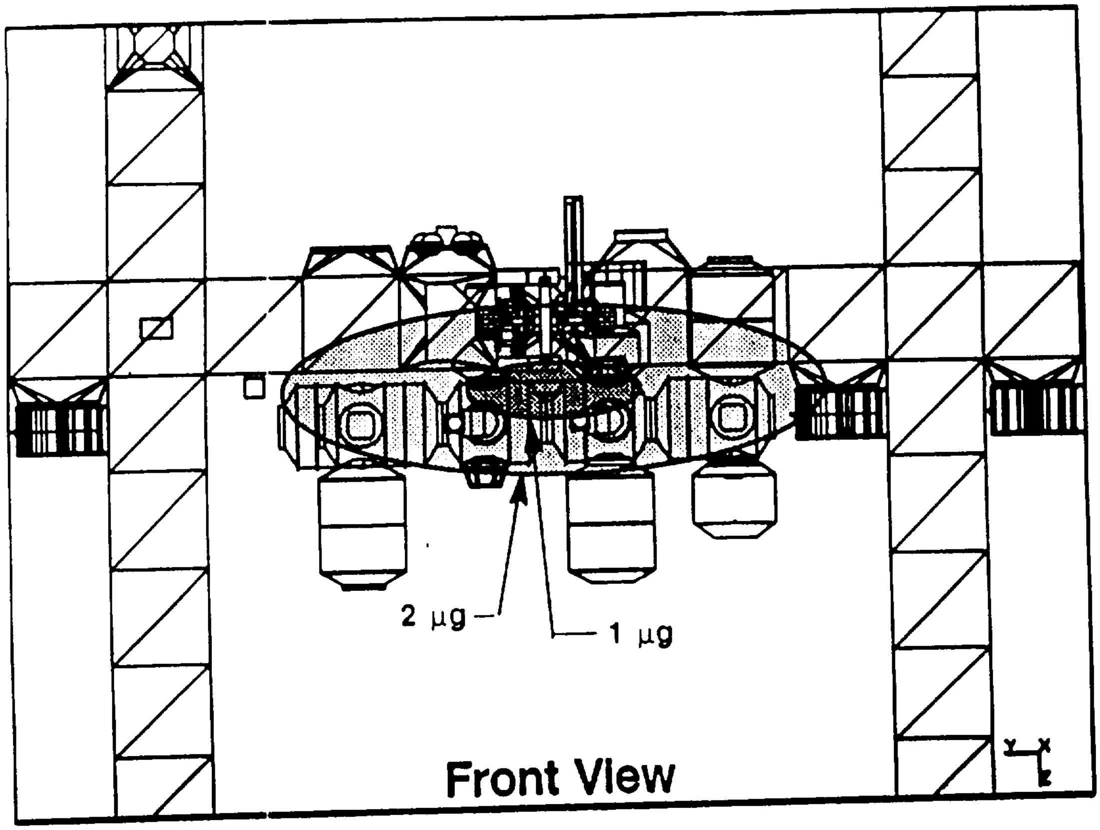


Figure 2.3.2-2 : R&D Configuration Control Momentum History
(Assumes Wet Tank Farms and Fueled STV)



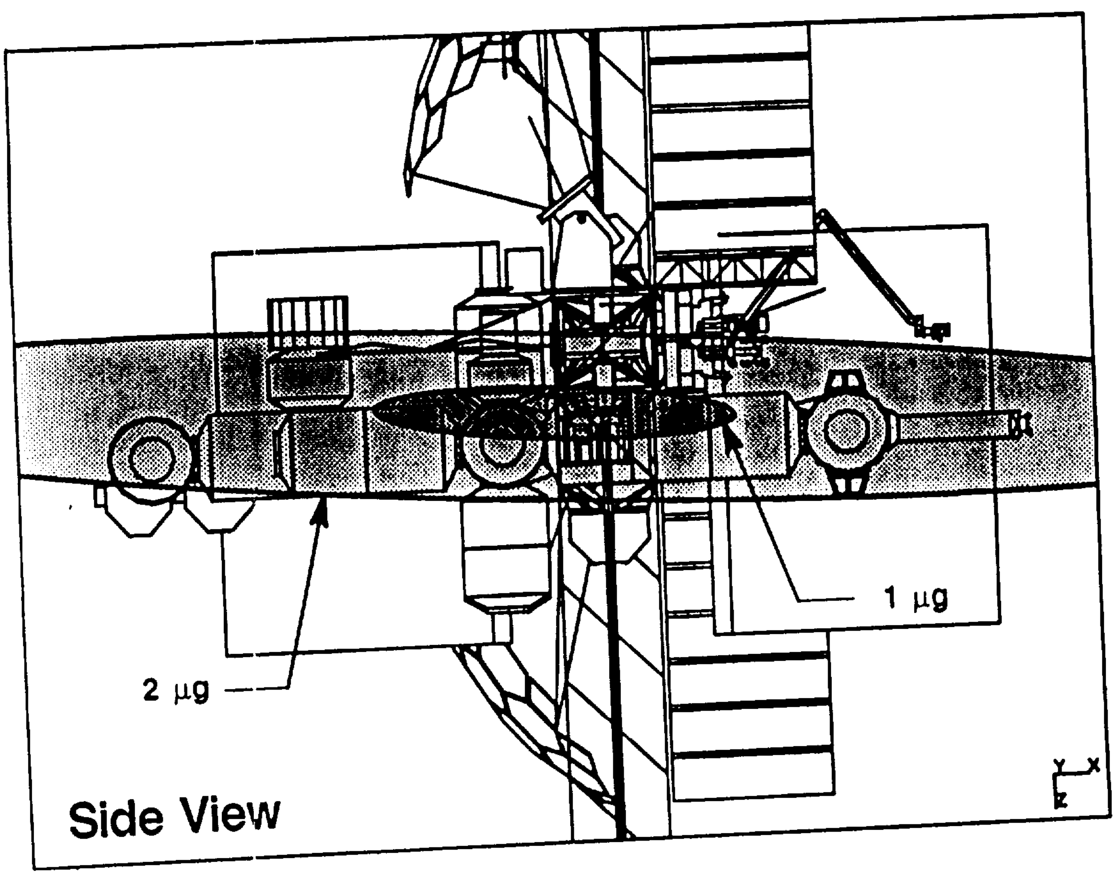
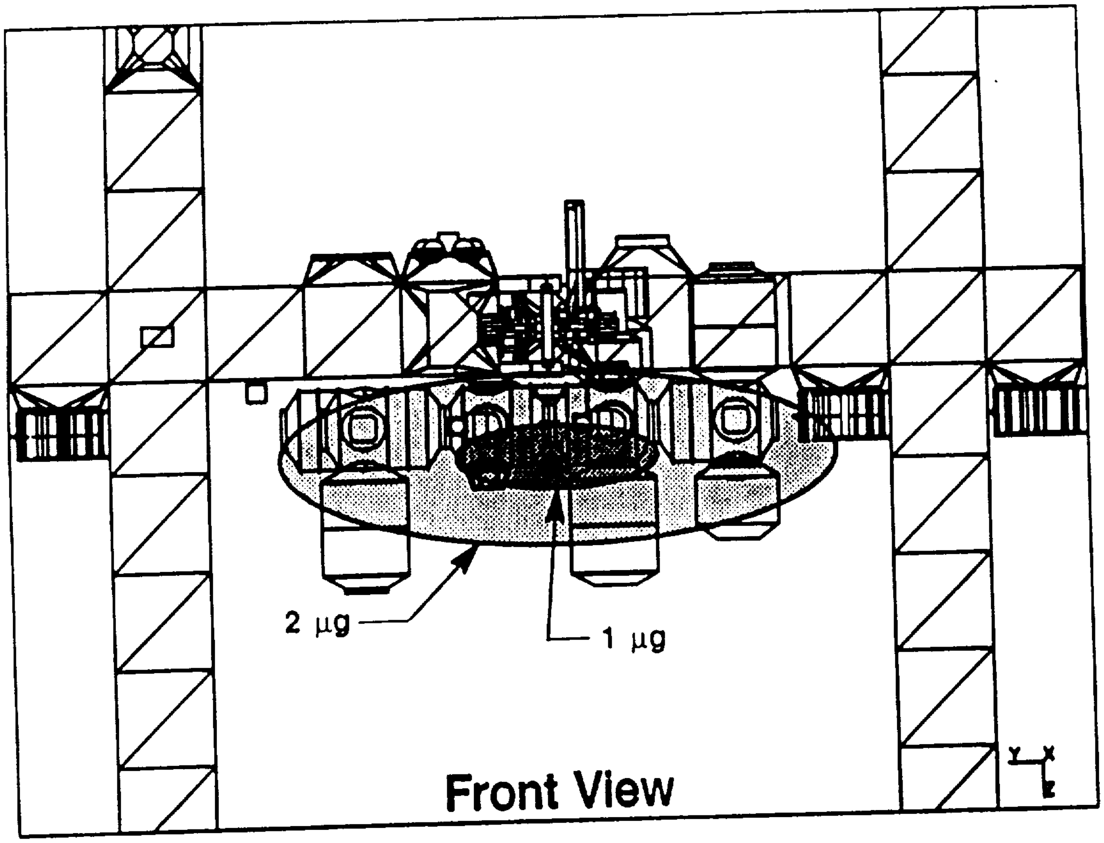


Figure 2.3.3-1 : R&D Configuration Steady State Microgravity Profile
(Assumes Dry Tank Farms and No STV)



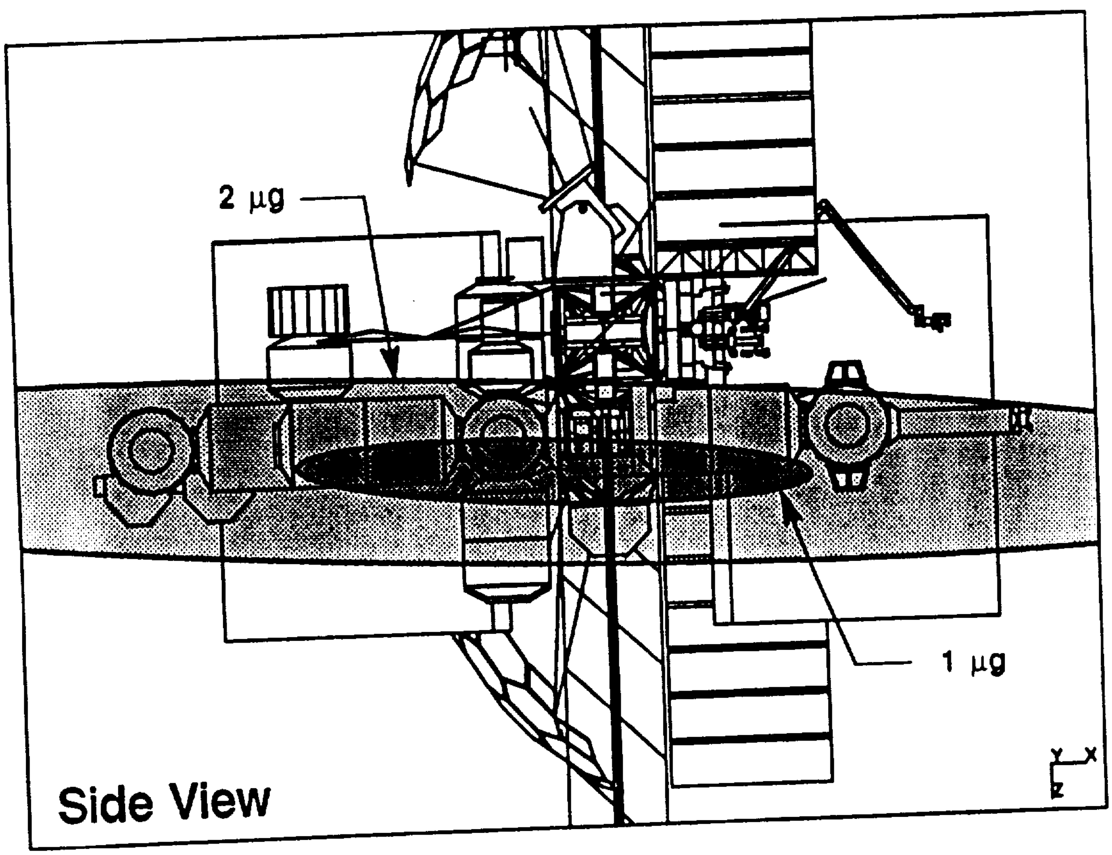


Figure 2.3.3-2 : R&D Configuration Steady State Microgravity Profile (Assumes Wet Tank Farms and Fueled STV)

Space Station Configuration	Ballistic Coefficient (kg/m ^{2})	90 days reboost fuel (lbm)	Reboost Altitude (nmi)	Lifetime from 220 nmi
Wet tank farm and STV, minimum solar cycle*	60.1	1,380	223	635
Dry tank farm and no STV, minimum solar cycle*	54.1	1,344	223	601
Wet tank farm and STV, maximum solar cycle**	60.1	9,759	241	117
Dry tank farm and no STV, maximum solar cycle**	54.1	11,305	246	104

*Minimum solar cycle (Flux=86.4, AP=16.0)

**Maximum solar cycle (Flux=243, AP=19.6)

Table 2.3.4-1 : Orbit Lifetime and Reboost, and Ballistic Properties for R&D Configurations

2.3.5 Structural Dynamics Analysis

The typical approach for structural analysis of Space Station *Freedom* growth configurations is outlined in section 5.0. No analysis has been performed on the specific R&D configuration described in this document, but a few general comments may be made based on previous analyses of similar configurations.

The major areas of concern for the R&D configuration are the deflection of the transverse boom and loads on the alpha joint due to the large masses of the solar dynamic modules, and the potential for buckling of members at the interface of the boom and the upper and lower keels. For example, a study of a concept which had a nearly identical lower keel configuration and similar module cluster mass showed that during a typical reboost critical loads could be developed in truss members near where the upper and lower keels met the transverse boom. It can be expected, since the material properties, load paths, and mass distributions are similar on the R&D configuration, that the potential exists for critical loads at similar locations. In general, this is not an issue which would cause outright rejection of a conceptual design, because slight modification to the diameter or the material properties of the struts or inclusion of support structure can eliminate the potential failure. It is important during conceptual design to identify those areas of concern to better plan the detail design stage.

The transverse boom of the R&D configuration includes four solar dynamic modules on each of its ends, with corresponding extensions to the structure. It has been shown that the dynamic behavior of the boom during intense disturbances, such as reboost or docking, is dominated by its overall length, the amount of mass at the ends, and the stiffness of the alpha joint. Other studies, which investigated concepts with up to two SD modules on each end, have consistently shown a fundamental boom bending mode at approximately 0.07 Hz. With the additional mass and length, the R&D station's boom configuration can be expected to have a corresponding mode at 0.06 Hz or lower. The implication is that, as this fundamental mode frequency decreases, it approaches the RCS jet pulsing frequencies for reboost and the deadband frequencies of the control system. The potential control/structures interaction can result in build-up of member loads and potential failure of the structure. Thus, while four SD modules on each end of the boom may be accommodated safely, analysts and designers should be aware that structures of this sort will eventually reach a limit beyond which the structure and control system cannot operate. In the same vein, previous work has shown that pointing of the SD modules is sensitive to the fundamental frequency of the transverse boom, such that, as the boom is lengthened and made more massive near the ends (i.e. as SD modules are added), the pointing capabilities are degraded somewhat. Again, results indicate that four SD modules should not pose a significant problem, but, if growth beyond this R&D concept should require additional power, alternative approaches may be necessary.

3.0 TRANSPORTATION NODE CONFIGURATION CONCEPT

The baseline station design can be augmented through evolution to provide the scientific and technological foundation necessary to accommodate the Space Exploration Initiative (SEI). These enhancements include additional pressurized volume, crew, power, truss structure, and specialized facilities. For the transportation node function, the growth station will support advanced technology development, demonstration, and verification programs; exploration systems development; and the assembly, servicing, and processing of exploration vehicles. It will also serve as a laboratory to determine acceptable limits and/or countermeasures to long-term human exposure to low gravity and space radiation environments and will serve as a testbed for developing long-life, self-sufficient life support systems.

3.1 FUNCTIONAL REQUIREMENTS

The facility and resource requirements necessary to support human exploration missions are driven by a myriad of functions ranging from orbital technology demonstration and verification of advanced space systems and precursor life sciences research to the in-space assembly, servicing, processing, and refurbishment of the lunar vehicles (LVs) and Mars Transfer Vehicles (MTVs).

Comprehensive analyses of the growth of the station as a transportation node have been conducted during the past two years and are reported in the "Exploration Studies Technical Report, FY 1988 Status, Volume 1: Technical Summary" and the "Exploration Studies Technical Report, FY 1989 Status, Volumes I through VI". Following President Bush's July 20, 1989, speech, a task team was created by the NASA Administrator to conduct a study of the main elements of a Space Exploration Initiative. The results of this study are reported in the "Report of the 90-Day Study on Human Exploration of the Moon and Mars". A summary of several key sections of the 90-Day Study Report is presented below and served as the basis for the functional configuration requirements discussed in this section.

In the referenced study, station requirements were developed for two crucial functions in the SEI. First, the station serves as an orbiting laboratory for conducting the basic research and technology development necessary to implement the Initiative. Research in the life sciences will determine acceptable long-term microgravity and space radiation limits and/or countermeasures and support the development of long-life, self-sufficient life support systems. In the technology area, the station will serve as a test-bed for the on-orbit verification and testing of unique lunar and Mars systems, as well as for technology developments needed for in-space assembly and operations. Second, the station serves as a transportation node for the assembly, test, processing, servicing, recovery, and refurbishment of the lunar and Mars vehicles.

In addition, the station must support the R&D users, including NASA experimenters, commercial users, university investigators, and international participants. In developing the Transportation Node evolution configurations, these activities were included in the design to insure that the multidisciplinary character of the growth station would be preserved to the maximum extent possible. The Transportation Node configurations presented in this section are responsive to these stated requirements.

The Transportation Node configuration concept has two major phases: a lunar operations configuration to support early lunar missions and a lunar/Mars configuration. The lunar operations configuration will also support the life science and technology research and development required for manned Mars missions. The lunar operations configuration evolves to the lunar/Mars reference configuration by the addition of a Mars Transfer Vehicle processing facility attached to the upper keels and boom.

The growth resource requirements of these Transportation Node configurations are summarized in Table 3.1-1. A detailed description, including the physical characteristics, of the growth elements and the distributed systems is contained in Section 4.0.

Table 3.1-1: **TRANSPORTATION NODE GROWTH REQUIREMENTS**

	Baseline	Transportation Node	
		Lunar Operations	Lunar/ Mars
Average Power	75 kW	225 kW	225 kW
Crew	8	18 plus 4 transient	23 plus 4 transient
Pressurized Modules			
US Habitation	1	3	3
US Laboratory	1	1	1
ESA Laboratory	1	1	1
JEM Laboratory	1	1	1
Pocket Laboratory*	N/A	3	3
Structures			
Lunar Vehicle Assembly/Servicing Facility	N/A	1	1
Mars Transfer Vehicle Processing Facility	N/A	N/A	1
APAE	2	TBD	TBD
Airlocks	1	2	2

*Alternately referred to as "User Supplied Pressurized Modules"

3.2 CONFIGURATION DESCRIPTION

As mentioned previously, two configurations were developed for the Transportation Node function in support of the SEI. Figure 3.2-1 shows the front and side views of the lunar operations configuration. The module cluster at the center of the transverse boom will be expanded from the baseline configuration to include 2 additional habitation modules, 3 pocket labs, and 3 additional resource nodes. This extra interior volume will house a permanent crew of 18, as well as 4 transient lunar mission crew members, and will provide space for manned Mars precursor life sciences experimentation and materials processing activities. Figure 3.2-2 illustrates the top view of the module cluster.

Upper and lower booms and keels are added to the transverse boom to accommodate the Lunar Vehicle Assembly/Servicing Facility and to provide additional attached payload locations to support precursor and concurrent science activities. The lunar facility, located on the lower keels and boom, is described in Section 4.0. Capability to produce a total of 225 KW of power will be obtained by adding six 25 kW solar dynamic (SD) power modules to the baseline 75 KW of photovoltaic (PV) power. Additional structure will be included on each end of the transverse boom to accommodate the SD modules, and corresponding levels of thermal rejection capacity will be provided to keep pace with the increase in power.

Figure 3.2-3 shows the front and side views of the lunar/Mars node configuration. The module pattern is unchanged from the lunar operations configuration (Figure 3.2-2) and can accommodate the additional station crew required for lunar/Mars operations. The Mars Transfer Vehicle (MTV) Processing Facility is attached to the upper keels and boom, and no provisions are made for debris/meteoroid and thermal protection, since it is assumed that such protection will be integral to the Mars vehicle.

3.3 TRANSPORTATION NODE CONFIGURATION CONCEPT ANALYSES

The results of the analyses performed for the Transportation Node configurations are provided in this section.

3.3.1 Mass Properties

The mass properties of the Transportation Node configurations depend on the presence and operational state (i.e., fueled or unfueled) of the lunar and Mars mission vehicles. The Mars vehicle used in this analysis is the same as one of the vehicles derived during the 90-day study (138,000 kg including 62,000 kg of fuel). The lunar vehicles used in this analysis are also taken from the 90-day study, with a partially-fueled lunar vehicle stack having a mass of 32,000 kg and a fully-fueled lunar vehicle stack with a mass of 190,000 kg. Table 3.3.1-1 shows the mass properties of the Transportation Node for several possible lunar and Mars vehicle configurations, as well as one case with a shuttle attached. The origin of the geometrical coordinate system, shown in Figure 3.2-1, is located in the middle of the center truss bay of the transverse boom. The first row in Table 3.3.1-1 is the lunar operations configuration. The second

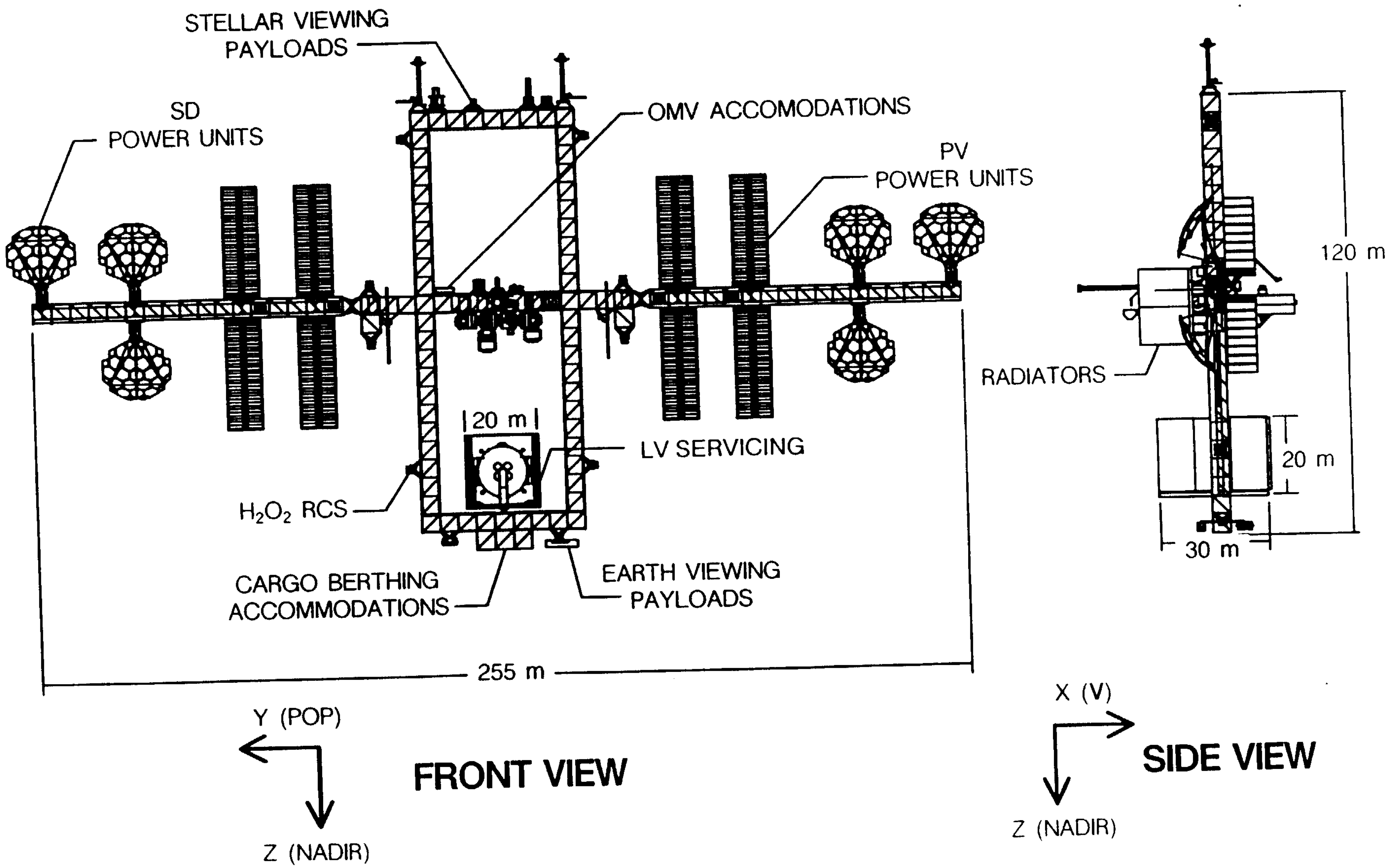


Figure 3.2-1 : Front and Side Views of Lunar Operations Transportation Node Configuration

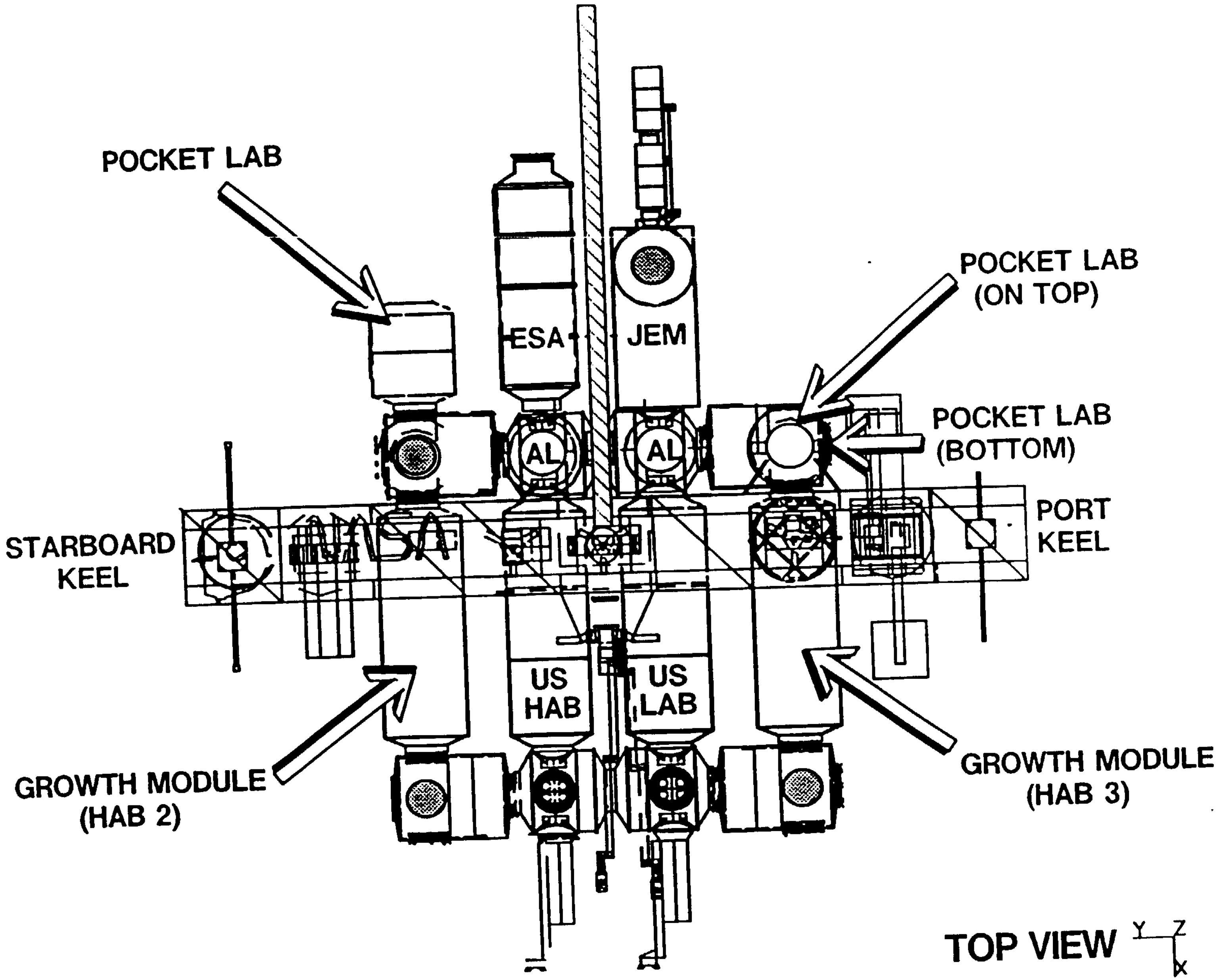


Figure 3.2-2 : Transportation Node Configuration Module Cluster

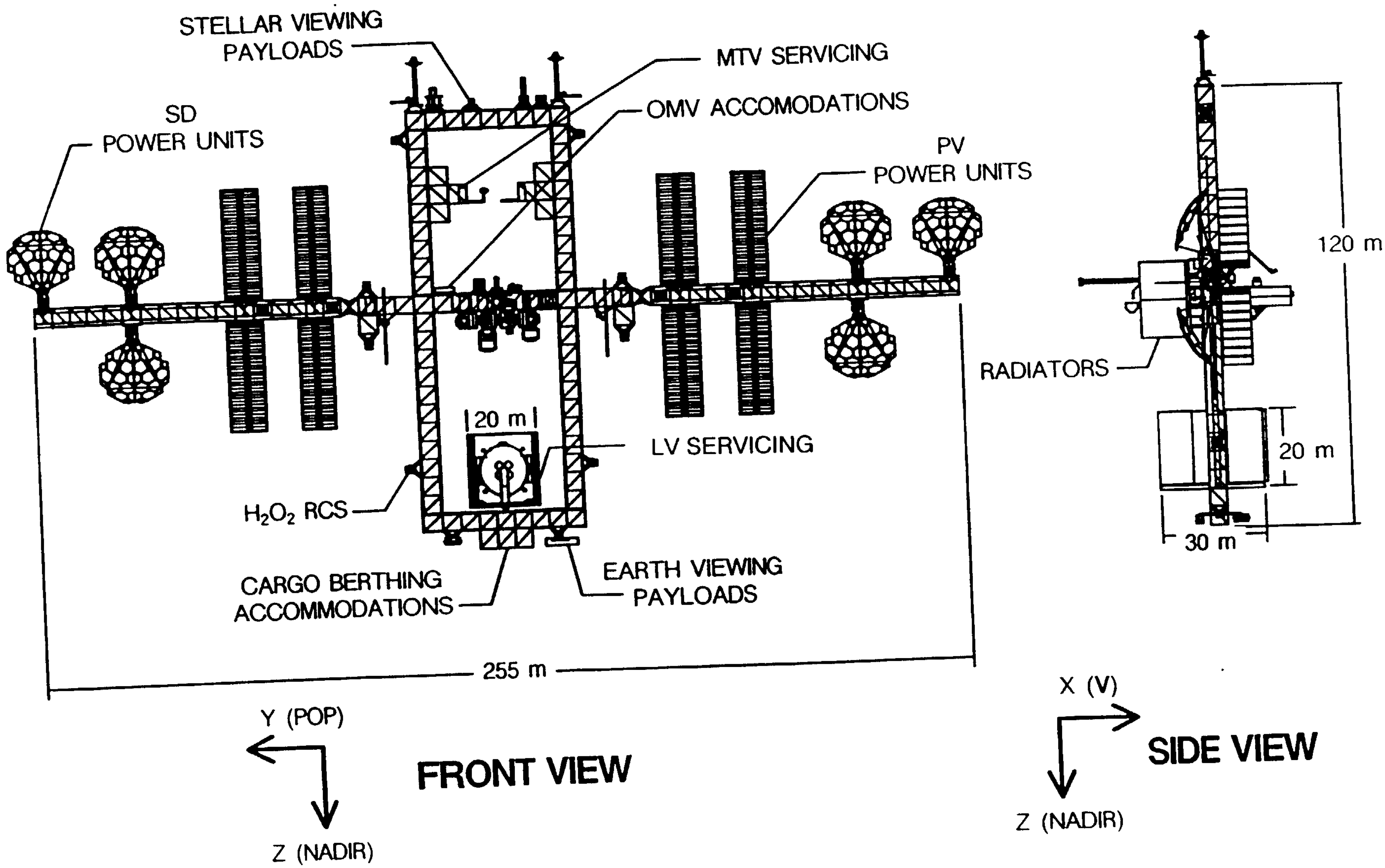


Figure 3.2-3 : Front and Side Views of Transportation Node Configuration

Space Station Configuration	Mass (kg)	Center of Mass (m)			Inertias (kg•m•m)					
		X	Y	Z	IXX	IYY	IZZ	IXY	IXZ	IYZ
Lunar operations node, fueled LV	734,000	-1.0	-0.1	15.4	1.19+E9	5.52+E8	7.07+E8	1.92+E5	-2.27+E6	-2.36+E6
Fueled MTV, part fueled LV	715,000	-1.8	-0.1	-0.4	1.15+E9	5.21+E8	7.06+E8	1.45+E5	7.95+E6	-330+E6
Fueled MTV, fueled LV	873,000	-1.5	-0.1	8.0	1.44+E9	8.08+E8	7.11+E8	1.67+E5	1.64+E7	-2.83+E6
Fueled MTV, no LV	683,000	-1.8	-0.1	-2.6	1.08+E9	4.47+E8	7.05+E8	1.46+E5	7.85+E6	-3.43+E6
No vehicles	544,000	-1.1	-0.1	4.6	9.37+E8	3.02+E8	7.01+E8	1.86++E5	-5.12+E6	-3.01+E6
Fueled MTV, part fueled LV, and docked NSTS	823,000	1.1	0.3	1.7	1.19+E9	6.02+E8	7.53+E8	6.94+E6	4.07+E7	1.66+E6

Table 3.3.1-1: MASS PROPERTIES FOR THE TRANSPORTATION NODE CONFIGURATIONS

row reflects the Transportation Node in the lunar/Mars configuration with a fueled Mars vehicle and a partially-fueled lunar vehicle. The third row represents the most massive case, assuming a fueled Mars vehicle and a fully-fueled lunar vehicle stack. Case four (fourth row) has the center of mass farthest above the modules, while case one has its center of mass farthest below the modules. The fifth row corresponds to a case with no lunar or Mars vehicles, resulting in the lightest configuration. The last row represents the mass properties of the lunar/Mars Transportation Node with a berthed orbiter. It should be noted that the mass properties of the Transportation Node configurations are highly dependent on the vehicle definitions derived during the 90-day study. The center of gravity varies from 2.6 meters above the module pattern to 15 meters below. The inertias yield gravity-gradient stability in pitch (IXX>IZZ) and small body-to-principal-axis rotations, i.e., flight attitudes will be near to LVLH.

3.3.2 Attitude Control Analysis

Steady-state attitude flight mode characterization and control system sizing were performed using Attitude Predict (ATTPRED) of IDEAS[2]. The CMG controls analysis performed assumes only steady-state environmental disturbances, such as aerodynamic and gravity-gradient torques. Large dynamic disturbances, such as the orbiter berthing or lunar vehicle deployment, and the corresponding interactions between the CMGs, RCS, and station attitude will be evaluated in future studies.

Table 3.3.2-1 summarizes the microgravity, flight mode, and CMG control characteristics of the Transportation Node configurations for various combinations of atmospheres, vehicle and fuel accommodations, and control system assumptions. Maximum solar cycle equates to a worst case (year 2001, flux=243, geomagnetic index=19.6), two-sigma atmosphere at an orbital altitude of 407 kilometers (220 nmi). Minimum solar cycle equates to a best case (year 2007, flux=86.4, geomagnetic index=16.0), nominal atmosphere at the same altitude. The gains chosen for the CMG controller were optimized to provide minimal deviations in pitch attitude ("pinched pitch" method), except for certain cases where the gains were adjusted to emphasize pitch momentum reduction at the cost of increased pitch deviations ("relaxed pitch" method). All cases studied yielded average flight attitudes within two degrees of LVLH for roll, pitch, and yaw, except for the berthed orbiter case (pitch = -5.3 degrees). Deviations over one orbit from the average flight attitude were less than +/-0.2 degrees in roll and yaw and less than +/-0.2 degrees in pitch for the pinched pitch control gains and less than +/- 1.1 degrees for the relaxed pitch control gains. Attitude error rates for all cases and all assumptions were below 0.005 degrees/second. The CMG peak momentum control requirements for maintaining attitude were all below 15,000 Nms for the pinched pitch method and below 4,500 Nms for the relaxed pitch method. All momentum requirements are well within the capability available from the six 4,750 Nms CMGs on the baseline station. Figure 3.3.2-1 represents the flight attitude history over five orbits for the lunar/Mars Transportation Node with a fueled Mars vehicle and partially fueled lunar vehicle stack for: 1) a maximum solar cycle, pinched pitch case, 2) a minimum solar cycle, pinched pitch case, and 3) a maximum solar cycle, relaxed pitch case. Figure 3.3.2-2 represents the corresponding momentum control requirements over the same five orbit period. The roll and yaw values displayed in the figures are nearly identical for all cases, with the only major differences noticeable in the pitch channel.

Space Station Configuration	Micro-G at Lab Center	Average Flight Altitude (degrees)			Attitude Drift per Orbit (degrees)			Peak Momentum (N•m•s)
		Yaw (Z)	Pitch (Y)	Roll (X)	Yaw (Z)	Pitch (Y)	Roll (X)	
Lunar operations node, fueled LV, max solar cycle, relaxed pitch	4.3	0.0	1.5	0.9	< 0.1	1.1	0.2	3,000
Lunar operations node, fueled LV, max solar cycle	4.3	0.0	1.5	0.9	< 0.1	0.2	0.2	15,000
Fueled MTV, part fueled LV, max solar cycle	2.6	0.0	-1.2	1.0	< 0.1	< 0.1	< 0.1	10,000
Fueled MTV, part fueled LV, min solar cycle	2.5	-0.1	-1.1	1.0	< 0.1	< 0.1	< 0.1	6,000
Fueled MTV, part fueled LV, max solar cycle & relaxed pitch	2.6	0.0	-1.2	1.0	< 0.1	1.0	< 0.1	1,000
Fueled MTV, full LV, max solar cycle	1.4	0.0	-0.7	-1.7	< 0.1	< 0.1	0.2	8,000
Fueled MTV, full LV, max solar cycle, relaxed pitch	1.4	0.0	-0.7	-1.7	< 0.1	0.6	0.2	4,500
Fueled MTV, no LV, max solar cycle	3.5	0.0	-1.8	0.8	< 0.1	< 0.1	< 0.1	11,000
No vehicles, max solar cycle	1.0	0.0	1.4	0.4	< 0.1	0.1	< 0.1	10,000
Fueled MTV, part fueled LV, docked NSTS, max solar cycle	1.8	0.7	-5.3	-0.9	< 0.1	< 0.1	< 0.1	10,000

Table 3.3.2-1: MICRO-G AND CONTROL PROPERTIES FOR THE TRANSPORTATION NODE CONFIGURATIONS

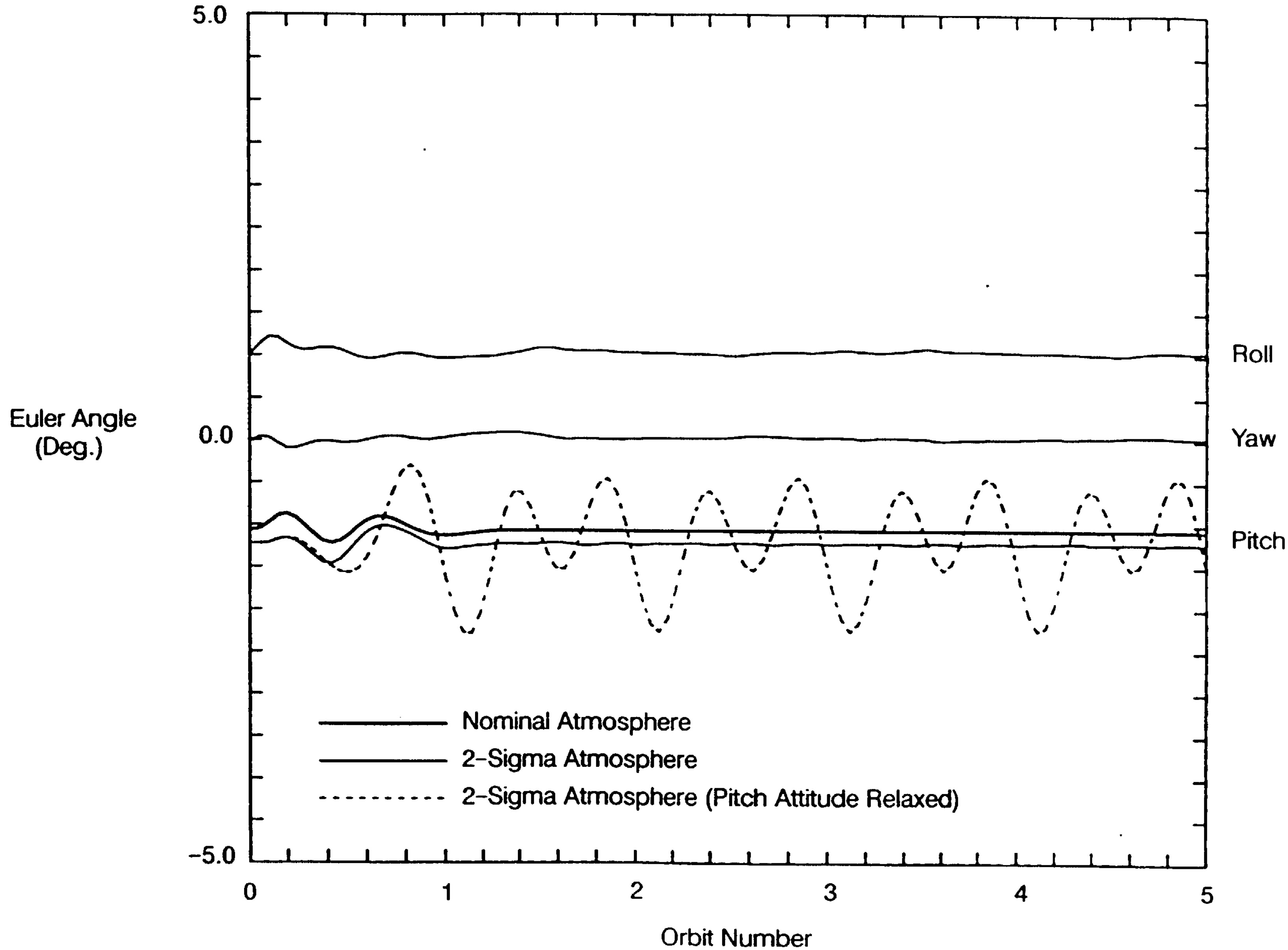


Figure 3.3.2-1 : Lunar/Mars Transportation Node Configuration Attitude History Comparison (Assumes Fueled Mars Vehicle and Partially Fueled Lunar Vehicle)

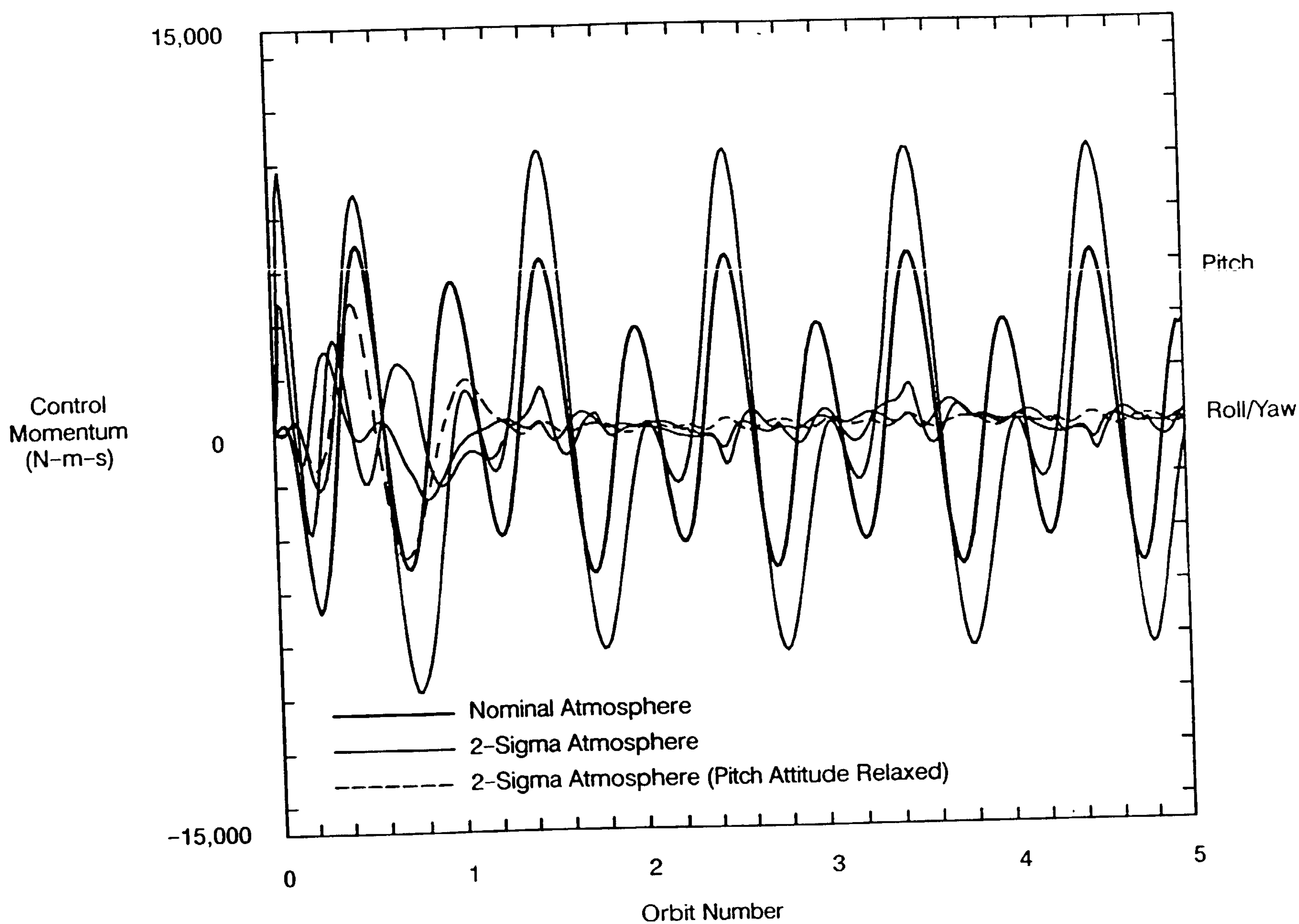


Figure 3.3.2-2 : Lunar/Mars Transportation Node Configuration Control Momentum History (Assumes Fueled Mars Vehicle and Partially Fueled Lunar Vehicle)

3.3.3 Microgravity Environment Determination

The steady-state microgravity environment changes with each operational configuration. Microgravity profiles have been generated for a subset of the analysis cases in order to show the wide range of possible environments encountered with the Transportation Node configurations. These cases include the nominal lunar/Mars operational configuration, the optimal microgravity case, and the worst-case microgravity configuration. Since the microgravity environment is lowest at the center of mass, the analysis cases with the highest and lowest center of mass were selected. Figures 3.3.3-1 through 3.3.3-4 show the one and two micro-g regions for the various operational cases at an altitude of 220 nmi and a worst-case, 2-sigma atmosphere (flux = 243, geomagnetic index = 19.6). Note that a less severe atmosphere or higher altitude will decrease the sensed acceleration by as much a 0.3 micro-g.

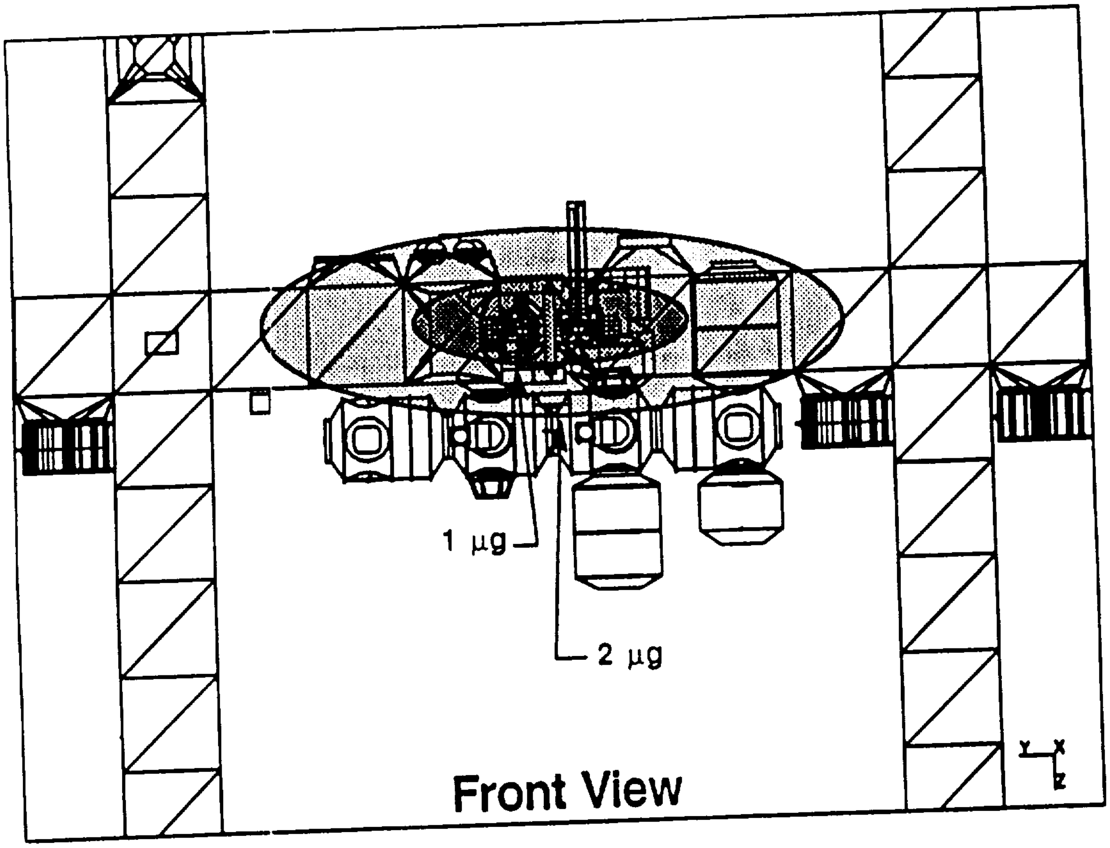
The nominal configuration (fueled Mars vehicle, partly-fueled lunar vehicle) in Figure 3.3.3-1 shows that the modules are not in the one micro-g region, but a small portion of the modules is in the two micro-g region. Figure 3.3.3-2 displays the optimal microgravity configuration (no vehicles), where the U.S. lab module is almost entirely encompassed by the one micro-g region, and the entire module pattern is within the two micro-g region. Notice that, for this case, the center of mass is located near the center of the module pattern, producing an ideal environment for microgravity. Figures 3.3.3-3 and 3.3.3-4 (fueled Mars vehicle with no lunar vehicles and lunar operations node with fueled lunar vehicles) show that the modules fall completely outside the one and two micro-g regions. For the other analysis cases, the microgravity envelopes are between the upper and lower bound regions shown in Figures 3.3.3-3 and 3.3.3-4.

The lunar operations case with fueled lunar vehicles provides the worst microgravity environment to the laboratory modules (i.e., the center of mass is farthest from the module pattern center line). It is important to note that there are opportunities to perform microgravity-sensitive experiments on the Transportation Nodes during the quiescent periods. Figure 3.3.3-5 shows the steady-state microgravity levels sensed at the geometric center of the U.S. lab module on the lunar operations transportation node during the lunar vehicle processing phase. The first six months are scheduled for preparing the lunar vehicles (LVs). In this phase, the laboratory microgravity levels increase from under one micro-g to just over four micro-g. However, subsequent to LV departure, the levels return to acceptable limits and sensitive R&D experiments can be performed. At a rate of one LV flight per year, approximately six months of "uninterrupted" low gravity research time is available to users.

It should also be noted that for the evolution path discussed here, there are several years between completion of the baseline configuration and the start of lunar operations, where "undisturbed" gravity-sensitive R&D can be conducted. Also, several years of lunar operations occur before both the lunar and Mars vehicle operations on station begin.

3.3.4 Orbit Lifetime and Reboost Analysis

Table 3.3.4-1 shows the reboost/orbit lifetime characteristics of the Transportation Node configurations. Four cases were examined: 1) lunar operations



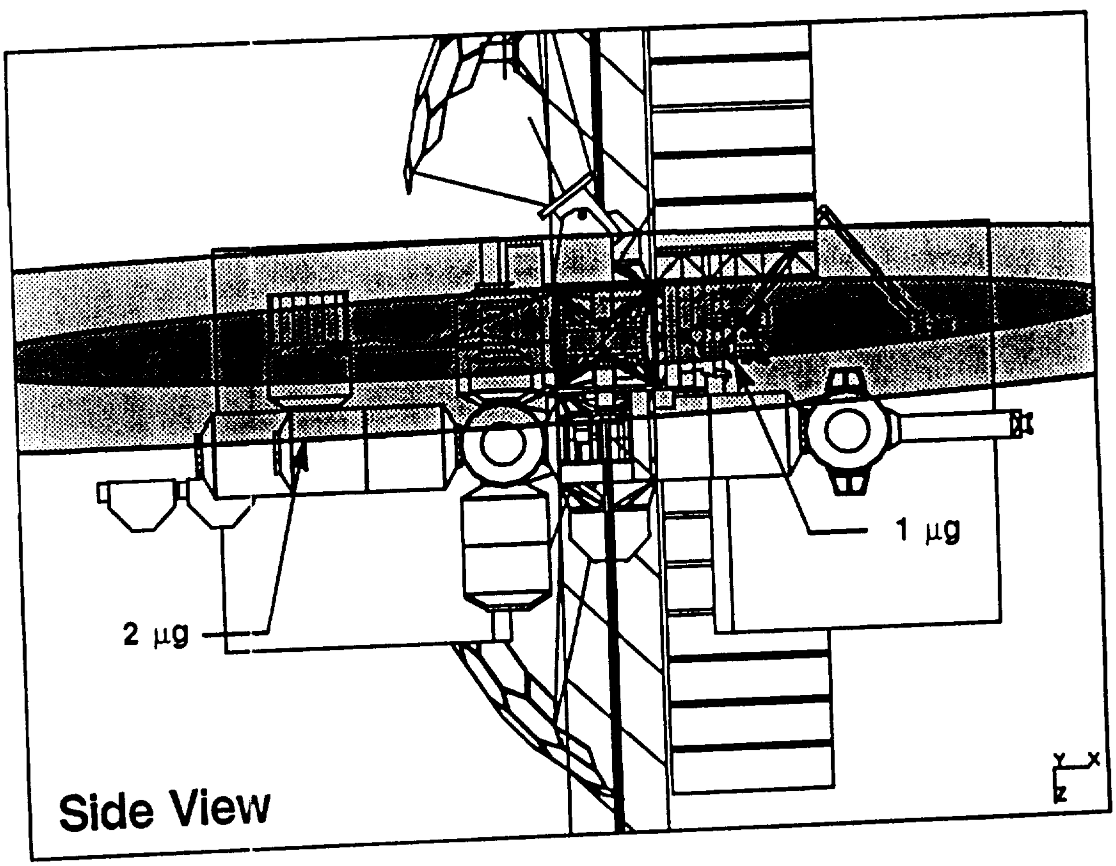
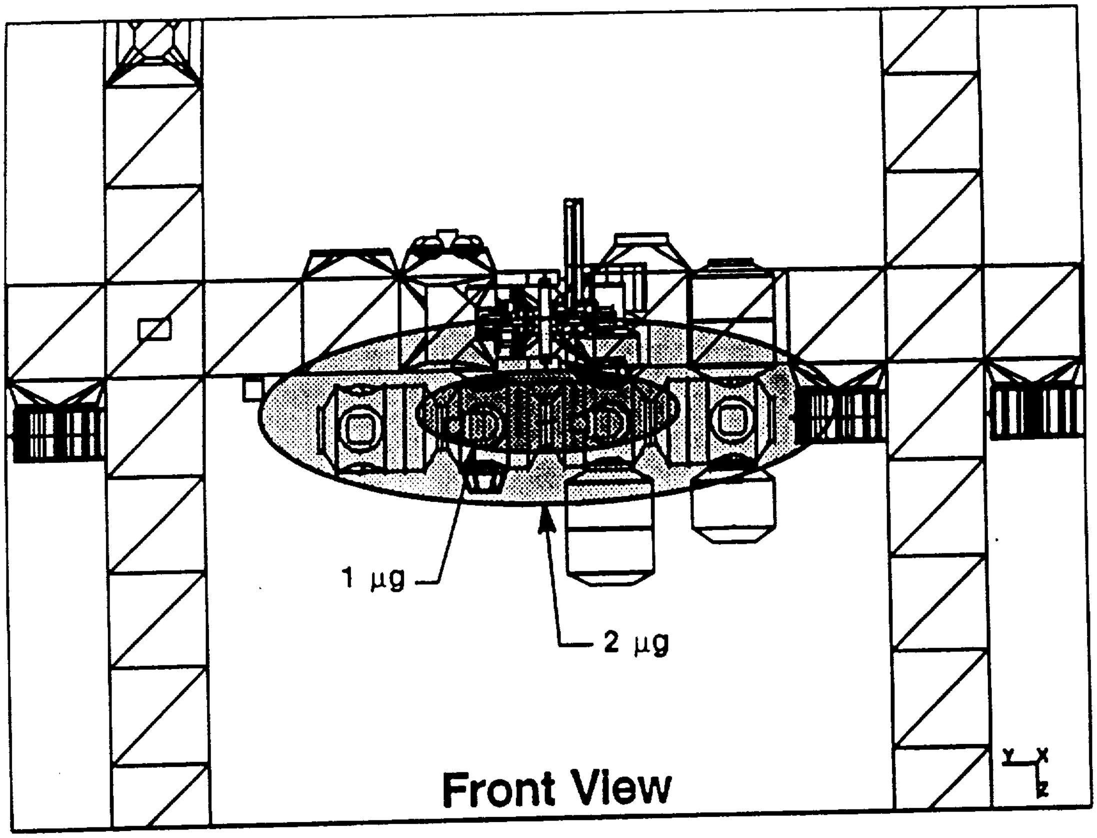


Figure 3.3.3-1 : Lunar/Mars Transportation Node Configuration Steady State Microgravity Profile (Assumes Fueled Mars Vehicle and Partially Fueled Lunar Vehicle)



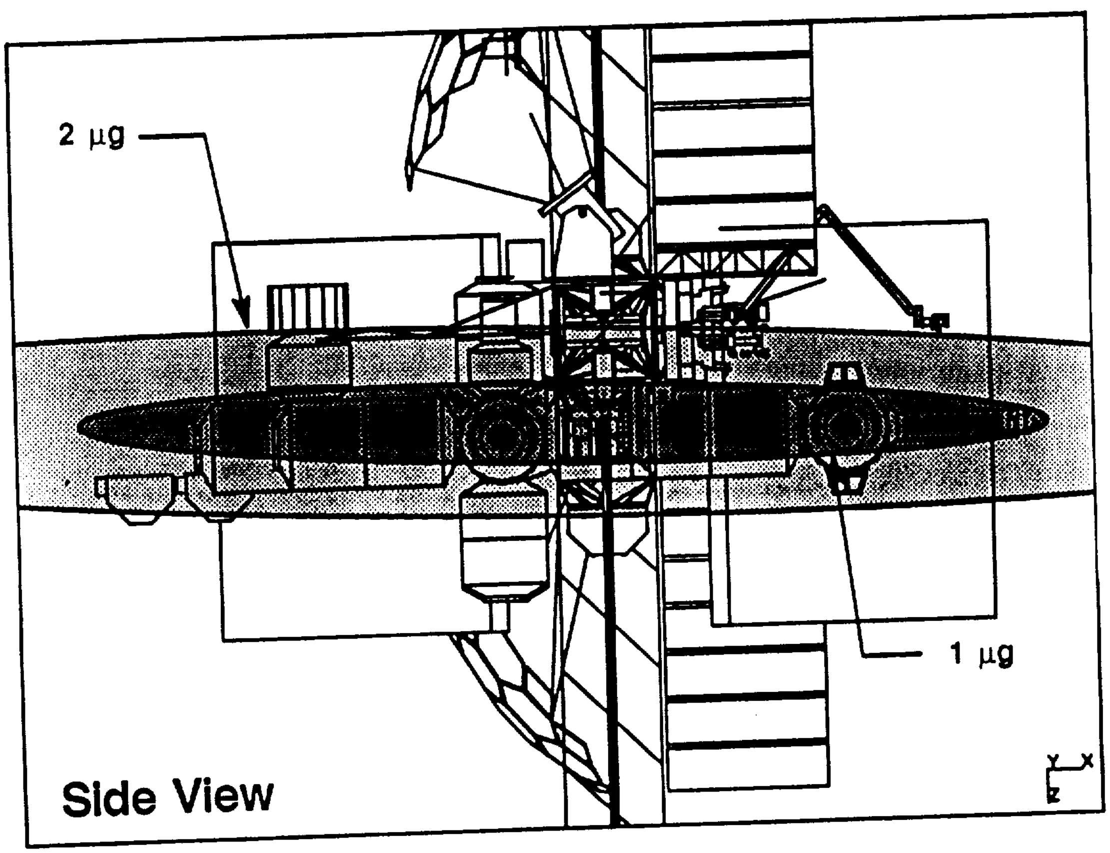


Figure 3.3.3-2 : Lunar/Mars Transportation Node Configuration Steady State Microgravity Profile (No Vehicles)

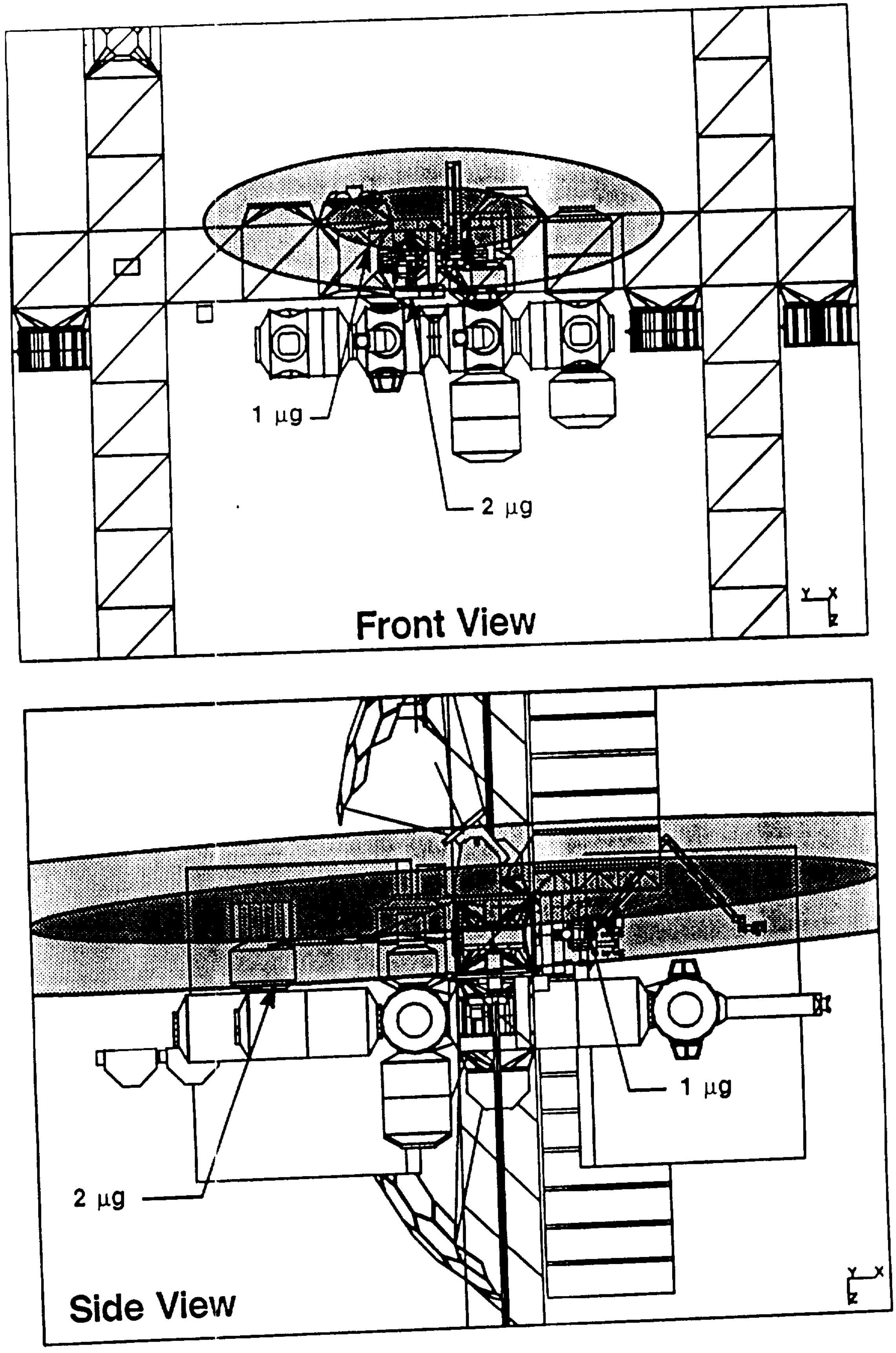


Figure 3.3.3-3 : Lunar/Mars Transportation Node Configuration Steady State Microgravity Profile (Assumes Fueled Mars Vehicle and No Lunar Vehicle)

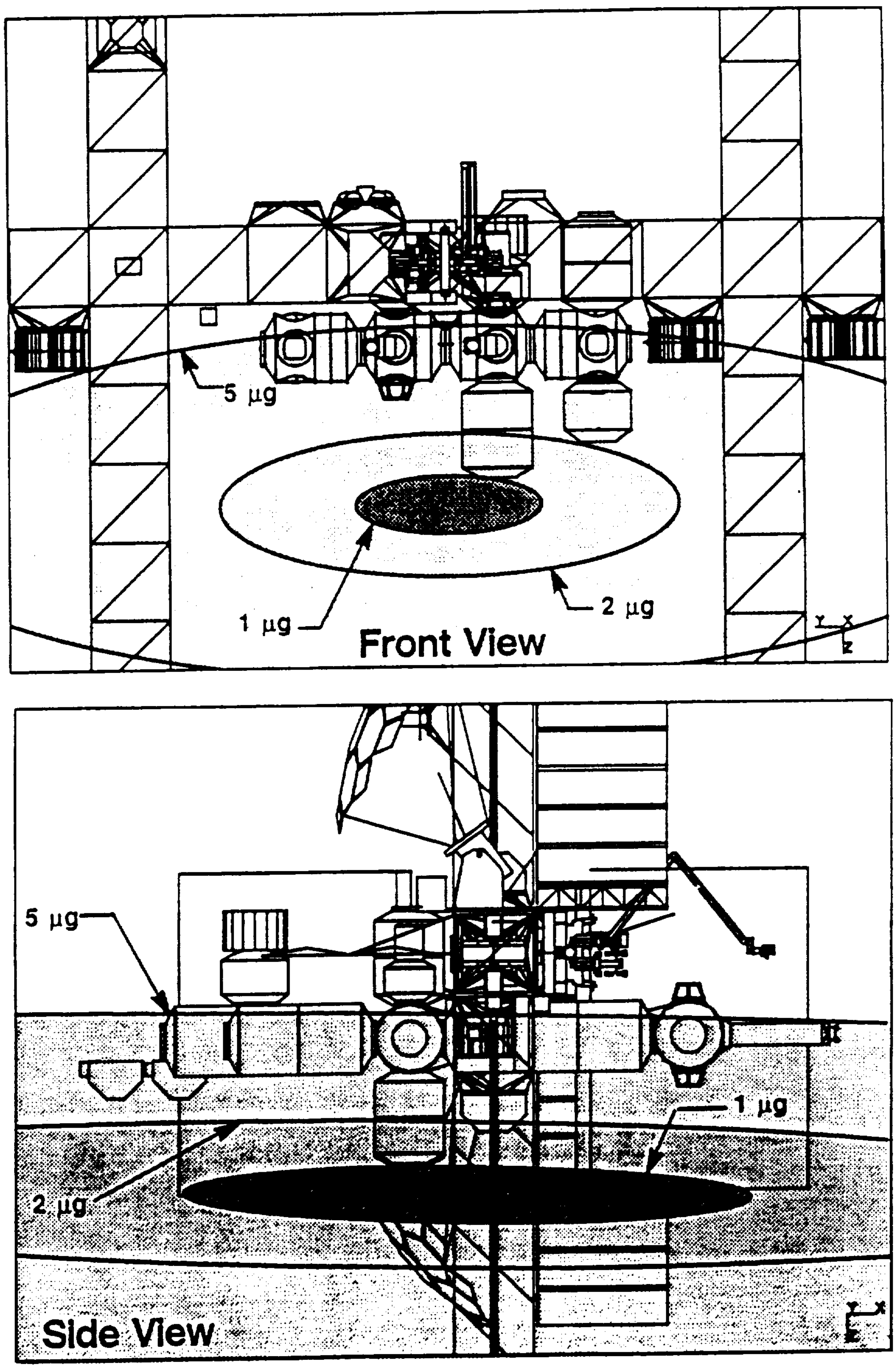
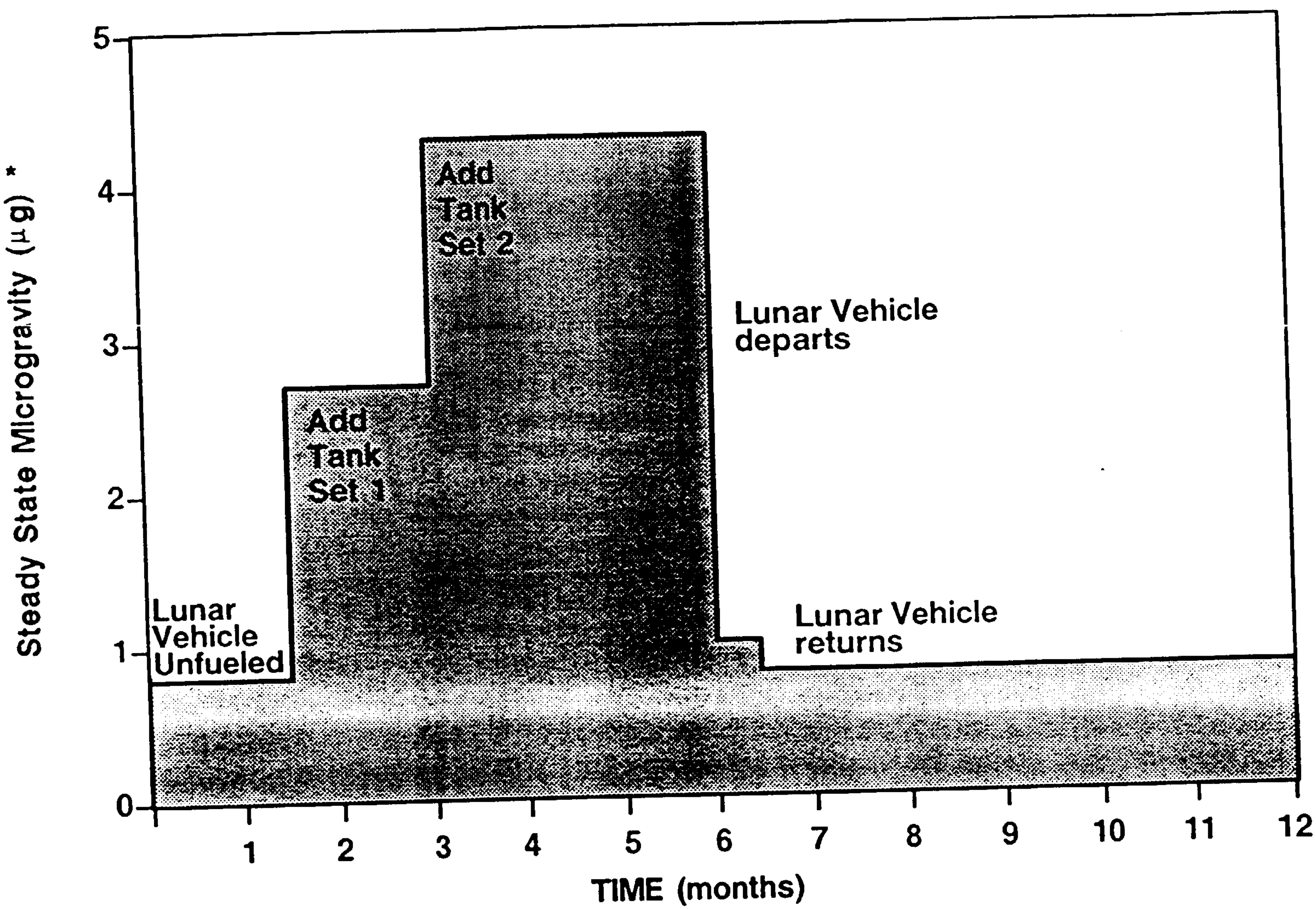


Figure 3.3.3-4 : Lunar Operations Transportation Node Configuration Steady State Microgravity Profi
(Assumes No Mars Vehicle and Fueled Lunar Vehicle)



* μg level at geometric center of U.S. Lab; levels at potential equipment locations may vary by as much as 0.5 μg

Figure 3.3.3-5 : Lunar Operations Transportation Node Configuration Time Phased Steady State Microgravity Levels

Space Station Configuration	Ballistic Coefficient (kg/m ^{2})	90 days reboost fuel (lbm)	Reboost Altitude (nmi)	Lifetime from 220 nmi
Lunar operations node, fueled LV, minimum solar cycle*	68.8	1,253	223	684
Lunar operations node, fueled LV, maximum solar cycle**	68.8	11,000	242	133
Fueled MTV, partly fueled LV, minimum solar cycle*	60.7	1,376	223	636
Fueled MTV, partly fueled LV maximum solar cycle**	60.7	11,640	244	117
Fueled MTV, fueled LV minimum solar cycle*	74.2	1,354	222	710
Fueled MTV, fueled LV maximum solar cycle**	74.2	11,999	240	139
No vehicles, minimum solar cycle*	51.0	1,265	223	581
No vehicles maximum solar cycle**	51.0	10,106	248	101

*Minimum solar cycle (Flux=86.4, AP=16.0)

**Maximum solar cycle (Flux=243, AP=19.6)

Table 3.3.4-1: ORBIT LIFETIME AND REBOOST, AND BALLISTIC PROPERTIES FOR THE TRANSPORTATION NODE CONFIGURATIONS with fueled LVs, 2) fueled Mars vehicle and partially-fueled lunar vehicle stack, 3) fueled Mars vehicle and fueled lunar vehicle stack, and 4) no vehicles. Both the solar cycle maximum and solar cycle minimum cases were analyzed for each operational configuration of the Transportation Node. Almost an order of magnitude more fuel is required for altitude maintenance during the solar cycle maximum, as compared to the solar cycle minimum for the same altitude. Although the configurations differ in mass in some cases by over 50%, there is no significant difference in fuel requirements due to station mass, because the more massive configurations have higher ballistic coefficients.

3.3.5 Structural Dynamics Analysis

No detailed structural analyses of the specific Transportation Node configurations have been performed for inclusion in this document. However, a recent study investigated the response to reboost loading of a node concept which had essentially the same transverse boom configuration as the lunar operations concept, but a somewhat altered mass distribution on the upper and lower keels. A second study evaluated a concept whose only substantial differences from the lunar concept was one less habitation module and no upper boom. These concepts exhibited 126 and 113 modes respectively below 2 Hz and showed very good correlation in both shape and frequency for transverse boom and appendage modes. For example, in both cases the fundamental boom bending mode, which was the mode that most dominated the pointing response of the solar dynamic modules, had a frequency of approximately 0.07 Hz. Each concept maintained solar dynamic pointing accuracy to within 0.05 degrees (the requirement is 0.1 degrees), and experienced only a few inches of motion at the tips of the PV arrays and the end of the transverse boom. It is expected that the Transportation Node configurations will exhibit similarly high modal density, with comparable mode shapes, frequencies, and response levels.

The Transportation Node configurations have an additional solar dynamic module on each tip of the transverse boom. The effects of this additional mass will be to lower the frequencies of the transverse boom modes (but not significantly alter their shapes) and to increase the displacements of the transverse boom tips and the tips of the PV arrays. It may also somewhat degrade the pointing accuracy of the solar dynamic modules.

Both of the studies mentioned above showed some buckling failure of truss members near the interface of the keels and the transverse boom during reboost. This is not surprising since models of the baseline station also indicate failure of truss members during reboost and NSTS docking. The point is that for any such large structure, there will be members that will have to be stiffened to avoid failure. The transportation node concepts described here will certainly require either stronger materials, larger diameter struts, or additional support structure at the interface of the boom and keels. Also, depending on the effects of the added solar dynamic mass, it is possible that the truss outside the alpha joint, or the joint itself, will require additional stiffness. Detailed analysis of these specific concepts will determine precisely which members are subject to buckling loads.

4.0 PHYSICAL CHARACTERISTICS OF ELEMENTS AND SYSTEMS

The evolutionary space station will be composed of elements and distributed systems. Elements are major pieces of self-contained hardware such as the pressurized modules. They are separated into two categories: replicated baseline elements and growth elements. Replicated elements are those that are identical to baseline elements and are duplicated in the evolution station. Growth element categories include those common to both evolution configurations, elements unique to the R&D configuration, and elements unique to the Transportation Node configurations. The distributed systems will be distributed throughout the station to provide resources to the station elements and users. This section contains physical and functional descriptions of the growth elements and the distributed systems for the evolution configurations.

4.1 REPLICATED BASELINE ELEMENTS

For station growth, it is desirable to replicate as much of the existing hardware as possible to reduce costs and unique spares. Several elements that will be added to the reference configurations will be nearly identical to baseline elements. For example, the R&D configuration will have two additional lab modules which are identical in design and fabrication, but not outfitting, to the initial U.S. lab module.

Table 4.1-1: REPLICATED BASELINE ELEMENTS*

ITEM	BASELINE	R&D STA.	TRANS.NODE Lunar Ops	Lunar/ Mars
U.S. Laboratory	1	3	1	1
Hab Module	1	3	3	3
Resource Node	4	4	4	4
Airlocks (H=Hyperbaric)	1H	1+1H	1+H	1+1H
Cupola	2	2	2	2
NSTS Docking Mast	2	2	2	2
APAE	2	18	TBD	TBD
Mobile Transporter	1	1	1	2
MSC	1	1	1	2
MMD - MSC Maint. Depot	1	1	1	1
FTS	1	1	1	1
PLC - Press. Log. Carrier	1	1	1	1
ULC - Unpress. Log. Carrier	3	TBD	TBD	TBD
Truss Structure (5m Bays)	27	107	110	118

*Quantities are totals, not the number replicated.

Table 4.1-1 provides a list of the replicated baseline elements, along with the quantity that will be incorporated into each configuration. Descriptions and physical characteristics for these and other baseline elements can be found in the Preliminary Space Station Freedom Technical Overview dated October 1988 (no document number assigned and not presently under configuration control) and the Weights White Paper: SSPO SE&I, Weight Allocation, Control Weights, and Associated Matrices with Weights Database, Rev. 3.0, January 1989 (SSE-E-88-R3.0).

4.2 GROWTH ELEMENTS

Elements which are new or enhancements of existing designs are considered growth elements. Some of the growth elements are common to all configurations, while some are unique to individual concepts. This section presents functional and physical descriptions of the growth elements in the following order: elements common to both configurations, R&D-unique elements, and Transportation Node-unique elements. Table 4.2-1 provides a list of the manned-base growth elements along with the quantity that will be incorporated with each configuration. Evolution transportation elements, co-orbiting platforms, and co-orbiting facilities such as a fuel depot are not addressed in this report.

Table 4.2-1: STATION GROWTH ELEMENTS

ITEM	R&D STA.	TRANS.NODE	
		Lunar Ops	Lunar/ Mars
Solar Dynamic Power Module	8	6	6
Resource Node - Extended	5	4	4
Pocket Lab	3	3	3
STV Servicing Facility	1	-	-
LV Assembly/Servicing Facility	-	1	1
MTV Processing Facility	-	-	1

4.2.1 Solar Dynamic (SD) Power Systems

An SD power module provides up to 25 kW of power by transforming concentrated solar energy into electrical power. The collector in the SD power system concentrates solar energy into a receiver filled with Helium-Xenon gas. The excited gas drives a thermodynamic, Brayton-cycle turbomachinery to generate electricity. To maximize the solar impingement on the concentrator, the SD makes use of a solar-tracking pointing system. The SD stores energy in thermal energy salts (TES), thus eliminating the need for batteries during orbital eclipse. An electrical equipment assembly controls module operation and conditions the alternator power to the required transmission frequency and voltage. Both the R&D and the Transportation Node configuration concepts will require the addition of SD modules to the baseline station.

An SD module is shown in Figure 4.2.1-1. The concentrator is a 18.2 m (60 ft) diameter concave mirror composed of several one-meter, spherically-contoured mirror facets. At the focal point of the concentrator is the receiver assembly and the power conversion unit. The SD assembly is mounted on a beta-joint gimbal assembly, which in turn is mounted on the transverse boom extension. The gimbal assembly points the concentrator at the sun and transfers power to the power management and distribution system (PMAD). Aft of the concentrator is the heat rejection assembly, which is slightly under 10 m (33 ft) long and 9 m (29.5 ft) wide. This assembly radiates excess thermal energy to space to maintain necessary power levels and operating temperatures.

4.2.2 Truss Structure

4.2.2.1 Booms and Keels

Booms and keels are added to the baseline station to provide greater stability and additional locations for items such as attached payloads, servicing bays, and antennas. The addition of booms and keels will also provide accommodations for hangars and construction facilities.

Booms and keels are the same type of erectable truss bays that comprise the baseline transverse boom. Each truss bay is a 5 m (197 in) cube with a mass of 274 kg (603 lbm). Running within the length of the truss bay is a utility tray which provides the wiring and plumbing used by the resource distribution systems, e.g., power, thermal rejection, and data communication systems. The utility trays have a 0.15 m (6 in) height by 1.5-2.3 m (60-90 in) width cross-section.

4.2.2.2 SD Truss Extension

Additional truss structures or extensions are added for all configurations to support and provide proper clearance for the SD modules. The truss extensions will be located at either end of the transverse boom. These truss extensions will house utility trays that contain command and data lines and sufficient cabling for 25 kW of electrical power per module.

Like the booms and keels, the SD truss extensions will be constructed of 5 m (197 in) cube bays. Each SD truss extension bay will have a mass of about 189 kg (416 lbm).

4.2.3 Extended Resource Node

The baseline interconnect for laboratory and habitation modules is the resource node. In addition to providing a shirt-sleeve environment for travel between modules, the resource node is sized to allow accommodation of much of the space station system hardware. All configurations will require additional resource nodes; however, they will be different from the baseline station nodes.

The clearance between modules connected by resource nodes are determined by the distance between axial berthing ports and the location of the radial ports along this

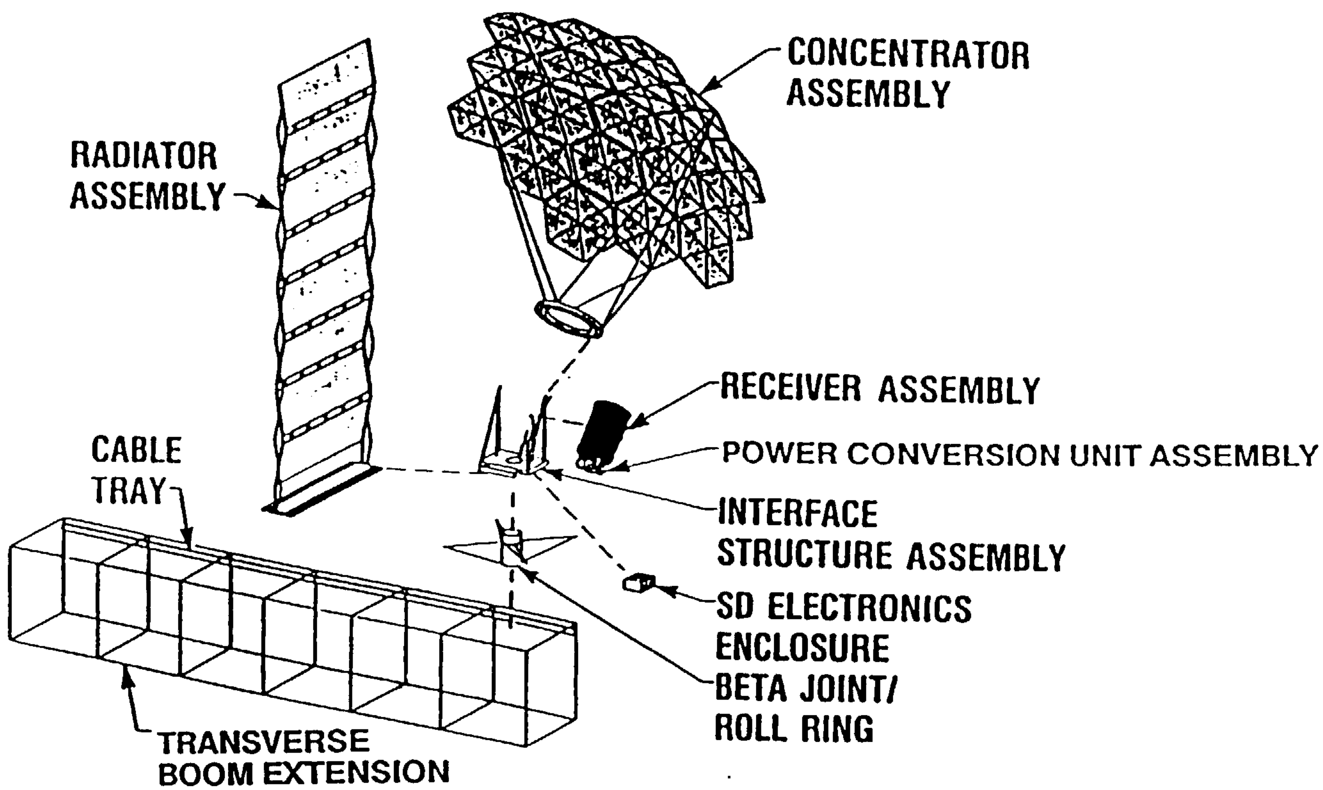


Figure 4.2.1-1 : Solar Dynamic Module Components

axis. Since the location of the berthing ports in the baseline design is not in the geometric center of the resource node length, a resource node has an "extended" side and a short side. The baseline requirement for module clearance of approximately 2 m (79 in) is achieved by interconnecting with two resource nodes attached with extended side to extended side. Growth resource nodes in the same plane will have to attach to the short side of a baseline resource node, resulting in a reduced clearance (approximately 1 meter) between baseline modules and growth modules. Attaching the short ends of two resource nodes is not viable because contact between the modules would occur. The 2 m (79 in) clearance requirement will not allow the use of baseline nodes for growth module interconnects. Several solutions have been considered; the most promising is to lengthen the cylindrical section of the baseline resource node with the addition of a cylindrical rack section. See Figure 4.2.3-1.

The resource nodes will be extended versions of the baseline resource nodes. The overall length will be about 6.1 meters (254 in), about 1 m (42 in) longer than the baseline node. The extended node will be 4.4 m (174 in) in diameter and have a mass of 7432 kg (16,380 lbm).

4.2.4 Pocket Laboratory

All growth configuration concepts have pocket labs. A pocket lab is a short, single-ended module (laboratory) that can be located at many spare resource node ports. Uses for pocket labs have been identified by the life sciences community for Space Exploration Initiative support and by the microgravity and materials processing community for commercial materials processing.

The pocket labs will provide physical separation from the common modules in order to promote safety and isolation of environmental contamination sources. They can be used to house equipment not readily adaptable to the common module due to assembly constraints or configuration incompatibilities. Pocket labs are also readily detachable for possible return to Earth. Lastly, they provide incentive to the private sector to participate by providing a standard interface and attach mechanism to the space station. Three pocket labs will be added to each configuration. The outfitting of the pocket labs will be determined by future studies.

Pocket labs have a number of potential configurations. The most likely of these are ones derived from elements already being fabricated for the baseline station, such as the common module (lab and hab), the baseline resource node, or the pressurized logistics module. These concepts will reduce costs by using existing designs and tooling. The proposed applications indicate that a pocket lab should have a volume of between 20 and 40 cubic meters and power/heat rejection of up to 25 kW. Temperature requirements will range from 3 degrees C (minimum) to 30 degrees C. Other resources that may be required include data links, video, waste gas removal, and crew time. These labs will, of course, have a shirt sleeve environment for crew operations.

If a common module design is used, a pocket lab would be 4.3 m (14.2 ft) in diameter. The estimated mass of pocket labs of differing lengths is 3,292 kg (7256 lbm) for the two end cones and one interface adapter, plus 3704 kg/m (2475 lbm/ft) of cylindrical section length. A sample pocket lab configuration having a length of 3.7 m (12.2 ft), a diameter of 4.3 m (14.2 ft), and a cylindrical section of 1.9 m (6.3 ft), would have a mass of 10,233 kg (22,554 lbm). Figure 4.2.4-1 illustrates a typical pocket lab and gives its dimensions, mass, moments of inertia, and projected areas.

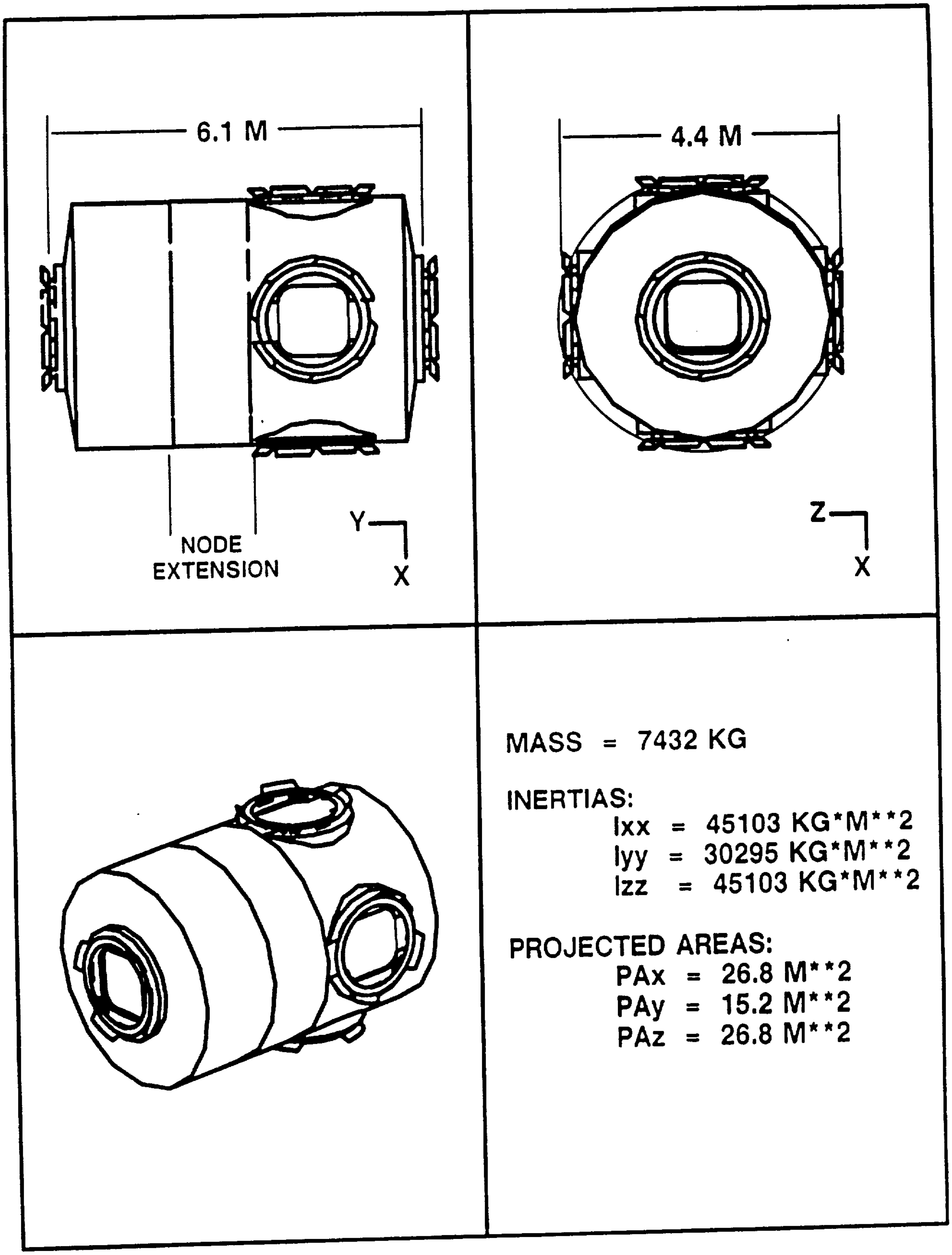


Figure 4.2.3-1 : Extended Resource Node

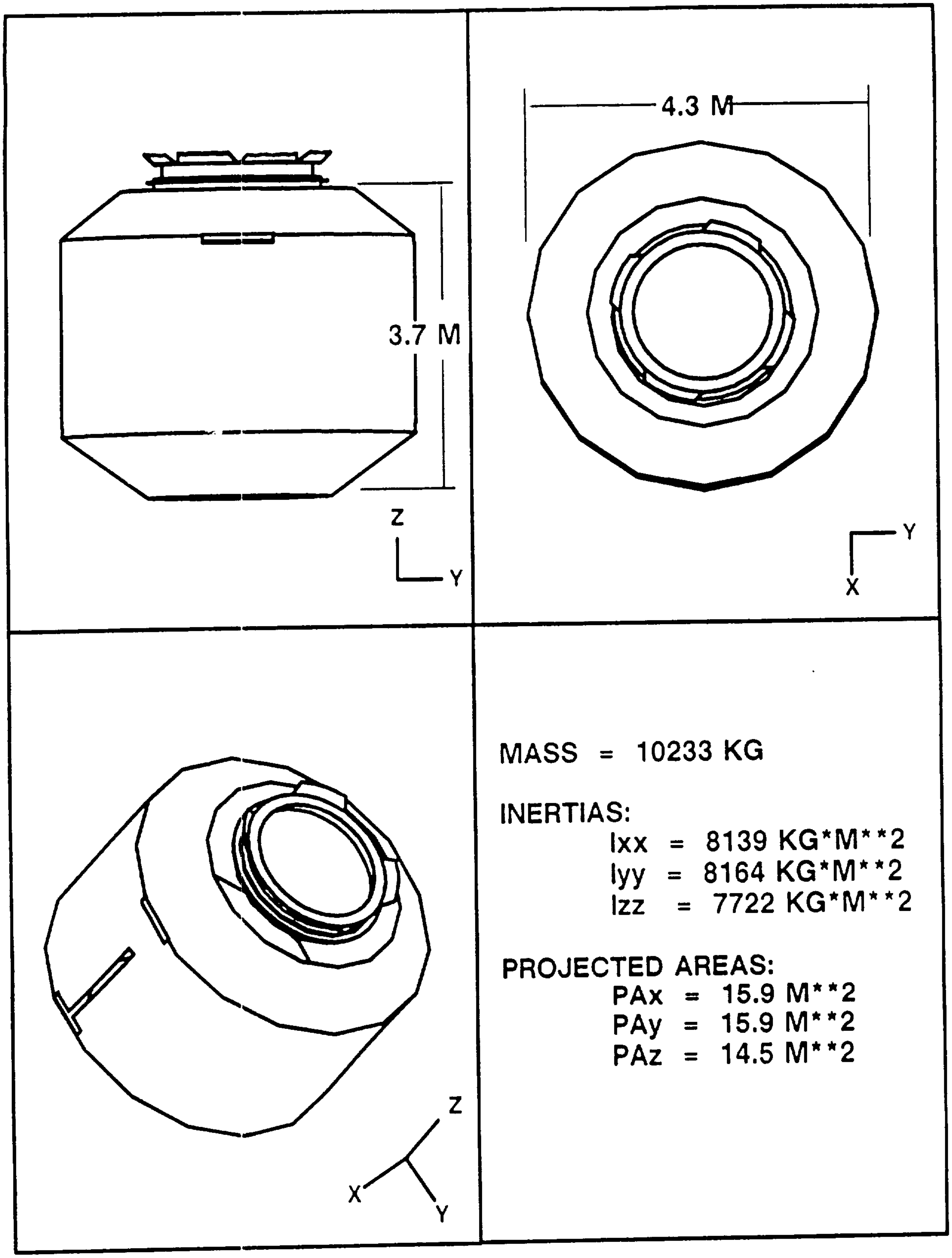


Figure 4.2.4-1 : Typical Pocket Lab

4.2.5 Space Transfer Vehicle (STV) Servicing Facility

The STV Servicing Facility is an unpressurized enclosed structure on the R&D configuration that provides a thermally controlled and meteorite protected volume for the STV and payload servicing, as well as for orbital replacement unit (ORU) and orbital servicing equipment (OSE) storage. The hangar is equipped with a robotic manipulator and EVA support equipment to accommodate STV processing, payload mating, and hangar maintenance. Interfaces to STV propellants and STV payload fluid services are provided. Electrical/data umbilicals, along with thermal control and structural support, are also available.

The STV enclosure is 15.3 m by 15.3 m by 29.3 m (50 ft by 50 ft by 97 ft). Inside the facility is a dedicated manipulator and a service track assembly. The bay has a mass of 19,353 kg (42,650 lbm) (see Figure 4.2.5-1) and will accommodate storage of a spare aeroshell.

4.2.6 Lunar Vehicle (LV) Assembly/Servicing Facility

The LV Assembly/Servicing Facility is made up of a number of distinct pieces of hardware which provide the capability to perform the assembly, integration, checkout, and refurbishment of an LV. These capabilities include power and data systems, robotic manipulators, thermal control, debris/meteoroid protection, EVA support systems, and structural supports. The facility includes a large retractable, unpressurized hangar-like structure attached to the lower boom between the lower keels of the Transportation Node. Within this hangar, the Service Track Assembly (STA) provides vehicle interface attachments and assembly fixtures, storage areas, and guide rails for two mobile manipulators. With the STA and the mobile robotic arms, the LV can be accessed for assembly and checkout, ORU changeout, payload integration, and vehicle refurbishment and refueling.

The LV Assembly/Servicing Facility enclosure (shown in Figure 4.2.6-1) is a 30 x 20 x 20 meter rectangular shield whose sides can be retracted along its centerline when clear access is needed for manipulator arm operations or vehicle ingress or egress. The front wall is a garage-type door which opens for smaller hardware transfers. The enclosure includes debris protection shielding consisting of a main aluminum alloy wall and a thinner alloy bumper, separated by a few centimeters of Multi-Layer Insulation (MLI).

The STA makes up the entire floor of the enclosed area. It is 17 meters wide and 30 meters long when fully deployed, and is composed of LV interface and attach fixtures, the servicing base, a strongback and utility trough, and guide rails for robotic access. Storage lockers and support equipment are located along the top of the trough in areas not occupied by the vehicle attachment hardware.

There are three vehicle interface and attachment fixtures provided in the facility. These fixtures serve as gantries which disconnect and swing to one side to allow the vehicle to enter or leave the facility. Two of the fixtures are dedicated to LV processing, while the third is used only for aerobrake assembly and attachment. Two duplicate mobile manipulators run on parallel tracks on each side of the LV stack. These manipulators consist of a mobile base and a multi-segment arm derived from the

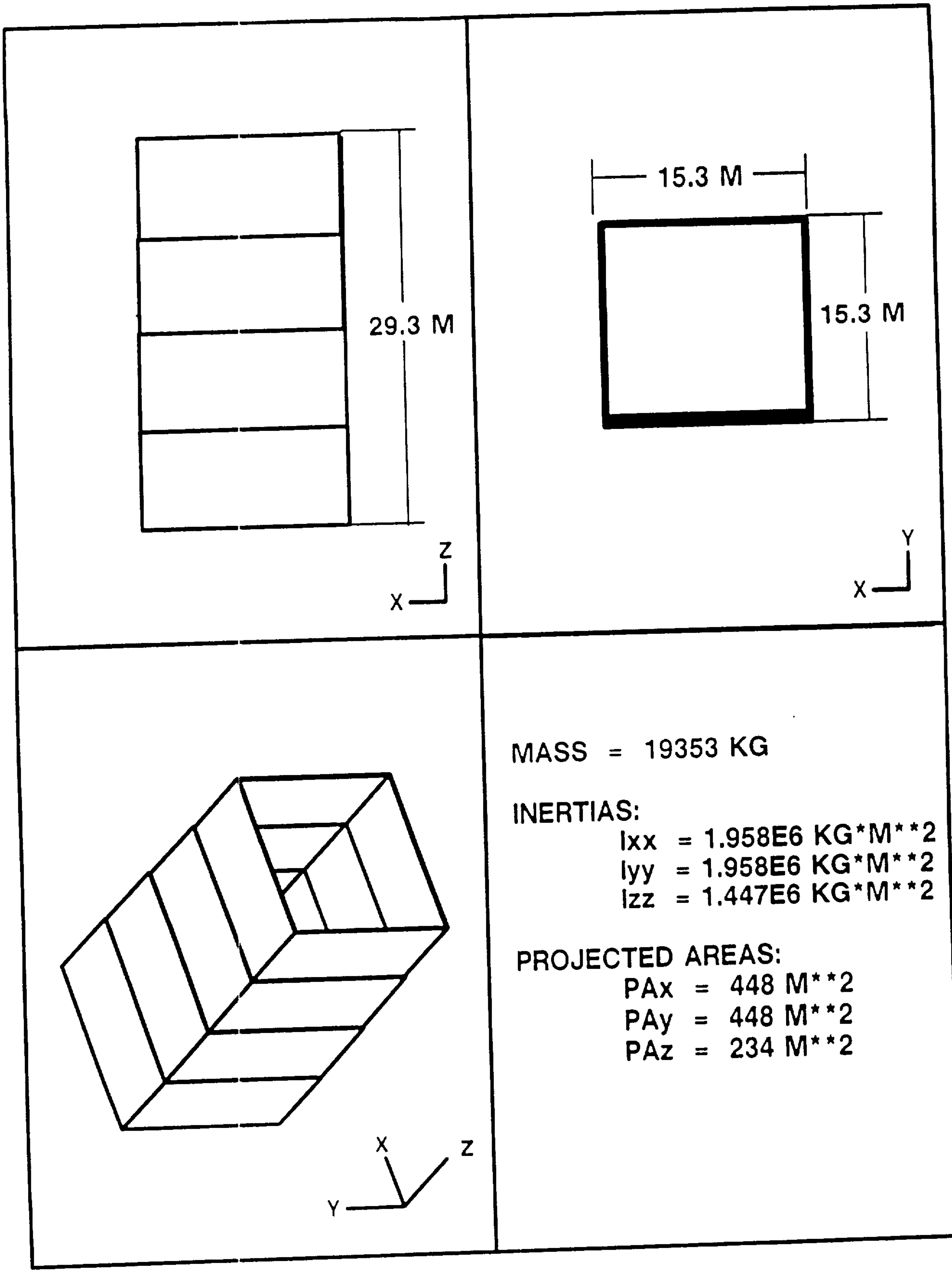


Figure 4.2.5-1 : STV Servicing Facility

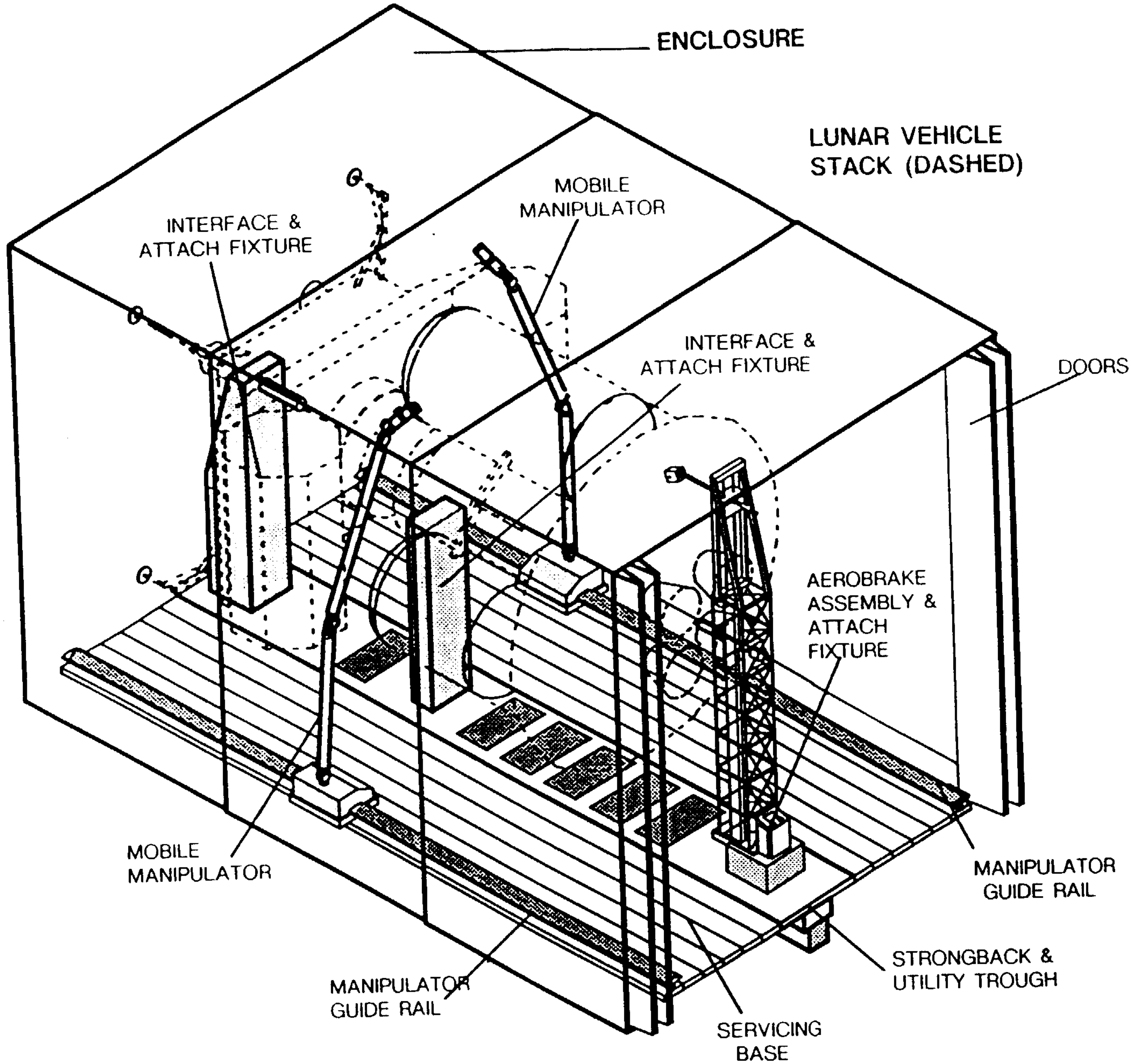


Figure 4.2.6-1 : Lunar Vehicle Assembly/Servicing Facility (ASF)

Space Station *Freedom* remote manipulator arm. Two stationary EVA work stations are also included to assist in vehicle processing.

4.2.7 Mars Transfer Vehicle (MTV) Processing Facility

Like the LV Assembly/Servicing Facility, the MTV Processing Facility consists of a number of hardware elements which make up a set of on-orbit capabilities that enable vehicle processing. In this case, it is expected that the vehicle will provide its own thermal control and collision protection. Therefore, there is no hangar to provide debris/meteoroid and thermal protection. Instead, the MTV Processing Facility is limited to power and data systems, robotic manipulators, EVA support systems, and structural supports.

The MTV Processing Facility concept is less well defined than that of the LV Assembly/Servicing Facility. They will both provide many of the same functions; however, the physical details of the MTV Processing Facility have not been defined in detail. Several bays of truss and support structure will be added to allow the MTV to attach between the upper keels of the Transportation Node where robotic manipulators can access the vehicle for assembly, checkout, and refurbishment. The size and number of manipulators will depend on the length and diameter of the MTV and the operational details of vehicle processing.

4.3 DISTRIBUTED SYSTEMS

Unlike elements, distributed systems are not self-contained but are distributed throughout the space station to provide resources to the station elements and users. Common user resources are power, active thermal control, data, communication and tracking, fluids, and environmental control and life support. Also classified as distributed systems are EVA, crew support, station propulsion, and station guidance, navigation, and control. This section describes distributed systems for the baseline and growth configurations. Descriptions of the growth distributed systems are presently high level and will be defined in more detail as the system designs mature and specific system evolution studies are completed.

4.3.1 Electrical Power System (EPS)

The EPS provides distributed power throughout the space station for housekeeping and customer use. It consists of three major subsystems: the power generator subsystem, the energy storage subsystem, and the power management and distribution (PMAD) subsystem.

4.3.1.1 Baseline

The baseline EPS provides 75 kW. It uses four photovoltaic (PV) modules located on the transverse boom, outboard of the truss element alpha gimbals, to convert solar into electrical energy. A PV module consists of a pair of PV arrays which are made up of two solar arrays that are 29.1 m (96 ft) long and 4.37 m (14.4 ft) wide. Each array is attached to the truss by a rotating beta joint.

The PV arrays operate in a temperature range from 160^{o} to -85^{o} Fahrenheit. Array voltage is controlled by a sequential shunt unit (SSU). Under rapidly changing load conditions, the SSU controls the voltage by shunting a small portion of the power and converting it to heat.

Throughout every orbit, the solar arrays must maintain a sun-facing orientation. The main truss structure alpha joints, which can rotate 360^{o}, continuously adjust the orientation of the arrays. To provide seasonal tracking of the sun as it moves from the north sky to the south sky, the beta joint can rotate up to 55 degrees.

Since all electrical energy on the station comes from the Sun, energy must be stored to provide power during the periods of orbital eclipse, which occur for about 30 minutes out of every 90-minute orbit. The baseline energy storage subsystem consists of 20 high-efficiency, lightweight, nickel-hydrogen batteries. The batteries supply the same amount of power during orbital eclipse as that provided by the PV during the sunlit portion of the orbit.

The power management and distribution (PMAD) subsystem distributes and conditions electrical power throughout the station elements. The PMAD subsystem monitors and controls the functions of the EPS and protects the system from damage by failed components, short circuits, and operator error. Since the PV modules and the energy storage subsystem provide dc power at the 160Vdc level, the PMAD subsystem is also responsible for the dc/dc conversion to 120 Vdc for secondary distribution throughout the station.

4.3.1.2 Growth

The addition of the SD power modules (Section 4.2.1) will constitute the primary growth path for the EPS. Each alpha joint must either be initially sized to allow transfer of peak power, or be designed to facilitate future upgrades. The baseline beta joint used with the PV arrays can be replicated for use with the solar dynamic power modules. Additional distribution capacity will be provided by replicated utility trays.

4.3.2 Thermal Control System (TCS)

By a combination of active and passive means the TCS maintains the station's elements, systems, and payloads within allowable temperature ranges. Waste heat is collected by the TCS active subsystems and transported to a location on the station where it is radiated into space. The TCS also uses passive thermal control techniques to insulate most station elements from the cyclic effects of solar inputs and radiative losses.

4.3.2.1 Baseline

The baseline TCS is sized to accommodate an 82.2 kW heat load which is comprised of the 75 kW input of the EPS plus 8% power conversion losses and a 1.2 kW metabolic load. The active thermal control system (ATCS) consists of an external ATCS, an internal ATCS (ITCS), and a solar power module ATCS (PV ATCS) for the EPS outboard of the alpha joints.

The central heat collection and transportation function is accomplished with a redundant external pumped two-phase system that uses ammonia as the working fluid.

Two separate external thermal loops operate at 2°C (35°F) and 21°C (70°F), respectively. Waste heat is collected from the pressurized modules using interface heat exchangers and cold plates and transported by the thermal buses to two radiator panels located on the transverse boom. Modular condensers in the radiator assemblies transfer the heat to erectable heat-pipe radiators. The 15.2 m (50 ft) long by (31 ft) wide radiators are mounted on anti-Sun tracking rotary fluid couplers.

The ITCS is used within the modules and nodes for temperature control of system components and user experiments. Single-phase water (pumped through the ITCS loops) acquires the heat, holds it during transfer, and rejects it to the external two-phase buses via interface heat exchangers. Each of the four deployable PV modules has an independent active thermal control system consisting of heat acquisition coldplates, redundant single-phase ammonia transport loops, and a radiator.

The TCS uses passive methods to maintain acceptable temperatures whenever heat loads do not dictate the need for active cooling. Thermal control tapes and paints are used on external surfaces to control heat absorption and rejection. Thermal insulators are used to "isolate" elements from heat changes. Supplemental heaters are used when necessary to provide close-tolerance temperature control of critical subsystems or to provide survival heating.

4.3.2.2 Growth

The growth requirement for the TCS is driven by increases in power, additional conversion losses, and increased metabolic loads. Additional fluid lines and pumps may be necessary for growth resource nodes, modules, and pocket labs and lines may be routed along the vertical keels to the upper and lower booms. Additional radiator panels may be required to dissipate the increased the increased heat load. Active thermal control may be installed for keel and boom mounted APAEs. The SD power modules will have local, independent, active thermal control systems similar to the baseline PV ATCS.

4.3.3 Data Management System (DMS)

The DMS provides the hardware and software resources necessary to support the data processing and control needs of the station's systems, elements, and payloads. It also provides a common operating environment and human-computer interface for the command and control of systems and payloads by both the crew and ground operators.

4.3.3.1 Baseline

The DMS is made up of five subsystems corresponding to the five major DMS functions: human-computer interface, data acquisition and distribution, data storage and retrieval, application program processing, and time generation and distribution. The components that make up the five subsystems, and the subsystems themselves, are physically distributed throughout the station.

The human-computer interface is provided by the workstations which are called multipurpose application consoles (MPACs). The MPAC contains the electronic hardware and software components necessary to provide a multipurpose window into all operations and experiment monitoring, station command and control, training, testing, caution and warning, and user services. To support various functional needs throughout the station and its interfaces, the hardware comes in three configurations, fixed, portable, and orbiter MPACs.

The data acquisition and distribution subsystem is composed of many hardware and software components which work together to provide the rapid transmission of data between distributed systems, sensors, effectors, elements, and payloads. The primary components which contribute to the data acquisition and distribution include; the multiplexer/demultiplexer (MDM), the standard data processor (SDP), and the DMS optical and local networks. The MDM is the DMS interface to sensors, effectors, and unique devices of subsystems and payloads. The MDM interfaces to the rest of the DMS through a local network connection to a SDP, then via the DMS optical network to other DMS components.

The data storage and retrieval subsystem provides the hardware and software components necessary for the storage and retrieval of application programs and data. These components are packaged in a standard (MIL-STD-1788) enclosure and is called the mass storage unit (MSU). Hardware components in this subsystem include; a network interface unit (NIU), a user provided embedded data processor (EDP), and a mass storage device (MSD) with at least 250 megabytes of rapid, direct access, non-volatile memory. The EDP provides the processing capability to manage the programs and data stored on the MSD. The NIU enables program and data read and write requests via the DMS communications network with other DMS components.

The application program processing subsystem includes the hardware and software required for execution of all distributed system, element, and payload management applications. The primary hardware component used to perform this function is a standard data processor (SDP), which consists of; a NIU, an EDP, a Multibus II parallel system bus (PSB), a bus interface unit (BIU), and a power supply.

The EDP, which provides the core processing function for most of the DMS components consists of a single printed circuit card, general purpose processor which executes the Intel 80386 microprocessor instruction set architecture, and the 80387 numeric co-processor IEEE 754 compatible floating point instructions. The EDP includes four (4) megabytes of dynamic random access memory (DRAM) with error detection and correction capability. The EDP provides external interfaces with; the PSB, a 32 bit IBM Micro Channel, and the precision time system (PTS). In addition to its use in DMS components, the EDP may be used by other subsystems as the core processor embedded in an orbital replaceable unit (ORU).

The software components of the application processing subsystem include the operating system (OS), the system management (SM) application program, and the operations management application (OMA) program. The OS isolates the application software from the hardware on which it is running, manages the advanced features of the 80386 microprocessor, and provides the capability of running multiple programs concurrently. The SM application program performs subsystem and component management functions, including monitoring the health and status of DMS hardware, auditing the integrity of DMS software, accommodating system growth, initializing new hardware and software components, controlling data overloads, detecting and isolating faults, managing redundant DMS components, and providing the appropriate automatic and manual controls to keep the DMS functional. The OMA program provides top-level operations control for all systems, elements, and payloads on the station and acts as the primary control interface with the ground. Its functions include maintaining and executing the short term plan, maintaining a log of the status of systems, elements, and payloads, and supporting training and simulations.

The time generation and distribution subsystem is composed of hardware and software that generate a stable and accurate time and frequency source, interface with the universal time broadcast by the Global Positioning System (GPS) satellites, and distribute time information to all processors on the station. This subsystem generates a stable 1 million pulse per second frequency source and produces a standard time code accurate to 10 microseconds relative to universal time. The time is distributed over the core and payload networks using a dedicated bus.

4.3.3.2 Growth

The overall modular design with expandable networks of the baseline DMS facilitates growth of the system. The baseline network also contains extra nodes for growth additions. Although the baseline processors have spare memory, the incorporation of optical storage media into the evolution configurations will provide a significant increase in data storage capacity. In addition, the software will be modular and use standard protocols for communication, facilitating ease of growth.

4.3.4 Communications and Tracking (C&T)

The C&T system provides for the transmission, reception, multiplexing, distribution, signal processing, and generation of audio, video, telemetry, command and control, and tracking data. It also provides for the manipulation of antennae on the station.

4.3.4.1 Baseline

The transmission of data between the station and the ground is provided primarily via the Tracking and Data Relay Satellite System (TDRSS) Ku band (13 to 15 GHz) link. Using the Ku band link, transmission of 300 Mbps return (space to ground) and 25 Mbps forward (ground to space) can be achieved. In addition to the Ku band link, TDRSS provides an S band (2 GHz) link. The S band provides transmission rates of 16 kbps return and 3 kbps forward. It will be used during early assembly flights and as a contingency link in the event that the Ku band becomes inoperative. Some payload packages may also provide independent user provided links to ground.

Space to space or "cluster" communications between the station and nearby vehicles occur within a command and control zone (CCZ) that is roughly 37 kilometers (20 nmi) ahead, behind, above, and below the station and 9 kilometers (5 nmi) to the port and starboard. These communications are of two classes: proximity operations and longer-range communications using tracking antennas. Proximity operations are those which take place within one kilometer of the station and include EVA and FTS operations, as well as NSTS docking and berthing. Transmissions are omnidirectional at both ends of the proximity operations links. Long-range communications, such as with the approaching shuttle or a Man-Tended Free Flyer, occur from one kilometer away from the station to the boundaries of the CCZ. Long-range transmission and reception at the station require the use of directional antennas.

The tracking subsystem provides station and cooperating vehicle positioning data via RF links and Universal Time Coordinated (UTC) time through the use of the Global Positioning System (GPS). This information will be sent to the guidance, navigation, and control (GN&C) system which computes the pointing angles for the TDRSS Ku band antennas and pointing payloads. GPS data is also used to track vehicles during rendezvous and departure. The same information that an approaching vehicle receives from the GPS is transmitted to the station's GN&C system, where antenna pointing angles for the vehicle are determined. A space to space tracking antenna is then assigned to track the vehicle. The GN&C system derives range and rate information from the data transmitted by the vehicle.

The video subsystem receives or distributes video signals to and from cameras and monitors throughout the station. The subsystem also provides the crew with video processing capabilities to record, edit, and play back images. Video to be transmitted to ground via the TDRSS link are digitized prior to transmission.

The audio subsystem distributes audio communications internally throughout the station and to the space-to-space and the space-to-ground communication systems. Internal audio is wireless to allow the crew to operate with minimal encumbrance. Crew members can also record experimental and operational observations for later playback and analysis.

As part of the C&T management function, the C&T system monitors the health and status of its own equipment, diagnoses faults in that equipment, and controls its configuration and operation. This control and monitoring subsystem interfaces with the DMS orbital management application (OMA) program to receive and execute the C&T's portion of the short-term plan in scheduling communications resources. Caution and warning information is also exchanged with the OMA program.

4.3.4.2 Growth

To accommodate growth, the baseline space to space subsystem patch panel is of modular design with spare connectivity. The baseline space to ground link is also designed to operate at TDRSS full capacity (300 Mbps). However, growth requirements may necessitate upgrades to enable utilization of a possible advanced TDRSS which will have a 650 Mbps downlink and a 50 Mbps uplink capability. The baseline design does not preclude either the addition of direct links to ground or the incorporation of voice recognition into the audio subsystem. The video distribution subsystem bandwidth does accommodate high-resolution video requirements, and its design is modular to allow incorporation of future technology upgrades. To facilitate growth, the audio subsystem also has spare connectivity. The station is designed to accommodate automated support for traffic control, proximity operations, docking of free flyers, and control of multiple free flyers. Radar and laser ranging may be added for automated docking and berthing operations.

Possible technology upgrades for the C&T system include evolution to the Ka band or optical for space-to-space links, upgrading signal processing to accommodate high definition TV, and application of expert system technology to the control and monitoring subsystem.

4.3.5 Guidance, Navigation, and Control (GN&C)

The GN&C system controls the station's attitude, maintains its altitude between reboost and rendezvous, calculates pointing angles for systems and payloads, controls proximity traffic, and maneuvers the station to avoid possible collisions with space vehicles, debris, or meteoroids.

The station flies in a local-vertical local-horizontal (LVLH) attitude which keeps the station perpendicular to the Earth. In the LVLH mode, the truss is perpendicular to the direction of flight, and the bottom of the station always point towards the Earth. This attitude is maintained within five degrees in each axis.

4.3.5.1 Baseline

The GN&C system is divided into two subsystems: the core subsystem and the traffic management subsystem. The core GN&C subsystem is responsible for controlling attitude and altitude and for calculating pointing angles. Attitude control is accomplished primarily through the control moment gyroscopes (CMGs) mounted on the GN&C pallet. The CMGs act to absorb torques which cause disturbances to the attitude of the station.

Atmospheric drag will decay the station's orbit, requiring periodic station reboost. The RCS thrusters and the resistojets, controlled by the GN&C, are used to increase the velocity of the station in the direction of flight. The resultant increase in centripetal acceleration forces the station away from the Earth. The GN&C may also be used to decrease station altitude during rendezvous operations or collision avoidance maneuvers.

The GN&C performs attitude calculations using data collected by star trackers and inertial sensor assemblies (ISAs). These sensors are strategically located on the space station to minimize viewing obstruction from added elements in the growth configurations. Star trackers are devices which measure the positions and magnitudes of stars. This data is compared to data stored in the star catalog to uniquely identify the star in the star tracker's field of view. The angle from the navigation base, a rigid structural mount for the star trackers that provides a stable reference, to several known stars can be measured with a maximum error of 60 arc-seconds. The ISAs consists of three ring laser gyroscopes and are used to sense small rotations with extremely high accuracy.

The GN&C traffic management subsystem is responsible for controlling incoming, outgoing, and stationkeeping traffic within the CCZ, controlling docking and berthing operations, monitoring the trajectories of cooperating vehicles which intersect the orbit of the station, performing collision avoidance maneuvers, and supporting flight planning of the traffic around the station. Data is gathered from the GPS, radars, and optical sensors on cooperating vehicles and from ground tracking for noncooperating vehicles and debris. Noncooperating vehicles are defined as those which do not communicate with the station. Using this data, a vehicle's position, velocity, and attitude is calculated by the GN&C traffic management SDPs. Closed-circuit television and direct viewing support close-proximity operations for berthing and docking.

4.3.5.2 Growth

Additional capacity will be required in the areas of momentum absorption (attitude control) and fuel for reboost. There will also be a need for automated support of the traffic management functions to accommodate expected increased volume of traffic within the CCZ. Other growth areas will include software and hardware support for an increased number and variety of payloads requiring pointing control and for the possible addition of tethered payloads. If operations analyses indicate the need for additional CMGs, they will be co-located with baseline CMGs to minimize interactions due to flexure of the station.

4.3.6 Extravehicular Activity (EVA) System

The EVA system (EVAS) provides the capability for pressure-suited crew members to perform a wide variety of tasks external to the station's pressurized volume. These tasks include assembly and servicing of the station elements, distributed systems, and attached payloads. The system includes EVA Mobility Units (EMUs), EVAS Service and Performance Checkout Unit (SPCU), airlock depress/repress equipment and controls, EVA hyperbaric life support and chamber pressurization equipment and controls, EVA translation and mobility aids, EVA external lighting, EVA support equipment and generic tools, EVA external equipment storage, and EVA contamination detection and decontamination unit. The EMU provides an anthropomorphic pressure suit, portable life support, and EVA crew communications and physiological monitoring. The SPCU provides for the servicing of EVA equipment between excursions.

4.3.6.1 Baseline

The baseline EVAS will be station-based with the NSTS-design EMUs and will perform only contingency operations. All other EVAs to perform maintenance, repair, and inspection tasks will be scheduled only when an Orbiter is present. A single hyperbaric airlock supports the extravehicular activities.

EVA subsystems are located both internally and externally to the airlock and on the transverse boom. The EMU consists of the space suit assembly (SSA) and the personal life support system (LSS). It is a self-contained pressure vessel that provides the radiation and micrometeoroid protection necessary to work in the space environment. The NSTS-design suit's operating pressure is 4.3 psia and requires substantial pre-breathing time to allow the removal of nitrogen from the body tissue prior to airlock depressurization.

Thermal control is accomplished with a non-venting, regenerable, thermo-electric/wax/radiator system. This system automatically controls the temperature of cooling water circulated through the liquid-cooled garment (LCG) worn under the space suit. Carbon dioxide is removed by circulating the atmosphere through a removable, on-orbit regenerable cartridge. Two silver-zinc rechargeable batteries provide power.

Communications for the EVA/IVA crew consist of voice communication to and from the station, data communications to the station, and voice communications between EVA crew members via the C&T system's space-to-space and internal audio subsystems. The EVA crew communicates with the ground via the station.

The SPCU provides for on-orbit reservicing of EVAS equipment between EVAs. The SPCU provides the interface for the EVAS equipment and the service equipment necessary to support IVA and EVA operations during EMU donning and transition to the vacuum environment. It also provides for performance checkout and instrumentation verification of all EVA serviceable hardware.

Translation aids are located on the station modules and truss structure to facilitate the transport and restraint of EVA crew members and equipment. These aids include handholds, handrails, and restraint attachment points located along all EVA routes, at each EVA hatch, inside and outside the airlock, and at appropriate EVA work sites.

The Contamination Detection and Removal System (CDRS) is located outside the airlock and uses a quadrupole mass spectrometer to detect, identify, and measure external contamination on the EMU. If contaminants exceed tolerance levels, heat lamps will be used to vaporize the contaminants.

4.3.6.2 Growth

Evolution in the EVAS will provide the capability for the crew to perform routine tasks in the unpressurized environment. In addition to the basic maintenance, repair and inspection functions, the EVAS will support installation, assembly, and servicing of on-orbit systems and user hardware. The EVAS will incorporate the space station-design, 8.3 psia, rear-entry EMU which will minimize the time required for pre-breathing and space suit donning/doffing. The pressurized suit assembly will allow greater crew mobility and have an automated checkout capability.

An Extravehicular Excursion Unit (EEU) will be available to provide for free-flying proximity operations of up to 300 meters from the station. The EEU will be on-orbit serviceable and will be stored outside the airlock.

The Service and Performance Checkout Subsystem (SPCS) will replace the SPCU. The SPCS will provide for automated performance checkout and reverification following maintenance and ORU replacement. The servicing and checkout operations that the SPCS provides include LCG water servicing, suit leak check-out, suit drying, carbon dioxide/humidity control subsystem regeneration, heat sink regeneration, and battery recharge. The SPCS completely regenerates the EMUs in 12 hours and can also provide one hour turn-around for contingency EVA. A one hour oxygen recharge provides about 80% of the oxygen normally provided by a 12-hour recharge. The EMU thermal control subsystem is fully rechargeable in one hour. The carbon dioxide and humidity control unit and the EMU batteries can be manually changed out for a contingency EVA.

A Crew Rescue and Equipment Retrieval Subsystem (CRERS) will be provided to rescue an EVA crew or to retrieve equipment accidentally detached from the station. This capability accommodates separation of a crew member from any point on the station and provides acquisition and return to the airlock within the EMU expendables' reserve time. This capability will also be utilized for detached equipment retrieval when deemed appropriate.

Communications for the EVA crew will be augmented during growth to include voice and data to and from the station, video to the station, and the transfer of text and graphics from the station to the EVA crew member.

Technology upgrades can be expected in the EVAS during the 30-year life of the station, especially in the suit systems. However, accommodation of the SEI on station will require extensive operations in the unpressurized environment to support the inspection, assembly, processing, and servicing of the exploration vehicles. Advancements in the areas of autonomous and telerobotic systems and cooperative manned and telerobotic EVA systems will be needed not only to reduce the anticipated number of manned EVAs, but also to reduce risks and to increase productivity.

4.3.7 Man Systems

Man systems consists of equipment necessary to support the crew members while they live and work on-board the station. Although the majority of the man systems hardware is in the habitation modules, man systems hardware and functions are distributed throughout the pressurized volumes and interact with many other station systems. Design emphasis for the man systems was placed on creating a good man-machine interface (MMI) which allows the crew to be productive in work areas and to relax in the rest areas.

4.3.7.1 Baseline

Man systems are functionally partitioned into fifteen subsystems: crew quarters, restraints and mobility aids, crew health care, operational and personal equipment, portable emergency provisions, galley, wardroom, personal hygiene, illumination, stowage, housekeeping/trash management, interfacing partitions and structures, in-flight maintenance, integrated workstations, and inventory management.

Restraints and mobility aids are located throughout the pressurized elements to facilitate the microgravity movement of crew and hardware. Crew member health needs are addressed on board the station and supplemented as necessary by communication with ground-based physicians. Nutritional requirements are met with an extensive galley and food management system. Maintenance of personal hygiene is supported along with station-wide housekeeping and trash management. Personal and crew-wide stowage accommodations are also provided.

Specific areas within the pressurized volume of the station are dedicated as integrated workstations which provide communications between the crew and station systems. There are two varieties of workstation: fixed and portable. Fixed workstations provide distributed system and element control, monitoring, verification, configuration management, manual override of automated functions, access to procedures, caution and warning display and annunciation, training, word processing, electronic mail, and inventory management. The fixed workstations are configured with high resolution color monitors that provide multifunction capability, including image windowing, video, graphics, and text overlay.

Portable workstations consist of a portable multipurpose application console (MPAC), a flat panel display, and a keyboard. Crew members can select and interconnect portable workstation components in a variety of combinations anywhere that ports are located.

Workstations located in each cupola can be used for docking and traffic management operations. Video, graphics and text overlay, or video windowing generated at any fixed workstation can be switched to the cupola workstation to create templates and cross hairs to assist in judging distance and alignment. Hand controllers are provided for precision manual vehicle control.

The maintenance workbench, located in the U.S. lab, supports intravehicular activity (IVA) maintenance and servicing of the station and other hardware. The workbench occupies two racks and accommodates the laboratory science maintenance servicing functions. The workbench also provides stowage for tools, supplies, support equipment, and test and diagnostic equipment.

4.3.7.2 Growth

Evolution in the man systems is expected to be by replication of the baseline habitation module. Each habitation module is designed to provide crew quarters, crew health care, galley, wardroom, housekeeping and trash management, and personal hygiene for a crew of eight. Therefore, the addition of two habitation modules during the evolution phases will accommodate a total permanent crew of 24, which has been deemed adequate for all configurations. Judicious outfitting of the replicated habitation modules could increase this crew size or accommodate transient personnel by replacing galley, wardroom, and health care facilities with crew quarters. The provisioning of restraints and mobility aids will continue for the evolution habitation and laboratory modules.

Modularity and design-for-maintainability requirements will facilitate implementation of technology upgrades as they become available. Areas of technology upgrade include health care facility, galley, housekeeping/trash management, personal hygiene, and MMI. In many cases, technology upgrades will be accomplished on orbit.

4.3.8 Environmental Control and Life Support System (ECLSS)

The ECLSS maintains a safe, shirt-sleeve environment (at sea-level atmosphere) within the pressurized elements of the space station. It controls the temperature, humidity, and air composition of the atmosphere. It also supplies water for drinking and personal hygiene, processes and stores the crew's waste material, and detects and suppresses fires. The baseline design allows the ECLSS fluid makeup requirements to be satisfied by the water contained in food and by a nominal resupply quantity of nitrogen. A key feature of ECLSS is its use of oxygen and water regeneration technology to minimize resupply.

4.3.8.1 Baseline

The majority of ECLSS hardware is located in the U.S. lab and hab modules. Redundant temperature and humidity control, atmosphere revitalization, and water recovery and management assemblies are packaged in identical racks or mounted at identical end-cones of the hab modules. Each life-critical ECLSS assembly is designed to support the entire eight member crew for 45 days under safe haven conditions. ECLSS uses distribution hardware that interconnect the station's pressurized elements with air, water, oxygen, and nitrogen. For safety, the fluid resource lines are provided with isolation valves at element bulkheads.

There are six ECLSS subsystems: temperature and humidity control, atmosphere control and supply, atmosphere revitalization, water recovery and management, waste management, and fire detection and suppression.

The ECLSS temperature and humidity control (THC) subsystem controls the cabin air temperature, humidity, and ventilation, the air cooling of rack mounted equipment, and the temperature-controlled storage of food. The cabin air temperature and humidity is controlled by circulating the air through condensing heat exchangers. Power consuming equipment are air cooled with a variable speed fan assembly and a heat exchanger which duct air to the individual racks. Additional refrigeration is provided in the pressurized logistics carrier for storage of food.

The atmosphere control and supply (ACS) subsystem regulates the total pressure and oxygen partial pressure for the pressurized elements. It compensates for atmospheric leakage and airlock losses and provides for pressure venting and relief.

The atmosphere revitalization subsystem (AR) removes carbon dioxide and trace contaminants from the air and provides oxygen regeneration. The AR subsystem is designed to accommodate a nominal metabolic oxygen demand of 0.83 kg/day (1.84 lbs/day) per crew member and carbon dioxide reduction of 1.00 kg/day (2.20 lbs/day). In addition to the nominal eight member crew, the AR subsystem can also accommodate the demand of another 1.3 "crew member" for use by animal life sciences.

The water recovery and management subsystem (WRM) recovers water from various waste water sources, distributes the reclaimed water, controls the microbacterial and chemical composition of the water, and thermally conditions the water supply. Potable water is reclaimed from humidity condensate and carbon dioxide reduction using a multifiltration process. Hygiene water is reclaimed from other waste water by reverse osmosis processing through membrane filters and an evaporative process.

The waste management (WM) subsystem separately processes human metabolic wastes and urine. Solid wastes are compacted, allowed to biodegrade, and stored for return to Earth. Urine is processed by the waste WRM for hygiene water. The urine brine concentrate that is a by-product of the reclamation process is also stored and returned to Earth.

The fire detection and suppression (FDS) subsystem consists of the hardware required to detect and suppress fires within the pressurized elements. Ionization sensors are installed in enclosed racks, infrared and ultraviolet sensors are used in open areas such as aisles and nodes, while thermal sensors are used in enclosed areas containing electrical cables. Carbon dioxide is the fire suppressant used in both the fixed and portable fire extinguishers. Halon suppressants may also be used.

4.3.8.2 Growth

Evolution in ECLSS is expected to be primarily through the replication of the baseline laboratory and habitation modules. However, the implementation may differ due to the module pattern growth and ECLSS support requirements for adjacent resource nodes, pocket labs, and airlocks. These requirements may be equal to or less than those of the baseline module pattern in which the U.S. hab and lab ECLSS must support the international modules, as well as adjacent resource nodes, airlocks, logistics module, and cupolas. A possible higher ECLSS load may occur if the evolution hab module is outfitted to support more than a crew of eight.

Baseline modularity requirements of the ECLSS will facilitate technology upgrades. Although in most cases, the upgrades can be accomplished on orbit, they should be performed on the ground due to the criticality of the ECLSS functions.

4.3.9 Fluid Management System (FMS)

The FMS is a central management and distribution system for fluids common to the stations elements and systems. The baseline FMS performs three major integrated functions: resupply and distribution of nitrogen; resupply, distribution, and disposal of water; and collection and disposal of waste gases.

The FMS delivers nitrogen and water to the laboratory modules for use in experiments. It supplies nitrogen and water to ECLSS for use in maintaining the on-board atmosphere. It also supplies nitrogen to the TCS for use in purging the ammonia working fluid from its lines during maintenance operations. The FMS sends waste gas to the propulsion system to fuel the resistojets.

The FMS also collects waste fluids produced by daily operations. The FMS receives excess water from ECLSS and stores it for later use in the labs. It collects waste water not recoverable by on-board systems from the labs and delivered it to the logistics carriers for return to Earth. It gathers waste gases from the lab modules, waste gases purged from the TCS, and excess hydrogen gas from ECLSS and delivers them to the propulsion system.

4.3.9.1 Baseline

The baseline FMS consists of three major subsystems: the integrated nitrogen subsystem (INS), the integrated water subsystem (IWS), and the integrated waste gas subsystem (IWGS). These three subsystems each contain the hardware, software, and interfaces with the other station systems needed to complete the overall FMS network.

The Unpressurized Logistics Carrier (ULC) resupplies the FMS with nitrogen and water. Because the ULC remains with the station until the next shuttle resupply flight, it augments the INS and IWS on-orbit storage capability. System sizing is driven by both the baseline, 90-day resupply interval and the requirement for contingency storage to accommodate a missed launch.

The main truss assembly supports the distribution lines of the FMS external to the pressurized elements. The external distribution lines allow the FMS to interface with users on the truss (the TCS and the propulsion system) and users internal to the pressurized elements through an interface with internal distribution lines located at the nodes.

To improve safety, high-pressure storage tanks for the INS and the IWGS are located on the truss away from the pressurized modules. A majority of the internal distribution lines are located in the resource nodes to supply the elements with common fluids. Water is stored in the nodes to eliminate the need for dedicated thermal conditioning and meteoroid debris shielding. Water produced by the shuttle's fuel cells while docked to station is scavenged by the IWS as additional resupply. This scavenged water is transferred from the node docking port to the water storage tanks. The IWS low storage pressure, approximately 20 psia, does not pose a crew safety hazard. Each of the lab modules contains its own internal distribution system which interfaces with the INS and IWS. Likewise, waste gases produced within the labs are transferred to and collected by the IWGS.

4.3.9.2 Growth

Potential evolution of the FMS exists in three distinct areas: expansion of station science activities, accommodation of Transportation Node requirements, and reduction of available EVA maintenance support. Expansion of station science activities will require the FMS to increase the capacity of the baseline nitrogen and water supply and waste gas collection services and be capable of supplying additional fluid services (Kr, Ar, He, and CO_2).

Transportation Node requirements entail the addition of significant cryogenic fluid handling services, expansion of baseline nitrogen and water supply and waste gas collection services, expansion of baseline nitrogen services to include high-pressure nitrogen lines, and the addition of Earth-storable propellant (hydrazine and bi-props) storage, distribution, and transfer services.

4.3.10 Propulsion System

The space station will orbit the Earth at altitudes of 190 nautical miles and higher. At these altitudes, the station is subject to drag forces produced by interaction with the Earth's atmosphere. The propulsion system is designed to periodically reboost the station to maintain the nominal orbital altitude. In addition to reboost, attitude control, and collision avoidance, the propulsion system also provides for disposal of certain waste fluids.

4.3.10.1 Baseline

The baseline propulsion system consists of a blowdown hydrazine system augmented by a resistojet system. The hydrazine system provides the primary thrust for attitude control torques and translation maneuvers. While the primary attitude control is accomplished by the CMGs, the station propulsion system is used to desaturate the CMGs, as a CMG back-up, and to damp out any disturbances that exceed the CMGs' capability. The resistojet system utilizes waste fluids to produce useful impulse to provide a supplemental reboost capability.

At each end of the transverse boom are two propulsion locations, one each above and below the boom. At each of the propulsion locations, there are two module interfaces, such that two modules can be collocated next to each other. When one of the modules is depleted of propellant, it is returned to the ground, and the adjacent module is utilized. The propulsion system will be entirely contained in the modules, which will have everything required to produce station thrust: propellant tanks, isolation valves, thrusters, heaters, instrumentation, and avionics. The only interfaces with the truss will be those required for power, data, and structure. Each module will be dual fault tolerant, since reboost performance is a station-critical requirement.

The resistojets provide for disposal of station waste fluids and produce some supplemental reboost capability. The resistojet assembly consists of a module of six thrusters, each developing one pound of thrust. To conduct the heated fluids away from the station's optical viewing areas, the thrusters are located at the end of a 30 meter boom (stinger). Waste fluids are heated and expelled out of one of these six thrusters. The resistojets use 500 watts of power to heat the waste products to 760^{o} C (1400^{o} F) before expelling them from the thrusters.

4.3.10.2 Growth

For the evolutionary reference configurations, growth requirements on propulsion system performance dictate major changes in the system. Although several candidate systems are being analyzed as replacements to the baseline, initial results favor a water electrolysis/H_2-O_2 bipropellant system.

The major elements of the proposed H_2-O_2 propulsion system include four reaction control modules (RCMs), two propellant production and storage modules, two supplemental storage modules, and two propellant transfer and distribution subsystems.

The RCMs will be located on the upper and lower keels and the transverse boom hydrazine modules will be removed. Each module contains six thrusters. Each propellant production module contains both an electrolysis unit for generating the O_2 and the H_2 and a graphite storage tank for the gaseous O_2 and H_2. Additional gas storage will be provided by the supplemental storage modules. The propellant distribution system carries the propellant from the electrolysis units to the storage tanks via 3000 psia high pressure lines. The propellant is then regulated to 300 psia prior to transfer to the RCMs.

The baseline resistojet system will still be used for disposal of waste fluids and to provide supplemental propulsion.

5.0 GROWTH DELTA ANALYSIS

The results of the analyses for the configuration concepts were provided and discussed earlier in this report. This section provides a more detailed explanation of the analyses methodology and the supporting data for intermediate configurations (deltas) attained during build-up from the baseline station.

5.1 ANALYSIS METHODOLOGY

Most of the analyses presented in this report were performed using the IDEAS^2 integrated space station analysis software. These analyses include:

- rigid-body controls analyses and flight mode characterization
- evaluation of microgravity environments
- orbital lifetime and reboost analyses
- determination of payload viewing envelopes
- structural dynamics analysis

To ensure consistency, a single geometric model was created for each of the delta configurations using an enhanced version of the GEOMOD solids modeling program. These models were used to form the basis for all of the various analysis functions of that configuration. The geometric data was then processed by MODGEN which creates analytical models compatible with the analysis modules.

All analyses used the Cartesian coordinate definitions of the baseline station, i.e., "+x" for line of flight and "+z" for the nadir (toward Earth) direction.

5.1.1 Attitude Control Analysis

Attitude control analysis was used to determine the Torque Equilibrium Angle (TEA). The TEA is the flight angle that minimizes the force/torque effects of environmental forces. Flying the station at the TEA allows the minimization of the size of the space station's control system. The Articular Rigid-Body Control Dynamics (ARCD) module was used to estimate the TEA to be used for control and microgravity analysis.

The ARCD module determines the environmental forces and torques acting on the Space Station *Freedom* over an orbit. The environmental effects modeled by the ARCD program are:

- Aerodynamic drag
- Gravity gradient
- Solar radiation pressure (absorption only)
- Gyroscopic effects (i.e., due to motions of articulating parts)

Inputs to the ARCD module include:

- Space Station *Freedom* mass and projected area properties
- Orbit geometry
- Environmental constants

- Articular part characteristics (feathering, sun-tracking, axes of rotation)
- Control system parameters

ARCD models the *Freedom* Station as a rigid body. The articulating parts are modeled as rigid free bodies constrained to the station. Using the model input, the ARCD module computes the station's mass properties and projected areas and the torques generated throughout an orbit, accounting for variations due to the articulating parts and their motions.

The outputs of ARCD include time histories of the following quantities calculated about 60 times per orbit:

- Environmental forces and torques
- Required control forces and torques
- Angular momentum requirements
- Motions of articulating parts
- TEA
- Propellant mass required for orbit-keeping and attitude control

Steady state attitude control system sizing was performed using the Attitude Predict (ATTPRED) module of IDEAS[2]. The modified ATTPRED software module allows the simulation of Control Momentum Gyroscopes (CMGs) for attitude control. A CMG control law/momentum management algorithm, steering law, and model has been implemented into the software. This controller generates a torque command which provides continuous closed-loop control of both the spacecraft attitude and CMG angular momentum via state feedback and disturbance rejection. Given a torque command, the steering law generates appropriate gimbal rate commands, which distribute the CMG momentum vectors such that all inner gimbal angles are equal and all outer gimbals are equally spread out. The double-gimbaled CMGs are modeled as error-free actuators, which deliver the gimbal rate command subject to user-defined gimbal freedom limits and gimbal rate limits.

5.1.2 Microgravity Environment Determination

A major requirement for the station is to provide a steady-state microgravity-free environment for scientific experiments and commercial research and materials manufacturing. Microgravity requirements for these activities range from 0.1 to 100 micro-g's. The Program Definition and Requirements Document (PDRD) for the baseline station states that the steady-state acceleration level in the pressurized modules should be limited to 10 micro-g's. In order to assess the capability of the evolution options to accommodate microgravity experiments, gravity level contour plots in the form of ellipses overlaid on the ZX and YZ planes of configuration models were generated using ARCD module data as input. The ellipses circumscribe areas of the space station in which the gravitational acceleration field is less than any given input level. The ellipses are determined by the values of the following steady-state parameters:

- Gravity gradient
- Centripetal acceleration gradient
- Atmospheric drag

- Attitude drift

Dynamic inputs, such as crew activities, Mobile Servicing Center (MSC) translation, and orbiter docking and berthing were not considered in this analysis.

5.1.3 Orbit Lifetime and Reboost Analysis

The assumed altitude strategy allowed the station's orbit to decay cyclically from its nominal altitude to its lowest altitude of 220 nautical miles (nmi). At the lowest altitude, the space station will conduct shuttle resupply rendezvous, and space station reboost. For all evolution configurations, the additional mass and drag from the growth elements will affect both the rate of decay and the amount of propellant required for reboost. The Orbit Lifetime (OL) module was used to calculate the orbital lifetimes of the configurations and to determine the post-assembly reboost propellant requirements.

Given the spacecraft physical characteristics (mass, cross-sectional area, etc.), initial orbit parameters, and launch date, the OL module calculates changes in spacecraft orbits. It considers orbit decay due to the environmental perturbations of atmospheric drag, solar radiation pressure (including effects of the Earth's shadow), Earth oblateness, and the gravitational attractions of the sun and the moon (both on spacecraft and on the Earth). Only long-term changes are considered. Short-term variations are assumed to average out over one orbit.

5.1.4 Structural Dynamics Analysis

To validate the concepts which have been developed for evolution of Space Station *Freedom*, a structural dynamics and loads analysis will be performed for both the Transportation Node and R&D evolution configurations. Detailed structural analyses have not been completed for any of the configurations contained in this report. However, several similar configurations have been analyzed, and the results provide meaningful insight into the structural characteristics of these concepts. The following discussion outlines the analysis approach taken to assess the feasibility of large structures such as the growth configurations. Sections 2.3.5 and 3.3.5 of this report contain qualitative extrapolations from previous analyses to the R&D and Transportation Node configurations.

Previous structural analyses of conceptual designs have roughly followed the approach described below.

1. *Generate finite element structural model.* This first step requires identification of the mass properties, stiffnesses, and orientations of all components of the system. In particular, it has been shown that the behavior of large structures such as these is highly sensitive to the stiffness of the alpha joint and to the amount of mass near the ends of the transverse boom and somewhat less sensitive to the mass and stiffness of appendages (solar arrays and solar dynamic modules) and of components near the module cluster. This will be the case for the configurations described here.

2. *Solve for normal modes of the system.* Past analyses have used a graphics-based program such as SDRC/SUPERTAB to piece together the finite

element model, but the actual calculation of system modes was performed in MSC/NASTRAN.

3. *Determine appropriate forcing functions.* The most intense loadings experienced by this type of structure occur during reboost and docking. Docking loads can be approximated by impulses applied at the docking ports. Approximate reboost functions can be determined from rigid body equations of motion and mass properties, but more precise functions are gained by incorporating flexible body effects.

4. *Determine system response to forcing functions.* By assembling the normal modes of the system into a modal formulation, the response (displacements, accelerations, and member loads) of the system due to the given forcing functions can be determined at key locations about the structure. Locations such as the tip of solar arrays, the center of the modules, the interface between the boom and keels, and the base of the solar dynamic pointing unit are investigated to be certain that reasonable limits are not exceeded.

Data produced from detailed analyses of the specific R&D and Transportation Node reference configurations will be included in future updates of this document as the analyses are completed.

5.2 R&D DELTA CONFIGURATION CONCEPT ANALYSES SUMMARY

The R&D configuration is divided into twelve growth deltas. Table 5.2-1 provides the elements added for each delta. It should be noted that these deltas do not necessarily correspond to ETO flights and were conducted only to establish that the station maintains the required control characteristics during growth.

Analyses were performed for each of the R&D deltas to assess the physical characteristics of *Freedom* as it grows from its baseline configuration to the R&D configuration. A summary of the results of the delta analyses is presented in Table 5.2-2. The mass of the station more than doubles during the growth process, with the biggest increase occurring at delta six where the STV servicing facility and fuel depot are added to the lower keels.

The origin of the geometrical coordinate system used is located in the middle of the center truss bay of the transverse boom. The coordinate system has the station X axis parallel to velocity vector, the station Y axis aligned perpendicular to orbit plane, and the station Z axis directed toward the center of the Earth. The center of mass varies from zero to -2.6 meters in X, from -0.2 to 0.7 meters in Y, and from zero to 7.8 meters in Z. The moments and products of inertia increase by an order of magnitude during station evolution, with the larger increases associated with the deltas that include solar dynamic power units and STV equipment. Throughout the buildup, the products of inertia are always about two orders of magnitude smaller than the moments of inertia leading to small body-to-principal-axis rotations once the keels are attached.

Once the keels are added as part of the second delta, all subsequent deltas yield average flight attitudes within three degrees of local vertical-local horizontal (LVLH) for roll, pitch, and yaw. The small flight attitudes, coupled with a center of mass near the module pattern, result in a one to two micro-g environment for the laboratories depending on payload placement and STV payload/fuel status. Steady-state control

Characteristics	Range	Comments
Mass (kg)	266,000 to 687,000	Largest mass increase is at delta 6
Center of mass (m) from geometric center of transverse boom	X = -2.6 to 0.0 Y = -0.2 to 0.7 Z = 0.0 to 7.8	Where applicable, STV and full STV tank farms were assumed. min X delta 10 max X delta 5 min Y delta 2 max Y delta 4 min Z delta 2 max Z delta 6
Inertias ($kg \cdot m^2$) with respect to the center of mass	IXX =1.2E8 to 1.2E9 IYY = 2.3E7 to 3.9E8 IZZ = 1.3E8 to 9.2E8	Where applicable, STV and full STV tank farms were assumed. Products of inertia are two orders of magnitude below the moments of inertia.
Average flight attitude (degrees) from LVLH	Deltas 2 thru 12 X (roll) = 0.0 to 3.0 Y (pitch)= 0.0 to 2.4 Z (yaw) = -0.5 to 0.5	Both the assembly complete and deltas have pitch values over -5 degrees. min X delta 1 max X delta 7 min Y delta 5 max Y delta 12 min Z delta 7 max Z delta 3
Control momentum (N•m•s) peak requirement for steady-state operations	4,000 to 15,000	Values depend on atmospheric and control assumptions. For all deltas, the flight attitude is maintained with less than +/- 2 degrees per orbit deviation from the average flight attitude using the baseline CMGs.
Ballistic coefficient (kg/m^2)	47 to 64	min delta 1 max delta 7

Table 5.2-2 : Analytical Characteristics Summary for the R&D Deltas

momentum requirements are all within the capability of the six baseline CMGs with attitude deviation (all less than +/- two degrees per orbit) depending on atmosphere and control law assumptions. Attitude error rates for all delta configurations and for all assumptions are below 0.005 degrees/sec.

Table 5.2-1 R&D CONFIGURATION DELTA COMPONENTS

DELTA	COMPONENTS
D0	Baseline Configuration
D1	1 Solar Dynamic Module Pair, Space-Based OMV & Accommodations
D2	Upper/Lower Keels & Booms
D3	1 Hab Module, 2 Resource Nodes
D4	1 Solar Dynamic Module Pair, Attached Payloads
D5	1 Large Pocket Lab, 1 Lab Module, 2 Resource Nodes, Attached Payloads
D6	STV & Hangar, Assembly Platform, Attached Payloads
D7	1 Hab Module, 1 Resource Node
D8	1 Solar Dynamic Module Pair
D9	1 Lab Module
D10	1 Small Pocket Lab
D11	1 Solar Dynamic Module Pair
D12	1 Large Pocket Lab

The average drag area of *Freedom* increases by more than 100% as it evolves from the baseline configuration to the R&D reference station. The corresponding increase in mass offsets the increase in area, resulting in small variations in the ballistic coefficient ranging from 50 kg/m^2 (no STV, fuel) to 60 kg/m^2 (STV and fuel) for the R&D configuration. During the buildup process, the ballistic coefficient peaks at 64 kg/m^2 at delta 7. As compared with the baseline configuration, the R&D configuration will decay at a slower rate, but require more than twice as much fuel per reboost.

5.3 TRANSPORTATION NODE DELTA CONFIGURATION ANALYSES SUMMARY

The interim configuration for the lunar/Mars Transportation Node is the Lunar Operations Transportation Node. Analysis of the lunar concept was discussed earlier in this document. Further deltas for station augmentation to accomplish growth to the transportation nodes is discussed in the Station Evolution Reference Configuration Databook.

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16. Abstract

Two conceptual evolution configurations for Space Station Freedom, a Research and Development configuration, and a Transportation Node configuration are described and analyzed. Results of pertinent analyses of mass properties, attitude control, microgravity, orbit lifetime, and reboost requirements are provided along with a description of these analyses. Also provided are brief descriptions of the elements and systems that comprise these conceptual configurations.

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