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Analyses of a Rotating Advanced-Technology

Space Station for the Year 2025

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ABSTRACT

Analyses have been made of several aspects of a rotating Advanced-Technology Space Station configuration generated under a previous study. The analyses included examination of several modifications of the configuration, interface with proposed launch systems, effects of low-gravity environment on human subjects, and the Space Station assembly sequence. Consideration also was given to some aspects of Space Station rotational dynamics, surface charging, and the possible application of tethers.

ABBREVIATIONS AND SYMBOLS

a	Acceleration, meters/second^2
A_1	Area, meters^2
d	Moment arm, meters
CLO	Closet
EMI	Electromagnetic Interference
EVA	Extra Vehicular Activity
GEO	Geostationary Earth Orbit
HLLV	Heavy Lift Launch Vehicle
I	Moment of inertia, kilogram-meters^2
I_1	Current, amperes
I_{sp}	Specific Impulse, Newton-seconds/kilogram
IOC	Initial Operating Capability
IVA	Intra-Vehicular Activity
L	Torque, Newton-meters
LAV	Lavatory
LEO	Low-Earth Orbit
N	Number of thruster
OMV	Orbital Maneuvering Vehicle
OTV	Orbital Transfer Vehicle
P	Power, Watts
PC	Pressure Cure
ppbv	Parts Per Billion by Volume
R	Major radius of torus, meters
R_1	Resistance, ohms
STS	Space Transportation System

S L   Stairs, Landing, direction indication

T   Thrust per rocket, Newtons

w   Weight of fuel, kilogram

WAO (sc) Wet Air Oxidation (super-critical)

ℓ Length, meters

ρ Resistivity, ohm-cm

ω Angular velocity for rotation, radians/second

Ω Angular velocity for precession, radians/second

ρ Density, kilogram/meter^3

σ Stress, Pascals

A dot (·) over a symbol designates a time derivative of that factor.

ANALYSES OF A ROTATING
ADVANCED-TECHNOLOGY SPACE STATION
FOR THE YEAR 2025

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SUMMARY

The Bionetics Corporation was tasked by the NASA-Langley Spacecraft Analysis Branch to perform further analyses of an Advanced-Technology Space Station conceptual configuration which was generated under a previous study. The Advanced-Technology Space Station was projected as being operational around the year 2025. The purpose of the present study was to use the configuration as a starting point to perform several tasks, which included:

1. Generate alternate Space Station configurations as additional thoughts or analyses might suggest.

2. Examine interfaces with proposed space transportation systems.

3. Generate proposed layouts for the Space Station concepts.

4. Suggest assembly sequences.

5. Perform quantitive and qualitative analyses pertinent to the Space Station operation, and provide inputs necessary to perform systems analyses, using the Integrated Design and Evaluation Analysis System (IDEAS) programs.

6. Identify pacing technology areas.

The above items are interactive, so that a change in one may cause changes in the others. Also, item 5 is all inclusive, since it implies analyses of the Space Station operations, structures, interior layouts, and so on.

Each of the topics has been studied in some detail, and the results have led to some suggested configuration changes. The size and weight of the Space Station components are such that large boosters are required for launching the components into orbit. The required launch capabilities are in the range of proposed advanced systems.

General layouts of the various parts of the Space Station are suggested, based on the function of the station, the number of inhabitants, and taking into account the fact that the Space Station is rotating. An assembly sequence is suggested, based on providing a safe haven for an assembly crew and obtaining useful data or products as soon as possible. Several pacing technology areas, some rather general and others unique to Space Stations with rotating portions, are identified. Finally, several research areas, or areas of additional study, have been identified for the suggested Advanced-Technology Space Station configuration.

ANALYSES OF A ROTATING
ADVANCED-TECHNOLOGY SPACE STATION
FOR THE YEAR 2025

1.0   INTRODUCTION

A logical step in the exploration and utilization of space is establishment of manned space stations. To this end, the United States space program has as one of its objectives the construction of a low-Earth-orbit Space Station by about the year 1994. The initial configuration is envisioned to be a large grid framework on which are mounted tanks, solar collectors, and operational equipment. (See Figure 1.0-1 and References 1-1 and 1-2.) The configuration has been described in some detail in many published documents, although the design is still evolving.

As functions of initial Space Stations are expanded, there will be new requirements that may dictate new configurations and characteristics. A previous study (Reference 1-3) was a preliminary examination of possible functions of a Space Station for the time period around 2025. Consideration of the functions, and of projected advanced Space Station subsystems, led to a conceptual Sun-oriented configuration whose prominent features were a large rotating torus, a central non-rotating tube, a group of six solar-dynamic power generators, a docking and erection bay, and counterrotating circular tanks.

The purpose of the present study was to use the configuration as a starting point, and to perform several tasks to refine and possibly modify the configuration. The analyses included the following:

1.   Generate alternate advanced Space Station configurations as new or additional analyses suggested.

COMMUNICATION ANTENNA (TDRSS)

SOLAR POWER, 2 UNITS AT 12.5kWe PHOTOVOLTAIC 25kWe SOLAR DYNAMIC

SERVICE AND STORAGE BAY

RADIATORS

CROSS BOOM (5m TRUSS 175m LONG) WITH 2 ROTATING JOINTS

PRESSURIZED MODULES FOR HABITAT AND LABORATORIES (SHUTTLE BAY COMPATIBLE)

KEELS (5m TRUSS 100m LONG) (MAINTAINED LOCAL VERTICAL)

EARTH SENSING INSTRUMENTATION

SOLAR/SPACE INSTRUMENTATION

FREE-FLYER PLATFORM

SHUTTLE ORBITER

OMV

PANELS AND COLLECTOR FACE SUN

Figure 1.0-1   Baseline Configuration Dual-Keel Space Station, Principal Features

2. Examine interfaces with the proposed space transportation systems.

3. Generate proposed layouts for the Space Station concepts.

4. Suggest assembly sequences.

5. Perform quantitative and qualitative analyses pertinent to the Space Station operation, and provide inputs necessary to perform systems analyses to be made using the IDEAS programs.

6. Identify pacing technology areas.

References

1-1   Space Station Reference Configuration Description. NASA
        Report JSC 19989, August 1984.

1-2   Architectural Control Document. Preliminary Report, NASA JSC
        Space Station Office, June 1986.

1-3   An Advanced Technology Space Station For the Year 2025.
        Study and Concepts, NASA CR-178208, March 1987.

2.0 REFERENCE ADVANCED-TECHNOLOGY SPACE STATION EXTERNAL CONFIGURATION

The primary components of the starting configuration (from Reference 1-3) are shown in Figures 2.0-1 and 2.0-2, and pertinent masses, inertias, and dimensions are given in Table 2.0-1. The large-scale components of the Space Station are described briefly below.

2.1 ROTATING TORUS

The rotating torus is the primary human habitat and rotates to provide the desired level of artificial gravity. It is sectioned so that part is used for fuel storage and for operational equipment. The rate of rotation can be varied to obtain the desired artificial-gravity level. The dimensions of the torus (Table 2.0-1) are such that a lunar "g" (1/6 of the Earth gravity) can be obtained at about 1.14 rpm, and one Earth "g" can be obtained at about 2.8 rpm. These values, the corresponding angular rates, and the Space Station radius result in combinations which fall within the acceptable operating range as designated in Figure 2.1-1 (from Reference 2-1). The rotating torus provides some degree of inertial stabilization of the Space Station.

2.2 CENTRAL TUBE

The central tube is a large non-rotating structure to which all elements of the Space Station are attached. Its geometric characteristics are given in Table 2.0-1. The tube is the primary access path to the various components of the Space Station. It is about 16 meters in diameter, and houses the microgravity facility.

SOLAR FACING ORBIT WITH
SOLAR DYNAMIC POWER AS
6 UNITS AT 425kWe EACH

ROTATING
TORUS.
HABITAT AND
LABORATORY.
TORUS; 229m DIA.
RING; 15.3m DIA.

COUNTER-
ROTATING
INERTIAL
BALANCE AS
WATER
TANKS

NON-ROTATING
DOCKING AND ERECTION BAY
AS 67m CUBE (ATTACHED TO
CENTRAL TUBE).

NON-ROTATING
CENTRAL TUBE AND PLATFORM.
MICROGRAVITY, SOLAR AND
HORTICULTURE LABS.
TUBE; 15m DIA. 100m
PLATFORM; 5m TRUSS.
158m DIAMETER

RADIATOR

ROTATING
ENDS

OBSERVATION TUBE.
EARTH/SPACE INSTRUMENTS
290m LONG, (MAINTAINED
PERPENDICULAR TO
THE ECLIPTIC PLANE)

Figure 2.0-1 Advanced-Technology Space Station Concept, Principal Features of
Reference Configuration

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- SPACE STATION IN SOLAR FACING ORBIT

1. ROTATING TORUS

2. CENTRAL TUBE AND PLATFORM

5. SOLAR DYNAMIC COLLECTORS

6. INERTIAL BALANCE ROTATORS

2. CENTRAL TUBE

4. DOCKING AND ERECTION BAY

3. INSTRUMENTATION TUBE, (MAINTAINED PERPENDICULAR TO THE ECLIPTIC PLANE)
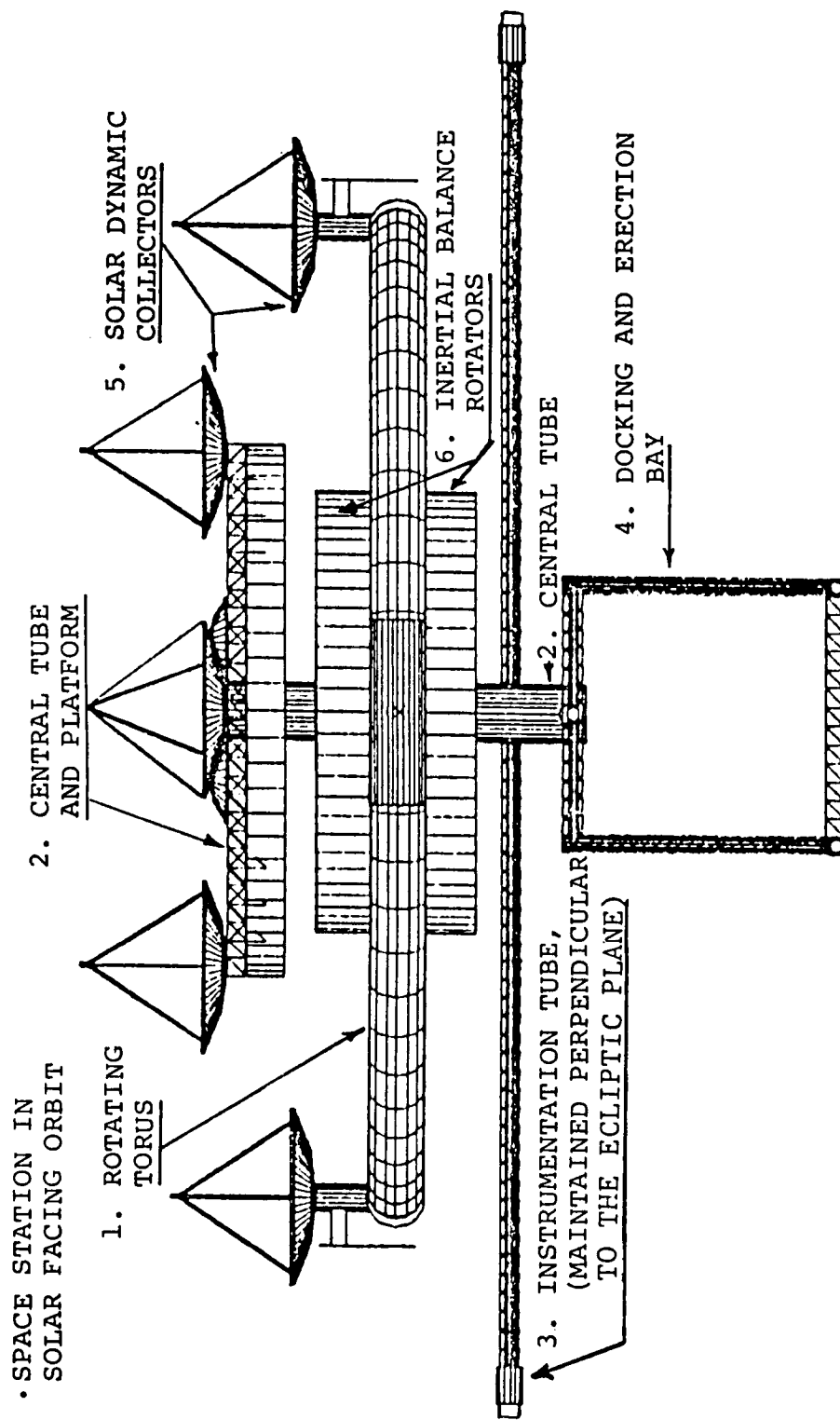
Figure 2.0-2   Advanced-Technology Space Station Concept, Features as Described in Table 2.0-1, Side View, Reference Configuration

TABLE 2.0-1 ADVANCED-TECHNOLOGY SPACE STATION, SUMMARY
OF PERTINENT FEATURES FOR THE REFERENCE CONFIGURATION

A. PRINCIPAL ELEMENTS AND FUNCTIONS

Element	Function
1. Rotating Torus	Habitat, medical, life support, fuel generation, communication and control center, variable gravity facility, component fabrication, storage
2. Central Tube and Platform	Structural core, materials transfer, microgravity processing, solar observatory, horticulture research, orbital science and technology, air lock, storage
3. Observation Tube	Earth and space instruments, communications antennas, energy relay beams, storage
4. Docking and Erection Bay	Rendezvous and docking to assemble, fuel, and deploy spacecraft; pressure ports for crew transfer; holding facilities for OMV, OTV
5. Solar Dynamic Power Collectors	On-board power generation by 6 units (4 units on the platform and 2 units on the rotating torus)
6. Inertial Balance Rotators	Angular momentum of the torus nulled by counterrotation, on-board water storage

B. ROTATING TORUS, DESCRIPTION AND FEATURES

1. Torus Diameter to Center of Ring	229 m	(750 ft)
2. Ring Diameter	15.3 m	(50 ft)
3. Spokes (Tube Inside a Truss)		
Tube Diameter	3.2 m	(10.5 ft)
Truss Bay Width	5.2 m	(18.3 ft)
4. Torus Volume	1.305×10^5 kg	$(4.61 \times 10^6$ lb)

B.   ROTATING TORUS, DESCRIPTION AND FEATURES (cont.)

5.   Torus Mass
     Shell (Aluminum, 10 mm, 8.15×10^5 kg $(1.80 \times 10^6$ lb)
     0.375", walls)

     Floor Loading, 50 percent 8.02×10^5 kg $(1.77 \times 10^6$ lb)
     of Ring, 1436 Pa (30 psf)

     O_2 and H_2 in 50 percent of 3.00×10^4 kg $(7.24 \times 10^4$ lb)
     Ring Volume at Atmospheric
     Pressure

6.   Moment of Inertia 2.16×10^{10} kg-m^2 $(1.59 \times 10^{10}$ lbm-ft^2)

7.   Angular Momentum at 1.141 rpm 2.58×10^9 kg-m^2-sec $(1.90 \times 10^9$ lbm-ft^2-sec)
     (Provides 0.166 g in Ring)

C.   CENTRAL TUBE AND PLATFORM, DIMENSIONS AND FEATURES

1.   Platform (Truss Structure)
         Truss Bays   5 m   (16.4 ft)
         Platform Diameter   158 m   (520 ft)

2.   Horticultural Domes (Spherical
     Caps)
         Cap Diameter   25 m   (82 ft)
         Cap Height   5 m   (16.4 ft)

3.   Central Tube
         Diameter   15 m   (49 ft)
         Length   100 m   (329 ft)
         Volume 1.762×10^4 m^3 $(6.24 \times 10^5$ ft^2)

4.   Microgravity Facility (Cylinder)
         Diameter   8 m   (26.2 ft)
         Length   25 m   (82 ft)
         Volume   1256 m^3 $(4.44 \times 10^4$ ft^3)

5.   Solar Observatory Volume   1767 m^3 $(6.24 \times 10^4$ ft^2)
     (Solar-facing end of Central Tube)

6.   Air Locks (Concentric Doors)
         Maximum Diameter   13 m   (42.5 ft)
         Half Diameter   7 m   (23 ft)
         Minimum Diameter   3 m   (10 ft)

TABLE 2.0-1 ADVANCED-TECHNOLOGY SPACE STATION, SUMMARY OF PERTINENT
FEATURES FOR THE REFERENCE CONFIGURATION (cont.)

D. OBSERVATION TUBE, DIMENSIONS AND FEATURES (TUBE INSIDE A SQUARE TRUSS)

1. Truss Bays   5 m   (16.4 ft)

2. Tube Diameter   3.2 m   (10.5 ft)

3. Tube Length   290 m   (950 ft)

4. Tube Volume (Total)   2211 m^3 (7813 ft^3)

E. DOCKING AND ERECTION BAY, DIMENSIONS AND FEATURES

1. Cube Sides (12)   67 m   (220 ft)

2. Tube Inside a Square Truss
      Tube Diameter   3.2 m   (10.5 ft)
      Truss Bays   5 m   (16.4 ft)

3. Pressure Port Locations:

A pressure port for transfer of crew located at each of the 4 bottom
corners of the bay.

4. Manipulator Support:

   • Every point within the bay can be reached by at least 2
     manipulators.

   • For a distance of 15 m (49 ft) outside the bay, all points can be
     reached by at least 2 manipulators.

   • For a distance of 35 m (100 ft) outside the bay, all points can be
     reached by 1 manipulator.

   • All manipulators have the capability to interchange end effectors.

F. SOLAR DYNAMIC POWER GENERATION WITH 6 UNITS OF 425 kWe EACH

1. Collector Diameters   39 m   (126 ft)
   (Overall Energy Conversion
   0.4)

2. Radiator Area Total (Equal   6950 m^2 (74846 ft^2)
   to Collector Area)   (Divides between torus and platform)

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F.   SOLAR DYNAMIC POWER GENERATION WITH 6 UNITS OF 425 kWe EACH (cont.)

3.   Mounting and Application,
     Four Units on Torus   Power for solar observatory
                                   microgravity processing, Earth/
                                   space experiments, communications,
                                   spacecraft servicing and assembly.
                                   (Excess power to torus for fuel
                                   generation.)

     Two Units on Torus   Power for life support, fuel
                                   generation, control system, data
                                   systems, on-board fabrications.

G.   INERTIAL BALANCE BY A WATER RESERVOIR COUNTERROTATING AT 10 RPM

1.   Reservoir Dimensions O.D.   91.4 m   (300 ft)
                          I.D.   30.4 m   (100 ft)
                    Thickness   15 m   (49 ft)

2.   Inertial Balance Estimate

     Moment of Inertia 2.47×10^9 kg-m^2 (1.82×10^9 lbm-ft^2)
     Required

     Weight of Water Required 1.30×10^6 kg   (2.90×10^6 lb)
     (Water Depth at Reservoir   0.3 m   (1 ft)
     Rim)

3.   Options for Final Trim to Null Balance:

     · Vary the rotational speed of the reservoir.

     . Vary the water level in the reservoir.

     . Provide an auxiliary water channel and control the flow velocity.
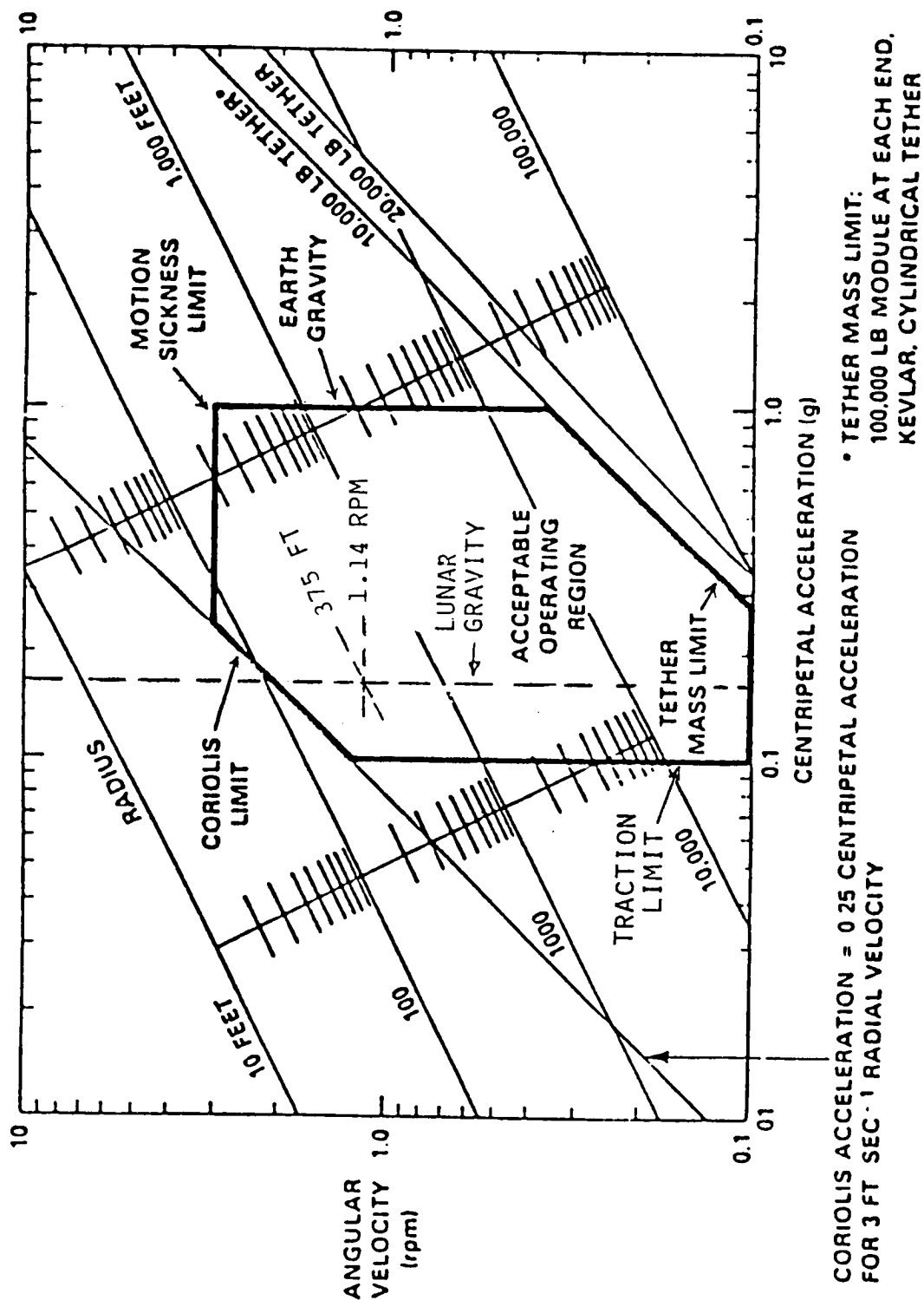
Figure 2.1-1 Artificial Gravity Parameters (Reference 2-1)

2-8

The upper end of the tube is Sun-pointing and contains scientific instrumentation for viewing the Sun.

2.3   SPOKES

The spokes provide pathways from the central tube to the torus and provide levels of gravity from near zero (close to the hub) to near torus gravity levels.

2.4   OBSERVATION TUBE

The ends of the observation tube contain sensors and viewing equipment for Earth and sky observations. The observation tube is rigidly attached to the central tube and remains perpendicular to the plane of the ecliptic in order to provide for direct Earth observation at all times.

2.5   DOCKING AND ERECTION BAY (BERTHING AREA)

The berthing area provides a location for docking a Shuttle or other spacecraft and also mechanisms for loading or unloading them. It also has tracks along which the mechanisms can move. It is a large non-rotating section, rigidly attached to the central tube.

2.6   SOLAR COLLECTORS

Six solar collectors are shown on the Space Station. Four are on a platform that is rigidly attached to the non-rotating central tube, and two are shown on the rotating torus. Solar dynamic energy sources were selected over solar panels because of their greater overall efficiency and because they create less aerodynamic drag.

References

2-1   Cramer, D. Bryant: Physiological Considerations of
        Artificial Gravity, Applications of Tethers in Space.   NASA
        Conference Publication 2364, Volume 1, June 15-17, 1983.

3.0 PURPOSE OF THE PRESENT STUDY

The present study is a continuation of the work done under Reference 1-3. The configuration proposed in that Reference was based on providing capabilities to perform a list of functions that appeared to be appropriate for the time frame around 2025. As the functions have been studied in more detail, and as operational aspects were examined, some internal and external configuration modifications were suggested. The general tasks to be addressed in the present study are listed in Section 1.0. Some of the issues to be studied under each task are given in the following sections.

3.1 ALTERNATE CONFIGURATIONS

The Reference configuration, shown in Figures 2.0-1 and 2.0-2 was determined to a large degree by two factors: (1) provision of a rotating habitat to create an artificial gravity field, and (2) a non-rotating section to simplify docking. One of the proposed features was a pair of counterrotating tanks to permit varying the angular momentum of the Space Station. It was felt advisable to examine in more detail the implication of the rotating tanks with respect to added complexity, mass, and launch requirements.

3.2 INTERFACES WITH PROPOSED TRANSPORTATION SYSTEMS

The Space Station in this study is relatively large and heavy. It was necessary to make some judgements relative to size and mass of components that could be lifted into orbit, using launch vehicles which are being considered for future applications. These considerations have

direct impact on the number of launches required for assembly of the Space Station.

3.3 PROPOSED LAYOUTS FOR SPACE STATION CONCEPTS

It was felt that time would permit a reasonably detailed layout for only one configuration. However, since the configurations considered were generally similar, this was not a serious limitation. The layouts considered equipment and areas needed for the functions identified in Reference 1-3, and also the influence of rotation on preferred equipment orientation.

3.4 ASSEMBLY SEQUENCE

Several factors influenced the selection of an assembly sequence. These included the volume and weight-lifting capability of proposed launch vehicles, provision of a safe haven for any assembly crew, and early return of data or products from the Space Station.

3.5 ANALYSIS OF SPACE STATION OPERATION

There are many aspects of Space Station operation that could be examined. However, since the configuration under study has large rotating elements, most of the operations considered were related to rotational aspects concerning attaining desired spin rates and maintaining orientation of the Space Station.

3.6 PACING TECHNOLOGY AREAS

Since the operation of the Space Station under study would begin about the year 2025, there will probably be many advances in materials,

propulsion, control systems, and other key areas. One of the purposes of the present study was to search for areas in which technology must advance to make this Advanced-Technology Space Station feasible in the designated time frame.

4.0   CONSIDERATIONS FOR ARTIFICIAL GRAVITY

4.1   THE EFFECTS OF WEIGHTLESSNESS

The various physiological systems of the human body respond differently to the weightless environment of space. Some systems, specifically the vestibular and cardiovascular systems, have limited responses in extent and time by adaptation and/or stabilization to the new environment. Other systems, particularly the muscle and skeletal, seem to have more unlimited or unstabilized responses to weightlessness, at least for the times thus far experienced. These effects of weightlessness are considered critical to man's continued presence in space for extended periods and are thus examined herewith. As in all problems of physiology, there is great variability in man's response to weightlessness. In addition, as man's experience in weightlessness has progressed, there has been an evolving change in the regimen followed by the various crews which have spent long periods in space. These factors impact the correlation of physiological responses with time of exposure to weightlessness.

4.1.1   Vestibular System

The first problem is rooted in the vestibular mechanism of the inner ear (Figures 4.1-1 and 4.1-2). This mechanism, which evolved with man in an environment of weight, experiences no weight in space. The vestibular system consists of two basic elements, linear accelerometers (otoliths, the utricle and saccule of Figure 4.1-2) and angular accelerometers (semicircular canals) (Reference 4-1). The otoliths are fundamentally "down" locators, indicating the direction of Earth's
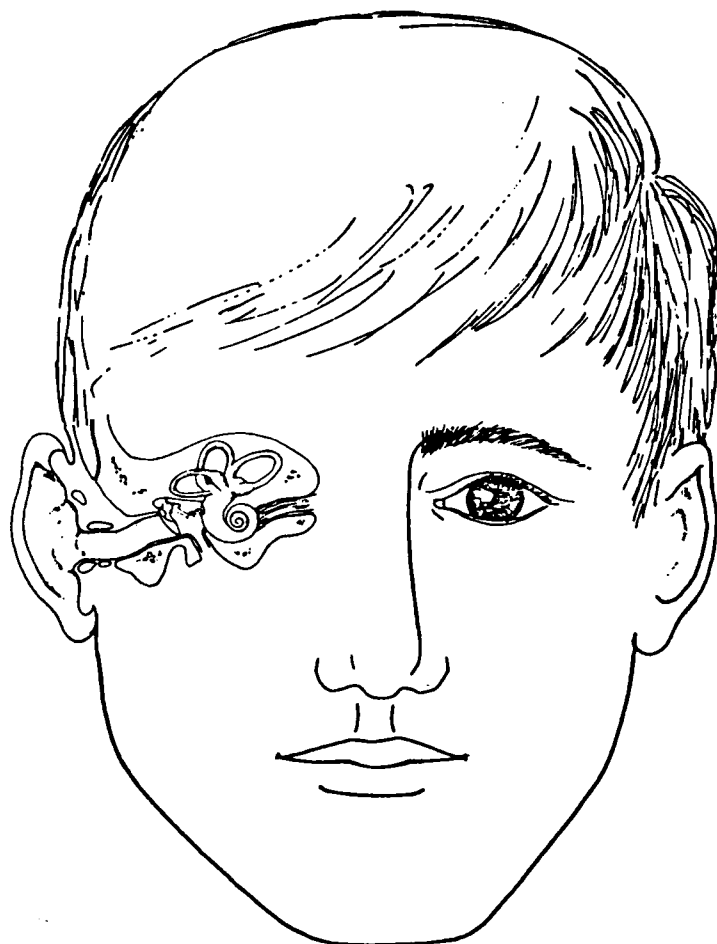
Figure 4.1-1 The Location of the Vestibular System

ANTERIOR (VERTICAL) SEMICIRCULAR CANAL

LATERAL OR HORIZONTAL SEMICIRCULAR CANAL

VESTIBULAR NERVE

COCHLEAR NERVE

SCARPA'S GANGLION

COCHLEA

POSTERIOR (VERTICAL) SEMICIRCULAR CANAL

MACULA OF THE UTRICLE

MACULA OF THE SACCULE
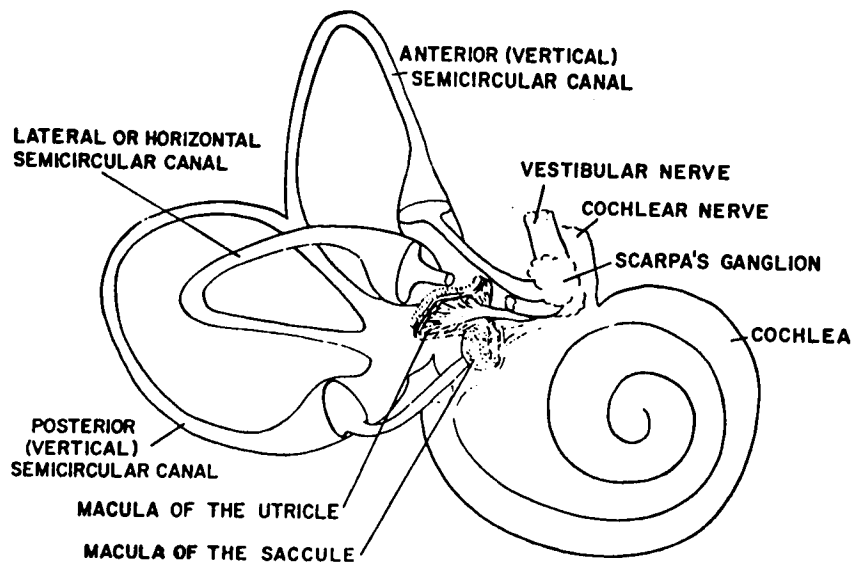
Figure 4.1-2 The Vestibular System (Reference 4-1)

gravity. In weightlessness there is no "down", and because the semicircular canals and vision are not basically affected by weight, a conflict of sensory cues going to the brain from the sensors exists, especially when head and body movements are made. Such conflicts are the fundamental cause of vertigo and motion sickness (Reference 4-2). Thus, in weightlessness there are illusions such as falling, of body motions, of viewed objects moving, and of body orientation, as well as dizziness, stomach awareness, nausea, and vomiting (References 4-1, 4-2, 4-3, 4-4, 4-5, 4-6, 4-7, 4-8, and 4-9). Adaptation to these disturbing features generally occurs in two to three days (References 4-3, 4-4, 4-5, 4-6, 4-7, and 4-10). For sensitive persons, slower adaptation is possible. Some persons, on rare occasions, have had these related sensations reoccur well into a long flight (Reference 4-5). Generally, there are no complexities after adaptation. A regimen of regulated head motions can enhance adaptation in the weightless environment or in any vestibularly strange environment. On return to Earth, there is a period of readaptation with similar adverse symptoms for a period equal to or longer than the initial adaptation period (References 4-5, 4-6, and 4-8). Clearly, the sensitivity of the vestibular mechanisms is a significant consideration in crew selection.

4.1.2 Cardiovascular System

The second limited problem is associated with the heart and the blood distribution system (the cardiovascular system). The environment of weight produces a hydrostatic pressure in the cardiovascular system. On Earth, the blood and tissue fluids tend to pool in the lower extremities of the body, where the elasticity and strength of the

vascular and surrounding muscles are important in returning blood to the heart. In the weightless environment, the hydrostatic pressure is no longer present, and the blood returns more easily to the heart. The center of mass of the blood and tissue fluids moves toward the heart and head; fullness of the chest and head, with face puffiness, occurs (References 4-5, 4-6, 4-7, 4-8, 4-9, 4-10, 4-11, 4-12, and 4-13). The venous blood receiving chamber of the heart (the left auricle) senses excessive blood volume and, through neural processes, causes the fluid portion of the blood (plasma) to decrease until such time as adequate blood volume exists for the weightless state (Reference 4-9). There is an accompanying decrease in weight due to this fluid loss and a reduction in the volume of the legs which contain less blood than in a condition of weight (References 4-5, 4-6, 4-7, 4-9, 4-13, 4-14, 4-15, 4-16, and 4-17). The result of a decrease in plasma is a thickening of the blood because of the relative increase in cells for the reduced volume (Reference 4-9). The inner sensory processes, through hormonal action, then reduce the number of red cells, etc., until the normal density is attained. The amount of plasma loss varies with individuals but is about 12 percent as an average. This loss is followed with a red cell mass loss of about 15 percent (Reference 4-14), and total leg volume drops about one liter. All of this occurs and stabilizes in a very few days in the weightless environment (References 4-12 and 4-15). On return to Earth, these factors, along with others to be discussed later, cause immediate difficulties. In the environment of weight, the hydrostatic pressure is again present, and the center of mass of the blood moves downward from the head and heart. This downward movement, with the reduced volume of blood, reduces the blood flow to the brain, causing vision impairment,

dizziness, fainting, and inability to stand erect (orthostatic intolerance) (References 4-5, 4-6, 4-7, 4-8, 4-10, 4-11, 4-13, and 4-14). Restoring the blood volume to normal in the presence of weight is essential. Depending on the extent of water and salt intake prior to reentry, recovery may take a few to several days (References 4-6, 4-7, 4-9, 4-10, 4-12, and 4-14). The drop in red cell mass, of course, is triggered through the bone marrow, and the recovery after return to Earth is rather long, as many as 100 days (Reference 4-14). In addition, the new cells developed in the weightless state appear to be smaller than preflight cells.

4.1.3 Musculoskeletal System

There are a number of problems associated with weightlessness that occur in the muscles and bone structure (the musculoskeletal system). These problems occur primarily from disuse of these systems which normally support and move the body in the environment of weight. Thus, in the weightless environment with the lack of need to actively oppose gravity, the demands on the musculoskeletal system are greatly reduced. The elements most affected are known as antigravity muscles and bones. The effect is greatest in the legs. A loss of muscle mass and tone is experienced and flabbiness and atrophy occur (References 4-5, 4-6, 4-7, 4-18, and 4-19). This effect is known to most of us through the effects of disuse and recovery by exercise in our normal lives. The skeletal system is a living system, with a continual exchange of its sundry minerals and other elements, and maintains sufficient bone density and size for the conditions present that is, for the load being supplied to the system. Thus, weightlessness unloads the bone structure (References

4-5, 4-6, 4-7, 4-20, 4-21, and 4-22). The legs are most affected, and the other bones are affected to a lesser extent.

4.1.3.1 Loss of Muscle Mass, Tone, and Strength

The loss of muscle mass, tone, and strength and atrophy (and their reversal) are common occurrences in life as evidenced by medically bed-ridden people who, after medical recovery, recover muscle strength, tone and mass while readapting to normal life. For long space flights to date, the extent of the muscle problem progresses with time and is affected by exercise during the flight (References 4-5, 4-6, 4-7, 4-8, 4-11, 4-18, and 4-19). The amount of volume lost from muscle disuse ranges from about 3-8 percent over and above that lost from the fluid losses previously discussed. Muscle strength, depending on exercise regimen used, reduces up to 25 percent in 84 days of flight (Reference 4-18). Such losses appear to continue for longer flights. In available documents, the Russians have not reported specific losses of muscle strength but have reported fatigue and weakness with a sense of apparent increase in weight of the body and objects at the end of all flights. One cosmonaut reported feeling as if he was at 2.5 g's when back on Earth (Reference 4-8). One muscle affected by general disuse is the heart, because of a much smaller demand without weight. The dimensions of the heart appear to decrease by about 7.5 percent (References 4-15 and 4-23). The vascular muscles are similarly affected. Upon return to Earth the loss of elasticity and strength of those in the legs compounds the problem of blood return to the heart and head caused by the blood volume reduction previously discussed. Also, on return to Earth, these various effects on the muscles cause serious losses of motor coordination in

both static and dynamic conditions (References 4-5, 4-6, 4-7 and 4-9). Orthostatic tolerance is greatly reduced and the natural ability to walk is seriously affected, as are other motions requiring coordination. Work capacity and tolerance to muscle use also are decreased markedly. Several days to weeks may be involved in recovery to reasonably normal conditions after returning to Earth. Clearly, the effects of muscle disuse remain a problem of concern.

4.1.3.2 Loss of Bone Minerals

The loss of bone minerals, especially calcium, may be the most critical physiological problem of weightlessness. There is no definitive evidence that calcium loss stabilizes during extended space missions (References 4-5, 4-6, 4-7, 4-8, 4-19, 4-20, 4-21, and 4-23). There appears to be a calcium imbalance throughout the flights. The phenomenon of calcium loss is experienced on Earth by paralytics, bedridden patients (including those in simulated weightlessness experiments), and, of course, those with osteoporosis. There is some evidence that paralytics may attain calcium balance in a year or more. The sundry effects of mineral and chemcial changes in the bones may have an inhibiting influence on the production of red cells, at least for a time (References 4-9 and 4-24). Calcium losses of 0.3 percent to 0.4 percent of total body calcium per month were experienced in Skylab (Reference 4-21). The suggestion is that conditions like osteoporosis may occur in 4 to 8 months. The bone most stressed by weight, the heel bone, loses 15 to 20 percent of its density. The mechanism of calcium loss is complex; the heel bone does not lose density for about 30 days, and then, on an average, lost 7 percent in 59 days and 11 percent in 84 days in Skylab

flights (Reference 4-9). Density losses in the heel bone of up to 40 percent have been observed in bed rest studies of 120 days duration (Reference 4-22). There is no evidence of bone density changes in the bones of the forearm (Reference 4-22). Upon return to Earth, the recovery of normal urinary calcium excretion occurs in a very few days (Reference 4-22). No data that show the time required to regain the bone density of preflight conditions have been reviewed. However, one cosmonaut who flew for 175 days was sufficiently recovered from all effects to fly for 185 days about 6 months later (Reference 4-5). The loss of calcium causing kidney stones remains a concern, although no evidence of such problems in space flight is apparent. The loss of bone minerals remains as a most critical physiological problem.

4.1.4 Other Problems Associated with Weightlessness

Changes in heart rates, blood pressures, blood stroke volumes, and peripheral blood flow are all affected in accordance with the cardiovascular system changes previously discussed, i.e., the physiological aspects encountered in, and generated by, space flight and weightlessness. Nutrition, body use including exercise, and work-rest-sleep cycles all have an impact on space crews.

4.2 COUNTERMEASURES

4.2.1 Physical and Mechanical Countermeasures

4.2.1.1 Vestibular System

Relative to problems rooted in the vestibular system, a well

regulated regimen of head and body motions can enhance adaptation to the vestibular disturbances, as has been previously mentioned.

4.2.1.2 Cardiovascular System

The loss of blood volume and its related difficulties have received considerable attention. A number of devices have been considered and used in space. The simplest of these are cuffs for the lower extremities, the intent being to restrain venous blood flow back to the heart from the legs. There appear to be no specific data as to their effectivness. Apparatuses which apply negative pressure from the waist to the lower legs have been used both by the U.S. in Skylab and the USSR in Salyut. Figure 4.2-1 shows these lower body negative pressure (LBNP) devices.

The U.S. version is a canister that has seals at the waist, it has been used as an experimental device to check its influence on the cardiovascular system and how weightlessness affects the results (References 4-25 and 4-26). The results have a relationship to orthostatic tolerance and its prediction. A loss of orthostatic tolerance was developed by the time of the first test, 4 to 6 days into flight. The results from this show a stabilization of LBNP response after 5 to 7 weeks (Reference 4-26).

The Soviet apparatus is a unique pant-like garment which seals at the waist and encompasses the feet; in it, the cosmonaut presumably remains mobile. The apparatus is used as a therapeutic device, along with water and salt intake, for a few days before reentry (References 4-5, 4-6, and 4-7). There are no data showing its specific influence, but the fact that it has become a normal part of reentry preparations along

Vacuum release valve

SIB

Waist seal shroud

Ankle restraint

LVMS leg band

Utra vertical release

Upper torse restraint assembly (utra)

Velcro chest restraint

Knee restraint

Utra horizontal release

Rotated 180°

Right

Left

Leg band connectors
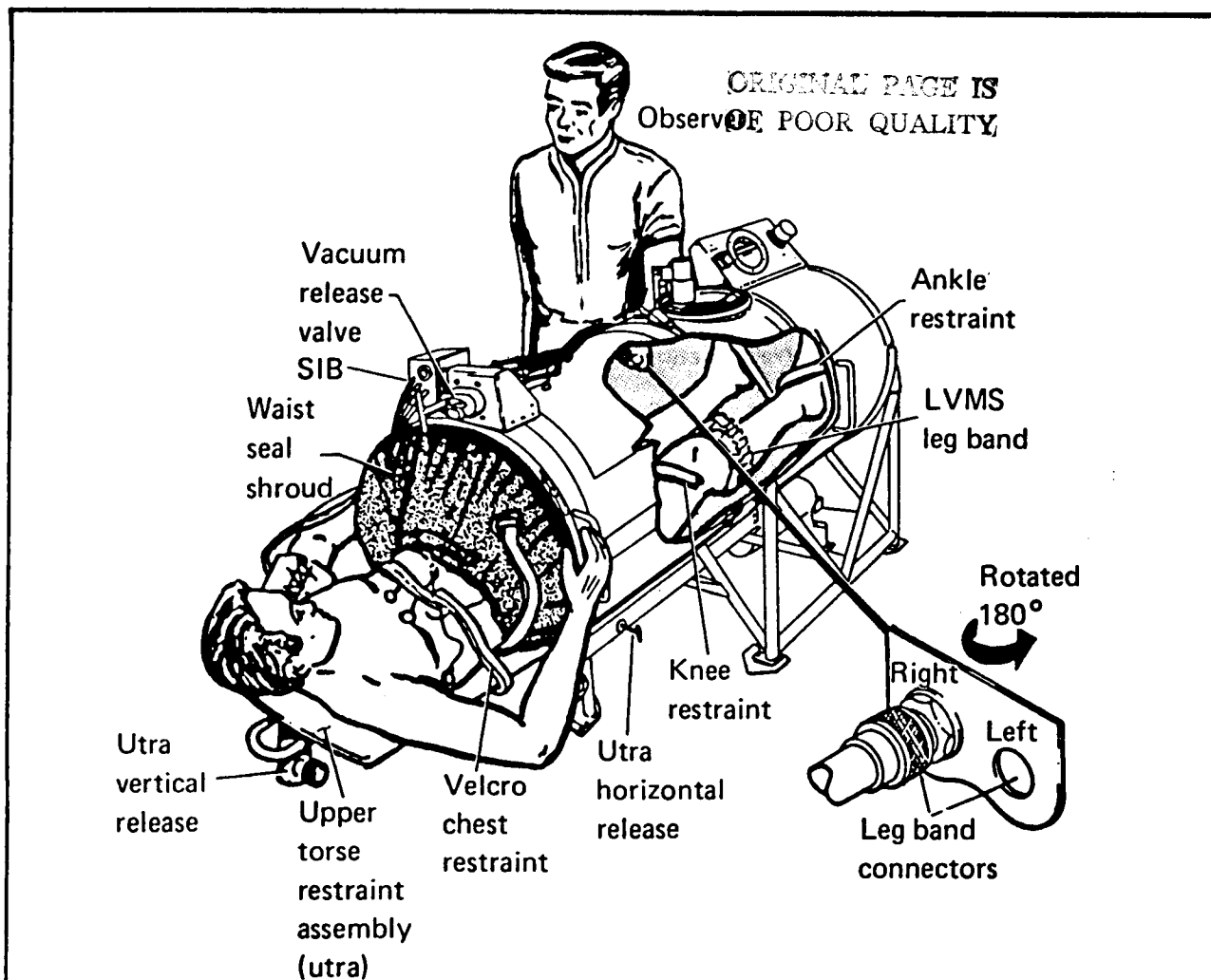
(a) NASA Device used in Skylab (Reference 4-25)

3

5

1

A

6

2

3

4

Inset A
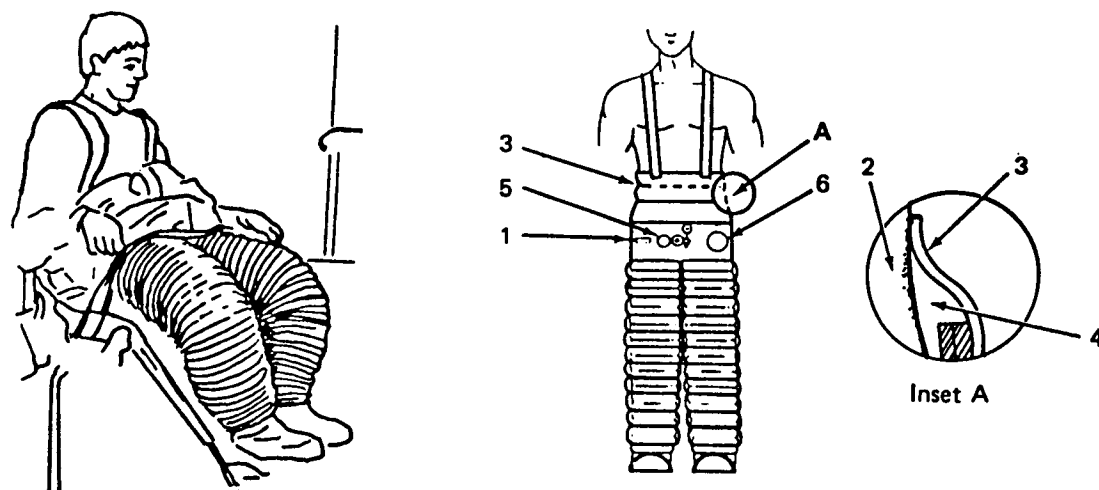
(b) Russian Device used in Salyut (Reference (4-28)
    (1) Micropump, (2) body, (3) rubber shutter, (4) air space,
    (5) air intake valve, (6) manometer

Figure 4.2-1 Lower Body Negative Pressure (LBNP) Devices

with special fluid intake indicates an apparent value of the apparatus.

Another applicable device, which has never been used in space, is a suit that applies a pressure gradient to the body from head to toe, emulating the effects on Earth of the hydrostatic pressure on the cardiovascular system, wherein the blood is caused to flow more readily to the legs and less readily to the heart from the legs (Figure 4.2-2). An experiment on one subject, using water immersion and bed rest to simulate weightlessness, showed that the suit prevented the deterioration in orthostatic tolerance, the impairment in tolerance for mild exercise, and a reduction in maximum work capacity which had been observed in a controlled experiment. The suit was used from 2 to 4 hours per day from the 6th to 14th day of a 14-day experiment (Reference 4-27).

During reentry, and for a period following landing, an anti "g" type suit was used both by the Soviets in Salyut missions and the Americans in Skylab missions. These suits are to counter the renewed effect of weight upon returning to Earth. The US suit is shown in Figure 4.2-3. This suit applies a high pressure at the ankles and a much lesser pressure at the waist. These suits were not therapeutic devices designed to prevent the effects of weightlessness but to help cope with these effects when weight is again encountered, just as a "g" suit is used in high "g" airplane maneuvers (References 4-5 and 4-26).

4.2.1.3 Musculoskeletal System

Countermeasures to diminish the effects of weightlessness on the musculoskeletal system are bicycle-type ergometers, treadmills, and loading devices for arm and leg exercise (Figure 4.2-4). Both the Americans and Soviets use such devices. An astronaut on the NASA
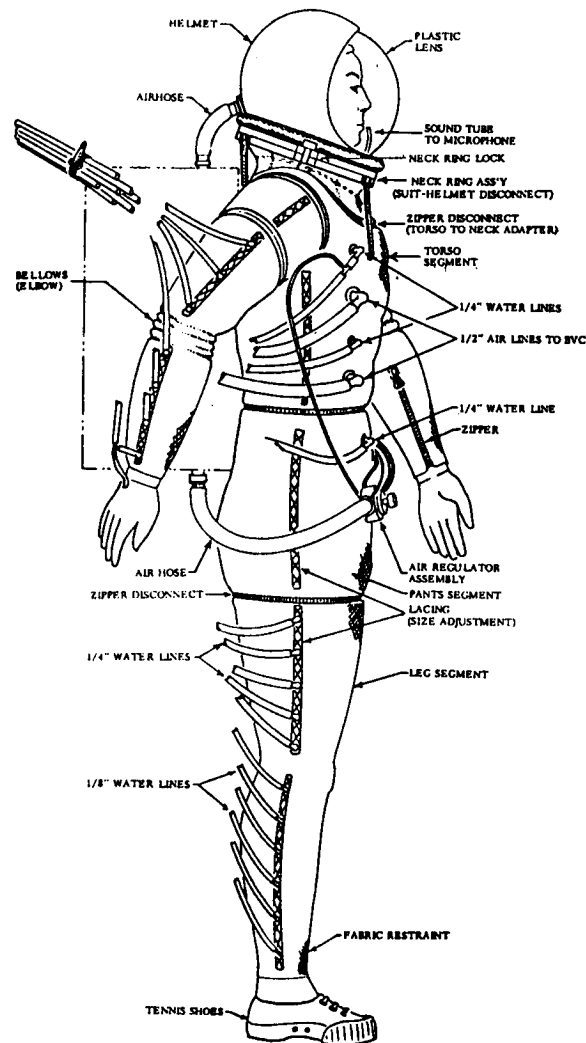
Figure 4.2-2 The Cardiovascular Conditioning Suit
(Reference 4-27)

PRESSURE GUAGE

INFLATING BULB

INFLATION PROVIDES A
PRESSURE GRADIENT
FROM 12000 PA (1.7 PSI)
AT THE ANKLE TO
1333 PA (0.2 PSI)
AT THE THIGH

TENSIONING ADJUSTMENT
FOR PRESSURE GRADIENT
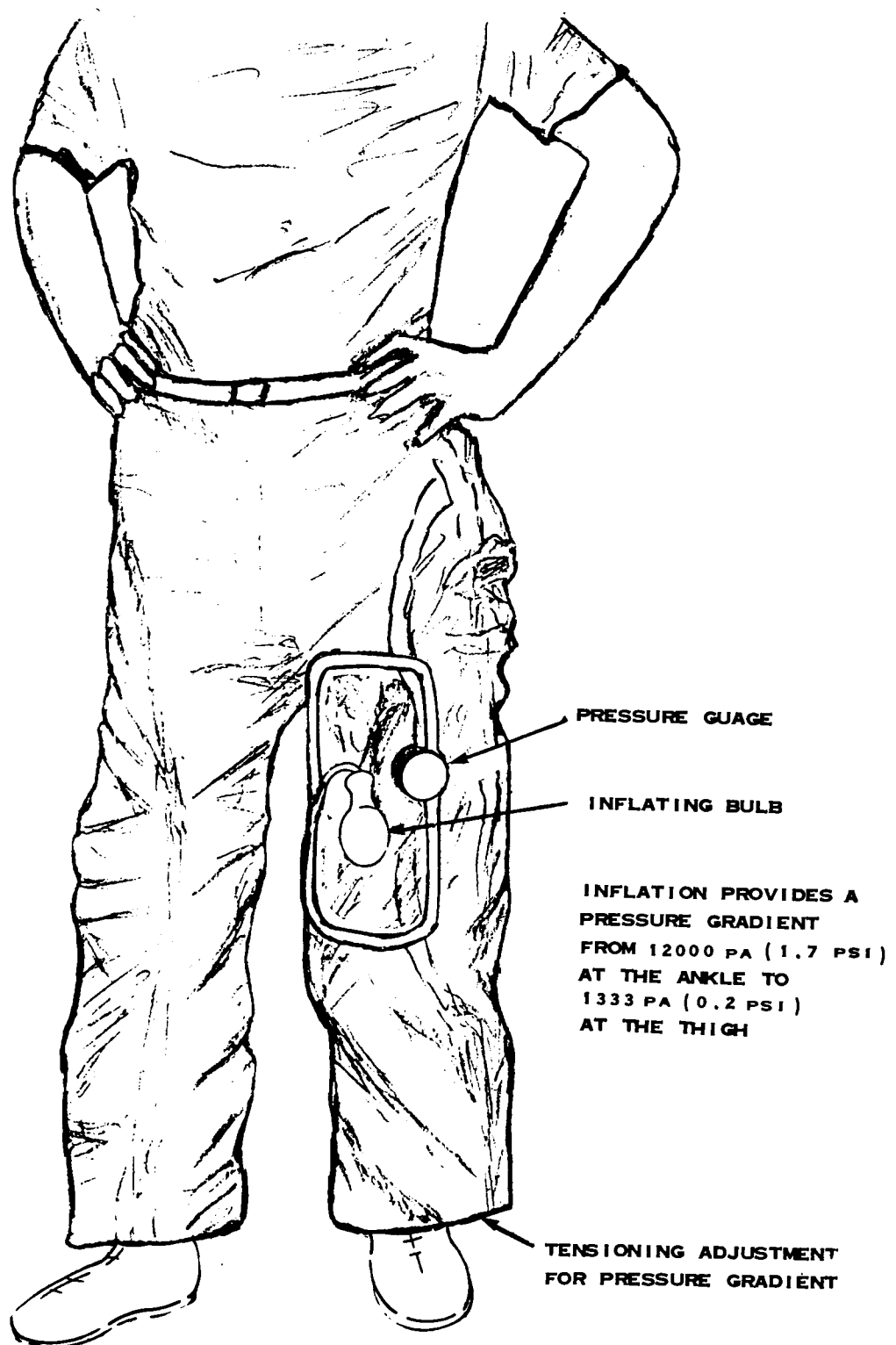
Figure 4.2-3   Skylab Cardiovascular Counterpressure Garment
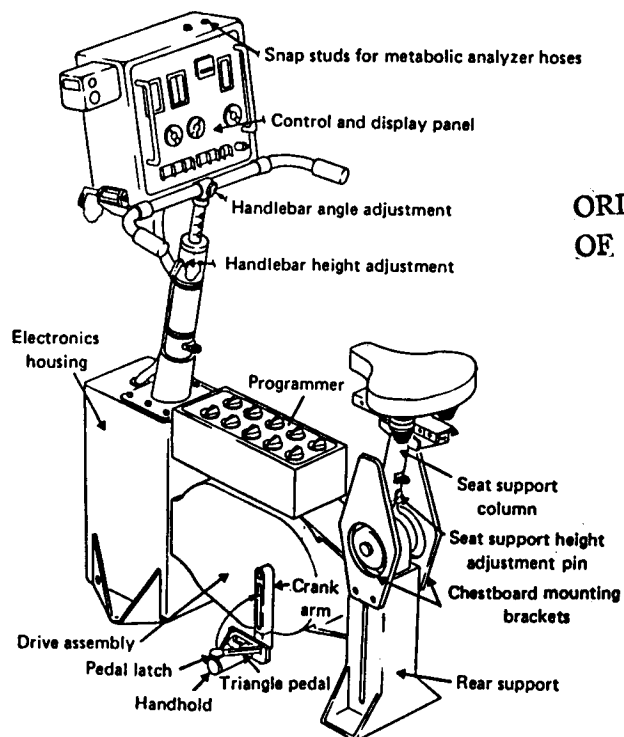
(a) Bicycle Ergometer (Reference 4-25)
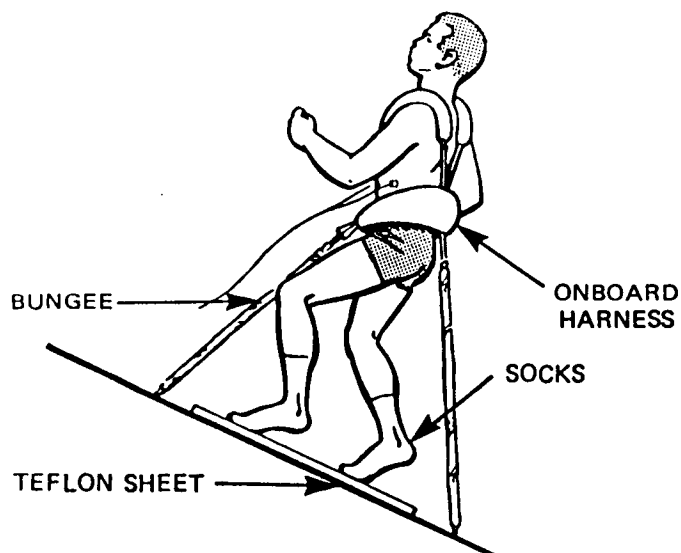
(b) Treadmill (Reference 4-28)
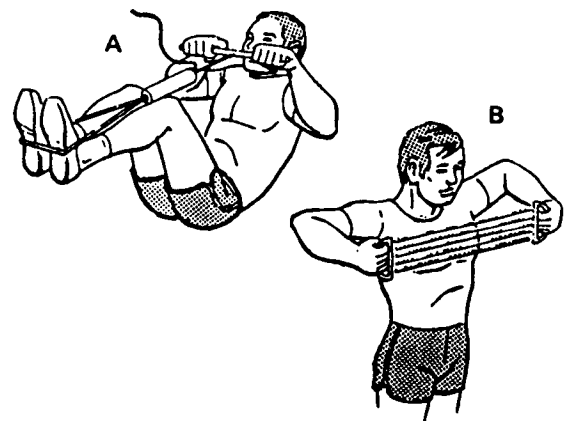
(c) Loading Devices (Reference 4-28)

Figure 4.2-4 Exercise Devices

ergometer could develop up to 300 Watts (221 ft pounds per second). This ergometer required only tens of pounds to operate, and, in as much that legs are normally stressed to hundreds of pounds, the ergometer did not maintain leg muscle tone or strength. When pumped by hand, the ergometer did maintain the strength and tone of the arm muscles which are normally stressed to tens of pounds (Reference 4-18). The ergometer and other such devices also exercise the cardiovascular system, including the heart muscles. The treadmill used on Skylab had the effect of maintaining the strength of the extensor muscles of the legs but not the flexors (Reference 4-18). A loading of 176 pounds (80 kilograms) was applied by the bungee cords of the treadmill. There were no available data as to the specific influence of the use of Salyut treadmills. Arm and leg loading devices (Figure 4.2-4) were used in both Skylab and Salyut. The use of all three devices, the ergometer, treadmill and loading devices, on the 84 day Skylab mission was successful in inhibiting to a limited degree the loss of muscle strength in the legs and arms. It is not clear how long these devices were used each day and, therefore, how much astronaut time would be required to maintain muscle tone and strength. It is evident, that in the weightless environment, some devices and time must be used or grave loss could occur. There are no available data from the Soviets as to the loading values and the effectiveness of their systems.

The Soviets in Salyut are also using a device known as the "Penguin" suit (Figure 4.2-5). This is a constant-loading device that applies load to the legs and torso (References 4-5 and 4-8). It is worn by cosmonauts from 12 to 18 hours a day. The intent supposedly is to load the skeletal system. It would appear that to have an effect on the

4-16
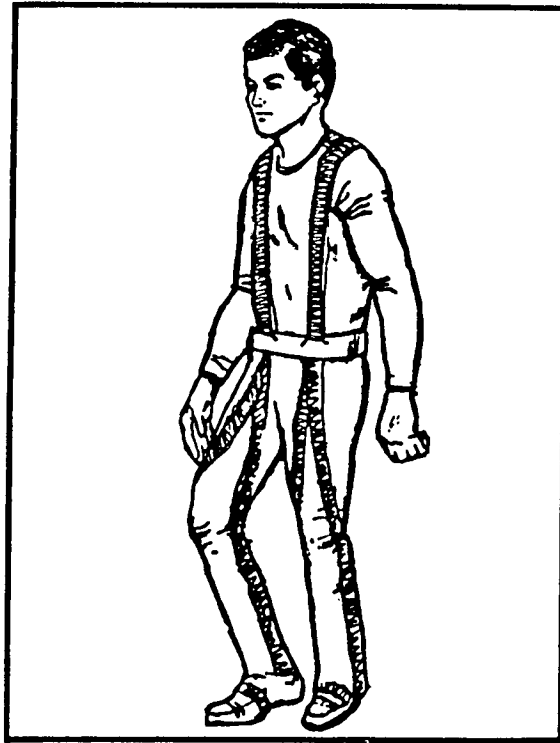
Figure 4.2-5   The "Penguin" Constant-Loading Suit Worn by Cosmonauts
(Reference 4-28)

leg bones, the cosmonauts would have to remain stiff-legged during its wear. If the legs were bent, certainly the extensor muscles of the legs would be favorably affected. The magnitude of the loads applied are not available. However, its continued use by cosmonauts throughout their extensive Salyut, and now Mir, programs implies a favorable effect of this suit (References 4-5, 4-6, and 4-7).

On-board centrifuges, in which crew members can periodically experience relatively high head to foot acceleration, have long been considered as a viable countermeasure (References 4-29, 4-30, and 4-31). A device is shown in Figure 4.2-6. Centrifuges may inhibit the cardiovascular system from experiencing the various degradations previously discussed. It is not clear that a seated restrained individual would experience any significant effect in the musculoskeletal system, especially the legs. Perhaps a standing man, thus exposed, may experience favorable effects on the bone mineral problem previously mentioned. The amount of acceleration and the time of exposure required are not established. Such a centrifuge can have serious limitations (Figure 4.2-7).

Through the extensive Soviet experience in space, a post flight recovery program has evolved (Reference 4-5). The program starts in a clinic at their space ports where bed rest, seated exercising, limited walking, and swimming are used. The extent of the exercise, especially walking, is increased until reasonable normalcy exists. The cosmonauts then are sent to a resort area until able to return to normal life. The time in the clinic may be several days with the whole process lasting a month or more. Each individual responds differently, and therefore the total program appears varied in length. The general results of this
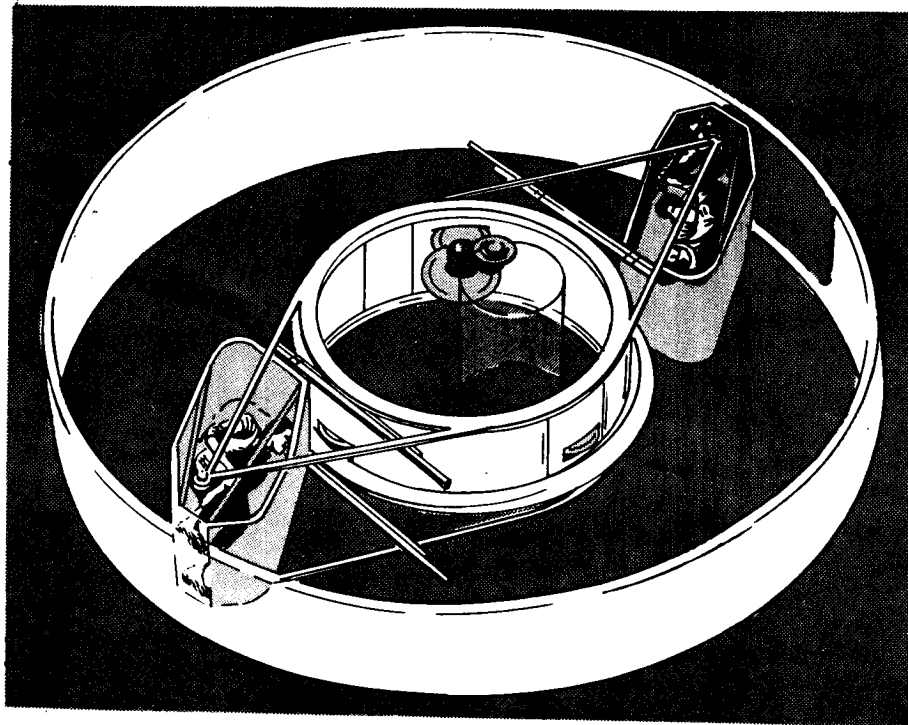
Figure 4.2-6 An Onboard Short-radius Centrifuge (Reference 4-29)
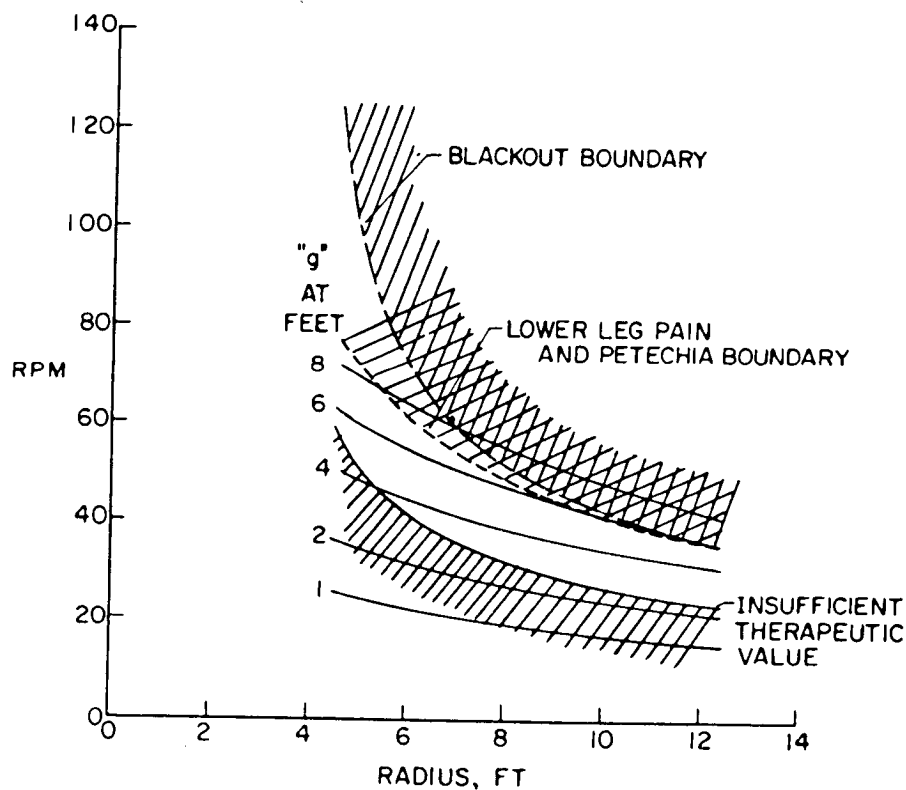
Figure 4.2-7 Critical Boundaries in Short-radius Rotating Systems Related
to Hydrostatic Pressure Variations. The Results are for a
Seated Man (Reference 4-31)

recovery program imply a serious if not critical response to the weightless environment for extended periods of time for Soviet cosmonauts.

4.2.2 Pharmacological Countermeasures

Pharmacological countermeasures have and are being considered to cope with the effects of weightlessness. Aside from routine medications (aspirin, antihistamine, stimulants, and sedatives), drugs for motion sickness brought about through the vestibular system, for blood and fluid losses caused by the absence of hydrostatic pressure, and for bone density losses brought about by the absence of weight have been studied in flight and in simulations. Relative to motion sickness, scopolamine with dextroamphetamine taken orally seems to be a reasonably effective drug (Reference 4-3). For the reduction in blood and fluid volume, vitamins, amino acids, and minerals are used to retain or replenish fluids and electrolytes (Reference 4-28). The maintenance of normal Earthbound blood and fluid volumes, could cause the continuation of chest and head fullness and face puffiness and their associated discomfort. The natural continuation of the body effort would also be expected to reduce its fluid volume in weightlessness. The use of water and salt intake in preparation for reentry and return to Earth, as is done by the Soviets (Reference 4-5), seems most appropriate. Relative to the loss of bone density, nutritional supplements of calcium and phosphorus show some positive effects (Reference 4-21). As in the effects of weightlessness itself, there is a great variability in the responses of subjects to the various pharmaceuticals that have been tried.

4.2.3 Artificial Gravity

Artificial gravity is also a mechanical countermeasure for weightlessness and the one most technically complex to attain. NASA first presented its thoughts on the subject in Reference 4-32. It is the countermeasure most likely to succeed in preventing the various problems of weightlessness previously discussed. In artificial gravity, man lives, works, plays, relaxes, and sleeps in an environment of "artificial" weight just as he lives, works, plays, relaxes, and sleeps in an environment of weight on Earth. In this environment, there is no need to schedule specific times for using and being encumbered by devices designed to cope with the physiological problems of weightlessness previously discussed. The time required to re-adapt to weight on return to Earth should be appreciably shorter than the time span experienced after weightless flight. The magnitude of "artificial" weight required to adequately maintain man's physiological conditioning is not known. The equivalent of Earth weight would certainly be adequate.

There are, of course, a number of concerns associated with artifical gravity that involve human physiological responses to such a unique environment. These concerns are caused by the ever present rotation and the effects of moving and working in such a rotating environment.

4.2.3.1 Vestibular System

Like weightlessness, there are problems associated with artificial gravity that are rooted in the vestibular system (Figures 4.1-1 and 4.1-2). The cause is not in the lack of response of the otoliths, as in the case of weightlessness, but in the cross coupling effects experienced by the semicircular canals due to the combination of head and/or body

motions and vehicle rotation. A number of studies have been made of these effects and encompass a considerable portion of five symposia held by NASA (dating from January 1965 to August 1970) on the role of the vestibular organs in the exploration of space. The problems are a function of the orientation of the head relative to the axis of rotation of the Space Station and its rate of rotation, and the type and rate of head motion. Consider a crewman facing tangentially in a rotating vehicle. His head is pitching at the rate of rotation of the vehicle while just standing still. If he turns his head 90 degrees, his vestibular system will experience a deceleration in pitching velocity and an acceleration in rolling velocity until the head is turned to the 90 degrees position, at which point the rotation relative to the head will be all rolling and no pitching. The magnitude of the accelerations and decelerations experienced depend on the product of the vehicle rate of rotation and the head-turning rate. The crewman senses through his vestibular system the intended head-turning and the unexpected pitching and rolling. Yet, inside the vehicle, he visually experiences only the head turning which creates a conflict of sensory cues. As in the case of weightlessness, this conflict of cues is being sent to the brain from the various senses. Apparent motion of the visual scene or of one's body resulting from oculogyral illusions from uncontrolled eye motion (nystagmus) may cause dizziness, drowsiness, fatigue, stomach awareness, nausea, and vomiting. The problem of nystagmus is discussed in Reference 4-33. The problems of oculogyral illusions and symptoms of nausea, vomiting, drowsiness, and fatigue are discussed in Reference 4-34. Adaptation to these problems of rotation does occur, and a stepwise process of attaining the full rotational rate intended has also been

shown to be desirable (References 4-35 and 4-36). The results (Reference 4-36) are especially significant in that subjective adaptation to a rotation of six rpm is demonstrated to occur in two to three days, which is commensurate with the time for the adapation of the vestibular system to weightlessness (Figure 4.2-8).

The oculogyral illusions common in rotation also diminished within 2 days, Figure 4.2-9. Tandem walking (heel-to-toe) is a standard test of human balance. The results of such tests with eyes open and eyes closed are shown in Figures 4.2-10 and 4.2-11, respectively. Here the subjects were walking tangentially. The results show that, especially with eyes closed, adaptation may take longer than subjective adaptation, or adaptation to visual illusions. Whether such tests have significance for actual Space Stations, especially with eyes closed, is doubtful. Figure 4.2-12 shows balancing, heel-to-toe, with eyes closed. Clearly this was nearly an impossible task in the rotating environment, but its significance for real missions seems remote.

4.2.3.2 Human Performance

Other problems associated with artificial gravity do not affect human physiology directly as does weightlessness. The problems are in human performance while coping with certain unique forces experienced in rotating environments. Figure 4.2-13 illustrates these various forces, termed Coriolis forces. In this Figure a man is depicted as walking and climbing in a rotating cylinder representing a Space Station having artificial gravity. In Figure 4.2-13a, the man is walking (or running) tangentially in the direction of rotation and experiences a Coriolis force which adds to the artificial gravity vector causing his artificial
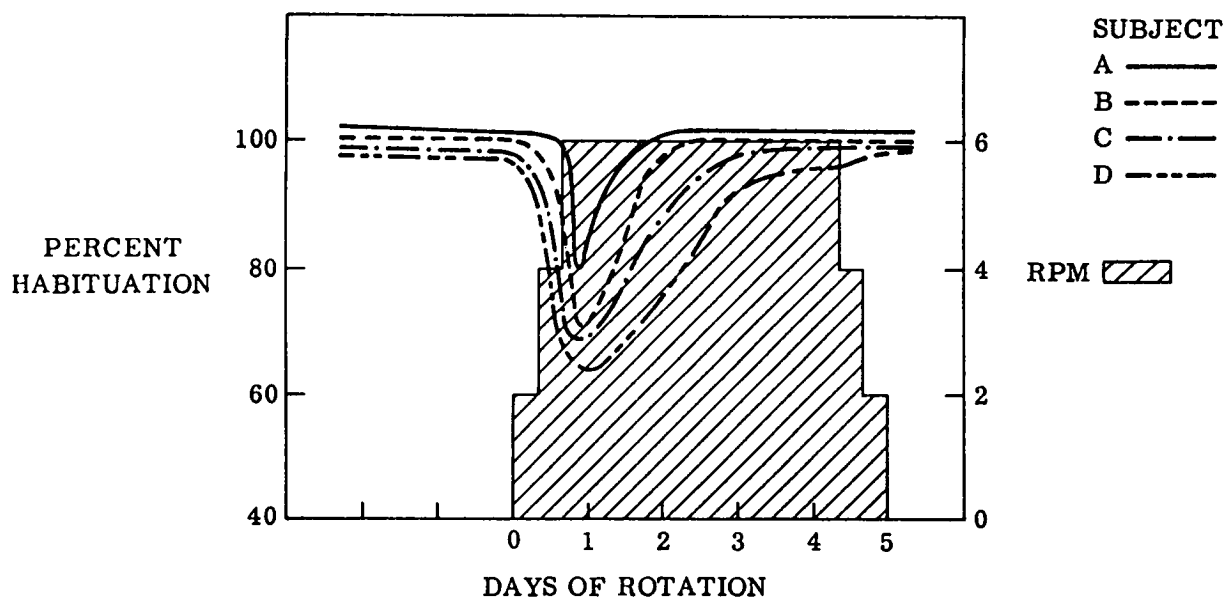
Figure 4.2-8 Subjective Habituation vs. Days of Rotation. Based on Subject's
Evaluation of His Well Being Relative to Static Baseline.
(Reference 4-36)
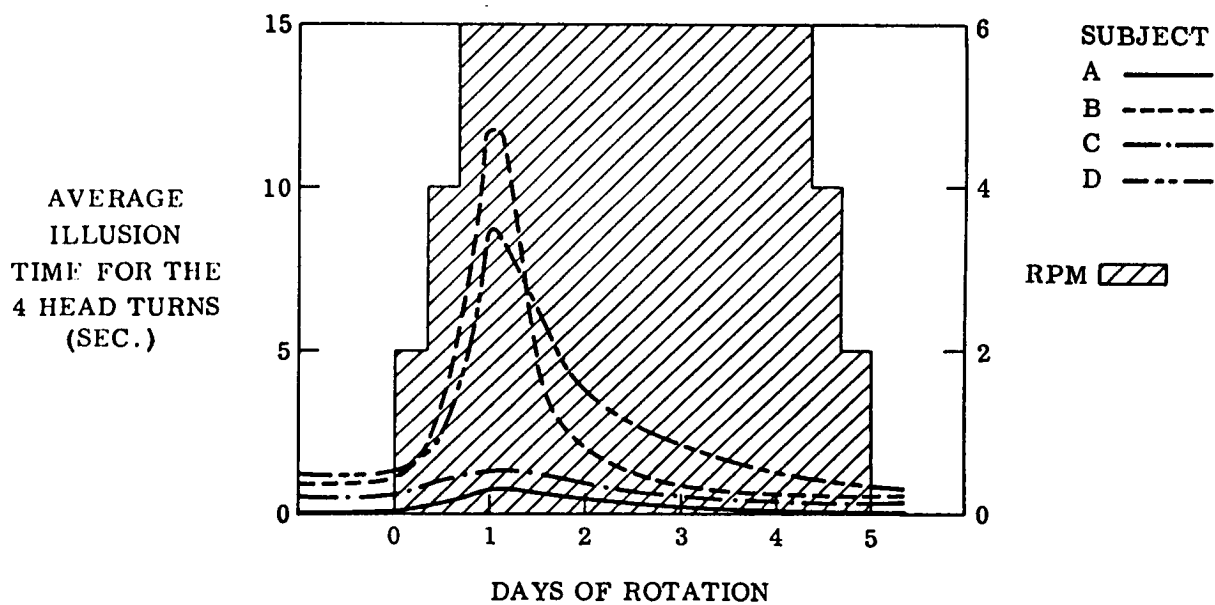
Figure 4.2-9 Oculogyral Illusion vs. Days of Rotation
(Reference 4-36)
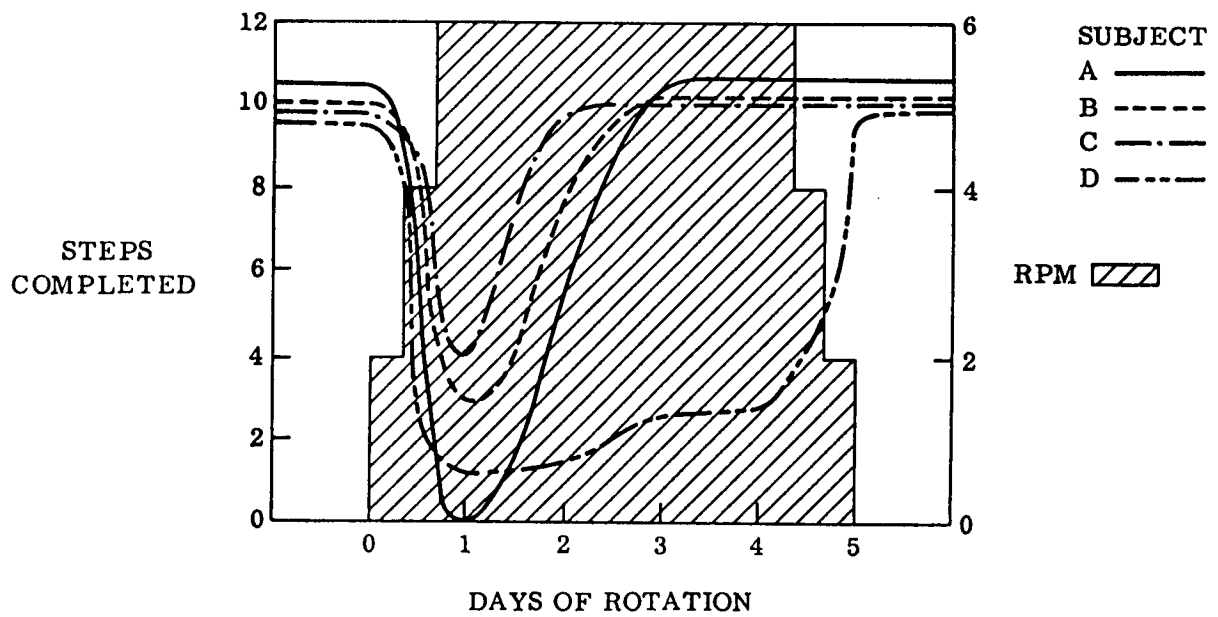
Figure 4.2-10 Visual Tandem Walking vs. Days of Rotation
(Reference 4-36)
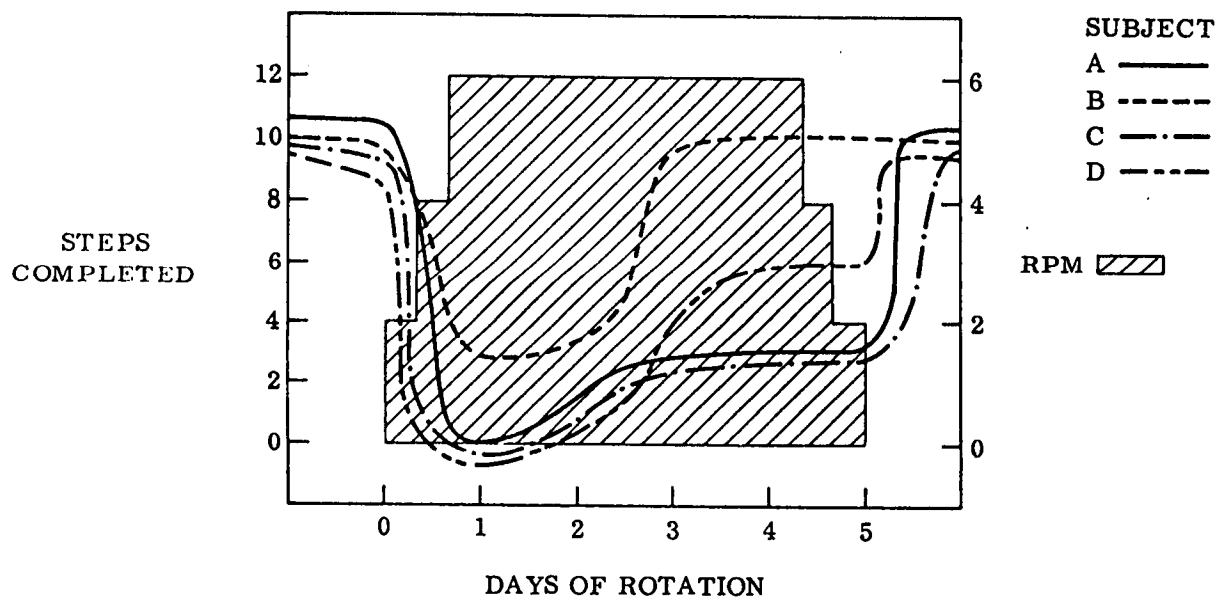
Figure 4.2-11 Blind Tandem Walking vs. Days of Rotation
(Reference 4-36)
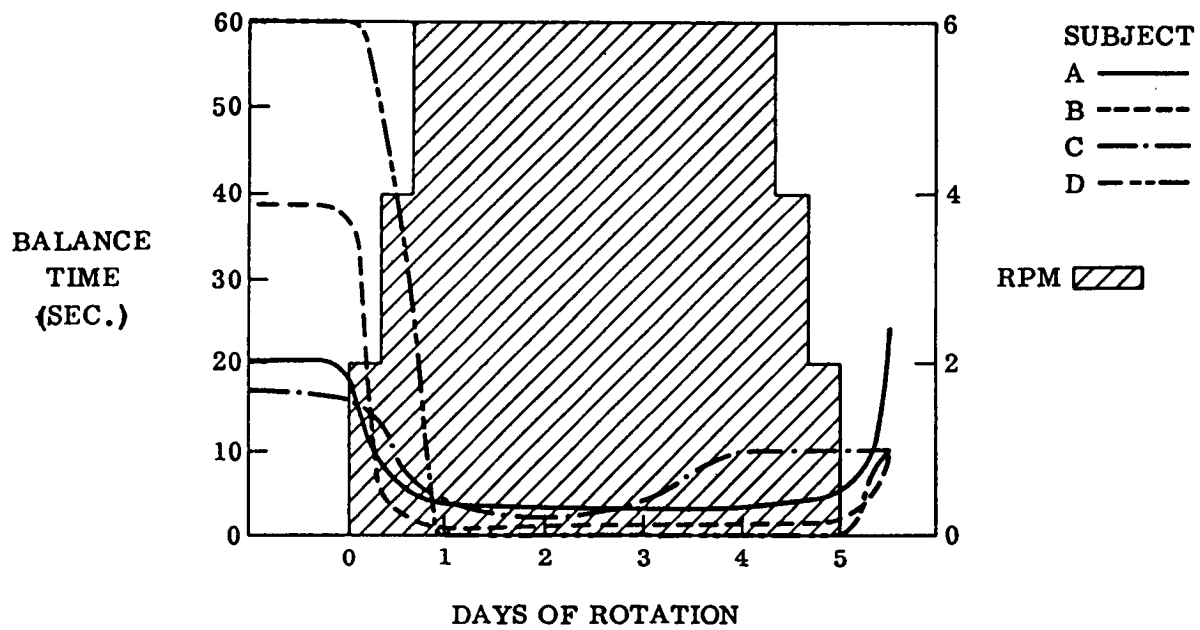
Figure 4.2-12 Blind Tandem Standing vs. Days of Rotation
(Reference 4-36)
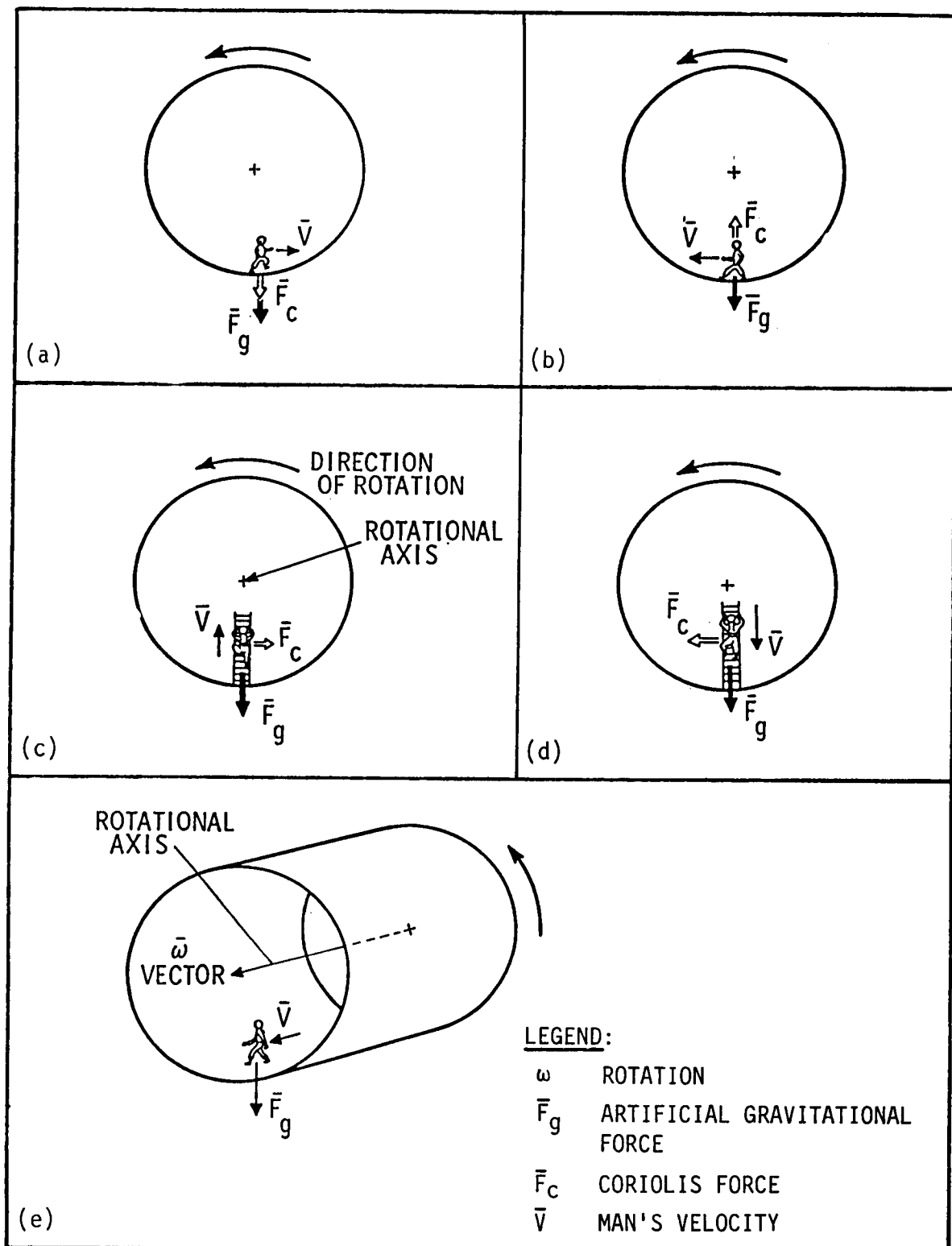
Figure 4.2-13 The Coriolis Forces Experienced when Moving in a Rotating
           Environment

4-27

weight to increase, as if in a vehicle having a larger rotational velocity. In Figure 4.2-13b he is walking against the direction of rotation and his artificial weight is decreased. In Figures 4.2-13c and 4.2-13d the man is ascending a ladder toward the center of rotation and descending from the center of rotation, respectively. When ascending, the climber must resist a force tending to pull him from the ladder tangentially toward the direction of rotation. When the subject is descending, the force tends to pull him from the ladder tangentially against the direction of rotation. In Figure 4.2-13e, the man is walking axially and generally senses no forces relative to the vehicle. In short, a straight line relative to a rotating environment is a curved path in inertial space. Forces, known as Coriolis forces, are required to attain these curved paths in space. Figure 4.2-14 shows such a straight line in a rotating environment.

Studies and experiments to evaluate man's performance in a rotating environment have been made in past years. References 4-37, 4-38, 4-39, 4-40, 4-41, and 4-42 relate to the general problems of the rotating environment. Reference 4-41 is an overview of artificial gravity and identifies certain performance criteria that may apply. Mathematical expressions of the various static and dynamic characteristics of artificial gravity are expressed in Reference 4-41. Also shown are potential criteria for artificial gravity. The criteria generally relate to man's performance in this unique environment and do not indicate or evoke any knowledge as to the amount of artificial gravity that will be required to maintain the cardiovascular and musculoskeletal systems. References 4-43, 4-44, 4-45, 4-46, 4-47, and 4-48 present the results of experiments performed in a rotating environment by the North American
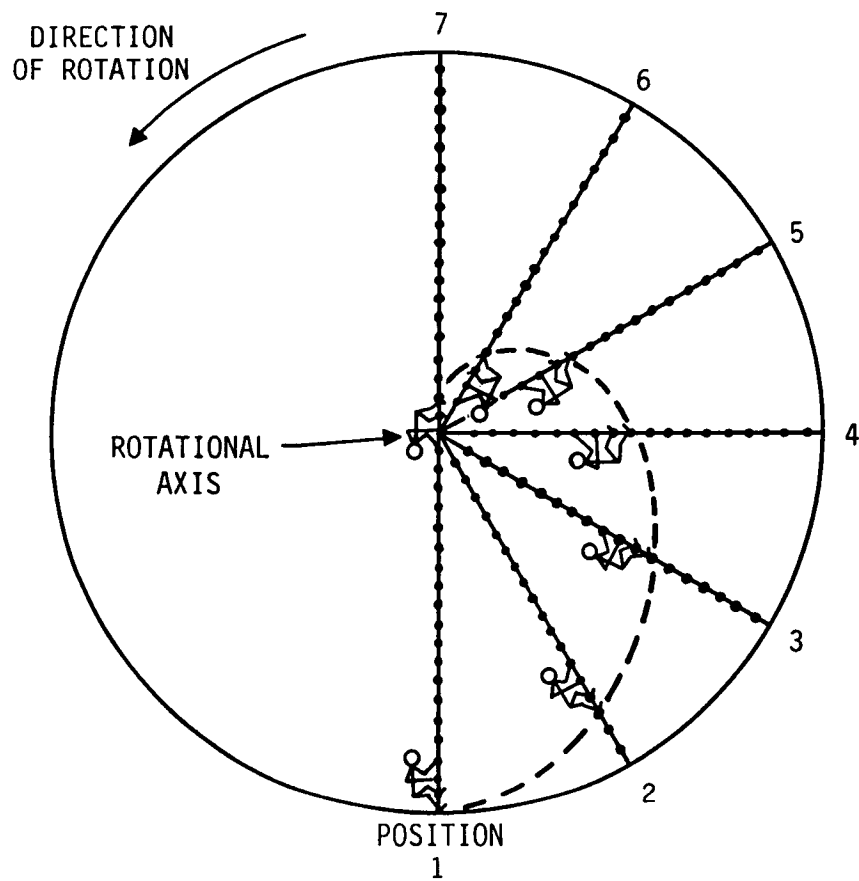
Figure 4.2-14 A Straight Line in a Rotating Environment

Rockwell Corporation Space Division for the NASA Langley Research Center regarding human performance in such an environment.

Figure 4.2-15 shows the facility used for these studies. There was a movable enclosure where tangential walking (Figure 4.2-16) and materials handling (Figure 4.2-17) could be examined at radii of 6.1, 12.2, 18.4, and 21.3 m. There was a radial complex where ladder climbing (Figure 4.2-18) and elevator riding were examined from a radius of 1.5 to 18 m. Psychomotor tests (Figure 4.2-19) were performed at stations with 12, 23, and 24 meter radii. The study used rates of rotation of 3, 4, 5, and 6 rpm, and elevator rates of 1.2, 1.8, and 2.4 m per second. Figure 4.2-20 shows the effect of artificial gravity level and radius of rotation on self-locomotion. The short radius of 6.1 m with curved floors allowed better performance below 0.2 "g" units. The larger radii with flat floors, showed the best performance above 0.2 "g" units. The Space Station proposed in this report has a radius of about 114 m at the main floor and will be very tractable to locomotion.

Figure 4.2-21 shows similar data as a function of rate of rotation rather than radius. These results show leveling of the rate of locomotion at about 0.6g's and little influence of curved or flat floors. On flat floors there are lean angles that occur as one moves from the radius perpendicular to the floor to the intersection of two flat floors. Reference 4-48 suggests that such leanings should not exceed 30 degrees from the local floor vertical. However, 30 degrees seems excessive. The proposed Space Station at its main floor would have maximum lean angles of about 7.5 degrees; however, control panels and storage cabinets should be aligned with the local radial axis. Figure 4.2-22 shows the time to perform a material handling task as a function of artificial
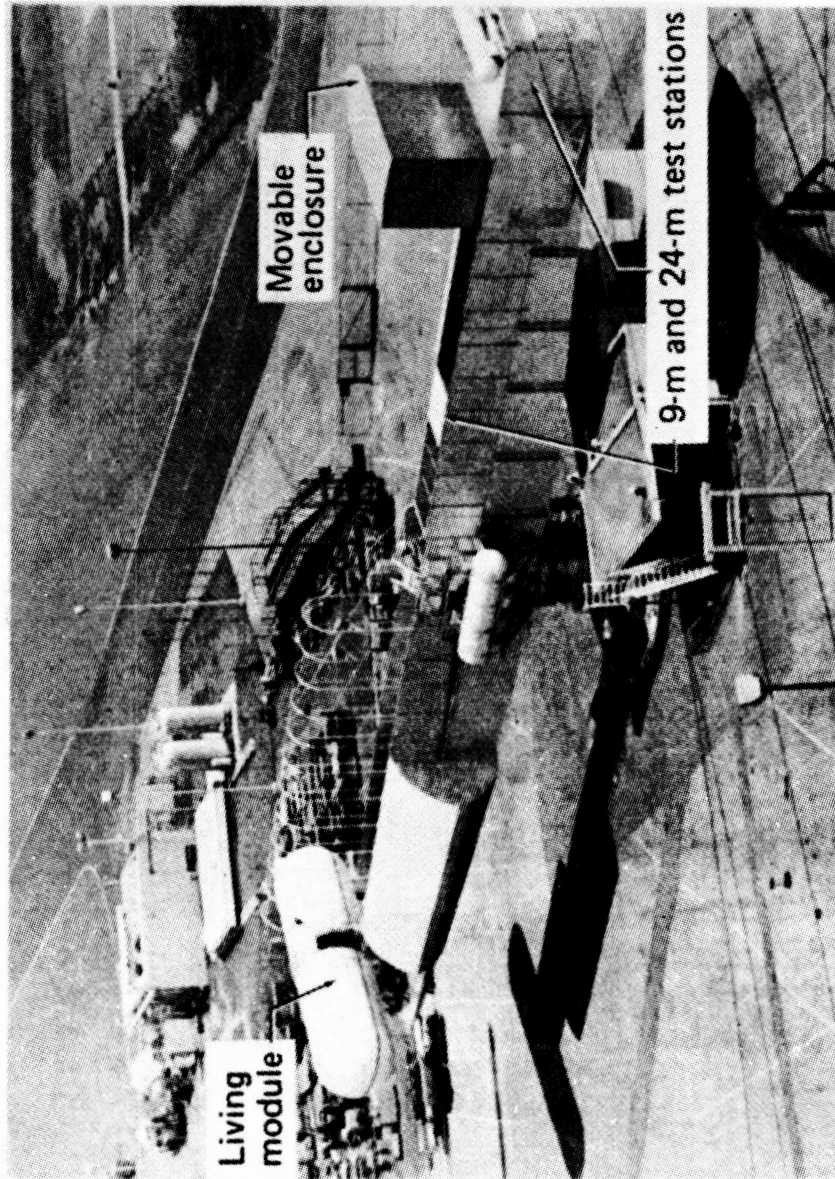
Figure 4.2-15 The North American Rotational Test Facility (Reference 4-43)
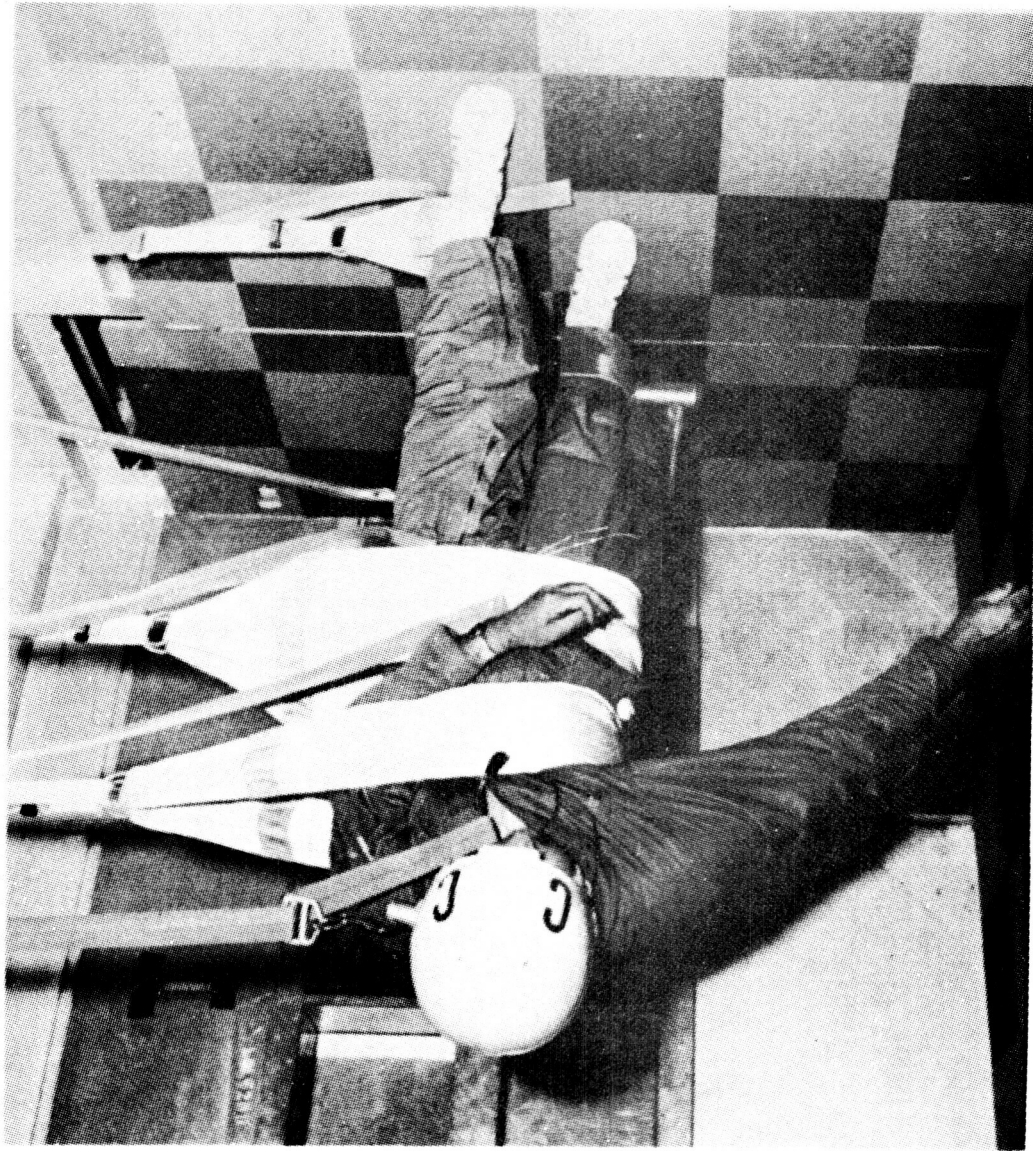
Figure 4.2-16 Tangential Walking Experiment (Reference 4-43)
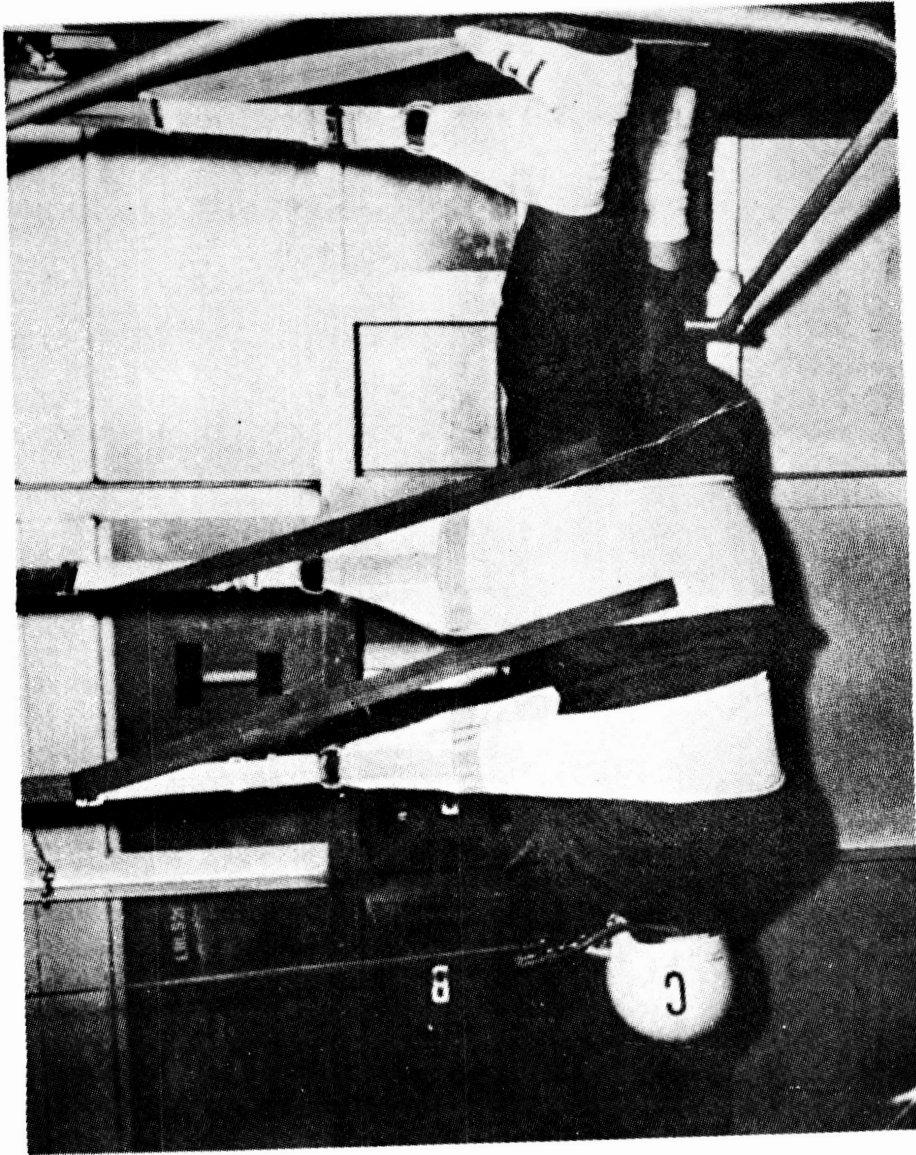
Figure 4.2-17 Cargo Handling Experiment (Reference 4-43)
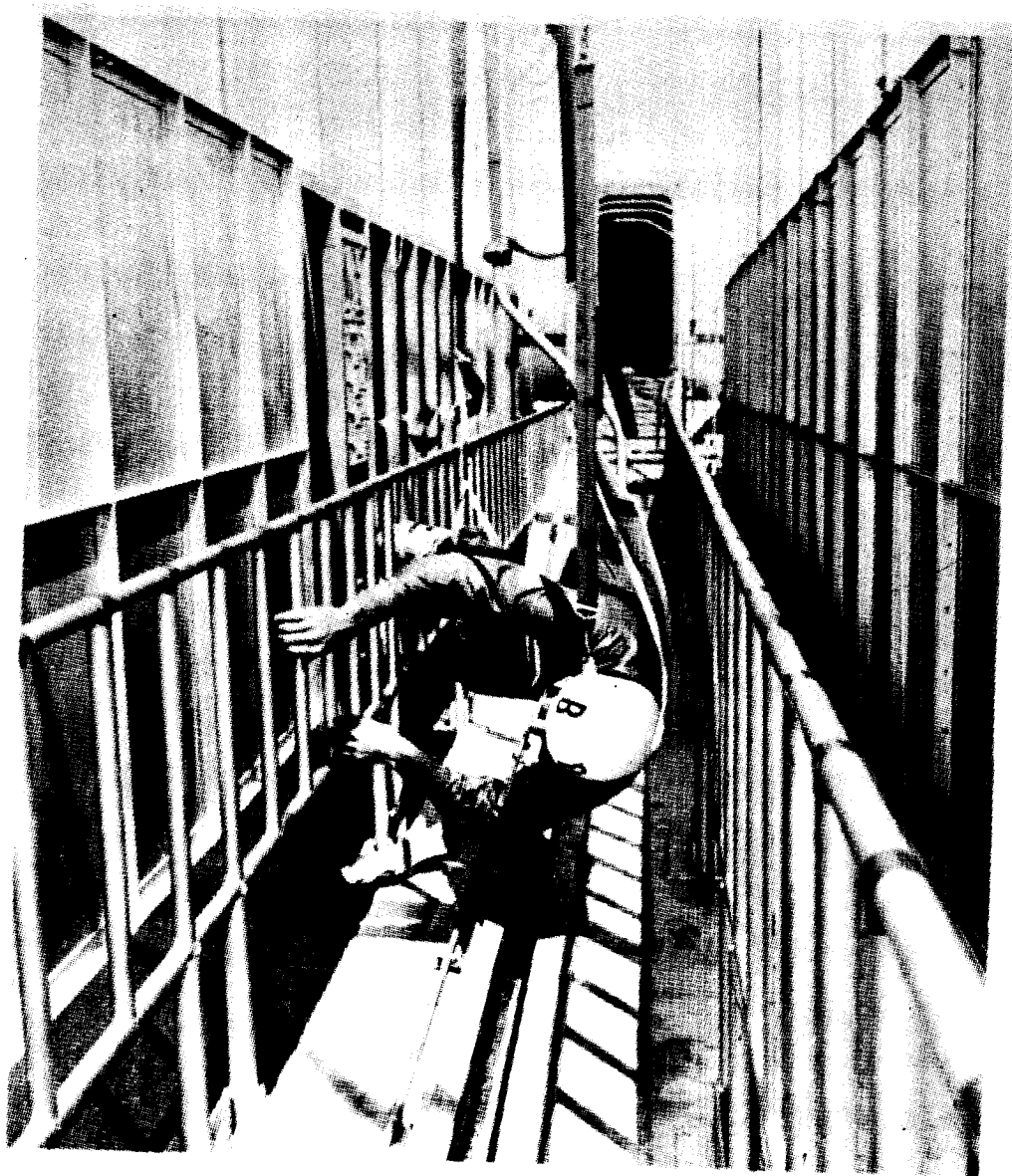
Figure 4.2-18 Ladder Climbing Experiment (Reference 4-43)

Figure 4.2-19 Decision Response Time Device (Reference 4-44)

WALKING SPEED, m/sec

RADIUS

□	6.1 m
○	12.2 m
●	18.4 m
△	21.3 m

—— FLAT FLOORS

——— CURVED FLOORS

ARTIFICIAL GRAVITY LEVEL, "g" UNITS
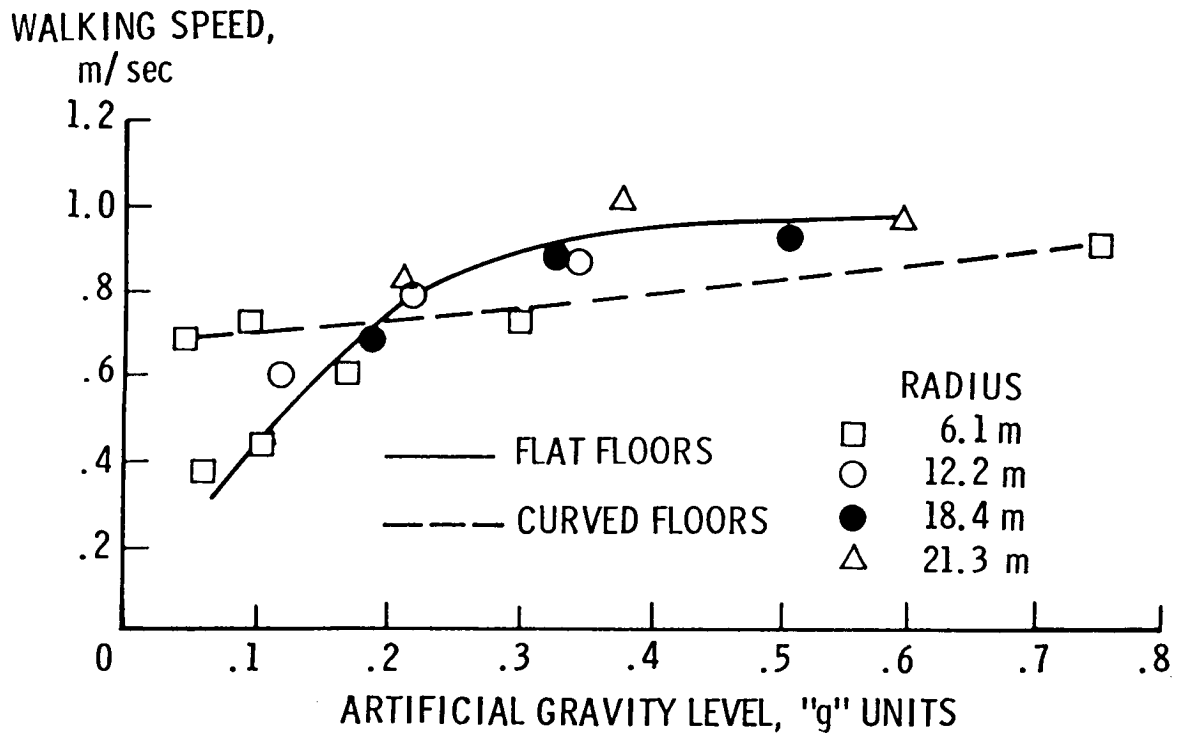
Figure 4.2-20 The Influence of Simulated Artificial Gravity Level on the Speed of Self-locomotion (Reference 4-47)
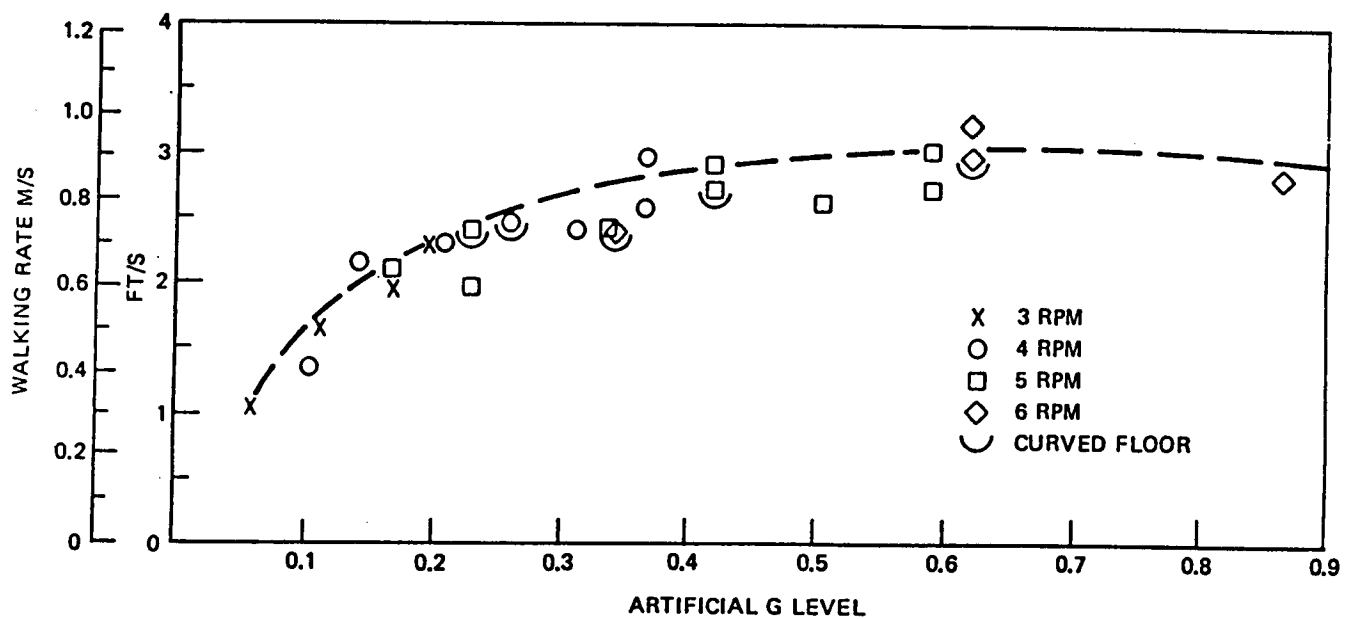
Figure 4.2-21 Variations in Walking Rate Relative to Rotation Rate, Floor
Configuration, and Artificial g Level (Reference 4-48)
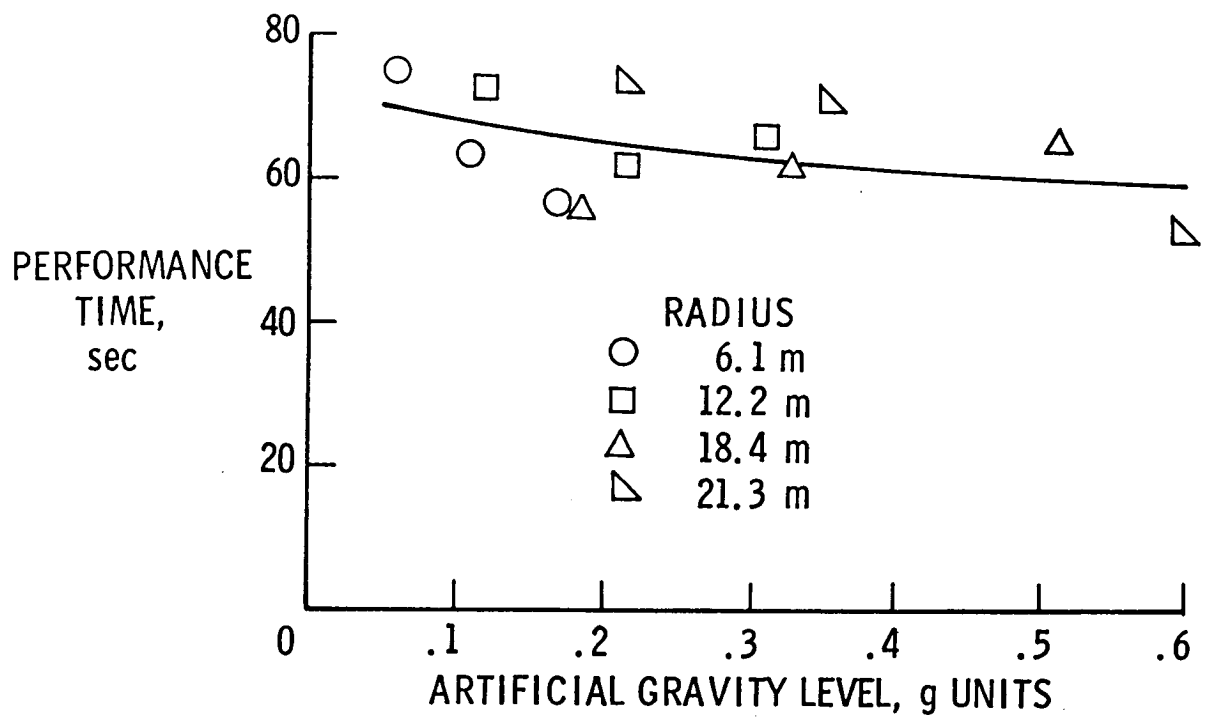
Figure 4.2-22 Influence of Simulated Artificial Gravity on Material Handling
Performance (Reference 4-47)
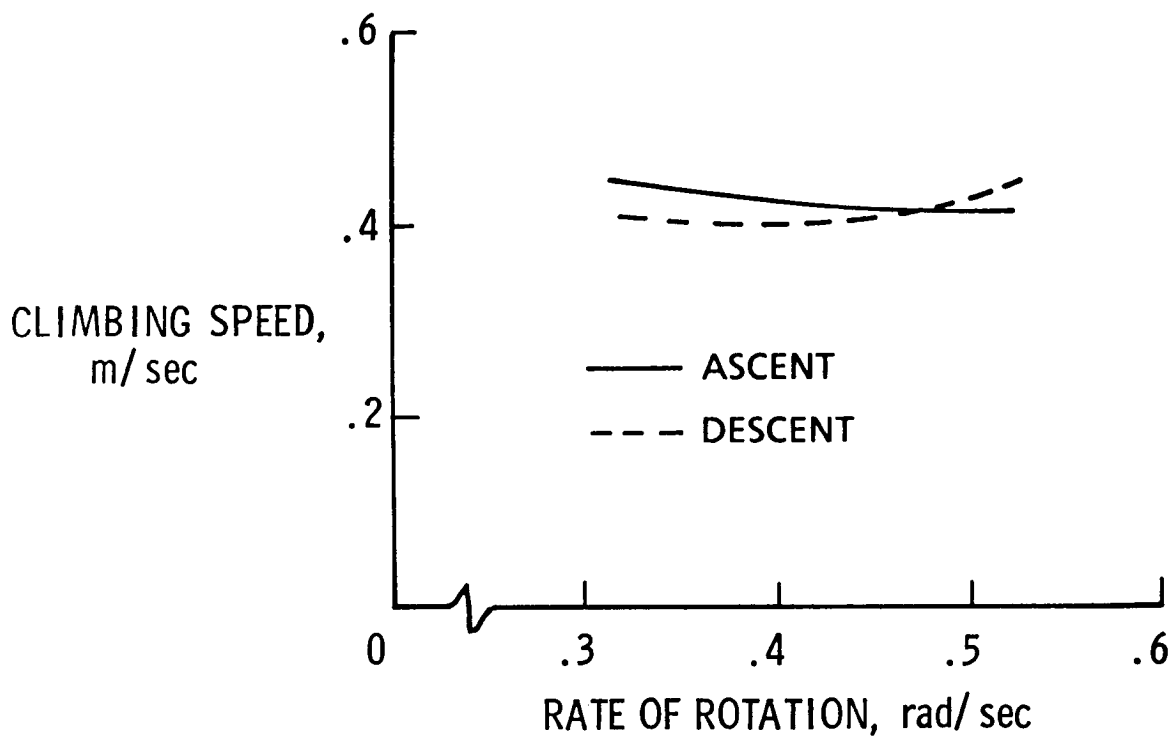
Figure 4.2-23 Influence of Rate of Rotation on Ladder Climbing Rate in
Simulated Artificial Gravity (Reference 4-47)

gravity level. The performance time is improved with increasing gravity level and probably with increasing radius. In Figure 4.2-23 the results indicate little influence of rate of rotation on ladder climbing rate. Variable rung spacing on ladders was examined, and the results showed that a spacing from 0.51 m (20 in) near the center of rotation with very low g's to 0.30 m (12 in) at the larger "g" levels was desirable. Another effective use of a ladder was found to be holding the side rails and sliding. In these experiments the ladder was arranged so the climber faced tangentially in either prospin or antispin directions. The results showed that facing the prospin direction when descending or the antispin direction when ascending where the climber is held away from the ladder was good until Coriolis forces causing accelerations of 0.8 m/sec^2 or more were attained. Facing prospin while ascending or antispin while descending, where the climber is held against the ladder, was desired at larger Coriolis acceleration levels. Handholds in elevators in radial motion should be used when the Coriolis forces cause accelerations of 3.0 m/sec^2 or less. With larger values of Coriolis forces, restraints should be used.

Short term memory and mental functions are affected by the rate of rotation. Performance tasks presented in Reference 4-48, requiring extensive arm and head motions, were degraded up to 11 percent by rotation of 6 rpm. Degradation was greatest when facing in the prospin direction. Facing axially or in the antispin direction was better. The effects on the vestibular system caused by head motions reduced psychomotor performance at the onset of experiments, but in about 2 days normal performance was essentially regained.

Of 175 persons used in short term exposure to rotation in Reference

4-48, none were adversely affected at 3 rpm. Two percent were affected with motion sickness at 4 rpm, 15 percent at 5 rpm, and 80 percent at 6 rpm. Two days of conditioning reduced the incidence of motion sickness to zero at 4 and 5 rpm and to about 3 percent at 6 rpm.

The results of the experiments of References 4-43 thru 4-48 give substantial merit for the use of artificial gravity for extended space flight. Figure 4.2-24 shows performance limits and evaluations from Reference 4-48.

4.3 A REASONED JUDGEMENT FOR ARTIFICIAL GRAVITY

Weightlessness through experience has been shown to have serious physiological consequences. These consequences center on the musculoskeletal and cardiovascular systems and result from disuse because of the lack of weight and from the lack of hydrostatic pressures. The results show that the countermeasures used thus far, ranging from exercise to the use of special devices, have not sufficed to maintain conditioning and well-being of men in space. Also, the evidence is unclear whether, as flights are extended in time, i.e., in excess of 8 months, some of these physiological consequences will continue to degrade in spite of the many efforts and countermeasures to oppose them. The use of special countermeasures, including exercise, requires an appreciable amount of the very valuable time of the crew members to say nothing of encumbering them during working periods.

Artificial gravity, on the other hand, supplies weight and hydrostatic pressure, the missing ingredients in weightlessness. The crew members, in artificial gravity, as was noted before, live, work, play, rest, and sleep in a condition of weight as they would on Earth,
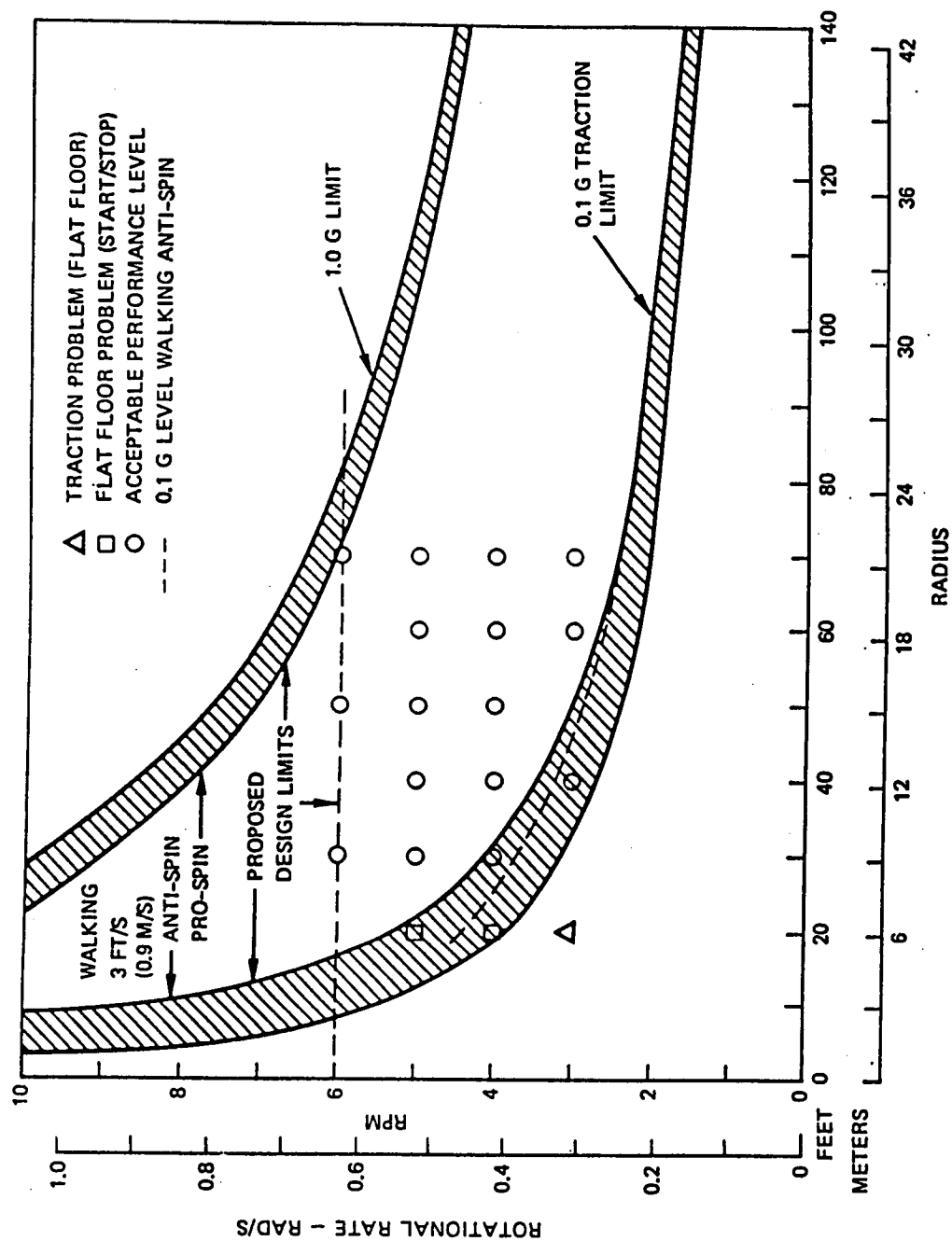
Figure 4.2-24 Predicted Performance Limits and Performance Evaluation
(Reference 4-48)

without special time for countermeasure use and without the confining encumbrances from them. There is no evidence on how much artificial gravity will adequately maintain the well being of the musculoskeletal and cardiovascular systems. However, it is evident that a value of artificial gravity equivalent to the Earth's gravity will suffice. Accordingly, the proposed Space Station of this report is planned to have one Earth "g" capability, with the ability to use lesser values.

The unfavorable effects of artificial gravity because of its rotational environment are greatly ameliorated by the large radius of rotation of the proposed spacecraft (114 m). With this radius and an effective 1 "g" environment only 3 rpm is required. Existing data show only small (and easily adapted to) vestibularly induced consequences at this rotation rate. The effects of Coriolis forces consequent to this rotation seem readily manageable. The special features and factors previously mentioned should be observed.

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5.0 OPERATIONAL ASPECTS RELATED TO ROTATION

Because of the physiological problem generally associated with working and living under zero-gravity conditions, it was deemed advisable to make provisions for some level of "artificial" gravity by rotating part of the Space Station (Section 4). This section is concerned with some implications other than the physiological effects of rotation. The primary focus is on fuel or electrical power costs of spinning and orienting the Space Station. The 2025 Space Station is designed to provide any desired "g" level up to one Earth "g". The calculations given here are for one Earth "g" to illustrate worst case requirements, and for two configurations of the Space Station with and without counter-rotating tanks.

5.1 FUEL REQUIRED TO ROTATE SPACE STATION ELEMENTS

The masses and inertias used in these calculations are listed in Table 5.1-1.

5.1.1 Spin Torus Assembly

The rotating torus will provide some degree of inertial stabilization. However, the Space Station must precess once per year to remain Sun-facing. Since it might be desirable to reduce the inertial stabilization (make it easier to precess the Space Station), the use of two counterrotating tanks was suggested in Reference 1-3. The torus assembly consists of the torus, spokes, central hub, and the two solar dynamic units located on the spokes.

TABLE 5.1-1 MASS AND INERTIAS
USED IN CALCULATIONS OF SECTION 5.

ELEMENT	MASS, kg	MOMENT OF INERTIA, kg-m^2
Torus Assembly	2.94×10^6	$I_z = 3.20 \times 10^{10}$
Counterrotating Tanks (2)	4.28×10^6	$I_z = 8.95 \times 10^9$

An estimate of the amount of fuel required to spin the torus to the speed required to create an Earth "g" environment is made under simplifying assumptions. It is assumed that rocket thrusters can be placed on the outside of the torus with thrust tangent to the torus. The equation of motion is

$$I\dot{\omega} = TNd$$

and on integrating, assuming $\omega_o = o$,

$$I\omega = TNdt \qquad (5.1)$$

Since

$$T = \dot{w}I_{sp} \qquad (5.2)$$

equation (5.1) becomes

$$I\omega = \dot{w}I_{sp} Ndt$$

from which

$$\dot{w}Nt = I\omega/dI_{sp} \qquad (5.3)$$

and is the total fuel required to attain a rotational velocity ω.

The value of ω to be attained depends on the "artificial gravity" level required, and the relation is

$$a = R\omega^2 \qquad (5.4)$$

An estimate of the fuel required to spin the torus assembly is made using the following values:

I_{sp} = 4312 (H_2-O_2 fuel) N-sec/kg

R = 114 m

d = 122 m

a = 9.8 m/sec^2

I = 3.198 x 10^{10} kg-m^2

Using equation (5.4) to obtain ω yields a value of 0.293 radians per second (2.80 rpm). Substituting this value and the above parameters into

equation (5.3) yields a total fuel weight of 19,000 kilograms.

Spinning the torus assembly could be accomplished using coils wrapped around the torus tubular cross section at an energy cost of 1.4 X 10^9 Joules. Spinning the torus and counterrotating tanks could be done with electric motors.

5.1.2 Fuel Required to Spin Counterrotating Tanks

Assuming that it is desirable to reduce the total angular momementum to zero and that thusters could be mounted on the rim of the tank, the fuel required to spin the tanks can be determined. The tanks are assumed to rotate at a rate of 10 rpm counter to the direction of the torus. The angular momentum to be cancelled is that of the torus and amounts to

$$I\omega = (3.198 \times 10^{10})(0.2930) = 9.370 \times 10^9 \ kg\text{-}m^2/sec$$

Using the assumed value of 10 rpm (1.047 radians per second), the required moment of inertia of the two tanks is

$$I = 8.95 \times 10^9 \ kg\text{-}m^2$$

The fuel required to spin the tanks can be determined by use of equation (5.3), based on the following parameters.

$$I = 8.95 \times 10^9 \ kg\text{-}m^2$$
$$d = 45.73 \ m$$
$$I_{sp} = 4312 \ (H_2 - O_2 \ fuel)$$
$$\omega = 1.047 \ rad/sec.$$

The mass of the fuel used is 47,500 kg.

The use of counterrotating wheels adds complexity to the Space Station and requires a fairly large amount of fuel. However, it is of interest to determine if their use provides any advantages when orienting

(precessing) the Space Station.

5.2 ORIENTATION CONTROL

The Space Station is Sun oriented and therefore must precess one revolution per year.

Precession can be accomplished by applying an external torque to the spinning Space Station. Since the force applied is orthogonal to the motion, no energy is expended. Providing the torque may involve expenditure of unrecoverable energy. Two such cases are discussed below: precession thruster jets and the I^2R losses in producing a magnetic field for magnetic torquing. The use of tether torquers is also mentioned in Section 9. Tether torquers may have a set of application problems that will be better understood after some experience with tethers in space is acquired. Other methods not discussed here are: Off-set reboost thrust, off-set atmospheric drag configuration, solar pressure, and permanent magnets or electrodynamic space discharge current interacting with the Earth's magnetic field.

5.2.1 Precession Using Thruster Jets. No Counterrotating Tanks.

The torque necessary to precess a spinning body about an axis perpendicular to the spin axis is given by

$$L = I_\omega \Omega \qquad (5.5)$$

Using the values of I_ω for the torus assembly, given in section 5.1.1, and a precession rate of one revolution per year results in

$$L = 1866 \text{ N-m}$$

If the torque is to be provided by jets, then

$$L = NTd = NI_{sp}\dot{w}d \qquad (5.6)$$

Assuming that the thrusters fire continuously, the amount of fuel used for a given time can be determined using equation (5.6),

$$N\dot{w}t = Lt/I_{sp}d$$

If the thrusters are located on the observation tube at a distance 125 meters from the Space Station centerline, the fuel used in one year is

$$N\dot{w}t = 109,200 \text{ kg.}$$

If structure is added to increase the distance of the thruster from the station, the fuel requirement will be decreased proportionally to the ratio of distances from the center of mass.

5.2.2 Precession Using Thruster Jets With Counterrotating Tanks

The rather large amount of fuel required to precess the spin-stabilized torus assembly led to an assessment of fuel savings resulting from a reduction in the total angular momentum of the station. This is the consideration that led to the thought of using counterrotating tanks, which would also serve as water reservoirs. If the total angular momentum is reduced to zero, then the equation of motion for precessing the Space Station is given by equation (5.3), with the proper moment of inertia. In this case, fuel used is negligible because of the low precession rate.

5.2.3 Precession Using Electromagnetic Torquing

One method of precession which appears attractive is the use of magnetic torquing (Reference 5-1). The torus provides a large area current loop support. If a closed plane loop carrying a current I_1 is placed in a magnetic field having strength B, with the magnetic lines of force parallel to the plane of the coil, a torque is produced. The

torque is given by

$$L = 10^{-4} \, p I_1 A n B \quad \text{N-m} \qquad (5.7)$$

where

A = enclosed area of the loop

p = number of coils in the loop

B = magnetic field strength, Gauss

n = unit vector normal to the coil

I_1 = current in the coil

For the configuration with no counterrotating tanks, the torque required to precess the station is 1866 N-m (Section 5.2-1). Equation (5.7) can be used to determine the ampere-turns necessary to produce the required torque.

For the Earth's magnetic field at low-Earth orbit, B = 0.3; therefore, the current required for a single-wire loop is 1330 amperes. An estimate of the size and mass of the required conductor can be made as follows:

Assume allowable power loss is 10 kW.

$$R_1 = P_1/I_1^2 = 5.6 \times 10^{-3} \text{ ohms}$$

$$A_1 = \delta \times \ell / R_1 = 2.3 \times 10^{-3} \text{ m}^2$$

Mass of copper = $A_1 \ell \times$ (density Cu.) = 1.5×10^4 kg

It appears that the conductor mass is quite large even for an allowable loss of 10 kW.

However, if recent trends in super-conducting materials improvement continue, electromagnetic torquing could be a very viable technique for precessing the Space Station.

5.2.4 Discussion Of Some Operational Aspects Associated With A Rotating Space Station

The primary results of Section 5.0 are summarized in Table 5.2-1. The results shown are useful in comparing two possible configurations, but are not to be considered the primary factors in selecting a final configuration. The use of counterrotating tanks provides an advantage in reducing the fuel to precess the Space Station, but that appears to be negated by the added complexity and the fuel used to spin the counterrotating disks. Using electromagnetic torquing for precessing the station is a viable option that should be studied in more detail.

Of course, eliminating the counterrotating disks removes their use as water storage units. Water, therefore, would have to be stored either in the torus or in some non-rotating section of the Space Station. Storing water in the torus would increase the inertia of that unit, thereby increasing the fuel required to initiate the spin. Further study is required for ways of precessing and spinning the Space Station.

TABLE 5.2-1   ENERGY USED TO SPIN AND
PRECESS SPACE STATION ELEMENTS

	SPIN			PRECESS	
	Energy		Fuel	Fuel	Ampere turns
	Joules	kW-hrs	kg	kg	
Torus Assembly	1.37×10^9	381	19,000	109,200	1330
Counterrotating Tanks	4.91×10^9	1366	47,500	--	--
Torus Assembly and Counter-rotating Tanks	6.28×10^9	1746	66,500	Negligible	

References

5-1 White, John S., Shigemoto, Fred H., and Bourquin, Kent:
     Satellite Attitude Control Utilizing the Earth's Magnetic
     Field. NASA TN D-1068, 1961

6.0 ALTERNATE CONFIGURATIONS

Several variations of the baseline configuration were examined briefly during this study. These included the following:

1. Elimination of the counterrotating tanks.

2. Inboard shift and lowering of the solar dynamic units on the torus.

3. Polygon instead of a torus for the primary rotating section of the Space Station.

6.1 COUNTERROTATING TANKS

As discussed in Section 5.0, the counterrotating tanks of the reference configuration were to be considered as a means of controlling the total angular momentum of the Space Station. This concept was beneficial in that it could be used to reduce the energy required to precess the Space Station. However, it created several problems, such as, (1) requiring much energy to spin the tanks, (2) increasing the mass that must be lifted into orbit, and (3) requiring additional construction in the space environment.

6.2 INBOARD SHIFT AND LOWERING THE SOLAR DYNAMIC UNITS ON THE TORUS

Both of these changes were made because of the large loads and moments which would be created by rotation of the torus. Another consideration was that maintenance of the units might present some difficulties because of the artificial gravity-vector orientation. Several other considerations were discussed, but are not reported in detail. These included relocation of all solar dynamic units into the non-rotating platform at the Sun-facing end of the Space Station.

Another solar collection system considered was that of multiple parabolic collectors on the platform, focusing on a single power-generating unit. The entire assembly would be mounted on the non-rotating part of the Space Station. This approach probably should be examined in any further study.

6.3 REGULAR POLYGON INSTEAD OF A TORUS

Use of a polygon instead of a torus simplifies packaging for launch and might simplify sealing of joints between sections in space. However, there might be some disadvantages in living and operating inside the rotating structure for several reasons, such as, (1) the "gravity" vector generally is not perpendicular to the "floor" and (2) materials tend to slide to the joints between sections.

7.0 SPACE STATION INTERNAL CONFIGURATION

The 17 functions identified for the 2025 Space Station provide the basis for defining the internal configuration. Table 7.0-1 lists the 17 functions and indicates the locations where each function is performed or supported; Figure 7.0-1 shows an overview for the 2025 Space Station which identifies the principal locations. The descriptions which follow include the detail necessary to implement each function. For example, the requirements for crew support and system control involve a comprehensive assessment, the elements in the rotating sections have definitions that include the masses as inputs to the prediction of inertial effects. The descriptions of the internal configuration begin with the rotating section and then continue with the central tube, observation tubes, and the berthing area.

7.1 THE ROTATING SECTIONS: TORUS, SPOKES, HUB, AND COUNTERROTATORS

The artificial gravity induced by rotation produces an environment-of-comfort for the continuously inhabited sections of the 2025 Space Station. Accordingly, the command, control, and life support related functions are concentrated within the torus. The spokes provide the access elevators to the torus, and the hub provides for two-way transfers between the rotating and non-rotating sections of the Space Station; the general layout of the rotating section is shown in Figure 7.1-1. For the purposes of discussion, the torus, as viewed from the direction of the Sun, has a clockwise rotation, with spoke numbers also assigned clockwise. Since the major functions within the rotating sections are performed within the torus, the description of the sections begin with the torus.

TABLE 7.0-1 FUNCTIONS AND ASSOCIATED LOCATIONS WITHIN THE
2025 SPACE STATION

FUNCTION	LOCATIONS FOR PERFORMANCE AND SUPPORT

HABITATION AND MEDICAL

o CREW LIFE SUPPORT

Torus: General living, atmosphere revitalization
Observation Tube: Short term living, safe haven for emergencies

o VARIABLE GRAVITY ADAPTATIONS

Spokes: Habitat and laboratory
Torus: Life and technical support

o TRANSIENTS ACCOMMODATION (TOURISTS)

Torus: General living

o MEDICAL CARE FOR CREWS AND TRANSIENTS

Torus: Treatment and physical conditioning

OPERATION SUPPORT

o SPACECRAFT SERVICE AND REPAIR

Berthing Area: Spacecraft support
Central Tube: Repair and assembly
Torus: Parts fabrication, fuel generation, remote handling controls

o TRANSPORTATION NODE, RETRIEVE-FUEL-DEPLOY

Berthing Area: Retrieve, fuel, deploy
Observation Tubes: Tracking antennas for berthing and deploying
Torus: Fuel generation, controls for berthing, handling and deployment

o COMMUNICATION CENTER AND RELAY POINT

Torus: Control center for acquisition recording and relay transmission
Observation Tube: Antennas and laser telescopes for r.f. and optical links

o CONTROL CENTER FOR OTHER SPACECRAFT

Torus: Controls and mission planning support
Observation Tube: Relay antennas for r.f. link, laser telescope for optical link

o ENERGY COLLECTION AND RELAY

Torus: Controls for fuel transfer and reflector operation, O_2-H_2 fuel generation

TABLE 7.0-1   FUNCTIONS AND ASSOCIATED LOCATIONS WITHIN THE
2025 SPACE STATION (concl.)

OPERATION SUPPORT (cont.)

o ENERGY COLLECTION AND   Observation Tube: Deployable reflector for
   RELAY (cont.)   laser light beams

o STORAGE AND SUPPLY   Central Tube: Ready storage
   CENTER   Berthing Area: External storage
                              Torus: Fabrication stock, technical
                                      supplies, food supplies, medical
                                      supplies

MANUFACTURING

o COMPONENT MANUFACTURE   Torus: Parts fabrication and assembly
   SPACECRAFT ASSEMBLY   operations
                              Central Tube: Spacecraft assembly
                              Berthing Area: Spacecraft final assembly
                              Torus: Remote manipulator operation

o COMMERCIAL MICROGRAVITY   Central Tube: Microgravity facility
   PROCESSING   Torus: System operation

SCIENCE AND RESEARCH

o OBSERVATORY FOR EARTH,   Central Tube: Solar observatory
   SPACE, SOLAR   instruments
                              Observation Tube: Earth and space viewing
                                                 instruments
                              Torus: Central data processing

o ORBITAL SCIENCE RESEARCH   Platform: Experiment mountings
   LAB   Observation Tube: Experiment mountings
                              Central Tube: Experiment mountings
                              Torus: Central data processing

o VARIABLE GRAVITY RESEARCH Spokes: Platform location and service
   FACILITY   elevators
                              Torus: Support, control, planning and
                                      data processing

o HORTICULTURE RESEARCH   Platform: Solar facing domes, microgravity
   FACILITY   environment
                              Spokes: Variable gravity under artificial
                                       light
                              Torus: Control, planning, data processing

o TECHNOLOGY DEMONSTRATION   Platform: Exterior mounted items
   FACILITY   Central Tube: Microgravity items
                              Spokes: Variable gravity items
                              Torus: Control, planning, data reduction,
                                      parts and equipment fabrication

SOLAR OBSERVATORY (1 REQ) - 15.2 m Dia x 9.2 m

SOLAR DYNAMIC UNITS { (4 REQ) 425 kWe - 39 m Dia
{ (2 REQ) 25 kWe - 10 m Dia

PLATFORM - 5 m x 158.5 m Dia

SPOKES (4 REQ) - 9.1 m Dia x 89.9 m

TORUS CYLINDER (24 REQ) - 7.62 m Radius
EACH CYLINDER - 15.24 m Dia x 29.9 m

9.1 m Dia

39 m

5 m

128.6 m

167.6 m

CENTRAL HUB
33.5 m Dia x 30.4 m

114.3 m Radius

47.24 m

67.1 m

67.1 m

CENTRAL TUBE
15.2 m Dia x 100.3 m

HORTICULTURAL DOMES (4 REQ) - 5 m H x 25 m Dia

RADIATORS (100 REQ)
5 m x 10 m

SOLAR DYNAMIC UNITS
(2 REQ) 425 kWe - 38.7 m Dia

RADIATORS
(150 REQ) - 3.1 m x 5.1 m

COUNTER ROTATOR (2 REQ) - 7.6 m x 91.4 m Dia

9.1 m Dia

5 m

BERTHING AREA

Figure 7.0-1 Overview of the 2025 Space Station Showing Principal Features and Dimensions

CONCEPT FOR THE TORUS INTERNAL CONFIGURATION

CIRCUMFERENTIAL PASSAGE

HEMISPHERICAL END
(PRESSURE BULKHEAD)

SPOKE #2, MANUFACTURING/LIFE SUPPORT
METAL FAB. ELECTRONICS

DIRECTION OF
ROTATION

SPOKE #1, HABITAT; COMMAND AND
INTERNAL CONTROLS

O_2 VOLUMES

H_2 VOLUMES

SPOKES, 30' DIA.
(WITH ELEVATORS)

HUB

SPOKE #3, HABITAT; EXTERNAL CONTROLS
MEDICAL

CENTRAL TUBE
(NON ROTATING)

SPOKE #4, MANUFACTURING/LIFE SUPPORT
COMPOSITES FAB. FIBER OPTICS

FUEL STORAGE SECTIONS
O_2, H_2 AT 14.7 PSI IN
EQUILIBRIUM WITH ULLAGE
GASSES

Figure 7.1-1, Rotating Sections of the 2025 Space Station Showing the Direction
of Rotation and the Convention for Numbering the Spokes

7.1.1 The Torus

The torus concept shown as Figure 7.1-1 continues to use the established diameter of 228.6 m (750 ft) with a ring diameter of 15.2 m (50 ft) (Reference 7-1). The concept for on-orbit assembly described later (see Section 8.0) utilizes a polygon of cylindrical sections; however, the internal configuration described below can be accommodated within either a ring or polygon exterior. The layout for the internal sections divides the torus into eight equal segments with an inhabited section at the end of each spoke; the four "separating" volumes provide storage for the O_2 and H_2 gases generated on-board by electrolysis of water. The concept assumes a one atmosphere internal pressure throughout the entire torus, spokes, and hub. In effect, a shirt-sleeve environment will exist throughout the inhabited areas such that crew members and equipment can move freely about the entire circumference of the torus. In the descriptions that follow, the individual sections of the torus are ranked according to their principal function which determines their order of presentation as:

> Section at Spoke 1, Command, Control, and Crew Support
>
> Section at Spoke 3, Control and Medical
>
> Section at Spoke 2, Metal Fabrication and Life Support
>
> Section at Spoke 4, Composite Fabrication and Life Support.
>
> The Gas Storage Volumes.

7.1.1.1 The Habitat at Spoke 1: Command, Control, and Crew Support

The concept for the configuration of the inhabited section at Spoke 1 appears in Figures 7.1.1-1 and 7.1.1-2. Table 7.1-1 lists the functions accommodated and the assumptions which led to the
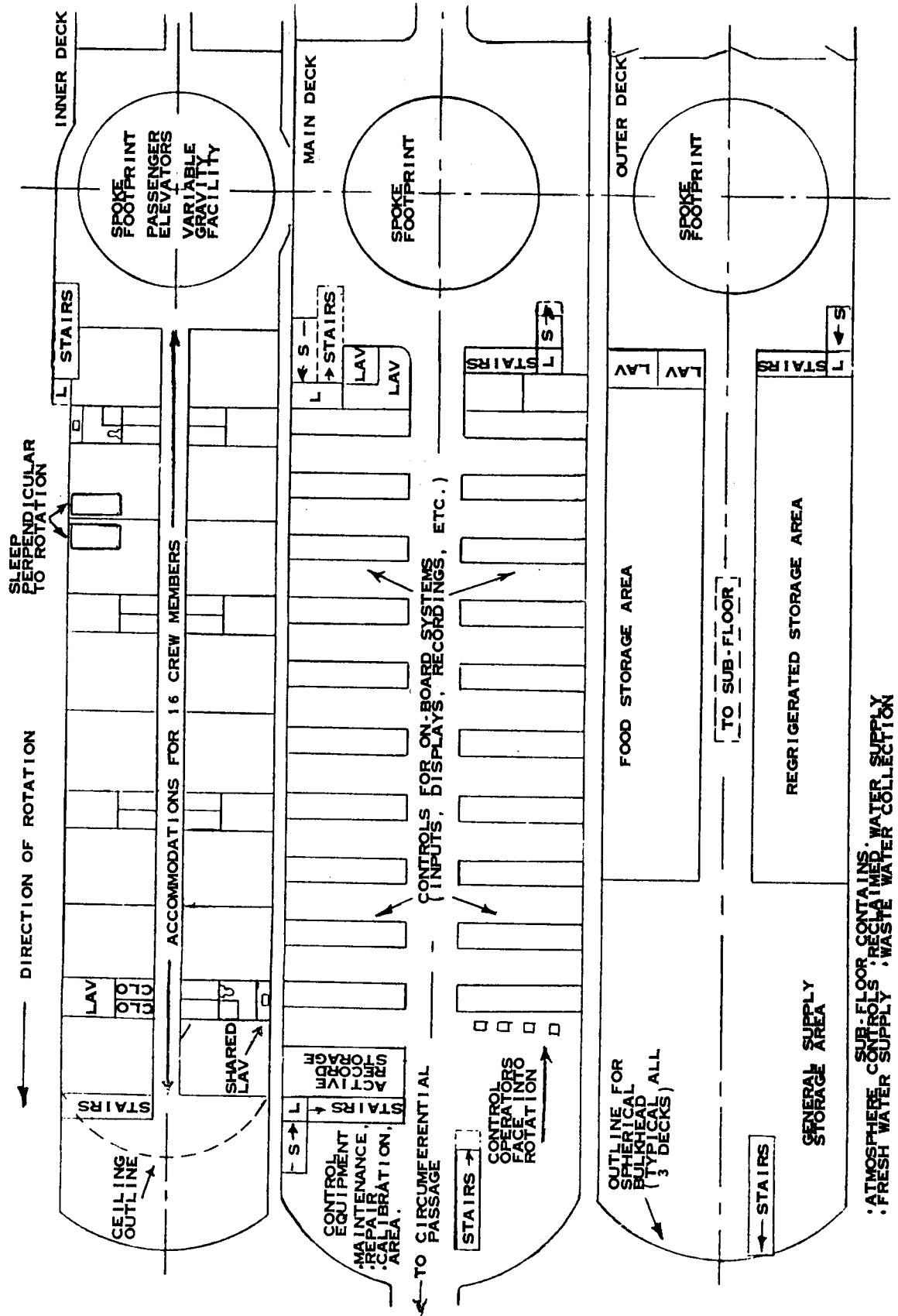
Figure 7.1.1-1, Functional Layout for the Habitat at Spoke 1, Leading Portion

C-2

INNER DECK

DIRECTION OF ROTATION

STAIRS

CLO
CLO
LAV

LAV

ACCOMMODATIONS FOR 16 CREW MEMBERS

CLO
CLO

SPOKE FOOTPRINT
PASSENGER ELEVATOR
VARIABLE GRAVITY FACILITY

MAIN DECK

CURVED STAIRS TO INNER

CURVED STAIRS TO OUTER

S
S
S

STAIRS

L S
S
L

MISSION PLANNING CENTER

LAV
LAV
LAV

EXECUTIVE OFFICES

SPOKE FOOTPRINT

OUTER DECK

STAIRS — S

CREW DINING AND LOUNGE AREA
•AREA OPEN TO MAIN DECK CEILING

SEATED DINERS FACE PARALLEL TO ROTATION

STAIRS
L S
S
S
L

MAIN GALLEY
(PREPARATION)
(SERVING)
(SCULLERY)

SPOKE FOOTPRINT

SUB-FLOOR CONTAINS:
•ATMOSPHERE CONTROLS •RECLAIMED WATER SUPPLY
•FRESH WATER SUPPLY •WASTE-WATER COLLECTION

Figure 7.1.1-2, Functional Layout for the Habitat at Spoke 1, Trailing Portion

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TABLE 7.1-1 SUMMARY OF FUNCTIONS AND
ASSUMPTIONS FOR THE INHABITED SECTION AT SPOKE 1

A.   FUNCTIONS PERFORMED OR PROVIDED:

1.   Space Station command and on-board mission planning.

2.   Control operations for on-board systems such as inputs, monitor,
      and display.

3.   Redundant control operations for external functions such as
      inputs, monitor, and display.

4.   Living quarters for half the crew.

5.   Food storage and preparation for the crew.

6.   Off duty recreation facility for crew.

7.   Life support functions such as ventilation, local fresh water
      distribution, and waste water collection

B.   STRUCTURE AND EQUIPMENT RELATED ASSUMPTIONS

1.   The internal structure of the torus provides its own support.
      Centrifugal loads are carried as tension in the decks and
      interconnecting tubes. (The skin of the torus provides structural
      stabilization rather than load reaction.)

2.   The structural elements employ aluminum 2024 alloy to provide
      conservative estimates for size and weight.

3.   The structure will be configured for 1g operation.

configuration. The concept consists of three decks with the main deck at a radial position which provides the floor to a continuous circumferential passage at the centerline of the torus. The circumferential passage will accommodate the movement of a cube 2.4 m (8 ft) around the entire torus. An inner deck 3.9 m (13 ft) radially inward and an outer deck 2.9 m (9.5 ft) radially outward provide the floor areas for the section with envelope dimensions as follows:

	Radius	Length	Width	Ceiling to Floor
Inner Deck	112.2m (368ft)	101.2m (332ft)	9.7m (32ft)	3.5m (11.5ft)
Main Deck	116.1m (381ft)	104.8m (344ft)	14.0m (46ft)	3.9m (13ft)
Outer Deck	119.3m (392.5ft)	101.3m (334ft)	11.6m (38ft)	2.9m (9.5ft)

The configuration allows about a 1.6 m (6 ft) arch above the inner deck ceiling for ballast tankage and a 2.4 m (8 ft) clearance below the outer deck for support equipment and piping. The structural concept utilizes aluminum honeycomb for decks, walls, and ceilings plus aluminum "I" beams on 1.5 m (5 ft) centers as auxiliary supports. The section acts as a monocoque structure to support itself and the applied loads without dependence upon the outer shell that accepts the pressure loads. Table 7.1-2 summarizes the structure and contents for sizes and masses.

The functions and their support items can be summarized in terms of their locations within the section. The inner deck provides personal quarters for up to 32 members of the crew. The sizing and arrangement of accommodations recognize a need for comfort in an extended flight (e.g., more than the 90-day limit for IOC Space Station) and represent a compromise between a cruise ship and officer's quarters aboard a avy

TABLE 7.1-2 SUMMARY OF SIZE AND MASS
ESTIMATES FOR THE SECTION AT SPOKE 1

A. HONEYCOMB STRUCTURE ELEMENTS:

Aluminum honeycomb cores at 96 kg/m^3 (6 lb/ft^3) with 1 mm (0.042 in) skins unless otherwise noted.

1. Inner deck ceiling: Loading 478 Pa, (10 lb/ft^2); 13 mm (0.5 in) thick.

2. Inner deck: Loading 1436 Pa (30 lb/ft^2); 25 mm (1 in) thick.

3. Main deck: Loading 1915 Pa (40 lb/ft^2); 25 mm (1 in) thick.

4. Outer deck: Loading 1915 Pa (40 lb/ft^2); 25 mm (1 in) thick.

5. Walls: 38 mm (1.5 in) thick; 615 m (2018 ft) length.

6. Partitions: 25 mm (1 in) thick; 653 m (2144 ft) length.

7. End caps: 38 mm (1.5 in) thick; 2.4 mm (0.094 in) skins.

Total Honeycomb Mass: 81703 kg (180161 lb).

B. SUPPORTS AND TIE BEAMS

1. Deck supports: 1.5 m (5 ft) centers as "I" beams.

2. Joint stiffeners and supports: 1268 m (4160 ft) total, as angles.

3. Circumferential supports and ties: 0.3 m (12 in) box beams, 6 total.

Total Support Structure: 52418 kg (115587 lb).

Total Structure: 134121 kg (295748 lb)

C. AREA FUNCTIONAL SUPPORT

1. Crew 32: 362 kg (800 lb) per person including furnishings and carry-ons.

2. Control systems area: Footprint 1436 Pa (30 lb/ft^2), 22 equivalent racks.

3. General storage area: 75 percent of area at 957 Pa (20 lb/ft^2).

4. Food supply: 180 days; 2 kg/day (4.5 lb/day) per person.

5. Galley: 50 percent of area at 951 Pa (20 lb/ft^2).

C. AREA FUNCTIONAL SUPPORT (cont.)

    6. Dining lounge: 50 percent of area at 150 Pa (3 lb/ft^2).

Total Functional Support: 85076 kg (187600 lb)

D. SERVICE AND SUBFLOOR SUPPORT

    1. Cabin air circulation with CO_2 and H_2O extraction: 5 changes/hr.

    2. Power distribution and illumination: Estimate for wiring and fixtures.

    3. Communication and control lines: Estimate for wiring and optical fibers.

    4. Water distribution and waste water collection : 1 day tankage.

Total Service and Support: 16699 kg (36823 lb)

E. MASS OF ATMOSPHERE: 19742 kg (43534 lb)

    (Volume of 16371 m^3, 578299 ft^3)

Total Mass Estimate: 255640 kg (563706 lb)

ship. The 2025 Space Station anticipates a diverse crew. The allotment of 363 kg (800 lb) per crew member includes the individual, the personal carry-ons, and the furnishings of the quarters.

One of the major functions performed is the on-board command and the control for the Space Station. The main deck provides the locations for the required equipment and operators. The details of operation for the 2025 Space Station will require the on-board generation of the "Operating Time Line" for the station. Therefore, a mission planning facility and a station commander's office are provided. The computational equipment and support individuals required to plan and generate time lines are located therein. Approximately one half of the main deck has been dedicated to a central control room which contains the equipment for the input, monitor, and display functions. Table 7.1-3 lists the presently identified systems or functions which would require an active control station, and also indicates a primary or redundant role in terms of the functions performed. Spoke 1 provides the primary control station for the functions internal to the 2025 Space Station. A number of the systems listed would generally operate unattended. The control station would become active in the event of a need to modify an operational sequence or to perform a function involving support from that specific system.

The inherent complexities in managing system operations appear in the synergies involved with the control of electrical power and the use of water for ballast. The power monitor and control system must distribute the electrical power throughout the station in response to demand and, at the same time, continuously utilize the electrolytic decomposition of water as the primary electrical load leveler.

TABLE 7.1-3   SUMMARY OF CONTROL FUNCTIONS AND LOCATIONS FOR OPERATION

FUNCTION	SPOKE 1	SPOKE 3
A. INTERNAL CONTINUOUS		
1. Electrical Power: Generation, Distribution, Load Management	Primary; All Functions	Partial; Distribution, Load Management
2. Inertial: CG Location, Trim Balance, Rotation	Primary; All Functions	Partial; CG Location, Trim Balance
3. Atmosphere: Temperature, Humidity, O_2 Recovery, CO_2 Reduction	Primary; All Functions	
4. Wastewater and Reclamation (WAO)	Primary; All Functions	
5. Gas Management: Fuel Generation, Storage, Ullage	Primary; All Functions	Partial; Fuel Transfer
6. Internal Communication: Audio, Video, Recording	Primary	Duplicate
7. Reboost	Primary	Duplicate
B. INTERNAL SUPPORT FUNCTIONS		
1. Central Tube Manipulators	Primary	Duplicate
2. Microgravity Operation	Primary	Duplicate
3. Solar Observatory	Primary	Duplicate
4. Astronomical Observatory	Primary	Duplicate
5. Earth Science	Primary	Duplicate
6. Horticulture	Primary	Duplicate
7. Variable Gravity	Primary	Duplicate
8. Elevators and Transfer	Primary	Duplicate
9. EVA Operations	Primary	Partial, Non-Rotating

TABLE 7.1-3   SUMMARY OF CONTROL FUNCTIONS AND LOCATIONS FOR OPERATION (concl.)

C.   EXTERNAL SUPPORT FUNCTIONS

1.	Communications: Relay, Earth, Beyond Earth Orbit	Partial; Relay and Earth	Primary
2.	Tracking	Partial; Berthing Functions	Primary
3.	Energy Relay		Primary
4.	Berthing Bay: Berth, Transfer, Service Using Manipulators	Partial; Transfer or Service	Primary
5.	Companion Spacecraft Operations		Primary
6.	Airlock Operations	Duplicate	Primary

Electrical power not used elsewhere provides the O_2 and H_2 needed for fuel, atmospheric reconstitution (O_2), and CO_2 reduction (H_2). If the N_2 and CO_2 recovered from the oxidation of wastes become the ullage gases in the storage system for H_2 (see discussion in 7.1.1.4 below), then the programming of operations for the Bosch CO_2 reduction system becomes an additional item included in the control for the load leveling. The complexities inherent in the momentum control system arise from the limits for center of gravity offset and for wobble allowed by the rotating torus. The overall inertial balance of the torus will tolerate crew members moving about within a section and individuals traversing the circumference. On the other hand, the shifting of a significant weight (200 kg, 440 lb) would require a balance trim such as the transfer of ballast water between holding tanks. A major shift of weight (all the crew to dinner at one sitting) would require a programmed and controlled counter-movement of ballast.

Most of the control systems will have a need for recording, with a particular emphasis for video records during the servicing and assembly of spacecraft. Operations performed by remote manipulators will need a video record of the sequences as the substitute for the visual inspections and check lists common to present ground operations. Recording disc supplies and the controlled storage of high density video recordings are considered important elements of the control operation. Finally, a control complex of the size and depth identified will have the requirement for a continuous on-board maintenance, repair, and calibration function. Commonality in system elements such as computers, signal conditioners, recorders, etc. can minimize the inventory of required spares; on the other hand, the critical nature of the control

requirements demands a continuous redundancy with support from an on-board capability for first level repair and calibration.

The assignment of masses for the control stations represents a goal for achievement and appears well within the technology projections for microelectronics and their ancillaries. Present equipment offers little for comparison. Ground equipment racks can exceed 4788 Pa (100 lb/ft^2) in floor loadings, and current Spacelab specifications allow up to 6800 Pa (145 lb/ft^2) defined as 580 kg (1278 lb) over a footprint of 0.83 m^2 (8.8 ft^2) (Reference 7-2). The allotments for control system racks assume a weight discipline which permits a footprint loading of 1436 Pa (30 lb/ft^2) for control racks and computer support equipment. The 20 racks illustrated in the control bay are supplemented by an additional rack for the command area and a half-rack for maintenance and support. These elements represent the principal operating mass contributions for the main deck.

The outer deck provides a storage facility for mission expendables, ranging from recording discs to bed linen, plus the storage for food and the main galley. At the present time, no airborne galleys operate in the same mode as required for the 2025 Space Station. Galleys aboard aircraft support ground prepared food. The expanded galley proposed for the IOC Space Station will also support ground-prepared foods. The extended stay times of the crews for the 2025 Space Station with artificial gravity suggests food preparation and service which approximates ship-board conditions. Food will be cooked, or otherwise appropriately prepared, and served conventionally. Service in a rotating field carries some constraints in eating positions (particularly for pouring liquids). After use, food service items will be washed for

reuse. The mass allotment for food includes a generous 180 day supply for 60 individuals. The galley equipment inventory contains stoves, ovens, preparation surfaces, a serving station, and a scullery. The area will probably operate continuously with nominally a third of the crew present at any serving.

The crew accommodations for extended flights include a lounge with some degree of openness. The area shown is open from the outer to inner decks to provide a combination of a dining area, lounge, recreation facility, etc.

The service and support elements include the need for lighting, power distribution, and data lines throughout the section, as well as the need for ventilation, a fresh water supply, and waste water collection. The ventilation requirements are based upon an average five changes of air per hour that include CO_2 extraction and humidity control. In addition, specialized areas such as the galley would have dedicated scrubbers or filters as part of their installation. The fresh water distribution system, e.g., drinking, food preparation, and the reclaimed water distribution (wash, flush, etc.), provides tank storage capacities for a one day need. The waste water collection and transfer will also have the capacity for one day storage. In addition, the area includes tankage which will accommodate as much as 10,000 kg (22,000 lb) of water for trim ballast distributed and transferred among four locations in response to inertial control requirements.

The total mass assigned for the section is considered conservative, and the large mass assigned to structure shows the need for a more mass efficient construction technique. As an example, within the estimates summarized in Table 7.1-3, the floor loadings required support from six

circumferential box beams (aluminum) which account for almost twenty percent of the total mass allotted for structure.

7.1.1.2 The Habitat at Spoke 3

The inhabited section at the end of Spoke 3 mirrors the general layout at Spoke 1 to provide the control center for "outside" functions and the medical facility. In addition, the section provides crew quarters, crew conditioning facilities, support for research, and general housekeeping functions. The conceptual layout of the section appears as Figure 7.1.1-3 and 7.1.1-4. Table 7.1-4 summarizes the mass estimates for the section.

The inner deck repeats the configuration at Spoke 1 and accommodates up to 32 crew members. Approximately half of the main deck repeats the configuration for control equipment as shown for Spoke 1. These controls focus on the external functions such as communication relay, energy relay, tracking, berthing, and deployment. The control redundancies, as indicated by Table 7.1-3, provide an assurance that spacecraft servicing can proceed throughout all the steps from initial tracking to redeployment. Servicing operations such as repair, replace, (including transfer into the central tube for rebuild), refuel, and redeploy will have the capability for man-in-the-loop control functions. The area assigned for medical functions will provide support for gravity conditioning (or deconditioning) of transient crews as well as performing the medical functions associated with a 60-person work force. The assessments of masses for equipment reflect a conservative extrapolation of the current approach to medical support for remote or isolated stations. The degree of medical capability correlates to the

Figure 7.1.1-3, Functional Layout for the Habitat at Spoke 3, Leading Portion

Figure 7.1.1-4, Functional Layout for the Habitat at Spoke 3, Trailing Portion

TABLE 7.1-4 SUMMARY OF SIZES AND MASS ESTIMATES FOR THE SECTION AT SPOKE 3

A. HONEYCOMB STRUCTURE ELEMENTS:

Aluminum honeycomb cores at 96 kg/m^3 (6 lb/ft^3) with 1 mm (0.042 in) skins unless otherwise noted.

1. Inner deck ceiling: Loading 478 Pa (10 lb/ft^2); 13 mm (0.5 in) thick.

2. Inner deck: Loading 1436 Pa (30 lb/ft^2); 25 mm (1 in) thick.

3. Main deck: Loading 1915 Pa (40 lb/ft^3); 38 mm (1.5 in) thick.

4. Outer deck: Loading 1915 Pa (40 lb/ft^3); 25 mm (1 in) thick.

5. Walls: 38 mm (1.5 in) thick; 615 m (2018 ft) length.

6. Partitions: 25 mm (1 in) thick; 854 m (2804 ft) length.

7. End caps: 38 mm (1.5 in) thick; 2.4 mm (0.094 in) skins.

Total Honeycomb Mass: 89573 kg (197517 lb)

B. SUPPORTS AND TIE BEAMS

1. Deck supports: 1.5 m (5 ft) centers as "I" beams.

2. Joint stiffeners and supports: 1469 m (4822 ft) total, as angles.

3. Circumferential supports and ties: 0.3 m (12 in) box beam, 6 total.

Total Support Structure: 54224 kg (119564 lb)

Total Structure: 143796 kg   (317082 lb)

C. AREA FUNCTIONAL SUPPORT

1. Crew 32: 362 kg (800 lb) per person including furniture and carry-ons.

2. Control systems and science planning and support areas: Footprint 1436 Pa (30 lb/ft^2), 22 equivalent racks.

3. Medical center and vivarium areas: Average floorload at 359 Pa (7.5 lb/ft^2).

C.   AREA FUNCTIONAL SUPPORT (cont.)

    4.   Galley and service area: 50 percent of main galley weight, 25 percent of lounge weight.

    5.   General storage area: 75 percent of area at 951 Pa (20 lb/ft^2).

    6.   Cryostorage area: 50 percent of area at 1436 Pa (30 lb/ft^2).

    7.   Controlled atmosphere storage area: 50 percent of area at 951 Pa (20lb/ft^2).

    8.   Crew conditioning area: Average floorload at 239 Pa (5 lb/ft^2).

    9.   Galley supply area: 25 percent of main food supply plus a lift at 500 kg (1200 lb).

    10.   Laundry area: 5 units at 120 kg (240 lb) each.

Total Functional Support: 84714 kg   (186,802 lb)

D.   SERVICE AND SUBFLOOR SUPPORT

    1.   Cabin air circulation with CO_2 and H_2O extractions: 5 changes/hr.

    2.   Power distribution and illumination: Estimate of wiring and fixtures.

    3.   Communication and control lines: Estimate of wiring and optical fibers.

    4.   Water distribution and waste water collection: 1 day tankage.

Total Service and Support: 16699 kg   (36823 lb)

E.   MASS OF ATMOSPHERE   19742 kg   (43534 lb)
    (Volume 16371 m^3, 578299 ft^3)

Total Mass Estimate: 264953 kg   (584241 lb)

difficulty of transport in the event of a life threatening emergency. Within the U. S. Navy and Coast Guard, small ships which have to operate alone carry additional medical support personnel and facilities in comparison to a similar vessel operating as part of a dedicated task force. For the 2025 Station, the level of capability would accommodate a diverse, changing crew and have the capability for responding to injury from accident or even cardiac emergencies. The on-board medical capability will permit stabilizing a patient to the point where he could be returned to Earth in the event of a major medical emergency. The medical functions in the torus would not include treatment under low gravity; such support activities would involve the variable gravity facilities contained in one of the spokes and receive support from the medical facility within the torus. The capabilities provide for patient rooms, plus laboratories and diagnostic equipment that includes x-ray. The capability also includes a surgical capacity that could respond to broken bone and trauma-type injuries. In addition, the medical facility would need a local capability for food preparation, particularly if a diet constraint became necessary. Such a galley could support the local activities as a supplement to the main facility at the opposite spoke. The auxiliary galley supplies inventory has been arbitrarily set at 25 percent of the main galley supply.

The observatory mission functions, plus the microgravity processing operations, imply a continuing on-board crew of scientists and their support personnel. The data from the on-board instrumentation will require some interpretation or preparation for ground return. Therefore, this section includes an area dedicated to science functions and has computational equipment for science support such as planning,

interpretation, and data reduction.

The outer deck provides areas which complement the crew support and the scientific support functions. Research into life-science effects will continue and will include a need for animal subjects. A vivarium will need a dedicated facility which can have a near-independent ventilation system. Potential future requirements, including preparation for interplanetary exploration, supports a need for cryogenic refrigeration plus a quarantine or controlled-atmosphere storage. Such facilities are included with an arbitrary mass estimate based upon the area assigned. Physical conditioning will continue as an element of crew support. The equipment items would duplicate the capabilities offered in a ground-based exercise facility. The 30 items of equipment used in ground facilities will require combining and a reduction in mass to match the assessments listed. In the evaluations for conditioning, the benefits of a swim facility were considered, and a pool would offer the synergies of a reservoir for reclaimed water while also serving as a trim ballast. This configuration does not include such a facility.

The last element in the outer deck is a laundry. A crew of 60 individuals will generate a significant quantity of apparel items for laundering as well as towels and bed linen. The use of disposables does not appear compatible with continuous operation of the Space Station. The principal compromise anticipated for Space Station operations would be the limitation of on board fabrics to those compatible with water-detergent washing (e.g., no dry cleaning). On this basis, the inventory for the laundry consists of an industrial grade washer, centrifugal extractor, a dryer of some type, and only a limited capability for any dry processing (no ironed shirts).

The sub floor operations match those at Spoke 1 and provide the capabilities for ventilation, electrical power distribution, illumination, fresh water distribution, and waste water collection. The ventilation system for this section would tend to operate as a number of nearly independent units; however, the same overall flow conditions would continue.

7.1.1.3 The Fabrication and Life Support Sections at Spokes 2 and 4

These sections together provide the on-board fabrication capability plus the required life support capacity in terms of CO_2 reduction, water reclamation, electrolytic decomposition of water, and gas management. Figures 7.1.1-5 and 7.1.1-6 illustrate the concept. Table 7.1-5 summarizes the estimates for the associated masses. Each of the sections has the inner deck as mezzanines at each end to provide a high bay area over the center portions of the main decks. Each main deck is divided into a fabrication area and an assembly area. The inventory of equipment carried, together with the capacity for fabrication, repair, or construction, provide the capability to reconstruct elements of supported spacecraft and elements of the Space Station itself, up to the size limit imposed by the circumferential tube (2.3 m, 8 ft) cube or the freight elevator system in the spoke (nominally a 7 m, 23 ft, cube). The installed capability for fabrication support is intended to assure a continuous operation of the 2025 Space Station. The support for spacecraft is expected to include repair or replacement of damaged antenna masts, deployable booms, etc. The ability for modest rebuilding or repair avoids the loss of operating time associated with replacement

SUB-FLOOR AREA CONTAINS
- DISTRIBUTION PIPING
- WATER TANKS
- GAS STORAGE RESERVOIRS
- CRYOGENIC GAS STORAGE

DIRECTION OF ROTATION

ASSEMBLY AREA

ACESS LIMITS FOR OVERHEAD TROLLEY

METAL FABRICATION AREA SPOKE 4 MAIN DECK

SAW

SHEAR/BRAKE

HYD PRESS

STRONG BACK (PIPE AND TUBE BEND)

SURFACE GRINDER

MILL

LATHE

RADIAL DRILL

SWAGE

SPOKE FOOTPRINT AND ELEVATOR

MAIN DECK

INNER DECK MEZZANINE:

SPOKE 4, FIBER OPTICS FABRICATION
SPOKE 2, STORAGE LOFT

STAIRS
LIFT
L

W POWER SUPPLIES WELD AND MELT
M

HEAT PROCESSING;
- WELD - TIG, SPOT, GAS.
- HEAT TREAT
- MELT AND CAST.

SMALL METAL-WORKING TOOLS;

D, DRILL, G, GRINDER, L, LATHE, M, MILL,
P, PRESS, RB, ROLL/BRAKE, S, SHAPER, SH, SHEAR.

STAIRS
LAV
LIFT
L
S

TOOL STORAGE

CIRCUMFERENTIAL PASSAGE

RB
P
SH
S
M
G
M
L
D
D
L
G

DRAW BENCH

O₂ PUMPS AND COMPRESSORS

H₂O CELLS

H₂ PUMPS AND COMPRESSORS

TO SUB-FLOOR

POWER DISTRIBUTION

STAIRS

SPOKE/ELEVATOR

OUTER DECK

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Figure 7.1.1-5, Functional Layout for the Areas at Spokes 2 and 4, Leading Portion Showing Metal Fabrication and Life Support

INNER DECK MEZZANINE:

SPOKE 2, ELECTRONICS FABRICATION

SPOKE 4, STORAGE LOFT

LIFT

STAIRS L

DOCUMENTS

STAIRS

FABRICATION CONTROL CENTER

CIRCUMFERENTIAL PASSAGE

FIRST AID

LIFT LAV L

S

STAIRS

LAY-UP

LAY-UP

RESIN

TRIM

STAIRS

WASTE WATER PUMPS

BOSCH CO$_2$

SC-WAO

SUB-FLOOR AREA CONTAINS:
• DISTRIBUTION PIPING
• WATER TANKS
• GAS STORAGE RESERVOIRS
• CRYOGENIC GAS STORAGE

COMPOSITES FABRICATION AREA SPOKE 2 MAIN DECK

RESIN

MAIN DECK

P.C. P.C.

PRESS. CURE (3x7M)

TRIM TABLE

PULTRUSION 25M

GAS SPRTRS.

RECLAIMED WATER PUMPS

LIFT

LAY-UP (3x7M)

FILAMENT WINDER 15M (WITH CURING MUFFLE)

ACCESS LIMITS FOR OVERHEAD TROLLEY

STAIRS

OUTER DECK

N$_2$ PUMPS

TO SUB-FLOOR

FRESH WATER PUMPS

LIFT

STAIRS

DIRECTION OF ROTATION

ASSEMBLY AREA

SPOKE FOOTPRINT AND ELEVATOR

SPOKE/ ELEVATOR

STAIRS

Figure 7.1.1-6, Functional Layout for the Areas at Spokes 2 and 4, Trailing
Portion Showing Composites Fabrication and Life Support

TABLE 7.1-5 SUMMARY OF SIZE AND MASS
ESTIMATES FOR THE FABRICATION AND LIFE
SUPPORT SECTIONS AT SPOKES 2 AND 4

A. HONEYCOMB STRUCTURE ELEMENTS (BOTH AREAS)

Aluminum honeycomb core at 96 kg/m^3 (6 lb/ft^3) with 1 mm (0.042 in) skins unless otherwise noted.

1. Inner deck ceiling: Loading 478 Pa (10 lb/ft^2); 13 mm (0.5 in) thick.

2. Inner deck mezz: Loading 1436 Pa (30 lb/ft^2); 25 mm (1 in) thick as 2 sections 22 m (75 ft) long at each end.

3. Main deck: Loading 1915 Pa (40 lb/ft^2); 50 mm (2 in) thick with 2 mm (0.080) skins.

4. Outer deck: Loading 1915 Pa (40 lb/ft^2); 50 mm (2 in) thick with 2 mm (0.080 in) skins.

5. Walls: 38 mm (1.5 in) thick, 608 m (1998 ft) long.

6. Partitions: 25 mm (1.0 in) thick, 240 m (789 ft) long.

7. End caps: 38 mm (1.5 in) thick with 2.4 mm (0.092 in) skins.

Total Honeycomb Mass: 85912 kg (189442 lb)

B. SUPPORTS AND TIE BEAMS

1. Deck supports: 1.5 m (5 ft) centers as "I" beams.

2. Joint stiffening and supports: 849 m (2787 ft) total, as angles.

3. Circumferential supports and ties: 0.3 m (12 in) box beams, 6 total.

Total Support Structure: 49239 kg (108576 lb)

Total Structure   135151 kg   (298018 lb)

C. FABRICATION SUPPORT AREAS, SPOKE 2

1. Electronics fabrication: Tools, equipment and supplies (sum of individual estimates).

2. Metal Stocks: 6800 kg (15000 lb).

C. FABRICATION SUPPORT AREAS, SPOKE 2 (cont.)

    3. Production support: Tools, first aid, lifts, overhead crane, and dollys (sum of individual estimates).

    4. Heat and weld area: Loading 957 Pa (20 lb/ft^2) plus equipment estimates.

    5. Metal fabrication equipment: Footprint load 1436 Pa (30 lb/ft^2).

Total Fabrication Support Spoke 2:   35375 kg   (78006 lb)

D. FABRICATION SUPPORT AREAS, SPOKE 4

    1. Fiber optics support: Tools, equipment, supplies (sum of individual estimates).

    2. Composite stocks: 6800 kg (15000 lb).

    3. Production support: Tools, first aid, lifts, overhead crane, and dollys (sum of individual estimates).

    4. Layup support area items: Footprint loading 478 Pa (10 lb/ft^2).

    5. Equipment items: Autoclaves, filament winder, pultrusion (sum of individual estimates).

Total Fabrication Support Spoke 4:   35291 kg   (77821 lb)

E. LIFE SUPPORT EQUIPMENT

    All items: Footprint floorload 1436 Pa (30 lb/ft^2).

Total Life Support Equipment   29754 kg   (65160 lb)

F. SUBFLOOR ITEMS

    1. High pressure gasses: O_2, H_2, N_2, CO_2, quantity plus tank.

    2. Fresh water ballast: 9070 kg (20,000 lb) plus tank.

    3. Reclaimed water, wastewater: 3 day supply plus tanks.

    4. Illumination and ventilation: Estimate of wiring and 5 changes/hr.

Total Subfloor Items   34788 kg   (76710 lb)

TABLE 7.1-5   SUMMARY OF SIZE AND MASS ESTIMATES FOR THE FABRICATION
AND LIFE SUPPORT SECTIONS AT SPOKES 2 AND 4 (concl.)

G.   MASS OF ATMOSPHERE   19742 kg   (43534 lb)
     (Volume 16371 m^3, 578299 ft^3)

Total Mass Estimate Spoke 2   254607 kg   (551428 lb)

Total Mass Estimate Spoke 4   254523 kg   (561243 lb)

from ground sources (particularly critical if the spacecraft has to operate within a "window of opportunity"). The capability for modest fabrication allows an immediate response to damage incidents involving the Space Station and, in addition, eases some of the requirements for on-board ready spares. The transport of raw stock is recognized as inefficient; however, some elements of raw stock could be recovered from supply flight discards, and the implementation of a lunar base could offer a source for raw stock with a reduced weight transport penalty. The operations aboard the 2025 Space Station will treat major modifications or changes as ground-fabricated items transported from Earth for incorporation into a spacecraft or the station itself. The "fixes" and repairs necessary to assure continuous operations will be available through a combination of on-board ready spares supplemented by a fabrication capability which includes:

1. Electronics Fabrication, Mezzanine, Spoke 2.

   The on-board capability would permit fabrication and population of circuit boards as immediate-need replacements, modifications identified from on-board operation, or circuitry to meet special short-term needs. New or replacement systems would be ground-fabricated, tested, and then transported to the station.

2. Fiber Optics Fabrication, Mezzanine, Spoke 4.

   Fiber optics are expected to provide the major portion of data transmission lines in future spacecraft and aboard the Space Station. The capability to repair, replace, or modify transmission lines will be available. Major system renovations or replacements

will be ground-fabricated and transported for scheduled maintenance.

3. Metal Fabrication, Main Deck at Spoke 2.

The metal fabrication items identified provide the capability to repair or modify existing equipment and produce replacements for critical elements of the Space Station or companion spacecraft. The capability exists to rework a damaged element of the truss, to recoat an element of a radiator, or to rebuild a damaged section of a manipulator boom or antenna mast. For service to the Space Station itself, the capabilities include bending or forming high pressure piping, refacing segments of the large rotating seals, and rebuilding elements of the hub drive systems. Although the station would nominally carry such items as spares, the rebuild capability adds to the integrity of the station and potentially eases the logistics for spares.

4. Composites Fabrication, Main Deck, Spoke 4.

The capability for the fabrication of composites would provide a complement to metal fabrication and support immediate needs of companion spacecraft or the Space Station itself. The capabilities include panel lay-up and cure, plus the ability to repair or rebuild antenna masts, truss elements, and other pultruded or filament wound items.

In a review to establish a mass which could be tolerated for the fabrication equipment, it was recognized that these items do not presently exist. For instance, a modest lathe (approximately 0.3 m by

1 m (12 in x 40 in) can have an installed mass approaching 1000 kg (2200 lbs) and generate a footprint floor loading of about 9500 Pa (200 lb/ft^2). In general, mass such as cast iron provides a combination of stiffness and damping that improves cutting or forming operations. Equipment intended for fabrication operations in orbit will not have that luxury of mass. A need to fabricate in space carries the implied need for the development of tools and techniques which can be carried aboard a host spacecraft.

The assembly areas provide the capability to perform portions of spacecraft servicing in a crew-efficient manner. The areas are equipped with transport dollies and tow vehicles appropriate for the tasks assigned. In addition, the assembly floors provide the storage area for the remote controlled EVA Unit used for maintenance and repair to the outside of the torus. A small spider crane (about 2000 kg, 5000 lb) will provide the EVA capability. The crane will have a transportable pressure shell unit that offers a 3 m (10 ft) square passage 9 m (29 ft) long as an air lock. The considerations for deployment of the spider crane and airlock are described in 7.1.2.3 below as an element of the spoke and elevator sections.

The outer decks at Spokes 2 and 4 carry identical redundant installations of the equipment which performs the life support functions of water electrolysis, water management, and gas management. Either section could provide the life support for the entire station with some degree of capacity margin. Present ground-based industrial installations include equipment which performs most of the life support functions defined for the 2025 Space Station but none of the equipment items have been configured for flight applications. The present industrial designs

do not have a requirement for low mass. The principal items for consideration in the outer deck are:

(A) Power Conditioning and Distribution.

The power conditioning and handling equipment at each of the two locations will have the capacity to condition and distribute up to 75 percent of the total generating capacity for the 2025 Space Station. These units provide the principal control and distribution functions. The conditioning requirements appear straightforward for functions such as lighting, motor drives, instrument power, and heating. The particular requirement is large direct current (up to 5000 amperes) over the range 12 to 250 volts for the electrolytic cells and magnetic torquing.

(B) Electrolytic Cells for Water Electrolysis.

The electrolysis of water will accept up to 50 percent of the total generated power. Large solar dynamic power systems operate with a continuous near-constant energy throughput; consequently, they must operate into a near-constant electrical load. The electrolytic cells provide the dynamic, controllable, electrical demand required for continuous load-leveling functions. The physics for electrolytic decomposition at atmospheric pressure show approximately 2 volts per cell at current densities of 5000 amp/m^2 (Reference 7-3). For the installation selected, absorbing 50 percent of the power corresponds to 125 cells. The installation shown represents 10 units of 6 cells each with plates of a square meter. Each unit would contain about 100 kg (220 lb) of water and

at full capacity the Space Station could dissociate about 230 kg (500 lb) of water per hour.

(C) The O_2-H_2 Pumps and Compressors.

The gas management pumps and compressors provide transfer to on-board storage, retrieval from on-board storage, and compression to the conditions intended for final utilization, such as inputs to cabin air, inputs to the CO_2 reduction, inputs to the wet air oxidizer, or as fuel. High pressure or liquified gasses will be transported in dedicated tanks or dewars.

(D) Fresh Water Distribution Pumps.

The fresh water supply for the living areas and food preparation will reach the torus from storage (central tube, counterrotator, etc.) by transfer down the spokes. The pumps will provide the pressure and flow capacity for distribution to the inhabited areas.

(E) Ullage Gas Pumps and Compressors for Fuel Storage Support.

The N_2 gas reserve for atmospheric support and the recovered CO_2 provide the ullage gases for the H_2 storage areas; cabin air provides the ullage gas for the O_2 storage. These pumps and compressors provide the management and transfer capabilities. The N_2 and CO_2 will involve interchange with high pressure storage, and include transfers at the exit pressures from the wet air oxidizer-gas separator elements.

(F) Gas Separation System.

   The gas stream from the output of the wet air oxidizer contains a mixture of water vapor, CO_2, and N_2. The separation technique has not been defined; however, a controlled reduction in temperature may be considered a solution. Water can be precipitated down to the critical point for CO_2 (e.g., 31° C (86° F) 73 atm) at which CO_2 liquifies. If chilling is continued, water will precipitate as ice, and the system will provide an acceptable grade of N_2 for cabin air replenishment.

(G) Reclaimed Water Distribution Pumps.

   The water released from the wet air oxidizers and recovered as condensate provides the clean water needed for purposes other than drinking and food preparation purposes. Reclaimed water can support ballast transfer purposes in addition to providing the total input for electrolysis. A reservoir of reclaimed water will exist; the pumps provide the flow and pressure needed for management of the system.

(H) Supercritical Wet Air Oxidizers.

   The utilization of supercritical wet air oxidation offers the capability to oxidize all carbonaceous wastes to CO_2 and H_2O, extract nitrogen as N_2, and precipitate the residual solids (salts of Na, Ca, K, etc.). The installation utilizes a pair of oxidizers, probably operating in a "batch" mode.

(I) Waste Water Management.

Waste water collection, homogenization, and pretreatment are performed as close to the source as practical (e.g., within the living-dining sections). Pumps at those locations transfer waste water to collection tanks which become feed reserves for the wet air oxidizer. The estimates for usage (Reference 7-4) indicate a daily usage flow of 1732 kg (3820 lb) and provide a 3-day reservoir capacity. The management system will provide the necessary chemical stabilization, the additional homogenization, and the high pressure injection system to feed the wet air oxidizer.

(J) Bosch CO_2 Reduction System.

The CO_2 reduction was planned to provide a capacity at least 4 times the nominal need. The use of CO_2 as an ullage gas will result in a fluctuating demand upon the reduction system. Therefore, an overall integrated operation with an efficient balance between power utilization, fuel generation, and waste oxidation is required.

The subfloor area provides the tankage and reservoirs necessary to maintain the balances between the interdependent operations of O_2-H_2 generation, waste water processing, and management of ullage gases. The estimates for reservoirs are as follows.

(a) O_2; up to 1000 kg (2200 lb) at 300 atm as reserve inputs for the wet air oxidizer or cabin replenishment.

(b) H_2; up to 2 times the O_2 volume, 125 kg (275 lb), at 300 atm, reserve for CO_2 reduction.

(c) N_2; up to 1000 kg (2200 lb) at 300 atm. Reserve for ullage gas and cabin air replenishment.

(d) CO_2; up to 1000 kg (2200 lb) liquid.

(e) Fresh water; up to 10,000 kg (22,000 lb).

(f) Reclaimed water; up to a 3 day supply 4500 kg (10,000 lb).

(g) Waste water; up to a 3 day accumulation 5000 kg (11,000 lb)

In summary, the manufacturing facilities described have been scoped at a capability that would defend the 2025 Space Station against equipment failures or needs for an immediate structural replacement, as well as quick response servicing of spacecraft. The life support related equipment items have been configured for redundancy with synergy for electrical power load leveling. The functional needs for significant power use during pumping or compression functions show a potential for contribution to the electrical load leveling by selection of operating times and operating combinations. In addressing the items of equipment for the functions performed, none presently exist in a form compatible with the Space Station. For those items which are presently operating in ground applications, the advantages offered by iron technology make it the material of preference. Design for space flight applications using low mass materials presents development challenges. These challenges become acute with respect to the need for multi-horsepower electric motors to drive pumps or compressors. The magnetic properties of iron dominate all present high-output electric motors.

7.1.1.4 Gas Storage Sections

The four gas storage sections provide the on-board capacity for containment of O_2 and H_2 at atmospheric equilibrium pressures. The general concept for the sections is shown by Figure 7.1.1-7, and Table 7.1-6 summarizes the masses associated with the sections.

The electrolysis of water produces O_2 and H_2 at volume ratios of two hydrogen to one oxygen and at weight ratios of one oxygen to eight hydrogen. Therefore any storage volume must be divided into three equal parts to accommodate the gas volumes and accept an 8 to 1 mass differential.

The present concept divides each of the four sections into three equal volumes and assigns the O_2 to the center portion of each section. Storage in equilibrium with atmospheric pressure implies a flexible membrane separator and an ullage gas. In this concept, a series of inflatable cells contain the O_2 and H_2, with cabin air as the ullage for the O_2 storage volume, N_2 as ullage for one of the H_2 storage volumes, and CO_2 as ullage for the other H_2 storage volume. The N_2 would operate as a reservoir for cabin air replenishment and have a partial resupply from the output of the wet air oxidation. (Super-critical wet air oxidation will reduce ammonia to N_2.) In a similar manner, the CO_2 would be processed through the Bosch reduction system and be replaced by CO_2 extracted from cabin air and the wet air oxidizer. With such an ullage system, a degree of local fill asymmetry could be accepted (e.g., more of the H_2 could be placed against the CO_2 ullage than against the N_2 as long as diametrical balance was maintained).

The structure for the configuration shown consists of the circumferential tube and two separating bulkheads. The circumferential
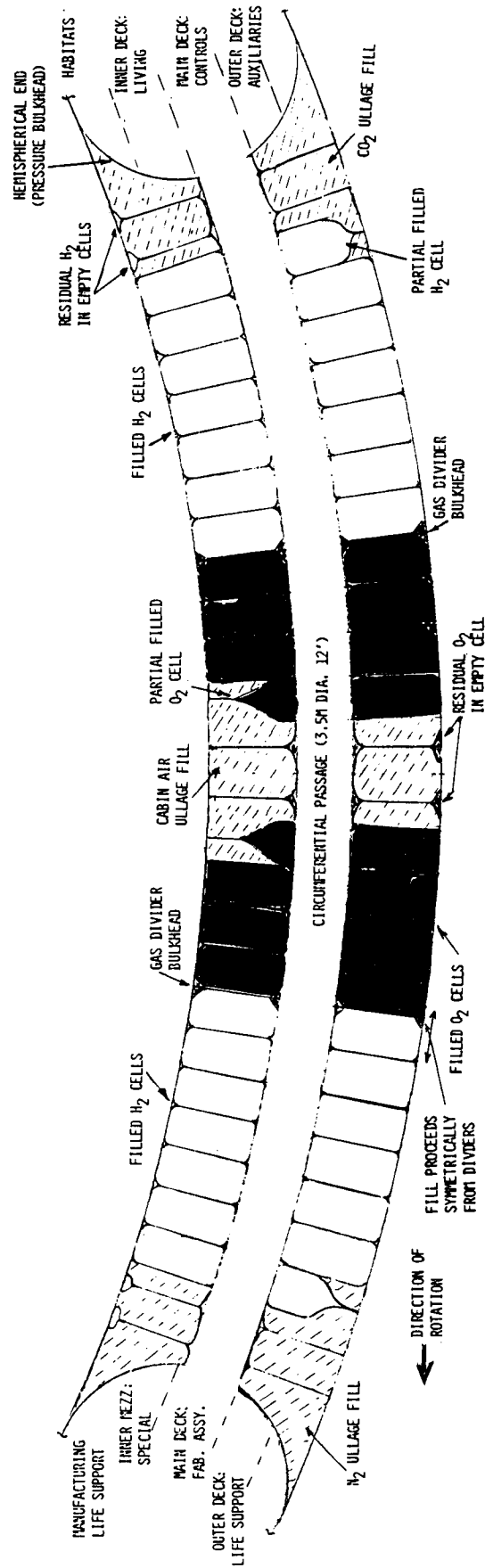
Figure 7.1.1-7, Functional Concept for the Gas Storage Sections of the Torus

HEMISPHERICAL END
(PRESSURE BULKHEAD)

HABITATS

INNER DECK:
LIVING

MAIN DECK:
CONTROLS

OUTER DECK:
AUXILIARIES

CO_2 ULLAGE FILL

RESIDUAL H_2
IN EMPTY CELLS

PARTIAL FILLED
H_2 CELL

FILLED H_2 CELLS

GAS DIVIDER
BULKHEAD

PARTIAL FILLED
O_2 CELL

CABIN AIR
ULLAGE FILL

CIRCUMFERENTIAL PASSAGE (3.5M DIA. 12')

RESIDUAL O_2
IN EMPTY CELL

GAS DIVIDER
BULKHEAD

FILLED H_2 CELLS

FILLED O_2 CELLS

FILL PROCEEDS
SYMMETRICALLY
FROM DIVIDERS

MANUFACTURING
LIFE SUPPORT

INNER MEZZ:
SPECIAL

MAIN DECK:
FAB. ASSY.

OUTER DECK:
LIFE SUPPORT

DIRECTION OF
ROTATION

H_2 ULLAGE FILL

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TABLE 7.1-6 SUMMARY OF SIZE AND MASS ESTIMATES
FOR THE GAS STORAGE SECTIONS

A. STRUCTURE ELEMENTS (EACH SECTION)

1. Circumferential tube: Aluminum, 3.5 m (11.5 ft) diameter, 74.6 m (245 ft) long with 4.7 mm (0.187 in) thick walls. Running surface is Al honeycomb supported deck with passages for piping and leads.

2. Volume dividers: 2 each as 4.7 mm (0.187 in) plate with angle reinforcers.

Total Structure and Support: 20745 kg (45745 lb)

B. GAS SERVICING ITEMS

1. Gas retention bags: 30 each section.

2. Fill and recovery lines: O_2, H_2 and ullage gasses.

3. Ullage storage tanks: 25 percent of volume required at 100 atm.

Total Gas Service: 9726 kg (21477 lb)

C. GAS CONSIDERATIONS, MAXIMUM FUEL (MINIMUM WEIGHT)

Maximum O_2	5643 kg (12445 lb)
Maximum H_2	711 kg (1568 lb)
Stored N_2	1294 kg (2850 lb)
Stored CO_2	1935 kg (4313 lb)

Total Gas Stored for Maximum Fuel Condition: 9604 kg (21176 lb)

D. GAS CONSIDERATIONS, NO-FUEL (MAXIMUM WEIGHT)

O_2 Volume Filled with Cabin Air:	5157 kg (11373 lb)
H_2 Ullage Volume Filled with N_2:	4983 kg (10989 lb)
H_2 Ullage Volume Filled with CO_2:	7824 kg (17253 lb)

Total Gas Stored for No-Fuel Condition: 17965 kg (39615 lb)

E. MASS SUMMARY FOR MAXIMUM FUEL (ALL SECTIONS COMBINED)

Fuel Total As O_2, H_2 25419 kg (56052 lb)

Total Mass, Maximum Fuel: 160299 kg (353472 lb)

F. MASS TOTAL FOR NO-FUEL: 193802 kg (427348 lb)

G. MAXIMUM MASS DIFFERENCE: 33503 kg (73874 lb)

tube has a diameter of 3.4 m (11.5 ft) for compatibility with the passage of a 2.4 m (8 ft) cube. The running-surface deck within the tube provides the clearance for the fluid, gas, electrical, and fiber optical links which interconnect the manufacturing and inhabited sections. The divider bulkheads provide gas-tight barriers but not the full pressure retention as built into the hemispherical ends of the manufacturing and inhabited areas. The gas containment shown utilizes 10 cells in each volume with a cell configuration based upon those used in rigid airships. The individual cells employ a diffusion resistant polymer (i.e., 0.25 mm (0.01 in) thick polyester) and form a segment of the volume between the torus and the circumferential tube (i.e., a flat-sided donut). Ties between the axial faces of the cell control the inflated shape; ties at the outer and inner surfaces maintain a shape for fill and recovery. Filling and recovery operations would proceed in a generally symmetric sequence working away from each of the separator bulkheads. The remainder of the system involves the leads to fill and recover the gases.

To conclude, it is recognized that other storage configurations may offer advantages in control, balance, and the inherent concerns for processing hydrogen. The storage concept is an area that needs further study. The present ullage and stored gas combinations appear compatible. The O_2 diffusion into cabin air is acceptable; H_2 diffusion into CO_2 before reduction will not affect the Bosch process. The H_2 diffusion into N_2 is not chemically active, and H_2 is present in ordinary atmosphere to about 500 ppbv (Reference 7-5) and is inert at ordinary temperatures. A small amount of H_2 in replenishment N_2 could be tolerated.

7.1.2 The Spokes and Elevators

The four spokes contain the elevators that provide controlled transition from the hub section to the torus. In addition, the spokes provide the locations for the variable gravity research or conditioning facilities. The variable gravity facility and a personnel-sized elevator operate in Spokes 1 and 3; freight platforms operate in Spokes 2 and 4. Figure 7.1.2-1 shows the concept for the spokes, and Table 7.1-7 summarizes the mass assignments for the spokes and elevators. The concepts for the elevators are described below for the personnel unit, the variable gravity facility, and the freight-EVA support units.

7.1.2.1 The Personnel Unit Concept

The most frequent transit requirement will involve crew members and small items of equipment moving between the central tube and the torus. The personnel transfer unit has been configured to minimize the effects of gravity change Coriolis forces and differential motions. The personnel carriage element becomes a 3 m (10 ft) cube which travels along the "shade" side of a spoke. The carriage has two sets of local-vertical opening doors. One set faces the wall of the spoke, and the other faces radially inward. In traversing the spoke, the elevator follows a pair of rails which include a rack gear on one face that engages the drive mechanism on the carriage (e.g., an electric motor with a worm drive into a reduction gear). Coriolis effects and power demands effectively limit the traversing velocities to 2 m/sec (6 ft/sec) maximum. In traversing operations, the elevator will require two independent counterbalances. The balance required for maintaining the angular momentum and center of gravity for the torus requires shifting an
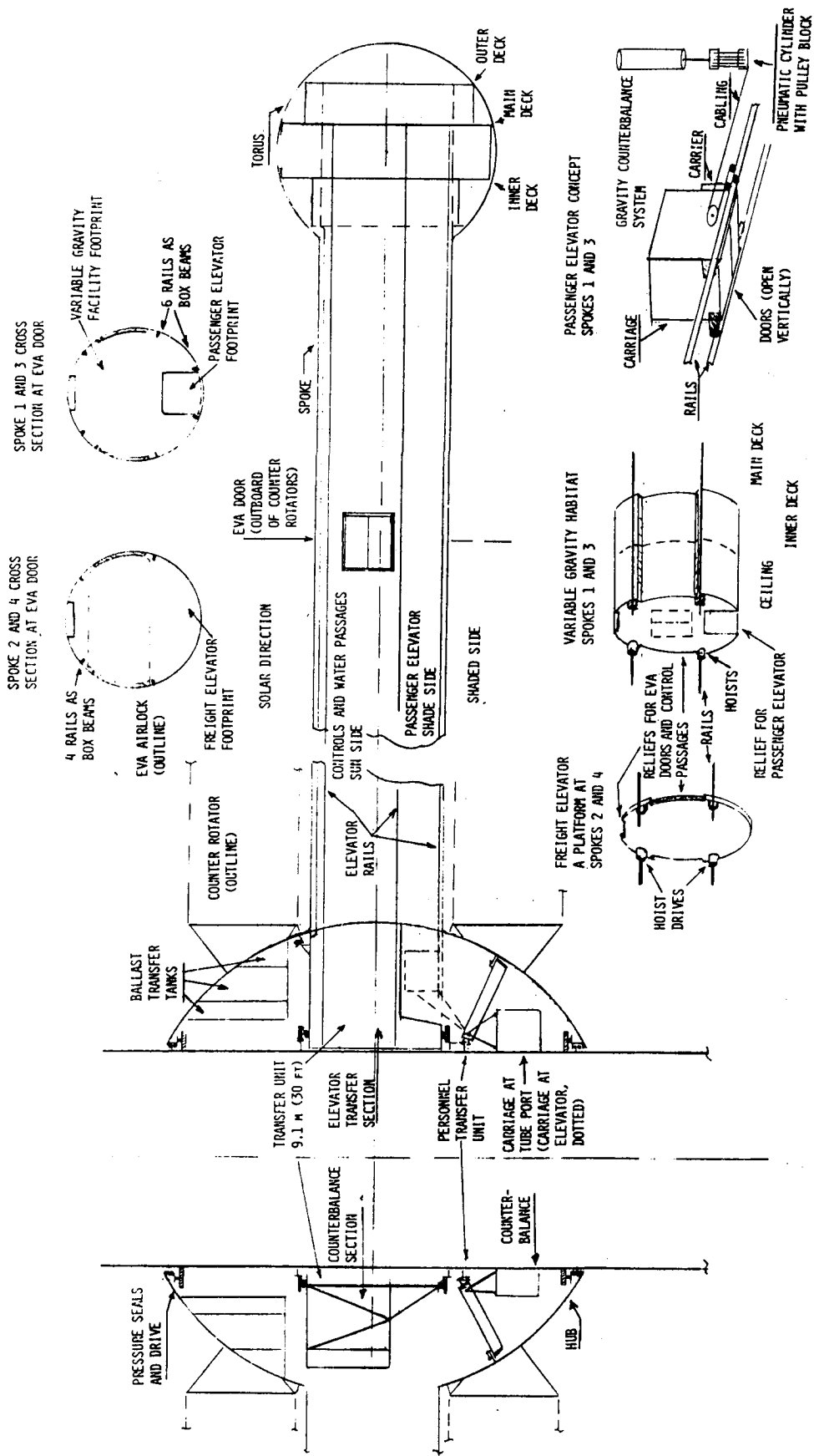
Figure 7.1.2-1, General Concepts for the Spoke, Hub, Elevator and Transfer Elements of the Rotating Section

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TABLE 7.1-7 SUMMARY OF SIZE AND MASS
ESTIMATE FOR THE SPOKE AND ELEVATOR SECTIONS

A. SPOKE SHELL STRUCTURE (4 UNITS)
Telescoping unit 9.2 m (30 ft) in diameter and 90 m (295 ft) long
formed from aluminum plate 9.5 mm (0.375 in) thick. Mass 66491 kg
(146618 lb) each.

B. PASSENGER ELEVATORS AND VARIABLE GRAVITY FACILITY, SPOKES 1 AND 3

    1. Elevator guide rails: 6, as box beams.

    2. Passenger elevator system: Carriage, hoist and pneumatic
        equilibrator.

    3. Variable gravity system: Enclosed 2 deck structure of Al
        honeycomb, hoist, and equilibrators.

Mass for each Spoke *   12152 kg (26796 lb)

C. FREIGHT ELEVATORS SPOKES 2 AND 4

    1. Elevator guide rails: 4, as box beams.

    2. Freight elevator system: Platform, hoist and equilibrators.

Mass for each Spoke *   3831 kg (8448 lb)

D. EVA UNIT AND AIR-LOCK TANK *   7426 kg (16377 lb)

E. MASS OF ATMOSPHERE: 28475 kg (62790 lb)

Mass Total for Spokes 1 or 3   107118 kg (236204 lb)

Mass Total for Spokes 2 or 4   98797 kg (217856 lb)

Mass Total Assigned *   419259 kg (924497 lb)

*   Elevators and EVA tank home position is in the torus;
    carriage, hoists, equilibrators added to torus for
    inertial consideration.

equivalent mass of ballast water in a direction opposite to the motion of the elevator. Ballast transfer tanks must be emplaced within both the torus and the hub together with pumps and controls. The effective suspended weight of the carriage will vary in proportion to the radial position along a spoke. A realistic drive system (less than 5 kW) dictates a force balancing system which inherently follows the force profile; a pneumatic accumulator has the appropriate characteristics. The force counterbalance system for the personnel transfer elevator utilizes a pair of pneumatic cylinders of 20 cm (8 in) diameter operating with a 3 m (10 ft) stroke through a set of pulley blocks (distance multiplier) and cables up the guide rails. In operation, the pneumatic cylinders would be pressurized to a level which matched the weight of the elevator and its load at the torus. The hoist requirement then would only need to overcome the friction and drag effects. Each lift or lowering would have the equalizing pressure tailored to that particular load. The configuration, as summarized, places these equilibrator cylinders and cable blocks in the torus.

7.1.2.2 The Variable Gravity Facility

The variable gravity facility appears as a two-deck-and-ceiling arrangement that will match the main to inner deck spacings in the torus. The units accommodate the personnel elevator by a cut-out in the floor plan; however, the units will have continuous walls such that they can provide totally enclosed volumes. In operation, the facilities would be configured according to the particular need. For crew conditioning, the facilities would be fitted with living quarters and life support items. When used for other types of research such as animal, horticultural,

physics, or chemistry, the facility would be outfitted in response to the particular operations planned. The units will ride in the torus when not in use and during preparations for use. During operation at a particular gravity, the personnel elevator performs the support functions for supplies and retrievals. The variable gravity facility rides on four separate rails along the walls of the spokes. In operation, the facility will utilize water transfer as the mass balance, and a system of pneumatic cylinders as the force balance, to achieve operation in the same manner as for the personnel elevator.

7.1.2.3 Freight Elevator and EVA Support Unit

The freight elevators operate in Spokes 2 and 4 to provide the means for transport of equipment and supplies to the torus as well as for the retrieval of fabricated assemblies and service elements. The freight elevators are not intended for the transit of personnel; consequently, the units are single platforms without walls or ceilings. In operation, equipment such as spacecraft assemblies, special fabrications, and service modules would be secured to the elevator platform for transit to the hub and central tube. The freight elevator will operate on four rails along the spokes; the circumferential position of the rails will match those for the variable gravity facility. The non-use position for the elevator will be flush with the main deck. Operation will involve a water transfer for mass balance and utilize a pneumatic cylinder system for force balance.

The requirement for self-maintenance of the Space Station will utilize a small remotely controlled spider crane as the principal EVA unit for servicing the torus. The crane will be stored on one of the

assembly floors of a manufacturing area (Spoke 2 or 4). Access to the exterior of the torus is through a pair of pressure doors in each spoke, located radially in the outer third of the spoke, beyond the envelope of the counterrotators. The airlock unit to support the access will consist of a sectioned cylindrical tank (see Figure 7.1.2-1) which can be transported around the circumference of the torus and attached to the elevators at each spoke. At Spokes 2 and 4 the air lock unit attaches to the deck of the elevator; the air lock suspends below the main deck of the variable gravity facility for Spokes 1 and 3.

The sequence for an EVA deployment begins with the emplacement of the air lock and positioning of the spider crane relative to the intended access port. The elevator is balanced and moved into position where the air lock can engage and seal to the frames of the access doors. After venting, the doors in the spoke open inward and the crane moves out to perform the activity. For activities that involve change out (such as repair to a solar collector), the airlock dimensions define the limits which could be accommodated. (In the event the EVA requires attention to a counterrotator, access would involve the transfer tank. See 7.1.3.4 below.) Retrieval and return operations reverse the steps for deployment.

7.1.3 Hub and Transfer Elements

The hub section provides the interface between the rotating and non rotating portions of the Space Station. The interface includes the driving elements which control the relative motion, the main rotating pressure seal, the mounting structure for the counterrotators, and those elements which accomplish the two-way transfer of items between the

central tube and the rotating portions of the Space Station. The overall configuration of the hub also appears in Figure 7.1.2-1; Table 7.1-8 summarizes the mass assessments. The principal elements for description become the shell with drive and seals, the large rotation transfer unit, the personnel transfer unit, and the water transfer tanks for the counterrotators.

7.1.3.1 Shell, Drive, and Seals

The shell structure consists of a sphere 33.5 m (110 ft) in diameter which serves as a common center for all four spokes. The shell also provides structural support to the rings that form the load bearing and running surfaces for the counterrotators. The rotational and gyroscopic forces are transferred through a series of stanchions and cross braces between the rings and the shell. The drive system and principal pressure seals position the shell with respect to the central tube. Figure 7.1.3-1 shows the concept for the drive and seals. The drive system consists of wheels, drive motors, and servo-controlled suspension arms. The drive system operates in a manner which applies the torque necessary to overcome the drag of the seals, and at the same time, responds to the balance controls of the torus such that torus disturbances do not transmit into the central tube. The seal system utilizes a number (up to 5) of inflatable elements to accept the pressure differential. The need for change out has been identified, and the inflatable concept would provide such a capability.

7.1.3.2 The Large, 9.1 m (30 ft), Rotation Transfer Unit

The Large Rotation Transfer Unit provides the means to exchange

TABLE 7.1-8 SUMMARY OF SIZE AND MASS
ESTIMATES FOR THE HUB AND TRANSFER SECTION

A. HUB STRUCTURE, PRESSURE SEALS, AND DRIVE

1. Shell: 33.5 m (110 ft) dia sphere, 9.5 mm (0.375 in) Al plate.

2. Seals: Labyrinth of rings and elastomers, 16.5 m (54 ft) dia.

3. Counterrotator running rings: 32.98 m (108 ft) dia.

4. Rotator drive system: Motors, wheels, actuators.

Total Structure and Related Items   97897 kg (215872 lb)

B. FUNCTIONAL INTERNAL ELEMENTS*

1. Rotation transfer unit 9.1 m (30 ft) dia: Includes the rings, drives, spoke extensions, ballast elements.

2. Rotation transfer unit personnel elevator: Includes the rings, drives, carriage handling section, ballast elements.

3. Ballast and inertial trim tanks

Total Functional Internals   20466 kg (45130 lb)

C. MASS OF ATMOSPHERE   16418 kg (36204 lb)

Total mass of hub unit: 134782 kg (297206 lb)

*   Elements of the internal systems are mounted on the central tube, within the hub and within the torus. The counterrotators include the transfer tanks in the estimates for inertia.
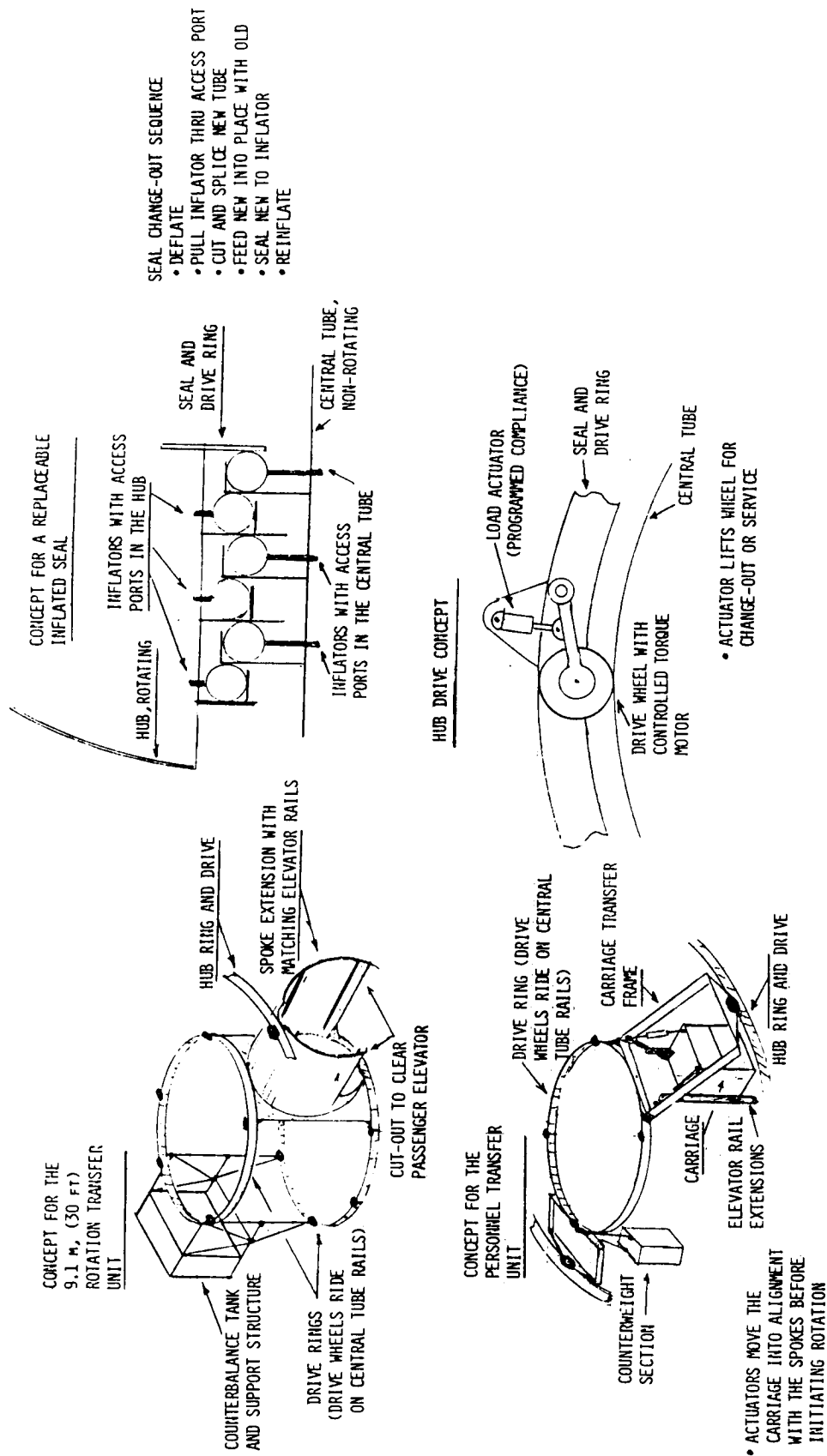
Figure 7.1.3-1, Concepts for Elements within the Hub

spacecraft sub-assemblies or items of equipment between the central tube and the rotating portion of the Space Station. The unit accepts the freight elevators from Spokes 2 and 4 plus the variable gravity facilities from Spokes 1 and 3. The variable gravity units have hatches in their ceilings and upper decks. Figure 7.1.3-1 shows the principal features of the unit. In an operation to transfer items from the torus to the central tube, the transfer unit would be rotating at torus speed relative to the central tube and be locked into a position that aligned the elevator guide rails. As the elevator moved into the spoke-extension sections, a ballast transfer would occur that put water into the counter-balance tank on the transfer section. In the same motion, the elevator would leave the carrier for the force equalizer and complete the travel against the partial gravity present at the hub.

With the trim completed, the drive systems engage to slow the rotation of the transfer unit, such that the energy goes into the rotating torus. A shift of trim ballast from hub to torus maintains a constant rotation (e.g., constant angular momentum). The transfer section comes to a rotational stop with the elevator registered to the main transfer port in the central tube.

The equipment is then transferred by manipulator into the bays of the central tube for use as intended (e.g., Spacecraft assembly or service). The transfer of equipment or elements for service from the central tube into the torus involves a reversal of the procedure. In all cases, the acceleration or deceleration of the transfer unit occurs with a balanced system. The adding or subtracting of rotational momentum interacts with the torus, and the rotation of the torus is maintained by a radial transfer of ballast.

7.1.3.3 The Personnel Transfer Unit

The personnel transfer unit engages either of the personnel elevators in Spokes 1 or 3. The operating principles are the same relative to the balancing of masses and exchanges of energy. The major difference stems from geometry; the personnel unit has to move aside when the large unit is in operation. Figure 7.1.3-1 also shows the concept for the personnel transfer unit. In a transfer of individuals or smaller items of equipment from the torus to the central tube, the unit is rotating and the elevator rail extensions are locked in alignment. The elevator carriage will leave the spoke and the force equilibrator to move into engagement with the transfer carrier. When balance is achieved, the rail extensions disengage and move sufficiently to clear the hub. The unit is then brought to a stop relative to the central tube. In a microgravity environment, the suspension actuators move the car through a 90 degree rotation and align the door of the elevator with the small transfer port in the central tube. The transfer of personnel and equipment from the central tube proceeds as a reverse of the sequence. For individuals (and equipment) moving between the central tube and the torus, the system offers the advantage that all the changes of position and rotation occur under conditions of least disturbance. Crew members making the transfer always have the same floor under their feet, even in microgravity.

7.1.3.4 Transfer Tanks for the Counterrotators

The transfer of water between the hub and the counterrotators utilizes paired transfer tanks which can fill and drain in unison. Water transferred from the hub to the counterrotator begins with the tanks

stationary relative to the hub. The process of velocity matching between the counterrotator and the hub will involve traversing through zero rotation and zero gravity; therefore, the transfer tanks will need ullage bladders to retain the liquid. The exchange operations involving momentum and energy will draw from or add to that of the torus. The need to operate the EVA crane on the counterrotator will also involve the transfer tanks. The crane will attach to a transfer tank during the rotational exchange, with the mass accommodated by a differential fill between the tanks. The movement of the spider crane on a counterrotator will require a combination of differential filling and circumferential positioning of the transfer tanks throughout the entire sequence. In summary, the hub provides a major pressure shell which in turn houses the transfer system for access between the central tube and the torus. In addition, the hub carries a comprehensive system of tanks and transfer pumps that continuously provides for the rotational balance of the torus during any transfer event. In such a context, the hub can experience relatively large changes in total contained mass throughout the course of operations. In principle, water provided during resupply would first appear in the central tube where it would serve for ballast transfer during a berthing or deployment operation before entering the storage volume in the counterrotators. The water would eventually move into the torus as part of the transfer operations associated with an elevator movement. After an initial use for food preparation or drinking, the water would be reclaimed. Reclaimed water then recycles for washing or flushing use and provides the local trim balance. Eventually, the reclaimed water would enter the electrolysis cells for decomposition into H_2 and O_2.

7.1.4 The Counterrotators

The counterrotators have been defined in terms of envelopes and function. The present configuration envisions two units of 91.4 m (300 ft) outside diameter riding on rails at an inside diameter of 32.9 m (108 ft) with a maximum width of 7.9 m (26 ft). The two units counterrotate at a nominal 10 rpm and, in combination, carry a water ballast that provides a match to the angular momentum of the torus. The counterrotators transfer water ballast by means of transfer tanks which corotate on the same set of rails. In addition to providing the null for the rotational angular momentum of the torus, the water represents the on-board reservoir for all further usage. With respect to the counter momentum, the two units also provide some capability for trim locations of the rotating center of gravity. A slight differential fill can be used to offset a mass bias elsewhere in the rotating system.

7.2 THE CENTRAL TUBE AND PLATFORM

The central tube and platform comprise the non-rotating core of the 2025 Space Station. The volume within the central tube provides the open bays needed for assembling or servicing spacecraft. In addition, the central tube provides the volume and support for a microgravity processing facility plus the solar-facing surface for a Solar Research Laboratory. The platform as an open truss provides the mounting for the solar dynamic power units together with their radiators, plus locations for the horticultural research domes. The remaining open area or volumes within the truss are available for installing other space or solar research instrumentation. Figure 7.0-1 includes the pertinent exterior

features of the central tube and truss; Table 7.2-1 summarizes the pertinent capabilities.

7.2.1 The Central Tube

The central tube initially serves as a core base for construction during the on-orbit assembly of the Space Station, and these operations are discussed in Section 8 below. The legacy from assembly operations provides the open bays which can be allocated to support a microgravity facility and perform assembly or servicing operations for other spacecraft. The internal configuration for the central tube appears as Figure 7.2-1 with the principal features summarized in terms of assembly bays with pressure bulkheads, a microgravity facility, the solar observatory, and materials transfer.

7.2.1.1 Assembly Bays With Pressure Bulkheads

The open bay section of the central tube extends for 90 m (290 ft), and reaches from the berthing bay to the divider bulkhead in line with the solar-facing surface defined for the truss. A series of pressure bulkheads as moveable airlock doors divide the central tube into assembly bays, which are adjacent to the berthing bay, and a microgravity area which is adjacent to the divider bulkhead. The assembly bays carry the stanchions and hold-down anchors, plus the tracks and robotic units necessary to support the assembly or servicing of spacecraft. The robotic units will move on rails and carry the manipulators necessary for the particular support operations planned. The units will be capable of remote operation from control stations in the torus, or in combination with manual operations. The robotic units will accommodate the transfer

TABLE 7.2-1   CENTRAL TUBE AND PLATFORM FEATURES AND CAPABILITIES

A.   CENTRAL TUBE

1.   Tube Structure Dimensions: The shell is aluminum plate 9.5 mm
     (0.375 in) thick.

Length	100.3 m	(329 ft)
Diameter	15.2 m	(50 ft)
Total Volume	1.762×10^4 m^3	(6.24×10^5 ft^3)

2.   Assembly Bays Lengths:

Bay#1, Main to No 2 Door	18.89 m	(62 ft)
Bay#2, No 2 to No 3 Door	23.16 m	(76 ft)
Bay#3, (Microgravity)	15.24 m	(50 ft)

3.   Microgravity Facility Volume: 1260 m^3 (44500 ft^3)
     (Levitated Cylinder with
     10 Decks 8 m Dia 25 m long)

4.   Supply and Storage Annulus   4810 m^3 (2.021×10^5 ft^3)
     Around Microgravity Volume

5.   Solar Observatory Volume   1760 m^3 (62400 ft^3)

6.   Truss Airlock Volume   70.6 m^3 (2965 ft^3)

B.   PLATFORM AND TRUSS

1.   Platform Dimensions: 5 m (16 ft) Matrix

Diameter	158.5 m	(520 ft)
Thickness	5 m	(16 ft)
Solar Facing Area	19729 m^2	(212372 ft^2)
Radiator Area (Circumference)	2640 m^2	(28421 ft^2)

2.   Solar Dynamic Power Units:

4 at 425 kWe each, Collector Dia	39 m	(128 ft)
Total Collector Area	4778 m^2	(51433 ft^2)
2 at 25 kWe each, Collector Dia	10 m	(33 ft)
Total Collector Area	157 m^2	(1690 ft^2)

3.   Horticulture Domes: (4)

Spherical Cap Diameter	25 m	(82 ft)
Cap Height	5 m	(16 ft)
Total Area	1963 m^2	(21135 ft^2)

4.   Open Solar Exposure Area: 12833 m^2 (138137 ft^2)
     (For Other Experimentation)

SOLAR
OBSERVATORY

AIRLOCK TO
PLATFORM

MICROGRAVITY
FACILITY

LOCATION FOR MAIN
TRANSFER PORT

ENTRANCE
AIRLOCK

MAIN BULKHEAD AND
ENTRANCE AIRLOCK DETAIL

LOCATION FOR PERSONNEL
TRANSFER PORT
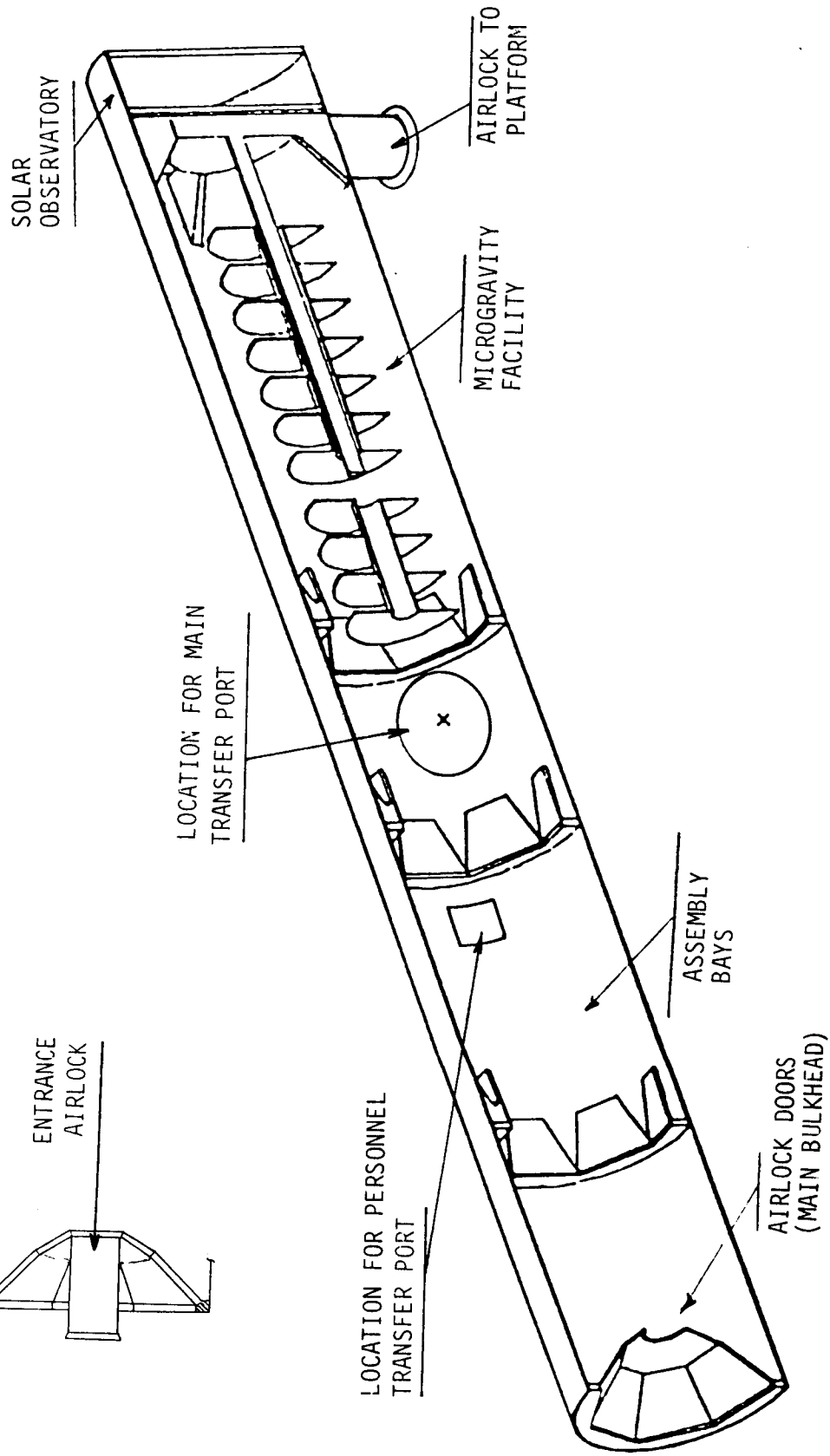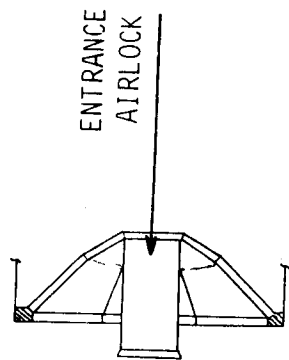
ASSEMBLY
BAYS

AIRLOCK DOORS
(MAIN BULKHEAD)

Figure 7.2-1, Central Tube Interior Features

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of supplies and equipment within the central tube and support the airlock operations associated with transfers from the berthing area. The arrangement of the pressure bulkheads within the central tube divides the volume into useful sections, with the main bulkhead and airlock opening into the berthing area. The main bulkhead contains the smaller cylindrical airlock which can function as an insert for any of the bulkheads. The second pressure bulkhead is located 19 m (62 ft) from the main door and provides a convenient volume for the transfer of spacecraft or supplies. The third pressure bulkhead at a distance of 42.7 m (140 ft.) provides the capability for assembling or servicing larger units and effectively utilizes more than one third of the volume available. The third and fourth pressure bulkheads can operate together to support microgravity operations, and these are part of the microgravity description which follows. Table 7.2-2 summarizes the pertinent features of the airlock and assembly volumes, together with some of the structural considerations associated with the airlock doors.

The pressure bulkheads which divide the central tube into airlocks or working volumes consist of segmented and articulated domes which act in compression. The one-atmosphere difference in pressure serves to compress the sealing elements at the interfaces and thereby eliminates leakage. In operation, the compressive loads are accepted by an internal ring structure which reacts in a combination of radial outward tension plus torsion to apply an axial tension to the walls of the central tube.

The moveable bulkheads all have the same configuration. The concept for the bulkheads is indicated in Figure 7.2-1. The selection of an octagonal pattern that results in a 17-element bulkhead corresponds to the airlock dimensions previously established (Reference 7-1). The

TABLE 7.2-2 SUMMARY OF AIR LOCK CAPACITIES
FOR ASSEMBLIES AND STRESS LOAD CONSIDERATION
FOR THE PRESSURE DOORS

A. AIR LOCK AND ASSEMBLIES CAPACITIES

		Useful dia	Work length	Work volume
1.	Transfer Lock	3m (10 ft)	7.6m (25 ft)	$46.73m^3$ (1963 ft^3)
2.	Assembly Bay #1	13m (42.5 ft)	18.9m (62 ft)	$2094m^3$ (87954 ft^3)
3.	Assembly Bay #2	13m (42.5 ft)	23.7m (76 ft)	$2565m^3$ (107768 ft^3)
4.	Combination 1&2	13m (42.5 ft)	42.0m (138 ft)	$4659m^3$ (195684 ft^3)
5.	Max Available*	13m (42.5 ft)	57.3m (188 ft)	$6347m^3$ (266584 ft^3)

*Requires disassembling part of the microgravity facility.

B. PRESSURE DOOR STRESS-LOAD CONSIDERATIONS

Radial Location Reference	Pressure Forces **	Reaction Forces or Stresses
15m (49 ft) dia at wall of the central tube	1.775×10^7 N axial (3.992×10^6 lb) (No radial)	39.89 MPa (5787 psi) axial tension 79.29 MPa (11574 psi) hoop tension
For the max octagonal opening of 13 m (42.5 ft)	1.408×10^7 N axial (3.167×10^6 lb) 1.408×10^7 N radial (3.167×10^6 lb)	4.642×10^5 N/m (2651 lb/inch) on joint faces
For an octagonal opening of 7m (23 ft)	4.126×10^6 N axial (9.277×10^5 lb) 7.148×10^6 N radial (1.607×10^6 lb)	2539×10^5 N/m (1450 lb/inch) on joint faces
For a circular opening of 3m (10 ft)	7.397×10^5 N axial (1.633×10^5 lb) 1.280×10^6 N radial (2.879×10^5 lb)	1.334×10^5 N/m (765 lb/inch) on joint faces

** Flat plate structure based upon simply supported beams leads to webs of 0.3m (12"), thicknesses of 12mm (0.5"), and reaction structure thickness of 35mm (1.5"), and is considered unacceptably massive.

octagon shape for maximum opening will accept up to a 13 m (42.5 ft.) circular diameter and still provide more than 0.3 m (1 ft) margin to the wall of the tube at each vertex. The intermediate opening offers a 7 m (23 ft) circular clearance. The 3 m (9.8 ft) opening provides for small item or personnel transfers. In the open position, the elements can be stowed within the outline of the support ring and thereby provide the full operating diameters listed.

An analysis for feasibility utilized flat plate construction as the means to estimate loads and stresses. The results appear as part of Table 7.2-2 and show structure compatible values for the force levels at joints. The comments refer to simply supported beams and plates based upon aluminum, and show the need for curved elements in the movable sections. Flat plate aluminum construction would impose an unacceptable weight penalty for these units.

An assessment of technology development requirements shows:

1. <u>Pressure sealing</u>. Openings must have seals, and movable bulkheads will require multiple seals. The concept identifies a technology need for a sealing technique which will accommodate multi-element articulated bulkheads.

2. <u>The outer support structure</u>. A moveable bulkhead will require some form of support to transfer and distribute pressure loading forces into the walls. The bulkheads impose a structural discontinuity similar to those for boiler heads or gas cylinders (Reference 7-6), and the structural member which accomplishes the transition will experience both tension/compression and torsional loadings. The support member may

represent a critical case for structure and thereby justifies a further independent evaluation for alternates.

7.2.1.2 Microgravity Facility

The techniques and technologies associated with microgravity processing will establish a commercial utilization for the IOC Space Station. The major portion of the commercial microgravity processing will utilize co-orbiting free-flyers. The principal microgravity processing support required from the 2025 Space Station will address pilot-plant production or evaluation for new processes, plus the continuing research into microgravity related effects. Therefore, the microgravity facility needs to provide a flexibility of operation, an ease of installation, a ready access for control or monitor, and a microgravity level that is the best attainable in a low Earth orbit.

The microgravity facility is positioned within the central tube and operates either adjacent-to or concentric-with the center of gravity for the entire Space Station. The facility is shown in Figure 7.2-1. The installation shows the microgravity facility axially centered within the central tube and configured as ten circular decks distributed along a support tube. The decks provide mounting attachment for equipment, and the support tube provides the access for operating supplies such as power, gases, or liquids. The entire facility will have the capability for an isolating levitation by air jets from the supply tube. The supply tube terminates into an equipment complex which includes the pumps, distribution manifolds, pressure regulators, and electrical power conditioning as needed for the operation. The annular volume which surrounds the facility provides storage for operating supplies as well as

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avenues for access to other portions of the Space Station. The operation of the facility has control from the torus and data links by a combination of optical and r.f. transmissions. In addition to the inherent flexibility in positioning the transmit-receiving links, the concept eliminates the need for special cabling within the facility. The specific capabilities provided for microgravity operation appear summarized in Table 7.2-3; the three operating modes relate to the orbit-imposed acceleration forces and are described individually below.

(1) <u>Full facility not centered relative to the center of gravity for the Space Station</u>. Operation with the entire facility away from the Space Station center of gravity (c.g.) permits the longest times between disturbing effects and has a minimum effect upon other operations within the space station. The levitation by a system of air jets eliminates bump or shock transients from interfering with the operation. Periodic reboost or a major docking transient represent the principal interrupting events, and both types of events are forecastable. Operation in this mode introduces the cyclic accelerations as the principal variations in the microgravity environment. The cyclic accelerations arise from the gradient within the gravity field of the Earth and the condition that any point away from the c.g. of the Space Station is in a slightly different orbit. The gradient effect has the larger magnitude and always points toward the Earth. For any particular point on the facility, the gradient effect is at maximum when the acceleration vector passes through the c.g. of the Space Station, and goes through zero when that point coincides with the orbit path. The distance-away-from-the-c.g. effect is a linear acceleration in the direction of the c.g., with maximums and zeros

TABLE 7.2-3 SUMMARY OF THE MICROGRAVITY FACILITY
AND ENVIRONMENTAL CAPABILITIES

A. FACILITY PRINCIPAL DIMENSIONS

Envelope Dimensions: 8 m (26.2 ft.) diameter x 25 m (82 ft.) long

Configured as 10 circular decks attached to a support tube

Support tube	1.83 m (6 ft.) diameter x 25 m (82 ft.) long
Supply Tube	1.22 m (4 ft.) diameter x 17 m (56 ft.) long
Power available (total)	1000 kWe

B. FACILITY ACCOMMODATIONS AND MASS

	Levitated	Free Floating
Number of mounting decks	10	4
Equipment bays	9	3
Structure mass	7951 kg (16572 lb)	2699 kg (5952 lb)
Equipment mass	42867 kg (94521 lb)	14299 kg (31507 lb)

C. MICROGRAVITY ENVIRONMENT (g)

Force and Application	Not Centered	Centered	Free Floating
Orbital drag, constant rotates one-per-orbit*	1.5×10^{-7}	1.5×10^{-7}	0
Distance from center of gravity (linear cyclic one-per-orbit)	3.44×10^{-6} max	1.68×10^{-6} max	6.72×10^{-7} max
Earth gradient (once-per-orbit, radial cyclic)	7.84×10^{-6} max	3.92×10^{-6} max	1.530×10^{-6} max
Solar-facing rotation (once per year)	Less than 10^{-12}, under any condition		

* Orbit drag at same deceleration as predicted for the IOC Space Station.

occurring at the same positions as for the gradient effect during the orbit. In assessing the maximum deviation from a microgravity environment, the two cyclic accelerations add as vectors in the same direction, with the orbit drag vector adding at 90 degrees.

(2) Full facility centered relative to the center of gravity of the Space Station. Operation with the center of gravity for the microgravity facility coincident with that of the Space Station reduces the cyclic components of the acceleration without any effect on the drag component. For this operation, the entire structure, including the central support tube and supply equipment, moves down the traveling rail system on the walls. In this position, the microgravity facility extends into the assembly and storage volumes to limit some of the access to the rotating section of the Space Station. Operation in this mode would represent some degree of dedication from the entire Space Station.

(3) Partial facility free floating at the center of gravity. In this mode of operation, the short section of the facility is placed for coincident centers-of-gravity and operates free floating in vacuum. The mode accommodates research which requires minimizing all residual effects. The only residual forces that apply are associated with the distance from the center of gravity and the effect of the solar-facing one-per-year rotation. The free floating concept requires reboost of the Space Station on a per-orbit basis. For optimum conditions, the Space Station would maintain a continuous boost force equal to the drag effect. Practical considerations lead to programmed reboosts at least two times per orbit, in which case the facility would move relative to the Space

Station but not collide with the walls. Free floating operation would be limited to relatively short time spans (up to 100 hours), since this mode of operation effectively dedicates much of the Space Station to low gravity support. Operation in the free floating mode also places stringent limits on the configuration of an experiment. The facility must operate self-contained for power and consumables; in addition, successful operation implies no inertial or similar related disturbances within the facility.

The summary of capabilities, such as sizes, masses, and microgravity levels, are based upon conservative estimates for each structure. The entire support structure utilizes 2024 alloy aluminum with the decks based upon aluminum honeycomb fillers 76 mm (3 inches) thick. The experiment loading at 957 Pa (20 lb/ft^2) is considered modest. The values listed for microgravity assume the same drag accelerations as predicted for the IOC Space Station. The other values are geometrical effects.

The concept for levitation by a system of airjets is based upon the knowledge that the velocity of a subsonic jet issuing from a plenum is a function of the pressure and independent of the area. Therefore, at short distances, the force produced by a jet impinging on a wall will vary in proportion to the orifice area of the jet (Reference 7-7). An array of uniform jets oriented to produce radial outward flows would impinge on the inside of a ring to produce a uniform force suspension. A controlled throttling of a jet or group of jets could produce a net unbalanced force in any particular direction. The levitation concept would utilize such a differential throttling to produce a counterforce to offset any unwanted acceleration. The jets would be sized to produce

counterforces equal to microgravity disturbance accelerations by a 10 percent reduction in the area of an orifice.

7.2.1.3 The Solar Observatory

The divider bulkhead in line with the solar-facing surface of the platform provides the boundary between the microgravity-assembly-bay areas and the volume dedicated to a solar observatory. The on-orbit assembly sequence initially utilizes this bulkhead as the end cap for the central tube; in full operation, the bulkhead is retained with the solar observatory as an added element to extend the central tube. (See Section 8 below.) The end cap which protects the central tube from the incident solar radiation will include a matrix of viewing ports which can serve as mounts for solar research instruments. The matrix will include six ports at 1 m (3 ft) diameter and six at 1.5 m (5 ft) diameter. The port covering will also have an associated sunshield for control of exposure for the instrument. Each of the ports will have a pressure container which surrounds the instrument during operation. In the sequence, the instrument is first mounted behind a closed port and sunshield. In the final step after electrical checkout, a pressure container is placed over the installed instrument. The container is evacuated and the port opened. Instrument operation proceeds as planned with the sunshield lifted for measurement sequences. In the concept outlined, all installation, checkout, and retrieval of instruments are performed from inside the Space Station and do not require any EVA operations. The concept and rationale are discussed further in Section 7.3.1.

7.2.1.4 Storage and Transfer Functions

The central tube will carry the tankage provisions for ballast transfer in support of berthing and shifting of supplies. The system operation will transfer water between bladder type tanks located in the annulus around the microgravity facility and along the divider bulkhead in the solar observatory space.

7.2.2 The Platform and Horticulture Domes

The platform as a truss structure provides the mountings for the solar dynamic power units together with their radiators and the domes for horticulture research. These mountings involve all of the fluid, electrical, gas, and supply leads necessary for control and operations as part of the Space Station. These areas are serviced by EVA, with the access port and airlock into the central tube carried within the boundaries of the truss structure.

7.2.2.1 The Platform

The pertinent features of the platform are summarized in Table 7.2-1. The platform has the capability to support electrical power and control leads, as well as the fluid leads that connect the electrical generators to their heat-sink radiators around the periphery of the platform. The sequence for construction will result in a total of six solar dynamic power units. The first two at 25 kWe provide interim power for construction support. The final sequence provides four units at 425 kWe each, at that time the 25 kWe units revert to standby status. The concept for the 425 kWe units remains as previously defined (Reference 7-8).

7.2.2.2 The Horticultural Domes

Four spherical segment domes provide the facilities to conduct horticultural research under unique conditions of solar illumination and atmospheric content. The units can be individually configured for plant growth or plant reaction measurements involving solar flux and atmospheric content in microgravity. The atmospheric constituents for experimentation will be provided from supplies located in the central tube and occupying part of the annulus volume surrounding the microgravity facility. Manned access will have the option to utilize passage tubes from the airlock or manned EVA. The selection would be based upon the atmospheric content and pressure within the domes. Control and data recording will be performed from the torus control center for the horticultural experiments.

7.3 THE OBSERVATION TUBE

The observation tube, as the inertially stable portion of the Space Station, provides the capability for astronomical and Earth viewing instruments, plus the mountings for communication antennas, tracking antennas, and the relay of energy as a controlled reflection of a radiant energy beam. In addition, the structure of the observation tube makes use of the initial life support modules that supported assembly operations to provide a housing for the safe haven and a point of access to the berthing area. The features provided by the observation tube are summarized in Table 7.3-1. An overview for the end sections of the tube appears as Figure 7.3-1. The descriptions which follow first address the end sections and then follow with the structure and safe-havens.

TABLE 7.3-1   OBSERVATION TUBE SUMMARY OF
CAPABILITIES AND CAPACITIES

A. OBSERVATION TUBE DIMENSIONS AND SIZES

1. End Sections

	Diameter	9.1 m	(30 ft)
	Length	39 m	(128 ft)
	Volume	2161 m³	(90776 ft³)

2. Tube with 5 m Truss Support (Provides Access Plus Auxiliary Air Storage)

	Diameter	3 m	(10 ft)
	Length	81.4 m	(267 ft)
	Volume	499 m³	(20970 ft³)

3. Safe Haven Habitats

	Outside Dia	9.1 m	(30 ft)
	Length	39.6 m	(130 ft)
	Passage Dia	3 m	(10 ft)
	Living Volume	2295 m³	(96414 ft³)

B. END SECTION ELEMENT CONTENTS

1. Astronomical Observatory
    Volume of 235.6 m³ (9896 ft³) as a 9.1 m (30 ft) hemisphere on a 1.2 m (4 ft) cylinder

Instrument Ports	90° to Axis	6 at 1.5 m	(5 ft) dia
	60° to Axis	6 at 1.2 m	(4 ft) dia
	30° to Axis	3 at 1.5 m	(5 ft) dia
	0° to Axis (Zenith)	1 at 1.5 m	(5 ft) dia

2. Earth Viewing Section
    Volume of 882 m³ (37056 ft³) as a 9.1 m (30 ft) dia
    Cylinder Faired to an 8.5 m (28 ft) face 14.3 m (47 ft) long
    Viewing Ports as 5 Rows of 4, Symmetric Distribution:

	6 at 1.5 m	(5 ft)
	6 at 1.2 m	(4 ft)
	8 at 0.9 m	(3 ft)

3. Communications Section:
    Volume of 319 m³ (13430 ft³) as a Cylinder 5.8 m (19 ft) long
    2 Relay Antennas 3 m (10 ft) Parabolics, (Quadrant Openings)
    2 Ground Communication 2.5 m (8.2 ft) Parabolics, (60° Openings)
    2 Laser-Telescopes, Ports 0.91 m (3 ft) by 3.6 m (12 ft)

4. Tracking Sections:
    Volume of 370 m³ (15550 ft³) as a Cylinder 6.7 m (22 ft) long

Phased Array Antennas	4 ports	2.4 m	(8 ft) square
Optical or r.f. Antennas	4 ports	1.8 m	(6 ft) dia

B.   END SECTION ELEMENT CONTENTS (cont.)

5. Energy Relay Sections:
    Volume of 353 m^3 (14844 ft^3) as a cylinder 6.4 m (21 ft) long
    2 Relay Mirrors as Mosaics 15.5 m (18 ft) square as single, or
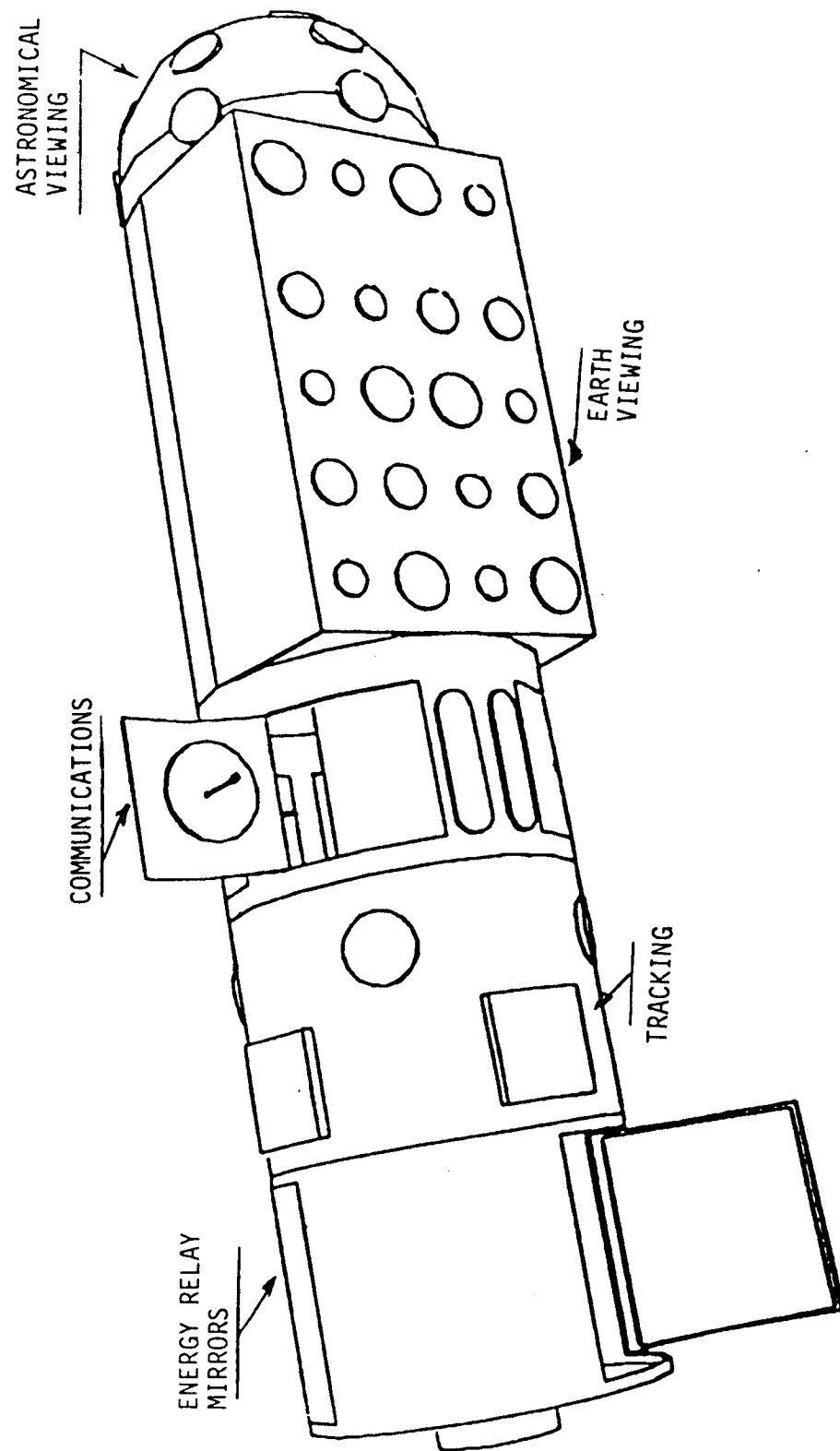   11 m (36 ft) square as folded deployable, (110° openings)

ASTRONOMICAL VIEWING

EARTH VIEWING

COMMUNICATIONS

TRACKING

ENERGY RELAY MIRRORS

Figure 7.3-1, Operating Elements at Each End of the Observation Tube

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7.3.1 The End Sections

The observation tube carries two identical end sections which perform those functions that require a combination of inertial stability and unobstructed view. The rotating section and solar facing platform constrain viewing angles to a hemisphere; the two end sections working in combination provide the full sphere field-of-view with some degree of overlap. The two end sections contain five subsections, each with individual pointing or tracking requirements. The section has been configured based upon a 9.1 m (30 ft) diameter pressurized structure centered around a 3 meter (10 ft) diameter tube. The entire unit has the installation and maintenance operations performed from within; yet, all instrumentation or equipment can operate with their detectors or sensors exposed to the space environment. The five sections are described as follows:

7.3.1.1 The Astronomical Observatory

The ends of the observation tube terminate in hemispheres that provide ten ports at 1.5 m (5 ft) diameter and six ports at 1.2 m (4 ft) diameter, which together provide a total coverage over the half sphere viewing area. One port is centered on the axis of the observation tube such that it permits viewing perpendicular to the plane of the ecliptic. The astronomical sections will have the capability to counter the one-per-year rotation of the Space Station. In such an operating mode, celestial objects would appear stationary when viewed from any of the ports, and a celestial body at zenith or nadir to the plane of the ecliptic would remain continuously in view. KSC launches can achieve 6 degree inclinations to the plane of the ecliptic. At a 500 km (275 nm)

altitude, the Earth will not occlude the line-of-sight to ecliptic zenith or nadir. The instrumentation is installed in an open space behind a port. After checkout, the last operation places a pressure container over the instrument. An evacuation of the container allows opening of the port for observation and measurements. Retrieval or servicing of the instrument involves closing the port, pressurization, and removal of the container as the first step. The concept allows change-out of instrumentation while others are operating, and has no EVA requirement associated with the emplacement or operation of the instrumentation.

The instrumentation for solar research, astronomical observation, and Earth viewing will either respond to some form of electromagnetic radiation, operate as a particle counter, or interact with the magnetic field of the Earth. Typically, the instruments will be telescopes, radiometers, interferometers, charged particle counters, or fluxmeters. All of these types of instruments either depend upon or benefit from direct exposures of their collector-detector element to the incident signals. The concept of a pressure-box behind an open port provides the desired access for measurement plus accommodation of pointing elements as trackers, followers, scanners, etc. If the instrument needs a window or a particular filter, that element becomes part of the instrument assembly. Solar facing instruments do have a recognized need for auxiliary protection which would be provided. Instrumentation that requires large-array collectors may be accommodated elsewhere on the station or would be candidates for flight aboard an auxiliary platform.

7.3.1.2 The Earth Viewing Section

The Earth viewing sections utilize the same concept for

accommodating instrumentation as outlined above for the astronomical observatory section. The Earth viewing section provides a total of 20 ports arranged as five rows of four each, with each row carried between decks within the support structure. The Earth viewing system will rotate relative to the support tube at one revolution per orbit. Instrument transport utilizes an elevator within the support tube, and a series of transfer doors along the tube with a door between each of the support decks. Instrument packages would pass through the doors into that portion of the annulus area away from the instrument face, as a place for storage before installation behind a viewing port.

7.3.1.3 The Communications Section

The communications requirements identified for the Space Station utilize parabolic antennas for microwave links to the relay satellites, parabolic antennas for direct links to Earth stations, and laser-telescope links for communication beyond orbits around the Earth. Each communication section contains two independent units of each type (i.e., redundancy at each end of the observation tube). Each antenna would be installed and serviced from the inside, but operate in space. For the laser telescope combination, the configuration utilizes a pressure box and moveable port combination similar to the approach for housing the instrumentation. The parabolic antennas are structures ranging from 2.5 m (8 ft) to 3 m (10 ft) in diameter, and would be mounted to swing-out doors that function as parts of the external walls. Each antenna would have its own bay and be capable of independent operation. The 9 m (30 ft) diameter of the structure provides clearance for the antenna installation around the center tube and will permit internal pressure

bulkheads. The operations of the communications links are planned events and will dedicate a section for the duration of that particular communication activity. This section will need to rotate in response to a line-of-sight requirement and requires a system for controlled positioning and traversing relative to the Space Station orientation.

7.3.1.4 The Tracking System

The tracking system operates line-of-sight to the horizon and supports all of the rendezvous, berthing, and deployment operations. The section utilizes the instrument-behind-a-port concept described above, with the port sizes and shapes compatible with phased array antennas, microwave transponders, and laser-optical telescope combinations. During rendezvous and berthing events, the sections are dedicated to the operation intended. The pointing and translations of this segment are independent of the other sections.

7.3.1.5 The Energy Relay Section

The use of laser beams to power remote spacecraft is an identified technique for energy relay (Reference 7-9). The ability to provide temporary local control by reflecting such beams has been included in the end sections of the 2025 Space Station.

The energy relay section utilizes the same door-in-the-wall concept as the communication section to provide a reflecting surface for power transmission by a beam of light (i.e., laser or equivalent). The configuration provides two deployable mirrors in each of the sections. When folded, the mirrors are 5.5 m (18 ft) square. A single fold (two surfaces) provides a reflection area 5.5 m by 11 m (18 ft by 36 ft) ; a

double fold (four surfaces) provides a reflecting area 11 m (36 ft) square. The combination of four surfaces at two locations provides a redundant capability for a reflective energy relay between orbiting spacecraft and platforms.

7.3.1.6 Summary of Technology Considerations

In summary, the end sections provide for both the scientific and operating support activities of the Space Station and thereby become critical elements of the entire system. The observation tube has to remain stable relative to the end section to provide the base for pointing and communication acquisition. To this end the astronomical observatory can become a contributor; a star tracker in a viewing port could provide the fixed reference needed for control of relative motion. The concept presents a need for large diameter pressure seals under conditions of slow and somewhat erratic motions. The structure shows a need for stability under varying conditions of internal pressurization. Finally, the end forces generated by atmospheric pressure acting on a surface 9.1 m (30 ft) in diameter impose heavy operating loads for the bearings that must accommodate varying rates of movement, to include reversals of direction and extended periods of no motion. Along with the bearing requirements exists the companion need for a servo drive system that can make the transition through change-of-direction without transients or loss-of-lock for a narrow communication beam such as a laser. Here the limits have been defined at one microradian for pointing and 0.2 microradian for allowable jitter (Reference 7-10).

7.3.2 The Tube Structure and Safe Haven Habitat

The tube structure connects the end sections to the safe haven, berthing bay, and central tube. The tube portion provides a 3 m (10 ft) diameter passage for instruments and support items moving between the active ends and the central tube. The tube structure will withstand extra atmospheric pressures and have additional stiffening from a surrounding truss. The truss, in turn, will provide a pathway for the EVA spider crane, and the bays of the truss are considered available for the mounting of passive experimentation. The safe-haven portion of the observation tube utilizes the sections originally configured as the crew quarters during the on-orbit erection and assembly operations. These cylindrical sections are 9.1 m (30 ft) in diameter by 39.6 (130 ft) long with a 3 m (10 ft) passage at the center line. The annulus formed in the structure will provide short-term living quarters for support operations within the observation tube, for operations in the central tube, for support to berthings, and during preparations for embarking of other spacecraft. For these transient occupations, the living areas will be supplied and maintained from the torus. In addition, the section will have shielding within the structure and will maintain an inventory of emergency supplies such that the crew could congregate for a rescue in the event of a catastrophic failure elsewhere in the station. The level of supplies would reflect the time span needed to launch a rescue spacecraft and accomplish a rendezvous (about 5 days). For these conditions, power, atmosphere, water, food, and sanitation would represent emergency conditions and depend upon the use of on-board stores only. It is recognized that the maintenance of such a capability would

represent a continuing activity for the on-board crew. Safe haven stores would always be full and fresh.

7.4 THE BERTHING AREA AND MANIPULATORS

The berthing area provides the spaceport facility associated with all of the functions listed for the 2025 Space Station. The structure has been configured to accommodate the unmanned booster space supply systems anticipated for the year 2025, and provide assembly or servicing support for the potential spacecraft intended for operation at that time. Figure 7.0-1 shows the berthing area relative to the Space Station. The principal features are described below as structure and manipulators.

7.4.1 Berthing Area Structure

The berthing area is configured by a structure which defines a cube with sides of 67 m (220 ft). The structural elements consist of tubes 3.2 m (10.5 ft) in diameter stiffened by a surrounding truss. The tube elements allow for passage of personnel and small items of equipment. The truss structure provides the rails for the travelling remote manipulators which perform the operations. The cube connects to both the central tube and to the observation tube within the safe haven length. The use of the tubes as passages for personnel includes ports at the outboard ends of the two sections which join to the safe haven and provide an airlock-type docking for a spacecraft. The principal airlock port for the Space Station is provided by the moveable section in the center of the main lock at the end of the central tube. In the concept as shown, air lock transfer of crew from the Shuttle or a similar "winged" configuration would employ one of the outboard ports. A

spacecraft which could enter the cube would utilize the port at the main door.

7.4.2 Manipulators and Berthing Operations

An inventory of telescoping booms with remotely controlled manipulators will perform the actual handling operations for the berthing area. The inventory will include one unit dedicated to each leg of the cube structure, plus three additional units which can be shifted between legs. The reach for each unit will extend past the midpoint of the cube to provide multiple hands for transfer. In addition, a series of stanchions, tie downs, and stabilizers will be carried on the structure as adaptor items to hold a spacecraft in place while servicing operations proceed. Control for these manipulators will reside primarily in the torus; local shared controls will be available from observation positions within the tube structure.

Berthing and assembly operations will all be preplanned and represent coordinated activities within the berthing bay and the central tube. Typically, a berthing would occur within the cube, with the docking spacecraft eased into position under control of the manipulators working in conjunction with vernier control jets aboard the spacecraft. An uncompensated transfer of the spacecraft from a position-controlled status into a hard lock with the Space Station would change the center-of-gravity position along the central tube. Therefore a hard lock to the Space Station must be accompanied by a corresponding ballast transfer within the central tube. The off-loading (or loading) of the berthed spacecraft will also require a corresponding ballast shift. The final release of the berthed spacecraft will involve a reverse of the berthing

sequence. A ballast return accompanies the relaxation of berthing constraints.

The activities which accompany the deployment of a spacecraft out of the central tube require one additional action element. The internal volume must be evacuated in a manner which does not shift the center of gravity. For such events, the middle sections of the observation tubes and portions of the berthing area structural tubes will serve as air storage reservoirs and accept pressures up to 10 atmospheres. After transfer of air, the final venting to space will be performed in a manner which does not perturb the attitude. Spacecraft transfer through the airlock doors will be performed jointly by the internal and external manipulators accompanied by an appropriate ballast shift.

In summary, the berthing area identifies the need for large versatile manipulators capable of remote operation. The units will need a number of end effectors or "hands" which can be changed out as part of an operating sequence (e.g., stored on structure). Operations will rely on video for both guidance and records, with camera locations both fixed to the structure and attached to the manipulators. Proximity detection and tactile (grip) force feedback are considered necessary elements of the system. To the extent practical, movements would be preplanned for hands-off type of motions, the need becomes real when the movements could influence the inertial configuration of the Space Station, since water ballast may need to move at the same time and rate. In addition, a computer would not forget the location of a stanchion or a tie brace that happened to be just outside the view field for the video monitor used by a manned operator.

References

7-1   Queijo, M. J. et al.: An Advanced-Technology Space Station for the Year 2025, Study and Concepts, NASA CR-178208, March 1987, Table 6.5-1.

7-2   Spacelab Payload Accommodations Handbook, Appendix B. European Space Agency, SLP/2104-2, Section 3.2.6.

7-3   Crawford, G.A.: The Greening of Large Industrial Electrolytic Hydrogen (EH_2), 119th Intersociety Energy Conversion Engineering Conference, Volume 3, 1984.

7-4   Queijo, M. J. et al.: An Advanced-Technology Space Station for the Year 2025, Study and Concepts, NASA CR-178208, Figure 5.2.3-1, March 1987.

7-5   Terrestrial Environment Criteria Guidelines for use in Aerospace Vehicle Development, NASA TM-82473, Table 15-2, Revision 1982.

7-6   Den Hartog, J. P.: Advanced Strength of Materials, McGraw Hill Co., Figure 5-6, 1952.

7-7   Marks, L.: Handbook for Mechanical Engineers, McGraw Hill Co., Section 3, Sixth Edition, 1958.

7-8   Queijo, M. J. et al.: An Advanced-Technology Space Station for the Year 2025, Study and Concepts, NASA CR-178208, Section 4.3, March 1987.

7-9   Garrett, L.B. and Hook, W.R.: Future Large Space Systems Opportunities, A Case for Space to Space Power, NASA Conference Publication 2035 Vol. 1. pp. 507-512, January 1978.

7-10   Queijo, M. J. et al.: An Advanced-Technology Space Station for the Year 2025, Study and Concepts, NASA CR-178208, Section 4.8, March 1987.

8.0 SPACE STATION ASSEMBLY SEQUENCE AND INTERFACES WITH PROPOSED SPACE TRANSPORTATION SYSTEMS

The design, size, and mass of the Space Station structural elements, components, and subassemblies will dictate the sequence of their assembly on low Earth orbit. The number of heavy lift launch vehicle (HLLV) launches will be related to the payload weight and volume limitations of the available HLLVs. Personnel will be transported via vehicles such as the Shuttle II to participate in the assembly process.

8.1 ASSUMPTIONS MADE TO FACILITATE ON-ORBIT ASSEMBLY OF THE SPACE STATION

The planning activity to determine a logical sequence of assembly of the Space Station required that several assumptions be made. These assumptions are based on the projected space transportation architecture and a proposed Space Station structural configuration.

ASSUMPTIONS

o The Space Station will be manufactured on Earth and be composed of structural elements and subassemblies compatible with the size and weight limitation of the space transportation architecture available in the 2025 time frame.

o The Space Station will be disassembled into structural elements, components, and subassemblies and manifested for launch to low Earth orbit to maximize the space transportation systems capabilities.

o The assembly and checkout of the Space Station will occur on

orbit at zero "g". The assembly crew personnel will change over at 90-day intervals to maintain their proficiency by staying psychologically and physiologically fit.

o The space transportation system architecture will consist of heavy lift launch vehicles (HLLV) capable of lifting greater than 2.72×10^5 kg (6×10^5 lb) per launch to low Earth orbit of 463 to 500 km (250 to 270 nautical miles) altitude at an inclination of 28.5 degrees. The payload size envelope would accept a cylinder 33.5 m (110 ft) in diameter by at least 39.6 m (130 ft) in length.

8.2 SPACE TRANSPORTATION SYSTEMS PROPOSED FOR THE 2000-2025 TIME FRAME

A survey of current literature pertaining to space transportation architecture provided several proposed HLLV concepts ranging from partially expendable to fully recoverable launch vehicles (References 8-1 and 8-2) (Figure 8.2-1).

Launch vehicle concepts are being studied that are capable of delivering up to 2.7×10^5 kg (6×10^5 lb) payload to low Earth orbit. The payload shroud size is 15.2 m (50 ft) in diameter by 60.9 m (200 ft) in length. The launch vehicle's initial operating capability is planned for about the year 2000 (Reference 8-3) (Figure 8.2-2).

Manned and unmanned booster components may be flown back to the launch site for refurbishment and reuse. Detachable payload enclosures may be manifested, preassembled, and joined with the launch vehicle at the launch pad to minimize the time required for payload integration. Fault tolerant electronics, artificial intelligence, robotics, and expert systems will contribute to reducing the man effort required for the
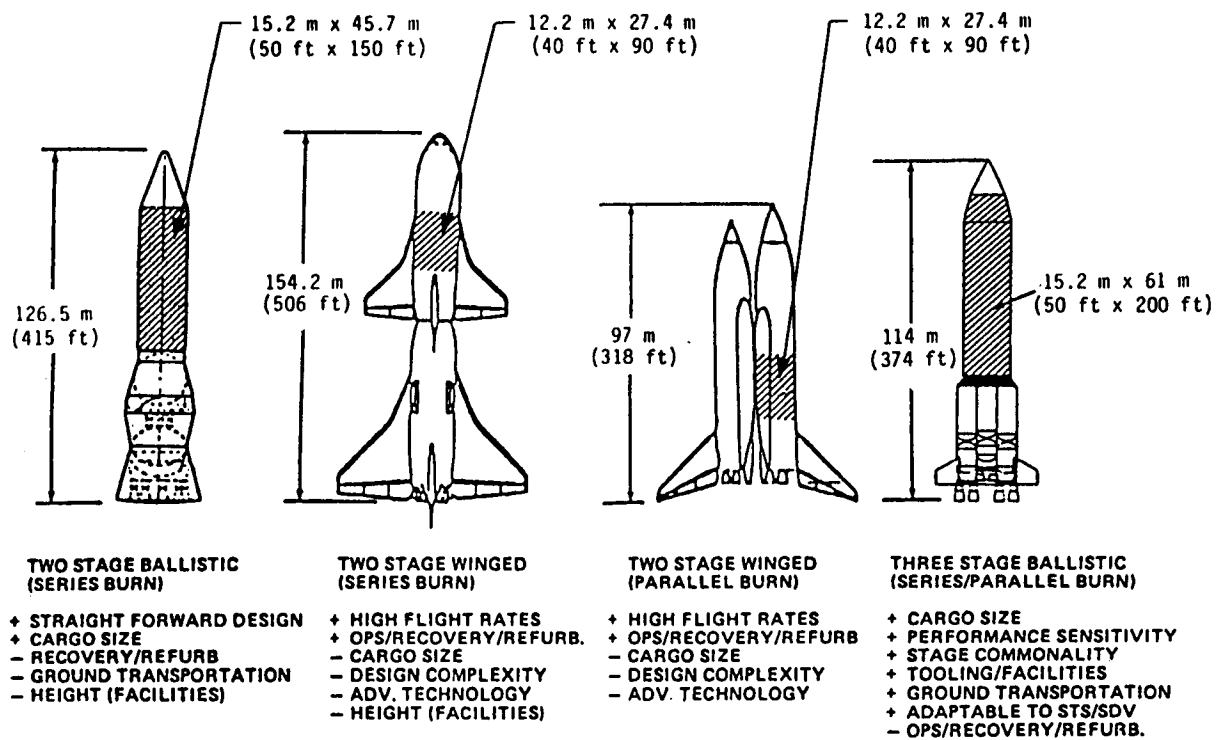
15.2 m x 45.7 m
(50 ft x 150 ft)

12.2 m x 27.4 m
(40 ft x 90 ft)

12.2 m x 27.4 m
(40 ft x 90 ft)

126.5 m
(415 ft)

154.2 m
(506 ft)

97 m
(318 ft)

114 m
(374 ft)

15.2 m x 61 m
(50 ft x 200 ft)

TWO STAGE BALLISTIC
(SERIES BURN)

+ STRAIGHT FORWARD DESIGN
+ CARGO SIZE
− RECOVERY/REFURB
− GROUND TRANSPORTATION
− HEIGHT (FACILITIES)

TWO STAGE WINGED
(SERIES BURN)

+ HIGH FLIGHT RATES
+ OPS/RECOVERY/REFURB.
− CARGO SIZE
− DESIGN COMPLEXITY
− ADV. TECHNOLOGY
− HEIGHT (FACILITIES)

TWO STAGE WINGED
(PARALLEL BURN)

+ HIGH FLIGHT RATES
+ OPS/RECOVERY/REFURB
− CARGO SIZE
− DESIGN COMPLEXITY
− ADV. TECHNOLOGY

THREE STAGE BALLISTIC
(SERIES/PARALLEL BURN)

+ CARGO SIZE
+ PERFORMANCE SENSITIVITY
+ STAGE COMMONALITY
+ TOOLING/FACILITIES
+ GROUND TRANSPORTATION
+ ADAPTABLE TO STS/SDV
− OPS/RECOVERY/REFURB.

Figure 8.2-1   Heavy Lift Launch Vehicle Concepts (2.27 x 10^5 kg or 5 x 10^5 lb Payload Class)(Reference 8-2)
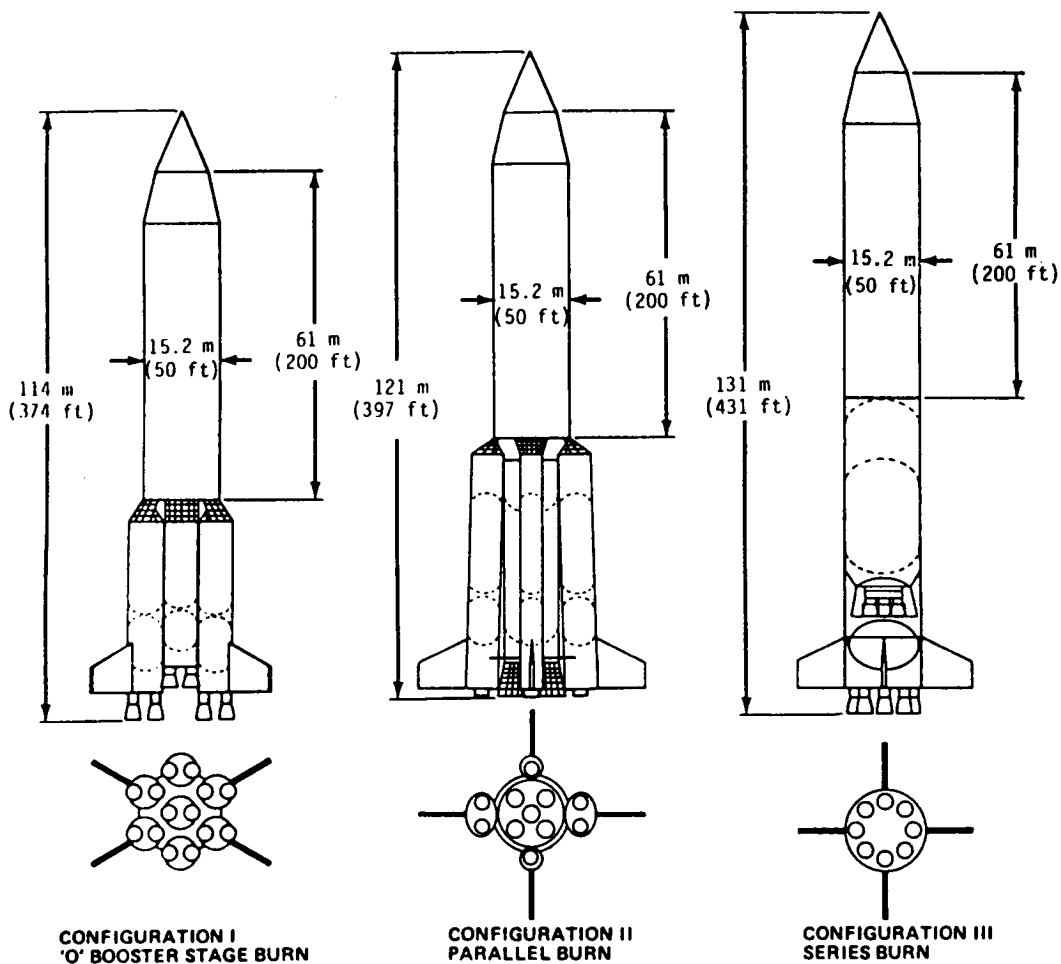
Figure 8.2-2 Heavy Lift Launch Vehicle (HLLV) Options Comparison (Reference 8-3)

launch, and Space Station rendezvous and assembly operations. Weather resistant thermal protection systems, lightweight structures, and reusable cryogenic tankage will contribute to reducing launch preparation costs and HLLV turnaround time prior to relaunch.

Personnel transportation will be provided by Shuttle II, the National Aerospace Plane, or comparable transportation to and from low Earth orbit. The current National Space Transportation System (Shuttle I) reflects aerospace technologies developed in the 1970's with a useful life of 100 flights per orbiter. Shuttle I should phase out in the 2010-2020 time frame and be replaced with personnel transportation vehicles having lower launch costs. Shuttle II is proposed for service about 2005 as a second generation manned launch system capable of delivering 9.1×10^3 kg (2×10^4 lb) to and from the Space Station orbit. A payload bay size of 4.57 m (15 ft) diameter by 9.14 m (30 ft) in length -- about one half that of the present Space Shuttle -- could be used to transport 10 passengers to or from the Space Station (References 8-4 and 8-5) (Figures 8.2-3 and 8.2-4).

Orbital maneuvering vehicles (OMV's) will be used to assist the astronauts to assemble the components and subassemblies of the Space Station on orbit. An OMV can be used as a space tug to maneuver large massive structures into position for assembly with other structures. The OMV performs a variety of functions when directed by telecommunication, and uses three independent propulsion systems to permit maneuvering of large payloads into precise locations. The Space Shuttle will deliver the OMV's to low Earth orbit, and at least two may remain permanently docked for service at the Space Station (Reference 8-6) (Figure 8.2-5).
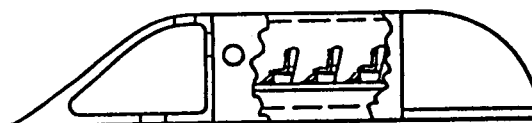
Detachable payload shroud
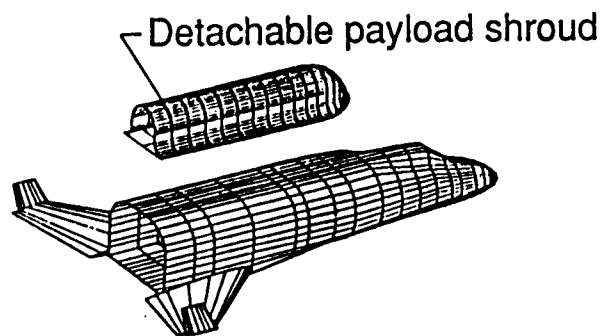
- Offline processing

- Standardized payload
  interfaces

- Specialized container
  systems for dominant
  mission types

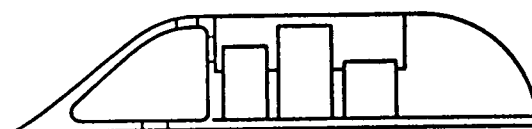- User access until
  installation at
  launch pad
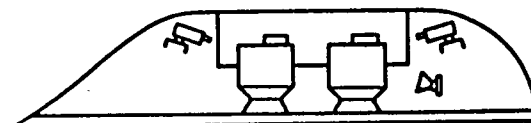
Deployment
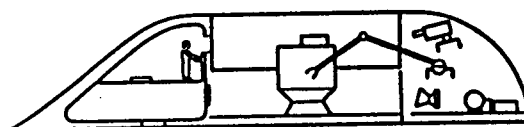
Servicing

Personnel Transport

Delivery

Figure 8.2-3 Detachable Payload Container System (Reference 8-4)

- 1992 Technology level
- Integral tanks
- Gross Weight: 9.23×10^5 kg (2.04×10^6 lb)
- Dry Weight: 1.2×10^5 kg (2.7×10^5 lb)

  Payload bay 4.6 m x 9.1 m (15 x 30 ft)

33.5 m
(110 ft)

42 m
(138 ft)
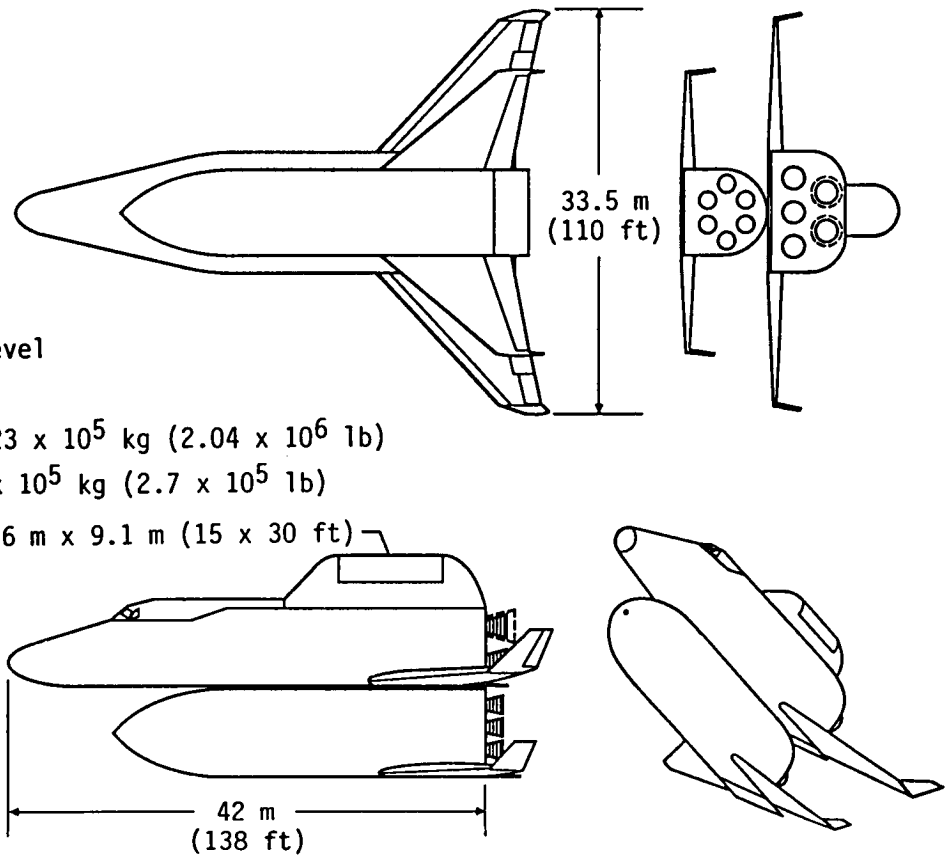
Figure 8.2-4 Shuttle II Two-stage Concept (Reference 8-4)
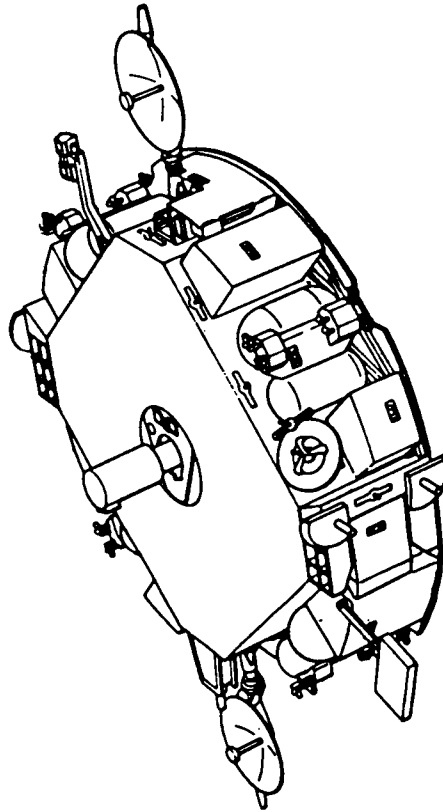
Figure 8.2-5 Orbital Maneuvering Vehicle (Reference 8-6)

An orbital transfer vehicle (OTV) is under study which will have the capability to be launched from low Earth orbit to geosynchronous equatorial orbit (GEO) and rendezvous with a satellite. The OTV can service the satellite on orbit or return the satellite to the Space Station for repair and servicing for later return to GEO. Advanced versions of the OTV may undertake manned missions to the Moon or serve as a lunar or Mars lander. The OTV would be docked at the Advanced Technology Space Station and fueled as required for designated missions (References 8-7, 8-8 and 8-9) (Figure 8.2-6).

8.3 LAUNCH CRITERIA BASED ON SPACECRAFT OPERATIONS REQUIREMENTS

The Advanced Technology Space Station celestial observatories are contained in the hemispheres of cylindrical modules located at the opposite ends of the observatory boom. Spacecraft guidance and control will be enhanced if the celestial observatory star trackers can maintain continuous lock on a star without obscuration by the Earth or its atmosphere. Continuous viewing capabilities can be achieved for the star trackers by adhering to the following criteria:

(1) The spacecraft will be assembled in a circularized orbit at an altitude of 463 to 500 km (250 to 270 nautical miles) at 28.5 degrees inclination to the Earth's equator.

(2) The plane of the spacecraft's orbit would be chosen to achieve a minimum angle (approximately 5.5 degrees) of obliqueness from the plane of the ecliptic.
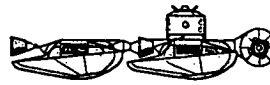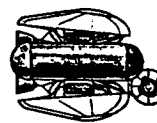
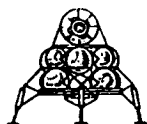**TRANSFER VEHICLE CONCEPTS**

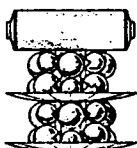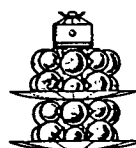CARGO   PASSENGER   PASSENGER   CARGO

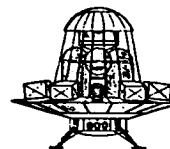**EARTH ORBIT VEHICLES**   **MARS ORBIT VEHICLES**

CARGO   PASSENGER

EARTH-MOON VEHICLES

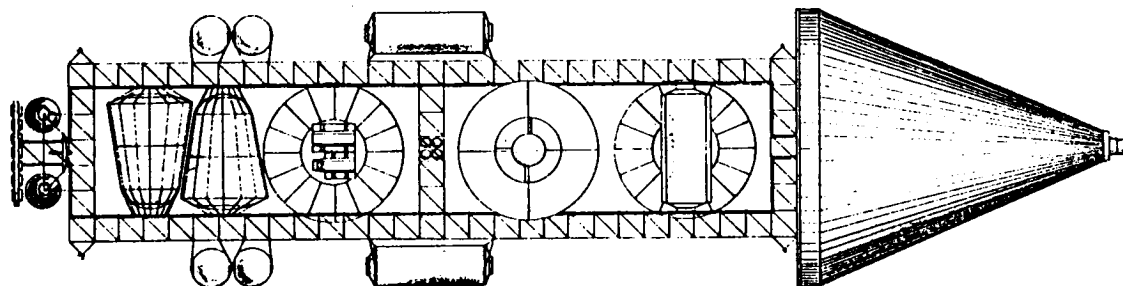**LUNAR LANDER**   **MARS LANDER**

SOLAR   NUCLEAR

SMALL ELECTRIC PROPULSION CARGO VEHICLES

LARGE NUCLEAR ELECTRIC PROPULSION CARGO VEHICLE

(COURTESY PAT RAWLINGS)

Figure 8.2-6 Transfer Vehicle Concepts (Reference 8-9)

(3) The axis of rotation of the spacecraft will be continuously pointed at the Sun. The observatory booms will remain oriented normal to the plane of the ecliptic.

The assembly operations of the spacecraft on orbit require that the launch vehicle rendezvous with previously delivered hardware in the assembly orbit.

An existing fully operational United States Space Station orbiting in a near coincident orbital plane could offer support for assembly of the Advanced Technology Space Station. The support capabilities might include:

o   Orbital maneuvering vehicle

o   Orbital transfer vehicle

o   Mobile remote manipulator system

o   Medical treatment

o   Communications backup

o   Safe haven

o   Emergency electric power

8.4 DESCRIPTION OF SPACECRAFT ASSEMBLY CONCEPTS

The Advanced Technology Space Station will be assembled on orbit from structural elements, components, subassemblies, and telescoped assemblies. A proposed structural concept is described as it applies to the sequence of assembly of the Space Station.

A central tube will be assembled on orbit from three cylinders. Two of the cylinders are modules 15.24 m (50 ft) in diameter by 30.48 m (100 ft) in length. One of these modules will serve as a temporary

habitat for an assembly crew of 20 people, and will be completely outfitted with personnel entry airlocks, environmental control and life support equipment, fuel cells for electric power generation, reaction control system, inertial platform, a control center for telerobotic operations, and other essential equipment and facilities. The second cylindrical module will also contain airlocks, essential life support equipment, and electric power generation fuel cells to assure a redundant safe haven during the early Space Station assembly phase. The cylindrical hub, an assembly 33.5 m (110 ft) in diameter by 30.48 m (100 ft) in length, will be outfitted with roller bearings, dynamic atmospheric gas seals, and electric motors programmed to prevent the central tube from rotating due to friction of the bearings and seals when the Space Station is fully operational.

The assembly operations of the central tube will proceed as follows:

(A)   The habitat I module (Figure 8.4-1) will be delivered to orbit by an HLLV.

(B)   A 20 person assembly crew and an orbital maneuvering vehicle (OMV) will rendezvous with the reaction control stabilized habitat (Figure 8.4-2). The life support systems can be activated prior to the crew boarding, and then food and medical supplies will be brought aboard. The Space Station will become man-tended during the assembly sequence and throughout its operational lifetime.
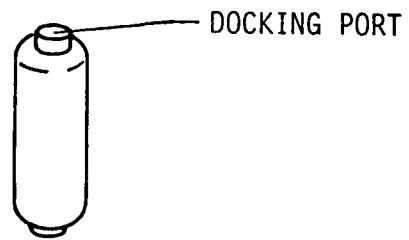
DOCKING PORT

Figure 8.4-1 Habitat I Module

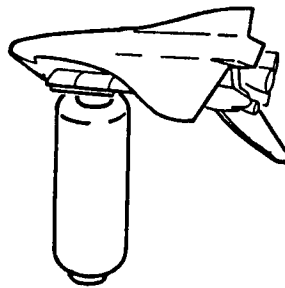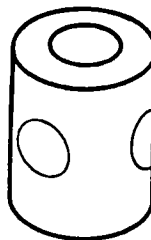
Figure 8.4-2 Shuttle Docked with Habitat I

Figure 8.4-3 Central Hub

(C) The central tube's hub (Figure 8.4-3) will be launched next as a one-piece fully assembled structure shimmed and locked to prevent rotational damage to the bearing assemblies during lift off. An OMV will be used to maneuver the hub to mechanically join with the habitat I module. The bearing shims and locks will be removed prior to assembly with the spokes.

(D) The second module, habitat II (Figure 8.4-4), will be mechanically joined to the opposite end of the hub on orbit (Figure 8.4-5). The central tube assembly will be oriented for gravity gradient stabilization to minimize the fuel consumption required during docking and spacecraft assembly operations.

(E) The safe haven modules will be launched next for mechanical attachment to the central tube to provide an emergency retreat in the event of a problem with the rotating Space Station. The safe haven will be scarred to receive the environmental control and life support systems from the central tube's habitat modules when the Space Station becomes operational (Figure 8.4-6).

(F) The next launch will deliver a telerobotic truss assembler along with bundles of truss structural elements for assembly of the berthing bay, the solar dynamic unit platform, and, later, the observatory booms. The truss construction will consist of 5 cm (2 in) diameter structural elements joined at nodes to form an orthogonal tetrahedral structure. The central tube's
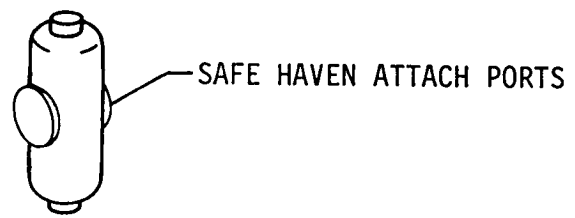
SAFE HAVEN ATTACH PORTS
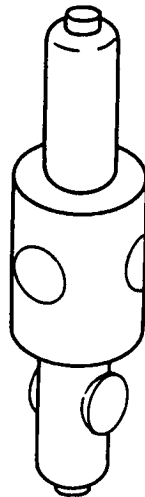
Figure 8.4-4 Habitat II Module

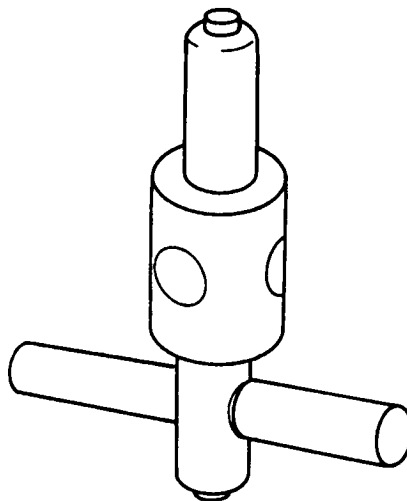Figure 8.4-5 Central Tube Assembly, Gravity Gradient Stabilized

Figure 8.4-6 Safe Haven Modules Joined to Habitat II Module

habitat II module and safe haven modules can be used for storing the element bundles until required for assembly.

(G) The telerobotic truss assembler will then construct the berthing bay structure at the zenith-pointed end of the central tube, thus permitting personnel and resupply vehicles to dock at the nadir-pointed end during assembly. Telescoped intravehicular activity tubing 2.9 m (9.5 ft) in diameter will be positioned inside the truss structure to interconnect the docking nodes with the safe haven modules and the central tube (Figure 8.4-7). The docking nodes permit personnel to enter or exit the visiting spacecraft in a shirt-sleeve environment. The OMV's will be berthed and serviced from one of the nodes. The completed berthing bay will be outfitted with remote manipulators to permit assembly, servicing, and storage of large structures during the Space Station assembly phase and, later, the assembly of spacecraft for lunar and planetary missions. All visiting spacecraft and telerobotic machines will be berthed at nodes of the berthing bay.

(H) The telerobotic truss assembler will assemble the truss structure platform at the nadir-pointing end of the central tube (Figure 8.4-8).

(I) Mobile remote manipulator systems will assemble two solar dynamic electric power generation units diametrically opposite on the platform. The solar dynamic units may be of standard
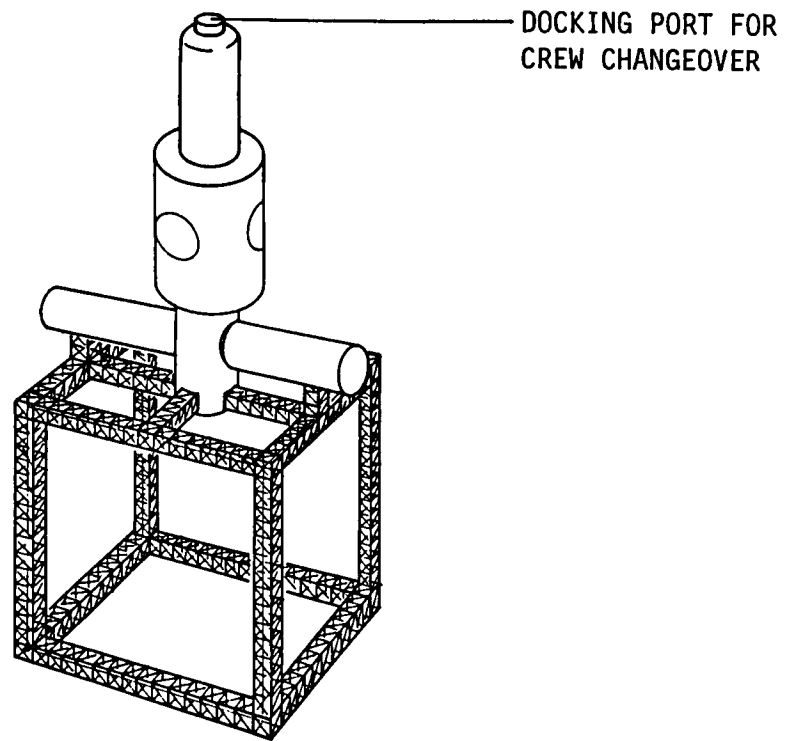
DOCKING PORT FOR
CREW CHANGEOVER

Figure 8.4-7 Berthing and Assembly Bay Truss Structure

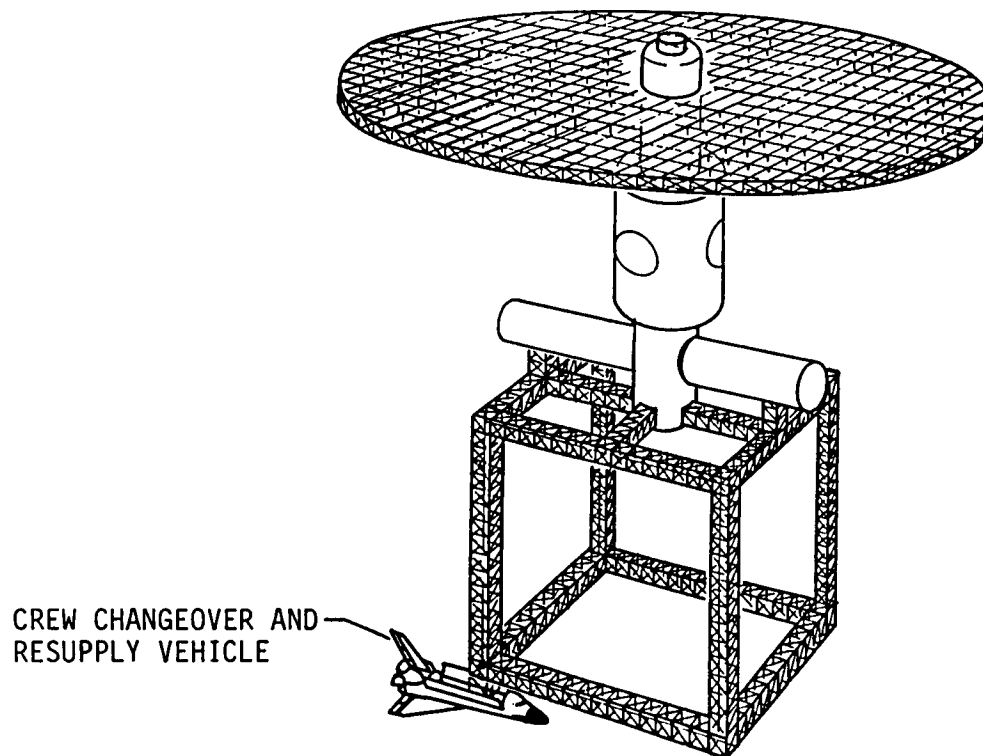CREW CHANGEOVER AND
RESUPPLY VEHICLE

Figure 8.4-8 Platform Constructed of Truss Structure

8-17

design, each approximately 12.2 m (40 ft) in diameter and capable of generating 25 kWe of electric power (Figure 8.4-9). The electric power systems of the habitat modules will be scarred to receive power from the solar dynamic units when the spacecraft's rotational axis is Sun-pointed. This option will reduce the demand for resupply of cryogenic gases of oxygen and hydrogen for on-board fuel cell generation of electricity. The electric power demands of the Space Station during the assembly phases may also be met by a co-orbiting Space Station maintaining a hard-wire connection to the Advanced Technology Space Station for electric power supply or by a co-orbiting power generation spacecraft transmitting energy by microwave beam or solar pumped laser. The partially assembled Space Station will be reoriented by use of its reaction control system so that the platform with the two solar dynamic units is Sun-facing, and the axis of the central tube is pointed at the Sun's center within ± 0.1 degree alignment. The safe haven's axis will be maintained normal to the plane of the ecliptic.

(J) The telerobotic truss assembler will construct the celestial observatory booms onto the safe haven ends. Telescoped intra-vehicular activity tubing 2.9 m (9.5 ft) in diameter will be positioned inside the truss structure to interconnect the safe haven to the observatory modules, which will be attached to the ends of the observatory booms at a later date (Figure 8.4-10). Mobile remote manipulator systems will be positioned onto the
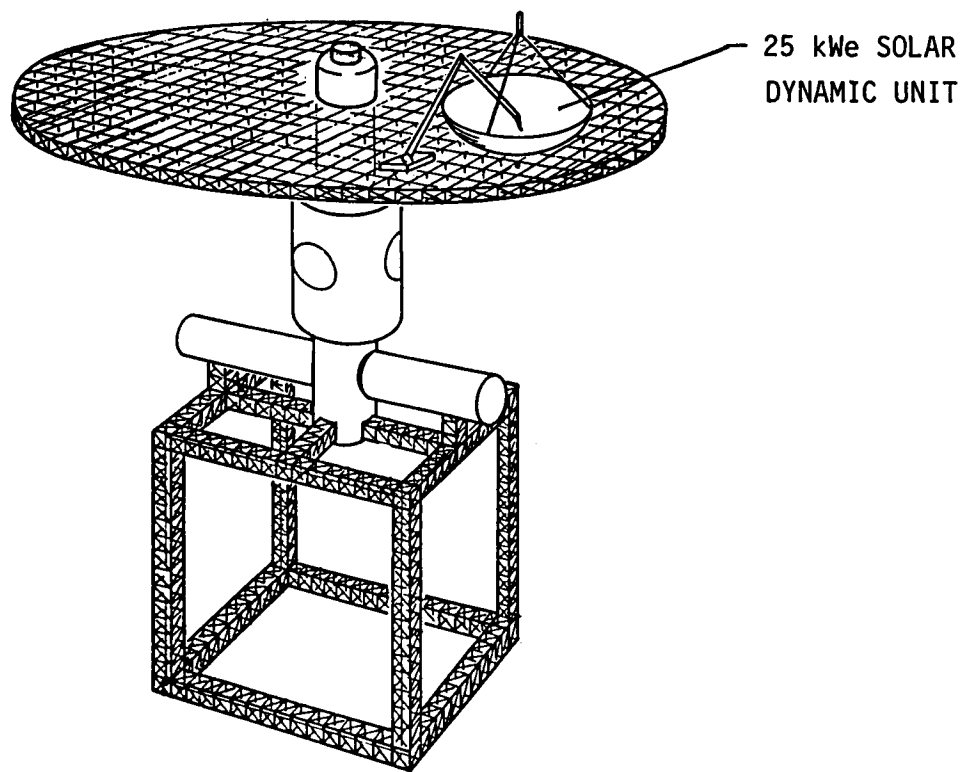
25 kWe SOLAR
DYNAMIC UNIT

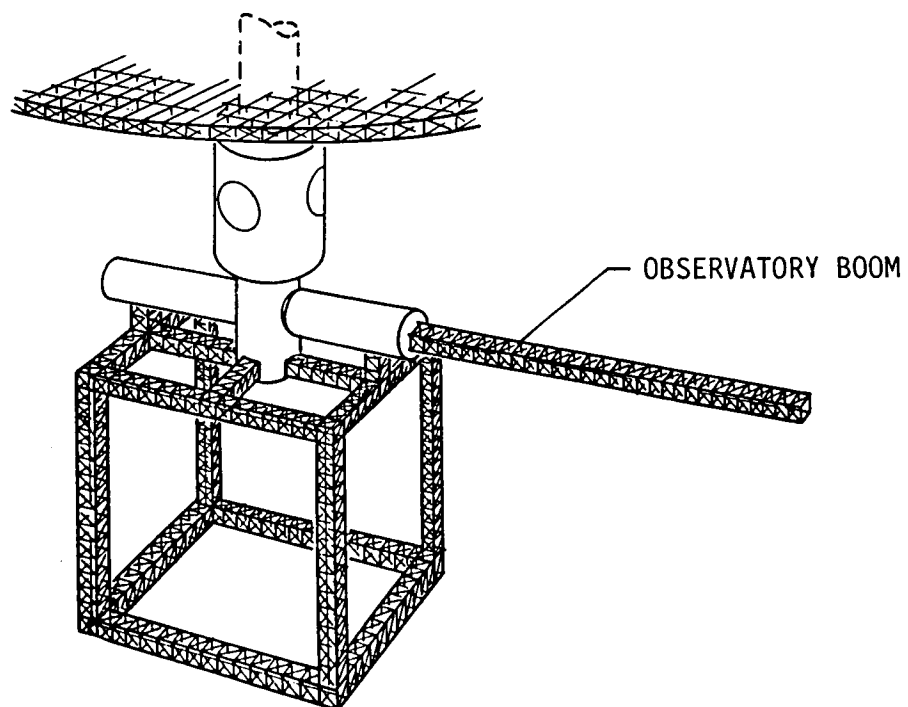Figure 8.4-9 Assembly of Solar Dynamic Unit

OBSERVATORY BOOM

Figure 8.4-10 Observatory Boom Truss Structure

assembled observatory booms to facilitate positioning the torus spokes and torus segments for assembly.

(K) The spokes will be telescoped and launched as a payload 9.1 m (30 ft) in diameter by 30.5 m (100 ft) in length. Each spoke will be extended to 89.9 m (295 ft) in length for assembly with the hub of the Space Station.

(L) The Space Station torus will be assembled from 24 equal length cylinders 15.24 m (50 ft) in diameter by 29.9 m (98 ft) in length. The torus cylinders will be designed for mechanical attachment to one another, and designated cylinders will mechanically attach to the ends of the spokes. The assembly operations will strive to achieve uniformity of mass additions to diametrically opposite spokes. Torus cylinders will be attached to the spoke ends, followed by joining the remaining torus cylinders together (Figures 8.4-11 and 8.4-12).

(M) Two 425 kWe solar dynamic units will also be installed on diametrically opposite spokes for electric power requirements within the torus. The unwanted heat from all the solar dynamic units will be radiated in a radial direction away from the Space Station's axis of rotation. Probable locations for radiator panels will be on the outside diameter of the platform and torus (Figures 8.4-13 and 8.4-15).

C-2

TELESCOPIC SPOKE

TORUS
CYLINDRICAL
SEGMENTS

MOBILE REMOTE
MANIPULATOR
SYSTEM

Figure 8.4-11 Spoke and Torus Assembly

TORUS CYLINDRICAL
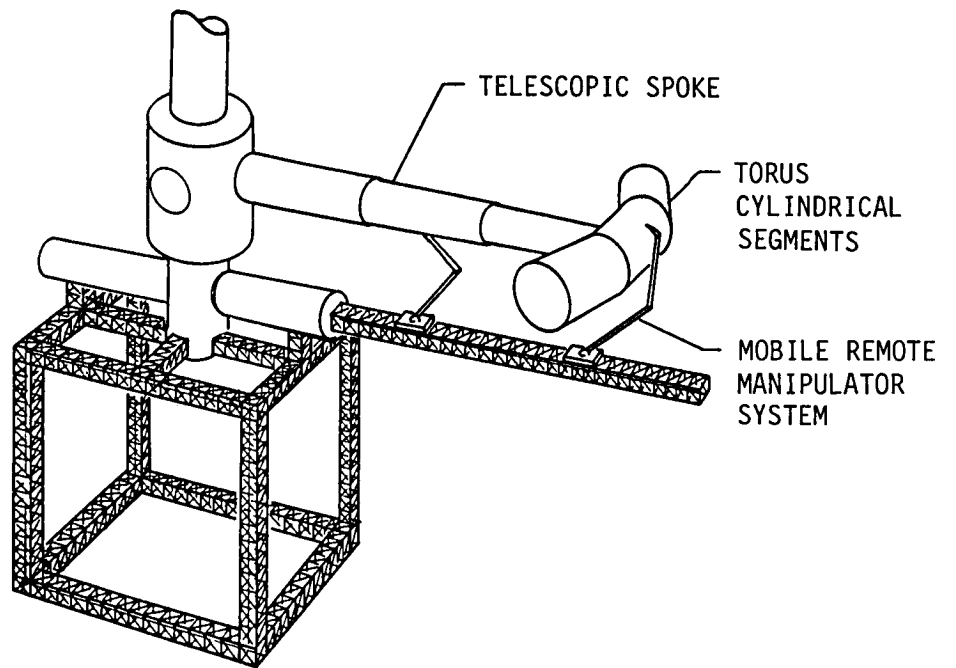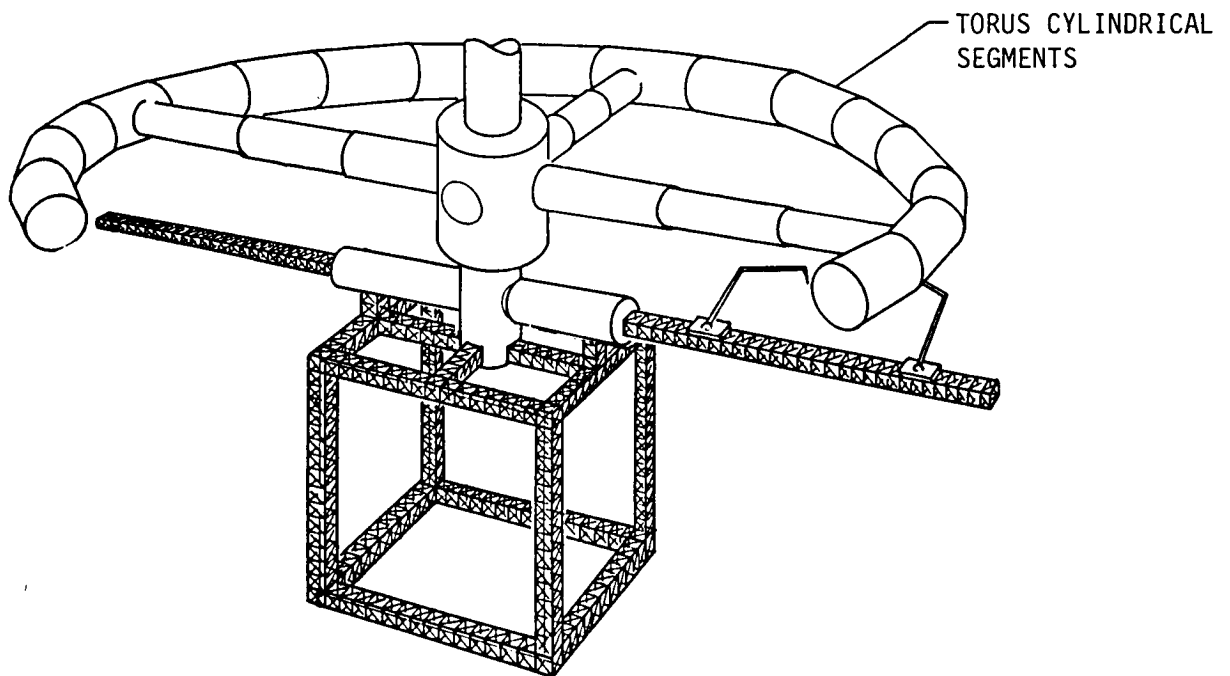SEGMENTS

Figure 8.4-12 Joining Cylinders to Form a Torus
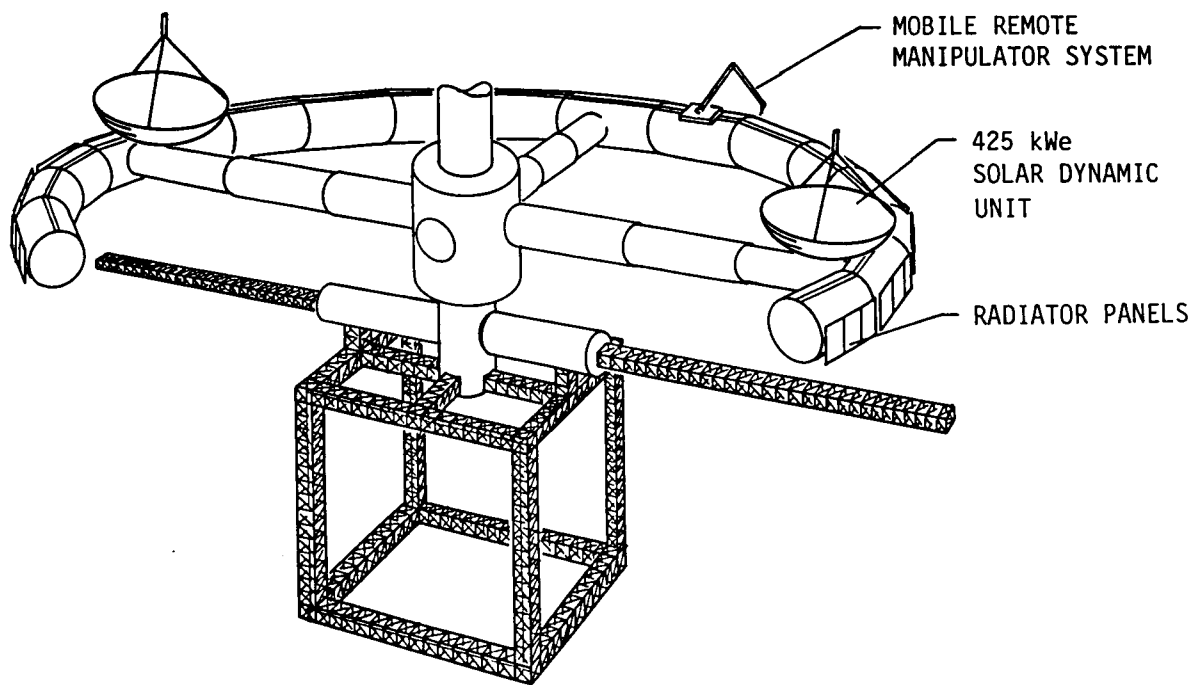
Figure 8.4-13 Two Solar Dynamic Units and Radiator Panels Installed

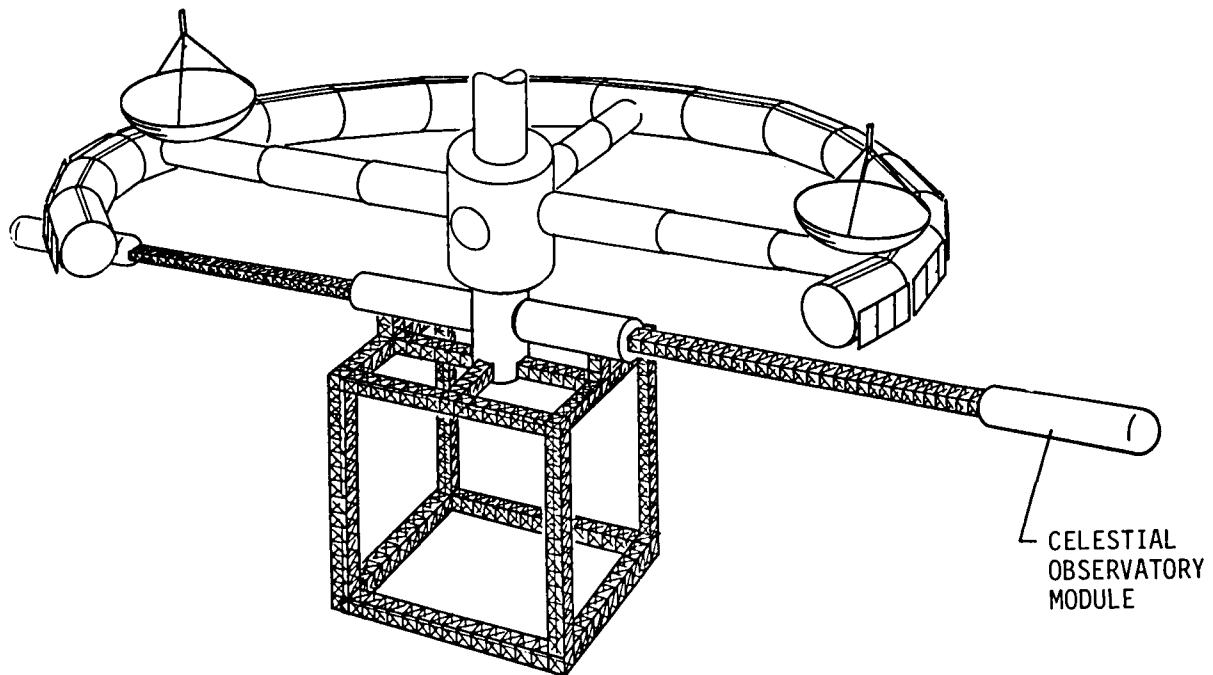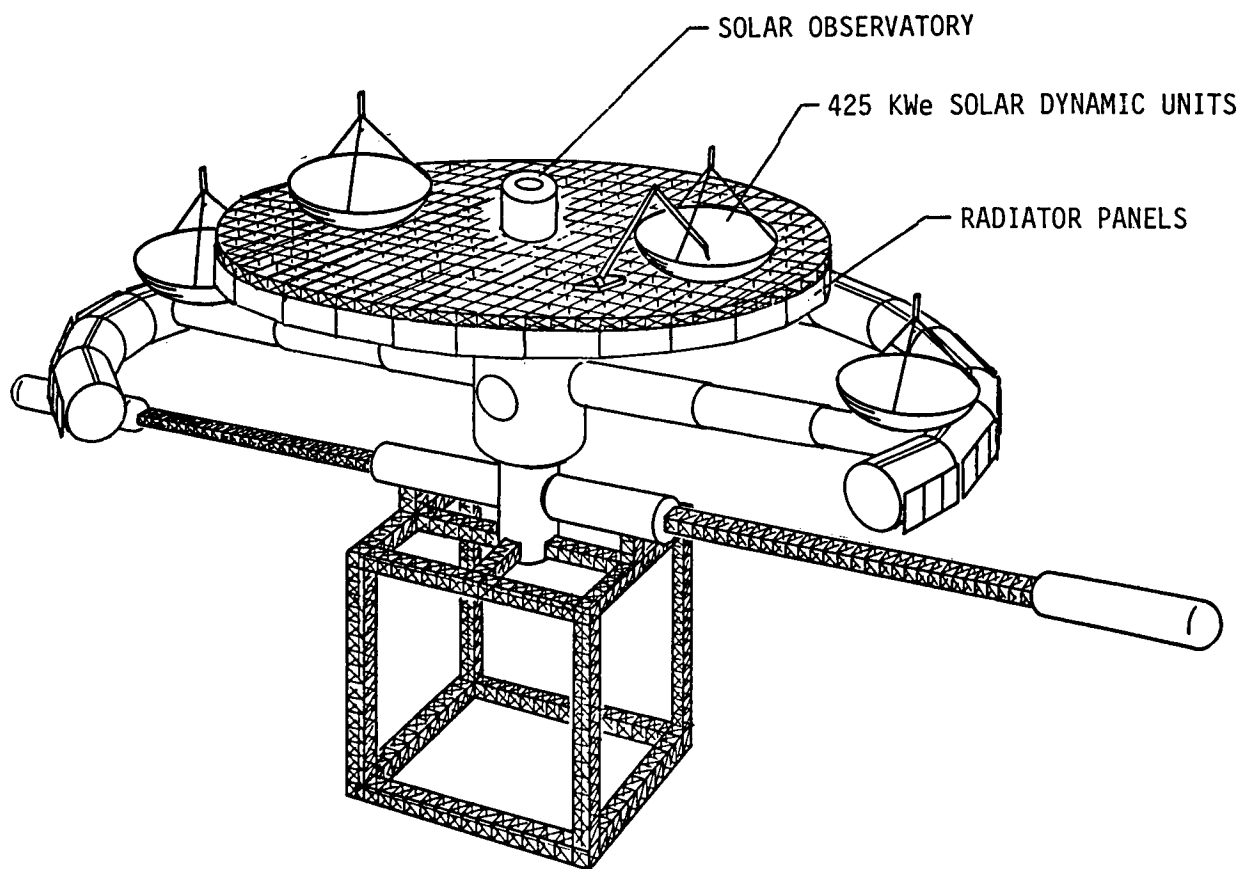Figure 8.4-14 Celestial Observatory Modules Installed at Boom Ends

SOLAR OBSERVATORY

425 KWe SOLAR DYNAMIC UNITS

RADIATOR PANELS

Figure 8.4-15   Four Solar Dynamic Units and Two Solar Observatories Installed

(N)   The two celestial observatory modules will be delivered to orbit completely assembled and ready for plug-in operation at the ends of the observatory module booms.   Mobile remote manipulator systems along with the orbital maneuvering unit will assist in joining the modules to the boom ends (Figure 8.4-14).

(O)   The four 425 kWe solar dynamic power generation units to be assembled atop the platform will be installed using the remote manipulator systems as assembly aids.   Sun shades must be provided during the solar reflector assembly operations to protect equipment and personnel from concentrated solar radiation.

(P)   The solar observatory will be delivered to orbit completely assembled ready for plug-in operation, and be installed at the Sun-pointed end of the central tube (Figure 8.4-15). Atmospheric gases will be transported to the Space Station for initial pressurization of the station to permit a shirt-sleeve working environment.   A complete functional checkout of the Space Station will assure an "all systems go" condition prior to spin-up of the torus.

(Q)   The torus will be rotated to the required revolutions-per-minute to create artificial gravity.   The forces to spin-up the torus will be provided by reaction control jets or magnetic torquing using meridionally-wound coils inside the torus to react against the Earth's magnetic field.

(R) Water will be transported to the Space Station for personal consumption, hygiene, and the electrolysis of water to generate atmospheric oxygen and fuel gases of oxygen and hydrogen.

(S) The assembly crew will prepare the central tube to receive the microgravity facility by transferring the environmental control and life support equipment from the habitat modules to the safe haven. Pressure-seal doors of articulated design will be installed at required locations in the central tube to permit installation of the microgravity facility equipment through the berthing bay door of the central tube. Mechanical installation and connection of utilities will complete the facility.

(T) The assembly crew will have completed their assignment at this time, and will be replaced with the 60-person Space Station crew to assume responsibility for operating the station and conduct research and development activities in space.

8.5 SPACE STATION SIZE AND MASS SUMMARY

The construction features of the Space Station will utilize engineering design concepts of modular structures, telescopic cylinders, erectable truss structure, and truss-structure-supported segmented parabolic mirrors. The modular structures will be fabricated on Earth and delivered on orbit as an assembly of fixed mass and volume. The telescopic cylinders will be delivered telescoped to minimum length, and then extended on orbit for assembly with other components. The erectable

truss structures will be delivered on orbit as bundles of structural elements along with the nodes required for assembly. All of the above structures can be delivered on orbit via the proposed HLLVs of the 2025 time frame.

The dimensions and masses of the Space Station's subassemblies are given in Figures 8.5-1 and 8.5-2. The masses of the subassemblies were derived by making the following assumptions:

o   The modular structures will be fabricated of aluminum alloy and designed so that the maximum allowable stresses will not exceed 2/3 the yield strength of the alloy.

o   The telescopic cylinders will be fabricated of aluminum skin honeycomb sandwich panel construction.

o   The erectable truss structure will be assembled of graphite fiber-reinforced epoxy tubing with aluminum cladding, end attachments, and nodes.

o   The parabolic mirrors will be of segmented low-expansion glass-ceramic composition backed with an erectable truss structure of graphite fiber-reinforced magnesium metal.

The masses of torus, erectable structure, and solar dynamic units were determined by the methods described below.
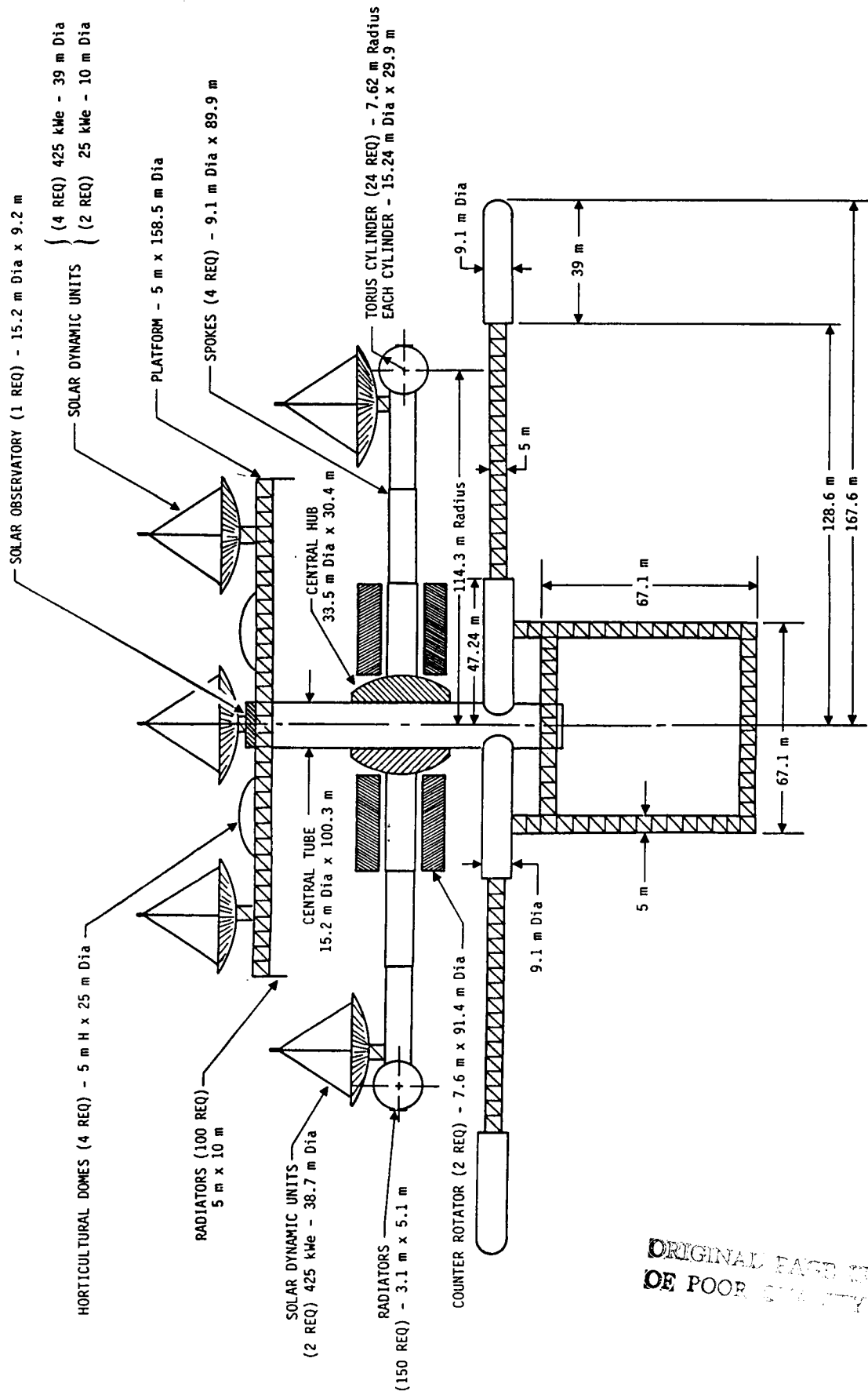
Figure 8.5-1 Space Station Dimensions

SOLAR OBSERVATORY (1 REQ) - 15.2 m Dia x 9.2 m

SOLAR DYNAMIC UNITS { (4 REQ) 425 kWe - 39 m Dia
                     { (2 REQ) 25 kWe - 10 m Dia

PLATFORM - 5 m x 158.5 m Dia

SPOKES (4 REQ) - 9.1 m Dia x 89.9 m

TORUS CYLINDER (24 REQ) - 7.62 m Radius
EACH CYLINDER - 15.24 m Dia x 29.9 m

CENTRAL HUB
33.5 m Dia x 30.4 m

CENTRAL TUBE
15.2 m Dia x 100.3 m

HORTICULTURAL DOMES (4 REQ) - 5 m H x 25 m Dia

RADIATORS (100 REQ)
5 m x 10 m

SOLAR DYNAMIC UNITS
(2 REQ) 425 kWe - 38.7 m Dia

RADIATORS
(150 REQ) - 3.1 m x 5.1 m

COUNTER ROTATOR (2 REQ) - 7.6 m x 91.4 m Dia

9.1 m Dia

39 m

128.6 m

167.6 m

67.1 m

67.1 m

5 m

5 m

9.1 m Dia

114.3 m Radius

47.24 m

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SOLAR OBSERVATORY (1 REQ) - 4.5 x 10⁴ kg

SOLAR DYNAMIC UNITS $\{$ (4 REQ) 425 kWe TOTAL MASS - 1.8 x 10⁵ kg $\}$ (2 REQ) 25 kWe TOTAL MASS - 4.5 x 10³ kg

PLATFORM AND ATTACHMENTS TOTAL MASS - 1.8 x 10⁵ kg

SPOKES (4 REQ) TOTAL MASS - 3.1 x 10⁵ kg

TORUS (24 SECTIONS) TOTAL MASS - 2.27 x 10⁶ kg

CENTRAL HUB - 2.7 x 10⁵ kg

* COUNTERROTATORS (2 REQ) TOTAL MASS - 4.28 x 10⁶ kg

SAFE HAVEN (2 CYLINDERS) TOTAL MASS - 9.1 x 10⁴ kg

BERTHING AREA TOTAL MASS - 4.53 x 10⁴ kg

HORTICULTURAL DOMES (4 REQ) MASS INCLUDED IN PLATFORM

RADIATORS (100 REQ) TOTAL MASS - 1.8 x 10⁴ kg

CENTRAL TUBE 4.5 x 10⁵ kg

SOLAR DYNAMIC UNITS (2 REQ) 425 kWe TOTAL MASS - 9.1 x 10⁴ kg

RADIATORS (150 REQ) TOTAL MASS - 8.5 x 10³ kg

CELESTIAL OBSERVATORY (2 MODULES PLUS BOOMS) TOTAL MASS - 9.1 x 10⁴ kg

* COUNTERROTATORS (ALTERNATE CONCEPT) ARE NOT INCLUDED IN THE ASSEMBLY SEQUENCE OF TABLE 8.6-1

SPACE STATION MASS

MASS WITHOUT COUNTERROTATORS   4.2 x 10⁶ kg

MASS WITH COUNTERROTATORS   8.5 x 10⁶ kg
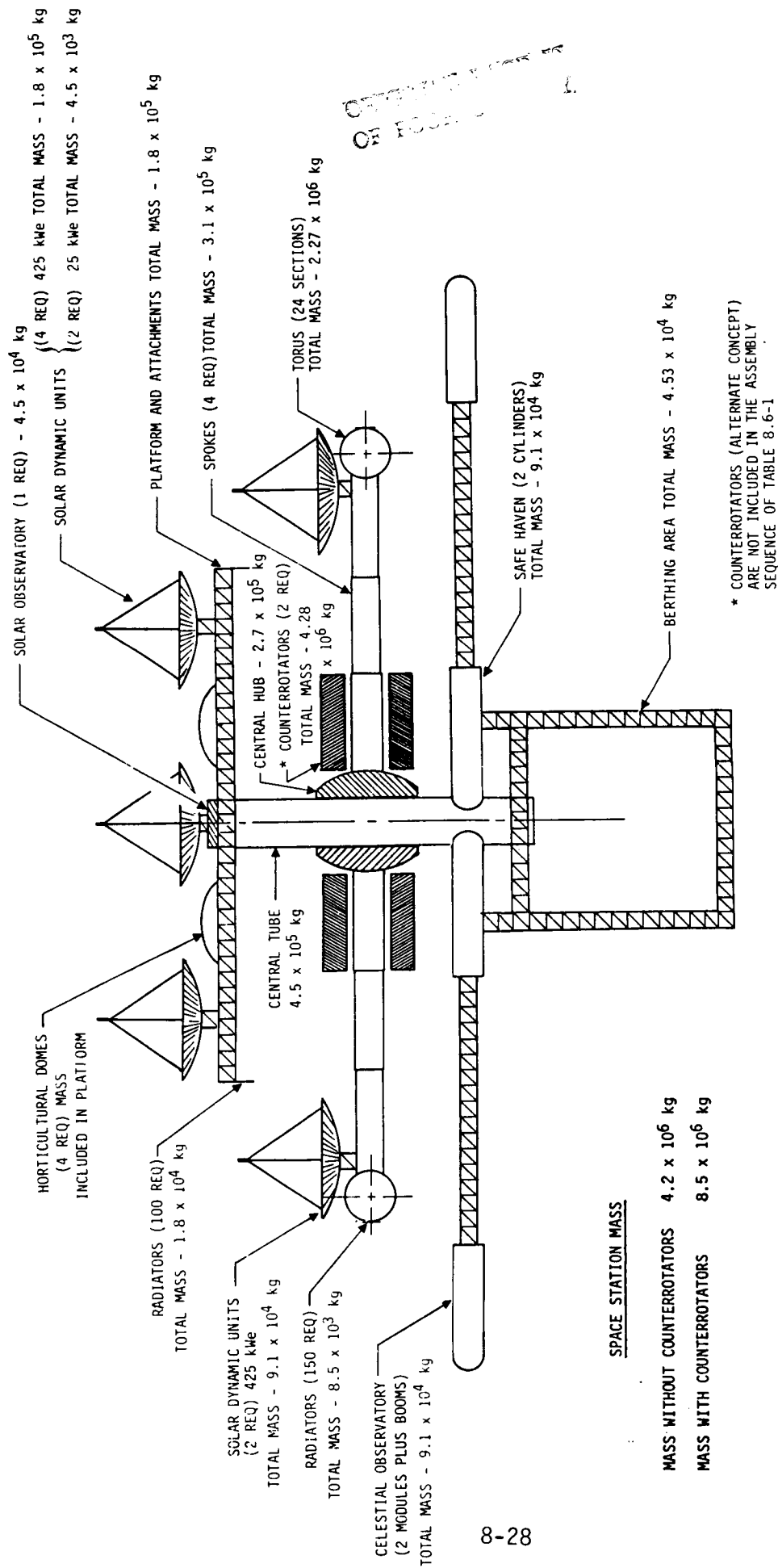
Figure 8.5-2 Space Station Subassembly Masses

8.5.1 TORUS

The torus is assembled on-orbit by joining 24 cylindrical modules.
Each module is designed of stressed skin structure fabricated of aluminum
alloys. The individual modules are 15.24 m (50 ft) in diameter by 29.9 m
(98 ft) long and have internal decking to support people and equipment.
The decks within the modules are curved as cylindrical bands whose axes
coincide with the torus axis of rotation.

The modules must withstand the stresses induced by a one atmosphere
internal pressure, and the pseudogravity forces equivalent to one Earth
gravity acting on the torus and its contents. The following formulas
were used to determine the torus skin thicknesses required in the
meridional and hoop directions, respectively (Reference 8-10).

$$t_m = p_0 r / \sigma_w \qquad\qquad (1)$$

$$t_h = \frac{(p_0/2)(r/R) + (p_g/\pi)}{\sigma_w - \rho R} R \qquad\qquad (2)$$

where
p_0 = atmospheric pressure

p_g = equivalent pressure of pseudogravity

ρ = density of structural material

R = major radius

r = minor radius

σ_w = working stress

The equivalent pressure of pseudogravity is determined as the
equivalent force of one Earth gravity acting on the total mass averaged
over the projected area of the torus. The projected area of the torus as
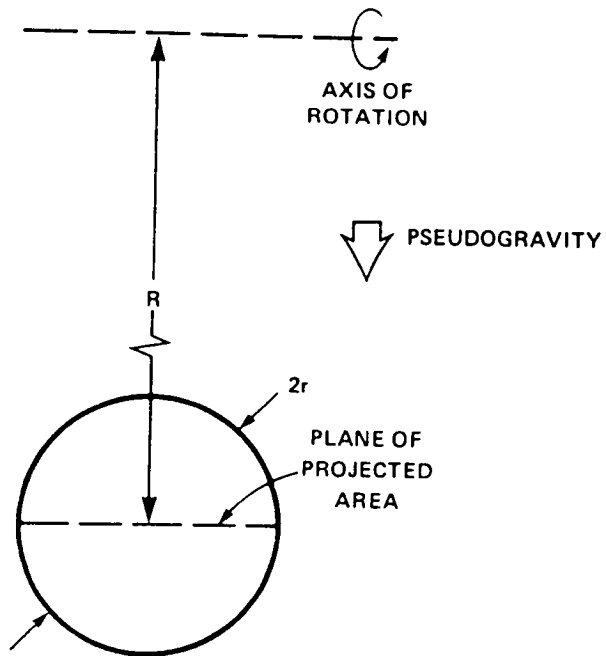defined in Figure 8.5-3 is $A_{pt} = 4\pi rR$.

Figure 8.5-3 Projected Area of Torus

The meridional stress for the torus shell containing one atmosphere internal pressure would dictate a skin thickness of at least 3.8 mm (0.150 in) when solved by formula 1 above. A graph of skin thickness versus pseudogravity is shown in Figure 8.5-4 and was derived using formula 2. The graph indicates that the torus could withstand a pseudogravity force of 1.06×10^4 Pa (221 lb/ft^2) acting on the plane of the projected area. The mass of the torus module shell is based on an average wall thickness of 9.5 mm (0.374 in) and should compensate for the increased skin thickness required at cutouts, bosses, and ribbed areas.

The total mass of the torus was predicted as 2.27×10^6 kg (5×10^6 lb) based on mass predictions for the internal equipment and supporting structures, gas storage facilities, contingencies, and the torus shell with contingency.

8.5.2 ERECTABLE STRUCTURES

The mass of the erectable structure is based on the mass of a repeating bay that forms an orthogonal tetrahedral truss structure having cubic bays 5 m on a side. Each bay is composed of eight longerons, five diagonals, and four nodes as shown in Figure 8.5-5, and the mass per bay is 68.19 kg (150 lb).[1]

8.5.3 SOLAR DYNAMIC UNITS

The mass of the solar dynamic units, which includes the segmented parabolic mirrors and supporting structures, is based on 90.7 kg/kWe (200 lb/kWe) (Reference 8-11).

_____

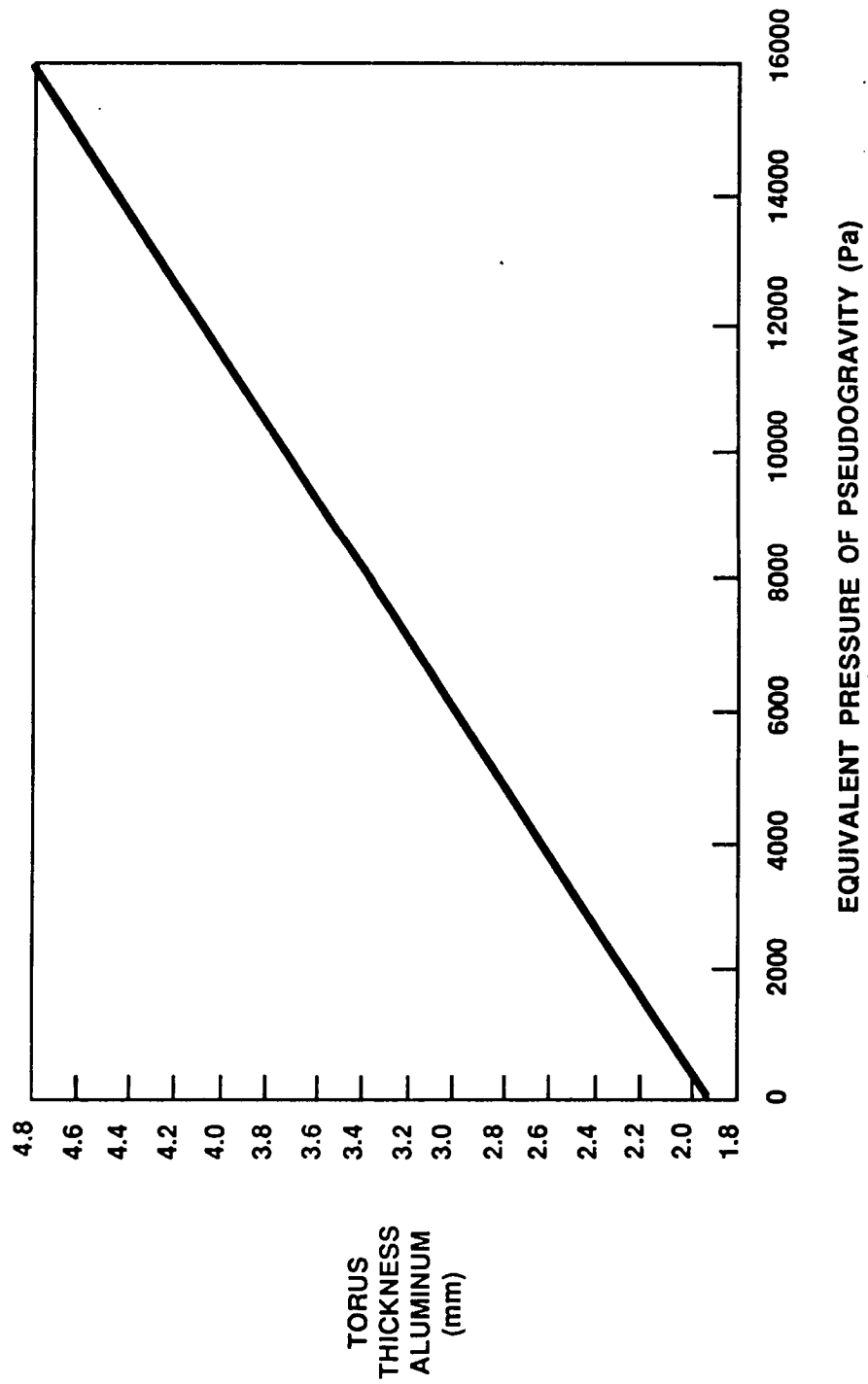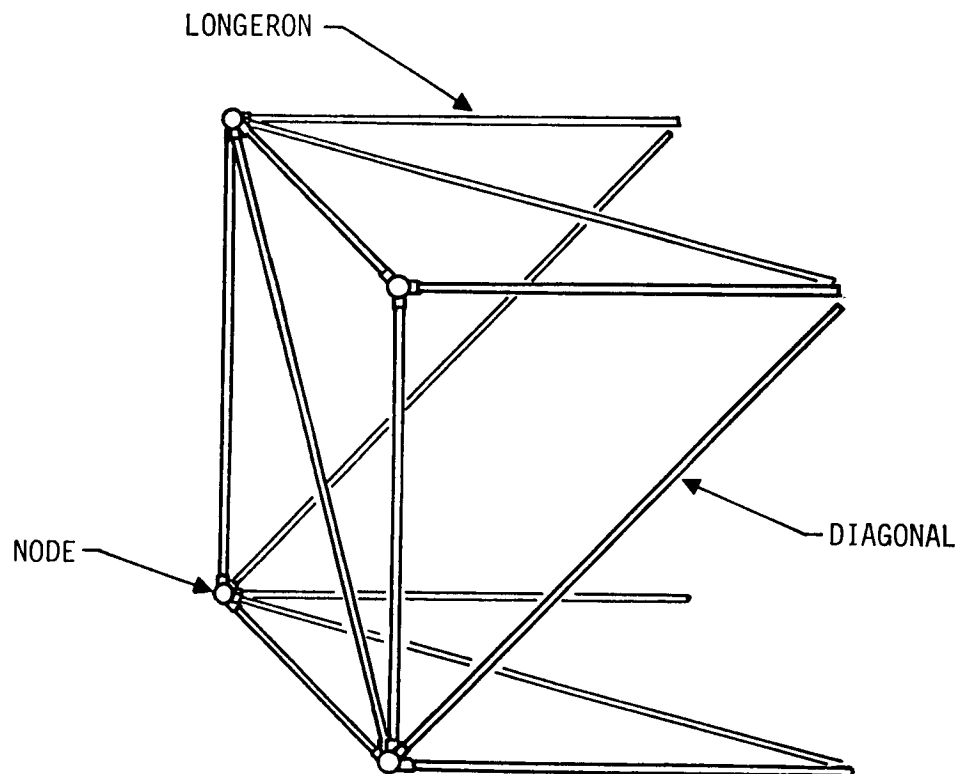[1]Telephone interview with Harold G. Bush, NASA-LaRC, April 28, 1987

Figure 8.5-4 Torus Skin Thickness Versus Pseudogravity

LONGERON

NODE

DIAGONAL

MASS COMPUTATIONS/BAY

8 LONGERONS x 3.67 kg = 29.42 kg (64.9 lb)
5 DIAGONALS x 4.85 kg = 24.26 kg (53.5 lb)
4 NODES   x 3.62 kg = 14.51 kg (32.0 lb)

TOTAL MASS PER REPEATING BAY = 68.19 kg (150.4 lb)

Figure 8.5-5 Orthogonal Tetrahedral Truss Bay. Sides are 5 m (16.4 ft).

8.6 SPACE STATION SEQUENCE OF ASSEMBLY

The sequence of assembly of the Space Station is pictured in graphic form in Table 8.6-1. The number of HLLV launches required for assembly of the Space Station is listed along with payload identification, size, mass, and the cumulative mass properties of the station as sequentially assembled on orbit.

The frontal area of the Space Station can best be determined at each of the station's sequential assembly steps by use of NASA-LaRC IDEAS computer software programs. The partially assembled station will be gravity gradient stabilized and present a uniform frontal area during Earth orbit. The station will become inertially oriented to the Sun after installation of two 25 kWe solar dynamic units, and thereafter present varying frontal areas which relate to the station's orbital location. The frontal area predictions will be used along with the cumulative mass properties for determination of the station's orbital decay characteristics.

A total of 25 HLLVs will be required to place the station's subassemblies in low Earth orbit. The HLLVs will be launched at a rate of approximately one per month. HLLVs payloads will include on-orbit assembly aids such as mobile remote manipulators and a telerobotic truss assembler. The assembly team will be transported to and from the assembly orbit via a 20-passenger shuttle. OMVs will be delivered to orbit aboard the shuttle on two of its early flights. The shuttle schedule of launches will be interspersed with HLLV launches, permitting crew changeover to maintain fitness for the assigned assembly tasks. A total of ten shuttle flights will be required for transporting the Space Station's assembly crews. Three additional shuttle flights will be

TABLE 8.6-1 SPACE STATION SEQUENCE OF ASSEMBLY (Page 1 of 6)
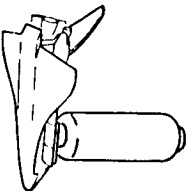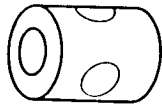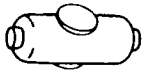
SPACE STATION SEQUENCE OF ASSEMBLY

ASSEMBLY SEQUENCE	HLLV LAUNCHES	SHUTTLE LAUNCHES	PAYLOAD DESCRIPTION	PAYLOAD SIZE AND WEIGHT	CUMULATIVE MASS PROPERTIES	EVA AND ASSEMBLY AID REQUIREMENTS
	1	0	CENTRAL TUBE HABITAT I	15.2 m Dia x 30.5 m (50 ft Dia x 100 ft) 2.27×10^5 kg (5×10^5 lb)	2.27×10^5 kg (5×10^5 lb)	NONE
	0	1	ERECTION AND ASSEMBLY CREW BOARDS HABITAT I ORBITAL MANEUVERING VEHICLE (OMV) DOCKED TO EXTERIOR	20 PEOPLE OMV 9.9×10^3 kg (2.2×10^4 lb)	2.4×10^5 kg (5.2×10^5 lb)	NONE
	1	0	HUB OF CENTRAL TUBE	33.5 m Dia x 30.5 m (110 ft Dia x 100 ft) 2.72×10^5 kg (6×10^5 lb)	5.09×10^5 kg (1.1×10^6 lb)	NONE
	1	0	CENTRAL TUBE HABITAT II	15.2 m Dia x 30.5 m (50 ft Dia x 100 ft) 2.27×10^5 kg (5×10^5 lb)	7.4×10^5 kg (1.6×10^6 lb)	NONE

TABLE 8.6-1 SPACE STATION SEQUENCE OF ASSEMBLY (Continued)(Page 2 of 6)

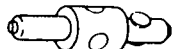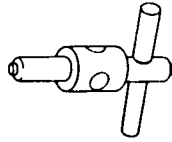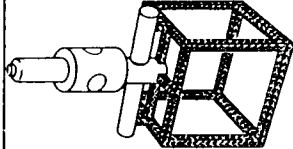## SPACE STATION SEQUENCE OF ASSEMBLY (Continued)

ASSEMBLY SEQUENCE	HLLV LAUNCHES	SHUTTLE LAUNCHES	PAYLOAD DESCRIPTION	PAYLOAD SIZE AND WEIGHT	CUMULATIVE MASS PROPERTIES	EVA AND ASSEMBLY AID REQUIREMENTS
	0	0	CENTRAL TUBE ASSEMBLY OPERATIONS	—	7.4×10^5 kg (1.6×10^6 lb)	LIMITED USE OF EVA FOR INSTALLATION OF FASTENERS EXTENSIVE USE OF OMV TO POSITION HUB AND HABITAT II FOR ASSEMBLY
CREW CHANGEOVER	0	1	ERECTION AND ASSEMBLY TEAM OMV DOCKED TO HABITAT I EXTERIOR	20 PEOPLE OMV 9.9×10^3 kg (2.2×10^4 lb)	7.48×10^5 kg (1.65×10^6 lb)	NONE
	1	0	TWO SAFE HAVEN MODULES	EACH MODULE SIZE 9.1 m Dia x 39.6 m (30 ft Dia x 130 ft) TOTAL WEIGHT OF TWO MODULES 9.1×10^4 kg (2×10^5 lb)	8.39×10^5 kg (1.85×10^6 lb)	EVA/IVA USED TO ASSEMBLE SAFE HAVENS USING OMV AS AN ASSEMBLY AID
	1	0	BERTHING AND ASSEMBLY BAY	TRUSS ELEMENTS FOR BERTHING BAY, OBSERVATORY BOOMS, PLATFORM AND TELEROBOTIC TRUSS ASSEMBLER 9.1 m Dia x 39.6 m (30 ft Dia x 130 ft) 2.27×10^5 kg (5×10^5 lb)	1.07×10^6 kg (2.36×10^6 lb)	EVA/IVA PLUS OMV AND THE TELEROBOTIC TRUSS ASSEMBLER USED TO ERECT THE BAY

TABLE 8.6-1 SPACE STATION SEQUENCE OF ASSEMBLY (Continued)(Page 3 of 6)

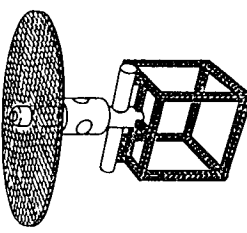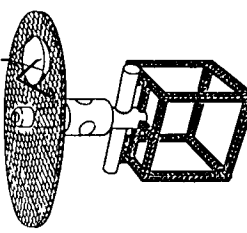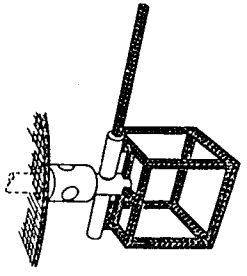## SPACE STATION SEQUENCE OF ASSEMBLY (Continued)

ASSEMBLY SEQUENCE	HLLV LAUNCHES	SHUTTLE LAUNCHES	PAYLOAD DESCRIPTION	PAYLOAD SIZE AND WEIGHT	CUMULATIVE MASS PROPERTIES	EVA AND ASSEMBLY AID REQUIREMENTS
	0	0	PLATFORM ASSEMBLY	—	1.07×10^6 kg (2.36×10^6 lb)	LIMITED EVA WITH EXTENSIVE USE OF TELEROBOTIC TRUSS ASSEMBLER AND OMV's
CREW CHANGEOVER	0	1	ERECTION AND ASSEMBLY TEAM	20 PEOPLE 2.3×10^3 kg (5×10^3 lb)	1.07×10^6 kg (2.36×10^6 lb)	NONE
	1	0	TWO 25 kWe SOLAR DYNAMIC UNITS TWO MOBLE REMOTE MANIPULATOR SYSTEMS (MRMS)	9.1 m Dia x 24.4 m (30 ft Dia x 80 ft) 4.5×10^4 kg (9.9×10^4 lb)	1.11×10^6 kg (2.5×10^6 lb)	LIMITED EVA WITH EXTENSIVE USE OF MRMS's AND OMV's
	0	0	OBSERVATION BOOM ASSEMBLY	—	1.11×10^6 kg (2.5×10^6 lb)	LIMITED EVA WITH EXTENSIVE USE OF TELEROBOTIC TRUSS ASSEMBLER AND OMV

TABLE 8.6-1   SPACE STATION SEQUENCE OF ASSEMBLY (Continued)(Page 4 of 6)

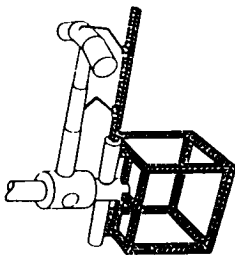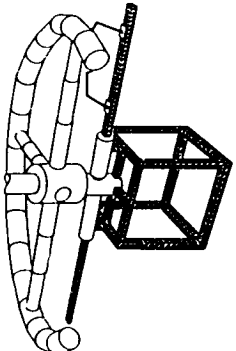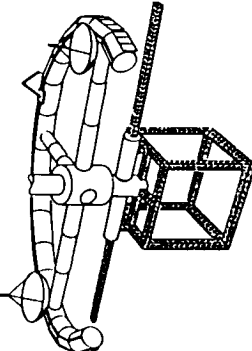## SPACE STATION SEQUENCE OF ASSEMBLY (Continued)

ASSEMBLY SEQUENCE	HLLV LAUNCHES	SHUTTLE LAUNCHES	PAYLOAD DESCRIPTION	PAYLOAD SIZE AND WEIGHT	CUMULATIVE MASS PROPERTIES	EVA AND ASSEMBLY AID REQUIREMENTS
	1	0	TWO TELESCOPIC SPOKES TWO MOBILE REMOTE MANIPULATOR SYSTEMS	9.1 m Dia x 61 m (30 ft Dia x 200 ft) 1.82×10^5 kg (4×10^5 lb)	1.29×10^6 kg (2.85×10^6 lb)	EXTENSIVE EVA/IVA AND MRMS's USED WITH THE OMV's TO MANEUVER THE SPOKES
CREW CHANGEOVER	0	1	ERECTION AND ASSEMBLY TEAM	20 PEOPLE 2.3×10^3 kg (5×10^3 lb)	1.29×10^6 kg (2.85×10^6 lb)	NONE
	1	0	TWO SPOKES AND TWO MRMS's	9.1 m Dia x 61 m (30 ft Dia x 200 ft) 1.82×10^5 kg (4×10^5 lb)	1.47×10^6 kg (3.24×10^6 lb)	EXTENSIVE EVA/IVA AND MRMS's USED WITH THE OMV's TO MANEUVER THE SPOKES AND TORUS SECTIONS FOR ASSEMBLY
	12	0	TWO TORUS SECTIONS PER LAUNCH	15.2 m Dia x 61 m (50 ft Dia x 200 ft) 1.82×10^5 kg (4×10^5 lb)	3.63×10^6 kg (8×10^6 lb)	
CREW CHANGEOVER	0	4	ERECTION AND ASSEMBLY TEAM	20 PEOPLE 2.3×10^3 kg (5×10^3 lb)	3.63×10^6 kg (8×10^6 lb)	NONE
	1	0	RADIATOR PANELS, MOBILE REMOTE MANIPULATOR SYSTEM WITH SUPPORT RAIL SYSTEM AND TWO SOLAR DYNAMIC UNITS	15.2 m Dia x 45.7 m (50 ft Dia x 150 ft) 9.1×10^4 kg (2×10^5 lb)	3.72×10^6 kg (8.2×10^6 lb)	EXTENSIVE EVA/IVA AND MRMS's USED WITH THE OMV's TO MANEUVER THE SOLAR DYNAMIC UNIT SUBASSEMBLIES

TABLE 8.6-1 SPACE STATION SEQUENCE OF ASSEMBLY (Continued)(Page 5 of 6)

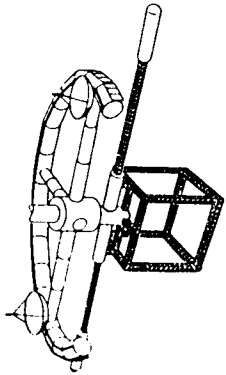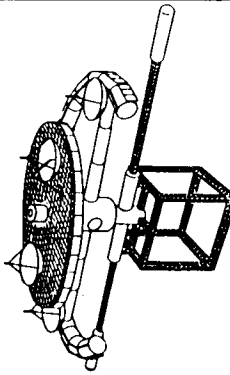## SPACE STATION SEQUENCE OF ASSEMBLY (Continued)

ASSEMBLY SEQUENCE	HLLV LAUNCHES	SHUTTLE LAUNCHES	PAYLOAD DESCRIPTION	PAYLOAD SIZE AND WEIGHT	CUMULATIVE MASS PROPERTIES	EVA AND ASSEMBLY AID REQUIREMENTS
	2	0	CELESTIAL OBSERVATORY INSTALLATION	9.1 m Dia x 42 m (30 ft Dia x 138 ft) 4.5 x 10^4 kg (9.9 x 10^4 lb) PER LAUNCH	3.81 x 10^6 kg (8.4 x 10^6 lb)	LIMITED EVA/IVA USED TO INSTALL OBSERVATORY MODULES USING THE MRMS AND OMV's
CREW CHANGEOVER	0	1	ERECTION AND ASSEMBLY TEAM	20 PEOPLE 2.3 x 10^3 kg (5 x 10^3 lb)	3.81 x 10^6 kg (8.4 x 10^6 lb)	NONE
	1	0	SOLAR OBSERVATORY INSTALLATION FOUR 425 kWe SOLAR DYNAMIC UNITS	15.2 m Dia x 61 m (50 ft Dia x 200 ft) 2.27 x 10^5 kg (5 x 10^5 lb)	4.04 x 10^6 kg (8.9 x 10^6 lb)	LIMITED EVA/IVA TO INSTALL SOLAR OBSERVATORY USING THE OMV. LIMITED EVA USED TO ERECT AND ASSEMBLE THE FOUR SOLAR DYNAMIC UNITS USING THE MRMS's AND THE OMV's
CREW CHANGEOVER	0	1	ERECTION AND ASSEMBLY TEAM	20 PEOPLE 2.3 x 10^3 kg (5 x 10^3 lb)	4.04 x 10^6 kg (8.9 x 10^6 lb)	NONE

TABLE 8.6-1 SPACE STATION SEQUENCE OF ASSEMBLY (Concluded) (Page 6 of 6)

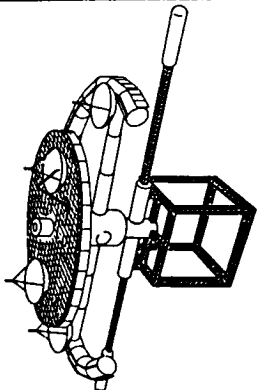## SPACE STATION SEQUENCE OF ASSEMBLY (Concluded)

ASSEMBLY SEQUENCE	HLLV LAUNCHES	SHUTTLE LAUNCHES	PAYLOAD DESCRIPTION	PAYLOAD SIZE AND WEIGHT	CUMULATIVE MASS PROPERTIES	EVA AND ASSEMBLY AID REQUIREMENTS
	1	0	MICRO "G" FACILITY	15.2 m Dia x 61 m (50 ft Dia x 200 ft) 2.27 x 10^5 kg (5 x 10^5 lb)	4.27 x 10^6 kg (9.4 x 10^6 lb)	LIMITED EVA WITH EXTENSIVE IVA TO INSTALL MICRO "G" FACILITY AND TRANSFER LIFE SUPPORT EQUIPMENT AND FUEL CELLS TO SAFE HAVEN
CREW CHANGEOVER	0	3	ERECTION AND ASSEMBLY CREW ACTIVITIES COMPLETE 60 PERSON OPERATIONS CREW TAKE OVER SPACE STATION RESPONSIBILITIES	20 PEOPLE 2.3 x 10^3 kg (5 x 10^3 lb) PER LAUNCH	4.27 x 10^6 kg (9.4 x 10^6 lb)	NONE
TOTAL LAUNCHES	25	13	—	—	—	—

required to change over from the assembly crew to the operations crew of 60 people. The overall Space Station assembly time span is projected as 30 months.

References

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8-9   Pioneering the Space Frontier. The Report of the National Commission on Space, Bantam Books, May 1986.

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9.0 SPECIAL CONSIDERATIONS

9.1 SYNERGIES RELATED TO THE INTERNAL CONFIGURATION

The descriptions of the internal configuration that responded to the functions identified for the 2025 Space Station have also identified potentials for synergistic interactions within the total system. The description of configurations, as they responded to operations, addressed the opportunities in conjunction with the mode or type of utilization and identified four major areas for synergy. These are summarized in Table 9.1-1. The principal areas are:

A. Synergies related to electrical power load leveling. The use of solar dynamic power generation techniques anticipates a need to tailor the load to the power generation system such that the generators operate close to their optimum power profile (e.g., a molten-salt-phase change collector may need to operate at a continuous power setting), and means for load matching to power output are identified.

B. Synergies related to the need for control of inertias and center of gravity locations. The combination of concentric rotating and non-rotating sections, plus the needs for reboost and continuing solar orientation, anticipates the need for a continuous control to maintain the necessary inertial relationships and parameters. The need to maintain coincidence for the center of gravity for both rotating and non-rotating sections is a potential requirement. The center of rotation

TABLE 9.1-1 POTENTIAL SYNERGIES IDENTIFIED FOR THE 2025 SPACE STATION RELATED TO THE INTERNAL CONFIGURATION

A. ELECTRICAL POWER LOAD LEVELING OR LOAD MATCHING (APPLICATION OR SCHEDULING OF POWER)

1. Excess power diverted to the electrolysis of water.

2. Excess power directed to compression of gasses for liquification or high pressure storage.

3. Power scheduling to accommodate mass transfer from non-rotating to rotating section and operation of the elevators.

4. Power scheduled or excess power directed to transfer of water into the torus, along with electromagnetic torquing to build up inertia in response to a transfer requirement.

5. Schedule for wet air oxidation operation.

6. Schedule for gas transfer operations.

7. Schedule for CO_2 reduction.

8. Balance the usage of electrical power and chemical power for solar-facing precessions.

9. Schedule for the on-board fabrication operations.

B. SYNERGIES FOR THE UTILIZATION OF WATER BY SCHEDULE OR FLOW SEQUENCE

1. Center of gravity control during berthing and deployment, by transfer of water ballasts.

2. Movement of water into rotating sections during materials transfer.

3. Utilization of water for inertial null by the counterrotators.

4. Water transfer to the torus during elevator operations.

5. Water transfer for trim balance of rotating section in response to torus movements.

6. Fresh water utilization for drinking and food preparation then reclaimed by wet air oxidation.

7. Reclaimed water utilized for flush, clothes wash, and housekeeping and then recycled.

8. Reclaimed water utilized for balance trim.

9. Reclaimed water feed to electrolysis for O_2, H_2 generation.

TABLE 9.1-1 POTENTIAL SYNERGIES IDENTIFIED FOR THE
2025 SPACE STATION RELATED TO THE INTERNAL CONFIGURATION (concl.)

C. SYNERGIES PRESENTED BY ON-BOARD GENERATED GASSES

   1. Cabin air as ullage gas for O_2.

   2. N_2 and CO_2 as ullage gasses for H_2.

   3. O_2, H_2 utilization as needed.

   4. O_2, CO_2, N_2 as atmosphere constituents for horticultural
       research.

D. SYNERGIES PRESENTED BY STRUCTURE AND CONSTRUCTION

   1. Assembly manipulators become berthing-bay units.

   2. EVA spider crane initially supports construction and assembly.

   3. Observation tube and berthing-bay tubes serve as air reservoirs
       for central tube air lock operations.

and dynamic balance requirements for the rotational portions of the station need allowances for small deflections. The rotational inertia of the torus must be controlled and presents the only opportunity for modification by means of convenient external forces (e.g., magnetic interactions or chemically powered thrust).

C. Synergies related to the use of on-board generated gasses. The need to generate O_2 for cabin air replenishment, and H_2 to reduce CO_2, have been well established. The availability of both N_2 and CO_2 from the output of super-critical wet air oxidation adds potential elements for additional utilization.

D. Synergies Related to Structure and Construction. The assembly of the large Space Station elements in orbit generates the precision and force requirements for cranes and manipulators, plus the maneuvering capabilities for the orbital transfer vehicle. These same requirements apply to the assembly of co-orbiting platforms and large space probes; therefore, the equipment items used to assemble the Space Station will continue in operation. The rigid structure required for the berthing bay and the observation tube, coupled with the need for compartmentalized internal pressurization, result in a strength margin which permits short-term usage for gas storage at higher pressure. Other areas of structure-related mutual benefit will exist throughout the Space Station as the result of material selections coupled with specific configurations. Typical

examples would be the use of metal-faced walls for local electromagnetic shielding, and the use of structural tubes or box beams for ventilation or fluid passages.

9.2 SPACECRAFT CHARGING

Spacecraft charging is a function of the electric current flow to and from the plasma environment around the vehicle. The density and energy of the charged particles constituting the plasma environment vary with altitude, day and night, magnetic field, and solar wind. This magnetospheric plasma and its effect on spacecraft are described in References 9-1 to 9-10. Much of the literature is devoted to geosynchronous altitude effects because potentially harmful high energy plasma (on the order of 1 to 10 particles per cm^3 at temperatures of 1 to 50 KEV) can exist during a geomagnetic substorm (Reference 9-1). Figure 9.2-1 from this reference shows charging current density and electron and proton temperature occurrence as a percentage of time for which they exist. Charging at synchronous orbit altitudes can cause a spacecraft to reach high potentials relative to the surrounding plasma. This charge may result in increased surface contamination and degradation of thermal properties. The charge buildup may also influence scientific measurements of the spacecraft environment. If portions of the spacecraft are electrically isolated, differential charging may result in an electrostatic discharge. This discharge can cause electromagnetic interference (EMI) or failure of on-board electronics, as well as degradation of the properties of dielectric or optical surfaces. The interaction of electrostatic discharge current flow with the prevailing magnetic field may produce undesired spacecraft torquing. Reference 9-1
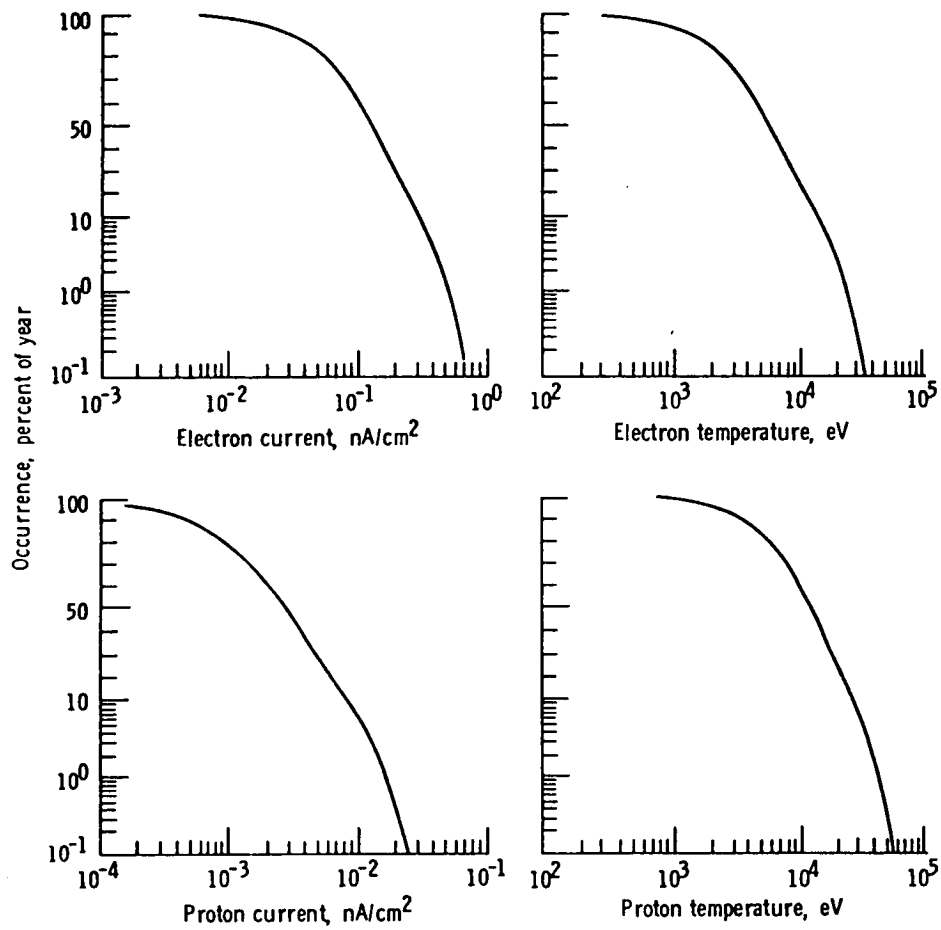
Figure 9.2-1 Geosynchronous Charging Current Density and Temperature as a
Percent of Occurrence Time (Reference 9-1)

provides design guidelines for assessing and controlling spacecraft charging effects at geosynchronous orbit.

For a low Earth orbit Space Station, the plasma densities are in the range of 10^6 times higher than those for a geosynchronous spacecraft. Reference 9-2 provides mathematical models of this region, and Figure 9.2-2 reproduces figures from this reference for some averaged profiles for altitudes up to 1000 km. Spacecraft charging at low Earth orbit can only reach a few volts due to the energy distribution and density of the plasma at these altitudes. Higher charging levels have been reported for special cases. Reference 9-3 reports spacecraft charging to above 100 volts negative potential for an 840 km altitude spacecraft in a locally depleted thermal plasma polar region for an intense energetic electron precipitation event during darkness.

The environment that limits charging at low Earth orbit may also be the cause of unwanted leakage currents that can occur at uninsulated high voltage terminals on the spacecraft. The 2025 Space Station point design for 2.5 MW continuous power level implies high voltage power handling. Solar dynamic, nuclear, or other power systems which generate power with rotating machinery will be designed to avoid breakdown during generation and transmission. Solar arrays, if used for high power generation, will present interesting design considerations because of the large area, high voltage panels exposed to space plasma. Some of these design considerations are discussed in Reference 9-4.

In summary, spacecraft charging is not expected to pose undue design constraints on a Space Station operating in non-polar low Earth orbit, although good design practice will consider grounding, EMI protection, high voltage protection, and preservation of surface thermal properties.
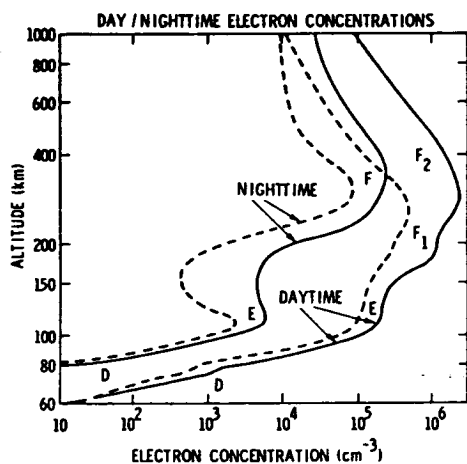
Typical midlatitude daytime and nighttime electron profiles for sunspot maximum (——) and minimum (— — —).
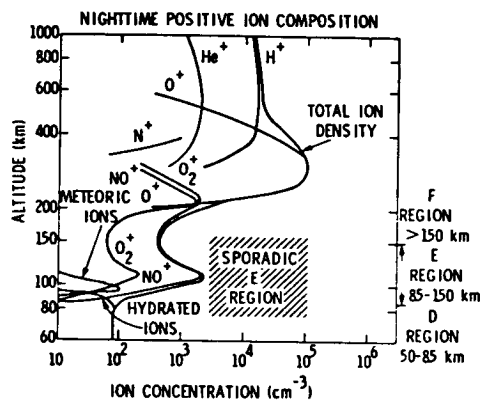
Typical ion profiles of the nighttime, midlatitude ionosphere at sunspot minimum.
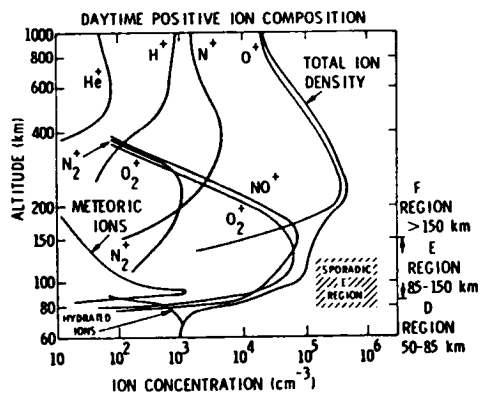
Typical ion profiles of the midday, midlatitude ionosphere at sunspot minimum.
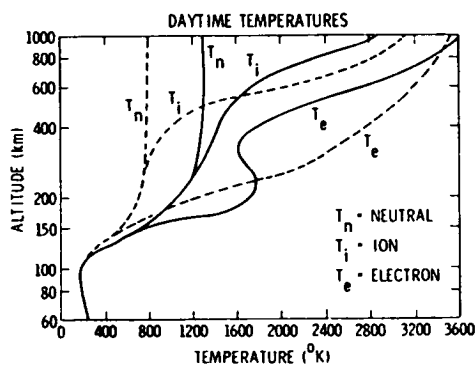
Typical neutral, ion, and electron daytime temperature profiles at equinox for a midlatitude ionosphere at sunspot maximum (——) and minimum (— — —).

Figure 9.2-2   60 to 1000 km Altitude Averaged Electron and Ion Profiles (Reference 9-2)

9.3 TETHERS

Tethers have been proposed for a variety of space applications because they provide a method of interchange of kinetic energy through angular momentum exchange. The energy may take the form of orbital rotation about the Earth, or of spacecraft-tether rotation about the system center of mass. After any reconfiguration, the laws of conservation of momentum and energy may be applied to determine the new state.

The Presidential Space Commission (Reference 9-11) recommends that "Tether demonstrations be carried out in space both on shuttle missions and as an integral part of the initial Space Station research program." Of interest to the Space Station configuration of this report are applications that can be applied to a relatively massive, Sun-oriented, low Earth orbit station with both rotating and non-rotating members.

The rotating spacecraft will require an attachment method that deploys tethers to or away from the nadir without entanglement. Several variations, all using the non-rotating observation tube as a pivot, are shown in Figure 9.3-1. The first two are impractical in that there will be a tendency to rotate the observation tube during portions of the orbit. The latter two, using a yoke arrangement, will allow torque to be applied selectively. The upper illustration of Figure 9.3-1 indicates how a torque can be applied during a portion of the orbit to provide the yearly precessional rate needed to track the Sun.

Table 9.3-1 lists tether applications from the current literature (References 9-11 to 9-17) that might be applicable to the 2025 Space Station, some more so than others. However, the rotating spacecraft will add complexity for tether applications that may limit their use

SUN FACING
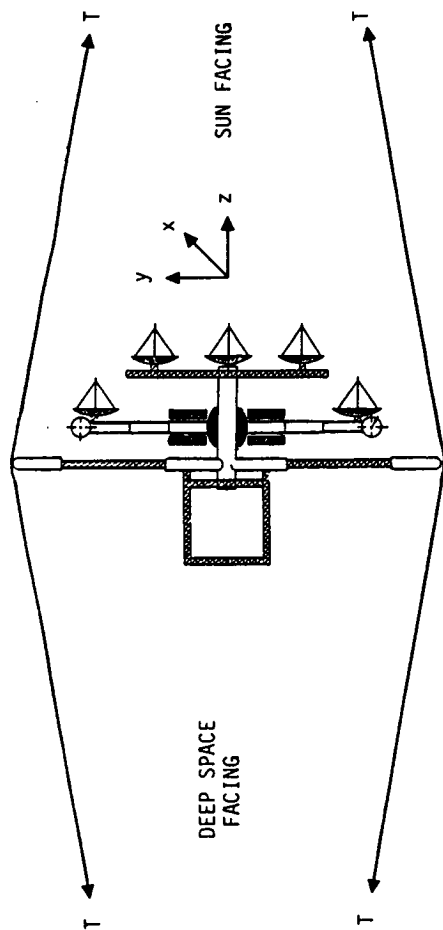
DEEP SPACE
FACING

WHEN SUN OR DEEP SPACE END OF SPACE STATION FACES EARTH,
MAXIMUM TORQUE ABOUT SPACE STATION x-AXIS TO PRODUCE
PRECESSION ABOUT y-AXIS

ALLOW SLACK IN LINE
TO PROVIDE TORQUE

AWAY FROM EARTH

SLACK LINE

SLACK LINE

TOWARD EARTH

TOWARD OR AWAY FROM EARTH

AWAY FROM EARTH

TOWARD EARTH

TETHER MASS

TOWARD OR AWAY FROM EARTH
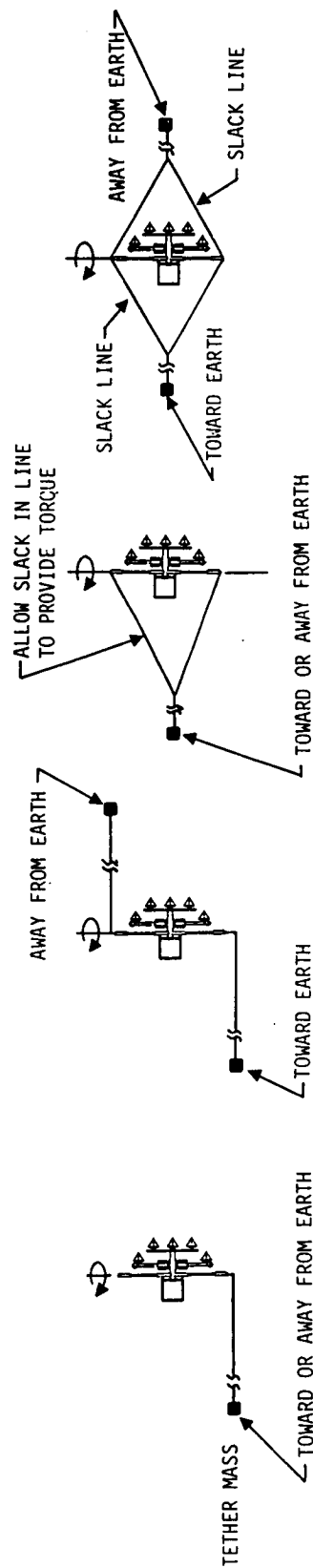
VARIOUS TETHER SWIVEL ATTACHMENTS TO OBSERVATION TUBE

Figure 9.3-1 Space Station/STS Tether Application

TABLE 9.3-1   TETHER APPLICATIONS FOR SPACE STATION

PROPULSION AND TORQUING

Reboost by lowering or deorbiting other mass.

Payload to higher orbit by lowering orbit of Space Station.

Torque for precession.

ELECTRODYNAMICS

Power generation or storage.

Thrust for orbit maintenance or maneuvering.

CONTROLLED GRAVITY

Variable-g experiments.

Fuel or liquid handling.

ISOLATION

Rocket fuel storage isolation.

Nuclear power isolation.

Docking.

Out-gassing and rocket exhaust isolation.

VLF ANTENNAS

LOWER ALTITUDE ACCESS

Atmospheric motions and composition.

Electron density and ion composition.

Fluid dynamics: Open wind tunnel for low
Reynolds number and large Mach number.

Magnetic or gravity field mapping.

Remote sensing and mapping.

beyond those applications that are found feasible for an inertial or gravity gradient satellite. These references also indicate that a number of factors require attention to apply tethers successfully, and some of these concerns are listed in Table 9.3-2.

TABLE 9.3-2   POTENTIAL TETHER PROBLEMS

DEPLOYMENT AND RETRIEVAL

Wrap-around.

Tangles.

Maneuvering to site.

Deployment and retrieval time.

Braking.

DYNAMICS

In-plane and out-of-plane librations.

Longitudinal and traverse oscillations.

Endmass attitude control.

Recoil at release or sever.

SEVERING OF TETHER

Micrometeorites and space debris.

Rendezvous vehicles.

Dynamic loads exceeding safety factor.

CHARGE BUILD-UP

Voltage breakdown.

Corona and EMI.

References

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Aerothermodynamic Research Facility, AIAA Atmospheric Flight Mechanics Conference and Guidance, Navigation and Control Conference, August 1985/Snowmass, Colorado.

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10.0 PACING TECHNOLOGIES

The Advanced Technology Space Station will require the advancement of existing technologies and development of new technologies to facilitate manufacture, delivery to orbit, assembly, and continuous space operation of the station. Artificial gravity considerations, the fabrication of structures in space using telerobotics, and new technology requirements based on the operational aspects of the station are reviewed.

10.1 ARTIFICIAL GRAVITY CONSIDERATIONS

Weightlessness brings about grave degradation to the musculoskeletal system. The end point in loss of bone density, muscle mass, and strength with time of exposure to weightlessness has not been reached and is not known. However, for any fixed amount of artificial gravity, there is probably a stabilization point in bone mineral loss and bone density reduction. Artificial gravity is the primary way to supply "weight" to the human musculoskeletal system in space. The amount of artificial "weight" needed to adequately maintain this system is not known. Fundamentally, the equivalent of Earth weight should suffice, and the Space Station proposed herein has that capability. However, lesser values of artificial weight would allow reductions in rate of rotation and, therefore, reduce the rotational energy that must be attained and dealt with in the operation of the Space Station. The variation of bone density reduction with artificial gravity level probably is not linear, given the grave effects of zero weight.

Laboratory experiments which could later be checked in the 2025 Space Station are desirable. Bedrest studies with beds tilted through

appropriate angles, supplemented with time on an inclined plane sling suspension system with the same tilt angles, should bring enlightenment to this problem.

10.2 STRUCTURE FABRICATION IN SPACE

The Advanced Technology Space Station is envisioned as being manufactured on Earth, assembled, functionally checked out, disassembled, and delivered to low Earth orbit via HLLV. The Space Station would be reassembled on orbit using orbital maneuvering vehicles, mobile remote manipulator systems, and a telerobotic truss assembler. The extravehicular activity requirements placed on the astronauts would be kept to a minimum by the use of telerobotic machines to perform the Space Station assembly and checkout operations in space.

The design of the Space Station embodies expandable and modular structural concepts. The expandable structural concept offers the advantage of high packaging density of the payload for the available HLLV payload envelope size. The structures are increased in size after delivery to orbit. Two examples of expandable structures considered in the design of the Space Station are the cylindrical telescopic spokes and the erectable truss structure.

o   The cylindrical spokes of the torus are 9.1 m (30 ft) in diameter by 89.9 m (295 ft) in length when assembled with the torus on orbit. The structure of the spoke would be designed to telescope to a cylinder having an overall length of 30 m (98.4 ft) and thereby permit two torus spokes to be launched via one HLLV launch. The spokes would be extended on orbit to

form rigid spokes with metal-to-metal contact structural joints. The gas-tight seals of the joints would permit pressurization of the extended spokes to create an internal shirt-sleeve working environment.

o   The truss structure would be erected on orbit using a telerobotic truss assembler to join the truss elements at nodes. The assembled orthogonal tetrahedral truss structure would be formed of repeating cubic bays 5 m (16.4 ft) on a side. The Space Station truss structures planned for erection on orbit are the berthing area, celestial observatory booms, and the platform. An intravehicular activity (IVA) tubing 2.9 m (9.5 ft) in diameter would be telescoped for launch packaging requirements and extended on orbit to be positioned inside the truss structure at assembly. The IVA tubing would have gas-tight seals at the structural joints and provide interconnecting passageways from the berthing and erection bay nodes to the safe havens and central tube, and from the safe havens to the celestial observatories.

The modular structural concept for the Space Station assembly would utilize pretested components and subsystems having fixed volume and mass for delivery to orbit. The habitat I, solar observatory, and two celestial observatories are examples of the modular structural concept considered in the Space Station design.

o   The first module delivered to orbit will serve as habitat I for

the erection and assembly crew. The module would be completely outfitted for immediate occupancy of the crew. The Skylab orbital workshop was an example of this concept and is shown in Figure 10.2-1 (Reference 10-1). The module will serve as a temporary habitat until the Space Station is assembled and operating. The crew will then occupy habitats located in the torus, and the habitat I module's interior will be modified to receive a microgravity facility.

o   The celestial observatory will be completely assembled as delivered to orbit, and require attachment to the observatory truss boom with connections to the Space Station's utilities. The two celestial observatories and the solar observatory will each use this module plug-in concept to minimize on orbit assembly efforts.

The assembly of the Space Station torus on orbit will use mobile remote manipulator systems, orbital maneuvering vehicles, and EVA as required to mechanically join the cylindrical torus modules with the spokes and central hub. Redundant gas-tight seals will be positioned at each mechanical joint. Examples of telescopic cylindrical structure are shown in Figure 10.2-2 (Reference 10-2) and Figure 10.2-3 (Reference 10-3). The Space Station assembly process will benefit by dividing the spacecraft into zones using airlocks so that, as each zone is assembled, it can be pressurized with atmospheric gases. The erection and assembly team can perform many assembly operations in a shirt-sleeve environment, and they can evacuate an unsafe area under emergency conditions without having to wear a pressure suit.
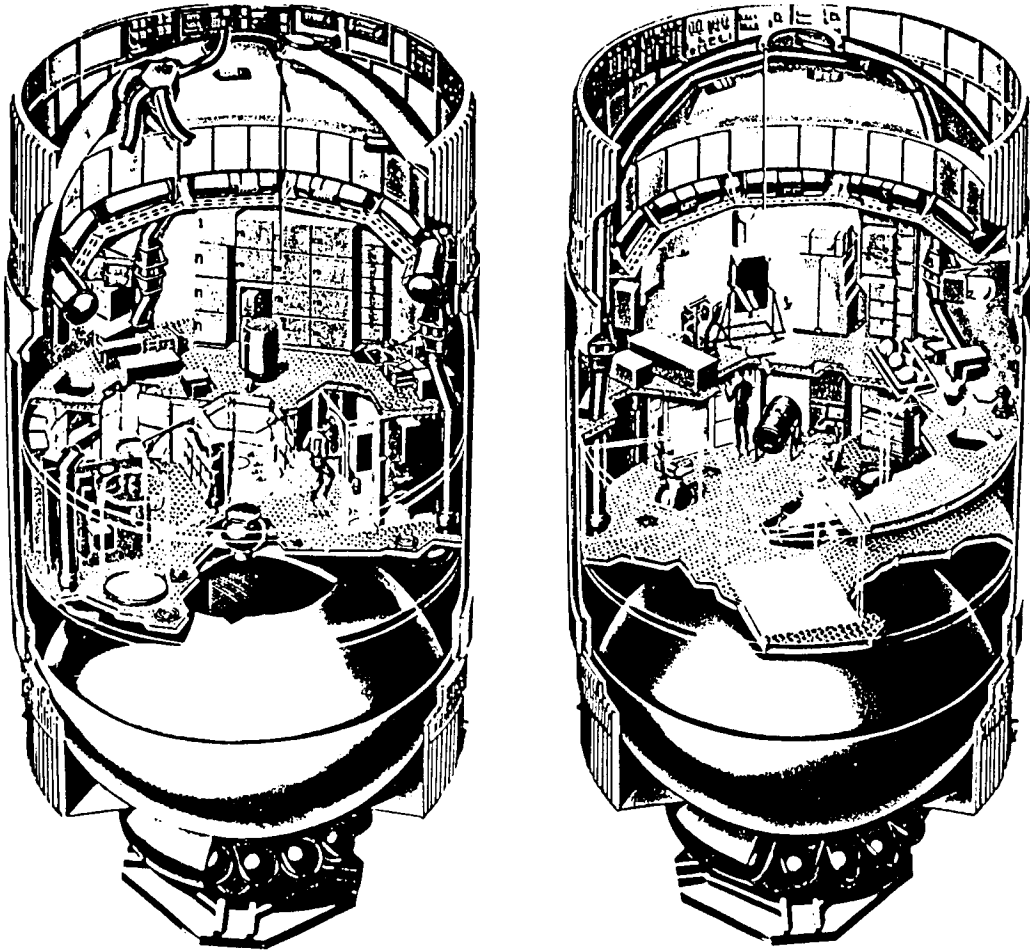
Figure 10.2-1   Skylab Orbital Workshop, Dimensions are 6.7 m (30 ft)
in Diameter by 14.6 m (48 ft) Long (Reference 10-1)

EXTENSION STOP LENGTH ADJUSTMENT NUT

EXTENSION STOP JAM RING

TEFLON LIP SEAL RING

TEFLON BUSHING RING (NO SEAL)

$\mathcal{C}$-TUBES
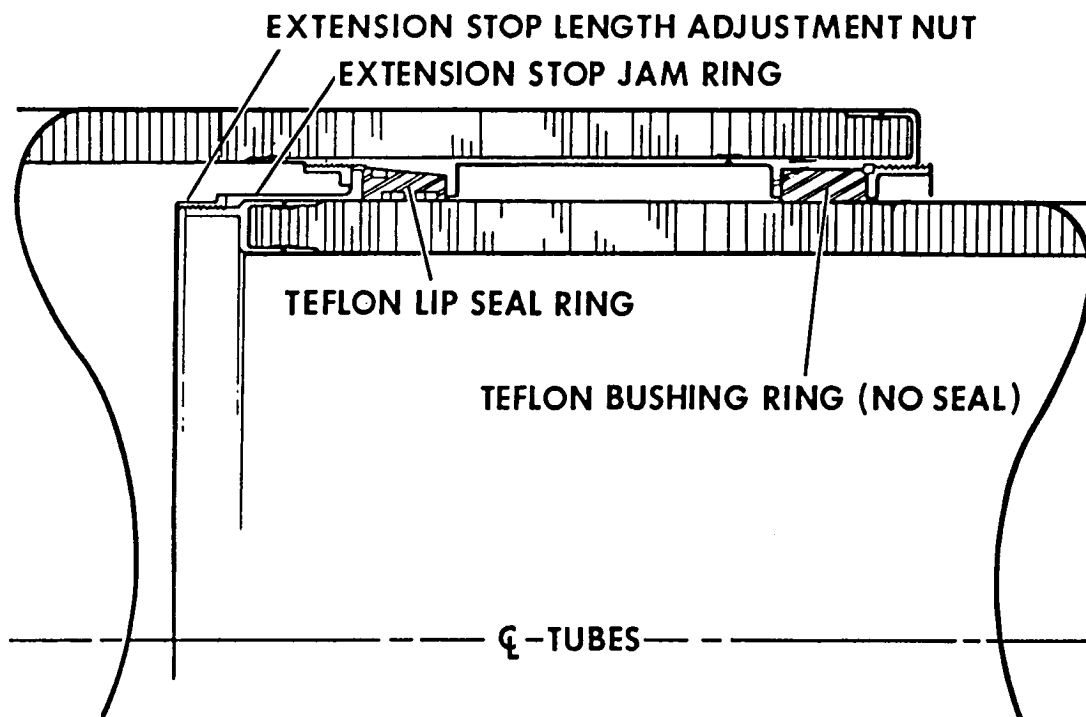
Figure 10.2-2 Telescoping Spoke Joint (Reference 10-2)

HONEYCOMB CYLINDER

GUIDE ROLLER

COLLAPSED BELLOWS

BELLEVILLE SPRINGS
TRANSMIT BENDING LOADS

SPACER RING

CYLINDERS EXTENDED

STEEL BELLOWS
RESISTANCE SEAM WELDED

CYLINDERS RETRACTED

STEEL HELICAL BELLOWS
ALTERNATING EDGE WOUND SPRINGS

EXTENDED   RETRACTED

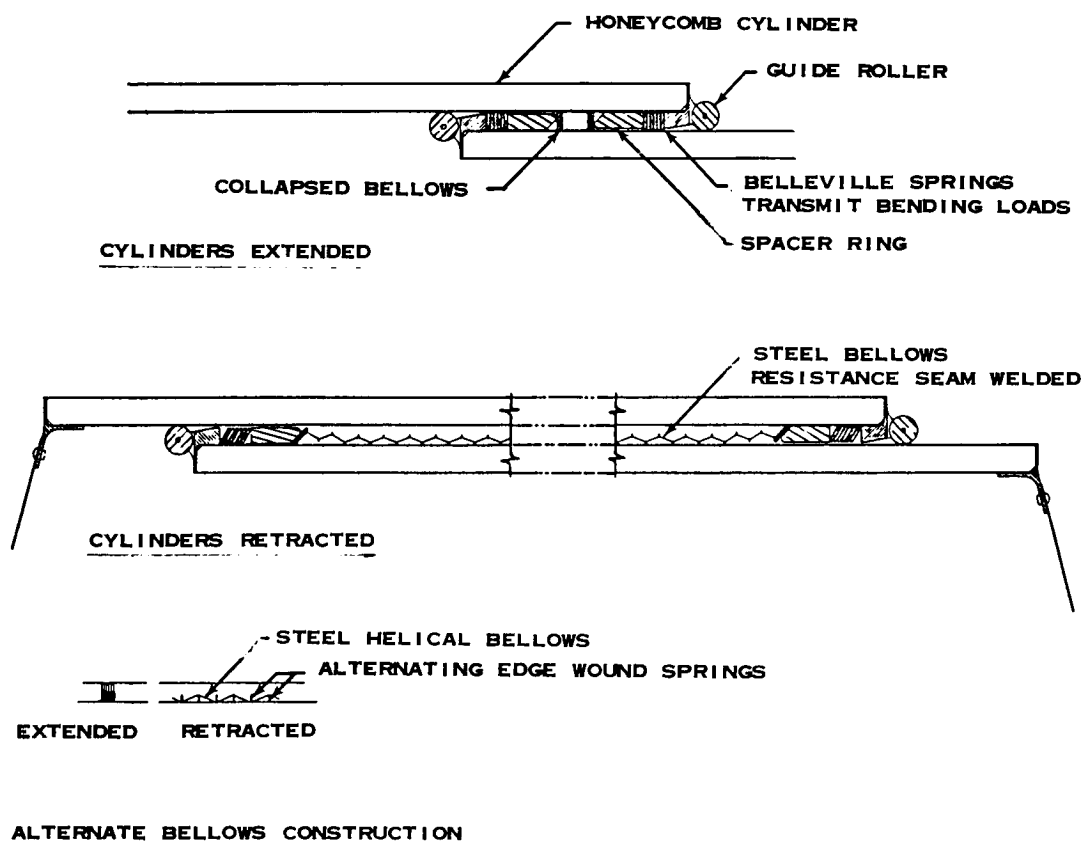ALTERNATE BELLOWS CONSTRUCTION

Figure 10.2-3   Telescopic Design Concept Utilizing Belleville Springs and Bellows
(Reference 10-3)

The habitat modules I and II and the safe haven modules will be "scarred" with built in hardware to accommodate increased capacity when required during the Space Station assembly phases. This concept will facilitate the moving of the environmental control and life support system from the habitat I module to the safe haven when the station becomes operational.

The fully operational Space Station will be an assemblage of mechanically joined modules, components, and truss structures. The mechanical joints provide for disassembly in the event of equipment failure or localized structural damage, and for changeout of components for upgrading a system's capabilities. Limited repair capability will be provided by the Space Station's operations crew using the on-board manufacturing and fabrication facility.

10.3 OPERATIONAL ASPECTS

The requirements for a rotation-induced gravitational field underscore the need for inertia control. A rotating system in a solar-facing orbit identifies the need for precision pointing in terms of precession torques. Rotation in the magnetic field of the Earth makes an attractive case for the synergy of electromagnetic coupling. The technologies involved become:

o   Develop techniques for reducing the rotational inertia of the Space Station by means of structure or innovative configurations.

o   Develop techniques for precise control of rotational dynamic

effects in terms of dynamic balance trim and velocity trim.

o   Develop a rotating joint and drive technique that can accommodate a degree of center shift and overcome the friction of the joint's bearings and the atmospheric seals.

o   Develop methods for electromagnetic coupling to provide velocity trim and precessional torques. In these applications, the need for large currents moving around the periphery of the rotating member makes the development of superconductors most attractive.

o   The development of high efficiency chemical thrusters for reboost and attitude control remains a priority.

10.4 TECHNOLOGY ASPECTS OF THE INTERNAL CONFIGURATION

An internal configuration which can perform the 17 functions identified for the 2025 Space Station requires a roster of equipment or capabilities which do not presently exist in a space-viable form. The areas identified become:

o   Mass-efficient structure for large pressure vessels.

o   Mass-efficient structure for internal accommodations.

o   Mass-efficient equipment of general industrial nature, such as motors, pumps, compressors, fabrication tools, hydraulic

cylinders, tankage, and the items for food preparation and laundry.

o   Multi-use mass-efficient medical equipment for diagnostic and laboratory purposes, plus the items necessary for crew physical conditioning.

o   Large-diameter gas seals for joints that can have motions ranging from steady state to cyclic, with reversals of direction and extended periods of no motion.

o   Servo drives for larger structural elements which can maintain critical pointing throughout cycles that include changes in direction of motion.

o   Remotely operated robotic arms and end effectors that can perform service functions for auxiliary spacecraft.

10.5   TRANSPORTATION AND ASSEMBLY ASPECTS

HLLV capability and telerobotic assembly machines are required to perform the following tasks:

o   Deliver up to 2.7×10^5 kg (6×10^5 lb) payload to low Earth orbit.   The payload size requirement of the central hub is 33.5 m (110 ft) diameter by 30.5 m (100 ft) in length.   All other Space Station modules, expandable structures, and assembly aids could be transported within a payload size

envelope of 15.24 m (50 ft) diameter by 60.7 m (200 ft) in length.

o   Assemble and service the Space Station by employing mobile remote manipulator systems, telerobotic truss assembly machines, and orbital maneuvering vehicles.

o   Telerobotic orbital transfer vehicles that can service satellites at geosynchronous Earth orbit (GEO), or transport components from GEO to the Space Station for repair and return to GEO.

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15. Supplementary Notes

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16. Abstract

An analysis has been made of several aspects of an advanced-technology rotating Space Station configuration generated under a previous study. The analysis included examination of several modifications of the configuration, interface with proposed launch systems, effects of low-gravity environment on human subjects, and the Space Station assembly sequence. Consideration also was given to some aspects of Space Station rotational dynamics, surface charging, and the possible application of tethers.

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