NASA Technical Memorandum 85772

OPERATIONAL MODULES FOR SPACE STATION CONSTRUCTION

L. Robert Jackson, Paul L. Moses, Stephen J. Scotti,
and Max L. Blosser

April 1984

NASA
National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

OPERATIONAL MODULES FOR SPACE STATION CONSTRUCTION

L. Robert Jackson, Paul L. Moses*,
Stephen J. Scotti* and Max L. Blosser
NASA Langley Research Center

SUMMARY

Identification of an effective construction concept for space stations is a current objective of NASA studies (ref. 1). A novel construction concept is described in this technical memorandum. With this concept, the space station is constructed by repetitive assembly of operational modules. The initial space station component inserted into orbit is a fully operational manned module. This construction concept minimizes on-orbit stay time of the shuttle, because the shuttle is not needed for life support during assembly of the station. The modules may be preassembled in a ground-based facility to enable integration and verification of systems. This feature improves reliability of space operations over stations constructed in space. For this concept, the structure of the modules also provides the primary structure of the space station. This feature eliminates the need for a large truss-type platform, so shuttle trips are minimized and stay time is further reduced.

The modules contain a 44 ft long compartment that may be pressurized having either a 10.5 ft or 14.5 ft diameter. Once in orbit, the smaller compartment module is fully operational and ready for immediate occupancy. The larger compartment module uses batteries for temporary operation, but must be connected to a smaller, fully operational module or have solar-cell arrays attached in orbit to become fully operational. The larger compartment, however, provides more useful volume. All modules have a common overall space requirement of 14.5 ft diameter and 46 ft length to enable transport to orbit by the shuttle.

* Kentron International, Inc.

The modules are interchangeable, and any module may be replaced without dismantling the space station. Various arrangements and numbers of modules may be selected to form a space station configuration. Convenient accessibility is provided by interconnecting tunnels for personnel and an assembly transport vehicle on tracks for transport of personnel and cargo. This novel construction concept makes maximum use of Skylab and Spacelab technologies. Moreover, space station growth is provided by adding modules when needed.

This memorandum describes and discusses space stations using the novel construction concept. Operational modules and an assembly transport vehicle are also described. Seven space station configurations and solar-cell-array orientations are presented, and analyses of solar power requirements are included.

INTRODUCTION

Principal justifications for the space shuttle were to provide the capabilities to construct and service a space station, and a principal justification for a space station is to enable production of specialized materials in the zero-gravity and vacuum of Earth orbit. Zero-gravity and the near-perfect vacuum of space uniquely enable production of selected pharmaceuticals and growth of single-crystal materials for electronic and structural applications. A further justification for a space station is to provide a space port for orbital transfer vehicles used to place payloads into distant orbits.

The construction of a space station is a formidable task requiring innovative solutions to be effective. Various space station construction concepts are being considered, but these concepts generally require extensive and expensive on-orbit construction and difficult system checkout in orbit, which may contribute to poor reliability. Some of these conceptual space station constructions are massive yet structurally flexible, so they have low natural frequencies making attitude control difficult or impractical. Other construction concepts make use of either extensive truss structures to which functional compartments are attached or interconnected modules that are not fully operational until completion of the station. Either of these concepts may require numerous shuttle flights and excessive on-orbit stay time for construction. Some concepts require difficult, awkward transportation of personnel and cargo to the extremities of the station. None of the above construction concepts provides immediate occupancy of the first space station component inserted into orbit. The shuttle orbiter, therefore, must remain on-orbit for a period of time to provide life support and its use rate is degraded.

An efficient, stiff, compact, user-oriented, reliable and economical, space-station-construction concept is needed that offers a minimum of trips and on-orbit stay time for the shuttle. The purpose of this memorandum is to describe such a concept.

SYMBOLS

A	solar-cell-array area
f	Ratio of amount of sunlight transmitted into solar cells at an angle of incidence compared to amount transmitted at normal incidence (contains reflection and cosine losses)
$\bar{f}$	average of f over an orbit of Earth
n_i	index of refraction in media of incident light
n_t	index of refraction in media of refracted light
P_B	power continuously supplied to the bus
$P_{S/A}$	power output of the solar-cell array
R	ratio of reflected to incident power normalized to zero at normal incidence
β	Angle between orbital plane and Earth-sun line

γ	solar-cell array "roll" angle (see text)
η_1	power distribution efficiency
η_2	energy storage system efficiency
ρ	ratio of reflected to incident power
$\rho_{\perp}$	ratio of reflected to incident power at normal incidence
θ	orbit position angle of the space station (zero for sun at zenith)
θ_D	orbit position angle of the space station when available solar-cell-array power just equals bus demand
θ_S	orbit position angle of the day-night terminator
ξ_i	angle of light incident on array plane (measured from plane normal)
ξ_t	angle of light refracted by array plane

ANALYSES

Regardless of the concept selected to construct a space station, the large area of solar-cell arrays necessary to supply power to the station is the dominant feature. Therefore, the construction approach must include provisions for supporting a large area of solar-cell arrays. The most important factors determining the amount of solar-cell-array area required to meet a specified, continuous power demand are the space station configuration and orientation of the arrays. In this study, the schematic configuration shown in figure 1 is used to describe several different configurations and orientations. The various configurations result from the location and number of swivel joints employed to effect the array orientation and Earth-pointing capability. The configurations are discussed in more detail in a later section of this memorandum. The remainder of this section describes the analytical method used to relate power output to solar-cell-array orientations and areas.

For a given minimum continuous power rating (75 kW in this study), the solar-cell-array orientation of a configuration with respect to the sun determines the amount of solar energy it can convert to electricity; and thus, the orientation sizes the arrays.

The primary optical losses of solar energy available for conversion to electricity are the cosine loss for some orientations and nighttime loss for all orientations. The cosine loss occurs when the angle between the normal to the solar cells and the sun direction (ξ_i) is non-zero. The available power is then reduced by the cosine of this angle. The nighttime loss is due to the shadowing of the array by the Earth. Figure 2 illustrates the geometry of this problem. The angle β is the angle between the orbital plane and the sun-Earth line. This angle varies slowly with the precession of the orbital plane and the change of seasons at a maximum rate of 3.5^{o}/day for a 28.8^{o} inclination orbit. The angle γ is defined for a configuration like that shown in figure 1 where the longitudinal axis is aligned with the orbital velocity vector. Then γ is a "roll" angle for the solar-cell arrays. The angle $\gamma = 0$ when arrays are horizontal and facing away from the Earth. The angle θ is the orbital position angle with $\theta = 0$ at orbital noon (sun at zenith), and θ_s is the angle when the Earth begins to shadow the arrays. With this definition of geometry, the cosine loss is:

$$\cos \xi_i = \cos \beta \cos \theta \cos \gamma + \sin \beta \sin \gamma.$$

Another optical loss of the solar-cell arrays for orientations having a cosine loss is reflection of incident light. Solar cell performance measurements include the loss due to reflection of the normal incident light, but the reflection loss resulting from increases in angle-of-incidence must be considered. A typical silicon solar cell consists of an optically absorbing semiconductor to which a film-coated glass coverslide is adhesively bonded. This composite construction makes exact analysis very difficult. However, because the reflectivity of both dielectrics and absorbing materials vary in the same qualitative manner with incident angle, one equation is used to characterize the amount of light transmitted to the cell. This equation is based on the reflectance (R) of a dielectric, which is normalized to zero reflection at normal incidence. The fraction of incident energy transmitted into the cell is then (1 - R) (Ref. 2); where:

$$1 - R = (1 - \rho)/(1 - \rho_\perp),$$

$$\rho = \tan^2(\xi_i - \xi_t)/[2 \tan^2 (\xi_i + \xi_t)] + \sin^2 (\xi_i - \xi_t)/[2 \sin^2 (\xi_i + \xi_t)],$$

$$\rho_\perp = [(n_t - n_i)/(n_t + n_i)]^2,$$

and

$$n_i \sin \xi_i = n_t \sin \xi_t.$$

The quantities n_i and n_t used for calculations were 1.0 and 1.5, respectively. Results using this equation compare well with tests of solar cells reported in Reference 3 up to an 80^0 angle of incidence.

The ratio of the amount of solar radiation transmitted into a solar cell at an angle of incidence compared to the amount transmitted into a cell at normal incidence is f; where:

$$f = (1 - R) \cos \xi_i.$$

The ratio f includes both cosine and reflection losses and is defined to be zero when $\xi_i > 90^0$.

To determine the power output of the solar-cell array, the array efficiency and degradation with time in orbit must be considered. The performance of a silicon SEP-type array (ref. 4) at beginning-of-life is 10.0 watts/ft^2 for sunlight at normal incidence (value obtained from John Dunning, NASA Lewis Research Center (PIR No. 29, June 1983)). The array degradation at end-of-life (10 years) will decrease the performance to 8.32 watts/ft^2, based on the measured degradation of Skylab arrays (Ref. 5). The solar-cell-array power at end of life is given by:

$$P_{S/A} = 8.32 \; f \, A,$$

where A is the array area.

To determine the solar-cell-array area required to meet a continuous power-bus demand, P_B, both the power distribution efficiency η_1 and the energy storage system efficiency η_2 need to be considered. The solar-cell-array power available for use in the space station is $\eta_1 \, P_{S/A}$, and the amount of available power that exceeds the demand P_B can be used to charge the storage system. When available power is less than the demand, the storage system must supply power $P_B - \eta_1 \, P_{S/A}$; and the power that was required to charge the system to meet that demand is $(P_B - \eta_1 \, P_{S/A})/\eta_2$. The array area must be sized so that the excess power, which is collected and stored during an orbit, equals the amount required to meet the demand when there is no excess. This relation is given by the following equations:

$$\int_0^{\theta_D} (\eta_1 \, P_{S/A} - P_B) d\theta = \int_{\theta_D}^{\theta_S} (1/\eta_2)(P_B - \eta_1 \, P_{S/A}) d\theta + (\pi - \theta_S) \, P_B/\eta_2,$$

and

$$\theta_D = P_B/(8.32 \, \eta_1 \, A \, f).$$

The angle θ_D is the orbit position of the station when the available solar-cell-array power just equals the demand. When the available solar-cell-array power cannot meet the demand throughout daylight hours, the two equations must be solved simultaneously for θ_D and A. When the array can satisfy the daylight demand, the first equation simplifies to give the solar-cell-array area; given as:

$$A = [(\pi - \theta_S)/(\theta_S\ \eta_2) + 1]\ P_B/[8.32\ (\pi/\theta_S)\ \bar{f}\ \eta_1],$$

where $\bar{f}$ is the average of f over an orbit and given by the following equation:

$$\bar{f} = 1/\pi \int_0^{\theta_S} f\ d\theta .$$

The solar-cell-array area calculations using these equations assumed $\eta_1 = 0.85$ for power distribution efficiency and $\eta_2 = 0.80$ for battery storage efficiency. (Values were obtained from Harold Huie, MSFC, by personal communication).

RESULTS AND DISCUSSION

Space Station Configurations and Orientations

The operational modules described in this paper may be arranged to form various space station configurations with different solar-cell array orientations. Two types of swivel joints, shown as A and B in figure 1, were considered for improving the orientation of the solar-cell arrays with respect to the sun and to provide an Earth-pointing capability for some configurations. The "A" swivel allows all solar arrays to be simultaneously rotated about the longitudinal axis of the station. This rotation is about an axis tangent to the orbital flight path when the longitudinal axis of the station is in the direction of motion (This corresponds directly to the angle γ in the analysis). The "B" swivel allows each solar-cell array to be rotated about its longitudinal axis. Seven space station configurations were considered. For each configuration the relative effectiveness of the solar-cell array orientation was calculated, and the arrays were sized to provide a minimum of 75 kW of continuous power. The array size was calculated for each configuration at orbits of 235 and 270 n.mi. and at the limiting β angles of 0 and 52 degrees, and results are shown in

Table I. The range of continuous power output available over a yearly cycle is shown in Table II. The seven configurations considered and their relative array areas and power output ranges are described as follows:

1. Sun-synchronous space station configuration: This configuration has no swivel joints. The entire space station is oriented so that the solar radiation is always normal to the solar-cell arrays ($\xi_i = 0$, $R = 0$). The arrays do not shade each other and, consequently, operate at full capacity when not in the shadow of the Earth. This configuration offers the least solar-cell-array area, but it has high aerodynamic drag and no Earth-pointing capability. When sized to provide a minimum of 75 kW of continuous power, the solar-cell arrays of this configuration produce between 75 and 87 kW during a yearly cycle in the 270 n.mi. orbit (see Table II).

2. Sun-synchronous-array configuration: This configuration has A and B swivel joints shown in figure 1, and the longitudinal axis of the station is perpendicular to the orbital plane. ($\xi_i = 0$, $R = 0$). The arrays must be spaced with gaps about equal to the array width. For a given module length, half as many arrays are used per module as for the first configuration, or the space station is twice as long to avoid shadowing. Full power capacity is achieved when not in the shadow of the Earth. This configuration shares least solar-cell-array area with the first configuration. It has Earth-pointing capability, but high drag. The arrays must be rotated about the longitudinal axis of the station during each orbit of the Earth and oscillated slowly about their longitudinal axes to correct for variations of beta angle. As indicated in Tables I and II, this configuration has the same array area and variation in yearly power generation as the sun-synchronous configuration.

3. Rotating-array configuration: This configuration also is oriented with longitudinal axis perpendicular to the orbital plane. The "A" swivel (see figure

1) is used to rotate the solar-cell arrays relative to the Earth-pointing modules each orbit so that the array orientation in inertial space is nearly constant. This orientation has reflection and cosine losses when the beta angle is not equal to zero ($\xi_i = \beta$, $R > 0$). It has high drag and requires 1.4 times the solar-cell-array area of the sun-synchronous space station (see Table I). The output power ranges from 75 to 108 kW over a yearly cycle (see Table II).

4. Oscillating-array gamma-controlled configuration: This configuration has both the A and B swivel joints, and its longitudinal axis is tangent to the orbit. It offers Earth-pointing capability and no reflection loss from the solar cells ($R = 0$), but some cells are shadowed by adjacent arrays and all arrays must be oscillated during each orbit ($\cos \xi_i$ is continuously maximized by varying the γ angle). It offers less drag than the first three configurations. The solar-cell-array area is about 1.9 times that of the sun-synchronous space station. Over a yearly cycle, the power output varies from 75 to 142 kW in the 270 n.mi. orbit.

5. Gamma-angle-controlled configuration: This configuration has only the "A" swivel joint, which is oscillated during each orbit of Earth ($\cos \xi_i$ is continuously maximized by varying the γ angle). It has Earth-pointing capability and no shadowing by adjacent arrays, but it has reflection and cosine losses ($R > 0$). Its longitudinal axis is tangent to the orbit. Its drag is the lowest of all configurations, but it requires about 2.0 times the array area of the sun-synchronous space station. Over a yearly cycle, the power output varies from 75 to 149 kW in the 270 n.mi. orbit.

6. Beta-angle-controlled configuration: This configuration is very similar to configuration 5 and has the same axis orientation. However, rather than oscillating the solar-cell arrays every orbit, this configuration oscillates the arrays over a longer period of 50 days (orbital plane precession period) to

match the beta angle at local noon ($\gamma = \beta$). It has Earth-pointing capability and no shadowing, but it has reflection and cosine losses. This configuration requires 2.1 times the array area of the sun-synchronous space station. Over a yearly cycle, the normal power output varies from 75 to 136 kW in the 270 n.mi. orbit; however, for periods of peak power demand the output varies from 157 to 183 kW when reoriented to become a sun-synchronous station (see Table II). Configuration 6 is about equal length to configuration 2, but has 2.1 times the array area. The slight increase in solar-cell-array size over the fifth configuration results in only a slight increase in drag. This configuration was selected for study and reporting in this memorandum.

7. Earth-pointing space station: This configuration has no swivel joints and the entire station is in an Earth-pointing orientation ($\gamma = 0$, $R > 0$). It has reflection and cosine losses. It requires the largest solar-cell-array area (about 3.6 times that of the sun-synchronous space station)and has low drag. Over a yearly cycle, the power output varies from 75 to 130 kW in a 270 n.mi. orbit.

The beta-angle-controlled configuration (6) was selected for this study. Although the sun-synchronous space station configuration (1) requires less than half of the solar-cell-array area, it was not selected because it has high drag and no Earth-pointing capability for any module. The sun-synchronous array configuration (2) also requires less than half of the solar-cell-array area of configuration 6 and, although the modules with arrays are rotated during each orbit about the longitudinal axis of the space station, only frictional forces in swivel joint "A" must be overcome to maintain Earth-pointing capability. Keeping the arrays perpendicular to the solar radiation requires only a slow oscillation (3.5°/day) of each array about its own longitudinal axis to correct for the variation in beta angle. Although the second configuration looks promising, it was not selected; because it has high aerodynamic drag, requires several swivel joints and requires a complete rotation during each orbit of swivel joint "A", which may complicate space station control and transfer of personnel and material across the joint. Configuration 3 is similar to configuration 2 but does not oscillate each array about its own axis and consequently requires a 40 percent larger array area. It was not selected, because it has high aerodynamic drag and its swivel joint is rotated 360 degrees during each orbit (240^{o}/hr). The configurations 4 and 5 also require rapid oscillation of solar-cell arrays during each orbit and were not selected; because, although their arrays are slightly smaller than configuration 6 (configuration 6 has a slow oscillation), the rapid oscillations may require considerable power consumption, produce structural dynamic instabilities and result in difficult control of space station orientation. The Earth-pointing configuration 7 does not have these control problems; however, it was not selected, because it requires much larger arrays than the beta-angle-controlled configuration (6). Moreover, configuration 6 offers flexible operation through its ability to double its power output for periods of peak demand. Although configurations 2 and 6 look promising, the beta-angle-controlled configuration was selected; because it potentially offers the best combination of performance and array size.

Space Station Description

The principal result of this study is a novel, space-station construction concept using modules that are operational upon orbit insertion and also provide the primary structure of the space station, as shown in figures 3 and 4. The use of operational modules permits assembly of the entire space station in a ground-based facility to enable integration and verification of systems. Additionally, a mock-up constructed of operational modules may be maintained on Earth to assist space operations throughout the useful life of the station. These features should improve reliability of station operations over that of stations constructed in space. Operational modules enable immediate occupancy upon orbit insertion, thus a minimum of on-orbit stay time is required of the shuttle. That is, the shuttle is not needed to provide life support as it would be for construction concepts that initially require either an extensive truss-type platform prior to mounting habitable compartments or an interconnection of several non-operational modules. Use of operational modules to provide the primary structure of the space station provides a volumetrically efficient, stiff structure for the station. This feature minimizes the need for additional structure and should reduce the number of trips and on-orbit stay time for the shuttle compared to other construction concepts.

The size of the station is based on sufficient solar-cell-array area (40,000 ft^2) to produce 75 kw of continuous power for periods of normal operation. For periods of peak power demand, the station may be temporarily reoriented to become a sun-synchronous space station producing 157 kw of continuous power. However, during this temporary reorientation, the space station will not have Earth-pointing capability. Because the solar-cell arrays are of the SEP type (ref. 4), they can be retracted for the reorientation maneuver. To minimize aerodynamic drag for normal operation, the plane of the solar-cell arrays is maintained tangent to the orbital flight path; and the solar-cell arrays trail the leading modules that have no arrays. However, an aerodynamically balanced configuration may be constructed by locating some of the modules having arrays forward of the Earth-pointing modules, but a second swivel joint is needed.

In addition to providing living quarters, a sufficient number of modules can be provided to satisfy the following functions: research, pharmaceutical production, crystal manufacturing, electrical power management, space station control, utility management, docking, and propellant storage. The propellants are needed for refueling orbital transfer vehicles based at the space station. The inhabited modules have on-board life-support systems, thus safety is enhanced in event of utility management module failure. Space station growth is provided by adding modules only when needed since all modules have common interfaces (interchangeability feature); that is, it is not necessary to initially construct an oversized support structure for future expansion of the space station.

As indicated, the use of a swivel joint in the structure of the space station permits efficient orientation of the solar-cell arrays while permitting an Earth-pointing capability for modules not having arrays. Swiveling about the longitudinal axis of the structure enables simultaneous reorientation of all solar-cell arrays to correct for variations in the β angle, resulting from seasonal changes and precession of the orbital plane. This oscillation is slow--a maximum rotational rate of 3.5 degrees per day for a 28.8° inclination orbit. The use of an Earth-pointing capability and a low drag orientation of the arrays result in a need to more than double the area of the solar cells (for a given power) over that of a sun-synchronous orientation of a space station. This increased solar-cell-array area is needed because of high cosine and reflection losses that occur for periods other than noon in an orbit. However, as indicated, this increased array area may be beneficial during periods of peak power demand. The selected configuration, using the operational module construction concept, provides considerable useful volume for each set of solar-cell arrays; and the need for many arrays automatically results in an abundance of habitable volume. An optimum ratio of power to useful volume may warrant consideration of larger solar-cell arrays than selected for this study.

Any module may be removed from the space station without dismantling the space station. Solar-cell arrays are disconnected and restrained by the assembly transport vehicle prior to removal of a module. As shown in figure 5, to remove a module, the disconnect sequence is utility conduits, airlocks-to-transport tunnel, inter-module connection devices and pressurized compartment-to-truss structure. When the inter-module connection devices are disengaged, a 3-inch clearance is provided between adjacent modules to facilitate removal of a module. The module is withdrawn from the station perpendicular to the tunnel. This withdrawal may be accomplished either by the assembly transport vehicle or by the reaction-control system provided in each module, but normally used to maneuver the space station. A replacement module is required to re-establish the original structural stiffness and normal operation of the space station, and this module may be installed by reversing the disconnect sequence. Replacement modules require no tunnel or surrounding truss structure when delivered to orbit; because once the tunnel and truss structure are installed, they normally remain an integral part of the station.

Figure 6 shows an inter-module connection device. Sixteen such devices are spaced about one end ring of each module, and mating fittings are spaced about the opposite end ring. Each device consists of two components--the first component provides locating and latching functions, and the second component completes the structural tie between modules. Each component is activated by electric-motor-driven leadscrews. Similar connection devices are used for the attachment of the compartment to the truss surrounding the transport tunnel.

Operational Modules

Operational modules are the basic construction components of the space station. All modules have a common overall space requirement of 14.5 ft diameter by 46 ft length, and each module contains a compartment that may be pressurized. Two compartment diameters are used, but the compartments (and modules) are interchangeable. The modules can be designed employing Skylab and Spacelab technologies and assembled to provide a space station. The following subsections describe and discuss these modules.

Small, Fully Operational Module.- The small, fully operational module is shown in figure 7 and consists of a 10.5 ft diameter by 44 ft long pressurized compartment of welded aluminum alloy with other components affixed. At each end of the compartment, a skirt extends to inter-module attachment rings resulting in a module length of 45.75 ft. A longitudinally-stiffened-skin is used for the skirts, which are also ring stiffened. Inter-module connection devices (16 sets) are spaced around one inter-module attachment ring, and mating fittings are spaced around the opposite end ring. Reaction control motors are mounted within the skirts, and since each module has motors, the thrust and inertial loads are distributed, which minimizes bending moments by load alleviation. A floor is provided within the compartment. Utility conduits, utility tanks (air, water, sewage, etc.) and batteries are located between the floor and the compartment wall. The utility conduits extend over the length of the module. At one end of the module quick disconnect-type fittings are translated a distance of about six inches to mate with the utility conduits of the adjacent module. Flexible conduits are used at the movable end of the quick-disconnect fittings to enable the translation. When the attachments between modules are engaged, the overall length of the module is 46 ft.

Above the pressurized compartment is a transport tunnel, surrounded by a frame and truss-type structure. The frames surround the tunnel and are interconnected by truss members. Tracks, integral with the truss structure, are used for attachment and guidance of the assembly transport vehicle. Airlocks are provided at each end of the pressurized compartment. These airlocks enable transfer of personnel from the tunnel and the compartment. Removable doors are provided at the ends of the transport tunnel.

On either side of the pressurized compartment, two arrays of solar cells are attached, and the arrays are shown deployed in figure 7. A radiator is attached to the lower surface of the module. This radiator is semi-circular to provide a maximum radiation area without requiring deployment or assembly in space. The cross section of the completed module fits within a 14.5 ft diameter mold line.

Inside the pressurized compartment, equipment suited to the user is installed prior to shuttle launch of the module. Moreover, the utility tanks may be filled to allow immediate occupancy of the module upon orbit insertion. This small, fully operational module is the first component of the space station to be inserted into orbit.

Figure 8 shows the small, fully operational module installed within the payload bay of the shuttle. As shown, the contracted solar-cell arrays are rotated about a longitudinal axis to fit within the payload bay. A rearward location of the module within the payload bay is necessary to satisfy shuttle center of gravity requirements. A tunnel is provided between the module and the crew compartment of the shuttle. This tunnel enables shuttle transport of the space station crew. Once in orbit, the crew can transfer into the module and perform a final checkout of systems prior to module release from the shuttle. A fully equipped module may have a gross liftoff weight of about 55,000 lb, and a landing weight of about 35,000 lb. However, the liftoff weight applies to an orbital plane inclination of 28.8 degrees. Should a much higher inclination angle be desired, the module weight may be halved by using 23 ft long modules to satisfy the reduced payload capability of the shuttle.

This small volume module may be designed to be a propellant storage tank, and when used for this purpose, it is equipped accordingly; however, a radiator may be preinstalled on the tanks to supplement radiators provided by the habitable modules.

Large-Useful-Volume Module.- The large-useful-volume module is shown in figure 9 and consists of a 14.5 ft diameter by 44 ft long pressurized compartment with end skirts extending the length to 45.75 ft. When installed into the space station, the total length is 46 ft; so the large and small compartment modules have identical space requirements of 14.5 ft diameter by 46 ft length. All structural and utility interface connections are identical to those of the smaller compartment module. This large, useful volume module has no tunnel, surrounding truss or solar-cell arrays attached when mounted into the payload bay of the shuttle. Several sets of these items are taken to orbit by a separate shuttle launch and attached to the modules in space. As with the smaller compartment module, reaction controls, two airlocks, a radiator and a floor, which covers utility conduits and tanks, batteries, etc., are provided. These items and user-oriented equipment are installed in a ground-based facility prior to launch. This large compartment module is not immediately habitable upon insertion into orbit, but becomes habitable either upon connecting it to a small, fully operational module or upon installing its solar-cell arrays. Temporary habitation is possible by using its on-board batteries for power, thus the large-useful-volume module may be considered an operational module, but for a limited period. This large-useful-volume module also may be designed to be a propellant storage tank with or without a supplementary radiator.

Assembly Transport Vehicle

Figure 10 shows an assembly transport vehicle (ATV) used to assemble the modules and large antennas or other peripheral equipment needed for space station functions. The ATV consists of a pressurized capsule, four drive wheels, two articulating arms and a storage rack. The capsule provides a shirt-sleeve environment for the operator. Windows and airlocks are provided at each end. A deployable airlock is also provided through the floor of the capsule, and this airlock can be connected to the transport tunnel of each module. The articulating arms are located at the mid-length of the capsule. Control consoles are provided at each end of the capsule to enable operation of the ATV from either end. On the upper surface of the capsule, a rack is provided that has two sets of bi-fold doors of truss construction. This rack provides a means of transporting various construction materials. The four-wheel drive system consists of four rack and pinion drives, powered by separate electric motors. The wheels are pinions; and the tracks, built into the truss structure surrounding the transport tunnel, are gear-tooth racks. A small retaining wheel, connected to the ATV, presses on the opposite side of the rack to clamp the ATV to the tracks. Support structure for the wheels is sufficiently deep to allow the ATV to pass over a corner at the end of the space station without contact between the capsule and the transport tunnel. Electrical power for the ATV is provided by a third rail similar to subway cars of our larger cities. Batteries and life-support provisions are stored within the capsule, so the ATV is essentially an independent spacecraft with limited life-support capability (it has no reaction control, guidance or propulsion systems).

CONCLUDING REMARKS

A novel space station construction concept employing operational modules that provide the primary structure for the space station and enable ground-based integration and verification of systems is described in this technical memorandum. The space station is constructed by connecting interchangeable modules that have common interface joints. The modules have an identical overall space requirement (14.5 ft diameter by 46 ft long) to enable transport to orbit by the shuttle. Two operational modules are proposed--one has a 10.5 ft diameter pressurized compartment, and the other has a 14.5 ft diameter compartment. Each compartment is 44 ft long and may be designed to serve as a propellant storage tank. The module with the smaller compartment has solar-cell arrays, a radiator, airlocks, a transport tunnel, tracks, utility conduits, storage tanks and sufficient life-support capability to operate immediately as a fully operational vehicle when inserted into orbit. This fully operational module is the first component of the space station to be inserted into orbit. The large-useful-volume module must use its on-board batteries for immediate power, and be either connected to the small, fully operational module or have its solar-cell arrays installed in space to become fully operational.

A space station constructed of operational modules may benefit from module fabrication, assembly and testing in ground-based facilitites. Additionally, pre-assembly and system checkout of the entire space station is possible on the ground prior to launch. These features minimize on-orbit construction time and enhance reliability. The modules provide efficient, stiff primary structure for the space station. Very few additional structural members are needed, thus the use of modules for space station structure should minimize on-orbit stay time and number of trips required for the shuttle to complete the station. Additionally, since each habitable module is capable of life support upon orbit insertion, the on-orbit stay time of the shuttle is further minimized.

Convenient transport is provided between modules by tunnels for personnel and by an assembly transport vehicle on tracks for personnel and cargo. The assembly transport vehicle enables assembly of the modules and fabrication of antenna or other structures on the space station, and the space station may be enlarged--as required--by adding modules. Any module may be removed without dismantling the space station. A replacement module is required to re-establish the original structural stiffness and normal operation of the space station.

A high volumetric efficiency is provided by the modular space station construction concept; that is, essentially all of the structure required to support the necessarily extensive solar-cell arrays provides useful volume. These operational modules may be used to construct space stations having any of the seven solar-cell-array orientations considered in this study. Two of these space station configurations are attractive--a sun-synchronous array and a beta-angle-controlled configuration. The latter was selected for study, because it has fewer swivel joints, less drag and an ability to increase power over normal operation for periods of peak demand. The use of operational modules makes maximum use of Skylab and Spacelab technologies.

Operational modules that provide the primary structure of the space station have potential to satisfy the need for an efficient, stiff, compact, user-oriented, reliable and economical, space-station-construction concept that offers a minimum of trips and on-orbit stay time for the space shuttle.

REFERENCES

1. Mikulas, Martin M., Jr.; Bush, Harold G.; Wallsom, Richard E.; Dorsey, John T.; and Rhodes, Marvin D.: A Manned-Machine Space Station Construction Concept, NASA TM 85762, February 1984.

2. Rauschenbach, M. S.: Solar Cell Array Design Handbook, Van Nostrand Reinhold Co., C. 1980.

3. Opjorden, R. W.: Solar Cell Optical Design Considerations. Presented at Ninth IEEE Photovoltaic Specialists Conference, May 1972.

4. "Solar Array Technology Development for SEP, Final Report," Lockheed Missiles and Space Company, NASA CR-161634, LMSC-D715820, NAS8-31352, January 9, 1981.

5. White, W. J.: Skylab Reactivation Data Analysis Final Report. McDonnell Douglas Astronautics Company - Huntington Beach, NASA CR 159074, June 1979.

TABLE I.- SOLAR-CELL-ARRAY RELATIVE AREAS AND AREAS FOR A MINIMUM CONTINUOUS POWER OF 75 KW FOR VARIOUS CONFIGURATIONS AND ALTITUDES.

CONFIGURATION†	235 N. Mi. ORBIT		270 N. Mi. ORBIT	
	Relative Area	Area (ft^2)	Relative Area	Area (ft^2)
1 and 2	1.00	18920	1.00	18650
3	1.45	27380	1.43	26730
4	1.85	35080	1.86	34770
5	1.95	36980	1.96	36640
6	2.07	39150	2.10	39150
7	3.58	67750	3.63	67750

† See text for description of configurations.

TABLE II.- RANGE OF CONTINUOUS POWER OUTPUT AVAILABLE OVER A YEARLY CYCLE FOR VARIOUS CONFIGURATIONS, β ANGLES AND ALTITUDES.

CONFIGURATION†	235 N. Mi. ORBIT		270 N. Mi. ORBIT	
	@ $\beta = 0^o$; Power, kW	@ $\beta = 52^o$ Power, kW	@ $\beta = 0^o$ Power, kW	@ $\beta = 52^o$ Power, kW
1 and 2	75.0*	86.2	75.0*	87.1
3***	108.5	75.0*	107.5	75.0*
4***	75.0*	139.8	75.0*	141.9
5***	75.0*	147.1	75.0*	149.2
6 normal	75.0*	134.3	75.0*	135.9
6 peak**	155.3	178.4	157.5	182.9
7***	129.8	75.0*	129.8	75.0*

† See text for description of configurations.
* Design point.
** When reoriented to become a sun-synchronous station.
*** Power output may be increased if reoriented to become a sun-synchronous station.

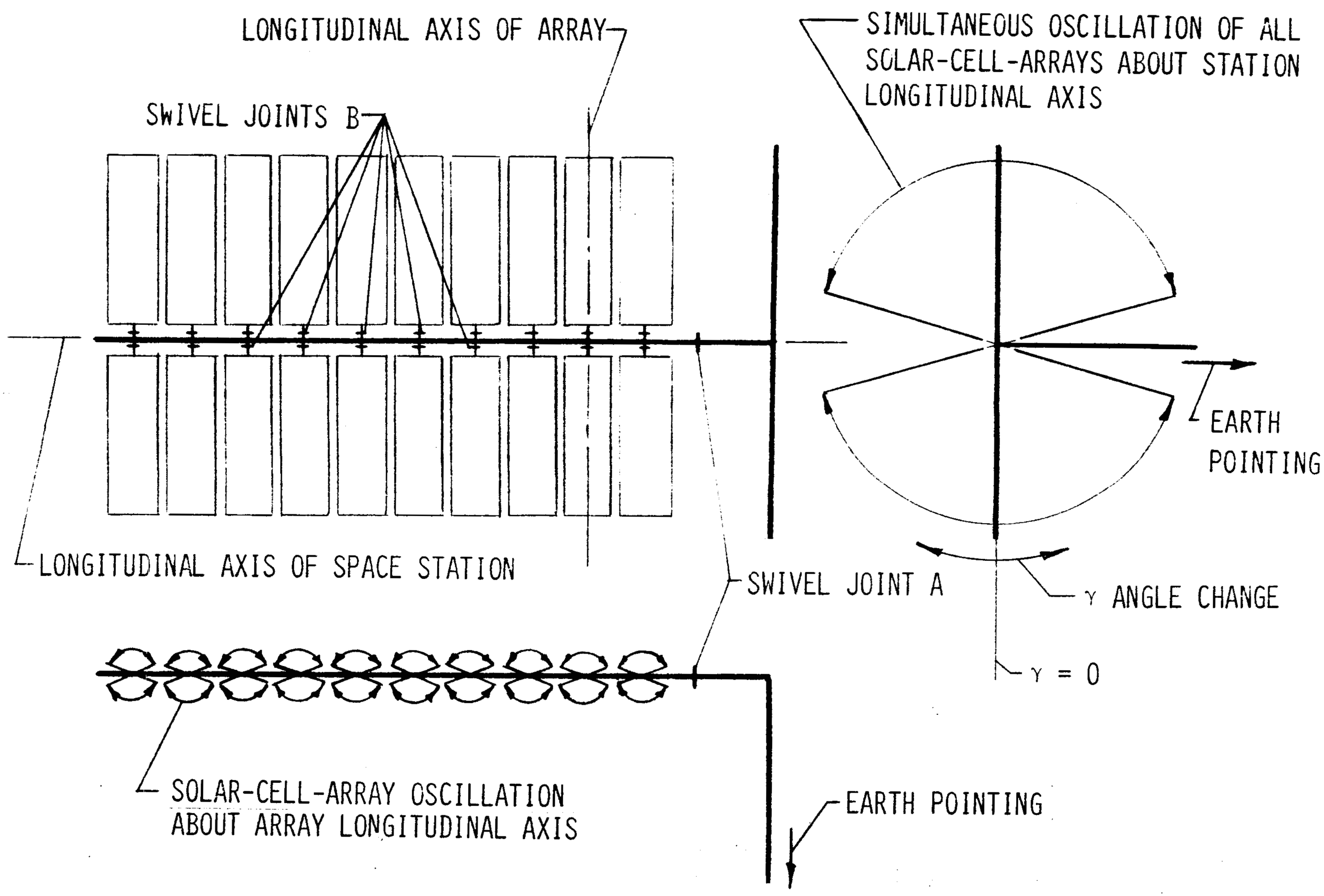


Figure 1.- Space station schematic configuration showing swivel joint alternatives and solar-cell-array orientation.

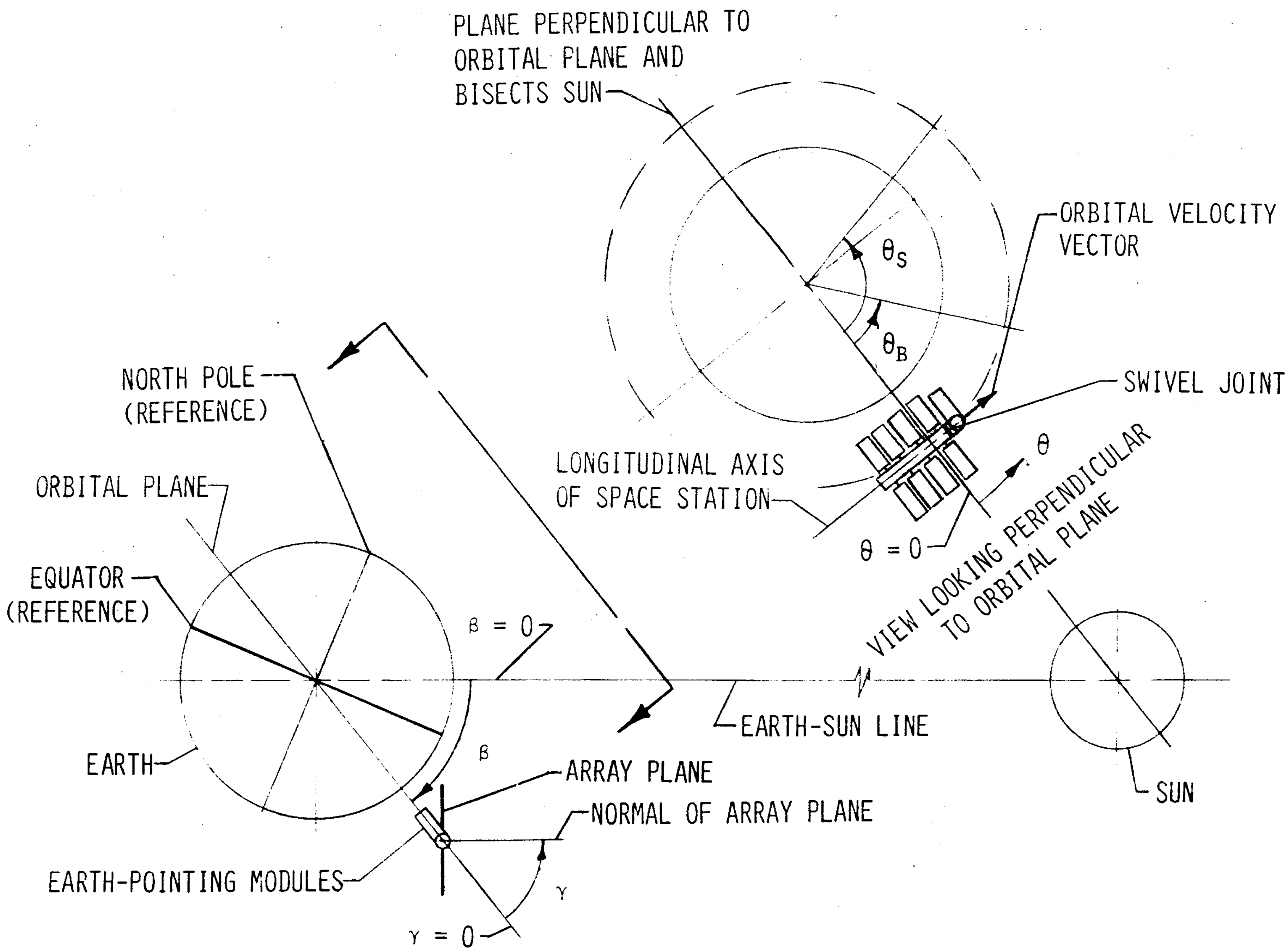


Figure 2.- Orbital Geometry.

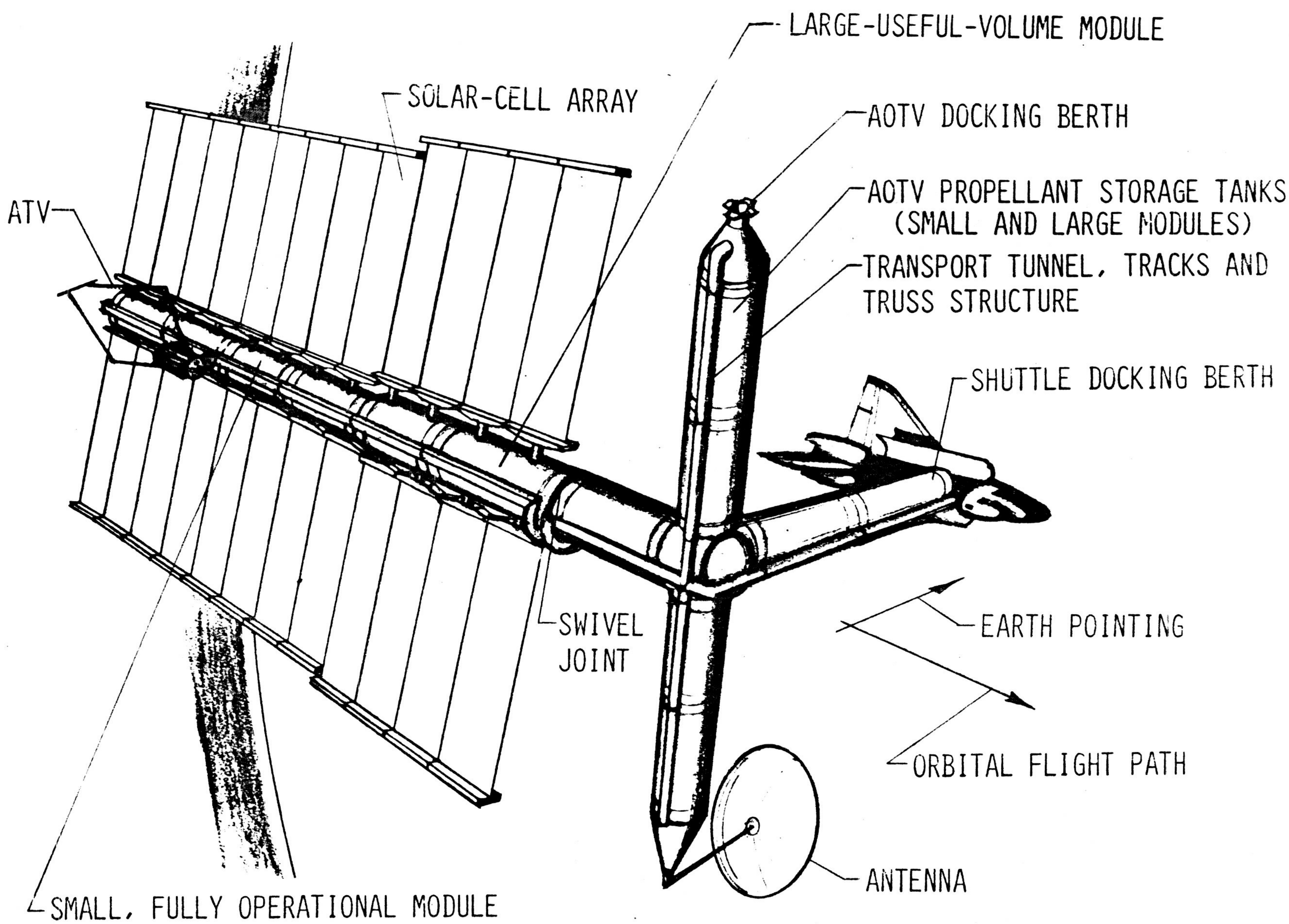


Figure 3.- Space station configuration constructed of operational modules.

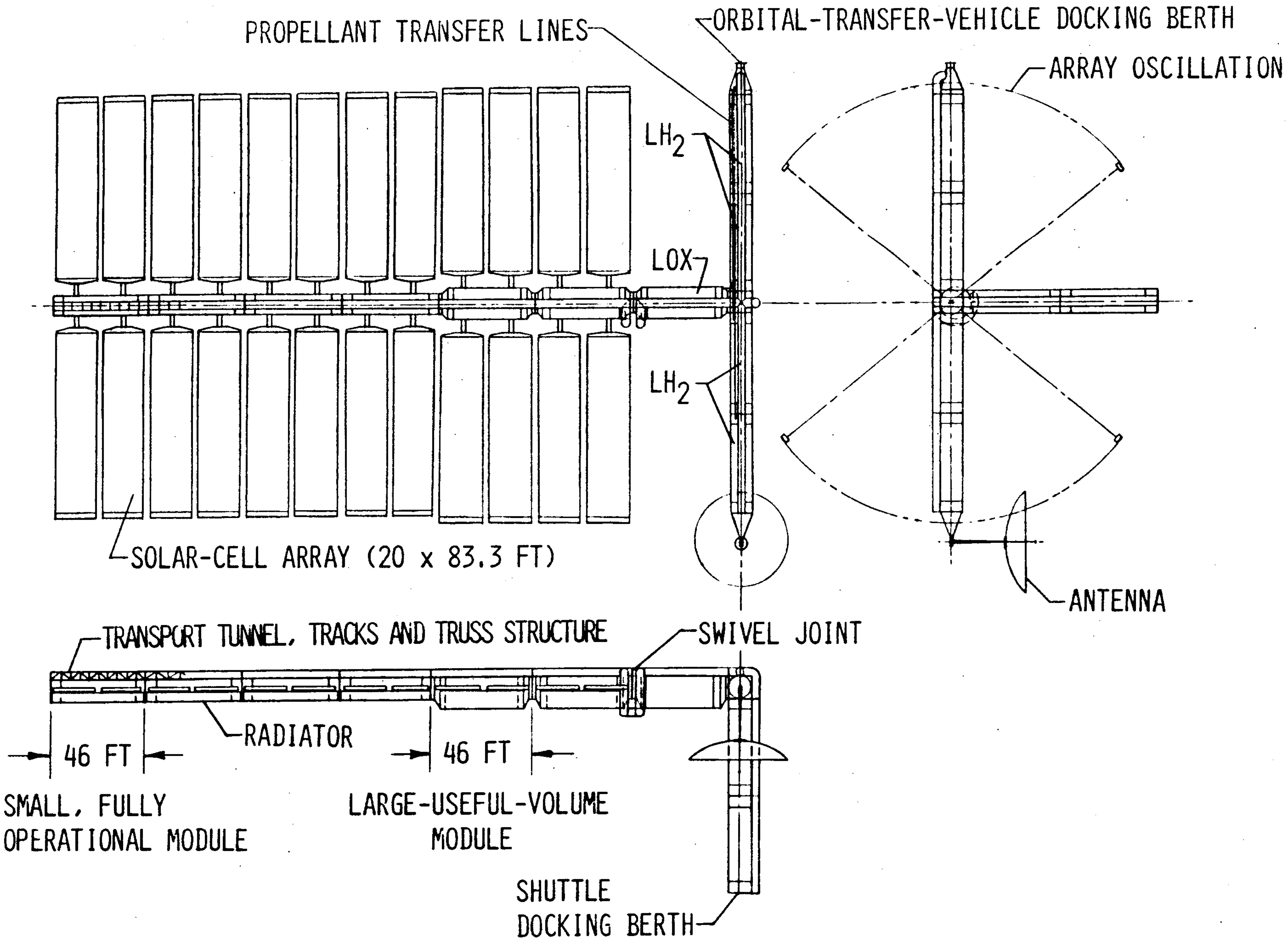


Figure 4.- Details of space station constructed of operational modules.

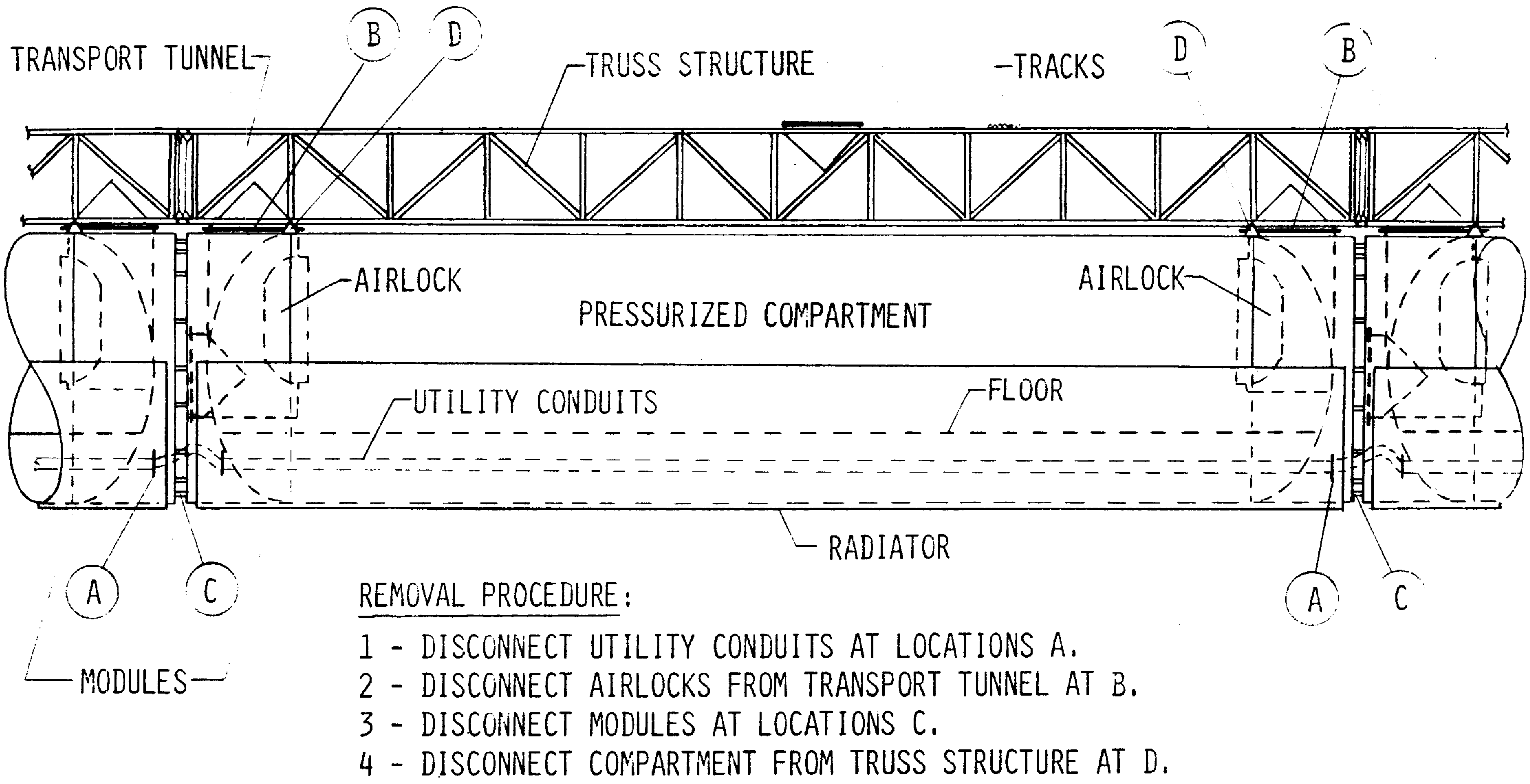


Figure 5.- Removal procedure for operational modules.

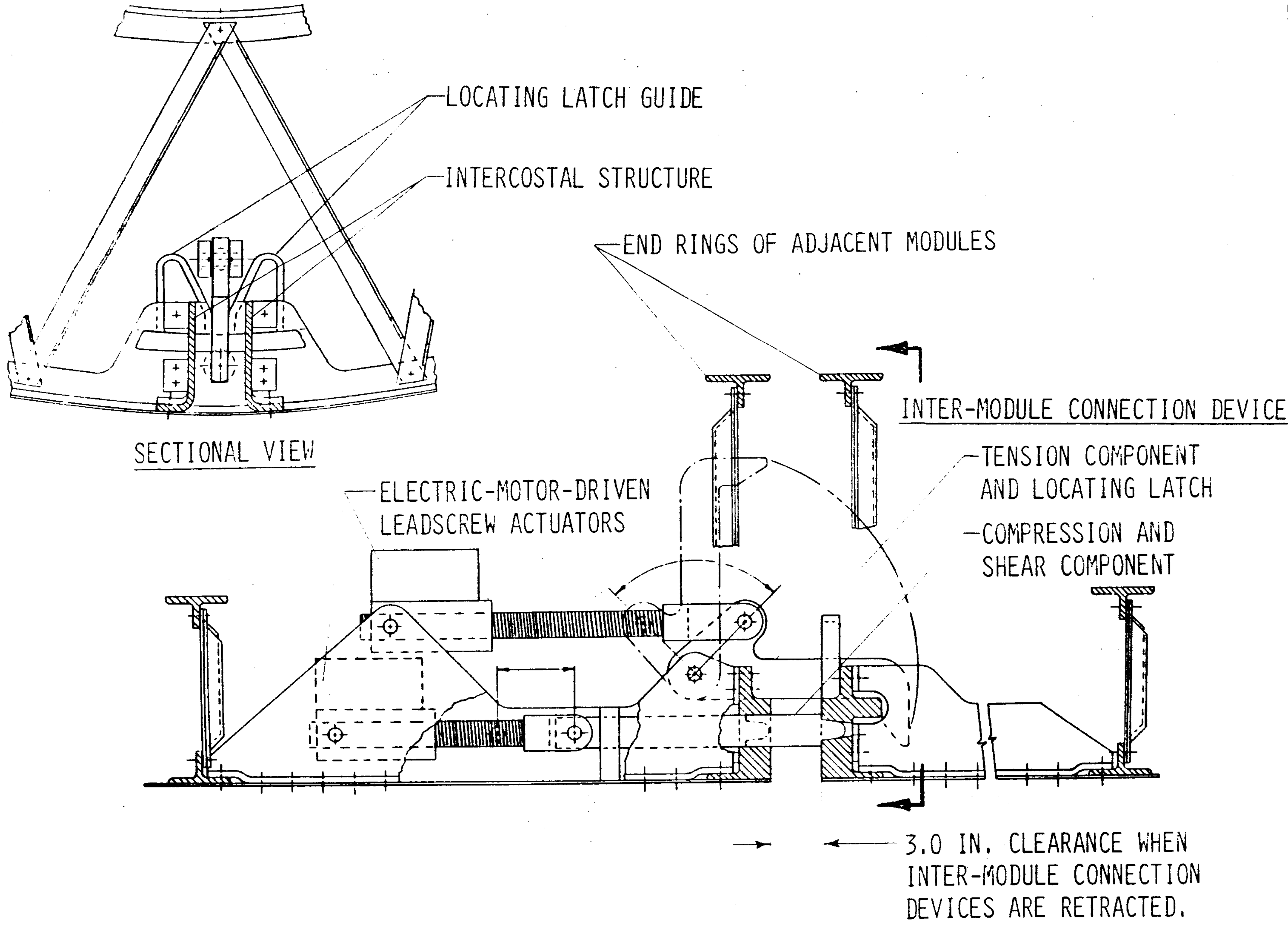


Figure 6.- Inter-module connection device.

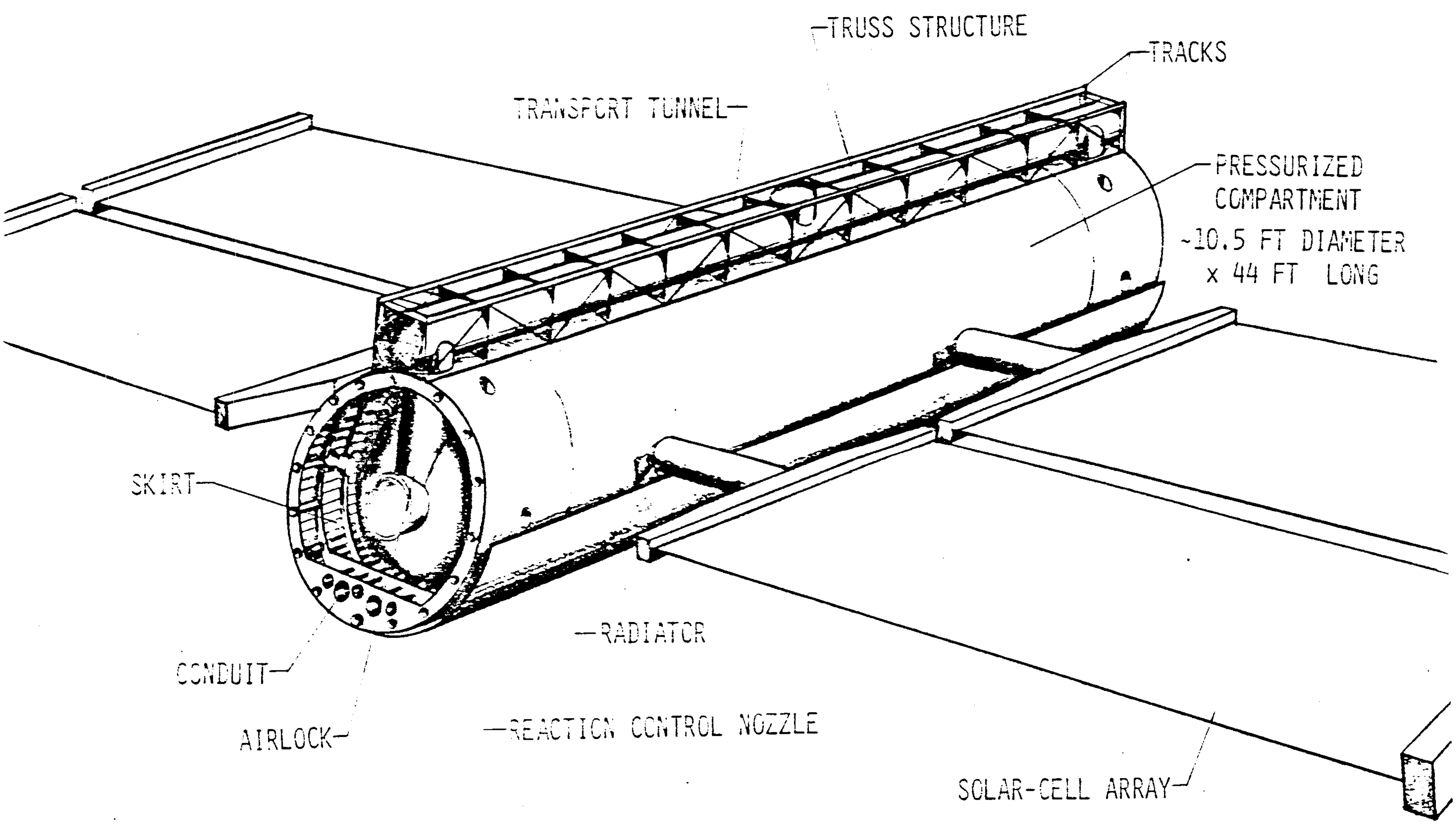


Figure 7.- Small, fully operational module.

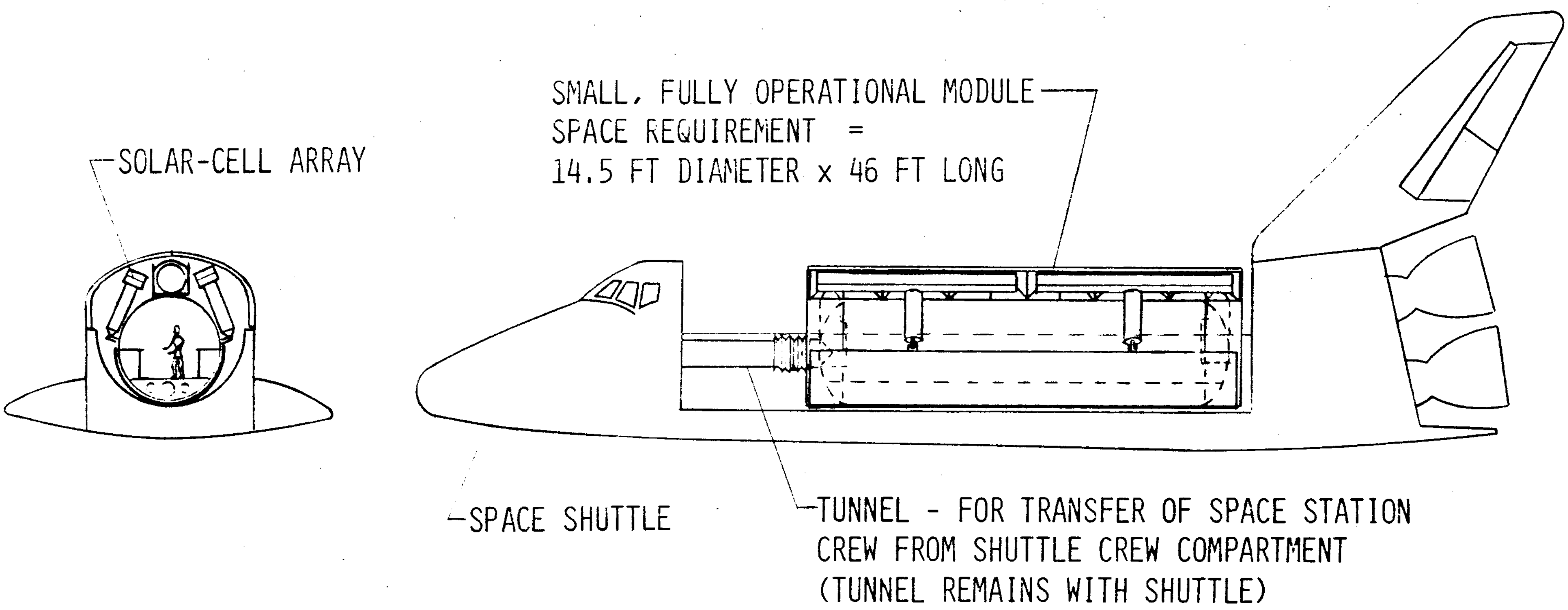
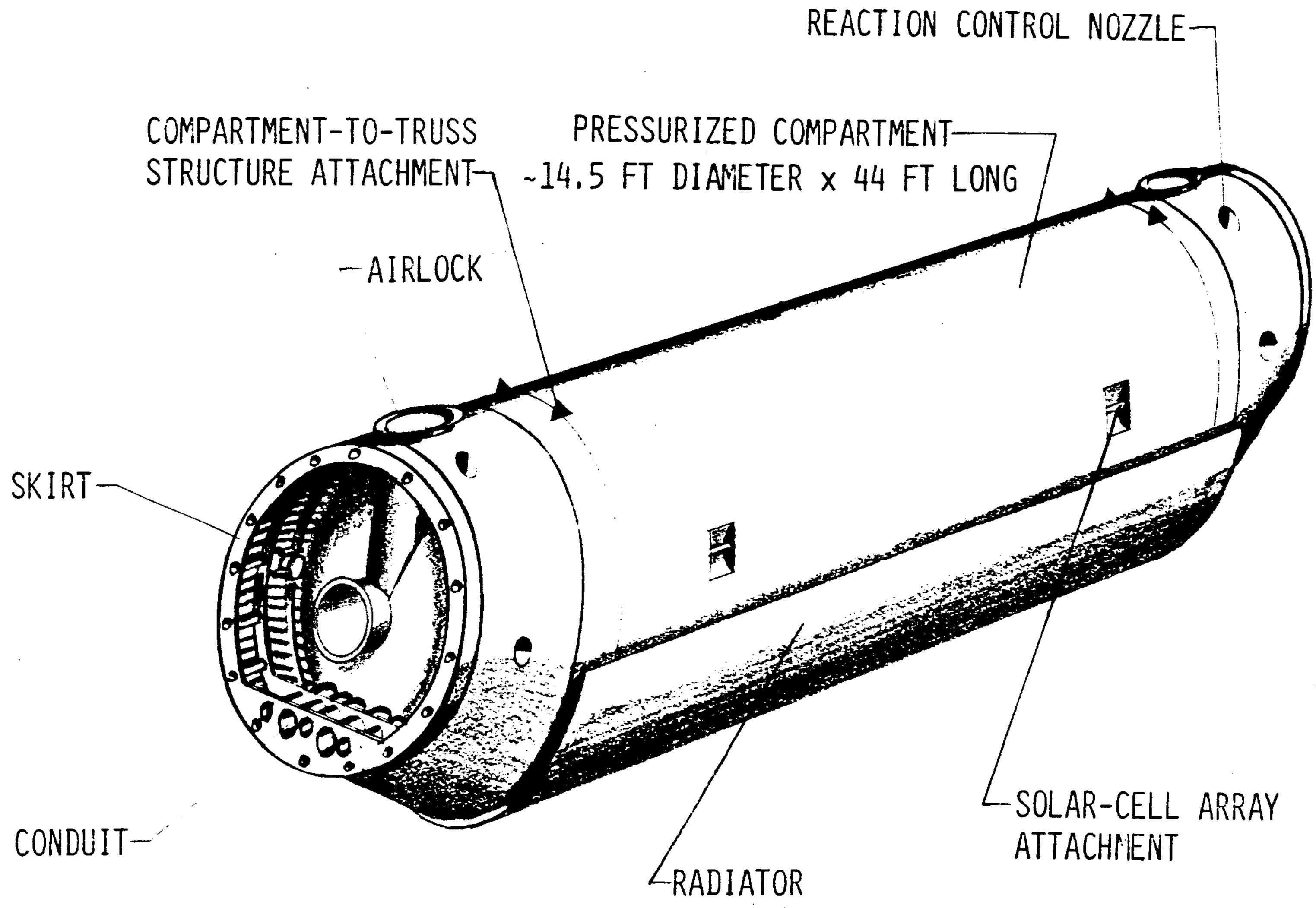


Figure 8.- Small, fully operational module installed within the payload bay of the space shuttle.



SPACE REQUIREMENT = 14.5 FT DIAMETER x 46 FT LONG

Figure 9.- Large-useful-volume module.

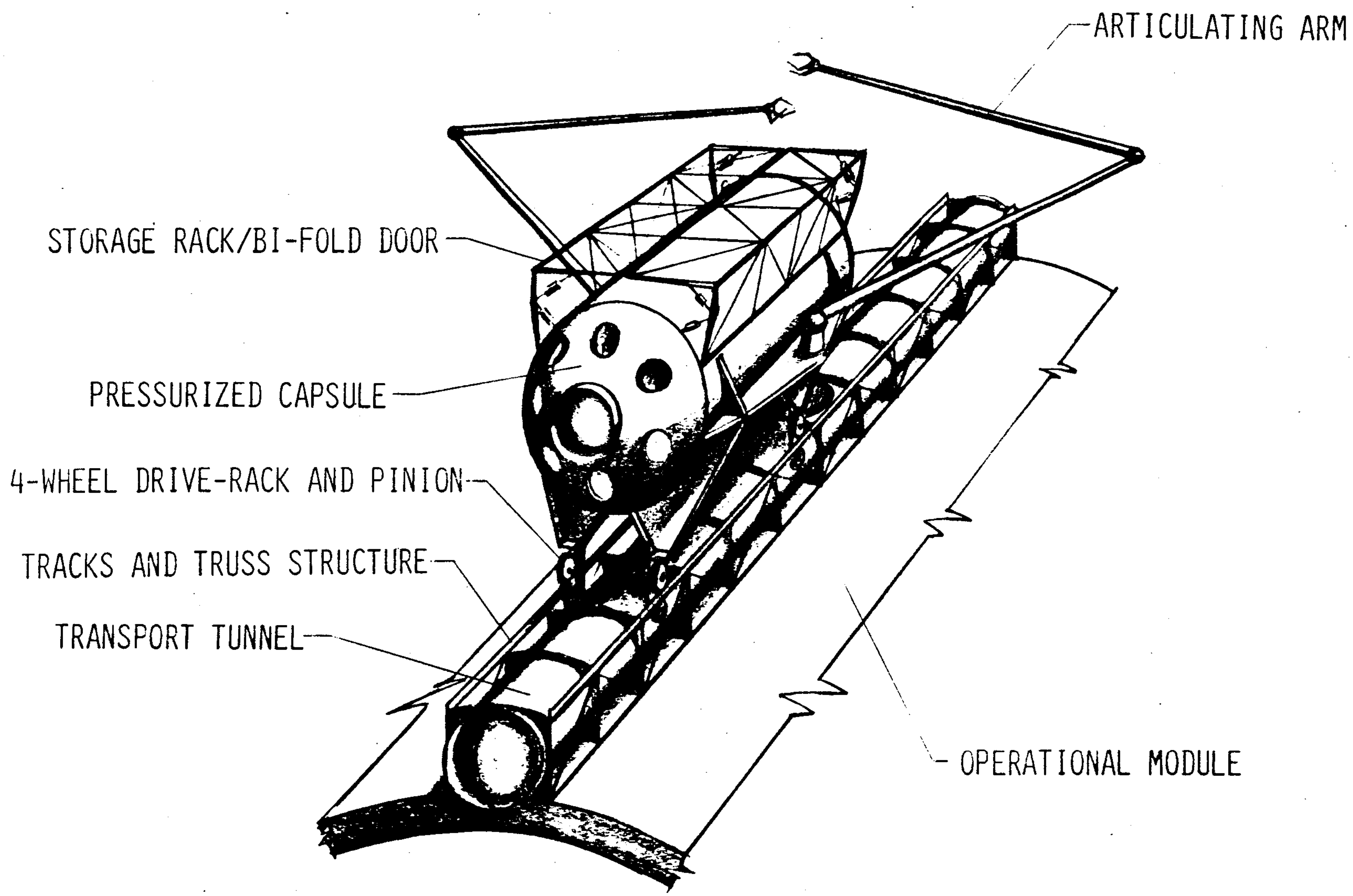


Figure 10.- Assembly transport vehicle attached to tracks on an operational module.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-85772		

4. Title and Subtitle

Operational Modules for Space Station Construction

5. Report Date

April 1984

6. Performing Organization Code

506-53-43

7. Author(s)

L. Robert Jackson, Paul L. Moses*, Stephen J. Scotti* and Max L. Blosser

8. Performing Organization Report No.

9. Performing Organization Name and Address

NASA Langley Research Center
Hampton, VA 23665

10. Work Unit No.

11. Contract or Grant No.

12. Sponsoring Agency Name and Address

National Aeronautics and Space Administration
Washington, DC 20546

13. Type of Report and Period Covered

Technical Memorandum

14. Sponsoring Agency Code

15. Supplementary Notes

* Kentron International, Inc.
Hampton, VA 23666

16. Abstract

Identification of an effective space station construction concept is a current objective of NASA studies. One concept, described in this memorandum, consists of repetitive use of operational modules, which minimizes on-orbit stay time for the shuttle.

A space station constructed of operational modules may benefit from fabrication and system checkout in ground-based facilities, and since the modules are the primary structure of the space station, a minimum of additional structure, and trips and on-orbit stay time of the shuttle are required.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Space Stations Space Station Construction Ground-Based Checkout of Systems Operational Modules Solar-Cell-Array Orientations	Unlimited - Unclassified Subject Category 18

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	33	A03

For sale by the National Technical Information Service, Springfield, Virginia 22161