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Notation

E	modulus of elasticity, GPa
EI	stiffness, MN-m^2
F_{TU}	failure stress level in tension (tensile ultimate), MPa
g	Earth gravity, $1g = 9.8$ m/s^2
I	moment of inertia about axis, cm^4 or m^4
k	radius of gyration, m
m	mass, tonne (1000 kg)
ω	angular velocity, rad/s

Abbreviations and acronyms:

Ad mat	advanced materials
Al mat	aluminum materials
ATSS	advanced-technology space station
cmg's	control-moment gyros
dia	diameter
FAB	fabrication
LH_2	liquid hydrogen
LO_2	liquid oxygen
SAP	standard atmospheric pressure

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Summary

The configuration for the advanced-technology space station (ATSS) was based upon the operational functions that it might be required to perform in approximately the year 2025. The dominant feature of the ATSS is a large, rotating torus that serves as the primary crew habitat and generates an artificial gravitational field by centrifugal force. Two of the objectives for developing and studying the concept were to identify the beneficial synergies between systems and to show the potential benefits from using advanced technologies. Because of the cost of transporting materials to orbit, mass reduction became the measurement criteria to evaluate the effects of synergies and the use of advanced technologies.

Many beneficial synergies were identified; some were specific to the configuration studied, and others could apply in general. The study showed that a system which had rotating components could have a beneficial synergy by also using them as control-moment gyros (cmg's). In the use of advanced technologies, this study underscored the need for a continuing development of advanced materials.

Advanced-technology requirements identified by means of the ATSS concept showed a continuing need for improvements in materials, power conversions, life-support system components, flight control techniques, and analytical techniques. In the particular case of advanced-composite materials, benefits directly convert into reductions in mass delivered to orbit. Such benefits compound if the artificial-gravity level can be reduced to less than Earth equivalent and can extend further if the operating internal-pressure requirement is less than an Earth sea-level standard. These items underscore the need for a continuous development of low-mass materials for structure and on-board equipment and also for an improved knowledge of the environments required by humans.

Introduction

The evolution and the establishment of Earth-orbiting space stations are logical steps in the exploration and colonization of space. Space Station *Freedom* has been approved for assembly in 1996. As spaceflight matures, the required capabilities of space stations are expected to increase significantly and to lead eventually to a new second-generation space station configuration. NASA's Office of Aeronautics and Space Technology sponsored a series of preliminary studies (refs. 1–4) to consider these future requirements and suggest missions and configurations to evaluate enabling and enhancive technologies for the year 2025 and beyond. The evolution of a conceptual configuration was guided by several criteria and technical assumptions that included the following:

1. A single, large space station would provide and house the facilities, crew, and power-generating systems needed to perform a multitude of functions anticipated for an advanced-technology space station (ATSS).
2. The ATSS design and operational characteristics would provide for long-term habitation without degradation of crew health or performance.
3. Advanced-technology materials and subsystems would be considered.
4. The definition of systems and operating subsystems would emphasize and quantify beneficial interactions and effects of technology improvements.

The resulting reference configuration for an ATSS concept is shown in figure 1; the principal dimensions and masses of this concept are given in figures 2 and 3, respectively.

The reference ATSS has a large (229-m-diameter) rotating torus that provides artificial-gravity conditions (via centripetal acceleration), a primary habitation and working area for the crew, and volume for gas storage. One Earth gravity (9.8 m/s^2) can be obtained at 2.8 r/min. Artificial gravity is required to maintain a satisfactory physiological condition of the crew members during long-term spaceflight. On the same axis as the torus are two counterrotating tanks that nullify the gyroscopic effect of the torus and function as water-storage reservoirs. Water sloshing in the reservoirs is minimized. The central tube, which is the nonrotating axis of the ATSS, has a berthing and assembly bay attached to one end and a platform attached to the other end. The technique for generating electrical power utilizes a modularized solar-dynamic concept that consists of six identical units; four of these units are mounted on the platform, and two are mounted on the rotating torus.

Several synergistic benefits were considered in developing the reference ATSS configuration and its operation. The purpose of this paper is to review the benefits accrued from the synergies and then to identify additional benefits that can be realized by the use of advanced technologies (such as materials and operational methods). Because the potential benefits just mentioned are dependent to some extent on configuration and operational aspects, a more detailed description of the ATSS is presented in the appendix.

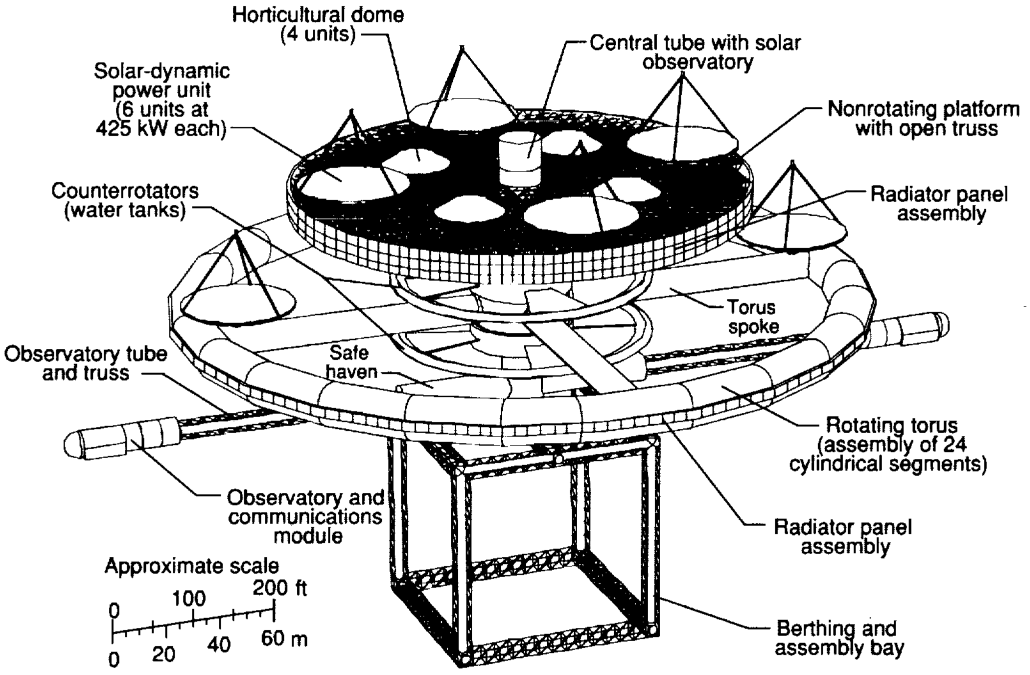


Figure 1. Principal features of reference ATSS. (From ref. 5.)

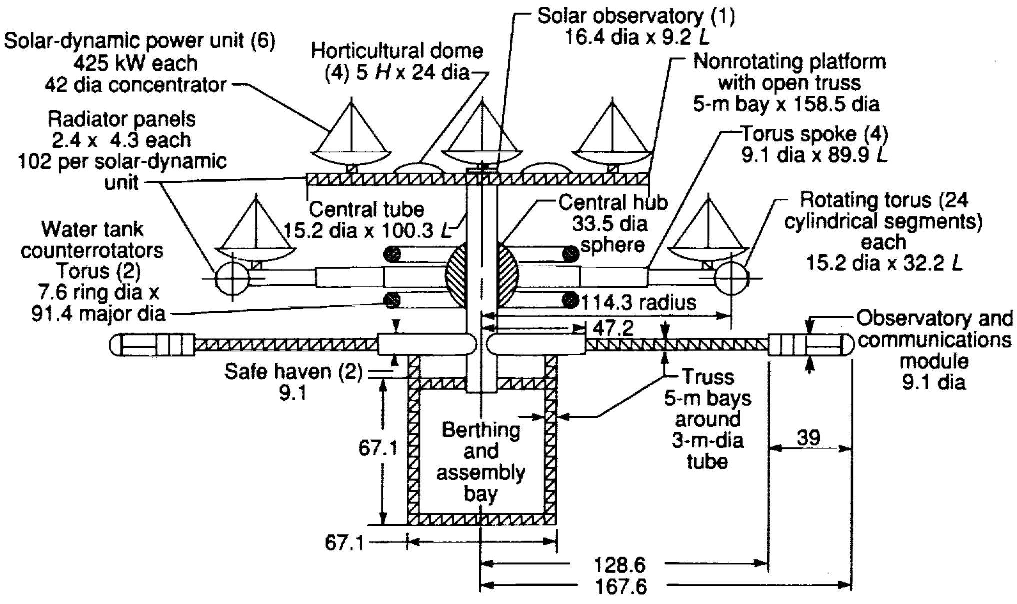


Figure 2. Principal dimensions of reference ATSS. All dimensions are in meters. (From ref. 5.)

Potential Synergies

Synergy is defined as a combined action or operation. In the context of interest, synergy is the interaction of several ATSS elements which results in simplified operations, improved efficiency, reduction in mass to orbit, or any combination of these. A number of potential synergistic interactions were identified inclusively in references 1–5, and they are summarized in table I. These interactions are reviewed in the following sections.

Synergies Based on Water as Control Mass

The counterrotators for the ATSS are tanks of water. Water, which is a vital resource for the ATSS, offers significant synergistic advantages, as shown in figure 4.

Angular Momentum Control

The mass of the water in the counterrotators provides the active ballast for control of angular momentum. The external configuration of the tanks minimizes sloshing by the use of baffles or a sponge-type material from which water can be easily extracted. Changes in the angular momentum caused by variations in the mass of the water are nulled by varying the angular velocity of the counterrotators.

Table I. Potential Synergies of ATSS

- Utilization of water by flow sequence:
  - ATSS angular momentum control
  - Trim control (center of mass and dynamic balance control)
  - Crew support (drink, hygiene, and food preparation)
  - Thermal control
  - Attitude control
- Electrical-power load leveling (scheduling of power):
  - Excess power diverted to electrolysis of water to obtain H_2/O_2 gases
  - Excess power diverted to H_2/O_2 liquefaction
  - Power scheduled for varying loads of systems for wet-air oxidation process, CO_2 reduction, on-board fabrication operations, and water transfer
- Utilization of on-board generated gases:
  - O_2 and N_2 used in life support
  - O_2 and H_2 used for propellants
  - O_2, N_2, and CO_2 used as atmospheric constituents in horticultural research
  - O_2 and N_2 used to replenish atmospheric loss due to leakage
- Structure and construction:
  - Assembly manipulators become berthing-bay cranes
  - Airtight tubes (observation and berthing-bay tubes) serve as air reservoirs for air lock operations

Trim Control

The large, massive, rotating elements of the ATSS make dynamic balance important because wobbling can upset experiments, make pointing of observation and power-collection units more difficult, and possibly cause crew discomfort. Trim control utilizes water redistributed within the ATSS to maintain the center of mass and dynamic balance.

Crew Support

Water provides crew support for drinking, hygiene, food preparation, and general cleaning purposes. Waste water can be used in trim balance or can be electrolyzed to produce oxygen and hydrogen. If required, water from storage also can be electrolyzed to produce the hydrogen and oxygen needed for atmospheric replenishment (O_2) and reduction of CO_2 (H_2).

Thermal Control

Water is an excellent medium for transferring heat both within the ATSS and to the radiators for radiating heat to space. The thermal-control system for the ATSS must include active temperature regulators, isolators for heat sources and heat sinks, heat pumps, heat exchangers for the internal transfer of energy, and external radiators to maintain an overall heat balance. Synergy within the thermal-control system ideally involves the utilization of heat rejected from high-temperature processes as inputs to operations that function at the next lowest temperature level. Therefore, on board the ATSS, the heat transfer into liquid loops is maximized.

Three liquid loops can provide the heat sources and sinks for temperature regulation. A high-temperature loop can draw heat from high-temperature operations (such as ovens, furnaces, or exothermic reaction chambers) and provide heat for lower temperature systems (such as dryers and hot water). An intermediate-temperature loop can accept heat from items such as control panels or power regulators and provide heat for atmospheric temperature control, laboratory chambers, or incubators. A low-temperature loop can extract heat from the atmosphere to control humidity and also provide a low-temperature sink for laboratory coolers or storage areas. Functions that require additional thermal conditioning (such as freezers or refrigerated storage) can operate with their heat pumps discharging heat into one of the two higher temperature loops. The principal heat sources and sinks are subsequently identified.

Electrolytic cells for decomposition of water (heat source). Electrolytic cells can absorb up to one-half of the electrical power supply from the ATSS and thereby act as the primary load-leveling element to a continuous-output power-generating system. The units will operate at temperatures near the boiling

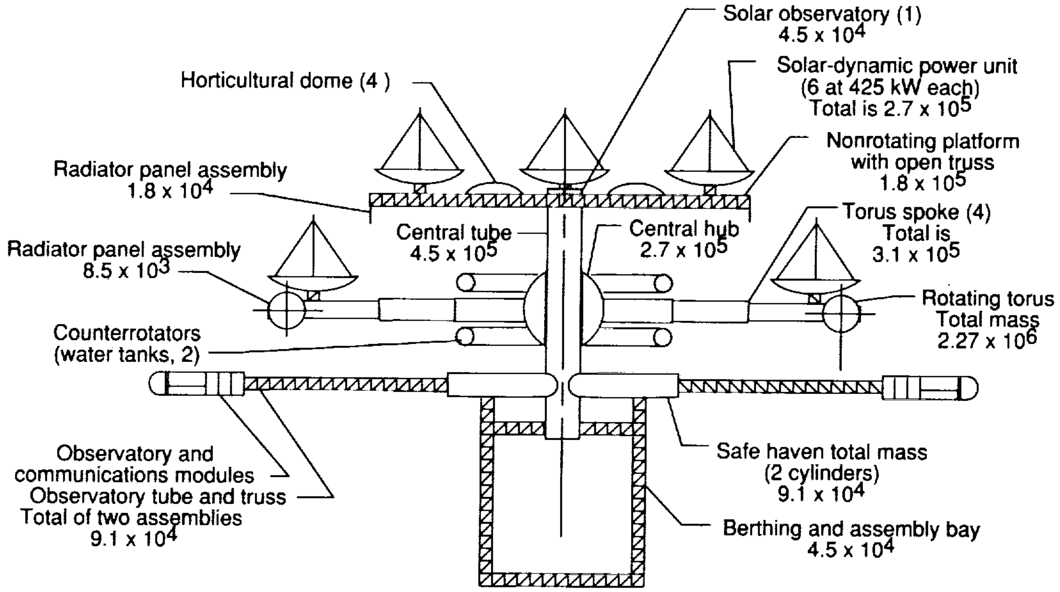


Figure 3. Principal masses of reference ATSS. Mass without counterrotators is 4.2×10^6 kg. Mass with counterrotators is 8.5×10^6 kg. All units are in kg. (From ref. 5.)

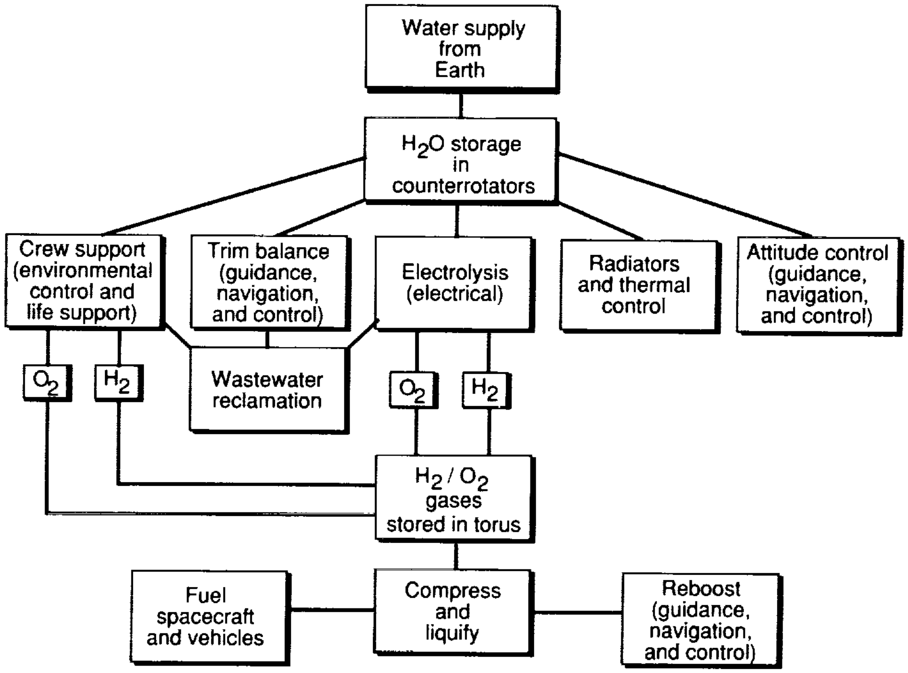


Figure 4. Water utilization on board reference ATSS. (From ref. 5.)

point of water and will dissipate heat. Insulation will contain some of the heat generated, but some degree of external cooling still will be required. These units then will contribute heat to the high-temperature loop.

Wet-air oxidizer (heat source). Wet-air oxidizers release the energy of combustion associated with the oxidization of carbonaceous wastes and the reduction of nitrogen to its elemental form. The energy output from the conversion can supply the compression power necessary for pumping as well as an excess of energy to be applied elsewhere.

Galley operations (heat source). Food preparation on board the ATSS approximates that of a nuclear submarine. The heat required to cook for a 60-person crew must be supplied and removed. The location of the galley in the ATSS torus offers the opportunity of having nearby an independent solar energy collection and storage unit. Food-preparation ovens and kettles require effective insulation. Liquid-to-liquid heat exchangers will recover the excess heat from scullery operations and minimize the heat absorbed by the cabin atmosphere.

Bosch CO_2 reduction reactors (heat sinks). These units run at elevated (full-red) temperatures and absorb the energy necessary to reduce CO_2 to H_2O and C. Electrical resistance provides the heat for this process. The units can operate as part of the electrical load-leveling requirement or accept the converted energy released from wet-air oxidization. The operation at elevated temperatures requires effective thermal insulation to minimize extraneous heat loss.

Metal-working operations (heat sinks). These operations, which include melting, machining, forming, and joining, all require energy inputs that have to be confined and eventually absorbed. The melting and casting processes require effective insulation and heat removal. Conventional machining processes require a fluid that combines the functions of lubrication and cooling. Forming operations (such as bending, drawing, and swaging) also generate heat. Joining operations (such as welding or soldering) involve a significant heat release. Each function must be integrated into the total thermal system.

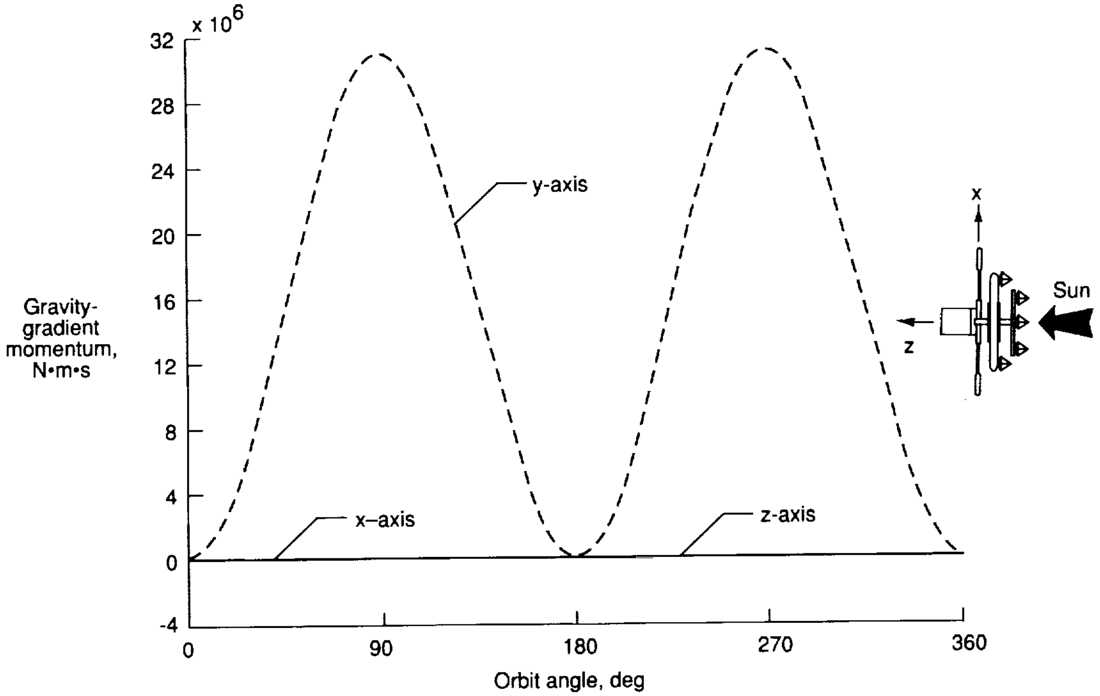


Figure 5. Gravity-gradient momentum on ATSS as function of orbit angle. (Adapted from ref. 5.)

Attitude Control

The ATSS is a large, massive structure that is subject to very large gravity-gradient torques and angular momentum variations because of its Sun orientation. As shown in figure 5, the gravity-gradient-induced angular momentum oscillates between 0 and 32×10^6 N·m·s. Control-moment gyros used for attitude control absorb or produce applied torques by changing the plane of rotation for a spinning mass. Applying this concept to the counterrotators on the ATSS as a means to null the applied gravity-gradient torques and absorb the momentum involves the following expressions for the angular change ν in the plane of rotation:

$$\sin\nu = \frac{H_T}{2H_\nu}$$

where

H_T	maximum gravity-gradient angular momentum, 32×10^6 N·m·s
H_ν	angular momentum of each counter-rotator (for 1 Earth gravity of torus), 4.68×10^9 N·m·s

For this case, $\nu_{\max} = 0.2°$.

The gravity-gradient forces imposed upon the ATSS can be accommodated by cyclically shifting the periphery of the counterrotators by 0.32 m over a period equal to one-quarter of an orbit ($\approx$22 min). For comparison, if these momentums and torques can be accommodated by the presently available cmg's, then the number of units and the additional mass can be estimated. The specifications for a current large cmg (ref. 3) show an angular momentum capacity of 6100 N·m·s and a mass of 295 kg. Absorption of the ATSS gravity-gradient angular momentum requires 2546 such units and involves an additional mass of 748 000 kg, which thereby incurs more than an 8-percent increase for the total mass of the ATSS. The synergy associated with using counterrotating members of spacecraft to compensate for gravity-gradient effects needs to be explored for any configuration that generates artificial gravity by rotation.

Synergies Based on Electrical-Power Load Leveling

The many ATSS functions, which are listed in table II, require substantial amounts of electrical power. The solar-dynamic units are constant-level power generators that are scaled to accommodate peak load. However, the power demand is expected to fluctuate, depending largely on the load due to manufacturing processes. In such instances, excess power can be scheduled for different functions to make use of the available power. Such uses become load levelers, and these levelers are listed in table I. Most of the items listed are self-explanatory. The many uses of O_2 and H_2 indicate that their production by the electrolysis of water becomes the primary load leveler.

Synergies Based on Utilization of On-Board Generated Gases

The principal on-board gases for the ATSS consist of O_2 and N_2 as the atmospheric constituents. These gases must be maintained in the proper proportion. In addition, CO_2, which is generated by the crew, must be removed from the atmosphere. The waste-processing system (wet-air oxidation) frees N_2 from nitrogenous waste while consuming O_2 in reducing carbonaceous waste to CO_2. The replenishment of O_2 for the atmosphere and the reduction of CO_2 by the Bosch process require O_2 and H_2, which are obtained by the electrolysis of water.

The operation of the ATSS as a propellant source for other spacecraft offers an additional synergy by the generation of hydrogen and oxygen from electrical load leveling. In such an application, specific advantages exist in the launching of water rather than cryogens. As a first-order effect, a cubic meter of water at standard atmospheric pressure (SAP) and temperature would become 0.78 m^3 of LO_2 at 90 K and 1.58 m^3 of LH_2 at 22 K. Therefore, in addition to a critical requirement for cryogenic insulation, the transported volume is more than doubled.

An assessment of on-orbit propellant generation, in quantities that would support six lunar missions per year using 100 000 kg each (ref. 6), shows this process to be capable of a net benefit in mass delivered to orbit by the end of the first year; this time frame is less than 10 percent of the baseline mission life for the ATSS. This assessment is based upon the description of the external tanks for the Space Shuttle, as shown by figure 6 (refs. 7 and 8). At a

Table II. Potential Functions, Power Estimates, and Personnel Requirements of ATSS

Mission support function	Personnel	Power, kW
Science and research	10	100
Observatory for Earth, space, and Sun		
Orbital science research laboratory		
Variable-gravity research facility		
Horicultural research facility		
Technology demonstration facility		
Habitation and medical*	26	750
Crew life support systems		
Variable-gravity adaption (spacecraft crews)		
Accommodations for transients (tourists)		
Medical care for crews and transients		
Manufacturing	12	1500
Component manufacture and spacecraft assembly		
Commercial microgravity processing		
Operational support	12	200
Spacecraft service and repair		
Transportation node and retrieve-resupply-deploy		
Communication center and relay point		
Control center for other spacecraft		
Energy collection and relay		
Storage and supply center		
Total	60	2550

*Habitation and medical category includes margin for contingencies.

nominal 1-atm pressure, the oxygen tank accommodates approximately 570 000 kg of cryogenic liquid or 500 000 kg of water. In the cryogenic liquid state, this mass of water becomes 390 m^3 of LO_2 and 793 m^3 of LH_2. The additional tankage mass can be estimated from the mass-to-volume ratios for the Space Shuttle tanks. The oxygen tank has a mass-to-volume ratio of 10.14 kg/m^3, which corresponds to a tank mass of 3954 kg. The hydrogen tank shows a ratio of 8.58 kg/m^2, which corresponds to a tank mass of 6804 kg; together these total 10 758 kg. Transport of 500 000 kg of water saves 5158 kg in the mass of tank metal alone and represents approximately 1 percent of the water mass.

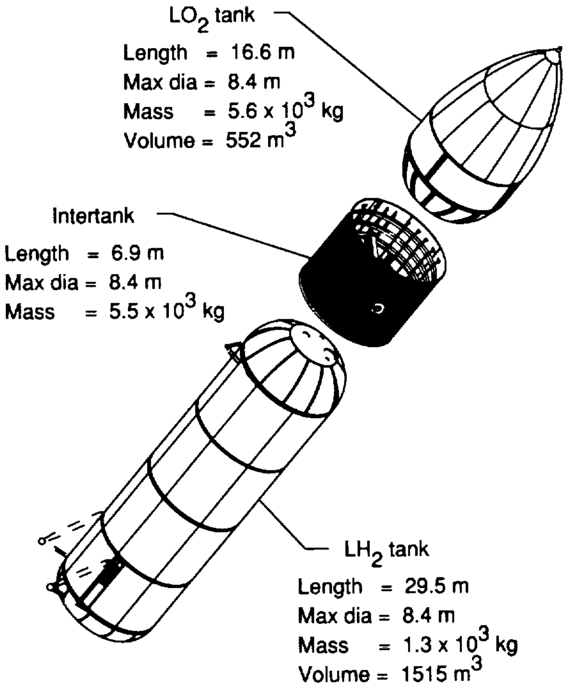


Figure 6. Features and masses of Space Shuttle external tank. (Adapted from refs. 7 and 8.)

Propellant estimates for the lunar missions show a need to electrolyze water at an average rate of 68.5 kg/hr. Electrolytic cells operating at an 80-percent efficiency will consume 356 kW, which represents approximately 28 percent of the load-leveling capability defined for the ATSS; this usage approximates the contingency allotment for the power-generation system listed in table II. Studies of cryogenic propellant generation on orbit have established estimates for both performance parameters and associated masses. Table III summarizes the results for an on-orbit production facility that processes water into cryogenics at 89 kg/hr. The total required power shown is 30 percent of the ATSS capability, and the total additional mass for on-board equipment is less than the total listed. The ATSS configuration includes the water tanks, electrolytic cells, cryogenic tanks, and mounting structure as part of the on-board capability. The added mass increment for the defined system will range from 5310 kg to 9490 kg. Therefore, considering only a 1-percent savings in mass of the transport tanks, the system listed will amortize in the course of 6 to 10 lunar excursions; considerations of insulation, handling equipment, and related operations indicate an amortization within the first 6 lunar excursions such that a mass-to-orbit benefit accrues over 90 percent of the ATSS baseline mission operation.

Table III. Estimates of Power and Mass Requirements for Orbiting Electrolysis–Cryogenic Facility That Processes 89 kg of Water Per Hour*

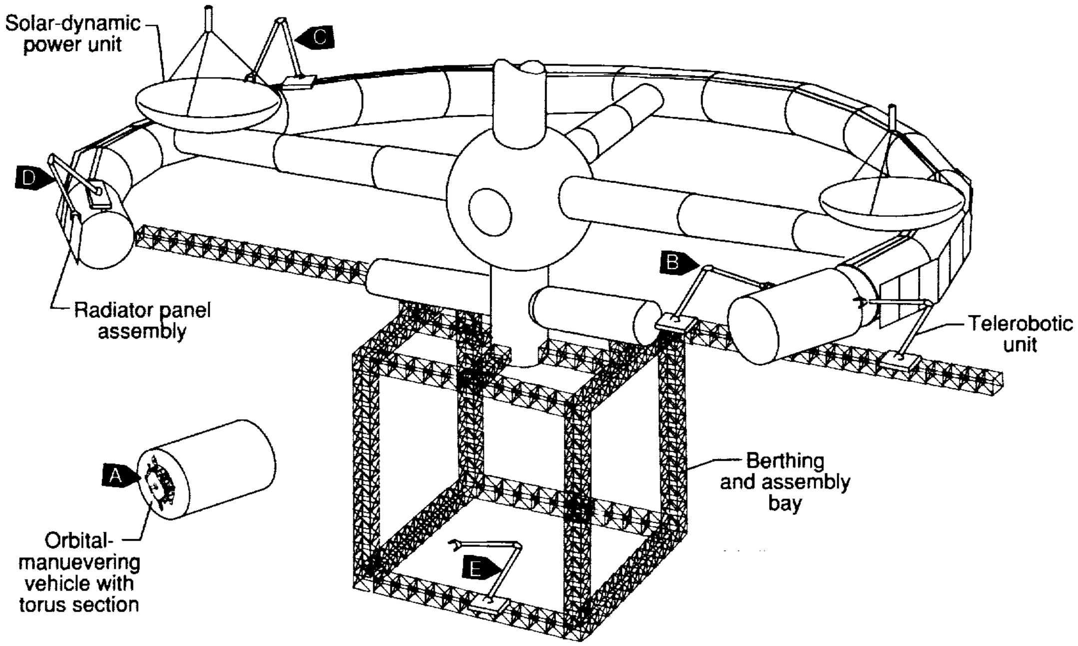
Power, kW		Mass, kg	
Electrolysis 5.20 kW-hr/kg (30 percent efficient)	465	Electrolysis LH_2 liquefier	2110 2330
H_2 liquefaction 17.20 kW-hr/kg	171	LO_2 liquefier	600
H_2 reliquefaction 5.73 kW-hr/kg	18	Radiator (405.5 m^2)	960
O_2 reliquefaction 1.32 kW-hr/kg	105	Insulation	1100
O_2 reliquefaction 0.88 kW-hr/kg	6	Structure	4180
Processor pumps and dryers	1	Process control and avionics	540
Processor control	3		
Total required	769		
Electrical conversion efficiency, percent	95		
Total power	810	Total mass	11 820

*Data courtesy of General Dynamics Corporation.

Synergies Based on Structure and Construction

The synergies related to structure and construction make multiple use of the equipment that assembles the ATSS in orbit. The concepts and equipment requirements for assembling the ATSS in orbit are illustrated in figure 7. The assembly of trusses and joining of sections require large telerobotic booms and manipulators that precisely position massive elements throughout each step of an assembly sequence. The assembly and servicing of large spacecraft also require the same telerobotic capabilities. Therefore, the telerobotic units used to assemble the ATSS move to the berthing and assembly bay and continue their support during assembly and servicing of other large spacecraft.

Within the ATSS, the structure of the berthing bay and observatory booms consists of pressurized tubes surrounded by a truss. Stiffness criteria define these elements such that the tubular elements operate with a significant margin relative to the loadings from internal pressure. The central tube has internal accommodations for assembly and checkout of smaller spacecraft, and an air lock door provides access to the berthing bay. The tubes within the berthing-bay structure function as temporary storage pressure vessels for the atmosphere within a central tube assembly bay during air lock transfer operations. The use of the structural margin available from such tubes allows air lock operations in the stationary portion of the ATSS to proceed without interacting with the atmosphere in the rotating section of the ATSS.



A Orbital-maneuvering vehicle transporting section to mate position
Telerobotics perform:
  B Positioning for assembly and joining
  C Assembly and installation of solar-dynamic power unit
  D Installation of radiator panel assembly
E At completion, telerobotic units move into berthing and assembly bay for assembly and service of other spacecraft

Figure 7. Concept for ATSS assembly in orbit showing berthing and assembly bay, orbital-maneuvering vehicle, and telerobotic units. (From ref. 5.)

Technology Effects and Interactions

The ATSS study examined the potential interactions between the advanced technologies and technical areas that were identified for investigation. A significant potential for beneficial interactions appeared in the assessment of effects due to the use of advanced composites for structural elements, operation at a lower gravity level by slower rotation of the torus, and operation at a reduced atmospheric pressure within the pressurized sections. Mass reductions are used as a measure of the effectiveness of these changes.

The items just mentioned are interactive, and their cumulative effects, in the mentioned order, have been examined. For convenience, the total mass of the ATSS is considered to be made up of three assemblies. These assemblies include the rotating assembly, which is composed of the torus, spokes, central hub, and two solar-dynamic units located on the torus, the stationary assembly, which includes all components that are inertially fixed, and the counterrotators. The rotating and stationary assemblies are composed of the following elements:

1. Pressure shells. These are structures in which the principal loading is defined by the internal atmospheric pressure.
2. Structure. The structure is composed of internal elements such as floors, walls, and tie beams. These units support the centripetal force (i.e., artificial gravity) loads within the rotating elements.
3. Equipment. The equipment includes the items that are mounted on floors or walls; these items provide the operating capabilities within the ATSS.
4. Atmosphere. The gas quantity within the habitable areas is maintained at a breathable quality level.
5. Variables. The variables include the crew, supplies, trim ballast, and consumables. The masses assigned are assumed to be constant for this comparison.
6. Power. The power consists of six identical solar-dynamic units; each unit continuously delivers 425 kW at a specific power of 100 kg/kW. The mass is assumed to be constant for this comparison.

Baseline Mass Estimates

The baseline mass estimates shown in figure 3 were based on an aluminum alloy structure, an internal pressure equal to 1 standard Earth atmosphere, and an effective gravity on the torus centerline equal to 1 Earth gravity. These conditions were selected because of the broad data base available. Mass estimates for each element just listed were made using the detailed weight listings of reference 2, and these estimates serve as a basis for measuring the changes resulting from interactions. These baseline masses are listed in the first column of table IV.

Estimates for the required mass of the counterrotators were based on nulling the angular momentum of the rotating sections. The relationship can be expressed as

$$(I\omega)_{\text{Rotating section}} = (I\omega)_{\text{Counterrotators}} \tag{1}$$

The rotating section is made up of the torus, spokes, central hub, and two solar-dynamic units. In order to avoid lengthy calculations but still show the qualitative effects of the variables under study, two basic assumptions were made: The torus, spokes, and hubs all had the same ambient internal atmospheric pressure, and the equipment, atmosphere, structure, and variables are distributed uniformly throughout the torus, spokes, and hubs. These assumptions allow a constant radius of gyration for the combination consisting of the torus, spokes, and hub throughout the calculations of this study. Equation (1), therefore, can be expressed as

$$(m_1 k_1^2 + m_2 k_2^2)\omega_1 = m_3 k_3 \omega_3 \tag{2}$$

where subscript 1 denotes the torus, spokes, and central hub assembly, subscript 2 denotes the two solar-dynamic units on the torus, and subscript 3 denotes the counterrotators.

The radii of gyration for the three entities were calculated to be approximately $k_1 = 106$ m (torus, spokes, and hub), $k_2 = 100$ m (solar-dynamic units), and $k_3 = 45.5$ m (counterrotators). The mass m_1 can be related to table IV as the sum of the masses of all elements in the rotating section except the power (solar-dynamic units). Equation (2) can be used with the mass estimates of the rotating section and the radii of gyration just noted to calculate the counterrotator mass required to null the angular momentum.

Benefits From Advanced-Composite Materials

The mass for the baseline design of the ATSS is based on the use of aluminum alloys; the alloy used has a density of 2700 kg/m^3 for the construction of all pressure vessels (such as the torus cylindrical segments, telescopic spokes, and observatories). Aircraft structures have been fabricated from structural composites that show mass reductions relative to conventional aluminum construction. The mass reductions range from 15 to 47 percent, depending on the design, matrix material, and reinforcement selected (ref. 5). Figure 8 indicates the ultimate tensile strength for present aircraft materials and for structural composites. Among the metals, aluminum has the broadest acceptance and the largest applications data base.

Metals have near-isotropic properties. In contrast, structural composites may be highly anisotropic due to a preferred orientation of reinforcement plies. The ability to achieve a preferred strength direction within a composite laminate by orienting the predominant strength direction of each ply can yield a composite structure with great strength in one direction, but strengths may be less in other directions. The comparisons in figure 8 show a synthetic resin matrix composite with a preferred reinforcement orientation; this composite attains ultimate tensile strengths comparable to both steel or titanium with densities less

Table IV. Effects of Material and Environmental Changes on Mass of ATSS for Torus Radius of 114.3 Meters

[Masses are in tonnes]

Defining parameters	Aluminum materials, Earth gravity, SAP	Composite materials, Earth gravity, SAP	Composite materials, 0.5 Earth gravity, SAP	Composite materials, 0.5 Earth gravity, 0.7 SAP
ATSS without counterrotators				
Rotating sections				
Pressure shells	1294	906	906	634
Structures	747	524	272	272
Equipment	307	215	215	215
Atmosphere	223	223	223	156
Variables	197	197	197	197
Power	88	88	88	88
Subtotal	2856	2153	1901	1562
Stationary sections				
Power	185	185	185	185
Variables	113	113	113	113
Atmosphere	46	46	46	32
Equipment	197	138	138	138
Structures	454	318	318	318
Pressure shells	349	244	244	171
Subtotal	1344	1044	1044	957
Total ATSS without counterrotators	4200	3197	2945	2519
Counterrotators	4300	3236	2053	1685
Total ATSS	8500	6433	4998	4204

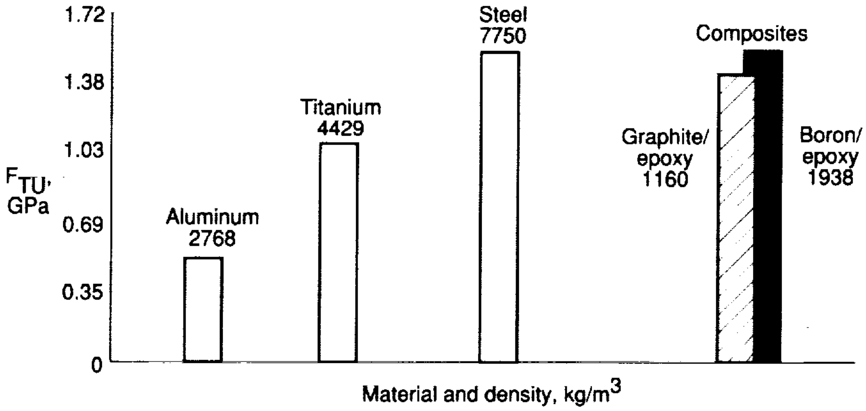


Figure 8. Comparison of ultimate tensile strength and densities for typical aircraft materials. (Adapted from ref. 5.)

than those of aluminum. As a further comparison, table V lists the mechanical properties for structural I-beams of identical cross sections formed from steel, titanium, aluminum, and graphite/epoxy composites. A comparison of the resistance to bending deflections (stiffness, EI) shows that the graphite/epoxy beam compares favorably with steel at only 20 percent of the mass. These comparisons illustrate the potential for mass reductions in the utilization of composites, particularly when the placement of reinforcement plies results in an equalization of stress levels throughout the structure.

In evaluating the benefits from composite materials within the ATSS, the 15- to 47-percent potential for mass reduction was averaged at 30 percent and applied to the pressure shells, structure, and equipment categories. The resulting values are tabulated in column 2 of table IV. These values show a net reduction of 700 000 kg for the rotating section and 290 000 kg in the stationary section. The reduction of mass in the rotating section results in a balancing reduction of 1 050 000 kg in the mass of the counterrotators as defined by equation (2). This comparison illustrates the compounding effects of mass reduction in a system that has to null angular momentum. In the example cited, a mass reduction in the primary element (i.e., the torus) was more than matched by the reduction in the counterrotating element.

Table V. Comparison of Properties for a Structural Shape

[From ref. 5]

Parameters	Steel A36	Titanium 6 Al-4V	Aluminum 7075-T6	Graphite/epoxy composite
Moment of inertia, I, cm^4	520.7	520.7	520.7	520.7
Modulus of elasticity, E, GPa	186.0	117.0	69.0	179.0
Stiffness, EI, MN-m^2	0.97	0.61	0.36	0.93
Ultimate tensile stress, MPa	552.0	1103.0	572.0	965.0
Mass of unit length, kg/m	7.2	4.3	2.8	1.5

Benefits From Reduced Artificial Gravity

The earlier studies (refs. 1–5) assumed that the torus rotates at 2.8 r/min to provide an artificial gravity equal to that at the surface of the Earth. This value was selected because of the indications that long-term low-gravity conditions may have detrimental effects on humans (refs. 2, 9, and 10). If research data indicate that partially reduced gravity levels can be tolerated, further reductions in ATSS mass are possible. A gravity of one-half of the Earth's value is used to quantify the possible benefit. Mass reductions are measured relative to the ATSS using advanced structures and operating at a 1g level. For this comparison, the reduction in artificial gravity changes the torus rotation from 2.8 r/min to 2.0 r/min. A direct benefit of lowering the artificial-gravity level is the reduced effective weight of the equipment in the rotating section, which in turn permits a reduction in the mass of the supporting structures. Assuming that the mass of the supporting structure is linearly proportional to the effective floor load, then reducing the floor load by 50 percent reduces the structure by 50 percent; for the ATSS, this results in a 260 000-kg reduction for the mass of the structure in the rotating section.

The reduced angular velocity of the torus (to obtain one-half gravity) and the reduction of mass in the rotating section result in a corresponding decrease in the angular momentum of the rotating section. Momentum balance thereupon allows a subsequent reduction in the mass of the counterrotators. For a constant angular velocity, the mass reduction in the counterrotator is approximately 1 240 000 kg, as shown by comparing columns 2 and 3 of table IV.

Benefits From Reduced Atmospheric Pressure

The reduction of atmospheric pressure in the torus, spokes, hub, and central tube shows effects that also permit mass reductions. The physiological requirements associated with humans operating under a reduced atmospheric pressure are discussed in references 11, 12 and 13; however, reduction to a 70-percent standard atmospheric pressure appears reasonable and is slightly below that of a jetliner cabin pressure (fig. 9). The mass reductions incurred by reducing the pressure derive from a corresponding decrease in the atmospheric density and in the

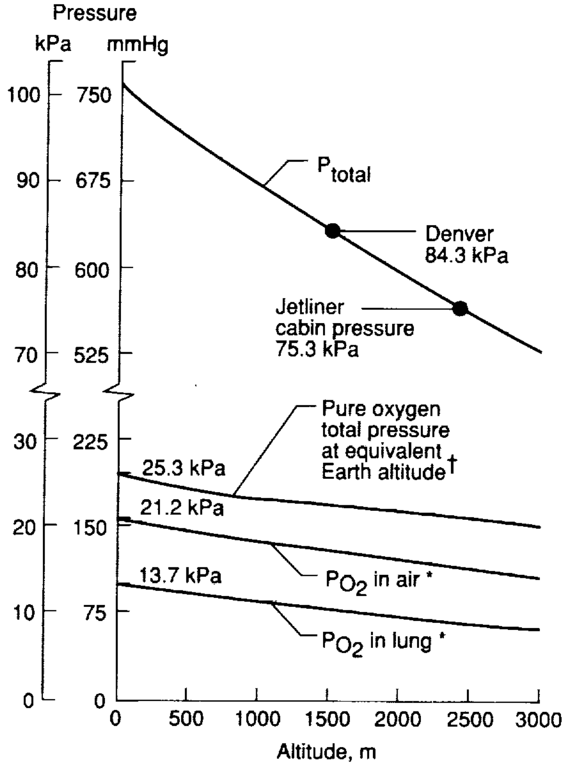


Figure 9. Partial pressure of oxygen in air and lung versus altitude. (Adapted from refs. 11* and 12†.)

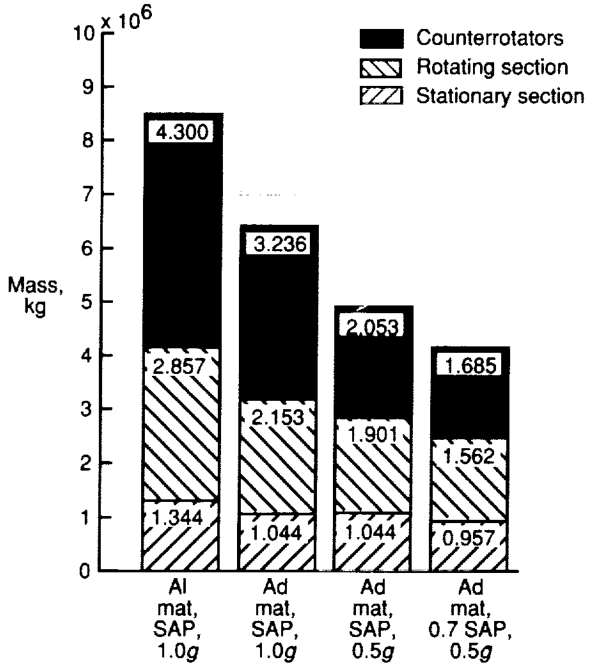


Figure 10. Effects of materials and operational changes on ATSS mass. Torus radius is 114.3 m. (From ref. 5.)

required shell thicknesses of the pressurized volumes. In this study, a 30-percent pressure reduction translated into a 30-percent reduction in the mass of the atmosphere and pressure shells. (Compare columns 3 and 4 of table IV.) The net result is a mass reduction of 340 000 kg in the rotating section and 250 000 kg in the stationary section. The reduction in mass of the rotating section results in a corresponding reduction in the counterrotator mass of 380 000 kg.

The combined effects on the ATSS mass from the use of composite materials, reduced artificial gravity, and reduced atmospheric pressure are summarized in table IV; the overall effects are illustrated in figure 10. Each of the examined changes produced large reductions in the ATSS mass. These results identify the need to establish actual gravity levels and atmospheric pressure requirements for astronaut habitability and to continue development of composite materials and their application.

Concluding Remarks

Configuration and system studies for an advanced-technology space station (ATSS) were conducted to identify the technological requirements for second-generation space stations. The technology of Space Station *Freedom*, which represents the present status for flight-ready availability, was the point of departure for determining and assessing future technology and synergistic benefits.

A review of proposed space missions identified the functions which determined that the ATSS would serve as a combined transportation, communications, and power node, as research and storage facilities, and as a haven for permanent and transient personnel. Consideration of these functions led to a large-scale system in which the synergistic use of resources between subsystems would become possible.

The overall configuration and size were substantially determined by the need to provide artificial gravity for long-term human activity and variable-gravity research. These requirements led to a concept in which the principal components included a torus with a major diameter of 228.6 m; this torus rotated on an inertially fixed central tube such that a torus rotation rate of 2.8 r/min produced 1 Earth gravity. Two large tanks rotating counter to the torus served as water-storage facilities and nullified the net angular momentum.

The concept shows a number of benefits derived from the usage of water.

1. Water, rather than cryogenic hydrogen and oxygen, is transported to the ATSS and thereby reduces the tank mass and eliminates the requirement for cryogenic insulation.
2. A constant-output electrical power plant that supplies a variable demand results in periodic

excesses that can be used to generate H_2/O_2 propellants from water stored on board.

3. The mass and cost of a facility to electrolyze water and produce cryogenic hydrogen and oxygen can be amortized in less than a year, or 10 percent of the initial mission time.
4. The gyroscopic properties of the counterrotating tanks also provide a means to counteract very large gravity-gradient induced torques and thus eliminate the need for auxiliary control-moment gyros.

The use of some technological advances in materials, coupled with the eased environmental conditions, can provide significant benefits relative to the total mass of the ATSS. If the basis for comparison assumes that the ATSS is an aluminum structure, has an artificial-gravity acceleration of 9.8 m/s^2, and uses pressure shells operating with a standard atmospheric pressure, then the overall mass of the ATSS is affected accordingly.

1. The use of advanced-composite materials in place of aluminum can reduce the ATSS total mass by approximately 24 percent.
2. The reductions in an acceptable level of artificial gravity, by slowing the rate of rotation, further decrease the overall mass. For the case cited, the use of composite materials and the reduction of artificial gravity to 0.5 Earth gravity provide a 36-percent overall mass reduction for the ATSS.
3. A reduction in atmospheric pressure from standard sea level to 70 percent of the standard lowers the mass of the atmosphere in the pressure shells and the mass of the pressure shells by 30 percent. The reduced mass in the rotating section affects the counterrotators such that the mass reductions total more than 50 percent relative to the baseline configuration.

In conclusion, the ATSS studies achieved their objectives of defining pacing technologies and showing potential beneficial synergies for a second-generation space station concept that produced artificial gravity by rotation. In addition, these ATSS studies also implied that artificial gravity by rotation requires the identified synergies. Electrical power generated from solar radiation sources requires stabilized pointing; such a spacecraft as the ATSS will have both rotating and nonrotating sections. A rotating spacecraft will experience cyclic gravity-gradient torques for all conditions except rotation in the plane of the orbit. A solar pointing spacecraft such as the ATSS must counteract gravity-gradient effects; therefore, nulling the cyclic torques and maintaining dynamic balances by trim ballasting become realistic continuous operating features. These effects, in turn, are related to the artificial-gravity level and masses involved. Because the total mass includes the internal on-board atmosphere, the technology items, synergies, and their interactions as just described identify on-board feature requirements imposed upon any such space station or spacecraft.

NASA Langley Research Center
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Appendix

Description of ATSS Configuration

ATSS Configuration Requirements

The ATSS defined for this study was not a design for advocacy, but it was a configuration that served as a basis to identify pacing technologies and benefits from advanced technologies. The configuration addressed a series of requirements considered pertinent to a second-generation space station.

Functional Requirements Defined From Future Mission Descriptions

NASA contemporary planning literature, such as references 14–16, identified the functions required for an ATSS. The identified functions were consolidated into a listing of 17 specific items that fell into four major mission support areas. The four areas included capabilities for research; for assembly, supply, servicing, and control of other spacecraft; for processing and manufacture; and a facility for medical and conditioning support for crews of other space vehicles. These functional requirements, in turn, generated the estimates for the crew complement and for the electrical power needs. The results are summarized in table II.

Physiological Requirements

The ATSS is considered a long-term habitat and a test bed to study gravitational effects on human subjects. However, previous spaceflight experience has shown that prolonged exposure to microgravity conditions can cause physiological problems such as bone demineralization and loss of muscle structure (refs. 2 and 9). Therefore, an artificial-gravity environment became a general requirement to study the physiological effects and to provide physical conditioning.

A rotating environment introduces its own set of problems (refs. 2 and 10). The criteria presented in figure A1 (from ref. 10) show rotating and acceleration constraints applicable to humans. A rotating torus with a radius of 114.3 m was selected as the best compromise to accommodate the mission functions within the acceptable operating region.

Operational Requirements

Functional support for other spacecraft, particularly those for interplanetary and lunar exploration missions, established requirements for the support and servicing features of the berthing and assembly bay and led to the selection of the open-face cube configuration.

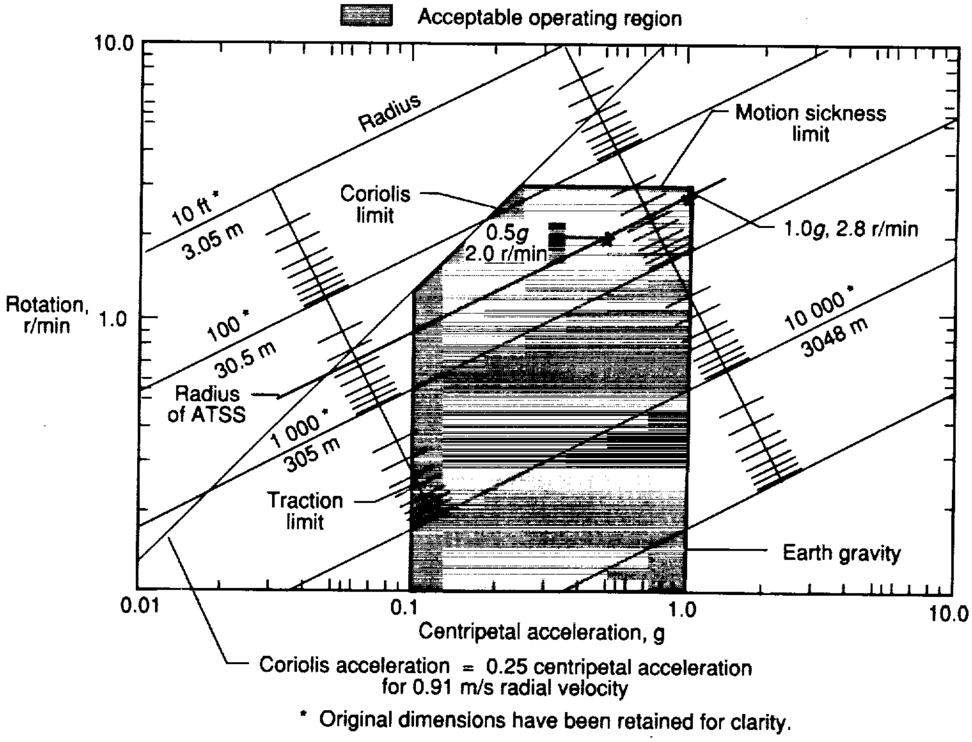

Figure A1. Acceptable operating region for humans in artificial gravity produced by rotation. (Adapted from ref. 10.)

Electrical Power Source

A modularized, solar-dynamic electrical-generating source was selected as the baseline from among the solar-photovoltaic, radioisotope, nuclear fission, and fusion power alternatives. Solar-dynamic systems represented the emerging technology and also presented the opportunity to explore synergies and evaluate the interactions between rotational dynamics and the stringent pointing requirements associated with solar concentrators focused into the apertures of collectors.

ATSS System Description

The major configuration components for the ATSS were derived from the functional, physiological, and operational requirements and are summarized to provide a basis for the synergy and technology discussions.

Torus, Spokes, and Hub

The large rotating torus generates artificial gravity by centripetal acceleration, provides the primary habitation and working areas for the crew, and provides volume for O_2 and H_2 gas storage (fig. A2). The minor diameter of the torus tube is 15.2 m, and the major radius of the torus is 114.3 m. An equivalent lunar gravity (approximately one-sixth of the Earth's gravity) can be obtained at 1.14 r/min; an equivalent Earth gravity can be obtained at 2.8 r/min. Both conditions fall within the acceptable operating region and result in a gravity field that varies less than 10 percent throughout the torus and less than 2 percent over the body length of a crew member.

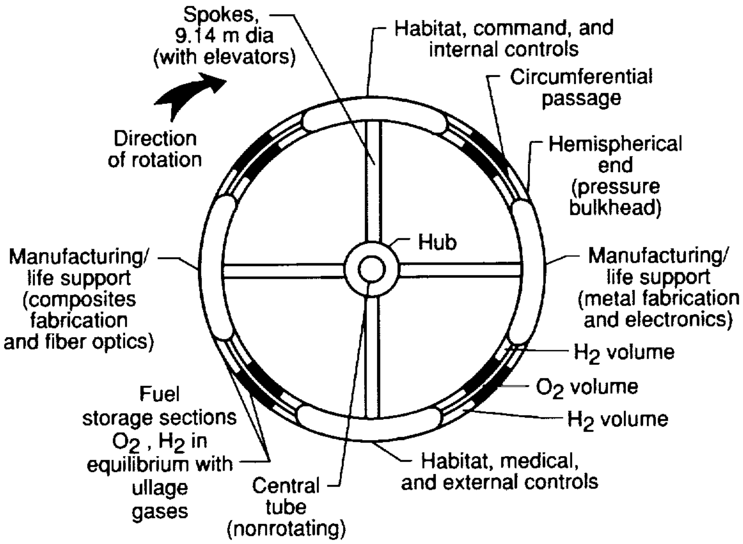

Figure A2. Rotating sections of ATSS. (From ref. 5.)

Four cylindrical spokes connect the torus to a spherical hub. These spokes provide the access pathways to the torus in the form of freight and passenger elevators. In addition, two of the spokes have provisions for a variable-gravity facility. The hub contains the mechanisms for transfer, or exchange, between the rotating and nonrotating portion of the ATSS. The hub carries the rotating joints and seals at the central tube and also provides the running surfaces for the two counterrotators. (See ref. 2 for details.)

Counterrotators

The counterrotators, which are toroidally shaped water tanks with an outside diameter of 91.4 m, null the angular momentum of the torus. This feature facilitates precession of the ATSS at the 1-revolution-per-year rate required to maintain the Sun-facing attitude required by the solar-dynamic power-generation units. For the purposes of this study, the counterrotation rate has been set at 10 r/min. The arbitrary selection of 10 r/min for counterrotation has a recognized result in large estimates of mass such that the counterrotators become a major contribution to the total estimate of mass for the ATSS. However, the synergistic use of water is one of the principal features of the ATSS. Water is the active ballast within the counterrotators and, at the same time, is the on-board fresh water reservoir. The ATSS studies recognized that the nulling of angular momentum could result in small changes would become a function of the construction used for the counterrotators. However, at a rotation rate of 10 r/min, the fluid-filled storage containers appear within the limits of present technology for materials and controls for fluid dynamics. The requirements for a pressurized torus equate to loadings compatible with presently available aluminum. The peripheral velocity for the counterrotators is 48 m/s, which approximates the takeoff or landing speeds of present transport aircraft, and the inertial effects are much less than those associated with either takeoff or landing. Present aircraft techniques for control of fluid-filled containers appear adequate for the ATSS application. The unique requirements for exchanging water ballast have been addressed in reference 2; the requirements for an interactive drive system have been identified in reference 3 as a configuration-related pacing technology.

Solar-Dynamic Units

Electrical power generation for the ATSS utilizes six identical solar-dynamic units that run continuously at a constant output. Each unit generates 450 kW and delivers 425 kW. Two of the units are mounted on the torus, and the remaining four are mounted on the platform so that the total installation distributes power throughout the ATSS and eases requirements for power transfer across rotating joints. The principal features of the solar-dynamic units are paraboloid-of-revolution concentrators that are 42 m in diameter. Collectors at the focus store energy in a molten-salt phase-change material and supply a continuous heat input to converters that transform 40 percent of the heat energy into electrical energy. Detailed descriptions of the solar-dynamic units and other components of the electrical power-generation system are given in references 3 and 4, which also include a comparison evaluation of the alternate sources for electrical power generation.

Central Tube, Berthing Bay, and Safe Havens

A Sun-facing, nonrotating central tube, illustrated in figure A3, provides a common axis for the rotating elements, an access pathway within the ATSS, and a point of attachment for all other elements. The central tube has a diameter of 15.2 m and a length of 100 m. The Sun-facing end provides a solar observatory. The remaining volume houses a microgravity facility and a number of bays which are separated by air locks for the assembly or servicing of other spacecraft. Transfer operations to the rotating portion of the ATSS utilize the two transfer ports. The main transfer port is concentric with the centerline of the spokes and is intended for large objects serviced by the freight elevators. The personnel transfer port leads to a passenger elevator that moves along the outer wall of a spoke. The main air lock, at the end of the central tube, opens into a berthing bay. The bay (fig. 2) consists of an open-faced cube with edges that are 67.1 m long; these edges are formed by tubes with diameters of 3.0 m. The tubes are surrounded by trusses that are formed as 5-m repeating cubes. The berthing bay accommodates supply flights and the assembly or servicing of large spacecraft by the use of robotic booms and manipulators that move along the edges of the cubes. The outboard ends of the tubes have air lock ports that permit the docking of crew transfer vehicles so that crews and carry-on items can be exchanged in a shirt-sleeve environment. The inboard ends of the berthing bay terminate in crew safe havens that are joined to the central tube and form the bases of the observation tube sections. These safe havens, which have a diameter of 9.2 m and a length of 39.6 m, provide temporary living facilities for crew members working in microgravity conditions and have the capability to support the entire crew should an emergency occur (ref. 2).

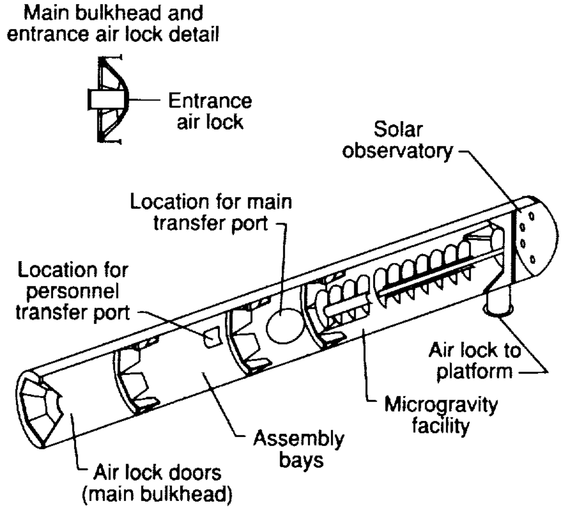

Figure A3. Central tube interior features. (From ref. 5.)

Platform, Solar Observatory, and Observation and Communications Modules

The Sun-facing end of the central tube supports a platform that is 158 m in diameter and is constructed as an open truss of 5-m repeating cubic bays (fig. 2). The platform provides an area for mounting experiments and supports four domes for horticultural research as well as four of the solar-dynamic units and their radiators. The remaining open area and the volume within the trusses are available for installing other space or solar research instrumentation.

The observation tubes carry identical observatory and communication sections at each end; these sections are illustrated in figure A4. The sections include a celestial observatory, an Earth observatory, a communication section, a tracking section, and an energy-relay section. The end sections are 9.2 m in diameter and 39 m in length. The incorporation of celestial- and Earth-viewing observatories requires the observation tube to be stabilized perpendicular to the plane of the ecliptic (see ref. 2 for details).

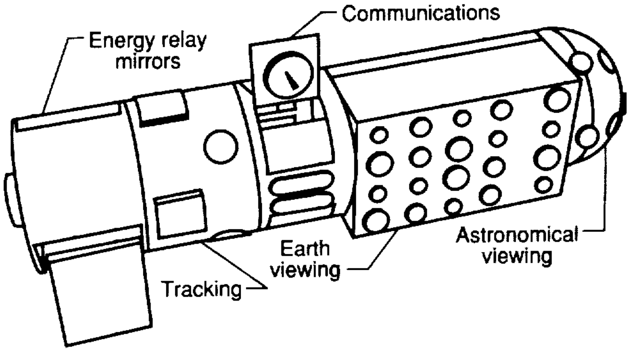

Figure A4. Operating elements at each end of observation tube. (From ref. 5.)

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16. Abstract

A configuration for a second-generation advanced-technology space station has been defined in a series of NASA-sponsored studies. Subsystem definitions have specifically addressed the opportunities for beneficial synergistic interactions, and this report identifies those potential synergies and their benefits. One of the more significant synergistic benefits involves the multifunction utilization of water within a large system that generates artificial gravity by rotation. In such a system, water not only provides the necessary crew life support but also serves as counterrotator mass, as movable ballast, and as a source for propellant gases. Additionally, the synergistic effects among advanced-technology materials, operation at reduced artificial gravity, and lower cabin atmospheric-pressure levels show beneficial interactions that can be quantified in terms of reduced mass to orbit.

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