# Clarke Station:
# An Artificial Gravity Space Station at the Earth-Moon L1 Point

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## Abstract

In order to perform deep space life sciences and artificial gravity research, a 315 metric ton space station has been designed for the L1 libration point between the Earth and the Moon. The station provides research facilities for a total of eight crew in two habitats connected to their center of rotation by 68 m trusses. A third mass is offset for stability. Solar arrays and docking facilities are contained on the axis perpendicular to rotation. A total of 320 $m^2$ of floor space at gravity levels from microgravity to 1.2g's are available for research and experimentation. Specific research capabilities include radiation measurement and testing, human physiological adaptation measurement, and deep space manned mission simulation.

## Introduction

Space is a harsh and unforgiving environment. In addition to basic life support requirements, radiation exposure, cardiovascular deconditioning, muscle atrophy, and skeletal demineralization represent major hazards associated with human travel and habitation in deep space. All of these hazards require special attention and prevention for a successful mission to Mars or a long duration return to the Moon. Greater knowledge of human physical response to the deep space environment and reduced gravity is required to develop safe prevention methods.

An artificial gravity space station would provide a facility for exploring these issues. The primary purpose of the station will be to explore the ability for humans to live and work in artificial gravity in deep space across a wide range of gravity levels up to 1.2g. In preparation for a future mission to Mars, the station will also simulate a full-length Mars mission. The simulation will acquire valuable data about the body's adaptation to Mars gravity, and will allow astronauts to test technologies at Mars gravity. Artificial gravity also provides opportunities for life sciences and advanced technology research with application to Earth based needs.

Positioning this station at the Earth-Moon L1 point provides an ideal location for study of the deep space environment. A human presence at the L1 point, over 300,000 km from Earth, will require the closed loop life support systems and increased radiation protection common to any deep space mission. An artificial gravity station at the L1 point could also serve as a transportation node for Mars missions, providing storage, supply, and crew recuperation in artificial gravity.

In 1961, Arthur C. Clarke predicted the establishment of a space station at L1 in his book "A Fall of Moondust." Clarke's "2001: A Space Odyssey" portrayed yet another incredible station with artificial gravity. In tribute to Arthur Clarke's vision and inspiration, the University of Maryland L1 habitat is named Clarke Station.

## Challenges

### *Artificial Gravity*

In 1966, astronauts Conrad and Gordon achieved a low level of artificial gravity when they tethered together the Gemini capsule to the Agena target vehicle and rotated slowly for 2 ½ orbits around the Earth. While artificial gravity production through rotation has been demonstrated on a small scale, knowledge of the ability for humans to live and work in a large scale rotating artificial gravity environment is limited. Research conducted in centrifuges on Earth has concluded that humans can adapt and live for extended periods to rotation rates as high as 8.5 RPM. To ensure that astronauts can live and work comfortably, Clarke Station will have a maximum rotation rate of 4.0 RPM. Changes in gravity level are accomplished through control of the rotation rate. Since the station generates a maximum gravity level of 1.2g, or $12 m/s^2$, and has a maximum rotation rate of 4 RPM, the radius of the station is 68.4 m. The station must also be capable of accepting a docking vehicle while it is spun up in order to dock to the station without disturbing the science missions and to reduce propellant expenses.

### *Floor Space*

Clarke Station will support 8 crewmembers during normal operations and has the capability of supporting 16 crewmembers for short durations during crew transfers. The crew must have enough space to live and work effectively for long durations. Because Clark Station has gravity, floor space area requirements, not volume, must be considered. For long duration space flight, the minimum floor space per crewmember is 40 $m^2$. The open floor space requirement is 8 $m^2$ per crewmember. This requirement results in a station with a total floor space of 320 $m^2$.

### *Radiation Exposure*

Space radiation consists mainly of high energy-charge particles such as protons and heavy ions. At the L1 point, shown in Figure 1, beyond the protection of the Van Allen Belts, radiation from Galactic Cosmic Radiation and Solar Particle Events threaten the health of Clarke Station inhabitants. Galactic Cosmic Radiation (GCR), originates from outside the solar system, and consists mainly of hydrogen. GCR is indirectly related to the 11-year cycle of the Sun, where its maximum is at the solar minimum. During a solar minimum, an unshielded dosage is about 60 rem/year, and a factor of 2.5 lower at solar maximum. Solar flares are explosions on the Sun that generate Solar Particle Events (SPEs), and shoot them into outer space. SPE's occur once or twice a solar cycle. One of the largest solar flares occurred in 1972, producing a dose of 350 rem for several hours.

According to NASA requirements, maximum radiation dosage for Blood Forming Organs is 50 rem/year. Since solar flares can occur throughout the solar cycle, the worst-case scenario is a large solar flare occurring during solar minimum, when GCR is largest.  This scenario requires shielding against GCR along with sufficient shielding for a solar flare.

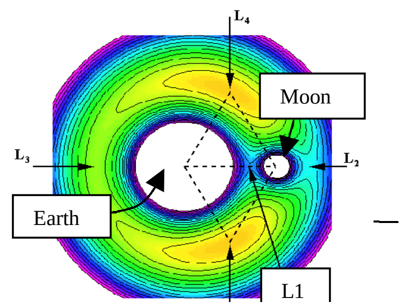



**Figure 1.** Libration points for the Earth-Moon system shown with contours representing gravitational and centripetal forces.
Adapted From: [Dr. Soho. 2001. "SOHO FAQ: Astronomy."*sohowww.nascom.nasa.gov/explore/faq/astronomy.html*]

## Mission

### *Bone and Muscle Research*

In microgravity, a significant number of bone forming cells die, and healthy bone cells produce fewer minerals. Muscle size decreases dramatically and there is a reduced capacity for muscles to burn fat for energy. Clarke Station science will determine the rate, location, and magnitude of bone and muscle loss as affected by gravity level. Changes in muscular performance as related to gravity level will be documented. Equilibrium bone/muscle levels, and the extent of bone loss reversal due to increases in gravity level will be determined. Exploring the relation between bone loss and decreasing muscle strength at other than Earth's gravity will aid in developing protocols for long duration space missions. Physical measurements and performance measurements, Dual Energy X-ray Absiorptiometry (DEXA) and ultrasound scanning will provide accurate measurements of bone structure and density.

### *Human Physiology Research*

In addition to causing changes in bone and muscle strength, microgravity is known to cause drastic changes in the lungs and heart.  Central venous blood pressure decreases, baroreflexes are impaired, and heart rate increases. There is a shift in body fluid toward the head, blood volume decreases, and red blood cell count decreases. Experiments in the cardiovascular field will help understand cardiac and circulatory hemodynamics, biochemical changes, baroreflexes, and dysrhythmias at different gravity levels. Reduced gravity environment adaptation and circadian rhythms will be analyzed and related to performance. Immunology research will focus on the ability for astronauts to respond to and recall antigens at different gravity levels. Neurotransmitter and overall neurosensory changes in response to a change in gravity remains incomplete. Experiments designed in the field of neuroscience will aim to understand space motion sickness, how sensory motor skills are affected, and rotating environment effects on the neurovestibular system.

### *Radiation Science*

Radiation science experiments will provide accurate radiation monitoring and measurements to assess and reduce health risks of the crew as well as chart the radiation environment of deep space. Dosimetric Mapping will provide a quantitative description of the radiation field inside and outside Clarke Station. Active dosimeters will measure localization of charged particles and the energy spectrum of radiation, and the crew will wear passive dosimeters to measure absorbed dose. Outside the station, the Phantom Torso, a torso and head constructed from a muscle-tissue plastic equivalent with over 350 passive dosimeters embedded in it, will be used to measure organ level radiation doses. The Bonner Ball Neutron Detector (BBND) uses six detector spheres filled with $He_3$ to determine neutron radiation effects. Results from these experiments will provide more accurate and reliable radiation prediction models for future missions.

### *Mars Simulation Science*

Mars simulation missions will allow for valuable experimentation and learning in preparation for a future mission to Mars. Physiological changes resulting from long-term exposure to Mars gravity will be documented. Communication time delays that would occur on a Mars mission, of 21 minutes maximum length, will be simulated. Astronauts will utilize the Range, an open area of approximately 10 $m^2$, for Mars suit mobility testing, structure building, and interaction with autonomous robots. To prove the ability to grow plants for consumption at Mars gravity, as necessitated in the Mars Reference Mission, three plant growth modules totaling 3 $m^2$ of growth area will be on Clarke Station. These plants will also be analyzed on the cellular level in the biology lab. Completion of the full-length Mars simulation in 2012 will allow time to integrate the lessons learned from the simulation into a Mars mission design for the opportune window of 2016-2018 when travel durations will be as short as 130 days.

### *Advanced Technology – Future Research*

After the full-length Mars simulation, Clarke Station will transition to a life sciences and advanced technologies station. Biotechnology, Microbiology, Materials Engineering, Reproduction and Development, Lunar research, Electrical Engineering, and Exobiology research will further help scientistics understand the human response to the space environment, the composition of the solar system, and lead to important medical and technological discoveries that have benefits on Earth.

### *Gravity Level Timeline*

Table 1 shows the station gravity levels for the first six years beginning with initial station operation in January 2007. Crew rotations occur once a year for the first three years. Gravity level step increases are conducted the first year to study adaptation and living abilities of astronauts at various gravity levels. The second year is a short-term Mars mission simulation. This short-term simulation assumes the astronauts will have a ½g artificial gravity transfer vehicle. The third year is devoted to another short-term Mars mission simulation. Mars transfer in this simulation is in microgravity. A comparative study of the second and third years will give scientists valuable insight into the transportation needs for a Mars mission. Following the short-term Mars mission simulations is a full-length Mars mission simulation. The gravity level for the first 5 and last 4 months of the full-length Mars simulation will be decided based on information gathered over the initial three years and Mars mission plans in 2010. The durations for the full-length Mars simulation match the durations of the long stay fast transit mission outlined in the Mars Reference Mission. Completion of the full-length Mars simulation in 2012 will allow time to integrate the lessons learned from the simulation into a Mars mission design for the opportune window of 2016-2018 when travel durations will be as short as 130 days. The station gravity levels following the full-length Mars will be selected based on experience gained from the critical six-year period and to accommodate research needs.

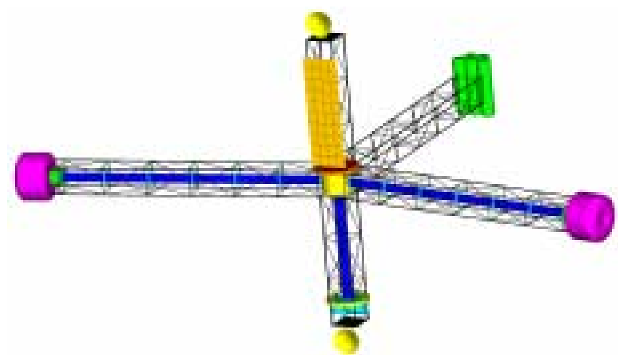
**Table 1. Gravity Level Timeline**

| Year | Gravity Level | Duration (months) |
|---|---|---|
| Year 1 (2007) | Lunar (.17g) | 2 |
| | Mars (.38g) | 2 |
| | ½ Earth | 2 |
| | ¾ Earth | 2 |
| | Earth | 2 |
| | Maximum | 2 |
| | Crew Change | |
| Year 2 (2008) | ½ Earth | 3 |
| | Mars (.38g) | 6 |
| | ½ Earth | 3 |
| | Crew Change | |
| Year 3 (2009) | Microgravity | 3 |
| | Mars (.38g) | 6 |
| | Microgravity | 3 |
| | Crew Change | |
| January 2010 – July 2012 | TBD | 5 |
| | Mars (.38g) | 21 |
| | TBD | 4 |
| | Crew Change | |
| July 2012 | TBD | TBD |

## Systems Design

### *General Configuration*

**Figure 2. Station Overall Configuration**



The crew and equipment for conducting these experiments is distributed into two manned habitats at equal distances from their center of rotation. To allow docking while spinning, a non-spinning truss was placed on the axis through the center of rotation, perpendicular to the plane of rotation (Fig. 2). The station fixed coordinate system used to describe the location of station components uses the spin axis as the z axis. The z truss serves two purposes: to eliminate the relative rotational motion of the rotating section from the docking procedure and to serve as a sun-tracking axis to accommodate solar array pointing with minimal support structure mass. Thus, the z truss will rotate at a rate of approximately 1°/day with respect to an inertial frame. Stiff trusses were chosen in order to adequately transmit torques required during station keeping and docking.

In order to maintain a stable spin situation, the rotating section of the station must have its center of gravity at the center of rotation and the station must be spinning about its minor or major principal axis. Modeling the station as a gyrostat, a dual-spin system with an axis-symmetric z truss, showed that having two collinear masses (habitats, labs, or other mass) spinning about the z truss is unstable because the spin axis would then be the intermediate principal axis. Therefore, three spinning masses were required to maintain spin stability.

Using expended transfer vehicle boosters for the third mass minimizes the expense of delivering additional mass to L1 while providing for station stability. Based on the assembly and delivery schedule, 5 expended boosters with 3 tons of inert mass each will arrive at Clarke Station. Because this mass totals only 15 tons compared to the 42-ton habitats, the habitat trusses must be at an angle of 160° from one another, and the boosters at an equal distance of 68.4 m from the center of rotation. By making use of this excess mass, only about 1½ tons of extra truss will be needed to connect the boosters to the rotational center.

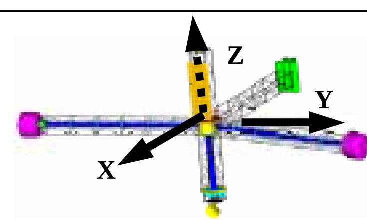
**The Z-truss**

The z truss is actually two separate free-spinning trusses, the +z truss and the –z truss, which are attached to each side of the rotating section perpendicular to the plane of rotation. The –z truss rotates with the habitats the entire way to the docking system and is sun-tracking from the docking collar to the –z end of the station. The attachment points will have rotational interfaces as described below. Although only the +z truss contains the solar arrays, both sections will track the sun to maintain alignment of the reaction control thrusters, which are housed at the ends of the z trusses.

The angular momentum of the rotating section will be on the order of $10^8$ kg-m$^2$/s. The reaction control thrusters are placed 30 m from the rotating plane on the + and - z trusses in order to produce a sufficient torque to adjust this angular momentum. The transfer vehicle docking system was placed 25 m away from the rotational section to reduce plume impingement on the structures from the transfer vehicle thrusters.

Depending on whether one, two, or no transfer vehicles are docked to the station, the center of mass and moment of inertia will change. The moment of inertia for the station was calculated using the coordinate system shown in Table 2, which depicts the center of mass and moment of inertia as a function of the number of docked transfer vehicles.

**Table 2. Station Center of Mass and Moment of Inertia**

| Center of Mass (m) as a function of Transfer Vehicles Docked | Moment if Inertia | |
|---|---|---|
| No x-fer vehicle docked: (0, 0, -4.6) | $I_X = 3.9 \times 10^8$ |   |
| 1 x-fer vehicle docked: (0, <<1, -9.2) | $I_Y = 0.84 \times 10^8$ | |
| 2 x-fer vehicles docked: (0, 0, -13.8) | $I_Z = 4.6 \times 10^8$ | |

**Habitat Modules**

An inflatable structure was chosen for the habitats because of its low weight, small packaging volume, strength in terms of pressure, ability to withstand impact of micrometeoroid debris and better radiation shielding as compared to conventional modules. The inflatable habitat is mounted longitudinally to the truss and has the inflated dimensions of 5.4 m radius, 7.6 m length, and 0.3 m wall thickness. The habitat interior consists of two floors with 2.5 m ceilings and 1m storage space located above the upper ceiling and below the lower floor. The floors are connected by a 3.5 m diameter core. The habitats were designed to accommodate crewmembers from the 5$^{th}$ percentile Japanese female to the 95$^{th}$ percentile American male.

The habitat's internal pressure creates both longitudinal and transverse pressurization loads on the habitat wall. In addition to the longitudinal pressure loads, the habitat also sees longitudinal loads due to centripetal acceleration. The habitat shell consists of multiple layers of woven Kevlar that are responsible for the module shape, loads, and protection from micrometeoroid debris. The micrometeoroid protection is made up of alternating layers of woven Kevlar and polyethylene foam. Inside those layers are bladders made up of viton to hold water for radiation shielding. The innermost layer is Nomex cloth protecting the viton bladders from scuffs and scratches. This design has a safety factor of 3 and a margin of safety of 1% for transverse stress and 2.7% for longitudinal stress. The total mass of the module is 42,000 kg, which consists of 15,000 kg empty mass, 23,000 kg radiation shielding mass, and 4,000 kg of equipment.

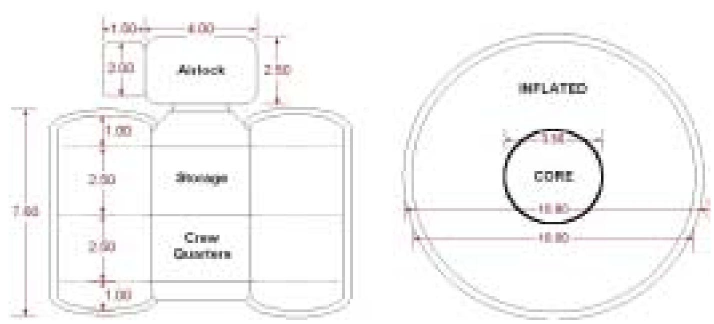



**Figure 3. Habitat Structure**

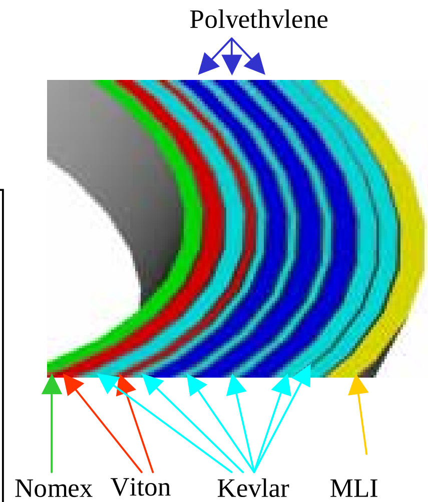



**Figure 4. Habitat Layers**

**Truss Structure**

The truss is the main structural backbone of Clarke Station. It is separated into three Rotating Truss (RT) spokes and two Z-Truss (ZT) elements (positive and negative). The truss provides a pass-through for the transfer tunnel and hard mounts for attached payloads. The RT passes around the hub module by means of a spoke interconnect structure, thereby decoupling the hub from reacting station bending and axial loads.

Both the RT and the ZT are 6m box trusses having four tubular main spars of outer diameter 250 mm and cross-members of 130 mm diameter. The main spars are two concentric tubes of a 1.5mm thick composite laminate. The laminate is Toray M55J/Fiberite 934-3 carbon/cyanate ester in a $[90/\pm30/\pm15/0]_S$ symmetric fiber orientation. The tightly woven plies offer superior micrometeoroid impact resistance and superior corrosion resistance. Furthermore, the laminate possesses ultra-high dimensional stability under thermal cycling.

The truss is weakest in its resistance to buckling. Bending in the RT due to angular rate adjustment thrusting loads truss members in compression and causes lowest M.S. on buckling. The truss design was driven both by resistance to buckling and resistance to natural frequency excitation in bending of the RT spokes. Longitudinal and Bending Natural Frequencies were calculated for both the RT and ZT spokes and are tabulated in Table 3. For the operational load environment, margins of safety are presented in Table 4 below.

**Table 3. RT and ZT Bending Natural Frequencies**

| *Natural Frequencies* | RT Spoke, Habitat at End | RT Spoke, Offset Mass at End | +Z-Truss | -Z-Truss, 2 Transfer Vehicles Docked |
|---|---|---|---|---|
| **Longitudinal, Hz** | 4.5 | 7.5 | 46.8 | 5.9 |
| **Bending, Hz** | 0.37 | 0.63 | 10.5 | 1.3 |

**Table 4. Truss Margins of Safety**

| Description of Limiting Load Case | Applied Stress | Failure Mode | Margin |
|---|---|---|---|
| **Axial Loads** | | | |
| Axial Stress in Rotating Truss Habitat Spoke at .42 rad/s (MPa) | 63 | Tension | 10.6 |
| Axial Stress in Rotating Truss Offset Mass Spoke at .42 rad/s (MPa) | 19 | Tension | 38.4 |
| **Bending Loads** | | | |
| Bending in Rotating Truss Spoke due to 1 Hour Spin-up from 0 to .42 rad/s (MPa) | 1.8 | Euler Buckling | 0.2 |
| Bending in -Z-Truss due to Worst-Case Docking Impact (MPa) | 2.2 | Euler Buckling | 0.0 |
| Bending in -Z-Truss due to Attitude Control Thrusting (kPa) | 4.6 | Euler Buckling | 483 |
| Bending in +Z-Truss due to Attitude Control Thrusting (kPa) | 4.9 | Euler Buckling | 451 |
| **Shear Loads** | | | |
| Shear in Rotating Truss due to 1 Hour Spin-up from 0 to .42 rad/s (kPa) | 87 | Shear | 994 |
| Shear in Rotating Truss and Z-Truss due to Worst-Case Normal Plume Impingement (kPa) | 13 | Shear | 6630 |
| Shear in -Z-Truss and +Z-Truss due to Attitude Control Thrusting (kPa) | 0.49 | Shear | 176000 |
| Shear in -Z-Truss due to Worst-Case Docking Impact (kPa) | 240 | Shear | 358 |
| Shear in -Z-Truss and +Z-Truss due to Worst-Case Mass Eccentricity at .42 rad/s (kPa) | 420 | Shear | 204 |
| Shear in +Z-Truss due to Solar Pressure (Pa) | 0.12 | Shear | 690000 |

### Transfer Tunnel

The transfer tunnel provides crew passage between the habitats and docking areas. It consists of four major parts: an inflatable tunnel, consisting of eight layers of material that are similar to the layers of the habitat module but without water filled bladders for radiation shielding; aluminum stiffening rings; Kevlar stringers attaching the tunnels to the trusses; and aluminum lockout doors located at every 10 m of the tunnel to maintain pressurization of the tunnel in the event of a breach in one section of the tunnel wall (Fig. 5).

Transfer through the tunnel will be by use of ladders or a winch mechanism. Two 10 m ladders will be placed along either side of the tunnel wall in each 10m section of the tunnel. The winch is a 12 VDC planetary gear winch for carrying loads and crewmembers up and down the tunnel.

The major loads on the transfer tunnel, given in Table 5, are the force of the lockout doors on the walls from centripetal acceleration, the pressure loading on the tunnel walls, the stress on a closed lockout door due to pressurization, the stress in the Kevlar stringers due to torsion in the truss, and the maximum stress on the aluminum stiffening rings.

**Table 5. Transfer Tunnel Margins of Safety**

| Load Considered | Applied Stress (MPa) | M.S. |
|---|---|---|
| Force of Lockout doors on walls from centripetal acceleration | 54.0 | **21.23** |
| Transfer Tube Pressure Load, Hoop stress walls @ 101 kPa | 108 | **10.13** |
| Stress on Lockout door from pressurization @ 101 kPa | 31.9 | **6.91** |
| Maximum Forces on Kevlar Stringers | 63.4 | **0.39** |
| Maximum Forces on Stiffening Rings | 121 | **1.09** |

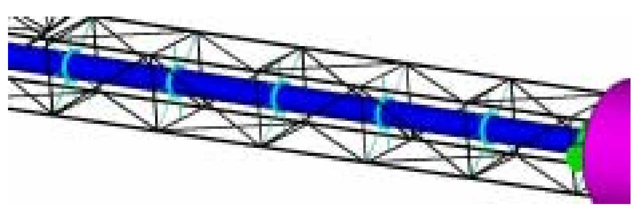


**Figure 5. Transfer Tunnel**

### Rotational Interface

Rotational interfaces are located on the positive and negative despun trusses to allow these sections to rotate independently of the rotating section. The –z interface has three modes of transmission: electrical, consisting of both power and data; biological, or life support and human passage; and structural resistance to moments created by spinning up and down the rotational section, thrusting for attitude and station keeping, and docking the transfer vehicle. The +z interface will need to handle only power, data, and structural loading. The –z interface is also the junction between the –z tunnel and Airlock-Docking System (ADS), which will be separated by an airlock that can be opened during transfer times. Therefore, the ADS will have a separate atmosphere control that will also be used for EVA pre-breathe.

Main loading on the rotational interfaces stems from either impact with the transfer vehicle or from thruster firing. Forces from docking are about 2250 N on a 1 m moment arm on the –z truss, and the thrusters fire at about 500 N on a 30 m moment arm on the +z truss. Thus, the greatest loading on the rotational interfaces comes from the thrusters on the +z section. Using this information, the thickness of each bearing collar and its flanges must be at least 0.045 m of aluminum. Stainless steel shims are used inside on contact surfaces to minimize the coefficient of friction.

Each rotational joint will also have a bearing assembly to overcome friction losses on the rotating interface and a vacuum seal to separate the internal atmosphere and the outside vacuum of space. To maintain constant relative angular velocity, the interfaces will also contain two redundant constant-spin motors.

**Hub**

The station hub serves as a storage center as well as a pass-through from the two spokes and the –z truss (Fig. 6). The hub shell is designed to handle only pressurization loads. To handle a maximum internal pressure of 101 kPa, the total thickness of inflatable material is 0.024 m. Since the hub and the transfer tunnel share similar functions and loading environments, their inflatable weaves are identical. Accounting for attachment points, the hub final dimensions are 7.0 m in diameter and 5.5 m high with an interior volume of 210 $m^3$.

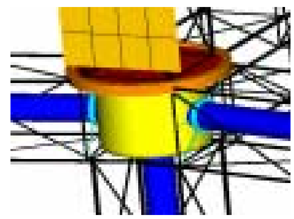


**Figure 6. Hub**

**Airlocks**

The station is designed to handle 2 person EVA's on a daily basis. Most EVA's would be for upkeep and repair of the station. In order to facilitate ease of mobility and safety about the trusses, an airlock is placed next to each habitat and one by the docking collar. The airlocks on the rotating section needed to accommodate two astronauts and their EMU's, so the dimensions of the chambers are 4 m diameter and 2.5 m high. An access tunnel allows the astronauts to pass through the truss to exit the station. The dimensions for this tunnel are 2.0 m in diameter and 1.5 m long. Because the loads on this structure are due mainly to pressure, an airlock skin thickness of 0.002 m results from the equation for hoop stress. A 0.001 m offset micro-meteriod shield is placed on the airlocks to increase crew safety. Kevlar stringers to the truss support any bending stress due to centripetal acceleration (Fig. 7). Both of these airlocks will have pressure doors to the habitat and to the transfer tunnel. These doors will be nominally open.

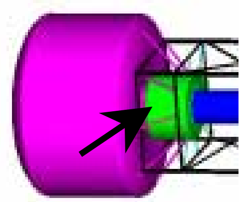


**Figure 7. Airlock**

The –z airlock (ADS) is designed in the same fashion as the airlocks on the rotating section. However, as a component of this assembly, two docking collars are required at this point, one for the escape vehicle docked at all times, and one for the transfer vehicle (Fig. 8). Loading on this structure came mainly from impulse impact loading during docking. However, due to the truss requirement that impact velocity be at a maximum of 0.033 m/sec, the stresses applied on this assembly are very low.

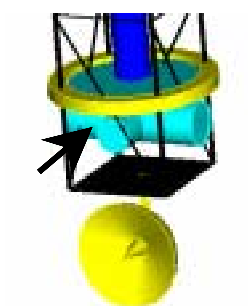


**Figure 8. Docking**

## *Subsystems*

**Guidance and Control**

***- Station-keeping -***

Clarke Station is required to orbit about the collinear libration point, L1, between the Earth and the Moon in the Earth-Moon system. The distance between the Earth and L1 is approximately 326,400 km and the distance between the Moon and L1 is about 58,000 km.

Lissajous orbits are the natural motion of a satellite around a collinear libration point (Fig. 9). Hoffman described a large lissajous orbit with diameters of 18,000 km in the x-direction, 50,000 km in the y-direction, and 50,000 km in the z-direction, using a coordinate system where the line from the earth to the moon is the primary direction and the earth-moon orbit plane is the primary plane. In this orbit, the Earth and the Moon can block the

Sun from the station, causing an eclipse. Eclipses of the Sun by the Earth will occur a maximum of 4 times per year and each will last a maximum of 160 minutes. Eclipses of the Sun by the Moon will occur a maximum of 3 times per year and each will last a maximum of 50 minutes. The minimum amount of time in between eclipses is 14 days.

This lissajous orbit was found to require station-keeping of 36 m/sec/yr and was chosen because of decreased station-keeping compared to a halo orbit. In general, all of the disturbances that require station keeping are quite small, but add up over time, making thruster maneuvers necessary. The largest disturbance is due to the Sun's gravity and it applies a constant force of 0.0058 N. Other disturbances from the Earth, the Moon, and solar radiation pressure are even smaller than the force from the Sun's gravity. Station-keeping will require a total of 50 m/sec/yr change in velocity including a 30% margin in maneuvers. Corrections should be performed about nine times per year, at about 4 m/s of $\Delta V$ per correction to provide the baseline 36m/sec/year. For 15 minute burns, the total force required is 1400N. Two thrusters at each end of the z-truss fire during station keeping, requiring each thruster to produce approximately 350 N of force.

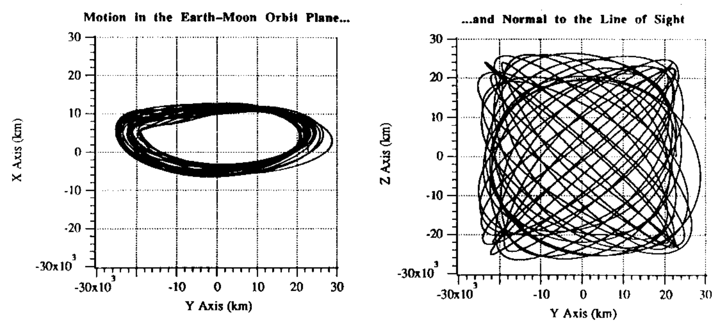



**Figure 9.** Lissajous orbit of Clarke Station.
From: [Hoffman, David. *Station-keeping at the Collinear Equilibrium Points of the Earth-Moon System*. 1993. NASA JSC-26189.]

When the total mass of the system is considered (mass of propellant, tanks, and structure), storable bipropellents are the best option, with a total mass of 3600 kg. Clarke Station will use $MMH/N_2O_4$ thrusters for station keeping and the propellant tanks for this system will be located on both the negative and positive z-axis, one fuel and one oxidizer tank on each.

In order to provide the station with its position, daily ephemeris will be generated on Earth by the Flight Dynamics team and uplinked to the station. This is the most efficient way of updating position onboard. The ephemeris is an instantaneous snapshot of the orbit at a given time, and will contain three – axis position and velocity, calculated on the ground using current orbital models.

***- Attitude determination and control -***

The most prominent external torques are from gravity, solar pressure radiation, aerodynamic forces, and magnetic field forces. In our case the gravity force ($1.1 \times 10^{-7}$ N-m), magnetic field force ($2.3 \times 10^{-17}$ N-m) and aerodynamic force are negligible. At L1, the solar pressure results in a constant torque of approximately .028 N-m, which effectively pushes the station around the y-axis since the difference distance between the center of gravity of the entire station and the center of solar pressure is offset from the geometric center of the station.

With the station's angular momentum in the positive z direction, the solar pressure torque rotates the station approximately 11 degrees per month if the spinning section is rotating to produce artificial gravity of $1 \times 10^{-4}$ m/s$^2$ and 0.03 degrees per month of the spinning section is rotating at 4RPM to produce maximum gravity of 1.2g.

The attitude sensors chosen for the station include one CT – 632 Star Tracker, one Precision Sun Tracking Sensor, and six coarse sun sensors. The star tracker will be the primary attitude sensor, placed on one of the pods on the rotating section facing away from the sun towards deep space. This particular tracker can track up to five stars at one time in its large field of view (FOV), 18° x 18°. It contains an onboard star catalog, which allows the sensor to provide a quaternion instead of raw sensor measurements. This prevents the need for extra flight software coding to process raw data.

The Precision Sun Tracking Sensor, also manufactured by Ball Aerospace, provides accurate information regarding any deviation from the sunline. This sensor will be located along the +Z truss, an inertial portion of the station, in order for the FOV to always face the Sun. The sun sensor has a 110° FOV, and outputs fully processed, ready-to-use 16-bit sun position angles to the onboard software.

The station's attitude control subsystem will also use ADCOLE Coarse Sun Sensors, one on each side of the rotating pods, for a total of six. As the station rotates, two of the coarse sun sensors will always detect the Sun in their FOV. This output will determine the rate of the rotating section by calculating the time it takes for one sensor to view the sun twice.

To obtain a more accurate rate of motion of the station for any station keeping or changing activities, Space Inertial Reference Unit (SIRU) Dual String Gyros, manufactured by Litton, were selected. The SIRU contains two sets of three-axis Inertial Reference Units with radiation hard internal components. The gyros will sense the rate of the spacecraft in all three axes, providing a measurement of the station's velocity (rate of change) and acceleration (rate of change over time). The box will be located along the +Z axis truss

All of the sensors will be designed to output data at 10 Hz over a single MIL-STD-1553 bus or multiple buses as needed (TBD). The software will take in data from all of the sensors, but will have the flexibility to choose how often it samples the 10 Hz output.

Hot gas thrusters have been chosen as the method for counteracting these disturbances. Attitude will be maintained to within 1°, with thrusters firing 30 seconds in duration. For a 3 year mission with varying degrees of gravity, the station will need to reorient approximately 650 times with a 4.7N thrust, producing a total propellant mass of 300kg. This includes a 100% margin to take into account internal disturbances and emergency circumstances. There will be a total of 56 thrusters, 8 on each spoke of the rotating section for control about the z-axis, and 16 on each end of the z-truss sections, two at the center of each straight section and 2 at each corner 90 degrees apart from each other for control about the x, y, and z axes (Fig. 10). The thrusters on the rotating sections, which also have habitat modules, are offset at least 2 m from the truss in order to avoid plume impingement on the habitats themselves.

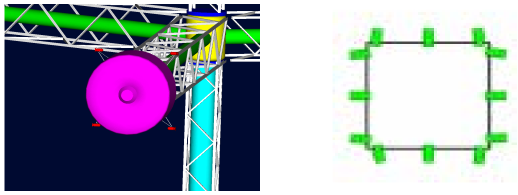


**Figure 10**: Left: Thrusters on spinning section. Right: Thruster placement on positive and negative z-truss sections.

***- Spin-up/Spin-down -***

In order to achieve full spin up or spin down of the station in one hour, 855 N must be applied at the 62.1 m point on each rotating spoke. Two thrusters fire on each spoke so each thruster must produce 428 N of force. Using MMH/ $N_2O_4$, the thrusters, propellants and tanks for a full spin-up or spin-down will have a mass of 2900 kg. The propellant storage tanks for this system will reside on the rotating spokes, one fuel and one oxidizer tank on each.

**Computer System**

A computer system in Clarke Station is necessary for monitoring and housekeeping. Connections used throughout the station will include ethernet, 1553 buses, RS-422, and RS-232 cables. The centralized computer system will store all information collected throughout the station. Laptops for each crew member will be available to connect to the main computer system anywhere on the station. The duties of the centralized computer system include data processing and housekeeping, sensing and processing of station structure and astronauts, attitude and orbit control functions, thermal control, power management, and communications. Station-ground communications include interface and telemetry, station monitoring, and station fault detection/recovery.

**Communications**

Clarke Station will have 4 channels of high definition television (HDTV) for both uplink and downlink. The 1.485 Gbits/s uncompressed HDTV can be compressed to 8 Mbits/s. Typical data rates will be on the order of 2 Kbits/s for command and 80 Kbits/s for status and telemetry. Modulation will be Differential Phase Shift Keying because it utilizes the frequency spectrum and because it is not susceptible to phase disturbances. The frequency band used will be the Ku band to allow for enough bandwidth for the data rate. Two parabolic center-feed transmitter antennas of 0.8m diameter, located at either end of the z truss, will communicate with the Deep Space Network with continuous link availability. Table 6 gives the link budget for uplink and downlink.

**Table 6. Link Budget for Station Communications**

| Communication | Frequency | Power Flux Density | Effective Isotropic Radiated Power | Link Margin |
|---|---|---|---|---|
| Uplink | 14.50 GHz | 2E-10 W/$m^2$ | 3E+8 W | 18 dB |
| Downlink | 12.75 GHz | 9E-14 W/$m^2$ | 1E+5 W | 20 dB |

**Power and Thermal**

***- Power generation -***

The systems on Clarke Station will require, with a 30% margin, about 62 kW of constant electrical power. This power will be provided by sun tracking solar arrays mounted on the inertial axis of the station. The solar arrays, which use gallium arsenide (GaAs) solar cell technology at an efficiency of 25%, are sized at 220 $m^2$ area and 1600 kg mass. Corrections to within 15-degree sun-normal conditions will be made for the arrays by a rack and pinion system incorporated into the mounting structure of the arrays. These measures provide for an average of 70 kW of power to the power conditioning and storage system.

***- Fuel Cells -***

Fuel Cells will be used to store power for use during the periods of darkness. Although regenerative fuel cells require reactants they are still much more efficient in mass than batteries or most other storable power sources. The fuel cell chosen for Clarke station is the hydrogen-oxygen fuel cell (referred to as "alkaline" because of the KOH electrolyte). The alkaline fuel cell has a specific power of approximately 275 kW/kg. It also has a low hydrogen and oxygen reactant mass, and a useful byproduct of water. All of the water will be held in the power circuit to use electrolysis to create more reactants for the fuel cell. The alkaline fuel cells have a 15 minute start-up time and a lifetime of approximately 2400 hours before refurbishment. A gas storage system was chosen over a cryogenic system for the fuel cells because of the small night cycle and low operating time. The total mass for the fuel cells and storage system is approximately five tons.

***- Thermal System -***

All of the computer systems as well as the astronauts produce heat. All 70 kW of input power becomes heat, and 70 watts per astronaut of heat must be dissipated to maintain an ideal living environment of 18-24 degrees Celsius. Another source of heat is the sun. Although the sun emits a large amount of energy, because of the large amount of radiation shielding and structural thickness there is a very small amount of heat transfer through the skin of the station. The radio antennas mounted on the exterior of the station, along with any storage tanks, will be coated with a white epoxy (high emittance, low absorbptance) to keep these devices within their operating temperature range.

All electronics will be mounted to cold plates with heat pipes connected to them. The electronics thermal control loop will operate at 10-20 degrees Celsius. A second thermal control loop operating between 0-6 degrees Celsius will cool the air inside the habitat modules. All excess internal heat will be removed through heat exchanges to exterior radiator panels.

The power required by the thermal control system is approximately 1 kW, mostly to pump the fluid through the various cooling components. The working fluid for the heat pipes is water, while the working fluid for the radiator is anhydrous ammonia. With water as the working fluid for the radiator panels, the necessary area to radiate the internal thermal energy of approximately 71 kW is 5 $m^2$ for each habitat module. Small heaters will be dispersed throughout the habitat and transfer tubes to ensure the temperature does not fall below the required 18 degree Celsius minimum. There will also be thermisters distributed throughout the station to monitor and control the temperature.

**Life Support**

***- Radiation Shielding -***

Hydrogen based materials are the most effective shielding materials, since these materials produce less heavy ions, which add to the radiation, when hit with high energy particles. Liquid hydrogen is the most effective shielding material, however it must be kept at temperatures near absolute zero (20 K) to remain in liquid state. Lithium hydride is also an effective material, however it is extremely difficult to handle. This material is extremely reactive to any water, even moisture in the air, and can spontaneously ignite due to rubbing or grinding. Water, however, is much easier to use and can be easily contained.

The crew quarters have heavier shielding so this smaller area can be used as a bunker to protect the astronauts against a solar flare, since these events produce a large amount of radiation in a short period of time. In addition, the astronauts will spend a minimum of 8 hours a day inside their quarters, and therefore will also have a much thicker shield against GCR radiation for this time, further reducing the shield thickness needed for the skin. Also, if an astronaut is exposed to more than their limit of radiation in a given period of time, that astronaut could remain in the crew quarters for a "quarantine" period, in order to have a thicker shield for an extended period of time.

The shielding needed to achieve the exposure limits was calculated from data received from the Johnson Space Center Spaceflight Radiation Health Program. The outer walls of the habitats contain 27 cm of polyethylene foam with a density of 36 kg/$m^3$, which is equivalent to a 1 cm thickness of water in terms of density. Polyethylene has roughly the same radiation protection qualities as water, and combined with a 4 cm thick water shield for the skin and a 16 cm thick shield for the crew quarters would reduce the radiation exposure in a worst-case scenario of a large solar flare at solar minimum to 50 rem/year. These thickness values give weights of 35100 kg for skin shield mass and 11500 kg for crew quarters shield mass. The total shielding mass for Clarke Station will then be 46600 kg.

***- Air -***

A given astronaut will consume up to .85 kg of oxygen ($O_2$) per day, and generates about 1 kg per day of waste carbon dioxide ($CO_2$). $O_2$ can be stored in a gaseous or liquid form, generated from decomposition of oxygen-containing compounds, or reycled from water ($H_2O$). $CO_2$ can be removed with either disposable or regenerable filters, or can be converted into $H_2O$ and waste carbon. For converting $CO_2$ into $H_2O$, the systems considered were the Bosch, Sabatier, and Advanced Carbon-formation Reactor System (ACRS). For releasing $O_2$ from H2O, Solid Polymer Water Electrolysis (SPWE) system was the best system. It was found that the combination of a Sabatier reactor and an SPWE had a lower overall mass than a system in which $O_2$ was stored onboard and wasted. For $CO_2$ collection, two and four bed molecular sieves (2BMS/4BMS), Solid Amine Water Desorption (SAWD), and Electrochemical Depolarization Concentration (EDC) were considered; SAWD was found to be the best. For emergency $O_2$ generation equipment, the optimal oxygen-releasing compound was found to be lithium perchlorate candles (LiClO4). $O_2$ lost to leakage and inefficiencies in the Sabatier/SPWE processes will be scavenged from fuel tanks. For emergency $CO_2$ removal, the optimal system is lithium hydroxide (LiOH). Both $O_2$ generation and $CO_2$ removal can be accomplished using plants, but the necessary mass of this alternative is prohibitively high.

Nitrogen ($N_2$) is an important non-reactive component of the air. Nitrogen lost to leakage must be replenished from a tank. Stored liquid nitrogen was compared to stored hydrazine, which decomposes into nitrogen. As hydrazine is a storable liquid, it was found to be the more efficient way of storing nitrogen.

***- Water -***

Humans in space generate about 1.2 kg per day of urine, 1.4 kg per day of water from sweat and breathing, and about 27 kg per day of waste water used for hygienic purposes (cleaning, bathing, etc.). For recovering urine, the systems considered were Vapor Compression Distillation (VCD), Vapor Phase Catalytic Ammonia Removal (VAPCAR), Thermoelectric Integrated Membrane Evaporation System (TIMES), and an Air Evaporation System (AES). For recovering water used for hygienic purposes, the systems considered were Reverse Osmosis (RO), Multifiltration Unibed (MF), and Electrodialysis. The only mechanical system considered for collecting humidity (from sweat and breathing) was that used on the MIR space station. In addition, for each of these three water losses, simply replenishing the lost water from a tank was also considered. The optimal solution was found to be to recycle all water using the VAPCAR, Electrodialysis, and MIR systems. However, a significant amount of water is lost mainly due to inefficiency in the Electrodialysis system, so about 2000 kg of stored water will have to be provided each year to replenish that loss. For removing human solid waste, the Supercritical Water Oxidation (SCWO) method was the only method available.

***- Mass and power -***

A 10% margin was included in all life support system masses, heat loads, volumes, and power requirements. The total mass of all systems in each habitable module is 1700 kg, which occupies 5.5 $m^3$. The floor space required to house these systems is 3.1 $m^2$. The total power required for life support systems for the entire station is 7.7 kW. The total heat generated by these systems, for the entire station, is 1 kW. The Sabatier reactor produces 12 kW of heat and for this reason is located outside the habitat modules. Masses external to the station are the Sabatier reactor, which weighs 730 kg, and LiOH and LiClO4 at 40 kg per day of emergeny $O_2$ generation/$CO_2$ removal.

***- Extravehicular Activity -***

For routine maintenance and attending to science experiments, Clarke Station supports daily 2-person Extravehicular Activities (EVAs) or spacewalks. EVAs may also be necessary in emergency situations. Airlocks are located atop each habitat module and at the docking collar. Each airlock has ample room for two suited crew members and their gear. Clarke Station will be equipped with 6 Extravehicular Mobility Units, two in each habitat airlock and two in the main airlock at the docking collar. Each EMU has a mass of approximately 127 kg. The EMU suits have interchangeable components, which allow for use by numerous crewmembers. Prior to every EVA, crewmembers are required to pre-breathe pure oxygen at ambient station pressure for 45 minutes. Because of the spin of Clarke Station, an extensive tether system will be used to ensure crew safety during EVAs.

***- Food -***

Food supplies aboard Clarke Station will be ambient instead of refrigerated to reduce mass and power required. In addition, ambient food has a longer shelf life than refrigerated food. For a one-year supply for eight crew, plus a week supply for sixteen crew during transfer and a 10% emergency margin, the required consumable mass is 5600 kg. The total volume needed for food and beverage is approximately 18 $m^3$.

***- Safety Systems -***

Several safety measures are built into the station design in the event of a structural emergency that may be caused by micrometeoroid impact. These safety measures include lockdown hatches in the transfer tunnels, tunnels that are passable even when decompressed, and strategically placed personal rescue enclosures. To ensure crew survivability, EVA access is available from every habitable section of the station. In a ‘worst-case’ scenario, sixteen crew could be trapped in a damaged module during a crew transfer period. To safeguard against this scenario, four pressurized spacesuits, 12 rescue enclosures, and a personal life support system for each individual are required in each habitat as well as at the hub and in the docking section.

In addition to structural safeguards, a Cautions and Warning System, Fire Safety System, Health Monitoring System, and a Medical Facility will be integrated throughout Clarke Station. The Caution and Warning System, similar to the one installed on the International Space Station, will allow the crew look up caution and warning messages and their required actions. In addition, The Caution and Warning System will consist of visual and audio cues that will alert the crew when any system has exceeded or strayed from its operational limits. Fire detection and suppression equipment, such as smoke detectors, alarm and warning lights, fire extinguishers, and breathing apparatus will be strategically placed in each habitat, the tunnels, and hub. Usage of nonflammable materials, such as fireproof bags to place worn clothing in, will further reduce fire risk.

Health monitoring equipment will insure crew livelihood and gather useful scientific data. Biomedical sensors will gather physiological data for telemetry, while Impedance Pneumographs will continuously record heart beat (EKG) and respiration rate. Individual dosimeters will measure the amount of absorbed radiation over a given period, while Telemedicine Instrumentation Packs (TIP), will be use to conduct telemedical examinations. Clarke Station will have a medical unit for each habitat containing a Monitor/Diagnosis System, a Medical Care System, and a Countermeasures and Medical Data Management System.

**Habitat Interiors**

Figures 11-15 show the interior of the habitat modules. Blue labels are crew systems related equipment while green labels are science related equipment. Habitat 1 focuses more on science that will be conducted across multiple gravity levels, physiology, bone and muscle research, and radiation detection. Habitat 2 is focused more on Mars simulation single gravity level science. There are a total of 4 International Standard Payload Racks (ISPR) in the habitats to allow for science expansion and commercial scientific use.

**Figure 11. Habitat 1 Bottom Floor**

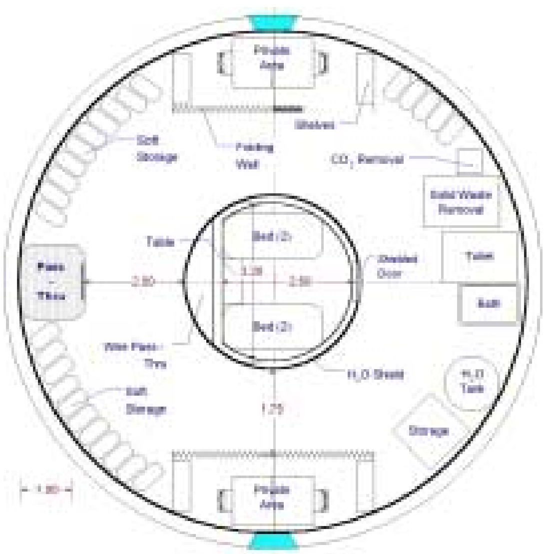



**Figure 12. Habitat 1 Top Floor**

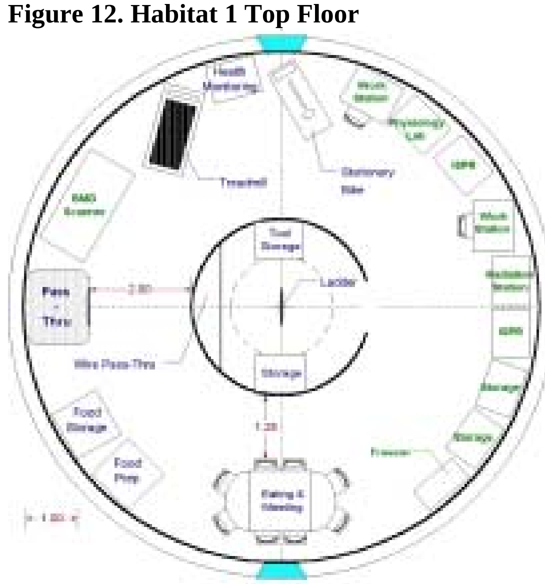


Figure 13. Habitat 1 Bottom Floor

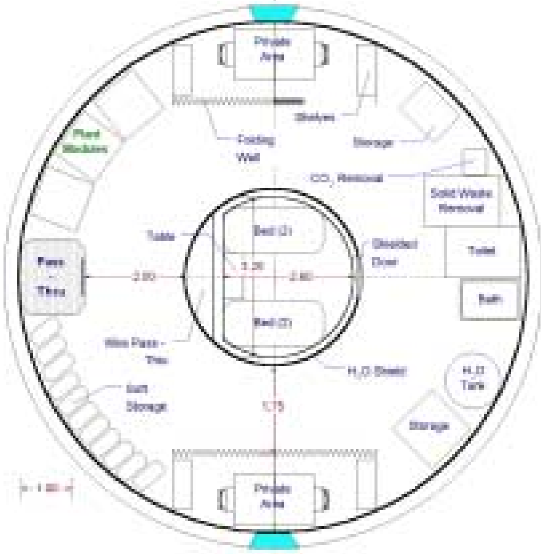
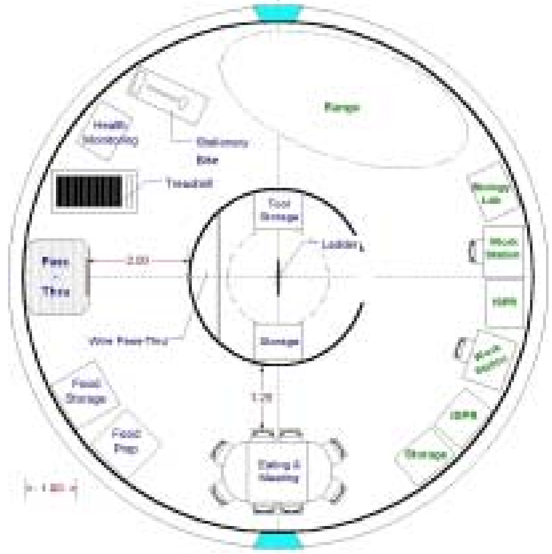



Figure 14. Habitat 1 Top Floor




**Assembly/Delivery**

***- Vehicles-***

The delivery and return of station hardware and personnel includes four distinct missions, the delivery of station hardware, the delivery of station supplies, the delivery and return of crew for rotations, and the return of crew in an emergency. From the orbit of the International Space Station (ISS) a delta V of 3.1 km/s is required to insert into a trajectory towards the moon. A second delta V of 0.7 km/s is required at the L1 point to insert into a Lissajous orbit around L1. The return trip requires the same deltaV unless aerobraking is used. A multi-pass aerobraking trajectory was designed for a bent bi-conic vehicle to save 3.1 km/s of deltaV on the return trip.

The delivery of station hardware is the largest of these missions, in terms of mass required, at 315 tons. Because the station hardware delivery does not require a round trip, expendable chemical boosters based on the currently flying Delta IV upper stage were selected for this mission. Each booster has a fully loaded mass of approximately 24 tons with an inert mass ratio of 0.12. One such booster can deliver 11 tons to the station, and staging two boosters enables the delivery of 26 tons. The expended booster weighs 3 tons.

A 24 ton manned transfer vehicle was designed to carry crew to and from Clarke Station. This crew transfer vehicle (CTV) is delivered to Clarke Station using two of the hardware delivery boosters. It is capable of returning independently using MMH/N2O4 propellents to de-orbit from the L1 point, and using the multi-pass aerobraking to return to an LEO orbit for rendezvous with ISS or the Space Shuttle. Because the propellants are storable, this vehicle can also be used as an emergency return vehicle. One CTV must be at the station for to provide a mission abort capability whenever the station is manned.

***- Launch and Assembly -***

The first hardware launches will be of the station truss, power supply and docking modules. Crew #1 will fly to ISS and construct the lower z truss, consisting of the docking module and the hub. The entire truss structure for the station, pre-assembled at ISS will then be launched to L1. Crew #2 will travel to L1 on the first crew transfer vehicle to do further truss assembly and inflate components. Then, #2 will return to ISS for construction of the habitat modules. Crew #3 will go to L1, install the habs and become Clarke Station's first inhabitants. There they will receive and install equipment packages. Crew #4 will arrive on the second crew transfer vehicle, marking the first crew transfer. Crew #5, arriving in July of 2006 will conduct final preparations of the station and station wide troubleshooting.

In addition to hardware, launches will be made for boosters. These cryogenic rockets will take hardware to L1. For a 20 ton payload, two boosters are needed, for a 40 ton, three are needed. The two crew transfer vehicles will also be launched. These two vehicles will transfer not only the construction crew, but handle future crew rotation.

### *Cost Analysis*

Top-level cost estimations were made for this project using Johnson Space Center's web based cost calculators. The cost estimate for development and production was primarily based on mass, and was calculated for the station using a total mass of 315 metric tons. The crew transfer vehicle also has a cost estimate based on a dry mass of 18 metric tons. Boosters for transfer to L1, while relatively light and simple systems, also need to be developed and produced. All estimates were calculated using a cost fraction of 0.5 and a peakedness of 1. The costs for developing the station were spread over six years (2001-2006), and the costs for the crew transfer vehicle and the boosters were spread over four years (2001-2004).

The calculated production and development costs do not include launch costs. The need to use US launch vehicles scheduled to be in use in 2005 led to examinations of the Atlas V-500 series, the Delta IV Heavy, and the Space Shuttle. A comparison of the three vehicles showed that launching everything on Atlas V's would be the most cost-effective approach. Unfortunately, because of time constraints and the need to transport crew, both of the more expensive vehicles were found to be necessary. This schedule calls for 28 Atlas V, 21 Delta IV, and 6 Shuttle launches over two years for a total cost of 7.9 billion dollars as seen in Table 7.

From calculated cost estimates for development and production a yearly estimate for mission operations and data analysis was obtained for each system, and a cost estimate for the first five years of operation was also calculated. The total program costs for development and production, plus the first five years of operation of Clarke Station are 50.7 billion dollars in 2001-year dollars. Performing a cost discounting analysis with a 10% discount rate showed that to start the program now and fund through the first five years 37.1 billion dollars should go in the bank today.

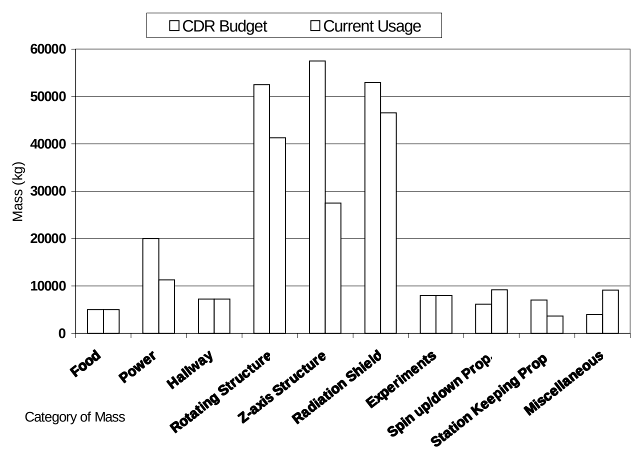
**Table 7: Cost Summary**

| **Development Costs** | 2001 $M | Cost Discounting |
|---|---|---|
| Station development cost | 23200 | 18400 |
| T. Vehicle development cost | 7600 | 6600 |
| Booster development cost | 2700 | 2300 |
| Launch costs | 7900 | 5100 |
| Total development costs | 41400 | 32400 |
| | | |
| **Operational Costs through 2011** | | |
| MODA station costs (5yrs) | 4000 | 1900 |
| MODA t. vehicle costs (7yrs) | 2300 | 1200 |
| Booster production cost (5yrs) | 500 | 400 |
| Operational launch costs (5yrs) | 2500 | 1200 |
| Total operational costs (5yrs) | 9300 | 4700 |
| | | |
| Total program costs: develop-5yrs | 50700 | 37100 |

### *Mass Budget*

The mass budget for Clarke Station was formulated by combining subsystem masses. The total mass at the time of final configuration design was calculated to be 220 metric tons. That mass plus a 30% margin was set as the mass budget (315 metric tons) for all calculations. Since then, subsystem designs have been refined and in many areas the current mass is less than the budgeted mass. The current total mass gives a 44% margin to the original mass budget. Figure 15 shows a comparison between the budget and the current usage. Masses that are over 5000 kg are individually represented; all others are folded into a miscellaneous category.

**Figure 15: Mass Summary**




## Conclusion

An artificial gravity space station at the L1 point is a feasible project that can return valuable scientific results about the ability of humans to live and work in deep space. Such knowledge would be a valuable contribution to efforts to develop manned missions to Mars and long duration lunar missions. The current design balances the need to maintain a rotating structure to provide artificial gravity with the complexities of maintaining and protecting life in deep space while minimizing the costs of developing and delivering the station.

## Outreach

A design project as exciting as an artificial gravity space station draws attention from aerospace professionals and nonprofessionals alike. To foster relations with the community, the University of Maryland community and guests were invited to attend formal Preliminary and Critical Design Reviews. Attendees at the design reviews included professionals from NASA, University of Maryland faculty, graduate students, undergraduates, and family members of the design team. During project development, relationships were fostered with engineers at NASA Goddard Space Flight Center, Swales Aerospace, and the MIT Man Vehicle Laboratory. The fourth member of the presentation team to the Lunar and Planetary Institute received funding for his trip from NASA Goddard. The development and design of Clarke Station is documented on an interactive website, www.clarkestation.com, with the hope and potential of reaching a global audience.

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