Kalpana One: A New Orbital Space Colony Design

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> ”For me the single overarching goal of human space flight is the human settlement of the solar system, and eventually beyond. I can think of no lesser purpose sufficient to justify the difficulty of the enterprise, and no greater purpose is possible.” Mike Griffin, NASA Administrator.

I. Abstract

We present a new orbital space settlement design for 5,000 residents, Kalpana One. Kalpana One is intended to improve on the designs of the mid-1970s: the Bernal Sphere, Stanford Torus, and O'Neill cylinders, as well as on Lewis One, designed at NASA Ames Research Center in the early 1990s. The Kalpana One structure is a cylinder with a radius of 250m and a length of 550m. Cylinders minimize shielding mass per unit of 1g living area compared with other feasible shapes. The radius is the minimum necessary to provide 1g at the hull when rotating at no more than 2rpm. The length is the longest possible while ensuring rotational stability. The axis of rotation is aligned with the solar system's north-south axis to provide continuous natural light through transparent end caps. Wobble control is provided by weights attached to cables on motorized winches under computer control. Exterior maintenance is by teleoperated, semi-autonomous robots. Up to ten tons of lunar/NEO regolith radiation shielding per square meter is placed inside the hull requiring greater hull strength relative to older designs but eliminating a major failure mode. Emergency power is provided by body-mounted solar cells, but primary power comes from solar power satellites beaming energy to a body-mounted rectenna. Thermal rejection is provided by a disk of thermal arrays. The 1g living area in the hull is supplemented by internal cylinders at lower g-levels for industry, storage, agriculture, retirement communities and recreation.

II. Introduction

Although humanity has always lived on Earth, mankind is space-faring and, as the great Russian visionary Konstantin Tsiolkovsky said, ”Earth is the cradle of Mankind, but one cannot stay in the cradle forever.” In the 1970s, Princeton physicist Gerard ONeill led two Stanford/NASA Ames Research Center summer studies that supported the feasibility of kilometer-scale orbital cities.[1,2] These studies assumed that the NASA space shuttle would operate as expected, a flight every week or two, $500/lb. to orbit, and one failure per 100,000 flights. The studies also assumed that a more efficient follow-on heavy lift launcher would be available. When the shuttle missed its design goals by an order of magnitude or more, it was apparent that there was no transportation system capable of supporting space settlement activities and interest waned.

The activities of the 1970s produced three space colony designs, examples of three of the four feasible shapes for orbital colonies that rotate to provide pseudo-gravity: the Bernal Sphere,[3] Stanford Torus,[1] and ONeill Cylinders.[4] All of these colonies featured natural sunlight directed into the colony by mirrors, rotation rates and radii consistent with 1g pseudo-gravity, and passive radiation shielding in non-rotating structures. Note that dumbell shaped colonies are also feasible but the authors are not aware of any well-articulated designs in the literature.

Even after it became well known that the shuttle would not meet expectations, low level space settlement technical activities continued. The Space Studies Institute, founded by Dr. O'Neill, funded research activities and held a bi-annual conference at Princeton until the early 2000s. The Lewis One[5] cylindrical space colony

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design was presented at one of these. Lewis One abandoned natural light so that agriculture could be conducted in smaller-radii cylinders at lower g levels, reducing the size of the hull and the required shielding mass. Eliminating the complex mirror geometry simplified Lewis One relative to the earlier designs. Like all the early colonies, Lewis One was woefully under-powered as insufficient area was allocated to solar energy collection. Also, Lewis One kept the rotating habitat a few meters from non-rotating shielding. Contact between these is a catastrophic failure mode not addressed by any of the studies. This is only one of many engineering problems between today and the opening of the first space colony.

Taken together, the earlier designs have a number of serious problems:

1. Excessive shielding mass (Bernal Sphere, Stanford Torus)
2. Extremely large mirrors to bring in natural sunlight (ONeill Cylinders)
3. Lack of natural sunlight (Lewis One)
4. Rotational instability (Bernal Sphere, ONeill Cylinders)
5. Lack of wobble control (Bernal Sphere, Lewis One, ONeill Cylinders, Stanford Torus)
6. Catastrophic failure modes due to rotating hulls with minimal clearance to non-rotating shield mass (Lewis One, Stanford Torus)

Orbital colonies, of course, are only one potential target for early space colonization. Indeed, Earth's Moon and Mars are usually considered better locations. While we are accustomed to living on the outside of large solid spheres and these bodies provide easy access to materials, there are substantial reasons why Earth orbiting colonies will come first. Specifically,

1. 1g (pseudo-)gravity levels are possible on orbital colonies (vs.1/3 (Mars) - 1/6g (Moon)); this is critical for raising strong children
2. Rapid resuppply from Earth
3. Continuous, ample, reliable solar energy
4. Better communication with Earth
5. Great views of Earth (and eventually other planets)
6. Weightless and low-g recreation near the axis of rotation
7. Relatively easy 0g construction of large living structures
8. Greater independence
9. Much greater growth potential
10. Near-Earth orbital colonies can service our planet's tourist, exotic materials and energy markets more easily than the Moon, and Mars is too far away to easily trade with Earth

The materials supply problems can be overcome, with some difficulty, by transporting materials from the Moon and Near Earth Objects (NEOs). It should be noted that no one location on the Moon or Mars is likely to have everything required, and substantial materials transport problems will be encountered there as well.

The next section describes the exterior morphology of Kalpana One and the reasons behind these choices. In the process, the controversy over the best shape: torus, sphere, or cylinder is decisively resolved in favor of the cylinder. For a reasonably sized colony, a cylinder requires millions of tons less shielding. The following section describes the interior morphology of the Kalpana One, in particular mechanisms to take advantage of the large interior space provided by a cylinder. This is followed by a section on power and thermal considerations.

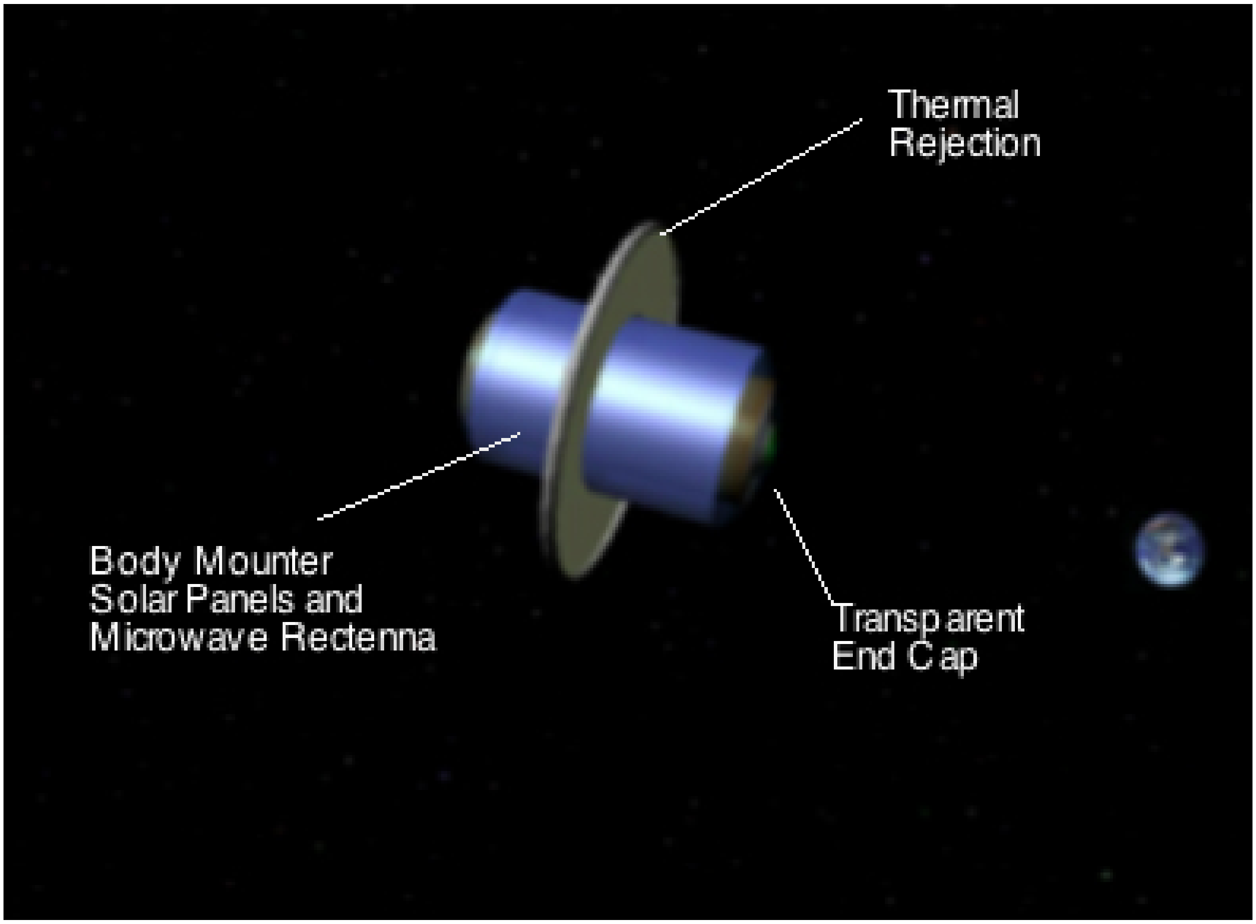

Figure 1. Kalpana One, a 250m radius, 550m length cylindrical orbital space colony.

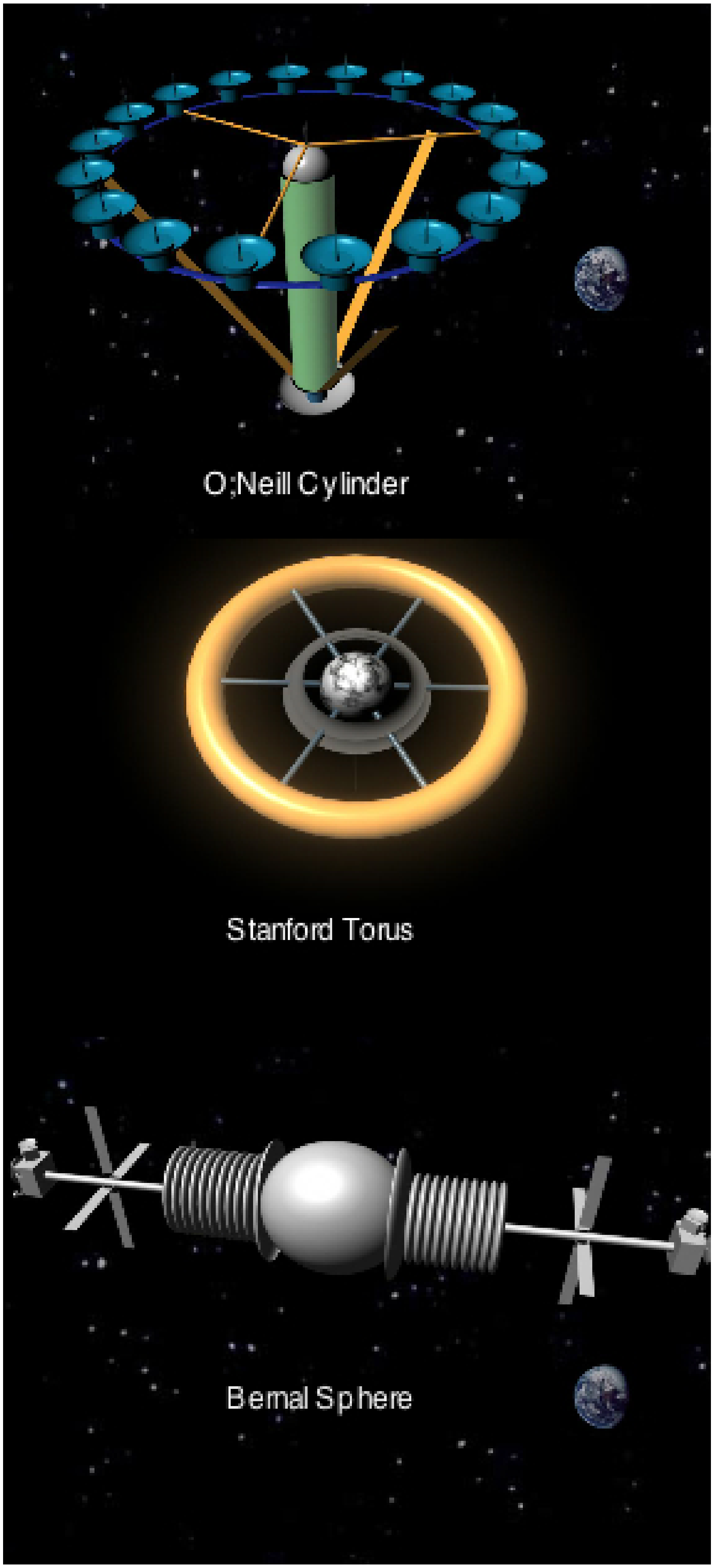

Figure 2. Earlier colony designs.

III. Hull Morphology

The primary point of space colonization is to provide living area for human beings, preferably very high quality living area. An unprotected human in high orbit (above the Van Allen Belts) cannot survive naturally occurring radiation for long periods of time. Not only will periodic solar events generate sufficient radiation to kill in a few hours, ubiquitous radiation of cosmic origin degrades biological tissue continuously. Adequate radiation protection, outside of solar flare events, can be provided by approximately ten tons of material per square meter of hull surface.[1] Radiation shielding thus dominates the material requirements of the system.

All materials must be imported from the Moon or NEOs (Near Earth Objects - asteroids and comets orbiting the Sun near Earth), and this is a very tall pole in colony design. It is thus necessary to choose a shape that minimizes the $hullSurfaceArea/1gLivingArea$, where $1gLivingArea$ is area available for people to live; assuming the first colonists are not willing to perform a major, uncontrolled experiment on their children's physical development with a high probability of serious problems, i.e., children with very weak bones and muscles from growing up in $<< 1g$. Without children, you don't have a colony, so 1g is a hard requirement for early colonies.

For children to grow up with normal strength, orbital colonies must provide a pseudo-gravity environment consistent with human experience over evolutionary time. In other words, residents in the primary living area must experience an acceleration of approximately $1g$ ($9.8m/s$). This can be accomplished by rotating the colony. Thus, orbital colonies must be rotationally symmetric around at least one axis. This limits the practical shapes to the sphere, torus, dumbbell and cylinder. Of these, the cylinder minimizes $hullSurfaceArea/1gLivingArea$. Consider:

1. Torus. The maximum $hullSurfaceArea/1gLivingArea$ corresponds to living area that intersects the center of the minor diameter. This means that $hullSurfaceArea/1gLivingArea = 2\pi r/2r \geq \pi = 3.1415...$. For a torus-like object with a rectangular cross section, $hullSurfaceArea/1gLivingArea > 2$.
2. Sphere. The surface area is $4\pi r^2$ (r = radius). The living area is a function of where the flat surfaces are placed. In the worst case this is one line corresponding to the maximum distance from the axis of rotation making $hullSurfaceArea/1gLivingArea$ infinite. To expand the living area, it must be brought closer to the axis of rotation, which simply yields a cylinder, albeit with more shielding area than necessary.
3. Dumbbell. The surface area is a function of the width of the arms and the size of the expanded area, but for all cases it is larger than the other shapes.
4. Cylinder. For an infinitely long cylinder $hullSurfaceArea/1gLivingArea = 1$, but long cylinders are rotationally unstable. For reasons described below, the maximum length of a rotationally stable cylinder is approximately $2.5r$, which leads to $hullSurfaceArea/1gLivingArea \approx 1.45$ including a safety factor.

Thus, the best shape for an orbital space colony is a cylinder because, for any given $1gLivingArea$, the total mass is substantially less than the nearest competitor. As a typical colony design has a mass of millions of tons and total mass is quite likely the key driver, this is a killer trade, meaning that this issue is so important there is no need for a more detailed comparison.

The size and shape of a cylindrical colony is determined by the radius, length, and the nature of the end caps. As Kalpana One is intended to be the first colony built, it should be as small a practical since the shear size of a colony is a major system driver. The minimum radius is determined by the desired pseudo-gravity level ($9.8m/s^2$) and the maximum rotation rate consistent with human needs. We assume a maximum rotation rate of $2rpm$,[1] so the radius must be approximately $250m$.

In an ideal space environment, any cylinder rotating about its longitudinal axis will continue to do so forever; but in the real space environment perturbations will cause the cylinder to eventually rotate about the axis with the greatest angular moment of inertia. If that axis is not along the cylinder length, this introduces a catastrophic failure mode where the colony gradually changes its rotational axis until it is tumbling end-over-end. This would be the fate of the O'Neill cylinders without active controls, and passive control is always preferred. To achieve passive rotational axis-of-rotation stabilization, assuming the hull has constant mass per unit surface area, the maximum length of a cylinder is determined by its radius. Experience with spin-stabilized spacecraft suggests that the desired axis of rotation should have an angular moment of inertia at least 1.2 times greater than any other axis.[6] For a flat-capped cylinder, this means the length must be less than $2.5r$. Considering that the end caps are curved and allowing a safety factor, we require a maximum length of $2.2r$, or $550m$ for $r = 250m$. This leads to $hullSurfaceArea/1gLivingArea = 1.45$ for cylinders. Thus, Kalpana One's $1gLivingArea$ is approximately $1500m$ by $550m$, for a total of $863,500m^2$, providing $172m^2$ living area for each of 5,000 residents. This is in excess of the 155.2 required by Johnson[1] and the 98.3 per resident of 1970s New York City.[1] The total size is only a little smaller than some very nice California beach towns with around 10,000 residents. This is important, because above all space colonies must be nice places to live. Otherwise, even if settlers can be convinced to move in, they will leave after a short stay.

Passive radiation protection may be provided by approximately ten tons of imported lunar regolith per square meter[1] on the inside of the hull. This implies a total mass for Kalpana One of perhaps 15 million tons. Rotating the shielding requires a stronger hull than earlier designs, but avoids catastrophic failure modes when a rotating habitat contacts non-rotating shielding only a few meters away. Shielding on the interior doubles as soil for plants. Along with air pressure matching Shimla, a large high-altitude city in India, the radiation shielding establishes the strength requirements for the hull. It appears that approximately $15cm$ of steel meets this requirement.[7] For omnidirectional radiation sources, i.e., cosmic radiation, radiation is minimized just inside the hull.[8] This is because, near the hull, radiation from an essentially infinitely distant source from some directions passes through the shielding at an angle and is thus more likely to be absorbed. In the center of the colony, all cosmic radiation passes through a minimal amount of shielding. This means that just inside the hull provides the most Earth-like living environment ($1g$ pseudo-gravity, soil for plants, and minimal radiation).

Although Kalpana One is rotationally stable, it will tend to wobble since the mass distribution is unlikely to be perfectly uniform and people, machines, and materials will be in constant motion. Thus, active control will be necessary to maintain smooth rotation and avoid the equivalent of earthquakes. This can be accomplished by placing large weights attached to cables controlled by motorized, computer controlled winches on the exterior of the hull. The cables can be let out and brought in to compensate for changes in mass distribution based on data from accelerometers placed about the hull. The size, distribution, and control algorithms for this system would be an excellent thesis topic.

To complete a description of the Kalpana One hull morphology we must determine the nature of the end caps. Surprisingly, this provides an opportunity to provide natural sunlight without appendages. Kalpana One's rotational axis is aligned with the solar system's north-south axis, so sunlight falls on half of each end cap continuously. If the end caps are designed to let this light in, not let too much of it out, and either reflect or diffuse the light into the interior, then Kalpana One will enjoy continuous natural sunlight. While most of humanity is accustomed to a 24 hour day/night cycle, people in the extreme northern and southern latitudes, such as Alaska, southern Chile, and the Scandinavian countries, have lived with continuous sunlight for months at a time for thousands of years. To choose the exact shape of the Kalpana One end caps will require a detailed analysis of lighting requirements and the properties of the feasible materials and coatings. While an opaque strong material readily available from lunar or NEO materials should be used for most of the hull, the end caps need to be either transparent with coatings to reflect light into the interior, must diffuse sunlight, or implement some combination.

All systems require maintenance, and Kalpana One's exterior will be no exception. Astronauts working on the hull exterior would experience $> 1g$ centrifugal acceleration away from the hull. This is an unacceptable risk, so all external maintenance must be accomplished by teleoperated or automated robots. For mobility, we propose single wheeled robots. The single wheel fits in gaps between the body-mounted reinforced solar panels. These gaps are sized such that the wheel cannot be forced through. Thus, with a sufficiently strong connection robots cannot be accidentally thrown into space. The reinforced solar panels double as micro-meteoroid bumpers.

IV. Interior Morphology

Cylinders have only a 40% $hullSurfaceArea/1gLivingArea$ advantage over torus-like colonies with square cross sections. However, cylinders have a much smaller $hullSurfaceArea/volume$ ratio. To take advantage of this feature, we propose placing nested smaller-radii cylinders inside Kalpana One's hull. This will have the added advantage of providing some vertical privacy for residents at the hull. The largest of the interior cylinders should have a radius on the order of $100m$ less than the hull to provide ample head room in the 1g living area. The number and spacing of interior cylinders can be varied to meet the needs of each colony. A great deal of area is available, far more than at the hull. For example, eleven internal cylinders at seven meter spacing provides approximately $4,870,000m^2$, over five times the space available at the hull. This is important since one of the primary disincentives to space colony life is restricted living space.

The interior cylinders can be attached to the hull and each other by cables (in tension) running from the innermost level to the outer hull. Cables passing completely through the interior can reinforce the hull and reduce hull material strength requirements. These cables may double as scaffolding for low-light-level vines, such as those found in tropical rain forests, to create a unique and beautiful interior. The presence of large number of vines can help keep the air clean and provide potable water via transpiration. Ideally, these vines might also provide food, but that may be too much to ask for the natural light levels available inside Kalpana One.

For transition between cylinders, elevators and ramps may be used. Ramps provide transport for heavy industrial and agricultural goods. Long trailing vines may be cultivated on the edges of the ramps to complete a scene perhaps reminiscent of the famous hanging gardens of Babylon. This is no mere fluff. To attract suitable colonists, who will need to technically capable and therefor fairly well off, space colonies must be attractive, wonderful places to live. Feeling nobel about colonizing the solar system will last until about the 30th diaper change, but no longer. Practical space colonies must take advantage of positive characteristics of space life that cannot be replicated on Earth.

One attraction of orbital living is low-g recreation. As most of the interior cylinders will rotate at the same rate as the hull ($2rpm$), the pseudo-gravity level will be less. Thus, the internal cylinders are ideal for low-g sports, dance, and other entertainment as well as industrial activities with minimal out-gassing. In a small, closed environment such as Kalpana One air pollution is absolutely unacceptable. Low-g internal cylinders are also ideal living areas for the old and infirm who may prefer low-g living to wheelchairs and walkers.

Inside the inner-most cylinder are $0g$ recreation areas. Besides open space for $0g$ sports, dance and general play, e.g., human powered flight, Kalpana One provides a cylindrical swimming pool and $0g$ hotel rooms for tourists and residents. Cylindrical swimming pools were proposed by Heppenheimer.[3] Since the swimming pool wraps around the axis of rotation, one can swim continuously without turns and dives straight up are possible. To provide sufficient pseudo-gravity to keep the water in the pool at a $30 - 40m$ radius, the pool may be spun at greater than $2rpm$ and maintained in place by electro-magnetic bearings. These bearings are similar to the levitation and propulsion systems used in maglev trains, but with much lower performance requirements. In addition to recreation, water is an excellent radiation shield, so the swimming pool can double as a solar storm shelter. For $0g$ hotel rooms, the $2rpm$ rotation rate is an irritation. People and objects will tend to collect on one wall. Hotel rooms may be despun and maintained on electro-magnetic bearings similar to those used for the swimming pool.

High intensity, controlled environment agriculture requires $50m^2$ to feed one person.[9] For a population of 5,000, the total agriculture area required is $250,000m^2$. This requirement can be easily satisfied by the first internal cylinder alone, assuming that sufficient food crop species are insensitive to lower gravity levels. In fact, low-g agriculture may be more efficient than $1g$ since species can be bred with weaker trunks and stems leaving more energy available for edible portions of the plant. The agricultural area may be divided into a number of chambers, each of which grows a particular species. Each chamber may be sized to provide one or a few day's need. These chambers can be operated under controlled atmosphere, temperature and lighting conditions for rapid, efficient growth of crops. Plants also cleans the air and provide clean water through transpiration. However, as there is no easy way to bring direct sunlight onto the entire outermost internal cylinder, Kalpana One's agriculture requires artificial lights which, in turn, require a great deal of power.

V. Power and Thermal Control

Small amounts of emergency power can be supplied by body-mounted solar cells. However, Kalpana One requires substantial energy resources. Approximately $60kW$ continuous energy per resident is required, $50kW$ for intensive artificial light agriculture[9] and $10kW$ for other purposes. The $10kW$ figure reflects total energy use per person in the U.S. today, including industrial use. For a population of 5,000, this implies $300mW$ continuous power. We propose using separate solar power satellites (SPS) for primary energy needs. The hull exterior then requires body-mounted microwave rectennas to receive energy from solar power satellites. Wireless transmission of electrical power has been demonstrated with > 90 percent efficiency.[10] This implies that the microwave power density must approach $400w/m^2$ on the hull $[1.1(300000000w/863,500m^2)]$.

The heat generated by electric power consumption and incoming sunlight must be dissipated. Kalpana Ones thermal rejection system consists of thermal radiators attached around the rotation axis of the colony in the middle as shown in figure 1. Placement in the middle further enhances rotational stability. Since the rotation axis is always normal to the sunward vector, short shades around the radiators are sufficient to avoid thermal interaction with the sun. The required surface area is determined by electrical power and solar lighting inputs. A disk with 450m radius outward from the hull appears adequate assuming the thermal rejection capacity of the International Space Station thermal rejection panels, 1 kW for a 12 x 4 ft panel.[11]

VI. Conclusions

Kalpana One is intended to be the first, and smallest, of a family of space colonies. The size is determined by the limited rotation rate humans are assumed to tolerate, $2rpm$. The rotation rate drives the radius to achieve $1g$ pseudo-gravity, and the radius drives the length due to angular moment of inertia requirements. For later, larger colonies in the Kalpana family, the rotation rate may be reduced, increasing the radius and the allowable length.

Kalpana One solves some of the problems found in earlier designs: excessive shielding mass, large appendages, lack of natural sunlight, rotational instability, lack of wobble control, and some catastrophic failure modes. Much is left to be done before a practical space colony can be fully designed and built. Just as our distant ancestors left the warm oceans and colonized dry land, it is our task to colonize the vast, empty reaches of space; thereby ensuring the survival and growth of civilization, humanity, and life itself. Let's get to work.

VII. Acknowledgements

The Kalpana family of space colony designs is named in honor of Dr. Kalpana Chawla, who was killed when the space shuttle Columbia broke up returning from orbit. Before joining the astronaut corps, Dr. Chawla worked at NASA Ames Research Center in an office next door to the first author. She shared her country of origin with the other two. It is our hope that this design will evolve into the first space colony built, and retain its name. We would like to thank the Priya Education Society, India for sponsoring this project.

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