GRAVITY, SPACE, AND ARCHITECTURE

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(August 1994 – April 2004)

This is a preprint manuscript submitted for inclusion in a catalog of an exhibition titled "2001: Building for Space Travel," hosted by the Art Institute of Chicago, 24 March - 21 October 2001, and the Museum of Flight in Seattle, 15 December 2001 - 15 May 2002. An edited and reformatted version was published as:

Hall, Theodore W. (2001). "Gravity, Space, and Architecture." In J. Zukowsky (Ed.), *2001: Building for Space Travel* (p. 168-174). New York, New York, USA: Harry N. Abrams, Inc.

The published manuscript went through several iterations to coordinate figures and references with other articles in the catalog, and to accommodate the chief editor's style preferences without mangling the meaning. I do not have a digital copy of the final publication, but of course, in any case, I prefer my original phrasing – presented on the following pages.

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> Such things do not exist and cannot exist and never have existed … Yet when people see these frauds, they find no fault with them but on the contrary are delighted, and do not care whether any of them can exist or not.
>
> — Vitruvius

> I am not in favor of compact designs which give an impression of solidity and recall heavy earthly buildings. Other laws prevail in space and there is no reason why the old architectural rules should be followed.
>
> — Hermann Oberth

Introduction

The history of architecture is, to a large extent, the history of a struggle with gravity. In the ziggurats and pyramids of Babylon, Egypt, and Mesoamerica; in the posts and beams of the Parthenon and Stonehenge; in Roman arches and Gothic flying buttresses; in Bedouin tents and tensile structures; in the domes of igloos and Olympic stadiums – architecture is shaped by gravity. The shape may or may not be intentional. An unintentional shape is often a symptom of structural failure.

What happens to architecture if gravity is increased, decreased, or removed altogether? What happens if natural gravity is replaced with an artificial substitute, such as centripetal acceleration (rotation)? Science and fantasy have often sought to answer these questions, with varying degrees of success.

Gravity and Architectural Design Theory

The force of gravity on architecture and architects is not only physical, but also psychological. Familiarity with gravity is not innate, but is learned in infancy. At 4 months, infants begin to realize that a rolling ball cannot pass through an obstacle, but are not yet aware that an unsupported ball will fall. At 5 months, they discriminate between upward and downward motion. At 7 months, they show sensitivity to gravity and the "appropriate" acceleration of a ball rolling upward or downward. By adulthood, people judge falling objects to move naturally only if they accelerate downward on a parabolic path. These judgments arise not from mathematical reasoning, but rather from visual experience. When asked to reason abstractly about such motion, many adults are prone to error [1, 2, 3].

Unabashed by their propensity for such errors, various adults have boldly gone to formulate theories and philosophies on the role of gravity in architectural design.

Gravity imparts a notion of *principal directions* that imbue space with an inherent structure. Six directions on three axes are innately perceptible: up-down (height), left-right (breadth), and front-back (depth). The up-down axis is tied to the force of gravity – the plumb line; the other axes are free to rotate around it. The up-down axis is called "vertical", while all possible left-right and front-back axes are called "horizontal". The anisotropic character of this space is judged by the effort required to move in any given direction: up and down are distinct irreversible poles; left, right, front, and back are interchangeable simply by turning around. Thus, gravitationally, there are three principal directions – up, down, and horizontal – and three basic architectural elements – ceiling (or roof), floor, and wall.

These common-sense ideas, rooted in the experience of terrestrial gravity, permeate architectural theory. Norberg-Schulz writes [4]:

> To be meaningful … the inventions of man must have formal properties which are structurally similar to other aspects of reality, and ultimately to natural structures … Natural and man-made space are structurally similar as regards directions and boundaries. In both, the distinction between up and down is valid, as well as the concepts of extension and closure. The boundaries of both kinds of space are moreover to be defined in terms of "floor", "wall", and "ceiling".

Thiis-Evensen proceeds to build his entire architectural grammar around the three elements of floor, wall, and roof [5].

Architectural design for a gravitational environment distinctly different from Earth's requires a fundamental reexamination of basic design principles. The characterizations of the directions and boundaries of natural and man-made space must be reevaluated – if not refuted – in extraterrestrial environments. Scully writes [6]:

> Human beings fashion an environment for themselves, a space to live in, suggested by their patterns of life and constructed around whatever symbols of reality seem important to them. Most of all, that environment and those structures invest the vast indifference of nature with meanings intelligible to, indeed imagined by, mankind.

People's patterns of life, and consequently their symbols of reality, depend largely on their experience of gravity. It taxes the imagination for terrestrial architects to fashion extraterrestrial architecture.

Architecture in Partial Gravity

Gravity is a vector that varies in magnitude as well as direction. Nevertheless, architecture for the Moon, Mars, and other planets has been inconsistent in its accommodation of gravities other than Earth's one g.

After careful consideration of the rugged, airless, low-gravity environment, Hermann Oberth envisioned his “Moon car” (Fig. 1) as a combination gyroscope, mobile home, pogo stick, and bulldozer. A whirling mass above the habitat would provide the momentum to keep the stack vertical. Just below, the inhabitants would survey their surroundings from their perch atop the pole. The foot of the vehicle would tread across the trackless landscape. When it came to an otherwise impassable crevasse, the vehicle would leap across on its retractable column, like some mechanical decathlete [7].

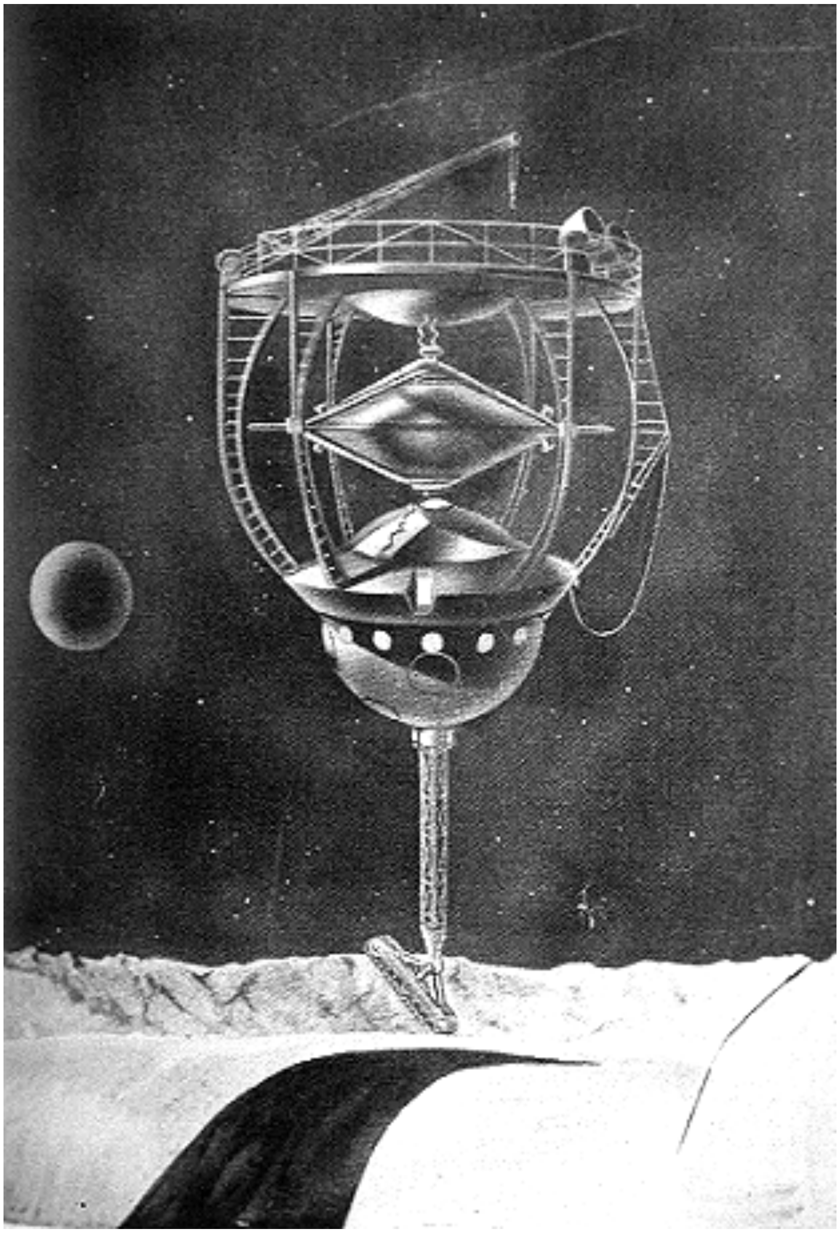

Figure 1: Oberth’s “Moon car”, 1957.
[Permission? See reference 7.]

Topps Chewing Gum issued a series of "Space Cards" in 1958 that brought images of space exploration to the adolescent masses. The illustrations drew from recent history as well as future projections. A card labeled "Gymnastics on Moon" (Fig. 2) shows a young man jumping easily 10 feet into the air, while behind him a weight lifter hoists a massive barbell with a single hand. The gymnasium ceiling is high enough to accommodate unrestrained exercise in the low-gravity environment of the Moon [8].

Figure 2: Topps card, "Gymnastics on Moon", 1958.
[Permission? See reference 8.]

Lunar athletes will soon learn the difference between weight and mass. It's true that a 100-kilogram mass, which weighs 220 pounds on Earth, weighs only about 36 pounds on the Moon. It's also true that it retains its full 100 kilograms of mass and inertia, and is 6 times as difficult to accelerate as a 36-pound weight on Earth. Unsuspecting Lunar jocks who attempt to clean-and-jerk such a mass may be in for a rude surprise. Weight lifting on the Moon will be a slow-motion exercise, compared to comparable weights on Earth.

As for Lunar basketball, how high should the net be? One approach (not necessarily the best one) is to consider the height of a jump necessary to touch the rim, measured from the initial squatting posture where the work begins. In the Moon's 1/6 gravity, a jump with equal energy will achieve 6 times the height. This implies that, as a first estimate, the rim should be raised by 5 times the Earth-jump height to match Earth-normal exertion. If on Earth a person could touch a 10 foot rim with a 3 foot jump, then on the Moon the rim should be raised by 15 feet, to a height of 25 feet.

Figure 3: *2001: A Space Odyssey*, Lunar conference room, 1968.
[Permission? See reference 9.]

Unfortunately, most current designs for early Lunar bases are spatially constrained to small, rigid, prefabricated modules that can be launched from Earth. High ceilings are a low priority. The recreation module might accommodate weight training, but Lunar basketball will have to await more generous quarters.

The film *2001: A Space Odyssey* paints an all-or-nothing picture of gravity. The conference room at the Lunar base (Fig. 3) appears to be a typical terrestrial design. The photographer scurries around as if on Earth, unfettered by reduced floor traction (proportional to weight) and unconcerned with bumping his head [9].

Even as this film was being produced, Apollo astronauts were practicing mobility in Lunar-gravity simulators. Still, they needed actual experience on the Lunar surface to develop their technique. Most of them favored a loping stride in which they alternated feet, pushing off with each step and floating forward before planting the other foot. Stopping and changing direction required some extra attention: partial gravity reduces weight and traction, but not mass or momentum.

The Moon's 1/6 g doesn't accommodate an Earth-normal stride. In the Apollo expeditions, the massive moon suits and backpacks partially compensated for the gravity deficit. That will not be the case in a larger Lunar base intended to provide a shirt-sleeve environment for extended stays.

Following debriefing upon his return to Earth, Buzz Aldrin expressed disappointment at the apparent lack of interest in lunar surface mobility [10]: "I had felt, really, that there would be a lot more evaluation made of what I was doing and maybe my comments."

Architecture in Micro Gravity

Since the time of Icarus, Earth-dwellers have dreamt of soaring like birds to the heavens. Unfortunately, Icarus's waxen wings melted when he flew too close to the sun, and he fell into the sea. Ironically, it's the falling, not the flight, that's the best analog for space travel. Orbit is simply free-fall, with a forward velocity so fast that the curvature of the fall matches the curvature of the Earth (or whatever celestial body one is orbiting).

Architects, in their exuberance for the novelty of space flight, have conceived it more like swimming or floating. In a rush to free themselves from the shackles of gravity, they've overlooked the down side of free fall and its attendant disorientation, and happily abandoned the notion of principle directions.

In September 1967, the architectural firm of Warner Burns Toan and Lunde (WBTL) began to work with Grumman Aerospace to develop zero-gravity space station design concepts (Fig. 4). Working with a stack of cylindrical modules, they explored several schemes for subdividing the volume, sometimes varying the up-down orientation from one chamber to another. *Progressive Architecture* commented [11]:

… its clear expression of the properties of space, of life in space, of the body freedom, are appealing to the imagination. Where is the fun, after all, if the Earth environment is too closely duplicated? Taken to extremes, it could mean lace curtains and French provincial in light-weight plastic.

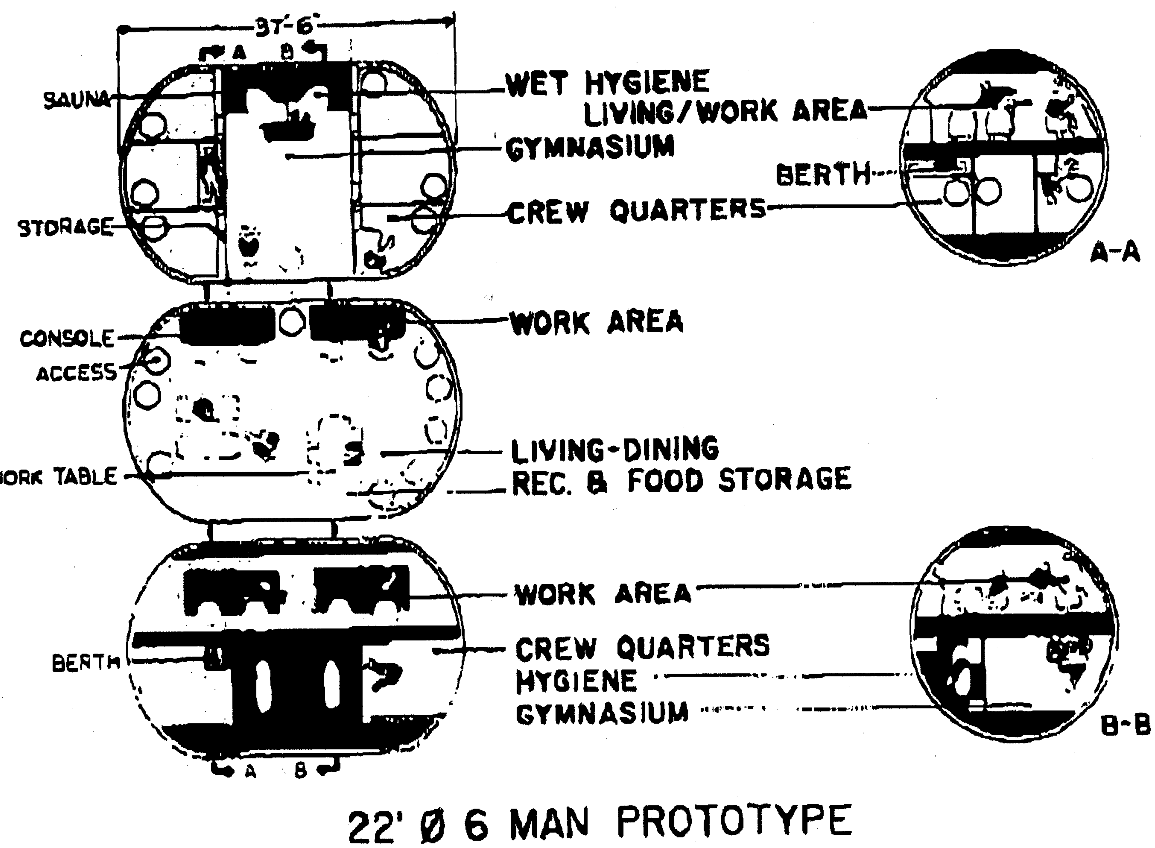

Figure 4: Warner Burns Toan and Lunde, zero-gravity space station concept, 1969. [Permission? See reference 11, page 139.]

In *2001: A Space Odyssey*, Kubrick and Clarke had fun with the notion of zero-gravity body freedom, particularly in the cislunar transfer vehicle (Fig. 5). A stewardess, equipped with special gripper shoes, steps “head up” into the galley, removes a tray of food from the oven, then trundles her way around a circular portal, up the wall and onto the ceiling, to emerge “head down” into the passenger cabin. This maneuver, and the odd interior design that demands it, serves no obvious purpose other than to entertain the audience. (In fact, since the craft must eventually land in the Moon’s non-zero gravity, the design may be seriously flawed.) After observing this action for a few seconds, the camera follows the stewardess’s lead and rolls 180 degrees to achieve a more comfortable orientation with respect to its new surroundings [12].

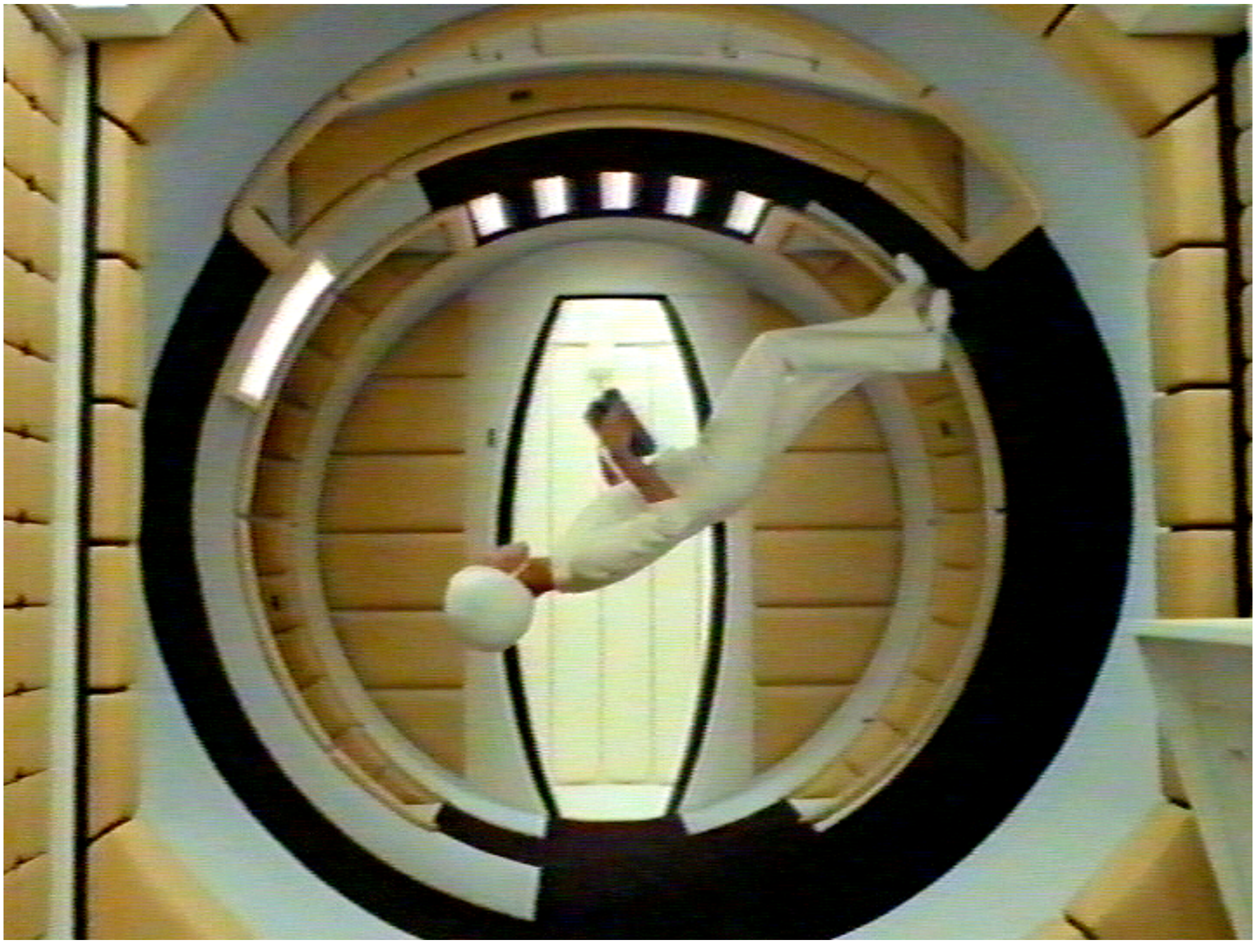

Figure 5: ***2001: A Space Odyssey*, cislunar transfer vehicle, 1968.**
[Permission? See reference 12.]

Skylab offered, in 1973, the first real experience with significant freedom of movement in micro gravity. Astronaut Ed Gibson reported [13]:

> Being upside down in the wardroom made it look like a different room than what we were used to. When I started to rotate back and go approximately 45 degrees or so off the attitude which we normally call "up," the attitude in which we had trained, there was a very sharp transition in my mind from a room that was sort of familiar to one which was intimately familiar.

The wardroom furnishings provided the astronauts with an important vertical reference for internal activities. Nevertheless, when looking out the window, they switched to an Earth-down reference even if this meant floating sideways or upside down relative to the furnishings.

In contrast to the wardroom, the workshop didn't provide any particular vertical. According to Oberg and Oberg, "the Skylab astronauts would sometimes become a little disoriented in it and preferred the lower [sic] decks with their smaller but more familiar spaces" [14].

Micro-gravitational space may be amorphous and isotropic, but the human body is not. Based in part on the Skylab experience, current micro-gravity habitat design shuns the disorientation of earlier architectural fantasies and presents the inhabitants with a consistent up-down axis. This is evident, for example, in the TransHab inflatable module (Fig. 6) – initially conceived at NASA Johnson Space Center as an Earth-to-Mars transit habitat and later proposed for the International Space Station (ISS). One of the "important design objectives" of TransHab is "to maintain a local vertical configuration" [15]. The orientation of the internal vertical axis with respect to external space is somewhat arbitrary. What's important is that the habitat is at least internally consistent with respect to vertical orientation.

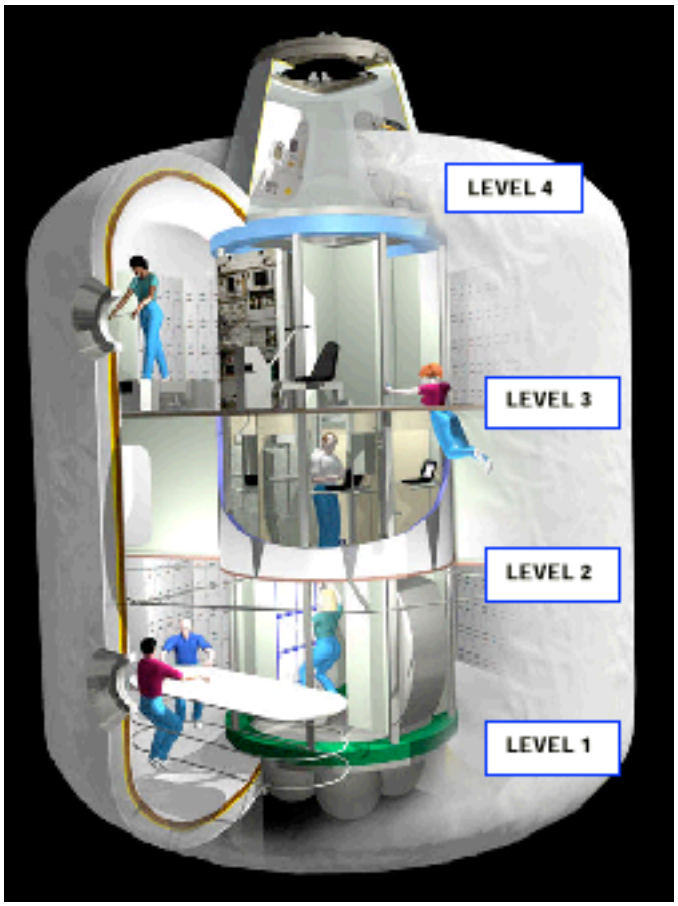

Figure 6: ISS TransHab Internal View, NASA JSC S99-05363, 1999. [Permission? See reference 15.]

Weightlessness isn't the euphoric experience that many people imagine – at least, not during the first few days, during which about half of all space travelers suffer symptoms of motion sickness. People adapt, and the overt sickness subsides. But, as bodily fluids shift from the lower extremities toward the torso and head, more insidious adaptations settle in: fluid loss, muscle loss, bone loss, weakened immunity, flatulence, and nasal congestion, to name a few [16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27].

Follow any discussion of space tourism long enough, and the subject of "sex in space" is bound to come up. People love to fantasize, but nausea and flatulence are generally poor aphrodisiacs. In any event, housekeeping in the micro gravity space hotel will be a major task; every surface of the chamber must be designed with this in mind.

Architecture in Artificial Gravity

Isaac Newton's *Mathematical Principles of Natural Philosophy*, published in 1687, contain everything necessary to explain the relationships of force, mass, acceleration, orbit, weightlessness, and artificial gravity. Decades before the first Sputnik achieved orbit, the early visionaries of space habitation foresaw problems with weightlessness and questioned whether people could long survive in such a state.

Artificial gravity dominated the early space station concepts. Only after substantial experience with weightlessness did micro gravity concepts come to the fore. Since the Salyut and Skylab missions of the 1970's, access to micro-gravity has been one of the main motivations for space flight. Ironically, while extended stays in weightlessness have revealed its dangers, they have also shown that it is survivable; several cosmonauts have survived micro-gravity missions of a year or more. Such missions are milestones of human endurance; they are not models for space settlement. Artificial gravity is both the past and future of long-duration space habitation.

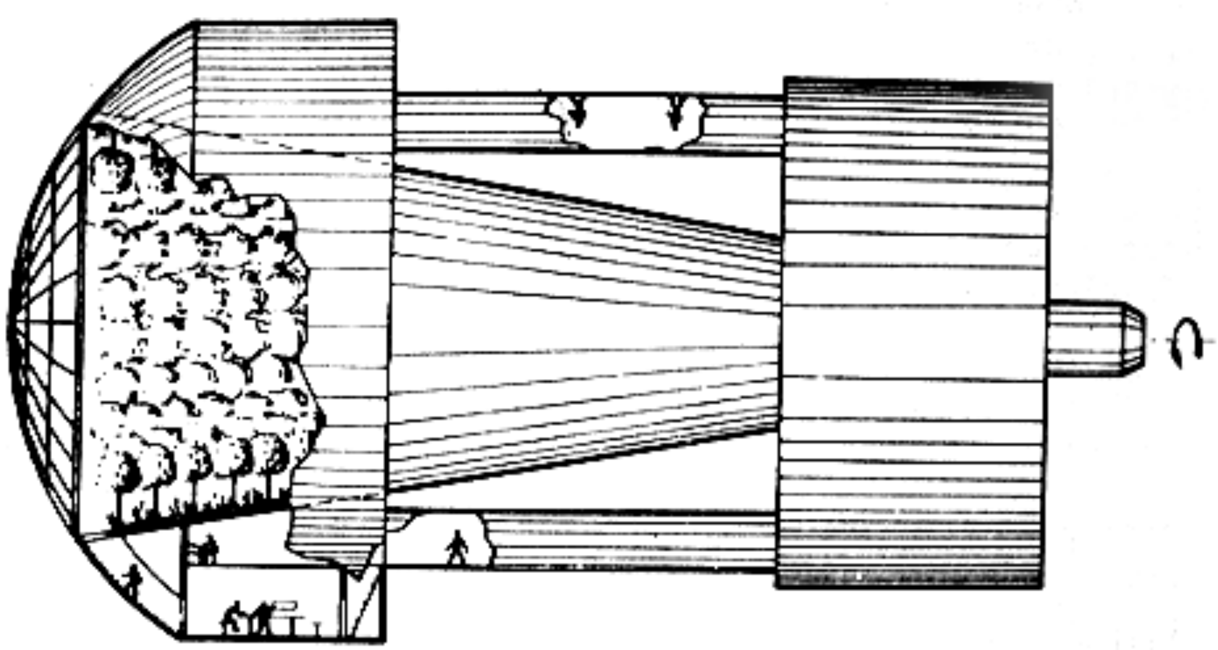

Figure 7: Tsiolkovsky space station concept, 1903.
[Permission? See reference 29.]

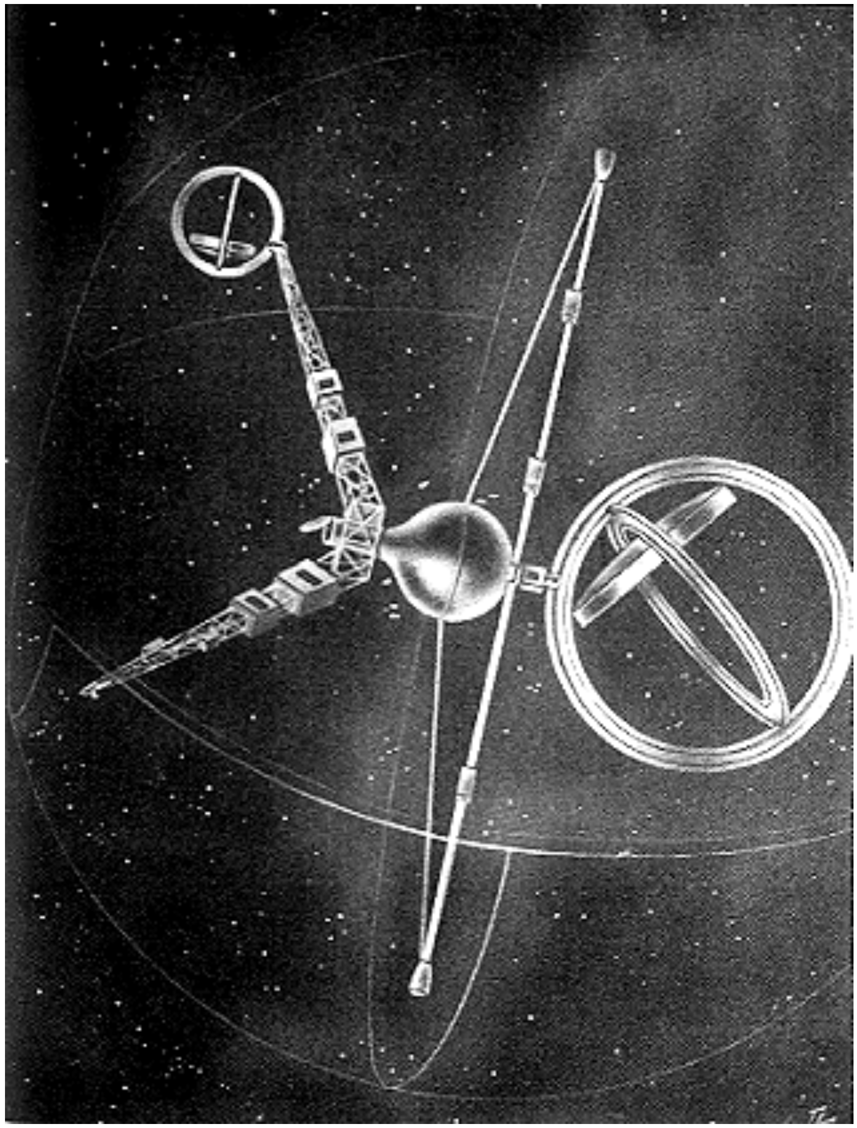

Figure 8: Oberth's "Springboard station", 1957.
[Permission? See reference 30.]

As early as 1903, Konstantin Eduardovich Tsiolkovsky published plans for orbital outposts incorporating artificial gravity (Fig. 7) [28, 29]. Twenty years later, Hermann Oberth independently developed similar ideas (Fig. 8), followed by Hermann Noordung (Fig. 9), Wernher von Braun (Fig. 10), and others [30, 31, 32]. By the 1950's, the image of the space station as a rotating torus was firmly established. Much of the credit (or blame) for this must go to von Braun, who brought his vision to the masses through the media of *Collier's* magazine and Walt Disney films [33, 34, 35].

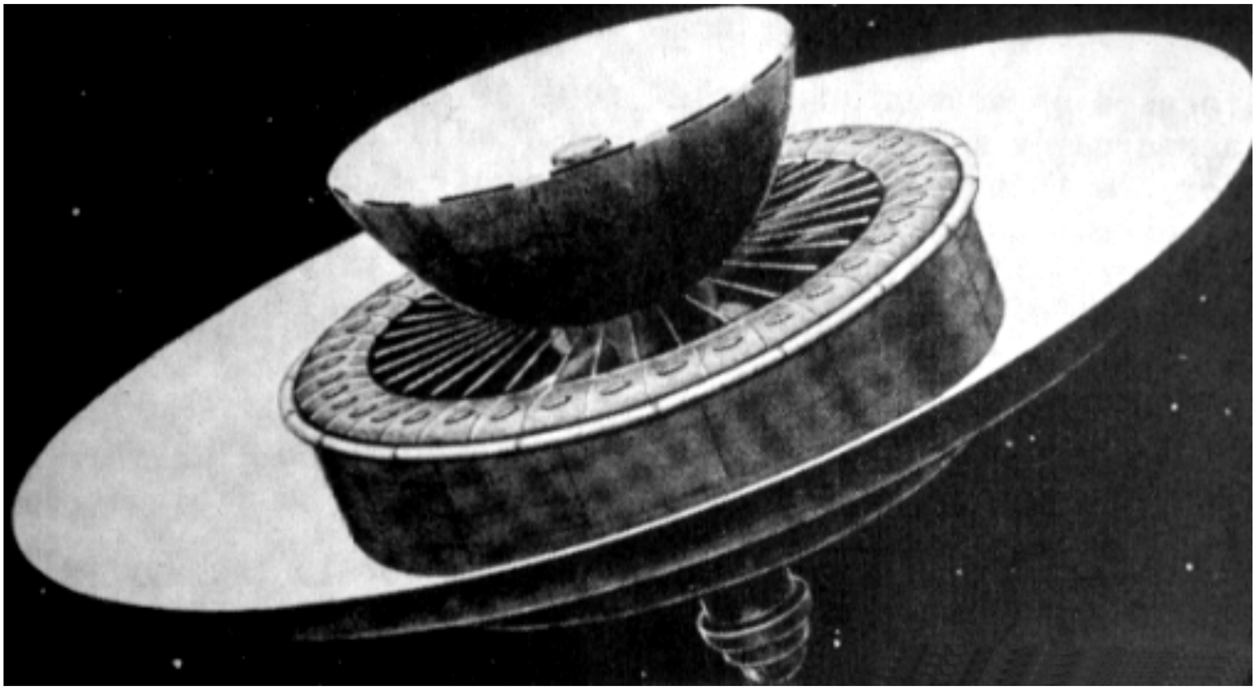

**Figure 9: Noordung's "Wohnrad" ("Living wheel"), 1928.
[Permission? See reference 29.]**

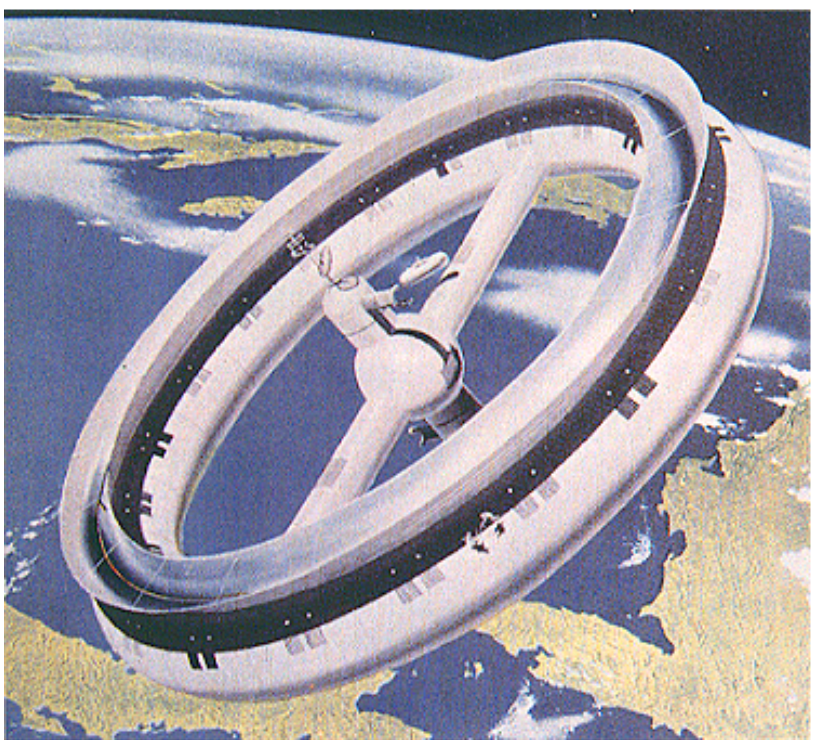

**Figure 10: von Braun space station concept, 1952.
[Permission? See references 33–35.]**

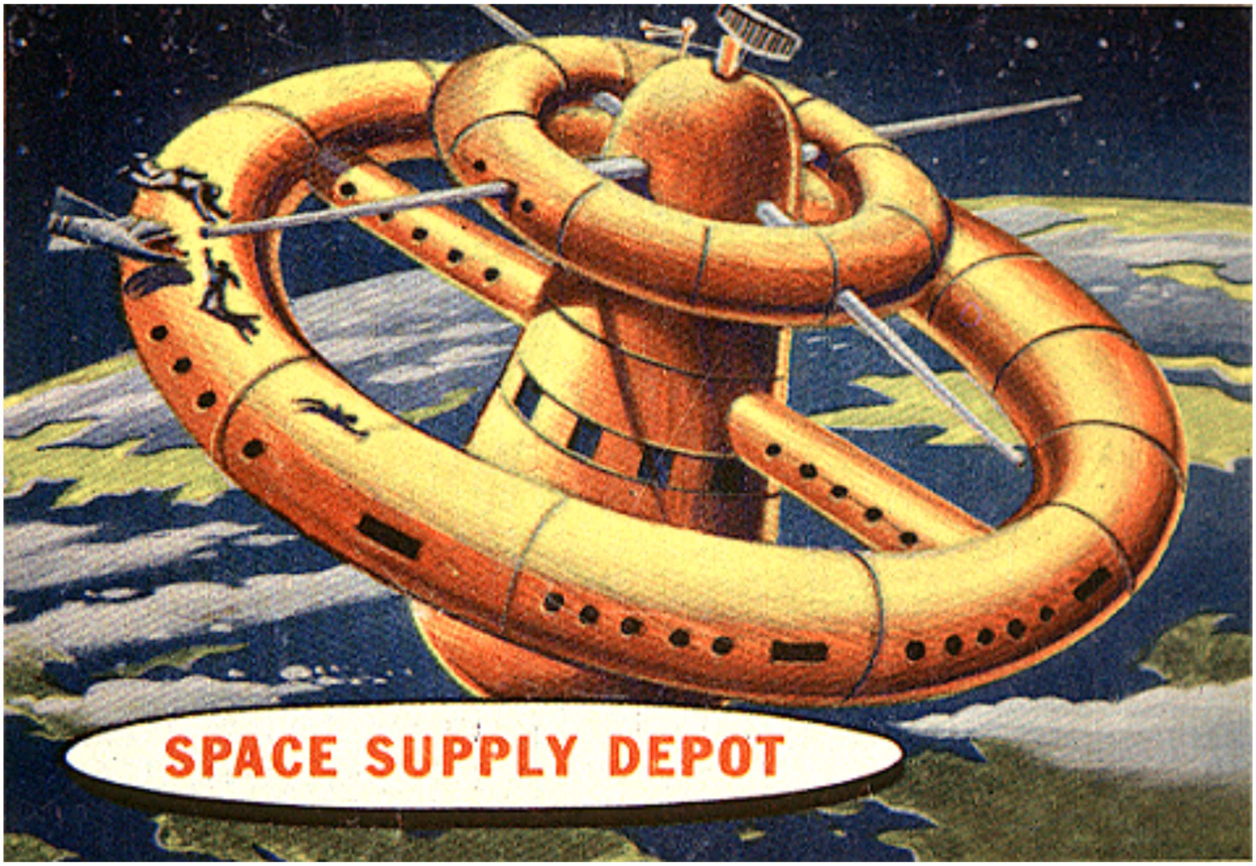

Figure 11: Topps card, "Space Supply Depot", 1958.
[Permission? See reference 36.]

The torus is a powerful gestalt. People "know" that it's what a space station should be, even if they don't understand why. The Topps card entitled "Space Supply Depot" (Fig. 11) is a case in point. It depicts the station as a pair of tori surrounding a roughly conical core. An astronaut stands on the outer skin of the structure, aligned with the axis. If this station rotated, as the wheel shape suggests it should, the artificial gravity would be at right angles to what the artist seems to expect: the windows would be in the floor and the astronaut would be flung from his precarious perch [36].

Before Sputnik, space station design was a pursuit of comic book artists, fantasy film producers, and engineers with perhaps too much time on their hands. After Sputnik, it became a national priority. With the dawn of manned space flight in the 1960's, teams of engineers began a concerted effort to materialize the visions of their forebears. Some of the biggest problems were packaging, launch, and deployment in orbit. In particular, they looked for ways to pack a rotating space station into the right circular cylinders of rocket payload fairings.

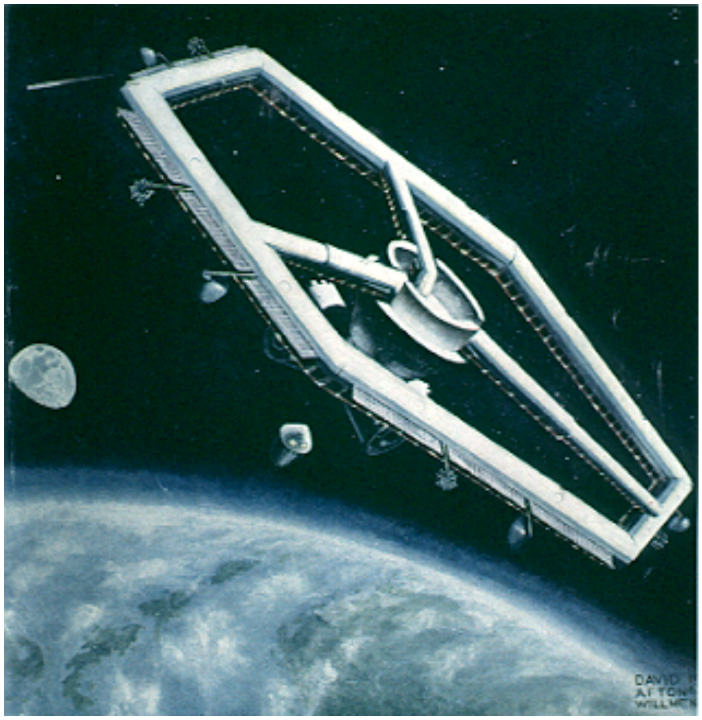

Figure 12: NASA Langley Research Center's and North American Aviation's AEMT, 1962.
[Permission? See reference 37.]

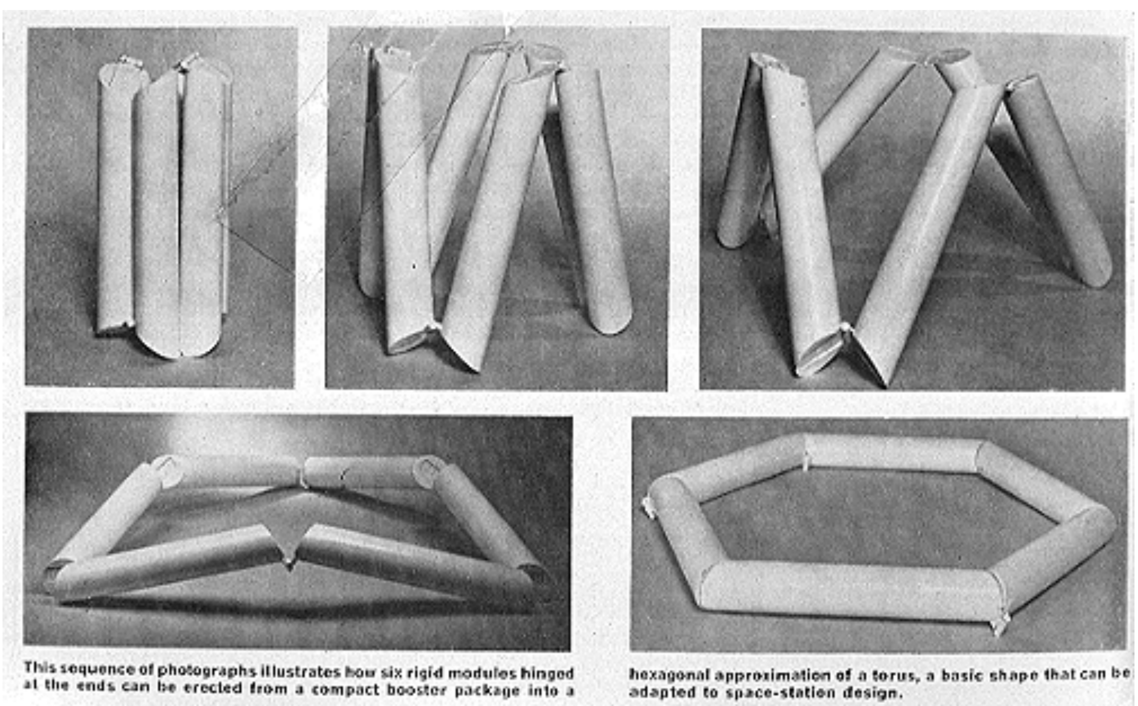

Figure 13: AEMT deployment, 1962.
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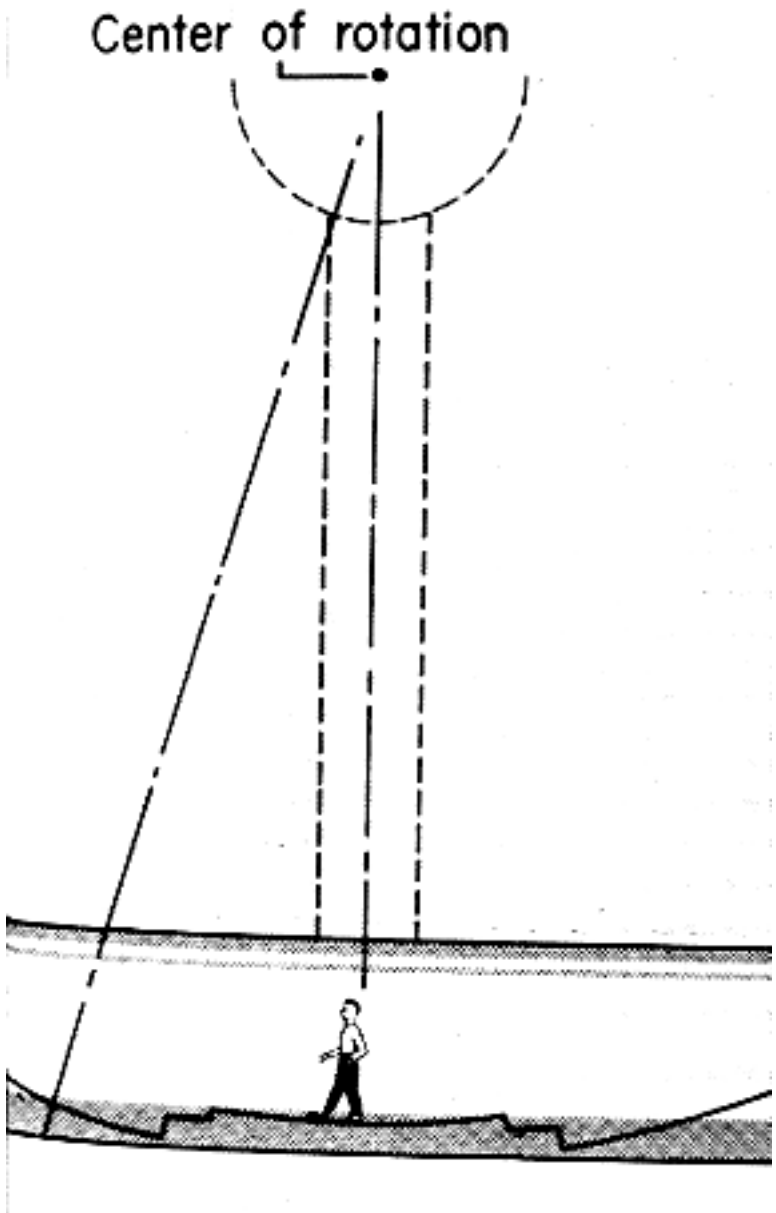

Figure 14: AEMT circular floor inscribed in a hexagonal torus, 1962. [Permission? See reference 37.]

NASA Langley Research Center and North American Aviation developed plans for an "automatically erectable modular torus" (AEMT). They conceived a hexagonal arrangement of cylindrical modules joined by hinges at the vertices (Fig. 12). The station would be constructed entirely on the ground, folded for launch, and unfolded in orbit (Fig. 13). Because spin-induced artificial gravity is centripetal, a "level" floor must be circular in the plane of rotation. A six-sided torus would feel as lumpy as a six-sided wheel. To avoid that, the designers arranged the finished floor as a series of concentric arcs stepping up and down across the length of each module (Fig. 14) [37, 38, 39].

The Lockheed Aircraft Corporation avoided that problem by stepping away from the torus paradigm and turning their modules parallel to the axis of rotation (Fig. 15). This has the added advantage of reducing the crew's encounters with Coriolis acceleration – a gravitational distortion that accompanies motion perpendicular to the axis (radial or tangential), but not parallel to it [40].

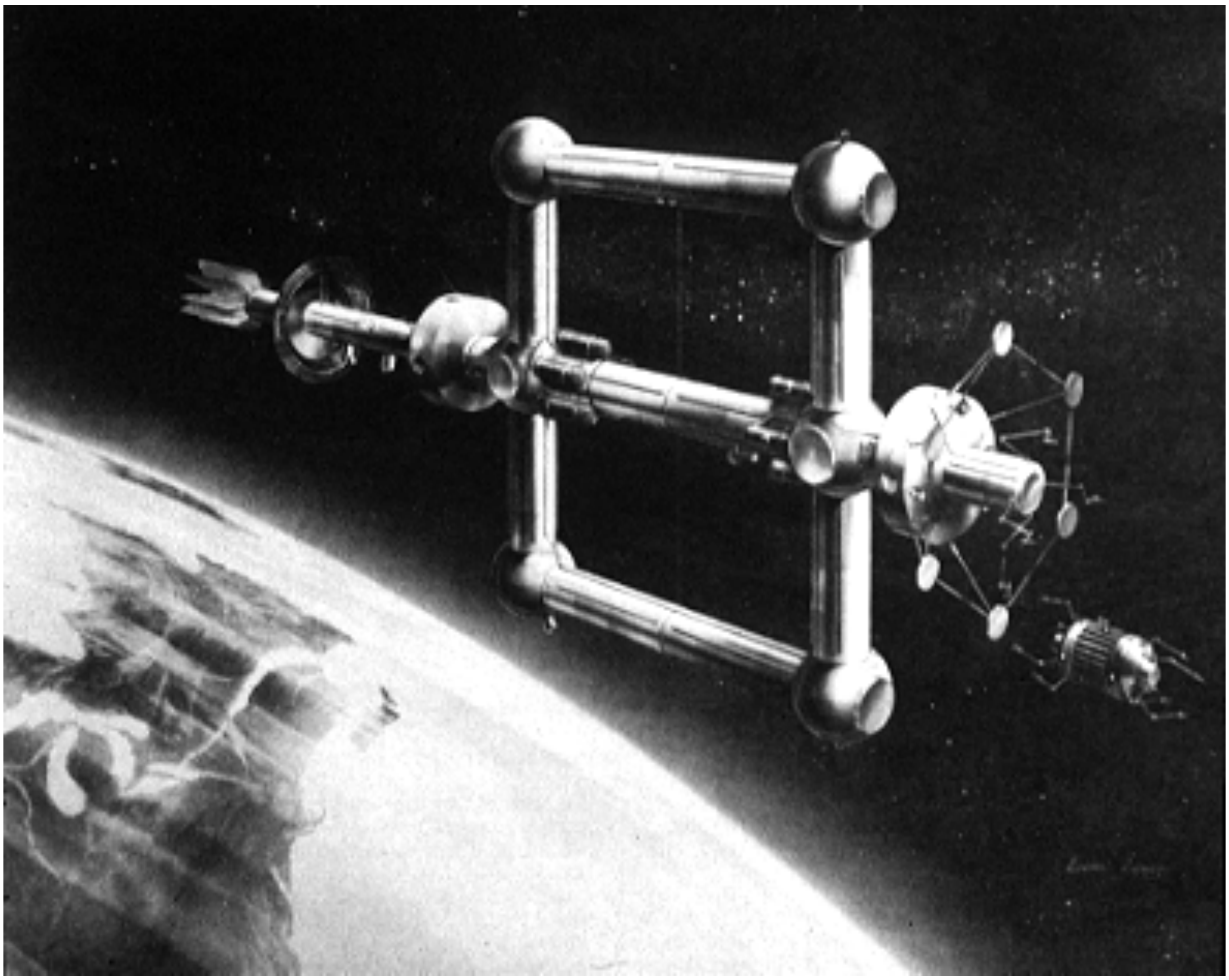

Figure 15: Lockheed's modular rotating space station concept, 1960. [Permission? See reference 40.]

Nearly forty years later, working at a substantially grander scale, designers at the Shimizu Corporation have assumed a similar strategy in their proposal for a space hotel. Echoing the relatively modest Lockheed proposal, they've assembled their structure from cylindrical modules arranged parallel to the rotation axis (Fig. 16). Unlike the earlier design, the prevailing gestalt here is still the torus [41].

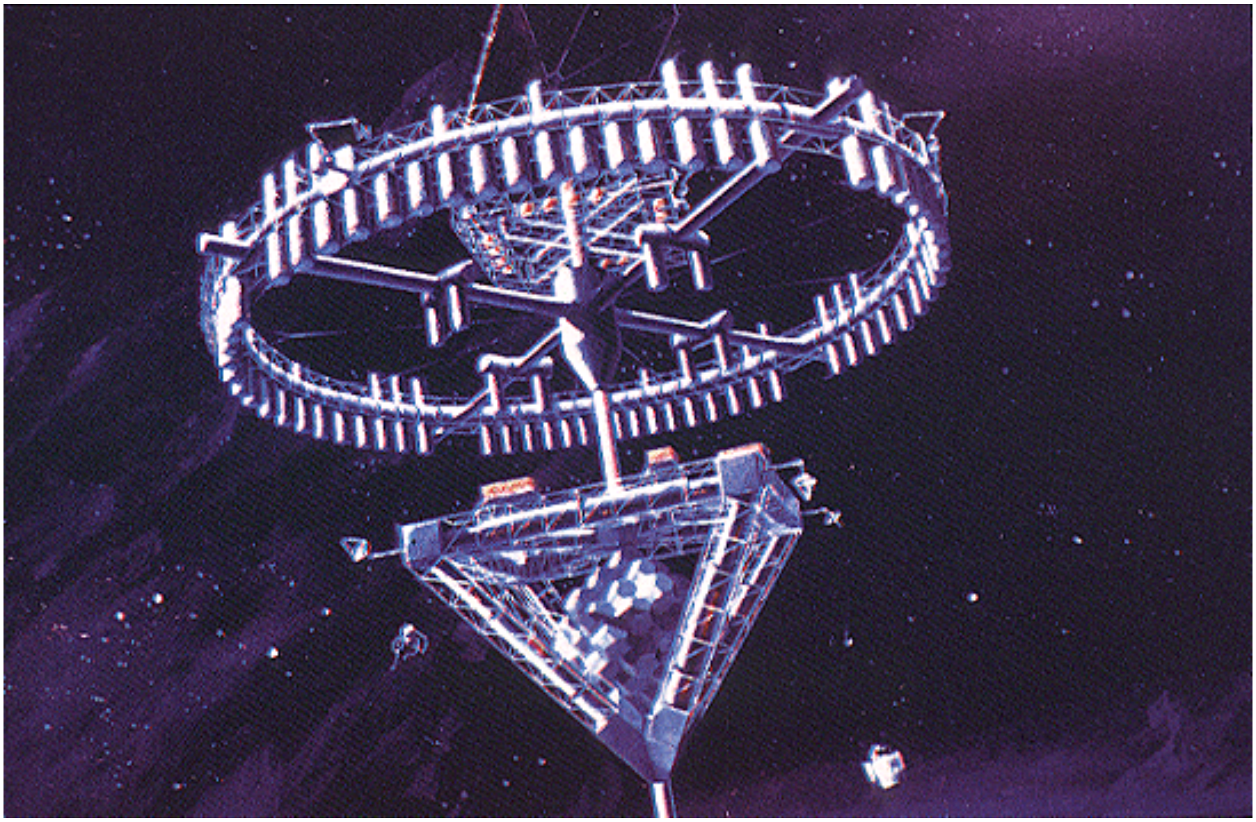

Figure 16: Shimizu Corporation's space hotel concept, 1997 (?).
[Permission?]

Grander still are the enormous space colonies championed by Gerard O'Neill, such as the "Stanford Torus" (Fig. 17), the "Bernal Sphere" (Fig. 18), and various models of cylindrical "islands" as much as four miles in diameter (Fig. 19) [42, 43]. Descriptions of life in the colony are rife with the incongruity of trying to transplant middle-class America into the concave environment of a self-contained spinning cylinder [44]:

> It would be like urban living in this country, with the difference that instead of looking into the windows of another apartment one would be looking out onto farmland. One could imagine having a promenade of shops, cinemas, restaurants, markets, and libraries, extending all the way around the cylinder.

Space colony architecture is often conceived as an idealization of Earth, rather than a departure from it.

Figure 17: "Stanford Torus", 1975.
[Permission? See reference 42.]

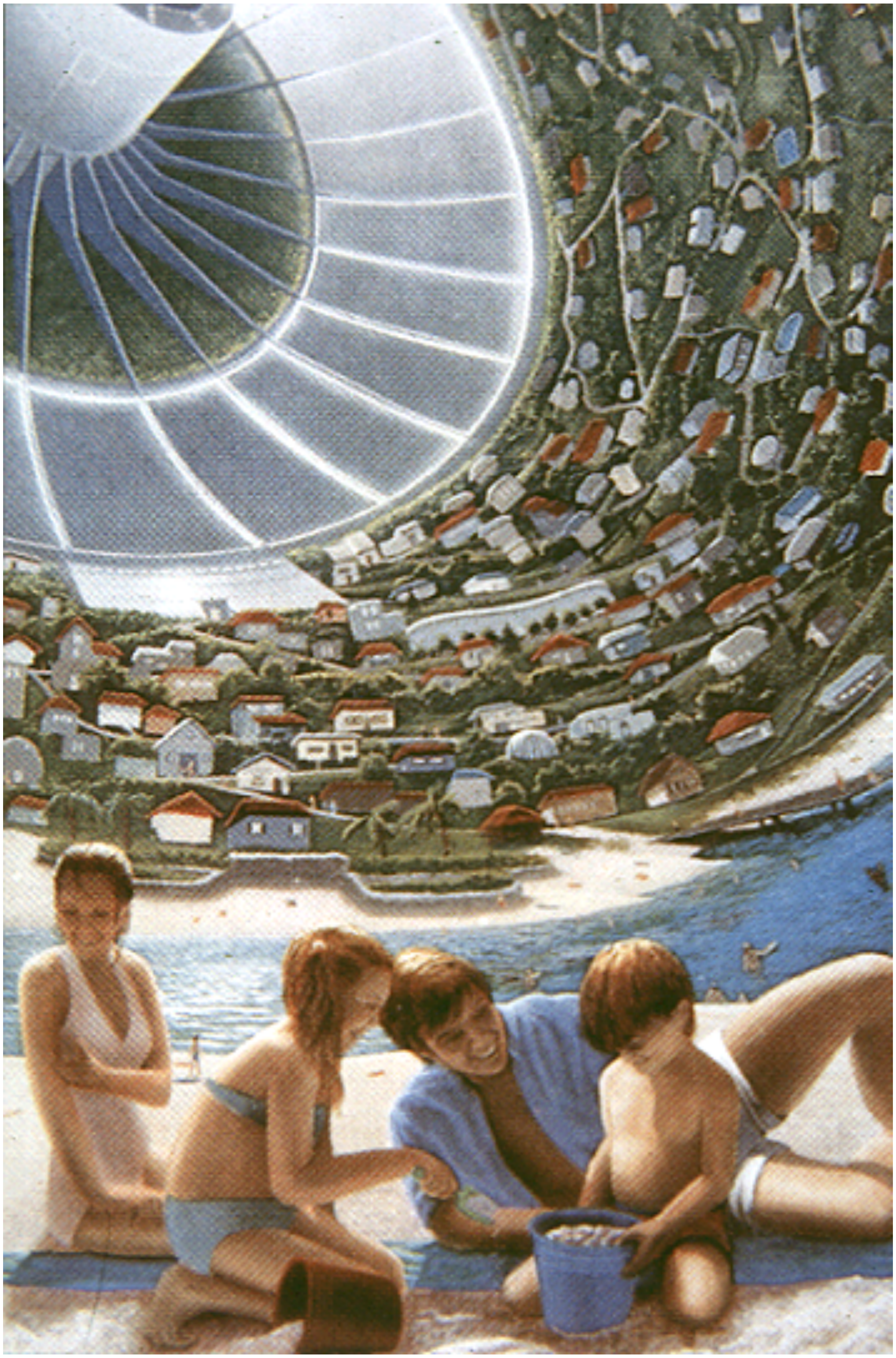

Figure 18: "Bernal Sphere", 1975.
[Permission? Contact Space Studies Institute.]

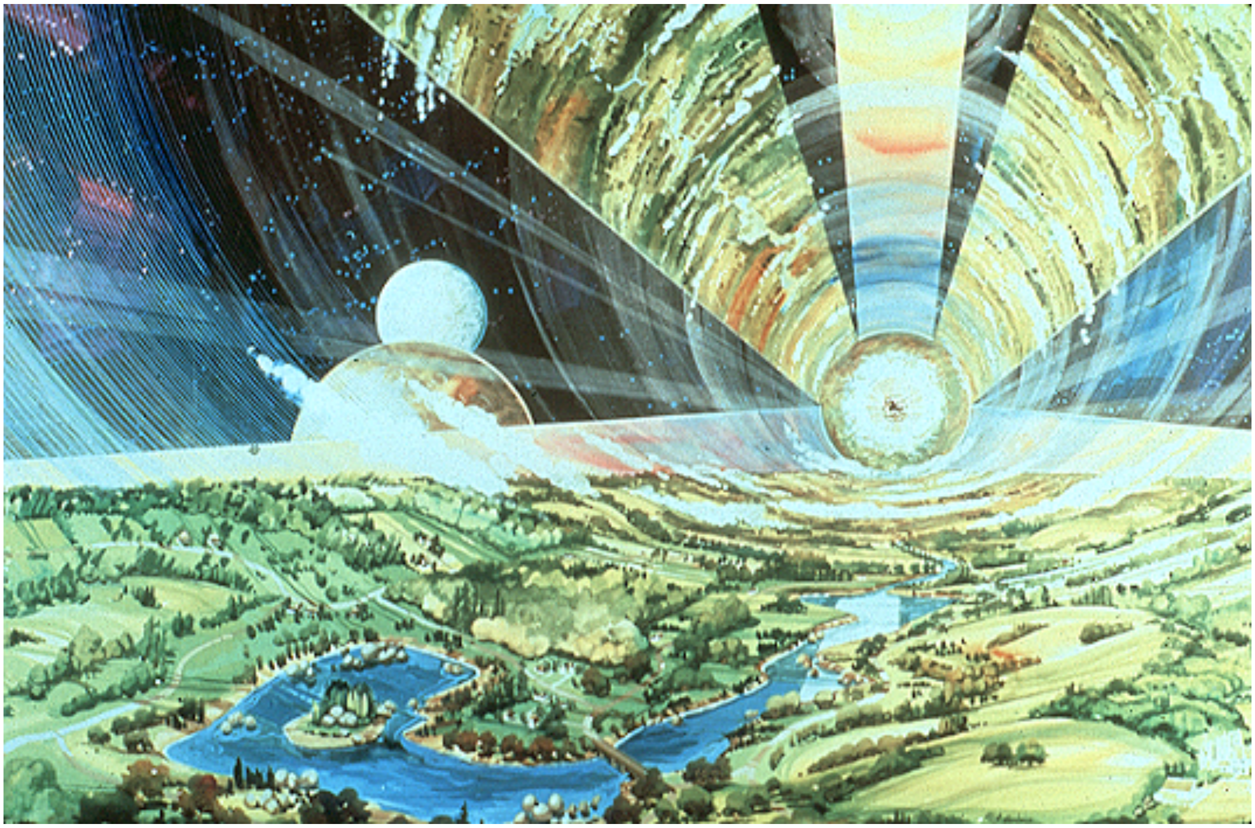

Figure 19: "Island Three", 1975.
[Permission? Contact Space Studies Institute.]

Perhaps the most famous footage of artificial gravity appears in the film *2001: A Space Odyssey*. The gracefully spinning space station waltzing its way around the Earth (Fig. 20 a-c), and the rotating ring in the spaceship "Discovery" on its journey to Jupiter (Fig. 21 a-c), are endearing images for many modern space enthusiasts. They're also among the most technically correct, with their upward curving toroidal floors and spin-despin interfaces [45].

Certain details, though not necessarily wrong, may leave room for improvement. As the Earth shuttle approaches the station, it begins to match the station's spin. While this looks poetic on film, it may be impracticable. Until they mate, the shuttle and station follow slightly different orbital tracks. Axial alignment with the station may be exceedingly difficult to maintain once the shuttle has started rolling.

In Discovery's rotating section, the ladder is mounted in the side wall, parallel to the plane of rotation. In this arrangement, Coriolis accelerations would tend to pull the astronauts sideways off the ladder, especially near the top where centripetal acceleration is small. It would be better to turn the ladder out of the wall, perpendicular to the plane, so that Coriolis accelerations work with the astronauts rather than against them.

Figure 20a: ***2001: A Space Odyssey*****, space station, 1968.**
[Permission? See reference 45.]

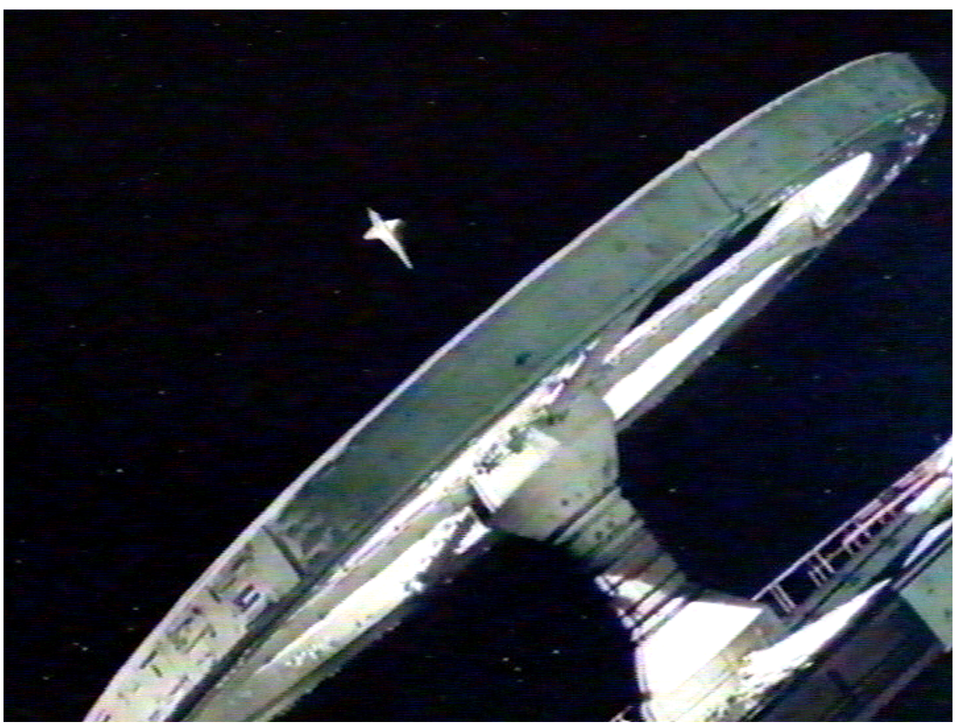

Figure 20b: ***2001: A Space Odyssey*****, space station, 1968.**
[Permission? See reference 45.]

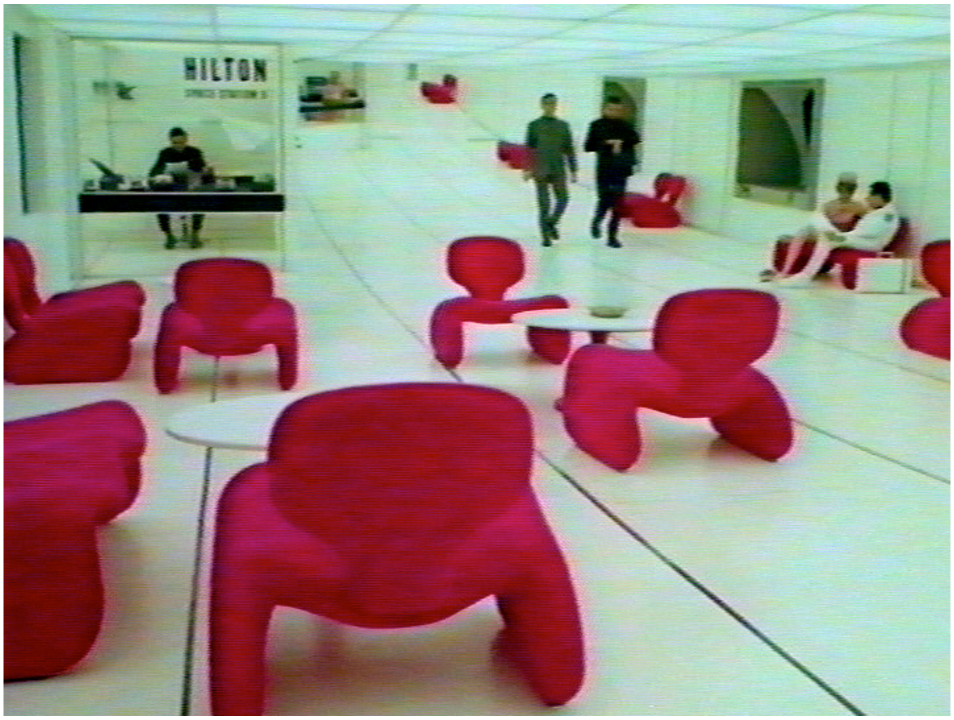

Figure 20c: ***2001: A Space Odyssey*****, space station, 1968.**
[Permission? See reference 45.]

Figure 21a: ***2001: A Space Odyssey*****, spaceship "Discovery", 1968.**
[Permission? See reference 45.]

Figure 21b: ***2001: A Space Odyssey*****, spaceship "Discovery", 1968.**
[Permission? See reference 45.]

Figure 21c: ***2001: A Space Odyssey*****, spaceship "Discovery", 1968.**
[Permission? See reference 45.]

By comparison, more recent attempts at artificial gravity have been dismal failures. In *Moonraker*, the space station is an oddly asymmetric jumble of tubes (Fig. 22). Though it supposedly rotates to simulate gravity, the designers evidently have no idea how it works. Shuttles align variously on their roll, pitch, or yaw axes, as if relying on trial and error to get the proper orientation with respect to the station's spin [46].

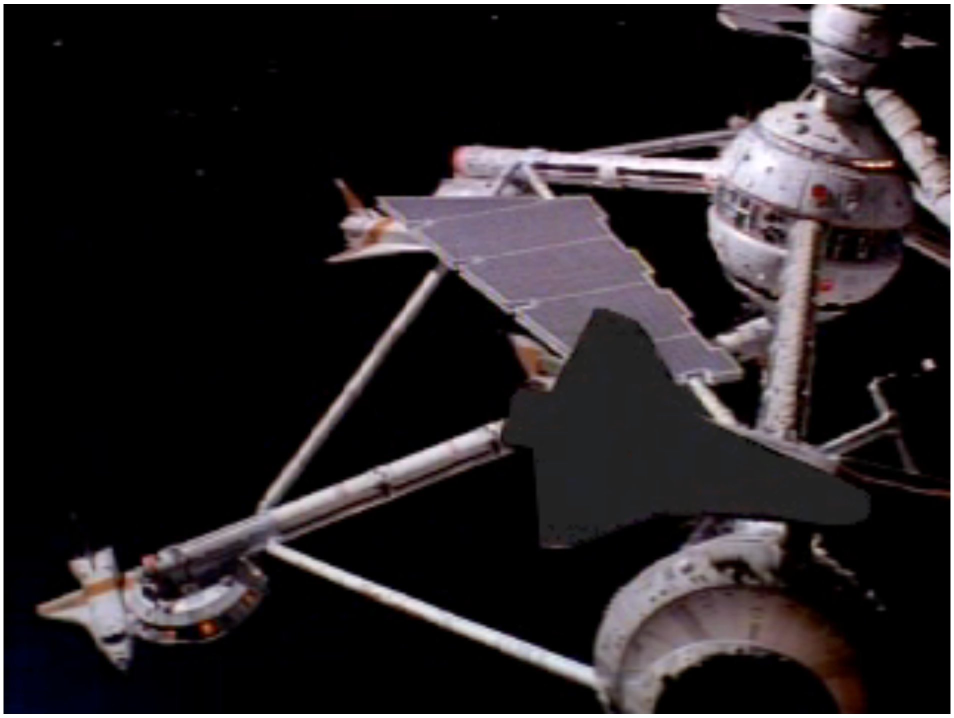

Figure 22: *Moonraker*, 1979.
[Permission? See reference 46.]

Armageddon is at least consistent, though consistently wrong (Fig. 23 a-c). Determined to do everything the hard way, the director sets the station spinning just as the shuttles arrive, turning what should be a routine docking maneuver into a navigational nightmare. The shuttles are now forced to perform the virtually impossible task of simultaneous tangential docking to the end points of rotating spokes. The spokes would be vertical shafts with respect to the artificial gravity, but the film portrays them as horizontal corridors [47].

Producers and movie fans may view such criticisms as picking nits, but architects ought to know, at a minimum, which way is up.

Designers continue to propose artificial gravity as a panacea for all of the ills associated with prolonged weightlessness. Engineers have devoted extensive study to the artifact (structure, stability, propulsion, and so on), but relatively little to the environment, from the point of view of an inhabitant living and moving within it. Authors have implied that artificial gravity should permit the adoption of essentially terrestrial designs. They've downplayed the *artificiality* of the gravity. But saccharin is not sucrose, and centripetal acceleration is not gravity as we know it.

Figure 23a: ***Armageddon*, 1998.**
[Permission? See reference 47.]

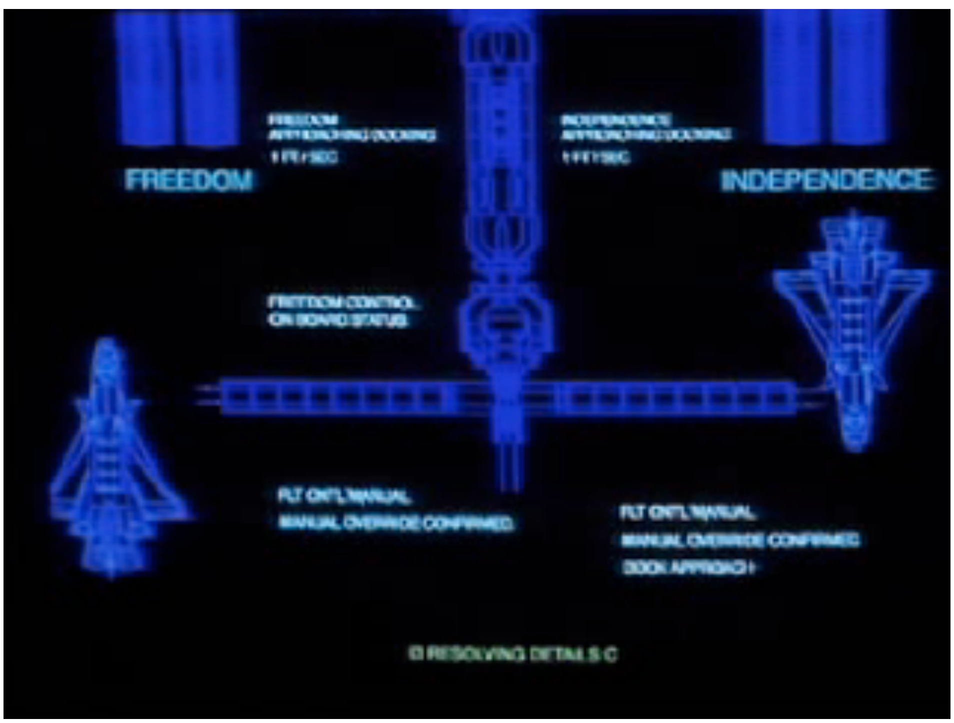

Figure 23b: ***Armageddon*, 1998.**
[Permission? See reference 47.]

Figure 23c: *Armageddon*, 1998.
[Permission? See reference 47.]

Off-axis motion in a spinning space station involves Coriolis accelerations and cross-coupled rotations that distort the apparent gravity. As a result, in artificial gravity, there are not only three principle directions, but at least five: up (toward the axis), down (away from the axis), east (prograde), west (retrograde), and axial. Architectural design for artificial gravity has barely begun to address its peculiarities. The goal is not to mimic Earth but rather to help the inhabitants adapt to the realities of their rotating environment.

Epilogue

Notably absent from this article so far is any mention of *Star Trek*, *Star Wars*, or several other popular space-theme adventures. The gravity they portray is without explanation, with no basis in known physics. These productions are essentially fantasies, mostly unrelated to the reality of space travel, with few pretensions in that regard.

It used to be said that pictures don't lie, but in this age of virtual reality and sophisticated special effects, the old saying no longer applies. Convincing visions of space habitation have progressed rather faster than reality, and not always in ways that reality can accommodate. Nevertheless, space station designers have always gleaned at least some of their inspiration from science fiction and fantasy. It should be interesting to see how the vision and reality of space habitation evolve in the coming decades.

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