Title: The next Land of Freedom is in Free-Space

Subtitle: Why 1G simulated gravity is important and mandatory for Gerard K. O'Neill

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ABSTRACT

While planet Earth is becoming tighter and tighter, and her Citizens are hit by a growing political madness, it becomes evident that a vast movement of migration will gain momentum, as soon as the first space destinations will become available.

Considering the possible choices – the Moon, Mars, and habitats in free-space – the last are preferable, as Gerard K. O'Neill has written in his book "The High Frontier - Human Colonies in Space". As a very key rationale, while the Moon and Mars have limited ground for human settlements, the enormous quantity of asteroid resources allow the building of virtually unlimited habitats, floating in free-space.

Physiological and social requirements where the main focus of Gerard K. O'Neill design of rotating space colonies. O'Neill required 1G simulated gravity because it simultaneously preserves human biology, natural social behavior, intergenerational development, and economic practicality. This made 1G not a preference but a mandatory condition for his vision of "truly human life beyond Earth."

Basic freedom requirements were considered equally important. If settlers were used to less-then-1G gravity they couldn't exercise this fundamental human right, should they change their mind about space migration, and wanted to return living on Earth. That strikes at the ethical and political foundations of O'Neill's space colony vision. Freedom — both physical and personal — is deeply linked to the gravity environment the colonists would live under.

For O'Neill, maintaining 1 g simulated gravity was not just a matter of health or habitability — it was a principle of liberty and human rights. A colony whose inhabitants physically cannot return to Earth would violate one of his central ambitions: that humanity's expansion into space increase freedom, not diminish it.

Gerard O'Neill was the first who dared to design space habitats based on humanist requirements: not only safety and survival, but beauty, ergonomics, well-being, culture, art, tourism, sports, entertainment. O'Neill can be considered the father of Civilian Space Development. Such a key characterization is very well shown in the work made by the Space Studies Institute[32]**.**

1 We well know why humanity should expand in outer space, we have now to choose where

Why space, and why now, as a subject, is just worth to be quickly recalled here, being the philosophical and political issue discussed in other sessions of our Congress, and in the Thesis 1. There are 8.5 billion citizens on one only planet, the anthropic pressure on planet Earth's environment is raising, and becoming unsustainable. Humanity is a cultural species, and this is in the same time the reason at the root of our growth and the reason why we need increasing energy and electronics, to satisfy the growing demand of culture. That's why we urgently need to expand into outer space, to sustain humanity's future. Earth's environmental and social deterioration prompts moving beyond our mother planet. And we shall do it NOW, while the historic and technology *launch window* is still open.

The space community has discussed for more than a century, what is the best choice, about where to live in space. So, among the Moon, Mars, and Habitats in free space, the last are preferable.

As of written by Gerard K. O'Neill in "The High Frontier, Human Colonies in Space", the Moon and Mars have limited ground for human settlements. The enormous quantity of asteroid resources allows the building of

virtually unlimited habitats floating in free space. Self-sustaining, rotating orbital worlds designed to simulate Earth's gravity, focus on human well-being, freedom, and creativity in space environment.

Gerald O'Neill is more alive than ever. Why? Because Gerald not only made a beautiful scientific work.

He also produced excellent philosophy in his book, The High Frontier. It's not just the design of a habitat, it is very much more, giving us a vision of what it might be our future in rotating habitats: not just survival in space, but thriving beautiful and free human civilization.

Main advantages are simulated gravity for human health and physiological needs, and sunlight energy continuously available. Furthermore, free-space habitats can be moved away from incoming killer cosmic objects. As to physiological requirements are concerned, the damages to human health caused by long, unprotected staying in space are well known, after the experience of astronauts who have spent up to one year in microgravity on the ISS.

Yet O'Neill introduced another, very key requirement: human rights, and freedom to migrate and return back to Earth, if at a certain point of their life, some people should decide so. To assure bi-directional migration, free-space habitats need 1G gravity, in a combination of dimension and rotating speed designed to minimize or fully eliminate the Coriolis effect. O'Neill also discussed the Coriolis effect, and the optimal (minimum) diameter and (maximum) rotating speed of a rotating colony. O'Neill's 1 rpm / 1 km radius rule is the cornerstone of all later rotating habitat studies (e.g., Kalpana One, Stanford Torus, and present day NASA artificial gravity evaluations). His approach to the Coriolis effect was both quantitative and human centered: large enough to feel like Earth, slow enough that you forget you're spinning.

Freedom of migration is not the only rationale for the 1G mandatory requirement. The O'Neill "Bible" (The High Frontier: Human Colonies in Space) also mentions a key industrial sector that will expand proportionally to human settlement in the Solar System: tourism, two ways. Earthly citizens will want to visit the colonies, and the settlers will like to visit Earth. The tourism industry will be a key pillar of the solar society economy: we definitely don't want visitors coming to Earth from space communities to have an uncomfortable experience, due to the Earth's gravity!

Konstantin Tsiolkovsky, 50 years before, had formulated the same concept: "People will live for months, for years, in free space… They will construct enormous dwellings in the shape of spheres, cylinders, and other figures, which will rotate to give all objects inside a pressure similar to that of gravity on Earth." This quotation—one of Tsiolkovsky's most poetic and descriptive—comes from his 1929 book titled The Space Rocket: Experimental Preparation (Kosmicheskaya Raketa: Opytnaya Podgotovka)[1]. This work is part of a larger collection of his writings where he outlined his famous "16 Stages of Space Conquest." The section describing Stage 10, is where he moves from temporary orbital stations to permanent habitation of the solar system. Tsiolkovsky was describing "Space Islands" (Efirnye Goroda or "Ether Cities"). He envisioned these not just as ships, but as giant greenhouses and cities designed to sustain human life indefinitely by capturing solar energy and simulating gravity. In this text, he elaborates that the shape—spheres and cylinders—is chosen for structural integrity under internal atmospheric pressure and to facilitate the "pressure similar to that of gravity" through centrifugal force. While the core of this idea was present in his 1883 manuscript Free Space (where he first did the math for centrifugal force), the 1929 text is where he explicitly used the phrasing about "months and years" and "enormous dwellings in the shape of spheres [and] cylinders." He specifically proposed that these habitats would use mirrors to direct sunlight into the interior to grow food, creating a self-sustaining ecosystem—an idea that directly inspired the "O'Neill Cylinder" concepts of the 1970s.

That line is the earliest known explicit proposal that artificial gravity should equal normal Earth gravity ("similar to that of gravity on Earth") inside a rotating free space habitat.

2 History

Many scientists and philosophers have discussed free-space habitats. Konstantin Tsiolkowsky has been the very first. And the whole discussion was not only about design or engineering, but also about philosophy, and art.

The following references to Tsiolkovsky's and German authors on the topic of rotating space habitats are due to the research dealt by Dr. Marie-Luise Heuser, communicated during a webinar the 11 April 2024[2]. Further research was done by the author.

2.1 Konstantin E. Tsiolkovsky

In a manuscript of 1883[3], Tsiolkovsky treats weightlessness not as a wonder, but as a technical obstacle to be overcome. This is the first time in history that the physics of a rotating "room" was proposed to simulate gravity in space. Writes Tsiolkovsky, in his manuscript: "One can imagine a room or a whole house rotating around an axis... Gravity will be felt on the inner surface of the walls, and the farther from the axis, the greater it will be. Objects will fall, and people will walk as on Earth."

In 1929, Tsiolkovsky had refined his "Plan of Space Exploration" into 16 distinct stages[4]. This work describes "Space Islands" which are essentially the precursor to the O'Neill Cylinder or Stanford Torus. "To produce gravity, the station should be given a slow rotation... Inside such a dwelling, everything would be the same as on Earth: there would be a floor, ceiling, and walls. Gravity would be directed toward the walls, which would serve as the floor."

2.2 Hermann Oberth

Hermann Oberth, a primary pioneer of astronautics, detailed his visions for rotating space habitats in his seminal 1929 work, "Wege zur Raumschiffahrt" (Ways to Spaceflight)[5]. This book was a massive expansion of his 1923 pamphlet and provided the mathematical and conceptual foundation for artificial gravity and orbital stations. In this text, Oberth proposed that large structures in space could be rotated to create a centrifugal force that mimics gravity, solving the physiological issues of long-term weightlessness.

Oberth envisioned a Rotating "Observatory" or Station**,** consisting of two modules connected by a long cable (tethers) or a rigid structure, rotating around a common center of mass. He specifically noted that rotation would be necessary for "the well-being of the passengers" and to allow for normal physical activities that require gravity.

While the original text is in German language, the 1972 NASA translation provides the definitive English versions of his 1929 thoughts (*Ways to Spaceflight, Section on "The Space Station")*: "If we want to have gravity on the station, we can achieve this by having two such stations... rotate around each other at a certain distance by means of a cable. In this way, any desired gravitational acceleration can be produced... It will be possible to live, work, and sleep just as on Earth."

Oberth's work influenced a generation of engineers, including Wernher von Braun, who later popularized the "Rotating Wheel" station (inspired by Oberth and contemporary Herman Potočnik Noordung) in the 1950s (Neufeld, 2006).

Oberth explicitly identified 1G (Earth-standard gravity) as a primary requirement for long-term human space habitation. In "Wege zur Raumschiffahrt" (1929), Oberth argued that while humans might survive short periods of weightlessness, the long-term physiological toll would necessitate a "gravity" that matches what we experience on the ground.

Oberth's most famous design for a habitat was the "Springboard Station" (a spaceport for refueling and living). He provided specific engineering parameters to achieve 1G:

- The Structure: He proposed two modules connected by a massive 8,000-meter (8 km) tapered tether.
- The Requirement: He calculated that to simulate Earth-standard gravity (approximately $9.8 \, m/s^2$) without causing dizziness or "tidal effects," the station needed a very large radius.
- Rotation Speed: This setup resulted in a slow, comfortable rotation of about 0.5 rotations per minute (RPM).

Oberth was one of the first to treat the "biological problem" of space with the same rigor as the "fuel problem." He insisted on 1G for several practical reasons:

1. Hygiene & Life Support: He noted that in zero gravity, water doesn't pour, and air doesn't circulate via convection (meaning a sleeping astronaut could suffocate in their own carbon dioxide bubble).
2. Physical Health: He predicted that without the constant "load" of 1G, the human heart and muscles would atrophy, making a return to Earth dangerous.
3. Mechanical Convenience: He wanted "things to stay put." He famously pointed out that a plate of food or a tool should remain on a table, which is only possible with a downward force.

"I believe that 8,000 meters is the optimum diameter... It will be possible to live, work, and sleep just as on Earth." — Hermann Oberth, 1929

While Oberth pushed for 8,000-meter tethers for a perfect 1G, his contemporary Hermann Potočnik (Noordung) proposed a much smaller 30-meter "Living Wheel" in 1929. Noordung also aimed for 1G but required a much faster rotation (nearly 8 RPM), which Oberth correctly identified as potentially nauseating for the inhabitants due to the Coriolis effect.

2.3 Otto Willy Gail

The work of Otto Willi Gail, specifically “Der Stein vom Mond” (The Stone from the Moon, 1926), holds a unique and important place in history. While Tsiolkovsky and Oberth provided the scientific and mathematical foundation, Gail provided the cultural bridge.

Gail was a novelist and a science journalist who worked closely with the VfR (Verein für Raumschiffahrt), the German Rocket Society. Gail based his *Technical Realism* strictly on the works of Hermann Oberth and Max Valier. Unlike Jules Verne, who used a "space cannon" (which would crush passengers), Gail described multi-stage liquid-fueled rockets and the physiological effects of weightlessness with such accuracy that his books read like mission reports. In *Der Stein vom Mond*, Gail introduces Astropol, one of the earliest and most detailed depictions of a modular space station in fiction. While Oberth calculated the physics of such a station, Gail gave it a "living" presence, describing the docking of supply ships, the daily life of a crew in a rotating habitat, and the use of space-based telescopes.

Tsiolkovsky and Oberth's books were notoriously difficult to read. Oberth’s Ways to Spaceflight was full of complex calculus that the average person couldn't grasp. Gail’s novels sold tens of thousands of copies, inspiring the young engineers (like Wernher von Braun) who would eventually build the V2 and the Saturn V.

In Der Stein vom Mond, the station is a massive terminal for interplanetary travel. It serves as a "springboard" (the same term Oberth used: Weltraum-Zwischenstation) for voyages to the Moon and Venus.

If Tsiolkovsky and Oberth were the architects of the dream, Otto Willi Gail was its chief recruiter. Without Gail's ability to translate complex orbital mechanics into a thrilling narrative, the social and political momentum required to fund actual rocket research in the 1930s might never have materialized.

The novel was first published as a sequel to his 1925 work Der Schuß ins All (The Shot into Infinity)[6]. Gail’s work was quickly picked up by Hugo Gernsback, the "Father of Science Fiction," for the American market. These translations are where many English speakers first encountered the concept of "Astropol."[7]

2.4 Hermann Noordung (Potočnik)

Herman Potočnik, writing under the pseudonym Hermann Noordung, published his landmark book "Das Problem der Befahrung des Weltraums – der Raketen-Motor" (The Problem of Space Travel: The Rocket Motor) in late 1928 (dated 1929). While Oberth provided the foundational physics, Noordung is credited with the first complete engineering blueprint for a modular space station, specifically focusing on the architectural and human-centric details of living in orbit.

Noordung's station was not a single unit but a decentralized system of three specialized modules connected by umbilical cables and hoses:

1. The Wohnrad (Inhabitable Wheel) - A 30-meter diameter wheel that rotated to provide artificial gravity.
2. The Power House - A separate cylindrical module containing a solar-powered boiler and turbines to generate electricity.

3. The Observatory - A non-rotating module designed for scientific research and astronomical observations in zero gravity.

These excerpts from the 1929 text (via NASA's 1995 English translation) highlight his focus on the mechanics of artificial gravity and life support:

- "The inhabitable wheel (Wohnrad) must be set in rotation. By means of the centrifugal force thus created, we can then replace gravity... and make it possible for the inhabitants to live in a normal manner."
- "Everything that we are used to doing on Earth—standing, walking, sitting, lying down, the use of vessels for liquids—can be done in the same way on the station."
- "Because it [the station] is located 35,900 kilometers above the equator... it will appear to hover constantly over the same point of the Earth's surface." (This was the first technical description of a Geostationary Orbit).

The diameter of the wheel was 30 meters (roughly 100 feet). He calculated a rotation of one full turn every 8 seconds to generate 1G of artificial gravity. (Modern science notes this might cause motion sickness, but at the time, it was a breakthrough calculation). He described "space-traps" (airlocks) that used rubber seals to maintain pressure—a concept still used in the International Space Station today. He envisioned a giant concave mirror on one side of the wheel to concentrate sunlight into a "boiler" to generate power.

The original publication was made in Germany in 1929[8]. We had to wait until 1995 for the first English translation, by NASA[9]. In 2025 the Noordung's "Wohnrad" was also subject of a presentation at IAC as a Scholarly Review[10]

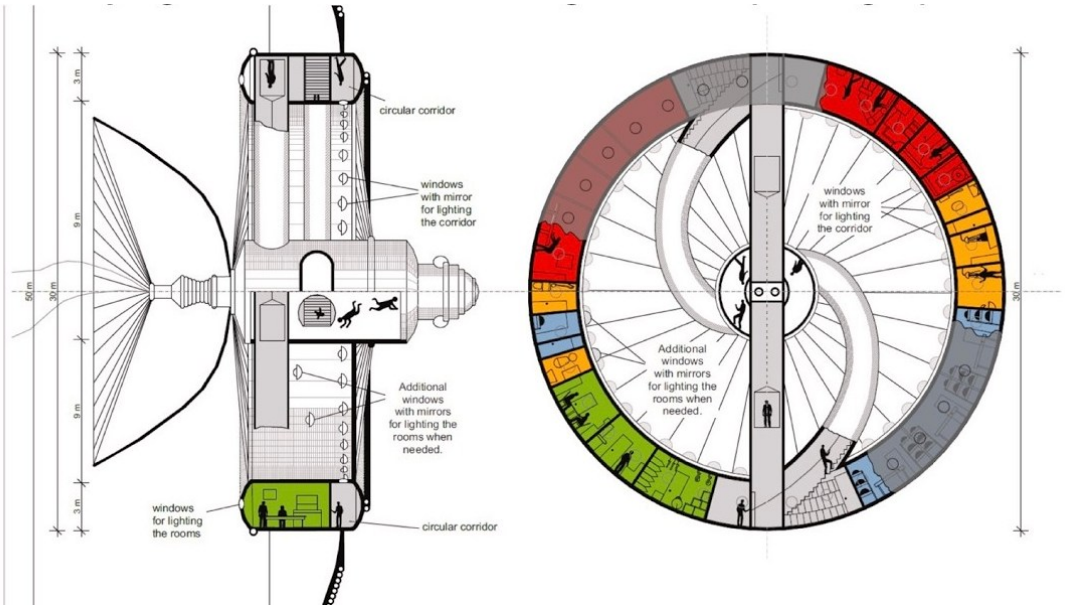

Figure 1. The 30 m. Norduung rotating space habitat[11]

2.5 Wernher von Braun and Willy Ley

Wernher von Braun's work on rotating space habitats was a cornerstone of early 20th-century astronautics, most famously popularized during the 1950s. While he drew heavy inspiration from earlier visionaries like Hermann Oberth and Herman Potočnik (Noordung), von Braun's specific engineering refinements and public advocacy helped transition the "space wheel" from science fiction to a serious technical proposal (Neufeld, 2006). Between 1952 and 1954, von Braun and his co-author Willy Ley, served as the technical lead for a highly influential series of articles in Collier's magazine[12] titled "Man Will Conquer Space Soon!". This series introduced the public to his vision of a 76-meter (250-foot) diameter wheel-shaped station.

The station was designed as an inflatable structure made of reinforced nylon fiber covered with protective plates. This allowed the massive structure to be launched in a compact form and expanded once in orbit. To combat the physiological effects of weightlessness, the wheel would rotate at 3 revolutions per minute (rpm).

This rotation would generate a centrifugal force providing approximately 0.3 g of artificial gravity for the crew[13].

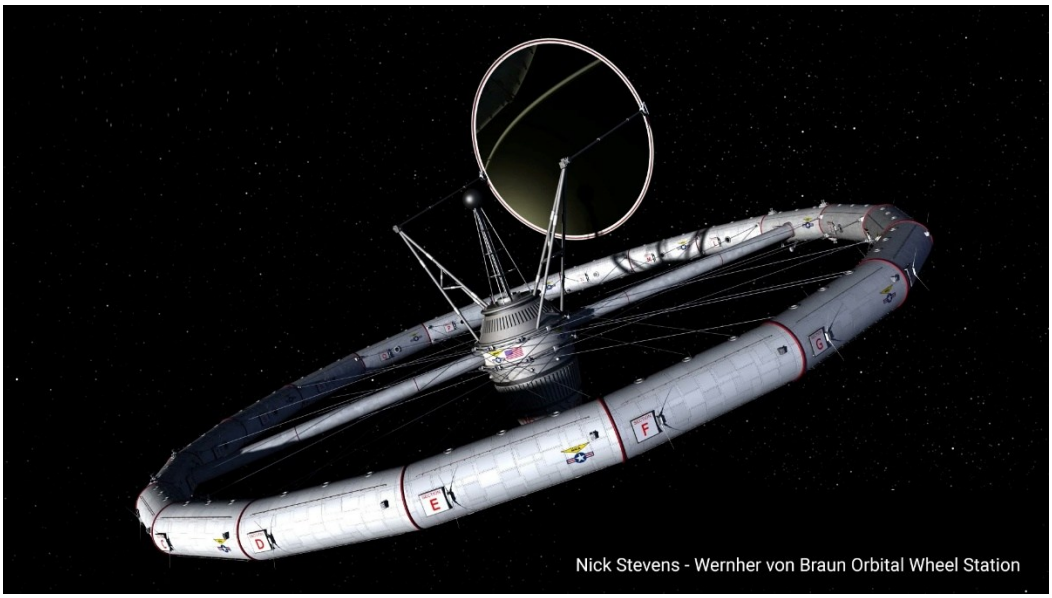

Figure 2. Wernher von Braun Orbital Wheel Station

Von Braun proposed placing the station in a polar orbit at an altitude of 1,730 km (1,075 miles), completing one revolution every two hours. The station was envisioned as a multi-purpose facility, serving as a meteorological observatory, a navigation aid, and a "harbor" or staging point for deep-space expeditions to the Moon and Mars.

Often remembered for its scientific potential, von Braun's proposals had a relevant importance, clearing simulated gravity as a theme worth of research and advanced conceptualization. Early proposals (dating back to 1946) also had a significant military focus. He initially framed the space station as a reconnaissance platform and a "battle station" to achieve "space superiority". He argued that such a station could serve as a vantage point for launching nuclear missiles, though these aggressive military aspects were softened in later public-facing collaborations with Walt Disney for the Man in Space television series.

In "Crossing the Last Frontier"[14], von Braun describes the station's 2-hour orbit, noting that "no country could hide any military preparations from the watchful eyes of the satellite's garrison." He famously describes it as a vital instrument for maintaining peace, acting as an unassailable watchdog over global military movements. Such concepts were also mentioned by Michael J. Neufeld, in his study "Space superiority: Wernher von Braun's campaign for a nuclear-armed space station, 1946–1956"[15]

Ley explicitly compared the social dynamics of the 80-person space station **to a modern submarine**, in a highly restricted, high-stress social environment. Because space and weight were at an absolute premium, private quarters were minimal. Ley anticipated that the total lack of true privacy would be a major psychological friction point. He advocated for rigorous psychological screening (as detailed in Collier's articles) to ensure that crew members possessed the emotional stability to tolerate cramped, repetitive social interactions without interpersonal breakdown. Evidently, they were thinking about **a "crew" of military space explorers**, more than civilian resident space settlers. Ley was however also discussing social and psychological issues, such as isolation, mandatory daily routines, forced cohabitation in small environments, indicating them as conditions to be addressed for future developments, advocating for artificial normalcy, foundational to maintaining human dignity and psychological stability. While Von Braun's early concepts leaned heavily on military dominance (using the station as a nuclear-armed high-ground for the U.S. during the Cold War), Ley's writing pushed for a more cosmopolitan, scientific, and eventually civilian future.

It will be only in 1956 that von Braun, working with Willy Ley on "The Exploration of Mars"[16], develops a maturation of their early 50s concepts, reflecting the changing political climate as the military pitch began

shifting toward scientific cooperation. This text reviews the early 1952 military assertions of the space station and begins reframing the wheel's purpose more toward pure science, foreshadowing the eventual civilian nature of NASA (established in 1958).

A comprehensive modern academic analyses of why von Braun leaned so heavily into the military angle, may be found in Howard E. Mc Curdy, "Space and the American Imagination"[17]. McCurdy devotes significant chapters to the Collier's era, analyzing how von Braun strategically used the fear of Soviet dominance to "sell" the immensely expensive rotating space wheel concept to the American public and military planners. Similarly, the German space visionary, working in Peenemünde under the Nazi regime during World War II, had built the first rocket (V2), reaching a record height of 175 km on June 20, 1944, thus becoming the first man-made object to cross the Kármán line and reach space.

Von Braun's "Space Wheel" became the definitive image of human habitation in space for decades. Its influence is most visible in:

- 2001 A Space Odyssey: The iconic "Space Station V" in Stanley Kubrick's film is a direct aesthetic and functional descendant of von Braun's design.
- NASA Planning: The concept of using a station as an "Earth-Orbit Rendezvous" (EOR) point was a primary strategy von Braun advocated for before NASA ultimately selected the Lunar-Orbit Rendezvous (LOR) for the Apollo missions (Neufeld, 2008).

Also see this quick essential reconstruction of the Rotating space habitats history.[18]

2.5.1 Why 0.3 g? The "Enough is Enough" Philosophy

Von Braun did not consider 1 g ($9.8 m/s^2$) essential for short-to-medium-term habitation. His choice of 0.3 g (about double Lunar gravity) was a pragmatic compromise based on several factors. Every increase in simulated gravity required a corresponding increase in the structural strength (and thus weight) of the station to withstand the outward stress. Since everything had to be launched via his (then-theoretical) three-stage rockets, saving weight and structural mass was the highest priority. Von Braun believed that 0.3 g was the "threshold of utility." It was enough to ensure that fluids stayed in cups, dust settled on the floor, and the vestibular system had a "down" orientation to prevent the worst effects of space adaptation syndrome. In 1952, we had zero data on long-term weightlessness. Von Braun assumed the human body just needed some gravity to function, not necessarily Earth-normal gravity.

2.5.2 The "Comfort Zone" and Coriolis Forces

To get 0.3 g out of a 38-meter radius, we have to spin the station at roughly 2.7 rpm.

Modern research (much of it conducted after von Braun's death) suggests that rotation rates above 2 rpm cause significant issues due to the Coriolis effect. In von Braun's 76-meter wheel:

1. Vestibular Nausea: If a crew member turned their head quickly, the semi-circular canals in their ears would perceive a phantom "tumbling" motion, leading to immediate motion sickness.
2. Gravity Gradient: Because the radius is so short, the gravity at your head would be noticeably lower than the gravity at your feet. This delta can cause blood pressure irregularities and a persistent sense of instability.
3. Cross-Coupled Accelerations: Moving across the direction of rotation would make a person feel like they were being pushed sideways.

2.5.3 Social and Human Hierarchy

Von Braun's social vision for the station was strictly technocratic and militaristic. He didn't envision "space citizens". He envisioned "space crews."

The 76-meter wheel was cramped. Habitability was secondary to function. Quarters were "hot-bunked" (shared beds), and common areas were minimal.

He viewed the station as a ship. The social requirements were discipline and technical proficiency, not leisure. This is why he was comfortable with the 0.3 g level—he assumed his "space explorers" would simply endure the discomfort for the sake of the mission.

It wasn't until the 1975 NASA Ames Summer Study (which led to the O'Neill Cylinder concepts) that the focus shifted to 1 g and kilometer-scale radii to support permanent civilian populations and "Earth-like" social structures.

2.6 Arthur C. Clarke and Stanley Kubrik

By connecting Tsiolkovsky to Kubrick/Clarke via von Braun, we may trace the "Evolution of the Space Wheel" from a mathematical theory to a military outpost, and finally to a civilian "Hilton in Orbit." While von Braun provided the engineering skeleton, 2001: A Space Odyssey (1968)[19] was indeed the first high-fidelity cultural vision of a civilianized, commercialized space habitat.

2.6.1 The Shift from Crew to Consumer

In Tsiolkovsky's and von Braun's visions, the "human requirement" was endurance. In 2001, the human requirement was hospitality. Space Station V in the film featured a Hilton Hotel, a Howard Johnson's restaurant, and Picturephone booths (operated by Bell Systems). This signaled that the "social requirement" had shifted from survival to luxury and familiar routine, a commercial Infrastructure. The station was no longer a cramped machine; it was an airport terminal. People were depicted lounging in "Djinn" chairs, wearing business suits rather than flight suits, and dealing with the bureaucracy of passports and customs.

2.6.2 Correcting the Physics: The 300-Meter Wheel

Kubrick and Clarke were meticulous about the "comfort zone" issues. They recognized that von Braun's 76-meter wheel was too small for a convincing civilian experience. Space Station V was designed with a diameter of roughly 300 meters (984 feet). To achieve a comfortable fraction of Earth gravity without inducing Coriolis-related nausea, the station rotated at approximately 1-2 rpm. This falls much closer to the modern "comfort zone" calculations than von Braun's 3 rpm design. Kubrick used the "curved floor" effect to emphasize that for a civilian to feel at home, the environment needed to look and act like Earth. The decks were oriented so that "down" was always toward the rim, allowing for natural walking and dining.

2.6.3 The Tsiolkovsky Connection

Konstantin Tsiolkovsky was the first to mathematically describe the use of rotation for artificial gravity in his 1903 work, The Exploration of Cosmic Space by Means of Reaction Devices[20]. However, Tsiolkovsky's vision was philosophical and "cosmist"—he saw the habitat as a way for humanity to evolve beyond Earth. Tsiolkovsky saw humans as "citizens of the cosmos." The Von Braun's vision was Cold War/Technocratic oriented, paramilitary; his social atmosphere was cold, functional, and cramped.

While earlier sci-fi films (like Conquest of Space, 1955) showed stations, they were strictly military. 2001 was the first to address the psychological and social architecture of space. Clarke and Kubrick wanted to show the "Normalcy" of Space. The film suggests that for humans to live in space long-term, space must become "boring." The social requirement is the removal of the "extraordinary" in favor of the "routine." The Gravity of Aesthetics: The bright white, sterile, yet elegant interiors were designed to prevent the "claustrophobia" inherent in von Braun's metal-heavy, submarine-like designs.

We might find some hints of such transition observing the Space X Dragon capsule interior design, based on ergonomic and comfort requirements, vs. the Sojuz and Space Shuttle's internal environment, still more oriented to astronautics.

2.7 Dandridge Cole

Dandridge Cole (1921 - 1965) was a visionary aerospace engineer and futurist who, alongside co-author Donald Cox, penned Islands in Space: The Challenge of the Planetoids (1964)[21]. Long before Gerard K. O'Neill

popularized the "O'Neill Cylinder" in the 1970s, Cole was laying the groundwork for how humanity could live within the hollowed-out interiors of asteroids. His specific logic included:

- **Hollowed-Asteroid Habitats**. Cole proposed taking a "planetoid" (asteroid), hollowing it out, and spinning it on its axis to create artificial gravity. This transformed a dead rock into a self-contained "island" in space.
- **The "Macro-Life" Concept**. He viewed these habitats as more than just buildings; he saw them as a new form of life—"Macro-Life"—where the habitat, its technology, and its inhabitants functioned as a single, evolving organism capable of interstellar travel.
- **Economic Feasibility**. He argued that it was cheaper and more efficient to use materials already in space (asteroids) rather than launching millions of tons of steel and water from Earth's deep gravity well.
- **The "Bubbleworld" Method**. He famously suggested using solar mirrors to melt the interior of a metallic asteroid and then injecting a "blowing agent" (like water) to inflate it into a massive, hollow sphere while it was still molten.

In "The Next Fifty Years in Space" (1963) Cole outlines the transition from exploration to colonization, emphasizing the need for centrifugal gravity in long-term habitats.

Cole's "Bubbleworld" concept is often cited as a direct precursor to the O'Neill Cylinder. While O'Neill used manufactured materials (aluminum and glass), Cole's vision was more "organic" to the cosmos, repurposing what was already there.

Cole was one of the first futurists to insist that long-term human habitation required Earth-normal gravity (1G). In his 1963 writings, Cole argued that while humans could "visit" space in zero or low gravity, they could not "live" there or raise children without 1G. He believed that to maintain Earth-normal bone density and cardiovascular health, the habitat's rotation must be calibrated to simulate Earth's gravity at the inner rim. He discussed the idea that different "floors" or levels within the hollowed asteroid would experience different gravity levels. The center (the axis of rotation) would be weightless, used for docking and industry, while the outermost living levels would be 1G.

Now that we know more about the asteroids composition we might observe that the Cole's idea remains a very valid one, yet some comments are due. In their vast majority, the asteroids are nothing more than conglomerates of rocks, which are kept together by weak gravity forces. Likely carving inside would not preserve the integrity of the asteroid body. Therefore, the outcome will not be a solid "container" for a space habitat. Furthermore, should we impress rotation, likely the crumbling process would result accelerated by centrifugal force. To conserve the asteroid integrity and solidity it would therefore be necessary to contain the whole body in some kind of net, and likely to cement the stones together by means of some kind of agglutinating agent. At that point, wouldn't it be more practical to reprocess the asteroid material, transforming it in powder for 3d printing, and then build the habitat as a cylinder of solid concrete?

2.8 NASA at Stanford University, the "Stanford Torus"

The Stanford Torus is a classic "wheel-style" space habitat design proposed by NASA during the 1975 Summer Study at Stanford University. It was envisioned as a self-sustaining colony that could house 10,000 residents at the Earth-Moon L5 Lagrangian point.

The station is shaped like a giant doughnut (a torus) connected to a central hub by six spokes. Total Diameter: 1.79 km, Habitation Tube Diameter: 130 meters, Mass: Approximately 10 million metric tons, 95% of which is a massive radiation shield made of lunar soil. The station rotates at 1 RPM, using centrifugal force to create a pull equivalent to Earth's gravity (0.9g - 1.0g) on the inner surface of the outer ring. The interior of the torus would feel like a "long, narrow glacial valley" that curves upward until it meets overhead.

The ring is divided into six alternating sections: three for residential/community use and three for agriculture. A massive, non-rotating primary mirror reflects sunlight onto a series of secondary mirrors at the hub. These mirrors then direct the light through glass windows into the torus, simulating

a natural day/night cycle. Since the center of the wheel has near-zero gravity, it serves as the docking port for spacecraft and a site for zero-g manufacturing.

The Stanford Torus was designed to be built using materials harvested from the Moon. Lunar soil would provide aluminum for the hull and silica for glass. The "slag" (leftover soil) would be used for the thick radiation shield. To get the materials from the Moon to the L5 orbit, designers proposed using a Mass Driver (an electromagnetic railgun) on the lunar surface.

The habitat was intended to grow its own food and recycle its own water and air, eventually serving as a base for further space colonization.

While the project was never built due to the staggering cost and the launch capacity required, it remains a foundational concept in megastructure engineering and has heavily influenced science fiction, most notably the "Citadel" in *Mass Effect* and the station in *Elysium*.

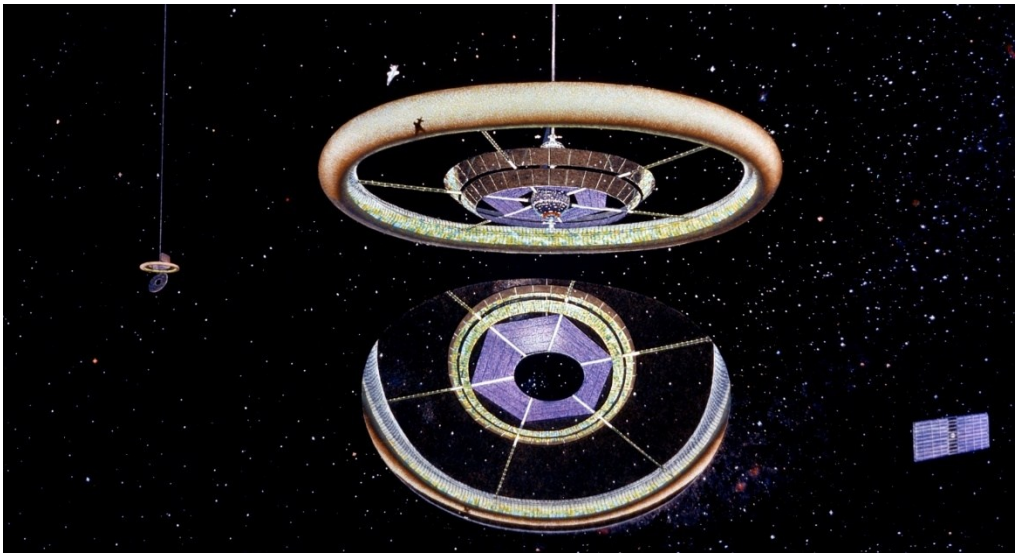

Figure 3. The NASA Stanford Torus (artist view by Don Davis)

2.9 Krafft A. Ehricke, “Androcells”

Krafft Ehricke, a visionary rocket scientist and contemporary of Wernher von Braun, proposed the Androcell as part of his "Extraterrestrial Imperative." Unlike the massive, wheel-shaped Stanford Torus, Ehricke’s Androcells were designed as modular, evolving habitats specifically tailored for the industrialization of the Moon and beyond.

Ehricke believed that humanity’s growth was limited on a "Closed Earth." To avoid stagnation or collapse, he argued that we must transition to an "Open World" model. The Androcell (a portmanteau of anér, andrós, meaning man, and *cell*) was the fundamental unit of this new extraterrestrial life—a "synthetic" environment where biology and technology integrated perfectly.

While the Stanford Torus focused on a giant, singular ring, the Androcell was often envisioned as a cylindrical or "capsule" shaped habitat. Androcells were designed to be linked together. As a lunar colony or orbital factory grew, new cells could be "docked" to the existing structure. Ehricke viewed the Androcell as a living organ. The machines handled the waste and life support, while humans provided the "nervous system" or decision-making logic. They featured high-intensity artificial lighting and tiered agricultural levels to maximize space, creating a dense, highly efficient urban-industrial ecosystem.

Ehricke’s visions were often more gritty and industrial than the "space suburbia" of the 1970s NASA studies. While the NASA’s Stanford Torus was conceived as a residential settlement, the Ehricke’s Androcell was intended for Industrial Production and Resource Extraction, modular in scale (from dozens to thousands), and its aesthetics and ergonomics were more shaped as technical-functionalist. Ehricke specifically mapped

out how Androcells would function on the Moon (a concept he called Selenopolis). He was a staunch advocate for nuclear-powered habitats to sustain the deep-space industrial base. He believed the Androcell would allow for "clean" manufacturing in space, moving polluting industries off Earth and leaving the home planet as a "garden" for leisure and nature. Krafft Ehricke's Androcells represent a more economically driven view of space travel. While the Stanford Torus was a utopian "city in the sky," the Androcell was a functional blueprint for a space-faring civilization that survived by mining, manufacturing, and expanding its reach across the solar system.

2.10 Contemporary free-space habitats concepts

Space Renaissance International is proud and honored to guest some advanced concepts, conceived and developed by SRI Members. Some of them were conceived and are being developed and enhanced in the framework of the Space Renaissance Academy Committees.

2.10.1 Isaac Arthur – space clusters, villages and counties

In one of his excellent webinars, Isaac Arthur added a quite interesting view of urbanization in free-space[22].

Arthur explores the evolution of space colonization from isolated stations to massive, interconnected societies. He argues that space will not be a collection of "lonely outposts," but rather a complex web of artificial worlds. Instead of building one massive megastructure, humanity is more likely to build many smaller habitats (like O'Neill Cylinders) in close proximity.

If one habitat fails or suffers a catastrophe, neighbors are minutes away to provide aid. Different habitats within a cluster can serve specific roles—one for heavy industry, one for agriculture, and others for residential "park" worlds. Clusters can share massive power plants – fusion or solar collectors – reducing the cost for each individual habitat.

Clusters aren't just groups of floating cans; they may be physically and logistically linked. Habitats may be physically connected by tethers or "space elevators" to allow for transit without needing rockets. When habitats are only a few kilometers apart, travel between "cities" is faster and easier than international travel on Earth today. One of the most radical concepts is the politics of mobility. Unlike a city on Earth, a space habitat is a ship. if a community disagrees with the local "cluster government," they can theoretically detach their entire world and move to a different cluster. Clusters can grow, merge, or split over time. This creates a highly fluid geopolitical landscape where "land" (living space) is something you can move.

Clusters might be arranged in different configurations: arranged like rungs on a ladder or along a central transit spine; loose collections that share the same orbital path but aren't physically linked; eventually, clusters could become so dense they form a literal shell of habitats around a planet or even a star (a Dyson Swarm).

Living in a cluster allows for "Digital Ecosystems." High-speed, low-latency communication between nearby habitats allows them to share a unified internet, culture, and economy, even if they are physically separate hulls. This enables a "Interstellar City-State" feel where the cluster is the primary unit of civilization.

Arthur provides the foundational breakdown of how artificial worlds can be organized into complex, mobile civilizations rather than remaining as isolated outposts.

The philosophical and anthropological entanglement is profound. Similarities with nature, vegetable life namely, are evident. A single tree cannot survive alone in a desert, while a forest will thrive, and create its own ecosystem. So, a multitude of habitats in free-space can create its own ecosystem, in the form of robust and resilient connected villages, or counties, or space regions, sharing distributed infrastructures.

2.10.2 Werner Grandl

Werner Grandl's research focuses on the construction of self-sustaining colonies in space using lunar and asteroid resources.

“Industrializing the Earth–Moon System: A Conceptual Study for a Space Factory at Lagrange Point L5.” Is a peer-reviewed publication[23], proposing the first industrial plant at the Earth-Moon Lagrange point L5, where lunar and asteroid materials could be processed and goods manufactured in zero gravity with 24-hour solar power availability. The facility includes a zero G central industrial hub, and rotating modules for crew living. The paper is a re-editing of the paper “Industrializing the Earth-Moon System – the role of space mining and material processing for human civilization on Earth and in space”[24], co-authored with Adriano V. Autino, presented at IAC 2024 in Milano.

Together with his longtime collaborator Clemens Böck, and Adriano V. Autino (SRI), Werner has designed the Artificial Gravity Orbital Station (AGOS)[25], a spinning modular station proposed as a successor to the International Space Station. The AGOS concept features hard-shell aluminum cylinders, each 18 meters long and 7 meters in diameter, weighing 20 metric tons, transportable via reusable launchers to low Earth orbit. In its final configuration, the station would expand to 32 living quarter modules supporting approximately 180 inhabitants.

Werner’s work on asteroid habitation – retaking the work made by Dandridge Cole (see 2.7) – proposes converting mined-out near-Earth asteroids, and potential killer cosmic objects, like hazardous near Earth asteroids and comets, into rotating colonies for up to 2,000 inhabitants. The hollowed asteroid shell provides natural shielding against cosmic rays, solar flares, and micrometeorites, while a rotating torus driven by magnetic levitation bearings generates simulated gravity inside. Such space settlements could also be described as a life insurance for the human species in the long run.

This concept, developed with Ákos Bázsó at the University of Vienna, was published in Asteroids – Prospective Energy and Material Resources in 2013 and later expanded in Asteroid Habitats – Living Inside a Hollow Celestial Body in the Handbook of Space Resources. Read Near Earth Asteroids – Prospection, Orbit Modification, Mining and Habitation.

Werner’s earliest published work in the field dates to 1993, when he copresented Astropolis – Space Colonization in the 21st Century with Antonio Germano at the 11th SSI Princeton Conference, organized by the American Institute of Aeronautics and Astronautics (AIAA). In 1995, he copresented Commercial Asteroid Resource Development and Utilization at the International Academy of Astronautics in Oslo, Norway. In 2009, he published Asteroid Impact – the Ultimate Disaster in Disaster Advances Journal, and in 2016, he authored the book “Utopia Solis – Leben im Sonnensystem”, a comprehensive German-language overview of human life in the solar system.

2.10.3 Jerry Stone

Jerry Stone is a free-lance British scientific disseminator, since long-time providing lectures and conferences on space and human space flight.

Island Zero is a proposal for a small-scale, rotating space habitat developed as part of The SPACE Project (Study Project Advancing Colony Engineering) at the British Interplanetary Society (BIS), initiated by Jerry in 2013[26].

It was designed to act as a "practical gateway" or "bootstrap" to larger space colonies, specifically updating Gerard K. O'Neill's "Island One" concept from the 1970s, making it suitable for modern construction techniques.

The purpose is to provide a base of operations for a workforce building larger habitats (such as Island One, Two, or Three), which are also part of the BIS study. Designed as eight modular, inflatable units (similar to those from Bigelow Aerospace) arranged in a wheel-like structure with a radius of Rotation & Gravity. The structure rotates at roughly 2 rpm to generate simulated gravity (1G) on its outer ring, allowing the crew to avoid the long-term health issues of weightlessness.

Island Zero is proposed for use at the L5 Lagrange point, in lunar orbit, or in Martian orbit.

The SPACE project focuses on technologies possible with existing, or near-future boosters (like SpaceX Falcon 9/Starship), rather than waiting for future, speculative tech.

The project aims to demonstrate that space colonization can be achieved in the 21st century by developing a step-by-step approach starting with smaller modules before moving to massive, sustainable cities

2.11 Gerard K. O'Neill

2.11.1 Living in free space, the O'Neill's concept

Gerard K. O'Neill was a Princeton physicist who radically shifted our perspective on space colonization. In the 1970s, he proposed that instead of settling on planetary surfaces (like Mars or the Moon), humanity should build massive, rotating habitats in free space.

His vision was popularized in his 1976 book, "The High Frontier: Human Colonies in Space".

O'Neill argued that planetary surfaces are actually "suboptimal" for large-scale civilization because:

- It is energy-intensive to move materials in and out of a planet's gravity well.
- Planets rotate, creating day/night cycles and blocking constant solar energy.
- A planet has a finite amount of land.
- Planets have gravity levels different than Earth's gravity 1G

By building habitats at Lagrange Points (specifically L4 and L5), colonies could have 24/7 access to solar energy and create "simulated gravity" through centripetal force.

O'Neill categorized his habitats into three progressive sizes, often referred to as "Islands."

1. **Island One - The Bernal Sphere**. The first generation was intended to be a cost-effective starting point. A rotating sphere approximately 500 meters in diameter, with a capacity of roughly 10,000 people. People would live on the "equator" of the interior, where the rotation creates a feeling of 1G gravity. Sunlight would be reflected into the sphere via external mirrors.
2. **Island Two - The Stanford Torus**. While O'Neill worked on various designs, the Stanford Torus (developed during a 1975 NASA summer study he led) is often grouped into this evolution. Structure is a giant "donut" or ring, with a capacity of 10,000 to 140,000 people. The ring rotates around a central hub, which serves as a docking bay for spacecraft.
3. **Island Three - The O'Neill Cylinder**. This is the most famous and ambitious of his designs. Two counter-rotating cylinders, each 5 miles in diameter and 20 miles long. By having two cylinders spinning in opposite directions, the habitat cancels out gyroscopic effects that would otherwise make it difficult to keep the station pointed at the sun. The interior consists of three land areas alternating with three giant glass windows. Massive external mirrors fold out to track the sun and simulate day/night cycles.

To build these massive structures, O'Neill knew launching materials from Earth was too expensive. He proposed the Mass Driver—an electromagnetic railgun located on the Moon. It would "shoot" lunar soil (rich in aluminum, titanium, and oxygen) into space, where it would be caught and processed at the construction site.

Though we haven't built an Island One yet, O'Neill's work remains the blueprint for modern space advocacy. Jeff Bezos was a student of O'Neill at Princeton and has explicitly stated that Blue Origin's long-term goal is to build O'Neill-style habitats.

Gerard K. O' Neill: "The main goal is to make it possible for every person who wants to, to live in a world which is beautiful, which is clean, and which is free of the limits of a planetary surface."[27] This statement was also often mentioned by Jeff Bezos, the founder of Blue Origin, in several speeches.[28]

"Did anybody in science fiction ever predict this [rotating space habitats], and if not why?" This question was given to Isaac Asimov by Gerard O'Neill. The answer was: "Nobody did really, because we've all been planet chauvinists, and we all believed people should live on the surface of a planet."

Figure 4. Interview to Geard O'Neill and Isaac Asimov 1975

Closing “The High Frontier” Gerard thanks a number of persons, including, among others:

- Freeman Dyson, who encouraged this work from its beginnings.
- Wernher von Braun, whose highest goal throughout several decades of work has been the human movement into space.
- Krafft Ehricke, whose originality and drive can be seen in ideas relating to almost every area of development in space.
- Mark Hopkins, for his tutelage in elementary economics.
- Keith and Carolyn Henson, Richard Hoagland, and Tom Heppenheimer, all of whom in their ways have sought to bring new ideas before a wider audience.
- Isaac Asimov, whose articles and lectures eloquently defend the humanization of space.

2.11.2 1 G simulated gravity, why O’Neill considered it a mandatory human requirement

Before the book, O'Neill published "The Colonization of Space" in Physics Today (Vol. 27, No. 9). This was the seminal academic paper that introduced his ideas to the scientific community. He emphasizes that we cannot assume humans can thrive or reproduce in low gravity. He posits that 1G is the only "proven" environment for long-term health. He discusses the "psychological comfort" of a familiar environment, arguing that to attract 10,000+ civilians (not just elite astronauts), the habitat must feel like Earth, not a laboratory.

“To live normally, people need energy, air, water, land and gravity. In space, solar energy is dependable and convenient to use; the Moon and asteroid belt can supply the needed materials, and rotational acceleration can substitute Earth's gravity.”[29]

O'Neill led a joint study between NASA Ames and Stanford University titled Space Settlements: A Design Study[30]. This document is much more technical than The High Frontier. Chapter 2 specifically addresses "Physiological Health." It explicitly lists 1G as a "mandatory" design constraint to prevent bone demineralization and cardiovascular decay. The study notes that a "civilized" space program requires that inhabitants are not "biological prisoners." It argues that if a person born in space cannot visit Earth for tourism or education because their bones are too brittle, their fundamental freedom of movement has been violated.

On July 23, 1975, O'Neill testified before the U.S. House of Representatives (Committee on Science and Technology). He argued that space colonization should be **a "human" endeavor, not a "military" one**. He highlighted that providing 1G was a way to ensure the "democratization" of space. If the environment is 1G,

then the elderly, children, and the non-athletic can all live there. Without 1G, space becomes an exclusive club for the physically "perfect." Al Globus provides a full transcript of the Testimony.[31]

O'Neill founded the Space Studies Institute (SSI)[32] in 1977 to continue this research. In early SSI Conference Proceedings (often published by AIAA), several papers discussed the "Legal and Social System of a Space Community."[33]

O'Neill also argued that the 1G requirement was also an economic mandate. For the habitat to be a viable "Island," it needed a tourism industry. If Earth-based tourists faced debilitating health risks from low-g, the business model for the habitat would fail.

As a summary of O'Neill's "1G" Philosophy, we may categorize his 1G requirement into three "Mandates":

- **Biological Mandate** - We have 400 million years of evolution in 1G. Any deviation is a high-risk medical experiment, especially for pregnancy and childhood development.
- **Civil Mandate** - Space settlers must remain "fully human" and compatible with Earth. To deny them the ability to return to Earth is a violation of their Human Rights.
- **Economic Mandate** - A colony must be able to trade and interact with Earth. If the labor force becomes biologically distinct (unable to handle Earth's gravity), the two economies will diverge and eventually become hostile.

3 Discussing the user requirements

3.1 Simulated gravity, for what?

A deep discussion on "Artificial Gravity" was done by Peter Diamandis in 1987, in his paper "Reconsidering artificial gravity for twenty-first century space habitats."[34]

For the sake of correct terminology, it is worth clarifying that artificial gravity is something we could achieve using some form of anti-gravitational force. If we are talking about centrifugal force by rotation, we'd better talk about *simulated gravity*, and not artificial gravity.

The paper postulates a few key questions:

- Why should we consider Artificial Gravity?
- How much Artificial Gravity is needed?
- When is Artificial Gravity inappropriate?
- What are the physiologic limits to radius and angular velocity?
- What are the cost limits to radius and angular velocity?

Yet, the very key question is missing: which kind of space habitat are we considering? Astronautical space station? Space hotel for tourists? Orbital settlement for permanent space citizens? If we don't clarify these requirements, our discussion will be totally inconsistent. In fact, starting from the first question (Why should we consider Artificial Gravity?) the answer will differ very much, according to the considered kind of habitat. Astronauts have demonstrated that a maximum of six months in microgravity doesn't cause unrecoverable damages. For astronautic purposes, even a <1G gravity level would be better than zero gravity. Space tourists as well, staying short periods in orbital venues, would not suffer too much by gravity differences. The problem, however, would matter for the resident personnel, yet it could be solved by proper shifts. The problem's relevance shows its whole heavy relevance only in the case of space habitats conceived and designed for permanent space citizens.

Writes Peter Diamandis: "Why do we need Artificial Gravity in orbiting habitats? Twenty years ago the answer would have been given by the human factors and space manufacturing groups — in particular, that artificial gravity is necessary *to allow astronauts* to properly handle materials, complete manual tasks, and maneuver easily about the space craft. Today however, after numerous experiences on Skylab, Spacelab and the Space Shuttle, we realize that gravity is not needed for work or construction in space, nor is it necessary for the run-of-the-mill activities aboard the spacecraft. Today the answer as to why we might need artificial gravity is

given by the physicians. Medical research on the long term medical effects of microgravity indicate that our major concern on long duration missions in orbit should be one of health, not productivity."

As we see, Diamandis is still talking about "missions", thus the discussion is still in the astronautic paradigm.

Going ahead, the paper questions: "How much gravity does an orbiting habitat require? Will a fractional G be sufficient to maintain an astronaut's normal physiologic condition, or will a full one G be necessary? These questions are critical because they relate directly to the cost and complexity of a rotating habitat — the higher the gravity level required, the larger the habitat's size and/or angular velocity." Of course the considered cost is the cost of an astronautic facility, not a permanent space residence.

As to the real need of artificial gravity the paper expresses a rather negative opinion. But why? Because the main requirement is making experiments, in micro-gravity environment. In that case, simulated gravity would be a useless and costly complication, forcing the experimentation activities to be developed in the central hub: "Only 1% of the experiments required gravity, over 83% required zero gravity or would be significantly hampered by gravity (Stone, et al., 1968)."

Diamandis goes on: "At this time it is worth mentioning that there are many significant benefits, in addition to the medical ones, which should be considered in the overall decision to pursue rotating habitats. In brief, these benefits include: improvement in ease of fluid and waste management, benefits to "orbital" agriculture, and potential benefits to crew psychological well-being and social interactions." The confusion persists: *crew* psychological well-being is mentioned, so we're still discussing astronautical facilities, yet orbital agriculture is also mentioned, and that is clearly a settlement item.

We are dedicating great attention to this Diamandis's paper because it is emblematic of the confusion that characterizes *any space study* during the transition phase from the astronautic to the space settlement paradigm. Researchers tend to look forward, to the nascent phase of space settlement, yet they keep on using the old categories, and the old user requirements.

The paper dedicates attention to medical & scientific aspects of microgravity, including renal/fluid shift, cardiovascular, musculoskeletal, immune system changes, and reproductive capability. Coriolis effect is also considered. The paper reports results of experimentation made by simulating facilities: "adaptation (and subsequent immunity) to this "Coriolis sickness" has been shown to occur for rotation speeds less than or equal to ten rpm. No Coriolis sickness is noted for speed of one rpm or less."

3.2 The compulsive experimentation policy, and the issue of implementation cost

The question of "how much artificial gravity is needed" is continuously re-proposed by the paper. A fraction-G facility with one-G jogging track is proposed, as an expedient to have some kind of daily workout… for who? Astronauts or resident space citizens? Astronauts are used to daily gymnastic exercises, some hours each day, to contrast the damages of muscular and bones microgravity. Once again: is it reasonable to force normal space residents to daily gymnastic practices? That would result in some kind of forced labor for life. The same concept should apply to any "medical" solutions to support human adaptation to gravity levels lower than 1G. Space citizens should not be forced to permanent medical therapies, except when their health requires it, as it happens on Earth.

In the conclusions, the Diamandis's paper comes back to the claimed key questions[35]. But why? Do we really need to know what is the maximum angular velocity an average group of individuals can adapt to, and what minimum gravity level is enough to maintain the normal physiological functioning of the body's systems, and if mammals can reproduce in microgravity? When designing a big space habitat for resident citizens, should we really be concerned about cost? The answer is no, to both these questions.

We don't need to know what happen to human physiology when adapting to a less-than-1G gravity level. It could be that humans can adapt, but then they will not be able to migrate back to Earth, or even to enjoy tourism on Earth.

And no, we should not be concerned about the development cost, when designing such a great infrastructure. Opposite, we shall be ready to allocate redundant budgets, since we are not working on some kind of astronautic mission, but we are working to the next upper level of human urban architecture. Just for

a quick assessment, we might compare it to a very luxury environment, yet it is very much more. It is to design a beautiful environment where humanity can thrive and flourish in a totally new cultural dimension. Such a vision should exclude any greedy consideration limited by terrestrial economy. Here we are working on an economy determined by space resources, and we shall give priority to the settlers' well-being, comfort, and beautiful environment.

Furthermore, I would add a third criteria. The entire astronautical era has been characterized by one primary goal: experimentation. That was reasonable, within certain limits. I would say the experimentation rationale was even a little bit over-intended and over-applied, on the skin of astronauts, military personnel. Their life and health were sadly considered "spendable". Should such a compulsive experimentation policy keep on ruling the space settlement first stages too, it would result in a poor outcome, and eventually in an abort of the first steps, due to insufficient funding and under-evaluation of the civil space settling requirements.

3.3 Countering the lower-than-1G options

O'Neill's 1G requirement reveals it as the "Non-Negotiable Pillar" of his entire philosophy. O'Neill strongly defended the 1G requirement against the "Partial Gravity" alternatives.

NASA SP-413: "Space Settlements: A Design Study" (1977)[30], already mentioned, is the technical "bible" that followed the 1975 NASA Ames/Stanford study. O'Neill and his team explicitly debated whether 1G was necessary or if they could save money by building smaller, slower-rotating habitats with less gravity.

O'Neill argued that anything less than 1G would lead to irreversible biological divergence. If children were raised in 0.38g (Mars) or 0.16g (Moon), their bone density and cardiovascular systems would adapt to those levels. They would be physically incapable ("exile") of ever visiting Earth without life-threatening injury.

He viewed this as a "genetic trap." To O'Neill, a colony that permanently physically disables its citizens from visiting the "home planet" was morally unacceptable and a violation of their fundamental freedom of movement.

In the "Human Needs" section of this study, the team noted that while we know 0g is bad, there was (and still is) no data proving 0.5g is "half as bad." They posited there might be a threshold effect where anything below a certain level of gravity causes the same decay as zero gravity. Therefore, 1G was the only "safe" design spec.

"The Colonization of Space" (Physics Today, 1974)[29] was O'Neill's first peer-reviewed foray into the subject. In it, he addresses the Social and Tourism Requirements. O'Neill stressed that for a colony to be economically viable, it needed a fluid labor market, allowing bidirectional migration. If workers could not return to Earth to retire or spend their earnings, recruitment would be limited to "desperate" individuals or high-risk pioneers, rather than the general public. O'Neill also argued that the goal wasn't just survival, but thriving. By providing 1G, the colony could support "Earth-normal" agriculture, architecture, and recreation (like swimming or track and field), which are essential for long-term psychological stability.

O'Neill's testimony before the U.S. House Committee on Science and Technology is a clear declaration about "Human Rights". He told Congress that 1G was necessary so that space wouldn't be limited to "the young and the super-fit." He wanted space to be accessible to the elderly and the handicapped. He argued that a 1G habitat is the most inclusive environment because it doesn't require the specialized, grueling physical training of an astronaut. 1G simulated gravity is necessary for democratization of space.

In various SSI (Space Studies Institute) conferences, O'Neill faced pushback from those who wanted to settle the Moon or Mars first. His counter-arguments were:

- **The "Gravity Well" Trap**. Even if 0.16g was "healthy enough," you are still stuck at the bottom of a gravity well. In a rotating habitat, you have 1G for living, but you can move to the Zero-G Axis of the cylinder in minutes for recreation or manufacturing. This "Gravity Gradient" (from 1G at the rim to 0g at the center) is a unique human freedom that planets cannot provide.
- **Medical Conservatism**. O'Neill often quoted the lack of data as a reason for 1G. He argued that it is easier to "spin down" a habitat if we discover 0.5g is fine, but it is impossible to "add gravity" to the surface of Mars if we discover 0.38g is lethal for fetal development.

3.4 The fundamental contribute given by Gerard O'Neill to the cause of civilization expansion into outer space

Writes Michael A. G. Michaud, in an excellent comprehensive paper[36] on the NSS website: "What O'Neill did, apparently without realizing that similar proposals had been made before, was to revive the idea of space colonies in more sophisticated form, with many of the numbers worked out." We only partially concur. For sure the O'Neill's work was more sophisticated vs. any previous efforts. Yet that is not the only, and not the main, merit of his work. The main point is that O'Neill finally has done a design based on humanist requirements. Tsiolkovsky, Oberth and Potočnik were too much in advance on their time, and their technological forecast couldn't but being limited. Von Braun's vision was essentially a military one: his wheel was a battle-spacecraft. Ehricke was more focused on the Moon surface, and conceived Androcells as Selenopolis's supporting facilities, more than an evolutionary level. His vision was however still conditioned by economic saving (military) philosophy. Gerard O'Neill was the first who dared to design space habitats based on humanist requirements: not only safety and survival, but beauty, ergonomics, well-being, culture, art, tourism, sports, entertainment. O'Neill can be considered the father of Civilian Space Development.

Such a key characterization is very well shown in the already mentioned work made by the Space Studies Institute from 1974 to 2001[33]. Gerard O'Neill and the SSI have systematized the method for humanist design of space habitats.

Keywords: democratization of space, biological prisoners, human not military endeavor, humanist design

4 The benefits of living in free-space rotating habitats

When discussing space habitats requirements, we are not talking about astronauts. We are talking about space settlers living and working in space. Longtime resident inhabitants, people endowed of full human rights, life, health, and reproduction warranted by proper technology solutions. And not only: legal conditions, warranties and insurances shall be considered. Any comparison among astronautic exploration missions, maximum one year, and civilian space settlement, longtime residence is inappropriate.

4.1 Requirements evolution

requirements / flight levels		low acceleration	safe re-enter in atmosphere	comfortable flight	cosmic radiation protection	simulated gravity	green environment
space exploration	short missions	NR	MR	LR	LR	NN	NR
	Moon	NR	MR	LR	LR	NN	LR
	Mars	NR	LR	MR	HR	MR	HR
	long missions	NR	LR	MR	HR	MR	MR
space tourism	sub-orbital tourism	HR	LR	HR	LR	NN	NN
	sub-orbital transport	HR	LR	HR	LR	NN	NN
	orbital tourism	HR	HR	HR	HR	MR	MR
	lunar tourism	HR	HR	HR	HR	NN	MR
space settlement	working in space	XR	XR	XR	XR	XR	XR
	living in space	XR	XR	XR	XR	XR	XR
LEGENDA:	XR mandatory						
	HR highly required						
	MR medium required						
	LR low required						
	NR not required						
	NN not needed						

Figure 5. Health & Ergonomics Requirements Evolution

Table in Figure 5 was made by the author a few years ago, for an article written for the US International Mensa Global Risk[37]. Three levels of space activities are considered: Exploration, Tourism, and Settlement. Requirements such as acceleration, safe reentering in atmosphere, comfortable flight, space radiation protection, simulated gravity, green environment have different importance, according to the level. Moving from space exploration short missions, to space tourism, to space settlement, working and living in space, the importance of the requirement is increasing. In the space settlement environment, all the requirements are extremely mandatory.

Space exploration is done by trained astronauts, and the mission duration – at least in the geo-lunar space – does not exceed 1 year. Physical and legal conditions are typical military conditions, with meaningful limitation of civil rights. Space tourism is even less stressing as far as duration is concerned. Space tourists enjoy a few weeks in space. Yet space tourism companies shall complain with all the regulations attributed to airlines, as far as civil right, protection of life and health, insurances and warranties. In the space settlement environment, not only civilian rights, warranties and safety conditions shall be 100% observed, yet all the conditions to assure a full beautiful life, even better than normal, shall be implemented. Space tourism may be considered a mid-status, where we can learn, improve technologies, and really start moving civilization into outer space.

4.2 Physiology, sociality, and human rights

While designing rotating space colonies Gerard O'Neill required 1G simulated gravity because it simultaneously preserves human biology, natural social behavior, intergenerational development, and economic practicality. This made 1G not a preference, but a mandatory condition for his vision of truly human life beyond Earth.

The basic freedom requirements were considered equally important. If settlers were used to less than 1G gravity, they couldn't exercise their fundamental human rights, should anybody change their mind about space migration and wanted to return living on Earth. That strikes the ethical and political foundations of an air-space colony vision. Freedom, both physical and personal, is deeply linked to the gravity environment the settlers will live under. Gravity was not just a matter of health or habitability, it was a principle of liberty and human rights.

A colony in which inhabitants physically cannot return to Earth would violate one of its central ambitions, that humanity's expansion into space shall increases freedom and not to diminish it.

4.3 O'Neill's Freedom requirement

> "We do not want to make emigration into space a one-way trip, without the option of return at will."

- "The High Frontier" Page 46
- William Morrow & Co. 1977 296 pages, ISBN: 0-688-03188-1 page 47
- Bantam edition 1978 - 356 pages ISBN 0-553-11016-0 page 46
- Page 29 192 pages - Gerard O'Neill SSI 3rd edition 2000

> "The colonies must be places where choice and opportunity are expanded, not restricted."

- "The High Frontier" Page 182
- Edition: 1977 (William Morrow and Co.) / 1989 (Space Studies Institute)
- Page Number: Page 182 (in the 1977 Morrow edition)

4.4 The O'Neill's Tourism requirement

Freedom of migration is not the only rationale for the 1G mandatory requirement. The O'Neill "Bible" (The High Frontier: Human Colonies in Space) also mentions a key industrial sector that will expand proportionally to human settlement in the Solar System: tourism, two-ways. Earthly citizen will want to visit the Settlements, and the space settlers will like to visit Earth. The tourism industry will be a key pillar of the solar society economy: we definitely don't want visitors coming to Earth from space communities to have an uncomfortable experience, due to the Earth's gravity!

> "Ultimately, if the L5 civilization nears maturity and the earth's population is stabilized, we can expect, in analogy with similar situations on Earth, that a two-way tourist trade will become an important part of the economic picture. We can be almost certain that such will be the case when we realize that in each passing decade the cost of transport, in constant dollars, will decrease as technology advances."

- "The High Frontier" Page 252
- Library of Congress Cataloging in Publication Data, Space Studies Institute - 345 pages

4.5 Simulated gravity for elderly and particular medical conditions

> What though of the elderly? Here on Earth, with age and the infirmities of age, the body must spend more and more of its reserves of energy in simply fighting gravity. In the institutions to which many elderly people migrate, a great deal of the equipment one sees is devoted to the single task of assisting the body in its eternal battle with gravity. In contrast, we can imagine that in a space habitat anyone with difficulty in walking will spend most of his time at a high elevation where gravity will be reduced; those who would be confined to bed on Earth could have freedom of movement in a region of near-zero-gravity. Cardiovascular ailments are among the major causes of death for the elderly. In space we can expect that people with problems of circulation can move to low-gravity regions, and there enjoy freedom of movement and moderate, nontiring exercise. In summary, it seems quite possible that people in a space habitat will live to a greater age than they would on Earth. Perhaps it is even more important that their later years could be spent in conditions of far greater freedom and independence than their physical condition would permit them on our planet.

- "The High Frontier" pg. 258 259
- Bantam edition 1978 - 356 pages ISBN 0-553-11016-0

Here on Earth, with age and the infirmities of age, the body must spend more and more of its reserves of energy. In a space habitat endowed with simulated gravity, anyone with difficulty in walking will spend most of their time nearer to the central hub, where gravity will be reduced. Those who would be confined to bed on Earth could have freedom of movement in a region of near zero gravity. Cardiovascular ailments would also benefit of reduced gravity levels. In space, we can expect that people with problems of circulation can move to low gravity regions and there enjoy freedom of movement and moderate non-tearing exercise. In summary, it seems quite possible that people in a space habitat will live to a greater age than they would on Earth. Perhaps it is even more important than their later years could be spent in condition of far greater freedom and independence than their physical condition would permit them on our planet.

4.6 More human requirements, beauty, fun, entertainment, and sports.

> We have talked of the necessities of life, but if we are to work and live in space by choice, and enjoy doing so, we will ask for more: the age-old human desires of comfort, good food to eat and good wine to drink, room to stretch our legs, good places to swim and to get a suntan, variety in travel and amusement. We humans have definite ideas of our needs for enjoyment and amusement, and any successful space community will have to accommodate them.

- "The High Frontier" page 48
- Bantam edition 1978 - 356 pages ISBN 0-553-11016-0

We have discussed the necessities of life, but if we are to work and live in space by choice, and enjoy doing so, we will ask for more. The old human desires of comfort, good food to eat, and good wine to drink. Room to stretch our legs, good places to swim and to get a suntan. Variety in travel and amusement. We humans have definite ideas of our needs, our enjoyment and amusement, and any successful space community will have to accommodate them. O'Neill has discussed all these important points.

5 A design oriented to redundancy

5.1 The comfort zone, and more

The Coriolis effect was discussed too. In Gerard O'Neill's immense visionary humanist vision, the comfort zone minimal parameters were just considered a starting point, a baseline on which to build very much more comfortable worlds!

This is maybe the greatest contribute given by O'Neill to the living-in-space conceptualization: a strong humanist approach, very much different from some previous military approaches, where *minimal conditions were considered enough*, for the sake of a narrow safety and survival criteria.

The minimum diameter and maximum rotating speed of a rotating colony were calculated.

Up to 2 rpm should be no problem for residents and require little adaptation by visitors. Up to 4 rpm should be no problem for residents but will require some training and/or a few hours to perhaps a day of adaptation by visitors. Up to 6 rpm is unlikely to be a problem for residents but may require extensive visitor training and/or adaptation (multiple days). Some particularly susceptible individuals may have a great deal of difficulty. Up to 10 rpm adaptation has been achieved with specific training. However, the radius of a settlement at these rotation rates is so small (under ~20 m for seven rpm) it's hard to imagine anyone wanting to live there permanently, much less raise children.

Radius (m)	Rotation Rate (RPM)	Comfort Level & Coriolis Impact
32 m	5.3 RPM	Upper Limit: Uncomfortable for most; requires extensive adaptation.
56 m	4.0 RPM	Challenging: Requires training; noticeable Coriolis effects when moving.
222 m	**2.0 RPM**	**Comfort Zone: Generally considered the threshold for long-term comfort. (Island Zero?)**
500 m	1.3 RPM	High Comfort: Coriolis effects are negligible during normal activity.
900 m	**1.0 RPM**	**Ideal: Near-perfect simulation; no noticeable motion sickness.**
4,000 m	0.47 RPM	O'Neill Cylinder Scale: Extremely stable; supports massive ecosystems.

Figure 6. Space Settlement Population Rotation Tolerance

Figure 6 represents the relation between habitat radius and rotation rate, as far as human tolerance is concerned, provided by Al Globus[38].

A 220 m radius and 2 rpm rotation velocity are considered the minimal comfort conditions. As we can see, 900 m R and 1.0 RPM is very much better, and an O'Neill's cylinder 4,000 m and 0.47 RPM is supposed to provide Earth-like conditions, free from any Coriolis effect. 1.0 Rpm and 1 km radius is the cornerstone of all later rotating habitat studies like Kalpana, Stanford, Taurus, and present day NASA artificial gravity evaluations.

The above are theorical values, never experimented so far. The 1st goal of experimentation is to validate or invalidate these values. In the already mentioned paper[38], Al Globus focuses on 1G simulated gravity, in full agreement with G. K. O'Neill's recommendations. Globus also reports about different studies on the theme of Coriolis Comfort Zone at 1G, and notes that they are not in agreement. That re-confirms the extreme urgency to kick-off experimentation.

5.2 Scope of a research demonstrator like the Jerry Stone's Island Zero

The concept of a rotating habitat was represented in different shapes, cylindrical, spherical, and toroidal. Island Zero[39] is a small demonstrator of the concept, the Gerard O'Neill concept of Island One.

Island Zero is a research project, having the main scope to develop research and to validate the calculations that were made so far on the effects of simulated gravity on the human physiology. E.g., understanding the best relation between the rotation speed and the habitat radius, to remain inside the so-called comfort zone, avoiding being disturbed by the Coriolis effect.

Among the scopes of the project, also the experimentation of some lower levels of simulated gravity. For instance, 0.9G, 0.7G, or the Moon (0.6G) and the Mars gravity (0.37G). Island Zero will have 1G in the peripheral ring, and several internal rings, even just only one or two modules for each level, to simulate different gravity levels.

The difference between the Jerry's definition and my definition is this one: Jerry wrote that among the scopes of the experimentation is to understand *what is the optimal level of gravity*, intending that it could even be less than one 1G. I disagree on such requirements, because the optimal level of gravity is 1G. There's no need to proof it. That is what human physiology, and other terrestrial forms of life, have been used for millions of years. Therefore, the main goal of this or similar projects should be to validate the so-called comfort zone parameters, for normal average people.

We already know what prolonged weightlessness provokes to human physiology[38]:

- fluid redistribution;
- fluid loss;
- electrolyte imbalances;
- cardiovascular changes;
- red blood cell loss;
- muscle damage;
- bone damage;
- hypercalcemia;
- immune system changes and "aging";
- vertigo and spatial disorientation;
- space adaptation syndrome;
- loss of exercise capacity;
- degraded vision;
- degraded smell and taste;
- weight loss;
- flatulence;
- changes in posture and stature;
- changes in coordination.

Many of the above effects were well documented by the NASA astronaut Scott Kelly, after his stay on the ISS for one year[40]. Do we really need to inflict such diseases to human beings, with the goal of maybe saving some % points in the future however big investments for big rotating space habitats?

The calculation so far says that a 220 meters radius station, rotating at about 2 rpm should outcome to be comfortable enough. So, such parameters should be subject of the first experimentation, while bigger dimensions will allow slower rotation speeds, with increased comfort. A configuration like that of Island Zero easily allows to have several different acceleration levels simultaneously, preserving the possibility to move quickly between them. Of course, lower G levels might be preferable in case of specific health diseases. Lower-than-1G levels might be desirable to give more freedom to some people. Zero G in the central hub, as well as intermediate G levels, will also be very useful for specific industrial production processes.

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