Considering Water Treatment in the High Frontier – Thoughts on water treatment in large scale colonies in space.

Anthropologists are unsure as to exactly when *Homo Sapiens* first appeared on Earth, but it was definitely at least **300,000** years ago and possibly as early as 500,000 years ago or more. Since then, in the most recent years, we have significantly advanced our technology. We began writing around 5,500 years ago. We invented the airplane in 1903, the electronic computer in 1945, and we landed on the moon in 1969.

Since the invention of writing, it has been a wild ride for *Homo Sapiens* and especially in the last 100 years, the acceleration of technology has been mind boggling.

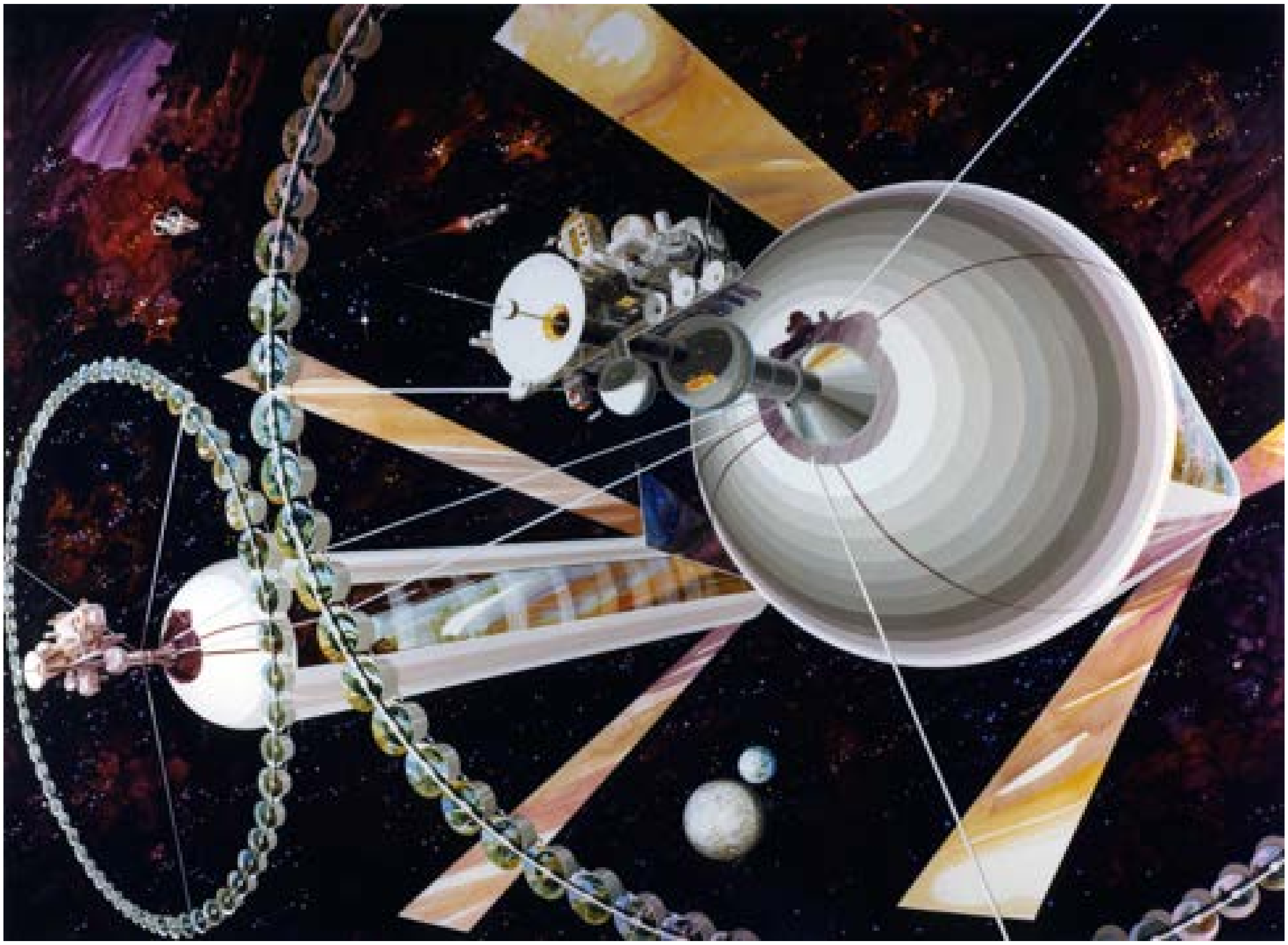
So, let us consider the possibility of what life for *Homo Sapiens* might be like **2,000** years in the future. Given all of the possible problems associated with life on Earth and the possibility of an extinction event, e.g., large volcanic eruptions, global cooling or warming events, asteroid impacts, lowered sea levels, changes in temperatures/salinity/oxygen of the oceans and changes in atmospheric compostion, sharp changes in population and demographics straining precious resources, nuclear war, pandemic, and the dramatic increase in the prevalence of facilities capable of producing deadly genetically engineered pathogens, supernovae radiation, etc. (let's face it, the universe is trying to kill us!), it will be necessary in order to assure that *Homo Sapiens* will survive, that we establish colonies off the Earth and be living in space. Not only on the moon or Mars, but also it's possible to be living on large spinning cylinders that create artificial gravity and can sustain populations in the hundreds of thousands, if not millions.

Let's also briefly consider how people manipulated water only **2,000** years ago. The Romans were building aquaducts to bring fresh pure water to ordinary citizens for bathing, fountains and drinking. In China, irrigation systems were already in widespread use. In the Americas, irrigation systems were in use and the Maya were using filters made from quartz sand and zeolite to perform natural water purification.

Now let's consider how we'll manipulate water **2,000** years from now, not on Earth, but in space.

O’Neill Cylinders

In 1976, Princeton University physics professor Gerard K. O’Neill published a book called “*The High Frontier: Human Colonies in Space*.” This book outlines an architecture for humans to build and inhabit colonies in space, not on planets or natural bodies, but on constructed “islands” that are orbiting in space. In addition to the O’Neill Cylinders, these constructed “islands” have been proposed in many forms, the Stanford Torus, the Bernal Sphere and more recently Kalpana One, but the one thing that they all have in common is that they spin in order to achieve 1G, i.e. Earth Normal, artificial gravity. It is the purpose of this paper to consider water treatment in constructed wetlands, lakes, streams, rivers, ponds and swimming pools on these space settlements. In 1973, Arthur C. Clarke in his science fiction novel, Rendezvous with Rama, considered a large scale space habitat and wrote, *“Naturally the system would have to be rigidly closed, recycling all food, air, and other expendables. But, of course, that’s just how the Earth operates – on a slighly larger scale.”* It is not the purpose of this paper to specify any particular biological treatment technique for the above nor for greywater, blackwater or drinking water. Nor is it to compare the different designs of these constructed habitats. In general, we’ll refer to all of them as O’Neill Cylinders.



Exterior view of a pair of O'Neill Cylinders. Each cylinder is 5 miles in diameter and 20 miles long. The modules on the large ring structure around the endcap are used for agriculture. Each module could have differing environments ideal for a particular set of food items. Painting by Rick Guidice courtesy of NASA.

It is the point of this paper to advocate that water on O'Neill Cylinders would best be treated naturally, i.e., biologically. We think that we should promote using tellurian nature-based solutions to control (or stabilize and sustainably manage) recreational water in wetlands, lakes, streams, rivers, ponds and swimming pools on these large-scale space habitats inhabited by homo sapiens for thousands of years, as opposed to attempting to disinfect, sanitize or control the water by using chemicals or other technologies like ozone injection, UV sterilizers, copper and/or silver ions, hydroxyl radicals, or other "artificial" means. The biotope that is the space habitat should be a sustainable subset of Earth's natural ecology. Because at the end of the day (which is the beginning of the night), as we learned in the movie Jurassic Park, "Life finds a way" and fighting nature with technology is far more difficult than working with nature. Letting nature "control" the water is the sustainable option that will require the least amount of energy and resource input and provide the best results. Let’s think this through.

O’Neill Cylinder endcap. The artist’s inspiration came after O’Neill suggested to him that the view of San Francisco and the Golden Gate Bridge from Sausalito would provide an excellent scale reference for a later model (full size, 20 mile long) cylindrical colony. Water dominates the scenery. Painting by Don Davis courtesy of NASA.

The Gravity of the Situation

One of the most important problems that we confront with living in space is the lack of gravity. We have evolved on Earth in an Earth Normal gravity, a 1G environment, and although we’re constantly fighting it, we actually need it for probably most of our lives. This has been borne out by experiments running on the International Space Station. The absence of gravity has a lot of deleterious effects on the human body and after living in a no gravity environment for 12 months, returning to a 1G environment is painful.

NASA Astronaut Scott Kelley wrote this about his return to Earth after almost a year in space.

"*I struggle to get up. Find the edge of the bed. Feet down. Sit up. Stand up. At every stage I feel like I'm fighting through quicksand. When I'm finally vertical, the pain in my legs is awful, and on top of that pain I feel a sensation that's even more alarming: it feels as though all the blood in my body is rushing to my legs, like the sensation of the blood rushing to your head when you do a handstand, but in reverse.*

I can feel the tissue in my legs swelling. I shuffle my way to the bath room, moving my weight from one foot to the other with deliberate effort. Left. Right. Left. Right. I make it to the bathroom, flip on the light, and look down at my legs. They are swollen and alien stumps, not legs at all. "Oh shit," I say. "Amiko, come look at this." She kneels down and squeezes one ankle, and it squishes like a water balloon. She looks up at me with worried eyes. "I can't even feel your ankle bones," she says."

Although we might be able to live in a Zero G environment for some length of time, like 6-12 months, returning to a 1G environment after an extended period of time in Zero G, might be almost impossible.

There's been a lot of consideration about going to Mars in order to make us an interplanetary species. For good reason, as in the next 2000 years (the timeframe we're using to discuss how we'll manipulate water), there's a fair chance that there could be an extinction event on Earth, because as we said above, the universe is trying to kill us!

Although it's often said that we'll be able to go to Mars, stay for awhile and then come back to Earth, there is a catch. Mars is far smaller than Earth and its gravitational field is only about 38% of Earth's gravity. So, if you weigh 200 pounds on Earth, you'll only weigh around 76 pounds on Mars. You will feel like Superman on Mars, you will feel like you're able to leap tall buildings in a single bound, but after living there for a few years when you return to Earth it will be a problem. If people on Mars have children, it's quite probable that the Martians will never be able to visit the planet of their genesis. The Moon, with only 16% of Earth's gravity, is even more dramatic.

How to Build a Large Scale Space Habitat

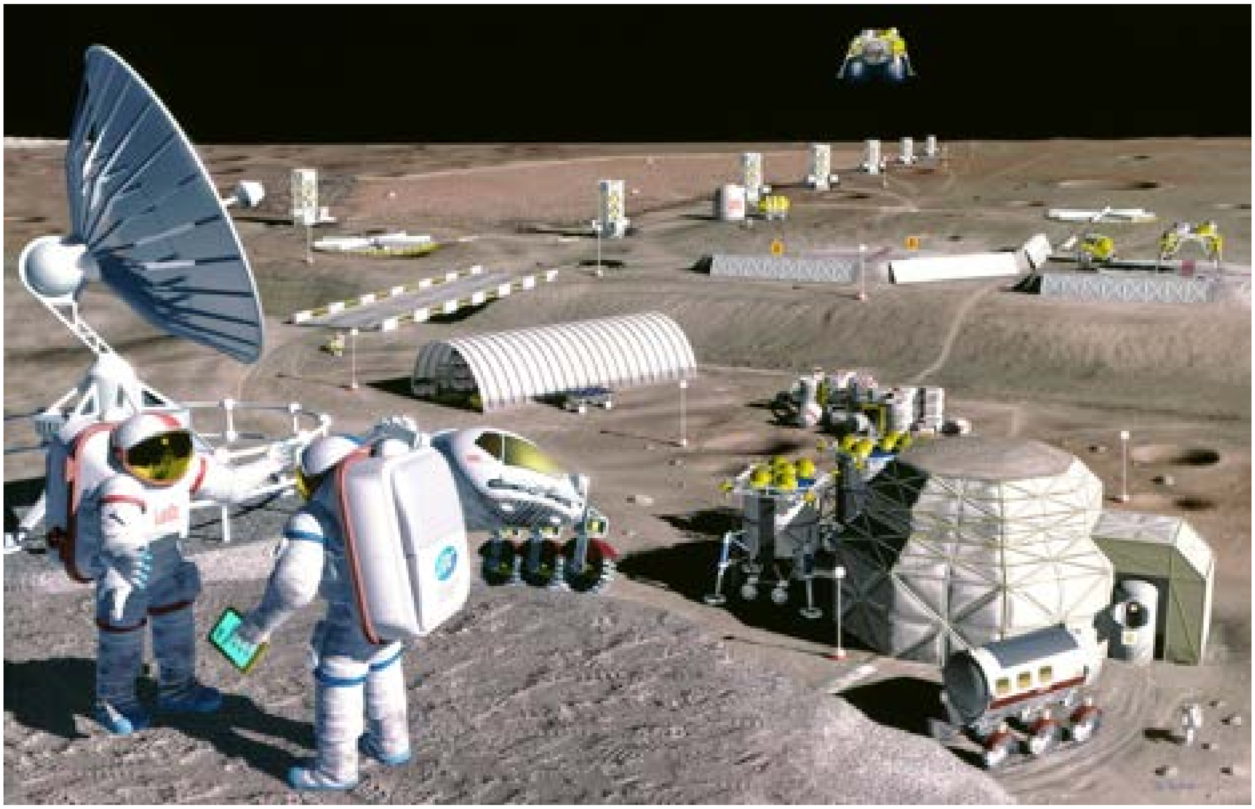
One thing is immediately obvious, bringing most of the building materials to construct an O'Neill Cylinder into space from the Earth is really not an option. The expense of hauling billions of tons of dirt, rock and water, out of the deep gravity well of the Earth is prohibitive and unsustainable. But, the availability of building materials in space is enormous. The Moon, our closest neighbor, has a relatively shallow gravity well and lots of dirt, rock and water in the form of ice. Constructing a solar powered electromagnetic rail gun or "mass driver" (similar to a maglev train) that can repetitively launch dirt and rock from the surface of the Moon was posited by Gerard O'Neill and has since been shown to be a viable technology. The mass driver would use the unlimited availability of solar energy to operate and since the Moon has no atmosphere, this would allow for the payloads to fly frictionless throughout the launch trajectory with pinpoint accuracy. These several billions of tons of dirt, rock and ice would be launched into cislunar space (the volume of space near the Moon), where the masses would be caught and used to assemble the O'Neill Cylinder.

Although several billions of tons may sound like a lot, that is only the typical mass of a comet (laden with ice) or an asteroid of about 1/2 mile in diameter – and there are a lot of them.

Artists conception of a solar electric powered mass driver based on the Moon. Mass drivers could be constructed and used anywhere that there is solar energy available. The Moon's lack of an atmosphere would allow for the payloads to fly frictionless throughout the launch trajectory and with pinpoint accuracy. Courtesy Wikipedia.

Clearly, an operation on the scale required to build an O'Neill Cylinder would require a large mining and mass driver launching operation on the moon. NASA, the European Space Agency, the Russian Roscosmos and the China National Space Administration, are all already making plans to explore mining operations at the Moon's south pole, where sunlight for solar power is available almost 24/7/365.

In 1984, Krafft Ehricke, a German rocket engineer who came to the US after World War II with Werner Von Braun, said "If God wanted man to become a spacefaring species, He would have given man a Moon." Ehricke also referred to the Moon as Earth's seventh continent. Geologically speaking, he had a good point. The Moon is mostly made of the same stuff as the Earth, including incidentally, the zeolites that the Mayans used to purify water.

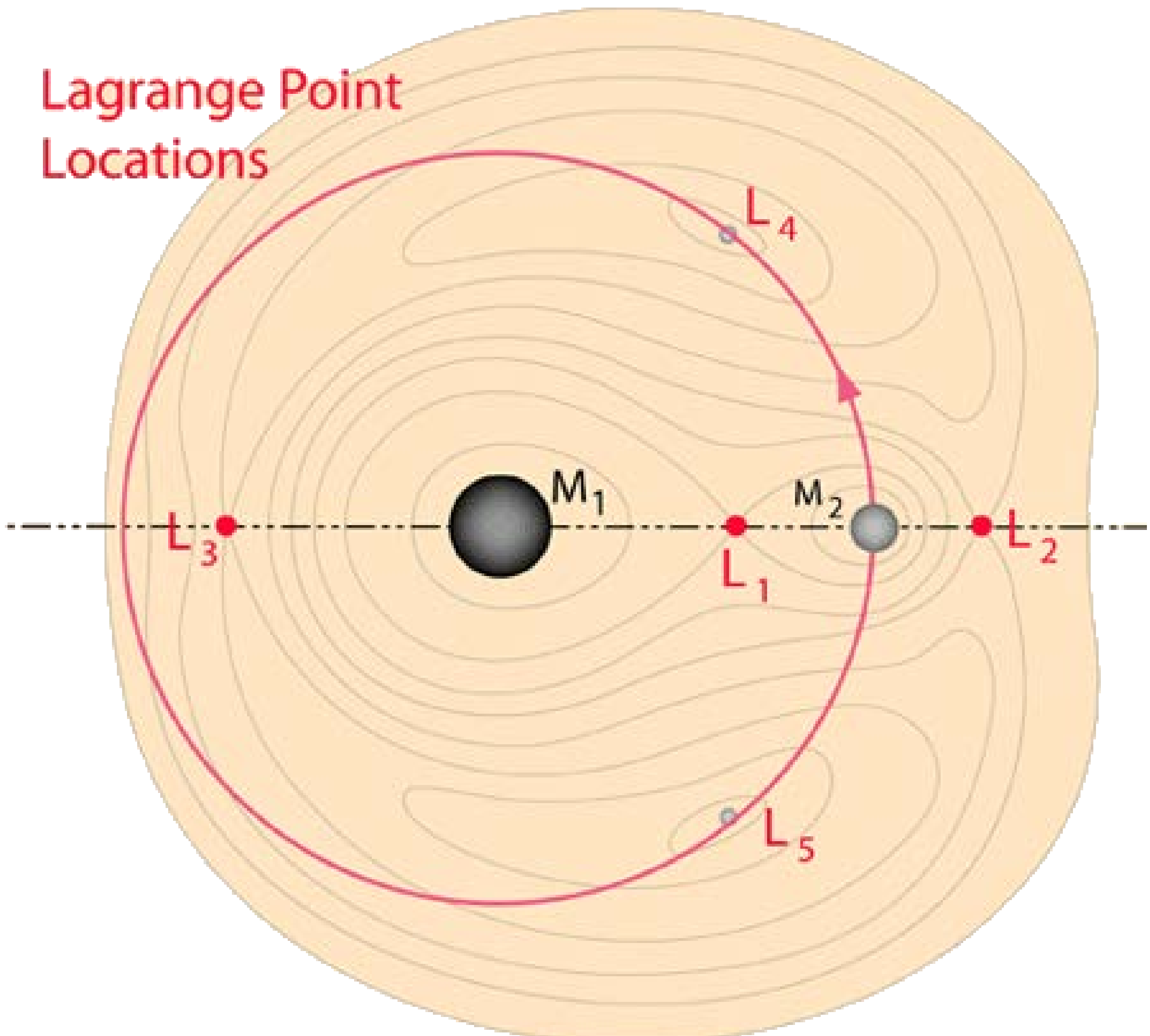


Artists conception of a lunar mining operation. Courtesy NASA 2001

Where to Build a Large Scale Space Habitat

The Moon is our closest neighbor in space and it is, relatively speaking, easy to get there. Because the Moon is in orbit around the Earth, a launch window to the Moon is always open, unlike to any other place in our solar system. And at the speed that chemically powered rockets can produce, we can get to the Moon in about 3 days – faster than it takes for a ship to cross our major oceans. Communications between the Earth and the Moon is also very quick – it only takes less than 3 seconds for light to travel roundtrip the distance between the Earth and the Moon.

So constructing an O'Neill Cylinder in cislunar space (somewhere near the Moon) would make sense because we could use the Moon as a base for mining operations and for launching dirt, rocks and ice, into position for creating the O'Neill Cylinder's structure. Orbital mechanics calculations show us that there are several places in cislunar space, called Earth-Moon Lagrange Points, that provide for stability of an orbiting object and "station-keeping" power is negligible. It is at one of these Lagrange Points, either L4 or L5, that the O'Neill Cylinders could be positioned.



The Lagrange points L4 and L5 constitute stable equilibrium points, so that an object placed there would be in a stable orbit with respect to the Earth and Moon. With small departures from L4 or L5, there would be an effective restoring force to bring a satellite back to the stable point. The L5 point was the focus of a major proposal for a colony in "The High Frontier" by Gerard K. O'Neill and a major effort was made in the 1970's to work out the engineering details for creating such a colony. There was an active "L5 Society" that promoted the ideas of O'Neill. The L4 and L5 points make equilateral triangles with the Earth and Moon.

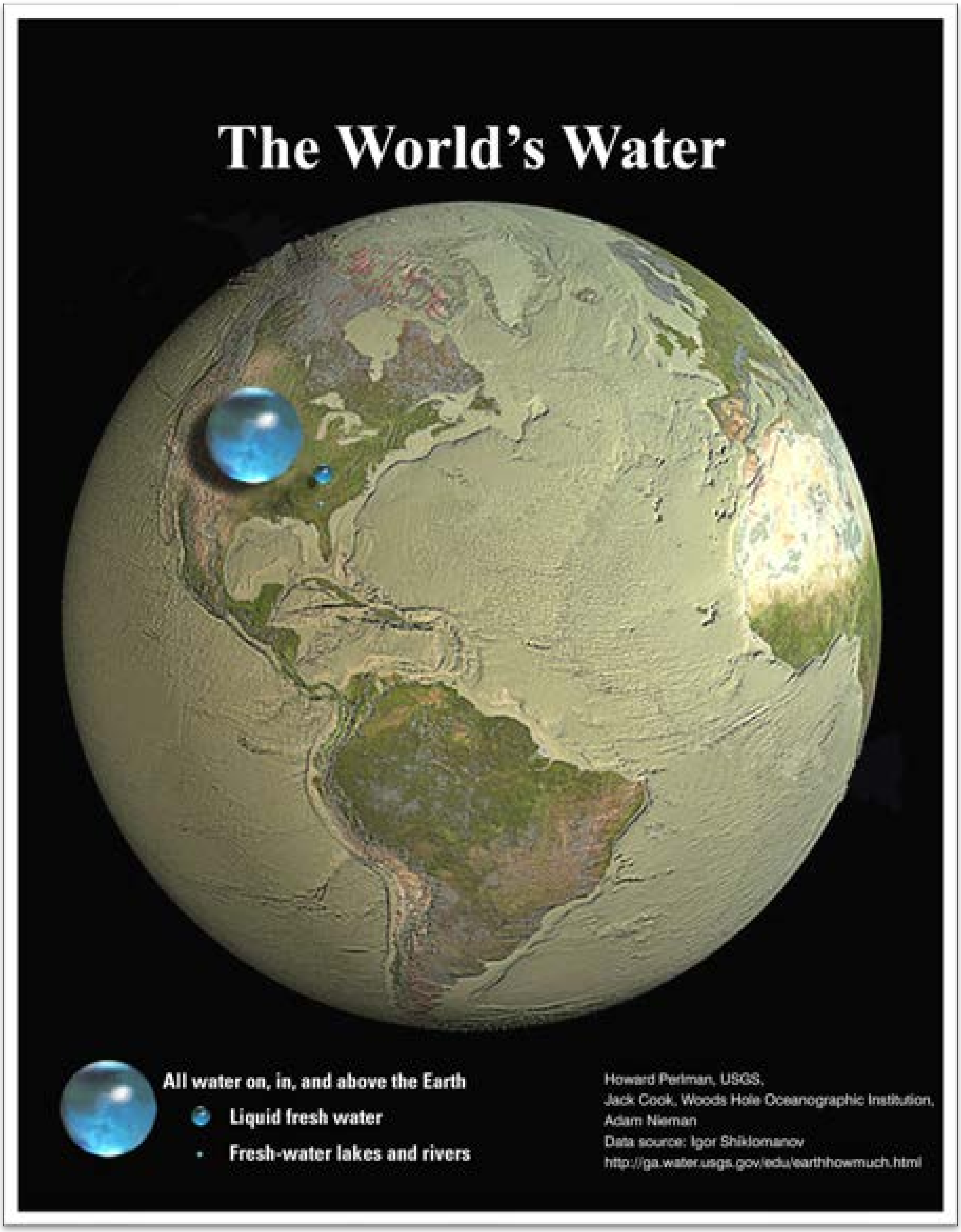
The Need for Water

For *Homo Sapiens* and for all life forms as far as we know, water is a necessity. Made of 2 parts of hydrogen, by far the most common element in the universe, and 1 part of oxygen, which is manufactured commonly in the death of stars even as small as our sun, water is common throughout the universe and it is certainly present, even common, beyond our Earth in our own solar system.

As NASA searches for signs of life on Mars, which incidentally is the only planet in our solar system inhabited solely by robots, NASA's mantra is to "follow the water". There is water on Mars and NASA hopes that there may be signs of life where the water is. Perseverance, the roving robot and its accompanying robot helicopter, Ingenuity, are seeking out signs of life in an ancient river delta and lakebed in Jezero Crater.

There are also perhaps billions of tons of water on our Moon in the form of ice. And Jupiter's moon Europa has a subsurface ocean that possibly has twice as much water in it than all of our oceans on Earth. Saturn's moon Enceladus also has a subsurface ocean that may hold as much water as the Great Lakes. And recently, NASA's Juno mission passed near Ganymede, the largest moon in our solar system, actually larger than the planet Mercury, and it is probable that Ganymede has a large subsurface ocean like Europa. Also, the asteroid belt that lies between the orbits of Mars and Jupiter is teaming with water and requires relatively little rocket fuel to go from the Moon and back.

So if we're going to build large rotating cylinders in space to live in, we're going to need water and that water *is* available in our solar system. But, first let's get a perspective look at how much water is here on the Earth.



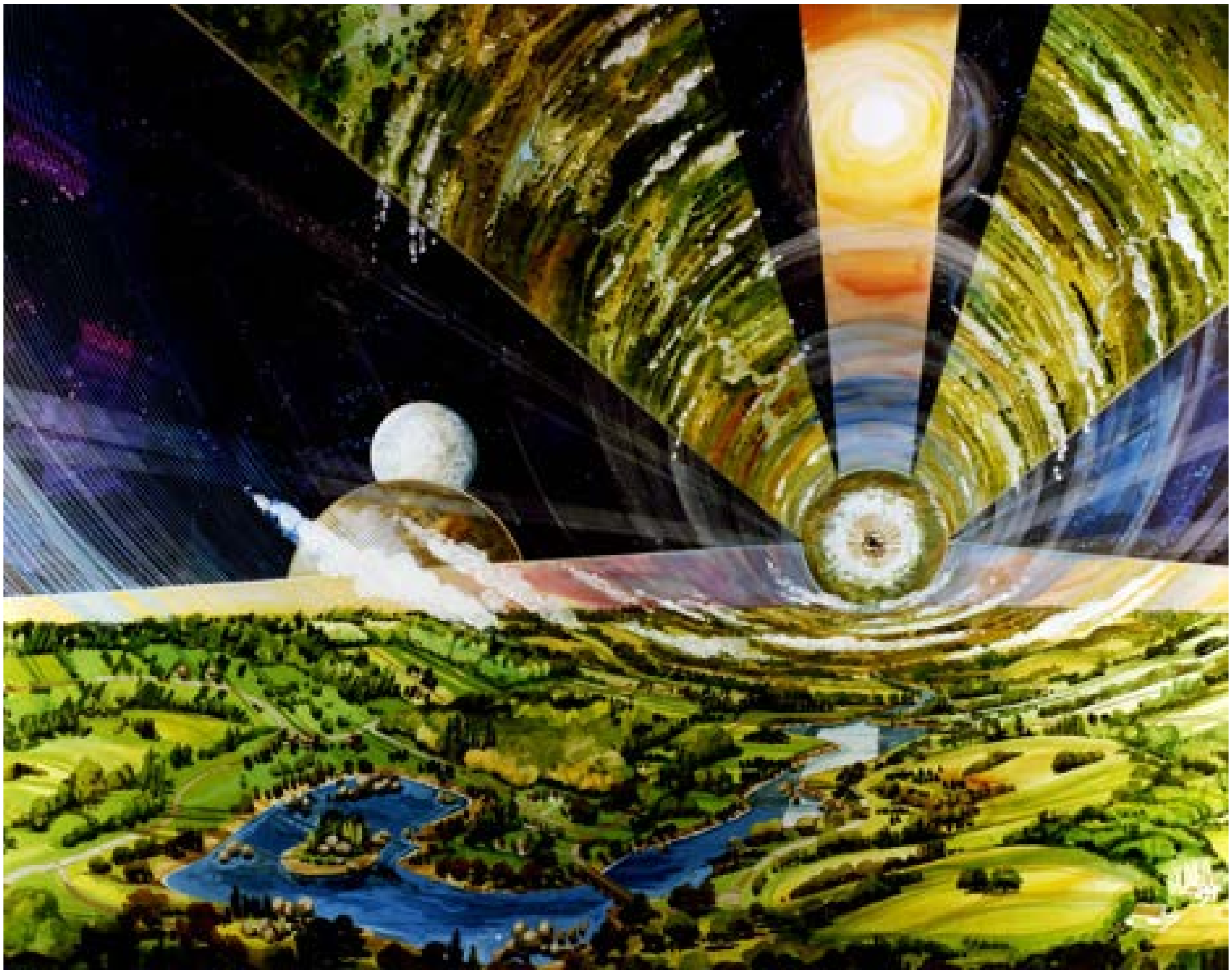
We all know that water is a very precious commodity on Earth. If all the water on the earth was removed and put into a sphere, the diameter of that sphere would be about 860 miles. In the illustration above, this is the large sphere covering about ⅓ of the continental US. ***That's all of the water on the planet!***

The smaller bubble that's sitting roughly over Kentucky, is all of the freshwater on the planet - 99% of which is underground and not readily accessible to humans.

The tiny bubble sitting approximately over Atlanta is the amount of water in lakes, rivers and streams, including all of the Great Lakes (which hold about 21% of all of the surface freshwater on the planet). This is the water that people use and need, and this sphere is only about 34.9 miles in diameter!

So, on Earth, there are around 220,000,000 gallons of fresh water potentially available for every person currently living. This translates into about 10,000 residential size swimming pools for every person alive. A ratio of fresh water per person like this would clearly not be attainable in an O'Neill Cylinder. However a far smaller ratio would still work if, and here's the important point, if we allowed the water to be treated with the natural, biological rhythms to keep it clean, pristine, pure, and alive, and we are not polluting it with chemicals.

The water systems in an O'Neill Cylinder, like the other systems needed for food and air, will be in a closed loop and recycling will be necessary. And that is exactly the same as it is on the Earth. The Earth is just a larger system, but its natural recycling systems have been abused by people on a small scale for thousands of years and on a now on a larger scale for hundreds of years, to the point where much of our fresh water is polluted and dead.



An O’Neill Cylinder interior provides a 20-mile vista. Children born here would think it totally normal to have “upside down” land areas overhead. Painting by Rick Guidice courtesy of NASA.

A pair of O’Neill Cylinders would have a total land surface area of approximately 314 square miles, which at a population density of 1275 people per square mile (which is about the density of where the author lives in suburban northwest New Jersey) would lead to a population of around 400,000 people. Allowing 60,000 gallons of fresh water per person, or about 3 residential size swimming pools yields 3.2 billion cubic feet of water in total or 535 million cubic feet of water for each of the 6 strips of “land” in the pair of O’Neill Cylinders. This water, in wetlands, ponds, lakes, rivers, streams and swimming pools,would be for recreational purposes, like boating, swimming, scuba diving and ice skating in the “winter”.

A Stanford Torus in winter. These space colonies are all large enough to have their own weather systems, with clouds, rain or snow and temperature control. Courtesy Bryan Versteeg, spacehabs.com

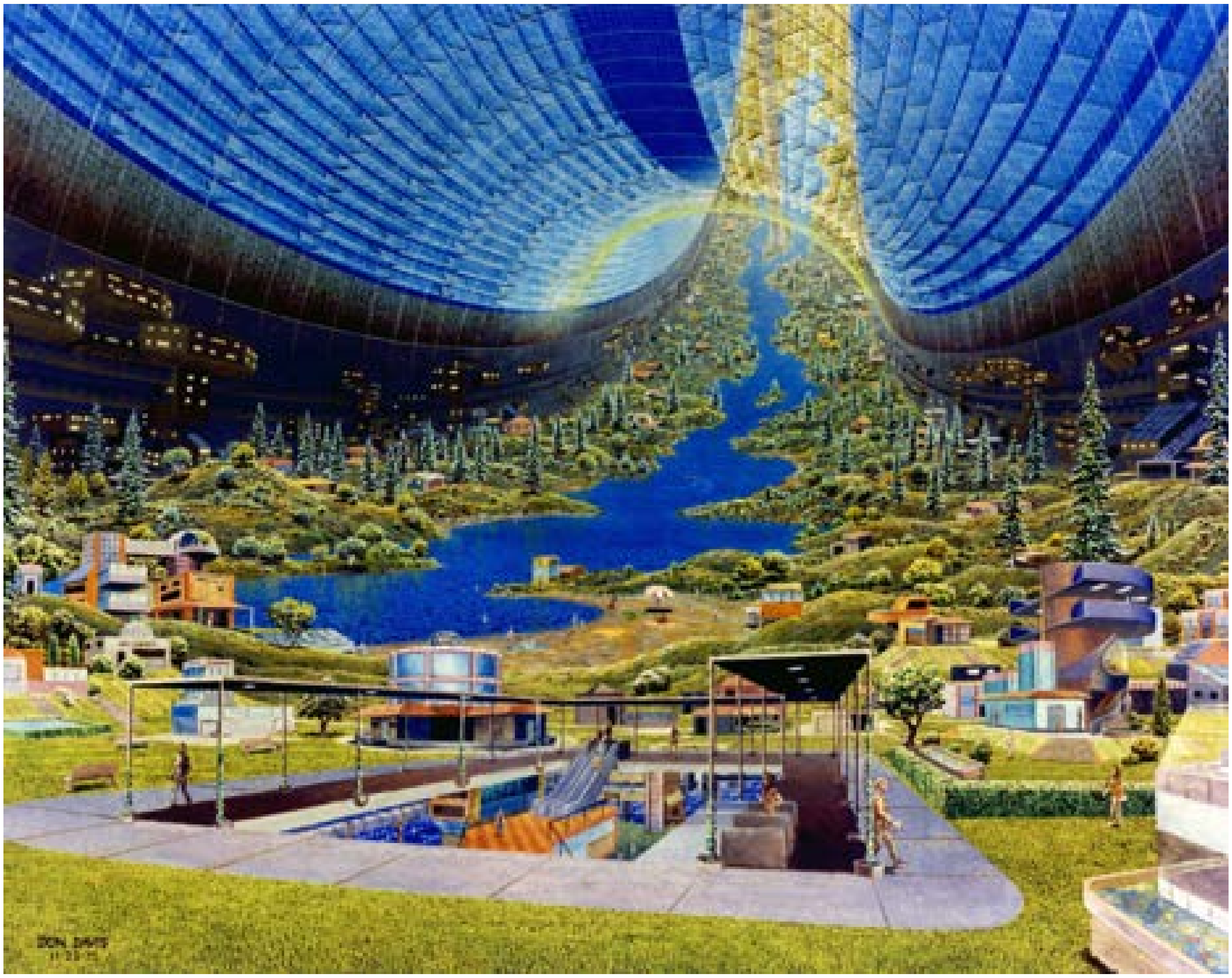
Each strip of land would have a central river or lake as well as ponds and streams feeding into the central lake. A 20 mile long lake or river that averaged being 10 feet deep would require an average width of around 535 feet in each 2.62 mile width of every strip of land in order to contain this volume of water per person. This would be clearly attainable.

A Stanford Torus in winter. Two colonies near each other could have different climates and residents could easily travel between them. Courtesy Bryan Versteeg, spacehabs.com

Treating the Water for Clarity and Purity

On Earth, prior to the Industrial Revolution, most fresh water on the planet was pristine. Water on Earth dates back at least 3.8 billion years and maybe even back to 4.5 billion years when the prevailing theory is that a Mars sized object impacted Earth and a large amount of Earth's material was ejected into orbit around the Earth and this material formed the Moon.

Over the billions of years of Earth's time, life eventually evolved and water was the key ingredient. With maybe the exception of perhaps the first appearance of liquid water on Earth, Earth's water has never been devoid of life. In fact, Earth's water always has been and continues to be teaming with life. And it is exactly for this reason, that the stability of the ecosystem surrounding water, has enabled Earth to be the cradle of all life as we know it.



A Stanford Torus design also with mountains, forests, trees and a central lake or river that flows around the entire torus. Painting by Don Davis courtesy of NASA.

Since the Industrial Revolution, much of our fresh (and salt) water has become polluted with chemicals that cause undesirable problems. This would need to be avoided on an O'Neill Cylinder and the natural ecosystem that evolved on Earth would need to be emulated or biomimicked in order to maintain water quality.

On an O'Neill Cylinder, we would want there to be a substantial ratio of fresh water per person and this water would need to be in environmental equilibrium, which is to say that we would need to use nature-based solutions for the water treatment. It would be very important for the recreational water in an O'Neill Cylinder to be "alive", i.e., to contain aquatic plants, phytoplankton, zooplankton and biofilm. Using chemicals or other artificial means to maintain water quality by killing everything in the water would be counterproductive and unsustainable.

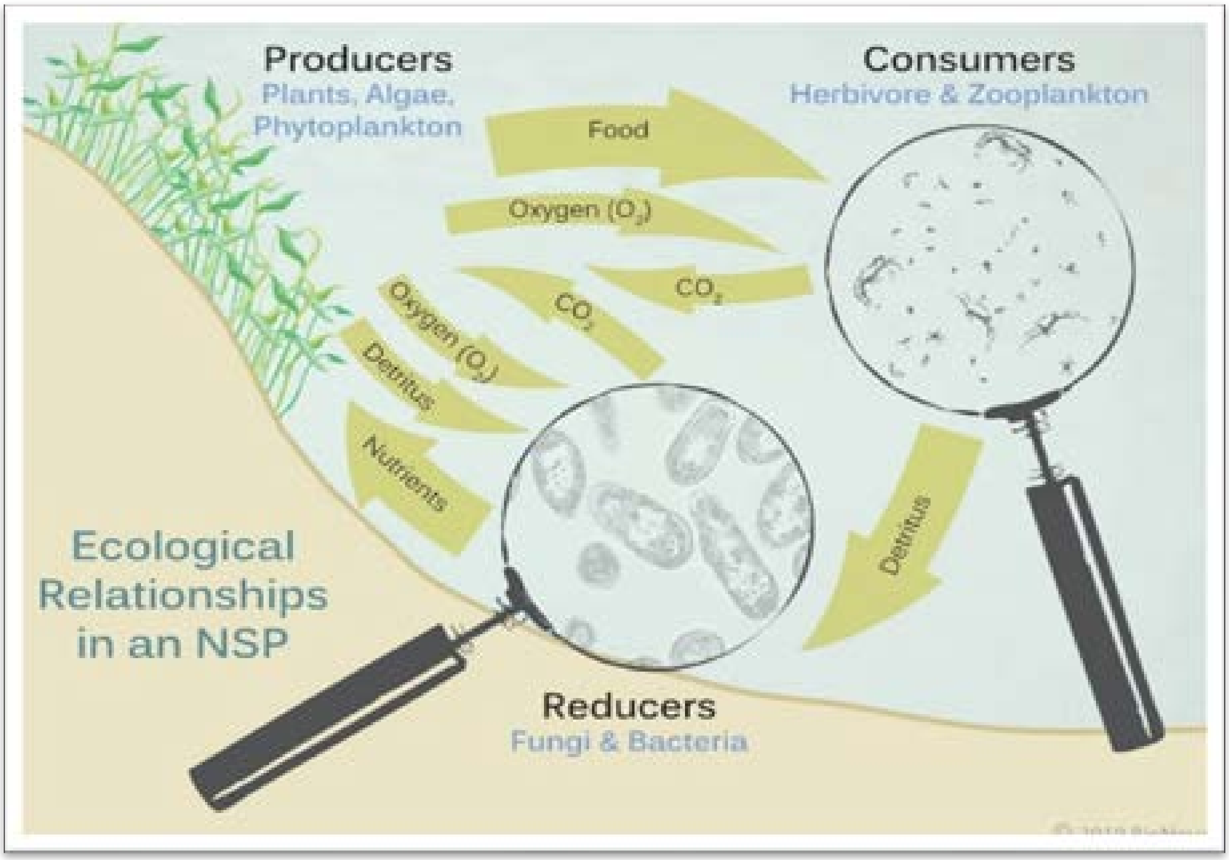
Terrestrial plants growing near the water will drop leaves and branches into the water. There will no doubt be some insects that are brought intentionally into the environment, like bees, that are needed to support the environmental cycles of plants. Earthworms may be sown into the environment to process the soil. Animals can also be introduced to make the environment more wholesome and to preserve biodiversity. Lions and tigers and bears – oh no! Chipmunks, squirrels, frogs, fish, otters, seals, dolphins and other species might be introduced and contained in certain areas. Alligators, crocodiles, piranha and poisonous snakes probably not! But dogs and cats of course will be our companions, even in space.

Limnology is the branch of science that concerns itself with the study of the biological, chemical and physical features of lakes and other bodies of fresh water. The limnologists will be very important citizens of the O'Neill Cylinders, chartered with implementing, monitoring and manipulating the fresh water systems on board. We cannot anticipate at this time what issues they will have with respect to the "source" water qualities that they bring on board from elsewhere in the solar system, but we do think that in the end, this water will need to biomimic the qualities of water on Earth.

Currently on Earth there are two different general types of nature-based water treatment methodologies for the implementation of treating isolated and contained bodies of water like swimming ponds and natural swimming pools which is effectively what the water vessels on an O'Neill Cylinder would be. The first is the sedimentation method, also called a "slow filter", which is the biomimicry of a lake or pond. The water is slow moving and the zooplankton and phytoplankon in the water are part of the nitrogen cycle that uses beneficial bacteria to reduce detritus by converting it into food for the plants living in the water.

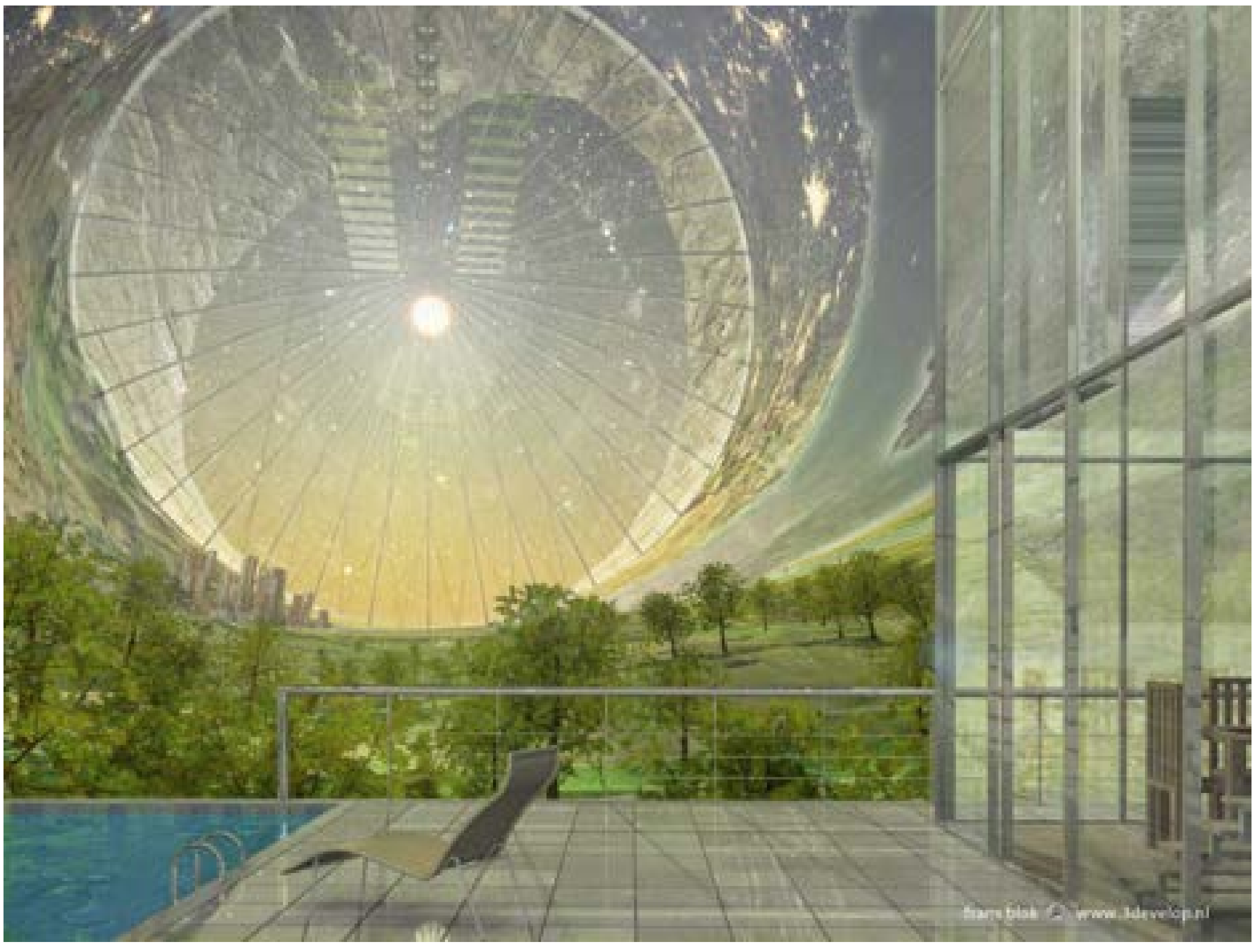
A Stanford Torus. It will be necessary for insects to be introduced into the environment in order to establish a stable habitat. Bees would certainly be needed, mosquitoes probably not! Painting credit Don Davis, NASA

Naturally purified water isn't manufactured, it gradually happens. What may seem like magic is simply crafting the right environment to nurture the growth of natural bacteria, thus creating microbial harmony. Producers like plants, algae, and phytoplankton, create energy for their own metabolic needs, as well as food and oxygen for others. This is a byproduct of photosynthesis (plants converting sunlight into energy). Consumers consume the gases and metabolic byproducts created by the producers and begin the breakdown of nitrogen. Reducers, like bacteria and fungi, feed on the remaining organic by-products, and this host of beneficial microorganisms multiply.



The Ecological Relationships in a Natural Swimming Pond. Large bodies of water in an O'Neill Cylinder would need to be in environmental equilibrium and clarified and purified through natural biological processes in order to be sustainable for thousands of years. Diagram courtesy BioNova Natural Pools.

These ecosystems occur naturally, but they do have some basic requirements. If provided with a surface on which to grow, this biotic community will form a biofilm. Biofilm is the result of free-floating microbes finding a spot to call home in the biological filter of the natural swimming pool. One of the key components of biofilm is the film itself. The film, called an Extracellular Polymeric Substance (EPS), encapsulates the community of organisms, providing protection from the elements and a means for the colony to capture nutrients and anchor to a suitable surface. This biofilm is home to numerous species of bacteria and fungi, each with a specific function and metabolic purpose. Imagine biofilm as a biological pantry—a sort of long term nutrient storage. An aquatic symphony of life sustenance emerges out of this microbial cycle. In faster moving aquatic areas like brooks, streams, rivers and swimming pools, this second type of treatment methodology, a biofilm filter, also called a “fast filter”, would be providing the clarification and purification of the water.



A residential swimming pool in an O’Neill Cylinder would be treated, clarified and purified, biologically. The introduction of chemicals to kill and oxidize everything in the water constantly would be undesirable, unnecessary and unsustainable. If chemicals were used, the subsequent release of chemicals into the environment during filter backwash, cleaning or splash out, would perturb and be harmful to the overall ecosystem of the colony. Drawing by Frans Blok, 3develop.nl

The ecosystems in an O’Neill Cylinder for maintaining the water quality would need to all work in harmony without mechanical intervention (other than solar powered pumps to move the water) or chemical intervention. (Solar power at an O’Neill Cylinder would be free and continuous.) Although these space colonies are large, from an ecological viewpoint they would be fairly small and any imbalance or perturbation pushing on their stability could have disastrous effects. And these colonies would require a huge investment, so we would want them to last for thousands of years with minimal input. In order to do that, natural solutions to the problem of maintaining water clarity and purity, would be the least expensive and most stable.

Two children enjoying a swim in a naturally purified stream in Freedom, Wyoming, USA in 2021. An environment like this needs to be preserved on Earth for the future and if we build colonies in space we need to build them to mimic Earth’s natural ecology to insure long term sustainability. Photo by Ryan Dorgan.

Will we ever build large scale space colonies like O’Neill Cylinders? It all depends on how long our species wants to, and is able to, remain. Earth is about 4.5 billion years old, of which our species has only been around for about 300,000 years. It’s only been in the last 2,000 years that we started to manipulate water, and less than 60 years since we flew to the moon. If we can avoid an extinction event in the next 2,000 years, that might be enough time to establish a High Frontier in space. The technology is actually already within our grasp. And the sustainable “technology” for the ecosystem on that High Frontier colony should be a natural one, based on life, based on being alive, just the way it evolved here on Earth. If we try to artificially control it through mechanical and/or chemical means, as we learned in the movie *Jurassic Park*, "life finds a way."

And since we think that a nature-based solution is the best choice for the environment on a High Frontier space colony, why shouldn't we move towards adopting the same nature-based solutions for problems here on Earth. After all, Earth is just a lower, bigger version of the High Frontier.

A constructed wetland on Kalpana One. Courtesy Bryan Versteeg.

On Kalpana One. Courtesy Bryan Versteeg