

Stern Habitat: Colonization of the Kuiper Belt With Current Technology

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Executive Summary:

This is a paper discussing the design, purpose, and operation of the *Stern* habitat, which orbits the Kuiper Belt object 486958 Arrokoth. The habitat is named after Alan Stern, who is the principle investigator of NASA's *New Horizons* mission. *New Horizons* flew by Arrokoth in January of 2019, providing a wealth of information on this object. This is one of the reasons why Arrokoth was chosen as the object for the habitat to orbit around, the others being its lack of abnormal characteristics, meaning that this design can be adapted to other Kuiper Belt objects fairly easily, as well as its low orbital eccentricity, meaning that its distance from the Sun does not change that much during its orbit. This is important, as the habitat relies on solar power for electricity. Solar power is used because this design only uses current technologies, with the exception of certain devices being slightly more efficient than available right now.

This design is quite detailed, and many important features, such as the size of the habitat, the amount of structural support in various sections, and the amount of area devoted to food production were calculated based off of other parameters, such as population and heat that must be radiated away, then made somewhat larger than strictly necessary to provide appropriate allowances. The auxiliary portions of the colony, such as reflectors and industrial areas, were also discussed in a large amount of detail. Other related subjects, such as trade and possible research opportunities near the colony, were also discussed.

The main aspect of this paper that stands out is that much of it is quite novel. To my knowledge, there has been only one academic paper published on the subject of colonizing the Kuiper Belt so far.¹ This also goes into a large amount of depth on the subject of processing material from Arrokoth, with a detailed composition estimate based off of many references and a description on how all of the different materials present would be processed. It also states what these different materials are useful for, and provides justification for why colonies in the Kuiper Belt would be quite profitable, producing many different goods.

There are also many novel ideas in this paper that can be applied to almost any habitat concept. There is a fairly detailed investigation of airflow and heat transfer inside of cylinders, although large parts of this are mainly conceptual. There are also several ideas on making the cylinders more pleasant places to live while also increasing the possible population density. Additionally, while many habitat concepts have auxiliary cylinders for agriculture and/or industry, in this design they spin more slowly to simulate reduced but still significant gravity, which makes many tasks easier while avoiding some of the difficulties inherent to zero-G environments

Overall, this is a detailed and fairly intricate design that explores colonizing areas generally ignored by many discussions about the possibility of colonizing different locations of space. While someone better educated than myself could definitely do a better job at exploring this subject, this is still a fairly good look into many of the issues and possibilities involving free-space habitats.

¹ Roy, K I, et al. "Colonizing the Plutoids: The Key to Human Expansion into the Galaxy." *Journal of the British Interplanetary Society*, vol. 66, 2013, pp. 318–327.

Why Colonize the Kuiper Belt?

The Kuiper Belt is essentially a larger version of the asteroid belt, with its inner edge 30 times as far from the Sun as the Earth, and no objects larger than Pluto and Eris reside in it. At first glance, it looks like a terrible place to colonize. The distance from the Sun means that its light is over a thousand times dimmer than at Earth's orbit, and solar panels will generate a

similarly miniscule amount of power in direct sunlight. It is so far from the inner Solar System that a radio signal from the Earth, Moon, or Mars would take many hours to reach anything in the Kuiper Belt, and the transport of goods and passengers from the inner solar system to a colony there would take several years at the absolute minimum with current technology. So why would anyone live there?

Despite these downsides, the Kuiper Belt has many advantages for colonization. Firstly, the distance from the inner Solar System can have many advantages. If a destructive war or disaster were to take place, habitats in sparsely populated areas far from the Sun would be more likely to survive than those densely packed near the Sun. The distance from populated areas would reduce the risks associated with research into nuclear bombs or similarly destructive technology (which can have peaceful applications which will be discussed more later), and the large distance between telescopes located in the Kuiper Belt would allow for the distances to other stars to be determined much more accurately via parallax than possible using telescopes located closer together. However, none of these are likely to provide enough motivation for extensive colonization by themselves.

The main reason why the Kuiper Belt is a fairly attractive target for colonization is the fact that it has a large amount of many different resources which are not at the bottom of a large gravity well. Its mass² is approximately fifty times larger than that of the asteroid belt³, and Kuiper Belt objects (KBOs) are much richer in volatiles such as water and ammonia than asteroids while still containing large amounts of useful silicate minerals and metals. The low temperatures of the Kuiper Belt means that many materials which would otherwise be too volatile to stick around on all but the largest objects closer to the Sun are still very abundant.

The most important of these materials is likely to be nitrogen. Nitrogen is extremely useful, and would be highly valuable to colonies in space. It is a major component of proteins, DNA, and many other substances in living animals. Nitrogen makes up almost 4/5ths of our air, and while people can survive without it, it is needed by many plants and microorganisms to synthesize the materials mentioned earlier. Additionally, most materials are very flammable in pure oxygen, which would be an extreme safety hazard for places intended for permanent human habitation. Nitrogen is also necessary for many plastics, including aramids like Kevlar®, which have often been proposed for use in free-space habitats due to their strength and low weight. It is also a major component of nearly all explosives and storable rocket propellants. While nitrogen-free propellants such as liquid oxygen and methane can be used, these must be stored at very low temperatures, and in cases where this is impractical storable propellants must be used. Additionally, there are many other, if relatively small, uses for nitrogen, such as in inert atmospheres to keep materials from oxidizing at high temperatures.

Nitrogen is extremely rare on many objects in the Solar System, as the substances it most often occurs in (diatomic nitrogen and ammonia) are quite volatile. Lunar regolith brought back by the Apollo missions is less than 0.01% nitrogen by mass, and almost all of that is from

² Pitjeva, E. V., and N. P. Pitjev. "Mass of the Kuiper Belt." *Celestial Mechanics and Dynamical Astronomy*, vol. 130, no. 9, 2018, doi:10.1007/s10569-018-9853-5.

³ Pitjeva, E. V., and N. P. Pitjev. "Masses of the Main Asteroid Belt and the Kuiper Belt from the Motions of Planets and Spacecraft." *Astronomy Letters*, vol. 44, no. 8-9, 2018, pp. 554–566., doi:10.1134/s1063773718090050.

the solar wind⁴, so anything below the very surface is essentially nitrogen-free. This is also likely true for Mercury and most other asteroids, although carbonaceous chondrites may contain a slightly higher amount of nitrogen. The atmosphere of Mars is 3% nitrogen by mass, but because it is much less dense than Earth's, this comes out to "only" about 650 billion metric tons of nitrogen in the entire atmosphere. This might seem like a lot, but if billions or even trillions of people eventually live in space, this would run out quickly. If nitrogen use was the same as global fossil fuel use (around 10 billion metric tons per year), it would only last for 65 years, so it cannot be a major nitrogen source in the long term. Additionally, if there was an attempt to terraform Mars, they would not export any nitrogen at all, and would likely have to import hundreds of trillions of tons of nitrogen in order to make an Earthlike atmosphere.

There are some possible large sources of nitrogen, but they all have problems. Earth's atmosphere is almost 80% nitrogen by mass, but launching material into space from the Earth is quite expensive, and even though the cost of spaceflight will almost certainly massively decrease by the time there are any large colonies in space this would likely still be an issue for bulk materials, where even a cost of \$10 per kilogram could add up to billions of dollars for large projects. Even if launching it from the Earth cost practically nothing, it might eventually be banned in order to keep the atmosphere from measurably changing, as even if it was too small to significantly change anything it seems likely that most people would oppose it. Additionally, colonies that became independent from Earth nations might not be able to easily trade with the Earth if their independence was not recognized internationally. Venus has even more nitrogen than Earth, as though its atmosphere is only around 3% nitrogen it is nearly a hundred times more massive than the Earth's atmosphere. However, it has nearly as much gravity as Earth, and has no industrial infrastructure to use for exporting nitrogen. Building any industry on Venus would be very hard, due to the extreme temperatures at the surface. The gas giants have large amounts of ammonia, but they have very deep gravity wells and no surface to build on or extract minerals and metals from, so it would probably be impractical to get nitrogen from them.

Probably the best sources of nitrogen other than the Kuiper Belt would be Ceres and the large moons of gas giants, such as Titan or Callisto. Ammonia-containing minerals have been detected on the surface of Ceres, and the hypothesized subsurface oceans of those large moons may contain ammonia. Titan also has a thick atmosphere which is nearly all nitrogen, with only a few percent of methane and other hydrocarbons in it. Neptune's moon Triton has very large amounts of pure nitrogen ice on its surface, but it is so far from the Sun that it can be considered part of the Kuiper Belt for the purposes of this paper. In fact, a popular theory for Triton's origin is that it was originally a Kuiper Belt object like Pluto before being captured by Neptune. However, these all have problems. The amount of ammonia in these moons is unknown and may be quite small, and the surface of Titan has even less sunlight than the Kuiper Belt because its thick atmosphere blocks almost all light, meaning that there is no easy source of energy there to use for industry. It would also be possible for the export of nitrogen to some or all colonies from these locations is impossible, either because life is discovered in their subsurface oceans or, more likely, they come under the control of states or other organizations which refuse to trade with certain other groups, as on Earth. Additionally, while much less bad than in the case of larger planets, cargo would still have to be moved out of both their gravity

⁴ Marty, B., et al. "Nitrogen Isotopes on the Moon: Archives of the Solar and Planetary Contributions to the Inner Solar System." *Space Science Reviews*, vol. 106, no. 1/4, 2003, pp. 175–196., doi:10.1023/a:1024689721371.

well and, in the case of moons, the planet they orbit before being sent to other destinations. In contrast, small KBOs have almost none of these issues. They have no significant gravity well, are too numerous to all fall under the control of a small number of groups, and have large amounts of nitrogen, as well as many other materials.

The main issue colonies in the Kuiper Belt would face is a lack of energy. If fusion power becomes practical, this would no longer be an issue, but in this case it cannot be used, as this design only uses currently available technologies. Therefore, the only really practical source of energy is sunlight. At the average distance of Arrokoth from the Sun, sunlight is nearly 2,000 times dimmer than at Earth orbit, with an irradiance of about 0.68 watts/square meter. However, concentrating this light is very easy. The almost total lack of forces due to gravity and wind means that very good reflectors can be made from thin, light foils with little structural support. Additionally, the irradiance at Earth orbit is nearly 10 times higher than the average on Earth's surface, meaning that the area needed for reflectors is really only about 200 times the area illuminated at the same intensity as Earth.

The time required for travel between the Kuiper Belt and the inner Solar System will still be quite long, but it can be reduced by several times compared to the time it took for *New Horizons* to reach Arrokoth (about 13 years), even with current technology. *New Horizons* had an extremely limited amount of delta-v, which is the amount a spacecraft can change its speed by before running out of fuel, because it used inefficient chemical rockets and therefore had to use an efficient, but slow, trajectory. Ion propulsion, which is used by many other spacecraft such as the *Dawn* probe, is much more efficient than chemical rockets, allowing faster but less efficient trajectories to be used. The main problem with ion propulsion is that it requires large amounts of electricity, but this can be supplied using either solar power concentrated by mirrors or nuclear reactors. The low thrust is not a major issue, as travel times would still be quite long. This is discussed in more detail later in the paper.

From all of this, it is clear that the Kuiper Belt is a surprisingly promising target for colonization, despite its drawbacks. The first true settlement in space will certainly not be located there, nor in all likelihood will the hundredth, but in the long term it will be absolutely crucial for providing volatiles and other goods to other free-space settlements. In the very long term, the simple fact that it contains so much material relative to the Asteroid Belt means that it may actually become the home of a majority of humanity, although predicting things that far ahead is almost certainly futile.

Habitation Cylinder Overview and General Requirements:

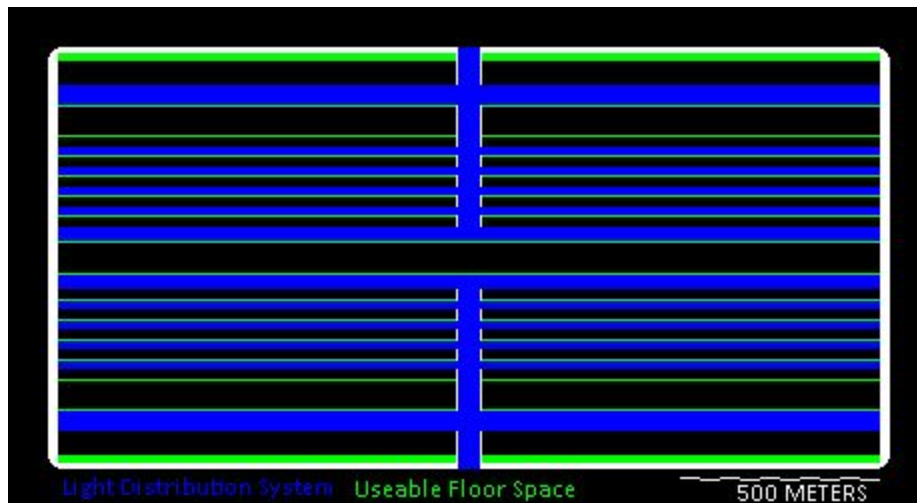


Diagram showing the general layout of a habitation cylinder.

There are four habitation cylinders, with the “ground” averaging at a radius of 500 meters, and the edge of the habitat’s hull at a radius of 525 meters. Each cylinder is split into two halves, each one kilometer long, with a 50 meter strip between them for light to pass through, and a 25 meter long section at each end which has no “ground” area. To generate an apparent acceleration of one G at this radius, the cylinder must rotate at 1.337 rpm. To more closely imitate a natural landscape by hiding the fact that the cylinder is curved, the ground is very hilly, with the highest hilltops only being 485 meters from the center and the deepest valleys at 515 meters. To save on mass, the hills will not be heaps of dirt but just a thin layer on top of a shell held up by structural elements. This also lets us use underground areas without having to excavate it out. Between these extremes, apparent gravity ranges between 0.97 G and 1.03 G, within three percent of Earth normal and almost certainly close enough to avoid health effects. In order to prevent a net torque being exerted on the superstructure, two of the cylinders rotate clockwise and two rotate counterclockwise, so that the torque they exert on the superstructure cancels out.

In order to decrease the apparent clutter on the surface, most indoor spaces will actually just under the surface of the ground. Ideally, the population density will be 100 square meters of Earth gravity surface per person, although due to belowground areas the total amount of living space at one gravity per person will be at least four times higher than this, and food will mostly be produced elsewhere so this figure does not include space used for agriculture. Each half-cylinder has 3.14 square kilometers of ground area, but with the area of lakes subtracted from this we have 3 square kilometers of useable land per half-cylinder, for a population of thirty thousand people per half-cylinder. With three of the cylinders being used for residential area, the habitat has a total population of approximately 180,000.

The habitat does not have a clear view from one side to the other. A translucent cylinder with a radius of 425 meters is positioned above the ground, which provides many functions. It

scatters light bounced in by the mirror system, moderates air movements, dehumidifies air, creates simulated rain, and simulates the sky. It might seem complicated to simulate the sky even somewhat convincingly, but in this case it merely consists of sheets of blue transparent plastic cut out in shapes that look like the sky surrounding white clouds.

Structural Requirements:

The habitat needs to be strong enough for the forces of its rotation and its internal pressure to not tear it apart. This requires structural support acting against both of these forces. As in the paper which contained the first ever detailed report on this type of habitat by O'Neill⁵, two main types of support will be used - circular rings around the axis of rotation to support the force of spin “gravity” and longerons that counteract the outward force of pressure. There are two main differences between this design and most others in the area of structural support. Firstly, cables of PBO (poly-p-phenylene-2,6-benzobisoxazole, also known as Zylon®) are used as the main supports instead of steel or titanium. Secondly, an issue is caused by the central band for the light distribution system. If the longerons went through here, they would block much of the light. Therefore, they avoid this area, only wrapping around each half instead of the whole cylinder. The glass still needs some structural support, but this is much smaller because it only has to deal with the forces acting on the glass instead of the whole habitat, and can therefore be thin enough to block a negligible amount of light. The center of the cylinder in this area is not part of the light distribution system, and does not have to worry about light. Therefore, it can be quite strong and stiff, which would be necessary to stop the two halves of the cylinder from wobbling around it.

Pressure is the easiest to calculate, as we do not need to know how much everything weighs to calculate how much force pressure exerts on the sides of the cylinder. As it is quite small, the pressure stays constant throughout the entire structure, unlike larger habitats that are large enough for the pressure in the center to be significantly lower in the center than on the “ground”. As it is meant to imitate the Earth as closely as possible, the atmospheric pressure is 100 kilopascals. One pascal is equal to one newton per square meter. A longeron wrapping around a cylinder 1,025 meters long and 525 meters in radius will be 4.15 kilometers long, but one face will be facing the light distribution system, which is pressurized to the same level as the rest of the habitat and is therefore under no net force. While the total length of the longeron will stay the same, we only have to factor in the force acting on 3.1 km of it. If 180 longerons are distributed evenly around the half-cylinder, each one will have to hold up a 9.16 meter strip on each side.

This gives us an area of 23,587 m² that each longeron must support, which comes out to 2.36 giganewtons. PBO has a tensile strength of 5.8 gigapascals⁶. From this, we can see that the absolute minimum diameter of a longeron is 72 centimeters. There are multiple factors that both increase the actual size of the longerons. Firstly, the threads that make up the cable are not perfectly packed together. If 25% of the cable is empty space, our diameter increases to

⁵ The Colonization of Space – Gerard K. O'Neill, Physics Today, 1974

⁶ “ZYLON® Fiber Properties.”, Toyobo Industrial Materials, 2015, www.toyobo-global.com/seihin/kc/pbo/zylon_bussei.html.

80.4 centimeters. This has the cable at its ultimate tensile strength, which is not optimal for several reasons. Firstly, even one cable snapping would result in the whole structure disintegrating, and secondly, many materials will slowly deform if held at their ultimate tensile strength for a long time. Therefore, the cables must be larger than this to ensure an appropriate margin of error. With a safety factor of 55%, which will have the cables be under much less stress than their ultimate tensile strength even if thirty of them snap, each cable is a meter in diameter.

We have not addressed the issue of “weight” caused by the spinning of the cylinder. Each level only needs to support its own weight, and no pillars need to go up from the “ground” to hold them up. This is because all levels are complete cylinders rotating around the same axis, and therefore the “weight” of any part of the cylinder is canceled out by the “weight” of the section opposite to it, resulting in no net force being exerted on the cylinder. However, it still needs to be strong enough to support the “weight” of itself, or else it will fly apart. The “ground” level is subject to the strongest forces by far, as it has much more mass per square meter than any other level, is under the strongest “gravity”, and has the largest circumference. To find the amount of force acting on each square meter of ground, we need to know how much mass is pushing on it.

	Thickness (cm)	Density (g/cm ³)	Weight (kg/m ²)	Notes
Dirt	200	1.5	3000	Average, includes mass of water.
Hull	5x2	2.7	270	Two layers, 6061 Al
Longerons	8.57	1.18	101	Average
Flooring	3x3	2	180	Average of three underground floors
Support for dirt	5	2.7	135	6061 aluminium alloy
Ring cables	3.12	1.18	37	Average
Other (furniture, people, ect.)			500	Estimate
Total			4223	

The ring cables circle around the axis of the cylinder, and therefore are as long as the circumference of the level they are on. If each cable holds up a five meter wide strip of “ground,” then each cable on the ground level has to hold up 16,493 m² of ground, or metric tons of weight. This gives us a minimum cable thickness of 43.2 centimeters. A safety factor of 55% gives us a cable 54 centimeters thick. The cables for other levels will be much smaller, due to other levels having much less mass, experiencing less “gravity,” and having a smaller radius (meaning each cable will be shorter and therefore have to hold up less weight).

Heat disposal and Light Distribution:

Distance from center (meters)	Apparent gravity (g)	Area (km ²)	Total light energy received (MW)
500	1	6.28	251.3
375	0.75	4.71	188.4
300	0.6	3.77	40
250	0.5	3.14	7.85
200	0.4	2.51	6.275
150	0.3	1.88	4.7
100	0.2	1.26	3.15
30	0.06	0.38	0.95
Total energy for lighting			502.6
Power generation (200 MW electricity, 25% efficient)			800
Losses due to absorption on mirrors (20%)			325.7
Total energy per cylinder			1628.3

The disposal of waste heat is a serious concern for objects in space. In space, objects can only cool down via radiating heat. This limits the amount of energy that the habitat can receive. While on first glance it looks like each cylinder can receive 1.759 gigawatts of energy, in reality this is an overestimation. Unless the entire structure conducts heat perfectly, which it does not, the middle will be hotter than the outside due to light being reflected into the center while heat only slowly diffuses to the outside of the structure. If the outside is at 25 C, already near the hotter edge of room temperatures, the inside would be uncomfortably hot. This is avoided by decreasing the amount of energy received to 1.628 GW, covering the outer hull with a coating that has an emissivity larger than 0.9, and using the systems described in detail in the section on climate control to spread heat around the habitat as much as possible so the middle is not much warmer than the surface. This also allows the temperature to be adjusted somewhat by turning some of the climate control systems off or on in order to control how much warmer the center of the habitat is than the surface.

The habitats are lit by direct sunlight, which is distributed throughout the habitat by a system of mirrors. Although this complicates the design by requiring lots of mass and space to be devoted to bouncing light to where it is required instead of using LEDs, it is still much better than that option due to not having to deal with the inefficiency of converting light into power, then back into light. As our solar panels are 25% efficient at converting sunlight to electricity,

slightly better than the best commercially available solar panels⁷, and the best LEDs are about 50% efficient at converting electricity into light⁸, using LEDs for lighting would only be 12.5% efficient, the remaining 87.5% of incoming sunlight being converted to heat. This would reduce the amount of lighting we could use for our habitat by a factor of eight, which would make the agricultural productivity and supportable population much lower. Therefore, using direct sunlight for lighting is the only viable option for the habitat, even though it requires a complicated light distribution system.

Light is concentrated and reflected to the habitats by parabolic mirrors, then passes through filters in the superstructure to block harmful ultraviolet light and mostly useless infrared to decrease the amount of heat that needs to be radiated away without decreasing the amount of visible light, but we have not covered how this light will be distributed around the habitat after it comes in. All of the light has been focused by the mirrors onto a narrow band only 50 meters wide when it reaches the hull of the habitat. As the mirrors are so far away relative to the diameter of the habitat, this size should stay pretty constant for the rest of the journey through the habitat.

This 50 meter wide strip goes through almost all of the habitat, stopping only 50 meters from the center so that light is provided to all major levels. Most of the light is used for power generation and lighting the “ground” level and agricultural level of the habitat, but all levels are lit by sunlight. The reason that these two levels use so much more sunlight than the others is that they are lit at a much higher intensity (40 watts per square meter for the ground and agricultural levels, while only about 11 watts per square meter for the 300 meter radius level and 2.5 watts per square meter for all other levels).

The largest light distribution system is 50 meters deep, taking up the space between 375 and 425 meters from the center. It lights both the ground from above and the solar panels that generate electricity for the habitat, as well as the agricultural level, from below. The ground gets an illumination of 80 watts per square meter (7440 lux) during the “day,” for a 24-hour average of 40 watts per square meter. While this does seem much lower than the solar irradiation at Earth orbit, due to Earth being a sphere and not a flat plane facing directly at the sun, absorption of sunlight by the atmosphere, ect. the global average sunlight is 164 watts/square meter. As our light has been altered to contain 80% of its energy in the visible range instead of 40% in natural sunlight by the filters it passed through in the superstructure, which will be explained in more detail later, the amount of visible sunlight at the ground is reasonable for the partly cloudy simulated sky. The solar panels are lit with a total of 800 megawatts of sunlight, corresponding to 200 megawatts of electricity. With a per capita power consumption of 3.5 kilowatts, 180 megawatts are used for residential and industrial purposes while the remaining 20 megawatts are used for powering the fans and refrigeration/condensation systems used for climate control.

⁷ “Solar Panel Efficiency.” *Solar Panel Efficiency*, Solar Learning Center, www.solar.com/learn/solar-panel-efficiency/.

⁸ GmbH, DIAL. “Efficiency of LEDs: The Highest Luminous Efficacy of a White LED.” *Efficiency of LEDs*, DIAL, 3 Feb. 2020, www.dial.de/en/blog/article/efficiency-of-ledsthe-highest-luminous-efficacy-of-a-white-led/.

The agricultural level at 375 meters radius has a total area of 4.71 square kilometers, and is all lit at a daily average of 40 watts per square meter, which requires 188.4 megawatts of light. It is used to grow crops that provide food for the habitat, as well as recycle oxygen for the habitat. Agriculture here would have very high yields compared to most farming on Earth because of control over temperature, light, day length, the absence of pests, ect. Complex plants need a day/light cycle, so we will assume that the average light level in these areas is the same as the ground - 80 watts/square meter during the “day,” with a 24-hour average of 40 watts/square meter. This isn’t synchronized across the whole cylinder, as different plants do best with different day/night cycles.⁹ The light distribution system for this level is probably the most complex, with different sections being lit on vastly different schedules. It is located just under the floor of the 300 meter level, making up most of the volume at a radius of between 310 and 325 meters from the center.

The 300 meter radius cylinder is mostly parks and public areas to supplement those on the “ground.” It is lit at an average of 10.6 watts per square meter, lower than optimal for intensive agriculture, but still bright enough to support many plants. It has a day/night cycle, unlike the other low-gravity cylinders, in order to support plant growth.

There are several layers lit entirely at 2.5 watts/square meter. These are located at a radius of 250, 200, 150, 100, and 30 meters from the center, with a total area of 9.17 square kilometers and a lighting requirement of 22.9 megawatts of light energy. As the amount of light entering the cylinder is constant, we can also use it to light large spaces close to the center, avoiding the inefficiency of converting light to electricity and then back to light. With our tailored light spectrum, 2.5 watts/square meter is equivalent to 465 lux, a level of illumination common in schools and classrooms¹⁰. As the two halves of the cylinder have day/night cycles offset by 12 hours, people will be using these spaces around the clock, so they will be lit consistently.

The light distribution system for the 300, 250, 200, and 150 meter radius levels are all pretty much the same, stretching from below the floor of the level above. Even though the 300 meter level gets much more light than the others in this list, due to both being larger and more brightly illuminated, it would be very hard to make the light distribution systems less than 20 meters thick. At this size, light heading from the central band to the edge of the habitat would be moving downwards at less than a 2 degree angle. At a smaller size, this would get so small that any imperfections could lead to some spots getting no light at all or too much light.

Both the 100 meter and 30 meter radius levels are lit by the same light distribution system. This is to avoid having stuff in the very center of the habitat. This means that the 30 meter radius level will be lit from below. The light distribution system takes up the space between 30 and 70 meters from the center, and it shares this space with structural supports that keep the two halves of the cylinder from flexing around the narrow “waist” between them.

⁹ “How to Manage Your Indoor Garden's Dark Cycle.” *Safer® Brand*, Safer® Brand, www.saferbrand.com/articles/light-dark-cycle.

¹⁰ 1926.56 - *Illumination*. | *Occupational Safety and Health Administration*, United States Department of Labor, www.osha.gov/laws-regs/regulations/standardnumber/1926/1926.56.

If we just reflected the light so it was spread evenly across the habitat, it would still look very concentrated, uneven, and harsh. This is okay for the solar panels and agricultural areas, but is unacceptable for areas meant for human habitation. This can be solved by having the light go through a material that scatters light without absorbing much of it, such as frosted glass. For the ground and 300 meter levels, there would be another layer of frosted glass below this, mostly white but with some bluish areas to simulate a mostly cloudy sky. The blue areas would have to absorb some red and green light for them to be blue, which is why the blue areas are as light and small as possible without ruining the illusion.

Life Support and Waste Disposal:

The most important needs for a person are air, survivable temperatures, water, and food. A lack of air will kill in minutes, extreme heat or cold in hours, thirst in days, and starvation in weeks. Clearly, we need to make sure that these are always abundant enough to avoid death. But for people to actually want to live in a space colony, these items need to be provided in excess. Very few people would like to live permanently on a habitat where the air was always stale, it was always either boiling or freezing, you were fed barely enough gruel to survive, and you could only shower once a month to conserve water. Fortunately, it is very easy to provide the inhabitants with a quality of life better than that on Earth in many respects.

Plants produce both oxygen and food using carbon dioxide, water, light, and nutrients such as nitrogen and phosphorus. Carbon dioxide is produced by people and animals in the habitat, water and nutrient recycling will be discussed later, and light is already being supplied in abundance. There is enough room on the agricultural levels to grow more than enough food for all the people and livestock in the colony. We also have the benefit that only three of the four habitation cylinders are heavily inhabited, while all of them have agricultural layers. According to Bubenheim et al¹¹, to recycle all of a person's carbon dioxide and provide them with oxygen requires less than seven square meters of crops, at the yields in the paper. Crop yields will be extrapolated from the paper, as the circumstances are different. While both are related to life support in space, our habitat is on a much larger scale, and also does not have nearly as high carbon dioxide levels as in the paper. Therefore, we will assume yields only half as high for our agricultural areas, with the exception of soy. Soy yields seem very low relative to wheat in the paper compared to soy vs wheat yields in normal farming, and there was much less focus on making soy grow well in the study compared to wheat. We will therefore assume that soy has a yield a third that of wheat, in comparison to yields half those of wheat in most farming.¹² Rice and corn were not mentioned in the paper, but we will assume that they have yields the same as that of wheat, which lines up pretty well with data on real-world agricultural yields.

Per m ² per day	Total yield (g)	Total yield (kcal)	Protein (g)	Fats (g)	Carbs (g)
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¹¹ Bubenheim, David L. "Plants for Water Recycling, Oxygen Regeneration and Food Production." *Waste Management & Research*, vol. 9, no. 1, 1991, pp. 435–443., doi:10.1177/0734242x9100900162.

¹² Ritchie, Hannah, and Max Roser. "Crop Yields." *Our World in Data*, 17 Oct. 2013, ourworldindata.org/crop-yields.

Wheat	30	98	3.8	0.5	21.3
Rice	30	98	2.1	0.2	24.0
Corn	30	98	2.8	1.4	22.2
Soy	10	44	4.0	2.2	3.3
Potatoes	15	23	0.3	0.0	4.8

To demonstrate that we have more than enough agricultural capability for our colony, the minimum amount of area to grow different staple crops will be calculated. This is not the diet our colonists would eat. It would be very bland, and probably wouldn't be very healthy either. Its purpose is to show the minimum amount of agricultural area we need to stop our colonists from starving. As we have almost twice this amount of area dedicated to agriculture, less efficient but more varied options can be used.

The recommended amount of nutrients for an adult human are about 2500 kcal/day, 250 g carbohydrates/day, 55 g protein/day, and 45 g lipids/day.¹³ There is no mixture of these crops that can satisfy all of these requirements. If we change the diet to be more like the typical American diet, with 300 g carbs and 85 g protein while keeping the amount of lipids the same, we do get a solution, but it is a very inefficient one that is not likely to be very good to eat. These crops just don't provide enough lipids to be useful on their own. One solution would be growing lots of crops that are high in fat, such as avocados, but a better one is farming animals. Many types of livestock basically convert carbohydrates into lipids and vegetable proteins into tastier meat, eggs, and milk, but this is at the cost of wasting much of the energy in the food they eat. Still, this is a viable option.

A dairy cow that produces milk will eat about 10 kilograms of protein and 20 kilograms of carbs a day, producing 120 liters of milk.¹⁴ This milk contains 3.8 kilos of protein, 4.7 kilos of lipids, and 5.8 kilos of carbohydrates. Assuming the cow isn't in peak condition all the time and only makes 60 liters of milk a day, to make 500 kcal of milk a day requires 2.3 square meters of area for wheat and 22.9 square meters of area for soy for cow feed. When drinking 500 kcal of milk a day, a person can get the rest of their daily requirements for calories, carbs, protein, and lipids from 13.5 m² for wheat, 5.6 m² for corn, and 2.3 m² for soy. If everyone ate this diet, the entire population of the colony could get by with 9.6 square kilometers of farmland. The total area of the agricultural levels in all cylinders is 18.9 square kilometers, almost twice the minimum. This means that the colony will not really have to worry about conserving their food

¹³ "Nutrient Recommendations: Dietary Reference Intakes (DRI)." *NIH Office of Dietary Supplements*, U.S. Department of Health and Human Services, ods.od.nih.gov/Health_Information/Dietary_Reference_Intakes.aspx.

¹⁴ Herdt, Thomas H. "Nutritional Requirements of Dairy Cattle - Management and Nutrition." *Merck Veterinary Manual*, www.merckvetmanual.com/management-and-nutrition/nutrition-dairy-cattle/nutritional-requirements-of-dairy-cattle.

supply, and they will be able to have a much more varied and healthy diet than what was used in this example.

So, we have enough food and oxygen, but what about water and nutrients for plants? This ties in well with the issue of waste disposal. Surprisingly, while real life waste disposal involves both bodily wastes and trash in general, only the former is often discussed in relation to space habitats. While this makes sense for small scientific outposts with only a few astronauts, a full-fledged colony will be producing trash on the scale of a city. We will start with discussing sewage treatment. In many aspects, it would be the same as on Earth, with the only real difference being disposal of sewage sludge. Two common methods for dealing with sludge, landfilling and incineration, are not practical. There isn't enough space for landfilling inside the habitat, and the amount of pollution created by incineration inside the habitat would be very bad, as it is a small, enclosed area. Just throwing it out into space would cause all the substances that are inside it - including large amounts of elements such as phosphorus, potassium, and chlorine that are necessary in large amounts for humans but only occur in low concentrations in KBOs.

The best waste treatment method for both sewage sludge and normal trash is probably wet oxidation. Wet oxidation involves heating the waste with water to 200-300 degrees Celsius while under pressure so the water doesn't boil.¹⁵ When air or pure oxygen is injected into the mixture, it dissolves and reacts with organic components of the mixture. Almost all organic substances are converted into either carbon dioxide or simple carboxylic acids such as acetic acid under these conditions. However, the conditions are much milder than in a flame, so no smoke or nitrogen oxides are formed, and nutrients remain in a bioavailable form, such as ammonium or nitrate ions, instead of being converted into an unreactive form such as nitrogen gas or vaporized and blown away in the smoke. This mixture can then be used to fertilize crops. As the oxidation reactions are exothermic, not very much energy is required to keep it at the required high temperature. Almost all trash that cannot be treated by wet oxidation, such as scrap metal, is easily recyclable.

Water recycling is fairly simple, and mimics the natural water cycle on Earth. The liquid from the wet oxidation treatment is used to irrigate the plants in the agricultural areas, as well as supply them with nutrients. Although carboxylic acids are weak acids and only occur in a low concentration in the liquid, the pH still might be too low for some plants. If this is a problem, bases such as ammonia, calcium hydroxide, or potassium carbonate can be added to the liquid, neutralizing the acids while adding even more nutrients to the liquid. This water will slowly be evaporated into the air via transpiration from the plants, where it is condensed by the climate control system.

Climate Control:

Without a climate control system, there would be many problems. Water vapor would build up in the air until humidity got to 100%, at which point it would start forming dew on every surface in the habitat. In addition to the problems caused by everything being wet, the high humidity would also be very uncomfortable to live in. Hot air would also rise into the middle of

¹⁵ Tungler, Antal, et al. "Wet Air Oxidation of Aqueous Wastes." *Wastewater Treatment Engineering*, 2015, doi:10.5772/60935.

the habitat, where it would have nowhere to radiate away its heat and will stay there for a very long time. Even if it did start to cool eventually, apparent gravity in the middle of the habitat is so low that it would fall back to the ground very slowly. This issue is addressed even less commonly than heat rejection, but it has been pointed out several times.¹⁶ Fortunately, this habitat has a climate control system that deals with this issue.

The climate control system runs off of electricity produced in the habitat. Earlier, it was determined that the maximum amount of electricity that could be produced without going over our energy budget was 200 megawatts per habitat. With a population of 60,000 per habitat and a per capita power consumption of 3 kilowatts, this leaves us with 20 megawatts of electricity to run our climate control systems. This might not seem like enough to control the climate of what is basically a small city, but remember that the amount of energy coming into the habitat is low enough that heat can be passively radiated away. Therefore, all the climate control system has to do is spread heat around.

The first problem is hot air building up in the center. As heat is radiated away by the outside of the habitat, air in the center of the habitat will not be able to cool down very much. Hot air rises, which makes this worse as all the hot air will be concentrated in the middle. This could be a very large problem for the classic rotating space habitat, as it has just one layer on the edge of the habitat and nothing in the middle where it might be able to help with this. Fortunately, our habitat has many layers. This both physically blocks hot air from moving to the center and gives us something to put air ducts on. Although it is slowed down, hot air will rise towards the center. To reverse this, fans in the center blow air through ducts that go back down to the ground level.

Heat also has to move through the hull of the habitat so it can be radiated away. Although it is mostly made of steel, which is a fairly good conductor of heat, the hull is several meters thick so this might not be enough on its own. To help heat get through this, water is circulated through pipes that run in loops from just below the ground to the outer hull. The water does not have to move any fast to transfer heat faster than conduction can, so the amount of force (and therefore electricity) needed to keep the water moving is minimal. To explain how humidity is controlled, we first have to explain how air moves in the habitat.

Each hab is just big enough for weather-like effects to exist. Light hitting the surface generates heat, which in turn heats the air in contact with the ground. Near the surface, the bumpy terrain prevents large air currents from forming, but above this, hot air rises. If we assume that drag with the surface only strongly affects air within five meters of it, air rising from 480 meters radius to 430 meters radius will speed up from 67.2 meters per second to 75.0 meters per second, while the speed of the cylinder's structure at a radius of 430 meters is 60.2 meters per second, so from the point of view of someone on the ground a windspeed of 14.8 meters per second is generated near the inner cylinder.

This fast-moving air is cooled down by spots of the "sky" which are cooled to just above freezing, well below the dew point, and generate condensation. These areas are designed to look like the rainclouds they simulate, and because of that they can have a rough surface in

¹⁶ Lechner, Tom. "Rotating Space Station Numbers." *Tom Lechner's Art*, www.tomlechner.com/outerspace/.

order to more efficiently cool and mix the air flowing through them without ruining their appearance. Cool air that falls from this will then fall, slowing down due to the Coriolis effect as it does so. From the point of view of someone on the ground, this would generate a wind of similar speed to the other one near the ground, before it is slowed down by friction against the ground, trees, buildings, ect.

These different air streams will meet in a diagonal line leading from the ground counterclockwise of the cold spot up to the clockwise edge of the cold spot. Fortunately, they will mostly cancel out near this edge, giving us more time to cool air and also simplifying calculations for where rain from this spot lands. However, we also need to factor in the Coriolis effect for the raindrop itself! If we make its destination lake five meters deep at most, this lets us place it at 510 meters from the center, 10 meters below the average elevation of land. As it falls from the inner cylinder, it would reach a horizontal speed of 21.8 m/s without air drag by the time it hit the ground. However, as most raindrops have a terminal velocity around 10 m/s¹⁷, it will not get that fast. As it will reach these speeds quite quickly, we will just assume this is its constant speed and direction for the sake of simplicity. With this in mind, we will calculate how much the Coriolis effect will move the raindrop counterclockwise. For simplicity, we will assume that the inaccuracy caused by assuming this will be constant throughout its fall is minimal. Each second, the drop falls ten meters. The speed of rotation of the habitat's structure increases at a rate of 1.4 m/s per 10 meters from the second, so the raindrop will be 1.4 meters backwards from where it started after falling 10 meters, giving it an apparent horizontal velocity of 1.4 m/s counterclockwise from the point of view of an observer on the ground. Assuming the raindrop is moving downwards at 10 m/s for its entire fall, it will take 8.5 seconds to fall from the simulated sky to the lake. Therefore, the center of the lake should be located about 12 meters counterclockwise from the center of the cold spot.

General Layout and Transportation:

People spend most of their time on the "ground" of the habitat. The ground is very hilly to hide the fact that the habitat is a small cylinder, with the lowest points on the ground at 515 meters from the center and the highest hills 485 meters from the center. The crests of these hills have lines of fruit trees planted on them to both further obstruct vision of the curving "horizon" and provide a source of fruit to the colony. The hills are not heaps of dirt, but hollow shells covered in a meter of dirt at the surface. This both massively reduces the weight of dirt that must be supported by the cylinder's structure and lets the inside of the hills be used for other purposes. The majority of most buildings are actually situated underground so they can take advantage of this area, with only an entrance, shed, and maybe a living room on the surface. This lets us have a population density of 10,000 people per km², significantly higher than most other space habitat concepts (O'Niell's original paper had a population density of ~5,900 people per km²) without crowding, as not much surface area is taken up by buildings.

The habitats are small enough that most people will be able to walk to wherever they want, although people could use bicycles or electric bikes/scooters if they wanted to or were in poor health. To move heavy loads, electric vehicles could be used. Vertical movement between

¹⁷ "How Fast Do Raindrops Fall?" *The Weather Guys*, 10 Sept. 2013, wxguys.ssec.wisc.edu/2013/09/10/how-fast-do-raindrops-fall/.

levels would use elevators at either end of the habitat. No elevator shafts are located in the middle, as this would ruin the illusion of a natural sky.

Many public areas, buildings, shops, ect. could be located on the 300 meter radius level. The apparent gravity at this level is 0.6 G, probably too low to actually live there but much more Earthlike than Mars or the Moon, so just going there for a few hours a day would be okay. This further increases the amount of area available inside the colony. The layer at 30 meters from the center could also be used largely for recreation, as it has an apparent gravity only 6% that of Earth.

Day/Night Cycles, “Time Management” and Specialization of Habitats:

Most space habitat concepts have night caused by just blocking off all the windows that let light into the habitat. This wastes all the light that hits the habitat during the night and means that almost everyone will be working at the same time, which is more efficient than having to let machinery and other resources used for work just sit there, unused, half the time because everyone is sleeping. These issues have been solved for this habitat. Day/night cycles are simulated not by closing and opening blinds but by moving mirrors in the light distribution system to alternately light the ground and 300 meter levels on either side of the central band. This effectively means that each half of the cylinder is twelve timezones from the other half.

This can be improved further. As three of these cylinders are residential, if their times are offset by four hours from each other, one half of a cylinder would be waking up every four hours. This might not seem like it would spread out activity evenly at first, as there is only a twelve-hour difference between the earliest and latest times between cylinders. However, this is long enough, as the twelve-hour difference between different sides of the cylinders means that the people in the earliest late cylinder will wake up four hours after those in the latest early cylinder.

Even though there are only three inhabited cylinders, there are four total habitation cylinders. The fourth cylinder is used for specialized purposes. The largest by land use are probably the farming of livestock and recreation. Most livestock probably need gravity similar to Earth's for proper development, need lots of space, and produce offensive smells. Many recreational activities require large amounts of space. While it would not be as good as the real thing, one could dedicate much of this cylinder to artificial forests and lakes for hiking and fishing. Lastly, facilities that require large amounts of specialized personnel would be located here, with the workers coming to the cylinder every day from their homes in other cylinders. It would be much better to have one hospital located here with six expert heart surgeons who could advise each other and fill in for one who is exhausted or sick than to have one hospital for each half of an inhabited cylinder with one heart surgeon each, who might have to do a twelve-hour operation all by themselves without any advice or help. The colony is large and isolated enough that it would need a university to train its citizens, and it would be much better to have one university that draws off the talent of 180,000 people than six universities that might only have a few dozen teachers each.

Superstructure Overview:

The superstructure is what holds the various other sections of the colony together, and also performs many other functions. The reflectors that concentrate light are located here, as well as zero-gravity industrial and construction areas, areas for other spacecraft to dock, facilities for power generation, tracks for transportation around the superstructure, and many other facilities are located here. It is mostly made of steel and pykrete, as the required materials for them are quite abundant. Strength and weight are not very important, as with no gravity or rapid rotation there are very few strong forces acting on the structure.

Parabolic Mirrors:

The stack containing the habitation cylinders needs 13.7 gigawatts of sunlight reflected towards it, and each stack of industrial cylinders needs 2.27 gigawatts of sunlight (not counting sunlight used for power generation). As mirrors located too close to the base of the stacks will be reflecting light almost perpendicular to the windows, the area of the superstructure within a ten kilometer radius of the base of the stacks is used for power generation instead of lighting the stacks. For the reflectors, 5 micrometer thick metallized PET film is used, with the layer of metal (aluminium) being one micrometer thick. This is already produced and used in space right now.¹⁸ Aluminium is about 92% reflective, meaning that the reflectors have to be somewhat larger than if they were perfect mirrors. From this, we get a radius of 83.9 kilometers for the reflector for the stack of habitation cylinders, and a radius of 35.3 kilometers for the reflectors for each stack of industrial cylinders. The industrial cylinders are placed an even distance apart at a radius of 168 kilometers from the industrial habitats, and the entirety of the superstructure is 504 kilometers across. The portions of the superstructure not used for the large reflectors mentioned above are devoted to smaller reflectors which supply light for solar thermal power generation, which will be described in further detail. While it is a gigantic structure, almost all of its area is very thin film for reflectors. In total, the reflectors consist of about 540,000 metric tons of aluminium and 1,100,000 metric tons of PET, which combined is worth a total of about four billion dollars at current prices - very cheap for something approximately the size of Great Britain, and worth about as much as just the gold and platinum produced by the colony every year, which is not even its main export!

The reflecting foil is kept in place via steel supports. As the only significant forces acting on the superstructure, radiation pressure from sunlight and tidal forces from Arrokoth's gravity, as extremely small, these do not have to be very massive or strong.

Cylinder stacks:

There are four main habitation cylinders, each 525 meters in radius and 2.1 kilometers long. They are all contained in one large "stack" in the middle of the superstructure, 16 kilometers long and 725 meters in radius. Habitation cylinders are spaced every 3 kilometers, starting two kilometers away from the "base" of this section, where it meets the supports of the parabolic mirrors. Two cylinders rotate clockwise and two counterclockwise, so no net torque is exerted on the structure. The space containing the cylinders is a vacuum, and habitats are rotated on magnetic bearings to virtually eliminate drag while preventing them from moving relative to the superstructure, as they are long enough to be slightly unstable without confinement. The superstructure contains a 25 meter gap between it and the edges of the cylinders, giving it an inner radius of 550 meters. Each cylinder is 2.1 km long, has 25 meters of space between it and the superstructure on each side, and the dividing walls after each end of the cylinder containing its restraints, as well as cooling equipment, is 25 meters thick, but as

¹⁸ "LightSail." *The Planetary Society Blog*,
www.planetary.org/explore/projects/lightsail-solar-sailing/.

there is only one cylinder every 4 kilometers there is a 0.8 km gap between each pair of dividing walls, as well as two 2.4 kilometer long empty spaces at the ends of the structure. This is pressurized and not directly connected to the vacuum surrounding the cylinders, and can be used for many purposes which will be explored later in this section.

Except for the windows used for letting light in, the outer surface of this section is made of steel ten centimeters thick, painted with a high-emissivity coating. Steel is used because its components are abundant in KBOs, it has a fairly high thermal conductivity, and its high strength and density will stop small fragments of debris that impact it. Pipes containing CO₂ for the cooling system are located right underneath the steel layer so that their heat can be rapidly radiated away. There is then a three-meter gap between the pipes and the next layer, in order to provide easy access to the pipes as well as allow fragments from any collision that makes it through the outer layer to spread out before hitting the next layer, which is steel forty centimeters thick. This is attached to the outer layer by many struts, so that the force exerted by the pressure (around 17 kpa) of the interior of the superstructure is held by both layers. With it effectively being one 50 centimeter thick layer of steel, the force exerted by the pressure is several times less than the steel's ultimate tensile strength, despite the large size of the structure. It should also stop any secondary fragments from a collision with the outer layer. On the inner edge of that is a ten centimeter thick layer of polybutadiene, followed by five and a half meters of a 50/50 composite of carbon dust in polystyrene. Polybutadiene is used because it has a fairly high carbon/hydrogen ratio (remember, there is a lot of excess carbon in the KBO material) and a very low glass transition temperature of -80 C.¹⁹ The glass transition temperature of a material is the temperature below which it transitions from a flexible rubber to a brittle, glass-like state, meaning that it will not shatter if the steel layer absorbs an impact. Polystyrene-soot composites are fairly easy to manufacture²⁰, and are used because they provide a use for the large amounts of carbon produced from processing the KBO material. Polystyrene itself has a 1:1 ratio of carbon to hydrogen atoms, and the carbon dust is nearly all carbon.

There is then a large distance between the inner edge of the polystyrene layer at 716 meters from the center and the section of the superstructure encapsulating the habitation cylinders at 551 meters from the center, although this layer only surrounds the cylinders, and is not present in the gaps between cylinders or on the ends of the "stacks" of cylinders. Most of this would be used for storage, and it has a large amount of pipes for the cooling system and structural supports between the outer and inner layers going through it. The inner layer is a meter of steel, which is several times more than strong enough to withstand both the normal pressure differential between the pressurized portions of the superstructure and the unpressurized area surrounding the habitation cylinders and the pressure differential between the superstructure and the area around the habitation cylinders in the event of a habitation cylinder becoming breached, which would cause the area around it to be pressurized to one bar. The ends of the containers of the cylinders are also made of meter-thick steel, and the whole section is kept in a vacuum so the rotation of the cylinders is not slowed down by air resistance.

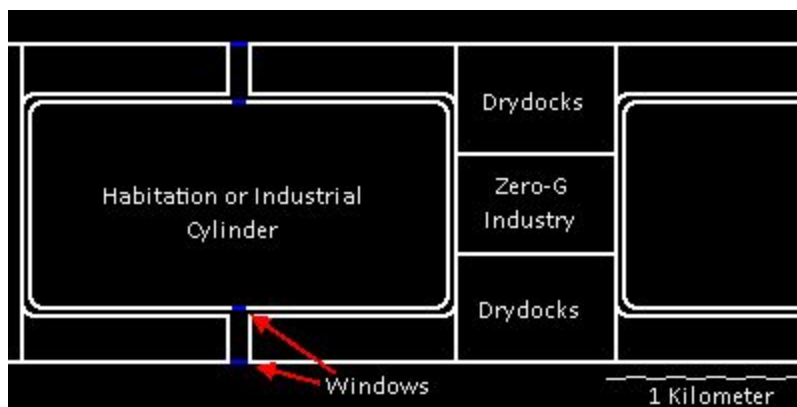
One issue with long, cylindrical habitats is that they are somewhat rotationally unstable. While this is a major problem for free-floating cylinders, it is not an issue for this design. Because the cylinders are mounted on magnetic bearings in a larger structure, they cannot freely wobble around. If it begins to move off axis, the repulsion from the bearing will counteract

¹⁹ Mallard Creek Polymers. "Glass-Transition Temperature (Tg)." *Mallard Creek Polymers*, 1 Sept. 2015, www.mcpolymers.com/library/tg.

²⁰ Sabbar, Ali N., et al. "Thermal and Optical Properties of Polystyrene Nanocomposites Reinforced with Soot." *Oriental Journal of Chemistry*, vol. 35, no. 1, 2019, pp. 455–460., doi:10.13005/ojc/350159.

this force. As it coming free would be extremely bad, there are several backups in place, such as redundant electromagnets and batteries for the magnetic bearings. Some people might point out that there will always be some risk of everything catastrophically failing. However, this is also somewhat true of settlements on Earth. Natural disasters and fires cause huge amounts of property damage, injury, and death, but no one refuses to sleep inside a house because it might burn down or collapse on them. There are also other failure modes, such as a massive hull breach, that are much more likely on free-floating toroidal habitats than for this design.

The superstructure around the habitats provides much more protection from radiation and debris than the shielding on most free-space settlement concepts. This is possible because the shielding is not part of a rotating section, and therefore is not limited by how much force it generates on the supports of the rotating section. The non-window sections have about twenty tons of material per square meter of the superstructure, and the windows have 16 tons per square meter. Most designs for habitats include several times less than this, and ten tons is generally considered enough to reduce radiation to negligible levels.²¹



Heat is transported from the layer around the cylinders to the exterior of the superstructure via tubes filled with liquid carbon dioxide. While it sublimates directly from solid to vapor at atmospheric pressure, at pressures over about 5 bars liquid CO₂ can exist. The liquid CO₂ is pumped from the exterior of the superstructure to the layer surrounding the cylinders, which is at a temperature of 250 K. In this section, the pressure is about 17 bars, which is low enough for the CO₂ to boil at this temperature. The gaseous CO₂ then travels through pipes and a turbine to the outer surface of the superstructure, where the pipes are at a pressure of 10 bars and a temperature of 220 K. Because of the lower temperature, the CO₂ condenses into a liquid despite the lower pressure. The liquid CO₂ can then be pumped back to the inner layer, repeating the cycle. This system actually functions as a heat engine exploiting the temperature differential between the inner and outer surfaces to generate power, although because of the low difference in temperatures between them it is very inefficient. Still, it should generate enough power to run itself and some additional lighting.

Energy and Heat Dissipation for Cylinders:

Each habitation cylinder receives 1.628 gigawatts of energy from light reflected from the parabolic mirrors on the superstructure. We already mentioned that the light was tailored to contain 80% of its energy in visible portions of the electromagnetic spectrum, while normal sunlight has only 40% of its energy in visible light, the rest being in infrared and ultraviolet radiation. This is done by passing the light through a UV-IR cut filter that only lets visible light

²¹ Globus, Al, et al. "The Kalpana One Orbital Space Settlement Revised." *American Institute of Aeronautics and Astronautics*, Apr. 2007, alglobus.net/NASAwork/papers/2007KalpanaOne.pdf.

through. There are many commercially available filters that transmit almost all visible light and very little ultraviolet or near-infrared radiation, but they let a large amount of infrared with a wavelength of over 1250 nanometers through. This could probably be removed too, but at an increased cost and with little benefit.

The performance of our filters will actually be a bit lower than many commercially available ones.²² This is in order to reduce production costs by making the requirements less stringent and allowing for a larger list of possible materials and less precise quality control. The filters used in this colony transmit 95% of visible light that hits them, as well as 18% of the infrared and 5% of the ultraviolet, giving the habitats filtered light that is 1% ultraviolet, 80% visible, and 19% infrared. The filters do a much better job at blocking ultraviolet than the Earth's atmosphere, and almost all of the remaining UV has a wavelength of between 340 and 380 nanometers, which isn't nearly as harmful as shorter wavelengths and stimulates the production of Vitamin D in humans. Ideally, the light that is not transmitted would all be reflected, as reflected light is not converted into heat that must be radiated away, but this is not possible in reality. Many of these filters are designed to reflect the light they do not transmit, but this is secondary to transmitting the desired wavelengths and not transmitting the rest. We will assume that the filters transmit 47.5%, absorb 12.5%, and reflect 40% of all the sunlight that hits them, with the composition of the transmitted light already being discussed.

If there are four main habitation cylinders in the superstructure, with each receiving 1.628 gigawatts of energy, together they require 6.513 gigawatts. This is all filtered light, so 13.712 gigawatts of raw sunlight needs to hit the filters, with 6.513 GW transmitted, 1.714 GW absorbed, and 5.485 GW reflected. This gives us 8.227 GW of total energy that must be radiated away. We will assume that it is covered by ground steel plating, which has an emissivity of approximately 0.9, and has a surface temperature of 220 Kelvin. This gives us a necessary surface area of 68.8 km², which is the surface area of a cylinder 16 kilometers long and 658 meters in radius. To provide leeway and allow for other heat-producing activities to take place in the superstructure near the habitats, we will make the radius a bit larger, at 725 meters. As it is pointed directly at the sun, only the front face is directly lit by sunlight, which has a negligible contribution to the amount of energy entering the system (only about 0.01% of what is being reflected to the cylinders). The industrial cylinders are located in an identical structure, although it receives less direct sunlight and much more electricity.

The filters would normally get very hot due to absorbing a large amount of energy in a small area, but this is averted by having the glass the filters are mounted on filled with tubes containing a liquid with a refractive index the same or very close to that of the glass (such as mineral oil or benzene). By having the same refractive index as glass, they do not cause the light passing through them to be bent more or less than light passing through the glass around them. This liquid is circulated through the window and then to heat exchangers connected to the heat transfer system of the superstructure to spread out the heat and prevent the window from getting too hot, which would otherwise radiate extra heat onto the habitats and possibly damage the filters if it got really hot. The fact that this area gets slightly hotter is actually a benefit, as many of those liquids have melting points below room temperature but above 220 kelvin.

The windows the filters are on are 75 meters across and consist of several layers. The outermost layer is a few millimeters of glass as many small tiles so it can easily be replaced when debris impacts it. This is located on top of centimeter of polycarbonate, which will not shatter with the glass above it, followed by five centimeters of glass which the cooling liquid

²² "Company Seven: Baader Planetarium UV / IR Cut Filter Description Page." *Company Seven | Baader Planetarium UV / IR Cut Filter Description Page*, 6 Sept. 2008, www.company7.com/baader/options/ir-uv.html.

discussed earlier flows through. This is then followed by five meters of polycarbonate to provide strength, and then four meters of glass to provide mass for radiation shielding. Polycarbonate will outgas in vacuum and can be damaged by UV light, which is why it is not directly exposed to vacuum and is instead sandwiched between layers of glass. The polycarbonate layer is strong enough to withstand the pressure differential caused in the event of a cylinder becoming breached.²³

“Drydocks,” Zero-G Industry, and Ship Docking:

As mentioned earlier, each “stack” of rotating cylinders will have three 0.8 kilometer wide gaps between the cylinders, as well as two 2.4 kilometer sections on each end. These areas are used for various purposes. The 2.4 kilometer section near the “base” of each cylinder is quite hard to access, and is used for the storage of bulk materials. With each one of these sections having a volume of about 4.5 km³, the storage capacity of the entire colony is over 30 km³. The smaller sections between cylinders are divided into many sections. A 250 meter radius section at the middle of each of these is used for zero-g industrial activities, such as making very high-quality mirrors or other items where gravity can cause harmful defects. Although the presence of many other zero-g industrial facilities in more populated areas of the solar system means that most of these items could not be exported at a competitive price, they would still be quite useful for the colony. The rest of each section is divided into wedges radiating out from the center, which are used as “drydocks” for construction in a microgravity environment. Zero-G environments are likely to be very useful for construction, as they allow large amounts of material to be moved easily, as well as for structures to be built without the constraints imposed by gravity. The main types of structures produced in these areas would be sections of the superstructure for expanding this habitat or creating another one, as well as ships. The large 2.4 kilometer long section on the end far from the base would be one massive drydock, used for building very large ships, larger sections of the superstructure, and more habitation or industrial cylinders.

All of these areas are pressurized, allowing people to work in them without the risk of death or requirement of bulky, cumbersome spacesuits inherent to vacuum. However, they are quite cold, at temperatures between about -20 and -50 C. While the low pressure and humidity of the atmosphere in these sections reduces heat loss somewhat, it would still normally require fairly thick clothing and gloves, which would make work harder. Additionally, a normal person cannot really move without pushing off of a solid surface in zero-G, which would be very annoying in such a large structure - accidentally letting go of a surface could lead to being stuck floating through the air for a fairly long time before hitting the other side of the superstructure. These issues can be ameliorated via what will be called, for lack of a better term, jetpacks. Due to the lack of appreciable gravity, almost no force is needed to move a person, and people can carry massive objects on their backs with little exertion. The “jetpacks” do not have actual jets or rockets, which can cause severe burns due to the large amount of hot exhaust they create and are inefficient, but fans driven by an internal combustion engine powered by propane. The engine has a power output of 100 watts (about an eighth of a horsepower) of mechanical power, which is enough to accelerate a person and their equipment weighing 100 kilograms at one m/s². There is also an alternator, which can be used to generate electricity for power tools using the engine. Some equipment used in tasks such as welding requires very large amounts of power, and people doing those tasks could use jetpacks with a larger, more powerful engine to power these tools. It also contains a propane burner to heat water, which is pumped through thin tubes in the person’s clothing to keep them warm without needing lots of insulation. As

²³ “Tensile Strength of Polycarbonate - Properties of Polycarbonate Sheeting.” *Tensile Strength of Polycarbonate - Properties of Polycarbonate Sheeting*, 2020, www.acplasticsinc.com/informationcenter/r/tensile-strength-of-polycarbonate.

propane has a high energy density, a tank containing just a few kilograms of it should be enough for a person using a jetpack to last a whole workday. This provides a way for people to maneuver in the air, and as there is no appreciable gravity to work against they do not need to produce much power, making them quite easy to design and operate as opposed to Earth. There is also no risk of the operator falling to their death, again unlike on Earth. Therefore, this seems to be a very practical way of getting around in zero-G, despite seeming somewhat fantastic at first glance.

On the opposite side of the mirrors from the cylinder stacks are the docking facilities, used to let ships dock with the colony as well as for storing ships not currently in use. These are located just behind where the reflectors meet the stacks. They consist of branching towers, with a docking port at the end of each branch, so that there is plenty of room for ships. Additionally, there are several rails approximately ten kilometers long to electromagnetically accelerate ships. These cannot produce very high accelerations, and mainly serve to get ships using ion drives and other efficient but low-thrust methods of acceleration away from the colony in order to avoid a high density of ships, which would pose a risk of collisions between ships. There are also some VASMIR engines of the type discussed later in the paper to efficiently provide thrust to counteract the forces generated by accelerating objects, as well as any other forces.

Heat Dissipation and Climate Control:

Due to its large size available for radiating away heat and low power consumption, heat dissipation is not a major problem for the superstructure. The only parts where it is important is in the portions of the superstructure which surround the cylinders. However, as these parts of the superstructure were built with significantly more surface area than necessary, a reasonable amount of power can be used without exceeding its energy budget. This means that the drydocks and industrial areas can be lit at a reasonable level.

The atmosphere in the pressurized portions of the superstructure is pure oxygen at a pressure of 16.7 kPa, equivalent to the partial pressure of oxygen at the altitude of Denver. It has essentially zero humidity and carbon dioxide, and its temperature varies between -20 and -50 C depending on what part of the superstructure it is in. Carbon dioxide and water are removed from the atmosphere by passing the air through pipes that go to radiators, where it cools enough that carbon dioxide and water vapor in the air freeze out before being collected and sent to the habitation cylinders, where the plants there regenerate the carbon dioxide. Fresh oxygen is brought into the superstructure by liquifying air from the habitation cylinders and distilling it to collect pure oxygen. As the habitation cylinders have much more plants than necessary to recycle the oxygen generated inside of them, and the amount of people in the superstructure is much lower than the number of people inside the habitation cylinders, having to recycle a bit of extra CO₂ will not be an issue.

Transport around Superstructure:

The very large size of the superstructure seems like it may pose a challenge for people who must commute over 160 kilometers each way from the habitation cylinders to the industrial cylinders every day. However, this is not a problem. Transportation around the superstructure is done using what are essentially maglev trains on the outside of the superstructure. As the outside of the superstructure is in empty space, which is a vacuum, the trains can go extremely fast. Assuming that the trains accelerate at 20 m/s², which is about twice Earth's gravity and not harmful to healthy people for relatively short periods, and the trains speed up during the first half of the trip before slowing down for the second half, this journey will take just over three minutes, with a top speed of about 1.8 kilometers per second.

A more complicated issue is travel between the superstructure and the rotating cylinders. Transportation between the two is also done via vacuum train, but the trains are specialized for this purpose only. There are two sets of tracks, one on the cylinder and one on the superstructure. To leave the cylinders, the train is accelerated opposite to the direction of rotation of the cylinder before going to the track on the superstructure. To return to the cylinder, the train is transferred to the track on the cylinder from the superstructure before being slowed down. If it was sped up on the superstructure to match the velocity of the cylinder, it would be pushed outward away from the cylinder because of centripetal force.

Overview of industrial cylinders:

Industry is the main purpose of the colony, and most of the colony's labor, materials, and energy goes towards this purpose. While there are several upsides to zero-g manufacturing, there are also many downsides. Without gravity, nothing is held down into containers, which would often lead to extremely bad consequences. Dense materials will not sink in fluids, and convection is nonexistent. The lack of convection means that flames will not rise or suck in fresh air, limiting their size. However, lower gravity makes moving objects much easier and decreases the amount of load that must be supported by structures. Therefore, our cylinders will have 1/20th of Earth gravity on the main level, which is high enough that stuff will still fall down but low enough that the average adult man could lift an object massing a metric ton unaided. As most people will only be here for 6-8 hours on weekdays, and they will only be able-bodied adults, the low gravity should not cause them any harm, because they spend most of their time at normal gravity.

To make construction simpler, the industrial cylinders are the same size as the habitation cylinders, which means that they can be built in a similar way. They are also placed in groups of four, with two rotating clockwise and two counterclockwise per stack. The temperature is kept at around 20° C like in the habitation cylinders, and the air is at a pressure of one atmosphere, with a composition of 90% oxygen, 9.9% nitrogen, and 0.1% carbon dioxide (not including water vapor), so the forces from pressure are the same. The higher carbon dioxide concentration helps plants grow faster, and is still below the maximum allowed concentration in the workplace

in the United States (0.5%). The higher oxygen concentration causes flames to burn hotter, making many processes more efficient. Carbon dioxide is recycled partially from the bamboo grown for use in pykrete, but mostly artificially using processes described later.

The light distribution system is much simpler than in the habitation cylinders. There is no effort to simulate a sky or day/night cycles, and only the 500 meter radius level has to be lit, as it is the only level that is actually being used. Because 1/3 of the population will be between 9 AM and 5 PM local time at any given time, there is no time of day when the structure is almost empty, unlike most factories on Earth. This means that work is always being done. The only exception are the areas in which bamboo is being grown, which must have a light/dark cycle for the bamboo to grow properly. The bamboo growing areas (0.925 km² per cylinder) are lit at around 40 W/m² on average, while the other areas are lit at 2.5 W/m². Fire suppression is a very large issue due to the high oxygen atmosphere, but water cannot be used because it would cause a steam explosion if it came into contact with molten material and would cause huge amounts of damage to any electrical equipment that got wet. Instead, there are many dry chemical fire extinguishers placed around the habitat, which have no liquid and instead smother fires with a dry powder. Due to the lower gravity, very large fire extinguishers massing hundreds of kilograms can easily be carried around to be used in extinguishing fires.

Power is generated outside of the cylinders via solar thermal generators, which will be discussed in more detail later in this section. It is transferred to the cylinders via slip rings, which are rings made of a conductive material that transfers current to a rotating object. To reduce friction, the rings are lubricated with graphite, which is conductive and non-volatile in addition to being a very good lubricant.

Composition of KBO Material:

For us to have any idea of how KBO material might be processed, we need to know what they are made of. Unfortunately, information in this area is somewhat lacking. Only one small KBO has been visited by a spacecraft, and that was a short flyby by a spacecraft with instruments specialized for Pluto, a much larger and vastly different object. However, it did collect a lot of data, and in combination with the more detailed data on Comet 67P²⁴ and Pluto we should be able to infer a reasonable approximation for the composition of an average KBO. From Fulle et al²⁵, we get a bulk composition of 54% organics, 20% ices, 22% silicates and 4% iron sulfides by mass. However, as carbon, oxygen, and hydrogen have a much lower molar mass than mineral-forming elements, by number of atoms the composition is 69% organics, 22% ices, 8% silicates and 1% iron sulfides. This will be important later, when we discuss the possible methods of processing KBO material.

²⁴ Filacchione, Gianrico, et al. "Comet 67P/CG Nucleus Composition and Comparison to Other Comets." *Space Science Reviews*, vol. 215, no. 1, 2019, doi:10.1007/s11214-019-0580-3.

²⁵ Fulle, M., et al. "The Dust-to-Ices Ratio in Comets and Kuiper Belt Objects." *Monthly Notices of the Royal Astronomical Society*, vol. 469, no. Suppl_2, 2017, doi:10.1093/mnras/stx983.

The ices are mostly water, but also include significant amounts of ammonia and carbon dioxide. Carbon monoxide, methane, and diatomic nitrogen are volatile enough that they will be lost from small KBOs over time, as they are still slightly volatile at the temperatures of the Kuiper Belt and will slowly escape from any object less than around a thousand kilometers across, according to Brown et al²⁶. There are also small amounts of hydrogen sulfide and hydrogen cyanide in the ices, which could pose a safety hazard for the people involved in processing it. As carbon dioxide is just under a fifth as common as water ice in most comets²⁷, with the other components being too volatile to stick around in small KBOs or significantly less common, we will say the ice is 80% water, 15% carbon dioxide, 2% ammonia, 2% hydrogen sulfide, and 1% other molecules (represented by 0.5% hydrogen cyanide and 0.5% sulfur dioxide, the most abundant of these).

formula	molar%	Molar mass	mass%
H ₂ O	80	18	63.8
CO ₂	15	44	29.3
H ₂ S	2	34	3.0
NH ₃	2	17	1.5
HCN	0.5	27	0.6
SO ₂	0.5	80	1.8

While they are organic compounds and not ices, many organic compounds will be removed with the ices, as they are either water-soluble or melt below room temperature. Most of the organic compounds are in the form of insoluble solids somewhat similar to tar or coal, but a decent chunk are in the form of methanol, formaldehyde, ethane, and other volatile and/or water-soluble substances, with methanol being the most common of these. Larger molecules in this category, such as ethanol, hexane, and benzene, are also probably quite common, but are harder to detect being less volatile and therefore not mentioned in any of the sources I am using. The presence of these substances is both a blessing and a curse. They are valuable chemical building blocks, and will react with many of the toxic substances in the ices. Ammonia and cyanides will react with aldehydes to form aminonitriles, which can then hydrolyze to form amino acids. Formaldehyde will also react with hydrogen sulfide to form 1,3,5-trithiane, which is still somewhat toxic but is much less dangerous because it is not a gas like hydrogen sulfide. However, many of these chemicals are themselves quite poisonous, such as formaldehyde, which is a potent carcinogen. Some of these will not dissolve in water and will either become gases at room temperature (for ethane-butane) or form a layer of liquid above the water (hydrocarbons from pentane onwards and many long-chain alcohols and fatty acids). Although the only real data available on this is the amount of methanol and formaldehyde vs water in comets, from this it seems reasonable to assume that around 5% of the organics are

²⁶ Brown, Michael E. "The Compositions of Kuiper Belt Objects."

²⁷ Bockelée-Morvan, D., and N. Biver. "The Composition of Cometary Ices." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 375, no. 2097, 2017, p. 20160252., doi:10.1098/rsta.2016.0252.

water-soluble and another 10% are not insoluble in water but are liquid or gaseous at room temperature, represented as equal parts benzene and hexane. The average composition of the solid, tarry organics is $C_{65}H_{75}O_8N_{1.1}S_{0.5}$.²⁸

Formula	% of atoms	Molar mass/# atoms	mass%
2 CH ₃ OH + H ₂ CO	5.5	5.9	5
C ₆ H ₁₄	7.6	4.3	5
C ₆ H ₆	5.1	6.5	5
$C_{65}H_{75}O_8N_{1.1}S_{0.5}$	81.8	6.8	85

Based off of the solar abundances of elements²⁹ and the fact that they make up most of the Earth's mantle, it seems reasonable to assume that the vast majority of the silicates will be olivine. Olivine is a mixture of forsterite (Mg₂SiO₄) and fayalite (Fe₂SiO₄). Calcium is chemically similar enough to magnesium that it replaces some of the magnesium atoms in forsterite to form monticellite, but due to the low amount of calcium relative to magnesium this is a small percentage of the olivine and isn't very important. Magnesium is slightly more abundant than iron, and some of the iron is in the form of iron sulfides, so the molar forsterite/fayalite ratio of the silicates is most likely around 65/35, although by weight fayalite is still more abundant by a small amount. Olivine makes up most of the Earth's mantle and is very abundant in many meteorites and on the surface of the Moon, but is not very common on the surface because it is relatively quickly altered into other minerals by the air and water. It also has a hard time getting to the surface in the first place, as it has a high melting point and is denser than most other minerals, which means that most of it will freeze out of magma before it gets to the surface and erupts. The most common mineral in the Earth's crust is feldspar, which is a mix of albite (NaAlSi₃O₈) and anorthite (CaAl₂Si₂O₈). Much of the calcium is in the olivine, so our feldspar will be mostly albite. However, due to the low amount of aluminium, calcium, and sodium relative to magnesium, iron, and silicon, feldspar makes up perhaps only 5-10% of the silicates.

The iron sulfides, despite their name, are not only iron sulfides. They also include nickel and most of the less reactive metals. Metals less reactive than iron are not often found in silicates, and on Earth almost all of them sank to the core with the iron. Therefore, most of the precious metals will be concentrated in the iron sulfides.

Formula	Molar%	Molar mass	mass%
Mg ₂ SiO ₄	39.9	140.7	37.3

²⁸ Mukhopadhyay, Prasanta K. "Hydrocarbons in the Solar System — Biogenic Source Rock Signatures in Carbonaceous Chondrites and Comet Dust." *Search and Discovery*, 7 Sept. 2015.

²⁹ Palme, H, et al. "Solar System Abundances of the Elements." *National Science Foundation*, par.nsf.gov/servlets/purl/10036398.

MgCaSiO ₄	3.6	156.5	3.7
CaAl ₂ Si ₂ O ₈	1.2	278.3	2.2
NaAlSiO ₄	1.2	142.1	1.1
NaAlSi ₃ O ₈	3.6	262.3	6.2
Fe ₂ SiO ₄	25.6	203.7	34.7
FeS	20.2	87.9	11.8
NiS	4.8	90.8	2.9

Total:

formula	% of atoms	Molar mass/# atoms	mass%
Mg ₂ SiO ₄	4.03	20.1	9.698
MgCaSiO ₄	0.36	22.36	0.962
CaAl ₂ Si ₂ O ₈	0.24	19.88	0.572
NaAlSiO ₄	0.12	20.3	0.286
NaAlSi ₃ O ₈	0.67	20.2	1.612
Fe ₂ SiO ₄	2.59	29.1	9.022
FeS	0.58	43.95	3.068
NiS	0.14	45.4	0.754
2 CH ₃ OH + H ₂ CO	3.82	5.9	2.7
C ₆ H ₁₄	5.24	4.3	2.7
C ₆ H ₆	3.47	6.5	2.7
C ₆₅ H ₇₅ O ₈ N _{1.1} S _{0.5}	56.40	6.8	45.9
H ₂ O	17.76	6	12.76
CO ₂	3.34	14.67	5.86
H ₂ S	0.44	11.33	0.6
NH ₃	0.58	4.25	0.3
HCN	0.11	9	0.12
SO ₂	0.11	26.67	0.36

Element	% of atoms	% of mass
Hydrogen	48.67	5.91
Carbon	29.67	42.92
Nitrogen	0.60	1.01
Oxygen	16.30	31.41
Sodium	0.07	0.19
Magnesium	1.20	3.51
Aluminium	0.11	0.36
Silicon	1.21	4.09
Sulfur	0.73	2.82
Calcium	0.07	0.34
Iron	1.03	6.93
Nickel	0.07	0.50
Other	0.27	0.46

This is different from the solar abundances of elements in a few respects. As a small body like Arrokoth cannot hold onto gases, no noble gases or hydrogen that was not part of a more refractory substance ever became part of the object. The carbon/nitrogen ratio in the Sun is 4.4 to 1, but in the KBO material it is 50 to 1. This is because diatomic nitrogen is a very stable molecule, and therefore is the most likely substance for nitrogen to occur in, but while it is solid at Kuiper Belt temperatures, it can still slowly sublimates away, so no diatomic nitrogen is left in the material. Other nitrogen-containing materials, such as ammonia, stick around, but they are less common than diatomic nitrogen so only about 10% of the nitrogen stays. The solar carbon/oxygen ratio is 0.6, but the carbon/oxygen ratio of our material is 1.8. This is somewhat odd, but it is backed up by observations of comets. Mousis³⁰ theorizes that this is due to, at least in part, volatiles in dust grains from the presolar nebula vaporizing as they fell towards the inner part of the cloud, a few AU away from the proto-Sun. As these were blown away from the Sun, the less volatile components would condense out onto dust grains in order of their volatility. Many organic molecules (ethane, propane, methanol, formaldehyde) are more volatile than water, but still refractory enough to condense before being blown out into interstellar space. This would cause a region of the protoplanetary disk to be enriched in carbon, and ultraviolet light would cause most of these to be converted into more complex molecules while they were still in the form of small grains.

³⁰ Mousis, O. "Constraints on the Formation of Comets from D/H Ratios Measured in H₂O and HCN." *Icarus*, vol. 148, no. 2, 2000, pp. 513–525., doi:10.1006/icar.2000.6499.

Many other elements are uncommon enough to not be a major component of the material, but are still important for many purposes, and are listed below. Their abundances are based off of the abundances in meteorites, and this should be pretty accurate as they are refractory enough that a negligible amount should escape as gases.

Name	Atoms per 10 ⁶	Grams per metric ton	Uses
Fluorine	10.1	23.0	Plastics, chemicals, water fluorination
Phosphorus	105	392	Nutrient, chemicals
Chlorine	65.0	277	Nutrient, plastics, chemicals
Potassium	46.0	216	Nutrient, chemicals
Titanium	29.0	167	Alloys, pigment, chemicals
Vanadium	3.48	21.3	Alloys, chemicals
Chromium	167	1040	Alloys, chemicals, nutrient
Manganese	116	761	Electronics, pigments, alloys, chemicals, nutrient
Cobalt	28.3	201	Alloys, pigment, chemicals, nutrient
Copper	6.80	51.9	Electronics, alloys, chemicals, nutrient
Zinc	15.6	123	Alloys, chemicals, nutrient
Bromine	0.133	1.28	Fire retardants, chemicals
Palladium	0.0167	0.213	Alloys, chemicals, jewelry
Silver	0.00606	0.0785	Jewelry, chemicals, electronics
Indium	0.00220	0.0304	Electronics, alloys
Tin	0.0450	0.642	Alloys, electronics, chemicals
Iodine	0.0136	0.207	Nutrient, chemicals
Neodymium	0.0108	0.187	Electronics
Tungsten	0.00471	0.104	Alloys, chemicals
Osmium	0.00837	0.191	Alloys, chemicals
Iridium	0.00876	0.202	Alloys, chemicals
Platinum	0.020	0.470	Alloys, jewelry, chemicals
Gold	0.00374	0.0888	Jewelry, chemicals, electronics
Mercury	0.00580	0.140	Electronics, chemicals, alloys

Lead	0.0410	1.02	Electronics, alloys, chemicals
Bismuth	0.00171	0.0446	Electronics, alloys, chemicals
Thorium	0.00042	0.0117	Nuclear technologies, electronics
Uranium	0.00011	0.00316	Nuclear technologies

The composition of the material is not the only important factor in determining how it might be processed. Its porosity and how much it has been consolidated is the main factor in determining how strong it is. Unlike large bodies, Arrokoth (and other KBOs smaller than a few hundred kilometers) are very porous and undifferentiated. This is because its gravity is small enough that the energy released when material was accreted onto it was not enough to melt the material or tightly compact it, and because their small size causes the heat generated by radioactive decay to radiate away before it can raise its temperature enough to melt the ices. This means that removing material from them requires very little effort, as it is not frozen together, is completely homogenous, and is not strong at all. As it does not have a moon, its mass has not been measured, but a common estimate for the density of similar objects is $\sim 0.5 \text{ g/cm}^3$.³¹

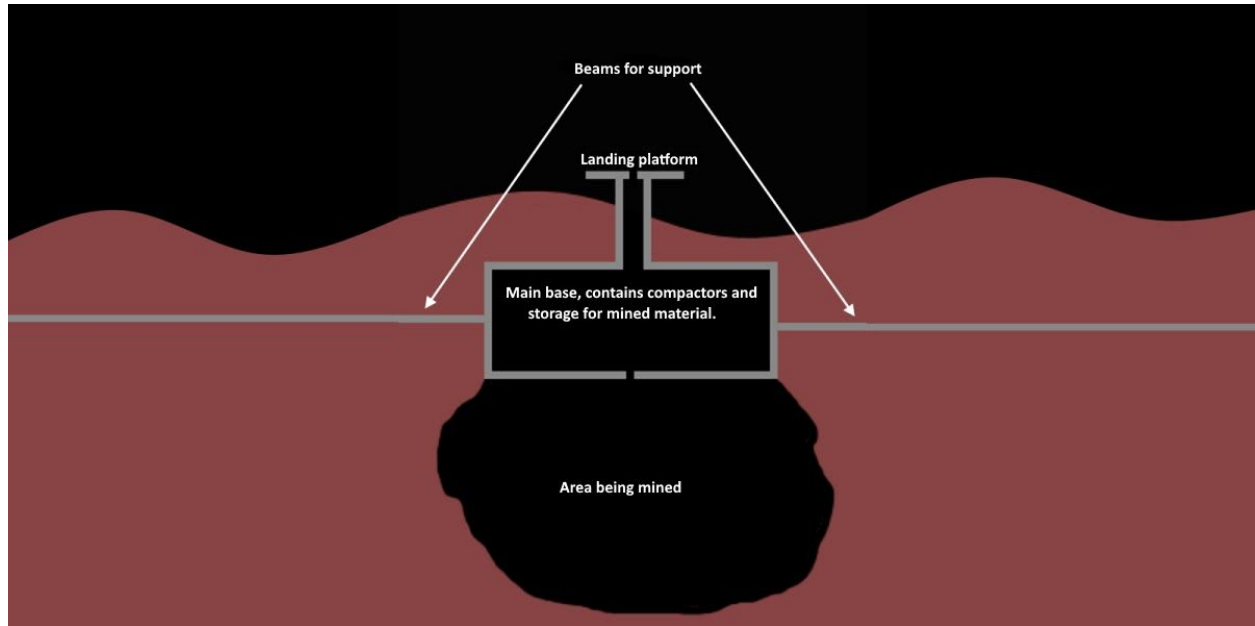
Mining and Transport of KBO Material:

The main problem with getting material off of the surface of Arrokoth is that it is almost too easy. As it is not a sphere, gravity significantly changes depending on where you are on the surface, but gravity is very low across the whole object. A rough approximation can be found by assuming that it is a perfect sphere with a diameter of 18 km (which has approximately the same volume as has been measured for Arrokoth) and a density of 0.5 g/cm^3 . This gives us a mass of $\sim 1.2 \times 10^{16}$ kilograms, a surface gravity of $\sim 0.0025 \text{ m/s}^2$, and an escape velocity of $\sim 9.5 \text{ m/s}$. This is high enough that just jumping probably wouldn't make you escape the object, but still poses a significant problem in getting enough force to remove objects from the surface. If someone weighing 100 kg with their spacesuit and other equipment wanted to just start digging up material with a shovel, they could not apply more than 0.25 newtons of force by standing on the shovel to drive it into the ground, and if they used their arms to push it in with more than this much force they would be thrown upwards! A 70kg person could apply ~ 690 Newtons of force in the same matter on Earth. While the idea of people in spacesuits digging up material is pretty absurd, it shows that anything on the surface of the object cannot apply much force on anything, and therefore cannot gather material very quickly. This means that the ships which transport the material to the habitat realistically cannot be the ones that mine material, as they will not be able to provide very much force.

Instead, material will be mined from a base slightly under the surface of Arrokoth, with structural supports branching out sideways a large distance from the base. This allows mining equipment to push against the base instead of their own weight to generate force. This massively increases the speed at which mining can be done for two reasons. Firstly, the

³¹ Britt, D T, et al. "SMALL BODY DENSITY AND POROSITY: NEW DATA, NEW INSIGHTS." *Lunar and Planetary Science*, 2006.

equipment is held down by not just the weight of the base but also all of the KBO material above it, which is far larger than the weight of a ship would probably be. Secondly, it is also held down by the strength of the material. It is very weak, but it has been compacted somewhat during the formation of the KBO, and the friction between the grains of ice and dust that is being pushed together is able to withstand a comparatively large amount of force compared to the force generated by its weight. The beams also stop the base from falling, as the area being mined is directly below it.



The base and mining are almost completely automated. This is relatively easy to do, as the tasks it has to do are not very difficult and very consistent. The material being mined is homogenous, and mining robots are not at risk at running into something that could cause them problems, such as a hard rock blocking their way, as there are none. The mining robots are attached to the bottom of the base by an inflexible pipe, which is mounted to the base by a pair of gimbals so that it can be moved relative to the base. The robot itself is mounted to the pipe by another pair of gimbals, as well as a piston which allows it to change the distance between it and the base by a few meters. When all the places it can reach have been mined, a section is added to the pipe at the base in order to let it reach a few meters further. This continues as long as practical. In addition to letting the robot push off of the base and moving it around, the pipe also lets the robot send material back to the base, and contains cables for it to be powered from the base. Once material has been sent to the base, it is compacted in order to increase its density somewhat (perhaps to $\sim 0.8 \text{ g/cm}^3$), increase its physical strength, and decrease the amount of space it takes up. The base is fueled by liquid oxygen and methane brought to it by the rockets that transport material back to the colony. This isn't optimal, but solar would regularly be cut out by the rotation of Arrokoth, and the massive parabolic dishes used for the habitats would be hard to place on the surface. If mining and compacting a ton of material takes a megajoule of energy (probably a vast overestimate, lifting a ton of material on Arrokoth a kilometer only takes 2.5 kilojoules), and the electrical generators using the methane and oxygen are 60% efficient, one kilogram of methane and oxygen is enough to mine and compact 6 metric tons of material. As it is automated, no power is needed for lighting, heating, or life support.

Material is transported from the base to the colony by cargo rockets, which also bring fuel to the base. The rockets use liquid methane and liquid oxygen in a 4:1 O₂/CH₄ ratio by weight, which should give the rockets a specific impulse of 380 seconds, which is a fairly good efficiency for a chemical rocket engine. Due to the low gravity of Arrokoth and the low orbital speed of the colony relative to the delta-v (how much the rocket can change its speed before running out of fuel) of the rocket, their trajectories are not very similar to more normal transfers, such as the trajectory taken by the Apollo rockets from the Earth to the Moon and back. Instead, the trajectory, speed, and travel time is a tradeoff between fuel use and travel time, with travel time increasing nearly exponentially as delta-v approaches the minimum to land and return to the colony (about 20 m/s). If it goes straight up from Arrokoth to the colony, gravity will slow it down by about 10 m/s, and it will be sped up by the same amount. Due to the low gravity, it does not have to accelerate very quickly, and can therefore have a very high ratio of cargo to dry mass as it does not have to withstand strong forces.

In this example, the rocket has a crew of five, a dry mass of ten thousand tons, a cargo capacity of two hundred and forty thousand tons, and starts off with 2,200 tons of fuel when it leaves the colony with no significant cargo. To save fuel, the rocket can be launched from the colony using a mass driver, which pushes on the ship using electromagnets, much like a maglev train. The colony will be slightly accelerated in the opposite direction of the ship, but this can be canceled out by the stationkeeping thrusters on the superstructure. It will leave traveling towards Arrokoth at 10 m/s, and it will reach about 20 m/s before it lands due to the acceleration of gravity. At this speed, one-way travel to or from Arrokoth to the colony should take about a day, which gives us a four-day workweek if loading cargo onto the craft, which is done automatically, takes a day or two. This ship brought in 240,000 tons of material using around 200 man-hours from the crew (not counting the time they were sleeping, eating, or relaxing) and 2,200 tons of fuel. This means that every ton of material “costs” 3 man-seconds of work from the crew and 8.6 kg of fuel (6.9 kg of oxygen and 1.7 kg of methane).

Processing of KBO Material:

Once material is offloaded, it must be processed into useful materials. The primary purpose of the colony is to produce nitrogen, so one might assume that we would only extract nitrogen from most of the material. However, almost all of the material is processed fully. This is because many other materials are needed for building the ships which transport the nitrogen and for fueling them, and because extracting all of the nitrogen requires heating the material anyways, which requires enough work that you may as well extract the other useful components instead of just throwing them all out. This starts by putting it into airtight containers capable of withstanding a decent amount of pressure. The containers are brought to the industrial cylinders and allowed to warm to room temperature. The increase in temperature causes some of the ices, mainly carbon dioxide, to vaporize, but the increase in pressure this causes makes it so most of the carbon dioxide remains liquid. At this point, the contents are a very complex mixture, consisting of solid silicates, sulfides, and organics, liquid organics, water with dissolved organics and gases, liquid carbon dioxide, and gaseous carbon dioxide. It is allowed to sit for a while in order to make sure the whole thing is melted and for reactions which destroy many of the toxic gases to take place. Formaldehyde reacts with hydrogen cyanide to form glycine, and with hydrogen sulfide to form trithiane. Ammonia reacts with sulfur dioxide to form ammonium sulfite. The exact time required for this to take place would have to be determined experimentally, but the individual reactions take place quickly in most circumstances, so it is reasonable to assume

they do not take longer than it takes for the ice to melt. It is possible that hydrogen sulfide is more abundant than aldehydes in the material, and in this case some would remain unreacted.

Once the material has been melted and the above reactions have gone to completion, the containers are depressurized. This is done from the bottom, and a fine mesh is placed over the hole it is depressurized from. This is so the liquids are pushed out from the material by the escaping carbon dioxide, but the mesh holds in the solids. As it is depressurized, the layer of carbon dioxide gas is at the top of the container because it is the least dense, and this creates a lot of pressure which expels the liquids. Most of the gases other than CO₂ which were not destroyed in reactions as it melted, such as ammonia and formaldehyde, are very soluble in water, and so do not vaporize. The CO₂ is scrubbed to remove any remaining toxic gases before being released into the habitat for it to be used by the bamboo. The solids are washed with clean water several times to remove any remaining liquids before being processed further.

The liquids form two layers. The water layer is several times thicker, and contains many dissolved organics and gases. On top of this, there is a thinner layer of liquid organics insoluble in water. The organic layer is siphoned off to be processed further and used for other purposes, as it is somewhat similar to crude oil on Earth. While they have boiling points below room temperature, due to their high solubility in organic solvents, many gaseous hydrocarbons such as ethane, propane, and ethylene will be dissolved in this, and are separated to be used in fuels and chemicals during the processing of this layer. The water layer contains a decent amount of dissolved organics and gases. These must be removed before it can be used for other purposes. Most of these can be removed by distillation. For example, methanol has a lower boiling point than water, and will distil over before water does. Glycine has a boiling point much higher than that of water, and will be left behind once the water is distilled over. However, the water cannot be fully purified this way, as some chemicals (such as ethanol) form an azeotrope with water. An azeotrope is a mixture of two compounds with a boiling point which is either higher or lower than the boiling point of both compounds. This can be dealt with by adding anhydrous magnesium sulfate to the water, which draws in water to form magnesium sulfate heptahydrate while leaving the organic components in solution. The magnesium sulfate heptahydrate can then be heated to drive off the water and leave anhydrous magnesium sulfate. Magnesium sulfate was chosen because all of its component atoms (oxygen, sulfur, and magnesium) are very abundant, it is not very reactive, and it is nontoxic. This needs to be done after the distillation, or otherwise the magnesium sulfate will be contaminated with solids dissolved in the water, such as glycine. The water will be very pure after being removed from the heptahydrate and can be used for almost any purpose, but the main ones are likely for it to be used by the bamboo or for use in pykrete for construction. The water-soluble organics can be used for many purposes, and the ammonia which was boiled out of the water is mostly converted into ammonium sulfate for the bamboo to use as a nutrient and nitric acid for another processing step.

We are now left with the solids, which consist of organics, silicates, and sulfides in approximately a 10:5:1 ratio by mass. The solids are heated to a temperature of several hundred degrees Celsius. This is similar to how oil shale is processed, and causes the remaining organics to decompose into lighter fractions, which boil off and are collected, and char, which remains, giving a ratio of about 5:5:1 char:silicates:sulfides by weight, with the char being mostly carbon and hydrogen in a 3:1 molar ratio. Many of the light hydrocarbons that are distilled off, like ethylene, are useful for plastics or other chemicals, but many, such as methane,

ethane, and carbon monoxide, are not. Assuming that 10% of the incoming solids becomes gases that are burnt gives us 5 kJ/gram of incoming material of energy generated, while heating the solids left after the water is removed to 1300 °C only takes about 1.5 kJ/gram, leaving us with a large excess of available energy. The char, silicates, and sulfides are moved to a furnace which is heated to about 1300° C using the gases from the previous step.

In the furnace, the sulfides and most of the silicates except for forsterite melt, and fayalite reacts with the char in the reaction $\text{Fe}_2\text{SiO}_4 \rightarrow 2 \text{Fe} + \text{SiO}_2 + 2 \text{CO}$. The iron contains a large amount of dissolved carbon, lowering its melting point, so it forms into drops and falls to the bottom of the furnace, where it dissolves the iron sulfides. Most other elements less reactive than iron, such as nickel, undergo similar reactions and are dissolved into the iron, as are noble metals such as gold which were always in metallic form. The carbon monoxide exhaust boils steam, generating power. Some volatile elements, such as zinc, are vaporized in the furnace and condense as their oxides in the exhaust, where they are collected.

At this point, two layers have formed: a fully liquid layer of iron with dissolved sulfur, nickel, carbon, and other metals, and a partially layer of liquid silicates (mostly silica left over from the fayalite and feldspars) covering solid forsterite and carbon. The two layers are separated and sent to different furnaces. The liquid iron has air blown through it in order to oxidize most of the sulfur and carbon dissolved in it to gaseous sulfur and carbon oxides. This heats up the molten iron, which compensates for the reduced carbon content increasing its melting point. The sulfur oxides are used to produce sulfuric acid, while the carbon monoxide and dioxide is used to boil water and generate steam. The molten iron is then cast into electrodes which will later be used for the electrowinning step.

The silicates and carbon are moved to another vessel. At high temperatures and in the presence of iron, silicon dioxide and carbon can react to form silicon (dissolved in iron) and carbon monoxide, but other silicates are more stable and will not react in this way. This is used to remove the extra silicon dioxide from the fayalite and the carbon from the mixture, so the more valuable aluminosilicate minerals, such as feldspar, can be easily removed from the fayalite. The silicates and carbon are moved to a different vessel for this because the high amounts of dissolved nickel and sulfur in the iron from that step may interfere with this process, and the iron would have to be heated to a higher temperature along with the silicates, wasting energy. Instead, there is a pool of molten iron which serves as a catalyst for this step. This requires a temperature of at least 1800 °C. This cannot be practically achieved on Earth with current technologies, but should be easily achievable with the same technologies here due to the 90% oxygen atmosphere. According to this paper, using pure oxygen blast furnace temperatures of 1800-1850 °C are practical in a blast furnace using pure oxygen and hot blast. Hot blast is when the air being blown into the blast furnace is preheated before entering the furnace, which allows for higher temperatures because less energy is needed to heat the air to the temperature of the furnace contents. Even higher temperatures should be achievable here, because on Earth the hot blast is heated with a flame in normal air (21% oxygen) with a relatively low temperature, but using electricity should allow for much higher temperatures, as we are really only limited by the melting point of the material being used in this case.

In this step, the extra silicon dioxide is reduced to silicon dissolved in iron and carbon monoxide using the carbon in the material. Some transition metals, such as titanium and vanadium, are too strongly bound to have been reduced to a metallic form with the iron in the

previous step, but will be reduced now. The carbon monoxide is used to heat the hot blast alongside the electrical heating. The pool of iron in the bottom of the furnace which serves as a catalyst for this reaction extends through a pipe into another furnace, where no materials are added. Here, air is blown through the iron to react with the silicon and the few metals removed with it to produce their oxides (>99% silicon dioxide) and heat. The silicon dioxide floats on top of the iron as slag, where it and the other oxides dissolved in it can be easily removed and cooled via dumping in water. The heat generated is used for generating electricity.

The heat in this step is high enough to melt the forsterite, and any carbon left in it is burnt in this step as well, generating heat and carbon monoxide for generating power. This leaves us with an entirely liquid mixture of silicates, which is removed into another container to cool. This container has many tubes in its side walls which have water flowing through them. The water is vaporized to steam by the heat of the slag, cooling down the slag while generating high-pressure steam which can be used to generate power. As the slag cools, forsterite is the first major component to solidify, and it sinks to the bottom of the vessel. Almost all aluminosilicates, such as feldspar, have much lower melting points, and will therefore stay in the liquid phase on top of the feldspar. It was important to remove the extra silica from the mixture earlier because it would react with the forsterite to form enstatite (MgSiO_3) as it cooled (enstatite decomposes to forsterite and silicon dioxide above around 1600 °C), which would contaminate the other silicates. The remaining liquid silicates crystallize as the temperature drops further, and finally the solid mass separates from the walls of the container as it shrinks from cooling to room temperature. Unlike the other vessels and furnaces used up to this point, which used normal firebricks like similar structures on Earth, this one pretty much has to be made of an iridium alloy. If the silicates were allowed to solidify on the firebricks, they would get stuck to the firebricks. This was not a problem for the silica slag produced earlier, as it was dumped into water and solidified before touching anything else, but if this slag was cooled the same way, the forsterite would not be separated from the other components because it would freeze too quickly. Iridium also dissolves in molten iron to some extent, so it cannot be used in places where it would come into contact with molten iron. While it is not used commonly for these applications on Earth due to its rarity, it is more common than most other refractory metals, such as tungsten, in asteroids, comets, and KBOs. It is also very unreactive with air at high temperatures, unlike tungsten, and keeps its strength at these temperatures too, with an ultimate tensile strength of nearly 70 MPa at 2000 °C. All of these materials will be processed further.

The iron will be electrowon, as mentioned earlier. Electrowinning is a process in which a metal is electroplated from an impure anode to a very pure anode, with impurities either remaining in solution or falling from the anode as a sludge. The liquid used for this will be water with iron (iii) sulfate as the electrolyte. Iron (iii) sulfate was chosen for this as it can be easily produced and is air-stable, unlike iron (ii) sulfate. During this process, pure iron is plated out on the cathode, carbon, sulfur, nickel, and other metals less reactive than iron stay in the sludge under the anode, while metals present in the iron which are more reactive than it (such as chromium) displace iron from the electrolyte and are dissolved as their sulfates. The sludge also contains some iron which fell off with the sludge before it could be transported to the cathode. The electrolyte is continually processed to remove other sulfates and replace iron (iii) sulfate that has been lost, with the metals in this fraction being separated and processed into pure metals. The anode sludge is removed, washed with water to remove the iron sulfate solution, and dried. It is then washed with hot xylene, which dissolves the sulfur, before being cooled,

decreasing the solubility of the sulfur and causing it to precipitate out. The sludge is then dried, powdered, and slightly heated under high-pressure carbon monoxide to cause the nickel to react with the carbon monoxide, forming nickel tetracarbonyl. Nickel tetracarbonyl is very volatile, boiling at just above room temperature, and is carried away in the stream of carbon dioxide, which is then heated to around 250 C. At this temperature, the nickel tetracarbonyl decomposes into very pure nickel metal and carbon monoxide. The remaining sludge, having had all of the nickel and sulfur in it removed, is now mostly leftover iron and carbon, with the other transition metals besides nickel being so much less common than iron that they are still many times less abundant than it is in the mixture, even though the vast majority of iron was already removed. Therefore, the powder is melted, has air blown through it to remove the residual carbon, and cast into electrodes for another round of electrowinning. This time, the composition of the sludge is much more balanced, with large amounts of cobalt, iron, and copper, as well as almost all of the rarer metals. The sludge is mixed with nitric acid, dissolving the more common metals while leaving most of the rare platinum-group metals behind to be processed further. Copper metal is added to the nitrate solution to precipitate all metals that dissolved but are less reactive than it (such as silver) as their metals by displacing them from solution. Cobalt is then added to this solution to remove the copper, and iron is added to remove the cobalt, leaving us with a solution of almost pure iron (iii) nitrate, which can be processed to regenerate the iron metal and nitric acid.

The silicon dioxide slag is crushed into a powder and leached with fuming sulfuric acid to dissolve the metal oxides while leaving the silicon dioxide untouched. Fuming sulfuric acid must be used because titanium does not form water-soluble salts with acids like most metals, but instead forms covalently bonded forms which react with water. However, it will react with fuming sulfuric acid to form titanil sulfate. This also dissolves the other metal oxides which are present. The metals are removed from solution to be processed further, while the silicon dioxide is basically very pure sand and can be used for the same purposes (concrete, glass, ect), as well as a component of soil.

The silicate slag is removed from the cooling vessels as a big cylinder, mostly forsterite with a layer of other minerals at the top. The other silicates are cut or chipped off from the mass, leaving us with forsterite, which can be used for several purposes. Most of it is used as an aggregate in soil or in concrete. In soil, forsterite will quickly weather into minerals such as talc and brucite, many of which are basic, raising soil pH. This can be either good or bad depending on the situation. For concrete, magnesium containing minerals are usually not a good choice for aggregates, as they can react with the calcium silicate based concrete to form magnesium silicate, causing an increase in a volume which leads to cracks. However, our concretes are based off of magnesium silicates, so this is not a problem, because replacing magnesium silicate with magnesium silicate will not change anything. The cement in concrete is another application of forsterite. The main reason magnesium-based concretes are much less common than calcium-based concrete on Earth is because magnesium-containing minerals are rarer and calcium-containing minerals in the crust, and because some of its properties are slightly inferior. However, the large excess of magnesium means that it is much more abundant than calcium here. Lastly, the forsterite can be used to create talc, one of the few clay minerals that does not contain aluminium. There are other possible uses for the forsterite, but they are minor.

The other silicates are mainly feldspar. They contain large amounts of aluminium, which is good, but the aluminium is so useful yet rare compared to silicon in the material overall that it

means it is fairly scarce. Aluminium is a very useful metal, being light, strong, and corrosion-resistant, and almost all clay minerals contain aluminium. Aluminium-containing clays are also necessary for bricks, pottery, and many other applications. Soil needs clay, as pure sand does not hold water or nutrients well and lacks strength. While it may be possible to have the main clay in our soils be talc, which contains no aluminium, totally replacing all other clays with it may make it hard for plants to grow in it. Talc definitely cannot be used for bricks and pottery, however, so aluminium is needed for them.

The feldspar is processed by separating its component elements. The first step in doing this is mixing the crushed feldspar with sulfuric acid and sodium fluoride. The sodium fluoride reacts with sulfuric acid to form sodium sulfate and hydrofluoric acid. The hydrofluoric acid then reacts with the feldspar, removing silicon from it as silicon tetrafluoride and destroying its structure, making it possible for the sulfuric acid to react with the other components. Silicon tetrafluoride is a gas, and it is then bubbled through a solution of sodium hydroxide in water. Here, it reacts with the sodium hydroxide and water to form silicon dioxide and sodium fluoride, which can be reused. The other components of the silicates form a solution of sulfate salts. While many sulfates, such as calcium sulfate, are not very soluble in water, they are soluble in concentrated sulfuric acid. The salts are removed from the acid and redissolved in water to be processed further. Very little calcium dissolves, and it can be filtered out. The remaining solution is almost entirely sodium and potassium sulfate. These can be converted to nitrates by adding calcium nitrate, precipitating out calcium sulfate and leaving the sodium and potassium nitrates in solution. The nitrates are then heated, causing them to decompose into hydroxides and nitrogen oxides. The nitrogen oxides can be used to regenerate nitric acid, and the hydroxides can be used as-is for many processes because they are all fairly similar. The calcium sulfate can be heated to high temperatures to form calcium silicate (useable for cement) and sulfur trioxide, which reacts with water to reform the sulfuric acid. The aluminium can be used for either producing aluminium metals or making clay via heating a mixture of alumina and silica gels in water at high temperatures and pressures.

Oxygen Regeneration and Power Requirements:

A large amount of carbon dioxide and monoxide is created via these processes, using up a lot of oxygen. The weight varies on how much carbon dioxide is produced vs carbon monoxide, with over a ton of CO₂ per ton of material if all burnt carbon burns all the way to carbon dioxide and around 700 kg of CO produced if all carbon ends up as that. Assuming a 50/50 split of carbon atoms ending up in either, with the carbon dioxide already in the material at the beginning included in this, gives us about 540 kg CO₂ and 350 kg CO per ton of material. This can be turned into carbon and oxygen in several ways. One is through photosynthesis, and while this is used for growing bamboo, it is very inefficient. Bamboo is grown using only the CO₂ already present in the material, as this can be removed without any carbon monoxide contamination. With about 8% of the pykrete being dry matter, if 80% of the water is used for pykrete we need 10 kg of CO₂ used for growing bamboo per ton of material. The rest of the carbon oxides are converted to carbon and oxygen chemically. This is much more efficient than using plants, but not used very often on Earth because we are not strongly limited by energy. Carbon dioxide can be electrochemically reduced to carbon monoxide and water with about 90% efficiency. However, this cannot be easily done for carbon monoxide. Instead, water must be electrolysed to form hydrogen and oxygen at about 80% efficiency, the hydrogen and carbon monoxide react to form formaldehyde, formaldehyde polymerizes to form sugars, which are

dehydrated to form carbon and water (which is used in the first part of the reaction). Overall, about 4.2 MWh of electricity are needed to convert one kilogram of carbon dioxide into carbon and oxygen, and 3.96 MWh are needed for a kilogram of carbon monoxide, with a total of 3.65 MW of electricity needed per day per ton of material.

Unlike for the power generation inside of the habitation cylinders, power generation for the industrial cylinders is done using solar thermal instead of photoelectric power generation. This is because the efficiency of heat engines, such as used in solar thermal power generation, is directly related to the difference in temperature between where they are getting power from and where they are cooling off. Inside the habitation cylinders, where it is hard to heat things to high temperatures using light and heat is rejected at room temperature, they are less efficient than solar panels, but in space it is very easy to focus light finely enough to get things very hot, and the heat can be radiated away at much cooler temperatures. In this case, power is generated by blowing gas through a target heated to very high temperatures by sunlight, which makes it expand, spinning a turbine. The expanded, hot gas then passes through a radiator behind the parabolic mirrors which focus light on the target. If the target is at 2300 K and the radiator at 150 K, the theoretical maximum efficiency is 93.5%. We will assume we will only get 80% of this, which is a bit better than currently practical but not by much, for an overall efficiency of 75%, three times better than the solar panels in the habitat.

With these numbers, each ton of material processed per day requires about 45 m² of area for growing bamboo, which is 4.3 kW of raw sunlight and therefore about 10,600 m² of aluminum reflectors, as well as about 320,800 m² of reflectors for power generation. If the whole area from 83.2 km radius from the habitat to 249.6 km radius from it is used for this purpose, about 530,000 tons of material per day can be processed. This is 194 million tons per year, but as some power would have to be used for other purposes, we will assume that only 180 million tons of material are processed per year. This includes 13 million tons of iron, 23 million tons of water from water ice (not including water produced via other reactions, such as combustion), 1.8 million tons of nitrogen, 650 thousand tons of aluminum, 190 thousand tons of chromium, 30 thousand tons of titanium, 9.5 thousand tons of copper, 85 tons of platinum, 16 tons of gold, 36 tons of iridium, and just under three tons of combined uranium and thorium. The people living in this habitat have plenty of raw materials to work with, and are definitely not poor - just the gold and platinum alone would generate an annual income of around four billion dollars at current prices. They do not have to worry about running out of material anytime soon - at this rate, it would take the colony tens of thousands of years to process all of Arrokoth's material, and even if the number of colonies doubled every 25 years it would still take many centuries.

Trade and Transportation between Colony and the Inner Solar System:

The distance between the colony and the inner Solar System is very large, at about 44.6 AU or 6.7 billion kilometers between Arrokoth and the Sun on average. At this distance, it takes light about 6 hours to travel from the colony to Earth or vice versa, meaning that a question to Earth will not get a response back for half a day after being asked. Transportation will take even longer, especially when limited to present technology. Fortunately, travel will not take quite as long as it did for NASA's *New Horizons* probe, which flew past Arrokoth well over a decade after it was launched. Ion and VASIMR engines are far more efficient than chemical rockets, allowing us to be freed from the constraints of efficient but slow transfer orbits which craft powered by chemical rockets, such as *New Horizons*, use. The main issue with these forms of propulsion are the fact that they produce little thrust, although their high efficiency means that they can reach much higher speeds in the long term, and that they require massive amounts of electricity to function. While the low thrust is not a concern due to the fact that they have plenty of time to burn all of their fuel at these distances, the power requirements are another concern. At these distances from the Sun, the only real sources of power for craft using these engines is solar concentrated by reflectors or nuclear power. The huge reflectors for solar pose a problem, and the miniscule amounts of thorium and uranium in KBO material means that these will likely have to be imported from the inner solar system, where they occur in relatively high concentrations in the crust of rocky planets, which will cost money.

To calculate how long travel will take, we first must calculate the delta-v of the craft we are using. Delta-v is a number stating how much a craft can change its velocity by before running out of fuel, and is calculated from the exhaust velocity of the rocket engine being used and the percentage of the spacecraft's initial weight that is fuel. Exhaust velocity in a vacuum with zero external pressure is dependent on the average molar weight of the exhaust from the rocket engine, the temperature of the exhaust inside the engine, and the isentropic heat-expansion figure of the exhaust. In this case, we will assume that all of these engines are of the VASIMR type. VASIMR uses radio waves to heat the propellant gases to extremely high temperatures, before expelling them out of a magnetic rocket nozzle. A normal rocket nozzle cannot be used, due to the extreme temperature of the exhaust. This type of engine is not used as often as electrode-based ion engines, but it is preferable in this case due to the lack of electrodes, which would be eroded by the exhaust if present. The temperatures of current VASIMR engines are often in excess of one million degrees Kelvin³², so a temperature of 2.5 million degrees Kelvin by this time seems reasonable. This high temperature means that all substances in the exhaust will become an ionized plasma of individual atoms, as the high temperature destroys all molecules, increasing exhaust velocity by decreasing molar mass of the exhaust and simplifying the calculations by giving the exhaust gases an isentropic heat-expansion figure of about 5/3 (the value for a monatomic ideal gas).

There are four major propellants that seem likely to be used for propelling these types of engines, which will be listed below.

³² *High-Power Electric Propulsion with VASIMR® Technology*. Ad Astra Rocket Company, www.unoosa.org/documents/pdf/psa/hsti/CostaRica2016/2-4.pdf.

	Formula	Avg. molar mass of exhaust (g)	Exhaust velocity (km/s)	Specific impulse (seconds)	Density (g/cm ³)
Oxygen	O ₂	16	80.6	8,200	1.14 @90 K
Coronene	C ₂₄ H ₁₂	8.33	111.7	11,400	1.37 @ 300 K
Methane	CH ₄	3.25	178.8	18,200	0.42 @ 120 K
Hydrogen	H ₂	1	322.3	32,900	0.07 @ 20 K

Hydrogen has the highest efficiency by far, but has many downsides. Hydrogen is in high demand, and is needed for many other purposes. It also has a very low boiling point and density, and causes many metals to become brittle when exposed to it for long periods. However, its much higher efficiency means that it will likely be used on craft with people on them, to reduce travel time. Methane has a higher boiling point and density, but still needs to be cooled and is less efficient than hydrogen. Coronene has a high carbon:hydrogen ratio while still being volatile enough to easily pump into the engine, but is less efficient than methane and is solid until about 200 degrees Celsius. This will likely be used in cases like bulk cargo, where time is not super important relative to cost. Oxygen is a bad choice in the outer Solar System, but it is likely to be very abundant in the inner Solar System, where separating metals from silicate minerals will produce large amounts of it as a side product. Therefore, many ships may be easily converted between using methane and oxygen as fuel depending on what part of the Solar System they are in. The densities were given at the boiling points of the substances, except for coronene where the density at room temperature is given.

The ratio of fuel mass to the rest of the ship is also very important. If a ship is only a few percent fuel, it will not be able to accelerate much before running out of fuel, even if it is very efficient. Travel time is very hard to predict accurately in these cases, as the acceleration of the ship will increase as its mass decreases over time, and it will also be affected by the gravity of the Sun and planets. However, the delta-v of these ships is large enough that the gravity of the Sun is a secondary factor, and a decent approximation can be achieved by just assuming it smoothly accelerates towards its target halfway, then flips around and decelerates at the same speed. The time for this can be found by making a triangle whose area is the distance traveled, and whose height is the maximum speed of the craft. The length of its base is then the amount of time the voyage took. The following table is a list of travel times from Arrokoth to the Inner Solar System for a few selected fuels and fuel:mass ratios of ships estimated using this method.

	Hydrogen	Methane	Coronene
90% fuel at start	1 yr 2 m	2 yr 1 m	3 yr 3 m
75% fuel at start	1 yr 11 m	3 yr 5 m	5 yr 5 m

From this, it seems like the minimum practical travel time for craft carrying passengers from the colony to the inner Solar System or vice versa is about a year, and most cargo will take about 2 to 5 years. This is really not that bad when compared to travel in the past. For example, Magellan's circumnavigation of the world took three years, and many 49ers took over half a year to travel across the country to California during the Gold Rush. The conditions on the craft

ferrying potential colonists to and from the colony would also likely be much better than these travellers endured. For cargo, many people have no problem investing in bonds that take decades, not just a few years, to pay out, so after the first few shipments arrived reliably there should be little problem in that regard.

However, the voyage is still long enough that most craft would likely have to spin in order to prevent the health effects of microgravity from severely affecting the passengers, and would have to have a decent amount of space and people on board them to prevent disaster. Critical roles, such as doctors and mechanics, would almost certainly at least need two people per ship, as the chance of one dying from a heart attack, stroke, accident, or other unpredictable event is not negligible over this time period, even with good conditions onboard the ship. A decent amount of space and people would also likely be necessary to prevent the passengers from going insane. While a few people have stayed on the International Space Station for this long without a mental breakdown, they were specially selected and trained for that job for years. Therefore, all ships carrying people these distances will likely have a few things in common. The vast majority of their volume will be tanks storing liquid hydrogen, as it has a very low density and therefore takes up a lot of room. They will all likely use VASIMR or similar engines due to their high efficiency. The section containing the living quarters of the passengers and crew will likely be in the form of a dumbbell or torus at least a hundred meters in radius and tens of meters wide. This size is necessary to allow a rotation of only a few RPM to simulate 1 G of apparent gravity, and to provide enough space for the number of people on board. This number will likely be at least one hundred, enough to ensure that all absolutely critical crew roles have a backup while still having more passengers than crew. They will almost always be powered by breeder fission reactors using either thorium or uranium to breed fissile uranium-233 or plutonium-239, respectively. The small amount of naturally occurring fissile uranium-235 relative to thorium and uranium-238, which are not fissile but can be converted to fissile isotopes in a breeder reactor, necessitates that breeder reactors are used. Nuclear reactors will be able to provide a constant, reliable amount of electricity for a long time no matter how far from the Sun they are, unlike solar which will generate massively more or less electricity if its distance from the Sun changes by more than a slight amount.

Craft which carry cargo will likely use methane or coronene for fuel, depending on what their cargo is. Relatively valuable cargo where travel time is more of an issue, such as computer chips or nuclear fuel, will likely use methane due to its balance between the efficiency of hydrogen and the ease of storage and cheapness of coronene, while bulk cargo such as nitrogen will likely use coronene. Coronene has one of the highest ratios of carbon relative to other atoms for a relatively simple molecule that is still somewhat volatile. Ideally, cheap waste carbon would be used, but it is extremely hard to melt or vaporize. While the extreme temperatures of the plasma in the engine would still totally vaporize it, it would be very hard to get it into the engine in solid form in the first place. If you just threw big chunks of carbon into the engine, the low density of the plasma means that lots of the carbon would likely be ejected from the engine before being fully heated or vaporized, massively reducing efficiency. Meanwhile, coronene can be vaporized much more easily and injected into the engine, where it will mix and heat very well. They will also likely use solar power instead of nuclear, where the variable power output can be compensated for by changing the size of the reflector, and it is less important for the engines to operate at full thrust all the time than for passenger craft, where time is critical.

As stated many times earlier, the main export of *Stern* and similar colonies will likely be nitrogen. Its main imports from the inner Solar System will likely be noble gases, nuclear fuel, and goods such as computer chips which require very large, advanced, and expensive facilities to produce. Due to their lack of a gravity well and atmosphere, small Kuiper Belt objects are almost entirely lacking in noble gases, which stay volatile down to very low temperatures. While not depleted in uranium and thorium relative to the solar nebula, the surface of the inner planets is heavily enriched in these elements relative almost everything else in the Solar System due to geological processes such as volcanism concentrating them there, much as those processes depleted their crusts in elements such as gold. The low concentration of these elements in most areas means that they will likely be unable to meet their needs for them just from the material they mine and process themselves, and importing it will therefore likely be necessary. The fabrication of computer chips and other complex integrated circuits currently requires massive facilities often costing billions of dollars, and the price and complexity of these facilities will likely get even higher in the future as their complexity increases. Therefore, fabricating cutting-edge chips will likely be out of the reach of the relatively small colony, as the facilities required would use up most of its resources. However, if larger habitats with millions of inhabitants or collections of dozens of habitats the size of *Stern* with combined populations of million become common in the Kuiper Belt, it would require a smaller proportion of their resources to construct these facilities. Therefore, it may be the case that only relatively small colonies import large amounts of these goods, before they become large enough to produce them on their own.

Research Opportunities:

Although the *Stern* and likely most other colonies in the Kuiper Belt will be focused on industry and not on research, colonies in the Kuiper Belt will be very useful to science due to their distance from other population centers. This will have the most benefit for two main areas. Firstly, many astronomical observations which rely on taking measurements from multiple locations work better if the distance between these locations is larger. Secondly, many dangerous technologies can be more safely handled if far from large population centers, such as inhabited planets.

There are two main types of astronomical observations likely to extensively utilize colonies in the Kuiper Belt. Firstly, the measurement of the distances to other stars using parallax will be much more accurate using two telescopes on the opposite sides of the Kuiper Belt than satellites near the Earth. Parallax works by measuring the apparent position of a star or other object from two different locations and measuring the difference in location. How far distance can be measured this way and how accurate these measurements are depends on both the resolution of the telescopes being used and the distance between them, as higher resolutions allow smaller angles to be measured and larger distances increases the size of the angles. The resolution of the telescope is limited by the effective size of its aperture and the wavelength of light it uses. The effective size of its aperture can be increased via interferometry, where the interference pattern of light from two telescopes can be used to simulate the resolution of a telescope as large as the distance between the two telescopes. However, this is limited because it will only collect as much light as hits the two telescopes, meaning that many objects can be too dim to see with small mirrors, and any vibration can mess up the interference pattern, making it useless. However, the zero-g environment should make fabricating large

mirrors easier, as they will not be distorted by gravity, and vibrations can be almost entirely eliminated by separating the telescope from all other structures.

We will assume that by this point there are two identical telescopes located on opposite sides of the Kuiper Belt, 100 AU apart. Each one has the resolution of an aperture a hundred kilometers wide, achieved via locating two smaller telescopes at least this far apart and using interferometry to achieve an effective resolution this large. They collect the same amount of light as an ideal telescope with an aperture 200 meters wide, enough to detect a star as bright as the Sun about 4 million light years away³³. The effective resolution will be about 6 picoradians in visible light at this size. At this resolution and separation, it will be able to detect the parallax of stars over 200 million light years away, and determine the distance to stars in the Andromeda galaxy with an error of about 1%. It will be able to create a 3-D distance map of all stars in the Milky Way visible from Earth, and not obscured by the galactic core, nebula, or other opaque features, to better than 0.05% distance inaccuracy. This large distance could also be useful to gravitational wave astronomy. Current gravitational wave detectors are currently not able to detect the direction of gravitational waves very well by themselves. Instead, the difference in timing between when the waves arrive at different detectors allows for the direction of the source to be triangulated. A larger distance between detectors should make it possible to triangulate the direction of the sources more accurately. These would likely not be attached to the main habitat, as the reflectors would block much of its view, and activities on the main structure would create lots of vibrations that would mess up measurements. Instead, they would be separate, free-floating structures located in orbits farther from Arrokoth.

The distance from major inhabited planets should also allow for some research to be done with fewer risks. The main area that would benefit from this would be certain proposed propulsion technologies that may allow for very high velocities to be reached, but emit very large amounts of radioactive exhaust. These are nuclear pulse propulsion and fission fragment rockets.³⁴ Both of these allow for extremely high exhaust velocities and efficiencies, but release huge amounts of extremely radioactive exhaust. Nuclear pulse propulsion involves the detonation of large amounts of nuclear devices, which also can cause EMPs that can damage electronics. However, as long as they travel a decent distance from the colony, they should be able to use these propulsion methods with very little risk of endangering uninvolved people.

Habitat Management:

As this is intended to be fairly general, this will not go into very much detail into the government of the colony. Many different political systems could build these sorts of habitats. However, there will be some characteristics in common to all of these. The large distance between the colony and the inner solar system means that it will, at minimum, be quite autonomous. People living in the colony cannot be sent to courts or jails in the inner Solar System a year's travel away, if the colony is even part of a country based in the inner Solar System. It is fairly likely that they will become entirely independent. It would be quite hard for a nation in the inner Solar System to retake a rebel colony this far out, as their approach would be

³³ "Limiting Magnitude." *Limiting Magnitude Table*, www.twcac.org/Tutorials/limiting_magnitude_table.htm.

³⁴ Dickson, Paul, and Bruce Schnitzler. "FISSION FRAGMENT ROCKETS -- A POTENTIAL BREAKTHROUGH ." *Idaho National Engineering Laboratory* .

detected well before they arrived to the colony, and resupplying ships would take a very long time. Additionally, economic sanctions are not likely to be very effective, as KBOs have a very diverse set of resources.

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