

# Habitable Conditions Required for Space Settlement

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## Abstract

Space colonization is an advanced scientific and technological endeavor aimed at creating Earth-like environments beyond our planet. It supports deep-space research, enhances Earth's economy through space-based industries, and ensures the long-term survival of humanity. First proposed in 1969, the concept of space habitation has evolved through various models, with the Stanford Torus—a donut-shaped habitat—emerging as the most feasible design. This study proposes a modified dual-torus model, where the upper torus accommodates human habitation, agriculture, and commercial zones, while the lower torus is dedicated to waste management and industrial operations. We examine the structural modifications and explore sustainable technologies, including advanced closed-loop systems, water recycling showers, and methane-based bioplastics. Our findings highlight the viability of this design in creating a self-sustaining habitat, providing insights into the infrastructure and operational strategies required for long-term space colonization.

## 1. Introduction

### 1.1. Background

Space colonization has been a subject of intense interest for ages owing to its potential for advancing deep space research, ensuring humanity's continued survival, and creating economic opportunities. With the idea to create an artificial habitat that would stimulate earth-like conditions, the concept of space habitats was first proposed by Herman Oberth in his book "The Rocket into Planetary Space" in 1923. His idea involved a wheel-shaped station that would rotate to replicate earth-like gravity. Upon further study space habitats like The Bernal sphere, The O'Neill cylinder, and The Stanford Torus were proposed gradually. These habitats used similar principles to generate gravity but they differed in their shapes, capacity to hold population, and uses. The Bernal sphere was a smaller spherical structure that held the capacity of a smaller population and could be considered for temporary stay for research purposes rather than a mass

settlement. The O'Neill cylinder, though could hold a large population, was still discarded due to its complex heavy cylindrical structure. Upon considering all the factors like population capacity, simplicity in structure, and linked term settlement in space, the donut-shaped habitat proposed by Stanford- the Stanford torus- becomes the most acceptable framework for the settlement.

Space settlement is a futuristic concept yet very crucial to study because of its implications:

- The continued survival of humanity: Earth is facing severe climatic changes, and these will likely worsen in the coming decades. Therefore a permanent space offers a backup for the survival of humanity.
- Advanced research opportunities: It will aid in deep space research and longer-duration missions.
- Economic Opportunities: Advanced technologies to build such habitats will also help develop space-based industries. Further research can also devise methods for asteroid minings which would boost Earth's economy.

In this paper we have kept the framework of the Stanford torus with a few structural changes. Here we aim to keep the donut-like structure of the torus and laterally divide it into two parts: 1) the upper part for the residential area and 2) the lower part for the industrial area. This is to keep the industries away from the residential area for safety and better environmental quality.

## 1.2. Objective

Since resources are limited in space and self-sufficiency is essential, effective waste management becomes even more important. It could be a deciding factor in suggesting the feasibility of making such a habitat. Here are some key considerations for waste management in a space habitat:

1. Closed-Loop Systems: Space habitats aim to achieve closed-loop systems, where waste is transformed into resources for other processes. For example, organic waste can be composted to produce fertilizer for plant cultivation, which in turn provides food and oxygen for the inhabitants. A present-day example is the International Space Station, where a closed-loop system is used to sustain the crew over a period, minimizing the need to resupply from Earth. Implementing closed-loop systems helps minimize resource consumption and waste generation.
2. Waste-to-Energy Conversion: Waste-to-energy technologies can be employed to convert non-recyclable waste into useful energy. Technologies like incineration or gasification can generate heat or electricity from waste materials, providing power for various systems in the habitat. Incineration involves the combustion of

organic materials in waste at high temperatures, resulting in the production of heat, ash, and flue gases with an efficiency of 85% when combined with heat and power systems. Gasification converts organic or fossil fuel-based materials into syngas—a mixture primarily composed of carbon monoxide, hydrogen, and carbon dioxide—by reacting the material at high temperatures (>700°C) with a controlled amount of oxygen and/or steam with an efficiency of 90% when combined with heat and power systems. The syngas can be used for electricity generation or as a fuel.

3. **Efficient Storage and Transportation:** Proper waste storage and transportation systems are necessary to manage waste within the limited space of a habitat. Compact and secure storage solutions should be designed, considering factors like waste volume, weight, and potential hazards. Therefore, the space habitat should be divided into two sections: one (upper ring) for residential purpose and second (lower ring) for waste management. This will help prevent hazards and will also provide enough space for effective storage, transportation and recycling of the waste.
4. **Water Recycling and Purification:** Water is a critical resource in space habitats, and efficient water management is vital. Advanced water recycling systems are required to treat wastewater and condensation, making it safe for reuse. Techniques like filtration, ion exchange, and reverse osmosis can be employed to purify water.

## 2. Structure of the Space Habitat (Torus)

### 2.1. Two-Tier Structure of the Habitat

The structure of the space habitat will be similar to that developed by Stanford University (Stanford Torus) (The 1975 Summer Faculty Fellowship Program in Engineering Systems Design. Space Settlement et al.), except for another different torus that will connect to the previous one via the central hub with spokes for transportation attached to both the toruses running parallel to each other.

The upper torus will consist of human settlements like residential areas, commercial areas, and space for agriculture, etc. The lower torus will uphold the industries, waste management units, and emergency rooms and health care facilities for the workers in case of immediate care for injuries. These accommodations are intended for occasional use to ensure that support is readily available when needed, without the necessity of being a permanent resident. This arrangement will separate the sources of pollution from the residents.

Upper torus	Lower torus
Accommodation, transport, commercial, health facilities, educational facilities, agriculture, and recreational facilities.	Industries, waste management units, emergency housing units, and emergency health care facilities.

TABLE 1. Illustrates the facilities available in each of the torus.

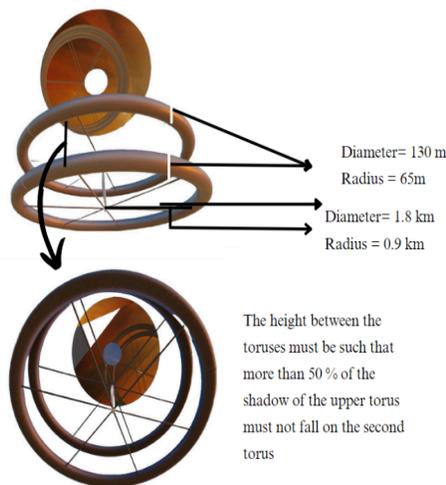


FIGURE 1. Arrangement of the torus and their dimensions.

## 2.2. Upper Torus

### 2.2.1. Phase 1

Imagine dividing the torus into four quadrants: the first quadrant will receive the least sunlight, the third quadrant will receive the maximum light, and the second and fourth quadrants will have relatively less sunlight. Thus, we will design the settlement in a way where the residential and mixed residential areas will be present in the second and fourth quadrants, commercial places and research labs will be in the third quadrant, and agriculture and non-polluting manufacturing units will be present in the second quadrant. Since rotation alone does not guarantee uniform sunlight distribution, and some regions will naturally receive less direct light due to the torus's orientation, agriculture is placed in the second quadrant, where controlled artificial lighting and reflective mirrors can be used to optimize plant growth. With this design, as the torus rotates, the residential areas in either the second or fourth quadrant will receive sunlight (i.e., have a day), but will never experience day and night simultaneously. It means that at a time, half of the population will always be awake and working. Thus it will increase the productivity of the industries efficiently.

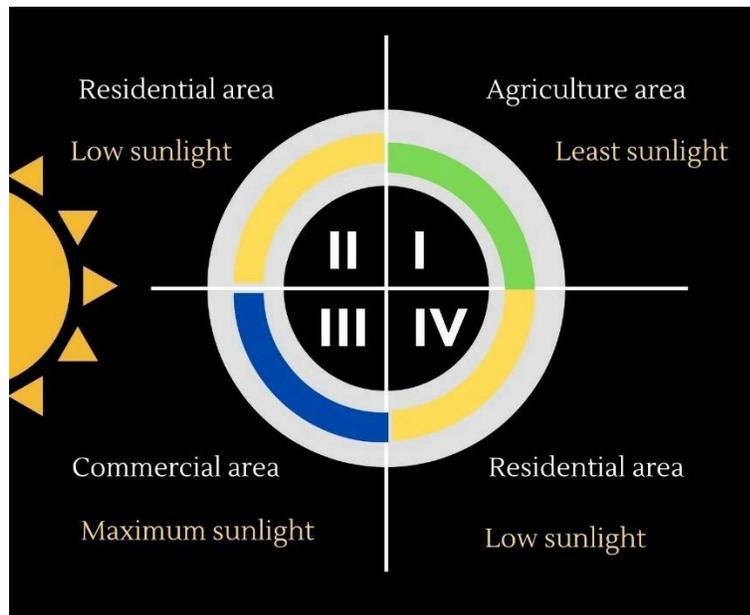


FIGURE 2: Division of the torus based on sunlight it will receive.

Space utility	% of the area allotted
Residential	< 30%
Commercial	20 % - 25 %
Recreation	15 % - 20%
Transport	Up to 10%
Agriculture	15 % - 20%

TABLE 2. Utility of space in the toruses

### 2.2.2. Phase 2

Casting a generalized view on the settlement of the upper torus, instead of dividing it into four distinct quadrants, we must divide it proportionately based on the requirements. The residential areas will not be purely residential since it will cause monotony; Rather, they will be mixed residential with small grocery shops, stationery shops, nursing homes, and recreational areas. The grey areas between the two mixed residential and agriculture will reside the animal husbandry. That way, it will increase the proximity of animals to their food sources.

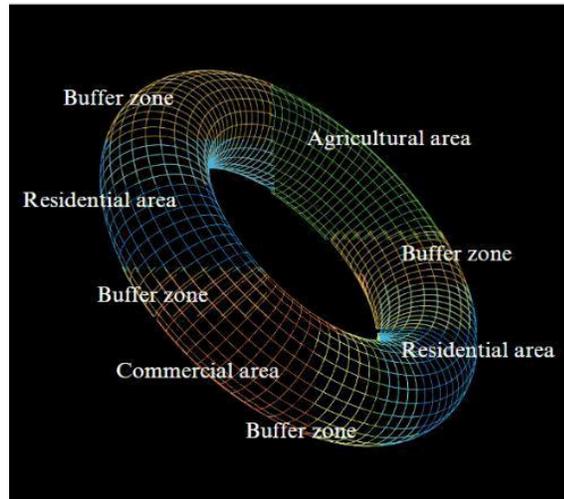


FIGURE 3: This shows the area allotted for the specific places/fields of work are nuanced, and proportions can change accordingly. The transition area between the agricultural land and residential place lies the animal husbandry.

### 2.3. Lower Torus

The lower torus will comprise heavy industries and waste management units. It will also contain small mixed residential areas with hospitals, housing areas, and stationery shops. The residential area will be for temporal or emergency use, not for permanent settlement since the lower torus would aim to reduce human exposure to pollution.

### 2.4. The Central Hub

The Central Hub will be used for docking spacecraft and transporting them from the upper torus to the lower one. Vacuum-propelled capsules (vertical hyperloop) will be used for transportation: some for raw materials, and industrial goods, and others for human transportation. Approximately 18 such hyperloops need to be placed in the central hub. Out of which, six will be for human transportation, six for raw material, and another six for waste material. There are six spokes each (12 spoke total) for connecting the central hub to each torus. In case of maintenance or breakdown, additional hyperloops ensure uninterrupted transport, while emergency evacuation and medical transport require spare capacity, making 18 hyperloops a practical number.

According to the studies conducted by Stanford University (National Space Society, 1977, Space settlement: A design study) the weight of the structure proposed by them is 10 million tons. Thus it is assumed that the total weight of our upgraded habitat (i.e. two torus) will be approximately 20 million tons. To keep all the other external factors the same, we need to have the mass of both the torus the same.

Since  $\text{Mass} = \text{Volume}(V) \times \text{density}(D)$ , the torus' volume and density must be equal. It can be done by adding/ removing the research labs in the torus to keep the balance.

- $V_1 \times D_1 = V_2 \times D_2$ ,

where  $D_1$  is the density of all the accommodations on the upper torus, and  $D_2$  is the density of all the accommodations on the lower torus.  $V_1$  is the volume of the upper torus, and  $V_2$  is the volume of the lower torus.

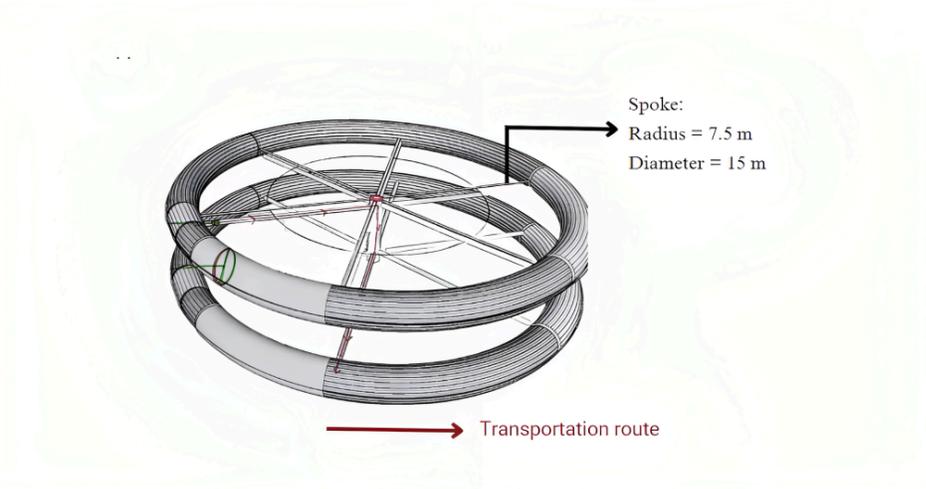


FIGURE 4: Show the dimensions of the spokes and the transportation route between the upper and the lower toruses.

## 2.5. Hyperloop

The 18 hyperloops will be used for transporting humans, goods, waste, and raw materials. The hyperloop transport system contains two main components: the hyperloop capsule and the tube. The capsule will move through the partially vacuumed tube due to the pressure difference.

Dimensions of hyperloop capsule (approx):

- The diameter of the capsule is 4.4m.
- The length of the capsule is 2.4 m.

The capsule length should be between 2.1m to 3 m. It would fit the average human height and simultaneously increase the efficiency of the capsule. Thus, an optimum height of 2.2m has been chosen since the lesser the length, the lesser the friction will be, and therefore, the more effective the transportation system will become.

### 3. Waste Management:

#### 3.1. Sources of Waste:

For the space habitat to be a desirable alternative for living, machines must run to produce the required things we have on Earth in the habitat itself. Along with the residential waste materials, unwanted substances will add up to create pollution. It will soon become a potential source for spreading disease

Thus for waste management, effective methods are devised to avoid contamination. In 1989, the U.S. Environmental Protection Agency (U.S. EPA) adopted a hierarchy of waste management practices (Henry & Heinke, 2008). Its elements are:

- Source reduction
- Recycling of materials
- Combustion

Similar protocols can be adopted in the space habitat.

Source	Typical Waste Generators	Type of Solid Waste
Residential	Household activities	Food waste, paper, cardboard, plastics, wood, glass, metals, electronic items, etc.
Industrial	Manufacturing units, power plants, process industries, etc.	Housekeeping wastes, hazardous wastes, ashes, special wastes, etc.
Commercial & Institutional	Hotels, restaurants, markets, office buildings, schools, hospitals, prisons, etc.	Bio-medical waste, Food waste, glass, metals, plastic, paper, special wastes, etc.
Construction and Demolition	New construction sites, demolition of existing structures, road repair, etc.	Wood, steel, concrete, dust, etc.
Municipal services	Street cleaning, landscaping, parks, and other recreational areas, water and wastewater treatment plants.	Tree trimmings, general wastes, sludge, etc.
Agriculture	Crops, orchards, vineyards, dairies, farms, etc.	Agricultural wastes and hazardous wastes such as pesticides

TABLE 3: Depicts the categorization of wastes based on source and type

### 3.2. Waste Segregation

This step is crucial to make waste treatment easier. Wastes will be segregated into three categories: biodegradable, non-biodegradable, and E-waste, to improve the performance of waste treatment units due to the good quality of feed and lesser impurities.

Practicing the 3Rs:

- Reduce: portable electronics will play a major role in the education system in addition to enhancing communication, health

monitoring, and entertainment. Thus increasing the efficiency of these devices will help to reduce the generation of E-waste.

- Reuse: it is necessary to reuse most of the goods available to the residents to reduce the amount of waste generated. This can be encouraged by establishing communal libraries for tools, appliances or other items and designing electronics and furniture that can be disassembled and reused.
- Recycle: Recycling waste will have a big contribution to managing biodegradable waste. Utilizing biodegradable waste to make manure is the best way to grow plants using organic fertilizers (Abhishek Nandan et al., 2017).

#### Treatment of the Non- biodegradable wastes and E-wastes

- Incineration: It is drying and burning waste to release heat, CO<sub>2</sub>, ash, and H<sub>2</sub>O (vapor). This process releases a large amount of heat which can be a source of energy generation. The calorific value must fall between 1200-1400 kcal/kg for energy generation. However, a disadvantage of incineration is that it releases toxic pollutants like CO, SO<sub>2</sub>, HCl. Thus, filters and detoxification should be used to minimize the effects.
- Pyrolysis: It is a thermal degradation process in the absence of air which yields recyclable products such as char, oil/wax, and combustible gases. It is used for treating wastes having less moisture in them. However, to treat the wastes having higher moisture content, more heat is required. Based on consumption, the total heat can be divided into three types: Q1 (10–30%) is the amount of heat required for moisture vaporization, Q2 (50–70%) refers to the caloric requirement of pyrolysis, and Q3 (5–20%) is the radiation loss during the process (Jerzak et al., 2022). To efficiently manage this heat in a space environment, moisture vaporization heat (Q1) can be recovered using phase-change materials or redirected into water-recycling systems. The heat needed for pyrolysis (Q2) can be preserved through thermal insulation. Radiation losses (Q3) can be minimized using reflective coatings and dissipated via external radiators and heat pipes. The advantage of using pyrolysis is it has very little effect on environmental pollution. ( Bert Van de Beld et al, 2013).

### 3.3. Energy Content in Municipal Solid Waste

The bomb calorimeter calculates the energy content in the waste. An average of 95 m<sup>3</sup> CH<sub>4</sub>/tonne, having a 19.43 MJ/m<sup>3</sup> calorific value, can

be extracted from the MSW. However, this amount depends upon the composition and moisture content of the waste.

Khan and Gharrarah et al. have developed an equation that predicts heating values based on paper and food fractions plus a term that accounts for plastic, leather, and rubber (1991):

$$\text{HHV (kJ/kg)} = 53.5 (F + 3.6 \text{ CP}) + 372 \text{ PLR}$$

where F is food, CP is cardboard and paper, and PLR is plastic, leather, and rubber, all expressed as mass percentages (Abhishek Nandan et al., 2017).

This proves that waste-to-energy conversion can provide a sustainable energy source. By optimizing waste segregation and processing—especially controlling moisture levels and maximizing high-energy-content materials like plastics and paper—space settlements can generate renewable energy for life-support systems, heating, and power generation. This closed-loop approach minimizes waste buildup while enhancing self-sufficiency.

### 3.4. Analysis of the Amount of Waste Generated and the Workforce Required to Run the Waste Management Unit

#### 3.4.1. Animal Waste:

Based on the diet required by the people living in the habitat, an approximate measurement of the number of animals required is made. And thus, the amount of animal waste, along with the other wastes, is measured.

Type Of Animal	Approximate Number	Amount Of Waste By One Animal Of Each Species Per Day	Amount Of Waste By Approximate Number of Each Species per Day
Cow	265	24 kg	6360 kg
Sheep	650	2.5 kg	1625 kg
Pig (100lb)	100	2.7 kg	273 kg
Hen	40	0.1 kg	4 kg
			<b>Total: 8262 kg</b>

TABLE 4: Approximation of the Number of Animals That Can Be Kept in the Torus and the Amount of Waste Generated

#### 3.4.2. Human waste:

The average solid waste generated per person per day = 200g (approximated). Thus, the total solid waste generated by the 10,000 population per day =  $10,000 \times 20 = 20,00,000 \text{ g} = \mathbf{2000 \text{ kg/day}}$  (approximated).

#### 3.4.3. Biodegradable plastic waste

The two types of bioplastic are PLA (Polylactic acid ) and PHA ( polyhydroxyalkanoate ). The PLA is made of corn by submerging corn kernels into sulfur dioxide and hot water to give starch, protein, and fiber. PHA is made with the help of microorganisms that provide plastic from organic material. Since biodegradable plastics are safe, they are used for one-time food packaging and medical purposes such as bone plates. According to the studies conducted in California, food waste; crop waste; garden waste; and paper waste are being converted into PHA, which will eventually be made into plastic (Renee Cho, 2017). Another type, as researched by Stanford University and startup Mango Material, uses methane gas to produce PHA through plastic-producing bacteria. They emit less amount of carbon dioxide than traditional plastic. (Renee Cho, 2017). The produced PHA can then be used to make plastic products for daily use such as bottles, plastic caps etc. It can also be converted into bio-polyester fibers and mixed with natural materials to make clothes. The PHA bioplastics decompose under anaerobic conditions, producing carbon dioxide and methane. This closed cycle would help keep the plastic waste in the habitat under control.

Biodegradable plastic can be used for packaging, medical implants, 3D printing, etc. Total biodegradable plastic waste generated = **150 g/day** (approximated).

#### 3.4.4. Biomedical waste

Category:

1) Yellow:

*Type of bag (yellow non-chlorinated)*

Waste type:

- Human anatomical waste, human tissue, and body parts.
- Soiled waste - cotton, dressing, linen, plastic, blood bags.
- Discarded medicine, expired medicine, cytotoxic drugs, and their contamination.
- Chemical waste - chemicals used in the production of biological products, discarded disinfectants.
- Chemical liquid waste- Lab washing, cleaning waste
- Microbiology, biotechnology, and other clinical laboratory waste

2) Red:

*Type of bag (red non-chlorinated)*

Waste type:

- Solid waste: tubing, urine bag, a syringe without needle.

3) White:

*Type of container (white translucent)*

Waste type:

- Sharp waste, including metal.
- Type of bag: puncture and leakproof container.

4) Blue:

*Type of container (blue hard container)*

Waste type:

- Any type of glassware

Biomed waste for 300 beds in a hospital per year:

- Yellow color: 11,553.66 kg/year
- Red color: 11,819.01 kg/year
- White color: 7,61.10 kg/year
- Blue color: 2200.80 kg/year

Total waste for 300 beds in a hospital per year: **12473 kg/year**  
(approximated)

3.4.5. Agricultural waste

Per head per day food grain required = 300 g (approximated)

10,000 population needs = 10,000 X 300 X 365 g food/year  
(approximated)

20g grain generated 50g waste

(10,000 X 300 X 365) g grains generate ( 50 X 10,000 X 300 X 365) / 20  
= **2,737,500 kg/year** (approximated)

4.4.6. E-Waste

Total e-waste= **7000 kg/year** (approximated)

From which the amount of plastic = 1400 kg/year (approximated) (Renee Cho, 2018)

And the amount of metal = 4200 kg/year (approximated)

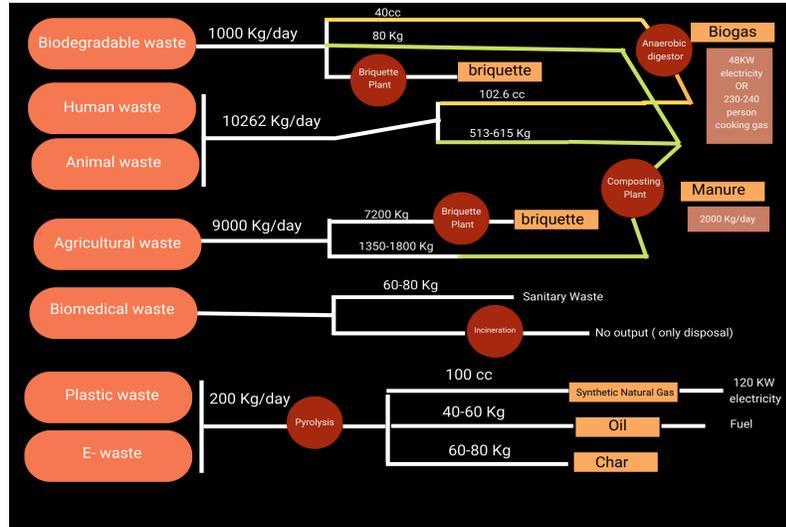


FIGURE 5: Overview of the waste management system along with the sources for obtaining energy

#### 4. Analysis of Water, Workforce, and Power

Operating Plant	Power	Workforce	Amount of Water
Anaerobic digester	5 KWh	2	1000 L
Composting plant	10 KWh	5	9000 L
Briquette plant	25 KWh	5	1000 L
Pyrolysis	20 KWh	3	20 L
Incineration	5 KWh	1	—

TABLE 5: Illustrates the water, labor, and energy required to run the waste management units

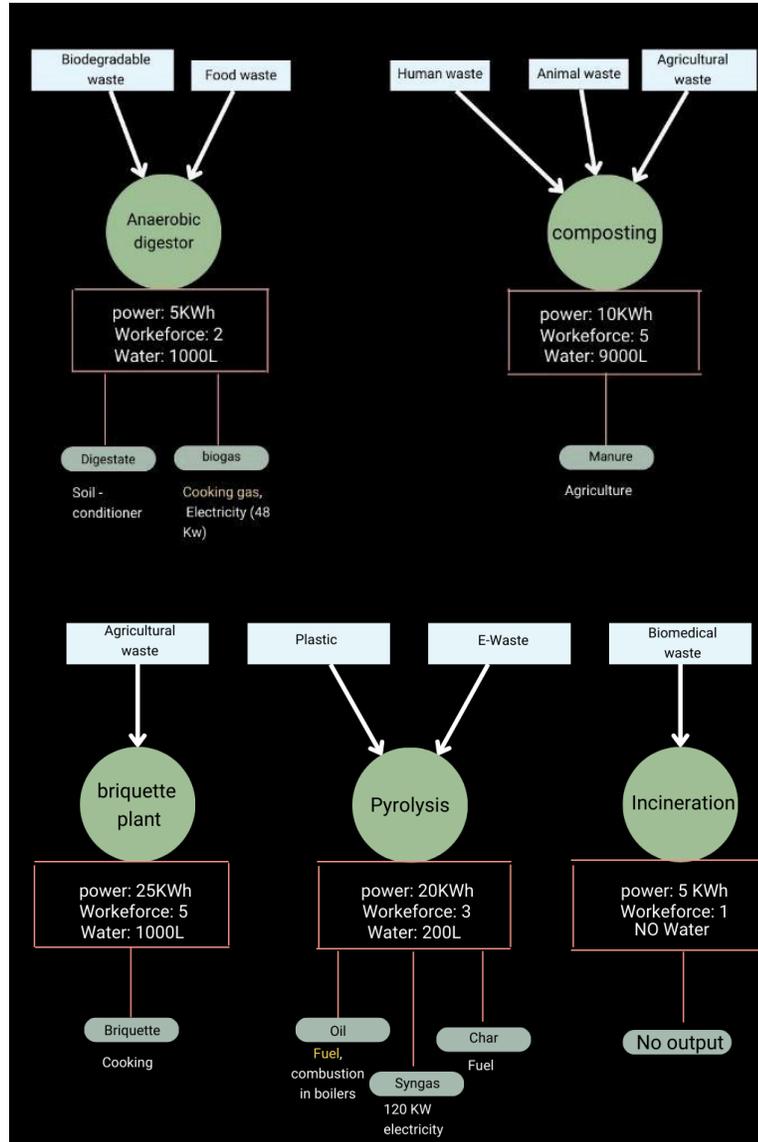


FIGURE 6: Demonstrates the transformation of the wastes into useful products

## 5. Water Management

Water, an essential part of life, is needed for all activities, from drinking purposes to industries. Since it is a challenge to produce water, it needs to be used and produced efficiently. It can be done by reusing water, reducing its use, and following other methods to generate water if necessary.

Initially constructing the torus, water must be transported from the earth using collapsible containers. The total amount of water required for the industries is 11000 L. For drinking purposes, a human should drink an

average of 2.5 L of water per day and thus need  $2.5 \times 10,000 = 25000$  L of water.

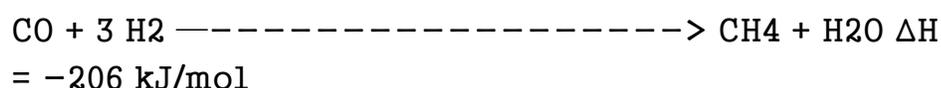
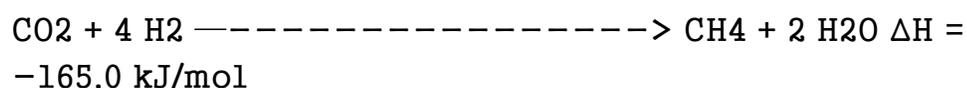
Animals	Total Water Required (Approximate)
265 cows	19,875L - 21,2000 L
650 sheep	2600 L - 9100 L
100 pigs	220 L - 420 L
40 hens	200 L (approximated)
Human	25000 L
<b>Total</b>	<b>47,895L - 2,46,720 L</b>

TABLE 6: Shows the approximate estimate of water that is required by the approximate number of animals to be transported to the torus. The number of animals is calculated approximately by formulating a diet chart that gives approx. 3000 Kcal energy required by the residents living there as stated by research conducted by Stanford (National Space Society, 1975)

Thus total water required is approximately  $(11,000+47,895)$  to  $(11,000 + 2,46,720) = 58,895L - 257,720 L$ . Most of this water has to be transported initially from the earth. After that, it must undergo several filtration methods before reusing them. From which, 60% of it can be reused while the rest 40% can't be.

#### 5.1. Sabatiers method

The 40 % non-reusable water will be produced using Sabatier's method. Sabatier's method is used commercially and approved by NASA for supporting life in space stations. In this exothermic process, nickel catalyst interacts with hydrogen and carbon dioxide at elevated temperatures and pressures to produce water and methane. Ruthenium or alumina (aluminum oxide) makes a more efficient catalyst. However, nickel is the most widely used catalyst for its high selectivity and low cost.



### 5.2. Microbes

For generating water, certain kinds of microbes can be introduced in the torus: The Antarctic bacteria, rich in RuBisCO, usually capture sunlight to perform photosynthesis. However, the RuBisCO-rich bacteria, which cannot trap sunlight, perform chemosynthesis. In this process, they use inorganic gases such as carbon monoxide, hydrogen, and methane; the byproduct is water. It extracts the inorganic gases required for synthesizing water from the air. Introducing these bacteria in the space habitat might be helpful for hydration on a smaller scale (Monash University, 2021).

### 5.3. Reusable water

The reusable water will undergo a filtration process where the water will pass through different mediums before obtaining fresh water. Water will first go through sand, then from filters with delicate pores, and finally, UV radiations will be passed through it to get the required filtered water.

Studies show that a lot of water gets wasted during showers. An average bath uses up to 20 gallons of water. Thus implementing water recycling showers developed by NASA and a Swedish University will be feasible. These showers reduce water usage by continuously filtering the same amount of water rather than consuming fresh water for each shower. This water filtration technology, known as NanoCeram, starts with less than a gallon of water and checks water quality 20 times per second. It replaces the highly polluted water with fresh water, and the rest undergoes UV light before recirculating again. Since the reused water is already warm, it takes minimal energy to heat it back to the target temperature (Mike DiCicco, 2021).

## 6. Conclusion

In conclusion, the advancement of space colonization is not only an exciting frontier for human exploration but also a necessity for our long-term survival and sustainability. Our proposed dual torus model enhances the original Stanford torus by effectively separating human habitation and commercial activities from waste management and industrial operations. This study addresses waste generation and management through advanced technologies like incineration and gasification, while promoting the 3Rs—reduce, reuse, and recycle. Additionally, innovations such as bioplastics offer sustainable alternatives for biodegradable plastics and fabrics. Efficient water management systems, including NASA-inspired water recycling showers, further

reduce resource consumption. This research highlights the feasibility of creating self-sustaining, habitable environments in space, laying the foundation for future missions and off-Earth industries. As we continue to push the boundaries of space habitation, the insights gained from this study will play a crucial role in shaping the future of human life beyond Earth.

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