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Energy Analysis of Growth Adaptable Artificial Gravity Space Habitat

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The USA has been in space for over 50 years in zero-g, and it is unhealthy. A project called "The Growable Artificial Gravity Habitat (GAGH)" seeks to solve four problems in space: providing gravity, food, radiation protection, and a growable technology that enlarges the habitat as economics dictate. This paper demonstrates the feasibility of the project by presenting a comprehensive analysis showing a livable thermal environment under energy equilibrium. Detailed energy calculation includes absorbed solar energy from sunlight, allocation of solar energy to crops and a green park, collected electricity from PV panels for personal activity consumption, and a solution to surplus heat via self-radiation and the radiator. This paper indicates that the incoming solar energy is sufficient to support food supply for 8000 inhabitants with a crop area of 300 m^2 per person, and a green park of 3.07×10^5 m^2. This paper also shows that electricity collected from PV panels can supply 8000 inhabitants for daily living and work. The thermal analysis also demonstrates that temperature inside the habitat stabilizes around 300 K with the assistance from the radiator. The radiation protection requires 5m thick shield.

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Nomenclature

T_e	Deep space environment temperature, K
T_s	Target surface temperature of the shield, K
1 AU	Distance between the Earth and Sun
q_s	Solar energy constant at 1 AU, W/m^2
G_s	Incoming Energy at the surface of the shield, W
$\dot{q}_{in}$	Energy flow into the habitat system, W
$\dot{q}_{out}$	Energy flow out of the habitat system, W
M	Mass of habitat shield, kg
V	Volume of habitat shield, m^3
X	Depth from the surface of habitat shield, m
A	Projected area of habitat shield, m^2
β	Angle between the sunlight and shield surface, rad
t_c	Time for a complete habitat rotation cycle, s
ρ	Surface reflectivity of habitat shield
ϵ	Surface emissivity of habitat shield
σ	Stefan-Boltzmann constant, kg/(s$^3 \cdot$ K^4)
k	Thermal conductivity of regolith, W/(m $\cdot$ K)
c	Specific heat capacity of regolith, J/(kg $\cdot$ K)
E_{solar}	Solar energy entering the habitat, kW
R_h	Radius of habitat, m
e_{glass}	Transparency of glass shield

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e_{mirror}	Reflectance of mirror
$E_{agriculture}$	Solar energy distributed to crops, kW
N_{human}	Population inside the habitat
A_{crop}	Crop area per person, m^2
$L_{habitat}$	Length of the habitat, m
e_{argi}	Solar energy intensity for crops, kW/m^2
$E_{greenspace}$	Solar energy distributed to the green park, kW
R_{green}	Radius of the green park, m
$S_{outdoor}$	Area of the green park, m^2
e_{green}	Solar energy intensity for the green park, kW/m^2
E_{PV}	Electricity generated by PV panels, kW
γ	Surface absorptivity of PV panel materials
e_{PV}	Efficiency of PV panels
R_{shield}	Radius of the shield, m
$R_{chandelier}$	Radius of chandelier, m
$E_{personal}$	Personal electricity consumption, kW
W_{person}	Average personal electricity consumption, kW
E_{heat}	Surplus heat to be radiated, kW
A_{pcone}	Projected area of side cones, m^2
A_{shield}	Surface area of the shield, m^2
$E_{coneradi}$	Self radiation of cones, kW
$E_{shieldradi}$	Self radiation of shield, kW
$E_{selfradi}$	Self radiation of habitat, kW
$E_{radiator}$	Radiation from the radiator, kW

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I. Introduction

Humans have explored space without the benefits of gravity and sufficient radiation protection for more than 50 years. Four fundamental problems must be solved before humans can survive long-term in space. This paper presents feasible solutions to these four problems: i.) sustainable food supply ii.) radiation protection iii.) gravity iv.) a growable technology that enlarges the habitat as economics dictate. First, a habitat spins to create centrifugal forces in order to provide artificial gravity. The centrifugal force felt by a human of mass m standing on the floor at a radius R from the spin axis rotating at ω radians per second is mg, where $g = R\omega^2$. A gravity gradient less than 6% across the human body is needed to avoid health issues, which poses requirements on habitat dimensions. A 2 m tall person experiences a gravity gradient of 2% at a radius of R = 100 m. At this radius, a rotational rate of 3 rpm would yield an artificial gravity of 9.8 m/s^2, the value on Earth. A space habitat is required to do research to find healthy values of gravity for humans in space. Such experiments cannot be done on the Earth. Healthy children might require 9.8 m/s^2. Our project, the Growable Artificial Gravity Habitat (GAGH), plans to establish a spinning habitat of 224 m radius, yielding only 1% gravity gradient, but the habitat starts small and adds radius only as economics allow. The outer floors are residential space, where the artificial gravity is the largest. Floors at small radii, where the artificial gravity is smaller, are allocated for agriculture space. These crops supply food for inhabitants. Sunlight directed to the habitat provides the energy to maintain the habitat temperature, to support plant growth and personal comfort.

Many researchers have studied the thermal environments of celestial bodies such as the Moon, and thermal protection solutions for spacecraft. Satellite systems that require some form of cryogenic cooling systems are well studied by Donabedian, 2003.[1] A systematic description of thermal issues of spacecraft at Keplerian orbit is presented by Meseguer, 2012.[2] Many other researchers also focused on the detail design of thermal protection parts: the radiator, PV panels and isothermal covers.[3–5] Soilleux, 2018 showed ventilation for heat and water transport and management study for large space habitat with artificial gravity and agriculture.[6,7] Some other researchers have considered the possibility of sustainable ecosystems. A well-known project, the Biosphere 2, has investigated the feasibility of maintaining a self-supported ecosystem on the Earth and presented a climate model including soil, moisture, vegetation cover, energy balance requirements, etc.[8,9] While fundamental work has been established in spacecraft or ecosystems, there is no quantitative analysis present for energy balance and thermal equilibrium for a space habitat with artificial gravity and agriculture.

A habitat suitable for long-term human presence in space must shield from space cosmic radiation and provide an adequate thermal environment with enough light for agriculture support and personal consumption. We propose 5 m shield of regolith and water from asteroids or Moon for radiation protection. Previous work from our group has discussed the structure design and control of GAGH in detail.[10] The tensegrity paradigm is used for the design of the growth adaptable space structure. Mass of the structure required to sustain the centrifugal forces and the atmospheric pressure is minimized using the tensegrity structural paradigm. Building on that, this paper extends the feasibility analysis of the habitat by presenting a methodology to approximately investigate thermal and energy issues under reasonable assumptions. A thermal analysis demonstrates that the habitat maintains a livable environment at a moderate temperature of 300 K under extreme environment of variant temperatures, with the assistance of the radiator. Solar light enters the habitat via glass, and PV panels are used to convert sunlight into electricity. A quantitative energy analysis also demonstrates solar light is sufficient for crop and plant growth, and generated electricity is sufficient for personal consumption.

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II. Space Environment

II.A. Habitat Location

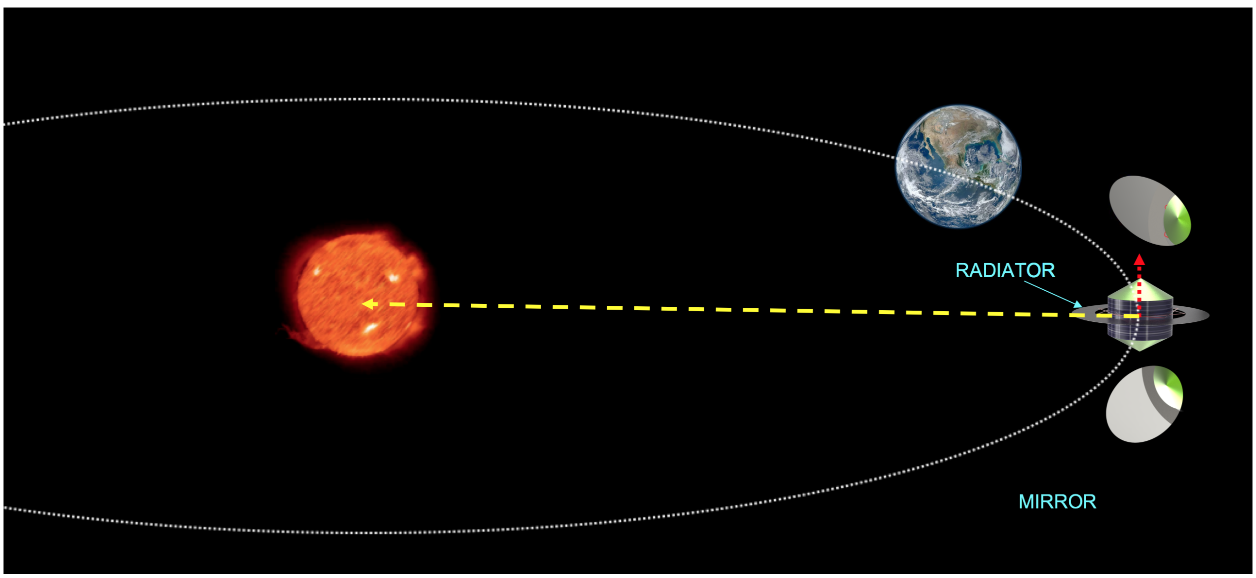

Figure 1. The habitat locates at sun synchronous orbit (SSO)

As sketched in Figure 1, the habitat spins about an axis perpendicular to the elliptical plane, stays in an orbit similar to the Earth, circling around the Sun.[11]

The habitat is surrounded by an extremely low temperature of $\mathrm{T_e} = 0 \sim 2.3\mathrm{K}$, but the continuously receives solar energy of intensity $\mathrm{q_s} = 1360\ \mathrm{W/m^2}$ on the surface (rotating) facing the Sun. Heat flux from absorption and radiation will reach a thermal equilibrium.[12] Table 1 gives the temperature range on some celestial bodies close to the Earth, at a similar distance to the Sun. To establish a thermal equilibrium of heat flux at a comfortable temperature (300 K) and to prevent harms from cosmic rays, we propose a 5 m thick shield consisting of lunar regolith and water.

Due to the negligible magnetic field and absent atmosphere surrounding the habitat, high energy galactic cosmic rays (GCRs), solar particle events (SPEs), and solar wind bombard the habitat surface and pose a serious threat to the humans inside. Estimates predict that humans in unshielded interplanetary space would annually receive roughly 400 to 900 mSv (millisievert) (compared to 2.4 mSv on the Earth). For example, a Mars mission (12 months in flight and 18 months on Mars) might expose astronauts to roughly 500 to 1000 mSv,[13] using existing space suits.

Table 1. Surface temperature of 1 AU (Distance Between the Earth and Sun) objects[14]

Objects	Temperature Range
Earth	185 K $\sim$ 331 K
Moon	100 K $\sim$ 390 K
ISS (International Space station)	116 K $\sim$ 394 K
LEO Satellites	103 K $\sim$ 396 K

II.B. Habitat Configuration

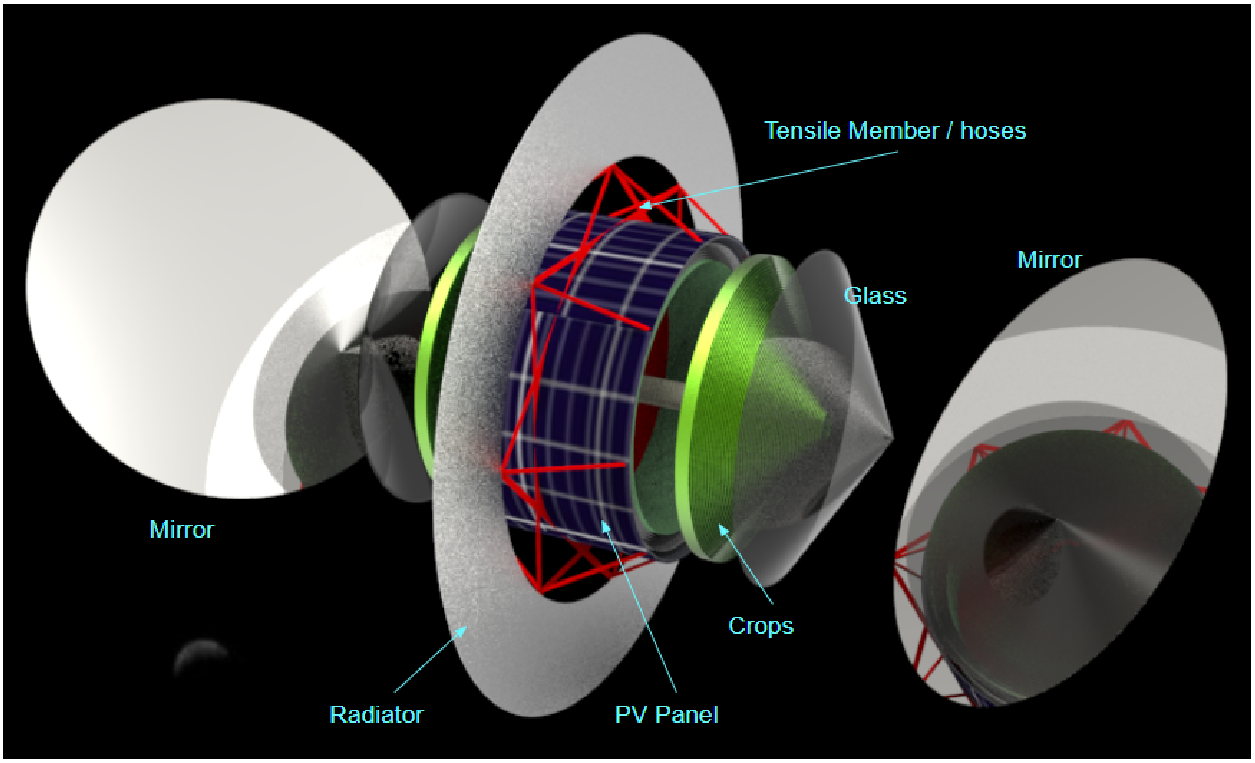

Figure 2. Habitat Configuration

The total habitat system is composed of four rotating bodies: the shield, the habitat, and the two isolated mirrors. Part of the shield is composed of a 5 m blanket of regolith and water on the outside surface away from the spin axis. To allow light inside while protecting from radiation, 5 m glass shields are present on the side faces pointing in the direction of the spin axis. Finally, there is a thin circular ring on the outside as a radiator. Figure 2 shows the exploded view of the radiator, glass shields, agriculture space (marked in green) and the PV panels attached on the outside of the spinning shield. The habitat system revolves at 1 degree per day to follow the Sun (orbital revolution). The cross-sectional geometry of the habitat could be approximated using a hexagon, where the axis of rotation is marked as a red dash line at the center, as shown in Figure 3. The shield is a cylinder with a radius of 239 m and a thickness of 5 m, rotating about the same spin axis as the habitat but at a slower rate of 0.2 rpm compared to the habitat spin rate of 2 rpm. The shield is a 3-layer structure consisting of 1 meter of regolith, 2 meters of water and 2 meters of regolith. This unique structure not only protects the habitat from cosmic rays and solar radiation but also helps in stabilizing to a thermal equilibrium, details of which are covered in Section III. In between the shield and the habitat, there is a 10 m vacuum. The two sides of the shield are composed of 5 m thick glass in the shape of a cone, that allows sunlight inside. This sunlight supplies energy for plant growth and outdoor park lighting. PV panels cover the outer surface of the shield, as marked in dark blue in Figure 2. Extended from

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PV panels are tensile members/hoses (pipes in tension) that attach to the circular ring of the solar radiator to dissipate the surplus heat, cycling the hot and cool water to and from the radiator.

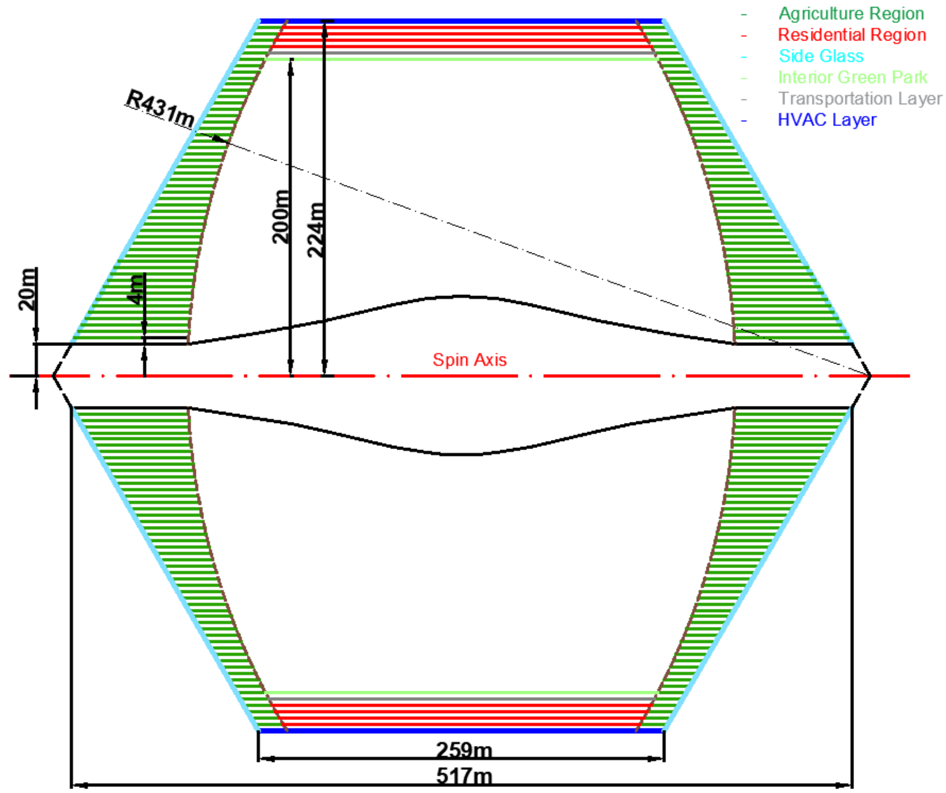

Figure 3. Habitat Cross-sectional View

Figure 3 shows a cross-sectional view of the interior configuration of the habitat. The habitat consists of 52 floors with a gap of 4 m between each floor. These floors are constructed by tensile membranes, designed to sustain centrifugal and pressure forces. The outer six floors provide most of the living space. Our design provides artificial gravity (centrifugal forces) of 9.8 m/s^2 at the outer floor. The outer-most floor (marked in blue) is designed for heat transfer, ventilation, and air supplement equipment. The 2nd to 5th floors (marked in red) are designed for human life, and the 6th floor (marked in grey) is designed for plant life and for transportation (buses and trucks). The 7th floor (marked in light green) is a huge outdoor green park which has trees, grass, terrains, and rivers. The agriculture space is shown in green in Figure 3 with 52 floors, where plants can be grown at a preferred-gravity level (more research would be ongoing to select the most efficient gravity level for any given plant species). This agriculture space will provide 300 m^2 per person for a total of 8000 inhabitants. Being close to the spin axis is the first cylinder as a chandelier, with an inlet radius of 20 m. This is also the start-up cylinder for construction of the habitat, where the other 51 floors built upon. During daytime, the outer surface of the chandelier is covered by polished surfaces to uniformly distribute light all over the outdoor green park by reflecting incoming sunlight. Mirrors are flipped at night that transform into PV panels to cancel sunlight reflection and forms a day-and-night cycle. The first start-up habitat cylinder also serves as a zero-g garage workspace or manufacturing workshop. The ends of this cylinder are docking ports for spacecraft. Figure 4 shows a 3D printed model of the interior structure. Notice PV panels and the radiator are not installed in this 3D printed model yet.

III. Thermal Analysis and Radiation Protection

Suppose the habitat is located in a deep space environment where the temperature is in the range 0 $\sim$ 2.3 K, simultaneously absorbing and radiating heat flux, and is exposed to cosmic radiation. We desire approximately 300 K inside the habitat for comfortable life support. On the Earth, the atmosphere provides protection to stabilize temperature and block most of the cosmic radiation.

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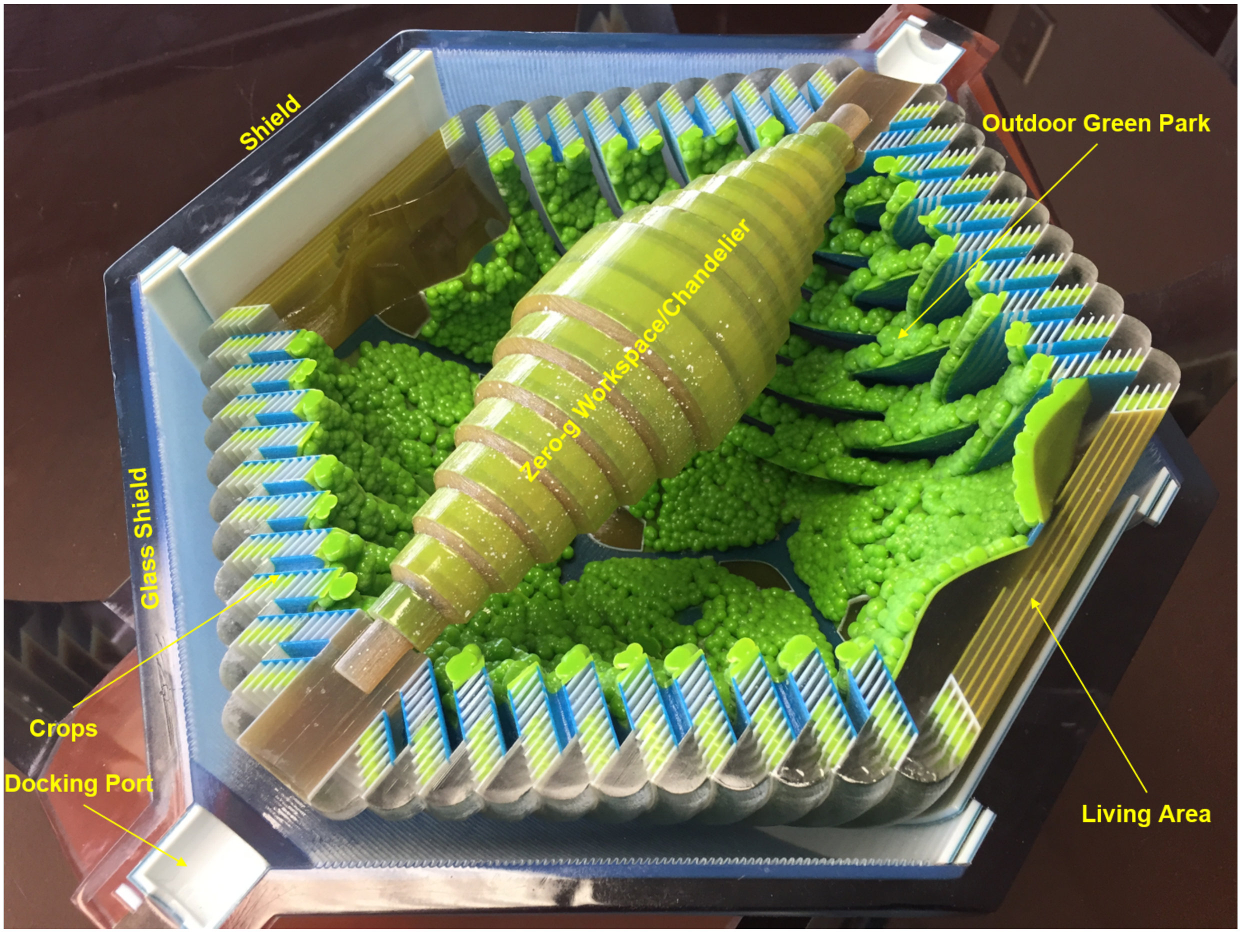

Figure 4. 3D Printed Model

As described in section II.B, the 5 m shield consists of regolith and water. Regolith is an efficient material that both absorbs the radiation and prevents heat leakage, yet more importantly, it is widely available on the Moon and asteroids. Water is also one of the most efficient materials for radiation protection due to its high density and molecular polarity.[15] The layer of water captures high atomic number particles dispersed after their first interactions with regolith, hence water is introduced in between two regolith layers.

III.A. Thermal Analysis

The habitat undergoes both heat absorption from the sun and emission to the deep space. An equilibrium will be formed after a certain amount of time. The fundamental governing equation for this thermal dynamics of lunar regolith system, given by Boley,[16] is:

$$kV\frac{\partial^2 T(X,t)}{\partial X^2} - Mc\frac{\partial T(X,t)}{\partial t} = \dot{q}_{out}(X,t) - \dot{q}_{in}(X,t) \tag{1}$$

where k represents the thermal conductivity of regolith, V represents the volume of habitat shield, t represents time, X represents the depth in regolith, T represents the temperature at certain depth X at time t, M represents the mass of habitat shield, c signifies the specific heat of regolith, $\dot{q}_{in}$ and $\dot{q}_{out}$ represent incoming and outgoing heat flux, respectively. Solving this PDE, one can simulate temperature distributions over the surface and along the depth of the regolith shield.

The incoming solar radiation is absorbed in the habitat system, while a portion of the radiation is reflected back into space. This radiation is characterized by the reflectivity of the PV panels covering the regolith bags. The heat energy absorbed by the shield, $\dot{q}_{in}$, is described by the following equation:

$$\dot{q}_{in} = (1-\rho)G_s A cos\beta_s \tag{2}$$

where ρ represents the surface reflectively, G_s represents the solar radiation power, A represents the projected area, and β_s is sunlight angle. The surface reflectivity is $\rho = 0.13$. The solar radiation power, G_s, varies during a day and night cycle, and is described below:

$$G_s = \begin{cases} q_s sin\left(\frac{2\pi}{t_c}t\right), & \text{Day} \\ 0, & \text{Night} \end{cases} \tag{3}$$

Here $q_s = 1360\mathrm{W/m^2}$ is the solar energy constant at 1AU, t_c represents the time for a complete habitat rotation cycle, and t represents the time during the habitat day.

The total released energy including emission of the habitat system and the radiator, $\dot{q}_{out}$, can be described by equation (4).[17] The emission of a non-black body is related to the body temperature and surrounding temperature. We seek to establish a stabilized system around a temperature of 300 K, and the radiator will be implemented as controls to the thermal environment.

$$\dot{q}_{out} = A\epsilon\sigma(T_s^4 - T_e^4) + E_{radiator} \tag{4}$$

Here σ is the Stefan-Boltzmann constant, ϵ is the surface emissivity, T_s is the surface temperature of shield, and T_e is the space environment temperature, $0 \sim 2.3$ K. While surface temperature has small pertubations around 300 K, we pick $\mathrm{T_s} = 300$ K as the desired stable state. The emissivity of lunar regolith, ϵ, is approximately 0.97.[14] The radiator dissipates an amount of heat $\mathrm{E_{radiator}} = 0.8017 \times 10^5$ kW, as calculated in Section IV.F.

Employing the above thermal dynamics, one could calculate the dynamic thermal responses of a lunar regolith object. First, we solve the thermal dynamics for the Moon to demonstrate its validity against known data, and then solve the thermal dynamics of our habitat. Using a period of 30 days, the temperature range of the Moon surface is computed as 100 K $\sim$ 390 K, and mean temperature is around 245 K, as shown in Figure 5. This result matches well with the surface temperature of the Moon.[18] Experimental data also shows that about 0.5 m beneath the lunar surface, the temperature stabilizes at this mean 245 K.[18] Considering a shield of regolith while covered by PV panels at surface (material properties of PV panels are discussed in section IV.F), and a period of 300 s (0.2 rpm) to our habitat, we apply the same approach, and get a dynamic response shown in Figure 6. The temperature range of the shield surface is 285 K $\sim$ 315 K, and the mean temperature is 300 K. This is an ideal temperature for inhabitants.

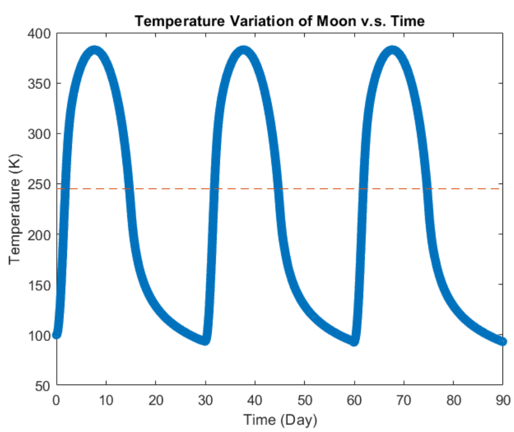

Figure 5. Temperature Variation of Lunar Surface

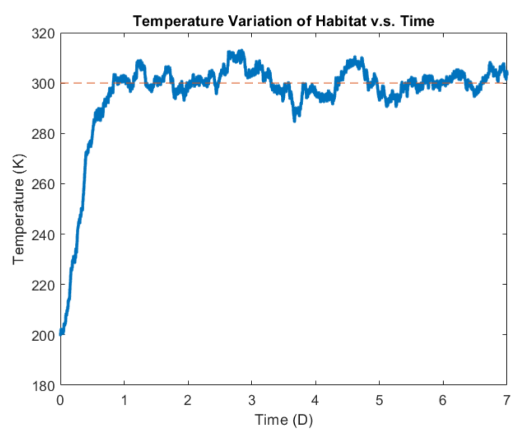

Figure 6. Temperature Variation of Habitat Shield Surface

III.B. Cosmic Radiation Protection

Some previous estimates of required regolith thickness for radiation protection appear in Table 2. We choose a 5-meter thick shield for reasons beyond the scope of this discussion.

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Table 2. Suggested lunar regolith requirements for radiation protection according to Malla and Brown's researches in 2015[19]

Suggested Regolith Thickness	Reference Study
$2.0 \sim 3.5$m	Siberburg,1985
0.46 m	Miller, 2009
0.5 m	Nealy, Wilson & Townsend 1988
0.5 m	Simonsen, 1997
2.5 m	Ruess, Schaenzlin & Benaroya, 2006

IV. Energy Balance

Here we seek energy balance at desirable values of heat, solar and electrical energy. To maintain a sustainable environment for habitat, energy needs to reach an equilibrium to avoid the surplus heat. A detailed quantitative analysis regarding inlet and outlet energy is necessary. The habitat collects solar energy when sunlight enters through the glass and collects electricity from PV panels attached outside of the shield. The habitat grows crops for food supply and a green park that consume solar energy, and people consume electricity in daily life. Figure 7 presents a schematic diagram of a solar light pattern and solar energy distribution. A summary of incoming energy and energy distribution is given in Table 3.

Table 3. Energy Summary

Energy Source (kW)		Energy Distribution (kW)	
Solar Energy, Eqn. (5)	$E_{solar} = 3.4730 \times 10^5$	Crops, Eqn. (6)	$E_{agriculture} = 2.9143 \times 10^5$
E_{solar}	$E_{agriculture} + E_{greenspace}$	Green Park, Eqn. (7)	$E_{greenspace} = 0.5587 \times 10^5$
Electricity, Eqn. (8)	$E_{PV} = 0.6521 \times 10^5$	Personal Consumption, Eqn. (9)	$E_{personal} = 0.5360 \times 10^5$
Surplus Heat, Eqn. (10)	$E_{heat} = 3.9158 \times 10^5$	Self-Radiation, Eqn. (11)	$E_{selfradi} = 3.1141 \times 10^5$
E_{heat}	$E_{selfradi} + E_{radiator}$	Radiator, Eqn. (12)	$E_{radiator} = 0.8017 \times 10^5$

IV.A. Solar Energy Directly Entering the Habitat

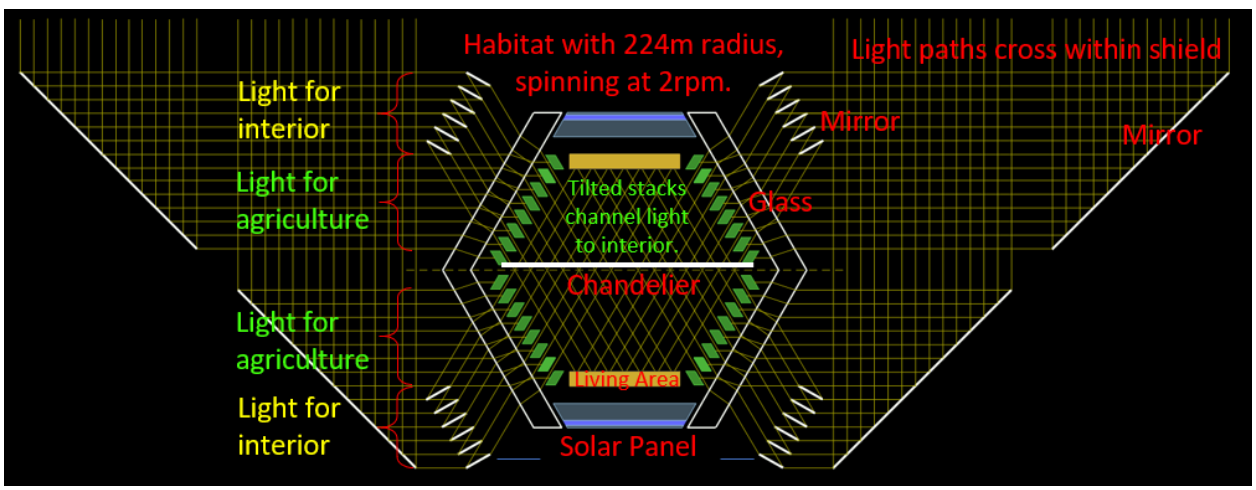

Figure 7. Sunlight Distribution (Courtesy to Mr. Anthony Longman)

Solar light reflected from side mirrors will pass through the glass shields and light the interior, as depicted in Figure 7. Several assumptions about reflectance of mirrors, transparency of glass and solar power constants are established to estimate the amount of absorbed solar energy.

As a reference, the reflectance of the James Webb Space telescope mirror ranges from 94.1% to 97.9%.[20]

Considering our mirrors are vastly greater in size, and must perform over decades of exposure in space, we assume a reflectance of our mirror $e_{mirror} = 90\%$ for estimation purposes.

The sunlight will go through the glass in the shield to reach the crops. Rather than using large blocks of glass, high-quality glass fiber bundles in a matrix form are implemented here. High-quality clear glass manufactured on the Earth can reach a transmittance of 90%.[21] While it is admitted that thickness (5 m) of glass will have a negative impact on glass transmittance by accumulating impurities, the manufacturing environment in space is considered vacuum, thus it is reasonable to argue that glass produced in space would contain less impurity. A transmittance $e_{glass} = 90\%$ is assumed for the glass.

The habitat lies in an orbit similar to the Earth, and the solar power at 1 AU is $q_s = 1360$ W/m^2.[12]

$$\begin{aligned} E_{solar} &= 2\pi R_h^2 e_{glass} e_{mirror} \times q_s \text{ W} \\ &= 2 \times (\pi \times 224^2) \times 90\% \times 90\% \times 1360 \text{ W} \\ &= 3.4730 \times 10^5 \text{ kW} \end{aligned} \tag{5}$$

This total solar energy, E_{solar} (projected into the habitat by both sides), will be allocated for crops and the green park for growth by photosynthesis.

IV.B. Energy for Agriculture

Crops and the outdoor green park will share the incoming solar energy. These crops feed a population of $N_{human} = 8000$ inhabitants, and in this subsection, we establish some assumptions to calculate the portion of solar energy allocated to crops.

A crop area of $A_{crop} = 300$ m^2 is assigned per person, and a crop area of 2.40×10^6 m^2 is grown on the habitat. As mentioned in Table 4, a light intensity of 25,000 lux, or equivalently $e_{argi} = 242.86$ W/m^2, is necessary for crops to reach maximum efficiency of photosynthesis. Notice that the incoming solar light intensity is 1360 W/m^2, which far exceeds the required intensity. Therefore, the incoming solar light requires diffusion to decrease its intensity (such as Fresnel lens applications).

Crops experience a day and night cycle. During the daytime, crops are exposed to sunlight for photosynthesis, and during the night they are left in dark for respiration. Therefore, crops receive sunlight for only half of a day-and-night cycle.

$$\begin{aligned} E_{agriculture} &= N_{human} \times A_{crop} \times e_{argi} \times \frac{1}{2} \\ &= 8000 \times 300 \times 242.86 \times \frac{1}{2} \text{ W} \\ &= 2.9143 \times 10^5 \text{ kW} \end{aligned} \tag{6}$$

Table 4. Sunlight Intensity Required for Plant Growth[22]

Sunlight Intensity	Plant Growth
1000 ∼ 5000 lux	Min. necessary for life
10000 ∼ 15000 lux	Min. necessary for consistent but sparse growth
20000 ∼ 25000 lux	Min. necessary for robust growth
25000 ∼ 30000 lux	Max. Efficiency for Sub Tropical varieties
25000 ∼ 50000 lux	Max. Efficiency for Equatorial varieties

IV.C. Energy for Outdoor Green Park

Open green space in urban environments can provide many advantages: youth development, public health, air purification, etc. They even reduce erosion of soil into our waterways. In the 1g area, there are 6 floors designed for living purposes, and the 7^{th} floor is designed as an open outdoor green park. This green park shares the incoming solar energy with agricultural crops. As established, the incoming solar energy is $E_{solar} = 3.4730 \times 10^5$ kW, and allocated portion for agriculture is $E_{agriculture} = 2.9143 \times 10^5$ kW. The solar energy for the green park is then calculated as follows:

$$E_{greenspace} = E_{solar} - E_{agriculture}$$

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$$
\begin{aligned}
&= 3.4730 \times 10^5 - 2.9143 \times 10^5 \text{ kW} \\
&= 0.5587 \times 10^5 \text{ kW} \qquad (7)
\end{aligned}
$$

The area of the green park depends on structure design and is given as 3.07×10^5 m^2 (can be calculated from Figure 3). If we divide energy by area, the solar intensity is calculated as 182.1 W/m^2, or equivalently 18,750 lux. This intensity ensures consistent growth for plants according to Table 4.

IV.D. Electricity from PV panels

PV panels are installed on the surface of the shield. PV panels efficiency is assumed to be $e_{PV} = 20\%$. Only half of the shield surface is exposed to the Sun at any instant of time. The chandelier will be flipped to expose PV panels at night to form a day and night cycle for the outdoor green park. Approximately, the chandelier is a cylinder with a radius of $R_{chandelier} = 20$ m and a length of $L_{habitat} = 259$ m. The solar energy stored in PV panels is E_{PV}.

$$
\begin{aligned}
E_{PV} &= e_{PV} \times (2\pi R_{shield}^2/\sqrt{3} + 2\pi R_{chandelier} L_{habitat}) \times q_s \text{ W} \\
&= 0.6521 \times 10^5 \text{ kW}. \qquad (8)
\end{aligned}
$$

IV.E. Personal Use

Personal use of energy includes living and working. The average personal electricity usage in New York is $\mathrm{W_{person}} = 0.8375$ kW, according to the U.S Department of Energy. We multiply this number by 8 to cover other energy requirements for research, manufacturing and extra life recycle and sustainability equipment that New York does not have.

$$
\begin{aligned}
E_{personal} &= N_{human} \times 8 \times W_{person} \\
&= 8000 \times 6.7 \text{ kW} \\
&= 0.5360 \times 10^5 \text{ kW} \qquad (9)
\end{aligned}
$$

IV.F. Radiation Analysis

Energy enters the habitat either as solar energy entering through the glass, or heat absorbed at the shield surface from direct exposure to the Sun. The solar energy entering the glass is calculated in the subsection IV.A as $E_{solar} = 3.4730 \times 10^5$ kW. Agricultural crops and outdoor green park absorb 34% of the solar energy for photosynthesis. The rest of the solar energy will be transformed into heat that requires radiation. Heat via absorption depends on the absorption factor of the shield surface material, which is covered by PV panels. There are various PV panel materials, but we assume a common material of crystalline silicon for estimation purposes. An absorption factor of crystalline silicon, $\gamma = 0.905$,[23] will be used. The total incoming heat to the habitat is calculated as follows:

$$
\begin{aligned}
E_{heat} &= E_{solar} \times (1 - 34\%) + E_{absorption} \\
&= 0.66 E_{solar} + \gamma A q_s \\
&= 0.66 \times 3.4730 \times 10^5 + 0.905 \times 1.3192 \times 10^5 \times 1.360 \text{ kW} \\
&= 3.9158 \times 10^5 \text{ kW}. \qquad (10)
\end{aligned}
$$

where $A = 2 \times 239^2/\sqrt{3} \times 2 = 1.3192 \times 10^5$ m^2 is the projected area of the shield.

Self radiation depends on the emissivity of the surface. The two cones at sides are glass with an assumed emissivity of $\epsilon_{cone} = 0.85$.[24] An emissivity of $\epsilon_{shield} = 0.9$ for crystalline silicon will also be used for radiation calculation of the shield.[25] The total radiation of the habitat is given by nonblackbody surface heat radiation and can be determined by the following relationship:[17]

$$
\begin{aligned}
E_{selfradi} &= E_{coneradi} + E_{shieldradi} \\
&= A_{pcone} \epsilon_{cone} \sigma (T_s^4 - T_e^4) + A_{shield} \epsilon_{shield} \sigma (T_s^4 - T_e^4) \\
&= (3.5890 \times 10^5 \times 0.85 + 4.1442 \times 10^5 \times 0.90) \times 5.67 \times 10^{-8} \times (300^4 - 2.3^4) \text{ W} \\
&= 3.1141 \times 10^5 \text{ kW}, \qquad (11)
\end{aligned}
$$

where $A_{pcone} = 2\pi R_{shield}^2 = 2\pi \times 239^2 = 3.5890 \times 10^5$ m^2 is the projected area of two cones, $A_{shield} = 2\pi R_{shield}^2/\sqrt{3} \times 2 = 4.1442 \times 10^5$ m^2 is the surface area of shield, $\sigma = 5.67 \times 10^{-8}$ W/(m$^2 \cdot$ K^4) is the Stefan-Boltzmann constant.

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The rest of the surplus heat will be dissipated using the radiator. Since a total surplus heat is $E_{heat} = 3.9158 \times 10^5$ kW and portion of it has been processed via surface radiation, $E_{selfradi} = 3.1141 \times 10^5$ kW, the radiator dissipates an amount of heat as following:

$$\begin{aligned} E_{radiator} &= E_{heat} - E_{selfradi} \\ &= 3.9158 \times 10^5 - 3.1141 \times 10^5 \text{ kW} \\ &= 0.8017 \times 10^5 \text{ kW} \end{aligned} \tag{12}$$

V. Conclusion

This paper presents a brief analysis of the thermal and energy environment for a spinning habitat in deep space. The thermal simulation demonstrates that temperature stabilizes around 300 K with the assistance of the radiator to dissipate excess heat. The radiator provides control capability for the habitat temperature. The energy budget shows the feasibility of maintaining a livable and sustainable environment in deep space, housing 8000 inhabitants with 300 m^2 of agriculture space per person. This is well beyond the 150 m^2 per person required for mere survival on a limited crop choice that would also be at higher risk of disease or crop failure. We demonstrate the incoming solar energy sufficient to supply more choices and amount of crops to feed 8000 inhabitants, and a green park built inside the habitat. We also demonstrate that electricity collected from PV panels can supply personal electricity consumption, plus a safety factor of 8 for use in research, manufacturing and recycling equipment. Surplus heat from the process of photosynthesis and heat absorption is calculated and will be handled by self-radiation of the habitat and the radiator. Future work involves more specific micro-climate elements, including air circulation, air composition, and humidity.

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