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Terraforming: Natural or Industrial

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Abstract

Science fiction has proposed many scenarios of humans inhabiting other planets, but those were created for entertainment. As humans continue to release greenhouse gases into the atmosphere, Earth's surface temperature rises and the environment changes. The direction of these changes suggest that humans will need to find another place to live in order to survive, but our current solar system doesn't have any immediate options. This paper discusses two methods of making planetary bodies such as Mars, Venus, Luna, and Ceres inhabitable: terraforming and Shell World construction. The time requirements, ethical considerations, and material requirements for both methods are examined in an attempt to select the best method for future inhabitation of other planets.

Introduction

Since the industrial revolution began in the late 1700's, Earth's environment has experienced changes leading to increases in temperature and alterations of chemical cycles (Rockström *et al*, 2009). These temperature increases can be visualized by the melting of the polar ice caps at an alarming rate (Kungzig, 2008). With these changes, the question has arisen if future generations humans will be able to continue living on Earth. Other issues such as population growth (and the associated problems of food shortages), worldwide resource shortages (for all living organisms), and continuous pollution released as a byproduct of manufacturing industries raise further doubts about the habitability of Earth in the future (Rockström *et al*, 2009). The Space Age has opened new possibilities for humans as we have traveled past the ends of the Earth the Moon, sent landers to Mars, and satellites to the far reaches of Earth's solar system. As humanity continues to extend its reach, the feasibility of establishing colonies on other bodies in space becomes more prominent and sought after by more and more people.

Furthermore, in order to support the growing human population, atmosphere-containing vessels (such as the planet earth) are needed that can support thousands more people than the 3-person spacecraft used in the Apollo missions to the moon. An ideal solution to this problem would be an Earth-like planet near Earth that has a similar gravity, atmosphere, and environment. It's disappointing that Earth's neighbor close sibling, Venus, is uninhabitable due to the surface temperature. The next candidate is Mars, a cold planet covered in dry deserts with an environment deadly to humans. Mercury is too close to the Sun, while Pluto is way too far away from the Sun for temperatures to be acceptable for human life. What options remain? Can a planetary environment be changed so that it is like Earth's? Can the atmosphere of a planet be altered so that humans can breathe and survive without a suit? Earth's history suggests that this can be done. Injecting greenhouse gases into the atmosphere of a planet could cause heating of the planet surface to a temperature acceptable for life to flourish (McKay *et al,* 1991). Plants and microorganisms placed on that planet could then produce oxygen, changing the composition of the atmosphere to make it habitable for humans. While this natural method, designated terraforming, makes sense and seems feasible, it would take between a few hundred to hundreds of thousands of years for a planet to reach conditions habitable for humans (Miller, 1998).

What about planets and moons that don't have an atmosphere such as Luna, Earth's moon? An atmosphere can't be created for a planet or moon that doesn't generate enough gravitational pull to hold on to that atmosphere. Many science fiction novelists have proposed the idea of domed cities with a habitable interior, but the thickness of the dome would have to be immense to contain the atmospheric pressure within (Roy *et al,* 2013). Kenneth Roy, Robert Kennedy, and David Fields proposed the construction of planetary shells that could contain an atmosphere while providing inhabitants protection from the harsh environment of space. They coined the term “Shell Worlds” for this idea. These shells would be composed of an airtight material that extends over the entire surface of the planet. Custom mixtures of gases would be injected under the shell, causing the shell to rise off the surface of the planet. As pressure builds within the shell, the planet’s gravitational pull would balance this pressure (with careful adjustment of the shell’s mass), resulting in no net force on the shell. Once fully “inflated” the environment inside the shell would be habitable for humans as well as other Earth organisms. Predicted construction time of this shell is limited to several centuries (Roy *et al,* 2009).

With the two options of terraforming and Shell World construction, which one is the most appropriate choice for humanity? In this paper, both terraforming and Shell World construction processes will be explored, addressing ethical implications, material and energy requirements, and the time requirements of both methods. Ultimately, prolong human inhabitation of other planetary bodies will require a stable atmosphere. How that atmosphere is produced and contained is the question.

Terraforming

When examining the process of terraforming for a planet, the current conditions of the planet must be analyzed as well as the available materials on the planet. These conditions include temperature, distance from the Sun, atmospheric composition, availability of greenhouse gases, and availability of water. The importance of each of these conditions will become apparent as the process of terraforming is discussed. The initial step of terraforming is temperature adjustment.

As later steps of terraforming require the use of plant and bacterial life for oxygen production, the surface temperature of the targeted planet must be modified in order to promote survival and reproduction. Ideally, the surface temperature must be above the freezing point of water and below a debated limit. As Earth's surface temperature averages 15°C, the proposed range for habitable surface temperature is 0-30°C (McKay *et al*, 1991). For adjusting the temperature of a planet such as Mars, the runaway greenhouse effect can be used. A current example of the natural success of this effect can be seen on the planet Venus. While at a greater distance from the Sun than the planet Mercury, Venus has a higher surface temperature due to the trapping of solar heat by greenhouse gases in the atmosphere. This phenomenon can be utilized to increase the surface temperature on Mars to make it suitable for plant and bacterial life. Exploratory missions to Mars have discovered significant amounts of frozen water and carbon dioxide at the poles as well as within the regolith (soil) of the frozen desert planet. Since both carbon dioxide gas and water vapor are powerful greenhouse gases, the presence of these frozen compounds on Mars would make temperature adjustment very possible. By melting and dispersing the frozen collection of these molecules into the Martian atmosphere (using a nuclear explosion, for example), a greenhouse warming effect would be initiated. The warming caused by this initial dispersion would melt and release more carbon dioxide and water vapor into the atmosphere. This positive feedback loop would lead to a runaway greenhouse warming of the planet to a point above water's freezing point (McKay *et al*, 1991). Once the surface temperature is raised above the freezing point of water, oxygen producing species can be introduced.

Temperature adjustment on a planet such as Venus would require the opposite attention a planet like Mars requires. With a surface temperature high above habitable levels, the runaway greenhouse effect would have to be reversed. In order to do this, solar radiation must be directed away from the planet and atmospheric heat must be allowed to vent into space. A proposal for solving global warming issues on Earth could be employed in this endeavor: a sunshield. Designed by J. Roger P. Angel, this sunshield is composed of transparent silicon nitride ceramic and filled with smaller holes that are smaller than one micron (Kunzig, 2008). Placing this sunshield at an appropriate distance between the sun and Venus would cast a planet-wide shadow on Venus, reducing the amount of solar radiation bombarding the planet.

In Earth's history, plant and bacterial species that utilized carbon dioxide in energy production released high concentrations of oxygen into the atmosphere as a waste product. Over hundreds of thousands of years, this waste product accumulated in the atmosphere to a point where organisms evolved to respire oxygen were able to thrive (Kump, 2008). This is same process would be utilized in terraforming a planet. After enough carbon dioxide and water vapor have been dispersed, and the surface temperature has been raised above the freezing point of water, photosynthesizing organisms could be introduced on the surface. Plants, bacteria, and algae would utilize the carbon dioxide in the atmosphere to produce energy for survival and reproduction, excreting oxygen as a waste product. Earth's history suggests that cyanobacteria would be the most efficient organism for oxidizing the atmosphere (Kump, 2008). Depending on the number of photosynthesizing organisms placed on the planet, the accumulation of oxygen in the atmosphere to the needed concentration for human survival would take around 100,000 years (McKay *et al*, 1991).

During the oxidation of the planet's atmosphere, other necessary compounds will need to be introduced into the planet's atmosphere, mainly nitrogen. The gas giant Jupiter and Saturn's moon Titan both contain high concentrations of nitrogen (Roy *et al,* 2009). Harvesting nitrogen gas from these bodies and injecting it into the Martian atmosphere would provide the necessary nitrogen for the survival and reproduction of the photosynthetic species already introduced. Another important molecule needed on a terraformed world is liquid water. Not only is water vapor a powerful greenhouse gas, the thermodynamic properties of liquid water are very important for temperature regulation (McKay *et al*, 1991). It is hypothesized that the majority of water on Earth came from asteroids and comets that impacted the Earth's surface. Harvesting icy bodies and directing them towards Mars would result in large impacts (the would release trapped carbon dioxide and water vapor into the air), heat generation, and the accumulation of water from these bodies in the impact craters (Roy *et al*, 2013).

As mentioned earlier, terraforming requires an immense amount of time and resources. The first step of extraterrestrial global warming requires the presence or introduction of greenhouse gases on the surface of a target planet. Once these needed gases are present in ample amounts, the process of global warming can take up to 100,000 years to raise the surface temperature above water's freezing point. Once this temperature is achieved, the next step involves introduction of Earth species for oxygen production. While some organisms that can tolerate low temperatures can be introduced before the desired temperature is reached, the majority of organisms would have to wait. Depending on the size of the planet, an incredible number of photosynthetic organisms would have to be transferred from Earth to the target planet for oxygen production. Even with an ample number of organisms, it would take around 100,000 years to produce enough oxygen to reach the needed concentration of atmospheric oxygen for human survival.

Another issue arises when looking at suitable planets for terraforming: the possibility of life already existing on the planet. Because planets suitable for terraforming require an atmosphere and certain compounds to be present, the possibility of life already existing on these planets is high. This raises the ethical question of whether or not the human race has the right to change the atmosphere of a planet already home to living organisms to an atmosphere that would result in the death of those organisms (Schwartz, 2013). The speed and scale at which this change is induced would not allow for adaptation of these organisms, and ultimately lead to their extinction.

Shell Worlds

The second option for sculpting a habitable world is the process of building Shell Worlds. As the name suggests, Shell Worlds involve building a shell or containment barrier to act as an atmosphere around a planetary body that has none. Many planetary bodies, such as Luna (Earth's moon), Ceres (a small planetoid), and asteroids, do not have sufficient mass (a minimum of 0.4 Earth-masses) to generate enough gravitational pull to maintain an atmosphere (Roy *et al,* 2009). As a result, these bodies cannot be terraformed using the method described above. An upside to this is that the ethics of exterminating existing life would not need to be considered. To make these balls of rock habitable, a containment field or shell must be placed around the entire planet to contain any gases introduced above the surface.

The first step in the formation of a Shell World is the selection of the planetary body. The main factors to take into consideration are gravity, distance from the sun, and shape. Data obtained from aircraft advancement and manned missions to space have determined that the maximum force of gravity tolerable to humans for an extended period of time is 1.5 gees, where one gee is equal to the force of gravity experienced on Earth while standing still (Roy *et al*, 2009). However, it is unknown what the adverse health effects of prolonged exposure to a gravitational force less than one gee. Most planetary bodies that lack an atmosphere will have a gravitational force less than one gee, hence further studies will need to be conducted on humans exposed to this weaker gravity. The second factor, distance from the sun, is not as important to Shell Worlds as it is to natural terraforming. Because Shell Worlds have a shell encapsulating the planetary body, solar radiation will be blocked from reaching the surface (Roy *et al*, 2013). The issues and benefits of this will be discussed later in this paper. To summarize, a greater distance from the sun would result in less solar radiation reaching the outer shell, limiting the amount of energy that can be harnessed by the inhabitants. On the other hand, this reduces the amount of damaging ionizing radiation that bombards the shell material. Finally, planetary shape plays an important role in the stability of Shell Worlds. The ideal shape for a Shell World is a perfect sphere as this allows for an equal distribution of mass about the shell, and any shift in the shell relative to the planet can be automatically corrected by air pressure and gravity (Roy *et al*, 2009). This will be addressed in further detail below.

The stability of a shell surrounding a planetary body relies on the equalization of two opposing forces: air pressure and gravity. As atmospheric gases are release on the planet's surface (beneath the shell), those gases will start to push outward on the shell, causing it to inflate like a balloon. However, the mass of the planet will exhibit a gravitational pull on the mass of the shell material, causing the shell to collapse toward the surface of the planet. In order to generate an atmosphere similar to that of Earth's, a precise mixture of gases will need to be released inside the shell with a pressure of 1 atm. The equal the force of 1atm of pressure exerted outward on the shell, the mass of the shell will need to be adjusted to modify the force of gravity exerted on the shell. One option for this modification is to thicken the shell, increasing its mass adding more shell material to it. This option is both costly economically and energetically for the party responsible for the construction of the shell. The more economical option is to transfer regolith from the planet's surface and place it on top of the planetary shell. By doing so, the mass of the shell is increased while the outer surface of the shell is protected from radiation and damaging impacts. Using regolith also allows easy transport of mass if structures were to be added on the inner or outer surface of the shell. If constructing an atmospheric shell around an object such as Earth's moon, depositing regolith on the outer shell would allow the reflective properties to be preserved, enabling the future inhabitants of Earth to experience moonlit nights.

A benefit of equalizing atmospheric pressure to the gravitational force experience by the shell is that the shell does not need to be secured to the planet's surface. The gravitational force exerted by the planet prevents the shell from expanding far away from the planet while atmospheric pressure prevents the shell from moving too close to the planet's surface. The combination of these two forces keep all sections of the shell at an equal distance from the planet's surface (Roy *et al*, 2013). If an impact on the external surface of the shell force one side closer to the planet's surface, the atmospheric pressure on this side would increase, pushing outward on the shell. On the opposite side of the impact, the atmospheric pressure would decrease, lessening the push on this side of the shell. In a vacuum, the combination of these differing pressures would result in simple harmonic motion of the shell as it moves side-to-side relative to the planet. However, friction between the atmosphere and the shell would eventually result in a slowing of the harmonic motion until the shell resumed its original position equidistant from the surface of the planet at all points. Because only the shell experiences these forces, inhabitants on the planetary surface would not experience changes in air pressure during the oscillation of the shell.

When constructing the atmospheric shell, an appropriate material must be selected. The main concern is that the material must be air tight in order to contain the atmospheric gases. In addition, this material must be sufficiently strong to resist forces exerted on it during the initial inflation of the shell as well as forces experience from impacts after inflation. Materials that are sufficiently strong include steel and titanium, but the cost of these materials would be extensive for the amounts required in the construction of the shell. Another property of the shell material that must be considered is the ability to respond to changes in atmospheric pressure as a result of changes in temperature (Roy *et al*, 2013). As temperature increases, atmospheric pressure increases, and the shell will be forced outward. A shell material with slight elasticity could adapt to these fluctuations without forming breaches and leaking. A promising material that satisfies these properties is woven carbon nanotube fabric. This material is lightweight, sufficiently strong, and has a 1% elasticity (Roy *et al*, 2009). With this material being lightweight, the amount of regolith required on the outer surface to balance gravity is increased, thickening the protective layer on the outer shell.

When designing spacecraft, engineers must be aware of the stresses exerted on the external materials by the environment of space. Specifically, materials can be damaged by photon radiation, ionizing radiation, micrometeoroid impacts, atomic oxygen from Earth's atmosphere (Dever *et al*, 2017). As mentioned before, the weight, durability, and flexibility of materials play an important role as well. Traditionally steel and titanium were considered sufficiently strong for construction, but new materials have been developed that have lighter weight and are more flexible. These materials include carbon fiber and carbon nanotube woven fabrics. Carbon fibers have been used to reinforce lightweight plastics, offering a structural support solution for a potential shell material (Diaz *et al*, 2003). In addition, studies performed on the interlacing of carbon nanotubes in epoxy-based plastics found a decrease in the electrical conductivity of these materials while increase the mechanical strength (De Vivo *et al*, 2012). If the mass of the atmospheric shell is distributed equally and increased to equate the force of gravity with the atmospheric pressure, the shell should experience a net force of zero after inflation. In addition, adding layers of regolith to the outer surface will provide a protective barrier against photon and ionizing radiation as well as micrometeoroid impacts that could damage the shell (Roy *et al*, 2013)

Because the selected planetary body for the construction of a Shell World will have no atmosphere to begin with, all atmospheric gases will have to introduced from other sources. Earth's atmosphere, assuming it is idea for human survival, is composed mainly of nitrogen, followed by oxygen, water vapor, and carbon dioxide. Several options exist in Earth's solar system for obtaining these gases without taking from Earth's atmosphere. For nitrogen, significant amounts exist on Jupiter and Titan, a moon of Saturn. Extensive concentrations of oxygen and carbon dioxide can be found in the atmosphere of Venus. Carbon left behind on Venus could potentially be used in the construction of the carbon nanotube shell. Both water vapor and liquid water are needed on a Shell World in order for humans to survive as well as for temperature regulation. Water can be harvested from comets and asteroids found in the solar system as well as from several of Jupiter's moons (Roy *et al*, 2009).

With the entire planetary body being encompassed by a solid, opaque, airtight shell, no sunlight will reach the surface. As a result, any humans living within the shell will be forced to live in darkness unless artificial lighting is installed (Roy *et al*, 2013). Energy required for artificial lighting could be supplied by solar farms and power plants located on the outer surface of the shell. This location would allow optimum exposure to solar radiation for solar panels and prevent pollution of the planetary atmosphere by power plants. Another option would be the collection and channeling of sunlight into the shell by fiber optics. This would be necessary for the growth of plants (crops) on the surface of the Shell World as well as the absorption of vitamins by humans. Another benefit of having a solid shell containing a planetary atmosphere is having a secondary surface for inhabitants. The original creators of the Shell World idea, Roy, Kennedy, and Fields, described dwellings and buildings extending from the sky while the original planetary surface is left wide open for forests, nature preserves, cropland, and oceans (Roy *et al*, 2013).

The process of Shell World construction, as a summary, consists of shell construction (including the placement of regolith on the outer surface of the shell), inflation by introducing atmospheric gases in the desired amounts, and the addition of artificial lighting, water, and technology. Estimates for the amount of time that this construction process would require extends from several hundred years to thousands of years.

Conclusion

While both terraforming and the construction of Shell Worlds offer humanity options for the production of habitable worlds, which one should be chosen? The natural processes required for the terraforming of a planet would require hundreds of thousands of years to form a habitable world for humans. The industrial processes of Shell World construction would only require a few hundred up to a few thousand years to complete this task. Material requirements must also be taken into consideration. While natural terraforming utilizes many of the materials already present on a planet, external gases, organisms, and water must be introduced to complete the process. Shell World construction requires the introduction all nearly all materials and gases required for the construction of a habitable world. At initial glance this seems to favor natural terraforming, but the size of the planetary body needed by either process must be taken into account as well. Terraforming requires a planet with a stable atmosphere, meaning the planet must be massive enough to retain the atmospheric gases. Unless the planet has a large density, it will most likely be a large planet (similar to Earth in size). The Shell World requirement of no atmosphere allows the conversion of smaller bodies into habitable worlds. Objects such as Luna and Ceres are significantly smaller than Earth, and would require fewer materials compared to Earth-sized objects. With the weaker gravitational pull, the mass of the shell would have to be increased to equal the atmospheric pressure experienced by the shell. However, the technique of placing regolith on the outer surface of the shell to increase its mass would allow this to be accomplished without the input of extra materials. In addition, a thicker layer of regolith on the outer surface would provide a thicker radiation shield and better protection from impacts on the outer surface of the shell.

As Earth's climate continues to change in a direction that could result in the need for a new planet for humans to inhabit, the lack of a planet with the same conditions as Earth within reach forces humans to look for other options. While there are a number of planetary bodies within reach, they do not possess an environment that is acceptable for human survival. For the planets that hold an atmosphere, inducing natural processes of oxygen production could, over hundreds of thousands of years, result in the planet being habitable for humans. This process of terraforming would require the input of atmospheric gases, plants, and water, and would require the raising of the planet's surface temperature. In addition, the presence of life on those planets before terraforming must be ethically considered. For planetary bodies that lack a stable atmosphere, the construction of a planetary shell to contain an artificially designed environment could be accomplished within a few thousand years. While this method would require the input of all needed materials (shell material, atmospheric gases, etc.), the smaller size of the planetary body could match the material requirement to that of terraforming. An important note to make on both methods is the heavy reliance on interplanetary travel, an activity that requires large amounts of energy. While humans currently do not possess the capabilities to generate the needed energy for either method, discoveries of reactions that could be harnessed to produce the needed quantities have already been discovered and/or theorized (i.e. matter and antimatter collisions). The human race is very close to being able to inhabit other worlds. Perhaps as the human race continues to innovate and discover new technologies to make this dream a reality, techniques and processes will be developed to reverse the changes done to Earth’s atmosphere to make this dream an impending necessity.

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