The Thermodynamics of Planetary Engineering on the Planet Mars

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THE THERMODYNAMICS OF PLANETARY ENGINEERING ON THE PLANET MARS

by

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ABSTRACT

Mars is a potentially habitable planet given the appropriate planetary engineering efforts. In order to create a habitable environment, the planet must be terraformed, creating quasi-Earth conditions. Benchmarks for minimum acceptable survivable human conditions were set by observing atmospheric pressures and temperatures here on Earth that humans are known to exist in. By observing a positive feedback reaction, it is shown how the sublimation of the volatile southern polar ice cap on Mars can increase global temperatures and pressures to the benchmarks set for minimum acceptable survivable human conditions. Given the degree of uncertainty, utilization of pressure scale heights and the Martin extreme terrain were used to show how less than desirable conditions can still produce results where these benchmarks can be met. Methods for obtaining enough energy to sublimate the southern polar ice cap were reviewed in detail.

A new method of using dark, carbonaceous Martian moon material to alter the overall average albedo of the polar ice cap is proposed. Such a method would increase Martian energy efficiency. It is shown that by covering roughly 10% of the Martian polar ice cap with dark carbonaceous material, this required energy can be obtained. Overall contributions include utilization of pressure scale heights at various suggested settlement sites, as well as polar albedo altering as a method of planetary engineering. This project serves as a foundational work for long term solar system exploration and settlement.

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INTRODUCTION

Mars: the red planet. Often considered as a strong candidate for the ability to support extraterrestrial life, it is believed that liquid water once flowed in massive quantities on its surface. Given Mars' relatively close proximity to Earth and the clues that tell a tale as to what could have been a once habitable planet, Mars makes for an excellent study case in so many regards. Particularly, it is a strong theoretical candidate for planetary engineering, and more specifically, terraforming. Planetary engineering refers to the altering of global properties of a planet through the usage of advanced technological methods. Here on Earth, it is shown to be more than just a thought – it occurs inadvertently in our everyday lives through the process known as global warming. Terraforming, on the other hand, refers directly to planetary engineering with a purpose of creating Earth-like surface conditions suitable for humans to survive in. In order for terraforming to be possible, the host planet must have certain intrinsic properties. Broadly speaking, the three most important intrinsic properties are a planet's size, composition, and the proximity of the planet with respects to its given circumstellar habitable zone (CHZ). Consequently, these properties also represent the necessary properties for human life to exist.

In the case of Mars, if one were to terraform it, it is important to establish these properties as compared to that of the ideal case of Earth. Mars' radius estimates 3,390 km, which is around 53.2% of that of Earth[1]. The mass of Mars is roughly 6.417 x 10^{23} kg, which is about 10.7% the mass of Earth[2]. Hence, the acceleration due to gravity on the surface of Mars estimates 3.71 m/s^2, which is 37.9% of that on Earth. While this may be an area of concern for human colonization, this is a topic of biological adaptation to low gravity environments. While it is observed that long term exposure to zero gravity environments has hazardous implications on human health, it is hypothesized that humans can evolve and adapt to lower gravity environments given time. For the purpose of this research, this hypothesis is assumed to be correct. The size of the circumstellar habitable zone in our solar system is a subjective case depending upon how it is defined. Ultimately, however, the goal of the CHZ is to pinpoint the region around the host star in which liquid water can exist. Venus, Earth, and Mars may all be considered within the CHZ. Mars' composition is similar to that of Earth in simple terms. A core composed primarily of iron and nickel, a silicate rich mantle, and a basaltic crust. This comes as no surprise, as Mars, much like Earth, is a terrestrial planet formed of the same material in the solar nebula 4.6 billion years ago as according to the nebular hypothesis[3]. The composition of the atmosphere is where the planets largely differ. While Earth's atmosphere is composed mostly of nitrogen (78%) and oxygen (21%), Mars' atmosphere is composed almost entirely of carbon dioxide gas (96%). The total size of the Martian atmosphere also dwarfs in comparison to Earth's atmosphere, totaling 0.6 kPa versus Earth's 101.3 kPa or 0.0059 atm/atm (5.9%)[1]. This is the key factor for terraforming. In order for human life to exist on Mars, Earth-like conditions must be replicated in temperature and atmospheric pressure.

In the general case, requirements for terraforming any planet must be set. That is to say, a final product of terraforming must be similar to conditions present on Earth. The requirements are as follows (but not limited to):

- Surface temperature
- Atmospheric pressure
- Atmospheric composition
- Carbon/oxygen cycles
- Nitrogen cycles
- Magnetic fields

Each requirement is critical to human survival, and thus part of Earth's identity with respects to terraforming. As addressed before, however, the absolute most critical requirements are to achieve temperatures and pressures similar to standard atmospheric temperature and pressure here on Earth.

Altering an entire planet's atmosphere or changing a planet's mean temperature is a task that is seemingly larger than life. Planetary engineering and terraforming stand as beneficial studies in that can be directly applied here on Earth (known as geoengineering). The ultimate survival and longevity of the human race depends upon the study and application of geoengineering. Mankind under technological and highly intelligent civilization has only been around for a very small period of time. The more that is understood of global warming and planetary climate cycles, the more evident it is that large scale action must be taken in order to continue to support human life for millennia to come. That is not to say that it is time to move civilization to Mars so much as it suggests that by understanding the past, present, and future of the atmosphere of Mars, these findings can shed light as to the future of Earth. Furthermore, understanding the ability of planetary engineering is a prospective tool for what science can do to alter the fate of Earth.

Several methods exist for planetary engineering. In fact, each subject for planetary engineering and terraforming is its own unique case, and working to a solution will take multiple methods working hand in hand. Naturally this means that there is likely no fix-all solution applicable to each individual case. Rather, a great deal of creativity must be achieved in order to tailor to each case. In the particular study of the terraforming of Mars, the most popular of suggested methods include but are not limited to: large solar mirrors, self-replicating systems (SRS), artificial greenhouse production, and kinetic impacting. Each method has particular advantages and disadvantages, and all methods will be considered. A particular emphasis will be placed on the artificial production of powerful greenhouse gases, as it is seen as the most practical and realistic method. Additionally, a new method is proposed. By altering the planet’s albedo, increasing the planetary energy budget, and constructing a new greenhouse system, warming the planet is possible through viable and realistic means.

The contents of this research will start with a thermodynamic analysis of Mars as the subject for terraforming. This includes what kind of work it would take to accomplish the desired quasi-Earth pressure and temperatures suitable for humans to live on Mars. Following this will be an extensive study of the previously aforementioned methods of terraforming as applied to the subject Mars. A link will be created between each method and the thermodynamic demands and consequences, as well as a brief overview of their individual practicalities. The method of constructing a greenhouse effect will be examined in depth. Lastly, the geoengineering implications brought about by this study will be approached, as well as a brief ethical view of terraforming Mars.

MARS, THE SUBJECT OF TERRAFORMING

Subjects of Terraforming

Planetary engineering takes a great deal to accomplish given its large scale nature. Hypotheses of planetary engineering and terraforming exist in different forms on different hosts, including but not limited to Mercury, Venus, the Moon, Mars, asteroid 1 Ceres, asteroid 4 Vesta, and Saturn's moon, Titan. In each of these cases, the aforementioned criteria of size, composition, and location with respects to the circumstellar habitable zone must be taken into account in order to consider the case as a practical candidate. Take the case of Venus into consideration. Venus is very similar to Earth in size at 4.867 x 10^{24} kg, equivalent to 81.5% the mass of the Earth[4]. Venus' radius estimates 6,052 km, or roughly 95.0% of that of Earth[4]. Venus' location can also be considered within the CHZ given the right atmospheric pressure, as according to Zsom et al.[5]. Unfortunately, Venus' candidacy falls short when considering the composition. Venus' atmosphere is overwhelmed with carbon dioxide gas, with an atmospheric pressure of 9.2 MPa, which is nearly 1000% the size of Earth's atmosphere[4]. Such an example of Venus shows why Mars is such an appreciable case, and why being creative with terraforming is key. Venus represents the hypothetical ideal case for terraforming; human limitations make atmospheric reduction on Venus nearly impossible. This is because fixating or solidifying one thousand Earth sized atmospheres into a physical state would take a much higher order of time. That is to say, even though Mars might not be the most Earth-like planet in the solar system, it represents the goldilocks planet for terraforming. Mars itself however is still a hypothetical case with much uncertainty involved. In theory, the tools and technology exist to terraform Mars (see chapter three). Given that Mars' size is adequate for terraforming, and that it rests well inside the circumstellar habitable zone, the only true variable, much like Venus, is the composition. Figure 1 depicts the planet sizes and the circumstellar habitable zone, respectively[6].

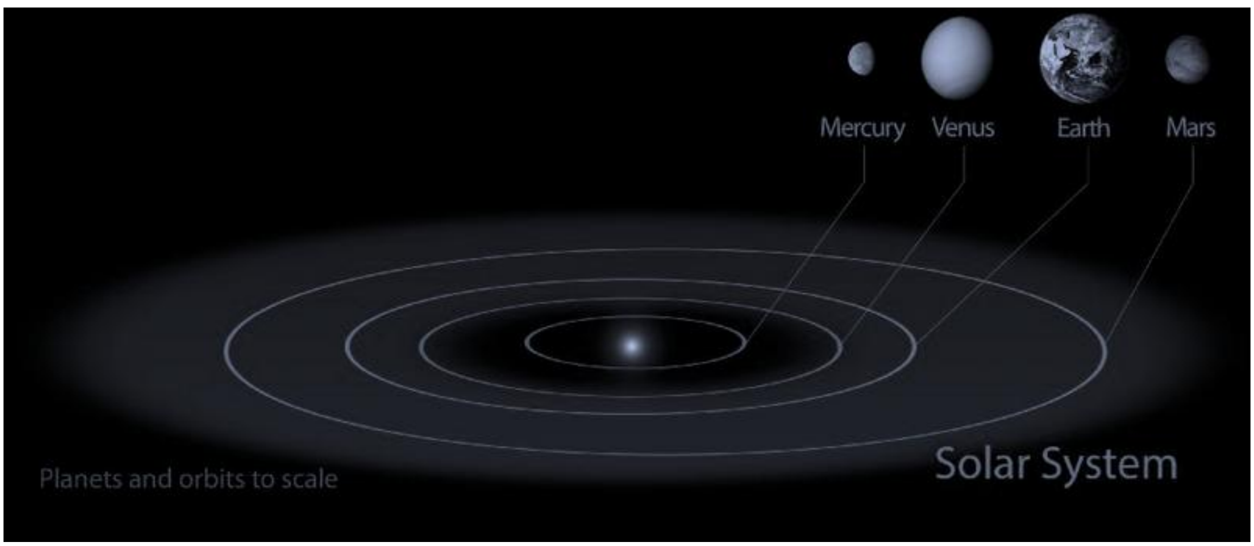


Figure 1: The circumstellar habitable zone, depicted by the shaded region

Mars' compositional issues, much like Venus, rest in the atmosphere. In this case, though, Mars' atmospheric pressure is too little. Table 1 shows the atmospheric pressures of the terrestrial planets, as well as other astronomical comparisons between the terrestrial planets.

Planet	Atmospheric Pressure	Mean Surface Temperature	Surface Gravity
Venus	9,200,000 Pa	733 ºK	8.87 m/s^2
Earth	101,230 Pa	288 ºK	9.81 m/s^2
Mars	600 Pa	213 ºK	3.71 m/s^2

Table 1: Physical facts of three terrestrial planets

Additionally, favorable criteria such as the axial tilt and rotation rate of Mars are similar to that of Earth. Mars axial tilt is roughly 25.2º, as compared to Earth's axial tilt of 23.4º[1]. This produces seasons much similar to here on Earth. Conveniently, the rotation rate of Mars also produces, among other things, a day equal in time to 1.03 Earth days. This creates encouraging conditions for human adaptations. Luckily, utilizing both the entire composition of Mars and modern technology, adding an atmosphere is significantly more attainable than removing one. Building an atmosphere also allows for flexibility of creating a desirable atmospheric composition as well. A good analogy is to imagine a problem of being too cold in bed. To solve this problem, add various types of blankets or coverings. The opposite problem of being too hot isn't as easy to solve. One can only be stripped down so far, and in one manner (being naked). Many other characteristics also support Mars as being the strongest candidate in our solar system. Mars is relatively close to Earth, ranging roughly 0.5-1.5 AU. Transit times are within reason for consistent visits to the red planet given modern technology.

Conveniently, it is also the most explored and most understood planet in the solar system.

Phases of Terraforming

Terraforming Mars can be broken down into two phases. Ultimately the goal is to achieve Earth-like suitable for human survival. Phase one is to achieve quasi-Earth atmospheric pressure and temperature. The average temperature on Earth is roughly 288.2 °K, while the standard pressure is 1 bar, equivalent to 101.2 kPa. The goal is not to achieve exact conditions, but rather to achieve survivable human *physical* conditions. Phase two is to achieve a habitable, breathable atmosphere. This is an entirely complicated process only necessary for full-scale human civilization, and deals with survivable human *biological* conditions. For this reason, simple colonization will only be considered here, and the difficult question of phase two will be reconsidered at the end of this chapter.

Setting the Target for Terraforming

Phase one requires that we achieve survivable human conditions. Before considering Mars, we must first set the bar for human conditions here on Earth. Human settlements exist in extreme conditions attainable on Mars. A study by Case Western University anthropologists on adaptation to high altitude hypoxia suggests humans have exhibited abilities to live in extreme conditions through means of human adaptation. The particular case study takes a look at the Tibet region, where the average altitude rests at roughly 4,875 meters[7]. At such an altitude, atmospheric pressure is about 55.0 kPa here on Earth[8]. This observation will be set as a rough benchmark for required conditions on Mars. Mars' atmospheric pressure lies at 0.6 kPa, a far cry from the both atmospheric pressure of 101.2 kPa at sea level on Earth and the lower acceptable limit of 55.0 kPa. Achieving this lower acceptable limit on Mars is the primary area of study. Importing gasses by conventional means is all but impossible given the vast quantity required. Importing gasses through small body impact is a potential solution although still would be incredibly difficult given varying compositions and the quantity required to achieve the required conditions. Conveniently, however, Mars is fully equipped with problem-solving deposits of frozen carbon dioxide gas on the surface located in the polar ice caps.

Additionally, a mean global temperature on Mars must be achieved on Mars, or, at the very least, a sustainable seasonal tropical temperature. A vital benchmark for human survival is the existence of liquid water. Data and observation from Mars exploration has shown substantial amounts of frozen water, and further exploration and study is required to fully understand what lies under the surface of Mars. Evidence that Mars once had flowing rivers and oceans exists is promising for water to be plentiful beneath the surface. Geological clues such as ancient shorelines and soil composition support the idea of Mars once having liquid water present above the surface[9]. Since there is a relationship between pressure and melting points, the lower acceptable limit for temperature is assumed to be the point at which liquid water can exist given the lower acceptable limit for atmospheric pressure, 55.0 kPa. Figure 2 shows the phase diagram of water under different pressures[10].

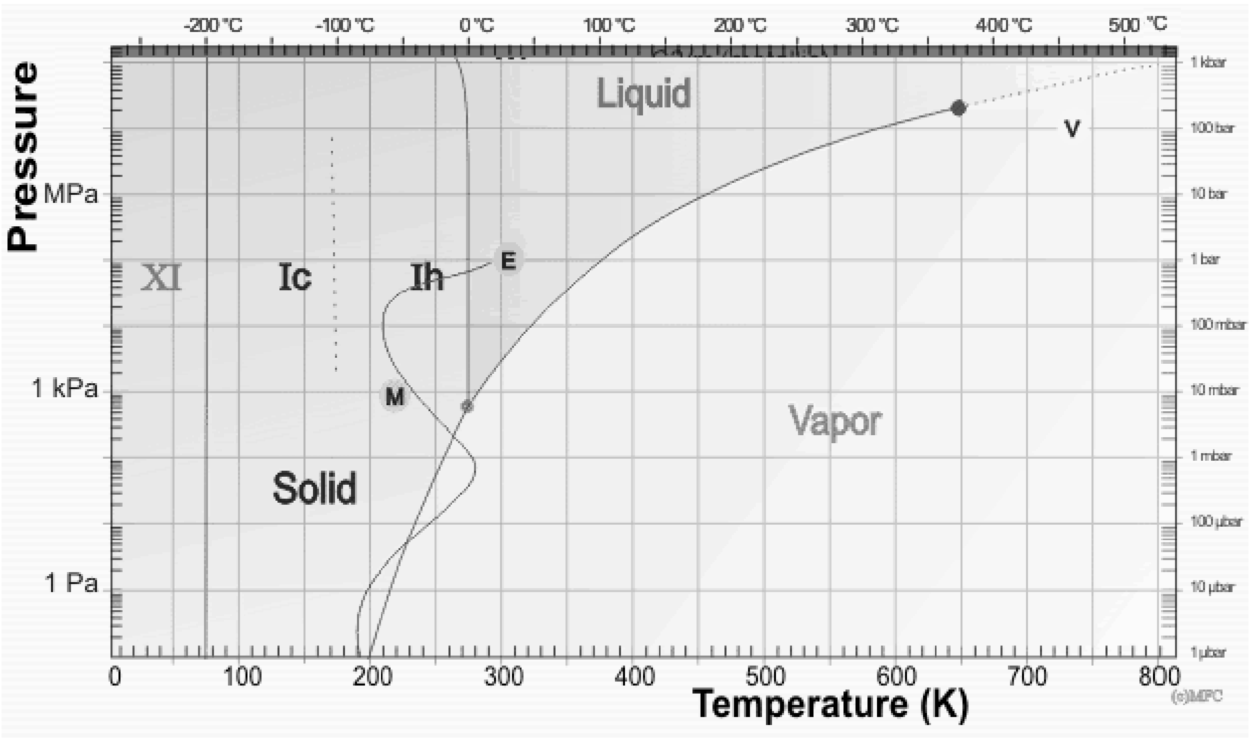


Figure 2: Water phase (Mars labeled at point M)

Note that Mars is very close to the triple point. By this observation, the temperature on Mars must strictly be greater than 274.0 °K for liquid water to flow, under 55.0 kPa of pressure.

Sources of Atmospheric Pressure

Southern polar ice cap.

Over the course of Mars recent astronomical history, its atmosphere has been either shed away or frozen to the surface. These reservoirs of frozen atmospheric gas are what make terraforming Mars a possibility. As shown by McKay and Zubrin, an estimated 5.0-10.0 kPa worth of frozen carbon dioxide gas exists in the southern

Martian polar ice cap[11]. More recent numbers show an estimated volume of carbon dioxide in the southern Martian polar ice cap to be 1.6 x 10^{15} m^3, which would result in roughly 9.2 kPa worth of carbon dioxide on the surface frozen in the southern polar ice cap. This is towards the upper end of McKay and Zubrin's estimates. Melting a planet's entire polar ice cap is by no means a small task. Again, luckily the problem fixes itself. By observing a runaway greenhouse effect, a full brute force would not be required to melt the entire cap. As shown in Figure 3 from McKay and Zubrin's modeling, certain equilibrium points exist with the southern polar ice cap[11].

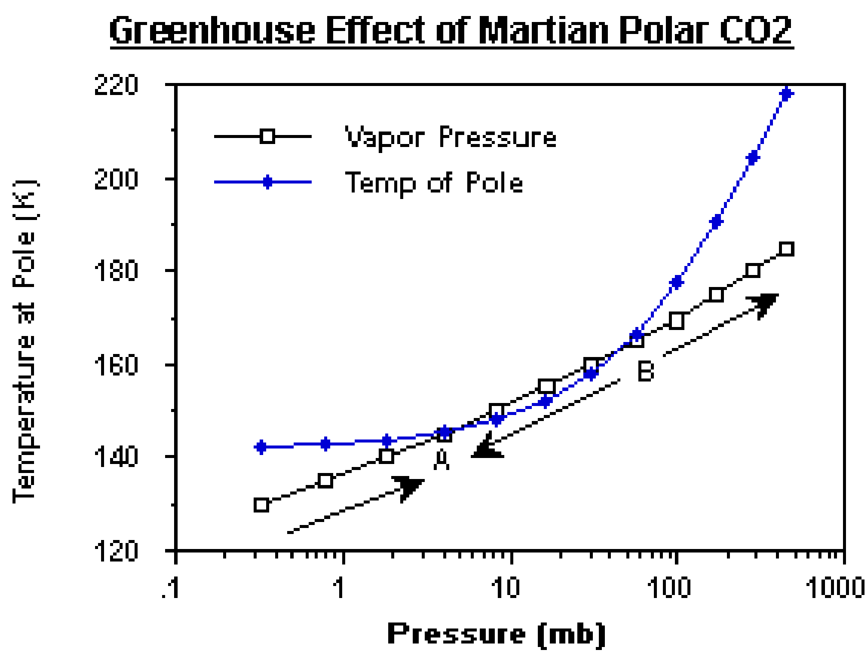


Figure 3: Modeled temperature and pressure relationships of southern polar ice cap

Mars today is at point A, an icebox, whereas point B represents a runaway greenhouse effect, capable of eliminating the entire polar ice cap in as little as a decade. By increasing the temperature of the southern pole from 147 °K to 151 °K and shifting the temperature curve up, equilibrium points A and B are driven together, allowing for this runaway greenhouse effect to occur. That is to say, the volatility of the materials in the southern polar cap creates a favorable conditions; the problem fixes itself with a fraction of the work required to otherwise melt the entire polar ice cap by brute force.

The Martian regolith.

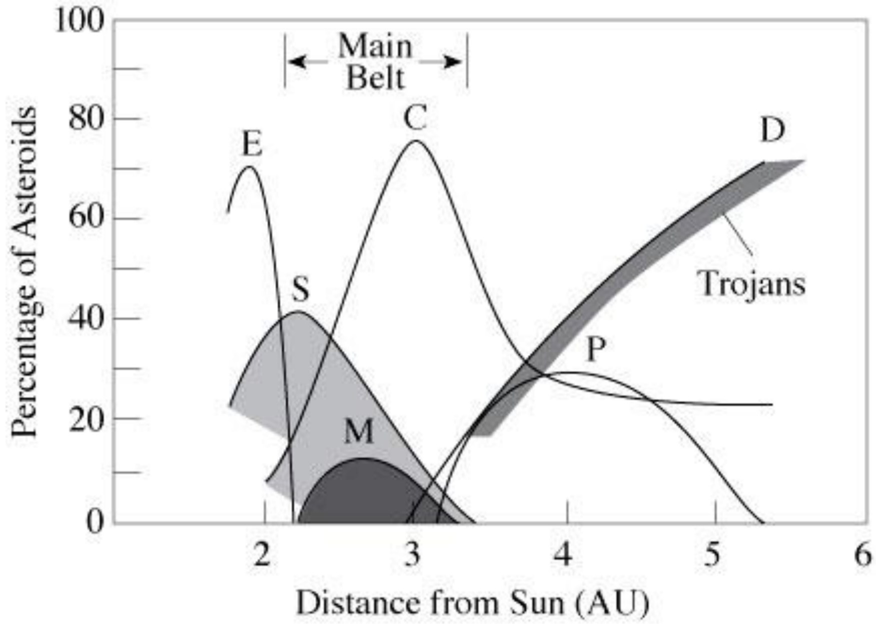
While the source in Southern polar ice cap is an important finding, more sources of atmospheric gasses are needed. Naturally, the most efficient source of building an atmosphere is still through volatile solids. Importing volatiles from Earth is not realistic, as both the cost and amount of substance required are unconceivable. However, further deposits of volatiles in mass quantities do exist both on Mars and in the solar system (see subsection iii). Focusing on Mars itself, deposits of carbon dioxide are potentially abundant. While the northern polar ice cap is known to be primarily composed of water ice, an understanding of Martian history gives hints as to where more sources of atmospheric gas may be. If liquid water once flowed on Mars as evidence suggests, a substantial atmosphere capable of producing a greenhouse effect must have been present. One common theory is that the atmosphere has been shed slowly over time by ionizing particles such as solar wind and cosmic radiation. The other explanation is that the largely carbon dioxide atmosphere was absorbed into the Martian regolith as carbonates. Both of these theories appear to have taken place, although to what degree is uncertain.

Understanding just how much carbon dioxide exists in the Martian regolith is pivotal. Evidence from both the Mars Phoenix Lander and Mars Exploration Rover Spirit through soil sample analysis have shown the carbonates to exist in the form of calcium carbonate ($CaCO_3$) and magnesium-iron carbonates ($MgCO_3$ and $FeCO_3$) respective to each mission[12][13]. Due to interactions with the polar ice caps, it is expected that a majority of the deposits of carbonates exist in high latitude regions. Unfortunately, without a mission dedicated to exploring the extent of the Martian regolith carbonate deposits, the true global quantity is unknown. Inconveniently, no rover missions have been dispatched higher than 60º latitude. Thus, assumptions must be made in regards to the Martian regolith system. McKay and Zubrin model a scenario where the Martian regolith system is poor in volatiles, as well as a scenario for where the Martian regolith system is rich in volatiles. These scenarios assume a poor regolith system to contain 44.4 kPa worth of vapor pressure, and a rich regolith system to contain 89.4 kPa worth of carbon dioxide vapor pressure. Even in a poor regolith system, utilizing all of the deposits assumed present in the Martian regolith by McKay and Zubrin would be nearly sufficient to reach the lower acceptable atmospheric pressure of 55.0 kPa as set earlier in this chapter. However, accessing these deposits is not so simple. McKay and Zubrin use the analogy of wringing out a wet sponge to conceptualize the effectiveness of utilizing the Martian regolith system. As the regolith is heated, it becomes increasingly less efficient at releasing the absorbed volatile compounds. Thus, it is impractical and inefficient to consider using up the entire source of the regolith system assuming a poor regolith system. Also, since the relationship between the Martian regolith system and the atmosphere is unknown and merely speculated at, the amount of work required to free the volatiles absorbed in the regolith is uncertain. More information on this will be presented in the subsequent section.

Importation of solar system volatiles.

Assuming Mars does not have a sufficient amount of volatiles in the southern polar ice cap and the regolith system to obtain the lower acceptable limit of atmospheric pressure, additional sources would be required. The solar system contains a seemingly endless supply of small body objects. Given the cold conditions of interplanetary space, icy volatiles exist with low sublimation temperatures. Particularly, it is conceivable that a small comet or asteroid with a favorable orbit could have its orbital path around the Sun altered via mechanical means to impact Mars.

zzAsteroids from the inner asteroid belt tend to be anhydrous and lacking in ice and volatiles, as they are closer to the Sun and have, since their formation, differentiated and lost their volatiles. Towards the outer asteroid belt and beyond, however, C, P, and D type asteroids are more abundant. Their surface compositions are shown to be hydrous, or potentially sub-surface in the case of P and D type asteroids.



(Courtesy of Kenneth R. Lang, Cambridge Guide to the Solar System, Second Edition, Cambridge University Press, 2011)

Figure 4: Distributions of asteroids in the solar system

Figure 4 depicts the distribution of asteroids in the solar system[14]. Assuming the inclination of any given object is similar to Mars inclination with respects to the Sun, the object's course will be easier to dynamically alter given increasing distance from the Sun. This is because as an object is farther away from the sun, the orbital velocity is slower. Thus, a smaller change in velocity is required in order to line up the orbits between Mars and the object. Consequently, less energy is required. With this being said, while the right asteroid is a potential candidate for importation of solar system volatiles, comets are much further away and far more abundant in volatiles.

Comets are the iciest known objects in the solar system, and a perfect candidate for importation of solar system volatiles if necessary. Given that most comets exist beyond the frost line at 5 AU, they are both eligible and expected to be carrying volatiles of carbon dioxide, water, ammonia, and methane. The frost line is defined as the distance from the Sun at which the temperature of empty space is cool enough for hydrogen compounds to be able to condense into solids[15]. Thus, any object that formed beyond this distance is a potential candidate for importation of solar system volatiles, asteroids included.

Molecular abundances in comets

	Relative molecular abundance (% with respect to H_2O)								
	H_2O	CH_3OH	HCN	NH_3	H_2CO	C_2H_2	C_2H_6	CH_4	CO
Sublimation temperature (K)	152	99	95	78	64	54	44	31	24
Comets									
C/2001 A2	100	3.5	0.5		0.1	0.4	1.6	1.0	2.8
C/1995 O1	100	2.0	0.4	0.7		0.3	0.6	1.3	12.0
C/1999 T1	100	1.7	0.4				0.7	1.4	17.0
C/1996 B2	100	1.0–2.0	0.2	0.5		0.1–0.5	0.6	0.8	16.0
C/2002 T7	100	4.0			0.8				1.4
153P/I-Z	100	2.5	0.2	<0.2	0.6	0.2	0.6	0.5	4.7
C/1999 H1	100	2.0	0.2		0.7	0.2	0.7	1.4	1.5
C/2006 P1	100		0.3	2.0	0.5	0.5	0.5	0.5	2.0
9P/Tempel 1	100	1.0	0.2		0.8	0.1	0.3	<0.9	4.3
C/2000 WM1	100	1.0	0.2		0.2	0.2	0.6	0.4	1.0
2P/Encke	100	2.0	0.1			<0.2	0.3–0.7	<0.2	
73P/SW3	100	0.2	0.3	<0.2	0.1	0.03	0.1		<1.9
C/1999 S4	100	<0.2	0.08			<0.1	0.1	0.1	0.3

Table 2: Chemical compositions of surveyed comets

Standard compositions of relative abundance to water of surveyed comets are shown in Table 2 above[16]. For a standard comet of an idealized spherical shape with a diameter of 2 km and idealized uniform density of 500 kg/m^3, with the assumption that half of the comet is icy volatiles, it is seen that it could take several dozen comets of a larger size to make a noticeable yet miniscule difference in atmospheric pressure on Mars. This is because of the large size of the Martian surface area. Results are shown on the order of Pascals rather than the necessary kilopascals. Thus, it is concluded that such an idea is inefficient and unrealistic. However, it stands as a highly critical finding in regards to greenhouse gassing. The following chapter will discuss this in detail.

Calculating the Work Required to Sublimate Volatiles

Vapor pressure from southern pole.

As the initial source of vapor pressure, calculating the overall energy required to increase the southern polar ice cap by 4 °K is done by observing the first and second laws of thermodynamics. These laws are listed below as equation (1) and equation (2), respectively:

$$W = dU - dQ \tag{1}$$

$$dQ = TdS \tag{2}$$

The first law of thermodynamics states that the work done on the system is equal to the change in internal energy minus the heat added. The system is assumed to be a closed system of the Southern polar ice cap. The second law of thermodynamics states that the heat added is equal to the temperature of the system multiplied by the change in entropy. By combining equations (1) and (2), equation (3) is created:

$$W = dU - TdS \tag{3}$$

Equation (3) describes the amount of work required in order to change the system from initial time to final time. A final equation is created by observing specific entropy and internal energy values at final and initial pressures and temperatures. Equation (4) uses the entropy relationship at constant volume.

$$W = m(u_2 - u_1) - \; Tmc_V \ln(\frac{T_2}{T_1}) \tag{4}$$

In these equations, m represents the total mass of the system, T represents the average temperature of the system, and c_V represents the specific heat capacity of carbon dioxide at constant volume. Table 3 shows the values used for the variables in calculating the work required to increase the Martian southern polar ice cap by 4 °K.

T	Average temperature of southern pole	147 °K
m	Total mass of southern polar ice cap	3.59×10^{17} kg
c_v	Specific heat capacity of carbon dioxide at constant volume	507.2 J/K
T_2	Desired average temperature of southern pole	151 °K
T_1	Initial average temperature of southern pole	147 °K
u_2	Specific internal energy of carbon dioxide at T_2	69798 J/kg
u_1	Specific internal energy of carbon dioxide at T_1	67695 J/kg

Table 3: Values used for calculating required work, $\boldsymbol{W}$

The total work required to increase the southern pole by 4 °K is calculated to be 3.64×10^{19} J. With this calculation, it is assumed that the entire polar ice cap is composed of carbon dioxide, and that the change in the volume of the atmosphere is negligible. Due to the large amount of uncertainties in values, the value of 3.64×10^{19} J is seen as more of a ballpark figure than an actual value. As a comparison, by observing the solar flux upon Mars annually, the entire planet absorbs 1.96×10^{24} J of energy. Thus, the amount of energy required to alter the Martian southern polar ice cap by 4 °K is a mere fraction of the annual energy absorbed by Mars in a year. This is an important finding, as it highlights the true significance of the Sun. It must also be noted that the Sun is the only real source of energy large enough to conceivably achieve this kind of energy through realistic means. Take into consideration nuclear weapons – it would take approximately 30,000 modern day standard thermonuclear warheads in order to achieve this magnitude of energy – double the amount of current nuclear weapons in the entire world. Making it even more unconceivable, considering average costs to build and maintain a single nuclear weapon alone, the total cost of such a venture would be just over $1 trillion. This cost does not take into consideration actually shipping 30,000 thermonuclear warheads from Earth to Mars. To underline the point, the Sun is the only realistic source of terraforming Mars. Several solutions for finding this order of magnitude of energy exist, and will be discussed in the subsequent chapter.

Vapor pressure from the Martian regolith system.

As significant of a finding as sublimating the southern pole is, it only accounts for and estimated 9.2 kPa worth of pressure. This would create a new global atmospheric pressure of 9.8 kPa, now 45.2 kPa away from the lower acceptable limit of 55.0 kPa. As previously mentioned, importing volatiles from Earth or from small body space objects such as comets is inconceivable and does not sufficiently supply an order of magnitude large enough to make a difference. The last true source of volatile substances exists in the Martian regolith system, where anywhere between 44.4 kPa and 89.4 kPa worth of vapor pressure may exist. The relationship between the Martian regolith system and the atmosphere is partially unknown. However, it is understood that the Martian regolith system is activated by eliminating the polar caps. McKay and Zubrin use an educated estimation of the relationship between the regolith system and the atmosphere, as modeled in *Technological Requirements for Terraforming Mars*[11]. The modeling assumes the Martian atmosphere as an effective means of transporting heat across the planet, which is a fair assumption. By modeling the mean temperature as a function of carbon dioxide vapor pressure, a global temperature distribution function was created. In the meantime, the parameter for characteristic release energy, T_d, is modeled at various different values ranging from 20 °K to 30 °K. The estimation presented by McKay and Zubrin for the relationship between the Martian regolith system and the atmosphere is given in equation (5):

$$P_R = \frac{CN}{0.275} e^{\left(\frac{T}{T_d}\right)} \tag{5}$$

The equation is a variation of the Van ‘t Hoff equation, which describes change in chemical equilibrium with temperature[17]. N is the amount of vapor pressure assumed to be absorbed in the regolith, in Bar. Input values of 0.444 Bar to 0.894 Bar are converted from kilopascals. C represents a normalization factor, T is the temperature of the atmosphere, and once again T_d represents the characteristic release energy that remains unknown. Several trials given different parameters of the characteristic release energy are shown by McKay and Zubrin in Figure 5, with an assumed regolith inventory of 44.4 kPa.

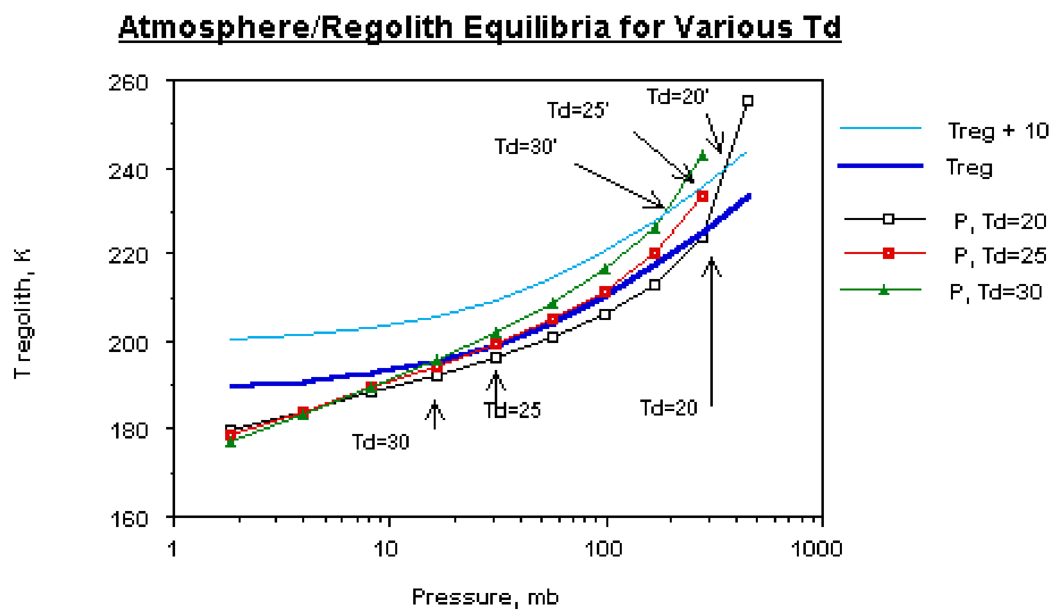


Figure 5: Relationship between release energy and P-T equilibrium

Notice the situations where the characteristic release energy is high (T_d at 25 °K and 30 °K). In these cases, equilibrium points with the regolith temperature curve exist at pressures of around 1.6 kPa for T_d = 25 °K and 3 kPa for T_d = 30 °K. This is value is simply too low to attain the lower acceptable limit of 55.0 kPa. When the characteristic release energy is low (T_d = 20 °K), equilibrium exists at around 30 kPa. While still too low, it is a move in the right direction.

Also shown in Figure 5 is a hypothetical situation where, in addition to the elimination of the southern polar cap, a constant induced increase in temperature was present. In this case, the change in temperature, dT, was set to 10 °K. This drives the equilibrium point to 20-30 kPa for T_d = 25-30 °K, and around 35 kPa for T_d = 20 °K. Such an assumption is optimistic since the characteristic release energy is unknown; however this is also under the assumption for a "poor Mars" regolith inventory. The results for both a "poor Mars" and a "rich Mars" are shown in Figures 6 and 7 below, with equilibrium pressure outputs shown. Various different induced changes in temperature are shown.

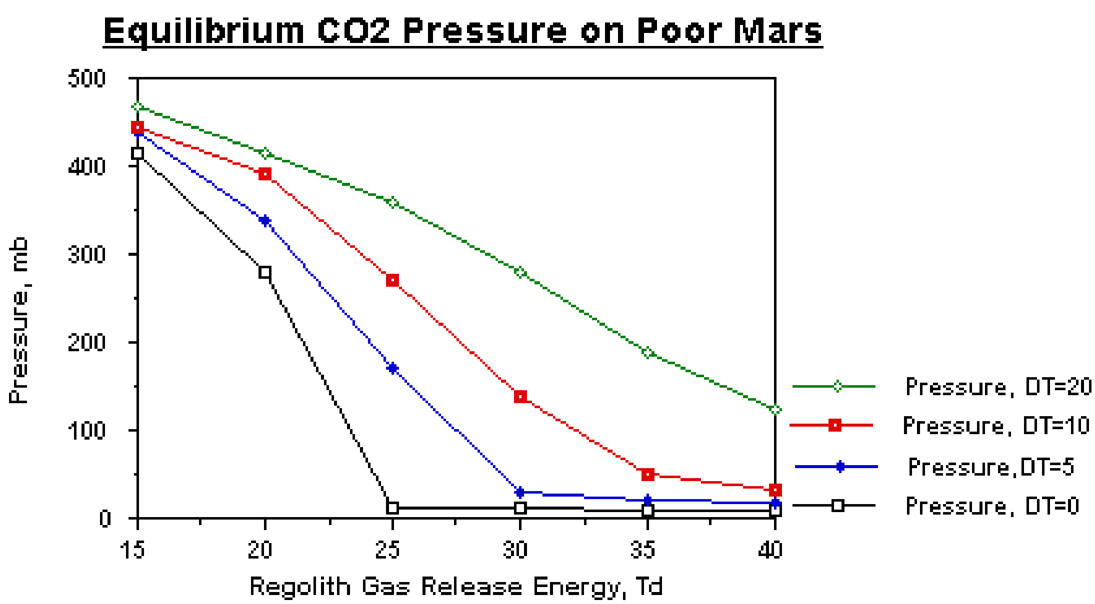


Figure 6: Pressure equilibria for different T_d and dT on a "poor Mars"

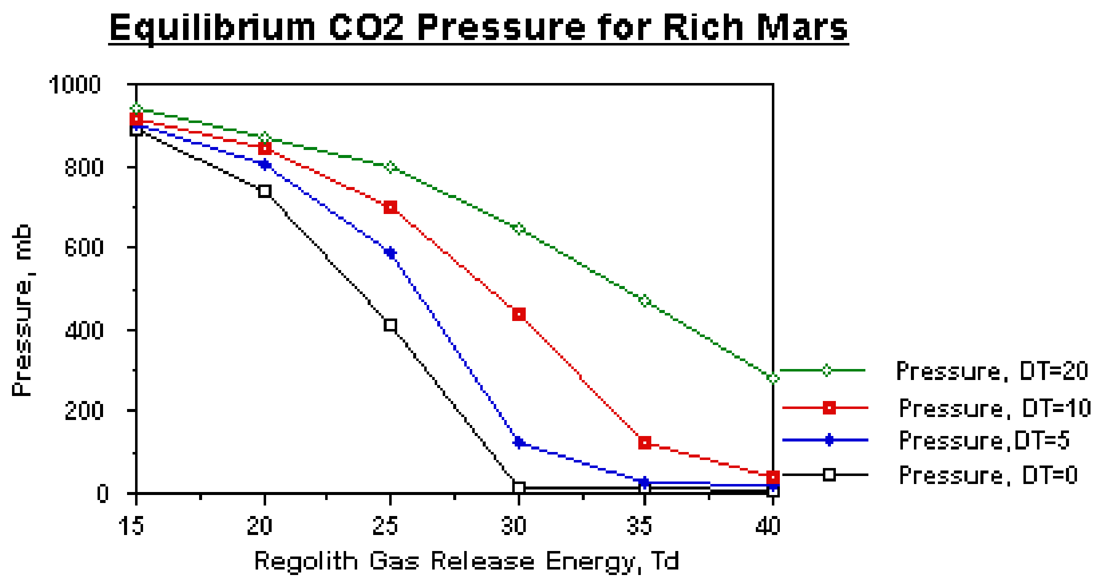


Figure 7: Pressure equilibria for different T_d and dT on a “rich Mars”

In the best of situations, Mars can actually have conditions very similar to Earth. While the large degree of uncertainty is present, as noted by McKay and Zubrin, the importance of inducing a change in temperature makes the entire system controllable. Given the relative amount of uncertainty, however, it is best to assume unfavorable to moderate conditions. For the remainder of this work, it is assumed that Mars exhibits a poor regolith system where the characteristic release energy is between T_d = 20 °K and T_d = 25 °K, such that the resulting equilibrium point exists at roughly 30 kPa. The result of this allows average tropical temperatures on Mars to rise up to 285 °K, or roughly 12 °C. This is a critical finding, because now one of the two conditions set forth at the beginning of this chapter has been satisfied. Liquid water can now exist at this pressure and temperature. The other condition, however, is still not met. The minimum acceptable atmospheric pressure of 55.0 kPa on a “poor Mars” with a moderate characteristic release energy in the Martian regolith system falls just short. After adding the initial atmospheric pressure of 0.6 kPa, the 9.2 kPa worth of vapor pressure as a result of eliminating the southern polar ice cap, and the 30 kPa as a positive feedback reaction in the Martian regolith system, the new atmospheric pressure sits at 39.8 kPa.

One of two of the required survivable human conditions is achieved, yet the other is not. Without a reasonable atmospheric pressure, human life is endangered and the entire prospect of terraforming is threatened. Again, this is under the assumption that the Martian regolith is not very rich in absorbed volatiles. Since there is such a large degree of uncertainty, this assumption must be kept. Also, the induced change of 10 °K in temperature is still required. In order to achieve this, artificial greenhouse gassing must occur. Under unfavorable conditions, a source of roughly 15.2 kPa is still missing.

Utilizing Pressure Scale Height to Assist in Additional Atmospheric Pressure

Pressure scale height.

In the situation where insufficient deposits of volatiles of atmospheric gas exist, utilizing the pressure scale height on Mars can assist to obtain the minimum acceptable atmospheric pressure of 55.0 kPa. Assuming the carbon dioxide released into the atmosphere from the sublimated southern pole and the regolith system becomes evenly distributed across the Martian surface, the atmospheric pressure at zero elevation could be as low as 39.8 kPa. An equation for scale height on Mars is given in equation (6):

$$H = \frac{kT_a}{Ma} \qquad (6)$$

In this case, k is the Boltzmann constant, T_a is the average atmospheric pressure, M is the average molecular mass, and a is the acceleration due to gravity on Mars. It is assumed that the atmosphere is entirely composed of carbon dioxide, with an average molecular mass of 44.01 kg/kmol. The average atmospheric temperature is taken to be 223 °K, up 10 °K after an induced greenhouse gassing in efforts for planetary warming as mentioned in the previous section. The result shows a pressure scale height of 11.35 km.

Since surface pressure is calculated as a simple column of gas over a unit area, any given surface area under zero elevation will exhibit pressures higher than average atmospheric pressure at zero elevation. This can be explained by the fact that there is simply more gas above lower elevations. In fact, the relationship between height and pressure is exponential, and can be described by equation (7) below:

$$P = P_0 e^{\left(\frac{-z}{H}\right)} \tag{7}$$

P_0 represents the average surface pressure, and z represents the elevation with respects to zero elevation on Mars. With a working relationship between elevation and atmospheric pressure, it is possible that locations on the Martian terrain exist that allow atmospheric pressure to be sufficient to assist the elimination of the southern ice cap and the activation of the Martian regolith system in reaching the lower acceptable limit of 55.0 kPa.

Hellas Planitia as a settlement site.

Hellas Planitia is an impact basin on Mars located 42 °S latitude. It is the largest visible impact crater in the solar system, and thus exhibits extremely low elevations. The deepest point in *Hellas Planitia* exists 8.2 km below zero elevation, and it is roughly 2000 km wide and circular in shape[18]. Figure 8 shows a color-coded elevation map of Mars.

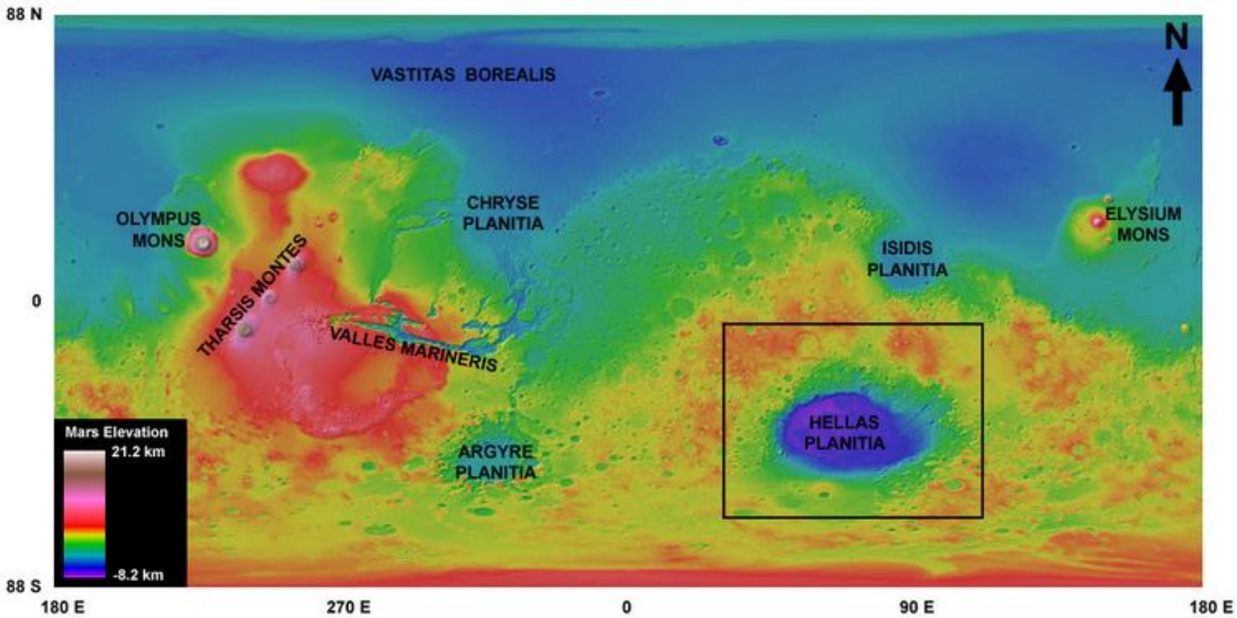


Figure 8: Elevation map of Mars

Given Mars Earth-like tilt upon its axis, promising summer conditions would allow liquid water to exist. At the lowest point in the basin, utilizing equation (7), atmospheric pressure could be as high as 80.1 kPa. As an example, this pressure is almost identical to that of Boulder, CO. Even across the average elevation of the basin, atmospheric pressures would range from 65-75 kPa. With such pressures, the lower acceptable limit of 55.0 kPa desired for survivable human conditions is achieved. However, winters at this latitude would not allow for liquid water to exist. Nonetheless, *Hellas Planitia* is a Martian location that successfully demonstrates the ability to achieve acceptable atmospheric pressures and temperatures without the necessity of complex life support systems.

***Valles Marineris* as a settlement site.**

Valles Marineris is another landmark location on Mars, potentially suitable for settlement through utilizing pressure scale heights. *Valles Marineris* is one of the solar system's largest canyon systems. It is roughly 4000 km long and 200 km wide, and rests nearly parallel to 15 °S latitude[19]. It is depicted in Figure 8. At certain points, it can be as low as 7 km below zero elevation. Much in the case of *Hellas Planitia*, the observed pressure in *Valles Marineris* at these lower altitudes is much higher. By utilizing equation (7) for regions at 5 km below zero elevation, pressures result at 60.4 kPa. Again, the minimum acceptable limit for survivable human conditions of atmospheric pressure is met. *Valles Marineris* also lies in the tropics on Mars, such that annual temperatures would allow liquid water to exist year round. Once again, it is successfully shown that survivable human conditions of atmospheric temperature and pressure can be achieved on Mars.

Oxygenating Mars

As a second phase of terraforming Mars, a breathable atmosphere must be created. The prospected atmosphere on Mars from the first phase of terraforming would be almost entirely composed of carbon dioxide, much as Mars thin atmosphere is today. Even after the first phase of terraforming, humans would require oxygen supplies in order to breathe. A large supply of elemental oxygen exists both in the water reservoirs on Mars and in the carbon dioxide gas in the atmosphere. Assuming preserving water on Mars may be critical for survival, processing diatomic oxygen from carbon dioxide could be done in at least two different ways. One way is to create a reverse combustion process with a byproduct of a hydrocarbons and diatomic oxygen. This is potentially a highly inefficient process but also creates a very useful byproduct. Another way to create diatomic oxygen is to plant large amounts of oxygen producing plants on Mars, through the process of photosynthesis. Such a process would also be highly inefficient and could take upwards towards a thousand years to fully oxygenate the planet. Arguably the best introductory species of plant life to Mars would be *Chroococcidiopsis gigantea*, which is one of the most primitive types of organisms known. It is capable of surviving in the harsh conditions on Mars – exposure to high radiation, extremely low temperatures, and low pressures[20]. As an algae, *Chroococcidiopsis gigantea* would be easy to cultivate and spread along masses of the planet given time.

Another problem arises from such a process, however. By creating an atmosphere largely composed of carbon dioxide and oxygen, a hazardous combustible condition is created. On Earth, the atmosphere is primarily composed of inert diatomic nitrogen. Nitrogen serves as a filler gas in Earth, limiting the combustibility of the oxygen present in the atmosphere. In the theoretical case on Mars, simply converting carbon dioxide into pure oxygen would create highly hazardous conditions for human settlement. Thus, a filler gas must be incorporated into the atmosphere on Mars. Filler gasses include diatomic helium, nitrogen, and the noble gasses. Considering helium and noble gasses are rare gasses both on Earth and Mars, the immediate source of filler gas likely would be of diatomic nitrogen. Further missions on Mars of soil analysis are required to understand the release energy of nitrogen from nitrates in Martian soil. It is understood that phase two of terraforming is an evolutionary process rather than a revolutionary process, and will take time.

METHODS OF TERRAFORMING

Introduction

In order to create atmospheric pressure on Mars, a 4 ºK shift in temperature must be induced at the poles. Several methods have been proposed in previous works. Such methods include but are not limited to large solar mirrors, artificial greenhouse gassing, and importation of powerful greenhouse gasses. The important piece of each of the proposed methods is that if a 4 ºK shift in temperature is to occur, thermal efficiency must improve. Inputting a direct amount of energy can be unpredictable and inefficient itself. Thus, a new method of altering albedo at the poles is also proposed to increase thermal efficiency at the poles of Mars.

Regardless of the method chosen, an energy budget must be set up in order to increase the temperature of Mars. Two possibilities for an improved energy budget may occur. Either the total input of energy towards Mars must be increased, or the amount of energy being sent out by Mars must in effect be sent back into the planet (i.e. a greenhouse effect). The overviewed and proposed methods following take into account such an energy budget.

Overview of Commonly Proposed Methods of Terraforming Mars

Large orbiting solar mirrors.

A method proposed by McKay and Zubrin suggests the idea of placing large solar mirrors in orbit with Mars, reflecting sunlight directed at the poles. Such a task would involve creating a mirror orbiting Mars at roughly 214,000 km. Said mirror would have a diameter of roughly 250 km, roughly equivalent to the width of the state of Florida. The material could be provided from the Martian moons, and would take roughly 3.79 x 10^{15} J to construct[11]. Building solar mirrors to increase thermal input on Mars is the simplest and most straight forward method of terraforming, although creates arguably the most difficult plan to implement. This project would be a marvel of engineering and could cost a tremendous amount of money. Nonetheless, given today's technology it is certainly a possibility despite sounding far-fetched. Ultimately, the method of large solar mirrors alters the Martian energy budget by increasing the amount of energy into Mars at any given time.

The idea of large orbiting solar mirrors has been suggested time and time again, dating as far back as 1923 by German physicist Hermann Oberth[21]. A general form of the energy contribution of a large solar mirror is shown in equation (8):

$$F_i = F_0 \frac{A_m}{A_i} \tag{8}$$

That is to say, the total input of solar flux from the orbiting mirror is equal to the total solar flux projected on the mirror, multiplied by the ratio of the mirror's area and the area that the mirror illuminates on the planet. Thus, while achieving one large 250 km mirror might be an engineering marvel, putting a series of any number of smaller orbiting solar mirrors in geostationary orbit would improve the energy input into Mars, and help to keep sunlight on Mars both day and night. The idea of orbiting solar mirrors has already been successfully tested on much smaller scales, such as the Russian Znamya-2 experiment in 1993[21]. The mission was successful, and effectively confirmed the plausibility of reflecting solar radiation back onto the planet. While such a method perhaps isn't the defining method for terraforming, it must be considered for implementation.

Artificial greenhouse gassing.

Perhaps the most promising method for terraforming Mars, artificial greenhouse gassing involves manufacturing "super" greenhouse gasses capable of creating a greenhouse effect on Mars with a mere fraction of the mass required with traditional greenhouse gasses such as carbon dioxide. This method would be increasing the amount of solar radiation trapped in the Martian atmosphere, blanketing the planet and retaining heat. Artificial greenhouse gassing is, in a sense, the equivalent to intentionally polluting Mars. Though global warming is seen in a negative light on Earth, this is exactly what the goal is on Mars. Particular "super" greenhouse gasses include chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs).

According to the Intergovernmental Panel on Climate Control (IPCC), CFCs and HFCs are anywhere between 1,000-20,000 times as powerful of a greenhouse gas as carbon dioxide on a molecule-per-molecule basis[22]. McKay and Zubrin model a temperature-pressure-production model, describing what kind of power would be required in order to alter the mean Martian atmosphere. In order to achieve the 4 ºK change in temperature at the poles, the typical power output of a nuclear power plant over two decades would be required. Such a project is expensive and requires ultimate commitment, but is entirely a possible task. This also assumes an atmospheric life of 100 years. The possibilities are endless depending upon the type of CFC or HFC being produced, each with their own independent case. Ultimately, the amount of additive super greenhouse gas would be along the order of 300 parts per million into Mars current atmosphere today, with a steady monitoring and replenishing in the future.

Artificial greenhouse gassing is the most promising method of terraforming Mars as it is an entirely controllable method. However, it requires major human presence on Mars on a colonization scale, previous to atmospheric alteration. This makes such a task very expensive. It is also noted that since radiation on the surface of Mars is an issue, subsequent phases require building an ozone layer over a long period of time. CFCs contradict ozone presence, thus such a method in the grand scheme of things would need to be weaned off of in order to fully tailor the Martian atmosphere. Nonetheless, artificial greenhouse gassing is a promising method that can be highly effective in a small period of time.

Importation of volatile greenhouse gasses.

Yet another popularly proposed method for increasing the Martian temperatures is importing volatile greenhouse gasses on small space bodies. Refer to Table 2 in chapter two. Chemical compositions of standard comets include hydrocarbons such as ethane and methane, as well as ammonia. Each of these greenhouse gasses is relatively more potent than carbon dioxide. Methane, for example, is roughly 70 times as powerful of a greenhouse gas as carbon dioxide[22]. By increasing the power by roughly two orders, the mass of gas required effectively is reduced equally.

For a standard and idealized 2 km comet, abundances of methane and ethane could be anywhere between 10^9 and 10^{10} kg. Assuming such a mass of methane was introduced into the current atmosphere of Mars, concentrations of methane would skyrocket to a significant 430 parts-per-billion (ppb). Equation (9)[23] describes a simplified model of the radiative forcing due to methane gas in the atmosphere, where Ω is a radiative forcing constant and M_{ppb} is the amount of methane in parts-per-billion.

$$F_{rad} = \Omega\sqrt{M_{ppb}} \tag{9}$$

The results show an induced radiative forcing of 0.744 W/m^2. By observing the Stefan-Boltzmann Law, such a downward radiative forcing on Mars would equate to approximately 0.1 °K. Though a fraction of the 4 °K desired, this only accounts for the methane contribution into the atmosphere. Several of such objects could make a substantial difference in the atmosphere, and should be considered as a possible method for increasing the temperature on Mars.

Bringing such massive objects to Mars would be cumbersome. Several methods for moving small body space objects exist. One such method is kinetic impacting, or nudging. This method would involve using a large differential in velocity, using kinetic energy to redirect the comet towards Mars. Since comets exist in the far regions of the solar system, their relative velocity is very slow. Thus, altering their course requires less energy than objects closer to the Sun. The downfall to such a method is that it would take a significant amount of time not only to reach the object, but for the object to encounter Mars as well. Another downfall is that it requires objects deep in space to have highly favorable orbits already, with the same inclination as Mars.

A similar variant of kinetic impacting, detonation of nuclear devices at a distance to nudge the comet into a colliding course could be used. The method is much less precise but would be favorable for large course corrections and would be used as a complementary and preliminary technique. The use of a “clean” neutron bomb would be favorable in this situation, as a downfall to nuclear devices is the irradiation associated with them. Another risk that runs is disrupting the object. Since comets and asteroids are often described as “rubble piles,” large impulses could simply dissociate the weak bond within the object. This task would require a heavy investigation into the object of desired course adjustment.

Another such method of moving a comet is the use of a gravitational tractor. A gravitational tractor applies a course correction through the use of gravity rather than kinetic energy. It is favorable and more realistic due to the fact that it creates a controllable or adjustable environment. The tractor itself is a spacecraft hovering near the asteroid for a long period of time, thrusting outward so as to not hit the surface of the object[24]. Gravitational tractors are the most effective way of moving a small space body. Without physically encountering the object, there is less likelihood of fracturing or disrupting the object, which would result in catastrophic failure of the mission. Nonetheless, similar downfalls to kinetic impacting occur. Comets of favorable orbit are required, and importing such a large object from deep space would take a significant amount of time.

One last method for small body control is that of implantation of engines or thrusters on the comet. This method allows for free control of the object at all times, allowing for thrusting at any given time, much like a satellite. The comet's dynamic elements come heavily into play here. A comet's spin, roll, and wobble must be taken into consideration. Using a reference point such as Earth would help to create the most precise conditions for dynamic elements of the comet. A variant of this proposed method is the usage of mass driving. By utilizing actual compounds present on the comet as propellant for the engine, a continuous fuel source is available for thrusting. The major downfall to such a technique is that surfaces of comets, asteroids, and other small body space objects are unpredictable. Stabilizing an engine on one of these objects would take tremendously accurate engineering, but not entirely impossible.

Altering the Albedo of Mars

Planetary albedo.

A newly proposed method, altering the albedo of the Martian surface would effectively increase the energy absorbed by Mars, increasing the temperature. Albedo refers to the reflectivity of light of an object. It is a dimensionless factor. Mars global albedo is 0.25[25]. This means that Mars reflects 25% of the incoming light. By decreasing the amount of light reflected and in turn increasing the amount of light absorbed, the expected blackbody temperature of Mars increases. The darker an object, the lower the albedo (and thus the lower the amount of light reflected). Decreasing the entire Martian albedo is impractical and largely impossible, but decreasing local areas of albedo is certainly not out of question.

Local albedo on Mars.

Focusing on the Martian southern pole, a particularly favorable condition is created for albedo altering. Ice, be it carbon dioxide ice or water ice, displays a very high albedo. Assuming an entire surface composition of carbon dioxide ice, the southern pole exhibits an albedo of 0.75 and an emissivity of 0.57[26]. This is critical to the method of terraforming, as it allows for plenty of room for alteration to increase efficiency of light intake. The carbon dioxide ice can effectively be made darker by introducing a darker material within the ice, creating "dirty ice." A comet serves as a perfect example of dirty ice. Cometary nuclei usually exhibit an albedo of roughly 0.02-0.04, hence why they are so difficult to detect without a coma and tail. They are, in fact, some of the darkest known objects in the solar system, despite having large abundances in water ice.

According to the Stefan Boltzmann equation, as listed in equation (10), the temperature of a blackbody can be described by the energy flux F_s, the albedo α, the material emissivity ε, and the Stefan-Boltzmann constant σ.

$$(1-\alpha)F_s = \varepsilon\sigma T_{BB}^4 \qquad (10)$$

For a perfect black body emitter, the emissivity $\varepsilon = 1$. Emissivity is material dependent, as is albedo. Finding the right material to alter the southern polar ice caps to induce heating is important. The southern polar ice cap covers roughly 9.6 x 10^{10} m^2. Thus, an equivalent amount of material must be produced in order to make a difference in the temperature. Ultimately a material with low albedo and a high ratio of absorption to emissivity is the desirable situation.

A source for this desirable material in mass quantities exists right on site in the Martian system. Mars, one last time, has the tools necessary for terraforming right within reach. This time, the source is the Martian moons, Phobos and Deimos. Both thought to be captured asteroids, Phobos and Deimos exhibit characteristics of D-type asteroids, consisting of dark carbonaceous material. Phobos in particular is the closer of the two moons in regards to orbiting distance. It orbits at a mean radial distance of 9,376 km from Mars. Table 4 presents all relevant characteristics of both Phobos and Deimos[27][28].

Martian Moon	Mean Orbital Radius (km)	Mass (kg)	Mean Density (kg/m^3)	Spectral Classification	Albedo
Phobos	9,376	1.066×10^{16}	1,872	D-type	0.071
Deimos	23,458	1.476×10^{15}	1,471	C or D-type	0.068

Table 4: Characteristics of Martian moons

The purpose of the Martian moons in this context is to use the dark carbonaceous material as an agent to increase the thermal absorption and emission of the Martian pole. As of now, the poles are highly inefficient at receiving energy. With an albedo of 0.75, only 25% of the incoming energy is absorbed. The rest is reflected away, unused. By grinding up the material and placing it on the surface of Mars, more energy can be absorbed and emitted back on the surface. Such an idea may at first appear as a stretch, with questionable effectiveness. However, here on Earth it is an observed phenomenon. It is estimated that black carbon aerosol particles contribute roughly 0.1-0.4 W/m^2 of warming on the planet. Such an input is actually almost three times as powerful at melting the arctic ice caps on Earth as the contribution of carbon dioxide gas[29].

Analysis of Martian moon material for albedo altering.

The Martian moon material must be significantly more effective than the carbon dioxide ice at absorbing and emitting incident energy. Since D-type asteroids are expected to be primitive chondritic material, it is expected that the interiors of both Phobos and Deimos are to be undifferentiated and relatively uniform throughout, exhibiting no differentiation. Emissivity features of Phobos in particular average around 0.95[30]. Referring to Table 4, Phobos also exhibits an albedo of 0.071. Again under the assumption of a uniform composition, Phobos alone has enough dark, chondritic material to cover the entire southern Martian pole 1 meter high, roughly 50 times over. This is an important finding because it makes prospective mining of Phobos possible. The entire moon itself cannot be fully mined, but portions of it can.

Overall, by observing the Stefan-Boltzmann equation listed in equation (10), in order to increase the Martian southern pole from 147 °K to 151 °K, the ratio of average absorption (the mathematical compliment to albedo) to average emissivity must rise from 0.438 to 0.488. This equates to changing roughly 9.3% of the surface in the southern pole with dark, carbonaceous material from Phobos. A key find, altering only one tenth of the Martian pole in surface composition makes the idea possible. The amount of material required from Phobos would equate to only 0.2% percent of Phobos mass. Thus, the sheer size of Phobos and the relatively small size of the southern polar ice cap must be appreciated.

Timescales for altering the temperature of the pole rest on the order of decades. Once the initial albedo alterations are complete, it would take roughly 23 years for the increase in power input, based upon equilibrium settling of the Stefan Boltzmann equation. Figure 9 presents the time versus temperature graph.

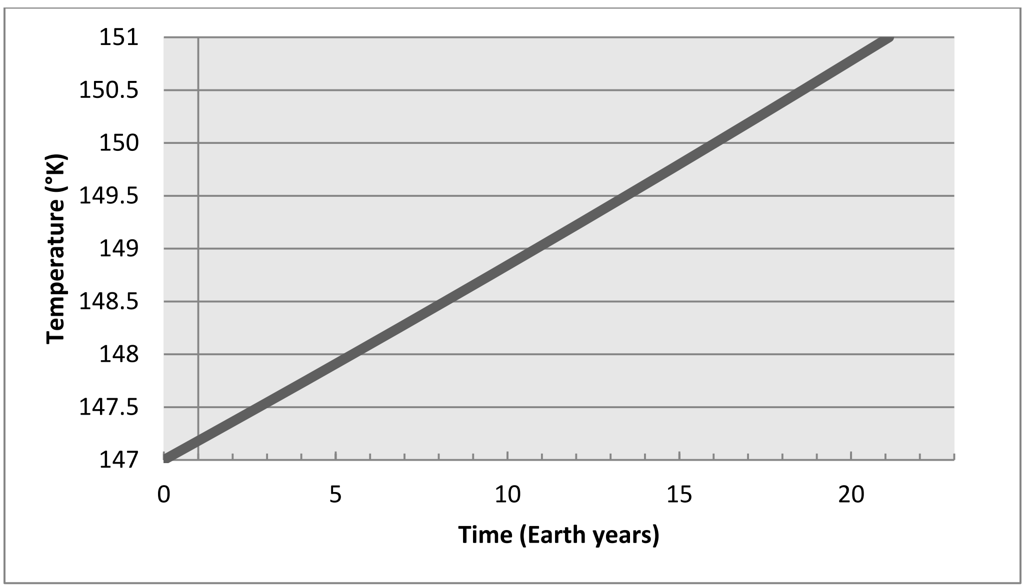


Figure 9: Time versus temperature for equilibrium settling of temperature

Despite timescales being seemingly short, it is important to note that mass is, itself, a function of time. Material would be required to be transported to the southern pole over time. The rate of this is unknown, and largely based upon the manned commitment and ability to transport large masses. A safe assumption would put such a mission on the order of a century, rather than two decades.

Methods of transporting Martian moon material.

The troublesome part of albedo altering at the southern pole to influence Martian global warming is moving the material required. While mining projects could be set up on Phobos, serious propulsion systems must be set up in order to deliver the material back to Mars. Conventional means of transporting goods would be of no use, requiring hundreds of thousands of trips between Phobos and the Martian pole. Such a venture would waste both time and money, and would be incredibly challenging given Phobos low gravity. The only conceivable solution to the problem is to take the approach of asteroidal control as suggested earlier in this chapter.

By fracturing portions of Phobos and inducing these “chunks” of Phobos into higher inclination orbits, these chunks can be equipped with tactical detonation devices to “rain” moon rocks on the southern poles.

Conclusion

Through the proposed methods of terraforming mentioned, such as large solar mirrors, artificial greenhouse gassing, importation of volatiles, and albedo altering, it is understood that no single method is the only approach required for terraforming. Instead, all approaches should be utilized at the same time, as none are entirely achievable on their own. Synergistic effects occur when utilizing more than one method, such as large solar mirrors in pair with altered albedo properties of the southern pole.

It is also noted that serious human commitment to any project is required. Issues of cost and time arise in all cases. Every suggested method of terraforming is not a likely possibility at first thought, but upon consideration is entirely feasible.

Albedo altering on a simplified scale showed how using portions of the Martian moon Phobos could cover roughly 10% of the area of the poles, increasing energy efficiency on an input to output scale, vaporizing the poles.

RELATED TOPICS AND ETHICS

What Can Be Learned

Though the prospect of terraforming Mars is very much science fiction despite its feasibility, exploring the idea of terraforming Mars scientifically has benefit in other topics. Topics covered include asteroidal and cometary control.

A vested interest in small space body control exists here on Earth due to the threat they pose on civilization. By learning how to control an asteroid or comet, Earth is effectively protected. Additionally, global warming is a commonly occurring topic for Earth. By learning methods of geoengineering, fighting global warming on Earth can be highly effective for protecting mankind. Often overlooked due to the microscopic timescales, temperature cycles on Earth on macroscopic timescales insist that large freezes are ahead. For the long term survivability, geoengineering is a pivotal tool.
By studying the atmosphere of Mars, its origins, and its fate, Earth's current atmosphere is better understood. Projects such as MAVEN (Mars Atmosphere & Volatile EvolutioN), the study of the carbon dioxide polar ice cycles, and the study of the effects of atmospheric retention can paint a better picture for the fate of Earth.

Ethical Approach to Terraforming Mars

The idea of forcefully evolving an entire planet is debatable on an ethical level. Mars is, for the most part, currently untouched by mankind. On one hand, Mars as an untouched, scientifically pure specimen allows mankind to learn about Mars to their greatest extent. On the other hand, by terraforming Mars, mankind is able to accomplish an ultimate achievement.

Regardless of what the future holds for Martian exploration and eventual settlement, human responsibility always exists to not spoil or exploit the planet. Surely mankind has already accidentally contaminated Mars in the name of science, though full scale terraforming involves full scale contamination. Introducing all forms of human species to Mars, be it man himself, plant life, algae, or bacteria, significantly blurs the question of whether or not life on Mars ever existed or currently does exist today.

With great power comes great responsibility. With mankind playing god of sorts, research and technological capability exponentially increases. In the same sense that man can learn from Mars on how to protect Earth, man must also not lose sight of saving Mars itself.

CONCLUSION

It has been shown that Mars serves as a suitable candidate for planetary engineering and terraforming, meeting the three suggested requirements of terraforming. Mars exhibits a significant size, composition, and proximity with respects to the circumstellar habitable zone. Phase 1 of terraforming set benchmarks for minimal acceptable atmospheric temperatures and pressures on Mars. The temperature of 274.0 ºK was based upon the existence of liquid water in the tropics, while the pressure of 55.0 kPa was based upon the lowest observable atmospheric pressure humans are shown to currently live in on Earth. It is understood that temperatures and pressures are functions of each other, thus positive feedback occurs.

Increasing the temperature of the southern polar ice cap by 4 ºK can create a positive feedback reaction, eliminating the entire southern polar ice cap and adding roughly 9.2 kPa of pressure into the Martian atmosphere. Depending upon the release energy of the absorbed carbon dioxide in the soil, perhaps an additional 30 kPa worth of pressure can be exhausted into the atmosphere. To compensate for the remainder of the absent atmospheric pressure, utilization of pressure scale heights allows for settlement sights in both *Valles Marineris* and *Hellas Planitia* to create suitable earth-like conditions of 60-80 kPa. These conditions are not far off from Boulder, CO, USA, for example.

Phase 2 of terraforming could be accomplished by introducing plant and algae species such as *Chroococcidiopsis gigantea* onto Mars would allow for an evolutionary process of oxygenation through photosynthesis, achieving partial oxygen pressures that humans require. In the meantime simple oxygen tanks would be required to settle on Mars. A filler gas such as diatomic nitrogen extracted from the soil would be required to keep the atmosphere from producing a highly combustible environment.

Methods of terraforming viewed include large orbital mirrors, artificial greenhouse gassing, and importation of volatiles through cometary or asteroidal control. A newly suggested method of terraforming, albedo altering on Mars, suggests that by using dark carbonaceous material potentially from the Martian moon system, energy absorption and emissivity could be increased to alter the Martian energy budget towards the poles. Simplified calculations suggest that by covering nearly 10% of the Martian southern polar ice cap with moon material from Phobos would produce a 4 ºK change in temperature, eliminating the cap and setting off the positive feedback reaction, achieving Phase 1 of terraforming.

APPENDIX

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Ken Lang

Hi Dr. McKay,

I am an undergraduate student at the University of Central Florida. I emailed you about a year ago about conducting research on terraforming Mars. Over the course of a year I have completed my undergraduate thesis.

As I wrap up my thesis, I am asking for permissions to reproduce four specific graphs presented in your paper *Technological Requirements for Terraforming Mars*. Thanks for your time,

Chris Barsoum

Chris,

You have my permission to us any figures from any papers I have published.

Chris McKay

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