PHY 315
Radiation in Planetary Atmospheres
Term Essay

Radiative Processes in Terraforming

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1. Introduction

It was not so long ago that the civilizations of the world were isolated from one another by the vast distances between them. However, whether lured by the prospect of economic gains, or forced by the pressures from within, these civilizations were forced to expand, taming the lands and oceans which separated them. As a result, these islands of civilization have merged together and now encompass islands of wilderness on our finite globe.

It is foreseeable that the same reasons which propelled these settlers and governments throughout time to increase their geographic domain will continue to persist into the future. Since the earth only has a finite size, this may lead to a desire to expand and to colonize other regions of our solar system. As such, it may be desirable to ‘tame’ the environments of these worlds to make them more conductive to the presence of human beings - that is to “terraform” them.

However, this paper has no intentions of discussing or rationalizing either the forces which drive the expansion of civilizations or the ethics of doing so. Thus, the ‘why’ and the ‘should we?’ of terraforming, much discussed in the literature, will be omitted. Instead, the concept of terraforming will be reviewed as a scientific thought exercise in making specific areas of the solar system more earthlike. As well, this paper will focus on the radiative aspects of terraforming, specifically as they relate to altering the temperature and pressure at the surface, while omitting much of the chemistry. Furthermore, while several proposed methods will be presented, emphasis will be given to the desired effect rather than the methods used to achieve this change.

To this end, let us begin by defining terraforming as *the intentional application of anthropogenic forcing to a planetary environment in order to effect a desired climactic change*. This can be viewed as global environment engineering and as such may require substantial maintenance even in steady state. Many of the methods of terraforming are broadly applicable and may be used in the context of any planetary body with an atmosphere, oceans or other radiative sinks. As well, the lessons of this thought experiment are applicable not only to other planets, but also to the earth (for instance to avoid the recurrence of a ‘snowball-earth’ event or a catastrophic ‘run-away greenhouse’ effect).

Another item which should be kept in mind during the course of this paper is the magnitude of the quantities involved. Naturally, the energy and mass transport required to remake the climatology of a planet are immense and as such in the early part of the space era (early 1950s to mid 1970s), terraforming was largely the domain of science fiction.

In recent years, however, renewed scientific attention has been paid to the problem, especially in the context of mars. This has been spurred mainly through an aggressive NASA probe campaign to the red planet over the last 10 years, a trend which will continue into the future with many ambitious proposals already finalized for every launch window through to 2011.

2. The Essentials

2.1 Minimum Requirements for Habitability

Before we may determine which pieces of the solar system real estate are the best candidates for terraforming, it is important to state what is meant by ‘earthlike’ or ‘habitable’ conditions and which factors dominate. Thus we begin with a description of the earth:

TABLE 1: Properties of the Earth

Property	Value
Equatorial Radius[20]	6378 km
Orbital Eccentricity[20]	0.0167
Orbital Semi-Major Axis[20]	149 600 000 km
Planetary Emissivity (IR)	0.62
Planetary Albedo (Visible)[20]	0.30
Mean Surface Temperature	288K
Mean Surface Pressure	1.013 bars
Length of Solar Day[20]	1 day
Surface Gravitational Acceleration	$9.81 m/s^2$
Inclination of Revolution Axis[20]	23.45
Solar Constant	$1380 W/m^2$

The most important factors, as far as human beings are concerned, are gravitational acceleration, surface pressure and surface temperature. These three factors are connected: any suitable body must be sufficiently massive to prevent the thermal escape of the major atmospheric constituents. This results in a buildup of surface pressure and an increase in the insulating properties of the atmosphere which affects the surface temperature.

It is also critical to recognize that there are ranges for each of these factors. For instance, it is not necessary to bring the entire surface of the body in question into the habitable range. Instead, in the case of a planet with varying terrain, it would suffice to establish sufficient temperature and pressure conditions in the equatorial lowlands to form a small but significant habitable zone.

If we expand this envelope still further we reach a situation in which environmental conditions are improved sufficiently that bases of considerable size may be self-sufficient but need to confine their own atmosphere and heat while requiring only minimal protection from the elements. This is referred to as ‘paraterraforming[14].’ Of course, the degree to which this process is taken depends upon the available resources and the incremental cost of the terraforming initiative.

Broadly speaking McKay et al.[12] define the bounds of habitability under which we can consider a planet to be entirely terraformed:

1. Global Average Temperature between 273K and 303K
2. Total Atmospheric Pressure between 0.5 bar and 5 bar
3. Less then 10 mbar of Carbon Dioxide (toxic above this level)
4. Greater then 300 mbar of inert buffer gas (such as Nitrogen or Argon)
5. Oxygen Partial Pressure between 130mbar and 300 mbar

At any point during the process of terraforming it may be useful to exceed these limits, especially in terms of carbon dioxide. In fact, the value of the gas as a greenhouse gas may outweigh the toxicity constraint in the initial stages of the project. If we wish to speak of plant habitability as opposed to human habitability the following conditions are required[12]:

1. Total Atmospheric Pressure greater than 10 mbar
2. Carbon Dioxide partial pressure greater than 0.15 mbar (photosynthesis limit)
3. Greater than 10 mbar of Nitrogen (nitrogen fixation)
4. Greater then 1 mbar of Oxygen (Plant respiration)

Note that these conditions place no constraints on other significant factors such as gravitational acceleration or the length of the day-night cycle which have often been the subject of terraforming proposals[4,7,24].

2.2 Suitable Venues

Since we are mainly interested in bodies which can be most easily be fully terraformed, we must exclude the vast majority of solar system objects. Asteroids are too small to maintain even the most tenuous of atmospheres. The gas giants have no surfaces upon which to build and their moons are situated so far from the sun that extensive energy addition is required. Mercury, for its part, is too close to the sun, and is tidally locked.

Thus we are left with our two closest neighbors – Venus and Mars. Of these two, the best opportunity is offered by Mars, while Venus also has a more limited potential. These will be discussed to illustrate the associated difficulties and advantages of each.

3. Venus

3.1 Current Properties

A data table of the properties of Venus is provided in Table 2.

TABLE 2: Properties of Venus

Property	Value
Equatorial Radius[20]	6053 km
Orbital Eccentricity[20]	0.0068
Orbital Semi-Major Axis[20]	108 200 000 km
Planetary Emissivity (IR)	0.25
Planetary Albedo (Visible)[20]	0.77
Mean Surface Temperature[4]	730K
Mean Surface Pressure[4]	95 bars
Length of Solar Day[20]	127 solar days
Surface Gravitational Acceleration	8.88m/s^2
Inclination of Revolution Axis[20]	177.4 (retrograde)
Solar Constant[7]	2640W/m^2

Venus has often been described as Earth's sister planet. Judging by the data above this is largely accurate description. Despite this, it can easily be seen that there is a 95-fold discrepancy in the thickness of the atmosphere which provides a very effective thermal blanket. As a result even though Venus absorbs roughly as much radiation as the earth (since the planets have similar size, but opposite albedo situations in the Visible and IR), the surface remains at an un-inhabitable 730K.

Additionally, many terraforming schemes provision for augmenting the rate of revolution, though there are no such proposals to increase the inclination to the ecliptic in order to give Venus seasons. Since this is unnecessary to stabilize conditions in the habitable range, only the effects of atmosphere will be considered.

3.2 Terraforming Requirements, Components and Effects

The atmosphere of Venus is composed primarily of carbon dioxide (93bars) with significant amounts of nitrogen (2bars) and trace amounts of other gasses (including significant amounts of sulfuric acid)[4]. Any successful terraforming initiative will require this large reservoir of carbon dioxide to be eliminated either by removing it from the planet entirely or locking it up in carbonate rocks or within the biosphere. The amount of carbon dioxide in the atmospheric inventory – 4.670 x 10^{17} kg - is not impossibly high[11]. For instance, carbonaceous deposits on earth are estimated at more than double this figure – 9.900 x 10^{17}kg[11].

How to remove these deposits? In 1961, Carl Sagan[22] suggested that the sulfuric acid clouds could be seeded with cyanobacteria, better known as blue-green algae. While the process involved would be long, the effort required would be minimal. Unfortunately, Gillett[11] has recently shown that this would need to be an industrialized process as the classic biological scheme suggested by Sagan is infeasible due to the self limiting behavior of the reaction at low conversions.

The structure of the atmosphere is also important. If we examine the following plot [Figure 1] it can be seen that the vast majority of the energy transfer in the Venusian atmosphere is occurring above 150km of altitude due to the presence of sulfuric acid aerosol clouds which cover the entire planet and are essentially opaque in the visible spectrum. As such, before the planet can be cooled, these clouds must be removed.

Additionally, it can be seen that the amount of heat transfer which occurs due to convection is low throughout the atmosphere. Since this is a more effective heat transfer mechanism the encouragement of convection would be highly beneficial.

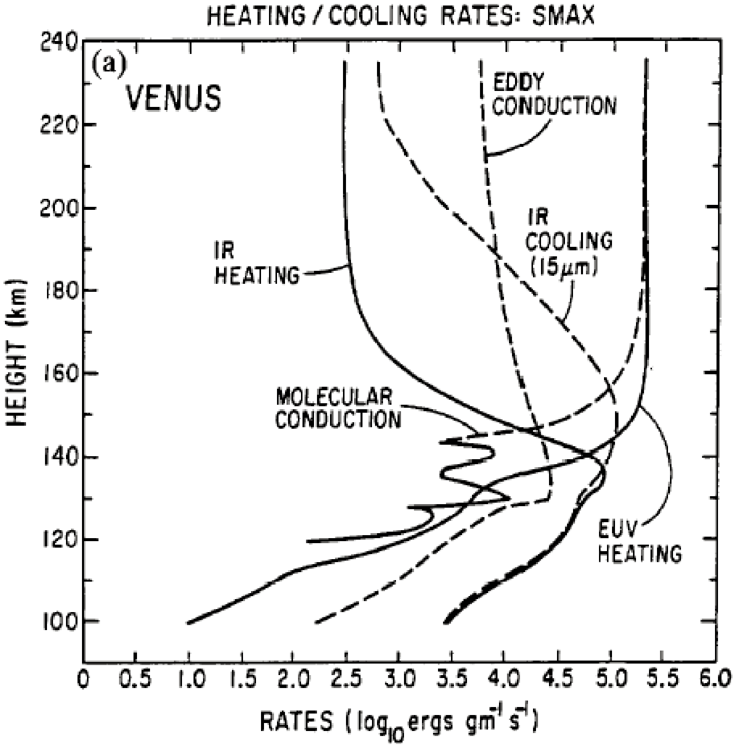

Figure 1: Energy Budget of the Venusian Atmosphere with Altitude [Reference 15]

It is insufficient to simply leave the products of any atmospheric conversion in the atmosphere – they must be removed to reduce the overall pressure at the surface. This could be accomplished easily if the forcing of the sun at the top of the atmosphere – almost twice that of earth at 2640W/m^2 – was to diminish. Were this to occur, the carbon dioxide in the atmosphere would begin to rain out. If the degree of cooling were sufficient, the vast majority of the atmosphere could be condensed, leaving the 2 bars of nitrogen and trace gasses. Birch[4] has provided a means to accomplish this by means of several thermodynamic stages.

3.3 Potential Terraforming Methods

The key to terraforming Venus is the removal of the atmosphere. While several schemes propose altering the paths of large asteroids to blow these compounds into space[24], the removal of the atmosphere is most effectively accomplished by condensing out the excess carbon dioxide. Since it is difficult to build industrial facilities to withstand the 95 bars of external pressure it is necessary to cool the planet.

The visible albedo of Venus is already very high, therefore simply adding more aerosols to the upper atmosphere will not have a significant cooling effect and it is necessary to take a more drastic approach. One such remedy is a sunshade – a thin semi-transparent film (such as that employed in a solar sail experiment to be launched this year[23]) suspended between the sun and the planet. Similar devices have already been proposed[1,2], for instance by Walter Seifritz[3] in *Nature*, as a possible means to curtail global warming on earth. However, these ignore the difficulties inherent with solar radiation pressure and tend to ignore the need for station-keeping altogether or require complicated networks of mirrors to reduce the station-keeping requirement.

Lastly, Sagan's suggestion to use cyanobacteria, while infeasible, does raise some interesting questions. For instance, could different reactions be exploited and biological or mechanical organisms be developed to take advantage of these reactions? Due to the high costs of launching materials, such Von Newmann (VN) devices[10,13] (self-replicating machines using locally available energy and materials) are attractive in terraforming processes.

3.4 Timescales

While many researchers assume that timescales on the order of thousands or even tens of thousands of years[7,24] will be necessary, it is possible that the planet may be brought to the brink of habitability within 500 years. This estimate, provided by Freeman Dyson[6], is similar to the minimalist approach taken in this paper in which the major objective is simply to improve the radiative balance and not to spin up the planet[7,24] or import oceans[4].

The thermodynamic cycling which is suggested by Birch[4] would take approximately 200 years to cool the planet and reduce the atmosphere to 2.8 bars of pressure. If we add to this Dyson's estimated 200 years to construct the necessary sunshade we arrive at nearly the same figure.

However, the key controversy has to do with the way in which the structure of the atmosphere will change over time. Currently, due to the low rate of revolution and the low inclination of the polar axis to the orbital plane, convection plays very little role in heat transfer (As evidenced by Figure 1). Dyson has assumed a model in which blocking the sun's energy allows for massive convective gradients to be created resulting in a cooling time on the order of 100-200 years which further assumes very little heat transfer from the crust below a few meters. If, instead – as Fogg[7] has done - it is assumed that no convection takes place and there is significant heat transfer between the crust and atmosphere, a figure closer to 1000 years is obtained.

3.5 Summary

Venus presents a daunting challenge for terraforming. Even using a best case approach, it would be several hundred years before the planet is even remotely habitable. As well, to accomplish this it is necessary to first build a large space-based sun shade which will need to be maintained as long as the planet is inhabited. However, there are sufficient raw materials that a solution could be engineered. Once complete, the planet will potentially be quite earthlike with the exception of a 3048-hour (127 earth days) day. Even so, Freeman Dyson[6] suggests that an array of sunshades and mirrors – properly positioned - can produce a regularized 24-hour day-night cycle.

4. Mars

4.1 Current Properties

Again, it is useful to begin with some tabulated data:

TABLE 3: Properties of Mars	
Property	Value
Equatorial Radius[20]	3527 km
Orbital Eccentricity[20]	0.0934
Orbital Semi-Major Axis[20]	227 945 000 km
Planetary Emissivity (IR)[25]	0.15 (dusty) to 0.8
Planetary Albedo (Visible)[20]	0.15
Mean Surface Temperature[9]	213 K
Mean Surface Pressure[8]	0.007 bars
Length of Solar Day[20]	1.03 solar days
Surface Gravitational Acceleration[8]	3.8m/s^2
Inclination of Revolution Axis[20]	23.98
Solar Constant[9]	593 W/m^2

When dealing with Venus, it was found that we were dealing with excesses of energy and atmosphere. Thus, Mars is an opposing problem in which the greatest problems require augmenting the present situation. As Fogg has pointed out, this is most easily accomplished by synergistic efforts on a number of fronts.

The major hurdle to be overcome, as on Venus, is one of energy. As a result of the low solar constant (only 43% that of earth) the greater part of the atmosphere has frozen out or become combined with the regolith. This has left the surface atmosphere sparse and cold despite geological evidence of a warmer and wetter past. However, unlike Venus, these conditions will allow for industrial processes to begin much sooner on Mars which could be partially terraformed quickly and colonized while the longer process continues over millennia.

4.2 Terraforming Requirements, Components and Effects

There are many factors which affect the Martian climate. As such, the following pages discuss the various processes which affect the radiative balance of the planet. Specifically, the thickening of the atmosphere and the suppression of atmospheric aerosols, the potential effects of aquifers, geological processes and finally some methods by which the solar constant can be increased will be described.

4.2a Atmospheric Effects

The first step in terraforming is to increase the surface pressure. As such, volatiles need to be added to the atmosphere retained.

There are a number of sources for these volatiles. In one of the early papers on the subject, it was suggested by Carl Sagan that the polar caps[21] could be used to accomplish this. These reservoirs were estimated at 1 bar using the data from that time period; however, more recent data show that there is unlikely to be more then a few millibars of atmosphere available here[12]. Volatiles can also be found adsorbed in the regolith[9], however, even these are somewhat restricted as the most optimistic studies place these reservoirs at less then 280 mb[9]. Even so, this is a significant amount: Fogg asserts that a complete terraform could be achieved with as little as 500mb of pressure[9]. As a result, we must look to chemicals trapped in rock to provide the necessary pressure.

Of course, the main aim of thickening the atmosphere is not only to permit movement by the inhabitants without pressure suits, but also to warm the atmosphere. For instance, if an industrial process was undertaken to release greenhouse gasses such as CFCs we could also improve the radiative properties of the current atmosphere[12]. For reference, the energy budget of the current atmosphere is provided below in Figure 2.

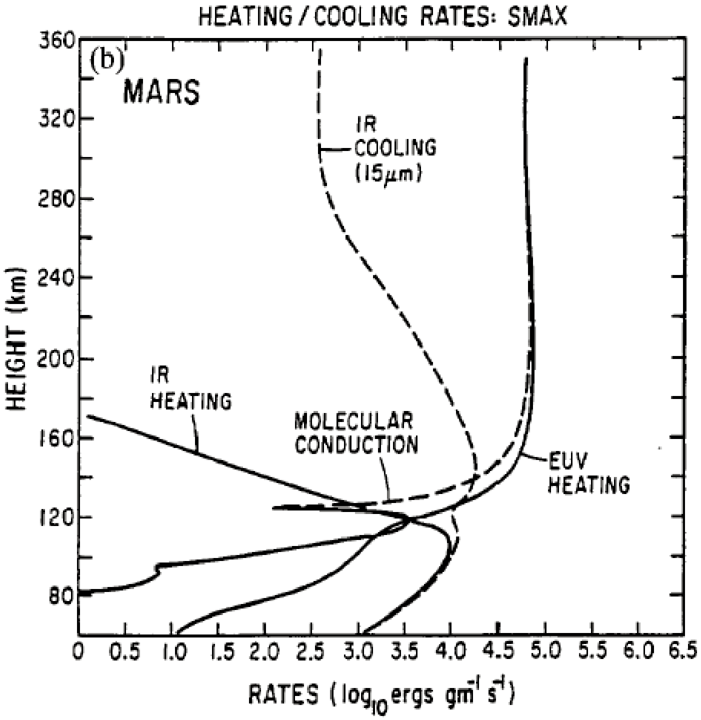

Figure 2: Energy Budget of the Martian Atmosphere by altitude [Reference 15]

At current, while IR cooling is the principal method of energy transport in the lower atmosphere, it is relatively insignificant at higher altitudes [figure 2]. Studies by McKay et al.[12] have shown that not only would halocarbons trap heat in the lower atmosphere, but they would also increase the IR cooling in the upper atmosphere. As such, compounds active primarily in the window region (800 to 1200 cm^{-1}) tend to asymptote to a maximum as depicted in figure 3. Note that this trend does not appear to be true of a perfect grey absorber and that as the total atmospheric pressure increases, the maximum also increases. Unfortunately, even with 1 bar of atmosphere an increase of only 40K is predicted. Therefore, a complicated cocktail of gases will be required[12].

Furthermore it is necessary to control the atmospheric content of aerosols and dust (i.e. from dust storms). Due to unfavorable conditions, weather on mars is typically subdued. For instance, typical weather can be seen on the negative image of mars which appears on the cover of this report in which the dark patches of clouds are confined mainly to the region over tharsis and to the polar caps. As the atmosphere thickens it is natural to assume that aerosols (for instance clouds) will form thereby increasing the planetary albedo. As for higher-altitude aerosols, the effect these particles have on the climate, even on earth is not yet fully understood[19].

In the short term, it is important to suppress dust storms as these can have a significant cooling effect both by increasing the planetary albedo and also by favorising convective heat transfer from the surface. Since the pattern of the majority of the larger dust storms is predictable – that is they originate in the southern hemisphere during southern summer and fall – it may be possible to address this problem regionally as opposed to globally.

4.2b Geological Effects

Although both Mars and Venus are both largely tectonically dead so far as we can tell, because of the lack of atmospheric volatiles on Mars, the crust is an important element in the terraforming. There are four components to this effect. These are geothermal heating[17], surface covering and other albedo effects, potential underground reservoirs of water[17,18], and crustal volatile content (as discussed in the previous section).

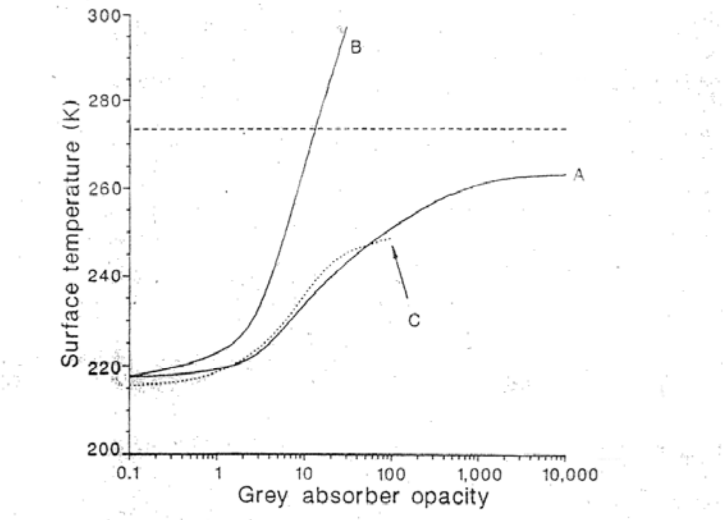

FIG. 2 The effect of adding an absorber on the surface temperature of Mars. For the 1-bar nitrogen–oxygen atmosphere (see Fig. 1), two types of absorbers were considered: curve A is for an absorber that is active in the 'window' region of the thermal infrared spectrum (800–1,200 cm^{-1}) only, curve B for an absorber that is active over the entire spectrum. Curve C shows the effect of adding an absorber active only in the window region to the present 6-mbar CO_2 atmosphere. The dashed line indicates the freezing point of water.

Figure 3 – Dependency of the Temperature of the Martian Surface on the absorptivity of the Atmosphere [Reference 12]

Firstly, the interior of Mars is still warm. If this heat could be accessed, the atmosphere could be warmed on a short term basis. While it is unlikely that this could be used to permanently act as a radiative source, it could 'kick-start' the process by supplying enough heat to begin the subliming of the polar caps and of removing the adsorbed volatiles from the upper regolith. Removing the greater part of the volatiles stored in the deeper crust, however, would involve processing a great deal of rock by vaporizing it to release the trapped gasses.

The second most important component after engineering the atmosphere is the issue of surface cover. Sagan was the first to suggest that altering the planetary albedo, for instance by sprinkling carbon on the polar caps[21], could be used to increase the radiation budget of the surface and atmosphere. Unfortunately, the surface of Mars is already absorbs a great deal of energy in the visible region, possessing an albedo of only 0.15. As such, efforts should be placed into keeping this figure as low as possible throughout the process[9].

However, this is difficult since once we attain 10mb of surface pressure it becomes possible to use plants to transform the surface and atmosphere in a process known as 'ecopoiesis[9]' (for limits to plant habitability see section 2.1). This necessitates the development of a hydrosphere[9]. While the regolith contains very little water, it is suspected, based on the geological evidence and recent observations, that there could be underground aquifers on mars[18]. Thus, the temptation will be to tap these aquifers and to allow them to flow out onto the Martian surface. However, doing so will put at risk the entire process, as a great deal of free water on the surface of the planet would have a highly detrimental effect on planetary albedo and could lead to substantial cooling.

4.3 Methods

As with Venus, the main stumbling block is an energy imbalance. In the case of mars, it would be very helpful to increase the amount of Solar forcing though the use of large orbital mirrors referred to as 'solettas[5]'. Naturally, this requires a fair bit of sophistication and is prone to the same pitfalls as the Venus sun shade. Despite this, if it is possible it constitutes the ideal solution – essentially moving the planet closer to the sun in radiative terms.

As a side benefit, such a soletta could be employed along with a much smaller orbital focusing mirror to vaporize large swaths of the Martian Crust[5] in order to release the volatiles held within. This would be significantly more desirable solution then the ‘thermonuclear Mining’ advocated by Fogg[9].

The larger advantage offered by mars is that of a self sustaining environment. Using current technology it is possible to place small self-sustaining outposts on the red planet[18]. As such, it is conceivable to build industrial machinery for terraforming, such as greenhouse gas-producing ‘factories’ in situ and to apply solutions locally. This allows for partial inhabitation before terraforming is complete.

Lastly, it is important to mention VN machinery[10] in the context of Mars. It may be possible in the future to genetically engineer or modify plants to survive in low-pressure, low-temperature and high-carbon dioxide environments[9]. Such organisms would greatly enhance the economic feasibility, rapidity and effectiveness of any solution, a state that could only be improved by the development of man-made VN machines. Such machines, especially if sufficiently small, might be able to do much of the chemical grunt work of separating volatile compounds from rock[13].

4.4 Timescales

As with Venus, there is a great deal of debate between different experts as to the timescales required for terraforming Mars. McKay et al.[12] have estimated that the planet could be warmed within 100 years if 2 bars of carbon dioxide could be obtained and 10% of the solar energy absorbed by Mars be used to extract the deposits. They go on to suggest that using ecopoesis it would take up to 100,000 years to complete the conversion of the resulting carbon dioxide atmosphere. However they do suggest that this figure can be substantially reduced if an industrial processing of the atmosphere is undertaken or if plants are engineered specifically for this conversion purpose.

Other estimates range from several hundred[5] to several thousands[16] or tens of thousands[11,9] of years, but in most cases this is more a disagreement about the stated objectives of the terraforming process – do we desire a copy of earth? – and the amount of effort that will be put into accomplishing this.

4.5 Summary

In the case of Mars, we are dealing with a radiative deficit, compounded by a lack of resources. This suggests that a number of techniques will be required to act synergistically in order to improve the habitability of the planet. However, since the planet is immediately able to support some form of industrialized terraforming it is a more viable location than Venus. The result will be a cold planet, but perhaps no more unbearably so then the Canadian high arctic and will possess many of the properties of earth, but only about a third of the gravity.

5. Comparison: Mars v. Venus

It is conceivable that at some point in their distant past both Mars and Venus have gone through periods of earthlike behavior. The geological evidence on mars suggests a wet past ending 3 billion years ago[9]. As for Venus, the fact that the sun’s radiative output is estimated to have increased by 30%[7] in the last four billion years suggests that it too may have exhibited these qualities.

However, a glance at the atmospheric temperature graph below illustrates how different these bodies are today:

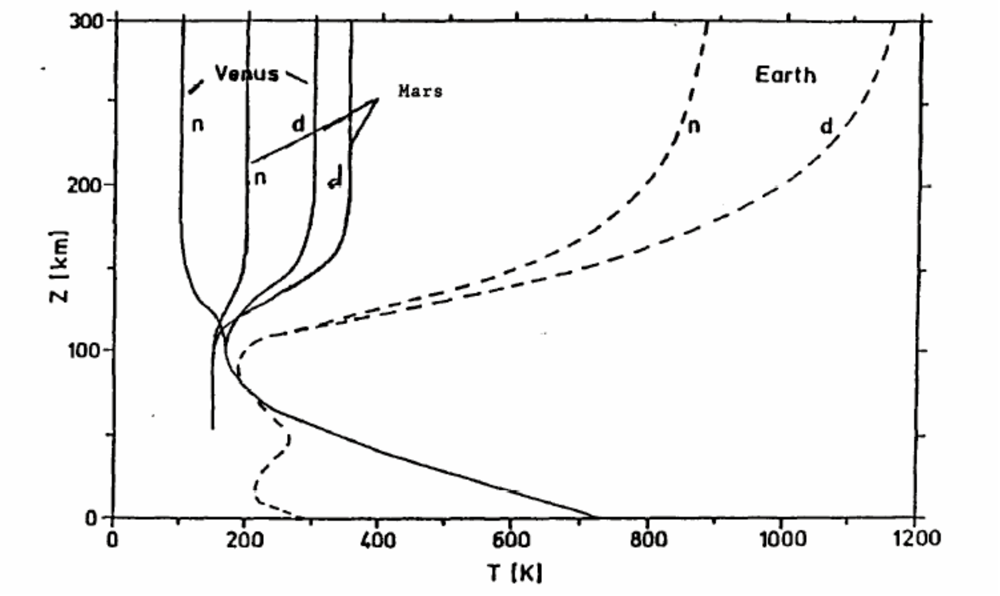

***Figure 4: Vertical Thermal Profile of the Earth, Venus and Mars**.*
'd' refers to daytime hemisphere conditions whereas 'n' refers to nighttime hemisphere conditions [Reference 15]

It is critical to emphasize the major difference in the conditions experienced on Mars and Venus. The first is the victim of a 'run away icehouse' effect suffering from a chronic lack of energy, whereas the second suffers from an overabundance. In both cases, the ideal solution is to correct this radiative imbalance, either by sun shade, as in the case of Venus, or by soletta as in the case of Mars. Unfortunately, such a system would be incredibly complicated and expensive.

If instead, we abandon such energy regulation techniques, it becomes almost impossible to successfully terraform Venus no matter what the timeframe. However, Mars may be made significantly more habitable if not entirely terraformed.

In either case, the key lies in altering the atmospheric radiative balance either by changing the composition of the atmosphere or by altering the planetary albedo properties. While it may be possible in the case of Mars to introduce new sources of energy by drilling deep into the planet, these sources should not be counted upon for long periods of time.

In the end, what have we learned from this scientific thought experiment? For one thing, sophisticated terraforming techniques will need to be developed before the majority or the bodies in the solar system are ripe for habitation. Even then, there are few other places aside from the earth which could support large numbers of human beings.

It is conceivable that we will learn to develop environmental engineering on a global basis. Terraforming is likely to be a side benefit of VN Machines which have attractive applications on earth, from land reclamation to building structures quickly and at a fraction of today's cost. Likewise, a solar regulation shade/soletta system may be desirable for the earth in order to regulate our own climate or to be able to compensate should a change in solar output occur. Thus, it is largely the development of these techniques that will determine whether or not the terraforming of other worlds will be possible.

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