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Title: **TERRAFORMING MARS: A REVIEW OF RESEARCH**
Post by: **Brooke** on **August 09, 2007, 12:11:02 am**

TERRAFORMING MARS: A REVIEW OF RESEARCH.

Martyn J. Fogg

mfogg at globalnet.co.uk

ABSTRACT

It is possible in the future that Mars might be transformed into a habitable planet by a process of global environmental engineering known as terraforming. This paper provides a thumb-nail sketch of the terraforming concepts that have appeared in the technical literature, focussing on the steps required in order to render Mars fit for anaerobic life. Its intention is to provide a referenced guide of progress to date for any future researchers of the subject.

INTRODUCTION

For many involved in the space exploration business, the ultimate goal of space exploration is space settlement, the founding of new branches of civilization remote from the Earth (National Commission on Space, 1986). However, missions such as visits to other planets, followed by outposts and pioneering settlements, are all likely to have their life-support subsidised in the way of machinery and consumables supplied from Earth. For space-based civilizations to achieve growth and permanency requires the harnessing of local resources in autonomous and stable bioregenerative life-support systems, energised by the sun.

Speculation in this area has divided into consideration of the colonization of planetary surfaces and interplanetary space. The latter involves the fabrication of large orbiting habitats with landscaped interiors (O'Neill, 1977; Johnson and Holbrow, 1977) which must import and rigourously contain all their bio-consumables. Any contained miniature biosphere such as this must inevitably submit to some mechanical involvement in life-support, in addition to keeping at bay the lethal vacuum outside. Colonizing a planetary surface, especially one such as Mars where all the chemical requirements of life are to be found, has the advantage of resources on one's doorstep. However, enclosed colonies on planetary surfaces are, in essence, little different from grounded spacecraft in that they must still resist, rather than incorporate, the surrounding environment. This strategy understates the habitable potential of a planet such as Mars which, due to its gravity well, is intrinsically capable of hosting a global, uncontained, biosphere similar to that of the Earth (Fogg, 1993a, 1995a). Since the biosphere of the Earth is the one known life-support system capable of self-maintainance over the indefinite timescales at issue, it follows that the ultimate strategy involved in space settlement will be to create counterpart Earths elsewhere, by engineering sterile planets to life. Such a hypothetical process is known as terraforming, a word originally coined in science fiction (Williamson, 1942), now adopted by science and, lately, officially admitted into the English language (Brown, 1993). It can be defined as (Fogg, 1995a), "...a process of planetary engineering, specifically directed at enhancing the capacity of an extraterrestrial planetary environment to support life. The ultimate in terraforming would be to create an uncontained planetary biosphere emulating all the functions of the biosphere of the Earth–one that would be fully habitable for human beings."

ECOPOIESIS

Any terraforming process is likely to take Mars on a path from sterility through a continuum of improving habitable states. "Full" terraforming however (the achievement of an aerobic planet suitable for humans and other animals) is likely to remain a distant, although not impossible, goal. Fortunately though, many advantages will accrue to human habitation well before full habitability is attained. The thicker atmosphere will provide improved shielding from cosmic rays, facilitate aerobraking and flight, and would permit the construction of ambient pressure dwellings and the replacement of pressure suits with simple breathing gear. Exterior atmospheric, hydrological and biogeochemical cycles could be exploited as sources of power and food.

The earliest biological stage in a terraforming process is known as ecopoiesis, a term coined by Haynes (1990) from the Greek roots oikoV, an abode, house or dwelling place, and poihsiV, a fabrication or production. It has been defined as (Fogg, 1995a), "...the fabrication of an uncontained, anaerobic, biosphere on the surface of a sterile planet. As such, it can represent an end in itself or be the initial stage in a more lengthy process of terraforming." Unfortunately, ecopoiesis cannot be carried out spontaneously–in the sense that no known biota can simply be emplaced and expected to thrive on the present martian surface. A modicum of environmental modification will be required to create the Precambrian-like conditions needed for even the hardiest of extremophiles to take on Mars as their new home. This initial planetary engineering, leading to ecopoiesis, has been the focus of most terraforming-related research.

In order to allow ecopoiesis four principal modifications must be applied to the martian environment:

1) mean global surface temperature must be increased by ~ 60 K;

2) the mass of the atmosphere must be increased;

3) liquid water must be made available; and

4) the surface UV and cosmic ray flux must be substantially reduced.

These changes would suffice to render Mars biocompatible for certain anaerobic ecosystems, but not, as is often stated, for plant life. An additional requirement for plants is the presence of sufficient atmospheric oxygen to support root respiration (Fogg, 1995c), and although this would be much less than that needed for animals to breathe (perhaps as low as pO2 » 20 mbar), such a quantity of oxygen is not expected to be released during initial planetary engineering. Thus, a fifth principal environmental modification will be needed for further terraforming:

5) atmospheric composition must be altered to increase its O2 and N2 fractions.

Whilst it may be simple to list such requirements, the prospects of engineering them on a planetary scale are daunting. However there are two mitigating features of the problem. The first is that all these modifications are interlinked–effecting one causes the others to shift in the desired direction also. For example, increasing the mass of the atmosphere improves its function as a radiation and meteor shield; enhances the greenhouse effect, hence raising surface temperature; and widens the stability field of liquid water. The second mitigating feature is the prospect of exploiting possible positive feedback processes inherent in the martian climate system which will serve to amplify any engineered climatic forcing. This would mean that not every additional kilogram of atmosphere, or every degree of temperature rise, would have to be directly "manufactured" by planetary engineers; rather, a comparatively small forcing could push Mars over an environmental cusp catastrophe whereupon its climate is spontaneously drawn towards a quasi-stable high temperature regime.

(http://www.users.globalnet.co.uk/~mfogg/fig1.gif)

THE RUNAWAY CO2 GREENHOUSE

The presence of numerous fluvial features on Mars suggests that the planet once possessed a much denser atmosphere, no doubt predominantly composed of carbon dioxide (Pollack et al., 1987). Ecopoiesis models of the climatic-feedback-type are predicated on recreating this hypothetical palaeoenvironment. The principal assumptions of these models are that much of this CO2 is still present on Mars and, more crucially, that it is present in a labile form accessible to planetary engineers.

It is proposed that an initial engineered warming of Mars (which need not be very great) will cause some CO2 to enter the atmosphere from surface reservoirs. This will add to the atmospheric greenhouse effect and increase advective heat transfer to the poles. An additional surface warming results which in turn causes further release of CO2, augmenting the process further and so on... Eventually, it is hoped that atmospheric growth will become self-driving, the original engineered warming having been the trigger for a climatic runaway that terminates in a new high pressure, high temperature regime. This is what these models have in common. Where they differ is in their assumptions as to the nature of the CO2 reservoir and the engineering method chosen to destabilize it. The first martian terraforming models to be published in the technical literature were by Burns and Harwit (1973) and Sagan (1973). They were based on the now defunct "Long Winter Model" of the martian climate (Sagan et al. 1973) which held that up to 1 bar-equivalent of CO2 ice was sequestered in the polar caps, the release of which was driven by the insolation changes caused by the 50,000 year precession cycle of the planet's equinoxes. Sagan (1973) speculated that the caps might be evaporated in

just ~100 years by artificially reducing their albedo, causing them to absorb more sunlight. A subsequent NASA study (Averner and MacElroy, 1976) suggested this darkening might only have to be quite subtle to initiate runaway conditions–a reduction in polar cap albedo by just a few percent, from 0.77 to 0.73. Blanketing the polar ices with layers of dust, or by the growth of psychrophilic plants were variously suggested as ways of effecting this darkening (Sagan, 1973). However, although the mass of dust indicated by Sagan's calculations did not appear prohibitive, the stability of any thin dust layer in the face of the martian winds is open to question. As for the plants: no known photoautotrophs are capable of survival and growth anywhere on the surface of Mars.

It is now thought likely that the Martian polar caps are composed principally of H2O ice with perhaps just a frosting of CO2 or an admixture in the form of CO2 hydrate. It is thus doubtful that the caps are a rich enough inventory of CO2to satisfy model requirements. However, it is possible that a substantial amount of CO2 might occur adsorbed on mineral grains in the upper kilometre of the martian regolith. McKay (1982) suggested that a modest heating might serve to trigger a runaway release of CO2 from this source, in an analogous manner to previous suggestions concerning the polar caps. This early speculation has been further explored by computer modeling (McKay, Toon and Kasting, 1991; Zubrin and McKay, 1993). It was shown that if the regolith carbon dioxide is distributed evenly over Mars then the gas must be very loosely bound for any runaway to occur. For a polar regolith containing an equivalent of 1 bar CO2 the effect works better: an initial warming of the martian surface by 5 - 20 K (depending on model parameters) increases the atmospheric pressure to a few tens of millibars at which point a runaway becomes established resulting in a stable end state of ~ 800 mbar and ~ 250 K. A 2 bar reservoir would runaway to give a mean surface temperature of ~ 273 K and a 3 bar reservoir, > 280 K.

Lovelock and Allaby (1984) suggested that regolith degassing could be triggered by releasing CFC gases into the martian atmosphere to create an artificial greenhouse effect. Since these chemicals have, molecule for molecule, a greenhouse effect > 10,000 times that of CO2, residence times of decades to centuries, and are non-toxic, the idea at first sight looked promising. McKay et al. (1991) looked at this question in more detail, modeling a cocktail of CFC gases active in the infrared window region between 8 - 12 mm where CO2 and water vapour have little absorption. They found that a concentration of ~ 10 ppm of such an absorber would be capable of warming Mars by about +30 K, but that any temperature excursion in excess of this would be prevented by the increasing loss of heat from other spectral regions. However, they also noted that CFCs on Mars are far less stable and long lived than on the Earth since UV radiation between 200-300 nm, which breaks the C-Cl bond, is not shielded from the surface by an ozone layer. Residence times for typical CFC molecules are reduced from many years to just hours! Thus, a CFC greenhouse on Mars might work (manufacturing the absolute quantity of trace gases appears feasible), if only for the fact that these gases would require replenishment at an absurd rate. A solution to this problem might be to use perfluoro compounds instead as the C-F bond is much more robust. Perfluorocarbons are so inert they can survive conditions on Mars, but most of their relevant absorption bands, at least for compounds of three carbon atoms or more, appear to be unpublished. Whether it will be possible to use perfluorocarbons to greenhouse Mars remains an open question (Fogg, 1995a).

Another way to warm Mars would be to increase its input of solar energy by reflecting light that passes the planet down to its surface. The use of orbiting mirrors to do this is a common suggestion in terraforming-related discussions (e.g. Oberg, 1981) and some outline designs have been published (Birch, 1992; Zubrin and McKay, 1993; Fogg 1995a). Whilst all are necessarily large in size, none are unfeasible in principle and their masses are surprisingly modest. A mirror system specifically designed as part of a runaway greenhouse scenario was presented by Zubrin and McKay (1993). By balancing gravitational and light pressure forces, they determined that a 125 km-diameter solar sail-mirror could be stationed 214,000 km behind Mars where it could illuminate the south pole with an additional ~ 27 TW. This should be sufficient to raise the polar temperature by ~ 5 K which, according to some models, should be sufficient for cap evaporation. At first glance, the size of such a mirror and its mass (200,000 tons of aluminium) may appear too grandiose a concept to take seriously

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Title: **Re: TERRAFORMING MARS: A REVIEW OF RESEARCH**
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(http://www.users.globalnet.co.uk/~mfogg/z_mirror.jpg)

Zubrin's proposed mirror system would illuminate the poles from a low angle and would appear in the opposite area of the sky from the sun. However such a mass is equivalent to just five days worth of the Earth's production of aluminium, and whilst this would be impractical to ship from the Earth, there seems no reason why it might not be obtained by mining and manufacturing in space. The first space mirror has already been tested in Earth orbit (the Russian 20 m by their heating of Znamia project) and vastly larger variants are possible about Mars. If sufficient CO2 is produced the planet's poles, then this might act as the trigger for a much more extensive regolith degassing.

PROBLEMS AND ALTERNATIVES

Runaway greenhouse scenarios of terraforming promise much: that through comparatively modest engineering (at a level far less than the integrated activity of humanity on the Earth) Mars can be transformed into a planet habitable for anaerobic life in roughly a century. Conditions would still be hostile, akin to an arid and chilly Precambrian, but far less so than those on the present Mars. Further terraforming might follow ecopoiesis by, for example, arranging for photosynthesis to oxygenate the atmosphere. Long timescales of > 100,000 years have been cited for this step (Averner and MacElroy, 1976; McKay et al.,1991) although it appears reasonable that this might be reduced by at least a factor of ten if the biosphere is actively managed to optimise net oxygen production (Fogg, 1993a, 1995a).

Although the runaway greenhouse is considered the preeminent model, it has been subject to useful criticism and suggestions of engineering alternatives. It seems quite possible (perhaps likely) that if Mars's original inventory of CO2 remains on the planet, then it will have ended up for the most part chemically bound in carbonate minerals, rather than physically bound as the more labile CO2 ice or regolith adsorbate. If this is the case, then re-release of this paleoatmosphere will require extremely energetic processes such as devolatilization of carbonate strata by buried nuclear explosives (Fogg, 1989, 1992), heat beams (Birch, 1992), or asteroid impacts (Zubrin and McKay, 1993). Such activities planet-wide would be highly destructive and are difficult to countenance. Another problem is to do with water–the surface of Mars must be moist to be habitable. Although Mars has visible reserves of water in the polar caps and may have an abundance in the shallow subsurface north and south of 30° latitude, it is difficult to make this available to any biosphere. The slow pace of heat conduction through regolith would greatly delay the melting of permafrost and it could be millenia before an appreciable quantity of water has pooled at low elevations (Fogg, 1992, 1995a). There are potential ways around this problem given that flash floods have occurred naturally on Mars, perhaps great enough to have rapidly flooded the northern plains (Baker et al., 1991). Should source aquifers still exist then it may be possible to destabilize them and duplicate this outburst flooding, but again the engineering required might be violent and unacceptable to many (Fogg, 1992, 1995a). However, a recent detailed model of the martian hydrological cycle (Clifford, 1993) suggests that the lowest regions on Mars might be underlain by aquifers under artesian pressure. If this is the case, then there is hope for the rapid creation of lowland lakes with little more hardware than pumps and drilling rigs (Fogg, 1998).

CONCLUSIONS

At the present time, all research into planetary engineering, whether applied to Mars or anywhere else, is concerned entirely with defining the boundaries of the possible, rather than in charting some definite route into the future. The concept can no longer be described as fantasy, although confirmation of its practicality awaits a detailed exploration of Mars, an inventory of its resources, a better understanding of the phenomenon of planetary habitability, and a future where the solar system is opened to technological civilization as a new and expanding frontier.

Apart from its possible role as a long range goal for space exploration, today, such work is valuable as a stimulating, interdisciplinary, thought experiment with uses in education, terrestrial planetology, and the entertainment media (Fogg, 1993b, 1995a). The range of subjects potentially within its remit is large. Recent interest has been shown in identifying species of cold and desiccation-resistant microorganisms that might be assembled into the first ecosystems to pioneer the Red Planet (Friedmann et al., 1993). The potential of genetically engineering even hardier "marsbugs" is being discussed (Averner and MacElroy, 1976; Hiscox and Thomas, 1995). If terraforming is possible, then ought it to be permitted? Can changing the face of a planet represent a moral act? What if extant life is found within still warm, deep-seated, martian aquifers? The extension of earth-bound environmental ethics into a cosmic setting opens up whole new areas of philosophical and cultural debate (Haynes, 1990; McKay, 1990; Haynes and McKay, 1992; MacNiven, 1995; Turner, 1990, 1996).

Currently though we know too little about Mars, and not enough about the Earth, to know whether life can really take root on the Red Planet. To find out for certain will probably require a human population on Mars, exploring the planet as part of living there (Fogg, 1995b; Zubrin, 1995).

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http://www.users.globalnet.co.uk/~mfogg/paper1.htm

Title: **Re: TERRAFORMING MARS: A REVIEW OF RESEARCH**
Post by: **Brooke** on **August 09, 2007, 12:13:52 am**

Technological Requirements for Terraforming Mars

Robert M. Zubrin. Pioneer Astronautics.

Christopher P. McKay. NASA Ames Research Center.

Abstract

The planet Mars, while cold and arid today, once possessed a warm and wet climate, as evidenced by extensive fluvial features observable on its surface. It is believed that the warm climate of the primitive Mars was created by a strong greenhouse effect caused by a thick CO2 atmosphere. Mars lost its warm climate when most of the available volatile CO2 was fixed into the form of carbonate rock due to the action of cycling water. It is believed, however, that sufficient CO2 to form a 300 to 600 mb atmosphere may still exist in volatile form, either adsorbed into the regolith or frozen out at the south pole. This CO2 may be released by planetary warming, and as the CO2 atmosphere thickens, positive feedback is produced which can accelerate the warming trend. Thus it is conceivable, that by taking advantage of the positive feedback inherent in Mars' atmosphere/regolith CO2 system, that engineering efforts can produce drastic changes in climate and pressure on a planetary scale.

In this paper we propose a mathematical model of the Martian CO2 system, and use it to produce analysis which clarifies the potential of positive feedback to accelerate planetary engineering efforts. It is shown that by taking advantage of the feedback, the requirements for planetary engineering can be reduced by about 2 orders of magnitude relative to previous estimates. We examine the potential of various schemes for producing the initial warming to drive the process, including the stationing of orbiting mirrors, the importation of natural volatiles with high greenhouse capacity from the outer solar system, and the production of artificial halocarbon greenhouse gases on the Martian surface through in-situ industry.

If the orbital mirror scheme is adopted, mirrors with dimension on the order or 100 km radius are required to vaporize the CO2 in the south polar cap. If manufactured of solar sail like material, such mirrors would have a mass on the order of 200,000 tonnes. If manufactured in space out of asteroidal or Martian moon material, about 120 MWe-years of energy would be needed to produce the required aluminum. This amount of power can be provided by near-term multi-megawatt nuclear power units, such as the 5 MWe modules now under consideration for NEP spacecraft.

Orbital transfer of very massive bodies from the outer solar system can be accomplished using nuclear thermal rocket engines using the asteroid's volatile material as propellant. Using major planets for gravity assists, the rocket DV required to move an outer solar system asteroid onto a collision trajectory with Mars can be as little as 300 m/s. If the asteroid is made of NH3, specific impulses of about 400 s can be attained, and as little as 10% of the asteroid will be required for propellant. Four 5000 MWt NTR engines would require a 10 year burn time to push a 10 billion tonne asteroid through a DV of 300 m/s. About 4 such objects would be sufficient to greenhouse Mars.

Greenhousing Mars via the manufacture of halocarbon gases on the planet's surface may well be the most practical option. Total surface power requirements to drive planetary warming using this method are calculated and found to be on the order of 1000 MWe, and the required times scale for climate and atmosphere modification is on the order of 50 years.

It is concluded that a drastic modification of Martian conditions can be achieved using 21st century technology. The Mars so produced will closely resemble the conditions existing on the primitive Mars. Humans operating on the surface of such a Mars would require breathing gear, but pressure suits would be unnecessary. With outside atmospheric pressures raised, it will be possible to create large dwelling areas by means of very large inflatable structures. Average temperatures could be above the freezing point of water for significant regions during portions of the year, enabling the growth of plant life in the open. The spread of plants could produce enough oxygen to make Mars habitable for animals in several millennia. More rapid oxygenation would require engineering efforts supported by multi-terrawatt power sources. It is speculated that the desire to speed the terraforming of Mars will be a driver for developing such technologies, which in turn will define a leap in human power over nature as dramatic as that which accompanied the creation of post-Renaissance industrial civilization.

Introduction

Many people can accept the possibility of a permanently staffed base on Mars, or even the establishment of large settlements. However the prospect of drastically changing the planet's temperature and atmosphere towards more earthlike conditions, or "terraforming" seems to most people to be either sheer fantasy or at best a technological challenge for the far distant future.

But is this pessimistic point of view correct? Despite the fact that Mars today is a cold, dry, and probably lifeless planet, it has all the elements required to support life: water carbon and oxygen (as carbon dioxide), and nitrogen. The physical aspects of Mars, its gravity, rotation rate and axial tilt are close enough to those of Earth to be acceptable and it is not too far from the Sun to be made habitable.

In fact computational studies utilizing climate models suggest that it could be possible to make Mars habitable again with foreseeable technology. The essence of the situation is that while Mars' CO2 atmosphere has only about 1% the pressure of the Earth's at sea level, it is believed that there are reserves of CO2 frozen in the south polar cap and adsorbed within the soil sufficient to thicken the atmosphere to the point where its pressure would be about 30% that of Earth. The way to get this gas to emerge is to heat the planet, and in fact, the warming and cooling of Mars that occurs each Martian year as the planet cycles between its nearest and furthest positions from the Sun in its slightly elliptical orbit cause the atmospheric pressure on Mars to vary by plus or minus 25% compared to its average value on a seasonal basis.

We can not, of course, move Mars to a warmer orbit. However we do know another way to heat a planet, through an artificially induced greenhouse effect that traps the Sun's heat within the atmosphere. Such an atmospheric greenhouse could be created on Mars in at least three different ways. One way would be to set up factories on Mars to produce very powerful artificial greenhouse gasses such as halocarbons ("CFC's") and release them into the atmosphere. Another way would be to use orbital mirrors or other large scale power sources to warm selected areas of the planet, such as the south polar cap, to release large reservoirs of the native greenhouse gas, CO2, which may be trapped their in frozen or adsorbed form. Finally natural greenhouse gases more powerful than CO2 (but much less so than halocarbons) such as ammonia or methane could be imported to Mars in large quantities if asteroidal objects rich with such volatiles in frozen form should prove to exist in the outer solar system.

Each of these methods of planetary warming would be enhanced by large amounts of CO2 from polar cap and the soil that would be released as a result of the induced temperature rise. This CO2 would add massively to the greenhouse effect being created directly, speeding and multiplying the warming process.

The Mars atmosphere/regolith greenhouse effect system is thus one with a built-in positive feedback. The warmer it gets, the thicker the atmosphere becomes; and the thicker the atmosphere becomes the warmer it gets. A method of modeling this system and the results of calculations based upon it are given in the sections below.

Equations for Modeling the Martian System

An equation for estimating the mean temperature on the surface of Mars as a function of the CO2 atmospheric pressure and the solar constant is given by McKay and Davis [1] as:

Tmean = S^0.25xTBB + 20(1+S)P^0.5 (Eq.1)

where Tmean is the mean planetary temperature in kelvins, S is the solar constant where the present day Sun=1, TBB, the black body temperature of Mars at present = 213.5 K, and P is given in bar.

Since the atmosphere is an effective means of heat transport from the equator to the pole,we propose (as an improvement over equation (1) in reference [2]:

Tpole = Tmean - DT/(1 + 5P) (Eq. 2)

where DT is what the temperature difference between the mean value and the pole would be in the absence of an atmosphere (about 75 K for S=1).

For purposes of this analysis it is further assumed based upon a rough approximation to observed data that :

Tmax = Tequator = 1.1Tmean (Eq. 3)

and that the global temperature distribution is given by:

T(q) = Tmax - (Tmax-Tpole)sin^1.5q (Eq.4)

where q is the latitude (north or south).

Equations (1) through (4) given the temperature on Mars as a function of CO2 pressure. However, as mentioned above, the CO2 pressure on Mars is itself a function of the temperature. There are three reservoirs of CO2 on Mars, the atmosphere, the dry ice in the polar caps, and gas adsorbed in the soil. the interaction of the polar cap reservoirs with the atmosphere is well understood and is given simply by the relationship between the vapor pressure of CO2 and the temperature at the poles. This is given by the vapor pressure curve for CO2, which is approximated by:

P = 1.23 x 10^7{exp(-3168/Tpole)} (Eq. 5)

So long as there is CO2 in both the atmosphere and the cap, equation (5) gives an exact answer to what the CO2 atmospheric pressure will be as a function of polar temperature. However if the polar temperature should rise to a point where the vapor pressure is much greater than that which can be produced by the mass in the cap reservoir (between 50 and 150 mb) then the cap will disappear and the atmosphere will be regulated by the soil reservoir.

The relationship between the soil reservoir, the atmosphere and the temperature is not known with precision. an educated guess is given in parametric form in reference 1 as:

P = {CMaexp(T/Td)}1/g (6)

where Ma is the amount of gas adsorbed in bar, g=0.275, C is a normalization constant set so that with chosen values of the other variables equation (6) will reflect known Martian conditions, and Td is the characteristic energy required for release of gas from the soil. Equation (6) is essentially a variation on Van Hofft's law for the change in chemical equilibrium with temperature, and so there is fair confidence that its general form is correct. However the value of Td is unknown and probably will remain so until after human exploration of Mars. In reference [2] McKay et al varied parametrically Td from 10 to 60 K and produced curves using equation (6) with T set equal to either Tpole or Tmean. In this paper we choose Td=15 to 40 K (a reasonable subset of the spectrum slightly on the optimistic side; the lower the value of Td the easier things are for prospective terraformers.) Because equation (6) is so strongly temperature dependent, however, we do not simply set T to the extreme values of Tmean or Tpole and solve equation (6) to get a global "soil pressure" however, as was done in reference [2]. Rather we use the global temperature distribution given by equation (4) to integrate equation (6) over the surface of the planet. This gives a more accurate quasi 2-Dimensional view of the atmosphere/regolith equilibrium problem in which most of the adsorbed CO2 is distributed to the planet's colder regions. In this model, regional (in the sense of latitude) temperature changes, especially in the near-polar regions, can have as important a bearing on the atmosphere/regolith interaction as changes in the planet's mean temperature.

Title: **Re: TERRAFORMING MARS: A REVIEW OF RESEARCH**
Post by: **Brooke** on **August 09, 2007, 12:15:47 am**

Results of Calculations

In figure 1 we see the results of our model when applied to the situation at Mars' south polar cap, where it is believed that enough CO2 may be held frozen as dry ice to give Mars an atmosphere on the order of 50 to 100 mbar. We have plotted the polar temperature as a function of the pressure, in accord with equations (1) and (2), and the vapor pressure as a function of the polar temperature, in accord with equation (5). There are two equilibrium points, labeled A and B where the values of P and T are mutually consistent. However A is a stable equilibrium, while B is unstable. This can be seen by examining the dynamics of the system wherever the two curves do not coincide. Whenever the temperature curve lies above the vapor pressure curve, the system will move to the right, i.e. towards increased temperature and pressure; this would represent a runaway greenhouse effect. Whenever the pressure curve lies above the temperature curve, the system will move to the left, i.e. a temperatures and pressure will both drop in a runaway icebox icebox effect. Mars today is at point A, with 6 mbar of pressure and a temperature of about 147 K at the pole.

Now consider what would happen if someone artificially increased the temperature of the Martian pole by several degrees K. As the temperature is increased, points A and B would move towards each other until they met. If the temperature increase were 4 K, the temperature curve would be moved upwards on the graph sufficiently so that it would lie above the vapor pressure curve everywhere. The result would be a runaway greenhouse effect that would cause the entire pole to evaporate, perhaps in less than a decade. Once the pressure and temperature have moved past the current location point B, Mars will be in a runaway greenhouse condition even without artificial heating, so if later the heating activity were discontinued the atmosphere will remain in place.

(http://www.users.globalnet.co.uk/~mfogg/Image1.gif)

Fig. 1 Mars polar cap/atmosphere dynamics. current equilibrium is at point A. Raising polar temperatures by 4 K would drive equilibria A and B together, causing runaway heating that would lead to the elimination of the cap

(http://www.users.globalnet.co.uk/~mfogg/Image2.gif)

Fig. 2 Mars regolith/atmosphere dynamics under conditions of Td=20 with a volatile inventory of 500 mb of CO2

As the polar cap evaporates, the dynamics of the greenhouse effect caused by the reserves of CO2 held in the Martian soil come into play. These reserves exist primarily in the high latitude regions, and by themselves are estimated to be enough to give Mars a 400 mbar atmosphere. We can't get them all out however, because as they are forced out of the ground by warming, the soil becomes an increasingly effective "dry sponge" acting to hold them back. The dynamics of this system are shown in fig. 2, in which we assume Td=20, current polar reserves of 100 mb, and regolith reserves of 394 mb, and graph the pressure on the planet as a function of Treg, where Treg is the weighted average of the temperature given by integrating the right hand side of equation (6) over the surface of the planet using the temperature distribution given by equation (4).

That is:

Treg= -Tdln{0S90Exp(-T(q)/Td)sinqdq} (Eq. 7)

Since Treg is a function of the temperature distribution and Tmean, it is a function of P, and thus Treg(P) can also be graphed. The result are a set of T(P) curves and P(T) curves, whose crossing points reflect stable or unstable equilibrium, just as in the case of the polar cap analysis.

It can be seen in fig. 2 that the atmosphere soil system under the chosen assumption of Td=20 K has only 1 equilibrium point, which is stable, and which will be overrun by the pressure generated by the vaporized polar cap. Thus, by the time the process is brought to a halt, an atmosphere with a total pressure of about 300 mbar, or 4.4 pounds per square inch, can be brought into being. Also shown in Fig. 2 is the day-night average temperature that will result in Mars' tropical regions (Tmax) during summertime. It can be seen that the 273 K freezing point of water will be approached. With the addition of modest ongoing artificial greenhouse efforts, it can be exceeded.

The assumption of Td=20 is optimistic, however, and the location of the equilibrium convergence point (point C in fig. 2) is very sensitive to the value chosen for Td. In fig.3 we show what happens if values of Td=25 and Td=30 are assumed. In these cases, the convergence point moves from 300 mb at Td=20 to 31 and 16 mb for Td=25 and Td=30 respectively. (The value of the Treg curve in fig. 3 was calculated under the assumption of Td=25; it varies from this value by a degree or two for Td=20 or 30.) Such extraordinary sensitivity of the final condition to the unknown value of Td may appear at first glance to put the entire viability of the terraforming concept at risk. However in fig 3 we also show (dotted line) the situation if artificial greenhouse methods are employed to maintain Treg at a temperature 10 K above those produced by the CO2 outgassing itself. It can be seen that drastic improvements in the final T and P values are effected for the Td=25 and 30 cases, with all three cases converging upon final states with Mars possessing atmospheres with several hundred millibars pressure.

Title: **Re: TERRAFORMING MARS: A REVIEW OF RESEARCH**
Post by: **Brooke** on **August 09, 2007, 12:17:35 am**

(http://www.users.globalnet.co.uk/~mfogg/Image3.gif)

Fig. 3 An induced 10 K rise in regolith temperature can counter effect of Td variations. Data shown assumes a planetary volatile inventory of 500 mb CO2.

In figs 4,5,6, and 7 we show the convergence condition pressure and maximum seasonal average temperature in the Martian tropics resulting on either a "poor" Mars, possessing a total supply of 500 mb of CO2 (50 mb of CO2 in the polar cap and 444 mb in the regolith), or a "rich" Mars possessing 1000 mb of CO2 (100 mb in the polar cap and 894 mb in the regolith). different curves are shown under the assumptions that either no sustained greenhouse effort is mounted after the initial polar cap release, or that continued efforts are employed to maintain the planet's mean temperature 5, 10 or 20 degrees above the value produced by the CO2 atmosphere alone. It can be seen that if a sustained effort is mounted to keep an artificial DT of 20 degrees in place, then a tangible atmosphere and acceptable pressures can be produced even if Td has a pessimistic value of 40 K.

(http://www.users.globalnet.co.uk/~mfogg/Image4.gif)

Fig .4 Equilibrium pressure reached on Mars with a planetary volatile inventory of 500 mb CO2 after 50 mb polar cap has been evaporated. DT is artificially imposed sustained temperature rise.

Title: **Re: TERRAFORMING MARS: A REVIEW OF RESEARCH**
Post by: **Brooke** on **August 09, 2007, 12:19:19 am**

(http://www.users.globalnet.co.uk/~mfogg/Image5.gif)

Fig. 5 Equilibrium maximum seasonal (diurnal average) temperature reached on Mars with a planetary volatile inventory of 500 mb CO2 after 50 mb polar cap has been evaporated

(http://www.users.globalnet.co.uk/~mfogg/Image6.gif)

Fig. 6 Equilibrium pressure reached on Mars with a planetary volatile inventory of 1000 mb CO2 after 100 mb polar cap has been evaporated

(http://www.users.globalnet.co.uk/~mfogg/Image7.gif)

Fig. 7 Equilibrium maximum seasonal temperature (diurnal average) reached on Mars with a planetary volatile inventory of 1000 mb CO2 after 100 mb polar cap has been evaporated.

The important conclusion to be drawn from this analysis is that while the final conditions on a terraformed Mars may be highly sensitive to the currently unknown value of the regoliths outgassing energy, Td, they are even more sensitive to the level of sustained artificially induced greenhousing ,DT Put simply, the final conditions of the atmosphere/regolith system on a terraformed Mars are controllable.

Once significant regions of Mars rise above the freezing point of water on at least a seasonal basis, the large amounts of water frozen into the soil as permafrost would begin to melt, and eventually flow out into the dry riverbeds of Mars. Water vapor is also a very effective greenhouse gas, and since the vapor pressure of water on Mars would rise enormously under such circumstances, the reappearance of liquid water on the Martian surface would add to the avalanche of self accelerating effects all contributing towards the rapid warming of Mars. The seasonal availability of liquid water is also the key factor in allowing the establishment of natural ecosystems on the surface of Mars.

The dynamics of the regolith gas-release process are only approximately understood, and the total available reserves of CO2 won't be known until human explorers journey to Mars to make a detailed assessment, so these results are must be regarded as approximate and uncertain. Nevertheless, it is clear that the positive feedback generated by the Martian CO2 greenhouse system greatly reduces the amount of engineering effort that would otherwise be required to transform the Red Planet. In fact, since the amount of a greenhouse gas needed to heat a planet is roughly proportional to the square of the temperature change required, driving Mars into a runaway greenhouse with an artificial 4 K temperature rise only requires about 1/200th the engineering effort that would be needed if the entire 55 K rise had to be engineered by brute force. The question we shall now examine is how such a 4 K global temperature rise could be induced.

Title: **Re: TERRAFORMING MARS: A REVIEW OF RESEARCH**
Post by: **Brooke** on **August 09, 2007, 12:20:13 am**

Methods of Accomplishing Global Warming on Mars

The three most promising options for inducing the required temperature rise to produce a runaway greenhouse on Mars appear to be the use of orbital mirrors to change the heat balance of the south polar cap (thereby causing its CO2 reservoir to vaporize), the importation of ammonia rich objects from the outer solar system [3], and the production of artificial halocarbon ("CFC") gases on the Martian surface. We discuss each of these in turn. It should be noted, however, that synergistic combination of several such methods may yield better results than any one of them used alone [4].

Orbiting Mirrors

While the production of a space-based sunlight reflecting device capable of warming the entire surface of Mars to terrestrial temperatures is theoretically possible [5], the engineering challenges involved in such a task place such a project well outside the technological horizon considered in this paper. A much more practical idea would be to construct a more modest mirror capable of warming a limited area of Mars by a few degrees. As shown by the data in fig. 1, a 5 degree K temperature rise imposed at the pole should be sufficient to cause the evaporation of the CO2 reservoir in the south polar cap. Based upon the total amount of solar energy required to raise the black-body temperature a given area a certain number of degrees above the polar value of 150 K, we find that a space-based mirror with a radius of 125 km could reflect enough sunlight to raise the entire area south of 70 degrees south latitude by 5 K. If made of solar sail type aluminized mylar material with a density of 4 tonnes/km^2, such a sail would have a mass of 200,000 tonnes. This is too large to consider launching from Earth, however if space-based manufacturing techniques are available, its constructing in space out of asteroidal or Martian moon material is a serious option. The total amount of energy required to process. the materials for such a reflector would be about 120 MWe-years, which could be readily provided by a set of 5 MWe nuclear reactors such as are now being considered for use in piloted nuclear electric spacecraft. Interestingly, if stationed near Mars, such a device would not have to orbit the planet. Rather, solar light pressure could be made to balance the planet's gravity, allowing it to hover as a "statite" [6] with its power output trained constantly at the polar region. For the sail density assumed, the required operating altitude would be 214,000 km. The statite reflector concept and the required mirror size to produce a given polar temperature rise is shown in figs 8 and 9.

Title: **Re: TERRAFORMING MARS: A REVIEW OF RESEARCH**
Post by: **Brooke** on **August 09, 2007, 12:21:42 am**

(http://www.users.globalnet.co.uk/~mfogg/Image8.gif)

Fig.8 Solar sails of 4 tonnes/km^2 density can be held stationary above Mars by light pressure at an altitude of 214,000 km. Wasting a small amount of light allows shadowing to be avoided.

(http://www.users.globalnet.co.uk/~mfogg/Image9.gif)

Fig.9. Solar sail mirrors with radii on the order of 100 km and masses of 200,000 tonnes can produce the 5 K temperature rise required to vaporize the CO2 in Mars' south polar cap. It may be possible to construct such mirrors in space.

If the value of Td is lower than 20 K, then the release of the polar CO2 reserves by themselves could be enough to trigger the release of the regolith's reserves in a runaway greenhouse effect. If however, as seems probable, Td is greater than 20 K, then either the importation or production of strong greenhouse gases will be required to force a global temperature rise sufficient to create a tangible atmospheric pressure on Mars.

Moving Ammonia Asteroids

Ammonia is a powerful greenhouse gas, and it is possible that nature has stockpiled large amounts of it in frozen form on asteroidal sized objects orbiting in the outer solar system. If moving material from such objects to Mars is envisioned, then such orbits would be quite convenient, because strange as it may seem, it is easier to move an asteroid from the outer solar system to Mars than it is to do so from the Main Belt or any other inner solar system orbit. This odd result follows from the laws of orbital mechanics, which cause an object farther away from the Sun to orbit it slower than one that is closer in. Because an object in the outer solar system moves slower, it takes a smaller DV to change its orbit from a circular to an ellipse. Furthermore, the orbit does not have to be so elliptical that it stretches from Mars to the outer solar system; it is sufficient to distort the objects orbit so that it intersects the path of a major planet, after which a gravity assist can do the rest. The results are shown in Fig. 10. It can be seen that moving an asteroid positioned in a circular orbit at 25 AU, by way of a Uranus gravity assist to Mars, requires a DV of only 0.3 km/s, compared to a 3.0 km/s DV to move an asteroid directly to Mars from a 2.7 AU position in the Main Belt. the time of flight required for such transfers is shown in Fig. 11.

Now we don't know for sure if there are numerous asteroid size objects in the outer solar system, but there is no reason to believe that there aren't. As of this writing, only one is known, but that one, Chiron, orbiting between Saturn and Uranus is rather large (180 km diameter,), and it may be expected that a lot of small objects can be found for every big one. In all probability, the outer solar system contains thousands of asteroids that we have yet to discover because they shine so dimly compared to those in the Main Belt (The brightness of an asteroid as seen from Earth is inversely proportional to the fourth power of its distance from the Sun.). Furthermore, because water, ammonia, and other volatiles freeze so completely in the outer solar system, it is likely that the asteroids to be found beyond Saturn are largely composed of frozen gases (such appears to be the case for Chiron). This makes it possible for us to move them.

Consider an asteroid made of frozen ammonia with a mass of 10 billion tonnes orbiting the sun at a distance of 12 AU. Such an object, if spherical, would have a diameter of about 2.6 km, and changing its orbit to intersect Saturn's (where it could get a trans-Mars gravity assist) would require a DV of 0.3 km/s. If a quartet of 5000 MW nuclear thermal rocket engines powered by either fission or fusion were used to heat some of its ammonia up to 2200 K (5000 MW fission NTRs operating at 2500 K were tested in the 1960s), they would produce an exhaust velocity of 4 km/s, which would allow them to move the asteroid onto its required course using only 8% of its material as propellant. Ten years of steady thrusting would be required, followed by a about a 20 year coast to impact. When the object hit Mars, the energy released would be about 10 TW-years, enough to melt 1 trillion tonnes of water (a lake 140 km on a side and 50 meters deep). In addition, the ammonia released by a single such object would raise the planet's temperature by about 3 degrees centigrade and form a shield that would effectively mask the planet's surface from ultraviolet radiation. As further missions proceeded, the planet's temperature could be increased globally in accord with the data shown in Fig. 12. Forty such missions would double the nitrogen content of Mars' atmosphere by direct importation, and could produce much more if some of the asteroids were targeted to hit beds of nitrates, which they would volatilize into nitrogen and oxygen upon impact. If one such mission were launched per year, within half a century or so most of Mars would have a temperate climate, and enough water would have been melted to cover a quarter of the planet with a layer of water 1 m deep.

While attractive in a number of respects, the feasibility of the asteroidal impact concept is uncertain because of the lack of data on outer solar system ammonia objects. Moreover, if Td is greater than 20 K, a sustained greenhousing effort will be required. as the characteristic lifetime of an ammonia molecule on Mars is likely to be less than a century, this means that even after the temperature is raised, ammonia objects would need to continue to be imported to Mars, albeit at a reduced rate. As each object will hit Mars with an energy yield equal to about 70,000 1 megaton hydrogen bombs, the continuation of such a program may be incompatible with the objective of making Mars suitable for human settlement.

A possible improvement to the ammonia asteroidal impact method is suggested by ideas given in reference [4], where it is pointed out that bacteria exist which can metabolize nitrogen and water to produce ammonia. If an initial greenhouse condition were to be created by ammonia object importation, it may be possible that a bacterial ecology could be set up on the planet's surface that would recycle the nitrogen resulting from ammonia photolysis back into the atmosphere as ammonia, thereby maintaining the system without the need for further impacts. Similar schemes might also be feasible for cycling methane, another short-lived natural greenhouse gas which might be imported to the planet.

Title: **Re: TERRAFORMING MARS: A REVIEW OF RESEARCH**
Post by: **Brooke** on **August 09, 2007, 12:23:48 am**

(http://www.users.globalnet.co.uk/~mfogg/Image10.gif)

Fig.10 Using gravity assists, the DV required to propel an outer solar system asteroid onto a collision course with Mars can be less than 0.5 km/s. Such "falling" objects can release much more energy upon impact than was required to set them in motion.

(http://www.users.globalnet.co.uk/~mfogg/Image11.gif)

Fig.11 Ballistic flight times from the outer solar system to Mars are typically between 25 and 50 years

(http://www.users.globalnet.co.uk/~mfogg/Image12.gif)

Fig. 12 Importing four 10 billion tonne ammonia asteroids to Mars would impose an 8 K temperature rise, which after amplification by CO2 feedback could create drastic changes in global conditions.

Producing Halocarbons on Mars

In Table 1 we show the amount of halocarbon gases (CFC's) needed in Mars' atmosphere to create a given temperature rise, and the power that would be needed on the Martian surface to produce the required CFC'c over a period of 20 years. If the gases have an atmospheric lifetime of 100 years, then approximately 1/5th the power levels shown in the table will be needed to maintain the CFC concentration after it has been built up. For purposes of comparison, a typical nuclear power plant used on Earth today has a power output of about 1000 MWe. and provides enough energy for a medium sized (Denver) American city. The industrial effort associated with such a power level would be substantial, producing about a trainload of refined material every day and requiring the support of a work crew of several thousand people on the Martian surface. A total project budget of several hundred billion dollars might well be required. Nevertheless, all things considered, such an operation is hardly likely to be beyond the capabilities of the mid 21st Century.

Title: **Re: TERRAFORMING MARS: A REVIEW OF RESEARCH**
Post by: **Brooke** on **August 09, 2007, 12:25:34 am**

Table 1: Greenhousing Mars with CFCs

Induced Heating (K)	CFC Pressure (mbar)	CFC Production (t/hr)	Power Required (MWe)
5	0.012	263	1315
10	0.04	878	4490
20	0.11	2414	12070
30	0.22	4829	24145

40
0.39
8587
42933

In a matter of several decades, using such an approach Mars could be transformed from its current dry and frozen state into a warm and slightly moist planet capable of supporting life. Humans could not breath the air of the thus transformed Mars, but they would no longer require space suits and instead could travel freely in the open wearing ordinary clothes and a simple SCUBA type breathing gear. However because the outside atmospheric pressure will have been raised to human tolerable levels, it will be possible to have large habitable areas for humans under huge domelike inflatable tents containing breathable air. On the other hand, simple hardy plants could thrive in the CO2 rich outside environment, and spread rapidly across the planets surface. In the course of centuries, these plants would introduce oxygen into Mars's atmosphere in increasingly breathable quantities, opening up the surface to advanced plants and increasing numbers of animal types. As this occurred, the CO2 content of the atmosphere would be reduced, which would cause the planet to cool unless artificial greenhouse gases were introduced capable of blocking off those sections of the infrared spectrum previously protected by CO2. The halocarbon gases employed would also have to be varieties lacking in chlorine, if an ultraviolet shielding ozone layer is to be built up. Providing these matters are attended to, however, the day would eventually come when the domed tents would no longer be necessary.

Activating the Hydrosphere

The first steps required in the terraforming of Mars, warming the planet and thickening its atmosphere, can be accomplished with surprisingly modest means using in-situ production of halocarbon gases. However the oxygen and nitrogen levels in the atmosphere would be too low for many plants, and if left in this condition the planet would remain relatively dry, as the warmer temperatures took centuries to melt Mars' ice and deeply buried permafrost. It is in this, the second phase of terraforming Mars, during which the hydrosphere is activated, the atmosphere made breathable for advanced plants and primitive animals, and the temperature increased further, that either space based manufacturing of large solar concentrators or human activity in the outer solar system is likely to assume an important role.

Activating the Martian hydrosphere in a timely fashion will require doing some violence to the planet, and , as discussed above, one way this can be done is with targeted asteroidal impacts. Each such impact releases the energy equivalent of 10 TW-yrs. If Plowshare methods of shock treatment for Mars are desired, then the use of such projectiles is certainly to be preferred to the alternative option [4] of detonation of hundreds of thousands of thermonuclear explosives. After all, even if so much explosive could be manufactured, its use would leave the planet unacceptably radioactive.

The use of orbiting mirrors provides an alternative method for hydrosphere activation. For example, if the 125 km radius reflector discussed earlier for use in vaporizing the pole were to concentrate its power on a smaller region, 27 TW would be available to melt lakes or volatilize nitrate beds. This is triple the power available from the impact of 1 10 billion tonne asteroid per year, and in all probability would be far more controllable. A single such mirror could drive vast amounts of water out of the permafrost and into the nascent Martian ecosystem very quickly. Thus while the engineering of such mirrors may be somewhat grandiose, the benefits to terraforming of being able to wield tens of TW of power in a controllable way can hardly be overstated.

Oxygenating the Planet

The most technologically challenging aspect of terraforming Mars will be the creation of sufficient oxygen in the planet's atmosphere to support animal life. While primitive plants can survive in an atmosphere without oxygen, advanced plants require about 1 mb and humans need 120 mb. While Mars may have super-oxides in its soil or nitrates that can be pyrolysed to release oxygen (and nitrogen) gas, the problem is the amount of energy needed: about 2200 TW-years for every mb produced. Similar amounts of energy are required for plants to release oxygen from CO2. Plants, however, offer the advantage that once established they can propagate themselves. The production of an oxygen atmosphere on Mars thus breaks down into two phases. In the first phase, brute force engineering techniques are employed to produce sufficient oxygen (about 1 mb) to allow advanced plants to propagate across Mars. Assuming 3 125 km radius space mirrors active in supporting such a program and sufficient supplies of suitable target material on the ground, such a goal could be achieved in about 25 years. At that point, with a temperate climate, a thickened CO2 atmosphere to supply pressure and greatly reduce the space radiation dose, and a good deal of water in circulation, plants that have been genetically engineered to tolerate Martian soils and to perform photosynthesis at high efficiency could be released together with their bacterial symbiotes. Assuming that global coverage could be achieved in a few decades and that such plants could be engineered to be 1% efficient (rather high, but not unheard of among terrestrial plants) then they would represent an equivalent oxygen producing power source of about 200 TW. By combining the efforts of such biological systems with perhaps 90 TW of space based reflectors and 10 TW of installed power on the surface (terrestrial civilization today uses about 12 TW) the required 120 mb of oxygen needed to support humans and other advanced animals in the open could be produced in about 900 years. If more powerful artificial energy sources or still more efficient plants were engineered, then this schedule could be accelerated accordingly, a fact which may well prove a driver in bringing such technologies into being. It may be noted that thermonuclear fusion power on the scale required for the acceleration of terraforming also represents the key technology for enabling piloted interstellar flight. If terraforming Mars were to produce such a spinoff, then the ultimate result of the project will be to confer upon humanity not only one new world for habitation, but myriads.

Conclusion

We have shown that within broad tolerances of uncertainty of Martian conditions, that drastic improvements in the life-sustaining characteristics of the environment of the Red Planet may be effected by humans using early to mid 21st century technologies. While our immediate descendants cannot expect to use such near-term methods to "terraform" the planet in the full sense of the word, it at least should be possible to rejuvenate Mars, making it again as receptive to life as it once was. Moreover, in the process of modifying Mars, they are certain to learn much more about how planets really function and evolve, enough perhaps to assure wise management for our native planet.

Beyond such near-term milestones, the tasks associated with full terraforming become more daunting and the technologies required more speculative. Yet who can doubt that if the first steps are taken, that the developments required to complete the job will not follow, for what is ultimately at stake is an infinite universe of habitable worlds.

Seen in such light, the task facing our generation, that of exploring Mars and learning enough about the planet and the methods of utilizing its resources to begin to transform it into a habitable planet, could not be more urgent, or more noble.

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Title: **Re: TERRAFORMING MARS: A REVIEW OF RESEARCH**
Post by: **Brooke** on **August 09, 2007, 12:28:45 am**

PLANETARY ENGINEERING BIBLIOGRAPHY (Revised July 2007).

Martyn J. Fogg (Probability Research Group, London, UK).

With previous assistance from: Tom Meyer (University of Colorado), Stephen Gillett (University of Reno, Nevada), Robert Haynes (York University, Ontario) and Richard Cathcart.

INTRODUCTION.

A listing of literature related to planetary engineering follows below. The entries are placed into one of three categories:

1. GEOENGINEERING.

2. TERRAFORMING.

3. ASTROPHYSICAL ENGINEERING/OTHER.

Definitions of planetary engineering, geoengineering and terraforming are taken from Terraforming: Engineering Planetary Environments (Fogg, 1995).

Planetary Engineering is the application of technology for the purpose of influencing the global properties of a planet.
Geoengineering is planetary engineering applied specifically to the Earth. It includes only those macroengineering concepts that deal with the alteration of some global parameter, such as the greenhouse effect, atmospheric composition, insolation or impact flux.
Terraforming is a process of planetary engineering, specifically directed at enhancing the capacity of an extra-terrestrial planetary environment to support life. The ultimate in terraforming would be to create an uncontained planetary biosphere emulating all the functions of the biosphere of the Earth, one that would be fully habitable for human beings.
Astrophysical Engineering is taken to represent proposed activities, relating to future habitation, that are envisaged to occur on a scale greater than that of "conventional" planetary engineering.
It is thought that the entries related to terraforming are near-comprehensive and include almost everything substantive written on the subject. However, this does not mean that all entries are essential to a programme of study. Researchers specifically interested in the terraforming of Mars will find a personal recommendation of the most essential literature in Section 2 indicated so ª.

The author would appreciate notification of other works, old or new, that would merit inclusion in future updates. Please contact:

mfogg at globalnet.co.uk.

CONTENTS.

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Title: **Re: TERRAFORMING MARS: A REVIEW OF RESEARCH**
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