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TERRAFORMING MARS: A REVIEW OF CURRENT RESEARCH

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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 Ḥaynes (1990) from the Greek roots οικος, an abode, house or dwelling place, and ποιεσις, 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 $pO_2 \approx 20$ 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 O_2 and N_2 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.

The Runaway CO_2 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 CO_2 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 CO_2 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 CO_2, 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 CO_2 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 CO_2 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 H_2O ice with perhaps just a frosting of CO_2 or an admixture in the form of CO_2 hydrate. It is thus doubtful that the caps are a rich enough inventory of CO_2 to satisfy model requirements. However, it is possible that a substantial amount of CO_2 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 CO_2 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 CO_2 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 CO_2, 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 µm where CO_2 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. 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 *Znamia* project) and vastly larger variants are possible about Mars. If sufficient CO_2 is produced by their heating of 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 CO_2 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 CO_2 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, in preparation).

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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