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TERRAFORMING MARS QUICKLY

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Mars would be inhabitable if it were warmer and had a denser O_2/N_2 atmosphere, but previous terraforming proposals have been incomplete or have described very slow processes. This paper addresses the problems of terraforming Mars quickly. It is shown that a solar mirror could be used to vaporise portions of the Martian regolith, liberating trapped volatiles including oxygen, nitrogen, carbon dioxide and water vapour. The creation of a breathable atmosphere could then be completed by photosynthesis. Illumination from the same soletta would then provide a warm climate around the new canals and sunlight on the high deserts, maintaining the 24½ hour cycle of day and night. It is claimed that terraforming could be completed in as little as fifty years.

1. INTRODUCTION

Mars is perhaps the most hospitable of all the planets — after the Earth. Although small ($R_♂$ =3393 km, $R_\oplus$=6376 km), with a correspondingly low surface gravity ($g_♂$=3.77ms^{-2}, $g_\oplus$=9.81ms^{-2}), it is a rocky planet with a terrain not unlike that of earthly deserts. For these reasons it is a prime candidate for future colonisation. Unfortunately, it differs from Earth in a number of important ways.

First, Mars is rather cold. Its temperature is about 220K, compared to 290K on Earth; this is partly because Mars is so much farther from the Sun (1.52 AU) and partly because of the absence of a warming blanket of air and water vapour.

Second, Mars has a very thin atmosphere, composed mainly of carbon dioxide; the pressure at the surface is about 7 millibars. There is almost no free oxygen and no liquid water.

Third, the Martian gravity is only about a third of Earth's.

Now *terraforming* is defined as making a planet over into an Earthlike planet. A *planetological terraform* leaves a fully Earthlike planet, stable over geological eras without further human intervention, whereas a *habitable terraform* uses artificial shortcuts to adapt the planet for human habitation, but requires continued maintenance [1].

This paper parallels my previous paper on terraforming Venus [1] in attempting to present a fairly complete and economically viable scenario, with emphasis on the colonisation of Mars during the next century. I have deliberately sought techniques that minimise the cost of terraforming, and the time taken, allowing a habitable terraform to be reached as quickly as possible. Afterwards terraforming may continue as far as is practicable towards the full planetological terraform.

Early ideas on terraforming Mars [2-6] relied upon warming the planet to free carbon dioxide and water vapour from the polar caps or regolith; a runaway greenhouse effect would, it was hoped, trigger the desired climate shift. Albedo reduction was to have been initiated through the introduction of plants or the scattering of carbon black. Others contemplated the use of mirrors or artificial suns, or bombardment with ice meteoroids. These proposals now appear overly sanguine and, of themselves, would prove largely ineffective.

Although some of the defects have been remedied in later proposals [7-9], most of these still deal in timescales of thousands of years; moreover, despite their planetological bias, they do not entirely eliminate the need for artificial upkeep.

I have previously argued [1] that in order for terraforming projects to be economically viable they should be capable of generating revenue — or of being completed — within a relatively short span of time, ideally less than a working lifetime. The process of terraforming also needs to be competitive with the construction of purely artificial space habitats [10-15].

Terraforming, especially of the planetological kind, may also be conducted as a precaution against the possibility of a catastrophe that might otherwise threaten the survival of Mankind.

For whereas a terraformed planet might sustain human life indefinitely (even without technological upkeep), artificial space habitats might then only survive for a limited period of time, ranging from less than a year to perhaps a thousand years.

Although the prospects for a universal and irreversible collapse of civilisation appear remote, it would nevertheless be wise to provide for a moderate number of terraformed planets, as a safety net (in addition to the plethora of artificial habitats likely to comprise the bulk of civilisation).

Now advanced space industrialisation is surely a prerequisite for terraforming; the costs presented in this paper are therefore compatible with a Gross Space Product $\sim$1 T£yr^{-1} (still only a tenth of *current* world income), by the mid-21st century [15], when the terraforming of Mars is assumed to take place.

The value of a fully terraformed Mars may then be in the region of 80T£ (in 1980 £'s), one third of the current Gross World Value ($\sim$10T£yr^{-1} × 25 yr, or £50,000 per person). The low gravity may however detract somewhat from its market value, as compared with rotating space habitats. Although a terraformed Mars may need maintenance, this is unlikely to be a major problem, since the annual cost should be no more than a small fraction of the cost of terraforming.

Without taking these figures too seriously, we note that they give a useful indication of the timescales and costs to be met. It is when technology is capable of meeting these demands that terraforming is likely to proceed; thus techniques appropriate to a space economy at the assumed stage of development have been considered. However, the final scenario is not by any means the most optimistic that could have been chosen, and more effective techniques may well become available.

This paper thus addresses the problem of terraforming Mars *quickly*, in the hope of finding solutions that are economically, psychologically and scientifically sound.

2. TERRAFORMING REQUIREMENTS

To terraform Mars we wish to:

1) Warm the planet to ~290K.

2) Increase the atmospheric pressure, supplying ~240 mbar of breathable oxygen.

3) Provide sufficient water for a water-table and seas.

Mars already possesses an eminently suitable rotation period of 24h 37m 23s, only 3% longer than Earth's; and it displays a slowly changing axial tilt of around 24°, almost the same as Earth's.

(Clocks showing local time on Mars can display to 24h 39m 35s, the length of the day or sol, before flicking back to 00h 00m 00s; the conventional twelve hour clock can also be used, with the addition of the 'tweenmidnight hours from 12 pm to 12.39 tm. Greenwich dates should be employed throughout. Similar protocols may be used on other planets where the day is not exactly 24 hours. Any suggestion that the duration of the second should be adjusted must be deprecated; the confusion this would engender would surely be insupportable.)

Because the Martian gravity is only 38% of Earth's it is doubtful whether Martian colonies are suitable for permanent residence; for once colonists become accustomed to the lower gravity, their tolerance of high accelerations and normal gravity is likely to be seriously impaired. After a few years they may therefore be barred from Earth — and from most space habitats and vessels. It is also unclear what additional physiological problems may arise from long exposure to reduced gravity.

In consequence, it is suggested that residence on Mars should be mainly on a seasonal basis, alternating with periods in full-gravity orbital space colonies. The provision of 1g centrifuges on the surface is also worthy of consideration.

A variety of techniques for fulfilling these terraforming requirements will be considered, then combined into a single scenario. The result will prove remarkably similar to the familiar fictional Mars of canals and high deserts [16].

3. WARMING MARS

Methods for warming Mars may be divided into those relying on modifications to the atmosphere or climate, and those attempting to increase the insolation from space.

In the short term, comfortable temperatures could easily be maintained within domed greenhouse colonies — which might ultimately be extended to roof over the entire planet. This has suggested to some authors that if the greenhouse effect of the Martian atmosphere can be sufficiently enhanced, the planet as a whole might be similarly warmed.

Techniques involving albedo modification, the impact of ice asteroids, or the release of artificial greenhouse agents (such as CFCs) have all been proposed [2-4, 6, 9], but in general appear inadequate, uncertain, costly, or slow.

Since the natural insolation of Mars is only 43% of Earth's, the feasibility of a stable planetological terraform must be in doubt (unless the planet itself is moved nearer the Sun). Although a life-bearing Mars may be able to avoid runaway glaciation, it is unlikely that fully earthlike conditions would persist without intervention. There would therefore seem small reason to refrain from the deployment of solettas capable of affording inexpensive climate control from space.

3.1 Warming Mars by Soletta

A large mirror or soletta, positioned in space between Mars and the Sun near the Lagrangian L1 point, could augment the mean insolation and warm the planet to any desired degree. Such solettas, utilising dynamic support techniques [17-20], are discussed further in refs 1 & 15.

Manufactured in space from lunar or asteroidal resources, the soletta would consist of solar sail material—aluminised film of areal density $\sim 3\times10^{-4}\,\mathrm{kg\,m^{-2}}$. To match Earth's insolation, an area $\sim 2.5\pi R_{\sigma}{}^2 \sim 9\times10^{13}\,\mathrm{m}^2$ would be required, massing $\sim 3\times10^{10}\,\mathrm{kg}$ and costing perhaps 30G£. The sun's track and appearance would then differ little from on Earth.

Since the greenhouse effect would be amplified by the greater atmospheric scale height on Mars, it appears that augmenting the Martian insolation by as little as ~30% may suffice for the maintenance of Earthlike conditions.

3.2 Inadequacy of Warming for Volatile Release

However, although a magnifying soletta will rapidly raise the surface temperature of Mars to ~290K, the temperature of the regolith or soil will lag far behind. Based on a thermal conductivity $\sim 1\,\mathrm{Wm^{-1}K^{-1}}$ and a heat capacity $\sim 3\,\mathrm{MJm^{-3}K^{-1}}$, we find that after a time τ the regolith is warmed only to a depth $\sim 3\mathrm{m}\sqrt{(\tau/\mathrm{yr})}$.

But to release a substantial fraction of the volatile inventory one would need to warm to depths ~3km, a process taking ~1Myr. Nor is it apparent that simple warming would by itself induce significant release of carbon dioxide, most of which is thought to be chemically bound in carbonate rocks.

Consequently, we must accept that mere warming of the Martian surface will not succeed (in an acceptable length of time) in liberating sufficient volatiles to re-form an atmosphere dense enough to breathe.

4 MARTIAN REGOLITH

4.1 History

In view of the lack of core samples and mineralogical surveys it must be admitted that the geological history of Mars is largely unknown. The limited evidence available has, however, permitted the derivation of a theory in which we may have some confidence, though many uncertainties remain [21, 22].

It is believed that in the distant past Mars possessed a dense greenhouse atmosphere containing some 5-10 bars of carbon dioxide. At that time Mars was warm and wet, with some 500-1000m of water available to form rivers, lakes, seas and shallow oceans. Geologically, the early Mars was not unlike present-day Earth. Many terraforming proposals are essentially attempts at recreating those primordial conditions.

It used to be assumed that the low gravity had allowed the Martian atmosphere to leak away into space, over the aeons. However, calculations now indicate that only a small proportion could have been lost this way. Instead, it would appear that, in the presence of water, carbon dioxide from the atmosphere combined with weathered silicate rocks, leaving deposits of carbonates at the bottom of the shallow seas.

As the initially widespread volcanic activity diminished, and mountains were no longer uplifted, the CO_2 atmosphere was no longer replenished from below. The shallow seas silted up, locking away water and carbon dioxide in the sediments. Sulphate and nitrate minerals were also laid down.

With the removal of carbon dioxide from the atmosphere, the global temperature fell, and runaway glaciation occurred.

Polar caps grew. Ground water froze into permafrost. Eventually, when most of the volatiles had been buried, only the thin-aired icy Mars of today remained.

Although the term regolith normally refers to surface material only, hereinafter it shall include the present regolith and the former regoliths — wherein we assume the volatiles to have been sequestered — down to depths ~5km.

4.2 Composition

According to current theory, the regolith now consists predominantly of sedimentary rocks containing an average ~10% by weight of carbonate minerals (ie ~5% CO_2) and ~20% by weight of water, with ~38% SiO_2, ~15% Fe_2O_3, ~5% Al_2O_3, ~7% MgO and ~7% CaO [23, 24]. These figures are highly uncertain and there is likely to be considerable variation from place to place. Only geological surveys *in situ* can be expected to provide significantly better data; it is recommended that such surveys be carried out as soon as possible.

It is reasonable to assume that the primordial Martian atmosphere may have contained some 300 mbar of nitrogen. If so, this has presumably been deposited in the form of nitrites and nitrates in the upper layers of the regolith.

Much of the water content is expected to be in the form of ground ice or permafrost (breaking surface at the poles), but at depth hydrates and hydroxides probably predominate.

The composition of the deep regolith is unlikely to correspond closely to that of the wind-blown surface sand and rocks, where prolonged exposure to ultraviolet light may have driven off most of the volatiles, breaking down the carbonates and nitrates into oxides or silicates.

4.3 Explosive Devolatilisation

After analysing the Martian volatile inventory in some detail, Fogg [8] concludes that simple warming is inadequate for the liberation of buried volatiles. He suggests that carbonate rocks may be devolatilised by meteoritic impact or by thermonuclear mining.

Although explosive devolatilisation is certainly feasible (he provides experimental evidence from underground thermonuclear tests), problems may include the number of high-yield devices required and the hazard to colonists already in residence. Moreover, if the carbonate minerals are widely dispersed, or the ore bodies small, high efficiencies may not be achieved.

More serious difficulties may arise in connection with reverse reactions like $CaO+CO_2+H_2O \rightarrow CaCO_3.H_2O$, which in a damp carbon dioxide atmosphere are likely to be rapid. An insufficiently powerful underground explosion will fail to breach the surface, whereas an overpowerful one will scatter quicklime through the air. Acid groundwater trickling back down through the pulverised rock may also lead to CO_2 reabsorption.

4.4 Devolatilisation by Regolith Vaporisation

Warming of the regolith to temperatures ~290K will not significantly change its chemical composition; the permafrost will melt, and small amounts of adsorbed CO_2 may be released. Further warming will drive off more of the adsorbed CO_2 and water vapour, but chemically bound volatiles will be unaffected.

Temperatures ≥1000K will produce glassy melts in which silicates predominate. Carbonate minerals will undergo thermal decomposition, through endothermic reactions of the form $CaCO_3.H_2O \rightarrow CaO+CO_2+H_2O$, evolving carbon dioxide gas and water vapour. Nitrates and hydroxides will also decompose, and water of crystallisation will be driven off. However, the limited thermal conductivity of the melt will still obviate the liquifaction of more than the top few metres of regolith in a reasonable time.

To expose new rock for devolatilisation we might again consider employing explosives. But the most direct method would appear to be simply to vaporise the rock, distilling it away and disclosing a new layer underneath.

Now most components of ordinary rock will be fluid by ~2000K and will vaporise in the range 3000-4000K. At these temperatures, the melt will consist mainly of oxides, with some pyrolytic decomposition to metals and semi-metals (especially iron and silicon) and consequent evolution of oxygen.

To vaporise the regolith, temperatures ~4000K and a heat input ~10MJ/kg are required. This includes a latent heat of vaporisation $\sim(83\text{J/mol})T_b \sim 4\text{MJ/kg}$ and a further ~4MJ/kg from the specific heat capacity $\sim 900\text{JK}^{-1}\text{kg}^{-1}$. The sensible heat of the decomposition products would come to ~4MJ/kg and therefore sufficient energy is available for pyrolysis (~6MJ/kg is needed to break down SiO_2 and Fe_2O_3 fractions).

Many of the more refractory elements, such as Iridium, Molybdenum, Platinum, Thorium, Tungsten and Uranium, will be left behind. However, they have high densities, and will therefore tend to sink to the bottom of the melt. They are also of relatively low abundance.

The most problematic component is Al_2O_3, which is highly refractory and resists decomposition up to ~6000K, yet is likely to be present to the tune of ~5% by weight. Some of it may evaporate as reduced aluminium, or in association with other oxides, but it is likely that most will be left behind in the melt (unless temperatures in excess of 5000K are employed).

Fortunately, alumina is quite dense (4.0 Mg/m^3 as compared to ≈2.0 Mg/m^3 for the new melt). We can therefore expect plumes of fresh molten rock to rise to the top, where the volatiles and less refractory fractions will distil out.

5. TECHNIQUES FOR REGOLITH VAPORISATION

In order to vaporise sufficient quantities of regolith material within an acceptable time, heat beams of suitably high power must be used. At a power level of $\sim 2.4\,L_{♂}$ or 5.3×10^{16}W (that is, 360W/m^2 over the Martian surface or 2.4 times the present solar radiation, equivalent to that which Mars would receive if repositioned in Earth's orbit), some 80,000 km^3 of regolith could be vaporised each year, amounting to ~1 tonne per square metre per year.

Various ideas for the heat beams might be considered, ranging from lasers to particle beams; the alternatives presented below appear to be the most suitable.

5.1 High Velocity Pellet Stream

A high-velocity pellet stream from a solar-orbiting light-sail windmill [19] could provide a tight beam of very high energy density, enabling arbitrarily high temperatures to be achieved, with excellent control over the heating profile. Beam intensities well in excess of 10^{20}Wm^{-2} are feasible.

It has been suggested [1] that a power capability $\sim10^{18}$W could be supplied for ~200G£. This is rather more than we need, but it is doubtful whether the capital cost of the windmill could be greatly reduced for lower power levels.

If a light-sail windmill has been fabricated for other purposes, such as the propulsion of interplanetary and interstellar spacecraft, it may be possible to buy $\sim5\times10^{16}$W of output for as little as ~10G£. This approach would then be highly cost-effective.

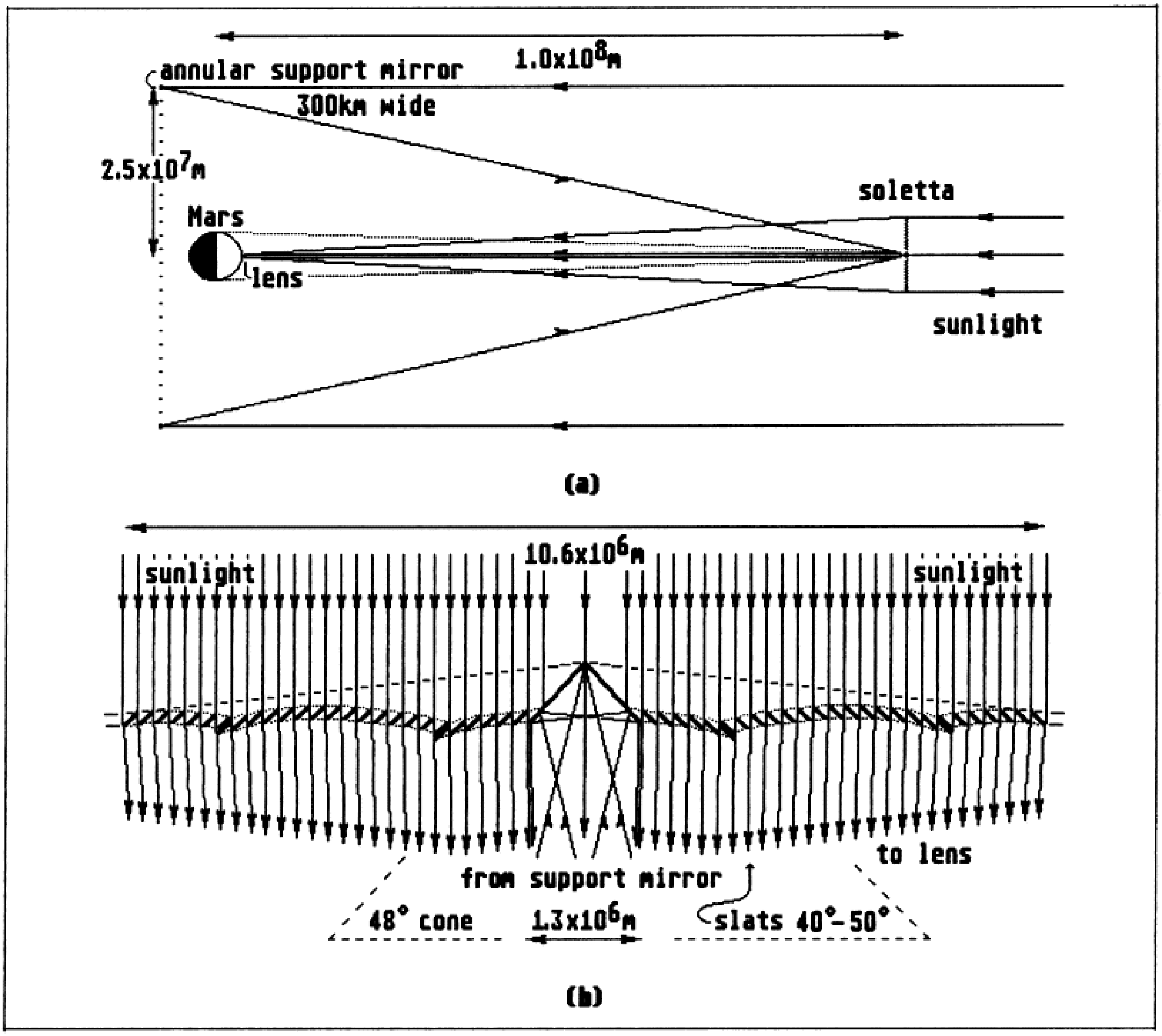

Fig. 1. Mars mirror system (a) Layout (b) Soletta geometry and light paths.

5.2 Soletta and Aerial Lens

A familiar method of obtaining high temperatures is by focussing the Sun's rays through a burning glass. On a larger scale, using a magnifying soletta and mirror lens (Figs. 1 & 2), this principle can be employed to vaporise the Martian regolith. This method has the advantage of utilising a soletta already needed for illumination after terraforming.

5.2.1 Soletta and Annular Support Mirror

The soletta (Fig. 1) can be placed 10^8m from Mars, between the planet and the Sun, and held in position by light reflected from the annular support mirror.

Constructed of solar sail material, reflective on both sides, the soletta comprises an inner cone of complementary half-angle 48°, and a series of annular slats tilted at approximately 40°-50°. The exact number of slats is not critical.

Light paths through the soletta are complex. First consider sunlight striking the inner cone. Reflected to the side, it is intercepted by the slats and redirected out along cones of half-angle 0°-13°, most of it missing the planet. The net photon thrust from this light, referred to the frontal area of the soletta, is a negligible 0.0001 units, where a mirror normal to the light receives 2 units, and 1 unit is approximately $2\mu N m^{-2}$.

Sunlight striking a slat is reflected to the next slat outwards, then onwards along almost its original path. Successive slats (nominally at 45°) are angled 0.2°-1.5° more steeply, deflecting the sunlight in to a focus just above Mars. The net photon thrust from this deflection is negligible (0.0007 units).

The outermost slat produces 1.65 units of thrust per unit normalised area; with ~10 complete cycles, the net thrust comes out at about 0.01 units.

Because the mirrors are imperfect and absorb some of the incident light, an additional photon thrust of about 0.05 units is generated (less than in ref. 1 because of the shallower incidence angles).

At an areal density of 3×10^{-4}kg m^{-2}, the weight of the soletta in a gravitational field of 4.3×10^{-3}m s^{-2} is equivalent to another 0.92 units of thrust. In all, the soletta must be supported against ~0.98 units of thrust (~165MN).

The soletta is supported by a *dynamic compression member* [20], utilising light reflected from an annular support mirror on the other side of Mars. The light strikes the reverse side of the inner cone, and bounces back towards the planet, which it illuminates with $\sim1.2L_{♂}$. The area of the support mirror is

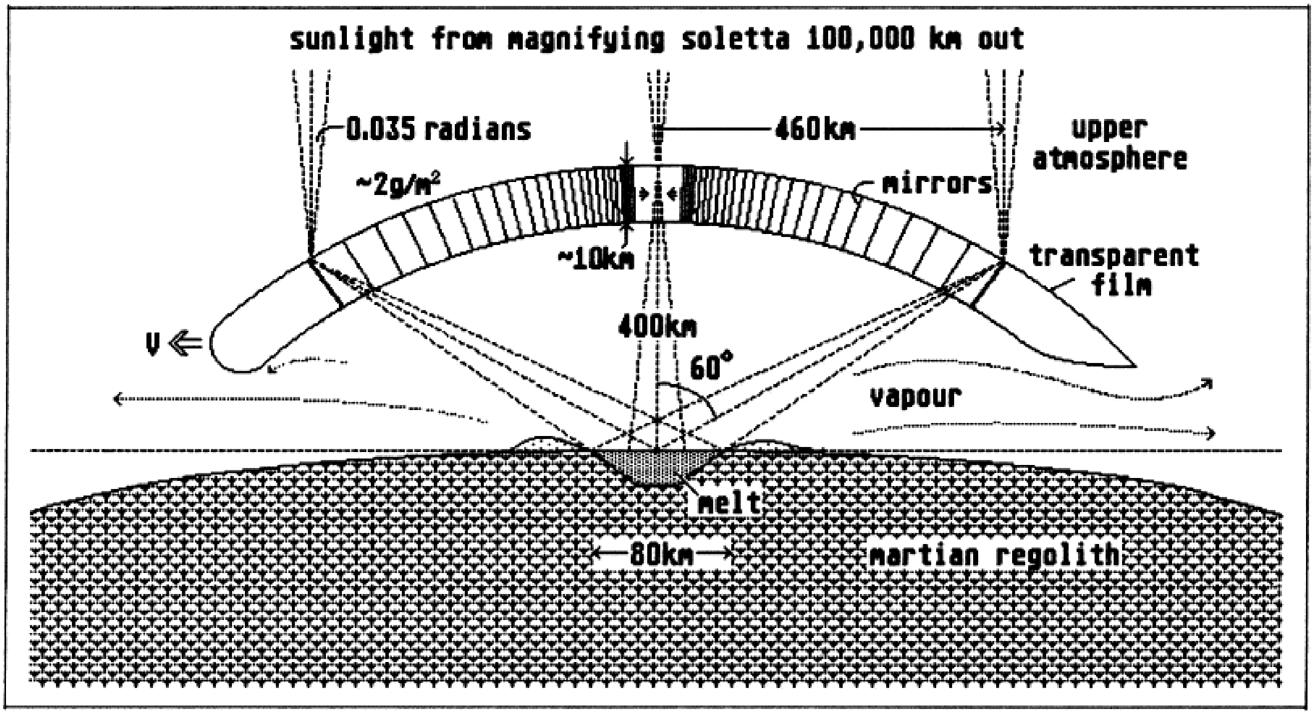

Fig 2. Aerial mirror lens and regolith melt. Lens motion would normally be at 90° to that shown, along the line of the canal.

about half the frontal area of the sunshade and its light produces the required net thrust of 0.98 units. The support mechanism is stable [1].

The annular support mirror is a strip 2.5×10^7m in radius and 3×10^5m wide, in a stable circular orbit whose plane is pushed back by light pressure through an angle $\sim17\frac{1}{2}°$. The orbital plane precesses once a Martian year.

The finite angular size of the Sun has been taken into consideration. At a distance of 10^8m, a spot size of 600km can be achieved; it is this which determines the size of the inner cone.

The distance of Mars from the Sun varies from 207Gm at perihelion to 249Gm at aphelion; the solar flux, angular size and light pressure vary accordingly. It will therefore be necessary to move the soletta back and forth in concert, between 0.91×10^8m at perihelion and 1.09×10^8m at aphelion, adjusting the slat angles to maintain the focus.

The total mirror area — including both soletta and support — is found to be $\sim 4.6\pi R_{\sigma}{}^2 \sim 1.7\times10^{14}\text{m}^2$. The mass is $\sim5\times10^{10}$kg and at $\sim1£\text{kg}^{-1}$ the cost may be $\sim$50G£.

If we add infra-red filters (transparent film with hexagonal grid metalisation) across the inner cone and increase the size of the annular mirror, in order to speed photosynthesis during terraforming [15], the cost may increase by $\sim$14G£.

5.2.2 Aerial Lens

Sunlight from the soletta must be further focussed by a lens ranging some 400 km above the Martian surface (Fig. 2). Since this is within the upper reaches of the Martian atmosphere, an aerial lens is used instead of orbital mirrors.

The lens is supported partly by aerodynamic lift ($L/W\sim0.1$), but mainly by the buoyancy of hot air trapped inside the lightly pressurised body and under the cup. At only $\sim2\text{g/m}^2$ (total mass $\sim1.5\times10^9$kg, cost $\sim$1.5G£) it will float at extreme altitude where the atmospheric pressure is $\sim10^{-7}$bar; even at the start of terraforming, this puts it over 200km up. Although far too flimsy to be assembled on the ground, or even to be allowed to descend into thicker air, it can be constructed using solar sail technology and dropped into the atmosphere from space.

At working altitude, aerodynamic and gravitational stresses on the lens structure (which is in tension) are well within the strength of the silica film (safety factor $\sim$20), being largely independent of areal density. Damping coefficients in roll and pitch are $\sim$10, and in yaw $\sim1/6$; ripples due to turbulence are also well damped. Flight Reynold's Numbers are $\sim10^6$.

The form of the lens approximates to a section of an 800km-radius sphere (rim $\sim$50km below peak), such that the radial annular mirror slats reflect incoming light directly to the focus. Although the slats are spaced proportionately closer towards the middle (the central $\sim$350m is left clear), the integrated mirror area is only four times the frontal area, contributing an areal density $\sim1.2\text{g/m}^2$ (this technique is inefficient for small angles of deviation and thus inappropriate for solettas). If the sun is not directly overhead, the slat angles can be adjusted and the slat axis rotated out of the vertical.

Since the soletta spot size is only $2/3$ the lens diameter, the soletta should actually be focussed to a point some 3000km below the lens (or else could be deployed half as far out again). Although the 80kWm^{-2} lens flux corresponds to a temperature $\sim$1000K, the lens itself should remain somewhat cooler.

On the ground, the solid angle subtended by the Sun's image is π steradians — half the sky — so the black body temperature could reach $\sim$5400K (or $\sim$5200K, including 15% losses through the soletta and lens). If the mean melt temperature is $\sim$3500K a further 20% will be reradiated, yielding an overall efficiency $\sim$66%. The core spot size is $\sim$30km ($\sim$80km at the margins).

The aerial lens holds station by riding on the flow of vapour that pours from the melt and spills out the sides. To keep pace with the rotation of Mars, or remain at the sub-solar point, it must surf along at $\sim$270m/s, a velocity readily achieved with a driving power of only $\sim0.02\text{Wm}^{-2}$, a tiny fraction of the flow kinetic energy (problems arise above Mach $\sim$0.85, but because of warming the local sound speed is likely to be $\gtrsim$500m/s).

As the lens moves along, a valley up to $\sim$10km deep is scored into the regolith. During the $\sim$330s beam passage (at 270m/s) a layer $\sim$16cm thick across the core is vaporised; at the beam edge only the volatiles escape, while the rest slips in towards the middle. This can be repeated at daily intervals.

The volatile fractions—mainly oxygen, nitrogen, carbon dioxide and water vapour—flood away under the lens rim. As the water vapour then rains out, it removes most of the residual dust and noxious oxides (NO_X, SO_X, ClO_X, etc) from the atmosphere.

Nonvolatile fractions of the vapour recondense rapidly, raising hills of glass and native metal alongside the melt. In this form they are protected from recombining with the volatiles. The flanking hills then constitute a barrier to the rain and melted ground water that might otherwise flow into the canals; during terraforming this will keep the uplands wet and prevent unnecessary loss of heat from the melt.

Any distillate deposited on the undersurface of the lens will weigh it down and obscure the sunlight. Although the problem is ameliorated by floating the lens at an altitude even dust cannot easily reach, a complete solution may require the introduction of a layer of clean air between the efflux and the lens.

The spot size can be reduced from ~80km by employing only the inner portion of the lens, or by partly defocussing the soletta. In the soletta's absence, the lens forms a pencil beam ~3km in diameter, enabling relief to be sculpted into the barrier hills, diminutive deposits to be worked and narrow water courses dug.

Throughout the process of devolatilisation, colonies situated more than 100km or so away from a melt site will remain habitable. Although domes could survive closer in, they would soon become coated with condensing rock — or even buried.

5.3 Choice of Devolatilisation Sites

Before devolatilisation can proceed, the first requirement is for exploratory boreholes to be drilled at intervals across the surface, enabling the most convenient deposits to be located. A million 10km-deep holes 15km apart on a hexagonal grid will greatly improve our knowledge of the Martian geology (extra boreholes can be sunk in locations of special interest). For this purpose, conventional diamond cores (~5cm diameter) seem less suitable than much finer bores drilled by high-intensity electron beams, which would permit continuous analysis of the vaporised rock. Costs ~10G£ are to be expected.

Prior to terraforming, we should place heavy emphasis on scientific studies of the undisturbed Mars, especially where regolith is to be destroyed. However, even afterwards, ~99% of the crust will remain unmodified, for the attention of future researchers.

It is suggested, mostly on aesthetic grounds, that regolith excavations should in the main form continuous valleys rather than isolated pits, ultimately furnishing a pleasing network of canals and flanking littorals instead of disconnected inland seas. Isolated pockets could be joined up via relatively constricted or shallow channels.

Let us examine a range of possibilities, based on a heat input of 5.3×10^{16}W, vaporising one tonne of regolith per year per square metre of the Martian surface. Since 240 mbar is equivalent to 6.4 tonnes of oxygen per square metre, the devolatilisation time $\tau \sim 6.4/\mu$ years, where μ is the mass fraction of oxygen liberated.

In a nominal worst case, with no net pyrolysis of iron or silicon oxides, no nitrates, and only the average concentration of carbonates in the regolith (10%), the liberated oxygen mass fraction $\mu \approx 0.035$ and $\tau \sim 180$yr.

Including the pyrolysis of iron oxides, $\mu \approx 0.08$ and $\tau \sim 80$yr. Complete pyrolysis of the silica also (not likely for the solar furnace) would give $\mu \approx 0.28$ and $\tau \sim 23$yr.

The pyrolysis of pure iron ore would yield $\mu \approx 0.30$, $\tau \sim 21$yr. Pure anhydrous carbonates would theoretically yield $\mu \approx 0.35$ and $\tau \sim 18$yr; in practise some water is sure to be present.

Sulphates, if as abundant in the regolith as in the topsoil (~6.5% SO_3), may add ~0.04 to μ indirectly: as the liberated sulphuric acid rains out, it will free additional carbon dioxide, converting carbonates in the ground to sulphates. Nitrates add to μ directly.

In the nominal best case, with high purity nitrate deposits of $Mg_{0.5}Ca_{0.5}(NO_3)_2.5H_2O$ yielding $\mu \approx 0.33$, we find $\tau \sim 19$yr. In fact, devolatilisation would proceed even faster, down to as little as ten years, since only about half the nominal 10MJ/kg would be required.

Because strongly differentiated deposits, including carbonates, nitrates and iron ore, probably do exist in the Martian regolith [25], one could expect to improve markedly upon the worst case quoted above.

Insofar as is practicable, effort should be concentrated first upon the nitrate beds, next on the iron ore, and then on the carbonates. All have devolatilisation periods of order twenty years. Heating inefficiencies may increase this to around thirty years; then with an allowance for gangue minerals and impurities a top figure under fifty years seems assured.

6. OXYGEN

On Mars, a breathable atmosphere will require ~240mbar of free oxygen. If the oxygen is liberated through the pyrolysis of regolith oxides or nitrates no further action will be required. However, any excess carbon dioxide will have to be converted into oxygen by photosynthesis, a comparatively slow process.

6.1 Photosynthesis

On Earth, certain grains are known to fix 50 g m^{-2} day^{-1} (an efficiency ~8%) under optimum field conditions [11, 14]. Similar rates could be achieved on Mars, where the abundance of carbon dioxide will compensate for the reduced insolation. The replacement of 330 mbar of CO_2 by 240 mbar of oxygen would then take ~140 years. This is longer than the ~30 years suggested for Venus [1] because the weaker gravity makes the atmosphere over twice as thick, and there is less sunshine.

Planetary insolation can be increased, without undue warming, using infra-red and ultra-violet filtered sunlight [15], which more than doubles the photosynthetic efficiency.

Also, the reconsumption of oxygen by growing plants can be inhibited by directing extra sunlight towards the back of the planet from another annular mirror, for 24-hour illumination.

Photosynthetic transformation of the atmosphere (under a mean flux ~350Wm^{-2}) can be accomplished within ~8.6yr/$\bar{\eta}$, where $\bar{\eta}$ is the averaged photosynthetic efficiency. However, it is doubtful whether this level of insolation (equal to Earth's) can be permitted, because of the excess heat during devolatilisation, and the powerful greenhouse effect afterwards.

The efficiency of reed beds, algal ponds or tented farmlands can be very high ($\eta \sim 20$% for filtered sunlight), but achieving the same productivity over open terrain will not be easy.

However, terraforming is an engineering process, radically different from the natural functioning of the terrestrial biosphere. Setting $\bar{\eta} \sim 0.1$% (as on Earth) would be a gross error — much greater productivities are to be expected. Distinctive features include: abundant CO_2, surface water, nitrates and other nutrients (permitting extensive eutrophic lakes); absence of animals, pests, heterotrophic organisms or other competitors; control of climate; use of only the most productive strains and species. Lack of space precludes more detailed argument.

A modest $\bar{\eta} \sim 5$% (equivalent to $\bar{\eta} \sim 2$% unfiltered) under ~$1.3L_{\sigma}$ (filtered) allows the photosynthesis of ~66 mbar of CO_2 concurrently with devolatilisation, over ~60 years.

6.2 Pyrolysis

It will be to our advantage to generate as much of the atmospheric oxygen as possible by the rapid pyrolysis of oxides and nitrates. Since the abundance of iron oxides, silica and silicates in the Martian crust can hardly be doubted, oxygen will be available from this source even if the regolith model is invalid and carbonate rocks are rare.

The principal uncertainties are the extent of nitrate deposits and the degree to which vaporised iron and silicon will tend to recombine with the liberated oxygen. Various heating profiles can be explored, such as flicking the beam rapidly back and forth, or gradually bringing it to full strength to allow the volatiles to escape before the more refractory components are distilled away.

It is probable that the considerably higher temperatures afforded by the impact of a high-velocity pellet stream would promote greater efficiency in pyrolysis, as well as providing greater control over the heating profile.

7. NITROGEN

It does not appear that more than ~300mbar of the ~760mbar of nitrogen in an Earth-normal atmosphere is available on Mars. Moreover, it is likely that only a fraction of that 300 mbar will actually be liberated.

At best, even with deposits of pure nitrate to be devolatilised and vaporised, over twice as much oxygen as nitrogen will be produced ($M_x(NO_3)_2 \rightarrow M_xO + N_2O_5 \rightarrow M_xO + N_2 + \frac{5}{2}O_2$).

Because nitrates are much more soluble than carbonates, and somewhat more soluble than either sulphates or chlorides, they ought not to have been deposited from the Martian seas until after the other minerals. We might therefore expect to find them close to the surface (*eg.* within the top kilometre) in the last surviving sea beds.

If such high-purity deposits exist, devolatilisation (liberating ~240 mbar of oxygen in a remarkably short time ~10 years) would yield a nitrogen partial pressure ~84 mbar.

However, bringing the nitrogen content up to terrestrial levels would necessitate its importation from extra-martian sources, such as Venus or the outer planets.

Unfortunately, this is likely to be expensive: although up to ~100 mbar might arrive as ammonia impurities in the raptured icemoon Hyperion (section 8.2), making up the full 760 mbar by orbital ring transport at ~10p/tonne [1, 15] would cost ~200T£. Moreover, large-scale nitrogen export from Venus [1] is not expected to commence until long after the completion of terraforming on Mars. Importing from Titan, which though smaller than Venus has copious supplies of nitrogen, may be slightly cheaper. Even so, the price seems excessive when set against the thousand-fold smaller cost of devolatilisation.

It is therefore worth considering whether or not this amount of nitrogen is truly essential. It would appear that it is not. Let us consider what part nitrogen plays in our atmosphere.

First, plants need nitrogen for growth. Many obtain it from nitrogen oxides, created by lightning and washed from the air by acid rain (the ecological utility of which is all too often neglected), others from nitrogen-fixing bacteria. Neither process demands a high concentration: in *Beijerinckia lacticogenes* nitrogen fixation can occur at partial pressures at least as low as the 0.3 mbar that obtains on Mars today [5], just as carbon fixation can occur on Earth with under 0.5 mbar of CO_2.

Second, the nitrogen diluent acts as a fire retardent (as does the carbon dioxide and water vapour). But on Mars the low density of the air and the low gravity will weaken convection and inhibit the spread of fire.

A terraformed Mars low in nitrogen might suffer more from forest fires than Earth, enhancing the geographical distinction between arid tablelands and humid canal zones — though during devolatilisation even the uplands should be quite wet. But fire would be a major hazard only within the colony domes, where an Earth-normal atmosphere could easily be maintained.

Third, nitrogen adds to the density of the air, bolstering the wind, aiding birds in flight, and assisting us in speech, in song, and in coughing. Again, maintaining an Earth-normal atmosphere within the colony domes would avert any difficulties. For aeroplanes — and birds in the wild — the lower density would be directly offset by the lower gravity.

On balance, we should endeavour to release as much nitrogen as possible from the regolith (up to ~100 mbar from nitrate deposits); but the importation of additional supplies is believed to be unnecessary and hence unlikely to be cost effective.

8. WATER

On a terraformed Mars the atmosphere would contain ~30cm equivalent of water vapour (three times more than on Earth or Venus because of the lower gravity and increased scale height), which can easily be supplied from the polar icecaps.

To allow for the establishment of a water table, along with running rivers and shallow lakes, a further ~10m of water would perhaps be needed.

More copious supplies would permit large areas of deep open water. But the planetary engineers will probably not demand amounts in excess of ~100m, since there seems little point in attempting to duplicate Earth's vast oceans on Mars.

8.1 Water from Martian Sources

The amount of water present on Mars today is not well established. However, it seems probable that up to ~1000m of water is available in the regolith, while the polar icecaps may contain up to ~15m. The quantity of water vapour in the Martian atmosphere is currently negligible (~10μm).

Water from the polar icecaps can be released without difficulty by warming. A similar amount (~10m), held as permafrost in the upper regolith, is expected to thaw within a period of about a century.

Additional regolith water will be released during the process of devolatilisation (principally intended for the production of a breathable atmosphere). The mass fraction for water is then likely to be a little greater than for the liberated oxygen. Devolatilisation will thus liberate ~10m of water, sufficient to fill the major canals to depths ~500-1000m, over ~30km in width.

If frozen lakes from the early Mars still exist beneath the drifts of sand they too could be freed by torching through the top burden and boiling them out.

8.2 Water from Extra-Martian Sources

If current estimates of the Martian water inventory are grossly in error, other sources might be considered [1, 15].

Hydrogen from the outer planets would yield water at a cost ~5p/m^3, a price possibly excessive for planetary oceans. Water transported from the outer planets' moons by orbital ring would be similarly priced [1, 15].

The icemoon Hyperion could provide ~100m of water (plus maybe 100mbar N_2) on Mars (the larger icemoon Enceladus is booked for Venus). Its gravity-assisted rapture [1] might be accomplished at ~100-200G£ with a steam rocket powered by a solar mirror or a solar-orbiting light-sail windmill [19].

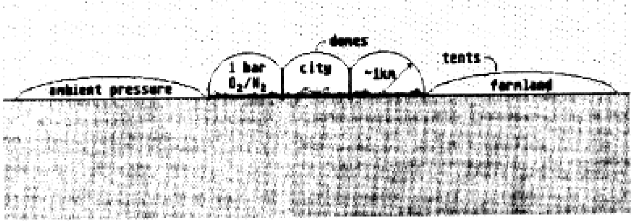

Fig. 3. Domed city colony on Mars

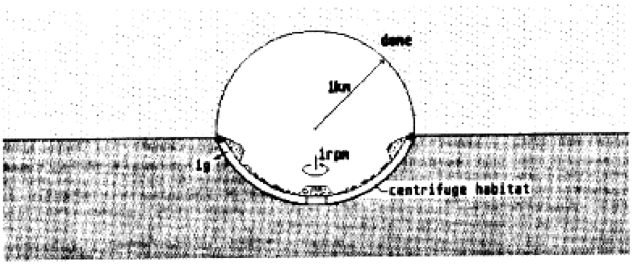

Fig. 4. Surface centrifuge within dome city.

Reaching Mars via gravity-assist passes of the inner planets the icemoon would strike at ~6km/s, producing temperatures ~1000K (on a direct trajectory from Jupiter it would strike at ~25km/s and lose much of its mass back into space).

The atmosphere would then contain ~4 bar of water vapour, starting to condense at ~150°C; the precipitation of ~100m of water would then take four or five years, during which time the climate would not be hospitable.

Icefall could be mitigated by dividing the moon into pairs of moonlets colliding just short of the planet every 343 days [1]. A reflecting canopy for the whole planet, as protection from the flash, would cost ~2T£ [1]; but protection for the domed colonies alone would be much less expensive.

With only ~3% of the icemoon introduced into the atmosphere at one time, condensation would commence at ~45°C, with ~3m of water precipitating in ~210 days. Although the climate might be very hot and humid, it would not be unbearable.

8.3 Water Bodies on Terraformed Mars

Water will drain from the uplands and melting icecaps into the canal valleys, cascading down to the sea through chains of broad lakes and sweeping falls, filling the main canals to depths ~1km. The canal sea, containing ~10m equivalent of water, will then cover ~2% of the planet's surface. Lakes may also form in the Martian craters, and shallow seas (which may or may not connect with the canal network) in the lowlands. Glaciers and snowfields will form on the mountains and in the polar regions. Rivers and streams will abound.

9. GEOTHERMAL POWER

After terraforming, the local demand of the Martian colonists for heating and electricity can conveniently be met by geothermal power, derived from the super-heated rocks along the new canals. Although a solid crust will quickly form, magma reservoirs from the recondensed rock and the original melt will persist for many thousands of years.

Water (or steam), forced at high pressure through pipes within this hot mass, can be heated to ~1000°C and allowed to expand through turbines, generating electricity at efficiencies ~50%; and then can be recycled after recondensing.

Heat transfer rates are found to be up to ~1kW/m, and a suitable pipe diameter is ~10cm. If we consider a population reaching ~5×10^9, requiring ~1kW of electricity and ~1kW of heat per person, then we shall need ~10^{10}m of piping.

Because drilling out half-molten rock may be troublesome, it may be better to make a start before regolith vaporisation by laying a network of interconnecting icefilled plastic tubes just above ground level (at a cost ≲1G£), then allowing the rock to recondense around them.

If geothermal power is extracted at the rate of ~10^{13}W, the heat store of ~2×10^{25}J can be expected to last for ~50,000 years. The Martian colonists can thus be provided with a long-lasting local robust source of power at minimal additional cost.

10. COLONIES ON MARS

The colonisation of Mars can begin at once, without waiting for terraforming to be undertaken, as it would not be difficult to build the Martian cities under large transparent domes (Fig. 3). This greatly improves the economics of terraforming.

A problem with such dome cities on Mars, by contrast with tent colonies on Venus [1], is the necessity to contain the Earth-normal internal atmosphere, the full pressure of which corresponds to a 10-20m thickness of Martian soil.

Simply heaping soil around the edge is unlikely to be effective and a construction similar to the domed aerial colonies of Venus [1] may be more suitable. However, an altogether more massive structure is required, with dome material ≳10cm thick.

For cities larger than a kilometre radius a plurality of domes may be butted together. If the domes are allowed to overlap a more open structure results (Fig. 3), in which the domes are connected by archways 500m high, merging at the base in 15m diameter columns.

The kilometre radius of a dome is sufficient to permit the construction of a 1g/1rpm centrifuge. Supported on liquid or magnetic bearings, it could be situated beneath the city and entered at the hub, or (as in Figure 4) placed within a dome, on the surface. Many daily activities, including schooling, physical exercise and defecation, could then be carried out under full gravity.

In principle, the original domed cities might be extended into expansive colonies, eventually roofing over the whole of Mars. This would have the not-inconsiderable advantage of reducing the amount of atmosphere required by a factor ~25 (for a 1km headroom), but would leave us with an artificial environment offering few advantages over rotating space habitats.

Consequently, it seems best to restrict these high-pressure domes to the Martian cities themselves. Farmlands surrounding the cities could usefully be covered with an unpressurised and inexpensive tent, within which temperature, humidity and $O_2/N_2/CO_2$ levels could readily be controlled.

With an average height ~1km the cities would contain ~250kg m^{-2} of oxygen, which photosynthesis could replace from farmland of ten times the radius in ~20 days, under Martian conditions (*cf.* ref. 1).

The CO_2 partial pressure can be maintained at ~15mbar in the farmlands, where it will encourage high yields and rapid photosynthesis, but in the city the concentration should be low, ~0.1% (~1mbar). In the absence of any internal source of carbon monoxide, its concentration will also be low, ≲0.1ppm.

As terraforming proceeds and the atmospheric pressure increases, the composition of the air inside the tents can be modified — maintaining the desired CO_2 partial pressure and allowing the proportion of oxygen and nitrogen to rise. Finally, when photosynthesis brings the planetary CO_2 level down to ~5%, the tents could be abolished.

Because of the shortage of nitrogen diluent, it will however be appropriate to retain the domed cities after terraforming and to allow subsequent residences to be similarly pressurised.

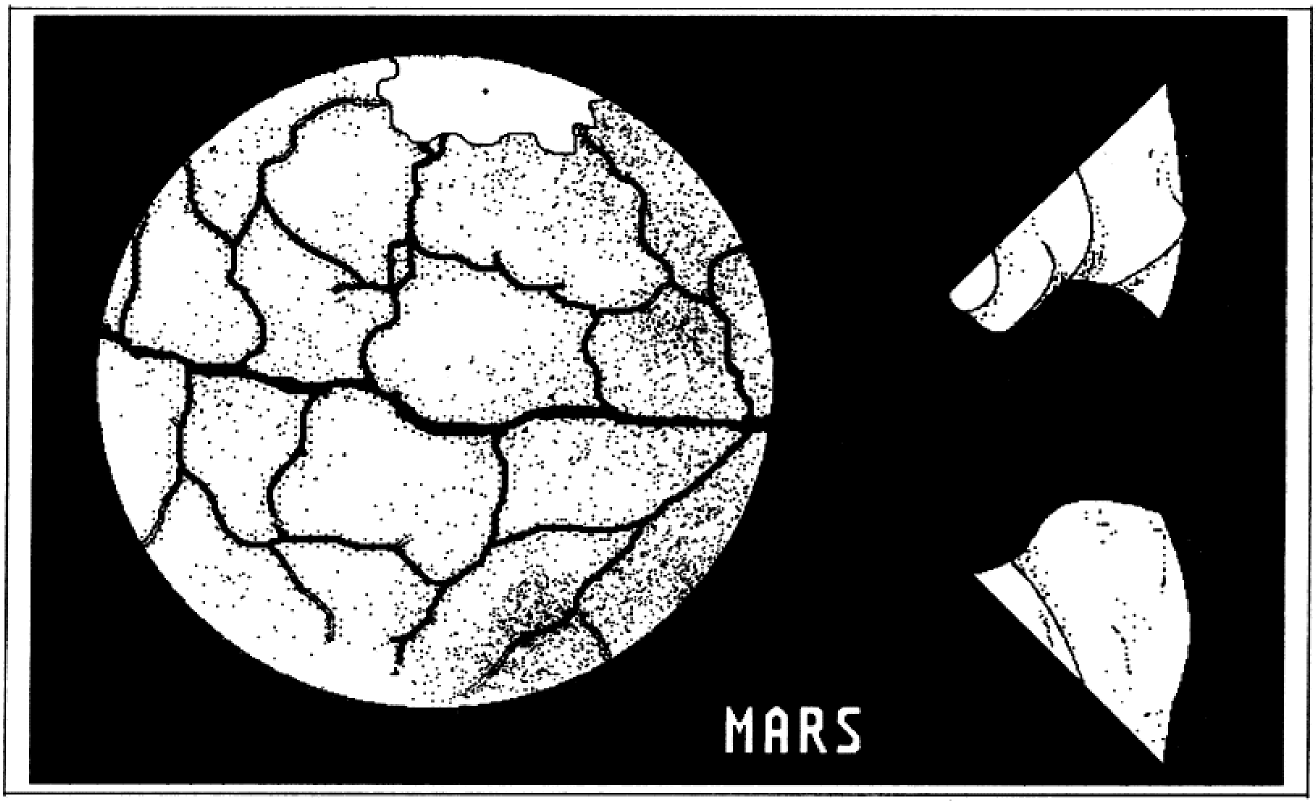

Fig. 5. Mars after terraforming, showing the canals scored into the regolith during devolatilisation.

11. THE NEW MARS

The end result of the process of regolith vaporisation will be a new Mars (Fig. 5), embracing a network of deep canals, scored several kilometres into the crust and flanked by kilometre-high chains of glassy hills. Away from the canals will lie the high deserts, the tablelands, the mountains.

During devolatilisation the barrier hills will prevent the upland rivers from draining into the canals. Afterwards, gaps can be melted through at intervals. Where the canals peter out – especially towards the poles – they can be opened out into the surrounding wilderness.

Because terrestrial geography has no close equivalents, we may call the canals and valley floors the *handramit*, and the uplands – the old Martian surface – the *harandra* [16].

It is in the *handramits* that most later settlement will take place, once the melted crust has been pierced and the exposed regolith broken down into topsoil. Fertile lowlands, reaching perhaps 25km on either side of the ~30km wide, ~1000m deep canal, will shade off into the gaunt barrier hills, then into the wide lonely *harandra*.

The number of canals (and their depths, lengths and breadths) will depend upon the distribution of volatiles and the volume of regolith vaporised: for devolatilisation over 50 years at $2.4\,L_{\sigma}$, scouring the canals to an average depth of 2km but making use of existing depressions like the *Valles Marineris*, the total *handramit* area (~40% as open water) comes to $\sim 3\times10^6\,\text{km}^2$ (~2% of the Martian surface), supporting up to 3×10^9 people at a population density similar to that of lowland UK.

The canal network may then comprise some 20,000km of roughly 80km-wide equatorial *handramit*, plus similar lengths of connecting *handramits* of progressively smaller widths down to a few kilometres, perhaps 120,000km in all.

By earthly standards, the air will be thin, even in the deep *handramits*; but fires will burn fiercely, with a bright core and little flame; birds will soar on updrafts from the valley walls or thermals over the *harandra*; and winds will blow down the gorges, raising waves like earthly waves upon the open water. Notwithstanding the lower gravity, mountainous seas will be rare, for in ascribing precipitous shapes to water waves in low gravity fiction-writers [16] are mistaken.

In the *handramits* the climate will be temperate or tropical, but on the exposed *harandra* it will be continental – ranging from arctic tundra to arid deserts. The climate of lowland basins, such as Hellas, which may suffer extensive flooding, will be of an intermediate or sub-tropical nature.

High-latitude *handramits* will face the sun, with steep north walls and shallow south slopes (in the northern hemisphere). Snow melt will cascade down to them from the cold *harandra*, and on through the network of canals to the equatorial sea.

Now greenhouse temperatures may be approximated by:

$$T \approx \left((Q/\sigma)(1+2\tau) \right)^{1/4}$$

where Q is the flux reradiated from the surface, σ the Stefan-Boltzmann constant and τ the optical depth. On Mars, $\tau \sim 0.10$ (for 10mbar CO_2) plus $\tau \sim 0.84$ (for water vapour at a surface temp. of 10°C, roughly doubling with every 10 degrees rise).

If the terraformed Mars received the full terrestrial insolation of $\sim 2.3\,L_{\sigma}$ the climate would then become unduly hot, with a greenhouse increment ≥76K compared to only ~33K on Earth; a hothouse runaway is likely. The deployment of infra-red filters can bring the net flux down to $\sim 1.3\,L_{\sigma}$, while maintaining the *visible* illumination at Earth levels. Even so, climatic variations must be evened out by defocussing the soletta so that sunshine is diverted from the subsolar point towards the planetary rim.

Without the soletta, the overall climate would be very cold; even at the equator the *harandra* temperature would fluctuate around freezing point, with bitter nights and harsh winters. However, the equatorial *handramits* would apparently remain habitable and runaway glaciation would probably be avoided. The existence of seasonal tundra vegetation would have a major beneficial effect, reducing the albedo and encouraging the arctic snowcover to thaw under the summer sun.

12. SCENARIO

A complete scenario for the terraforming of Mars can now be presented, choosing from amongst the techniques investigated above. For definiteness I insert actual dates into the scenario, assuming that terraforming commences in 2020 (earlier than for Venus [1], but the technology is much less demanding and the costs lower). Almost from the outset the project can be funded from its own revenues and most of the work is accomplished by ~2080.

2010 Planning, design and research phase. The first Martian settlements are planted and the building of dome cities is begun. Explorative boreholes are drilled into the crust. Scientific work on the undisturbed Mars must be concluded during this period.

2020 Terraforming begins. On Mars, geothermal piping is laid along the route of the planned canals. In orbit, construction of the soletta, support mirror and aerial lens takes place.

2021 The magnifying soletta is deployed and the aerial lens dropped into the atmosphere; vaporisation of Martian regolith and excavation of the canals commences. The rest of the planet is continously illuminated with $\sim 1.2 L_{♂}$ (IR & UV filtered for maximum photosynthetic efficiency). Geothermal power becomes available from the buried piping.

2022 Selected species of plant life are distributed over the Martian surface; photosynthesis will generate up to 20% of the required atmospheric oxygen from CO_2 over the next 58 years. Continuing devolatilisation causes a progressive rise in atmospheric pressure and planetary temperature.

2070 Devolatilisation complete. Infra-red filters are added to the soletta, which is moved back and refocussed to give a net insolation $\sim 1.3 L_{♂}$. The canals fill with water; exposed regolith is broken down into topsoil.

2080 The atmosphere, although thin (~330 mbar), is fully breathable; the climate is Earthlike. Settlements spring up along canals now bordered in vegetation. Terraforming is complete.

TABLE 1: *Summary of Costs and Benefits*

DATE	EXPENDITURE	INCOME	POPULATION
2010	~ 10G£	—	$\sim 2.0\times10^4$ (1)
2020	~ 65G£	~ 2G£	$\sim 2.0\times10^5$ (2)
2021	~ 10G£	~ 5G£	$\sim 3.0\times10^5$
2022	~ 10G£	~ 10G£	$\sim 5.0\times10^5$
2030	~ 20G£	~100G£	$\sim 2.5\times10^6$
2040	~ 75G£	~375G£	$\sim 1.0\times10^7$
2050	~250G£	~ 1T£	$\sim 3.5\times10^7$
2060	~250G£	~ 1T£	$\sim 6.0\times10^7$
2070	~400G£	~ 2T£	$\sim 1.0\times10^8$
2080	~ 1T£	~ 10T£	$\sim 2.0\times10^8$
TOTAL	– *2.1T£*	+ *14.5T£*	= *12.4T£ net.*
TOTAL(3)	– *5.7T£*	+ *23.6T£*	= *17.9T£ net.*

(1) In orbit & temporary accomodation. (2) In dome colonies (3) Effective total with interest at 4.8% per annum.

13. CONCLUSIONS

We have seen that, with the employment of appropriate techniques, it will be possible to terraform Mars both quickly and economically (Table 1). The profitability of the project becomes even more apparent when we realise that most of the expenditure is allocated to the building of settlements — money that would have to be spent wherever the colonists chose to live. Actual terraforming expenditure is only ~85G£.

Because of the low gravity and the shortage of nitrogen, the final state will not be entirely Earthlike. Accordingly, the planet cannot be recommended for lifelong residence.

Nevertheless, in the untoward event that Mars were to be cut off from the rest of Mankind, there is reason to believe that the planet would remain inhabitable indefinitely — at least for a hundred thousand years and perhaps for gigayears. The loss of the space-based soletta would render the climate uncomfortable, but not unendurable.

Both the habitable and planetological terraforming of Mars have therefore been satisfactorily described and their purpose amply justified; the terraformed planet would be an attractive and distinctive habitat, a fulfillment of the popular myths.

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