Chapter 6

The Terraforming of Mars

Now the new gases of the planetoid
Burst into flame with Mars's native air;
A firestorm rages round the globe, as blue
As hydrogen balloons set on a flare;
The funguses, which briefly ruled this world,
Burn to a fertile ash; a great cloud forms;
Last, out of skies as black as Noah's flood
Falls the first rain that Mars has ever known.

Frederick Turner

6.1 Problems with a Popular Paradigm

It is true to say that the runaway greenhouse model of Martian terraforming, dating as it does back to the early seventies, represents a sort of "standard paradigm" — a framework in which the most influential and cooperative studies of the problem have been conducted. Alternative approaches exist, but these are almost exclusively the work of isolated researchers. The standard paradigm therefore is also the most popular one, receiving the largest share of publicity and media attention.

This enthusiasm is perhaps not too surprising as the model promises much — a habitable planet in a period as short as a century — for the cost of a planetary engineering effort involving mass and energy fluxes of which present day civilization is more than capable. The notion that it might be possible to transform the Martian climate by merely tweaking the planet's environmental parameters, so that free solar energy runs away with the process, not only greatly reduces the amount of planetary engineering that might be involved but also helps to head off any criticism concerning, man's interference with nature. Returning Mars to a state that was once natural to it, however long ago, will obviously be easier to sell than a wholesale anthropocentric restructuring of the planet into an image of something it never was [1]. In its most optimistic guise therefore, the Runway Greenhouse model offers a vision of a near-miraculous Martian genesis, triggered by a modest and benign human intervention, untainted with that flavour of the homocentric technical fix that Lovelock finds so distasteful [2]. One can therefore be a planetary engineer whilst simultaneously keeping one's "green" credentials intact. One can argue for ecopoiesis as being a creative act for life as a whole, rather than for man in particular.

Such an awesome concept is naturally attractive to popular science writers. However, since the job of such people is to entertain as well as inform, scenarios presented to the public therefore often portray Mars being *fully* terraformed within a century, i.e. made habitable for higher organisms as well as bacteria [3,4]. Such timescales are unsupported by calculation, or based on unlikely assumptions and are most definitely *not* predicted by the work that is being reported. However what such coverage demonstrates is that, although the rapid "greening" of Mars is exciting in itself, what the public *really* wants to hear is that we can make Mars into a new Earth.

Views about the nobility of taking life out into the Universe are all well and good; however, it is not unreasonable to suppose that future planetary engineers will have a more personal stake in terraforming, if not for themselves, then for their descendants. Societies who invest in terraforming may therefore find themselves in a position of not just having to justify it scientifically and aesthetically, but *economically* — in a way that makes sense to *people*.

Thus, the standard paradigm and its associated ecocentric philosophy is open to criticism as an overall vision of the future and, as was hinted in the last Chapter, the success of the runaway greenhouse mechanism is also far from guaranteed. We examine these difficulties further below from a more anthropocentric viewpoint and then look at whether there exist alternate paths that might permit a more complete terraforming of Mars.

6.1.1 Practical Limitations of Ecocentrism as Applied to Mars

Terraformed planets as life-support systems were discussed in Chapter 2. Their potential qualities of autonomy and stability and their provision of a large, *gratis* energy flow, render them the most suitable long-term locales for extraterrestrial civilization. In Section 2.7.5, it was suggested from ecological arguments that *gratis* life support can be accorded an *economic* value in the sense that it represents energy flow which does not have to be manufactured or subsidized by technological means. It is valid therefore to pose this question: assuming the runaway greenhouse scenario works and that planetary engineering ceases after ecopoiesis, how do Martian colonists benefit from the new biosphere?

A comparison of the energy flow to a civilization on Mars in the two cases of ecopoiesis and terraforming is shown in Figure 6.1. (The life-support model in this case is simplified, emphasizing ecosystemic energy flows [5]; not illustrated, but implicit, are subsidies from weather and hydrological cycling and the capture of energy for electrical power generation; greater detail can be found in Figures 2.7 and 2.15).

Figure 6.1a illustrates the scenario of ecopoiesis, described in the last Chapter, in which minimalist methods of planetary engineering have produced an environment suitable for microorganisms and primitive plants. Atmospheric pressure is now ~ 1 bar and consists of almost pure CO_2. Average global temperatures are above freezing but the planet remains largely dry, being moistened only where water, melted from permafrost or the caps, has collected at the surface. Mars is a slowly thawing anaerobic desert and will stay this way, for a long time into the future, without further technological intervention (see Section 6.1.2). Even so, energy can flow through a biosphere on a *global* scale — a phenomenon not possible on a planet where life is confined solely to within dispersed biosphere habitats. In the more pleasant of Martian oases, mats of cyanobacteria and growths of lichens might achieve a net primary productivity (NPP) of 10 - 100 g (dry biomass)/m^2/yr, equivalent to semi-desert scrub on Earth (see Table 2.10). Dry regions might remain almost lifeless, except for scattered sublithic and endolithic communities, being equivalent to the interiors of the most extreme terrestrial deserts (NPP: 0 - 10 g/m^2/yr). The most productive locales on Mars might be the rare, but expanding, lakes and streams: ecosystems perhaps yielding 100 - 1000 g/m^2/yr. Whilst the average of such NPP values would be low compared with the continental average on the Earth (773 g/m^2/yr), it would still represent a diversion of several terawatts of Martian solar energy into autonomous biological production.

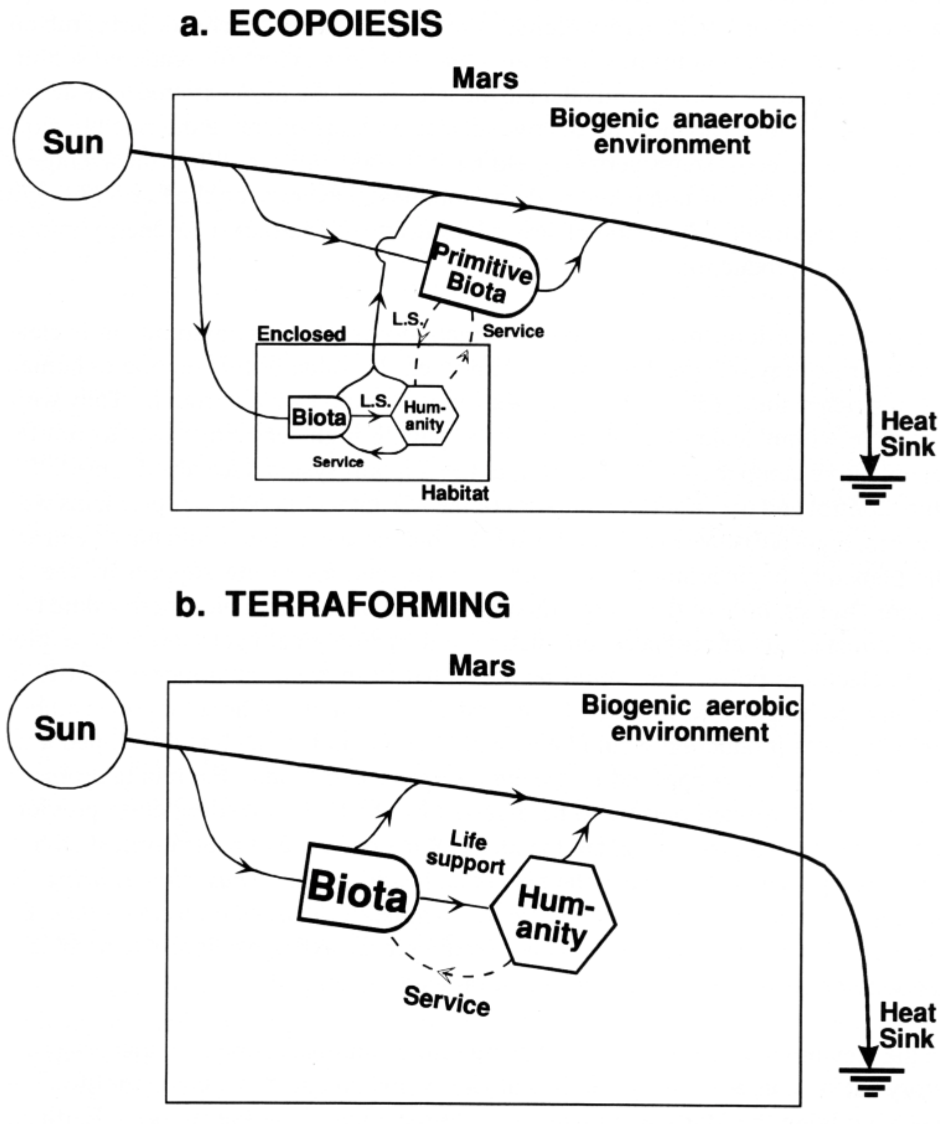

***Figure 6.1 a**. Ecopoiesis produces an anaerobic biosphere suitable for bacteria and primitive plants. Ecosystemic energy flow is now possible on a global scale. However, the usefulness of this for humans is rather limited. Aerobic life must still be carefully regulated and contained within sealed habitats. **b**. Terraforming produces an aerobic biosphere in which humanity can play a full part. Like on Earth, recycling of atmosphere, water, wastes, and the supply of food is largely an automatic process. Running the life support system is now a task similar to that of civilized terrestrial agriculture rather than the ceaseless monitoring and control of a space station.*

The economic worth of this new, more information-rich, Martian environment is clearly enhanced over its previous dead-end state. However, the value of this regime to human colonists is restricted since, for the most part, they must remain isolated from it. They would still have to live within sealed biosphere habitats, paying high servicing costs to run the non-bioregenerative components of their internal life-support system (see also Figure 2.7). Temperature control and the structural integrity of the of the habitat would now be lesser problems within the new warm, high-pressure, external atmosphere, but these benefits would have been achieved by the planetary engineering process, *not* as contributions to life support by the external biosphere. In fact, little of the energy fluxing through the external biosphere would be of any use for humans. Its atmospheric circulation and hydrological cycle might be exploited to generate electrical power, but would be prevented from being of *direct* benefit to human-containing ecosystems. As Figure 6.1a suggests, little or none of the solar power embodied in external biomass production would be available either, unless settlers developed a taste for processed algal mats, as opposed to greenhouse produced foods. Excreta and other wastes might perhaps be ejected outside to be digested by the biota, avoiding costs previously incurred by chemical reprocessing, but the idea that the main use of a terraformed environment might be as a planet-wide sewage plant is not an inspiring one. *Thus whilst sharing the same planet, the two living systems would be almost completely divorced from each other.* Even the aesthetics of the outside would be less than exciting to the average colonist, anaerobic ecosystems not being renowned for their visual or olfactory qualities!

From the point of view of the economics of energy flow, minimal ecopoiesis appears as an unsatisfactory half-way-house, only partially realising Mars' potential as a home for life. Whilst the notion of nudging the Martian climate into a drier analogue of the Precambrian Earth and then "letting nature take its course" is of obvious fascination, it is perhaps unrealistic to expect colonists to be satisfied with the vague *possibility* of an Earth like environment at some unspecified time in the remote future. However long it takes, the greater *certainty* that is afforded by continued human participation in planetary change, may prove much more inspiring. Actual Martian colonists are therefore more likely to design ecopoiesis *specifically* as being a first stage in as full a terraforming as possible, a phase in which living soil is created and the most crucial biogeochemical cycles are set in motion. If this argument is valid, then ecopoiesis will be an anthropocentric, rather than ecocentric process, being one rung on a planetary engineering ladder leading to the purposeful oxygenation and total terraforming of Mars [5].

Figure 6.1b shows energy flows characteristic of a fully terraformed Mars. With increasing oxygenation of the atmosphere, higher plants and animals are able to survive in the natural environment. *The global biota and humanity now participate in the same ecological arena*, Martian civilization benefiting from the automatic life-support services of the biosphere and merely having to run agriculture, as opposed to the whole biotic system (see Figure 2.15). As is shown in Section 6.3.3, small-scale ongoing planetary engineering may be required to stabilise some of the physical and chemical parameters of the terraformed climatic regime, which now exist far from the planet's natural equilibrium. However, because of the slow response of an uncontained global system to perturbation, compared with that of contained biospheres, this upkeep will neither be as urgent, nor as fraught with potential for sudden catastrophe.

A rejection of ecocentric minimalism will permit the use of more energetic planetary engineering techniques to release water from deep aquifers (see Section 6.2). The planet might more rapidly become wet enough to make most of the surface habitable. The Martian biosphere in Fig. 6.1b is still mainly land-based, but is able to channel energy flow similar to that of terrestrial continental interiors: ecosystems such as temperate forest (NPP: 200 - 1500 $g/m^2/yr$), cultivated land (NPP: 100 - 3500 $g/m^2/yr$) and tundra and alpine regions (NPP: 10 - 400 $g/m^2/yr$) might be common. Clearly, since the area of Mars is similar to the continental areas of Earth (where two thirds of the Earth's NPP is concentrated), there exists a potential to create a biosphere on Mars providing *gratis* life-support which, when assessed on the basis of energy flow, would be of an Earth like measure.

Terraforming thus raises the economic value of Mars to the ultimate [5]. Since human beings will be the inevitable driving force behind any planetary engineering venture, the case seems irresistible for having, from the very outset, total terraforming — the creation of an aerobic biosphere — as the proper objective of the long-term settlement of Mars.

6.1.2 How Certain Is the Runaway Greenhouse?

The standard paradigm, as applied to Mars, is fundamentally reliant on the Martian climate system being unstable and susceptible to modification with large feedback factors (e.g. Figure 5.4, trajectory **a→c**). Having made this assumption, it is possible to logically propose transforming Mars with a minimum of planetary engineering. The runaway CO_2 greenhouse model provides the physical basis for such an approach, being theoretically capable of a powerful, self-amplifying greenhouse warming, that runs to completion over a relatively short timescale [6,7].

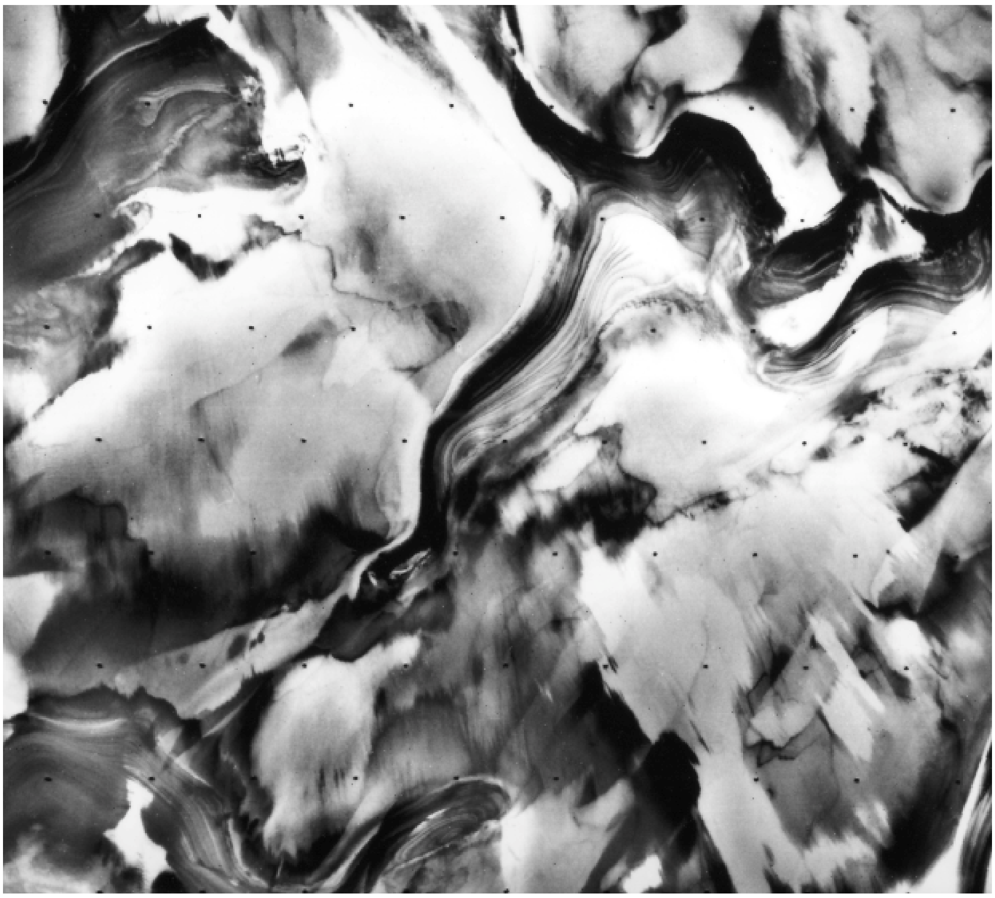

Plate 6.1 *Volatile saturated ground? The layered terrain surrounding the Martian North pole, the strata of which are thought to consist of accumulations of volatiles and dust, best observed on partially defrosted slopes. (Photo courtesy of NASA.)*

For the runaway greenhouse to operate as a *total* solution to ecopoiesis it has to produce sufficient CO_2 to warm at least part of the surface of Mars above freezing. We therefore require ~ 1 bar surface pressure to endow the tropics some degree of habitability and ~ 2 bars to raise the mean global temperature above freezing. Now, as was outlined in Section 5.2.2 (Table 5.4), the original volatile inventory of Mars may have been well in excess of this requirement and thus the required quantity of CO_2 may still remain on the planet, hidden in a surface, or sub-surface, reservoir. However, what is equally as crucial as the absolute amount of CO_2 sequestered on Mars, is that it should be in some *labile* form susceptible to mobilization by *modest* heating. The polar caps and regolith are two locales where the gas might exist in such a form as dry ice and adsorbed gas respectively (see Plate 6.1).

Although we cannot know for certain how well stocked these reservoirs are, their inventory has been constrained by theoretical models of the circulation of CO_2 between regolith, atmosphere and polar caps. As shown in Table 6.1, such models predict that the amount of carbon dioxide expected to reside in both the polar caps and regolith may fall far short of requirements. Whilst it can be argued that the South polar cap could contain up to ~ 100 mbar of CO_2 (before it started melting at its base), it seems more likely that only a few millibars-worth is present [8] (unless what is thought to be water ice exposed on both caps is actually CO_2 clathrate). Similarly the regolith capacity has been similarly constrained by experimental data on the absorptive capacity of powdered basalt and clay minerals. Models of ideally absorptive regoliths ~ 500 m thick have maximum storage capacities of about a fifth of a bar, 5 - 10 times less than needed [8,9].

TABLE 6.1 CARBON DIOXIDE RESERVOIRS

Constrained		
Atmosphere	~7 mbar	
Polar Caps	< a few mbar	Fanale *et al.* [8]
Adsorbed in regolith	< 280 mbar	Fanale *et al.* [8]
	< 190 mbar	Zent *et al.* [9]
Loss to space over past 3 Gyr	< 10 mbar	Pollack and Yung [10]
Unconstrained		
Carbonate formation	several bars	Pollack *et al.* [11]
Early impact erosion.	> 1 bar	Melosh and Vickery [12]

The answer to where the great bulk of Mars' early CO_2 atmosphere might have disappeared lies in the two unconstrained reservoirs listed in Table 6.1, which have an arbitrarily large capacity. If the planet's volatiles were blasted away into space by impact erosion during the late heavy bombardment [12], then planetary engineers will be in severe difficulty, facing the prospect of having to import an atmosphere from elsewhere in the Solar System. A likely locale however for much of the CO_2, are carbonate minerals in sedimentary rocks [11] which would have formed naturally via chemical weathering during the planet's warm and moist early history (see Equations 2.17 & 2.18). Although carbonates have not yet been unambiguously detected on Mars, a recent analysis of the planet's spectrum suggests the presence of the complex carbonate-containing mineral *scapolite* [13]. It may be that massive carbonate deposits await discovery, perhaps blanketed by drifts of sand and dust, in the sites of ancient lakes and watercourses. At least in this case one has Martian volatiles remaining on Mars. However, as was first pointed out by Fogg [14], carbonate rock will *not* be amenable to devolatilization by a gentle warming as it only decomposes at high temperatures.

There is sufficient uncertainty in models of Martian climatic evolution however that one cannot rule out the possibility that sufficient labile CO_2 exists for the needs of the standard paradigm. It seems unlikely, but not impossible. There is another problem though and that is with the proposed length of time it will take to degas the regolith. Heat conducts through rock very slowly and so, if the degassing of CO_2 is to be driven by a thermal wave travelling downwards through rock from a warmed surface, release of volatiles could take much longer than 100 years. McKay *et al.* [6] admitted to worst-case scenario of 100,000 years to liberate the CO_2 this way, unless it was susceptible to mobilization by a pressure gradient. The atmosphere might therefore not accumulate with a 100 year "bang", but with a 100,000 year "whimper."

Even if it is still possible for the runaway greenhouse mechanism to operate as claimed, there is another problem related to the thawing of the regolith for which the standard paradigm has no answer, and that is the activation of Mars' hydrosphere. In the last Chapter we hinted that Mars would still be a very dry planet once ecopoiesis in certain locales was possible and would remain so for a long time if release of water was left to the passive melting of permafrost. Just how long has been estimated by Fogg [15], who assumed the presence of an ice-saturated regolith, pole wards of 40^o latitude, containing 10% water. Once the surface temperature has risen above 0^oC, the time t taken for the thermal wave to conduct a distance D downwards is approximately [16]:

$$t \approx \pi D^2 / \kappa \tag{6.1}$$

where κ is the thermal diffusivity of the rocks. Here we choose a value for κ which is an average of the upper and lower estimates in Ref [8]: $\kappa = 2.8\times10^{-7}$ m^2/s.

TABLE 6.2 MELTING OF MARTIAN PERMAFROST

Time (years)	Depth of melting (m)	Global equivalent depth of melted ice (metres)†
100	17	0.6
200	24	0.9
1000	53	1.9
2000	75	2.7
5000	118	4.2
10,000	168	6.0
20,000	237	8.5
100,000	530	19
1,000,000	1676	60

† Assumes regolith has 10% ice content polewards of 40^o latitude.

Table 6.2 shows the approximate depth of melting tabulated against time in years; also listed is the global equivalent depth of liquid water produced. It is apparent that, even though these figures are very uncertain, the water required for a Martian hydrosphere would only be produced *very gradually*. After a century, < 1 m of ice will have melted. After a millennium, this will have increased to just ~ 2 m and even after ten thousand years only a paltry ~ 6 m of liquid water will be present. In reality the melting would probably be faster than this as Equation (6.1) does not take into account the natural Martian geothermal gradient and the fact that the thermal diffusivity of rocks should increase with depth due to compaction. In addition, once a groundwater flow becomes established, then heat would be carried into the ground in the form of latent heat of fusion of water, a process much more efficient than conduction [17]. However, timescales for the production of substantial quantities of melt water are still likely to be long: even on our moist planet Earth, the thermal inertia of the crust is such that century-old thermal signals are still detectable in the upper few tens of metres of ground [18]. Thus the estimates in Table 6.2 may not be completely spurious and even if pessimistic by a factor of ten, the quantities of melt water released are insignificant compared with the globally averaged depth of ~ 2700 m of water on the Earth and compares poorly with some of the more optimistic estimates of ~ 500 m sequestered on Mars. Another problem would be to get this small quantity to pool at the surface as there might be insufficient of a hydrostatic head to drive melt water from higher elevations to lower areas where it might collect. Even if this were to happen, it seems that the production of sufficient water to build bodies of oceanic proportions might take up to a million years. One is therefore drawn to the conclusion that, if planetary engineers rely upon passive processes to create a Martian hydrosphere, a terraformed Mars will be, for many millennia, a world of sparse oases amidst a near-lifeless desert.

Likely difficulties in releasing enough carbon dioxide to unfreeze Mars also have a bearing on the problems of generating a breathable atmosphere. (The lack or inadequacy of proposals for oxygenating the Martian atmosphere, within the context of the standard paradigm, were covered in Section 5.6). On the assumption that some workable method of net O_2 production from CO_2 is available, then we actually have *too much* CO_2 at the ecopoiesis stage for conversion into a breathable composition. Reducing 1 bar of CO_2 to 10 mbar (the toxic limit), by replacing it with oxygen, would give a toxic ~ 720 mbar pO_2. The fully realised runaway CO_2 greenhouse is therefore an *obstacle* to the future creation of a breathable atmosphere. Only if CO_2 outgassing is less than ~ 700 mbar (preferably between ~ 150 - 400 mbar), can we generate a suitable pO_2 — in which case insufficient CO_2 is outgassed to unfreeze Mars in the first place, unless other artificial warming methods are employed.

Thus, however much CO_2 is outgassed, there remains a strong case of further planetary engineering to improve on what has been achieved and to make further long-term progress. Study of ecological succession on the Earth has shown that life can colonize sterile, bare and nutrient-poor ground (such as lava flows [19], glacier forelands [20] and spoil tips [21]) and develop into complex, climax ecosystems in as short as ~ 100 years. Restoration ecologists are developing ways to accelerate this process, usually on land denuded or degraded by human activity [22]. This suggests that if planetary engineering can create suitable environmental conditions *first* (see Section 3.4), then it might be possible to establish *any* desired biotic community by a successive introduction of species. So long as the environment is not lethal, or limiting in essential nutrients, the rapid spread of life into all possible niches is assured by the self-replicating abilities of organisms and the self-organizing properties of ecosystems.

The standard paradigm is therefore, to some degree, a thought experiment that is voluntarily incomplete. Since the Martian biosphere is left at a primitive, Precambrian-like, stage of development, the questions raised by the procedure are more relevant to the habitability of the ancient Earth than to our planet at the present time. The restriction of technological input to so-called "foreseeable" technology, results in a necessity to restrict the goals of terraforming itself. Yet a glance of the contents of this foreseeable planetary engineering toolkit reveals an inventory falling far short of a comprehensive list of the utensils likely to be available to a space-faring civilization. (In fact it is curious to note that the tools proposed for the purposes of geoengineering that are listed in Table 4.5, are in some respects less conservative than those proposed for terraforming in Table 5.7). It is not necessary to invoke outrageous, or unscientific, technology in order to improve on the standard paradigm. However, it does require the acceptance of a more futuristic aspect to the speculation, possibly involving a powerful industrial effort both on Mars and in space, the use of extremely energetic planetary engineering techniques and continuing, conscious, intervention in Martian biogeochemical cycles.

Such technocentric alternatives, and a more complete thought experiment, in the form of a scenario for the total terraforming of Mars and subsequent upkeep of the habitable regime, comprise the rest of this Chapter.

6.2 Tackling the Volatiles Problem

Mars may have been close to its present, cold, dry and quiescent state for as long as ~ 1 - 3 billion years. Thus, there has been ample time for the planet's climate to approach a physical-chemical equilibrium consistent with its distance from the Sun and lack of vigorous volcanic activity. If this equilibrium has entailed the loss of most of the ancient hydrosphere to ground ice and the atmosphere to carbonate and nitrate deposits then both the artificial warming methods listed in Table 5.7 and their amplification by the greenhouse effect will be ineffective at releasing volatiles and triggering a rapid transformation of the planet. It is therefore not unreasonable to suppose that Mars might be firmly grounded in its present "runaway icehouse" condition, requiring a much greater planetary engineering effort to dislodge its climate and to force it along a habitable trajectory (e.g. Figure 5.4, trajectory **d→e**).

Ecopoiesis itself therefore becomes a major undertaking; however, one mitigating consequence would be that if an atmosphere has to be directly manufactured from stable deposits, as opposed to discharging labile reservoirs of arbitrary capacity, planetary engineers will have much more control over atmospheric composition. This ability to *design* the atmosphere from the outset, rather than having to work with whatever quantity of regolith CO_2 outgasses, will facilitate the future direction of Mars to full habitability. Possible sources of water, carbon dioxide and nitrogen are shown in Table 6.3, most of them demanding different types of energy input than normally included with the standard paradigm in order to liberate their volatile component. Figure 6.2 shows rough, 100% efficient, estimates of the quantity of this energy needed in J/kg to warm the regolith sufficiently to drive out adsorbed gas; to melt ice; and to extract CO_2, O_2 and N_2 by devolatilization.

In order to melt ground ice in an acceptable period of time and to release adsorbed CO_2 at great depths, *heat must be injected deep underground* in order to short-circuit the slow conduction process. On a sufficient scale, this might simulate past natural volatile-releasing events where the cause may have been the melting of permafrost by the intrusion of hot magma (see also Section 5.2.2).

Clay minerals, carbonates and nitrates must be heated sufficiently to decompose and evolve the volatile component. These temperatures can be quite high. Dolomite devolatilizes at ~ 600°C and calcite at ~ 1000°C:

$$\begin{aligned} CaMg(CO_3)_2 &\rightarrow MgO + CaCO_3 + CO_2 \\ CaCO_3 &\rightarrow CaO + CO_2 \end{aligned} \tag{6.2}$$

TABLE 6.3 POSSIBLE SOURCES OF VOLATILES ON MARS

Resource	Typical Mineral	Formula
WATER		
Surface ice		H_2O (s)
Ground ice		Rock + H_2O (s)
Clay minerals	Kaolinite	$Al_4Si_4O_{10}(OH)_8$
	Illite	$K_2Al_4MgSi_7O_{20}(OH)_4$
Salt hydrates	Epsomite	$MgSO_4.7H_2O$
	Gypsum	$CaSO_4.2H_2O$
	Hydrohalite	$NaCl.2H_2O$
CARBON DIOXIDE		
Surface dry ice		CO_2 (s)
Adsorbed gas		(Rock).CO_2
Carbonates	Calcite	$CaCO_3$
	Dolomite	$CaMg(CO_3)_2$
	Scapolite (Meionite)	$3(CaAl_2Si_2O_8).CaCO_3$
NITROGEN		
Nitrates	Soda-nitre	$NaNO_3$
	Saltpetre	KNO_3

Sudden shock pressures of > 100,000 bars also induce devolatilization on pressure release [23]. Alkaline earth metal oxides however are reactive and would rapidly reabsorb CO_2 dissolved in groundwater. This would be less of a problem if the carbonate deposits are impure. In this case, baking the mixture at ~ 1500^{o}C produces a glass:

$$CaCO_3 + SiO_2 \rightarrow CaSiO_3 + CO_2 \qquad (6.3)$$

If the contaminant is silica, a 1:1 molar ratio with calcite is optimum. (Note that Equation 6.3 is identical to 2.19 and is analogous to the outgassing component of the geochemical carbon cycle). Chemical weathering in this case would only reverse the above reaction at a very gradual rate.

The conversion of nitrates to nitrogen on Mars through biological means might be too slow to create an adequate atmospheric reservoir in an acceptable period of time. On the Earth, ~ 3×10^{11} kg/yr of N_2 and NH_3 are returned to the atmosphere by biological denitrification and decomposition [24]. Application of this rate to Mars means that ~ 13,000 years would be required to augment pN_2 by 1 mbar. Industrial methods may therefore provide a partial and more rapid alternative.

Sodium nitrate decomposes to sodium nitrite on strong heating, releasing oxygen:

$$2\ NaNO_3 \rightarrow 2\ NaNO_2 + O_2 \qquad (6.4)$$

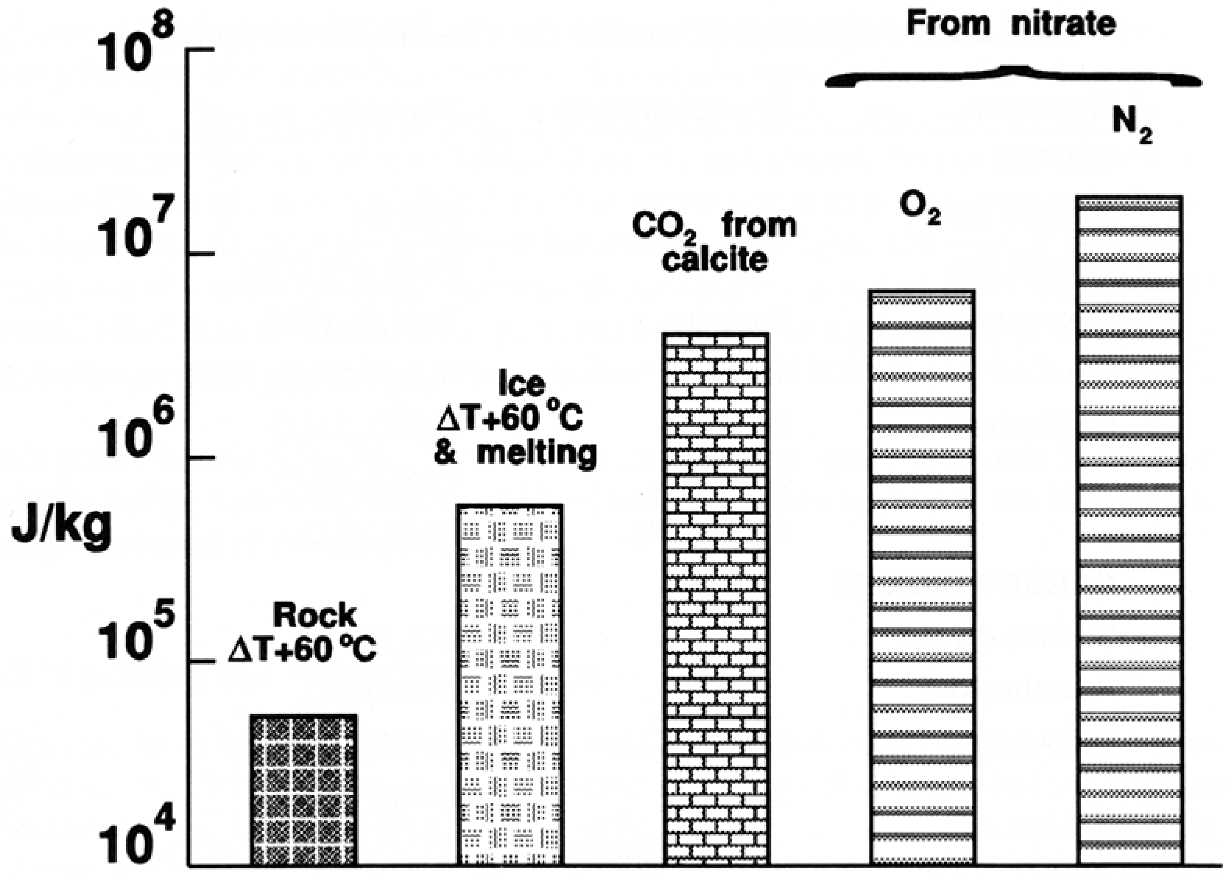

Figure 6.2 *Energy required in Joules per kilogram for warming Martian regoliths, melting ice, and devolatilizing carbonates and nitrates. Assumed quantities: specific heat capacity of rock ≈ 900 J/kg/K; enthalpy change of decomposition of calcite ≈ 178.3 kJ/mol; enthalpy change of decomposition of nitrate ≈ 260.7 kJ/mol.*

Further heating would break down the nitrite into the metallic oxide and nitrogen oxide, which itself decomposes to nitrogen and oxygen at ~ 1000°C. Strong heating of an impure nitrate deposit might also be expected to convert it into a glass:

$$4\,NaNO_3 + 2\,SiO_2 \rightarrow 2\,Na_2SiO_3 + 2\,N_2 + 5\,O_2 \qquad (6.5)$$

Two and a half moles of oxygen are evolved for every mole of nitrogen.

Accelerating the terraforming process therefore, or maybe even initiating it, may demand a more varied and powerful technological input to melt ice, devolatilize regolith minerals and possibly import volatiles from elsewhere. The different terraforming techniques proposed to this end are listed in Table 6.4 and discussed in the following Subsections.

TABLE 6.4 TECHNIQUES PROPOSED TO FACILITATE THE RELEASE OF MARTIAN VOLATILES

Application	Technique	Tools	Authors
Intrinsic terraforming			
Rapid melting of shallow or deep permafrost; regolith devolatilization; landform modification.	Deep seated release of thermal energy.	Thermonuclear explosives, manufacturing and emplacement infrastructure.	Fogg [14,15].
Extrinsic terraforming			
Melting of shallow permafrost and exposed ice deposits.	Augmentation of insolation with reflected sunlight.	Space mirrors, station keeping mechanisms and ancillary infrastructure.	Mentioned in passing in many texts, but see Zubrin and McKay [7].
Rapid melting of shallow permafrost; regolith devolatilization; landform modification.	Intense focussing of sunlight sufficient to vaporize regolith.	Dynamically supported soletta and aerial lens system, ancillary infrastructure.	Birch [25].
Rapid melting of shallow or deep permafrost; regolith devolatilization; landform modification; importation of volatiles.	Diversion of cosmic body to impact Mars.	Asteroid or comet and propulsion systems.	Mentioned in passing in many texts, but see Zubrin and McKay [7].

6.2.1 Nuclear Mining

The process of releasing CO_2 from carbonates has been investigated by Fogg [14,15] in order to illustrate just how difficult the manufacture of a dense atmosphere might be. The prospect of digging up carbonate rock, transporting it to furnaces and baking out carbon dioxide in the conventional way seems impractical, as to provide ~ 300 mbar CO_2 would require mining a pure deposit equivalent to a depth of ~ 7 m spread over the entire globe. This represents the processing of a minimum volume of ~ 10^{15} m^3, ~ 1000 times the upper estimate for the annual anthropogenic mobilization of rock on Earth (see Section 4.1.1).

The most compact energy sources currently available, and which are suitable for emplacement deep underground, are thermonuclear explosives. Thus, an option which involves the removal and transport of a far smaller amount of rock is to devolatilize carbonates *in situ* with thermonuclear explosives, buried in bore holes drilled into carbonate-rich strata. The intense shockwave and heat from the explosion would release CO_2 and drive a high-pressure flow of gas outwards. Volatiles from ground ice and nitrate deposits might be similarly "mined" by this method.

Theoretically, ~ 10^9 kg of CO_2 would be released by a 1 Mt ($\approx 4 \times 10^{15}$ J) explosion in pure calcite (see Figure 6.2). In practise, a little less than half this amount might be recoverable as evidenced by the results of the "Project Gasbuggy" 26 kt underground nuclear test [26]. Gasbuggy was part of the now-defunct "Plowshare" Program, the purpose of which was to assess the civil uses of nuclear explosives. It was intended to stimulate an unproductive gas well by fracturing the gas-bearing strata, thus improving their permeability. An improved well head gas flow was achieved, but was heavily contaminated with carbon dioxide that was later accounted for by the fact that the shale in which the device was detonated contained 4.7 wt% in the form of dolomite. About 1.86×10^6 kg of CO_2 were produced by Gasbuggy and we can scale this amount to the case of 1 Mt in pure calcite with the following factors:

$$\frac{\text{The mass fraction of } CO_2 \text{ in dolomite}}{\text{The mass fraction of } CO_2 \text{ in the rock}} = \frac{0.48}{0.047} = 10.2$$

$$\frac{\text{One megaton}}{\text{Gasbuggy yield}} = \frac{1000}{26} = 38.5$$

$$\frac{\text{Enthalpy change of decomposition of magnesite}}{\text{Enthalpy change of decomposition of calcite}} = \frac{100.6}{178.3} = 0.56$$

Multiplying 1.86×10^6 by these factors gives a carbon dioxide production rate of 4.1×10^8 kg/Mt. The efficiency of the process is quite good at ~ 40%.

The total amount of energy needed to devolatilize 300 mbar of CO_2 is therefore 1.17×10^{18} kg $CO_2 \times 9.8\times10^6$ J/kg $\approx 1.14\times10^{25}$ J. Assuming lithium deuteride (^{6}LiD) is to be used as the thermonuclear fuel, which has a mass to energy conversion efficiency of $\varepsilon \approx 0.3\%$, then the total mass required (assuming 100% fusion) would be $1.14\times10^{25}/(\varepsilon c^2) \approx 42$ million tonnes. The mass of deuterium needed would be ~ 11 million tonnes which, since it occurs as a fraction of only ~ 0.016% of ordinary hydrogen, would have to extracted from ~ 305 billion tonnes of ice, equivalent to a ~ 6.7 km ice cube, or a 2 mm global layer. This is well within the visible inventory of water present on Mars and is similar to the annual mass of rock being shifted in terrestrial mining activities (see Section 4.1.1). Lithium-6 should also be available on Mars, however if its extraction is uneconomic, then it may be feasible to substitute pure deuterium for the fusion fuel, even though the DD reaction is harder to ignite.

An estimate of the minimum number of explosives required can be arrived at by modelling the inventory of carbonate rocks as a pure layer of calcite of a uniform thickness. Assuming the explosives are not stacked vertically which, in any case, would be less economic as the cost of nuclear explosives is only very weakly dependent on yield, then the stratum thickness chosen determines the optimum yield. From this, the number of explosives needed to be detonated can be calculated [14]. These data are displayed in Table 6.5. Also shown are the minimum total volume of drill holes for emplacing the devices, presupposing a depth of burial of half the stratum thickness. The first figure in this row assumes borehole diameter estimates from Plowshare data [27] (48" for a 1 Mt charge, extrapolated for higher yields); and the figure in parentheses assumes the use of long, thin explosives, emplaced down a 10" diameter hole (narrow bore tactical nuclear warheads are available, e.g. as 8" artillery shells, but are more expensive). The total cost of the devices and their emplacement are listed too, also estimated from Plowshare data.

It is apparent from Table 6.5 that very large numbers of devices are required (on the order of tens of millions) and that, unless massive thicknesses of fairly pure carbonate rock are present on Mars, nuclear mining for CO_2 would be impractical as it would involve the brecciation of most of the planet's crust. Other obvious difficulties include the probable need to evacuate at least portions of the planet as the program proceeds and the danger of fallout contaminating the Martian environment with long-lived radioactive isotopes.

TABLE 6.5 NUCLEAR MINING OF CARBON DIOXIDE ON MARS

Sediment thickness (m)	100	200	500	1000
Most efficient device yield (Mt)	0.7	5.6	88	707
Millions of devices to devolatilize 300 mbar CO_2	4070	509	32	4
Minimum total drill hole volume (10^9 m^3)	240(11)	90(2.6)	21(0.41)	7(0.1)
Total cost of devices and emplacement ($\$10^{12}$ - 1975)	2490	390	36	7
Cost equivalent (World GNP - 1975)	414	66	6	1

Superficially therefore, devolatilization by nuclear mining does not appear promising. However, fairly pure carbonate deposits may be present in the Valles Marineris [28], in possible Karst terrain on the Northern plains of Mars [29] and under sites of ancient lake beds [30]. The Mariner valley "layered deposits" are the most interesting, consisting of strata rising as high as 5 km above the canyon floor (see Plate 6.2). Their regular lamination and lateral continuity suggest an aqueous origin [31], possibly being laid down under ice-covered paleolakes, supersaturated with atmospheric gases and supplied with cations, leached from surrounding rocks by groundwater. The thickness of some of these deposits, in the various sectors of the Mariner Valley are shown in Table 6.6 and, if they do indeed consist of limestone, could constitute a reservoir of ~ 30 mbar of CO_2.

The number of individual explosives indicated in Table 6.5 could be substantially reduced by increasing yield. Since there appears to be no theoretical upper limit to the power of a thermonuclear explosive [32] and since their cost is only a very shallow function of yield [27], scaling up the individual explosive units hugely increases net energy return and substantially reduces the overall cost. Very powerful explosives would naturally be much more destructive and might waste more of their energy in the cratering process. However, the ability to emplace charges with great accuracy and to optimise the yield for the job at hand renders them a more precise planetary engineering tool than the impacting comets considered in Section 6.2.4.

Since the most dangerous fallout from a thermonuclear explosion comes from its fission trigger, the hazards of long-lived residual radioactivity can be significantly lessened by increasing the average yield of explosive and hence decreasing the number. If it is possible to design an explosive which dispenses with the fission trigger then the explosion becomes relatively "clean." Figure 6.3 shows the activities of radioactive isotopes produced after a nominal 1 Mt underground thermonuclear explosion triggered by 10 kt fission [33]. Eliminating the fission component would remove all the activities marked by dotted lines. This leaves neutron activation products (elements in the surrounding rock which have become radioactive by absorbing neutrons), which nearly all decay very rapidly, and unburned tritium, which has a half life of 12.3 years.

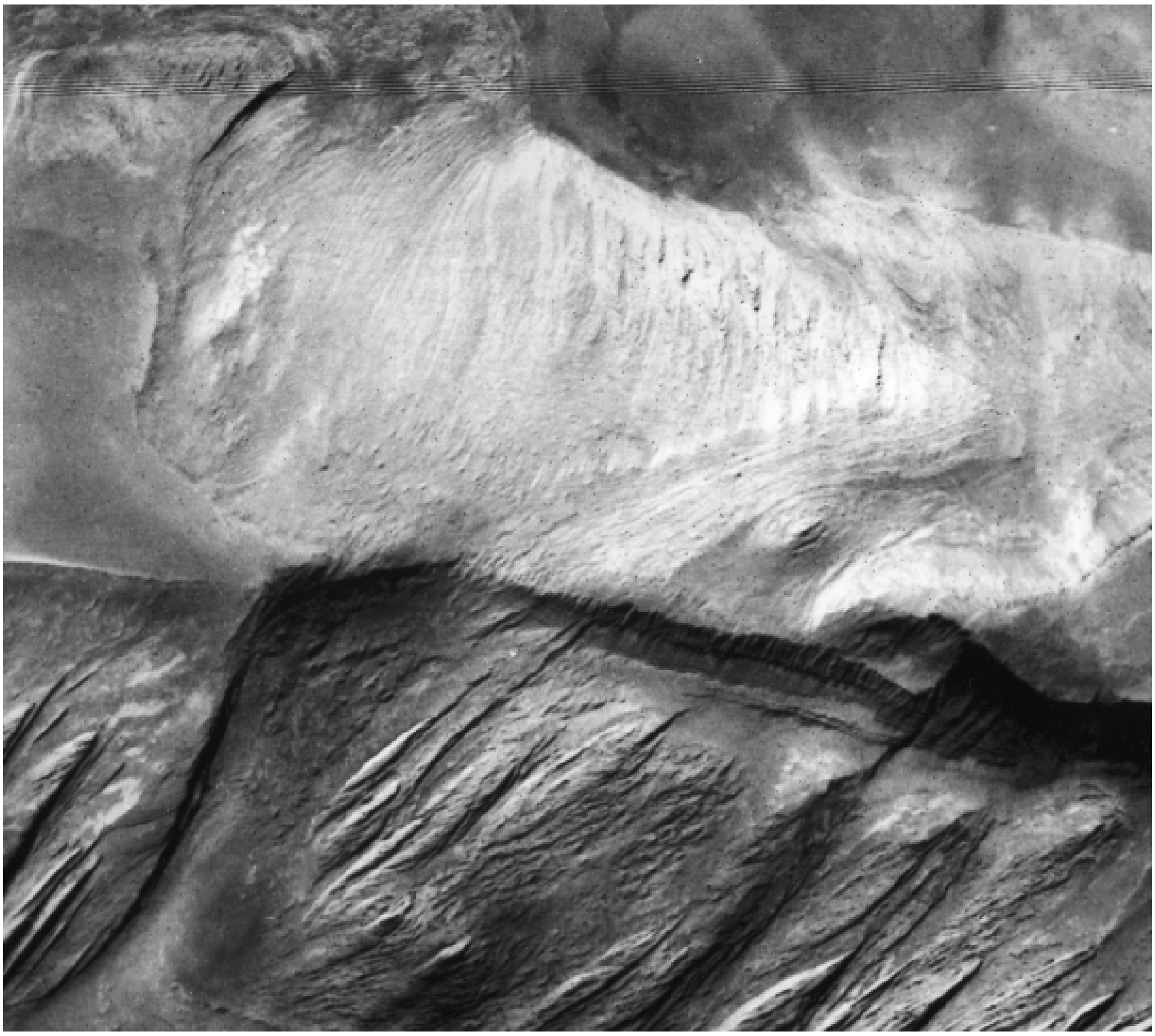

Plate 6.2 *Eroded layered deposits in eastern Candor Chasma. Resistant cap rock tops a mesa on the right. A number of features characteristic of a sedimentary origin are visible, and these strata may represent carbonate deposits that accumulated in ice dammed lakes. The scene is 25 km across. (Photo courtesy of NASA.)*

TABLE 6.6 LAYERED DEPOSITS IN THE VALLES MARINERIS

Locality	Thickness in km
Hebes Chasma	~ 5.0
Ophir Chasma	~ 5.3 - 5.5
Candor Mensa	~ 4.3
Candor Chasma	~ 2.4 - 4.2
Melas Chasma	~ 2.0 - 3.0

Tritium (T) only emits β radiation and is thus not a great external danger. However, it is normally taken up rapidly into water to form HTO. Thus it would be a hazard in drinking water and embodied in food and so the time taken for it to fall to a maximum safe concentration (MSC) in the environment can be regarded as a rough timescale for any nuclear mining

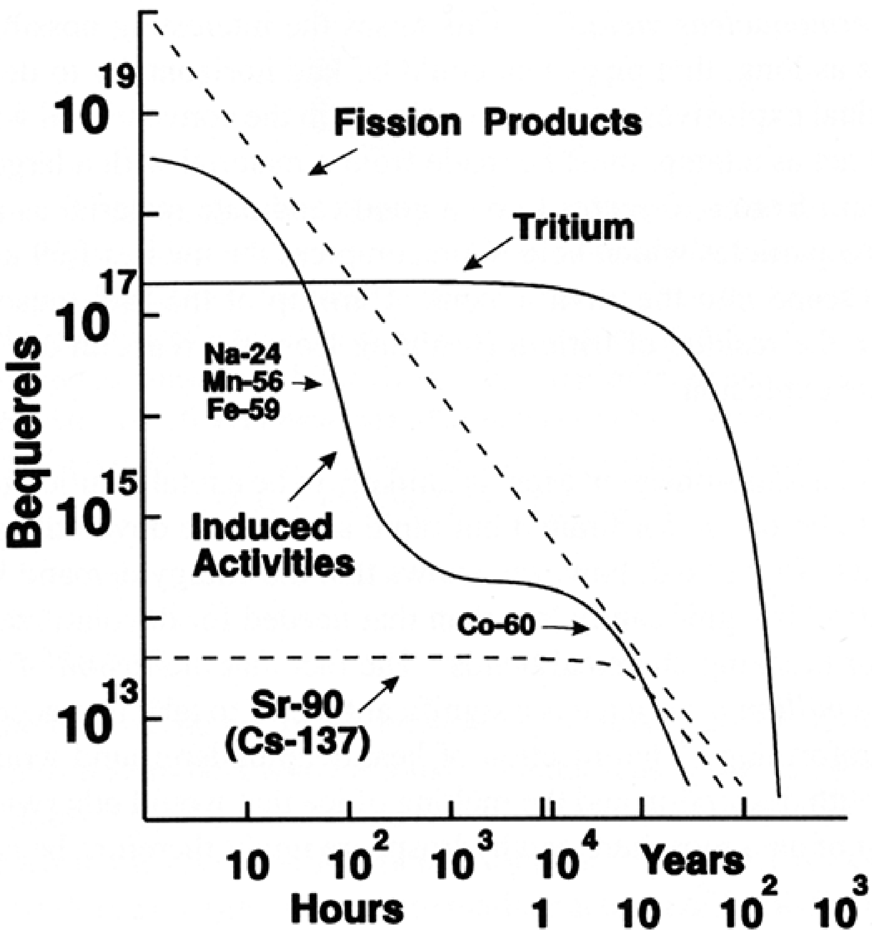

Figure 6.3 *Radioactivity produced by a nominal 10-kt fission/1-Mt fusion explosion (modified after ref. [33]. In a pure fusion explosion, the products represented by the dotted lines would not occur.*

programme. Nearly all of the energy of an underground nuclear explosion ends up as residual heat in the rocks. Assuming a detonation in permafrost containing 10% water, a 1Mt explosion would melt ~ 6.8×10^8 kg of ice at -60^{o}C. If burning of thermonuclear fuel is 90% efficient, then ~ 2.5×10^{17} Bq of tritium are left unburned per Mt so the concentration in the water would be ~ 3.7×10^{11} Bq/m^3. This amount is ~ 37,000 times the MSC (10^7 Bq/m^3) and so the time for this to decay to the MSC is 12.3 × log(1/37000) / log(0.5) ≈ 187 years. Since this safety limit applies to human health, ecopoiesis might proceed well before this period is up, with little risk. People would not be in jeopardy so long as they are provided with an uncontaminated water and food supply.

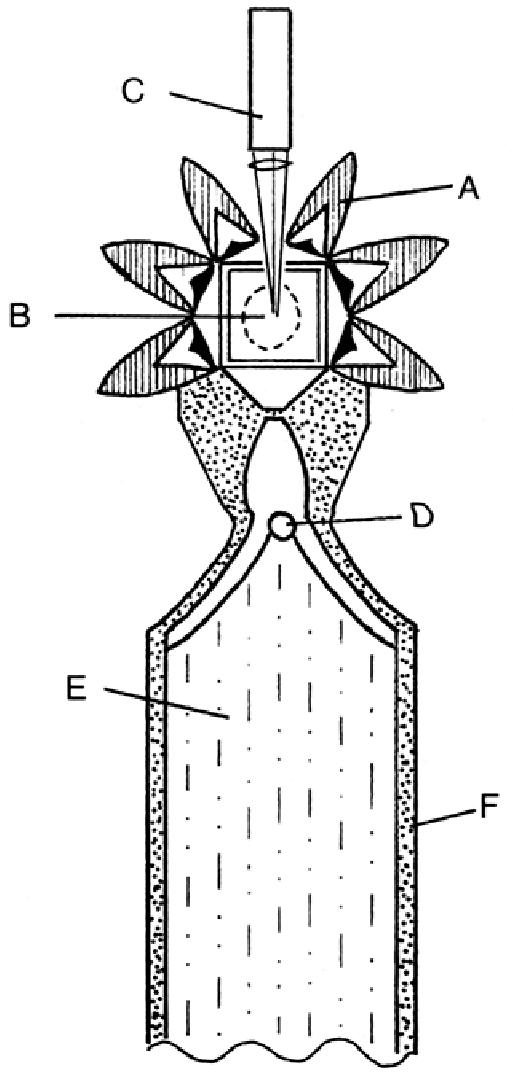

Figure 6.4 *One possible design for a non-fission triggered thermonuclear explosive for planetary engineering usage. High explosive shaped charge lenses (A), implode a magnetic DT plasma (B), which has been preheated by a chemical laser (C). Energy from the resulting thermonuclear micro-explosion is then focused on the ignition point for autocatalytic thermonuclear detonation (D), which then propagates down an arbitrary length cylinder of thermonuclear fuel (E). The tamp (F) is made from* ^{10}B *which reacts with neutrons , thus helping to precompress the thermonuclear fuel and reducing the flux of neutrons which escapes into the environment. (Design modified from Ref. [32].)*

Thus, the design of a nuclear explosive for planetary engineering would have little in common with present devices meant for military use. A schematic of such a device is shown in Figure 6.4. Thermonuclear fusion is triggered by high explosive shaped charge lenses which implode a magnetised deuterium-tritium plasma that has been pre-heated to ~ 10^6 K by a chemical laser. Energy from the resulting thermonuclear micro-explosion is then focussed onto an ignition point, whereupon an autocatalytic detonation wave propagates down a canister of ^{6}LiD thermonuclear fuel. The canister can be fashioned as a long cylinder to attain an, *"..arbitrarily large thermonuclear yield"* [33]. This raises the interesting possibility of fashioning explosive devices as long, thin, pipes that could be laid horizontally to do the job of a large number of individual explosives emplaced vertically in the conventional way [34]. The cylinder wall, which must act as a tamp, must be made from a material with a large cross section for neutron absorption. Boron-10 seems to be a good candidate material as it reacts with neutrons to form alpha particles, which help to pre-compress the nuclear fuel and reduce the flux of neutrons that escape into the environment. Burn-up of the fuel must be as efficient as possible to reduce the residue of tritium (resulting from the reaction of ^{6}Li with neutrons) remaining after the explosion.

Nuclear mining of an atmosphere on Mars is unlikely to be a total solution to the problem, but has the potential to be of use for limited, but rapid and precise, devolatilization of carbonate and nitrate deposits. Figure 6.2 however, shows that the energy demand for simply heating rock and ice by 60^{o}C is significantly less than that needed for devolatilization since there is no requirement for breaking chemical bonds. Hence, the fact that the fusion of 1 kg of deuterium can melt up to *one million tonnes of ice* is a significant factor to take into account when considering Martian terraforming. The injection of heat deep underground would therefore greatly help to speed up any regolith desorption and the melting of ice that would otherwise take millennia to thaw. The mining of an atmosphere and hydrosphere might therefore be combined.

6.2.2 Space-Based Mirrors

Not surprisingly, the large-scale use of nuclear energy to accelerate the terraforming of Mars is anathema to most researchers who variously dismiss it as being, *"... either impractical or ethically (and probably legally) unacceptable"* [35]. The point is often made that the sheer quantity of power available from the Martian insolation (~ 21,000 TW) dwarfs that of any intrinsic source. The stored energy in the entire nuclear arsenal of Earth for instance (≈ 10,000 Mt), is equivalent to just half an hour of Martian sunlight, whereas the devolatilization programme described above requires an energy input equivalent to 17 years. Thus, it is argued that a practicable planetary engineering programme should aim to exploit with maximum efficiency the immense, *gratis* flow of solar power impinging on Mars, or passing through nearby space.

However whilst this reasoning has undoubted merit, it should also be pointed out that the potential fusion energy available from the quantity of deuterium in the polar caps alone is equivalent to ~ 2000 years of Martian sunlight. Sunlight is also a more *dilute* form of energy that is best suited to heating the atmosphere and irradiated surfaces; as we have seen above (in Table 6.2), it is extremely inefficient and slow at changing the temperature of the crust at depth. Nonetheless, a terraformed Mars would undoubtedly benefit from the increase in insolation that could be afforded by a substantial array of space-based mirrors. This would help reduce Mars' deficit in total insolation relative to the Earth, reducing planetary engineers' dependence for global warming on a super-powerful greenhouse effect, and would also increase the photon flux available for photosynthesis. Space mirrors might be employed in a more flexible manner in the initial stages of terraforming where their power could be focussed onto superficial volatile deposits. Volatiles that would be the most amenable to mobilization by this method would be ices that sublime or melt, exposing a fresh layer beneath. Such ices would be found in the polar caps and layered terrain and perhaps, if they exist, in frozen lakes which would first have to be prepared for melting by removing any protective sedimentary cover that is present. Only the top ~ 20 m of regolith can be influenced by augmented solar heating during a reasonable period of time, as heat from the surface takes > 100 years to penetrate deeper than this.

Zubrin and McKay propose that their statite mirror (see Figure 5.10b) could be employed elsewhere on Mars, once its job volatilising the South polar cap is complete. In their most recent paper they state [7], *"... 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 and volatilise nitrate beds... A single such mirror could drive vast amounts of water out of the permafrost and into the nascent Martian ecosystem very quickly. Thus, whilst 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."*

This statement is in one sense too optimistic and, in another, too conservative. Twenty seven terawatts of power is only a minor augmentation of Martian sunlight. At 100% efficiency, it could melt ~ 4.6×10^7 kg H_2O/s from - 60°C, equivalent to a global depth of ~ 1 cm of water per year or ~ 1 m per century. This is comparable to the natural melting rate shown in Table 6.2 and, since it will be constrained by the same limitations, may be far less effective than the above calculation implies. The claim that the mirror might also devolatilize nitrate beds is also unrealistic as the finite angular size of the Sun prevents the focussing of a mirror's beam down to an arbitrarily small spot size. The reflector configuration considered by Zubrin and McKay is far too underpowered to raise temperatures in its service area to the > 1000°C necessary for devolatilization.

The possibility of building two other such mirrors is mentioned, with a total output of ~ 90 TW, but this still understates the true potential of augmented solar heating. If we restrict ourselves to considering statite mirrors 250 km across, a glance at Figure 5.10b shows that a mirror to illuminate the North pole is possible, as is one for any place on the terminator. One can therefore imagine a ring of such mirrors, illuminating the planet from behind, its inner radius approximating to that of Mars itself. The potential mirror surface area is therefore $2\pi(3.39 \times 10^6 + 1.25 \times 10^5) \times 2.5 \times 10^5 \approx 5.5 \times 10^{12}$ m^2; giving a power output of ~ 3240 TW, equivalent to 120 of the original mirrors. Thus, although the construction of even one 125 km radius statite is indeed somewhat grandiose from the standpoint of the present day, once the capability is present there is no reason that construction should necessarily stop at just a handful of units.

A space-based mirror capacity equivalent to ~ 15% of Martian insolation, of whatever design, would certainly be an extremely useful planetary engineering tool, capable of warming the mean global temperature by $\Delta T \approx 7.5$°C (without feedbacks) and of being focussed on specific areas as outlined above. To use sunlight however for effective devolatilization of the regolith, one is forced to consider mirror systems far bigger than even this.

6.2.3 Regolith Vaporization

If regolith devolatilization by *surface heating* is to be effective in a reasonable period of time, higher temperatures are demanded than those sufficient to melt a given sample of rock. This is because the limited thermal conductivity of a silicate melt will prevent the liquefaction of more than the top few metres of regolith. However, if we choose instead to apply sufficient energy to vaporize the surface, then the topmost layers can be distilled away to continually expose fresh rock. The temperatures required to achieve this range from ~ 3000 - 4000 K and, at steady state, one might expect to approach a situation where solid regolith is overlain by a layer of boiling lava. This molten rock would become enriched with refractory oxides (such as Al_2O_3) and metals which, being denser than the fresh plumes of silicate liquid rising from below, would sink to the base of the layer. The less volatile vaporized fractions would condense very rapidly once away from the heated area to form glassy deposits, whereas the water, CO_2, N_2, O_2 and SO_2 that would be given off would be free to mix with the atmosphere. The first four of these compounds are desired ingredients of the Martian biosphere (although not necessarily in their relative proportions), the fifth — sulphur dioxide — should rain out in the form of sulphuric acid which one might then expect to become neutralised by reacting with carbonates, evolving more CO_2 in the process.

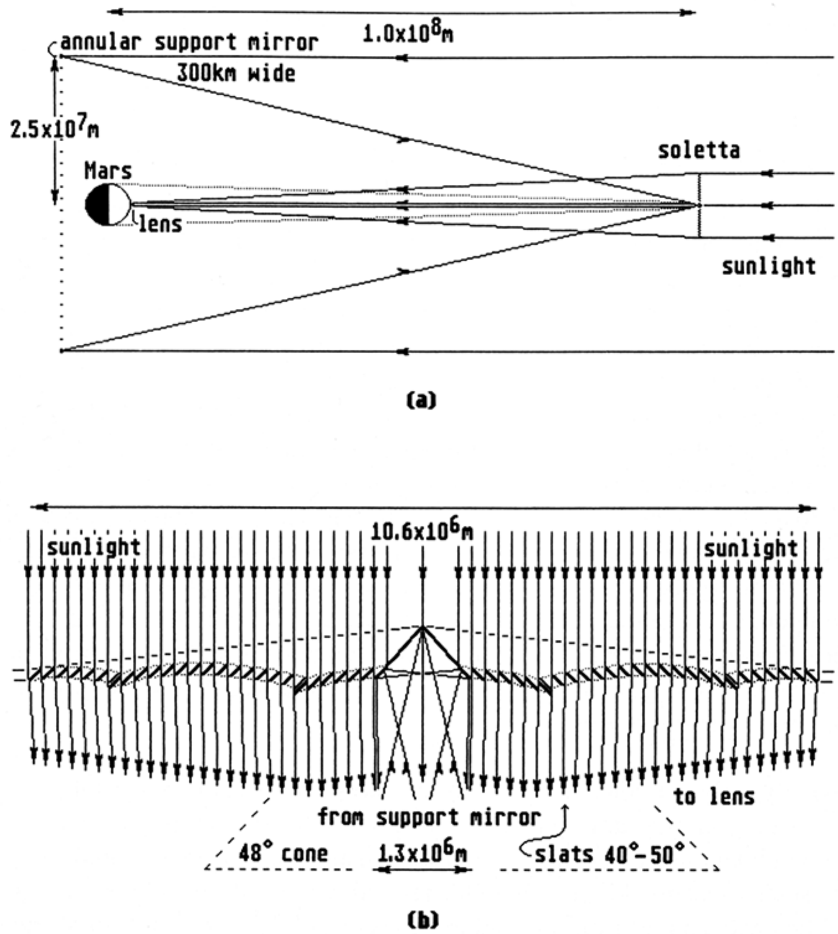

Figure 6.5 ***a.*** *Schematic of Paul Birch's magnifying soletta positioned between the Sun and Mars, dynamically supported by the light reflected from an annular support mirror.* ***b.*** *Detail of soletta structure. Annular slats are configured to bring sunlight to a focus ~400 km above Mars. Light from the support mirror strikes the inner cone and is back reflected to illuminate Mars with diffuse radiation of ~1.2 S_0. (Reprocuced with permission from Ref. [25].)*

Not surprisingly, only extremely powerful heat beams could vaporize regolith on a sufficient scale to provide a planetary atmosphere. If sunlight is to be used, then space reflector systems of greater complexity and dwarfing those of Zubrin and McKay are required. An ingenious concept for such a system, designed both for regolith vaporization and for subsequent use in providing Mars with an Earth like insolation, has been published by Paul Birch [25] and its extrinsic components are illustrated in Figure 6.5. Since its guiding analogy is that of a burning glass used to concentrate the Sun's rays, one can see that he chooses not to back-light Mars with mirrors from behind, but instead employs focussed sunlight with a *magnifying soletta* interposed between the planet and the Sun. This soletta is very large indeed, being 10,600 km across and consisting of a 1300 km-wide reflective inner cone and annular slats made from solar sail material (see Figure 6.5b). Sunlight striking a slat on the sunward side is reflected onto the next slat out where it is reflected again towards Mars, almost along its original path. Successive slats are angled 0.2° - 1.5° more steeply to bring sunlight into a focus ~ 400 km above the planet's surface. This direction of sunlight *inwards* gives rise to an *outwards* reaction force that helps to keep the soletta in radial tension. (Birch however did not address the issue of whether this force would be sufficient to maintain its shape or whether some spin is needed in addition.) The minimum spot size achievable from the soletta's 100,000 km distance is just ~ 600 km across (Birch assumes a working size of ~900 km), where sunlight will be focussed to a flux of ~ 80 kW/m^2. This device therefore can deploy a *huge* ~ 51,000 TW of solar power, either as a heat beam for devolatilization or, when defocused to a spot size the diameter of Mars itself, to multiply the planet's insolation (S_0) by a factor of 2.4, providing a global insolation equivalent to that of Earth.

A structure of the size and position of the magnifying soletta is unstable, being placed much closer to the planet than the Sun-Mars L1 point, and so must be actively supported. This is done with another, 300 km-wide annular-shaped mirror, circling Mars in a 25,000 km polar orbit that precesses once per year (see Figure 6.5a). Its stable position is actually slightly behind the planet as light pressure forces it back through an angle of ~ 17.5°; this light is reflected onto the inner cone of the soletta where it bounces back to illuminate the sun-facing planet with 1.2 S_0 — reflected sunlight augmented by 20% over the present insolation. The soletta therefore is being *dynamically* supported by countervailing beams of light [36] and Birch was able to show, by balancing the photon thrust against gravity for each component that the entire arrangement would be quasi-stable. As with all the space reflector systems discussed in this book however, active stabilization is still required to fine tune the configuration, compensating for any deviations away from equilibrium. Computer controlled tabs that create subtle shifts in the photon pressures at various points of the assembly seem to be the best way to achieve this. The fact that the Martian orbit is quite eccentric means that a regular oscillation must be imposed on the soletta's altitude from 91,000 km at perihelion to 109,000 km at aphelion and the slat angles adjusted to maintain the focus.

An additional demand of Birch's design is that it is fabricated from solar sail material, of areal density ρ_a = 0.3 g/m^2, ≡ 0.1 μm-thick aluminium. This is ~ 100 times thinner than commercial plastic wrapping and ~ 20 times thinner than the $\rho_a \rightarrow 4$ g/m^2 sails assumed for other space reflector scenarios (see Sections 4.2.6 and 5.5.2). Large scale manufacturing of such hyper thin films is not presently practised, they are however feasible and have been cited as the type of advanced materials that it may be possible to mass-produce in space [37]. Since Birch's concept itself is advanced and could only be realised by a civilization experienced at space manufacturing, his assumption of fabricating its components from the most high tech material is therefore reasonable. It allows the mass of the whole assembly to be reduced to 50 million tonnes (just ~ 3 years worth of the current world production of aluminium [38]), which reduces both the size of the support mirror and the distance of the magnifying soletta from Mars. This latter point is particularly important for effective regolith vaporization because it is desirable to have as small a spot size as possible at the soletta's focus.

Nevertheless, the flux passing through the ~ 900 km wide focus of the soletta is still insufficient and the beam will require additional concentration. Birch proposes to do this with an enormous lens, illustrated in Figure 6.6, which floats in the upper reaches of the atmosphere, ~ 400 km above the surface, where the pressure is ~ 10^{-4} mbar. Its form approximates to a section of an 800 km radius sphere, with its rim ~ 50 km below its peak, and would be constructed from transparent silica film, encapsulating an array of radial mirror slats with a focal length of 400 km. This structure would be extremely lightweight, having an areal density of $\rho_a \approx 2$ g/m^2 and would be far too flimsy to be constructed on the planet itself. Fabrication and assembly would therefore have to occur in orbit and the lens manoeuvred to its working altitude from above, where Birch calculates that it will be capable of stable flight and of resisting aerodynamic and gravitational stresses.

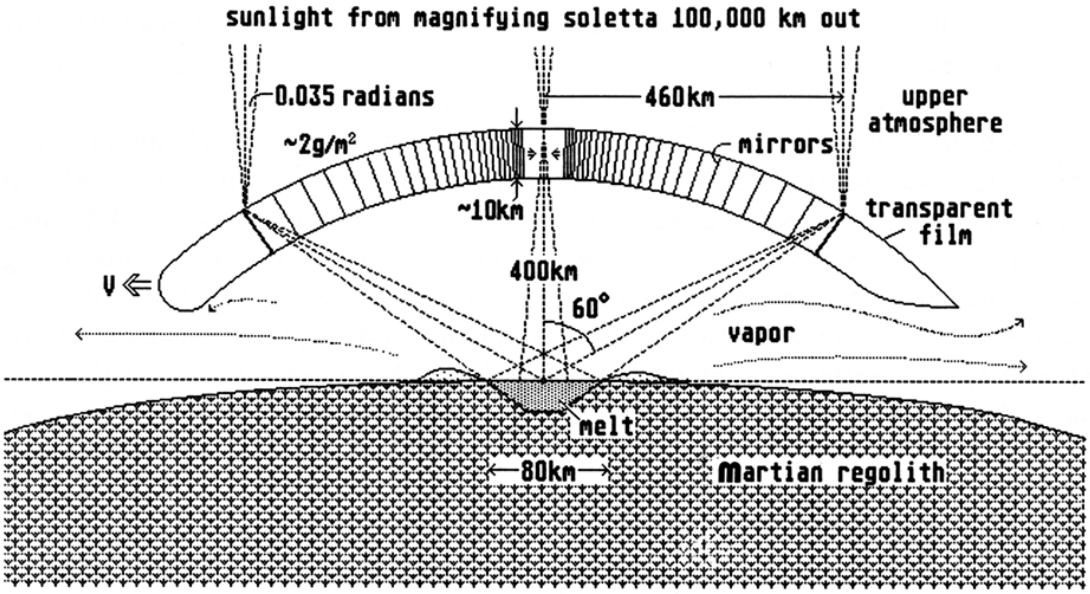

Figure 6.6 *The lightweight aerial lens conceived by Birch to work in partnership with the magnifying soletta system. It further focuses sunlight down to a spot size of <80 km where regoliths vaporization occurs. The heated atmosphere compressed underneath helps keep the structure aloft. (Reproduced with permission from Ref. [25].)*

The additional focussing of the soletta's beam by the *aerial lens* reduces the core spot size on Mars' surface down to a mere ~ 30 km (~ 80 km at the margins), producing a flux density as high as ~ 70 MW/m^2. In Birch's words [25], *"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 ~ 5400 K (or ~ 5200 K including 15% losses through the soletta and lens). If the mean melt temperature is ~ 3500 K a further 20% will be re-radiated, yielding an overall efficiency of ~ 66%."* Such a concentration of energy will cause the atmosphere beneath to expand, both because of heating and addition of vaporized surface material. It is the buoyancy generated by the hot air, both within the lightly pressurised lens body itself and rising from below, that maintains it aloft. As the planet rotates underneath, the lens surfs along at ~ 270 m/s, generating additional aerodynamic lift and powered by a tiny fraction of the outflow's kinetic energy.

The core of the heat beam passes over a given area of surface in ~ 5.5 minutes and in that time vaporizes a thickness of ~ 16 cm of rock. About the beam's margins, the heat is less intense — volatiles are driven off and a melt is formed that can flow into the middle. This process can be repeated at daily intervals and Birch predicts that it could result in the eventual sculpting of ~ 80 km wide valleys, up to ~ 10 km deep, flanked by glassy hills. The lens spot size could be reduced by using just its inner portion or by defocusing the soletta; in this case, a beam ~ 3 km in diameter is produced, *"... enabling relief to be sculpted into barrier hills, diminutive deposits to be worked and narrow water courses dug."*

Full time use of the soletta-aerial lens system is capable of vaporizing ~ 80,000 km^3 of rock per year. The rate at which fresh atmosphere is produced depends on the chemical composition of the regolith and how this changes during pyrolysis. The details of this are unknown and so Birch examined a range of possibilities involved in releasing the equivalent of ~ 240 mbar of oxygen. Assuming the devolatilization of rock of average regolith composition, then the worst-case timescale is ~ 180 years if it is only possible to break down carbonates; this is reduced to ~ 80 years by the additional pyrolysis of iron oxides. If massive deposits of iron ore, carbonates and nitrates are present, then these could be worked preferentially, reducing the timescale still further. Substantial quantities of water will be released during devolatilization, from the ubiquitous clay minerals and wherever the permafrost contains ground ice; the approximate quantity indicated is a mean global depth of ~ 10 m.

Evidently the scheme, in its violent quest for an atmosphere, substantially alters the appearance of Mars, a fact Birch was fully aware of: *"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."* The process therefore does not necessarily involve an ugly scarring of the planet, but instead a sort of recreation of the original Lowellian vision. The amount of water liberated during planetary engineering would fill the canals to a depth of several hundred metres. Much of Mars though, would remain largely untouched since volatile release is occurring from deeply excavated trenches, rather than by torching off a shallow, globally distributed layer. To quote again, *"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."*

Subsequent operations to complete terraforming are also described in Birch's paper, but are not covered here. His devolatilization technique however is the most crucial component of the entire scenario, creating an oxygen-containing atmosphere from the start and allowing the establishment of advanced plants from very early on. Its details are naturally sketchy and for the concept to become a practical proposal would require a great deal more theoretical work, followed by experimentation and the advances in engineering expected of a space-based civilization. These demands of course apply to all terraforming techniques, but more so to those of Birch which are more remote from any present day capacity.

Questions that require further study for instance are those posed by the dynamics of rock ablation, which occurs for only five and a half minutes every Martian day. How much residual heat remains in the effected area each beam cycle? Would it build up to form a stable layer of melt, being fed by inflow from the sides? What effect would there be on the efficiency of the process if rock re-condenses on ablated areas? — And how about the sinking of refractory compounds to the bottom of the melt: could this insulate the solid layers below?

Then there are questions concerning the precision with which Birch's apparatus can be manoeuvred and controlled. The Russian *Znamia* mirror was a mere 20 m across; the statite of Zubrin and McKay [7] is scaled up from this by a factor of ~ 12,000 and Birch's soletta by ~ half a million. It is not unreasonable to suppose that with an enlargement in size would come greater handling and stability problems, not in direct proportion to the increase, but greater nonetheless. Construction and operation of substantial scale models of such systems are needed to prove their practicality. Again, this is particularly so with Birch's designs which are far from passive structures, having moving parts and implying a superstructure that does not significantly add to their very low areal density. Can such systems, with their fragile internal components, be realistically reconfigured — switched on and off — without damaging them? The answer is probably yes, but working models are required to be sure. The question of steering the aerial lens is also unexplored, although perhaps this might be done by opening panels around the rim or by asymmetrically repositioning the mirror slats. Even with a reasonably precise control of the lens however, it is difficult to imagine how it would be possible to create canals roughly orientated along lines of longitude. Etching Percival Lowell's map onto the face of Mars therefore is doubtful.

Of all planetary engineers, it is Birch who has the reputation for sticking his neck out and proposing solutions on the largest possible scale. For most observers, there is an instinctive tendency to recoil from his approach and conclusions, firstly because of their sheer grandeur and secondly because their distance from anything that is presently practicable. However, all he has really done is to take the pleas of those like McKay — that sunlight should be the primary energy source for terraforming — to their logical limit. His speculations are a reminder that when terraforming ultimately becomes possible, planetary engineers may choose to employ techniques that would seem fantastic to us now.

6.2.4 Impact Devolatilization and Importation of Volatiles

The Solar System contains many volatile-rich bodies. An alternative method of providing Mars with an atmosphere is to import it. Comet nuclei contain plenty of water ice and perhaps a few percent CH_4, CO_2 and NH_3. The atmosphere of Venus contains massive reserves of CO_2 and N_2 and the atmosphere of Titan is mostly N_2 along with a little CH_4. It is technically feasible, even with present technology, to alter the orbits of small objects, such as Apollo asteroids to bring them close to Earth for mineral extraction [39], so it is not difficult to envisage a time when larger amounts of material, either in bulk, or in mass streams, could be put to use for terraforming (see Plate 6.3). In addition to direct importation of volatiles, the enormous input of kinetic energy from free falling objects, which must strike Mars at velocities of > 5 km/s, would release indigenous volatiles from the regolith due to permafrost melting and devolatilization. In fact since an impactor of any considerable size will survive passage through the planet's atmosphere and will breach the surface, most of its energy will be dissipated underground. Thus, as in the case of buried nuclear explosives, heat is being injected into deep strata where it is needed.

In "New Earths" Oberg [40] envisages the importation of volatiles, frozen in bodies such as comets and ice-moons —"*iceteroids*" he calls them — as being the cure-all for terraforming planets short of atmosphere. In the case of Mars he also cites an idea due to A.G.W. Kunze of the University of Akron who envisages their use as impactors to excavate fresh craters that are ~ 4 scale heights deep: even without augmentation of its mass, the Martian atmosphere would flow down into the depression exerting a pressure at the bottom of > 300 mbar.

Other solutions have been proposed to solve the entire atmosphere problem in one go. It is simple to calculate that the volatile inventory contained in one of the small or medium sized icy moons of Saturn would be ideal if transferred to Mars. Frederick Turner, in "Genesis", chooses the satellite *S26* which he names "Kali," a body ~ 100 km across, containing enough ice to flood the planet to a mean depth of ~ 4 m.

An excerpt from his description of the aftermath of Kali's impact is quoted at the beginning of this Chapter [41].

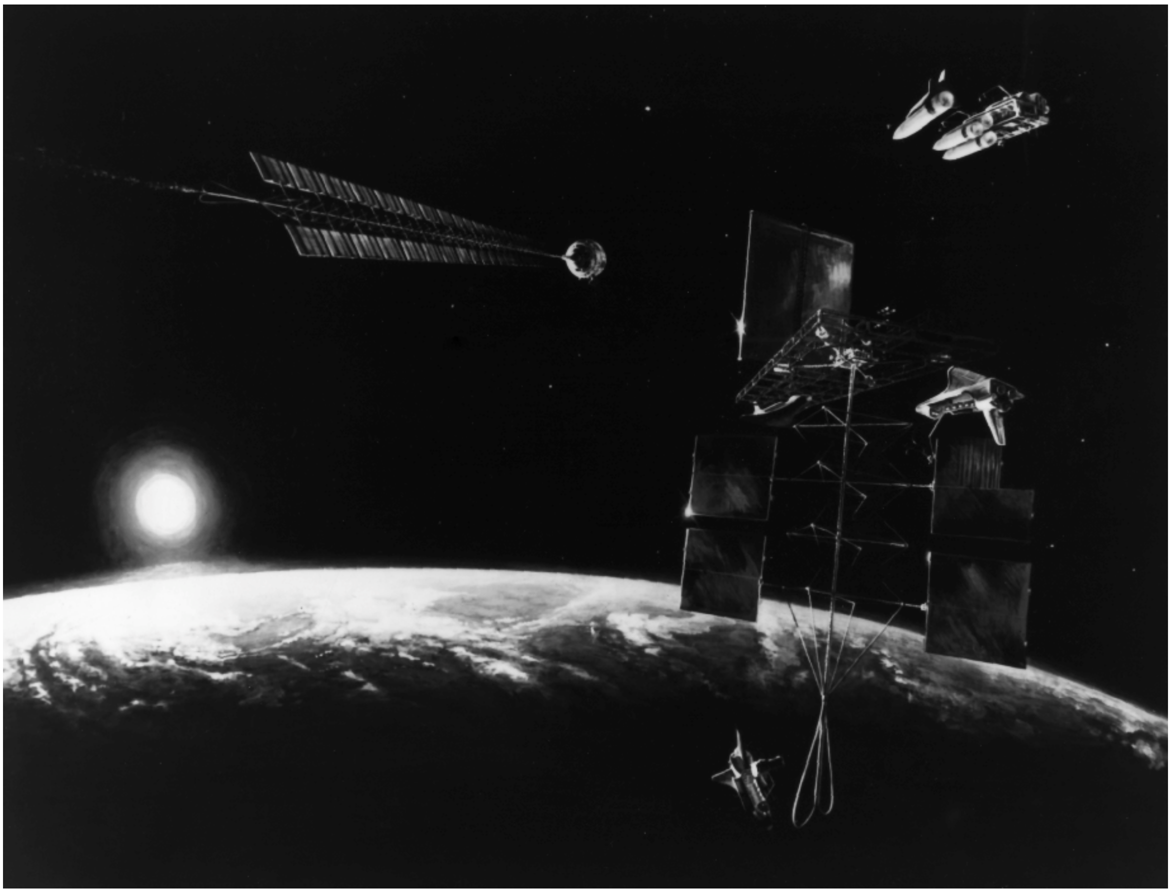

Plate 6.3 *Mass drivers could be used to propel small asteroids, as illustrated by this painting inspired by design work done at the NASA-Ames Research Center in 1977. Here we see a scene close to Earth where an operating mass driver, essentially a solar-powered electromagnetic launcher, is accelerating out of orbit to rendezvous with an asteroid. In the foreground a second mass driver unit is under construction. (Artist: Denise Watt; photo courtesy of NASA.)*

With characteristic ambition, Paul Birch nominates *Hyperion* for the job [25], an irregular satellite of width ~ 400 × 250 × 240 km containing perhaps the Martian equivalent of ~ 100 m of water and ~ 100 mbar N_2. He envisages giving Hyperion an initial impulse by generating a jet of steam from its own mass; this would be done by using solar energy from enormous mirrors or a high velocity pellet stream launched from near the Sun, effectively turning the satellite into a very large rocket. A series of gravitational assist manoeuvres with other moons, starting with Titan, should suffice to release Hyperion from Saturnian orbit; the ΔV (velocity increment) required of the steam rocket therefore is just 0.25 km/s. Further encounters with inner planets would serve to steer it on a collision course with Mars and to keep down the impact velocity to reduce the amount of material blasted back into space. If Hyperion strikes Mars in one piece the effects would be devastating, creating an impact basin almost as large as the ~ 1800 wide Hellas basin in the Southern hemisphere. The Martian air, with its new watery burden, would take some time to clear afterwards; in

Birch's words, *"The atmosphere would then contain ~ 4 bar of water vapour starting to condense at ~ 150°C; the precipitation of ~ 100 m of water would then take four or five years, during which time the climate would not be hospitable."* The solution he proposed was to divide the ice-moon into smaller chunks in advance of the encounter, *"With only ~ 3% of the ice moon introduced into the atmosphere at one time, condensation would commence at 45°C, with ~ 3 m of water precipitating in ~ 210 days. Although the climate might be very hot and humid, it would not be unbearable."*

Freeman Dyson, in his book "Disturbing the Universe" [42] has outlined what might be described as the ultimate method of importing a Martian atmosphere. He describes a scenario where a von Neumann machine (a hypothetical self-reproducing robotic factory) is allowed to replicate on Enceladus, a ~ 500 km diameter Saturnian satellite. When Enceladus is covered with copies of the original machine, they then proceed to take it apart into numerous chunks of ice, each equipped with a solar sail to take it to Mars. Thus Mars gets ~ 450 m of water for the investment in just one machine! Whether such a thought experiment would ever be possible in reality is open to question, but Dyson's reason for indulging in it was to show just how unbounded the future might be. However, most terraforming researchers leave von Neumann machines alone as one of those tools of the “arbitrarily advanced civilization” mentioned in Section 3.1. Once such a capability is attained, all bets are off and almost anything not ruled out by physical law is possible.

These grand solutions to dumping an atmosphere and ocean on Mars require huge energies or the most hand-waving type of technology and it is difficult to imagine the steering of large rotating bodies, such as intact moons, as being all that efficient or precise. This is not to say that such options are impossible, but that they are probably reserved for the more distant future. However, the capability of moving smaller objects, such as asteroids and comets, may be one we acquire fairly soon. Objects of diameter $D_i \approx 1$ - 10 km might be diverted by the sort of methods discussed in Section 4.2.7, such as continuous thrusting by propulsion systems attached to the object which use its substance as reaction mass, and impulsive thrusting by surface or standoff-detonated nuclear explosives. The ΔVs demanded will be higher than those tiny centimetre per second velocity increments quoted for remote interdiction of Earth impacts: to direct outer solar system objects (from out to a distance of 50 AU) on a course to Mars by using gravitational assist from the giant planets will typically require ΔVs of ~ 300 - 500 m/s and without such encounters ΔVs of ~ 1 - 4 km/s. Flight times will be on the order of decades. (Acquiring objects from the Sun's comet cloud, at distances of > 1000 AU, demands much less energy, but it would take thousands of years for them to fall into the inner Solar System).

Propulsion methods therefore will have to be more powerful than those in Section 4.2.7 and will consume a larger fraction of the impactor's mass. This however does not render them beyond present, or near-future capability. Zubrin and McKay [7] illustrate this with an example of a 2.6 km diameter ammonia-rich asteroid orbiting at 12 AU, which requires a ΔV of 0.3 km/s to take it to Saturn, whereupon it is slung the rest of the way to Mars for free. This could be done with the simple expedient of using four 5000 MW nuclear thermal rockets, such as the NERVA engines tested in the 1960's, using ammonia as propellant, at an exhaust velocity of 4 km/s. Ten years of steady thrusting would be required during which 8% of the object would be consumed as reaction mass; this would then be followed by a 20 year coast to impact. Such a technique could be scaled up further by simply adding more rockets, electromagnetic mass drivers or whatever. The prospects of diversion by explosives could be improved by increasing the number of devices and their yield and perhaps by pre-forming one face of the impactor so as to optimise the surface interception of energy and to focus the ejecta into a collimated exhaust.

Moving small asteroids and comets of kilometre dimensions is therefore already technically feasible (see Plate 6.4). It is also possible to conceive of moving medium sized objects, an order of magnitude larger, by scaling up the same technology by a factor of ~ 1000, or by thrusting for longer periods. We therefore examine here in more detail the outcome of bombarding Mars with impactors of this size. Our nominal asteroid is assumed to have a mean density of 2600 kg/m^3 and consists of 5% by mass volatiles (the rest is rock and metal); being diverted from the asteroid belt, it has an impact velocity of 10 km/s [43]. Our nominal comet has a density of 1000 kg/m^3, consists of 50% volatiles and impacts at 30 km/s [43]. From these data and choosing a diameter (D_i), it is simple to calculate the kinetic energy of impact on Mars (E_i) and the imported inventory of volatile material. However, we also wish to estimate the quantity of *indigenous* volatiles released from the regolith by shock devolatilization. The process of CO_2 release from a layer of carbonates has been modelled for the Earth and is governed by the following equations [44].

Plate 6.4 *Asteroid Ida, with its moon "'1993 (243) 1", as imaged by the space probe Galileo. Ida is about 56 km long, too large to steer effectively with near-future space hardware. Moving an object the size of its moon however (1.5 km across) could probably be done right now. (Photo courtesy of NASA.)*

The volume of vapour produced by an impact into carbonate strata would be approximately:

$$V_v \approx 0.264 \times E_i \times \rho_{rock}^{-1} \times \Delta E^{-1} \qquad (6.6)$$

where E_i is the kinetic energy of impact, ρ_{rock} is the density of the crustal rock (assumed here to be 2600 kg/m^3) and ΔE is the energy required for the shock devolatilization of calcite (assumed in Ref [44] to be ~ 9.5×10^5 J/kg).

The radius of the region shocked to pressures sufficient for devolatilization is:

$$R_v \approx \left(\frac{6}{4\pi} V_V\right)^{\frac{1}{3}} \tag{6.7}$$

The carbonate sequence itself is modelled as a uniform layer of thickness d, overlying a silicate half space. The volume of carbonate rock devolatilized turns out to be:

$$V_L \approx \pi(R_v^2 d - 0.33d^3) \tag{6.8}$$

where 44% of the mass of the rock contained in this volume is CO_2.

Here we optimistically presuppose the presence of a pure carbonate layer d = 500 m thick. This is equivalent to a global inventory of ~ 20 bars of CO_2, consistent with the upper estimates in Table 5.4. It is probably reasonable to assume a degree of stratification of Martian carbonates into the upper regolith since, unlike on the Earth, there has been less past tectonic activity that might have folded material back into the depths. In contrast, we assume the presence of ice in regolith pore spaces to an arbitrary depth and calculate melt water production merely on the basis of 10% of the impact energy going into thawing ice from - 60°C. (As discussed later this is in fact unrealistic for large impacts as they are capable of heating the crust to depths well below which water is frozen, or can exist in abundance).

It is also of interest to estimate the modification of the Martian surface caused by the bombardment. The landform created (see Plate 6.5) will be an impact crater of diameter in km [45]:

$$D_c \approx 1.96\times10^{-5} \times f_{conv} \times (E_i)^{1/3.4} \tag{6.9}$$

This formula takes into account crater collapse by slumping of the sides of the transient impact cavity and is converted to give results relevant to Mars by the factor f_{conv}, determined by the relation $f_{conv} \approx (g_{earth}/g_{mars})^{0.2} \approx 1.2$ [43].

Impact erosion, the process that may have been responsible for the loss of up to 1 bar of Mars' early atmosphere, must also be taken into account, so that the incoming projectiles do not blow off more volatiles into space that they liberate or import. Impacts of less than twice a planet's escape velocity are thought to be insufficiently energetic to eject much more atmospheric mass than that traversed by the projectile. For Mars, so are those where the impactor mass is less than ~ 4×10^{13} kg (equivalent to a 3 - 4 km diameter object) [12]. However, above this speed the vapour plume generated by the surface explosion may be powerful enough to lift the entire atmosphere above a plane tangent to the surface into space. This represents an appreciable fraction (~ 3×10^{-4}) of the entire atmosphere, indicating that Mars could be stripped comparatively rapidly by a population of fast-moving, medium-sized, impactors.

The results of this modelling for impacts of 1 - 100 km diameter asteroids and comets are shown in Tables 6.7 a and b, looking specifically at the requirement to devolatilize 300 mbar CO_2 and to produce 10 m of water. Salient data are the pressure equivalent of imported volatiles per impacting object (1 mbar ≡ 100 Pa) and the mean global depth equivalent if they all consist of water. Also shown are the pressure or depth of carbon dioxide and water respectively that are estimated to be driven from the regolith. As one would expect, the pressure of *imported* volatiles scales in direct proportion with the mass of impactor ($\propto D_i^3$), which itself (assuming a constant velocity) is directly proportional to the energy of impact. This also applies to the production of regolith-derived melt water. Thus, since the same initial ΔV compounds to the same impact velocity, whatever the size of the object, it makes no difference in terms of the total energy needing to be exerted whether planetary engineers choose to bombard Mars with many small objects, or an equal mass of larger ones. The leverage inherent in dropping objects onto the planet from a great height is considerable: an incoming comet at 30 km/s has 10,000 times the kinetic energy required to give it a ΔV of 0.3 km/s; according to our assumption of 10% of the impact energy going into the melting of water, ~ 150 times as much liquid water is produced from indigenous resources than from the object itself.

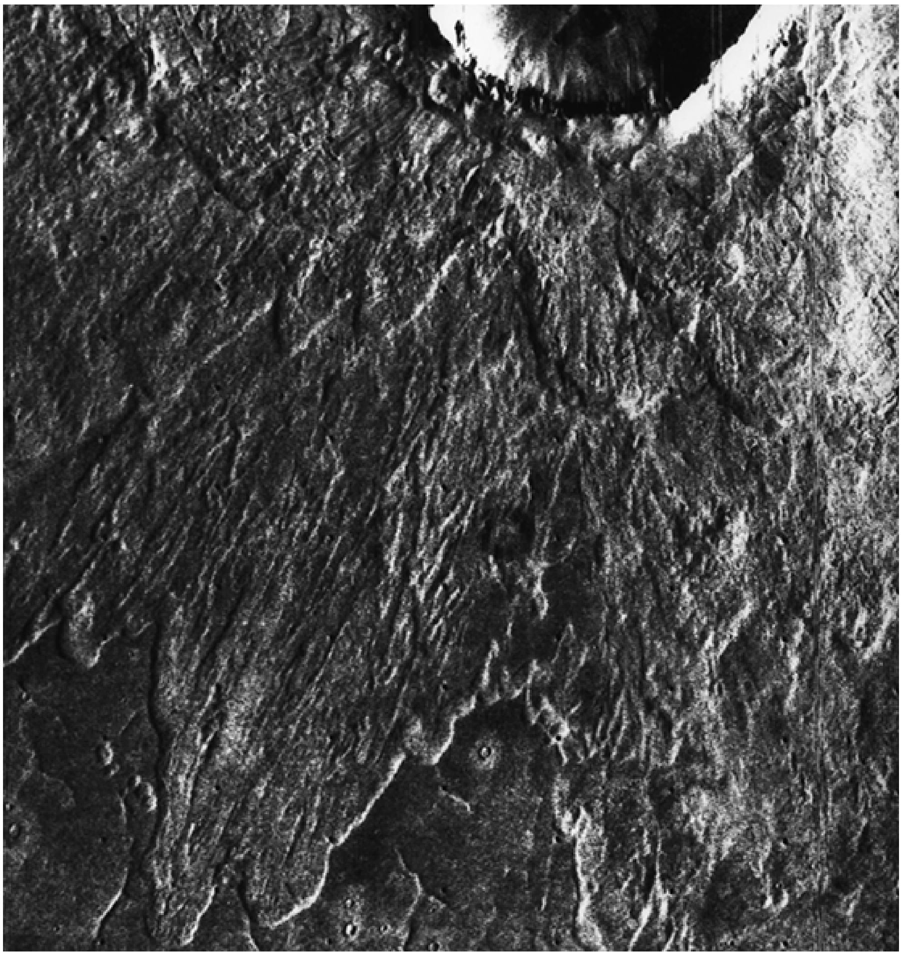

Plate 6.5 *Should permafrost on Mars still contain abundant ice, engineered impacts might create craters similar to this one: Arandas, 28 km in diameter at 43°N, 14°W. The energy released would release substantial volumes of water, mixing with rocky ejecta to flow as mud over the surrounding surface. (Photo courtesy of NASA.)*

The results differ however for the devolatilization of CO_2, which is seen to be $\propto E_i^{2/3} \propto D_i^2$. This is understandable because the gas is being released from a planar bed, which is thin compared to the total shocked volume of rock. Larger impacts are thus less efficient than smaller ones (i.e. less of their energy goes into useful work). Even the 1 km objects in Tables 6.7 a and b are more wasteful of energy than the nuclear explosives listed in Table 6.5, the yields of which are specifically set so that the devolatilization radius R_v is equal to half the carbonate stratum thickness. A 1 km asteroid only devolatilizes 20% as much CO_2 per joule than an 88 Mt explosive, falling with increasing size of impactor according to efficiency $\propto D_i^{-1}$. A 100 km impactor therefore only devolatilizes CO_2 at a 0.2% efficiency compared with an equal energy equivalent of optimised nuclear explosives. Devolatilization of nitrate beds would be expected to follow the same relationship. So might the production of melt water, for the larger impacts at least — if most Martian water lies within the top 10 km of regolith, then impacts of ~ 5 km or greater will 'see' this as a finite layer, rather than an arbitrarily large volume, meaning that the depth equivalent of melt water from left to right in Tables 6.7 a and b might only increase by a factor of 10^4, rather than 10^6. In this pessimistic case, large impacts might only free about double the amount of liquid, as is imported.

TABLE 6.7a IMPORTATION OF VOLATILES AND REGOLITH DEVOLATILIZATION ON MARS BY IMPACT

Asteroidal Impactor

Impact velocity:	10 km/s
Mean density:	2600 kg/m^3
Volatile mass fraction:	0.05
Carbonate sequence depth:	500 m

Diameter (km)	**1**	**5**	**10**	**50**	**100**
Impactor mass (kg)	1.4(12)	1.7(14)	1.4(15)	1.7(17)	1.4(18)
Impact Energy (J)	6.8(19)	8.5(21)	6.8(22)	8.5(24)	6.8(25)
Crater diameter (km)	16	66	122	505	931
Imported volatiles (kg)	6.8(10)	8.5(12)	6.8(13)	8.5(15)	6.8(16)
Pressure equivalent of imported volatiles (Pa)	1.8(-3)	0.2	1.8	221	1770
Depth equivalent of imported volatiles if all water (m)	4.7(-7)	5.9(-5)	4.7(-4)	0.06	0.5
Devolatilized regolith CO_2 (kg)	4.0(12)	1.0(14)	4.1(14)	1.0(16)	4.1(16)
Pressure of devolatilized CO_2 (Pa)	0.1	2.7	10.7	267	1070
Depth equivalent of regolith's meltwater (m)	8.1(-5)	0.01	0.08	10.1	81
Substantial impact erosion?	No	No	Some	?	?
Number of impactors needed to produce 300 mbar CO_2	~ 291,000	~112,000	~ 2800	~ 110	< 28
Number of impactors needed to produce 10 m of water	~ 123,000	~ 980	~ 120	~ 1	< 1

Note: exponents are in brackets; i.e. n(12) ≡ n×10^{12}.

It is seen that the comet scenario (Table 6.7 b) fares better in relation to both volatile importation and release, although their larger impact velocities (which bring in nine times the kinetic energy per unit mass) risk much greater impact erosion of the existing atmosphere and ejection of imported material straight back into space. An impacting swarm of small objects seems favoured therefore, although the numbers indicated are enormous, being $\propto D_i^{-3}$ for a total amount of imported volatiles and $\propto D_i^{-2}$ to liberate layered indigenous volatiles. Numbers in the thousands or greater are indicated, peppering 10 - 40% of the Martian surface with fresh craters (assuming no overlap). This demand for kilometre-sized objects would substantially deplete the asteroid belt and the contents of any feasible population of icy objects situated between Saturn and Uranus. Thus as well as being *inefficient* at converting energy release into useful work for terraforming, the impact scenario is also *wasteful* of interplanetary resources that could be better used for other purposes. (As was explained above, using material from the Sun's comet cloud, where comets probably number in billions, is impractical due to their long in fall time). However one looks at it therefore, one should not expect the realistic use of asteroids and comets for terraforming purposes to achieve major results.

TABLE 6.7B IMPORTATION OF VOLATILES AND REGOLITH DEVOLATILIZATION ON MARS BY IMPACT

Cometary Impactor

Impact velocity:	30 km/s
Mean density:	1000 kg/m^3
Volatile mass fraction:	0.5
Carbonate sequence depth:	500 m

Diameter (km)	1	5	10	50	100
Impactor mass (kg)	5.2(11)	6.5(13)	5.2(14)	6.5(16)	5.2(17)
Impact Energy (J)	2.4(20)	2.9(22)	2.4(23)	2.9(25)	2.4(26)
Crater diameter (km)	23	95	176	728	1342
Imported volatiles (kg)	2.6(11)	3.3(13)	2.6(14)	3.3(16)	2.6(17)
Pressure equivalent of imported volatiles (Pa)	6.8(-3)	0.9	6.8	851	6807
Depth equivalent of imported volatiles if all water (m)	1.8(-6)	2.3(-4)	1.8(-3)	0.2	1.8
Devolatilized regolith CO_2 (kg)	9.2(12)	2.4(14)	9.4(14)	2.4(16)	9.4(16)
Pressure of devolatilized CO_2 (Pa)	0.2	6.1	24	612	2448
Depth equivalent of regolith's meltwater (m)	2.8(-4)	0.04	0.28	35	280
Substantial impact erosion?	No	Some	Yes	Yes	Yes
Number of impactors needed to produce 300 mbar CO_2	~125,000	~ 4900	~ 1200	< 50	< 12
Number of impactors needed to produce 10 m of water	~ 35,500	~ 280	~ 35	< 1	< 1

Note: exponents are in brackets; i.e. $n(12) \equiv n \times 10^{12}$

Zubrin and McKay [7] notwithstanding have considered what a modest bombardment campaign might be capable of, assuming the existence of those ~ 2.6 km diameter ammonia "asteroids," orbiting just beyond Saturn, mentioned above. Their assessment is quite optimistic: if one impactor mission is initiated per year, then 40 years after the first strikes Mars, enough Martian ice would have melted to cover Mars by ~ 0.25 m of water and sufficient ammonia (~ 100 mbar) would have been imported to give a greenhouse warming of ~

20°C. Furthermore, *"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."* This assessment however may be overly sanguine, as it greatly overestimates the efficiency at which the heat released will couple to melting ice. Much of the ammonia may be dissociated in the hot vapour cloud following the explosion and, as for doubling the nitrogen content of the atmosphere — this is only equivalent to an extra ~ 0.2 mbar (and perhaps another ~ 1 mbar would be produced by devolatilization). Lastly, the notion of pure ammonia asteroids is the most speculative of all. Normal asteroids are thought to possess virtually no ammonia at all and all the comets that have been studied suggest that their volatile fraction consists of < 10% NH_3 [46].

However, whilst directed impacts represent the "blunt instrument" of terraforming tools, they still possess the benefit of bringing in additional volatile material from elsewhere. If the dry and near-airless state of Mars cannot be overcome by intrinsic planetary engineering, then massive importation remains the last hope for terraforming. Taking into account what has been said, the ideal parameters for such a scenario are therefore:

1. There is a massive source body to hand rich in volatiles, especially N_2.
2. It is situated in an orbit close to that of a giant planet to reduce the ΔV required for a gravity assist manoeuvre.
3. Impact velocities are < 10 km/s.
4. The impactors are small.
5. Impact sites should be volatile-rich.

This returns one therefore to the idea of Dyson [42], where a large object, such as a Saturnian moon is disassembled into a mass stream that feeds Mars gradually and safely. Adopting his example of Enceladus and assuming (pessimistically) that we just have Enceladian sunlight to work with, then we have to move a total mass of ~ 6.5×10^{19} kg with a power of ~ 2.8×10^{12} W. Furthermore, if we assume that the ΔV required is ~ 187 m/s (the escape velocity of Enceladus — escape from the Saturn system is by solar sail propulsion and gravity assist from other satellites) then the total energy needed is ~ 1.1×10^{24} J. This accrues over ~ 13,000 years during which the satellite is gradually taken apart, into a ~ 1.6×10^{8} kg/s mass stream spiralling in toward Mars. The manoeuvrability afforded by the solar sails attached to each package permit a minimum 5 km/s impact velocity and so the power dissipated in the Martian atmosphere amounts to ~ 2000 TW, equivalent to 9% of the total Martian insolation. To quote Dyson (whose calculations were evidently similar), *"... the night time sky of Mars begins to glow bright with an incessant sparkle of small meteors. The in fall continues day and night, only more visibly at night. Day and night the sky is warm... A little later, it rains on Mars for the first time in a billion years. It does not take long for oceans to begin to grow. There is enough ice on Enceladus to keep the Martian climate warm for ten thousand years and to make the Martian deserts bloom."*

Periods of this order may seem very long, but if shortened substantially, a mass stream results in an excessive continuous heating of the planet. In any case it may be matched by other planetary engineering timescales such as that determining the full oxygenation of the atmosphere (see Sections 5.6.2 and 6.3.2.1). So far removed from the present, Dyson's machines, or a more conventional industrial capacity of suitable scale, seem less speculative. In the near future however, impacts seem likely to play a comparatively minor role in terraforming.

6.3 A Synergic Scenario for Terraforming Mars

Without exception, all the terraforming techniques discussed so far, both in this and the last Chapter, have their individual difficulties.

1. The runaway CO_2 greenhouse effect is unlikely to work as completely and rapidly as some hope, and if it did, would produce too much carbon dioxide for subsequent photosynthetic processing into a breathable atmosphere.
2. Trace greenhouse gases currently appear to be capable of providing only about half of the 60°C warming that is needed and most of the chemicals proposed so far would be too short-lived and destructive of ozone.
3. Space-based mirrors could increment the Martian insolation to an Earth like value, but would be very large indeed and possibly beset with unforeseen challenges of stability and control; a complete reliance for habitability on such extra-planetary technology may be unwise.
4. Devolatilization methods, such as focussed sunlight, nuclear mining and impacts, have their own distinct problems or unknowns that render them less than fully applicable for the provision of a substantial atmosphere and hydrosphere.
5. And finally, unmanaged Antarctic-type ecosystems appear to be wholly inadequate at the task of oxygenating the atmosphere and transforming Mars into an aerobic planet.

None of them therefore are ideally suited to the initial task of ecopoiesis and any subsequent process of terraforming and yet all may be of utility to some degree. However, this state of affairs does not indicate that terraforming Mars is impossible and has more to do with scientists' tendencies to isolate aspects of a problem for more detailed study. The physical effects, or the realism, of any isolated technique may become limited at a level below which it becomes the full answer for any particular application; an intelligent union of such techniques though may allow planetary engineers to transcend their individual restrictions. This approach was first looked at by Martyn Fogg (see Plate 6.6), who named it *Synergic Terraforming*. To quote [15]: *"One avenue that has been insufficiently explored is the effect of synergy between all the processes already outlined which appear, individually, incapable of warming Mars adequately. If the techniques are combined within an overall plan it might be possible to exploit their advantages whilst cancelling out their flaws."*

Fogg used this synergic approach to propose a two-stage scenario for Martian terraforming that is specifically aimed at creating a fully-habitable planet [15]. A modified version is described below: it is not in any sense a predictive model, but merely *illustrative* of how the terraforming techniques in Tables 5.7 & 6.4 might be integrated and, more importantly perhaps, how it is possible to design a terraforming project with the ultimate goal of *human habitability* in mind from the outset.

The Martian climate model assumed as the basis for these speculations is not the warm and wet planet of the first billion years of its history, but a recapitulation of the "postdiluvian" Mars described by Baker *et al.* [47] (and outlined in Section 5.2.2) that may have briefly existed following the episodic outburst flooding events. Here, drastic and rapid changes in the Martian environment are brought about by energetic and violent means that create a temporary, "maritime" climate. In Mars' past, it was volcanism that may have been the trigger for destabilizing confined aquifers, draining them to lower elevations and driving huge quantities of adsorbed CO_2 from the regolith. Planetary engineers however will have to find a substitute for both Martian geothermal heat, which may be much weaker than it once was, and the greenhouse warming of CO_2, much of which will have been tied up in carbonates. Once the maritime state is reached, further planetary engineering could continue to improve the environment and maintain it against degradation. Unlike the standard terraforming paradigm therefore, with its need for huge quantities of CO_2 that must be released with minimal engineering, the model presented below accepts a much more conservative assessment of the Martian volatile inventory (e.g. Table 6.1) and whatever industry is necessary to attain the stated goal.

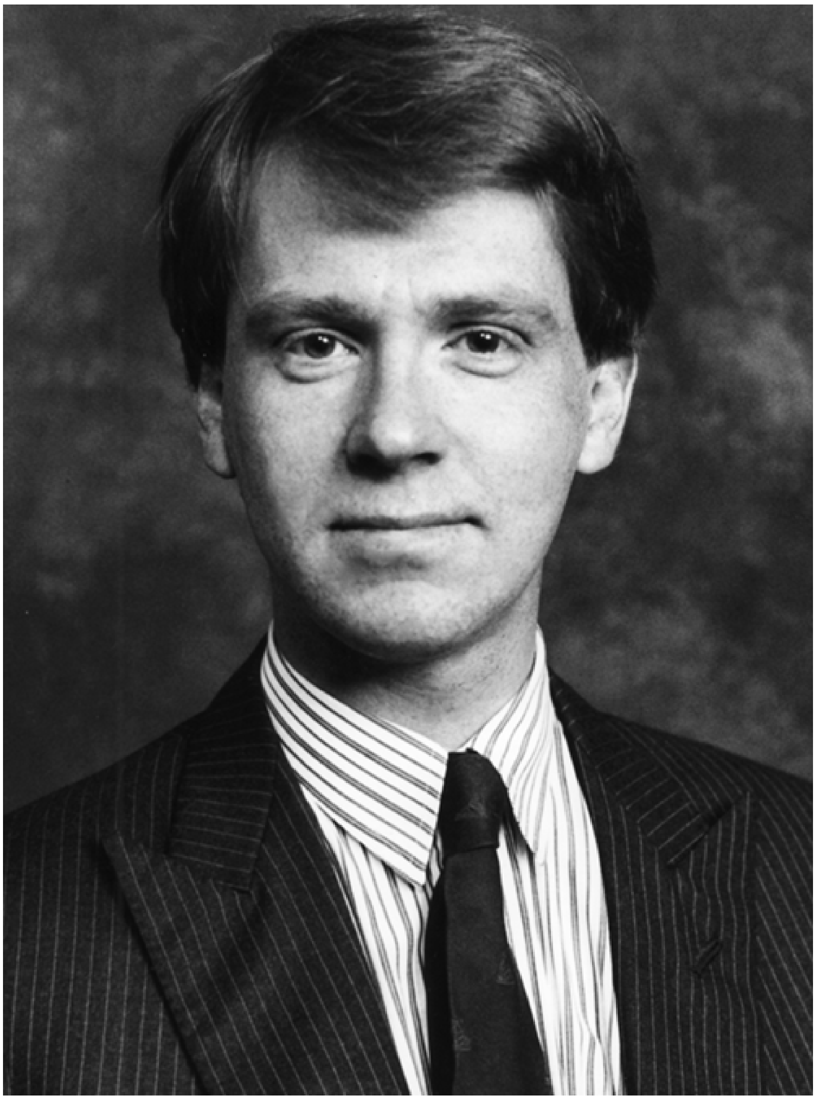

Plate 6.6 *Martyn Fogg: Editor of the Terraforming special issues of the Journal of the British Interplanetary Society.*

The effects of many planetary engineering techniques will not compound in a simple fashion. An additive approach however can still provide reasonable estimates and the results of Fogg agree fairly well with a more rigorous theory currently under development by McKay and Zubrin [48]. A useful empirical equation [49] that provides a guide to the climate of Mars is based on the CO_2/water vapour greenhouse effect model of Pollack *et al.* [11]. It predicts a globally averaged surface temperature of:

$$T_{surf} \approx [(1 - A)\, f_s\, S_0 / 4\varepsilon\sigma]^{1/4} + (19.5 + 20.4\, f_s) pCO_2^{1/2} \qquad (6.10)$$

where S_0 is the Martian insolation (589 W/m^2); f_s is a coefficient for varying the insolation which is valid between values of 0.7 - 1.3; A is the albedo (taken in this model to = 0.19); ε is the infrared emissivity (≈ 1); σ is the Stefan-Boltzmann constant and pCO_2 is the CO_2 partial pressure in bars.

6.3.1 Stage One: Ecopoiesis

The aim of this first stage of Martian terraforming is to render the global environment suitable for some sort of life — to create an uncontained biosphere that can capture solar energy and run biogeochemical cycles on a planet-wide scale. Since we are assuming that Mars will be much harder to dislodge from its current state than supposed by the standard paradigm, we double the nominal timescale for ecopoiesis to 200 years. Initially, this environment will only be habitable for the hardiest of forms, anaerobic microorganisms and perhaps algae, fungi and certain plants tolerant of cold and low oxygen partial pressure. Planetary engineering however, with both biological and technological tools, will continue to *consciously* improve on conditions so that a progressively wider range of organisms can be introduced. In line with the definitions given in Section 3.2, we count ecopoiesis as being the creation of Mars' first biosphere — the bringing of primitive life to the planet — and terraforming involving the subsequent deliberate engineering of an environment suitable for humans; this is despite the fact that where conscious direction of planetary evolution is intended to continue after the initial stage, there is no strict dividing line where ecopoiesis ends and terraforming begins. According to Table 5.6, the minimal requirements for ecopoiesis are $T_{surf} > 0^oC$, surface moisture, a reduction in the ultraviolet flux and an atmospheric pressure $P_{atm} > 10$ mbar with $pCO_2 >$ 0.1 mbar and $pN_2 >$ 1 - 10 mbar. To permit the survival of some plant life we should have $pO_2 > 1$ mbar, but for the widespread growth of higher plants we need $pO_2 > 20$ mbar. One further necessity is that the conditions created are such that permit a gradual progressive planetary engineering to an Earth like state. The following processes, acting in concert are proposed to this end [15].

6.3.1.1 An Increased Martian Insolation

Although the construction of large space reflectors around Mars is feasible, the difficulties of creating and maintaining a mirror system vast enough to give an Earth like insolation may outweigh the advantages. For this scenario however, such a structure is not necessary. A 30% increase in the Martian solar constant (f_s = 1.3) is considered sufficient and one can conceive of a number of mirror designs capable of reflecting the required 6370 TW onto Mars. The ring of statite solettas mentioned in Section 6.2.2 might be doubled in width for instance, or instead we might choose a system of reflectors that actually orbits Mars. Such a configuration is shown in Figure 6.7 and consists of an annular mirror in a polar orbit that would be made to precess once per year, so that it remains "sun synchronous", perpetually orbiting parallel to the terminator. Its orbital plane is deflected backwards from Mars by light pressure and a balance point occurs where gravitational force, photon force and centrifugal force cancel. As with the statite system, Mars would be illuminated from behind the terminator at all latitudes, but from closer to the zenith than the horizon. If using a train of discrete circular mirrors, they could be spun about a central axis perpendicular to their surface in order to rotate and tumble once per revolution. Each point on the mirror is then effectively in an independent orbit and a slight additional spin and orbital eccentricity would make them sun synchronous throughout the year [50]. As with other designs, precise control of positioning could be gained by varying the incident light pressure with moveable sections.

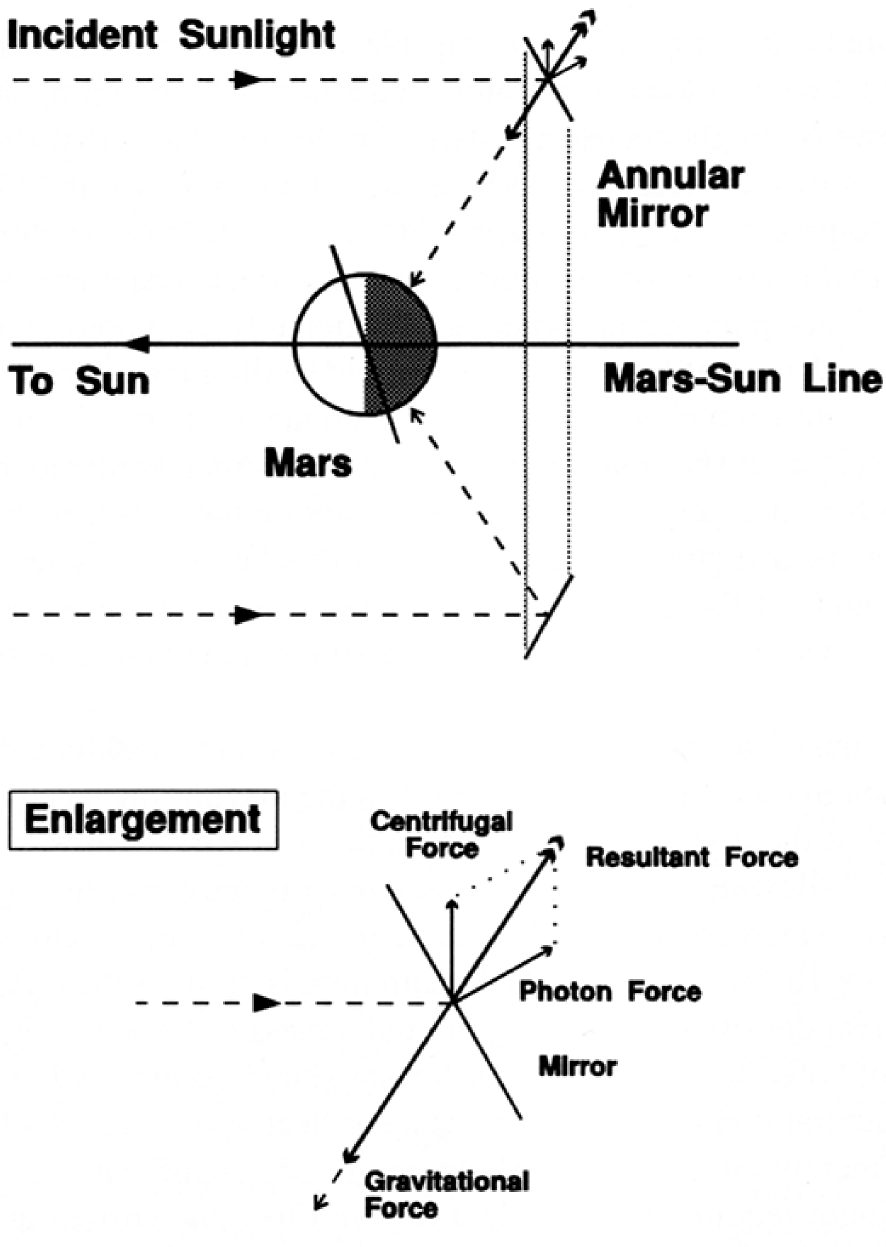

***Figure 6.7** Annular mirror in a sun-synchronous polar orbit about Mars. Light pressure deflects the mirror behind the planet until gravitational, centrifugal, and photon forces balance (after Birch, unpublished notes). Service areas would be illuminated from close to the zenith, rather than the horizon, as in the statite case (cf Figure 5.10b).*

The structural design of the mirror system in Figure 6.7 is not considered further here; suffice it to say that although it is much more modest than the magnifying soletta of Birch, interception of 6370 TW at the distance of Mars from the Sun still requires a large surface area of 1.1×10^{13} m^2. Allowing for the fact that the mirrors must be tilted to the solar beam by about 45^o we have to increase this area by a factor of $\sqrt{2}$ which gives a total area needing to be fabricated of $\sim 1.5\times10^{13}$ m^2. If 2 μm thick aluminium is used for the reflector surface then it would have an areal density of ρ_a = 5.4 g/m^2 and a mass of ~ 8×10^{10} kg (80 million tonnes). This is only about 80% the mass of the Earth solar shield designs of Early and Hudson [49,50], although the structural components of the space reflector system, which has to do a more precise job than merely intercepting sunlight, might add significantly to this estimate. The amount of aluminium required is equivalent to 5 times the current annual production, a quantity by no means unfeasible for a terraforming project. The metal would have to be mined in space, perhaps from the asteroid Vesta, which appears to have a spectrum similar to plagioclase-rich meteorites (Plagioclase ≡ $NaAlSi_3O_8 \leftrightarrow CaAl_2Si_2O_8$). As an alternative, it might be obtained and manufactured into thin foil on the Moon from anorthosite, a rock made mostly of calcium plagioclase, containing up to 30% Al_2O_3. The sections, which would be very similar to solar sails, could transport themselves to Mars, almost free of cost.

When operational, the effect of these mirrors, according to Equation (6.10) with f_s = 1.3, A = 0.19 and other parameters set as per Table 5.1, is to give an average Martian surface temperature of $T_{surf} \approx$ 232 K (-39°C), a temperature increase of $\Delta T_{surf} \approx$ +15°C.

6.3.1.2 A Mini-Runaway Greenhouse

The failure with the original CO_2 greenhouse scenario is that it seems likely that not enough loosely-bound gas would be available from shallow reservoirs. In a *synergic* scenario how ever, this is an advantage rather than a problem since too much carbon dioxide would interfere later with the engineering of a breathable atmosphere. Assuming the lower of the two estimates in Table 6.1 to be correct, then ~ 190 mbar of CO_2 could be available for release from the regolith. If it is loosely bound, outgassing could occur fairly quickly once warming commences. If, as is more likely, rapid desorption needs to be triggered more vigorously, then this might happen as a supplemental effect of hydrosphere production (see Section 6.3.1.5). Heating of deep seated ground ice, followed by the establishment of a hydrothermal circulation and the draining of aquifer contents to the surface, would have a flushing effect on the regolith, causing desorption and exsolution of CO_2 [47]. However, because of carbonate formation subsequent to Mars' last natural maritime epoch, we are postulating that only about a fifth as much CO_2 as the ~ 1 bar quantity proposed by Baker *et al.* will be released in this way.

It does not appear implausible that 190 mbar of carbon dioxide could be supplied to the Martian atmosphere in ~ 200 years. If it were possible to establish a classical runaway production (see Section 5.5.2), the bulk of the energy needed to drive this process would be sunlight.

6.3.1.3 Devolatilization of Carbonates and Nitrates

Since ecopoiesis is to be designed with eventual terraforming in mind, it would be desirable to drive more than 190 mbar of CO_2 into the atmosphere as photosynthesis could only convert this into a maximum of ~ 138 mbar of oxygen, which is towards the lower boundary of what is breathable. Initial planetary engineering should also increase the abundance of gaseous nitrogen and oxygen in the Martian atmosphere: to permit ecosystems to establish themselves in locales where nitrates are not present in the soil (by fixing atmospheric nitrogen) and to support aerobic respiration in plants. These gases must be released from chemical combination in Martian rocks or imported. If we discount the use of engineering structures on the scale considered by Birch — or resist the temptation to invoke self-reproducing von Neumann machines that turn themselves into atmosphere factories [53] — then we are left with nuclear mining or impact importation and devolatilization to do the job.

Nuclear mining is chosen here because of its advantages over the impact method in the following respects:

- It is an intrinsic method of planetary engineering not reliant on extra-planetary industry, or wasteful of extra-planetary resources.
- The potential energy contained in the *visible* Martian water deposits, in the form of deuterium, is about two orders of magnitude in excess of the demands of any likely devolatilization project.
- The ability to vary explosive yield and depth of emplacement mean that energy can be released with far greater precision and efficiency, exactly where it is needed.
- Deep, low yield explosions can be used to minimize surface damage.
- Ploughshare-type excavating blasts can dig landforms more sophisticated than crude impact craters.
- The principal activities of the exercise — prospecting, mining and refining large quantities of material, mass production of complex machines and drilling long distances of borehole and tunnel are already those in which the human race is experienced.
- There may be less of a need to evacuate the Martian population as the energy release is distributed among many more smaller, buried explosions.

Nuclear mining for carbon dioxide ceases being impractical if used on a much smaller scale than outlined earlier to devolatilize reasonably pure and thick carbonate deposits. In this scenario, it is proposed to produce just 30 mbar of CO_2 from the layered deposits in the Valles Marineris described previously in Section 6.2.1; if for whatever reason this region had to be preserved, then any other locality on Mars with carbonate sequences 2 - 5 km thick would similarly suffice. Strata this deep would be ideal for nuclear mining since their thickness would mean that a fewer number of larger yield explosives could be used, drastically reducing the cost. Their relative purity would mean that less energy would be wasted heating volatile poor rock, although sufficient contaminant to form a residual glass would be desirable. If the lacustrine hypothesis for the origin of the layered deposits is correct, then evaporite minerals may be present also. Assuming nitrogen is present in the ratio to CO_2 indicated for the Earth-scaling entry in Table 5.4, then devolatilization of Mariner Valley nitrates might produce an additional ~ 0.33 mbar N_2 and ~ 0.83 mbar O_2.

Ideal device yields for this task would range between 5700 - 88000 Mt, devices that are not implausible, being fabricated as long thin tubes containing thermonuclear fuel and with a non-fission detonator at one end (see Figure 6.4). They would be placed in bore holes drilled into the layered deposits so that the mid-point of the device coincided with the mid-point of the stratum. When triggered, a detonation wave passes down the length of the explosive sending a powerful shock wave out into the surrounding medium. The CO_2 gas and other volatiles would be vented directly to the atmosphere. The total yield required would be ~ 3×10^8 Mt from ~ 10^3 - 10^4 devices. The amount of ^{6}LiD thermonuclear fuel needed would be ~ 4.5×10^9 kg, the deuterium in which could be obtained from ~ 30 billion tonnes of ice, a globally averaged depth of ~ 0.2 mm. Obtaining the necessary lithium may be more difficult as the amount indicated is equivalent to about half of the Earth's mineable lithium reserves [38] and to obtain this in 200 years involves a five-fold increase the present rate at which it is extracted. If this is not practicable on Mars then there remains more than enough deuterium available with which to substitute the DD fusion reaction instead. Since the Valles Marineris is close to the Martian equator, the upper ~ 1 km of the layered deposits are likely to be devoid of ground ice and so we might expect only minimal quantities of water to be evolved.

Production of 30 mbar of carbon dioxide by nuclear mining would be a large, but plausible programme. Nuclear explosives already exist in the numbers required, although not the yield; scaling up this yield however may not be difficult and might consist primarily of obtaining more thermonuclear fuel. The location of all the activity in one geographical area might obviate the need for a global evacuation of the planet and would directly destroy only ~ 0.02% of the Martian surface. The Mariner Valley deposits would, of course, need to be thoroughly investigated before they were sacrificed to the cause of a habitable Mars. If substantial and massive nitrate deposits can be located elsewhere on Mars then the explosion of a further 5.6×10^6 Mt could serve to devolatilize a further 0.47 mbar N_2 and 1.2 mbar O_2.

At the end of two centuries of gaseous production, Mars' partial pressure of carbon dioxide will have risen to ~ 227 mbar, along with ~ 1 mbar of nitrogen and ~ 2 mbar of oxygen. Equation (6.10) predicts that with $pCO_2 = 0.227$, then $T_{surf} \approx 233$ K (-40°C) an increase of $\Delta T \approx +16$°C. The combined effects of both mirrors and CO_2 greenhouse, $f_s = 1.3$ *and* $pCO_2 = 0.227$, gives $T_{surf} \approx 251$ K (- 22°C) and $\Delta T_{surf} \approx +33$°C. Thus the two methods acting together give over half the warming increment needed.

6.3.1.4 Artificial Greenhouse Gases

The work of the *Nature* paper authors [6] showed that ~ 0.01 mbar of halocarbon gases that absorb in the infrared window region would warm Mars by about $\Delta T \approx +30$°C; the same quantity in an Earth like atmosphere would give $\Delta T \approx +40$°C (see Section 5.5.1). Such gases would not be adequate for warming Mars alone, but their successful use might be possible when applied in synergy with other methods.

The mirror/CO_2 greenhouse described above raises the surface temperature of Mars such that only an additional ΔT of 22°C is needed to reach the melting point of water. A mixture of long-lived, inert and UV-resistant, perfluoro gases (such as in Table 5.9) may provide a sufficient greenhouse effect to bridge this gap. The need to provide an, as yet unknown, uniform grey absorber would be less pressing. Carbon is abundant on Mars and so should be the elements sulphur and fluorine. The former of these pair was detected in the soil by Viking and is thought to exist largely as $(Mg,Na)SO_4$. The latter may have been concentrated as fluorite, CaF_2, by past hydrothermal activity. Assuming an average lifetime of 4000 years for these compounds (possibly a pessimistic estimate) about 40 billion tonnes of them, replenished at a rate of ~ 10 million tonnes per year, would be needed. This is only an order of magnitude higher than the present production of CFCs on Earth and is far from an impossible target in view of their vital role.

Assuming trace gases can be made to provide Mars with a ΔT of 30°C, then surface temperature rises to a global average of $T_{surf} \approx 8$°C — Mars would be above freezing. Of course this estimate is only very approximate as the greenhouse effect of water vapour would now also be very important. However, the point of the exercise, that of demonstrating the potential of synergy, is made.

6.3.1.5 Establishment of a Dynamic Hydrological Cycle

The above measures create a Mars with a warm surface where liquid water is stable. It is in fact similar to the planet envisaged by the standard terraforming paradigm, except that the atmosphere is only about a fifth as dense and most of the warming comes from direct anthropogenic forcing. However it would also be just as dry, requiring thousands of years to melt enough icy permafrost to supply the needs of a productive biosphere (see Table 6.2). It is *vital* therefore for any technocentric scenario of terraforming to address the need to speed up the creation of a surface hydrosphere. Thus, contemporaneous with the two centuries of planetary engineering described above would be activities intended to liberate water from sub-surface reservoirs.

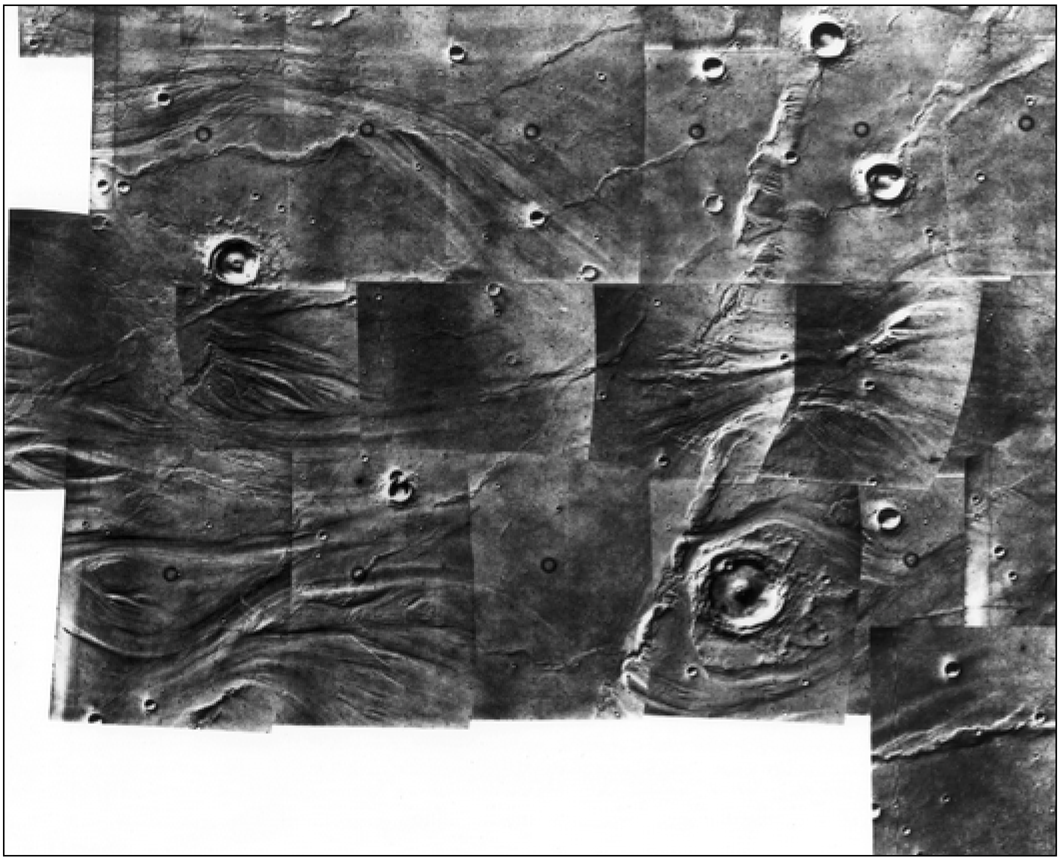

Plate 6.7 *The plains of Chryse, just to the East of the area shown in Plate 5.5. The deluges from Maja Vallis have spread out and eroded the surface. Resistant features have partially funnelled the flow through low points and gaps in the topography, cutting deep gullies in the process. Terraforming could be greatly accelerated if an engineering means could be found to repeat such outburst flooding, which brings water from below ground out to the surface. The scene is 155 km across. (Photo courtesy of NASA.)*

As was briefly outlined in Section 5.2.2, outburst flooding may have abruptly created large bodies of standing water several times in Martian history, on a surface that was previously dry (see Plate 6.7). This hypothesis, proposed in its grandest form by Baker *et al.* [47], is of obvious interest to terraformers because of the possibility that such floods might be repeated, greatly speeding up the accumulation of surface water and expanding the volume of the hydrological cycle. The parameters of this model are shown in Table 6.8

and describe Martian oceans of three different sizes, depending on which topographic contour is coincident with the shoreline. A reasonable maximum extent of any ocean is the 0 km contour, which roughly follows the boundary between the Southern Uplands and the Northern Plains. This full-blown Boreal Ocean is illustrated in Figure 6.8, along with the major zones of outburst flooding and the possible extent of Austral ice sheets, built up by the accumulation of snow. The data in Table 6.8 indicate that such a body of water would cover a quarter the area of the planet to an average depth of 1.7 km; spread out over the whole surface of Mars, it would be equivalent to a mean global depth of ~ 450 m. The enormous flow rates implied by the morphology of the outflow channels suggests that all of this water could have submerged the Northern Plains in just a few months to a couple of years.

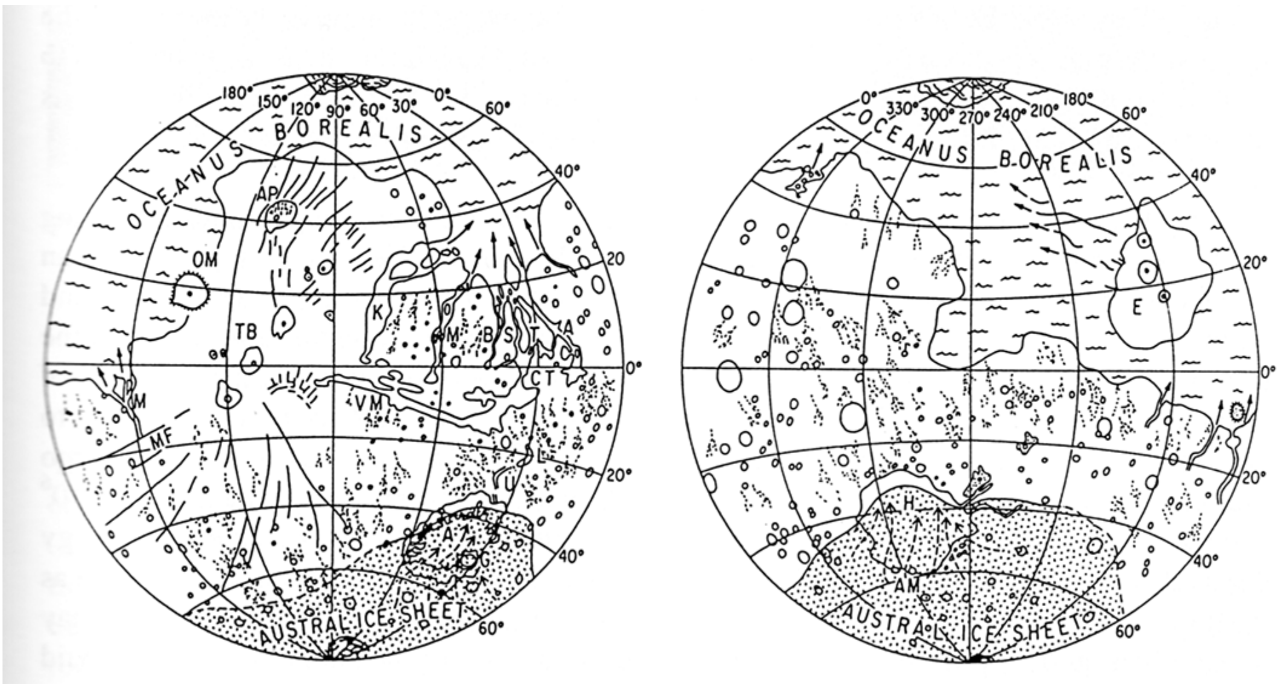

Figure 6.8 *Sketch maps of western (left) and eastern (right) hemispheres of Mars showing the maximum extent of the Boreal Ocean proposed by Baker et al.*[47] *Also shown are the possible size of the proposed austral ice sheet and flow directions of both flood water (solid arrows) and ice (dashed arrows). Patterns of dashed lines show general direction of flow od runoff channels. Key: TB = Tharsis Bulge; MF = Memnonia Fossae; VM = Valles Marineris; CT = Chryse Trough; E = Elysium volcanoes; OM = Olympus Mons; AP = Alba Patera; A = Argyre Impact Basin; H = Hellas Impact Basin. Outflow channels: U = Uzboi; L = Ladon; M = Mangala; K=Kasei; J = Maja; B= Shalbatana; S = Simud; T = Tiu; R = Ares. (Reproduced with permission from Ref. [47].)*

Evidently, such an ocean would be ideal for a terraformed Mars, buffering both the climate and biogeochemical cycles as occurs on the Earth. Perhaps however the release of this much is too ambitious a target for planetary engineers, since it involves completely draining a hypothetical deep aquifer from under virtually the entire Southern hemisphere; (for this reason it is also difficult to comprehend how this could have happened naturally). It may be much more feasible to create more modest seas, such as the smallest ocean listed in Table 6.8, covering ~ 10% of the planet's surface and being equivalent to a mean global depth of ~ 70 m. Whilst this would still leave Mars relatively arid compared with the Earth, it would be ~ 80 times wetter, in terms of the average mass of moisture per unit area, than the desert Mars of the standard paradigm.

TABLE 6.8 PARAMETERS AND FILLING RATES FOR A MARTIAN BOREAL OCEAN

	Water below	Martian topographic contour (km)	
	0	-1.0	-2.0
Volume (10^7 km^3)	6.5	3.1	1.0
Area (10^7 km^2)	3.8	2.8	1.4
Average depth (km)	1.7	1.1	0.7
Global equivalent water layer (m)	450	210	70
Fill rates:			
10^9 m^{3}s^{-1}	2 years	1 year	15 weeks
10^{10} m^{3}s^{-1}	11 weeks	5 weeks	10 days
Source zone thickness (km) at :			
25% porosity	2.6	1.3	0.4
10% porosity	6.6	3.2	1.0

Data taken with permission from Ref [47].

It may be that not all of this water would need to be melted. Baker *et al.* envisage the injection of ~ 3×10^{25} J of heat into ground ice by intruded magma over a period of about a million years. This melts ~ 5×10^6 km^3 of ice (assuming 5% of the heat goes into latent heat of fusion) and sets up a large circulating hydrothermal system, drawing in adjacent groundwater towards the thermal anomaly. The melting isotherm gradually rises towards the surface until, in the region of the Uplands/Plains boundary, especially where strata have become weakened by tectonic fracturing, the permafrost cap of the aquifer becomes unstable and bursts. The water backed up behind, 1 km or more higher than the elevation of the plains, is suddenly liberated in a huge torrent — collapsed, chaotic terrain and outflow channels result and a temporary ocean is born (see Plate 6.8).

Assuming these aquifers have been recharged by a past hydrological cycle, planetary engineers must substitute for the past magmatic heat source by artificially injecting heat to great depths. This might be done much more efficiently than natural magmatic heating since the most water-rich deposits might be preferentially targeted. In addition, steps could be taken to heat, fracture and destabilize the permafrost lid of any aquifer, facilitating the release of its contents, especially if the water within is liquid and gravitationally unstable.

The most feasible way these measures could be achieved is by returning to nuclear mining methods. Pessimistically, we might suppose that all Martian aquifers are frozen at the mean surface temperature and we need therefore to expend energy to heat both rock and ice by ~ 60^{o}C and additional energy for latent heat of fusion. The energy required to raise the temperature of the rock is ~ 54,000 J/kg and to melt the ice is ~ 584,000 J/kg (see Figure 6.2); so if 1 m^3 of regolith aquifer consists of 2340 kg of rock and 92 kg of ice (i.e. 10% ice by volume) then to heat this to 0^{o}C and to melt the ice requires ~ 1.8×10^8 J. Of this, ~ 5.4×10^7 J goes into melting the ice, which represents 30% of the total heat input. Overall, we must inject ~ 2×10^6 J to melt 1 kg of water; to produce a mean global depth of 70 m (~ 10^{19} kg), the total energy demand is ~ 2×10^{25} J ≈ $5\text{x}10^9$ Mt. However, since the melting isotherm on Mars may be as shallow as 1 - 3 km, much of the accessible ground ice will be warmer than -60^{o}C, or may already be liquid.

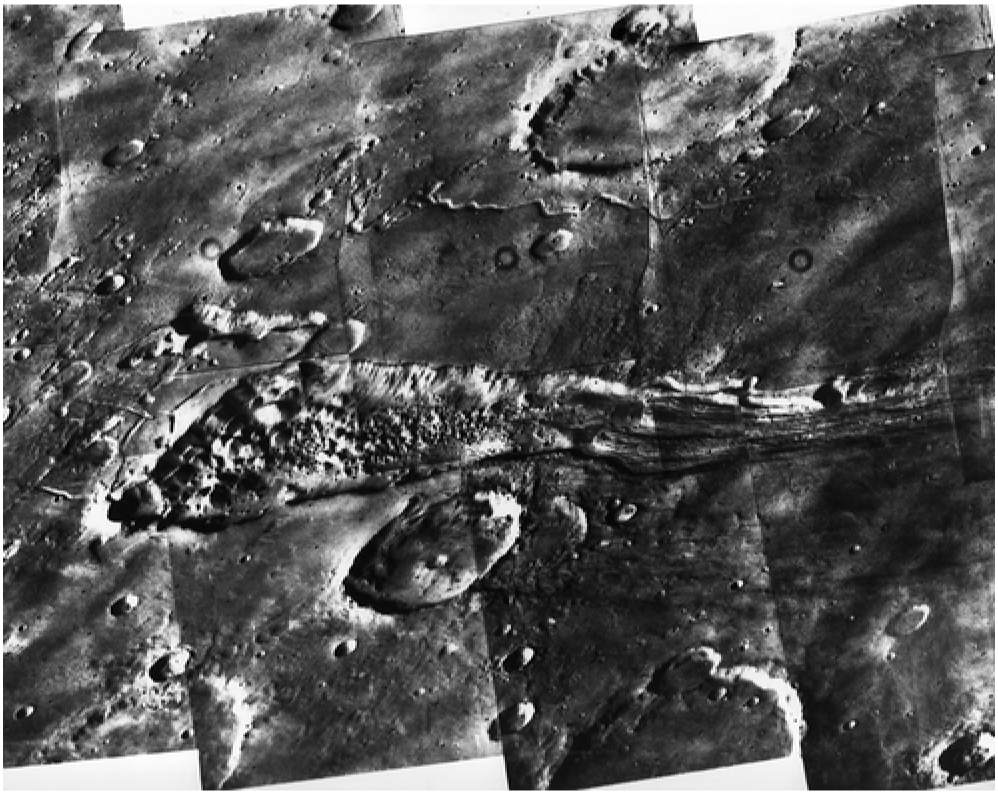

Plate 6.8 *The origin of an outflow channel from a 40 km depression where the ground has collapsed to form chaotic terrain (1°S, 42°W). Water withdrawn from beneath the surface flowed towards the East along a 20 km diameter channel to connect with Simud Vallis. Similar features might be created by the artificial melting and draining of aquifers by planetary engineers. (Photo courtesy of NASA.)*

Optimistically therefore, we might propose that the Upland aquifers contain liquid water, prevented from draining any further downhill by the permafrost at the Uplands/Plains boundary. It may merely be sufficient therefore to disturb this layer in order to trigger renewed outburst flooding. If we model the permafrost cap as a wedge of dry rock 2 km deep and 300 km wide (the rough overland distance between 0 and 2 km contours in favourable areas) and assume that we need to fracture and heat up by 60°C a length of boundary equivalent to a third of the planet's circumference, then the energy requirement is $\sim 3\times10^{23}$ J $\approx 7.5\times10^{7}$ Mt, almost two orders of magnitude less than the above estimate.

To create our Boreal Sea in 200 years therefore entails a power production between ~ 50 - 3200 TW, considerably in excess of the entire power usage of terrestrial civilization and equivalent to ~ 0.2 - 15% of the Martian insolation. However, comparisons with commercial power production do not apply to the *explosive* release of nuclear energy, which involves the uncontrolled burning of fuel with an energy density over ten million times that of coal. More revealing as to the feasibility of such a scheme is whether the raw materials to fabricate the explosives are available. The amount of deuterium required (assuming the DD reaction is used) is between ~ 1 - 70 million tonnes which could be obtained from 32 - 2000 billion tonnes of ice (≈ 3.2 - 12.6 km cube). This would need to be mobilized at the feasible rate of 160 - 10,000 million tonnes per year. To clear a total borehole volume of $\sim 10^{10} - 10^{12}$ m^3 in two centuries is also quite plausible given that civilization on Earth shifts this mass of rock annually. If the non-fission trigger for each charge can be reduced to a complexity no greater than that of an automobile and can be mass produced, then the manufacture of the number of explosives presents no conceptual problem — there are 540 million motor vehicles on the roads of Earth today [54]. The logistics of the project therefore are familiar, at least on a scale of terrestrial civilization as a whole. Whether the scheme would ever be viewed as practical from all perspectives is another matter and depends entirely on the true water content of the Martian regolith, its physical state and distribution. These unknowns will only be dispelled by an exhaustive geological survey of Mars by people living there.

Assuming a maritime Mars can be recreated by triggering the source aquifers of the outflow channels to discharge just one more, then this active intervention to create a Martian hydrosphere might succeed on a timescale ~ 4 orders of magnitude faster than by passive methods. Although nuclear mining techniques have impractical and undesirable attributes when considering the production of a massive atmosphere [14], these are considerably relaxed in the case of mining for an ocean. Explosions would not all need to vent to the surface but would be contained, the intention of many of them being to heat the crust at depth. The destruction of surface strata would be less, except where outburst flooding and ground collapse occurs, sweeping away old chaotic terrain in the torrent and creating new. These geologic features however are natural to Mars and are to be preferred to the blunderbuss spread of impact craters than would result from bombarding Mars with comets. Pure, surface deposits of ice are not required, a 90% rock impurity being assumed in the calculation and any CO_2 adsorbed in the rock would be carried to the surface with the water. Devolatilization products are also expected but are difficult to estimate because very impure deposits are being worked: if all the aquifer rocks contain up to 10% carbonate minerals contaminated with nitrates in the fraction assumed in Section 6.3.1.3 (an unlikely proposition), then an additional 10 - 50 mbar CO_2 might be produced along with up to ~ 0.5 mbar N_2 and ~ 1.25 mbar O_2. For the purposes of this scenario however, we ignore this extra gas production.

This violent transformation of Mars would involve the evacuation of settlers from roughly north of 20°S and perhaps the entire planet, though the benefits for the future that a Boreal Sea would bring might be worth it.

6.3.1.6 Stage 1: Completion

After about 200 years, Mars would have average surface temperature of ~ 8°C and an atmosphere with a total pressure ~ 240 mbar, consisting of $pCO_2 \approx 227$ mbar, $pN_2 \approx 1$ mbar $pO_2 \approx 2$ mbar and ~ 10 mbar of water vapour. A depth of ~ 70 m of water will have been released by nuclear mining and further melting of ice by natural processes will be underway. About 10% of the Martian surface would be covered with water (see Figure 6.9), the depth of the Boreal Sea reaching 1 km in places. Evaporation from this sea will provide the material for a hydrological cycle, moistening the Southern Uplands through precipitation, ponding in crater lakes or trickling back Northwards via the ancient runoff channels. The ozone produced from the small amount of oxygen present might be sufficient to stop ultraviolet radiation down to wavelengths of 215 nm, but would still allow some flux between 195 - 215 nm to reach the surface (see Section 3.4.3). However, aquatic life under > 10 cm of water, plants protected by a cuticle layer over their active cells or microbial mats that grow beneath a shielding layer of dead matter could survive. Conditions would now be similar to those on the early Earth and *much more habitable than the desert world of the standard paradigm*. Mars would be ready for a different kind of ecopoiesis and would have been rendered so not by the passive means of Chapter 5, but by an intensive effort on the planet's surface comparable with aspects of the present industry of the Earth, aided by manufacturing and construction in space.

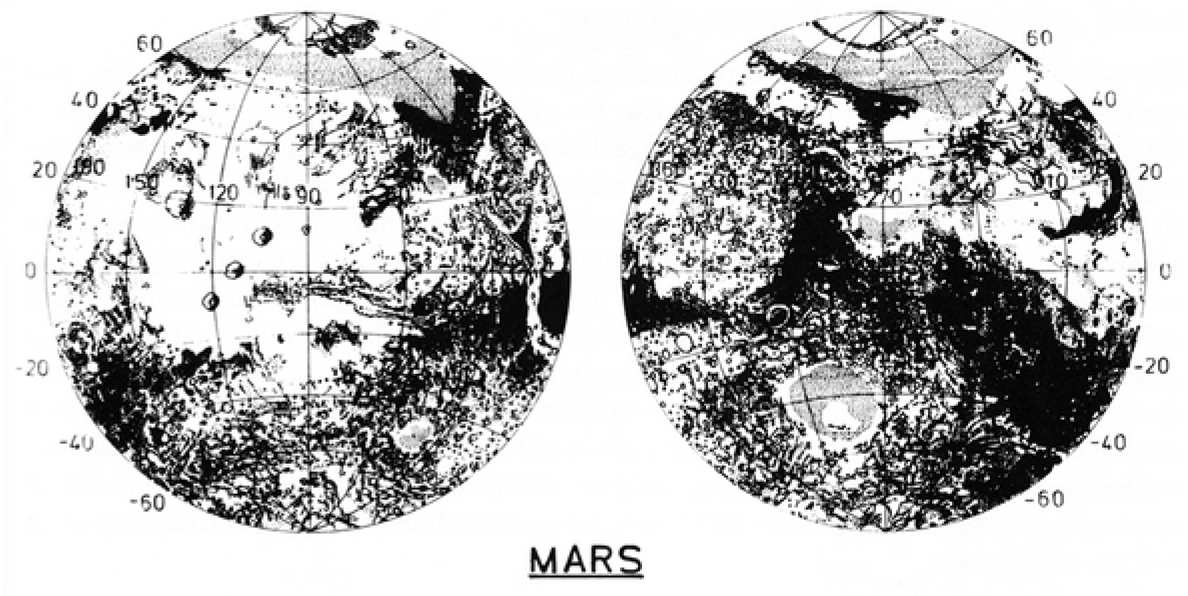

Figure 6.9 *A Lambert projection map of the result of flooding Mars with 70 m of water (to the –2 km contour). The two most substantial bodies of water (stippled areas) would be a ring-shaped Boreal Sea and a circular sea in the Hellas basin. (Artist: Roy Harvey.)*

Making Mars fully habitable would require much more time and a technological and industrial capability of a higher order.

6.3.2 Stage 2: Total Terraforming

The aim of this second stage of Martian terraforming is to create an Earth like environment suitable for human beings: a planet with a breathable atmosphere, an ozone layer, a comfortable range of surface temperatures and a diverse biota. Long term survival of such a regime would require biogeochemical recycling of elements essential for life and the replenishment of the atmosphere. Table 5.6 shows that the prime requirements for a habitable Mars are $T_{surf} > 0^oC$, $P_{atm} > 380$ mbar, $pN_2 > 285$ mbar, $pO_2 > 95$ mbar, $pCO_2 < 10$ mbar and an elimination of the remaining flux of dangerous UV radiation reaching the surface. Whilst the partial pressures of nitrogen and oxygen must be increased from their Stage 1 values, the partial pressure of carbon dioxide must be *decreased* to below the toxic threshold of 10 mbar. This means that as this reduction proceeds, an extra warming increment of $\Delta T > 15^oC$ would be needed to compensate for the reduced CO_2 greenhouse effect.

6.3.2.1 A Breathable Partial Pressure of Oxygen

The principal determinant of a breathable atmosphere is the partial pressure of oxygen. Assuming that we also wish $pCO_2 = 10$ mbar (to maximise the remaining CO_2 greenhouse effect), then 217 mbar of CO_2 from the Stage 1 atmosphere are available for processing into oxygen. A characteristic timescale for Stage 2 can be estimated from the time it would take to carry out the chemical conversion. Mars would effectively have to be transformed into a planet-wide atmospheric processing factory optimised for producing oxygen and disposing of organic carbon as efficiently as possible. Covering Mars with artificial machinery [53] to achieve this task is not an attractive solution when we already have natural self replicating machines that can do it, using the energy of sunlight — i.e. photosynthetic plants. Mars can therefore be lived on whilst terraforming proceeds, the Martian landscape having some semblance of a natural environment. However, the timescale could be very long; those estimates previously described in Section 5.6.2 indicating that it could be > 100,000 years, and only as short as this if some unknown process sequesters 100% of the organic carbon that has been fixed to protect it from re-oxidation.

This pessimistic outlook results from the ecocentric idea of endowing Mars with a primitive biosphere and then letting it evolve free from any conscious direction. In such a situation, the natural tendencies of ecosystems to approach some climax state where production ≈ consumption would result in biogeochemical cycles being balanced to the extent that any long-term drift towards an Earth like state might take as long as it did naturally on the Earth — i.e. billions of years. The obvious answer to this problem is to engineer a more habitable environment in the first place where the biota can be more productive and to *use the biosphere itself as a conscious planetary engineering tool* by deliberately perturbing it away from climax so that matter cycling does not balance. As Fogg noted [5], *"There would be no future terraforming of Mars without further planetary engineering* [beyond ecopoiesis] *involving conscious management of matter cycles to drive the biogeochemical state of the planet in the desired direction."*

What this means is illustrated in Figure 6.10. The maximum practical amount of biomass resulting from net primary production (NPP) is deliberately cropped and sequestrated, isolating it from recycling via respiration and decay so that free oxygen accumulates. The best way of doing this might be to bury the material in large landfill sites to emulate what occurs naturally on Earth where organic carbon accumulates in sedimentary basins (on a far longer timescale and much less efficiently). The great abundance of impact craters on Mars might prove very convenient sites in this regard, in that no excavation will be required, merely the covering of the area with soil once it is full. Most biomass could probably be buried in a raw state; however to avoid depleting ecosystems of many vital mineral nutrients, planetary engineers might have to recover them from some of the material before burial. If a combustion process is used, such as in the manufacture of charcoal, then volatile elements could be recovered from flue gases, turning the material to be buried into a sort of "artificial coal." These operations will need an industrial energy subsidy and the process is therefore equivalent to a scaling up of the managed plantations described in Section 4.2.1 intended to draw down CO_2 from the Earth's atmosphere (compare Figure 4.7 with Figure 6.10). In both these cases this *active management*, involving continuous cropping, sequestration and fertilization, maintains ecosystems in a state known as *pulse-stabilized sub climax*, a compromise between youth and maturity, where net community production (NCP) remains high and the conversion of a CO_2-rich atmosphere into an oxygen-rich one can proceed at a maximum rate [5].

At the end of Stage 1, planetary engineering leaves us with a warm and moist planet suitable for the widespread seeding of life. Pioneering ecosystems, adapted or genetically engineered to be productive in conditions of both low pO_2 and water availability, and high pCO_2 and UV flux, could colonize the Martian plains. The principal primary producer might be a fast growing moss or grass that sequesters some of its fixed carbon in substances that are difficult to digest. In the absence of grazers or rapid decomposition of dead material, a large fraction of NPP therefore might accumulate as beds of peat, which could either be left to stand, or quarried for deeper burial as the situation demands. Aquatic ecosystems could be based on the

NPP of algae, the relative lack of consumers meaning that more dead biomass will accumulate on the floor of bodies of water, escaping immediate reconversion back to CO_2.

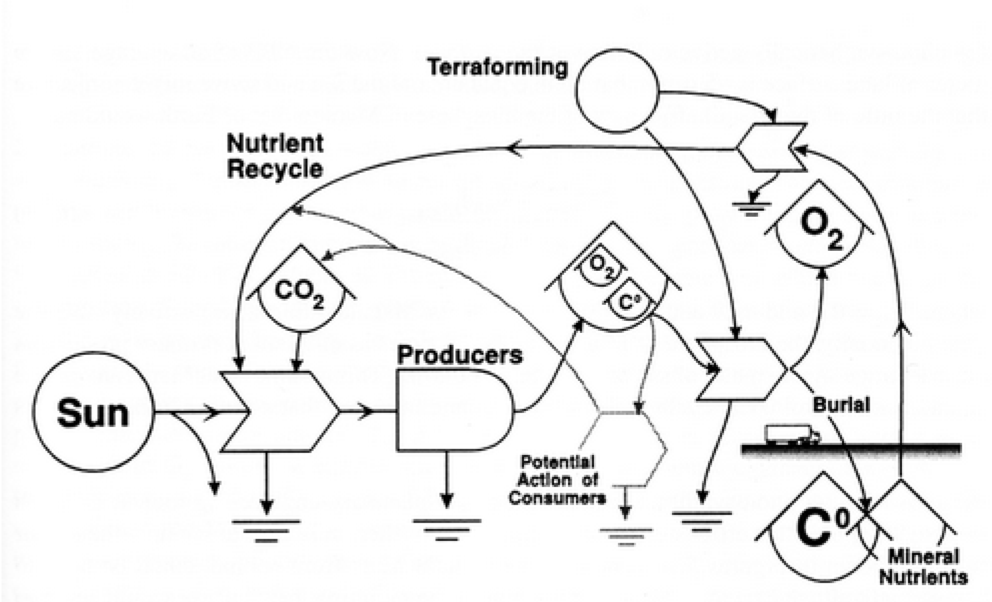

Figure 6.10 *The Martian biosphere as a planetary engineering tool for manufacturing atmospheric oxygen. Active management of ecosystems and deliberate burial of biomass (involving an energy subsidy) maximizes net conversion of carbon dioxide into oxygen. Artificial recycling of nutrients may be needed also. (Energy/mass flows are shown undifferentiated.)*

At an insolation of 1.3 S_0, the global average solar flux at the top of the atmosphere would be 191 $W/m^2 \approx 6x10^9\ J/m^2/yr$; at 100% efficiency, photosynthesis would use this energy to manufacture oxygen at a rate of ≈ 12,662 mol $O_2/m^2/yr$. Although Mars would still not be habitable for a diverse biota, it may be reasonable to postulate that both land and aquatic ecosystems specifically designed for the planet can be made as efficient as those on Earth. This efficiency is ~ 0.05% for the utilization of top of atmosphere sunlight and about ~ 0.2% for photosynthetically active radiation at the surface. Now the NPP of an average square metre of land surface is ~ 5 times that of an equal area of the sea and so we might conjecture that the ratio of the overall efficiency of the biosphere of Mars to that of Earth will be:

$$(5f_{land} + f_{sea})_{Mars} / (5f_{land} + f_{sea})_{Earth} \qquad (6.11)$$

where f_{land} = 0.9 and 0.29 and f_{sea} = 0.1 and 0.71 for Mars and Earth respectively. We see therefore that, potentially, the biosphere of Mars could be ~ 3 times as efficient at primary production on an average square metre of surface than that of Earth. (This of course assumes that Mars can operate an adequate hydrological cycle with its low sea/land ratio and no other limiting factors apply).

Because Martian photosynthesis is to be used as a planetary engineering tool, it is worth seeing how this efficiency might be improved further. It is easy to see how the mirror systems shown in Figures 5.10b & 6.7, which light Mars from behind, could be used to banish night altogether. A modest illumination of the night-time hemisphere would serve to reduce the net consumption of oxygen due to the respiration that plants carry out in darkness. Moreover, the conditions of high pCO_2 and low O_2 that obtain at the end of Stage 1 would help to suppress photorespiration, a wasteful process in C3 plants that competes with photosynthesis. Roughly 50% of gross production is lost by these two processes and so their elimination might permit a further doubling of the efficiency of Martian NPP to ~ 0.3%. We thus postulate a biosphere on Mars optimised for planetary engineering that is 6 times as efficient at manufacturing biomass as is that of the Earth. Extrapolating to higher values than this [25] on the basis of production figures for plants grown under carefully controlled, artificial conditions may be unrealistic. Whilst the biosphere of Mars will have to be actively managed, it will not be practical to constantly attend to every square metre.

The efficiency of oxygen production on Mars will depend on that fraction of NPP that is sequestered. Since we are assuming deliberate, rather than fortuitous, burial is occurring then we are free to choose a much higher value than is characteristic of the biosphere of Earth. However, it is perhaps unrealistic to conceive of Martian ecosystems being entirely devoid of heterotrophic organisms and so some production will be lost to respiration and decay. It will be desirable to enable some natural recycling of matter internal to ecosystems, removing only that biomass which has the highest ratio of carbon to any other nutrient element. Since it seems feasible to recover about 50% of the biomass from energy plantations on Earth [55], we assume this on a planet-wide scale for Mars, giving a total efficiency at which top of atmosphere sunlight is utilized for oxygen production of ~ 0.15%. This is undoubtedly an ambitious target but does not necessarily mean than the entire surface of Mars is being continually farmed for oxygen. The baseline biospheric efficiency that was chosen (0.05%) is an average of productive and unproductive natural ecosystems. It is therefore possible to conceive of a lesser fraction of the area of the planet being covered with highly productive "oxygen plantations" capable of the same task — a half, or two thirds of Mars where conditions perhaps remain too arid for luxuriant growth might be left as wilderness.

Plantations of trees however, will not be viable from the beginning of ecopoiesis since the partial pressure of oxygen (2 mbar) is too low to permit adequate root respiration. The next 18 mbar of this gas therefore will have to be generated as part of terraforming by the pioneering ecosystems mentioned above. Assuming planetary engineers attain the oxygen production efficiency that has been calculated (0.15%), then ~ 32 TW of solar energy is available with which to change the composition of the Martian atmosphere. About 600 years would be required to raise pO_2 to 20 mbar which would lower P_{atm} to 235 mbar and pCO_2 to 204 mbar; the amount of biomass fixed would be equivalent to a ~ 1 m global layer of peat. Once this stage is reached sufficient oxygen is present to generate an adequate ozone layer and to permit the growth of higher plants. From this point onwards, it is possible to grow forests on Mars (engineered to withstand high pCO_2) and these may be the preferred tool of planetary engineers for continued oxygen production. Ninety percent of the land biomass on Earth is in the form of tree trunks and so forests on Mars would accumulate massive standing crops of biomass which would only need to be sequestrated as they approached maturity every ~ 100 years. Wood is also convenient to gather, transport and store and does not contain a large proportion of nutrient elements, having a C:N ratio about ten times higher than leaves and other fleshy tissues [56]. Nevertheless the biological generation of a breathable atmosphere would be a long drawn out and exacting task, involving the disposal of ~ 5.7×10^{17} kg of cellulose. The density of hardwood is ~ 700 kg/m^3 and so a volume of 8×10^{14} m^3 would have to buried, equivalent to a globally averaged thickness of ~ 6 m. Fortunately, there are a number of natural features on Mars which accommodate such a volume, such as the Hellas basin which is 1800 km across, enclosing ~ 5×10^{15} m^3. The required annual burial rate of 27 billion tonnes is only ~ 1% of the present mobilization capacity of terrestrial civilization.

A near-pure oxygen atmosphere on Mars will not be desirable because of flammability problems. If we assume therefore that as oxygen builds up in the Martian atmosphere nitrogen is added in a molar ratio of 3:1

(see Section 6.3.2.2), then it would take ~ 7100 years to reduce pCO_2 to its upper breathable limit of ~ 10 mbar and the total atmospheric pressure would be $P_{atm} \approx 600$ mbar, with $pO_2 \approx 146$ mbar, $pN_2 \approx 435$ mbar and the remainder as water vapour. The atmosphere would now be breathable, with as much oxygen in the air as ~ 3 km above sea level on Earth.

6.3.2.2 A Solution to the Nitrogen Problem

As gaseous oxygen accumulates on Mars, it would be ideal to add nitrogen so that after 7000 years its proportion of the atmosphere by volume will be 0.75. Biological methods of releasing nitrogen from nitrate deposits will be about a thousand times too slow and industrial methods may have difficulties too, especially if nitrate deposits are widely mixed up with other rocks and are thus more difficult to obtain. In any case, if the Martian inventory of nitrogen is only 300 mbar (see Table 5.4), and even if this could all be mobilized, we would then end up with a ~ 450 mbar atmosphere containing ~ 33% oxygen. This fraction of oxygen may render the planet's flora dangerously liable to combustion, although for Mars this may be counteracted by the lower gravity lessening the strength of convection and hence the flow of oxygen to the flames [25]. If the amount of nitrogen available on the planet is much less than this then an intrinsic solution is insufficient. *Importation of the necessary amount from elsewhere in the Solar System would be the only remaining option.* Such a conclusion however does not necessarily spell the death of any attempt terraform Mars but it does entail pushing one's restraint on speculation further into the future. Since a biological timescale of > 7000 years is already under discussion, speculations concerning a fix to the nitrogen problem over such a long period can be made without resorting to fantastic or grotesque claims about future technology.

The atmosphere of the Titan, the satellite of Saturn, might be one of the favoured locales for nitrogen mining. It has more than enough available for Mars' needs and the gas is already ~ 90% pure and cold so that liquefaction would be easy. The energy required to transport a unit mass from Titan to Mars is less than for Venus, the other gaseous nitrogen source that might be tapped and the trace constituents of the Titan atmosphere, such as methane, might also be useful for their greenhouse effect. Despite the fact that massive atmospheric mining will not be a near future planetary engineering technique, there have been a number of proposals for how it might be done [40]. The details are not considered further here, but when compared to the mass transfer rates considered feasible by Dyson (see Section 6.2.4) the requirements of this scenario are quite modest. Dissipation of the kinetic energy of the nitrogen mass stream in the atmosphere of Mars would generate heat at a rate of ~ 100 - 2000 TW, depending on the impact velocity. The process could therefore augment other methods of warming the planet.

6.3.2.3 Topping Up and Maintaining the Martian Seas

If the 70 m of water produced during Stage 1 is sufficient for the needs of a Martian biosphere, further water production could be left to the passive process of melting ground ice by heat conduction. After 7000 years an additional ~ 5 m of water would be available — an amount that would not greatly alter the appearance of the planet (see Figure 6.9).

A dynamic hydrological cycle would become established after Martian ocean formation, which, as on Earth, would be crucial for the continuing supply of fresh water. Terraforming a planet with an immature cratered landscape however could pose a problem for such a cycle because precipitation onto high ground could become trapped and prevented from draining back into lowland seas from whence it came [57]. The extent of this potential problem on Mars is difficult to assess; whilst the Southern uplands are cratered, the ubiquitous runoff channels could provide ready made drainage networks (see Plate 6.9). Nevertheless it is interesting to address this potential problem with a rough calculation to give an impression of the magnitude of any technical fix that might be needed [5].

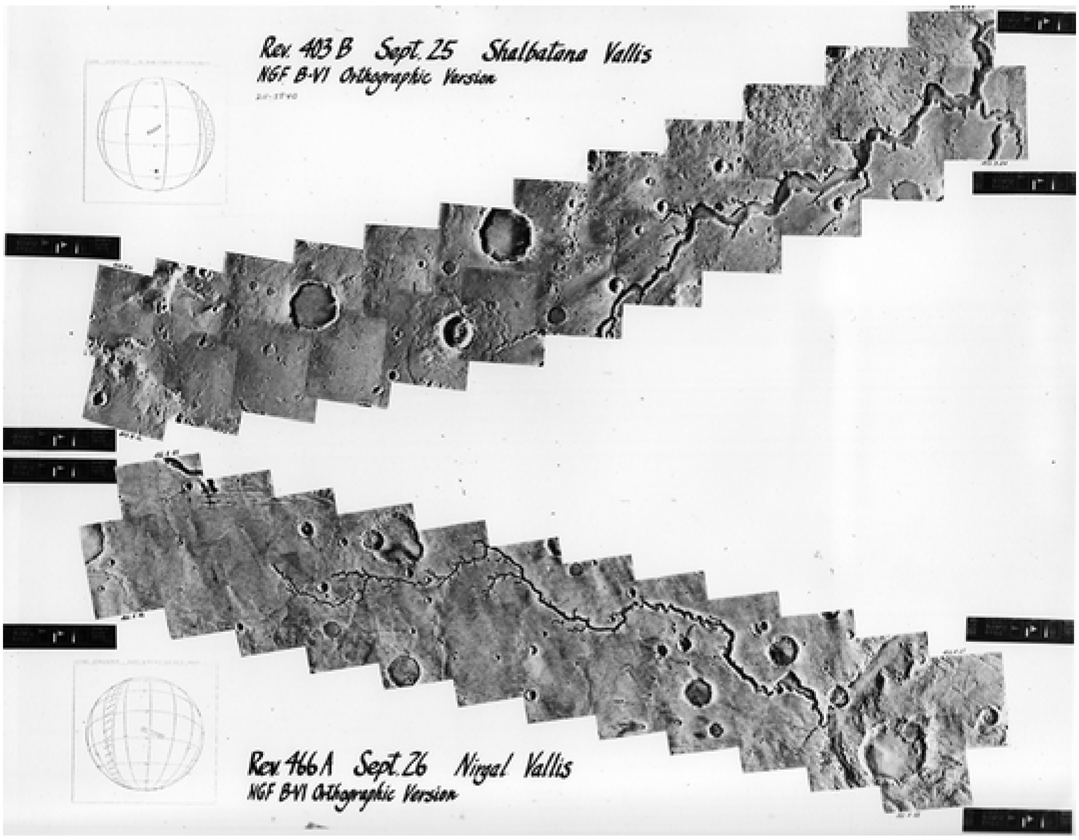

Plate 6.9 *The ancient drainage networks in Mars' southern hemisphere will facilitate, although not completely solve the problem of the "downhill" branch of the hydrological cycle. Nirgal Vallis, seen here at 28°S, 40°W, is 800 km long but drains only a narrow band adjacent to the trunk stream. (Photo courtesy of NASA.)*

On the Earth the rate of global precipitation is ~ 5×10^5 km^3/yr; 80% of this rain falls straight back onto the oceans, so the land receives ~ 10^5 km^3/yr. Scaling to Mars, we multiply by the ratio of planetary surface areas (0.28) and the ratio of the fraction of each globe covered with water (0.14), (the post-terraformed geography of Mars being that of Figure 6.9). Assuming further that 50% of land precipitation occurs in the Southern hemisphere and that a third of the return is dammed in unwanted crater lakes, gives the volume needing to be dealt with artificially as $10^5 \times 0.28 \times 0.14 \times 0.5 \times 0.33 \approx 650$ km^3/yr. Now, civilization on Earth already has a capacity in long distance inter-basin water transfer systems of ~ 300 km^3/yr, the total diversion of fresh water for other purposes is well over an order of magnitude higher than this [58]. Thus, should there be a need to build canal systems on Mars so as to optimise the irrigation of the planet, it would require mostly knowledge and ability already accumulated by terrestrial civilization. In fact by controlling this proportion of the return flow of a Martian hydrological cycle, a substantial energy return in the form of hydropower would be possible. Exploitation of the comparatively rapid 1 - 2 km drop in height characteristic of the boundary between Southern uplands and Northern plains could generate ~ 100 GW, a similar order to that produced currently on the Earth. In this case conscious management of Martian matter cycles and of the affairs of a Martian civilization would be one and the same thing.

6.3.2.4 Stage 2: Completion

Once planetary engineers have reached their targets, in terms of the desired environmental parameters of Mars, their control and diversion of the planet's biogeochemical cycles can be reduced. Artificial mass flows such as cellulose burial and nitrogen importation would be greatly scaled down or stopped altogether and Mars would now be free to receive a complete inventory of heterotrophic organisms. Martian forests would be allowed to develop to maturity. Individual ecosystems and hence the biosphere as a whole would naturally tend towards an ecological climax. Global matter cycling will then be balanced, bioregenerative and autonomous and would have no further net effect on the composition of the atmosphere. *Achievement of this state of affairs might therefore be used as a convenient definition of the completion of terraforming* [5].

Mars would now be a habitable planet, with a breathable atmosphere, an effective ozone layer and a diverse biosphere (see Plate 6.10). However, its terrain will be mostly land rather than ocean. There will be just two substantial bodies of water, the Boreal Sea, situated in a ring about the North pole and a circular sea centred on 45°S within the Hellas basin. Numerous lakes and small seas confined within crater walls and upland basins will be scattered about the Martian landscape, all ultimately connected to the Boreal Sea by rivers or canals. The dominant biomes might be equivalent to those of the temperate continental interiors of the Earth.

It was emphasised in Section 2.7.5 that a Martian biosphere could provide a life support system that would not require the day-to-day technological maintenance of an enclosed habitat. This is wholly true of the anaerobic Mars of the standard paradigm where a massive CO_2 atmosphere is created with enough greenhouse effect to keep the planet unfrozen. As far as a fully terraformed Mars is concerned, some degree of artificial regulation will be required, although not so much for internal biological processes — the biosphere would be so voluminous that any autogenic changes would develop over decades to centuries, as opposed to minutes or days, and could be countered by fairly modest measures. However, the planet will still need an technological infrastructure engineered to maintain a habitable temperature.

This is especially because of one outstanding problem that would have to be solved by the end of Stage 2, namely the provision of an extra warming increment to compensate for the decreased greenhouse effect of CO_2 that has been reduced from 227 mbar to 10 mbar. A ΔT_{surf} of ~ 15°C would be required, rising to ΔT_{surf} ≈ 25°C if the albedo of Mars were to rise to an Earth like value of 0.3. The albedo of a terraformed Mars is difficult to estimate. Extensive coniferous forests and bodies of open water would darken the surface, but this might be countered by the reflectivity of increased cloud cover and surface ice. Provision of this extra warming increment should not be a serious difficulty. Increased production of trace greenhouse gases, both artificially and biologically, would boost the greenhouse effect. Since many microorganisms are known to excrete greenhouse gases such as methane, nitrous oxide and ammonia, and some are thought to be capable of breaking down CFC molecules [59,60] (and hence might be able to synthesize them), then it might be possible to cybernetically engineer organisms to regulate the temperature of Mars above freezing. Other options would be to increase the surface area of space reflectors, or to generate the energy on the surface of Mars itself from nuclear power plants, which dump heat directly to the surrounding environment [61].

Plate 6.10 *Mars as a habitable planet, the Boreal Ocean covering what we know as the Northern plains. Mars as is was perhaps in the Hesperian and Mars as terraformers might make it. (Artist: Michael Carroll.)*

To reduce the criticality and volume of any maintenance cycle, it makes sense therefore to distribute the responsibility of warming Mars between a number of different techniques, one possible way being to combine the warming increments of orbiting mirrors, artificial greenhouse gases and a 10 mbar CO_2 greenhouse effect. The CO_2 concentration in the atmosphere will be stable, so long as the biosphere is at ecological climax. Artificial greenhouse gases would have to be replenished but, since they might have atmospheric lifetimes of a few millennia (for perfluoro compounds), they would buffer climate change over that time period even if manufacture, which would only be required at rates already possible for terrestrial civilization, was to cease. Only elimination of the orbiting mirrors would have a rapid effect on the terraformed climate (a timescale of weeks), however the entire mirror system is most unlikely to fail at once, unless by deliberate act of destruction. Spare mirrors could be stored in convenient locations in folded form to be deployed in an emergency and to obviate the need for any sudden increase in demand for material over and above the minimal flux required for routine repair.

None of these concerns however would impact as intimately and ceaselessly on the everyday lives of inhabitants as those issues of habitability facing the occupants of contained biospheres. The quality and expense of life on a terraformed Mars will be that of living on a boundless planet, rather than a bounded greenhouse.

6.3.3 Long-Term Maintenance of the Terraformed Environment

Having briefly considered short-term matter cycles and the terraforming infrastructure — the concerns relevant to the population that actually terraforms Mars — it is of considerable academic interest to consider those long term components of biogeochemical cycles that bring about a slower but more intractable change over geological timescales. As was noted in Section 2.7.3, the Earth's biosphere is not entirely closed to matter, both losing to and gaining material from the underlying lithosphere. The chemical balance of the biosphere is thus influenced by the rock cycle: sediments eroded off the land into ocean basins become buried and are tectonically subducted to great depth where physical and chemical metamorphism occur; some of this rock is eventually transported upwards rejuvenating the land surface by volcanism and mountain building. Essential volatiles and nutrients such as CO_2 and phosphorous, that would otherwise be irreversibly trapped under the sea floor are returned to the biosphere as by-products of this escape of the Earth's geothermal energy. Thus, it has been suggested that, irrespective of which terraforming paradigm is brought into reality, long term habitability of a planet without plate tectonics, such as Mars, is very doubtful [57]. Within $\sim 10^7$ years, much of the atmosphere would become mineralised into the crust by chemical weathering, essential biogenic elements would become trapped in inaccessible sediments and the land surface itself eroded down to sea level. Whilst such long term problems are unlikely to trouble many generations of Martians, it does make the future bleak for the ecocentric vision of ecopoiesis. Any Martian Gaia that is created is doomed to failure, in the absence of renewed planetary engineering, in a timescale equivalent to one geological epoch unless ecosystems can independently evolve biological innovations that might counter the degradation of their environment.

The technological intervention in biogeochemical cycles required to negate long term environmental degradation has been briefly examined by Fogg [5,15] who found that it would not be necessary to duplicate the Earth's plate tectonics on Mars. Consider Figure 6.11a, which shows a schematic Martian carbon cycle. Carbon dioxide would be cycled through a biota at ecological climax without net change in its partitioning between atmosphere and biomass. However, chemical weathering of silicate rocks to form carbonates gives rise to a potential deficit in the carbon cycle that on the Earth is made up by volcanic outgassing (the dashed lines on Figure 6.11a). If this return process could not occur on a terraformed Mars then the amount of CO_2 in the atmosphere would slowly decline at a rate, estimated from the Pollack *et al.* model of early Mars [11], of ~ 1 bar in 10^7 years. This is equivalent to a manufacturing requirement of 400 million tonnes of CO_2 per year to artificially close the cycle. Anthropogenic production of CO_2 on the Earth amounts to ~ 26 billion tonnes, but much of this is achieved by the burning of fossil fuels that would not be available on Mars. Instead carbonate rock, equivalent to a 750 m cube, would have to be mined and baked with silica to form a stable glass, driving off the carbon dioxide (see Equation 6.3). The quarrying of this material would amount to only $\sim 0.05\%$ of the present day rock shifting capacity of civilization and the power required for the chemical process only ~ 0.5% of the world power output. Thus a technological civilization on Mars might have little difficulty in closing its carbon cycle; yet it would not be a very pressing concern, after 1000 years with no maintenance, the CO_2 partial pressure would only have fallen by ~ 0.1 mbar.

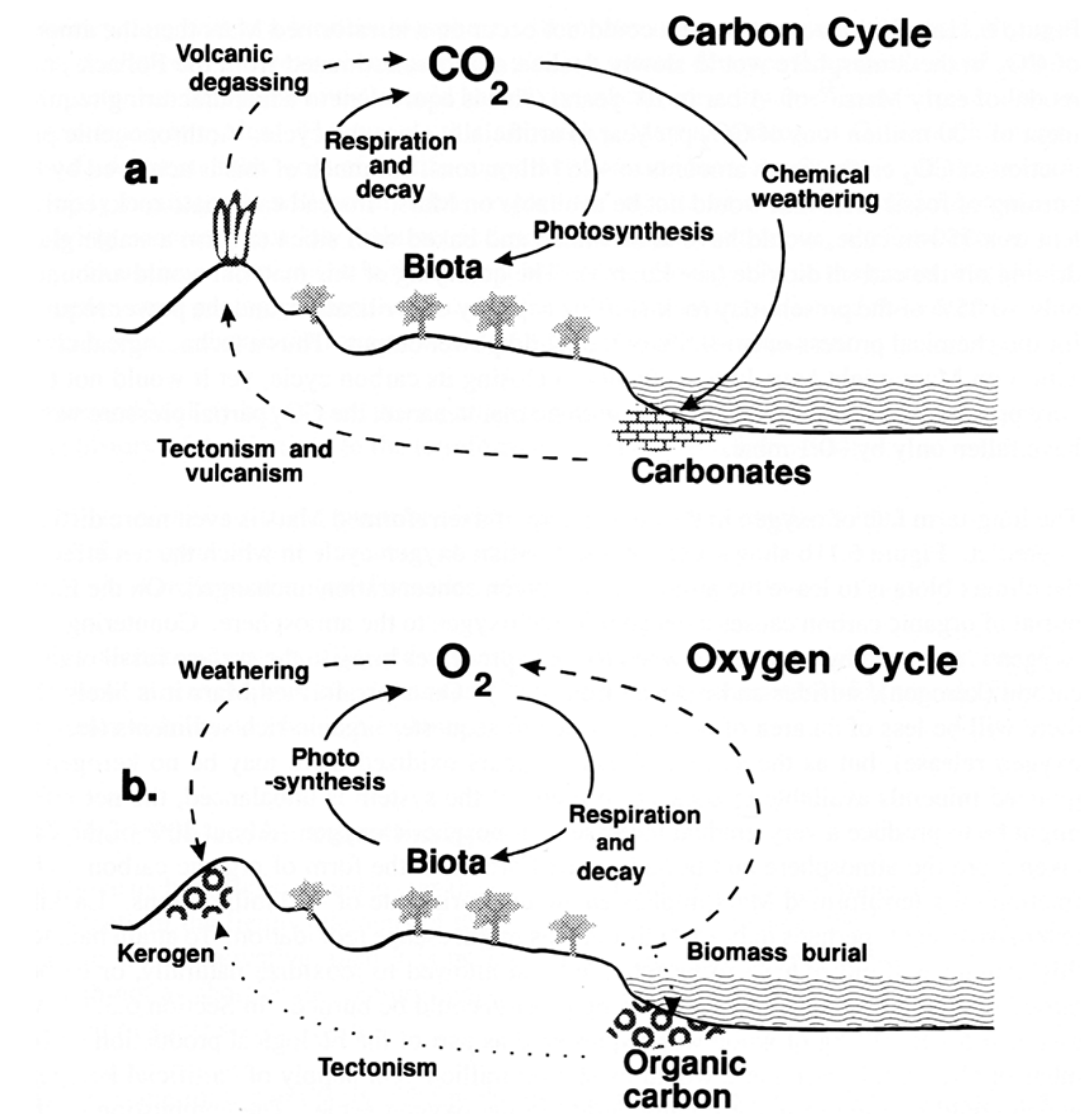

Figure 6.11 a. *Schematic carbon cycle on a terraformed Mars. Dashed lines are pathways which operate on Earth but which might not on Mars. A potential deficit in the cycle arises from the irreversible formation of carbonates.* ***b****. Schematic oxygen cycle on a terraformed Mars. Dotted lines show the flow of organic carbon. It is not possible to predict the long-term stability of oxygen in a terraformed atmosphere, as the relative efficiency of surface release and uptake processes (both dashed and dotted lines) are uncertain. However, any significant departure from the engineered climax condition is likely to take thousands of years.*

The long term fate of oxygen in the atmosphere of a terraformed Mars is even more difficult to predict. Figure 6.11b shows a schematic Martian oxygen cycle in which the net effect of the climax biota is to leave the atmospheric oxygen concentration unchanged. On the Earth, burial of organic carbon causes a net addition of oxygen to the atmosphere. Countering this, oxygen is removed by weathering when tectonic processes bring to the surface fossil organic carbon (kerogen), sulphides and reduced iron (Fe^{2+}). On a terraformed Mars it is likely that there will be less of an area of ocean in which to sequester organic rich sediments (less net oxygen release), but as the surface already appears oxidised there may be no kerogen or reduced minerals available to soak up oxygen. If the system is unbalanced, the net effect might be to produce a very gradual increase in atmospheric oxygen. About 20% of the CO_2 taken from the atmosphere and buried on the Earth is in the form of organic carbon. This fraction on a terraformed Mars implies an annual burial rate of ~ 50 million tonnes. Lacking extensive oceans however, perhaps only ~ 10 million tonnes might escape re-oxidation. To attain balance, this amount will either have to be retrieved and allowed to re-oxidise naturally or, alternatively, carbon buried or stored as part of the terraforming process could be burned. In Section 6.3.2.1, we assumed 5.7×10^{17} kg of wood was sequestered as part of the biological production of 146 mbar of O_2. In this case there would exist a 60 million year supply of "artificial kerogen," which could be used to make up any deficit in the oxygen cycle. The combustion of this material might actually be made to pay for itself in a minor way by generating ~ 5 GW of power. As with the carbon cycle, an incomplete oxygen cycle would not be a major concern, according to the above estimate only causing an 0.003 mbar rise in oxygen partial pressure in 1000 years.

Intervention in the rock cycle to combat long term denudation of the land surfaces and burial of biogenic elements may also pose only minor difficulties. Civilization on the Earth is now the major geological force reworking the planet's surface, shifting up to 100 times as much rock and soil as the natural processes of erosion (see Section 4.1.1). Although these activities are haphazard and exploitative and are not part of some global scheme of planetary management, the fact that anthropogenic landforms are springing up faster than nature can tear them down, is a demonstration that the capacity to run an artificial global rock cycle already exists.

Matter cycling within a Martian biosphere will for the most part operate automatically and bioregeneratively. However, because of the planet's greater distance from the Sun and lack of plate tectonics, the "loose ends" would have to be taken care of by intelligent intervention in biogeochemical cycles. This means that although a Martian analogue of Gaia might unconsciously do most of the work of the life-support system and have considerable robustness as a planetary regulator, it will nevertheless require the mantle of a terraformed infrastructure involving conscious, but low volume and not necessarily continuous, artificial matter cycling. Conscious intervention in the natural biogeochemical cycles of the planet would also be needed over geological timescales. Unlike on Earth, *Mars will need the presence of a civilization to maintain the long term order of the habitable environment*.

Haynes and McKay have listed three phases in planetary evolution that can be applied either to the history of the Earth or to the terraforming of Mars (see Figure 3.1):

1. *biopoiesis* (the formation of life)
2. *ecopoiesis* (the formation of an anaerobic biosphere)
3. *terraformation* (the formation of an aerobic biosphere)

To this technocentrists would add a fourth stage, that of *noogenesis* - the creation of a noosphere, an envelope of mind that controls the habitable parameters of Mars, securing its long term viability as a habitable planet [5].

6.4 The Problem of Attention Span

The above technocentric scenario cuts the timescale for the total terraforming of Mars to less than a tenth of the figure adherents of the standard approach consider likely. If its assumptions are too conservative, then it is possible to imagine further reductions in timescale, although not so short as the century-long miracles of popular science writers [3,4], or the *fait accompli* of some science fiction.

This raises the most commonly cited problem with the concept of terraforming — and that is not anything to do with science or engineering at all, but whether the attention span of the terraformers can withstand the long periods of time that will be required for the completion of planetary engineering projects. The contention goes that a return on initial investments will only be achieved in the remote future and centuries or millennia of patient work may be required before the benefits of terraforming become fully apparent to the local population — thus, there will be no motivation to start planetary engineering in the first place.

Whilst this argument has considerable merit, it is a superficial viewpoint that arises naturally from the paradigm of terrestrial culture, able until recently to take its life-support system for granted (see Section 9.2). On Mars, this luxury will not be present and will have to be *created*. Terraforming therefore, as so excellently illustrated in Turner's Genesis [39], is also a utopian concept that marries on the largest possible scale the dream of a better life for people, with that of a more vital environment. It is often a feature of newly established societies that they are unafraid of upholding grand ambitions and of entertaining a long-range vision. Some of these prove long-lasting and history shows evidence of many socially-motivating belief systems that do transcend the generations. Perhaps however, if "faith in a dream" is not enough, Martian terraforming can be sub-divided into discrete ~ 20 year steps. If each of these produce some noticeable improvement in the environment, then motivation might be sustained over a longer time span than suggested by our current experience of macro-engineering projects. We should also not forget another lesson of history — that *we are already planetary engineers*. Seven thousand years ago, few neolithic men perhaps would have predicted that their descendants would eventually render the Earth habitable for five and a half billion people. The habitation of Mars and its 7000-year terraforming appears to us now as no more *or less* likely a prospect.

Terraforming Mars therefore represents a distant, but not impossible, dream. However, the prospect of an earth like Mars holds out such immense advantages for the long-term habitability of the planet that the issue will not fade, so long as human interest remains.

6.5 Summary

- There is an economic case for the total terraforming of Mars in that it creates a global-scale uncontained life-support system of immense value, able to autonomously convert many terawatts of solar energy into useful work. Initial investment in terraforming would eventually be paid back through the automatic provision of goods and services previously requiring a substantial and ceaseless input of technological effort.

- The cessation of planetary engineering after Mars is rendered salubrious for anaerobes is unlikely to make economic or aesthetic sense to future Martian settlers. Since human beings will be responsible for planetary engineering, it is reasonable to suppose that any project would reflect human aspirations. Ecopoiesis should therefore be merely a first step in a programme of full terraforming, where Mars is ultimately made into an ecological arena for *Homo sapiens*.

- Planetary engineering schemes, such as the Runaway CO_2 Greenhouse, which envisage triggering the Martian environment into a quasi-spontaneous evolution to a habitable state may not be realistic. Specific problems include doubts over whether enough volatiles are present and whether they can be released by passive means in an acceptable period of time.

- A technocentric approach — favouring more active and energetic intervention in energy flow and matter cycling may be more likely to achieve results. Substantial planetary engineering may be needed to dislodge Mars from its current uninhabitable climatic state. The need to mine CO_2, N_2, O_2 and water, to provide minimal quantities required by life, will involve a large industrial effort on the planet's surface.

- The artificial injection of heat to the depths of the regolith is a particularly important demand of any scenario that aims to liberate volatiles in a timescale meaningful to civilization.

- No single planetary engineering technique, or extrapolation of it, can be realistically regarded as a universal panacea for terraforming Mars. A combination of such techniques however, optimised for just part of the job, and acting together in synergy, is much more promising. A synergic, technocentric approach permits one to envisage the complete terraforming of Mars in < 10,000 years — a timescale roughly equivalent to that separating the dawn of urban civilization from the present day.

- The usefulness of space reflectors and the likely need for imported nitrogen mean that terraforming Mars may need assistance from space-based industry and extrinsic planetary engineering tools.

- Conscious control of biogeochemical cycles can be used as a controllable method of planetary engineering (such as for the production of oxygen) and planetary maintenance. Terrestrial-type geochemical cycles on Mars may have to be closed with the assistance of technology. Unlike the biosphere of Earth, that on Mars may require the presence of a civilization for long-term survival. Technosphere and biosphere must co-exist in symbiosis: the ultimate goal of terraforming therefore should be the creation of a Martian noosphere.

- The habitable Mars of the future will be a planet predominantly of dry land. Its water will be gathered into a small ocean on the Northern Plains, connected to crater lakes and basin seas in the Uplands by rivers and canals. The flora and fauna might be predominantly temperate and continental. At certain times of day, reflected suns might make comparatively brief appearances in the sky, providing additional warmth and strange overhead “sunrises” and “sunsets.” Although terraformed and habitable, the planet will not lose its identity. Mars will still be Mars — an exotic and alien world providing a new and unique stage for the dramas of life and civilization.

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