

PLANETARY ENGINEERING

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Assuming commercial fusion power, heavy lift vehicles and major advances in genetic engineering, we survey possible late-21st century methods of working major transformations in planetary environments. Much more Earth-like temperatures may be produced on Mars by generating low freezing-point greenhouse gases (e.g., CO₂, NH₃, CFCs) from indigenous materials or by transporting them from elsewhere; on Venus by cancelling the greenhouse effect with high-altitude absorbing fine particles, or by a sunshield at the first Lagrangian point, and/or by sequestering or transforming CO₂ at the surface; and on Titan by greenhouse and/or fusion warming. To produce global environments suitable for plants and animals, including humans, requires modifying the atmospheric composition and mass and altering the surface temperatures on these bodies. In general, engineering congenial worlds for plants is much easier than for humans, and is also a useful means of working further modification of the atmospheric composition, especially the establishment of several hundred mbar of O₂ from H₂O. Establishing global habitats suitable for humans will require the addition of at least several hundred mbar of N₂ and O₂ into the Martian atmosphere; the removal of most of the CO₂ in Venus' atmosphere (most plausibly by forming carbonate minerals) plus the addition of large amounts of water; and the addition of several hundred mbar of O₂ to Titan's atmosphere. Climatologically active abundances of some gases may be toxic to humans. It is not clear that any of these schemes are technically feasible (much less cost effective) with technologies projected for the end of the next century. They also raise disturbing questions about environmental ethics. Global warming on Earth has already led to calls for mitigation by planetary engineering—e.g., emplacement and replenishment of reflective or anti-greenhouse layers at high altitudes, or sunshields in space. But here especially we must be concerned about precision, stability, and inadvertent side-effects. The safest and most cost-effective means of countering global warming of the Earth—beyond, e.g., improved energy efficiency, CFC bans and alternative energy sources—is the continuing reforestation of $\sim 2.5 \times 10^7$ km² of the Earth's surface. This can be accomplished with present technology.

I. GENERAL PRINCIPLES

Human technology is now able to affect the terrestrial atmosphere and climate

on a global scale. Three mechanisms have drawn particular attention in recent years:

1. Global warming through a side-effect of modern technology—the increasing greenhouse effect. It arises chiefly from the burning of fossil fuels (releasing CO₂), from the industrial production of chlorofluorocarbons (releasing CFC s), and from cattle and rice paddies (which release CH₄). Global warming of several K over the next century might, it is feared, lead to drought, desertification in mid-latitude continental interiors, massive agricultural failure and relocation, a global rise in sea level and the flooding of coastal cities and island nations (see, e.g., Hansen et al. 1988; Strong 1989; MacCracken et al. 1990).
2. Ozonosphere depletion. It is thought to arise chiefly from the industrial production of chlorofluorocarbons (CFC s) and threatens—through a significant increase in the surface flux of solar near-ultraviolet radiation (WMO 1985; NASA 1988)—not just increases in skin cancer and a weakening of the human immune system, but an assault on the primary photosynthetic producers at the base of the food chain.
3. Nuclear winter. This is a long-overlooked climatic consequence of nuclear war. Even 1% of the 1992 global strategic arsenals—if targeted on city centers and, especially, petroleum refineries and storage depots—seems capable of reducing Northern Hemisphere temperatures by as much as 10 to 20 K in continental interiors in a time scale of the order of 10 days (and then relax back to unperturbed conditions on a time scale of months). The principal mechanism by which nuclear winter works is by undoing the greenhouse effect (“anti-greenhouse effect”), which happens when appreciable sunlight is absorbed above the greenhouse gases (Turco et al. 1983,1990; Pittock et al. 1986; Sagan and Turco 1990). Among the predicted consequences of nuclear winter following a full nuclear exchange in Northern spring or summer is the devastation of Northern Hemisphere agriculture and the subsequent deaths by starvation of vast numbers of people (Harwell and Hutchinson 1985).

These three processes demonstrate the general proposition that humans can now alter environments on a planetary scale. This conclusion follows even if we were to entertain serious reservations about the canonical values of the speed or severity of these effects within the range of uncertainty in current atmospheric modeling. There may be mitigating effects that have not yet been identified and that just counterbalance each of these catastrophes, but such effects have certainly not been demonstrated, and hoping for such a *deus ex machina* may be tantamount to exercising what psychiatrists call denial.

In none of these three examples is a carefully designed stable change brought about; instead, the changes are haphazard and inadvertent, and almost always constitute an unpleasant surprise to those responsible for the relevant technology. It seems possible, therefore, if present trends continue, that

within the not-too-distant future human technology should be capable of even more major alterations, both intentional and inadvertent. An important issue is whether any can cause improvements rather than deterioration in the planetary environment—perhaps with high-precision negative feedbacks.

After the discovery of the inclement high temperatures at the surface of Venus, it was natural to try to imagine a possible technological fix to make that planet more Earth-like (Sagan 1961). A wide variety of schemes have been suggested in the subsequent scientific literature, usually to transform Venus or Mars into a more Earth-like environment (see, e.g., Averner and MacElroy 1976; Burns and Harwit 1973; Fogg 1987,1989; Oberg 1981). This subject was earlier described as “terraforming,” a term coined by the science fiction writer Jack Williamson under the pseudonym Will Stewart in a series of stories published in the 1940’s. However, it is possible to imagine a range of environmental alterations other than nudging a hostile world into more Earth-like conditions, and we here use the more general phrase “planetary engineering” (Sagan 1961,1973).

The traditional objective of planetary engineering is to generate an Earth-like environment on other worlds of the solar system, so that humans and other inhabitants of the Earth can live there without special protective gear (spacesuits, large enclosed habitats, etc.). A continuum of intermediate cases exists, usually more readily achievable, between the current environment of an extraterrestrial body and present Earth ambient conditions. An important special case for planetary engineering is to reverse significant perturbations (e.g., global warming) in the environment of our own planet. This is surely easier than planetary engineering on other worlds: the circumstances under which humans can survive unaided represent at most very small variations from present Earth ambient conditions; but many microbes and plants grow under less severe constraints (cf. Table I).

In this chapter we examine the likelihood of accomplishing significant planetary engineering, particularly towards more Earth-like conditions, on Mars, Venus and Titan, although opportunities exist for a number of other worlds in the solar system as well. We focus chiefly on proposals by which clement temperatures (0–30°C) can be realized on a global scale. Such a temperature range meets many essential requirements for habitability, including the potential availability of surface liquid water. As stressed by Sagan (1961) and by McKay et al. (1991), introducing plants first may lead with comparatively little additional effort to other desired changes (e.g., production of significant quantities of photosynthetic O₂). At the end of the chapter we address schemes for countering or mitigating global warming on Earth. We adopt the spirit of Henry David Thoreau’s remark, “What is the use of a house if you haven’t got a tolerable planet to put it on?”

We postulate a future with abundant heavy-lift vehicles, commercially available and safe nuclear fusion, major practical advances in genetic engineering and a dedication to the exploration of the solar system. Over the next century all of these developments seem plausible, although they are by no

TABLE I
Limits of Habitability^a

Parameter	Limits	Note
Global temperature	0–30°C	Earth mean temperature 15°C
Plants only:		
Total pressure	>10 mbar	Water vapor pressure plus O ₂ , N ₂ and CO ₂
CO ₂	>0.15 mbar	Lower limit set by photosynthesis No sharp upper limit
N ₂	>1–10 mbar	Nitrogen fixation
O ₂	>1 mbar	Plant respiration
Human breathable		
total pressure, Pure O ₂	>250 mbar	Lung water vapor, CO ₂ , and O ₂
Air mixture	>500 mbar <5000 mbar	Based on high elevation Buffer gas narcosis
CO ₂	<10 mbar	Set by toxicity
N ₂	>300 mbar	Buffer gas
O ₂	>130 mbar <300 mbar	Lower limit set by hypoxia Upper limit set by flammability

^a Table from McKay et al. 1991.

means guaranteed. We also assume that fusion power will provide us with the technology to move at will asteroids ten kilometers in diameter and smaller around the inner solar system. The energy requirements, as we discuss below, may by then be wholly within reach. Transport of small worlds within the inner solar system has long been proposed for other reasons—e.g., supplying large quantities of precious metals—but much smaller worlds would suffice for that purpose. This technology may be developed for other reasons as well: to deflect errant near-Earth objects from impact trajectory with our planet (cf. Morrison et al. 1992). However, such technology would also give its possessors an unprecedented ability to destroy life on Earth, and it is not clear that a cost/benefit analysis favors its development (Sagan 1992), at least in the near future. But in keeping with the optimistic assumptions of this chapter, we postulate a future in which adequate safeguards against the misuse of

this technology exist.

We assume that fusion power is based on either reactions between deuterium and tritium (D-T) or between deuterium and ^3He (D-He). This choice is based on the extensive work done over the last several decades in developing practical schemes for fusion power (D-T) and plausible projections (D-He) (Cordey et al. 1992; Wittenberg et al. 1986). Because of the very low reaction cross sections of the p - p cycle that helps power the Sun, we ignore the much more efficient fusion power based on this cycle. In the case of D-T fusion, ^6Li may provide the source of the tritium through reactions occurring in the blanket of the fusion chamber (Cordey et al. 1992). For D-He fusion, ^3He may be derived from solar wind implanted in the regolith of the Moon (Wittenberg et al. 1986), or asteroids. We assume an adequate amount of ^6Li and ^3He for the scenarios considered in this chapter. We do, however, provide estimates of the amount of water required, which serves as the source of D. For D-T fusion, about 20 times the mass of rock is required to provide the needed ^6Li as the mass of water required to obtain a given amount of D. In either case, the amount of energy released per mole of reactant is about the same. Below, we assume that 50% of the mass deficit between reactants and products is available as useful energy. Thus, we use a fusion power of 4.2×10^{18} erg g^{-1} of D or 7.5×10^{13} erg g^{-1} of H_2O , assuming a terrestrial D/H ratio of 1.6×10^{-4} . Utilizing Martian water may increase the yield per gram of H_2O by as much as a factor of 5 because of the higher D/H ratio of water vapor in the Martian atmosphere.

We do not consider the possible use of thermonuclear weapons for planetary engineering, because the Outer Space Treaty of 1967—which the United States, the Soviet Union (and presumably its successor states), the nations of Western Europe and Japan, among many other nations, have ratified—specifically forbids installation of such weapons on other celestial bodies, and in “outer space” in general. The 1963 Limited Test Ban Treaty also prohibits the explosion of nuclear weapons anywhere except beneath the surface of the Earth (A. C. D. A.1982).

It seems possible (Sagan 1986) that between increasing the abundance of greenhouse gases and placing fine particles at high altitudes to provide an anti-greenhouse effect, we will have the means to heat or cool a planetary surface at will; and that, for the latter, it might suffice to pulverize a small asteroid or cometary nucleus. In addition, large partially opaque sunscreens emplaced between the Sun and a given world could be used to cool that world, and fusion technology could be used to warm it. In principle, anticipated advances in human technology might, within the next century, provide us with practical planetary thermostats.

We take particular note of the time scale for planetary engineering implicit in various methods. It would seem foolish to implement today a scheme that would occupy 10^4 or 10^6 yr, say, to achieve its effects, when in, say, 100 yr we will likely have much more powerful technologies for the purpose. Current political realities suggest that an expensive project without a significant payoff

in 25 yr or less is infeasible. As a rough figure of merit, any planetary engineering scheme that takes more than several decades to achieve significant results (if not full implementation) should be rejected on such grounds alone.

Projecting technological trends more than a few decades into the future is in any case a forlorn exercise. But advances in genetic engineering far beyond what we assume in the remainder of this chapter seem possible. We therefore note that, at some time in the future, a much more elegant way to overcome our parochial habitat restrictions may be to genetically engineer humans for other worlds than to physically engineer other worlds for humans (cf. Stapledon 1948).

We find below that planetary engineering generally entails severe ancillary environmental costs. This may be because we have not yet conceived of the really elegant methods. But these costs, especially, raise a number of issues: given that any planetary engineering scheme entails a balance of benefits against costs, how certain must we be that key scientific information will not thereby be destroyed? How much understanding of the world in question do we need to have before planetary engineering can be relied upon to produce the desired end state? Can we guarantee a long-term human commitment to maintain and replenish an engineered world when human political institutions are so short-lived? If a world is even conceivably inhabited—perhaps only by microorganisms—do humans have a right to alter it? What is our responsibility to preserve the worlds of the solar system in their present wilderness states for future generations—who may contemplate uses that we are today too ignorant to foresee? These questions may perhaps be encapsulated into a final question: can we who have made such a mess of this world be trusted with others? At the end of this chapter, we briefly re-address some of these issues.

II. MARS

Today Mars is a frigid, desert planet. The fact that conditions seem to have been warmer and wetter 4 Gyr ago when the solar luminosity was $\simeq 0.75$ its current value (Sagan and Mullen 1972; Pollack et al. 1987) suggests that it may be possible to move the Martian climate into a more temperate range. Although today temperatures near the equator can rise above the freezing point of water during the warmest times of the day, the diurnally averaged temperatures are everywhere well below freezing. Here, we consider ways of increasing the globally, diurnally, and seasonally averaged temperatures to values comparable to the annually averaged temperatures at mid-latitudes of Earth. We note from the start that even if this were done gently, it would disturb or destroy some major Martian landforms—e.g., the polar laminae.

The low mean temperatures on Mars are due both to it being further from the Sun than the Earth (a unit area on Mars absorbs roughly half the solar flux as an identical area on Earth) and to Mars having a very thin atmosphere—so that the greenhouse warming is only about 7 K, in contrast to about 33 K for the

Earth. On present-day Mars, CO_2 , the major constituent of the atmosphere, is the chief agent responsible for its modest greenhouse warming, through the opacity it provides to thermal radiation emitted by the surface in the wavelength region around $15\ \mu\text{m}$. The apparently most cost-effective way to warm Mars is by enhancing the atmospheric greenhouse effect through the introduction of gases that absorb at thermal wavelengths outside the $15\ \mu\text{m}$ region. There are two possible sources of such gases—exogenous to Mars and endogenous. We could imagine, for example, transporting ice from the outer moons or rings of Saturn to Mars, but pure water, which appears to be the composition of the rings of Saturn, while an important greenhouse gas on Earth, would be ineffective on Mars, because the temperatures there are so low that water freezes out. In general for both Earth and Mars, the water abundance is buffered by reservoirs at the surface, so it can only amplify the greenhouse effect of other gases once they produce significant warming. We require gases that not only are effective infrared absorbers, but that also remain in the gas phase at present Martian temperatures. Below we discuss three candidates, NH_3 , CO_2 and halogen compounds.

A. Ammonia

It would be far more effective to utilize materials already on Mars. NH_3 absorbs strongly both near $10\ \mu\text{m}$ and longwards of $20\ \mu\text{m}$. Small amounts can greatly enhance the greenhouse effect on Mars. Calculations suggest (Sagan and Mullen 1972; Pollack 1979) that a partial pressure of ammonia of $\sim 10^{-4}$ bar is needed to warm the Martian surface to above the freezing point of water.

The required amount of NH_3 might be generated in several ways. First, consider appropriately designed microorganisms that convert atmospheric N_2 to NH_3 , an exothermic reaction, with the hydrogen derived from subsurface bound or frozen water. Nitrogen-fixing microorganisms are abundant on Earth and central to agriculture; they routinely convert N_2 to NH_3 . But none is known to metabolize under simulated Martian conditions. Cryophilic nitrogen-fixers that extract their water requirements from bound or solid water would have to be engineered; and/or heated artificial habitats created that would vent NH_3 to the outside atmosphere. As the partial pressure of N_2 on Mars is $\sim 2 \times 10^{-4}$ bar, about 25% of the available atmospheric nitrogen would be required to generate 10^{-4} bar of NH_3 . Properly engineered microorganisms might be placed on the permanent water ice north polar cap. Despite the summertime temperatures of about -30°C , the solar flux might be sufficient for such microbes to provide photosynthetically the energy needed to manufacture ammonia.

Alternatively, ammonia might be generated by chemical factories that use nuclear fusion as a power source to convert atmospheric N_2 to NH_3 . The hydrogen needed both for fusion fuel and for the chemical conversion of N_2 to NH_3 could come from the residual north polar cap, or perhaps from the regolith. If as much as 500 calories of activation energy were needed to

convert each N_2 molecule to NH_3 , $\sim 1.7 \times 10^{13}$ g of water for a terrestrial D/H ratio would be needed for fuel to produce 10^{-4} bar of NH_3 over the entire planet. (Even less water is needed if the observed Martian atmospheric D/H ratio is used). This corresponds to only about the top $40 \mu\text{m}$ of the north polar cap. However, about 30 cm of H_2O from the north polar cap would be consumed in supplying the H needed to convert 1/4 of the current atmospheric N_2 to 10^{-4} bar of NH_3 .

As a third possibility, especially if the budget of atmospheric N_2 and surface nitrates is not quite adequate to generate $T > 0^\circ\text{C}$ through an ammonia greenhouse, N_2 might be derived from the atmospheres of Venus, Earth, or Titan and transported to Mars. For example, to generate an NH_3 partial pressure of $\sim 1 \times 10^{-3}$ bar, amounts of N_2 equal to $\sim 5 \times 10^{-4}$, 1×10^{-3} , and 5×10^{-5} times the N_2 content of the atmospheres of Venus, Earth, or Titan, respectively, would be required. If liquified, the requisite amount of N_2 , $\sim 6.8 \times 10^{17}$ g, would measure about 10 km across. If a ΔV of 10 km s^{-1} were needed to transport the liquified N_2 to Mars, $\sim 4.5 \times 10^{15}$ g of H_2O would be required to power the fusion engine. This is equivalent to the amount of water in a 1-km-sized comet. Alternatively, the N_2 might be derived from the N in organic compounds contained in C or D asteroids, whose orbits come close to that of Mars. Such bodies may contain ~ 0.5 wt% N. Thus, a much lower ΔV might suffice for transporting nitrogen to Mars. An asteroid of diameter about 50 km would be needed to supply the requisite amount of N. The cheapest, although least responsible, method of extracting the nitrogen would be by simply crashing the asteroid into Mars; this would generate a crater hundreds of km across, destroying the underlying terrain.

There is, though, an important problem with any scheme to use NH_3 as a Martian greenhouse gas: ammonia is readily dissociated by solar ultraviolet radiation at wavelengths, λ , shortward of $\sim 0.23 \mu\text{m}$ (see, e.g., Atreya et al. 1978). In the Martian atmosphere, neither CO_2 nor H_2O would block ultraviolet radiation at $\lambda > 0.2 \mu\text{m}$. A net dissociation rate of only $\sim 50\%$, a reasonable lower bound, implies $\sim 2.4 \times 10^{12}$ molecules dissociated $\text{cm}^{-2} \text{ s}^{-1}$ at Mars (*ibid.*). Thus, 10^{-4} bar of NH_3 would be totally converted back to N_2 by solar ultraviolet radiation in about 30 yr.

However, 30 yr is much longer than the radiative time constant for the Martian atmosphere; so before NH_3 is appreciably photodissociated, its infrared opacity will have significantly warmed the surface. Thereafter, the gas phase dissociation products of NH_3 , N_2 and H_2 would be recycled to NH_3 by essentially the same technology used to produce it initially. Another potential problem is the reaction of NH_3 with atmospheric CO_2 to form ammonium carbonates and other salts at the low temperatures of the winter polar regions; but the kinetic time scales are unknown for these compounds, and any that form in winter may be vaporized the following spring.

B. Carbon Dioxide

A second possible way to augment the greenhouse effect on Mars is to increase

the carbon dioxide content of its atmosphere. At sufficiently high pressures, pressure-induced transitions and hot bands of gas phase CO₂ close the thermal infrared windows. Clement average temperatures can be achieved by raising the surface pressure from its current value of 7 mbar (millibars) to ~ 1 bar (Pollack et al. 1987).

One conceivable source of atmospheric CO₂ might be the dry ice contained in the polar caps. However, the large perennial cap in the northern hemisphere is composed, apparently exclusively, of water ice. The smaller perennial cap in the south had a surface layer of CO₂ ice during the first year of the Viking spacecraft mission (1976–77), but in other years this layer may be very thin or even disappear. An upper limit to the amount of CO₂ available in the Martian polar caps can be derived from the fact that under high enough hydrostatic pressures, solid CO₂ will liquify; this limit corresponds to a cap thickness of ~2 km (Sagan 1973). Even if all the south cap were CO₂ to a depth of 2 km and even if all of this carbon dioxide were liberated in the gas phase, it would amount only to some 60 mbar pressure when uniformly distributed over the planet. Thus, the available CO₂ from the polar cap falls short of the required abundance by more than an order of magnitude.

If, nevertheless, it were desirable to vaporize the dry ice in the polar cap to begin increasing CO₂ partial pressures, we might consider lowering the cap's albedo by depositing very dark carbonaceous material of asteroidal origin, or genetically engineering plants with dark, broad leaves that can survive on the polar caps (Sagan 1973).

Another source of CO₂ is carbonate anions in the rocks. Spectroscopic observations of Mars provide evidence for significant amounts of carbonates (Pollack et al. 1990). Suppose that these rocks in toto contain more than a bar of CO₂ and that they are preferentially concentrated in certain basin areas. If nuclear fusion were used as a power source to liberate this CO₂, then $\sim 5.7 \times 10^{17}$ g of H₂O would be required to generate 1 bar of CO₂—equivalent to about the top meter of water in the north polar cap. This solution for planetary engineering of the Martian climate, while much more energy-intensive than the NH₃ solution, has the advantage of being much more permanent. CO₂ would not be converted to some other gas species by solar ultraviolet light and would only very slowly be transformed into carbonate rocks by water-abetted weathering of surface rocks. The latter process would have a time scale of about 10 Myr (Pollack et al. 1987).

If the spectroscopically derived carbonate abundance is approximately correct and representative of the top several km of crust, the entire surface of Mars would have to be plowed up and processed to a depth of 2 km in order to generate a 1-bar CO₂ atmosphere. Apart from the daunting obstacles in practical engineering that this represents, it would also constitute the irresponsible destruction of a unique scientific resource and database—the Martian surface. If carbonate deposits are concentrated preferentially (by, say, an order of magnitude) in basins, then the basins would have to be excavated to a considerable depth—better, at least, than bulldozing the entire planet.

We find that both environmental ethics and probable cost argue against large augmented greenhouse effects from indigenous CO₂.

C. Chlorofluorocarbons (CFCs)

A number of CFCs have vibrational fundamentals that lie within the 8 to 13 μm window region of the atmosphere, and have been suggested as a significant potential agent for global warming of Mars (Lovelock and Allaby 1985; McKay et al. 1991). At current Martian temperatures, though, these absorption bands would cause only a small amount of greenhouse warming, because they lie on the short-wavelength tail of the Planck blackbody function. But they would give rise to a more substantial greenhouse effect as the surface temperature approaches 273 K due to other greenhouse gases, and the Wien peak of the blackbody function shifts to shorter wavelengths.

In principle, CFCs could be much more potent in significantly elevating the present Martian surface temperatures if they had pure rotational spectra that began near 20 μm and extended to longer wavelengths, as does NH₃. To do so, they must have permanent dipole moments and large moments of inertia. We suspect that HCFCs (e.g., CHCl₂F) might meet both these requirements. Unfortunately, we are not aware of any relevant laboratory measurements at the long wavelengths of interest. We defer a discussion of the source of CFCs until the next subsection.

For all greenhouse gases, the temperature increase would occur essentially on the time scale of release of the corresponding gases: the thermal time constant of the present Martian atmosphere is around 2 days; for ~ 1 bar CO₂, it would be around 300 days, still very short compared to the other time scales of the project. As temperatures approach the freezing point, water vapor partial pressures in the atmosphere would increase, water vapor would augment the greenhouse effect due to the other gases, and the final stages of reaching clement temperatures might become comparatively easy.

Direct fusion heating of the Martian surface from power plants distributed over its surface is briefly described in the section on Titan below.

D. Possible Completion Scenarios

So far we have focused exclusively on schemes for increasing the mean global surface temperature of Mars to above the freezing point of water, i.e., into a habitable temperature regime. We now consider scenarios by which Mars is made habitable in a more complete sense for microbes, plants, other animals, and humans, with Table I as our guide for what needs to be done to the atmospheric composition to achieve this ultimate goal. Here we draw heavily upon the discussion of McKay et al. (1991).

The first human settlements on Mars will result from much more modest planetary engineering. We imagine these settlements to be small, enclosed microenvironments, in which the conditions of Table I are met. From them, in time, flows the means for generating more and larger microenvironments, culminating in a full-scale remaking of the entire planet's climate into one

suitable first for microbes and plants, and later for widespread habitation by animals, including humans. How might this be brought about?

McKay et al. (1991) have suggested that the first milestone, that of habitation by macroscopic plants, could be achieved by priming the greenhouse pump and allowing for natural amplification mechanisms to greatly increase the resulting warming. In particular, they recommend introducing enough greenhouse gases to warm the surface by about 20 K above present ambient. Such warming, they suggest, will lead to a large outgassing of CO₂ from the regolith, where it is adsorbed onto grain surfaces, and from the small perennial south polar cap. In this way the CO₂ pressure may be increased to a value as high as 100 mbar. Additional release of CO₂ might either occur from regolith or polar CO₂ reservoirs, or be accomplished by releasing CO₂ from carbonate rocks, until a CO₂ pressure of a bar to a few bars was achieved, at which point surface temperatures would permit survival and growth.

However, we believe it is unrealistically optimistic to think that any significant fraction of one to a few bars of CO₂ could be released from the regolith or polar regions, based on what is known about the nature of the Martian surface (see above). Furthermore, even 100 mbar of CO₂ would not significantly enhance the surface temperature (Pollack et al. 1987). Therefore, this scenario must draw heavily upon the release of CO₂ from carbonate rocks. In this regard, fusion power may play an essential role because of the very large amount of energy released per gram of water, as illustrated in our earlier discussion in this section. However, as discussed above, it will still be a highly nontrivial task to generate the requisite amount of CO₂ from carbonate rocks. The introduction of much more modest amounts of NH₃ or hydrogenated CFCs appears to offer a much more viable approach to raising the surface temperature of Mars into the habitable regime. According to Table I, several chemical modifications of the Martian atmosphere would be needed to make the planet habitable for plants, apart from the greenhouse warming discussed above. Here too, fusion power may prove to be very useful by helping to generate modest but enhanced partial pressures of O₂ (e.g., by conversion of small quantities of CO₂) and N₂ (e.g., by conversion of nitrates).

Once this milestone is achieved, the second stage—making Mars habitable for animals and for humans—can be addressed (cf. Table I). McKay et al. (1991) suggest that plant photosynthesis could convert enough atmospheric CO₂ to O₂ to meet the oxygen requirements. However, this suggestion rests on a misunderstanding, as the O₂ released by green plants derives exclusively from H₂O and not from CO₂. Such a photosynthetic source of O₂ would require at least 260 mbar of H₂ (which need not all be in the atmosphere at the same time) and 130 mbar of CO₂. Alternatively, fusion power could extract the needed oxygen from the highly oxidized surface, although several meters of regolith would need to be converted on global average. In addition, an enormous amount of N₂ would need to be introduced into the atmosphere to buffer the O₂ and prevent ready combustion from occurring. It is not clear that Mars has the requisite amount of N in easily accessible reservoirs. The

importation of the needed amount of N_2 from elsewhere in the solar system would be a formidable task, as illustrated by our discussion of obtaining a much more modest amount of N for generating NH_3 .

Finally, the relative abundances of greenhouse gases would need to be carefully adjusted. Partial pressures of CO_2 greater than ~ 10 mbar are toxic for humans. Thus, the CO_2 pressure might need to be greatly reduced from its earlier value, and CO_2 could not a prominent role in the late stages of greenhouse warming for human habitability. Likewise (NIOSH/OSHA 1978; Sittig 1985), 0.05 mbar of NH_3 is the short-term inhalation limit for humans at 1 bar (although some microbes can survive much higher NH_3 mixing ratios), which is comparable to the NH_3 partial pressure needed for it to become the dominant greenhouse gas. Note that the required NH_3 partial pressure decreases from ~ 0.1 mbar to a much lower value as the total pressure increases from 7 mbar to ~ 1 bar, so it seems possible to engineer a significant NH_3 greenhouse effect without reaching toxic levels.

Alternatively, CFCs or related compounds which have very low toxicity and ultraviolet lability, might serve as the chief greenhouse gases in completion scenarios, but subject to the far-infrared absorption considerations cited above. Manufacture on Earth of enough CFCs to warm Mars can be readily foreseen, because in only a few decades with present technology we have managed to synthesize enough to contribute to global warming on our planet. Transportation to Mars would be expensive: using *Saturn V* or *Energia* class boosters would require at least a launch a day for a century. The manufacture of sufficient quantities of CFCs and allied substances on Mars from evaporites or igneous fluorite or fluorospar might be feasible (J. Lewis, personal communication, 1992; Fogg 1992). In either case, as the CFCs would be photolytically destroyed in about a century, judging from the situation on Earth, this delivery or manufacturing rate would have to be continued forever, although recycling procedures would become the method of choice. However, CFCs as a principal greenhouse gas on Mars have a different undesirable property: they inhibit the formation of a substantial ozonosphere. The temperatures may be made clement, but the solar ultraviolet flux would still pose a very serious hazard. Perhaps this in turn could be fixed with a high-altitude layer of ultraviolet-absorbing particles, but the difficulty of planetary engineering on Mars is thereby greatly compounded. Perhaps some nontoxic, long-infrared-absorbing, ozone-noninteractive, and preferably inexpensive gas phase molecule that would do much better than CO_2 , NH_3 or the CFCs remains to be synthesized. A more promising and less hypothetical alternative is to employ bromine- and chlorine-free halocarbons or related compounds (e.g., SF_6); F is much less effective in destroying O_3 than are Cl and Br (see, e.g., Fogg 1992; Chamberlain and Hunten 1987). Thus, NH_3 along with F compounds appear to offer the most promising means of warming Mars for habitation by humans.

In summary, it appears possible, although difficult to bring Mars globally to clement mean surface temperatures, more difficult to create conditions

suitable for plant habitation, and much more difficult to create conditions necessary for unprotected humans to live there. Even with rather optimistic assumptions on the progress of technology over the next century, and with very optimistic assumptions about the cost we will be willing to pay, it is not entirely clear that extensive planetary engineering of Mars is within reach.

III. VENUS

Because of its proximity to the Sun and its massive atmosphere, a very effective greenhouse operates on Venus that raises its surface temperature from what it would be without an atmosphere (about 240 K with the present albedo) to about 730 K. CO₂ is the major constituent of the Venus atmosphere and its opacity is the chief source of the greenhouse effect (Sagan 1960; Pollack et al. 1980). As the CO₂ pressure at the surface is ~90 bar, equivalent to ~10⁵ g cm⁻², engineering Venus by eliminating almost all its atmospheric CO₂ would appear to be a formidable undertaking.^a We say “almost,” because some residual greenhouse effect might be needed to bring the temperature from about 240 K to about 300 K. Alternatively, such fine tuning might be provided by adjusting the surface albedo or the albedo of high-altitude aerosols.

A. Impact Erosion

As a calibration of this formidability, we consider bombarding the planet with large, asteroid-sized bodies (tens to hundreds of km in size)—recognizing that such bodies may have been effective in eroding the atmospheres of the terrestrial planets, especially during the first billion years or so of their history when impact fluxes were much higher (Walker 1986; Melosh and Vickery 1989). High-velocity collision with the solid surface of a planet releases the kinetic energy of the impactor on a very short time scale. Several tens of percent of this energy is released into the atmosphere near the impact site as hot rock vapor, generating a shock wave that propagates outwards through the atmosphere. When the energy in the shock and vapor plume exceeds the gravitational binding energy of the portion of the atmosphere it traverses, this portion of the atmosphere can escape to space. For all but perhaps the largest impactors, the spherical geometry of the planet limits the affected portion of the atmosphere to the local tangent plane, corresponding roughly to 3×10^{-4} of the total volume of the atmosphere. According to calculations by Vickery and Melosh (1990), silicate bodies having masses $\gtrsim 5 \times 10^{18}$ kg (corresponding to objects larger than 150 km in diameter), and velocities in excess of ~ 20 km s⁻¹ are able to blow away all of the Earth's atmosphere above the tangent plane. The atmospheric mass dissipated falls rapidly as the

^a If we could wholly remove other greenhouse gases such as H₂O and SO₂, we could lower the surface temperature by hundreds of °C, but still not nearly enough to fall below the normal boiling point of water (cf. Pollack et al. 1980). However, if the CO₂ abundance were massively reduced, pressure-broadening of H₂O and SO₂ would be greatly diminished, and their infrared opacity would become comparatively small.

mass of the impacting object diminishes, with no loss occurring for objects smaller than ~ 2 km in diameter, regardless of impact velocity. Also, no loss occurs when the impacting velocity falls below 20 km s^{-1} , regardless of the impacting body's mass. Similar thresholds apply to cometary impactors, although limited blowoff can occur at velocities somewhat below 20 km s^{-1} .

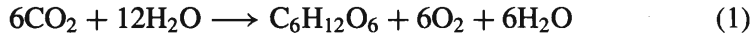
Because the escape velocity for Venus is similar to that for the Earth (10.4 vs 11.2 km s^{-1}), very similar limits on the minimum velocity needed to cause blowoff apply there. However, the mass requirements are increased by about a factor of 100 because of the greater atmospheric pressure at Venus' surface. Thus, impactors larger than ~ 10 km are required to produce any blowoff and ones larger than ~ 700 km are needed to blow off all the atmosphere above the tangent plane. To remove most of Venus' atmosphere through impact erosion would therefore require about 3000 impactors each larger than 700 km and traveling at velocities in excess of 20 km s^{-1} . There is nothing like this number of large bodies in the solar system, and if there were, it would surely be irresponsible to destroy them all (to say nothing of the present surface of Venus). Even with fusion power, excessive amounts of energy would be needed to accomplish the atmospheric removal. We conclude that impact stripping of the Venus atmosphere is an ineffective approach to planetary engineering.

B. Microbes

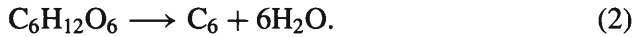
A much less energy-intensive and gentler approach is the introduction of genetically engineered micro-organisms into the clouds of Venus (Sagan 1961), where moderate temperatures prevail and where there is some water available. They would fix CO_2 into involatile organics or graphite, undoing much of the greenhouse effect, and lowering surface temperatures so that the sparse atmospheric water vapor would condense out on the surface in pools and shallow seas. Very special micro-organisms would be required because we now know the clouds of Venus to be a 75% solution of concentrated sulfuric acid which, among other disabilities, is a powerful desiccant. Nevertheless, there are micro-organisms known that live in concentrated solutions of H_2SO_4 and die in pure water (see also Seckbach and Libby 1969). We assume an H_2SO_4 -tolerant N_2 -fixing green plant photosynthetic micro-organism that could survive and replicate in the clouds of Venus. Biological solutions to planetary engineering have the advantage that microorganisms can rapidly replicate in the right environment; only a comparatively small number of such microbes then need be introduced.

This approach has been criticized for ignoring the fact that for every mole of CO_2 consumed in photosynthesis, a mole of water vapor is also required. As there is 3×10^{-5} as much H_2O in the Venus atmosphere as CO_2 , it has been suggested that the process would grind to a halt far short of the desired transformation. However, the original proposal addressed this

issue: photosynthesis goes according to the standard heuristic equation



in which the O_2 derives exclusively from the water. The carbohydrates thus synthesized will be circulated to the deeper hotter layers of the Venus atmosphere and pyrolyzed:



The carbohydrate is reduced to elemental carbon, or something approaching it, and the water is released, circulated back to the upper atmosphere and available for the next round of chemical reactions. The net chemistry is then approximately



There are two critical questions: (1) whether all (within 3×10^{-5}) of the carbohydrate hydrogen is released at depth and recirculated, and (2) whether the kinetic barrier to graphite oxidation will be maintained at the temperatures of the middle and lower atmosphere of Venus. These are matters accessible to laboratory experimentation and thermodynamic equilibrium-kinetic calculations. Preliminary evidence on (2) is unfavorable: everyday experience with self-cleaning ovens suggests that re-oxidation of carbohydrate pyrolysis products to CO_2 at 700 K and 0.2 bar O_2 occurs on a time scale ~ 1 hr.

Even if a microbiological approach to engineering Venus were feasible, however, the surface would be buried by hundreds of meters of fine graphite or organic particles sedimenting out of the atmosphere; and ~ 65 bars of O_2 would be generated—the first at least inconvenient for, and the second lethal for human settlers on an engineered Venus. Such microbiological schemes at best carry planetary engineering on Venus only part-way towards human habitability.

C. Anti-Greenhouse Effect

Greenhouses can be turned down or off by substantially reducing the amount of sunlight reaching the surface, as in nuclear winter (Turco et al. 1983; see also, Hoyle and Wickramasinghe 1978). In the case of Venus, this might be accomplished, despite the resulting lowered albedo, by introducing a planet-wide layer of highly absorbing particles into its upper atmosphere. Naturally, this layer will slowly sediment towards the lower atmosphere and ground, and so would need periodic replenishment.

Elemental C is a very good absorber of sunlight. Taking a typical value of 0.3 for the imaginary part of its refractive index (Turco et al. 1983), we find that particles of radius $0.1 \mu\text{m}$ or more absorb almost all of the visible light passing through them. Particles of such sizes have an interaction cross section comparable to their geometric cross section at mid-visible wavelengths. Small particles are desirable for this scenario because (1) the total mass required for

a given amount of solar attenuation varies as the mean particle size (as long as the interaction cross section is comparable to the geometric value), and (2) their fall velocity varies inversely (as the first or second power) as their size. If a particle radius of $0.1 \mu\text{m}$ is assumed and an elemental C particle absorption optical depth of 5 is needed to diminish adequately the amount of sunlight reaching the Venus surface, then $\sim 6 \times 10^{14}$ g of carbon are required. This is equivalent to a single 1-km-sized asteroid made of carbonaceous chondritic material. Particles $0.1 \mu\text{m}$ in radius would take several hundred years to fall to the surface at their sedimentation velocity (see, e.g., Ryan 1964), but might actually have lifetimes of only a few years when allowance is made for vertical transport by winds at a variety of length scales.

Carbon-rich (especially C- and D-type) asteroids that cross the Venus orbit might serve as the source of the carbon needed to create an anti-greenhouse effect on Venus. Orbital velocity changes needed to transport the asteroidal material to Venus are $\sim 10 \text{ km s}^{-1}$, corresponding to $\sim 5 \times 10^{11} \text{ erg g}^{-1}$ elemental C transported. Note that this specific energy is much larger than that needed to produce C from organic compounds found in asteroids. If once again fusion power is used, 1 g of H_2O would be required to transport about 2×10^3 g of C or a total of 2×10^{12} g of H_2O would be needed to create the opaque particle screen. We neglect the energy cost of pulverization and distribution of fine particles. This is clearly a low-mass, low-energy option for transforming Venus.

There are, however, several disadvantages to the anti-greenhouse option. It is still expensive in asteroids—requiring the periodic pulverization of a 1-km-sized organic-rich, water-rich asteroid. The thermal response time of the Venus atmosphere is a few decades, so if the high altitude layer of sedimenting opaque particles is not replenished, the carbon dioxide greenhouse effect reasserts itself on such a time scale and the surface temperature rises again to $\sim 730 \text{ K}$. In addition, by its very nature, this option plunges the surface of Venus into deep gloom, with ambient light levels in daytime perhaps only as bright as on a moonlit night on Earth, and the oppressive 90 bar atmosphere remains untouched. This might conceivably be acceptable for an exploratory mission with human crews, but seems rather stark for a self-sustaining community of people on Venus. Further, as for all schemes, settlers would have to adjust to the very unearthlike 243 day sidereal period and 125-day synodic period (sunrise to sunrise).

D. Sunshades

Another approach is to construct a system of sunshades, perhaps of adjustable opacity, in space around Venus (Dyson 1989; Birch 1991). Alternatively, we might place the sunshade at the first Lagrangian point, L_1 . The most efficient such sunshield, with sunlight assumed incident in parallel rays, would have a shadow the size of the object casting it. Were the shield as thin as $1 \mu\text{m}$, its mass would be $\sim 10^{14}$ g. But for Venus to be in the umbra rather than the penumbra of the shadow cast, the shield would have to be roughly an order

of magnitude larger and, therefore, have a mass $\sim 10^{16}$ g. We thus run into apparently daunting economic problems, as discussed below for the Earth. With sunshades the Venus surface temperature could be brought to very low values; Dyson (1989) and Birch (1991) even discuss the possibility of freezing out the atmospheric carbon dioxide into CO₂ oceans or glaciers.

E. Chemical Transformations

Birch (1991) further suggests that the condensed CO₂, when in the liquid phase, would flow to the lowlands, forming CO₂ oceans. He then advocates covering the CO₂ seas to prevent their re-evaporation, bringing a several hundred km ice-rich moon from the outer solar system to form water oceans on top of the covered CO₂ seas, and only partially blocking the sunlight to establish an Earth-like temperature at the surface. Finally, a soletta (a sunshade that opens and closes) could create a 24 hr day/night cycle, while the establishment of plants on land could generate O₂ from a residual amount of CO₂ in the atmosphere (perhaps leaked from the CO₂ oceans).

From a conceptual point of view, the Dyson/Birch proposal comes closest to making Venus into a habitat for plants, animals and people. One could imagine adjusting the amount of solar blockage during the early phases of the project so that CO₂, but not N₂ condenses out of the atmosphere, with a view of meeting the N₂ requirements of Table I. However, this proposal involves a massive engineering effort (e.g., to build the sunshade and to cover the CO₂ seas), far beyond anticipated human resources during the next century. Furthermore, preventing the leakage of CO₂ back into the atmosphere once an equable climate is established would be a formidable task: at room temperature, essentially all the CO₂ sea would become vapor. This sea would cover most of the Venus surface area. Could leaks be prevented from occurring?

A lower-energy method of removing the atmospheric CO₂ would be to convert it to carbonate rocks, because the net reaction is exothermic. However, this approach (whether microbiological or industrial) is complicated by considerations of the mass of reacting (and pulverized) materials needed. The converted CO₂ would form a layer 400 m deep over the entire surface area of the planet, and an equivalent depth of CaO, MgO, or other suitable materials for forming carbonates would have to be processed. Again, many surface features would have to be not just covered, but obliterated.

Nevertheless, let us examine the prospects of converting almost all the CO₂ to low vapor pressure materials. Two ways to do this have been suggested. Birch (1991) proposes importing massive amounts of Ca and Mg as metals from Mercury. These metals would first reduce CO₂ to C and their metal oxides. The oxides would then react with CO₂ to produce carbonates. To gather enough metals from Mercury, however, would require processing $\sim 0.5\%$ of the planet's mass. Birch imagines that this would be done by self-replicating robots.

Alternatively, J. Lewis (personal communication, 1992) has suggested

that hot liquid water circulating through the near-subsurface of Venus would chemically weather the crust (due to dissolved CO_2 in the ground water, forming carbonic acid), leading to the formation of alkali metal and alkaline earth carbonates (see also Gillett 1991). A similar process occurs at room temperature on Earth and is a major component of the long-term geochemical C cycle (cf. Pollack et al. 1987). One could imagine the following scenario by which Lewis' scheme is used to create habitats on Venus: After Birch (1991), a one to several hundred km ice-rich body (either a comet or a satellite of an outer planet) is brought to Venus. This is needed so that substantial quantities of water will condense at temperatures only somewhat below its critical point. Next, the amount of sunlight reaching Venus' surface is somewhat reduced—either by using a sunshade or by introducing a limited amount of dark absorbing particles into its high atmosphere. Hot liquid water now is present at the surface and greatly accelerates the weathering rate of atmospheric CO_2 , leading eventually to the elimination of almost all the atmospheric CO_2 . At this point, clement temperatures can be established and maintained by keeping the amount of sunlight reaching the surface somewhat below levels that would obtain if there were no attenuating screens. (Otherwise, a runaway greenhouse would occur, with the formation of a steam atmosphere [Pollack 1991].) Now, plants that grow at the comparatively low light levels can be introduced and the final steps taken to make Venus habitable for humans.

F. Summary

In summary, making Venus habitable for either plants or people is an extremely formidable task. There does not seem to be any elegant way to do it. The key is to eliminate almost all the CO_2 from the atmosphere. There simply are not enough big bodies in the solar system to strip away its atmosphere (and even if there were, we might not want to use them). Atmospheric CO_2 might be condensed at the surface or chemically transformed. The latter possibility appears to be more promising in that the CO_2 is permanently sequestered although hundreds of meters of carbonates would now cover the surface. In addition, there is a need to augment significantly the water content of Venus' atmosphere and surface through the importation of water from elsewhere in the solar system. Finally, a limited blockage of sunlight must be maintained to prevent a runaway greenhouse from occurring. None of these proposals seems feasible for the next century.

IV. TITAN

Titan, the largest moon of Saturn, is the only satellite in the solar system with a substantial atmosphere. Its surface pressure is ~ 1.5 bar (the column mass density is ten times that of Earth). The atmosphere is made mostly of N_2 , with significant amounts of CH_4 (5 to 10% at the surface) and H_2 (a few tenths of a percent), as well as trace amounts of gas-phase hydrocarbons and

nitriles. An optically thick organic smog layer (created by solar ultraviolet light and Saturn magnetospheric electrons) is present in its stratosphere. The surface may contain extensive reservoirs of organics, and water and ammonia ice deposits. Currently, the surface temperature is only about 95 K. A modest greenhouse warming of 10 K is produced by pressure-induced transitions of N_2 , CH_4 and H_2 (McKay et al. 1989). A major infrared window region, that extends from ~ 17 to $35 \mu\text{m}$ wavelength prevents a more substantial warming from occurring.

In principle, Titan's greenhouse could be significantly augmented by introducing gases that absorb strongly in the window region. However, the low surface and tropospheric temperatures greatly limit the vapor pressures of essentially all cosmically abundant potential candidates (e.g., NH_3 , CO_2 and H_2O), which makes this approach difficult to implement. Many less abundant organics do not absorb preferentially in this window region, because their vibrational fundamentals tend to lie at shorter wavelengths and their rotational transitions at longer wavelengths. However, there are molecules that absorb in this region, including some alkanes, alkenes, and amides, and it might be possible to manufacture substantial quantities of such molecules from indigenous or exogenous resources.

An alternative approach is to heat the surface directly. McKay et al. (1989) have estimated the greenhouse warming that may have occurred when the sunlight reaching the lower atmosphere and surface was augmented by accretional heating due to the planetesimals that helped to build this satellite. There exists a very strong feedback between total surface flux (sunlight and accretional heating) and surface temperature, because of the exponential dependence of the vapor pressures of ammonia and water on surface temperature and the potential of these molecules for closing the greenhouse windows. Surface temperatures comparable to terrestrial values can be achieved when the accretional heat flux reaches $\sim 10^5 \text{ erg cm}^{-2} \text{ s}^{-1}$, which is ~ 0.05 the solar constant at Earth.

Clement temperatures on Titan could also be achieved through heat released by nuclear fusion, with surface volatiles supplying the D fuel. (We assume that there are substantial deposits of ammonia and water ice in contact with the atmosphere so these greenhouse gases may be mobilized. There is no shortage of sources of H.) To generate a mean heat flux of $\sim 10^5 \text{ erg cm}^{-2} \text{ s}^{-1}$ across Titan's surface (with widely dispersed power plants), or equivalently $8 \times 10^{22} \text{ erg s}^{-1}$, $2 \times 10^4 \text{ g}$ of deuterium would need to be consumed per second. An equivalent depth across Titan of some $400 \mu\text{m}$ of H_2O (or NH_3 or CH_4 or C_2H_6) would be needed for fuel each year (assuming a terrestrial D/H ratio). Such a requirement might easily be met and could be sustained for an extended period of time without exhausting the supply of H (which is easy) or without doing extensive environmental damage (which is more difficult). We also recognize that just the act of warming Titan to room temperature might cause extensive modification of its surface, as well as its atmosphere. Indeed, the nature of Titan's surface after such a warming would be an important

element in determining the desirability of altering its climate. If Titan were not habitable or could not be made habitable after this change, there clearly would be little motivation to do it.

In certain ways, Titan might be the easiest extraterrestrial object to make habitable. Unlike Mars, there is enough N_2 in its atmosphere to meet the requirements of Table I. Very likely abundant water resides at or close to Titan's surface. There is also enough oxygen in the form of H_2O , CO and CO_2 to serve as source material for generating O_2 . However, the greatly reduced solar flux at Titan's distance from the Sun (down a factor of 100 from the Earth) would limit the rate of photosynthesis (and perhaps prevent it from occurring for some plants). Also, there is the question of how much dry land there would be once its surface temperature was raised above the melting point of water ice. Finally, the abundance of some atmospheric gases might need to be limited to prevent toxic levels from being reached (e.g., NH_3).

A similar scheme might be considered for Mars, but Titan has several advantages in this respect: the atmospheric pressure is much greater, and NH_3 and other greenhouse molecules (besides H_2O) are already present in the condensed phase. There is thus a much stronger greenhouse positive feedback to surface warming on Titan than on Mars. We estimate about an order of magnitude more technological power dissipation is required to bring Mars to $0^\circ C$ than to bring Titan, despite the much lower present temperatures on Titan. A similar scheme might apply to Neptune's moon Triton if it has near-surface NH_3 ice.

V. EARTH

Our own planet has a uniquely suitable climate for our kind of life—no coincidence because the environment and the biology have co-evolved. However, as mentioned in the introduction, human technology is swiftly and dangerously altering that environment. We here briefly consider ameliorating one such potential danger, i.e., countering global warming with some form of planetary engineering. We note immediately that the scale of global warming over the next century is predicted to be several degrees C, so any solution to the increasing greenhouse effect must have high precision. Beyond that, even if the global mean temperature increase can be slowed or stopped, we must be careful not to cause local and regional agricultural and economic disasters in the process. The cure must not be worse than the disease. The debate about incompletely understood and possibly highly nonlinear feedback effects in the global climate, aired in the greenhouse context (see, e.g., DOE Multi-Laboratory Climate Change Committee 1990), is a particular reason for caution. Such considerations already suggest that planetary engineering of the sorts discussed above may be inappropriate for an already inhabited planet.

A. Anti-Greenhouse Effect

In countering greenhouse warming, we might try to reduce slightly (by a few percent) the amount of sunlight reaching the lower atmosphere by creating a carefully titrated optically thin particle layer at high altitudes. A 1% change in the albedo of the Earth then buys us about a 1°C change in temperature directly, and about a 2°C change when we take account of the water vapor greenhouse feedback. The mass of fine particles required is some 10^{12} to 10^{13} g; they would not seriously diminish the light levels at the Earth's surface. If they were emplaced in orbit, the required mass would be the equivalent of some tens of thousands of shuttle launches. Even with a substantial improvement in the human species' heavy lift capability, this seems out of reach for some time. Moreover, the pollution generated by the required launcher traffic might cause significant damage to the ozone layer. Alternatively, the fine particles could be placed at stratospheric altitudes. As in the case of Venus, the layer would then have to be replenished about once a year.

One of the first suggestions on how to mitigate greenhouse warming was to carry sufficient elemental sulfur to the lower stratosphere, and to burn it to sulfur dioxide which is then converted into sulfuric acid droplets which scatter sunlight back to space (Budyko 1974,1977, and references therein; see also Broecker 1985; for a more general suggestion on cloud condensation nuclei see Latham [1990]). Alternatively, SO_2 could be carried up directly. A modern version of Budyko's calculation might go as follows: 1 to 10 Tg (1 Tg = 10^{12} g) of H_2SO_4 in small droplets would probably suffice to nullify a few degree greenhouse warming. This would require the transport of some 1 to 10 Tg of S or SO_2 to the lower stratosphere every year (assuming one year for the aerosols to fall out), or equivalently 10^6 to 10^7 metric tons per year. The military transport aircraft with the largest payloads in the world are the Russian AN 225, which can lift 250 metric tons, and the U. S. C-5B which can lift 125 metric tons (Cheney 1989). Allowing for the apparatus to oxidize the elemental sulfur at altitude (if SO_2 itself is not carried), and the desire to get to higher altitudes than just above the tropopause, let us assume aircraft with 100 ton payloads. This then requires between 30 and 300 flights per day into the indefinite future. Budyko points out that the resulting sulfur precipitation rate would be only a small fraction of that which occurs naturally (e.g., from volcanoes) without such intervention. However, the impact of aircraft effluents (via NO_x) on ozone, and on the greenhouse effect itself need to be examined.

An alternative is to pulverize and chemically process in orbital factories, one small Earth-crossing (Apollo object) or Earth-approaching (Amor object) asteroid a year. But this is a voracious waste of the limited number of Apollo or Amor objects, and much more expensive than delivering an annual layer of transparent fine particles to stratospheric altitudes from the surface.

The fallout of fine particles from the atmosphere, necessitating a replacement of the light scattering layer every year or two, can be avoided if

a continuous solid shield were in place at much higher altitudes (see, e.g., Fogg 1987). One proposal to mitigate greenhouse warming (discussed in Broad 1988) is to deploy a vast array of orbiting satellites constructed of thin (mylar-like) films that would attenuate sunlight. However, to compensate for a doubling in the CO₂ abundance, such a satellite array would require an area equivalent to a few percent of the Earth's surface, if the films were good reflectors. Such films may be expensive. At contemporary prices, 10⁷ km² of 6 μm thick aluminized mylar might cost nearly \$10¹³; kapton would be perhaps 100 times more expensive (Friedman 1989, personal communication). The progressive darkening of such films on continued ultraviolet and charged particle irradiation (the transparency lifetime of mylar films might be about a month) would be an additional complication. Conceivably, much cheaper radiation-nondegradable films might be developed in the future, but they do not appear to be competitive with some of the alternative possibilities for ameliorating global warming.

Another proposal (Early 1989) calls for a "glass" shield 2000 km in diameter and perhaps 10 μm thick, made from lunar materials and suitably coated, positioned between the Earth and the Sun near the first Lagrangian point, about 1.5×10^6 km from Earth. The cost is estimated between \$10¹² and \$10¹³ and the shield's long-term radiation and dynamical stability remains to be demonstrated. Dynamical instabilities may be addressed by equipping the shield with thrusters. In addition—unlike fine stratospheric particles, which take about a year to fall out and an orbital particle layer, which would be extremely difficult to remove—a sunscreen with an attached propulsion system can quickly be moved if unanticipated climatic side effects are found to be emerging on Earth. Better still for this purpose would be a sunscreen with louvers to fine-tune its effective opacity. We note also that reflecting shields need not be at high altitude or in space; massive reflectors floating in the oceans can also be envisioned, although at unknown environmental cost.

At best, however, the foregoing class of interventions in the Earth's climate might be considered as stopgap measures while the human species improves fossil fuel efficiency, terminates CFC manufacture, switches to alternative energy sources and takes other obvious groundbased measures. But why are any such heroic schemes needed, as we have already postulated abundant fusion power sometime in the next century? Why not simply assume that all power generation will derive from greenhouse-neutral fusion and consider the problem solved? The trouble is that even if cheap and safe fusion power were discovered in the laboratory tomorrow, its development to commercial scale and its deployment all over the world—including developing nations that have ready access to fossil fuels (China, for example, has the second largest coal reserves on Earth)—will take time. And in that time, the amount of CO₂ continues to build. Moreover, there are certain troublesome potential feedbacks—e.g., that a few degrees of global warming will release substantial quantities of now-sequestered bog methane, further augmenting the greenhouse effect. Even if much more serious efforts were made to deal

with global warming than now seem (politically) feasible worldwide, it is very difficult to imagine stopping the buildup of greenhouse gases altogether, at least in the next century: the world economy is far too dependent on fossil fuel energy sources. Many sources of greenhouse gases (some 30% of U. S. CO₂ emissions derive from automobiles) are not likely to be replaced by massive fusion power plants (although electric or hydrogen-fueled autos recharged from fusion power plants might solve this problem in the long term). So the consequences of continued greenhouse warming, even if somewhat delayed, might be considered sufficiently perilous to justify major, and costly, efforts at amelioration.

However, planetary engineering schemes utilizing extraterrestrial materials in Earth orbit or at L₁, or even terrestrial materials lofted to stratospheric altitudes, seem to us indeed to be cures that might be more dangerous than the disease—given both our present state of ignorance about climatic feedbacks and atmospheric chemistry, as well as our history of discovering unpleasant inadvertent side-effects of global scale technology. An additional deficit of many such schemes for planetary engineering of the Earth is that groundbased optical frequency astronomy would essentially cease. Although most (including us) would consider this an acceptable sacrifice to preserve the habitability of the Earth, it would be a tragic loss. Lagrangian point sunscreens would inhibit mainly solar astronomy, leaving the rest of the sky no more obscure than usual.

B. Trees

We advocate instead of particle shields or sunscreens, a well-tried biological solution, neither endangering astronomy nor posing unprecedented technological or climatic problems. We propose reforesting the world, especially in the tropics, in accordance with the ancient oriental wisdom, “He who causes trees to be planted lives long” (Polo 1300).

The added biomass would fix atmospheric CO₂, offsetting its continued buildup. It would buy time while massive conversion to nonfossil fuel energy sources was underway; it would also have positive ecological benefits (including relief for many endangered species); and it would be less likely to produce potentially disastrous regional shifts in climate. But is reforestation an allowable solution from the point of view of mass? The analysis of this issue was pioneered by Dyson (1977) and Dyson and Marland (1979). A restatement of the calculation goes as follows: doubling the CO₂ content of the atmosphere from its pre-industrial level would augment the CO₂ abundance by 0.55 g cm⁻², or equivalently by 0.15 g cm⁻² of C. The dry biomass in a typical rain forest is about 6 g cm⁻² (Lieth and Whittaker 1975), of which about half is C. Thus, about 5% of the Earth’s surface would need to be reforested with rain forests (or a higher percentage with other types of forests) to fix the added CO₂ (while leaving stored C in storage). This is equivalent to an area of about 2.5×10^7 km², or about 15% of the landmass of the Earth. By comparison, tropical rain forests currently cover somewhat less area, while

tropical rain forests, rain-green forests, and summer-green forests collectively cover a somewhat larger area than the required 2.5×10^7 km². A massive replanting would be needed, necessarily including tropical latitudes where forests are now being destroyed on a massive scale for purposes of short-term commercial profit and "development." Rain forests serve to stabilize thin layers of topsoil, which, unfortunately, promptly (after a few growing seasons) erode once the forest is cut down. This trend towards irreversibility in the destruction of rain forests makes the practice especially short-sighted.

Mature forests, on yearly average, fix very little CO₂. The desired steady-state CO₂ fixation rate can be achieved with a smaller fraction of the Earth's surface forested by felling mature forests and re-planting them with fast-growing timber. This must be done with care to minimize the penalty to key ecosystems. As much of this wood as possible should be used for construction, furniture and other products of domestic economy. The remainder should be sequestered so that it is gradually converted to involatile kerogens and, eventually, elemental C. Obviously, burning these trees or the lumber milled from them defeats the purpose of growing them. When the world energy economy moves significantly away from fossil fuels, these strictures could be relaxed.

Net primary production in a tropical rain forest occurs at a rate of ~ 0.2 g cm⁻² yr⁻¹ (Lieth and Whittaker 1975). Thus, ~ 30 yr is needed between the initial replanting and the achievement of a steady-state biomass. This time scale is only somewhat less than current estimates of the doubling time of atmospheric CO₂. It pays to plant soon.

At their current rate of increase, gases other than CO₂ (most notably CH₄, CFCs, and N₂O) are generating an additional greenhouse warming of the atmosphere (Lacis et al. 1981; DOE Multi-Laboratory Climate Change Committee 1990), which collectively constitute about 50 to 100% of the warming due to added CO₂. Thus, an adequate strategy for avoiding significant global warming over the next century must involve controls on these gases as well. Controls are already being exercised on CFCs for other environmental reasons. As cattle and rice paddies are among the primary sources of CH₄, controlling the increase in methane could be integrally tied to such sensitive issues as the need for animal protein (and other resources provided by ungulates) and population control in the developing world, which in any case is a key component of any solution, because the developing nations together already constitute (after the U. S. and Russia) the third largest source of CO₂ emission on the planet (Brown 1989).

It has been proposed that the phytoplankton productivity in the southern ocean is limited by the availability of iron as a metabolite, that pre-industrial global CO₂ abundances were much higher than would have been the case without this iron deficiency, and that the abundance of iron-rich atmospheric dust is anticorrelated with atmospheric CO₂ levels (Martin 1990). This has led to the suggestion (Martin et al. 1990; Davies 1990) that fertilizing the southern ocean with 10^5 to 10^6 tons of finely pulverized soluble iron may lead

to a phytoplankton bloom that would significantly mitigate CO₂ greenhouse warming. This is the oceanic equivalent of massive re-forestation and superficially is far easier—fiscally and politically. However, unlike re-forestation, this is an intervention where we have no large-scale experience. More recent evidence suggests that iron may be much more available to oceanic phytoplankton than had previously been thought (Wells et al. 1991), and that ocean dynamic considerations vitiate the idea (Peng and Broecker 1991). Even if the iron-deficiency hypothesis were confirmed (cf. Davies 1990; Joos et al. 1991), it seems wise to proceed with great caution. Propagating negative ecological consequences have been suggested; this is also true for alternative interventions such as massive, periodically harvesting towed seaweed farms or piping liquified CO₂ to the abyssal depths where, perhaps, it might solidify (Blakeslee 1990).

Likewise, a scheme for mitigating stratospheric ozone loss by massive (5×10^4 ton annually) injection of ethane or propane into the Antarctic stratosphere (Cicerone et al. 1991) is partially disavowed by the scientists who suggested it on the grounds that it could increase, not decrease, ozone depletion; one of them is quoted (Dye 1991) as saying that “the proposal was meant to illustrate that such a plan is not feasible.” (See also Cicerone et al. 1992.)

Since this chapter was prepared, an excellent survey of possible planetary engineering schemes to mitigate global warming on Earth has appeared (Committee on Science, Engineering, and Public Policy 1992). Favored options include re-forestation, delivery of dust to the stratosphere (using naval gunnery) and increasing oceanic cloudiness by supplying tropospheric cloud condensation nuclei (via SO₂). Possible side effects—such as enhanced ozone depletion and acid rain for the latter two schemes—are stressed. Clearly more work is needed, but comparatively inexpensive and environmentally prudent methods of mitigating greenhouse warming on Earth may be within reach in the next few decades.

VI. SUMMARY AND RECONSIDERATION OF SOLAR SYSTEM ENVIRONMENTAL ETHICS

We find that with optimistic estimates of late 21st century technology and physical principles at least moderately well-understood today, it may be possible to effect massive changes in the environments and climates of Mars, Venus, Titan and perhaps other worlds in the solar system. Some schemes—such as impact stripping the atmosphere of Venus or mining much of Mars or Venus down to depths of hundreds of meters or more—represent a wholly irresponsible waste of solar system resources and the loss of irreplaceable scientific knowledge. They are extreme examples of approaches that must be avoided. Fortunately, they are also prohibitively expensive. Other possible schemes (including those that utilize the self-replication of genetically engineered micro-organisms) are less destructive in their immediate impact, but

uncertain in their efficiency and long-term consequences. In particular, the introduction for a given purpose of microorganisms into a previously uninhabited planetary environment may, through evolutionary "adaptive radiation" into untenanted ecological niches, lead later to a set of entirely unexpected consequences.

Schemes that moderate atmospheric greenhouses by emplacing spherical shells of fine particles at high altitudes or sunscreens between the planet and the Sun to some extent avoid both of the preceding pitfalls: they are not wholly voracious in their appetite for asteroidal (or cometary) resources, and, because they naturally decay on a time scale of about a year or can be moved, do not seem to threaten dangerous long-term consequences. Because of the high specific energy of thermonuclear processes, some planetary engineering schemes that employ fusion power plants in a central role (e.g., by heating the surfaces of cold worlds) display both high efficiency and relative environmental responsibility.

It is clear that human technology is now able—even inadvertently, and certainly were there a concerted and purposeful effort—to alter entire planetary environments. Doubtless there will be schemes invented in coming years that are much less energy- and mass-intensive, much more precise, much freer of inadvertent side-effects, and much more stable than any proposed here.

We recognize that many people feel a powerful attraction to the idea of making other worlds in the solar system suitable for human habitation and then establishing observatories, exploratory bases, communities, or homesteads there. Because of its pioneering history, this may be a particularly natural and attractive idea in the United States. However, we believe that the motives for altering other worlds need much more serious consideration than they have received heretofore. Because some 240,000 more people are born than die every day on Earth, emigration to newly engineered worlds cannot be a feasible means of dealing with the world population crisis. If we are concerned that the human species might self-destruct, certainly it makes more sense to devote limited resources to preventing self-destruction than to preparing an escape hatch for a fortunate few. In any case, massive alteration of the environments of other worlds can be done competently and responsibly only when we have a much better understanding of those worlds than is available today. Advocates of planetary engineering should first be advocates of the long-term and exhaustive scientific exploration of other worlds.

A short-term imperative for planetary engineering exists only for one world in the solar system, our own. Careless or reckless applications of human technological genius have put the global environment at risk in several different ways. The Earth is not a disposable planet. It is just conceivable, as we have discussed, that some of the techniques that in the long term might be applied to engineering other worlds might also be utilized to ameliorate the damage being done to this one. Perhaps a safe way to test our protocols is to implement them in carefully circumscribed ways on other worlds. But considering the relative urgencies, a useful indication of when the human

species is ready to consider planetary engineering seriously is when we have put our own world right. We can consider it a test of the depth of our understanding and our commitment. The first step in engineering the solar system is to guarantee the habitability of the Earth.

Acknowledgments. This work was supported in part by two NASA grants. We thank C. Chyba, F. Dyson, M. Fogg, L. Friedman, J. Kasting, A. Lacis, C. McKay, G. Marland, J. Oberg, J. Pike, W. Rossow, R. Turco and, especially, J. Lewis for helpful comments.

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