Research Paper

The Physics, Biology, and Environmental Ethics of Making Mars Habitable

CHRISTOPHER P. MCKAY[1] and MARGARITA M. MARINOVA[1,2]

ABSTRACT

The considerable evidence that Mars once had a wetter, more clement, environment motivates the search for past or present life on that planet. This evidence also suggests the possibility of restoring habitable conditions on Mars. While the total amounts of the key molecules— carbon dioxide, water, and nitrogen—needed for creating a biosphere on Mars are unknown, estimates suggest that there may be enough in the subsurface. Super greenhouse gases, in particular, perfluorocarbons, are currently the most effective and practical way to warm Mars and thicken its atmosphere so that liquid water is stable on the surface. This process could take ~100 years. If enough carbon dioxide is frozen in the South Polar Cap and absorbed in the regolith, the resulting thick and warm carbon dioxide atmosphere could support many types of microorganisms, plants, and invertebrates. If a planet-wide martian biosphere converted carbon dioxide into oxygen with an average efficiency equal to that for Earth's biosphere, it would take >100,000 years to create Earth-like oxygen levels. Ethical issues associated with bringing life to Mars center on the possibility of indigenous martian life and the relative value of a planet with or without a global biosphere. Key Words: Mars—Terraforming—Planetary ecosynthesis—Greenhouse warming—Environmental ethics. Astrobiology 1, 89–109.

INTRODUCTION

THE SURFACE OF MARS is cold and dry, the regolith appears to contain dilute but powerful oxidants that have destroyed any organic material, and solar UV light down to wavelengths of 190 nm reaches the ground. There is no organism on Earth that could grow or reproduce under martian conditions (e.g., Clark, 1998). Table 1 is a comparison of selected environmental and physical properties of Mars and Earth.

Interestingly, Mars was not always this way.

There is direct evidence that early in martian history, liquid water was stable and present at the surface. The sinuous canyon in Fig. 1, Nanedi Vallis, shows what may be the best evidence for sustained liquid water flow on Mars (Carr and Malin, 2000). The large flood features on Mars indicate that the total inventory of water was considerable (Carr, 1986, 1996), possibly creating an ocean early in martian history. Recent altimeter data indicate shorelines consistent with an ocean (Head et al., 1999). Subsurface liquid water may even persist to the present time as indicated by

[1]Space Science Division, NASA Ames Research Center, Moffett Field, CA 94035.
[2]Massachusetts Institute of Technology, Cambridge, MA 02139.

TABLE 1. COMPARISON OF MARS AND EARTH

| Parameter	Mars	Earth
Surface pressure	0.5–1 kPa	101.3 kPa
Average temperature	−60°C	15°C
Temperature range	−145°C to 20°C	−60°C to 50°C
Composition	95% CO_2	78% N_2
	2.7% N_2	21% O_2
	1.6% Ar	1% Ar
Normalized sunlight	0.43	1
UV light	>190 nm	>300 nm
Surface gravity	0.38 g	1 g
Rotation rate	24 h 37m	24 h
Obliquity	25.2°	23.5°
Orbital eccentricity	0.093	0.017
Year length	687 days	365.25 days

groundwater seepage and surface runoff features that are <1 million years old (Malin and Edgett, 2000). Liquid water is the quintessence of life, and the past presence of liquid water on Mars is the primary basis for the search for evidence of past martian life (McKay, 1997).

The early wetter, warmer climate of Mars also motivates the question of purposefully restoring Mars to habitable conditions. This process is known as "terraforming" or "planetary ecosynthesis." The latter term is more accurate since it avoids the misleading comparison with Earth. Humans are demonstrably capable of altering the environment of a planet—we are doing so on Earth primarily through changes in the composition of the atmosphere. Alterations in the physical properties of a planet are far beyond current technology. However, as seen in Table 1, many of the physical properties of Mars are similar to those of Earth. The day length and obliquity (which controls the seasons) are very similar to the values for Earth. The major differences are the lower gravity, the lower average sunlight, and the longer year and season length. None of these differences is likely to present fundamental obstacles to the creation of a biosphere on Mars. Thus Mars, unlike all the other worlds of our solar system, can be made habitable just by changing the composition of its atmosphere—the approach considered in this paper.

The study of planetary ecosynthesis on Mars is now part of the Astrobiology program. In October 1997, NASA Headquarters released a Cooperative Agreement Notice soliciting participation in the new Astrobiology Institute. To frame the scientific questions that would be addressed by this Institute, the Notice listed six questions. The final question was: What is the potential for survival and biological evolution beyond the planet of origin? This question represents a new perspective for the NASA research program. For the first time the question of life beyond the Earth is now expanded to more than the mere survival of astronauts. "Biological evolution" is a process that is not a function of single individuals or even a single species. Biological evolution is a function of many species interacting together and changing their environment. Mars is the logical site for a first test of the possibilities for biological evolution beyond the Earth. Thus we consider as part of the Astrobiology program the question: Can ecosystems be established on Mars?

While the question of the habitability of Mars is just recently entering the research agenda of astrobiology, it has been discussed in the scientific literature for a number of years. The first scientific paper dealing with planetary ecosynthesis on any planet was the seminal work of Sagan (1961) suggesting the introduction of algae into the atmosphere of Venus. Early suggestions for making Mars habitable by altering its presumed natural climate cycle were due to Sagan (1971, 1973) and Burns and Harwitt (1973). The first comprehensive look at the habitability of Mars was the report of an interdisciplinary summer study by Averner and MacElroy (1976). This report was to set the stage for combined biological and physical approaches to the questions of restoring habitability to Mars. McKay (1982) followed this approach and suggested that the re-creation of a
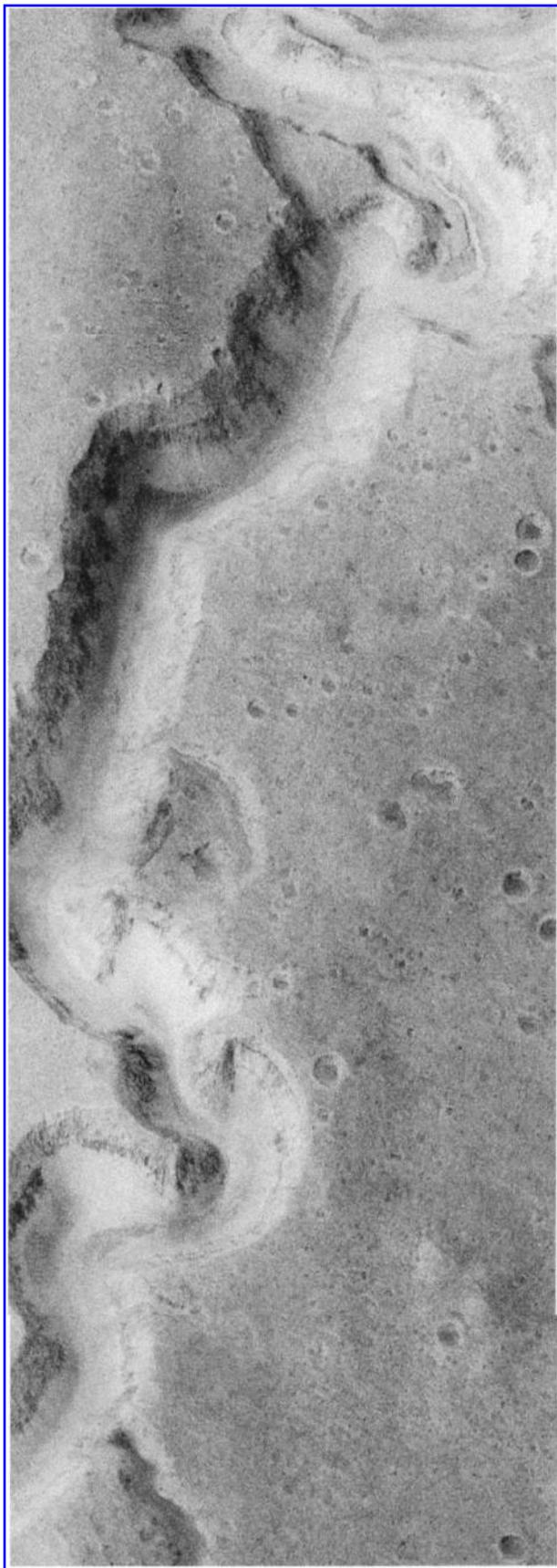
thick, warm CO_2 atmosphere would be more easily accomplished than the creation of "Earth-like" conditions with high O_2 pressures. Based on energy requirements and efficiencies, he estimated 100 and 100,000 years, respectively, for these two transformations. McKay (1982) also proposed that biological stability (*Gaia*) could play a role in maintaining a future biosphere on Mars. Lovelock and Allaby (1984) proposed a practical and specific plan for how to warm Mars using super greenhouse gases, in particular, chlorofluorocarbons (CFCs), carried from Earth. The use of super greenhouse gases remains at the center of current studies, although subsequent analysis has shown that perfluorocarbons (PFCs) produced on Mars are in fact more practical than transporting CFCs. McKay et al. (1991) published an overview in *Nature* of how Mars might be made habitable and brought the subject wide scientific exposure. They used climate models developed for the Earth to compute the amount of super greenhouse gases needed to warm Mars. Since 1990, numerous specialized papers have appeared in the *Journal of the British Interplanetary Society*. [See Fogg (1995a, 1998) for excellent overviews of these papers and a review of the basic science and proposed engineering schemes for creating habitable environments beyond the Earth.] It is interesting to note that several published papers consider the environmental ethics of planetary ecosynthesis (e.g., Haynes, 1990; McKay, 1990; Fogg, 2000).

The purpose of this paper is to review previous and ongoing work in planetary ecosynthesis from the perspective of how this topic fits within the overall field of astrobiology and thereby provide a basis for future research.

HABITABLE CONDITIONS FOR LIFE

The logical first step in considering making Mars habitable is to define precisely the limits of habitability. McKay et al. (1991) defined two limiting cases of habitability: with and without high O_2 levels (Table 2). The main requirement for a

FIG. 1. **Mars Global Surveyor image showing Nanedi Vallis in the Xanthe Terra region of Mars.** Image covers an area 9.8×18.5 km; the canyon is $\sim$2.5 km wide. Photo from NASA/Malin Space Science Systems.

TABLE 2.   HABITABILITY

Parameter	Limits	Note
Global temperature	0°C–30°C	Earth = 15°C
Composition for plants, algae, microorganisms		
Total pressure	>1 kPa	Water vapor pressure plus O_2, N_2, CO_2
CO_2	>0.015 kPa	Lower limit set by photosynthesis, no clear upper limit
N_2	>0.1–1 kPa	Nitrogen fixation
O_2	>0.1 kPa	Plant respiration
Composition for breathable air		
Total pressure		
Pure O_2	>25 kPa	Lung water vapor plus CO_2, O_2
Air mixture	>50 kPa	Based upon high elevation
	<500 kPa	Buffer gas narcosis
CO_2	<1 kPa	Set by toxicity
N_2	>30 kPa	Buffer gas
O_2	>13 kPa	Lower limit set by hypoxia
	<30 kPa	Upper limit set by flammability

Adapted from McKay et al. (1991).

habitable planet is a surface temperature in the range to allow for liquid water. In Table 2 the minimum mean surface temperature is listed as 0°C. This could be a reasonable value lacking an accurate determination of how cold Mars could be and still maintain a hydrological cycle sufficient to support life. The upper limit of 30°C (Dole, 1970) is listed for completeness, but is unlikely to be relevant to Mars. In a warm environment with high CO_2, but without high O_2 levels, microorganisms, plants, and possibly some invertebrates could survive. In this case the main requirements on the atmosphere is that the total pressure be higher than the water vapor pressure plus the minimal levels of N_2, CO_2, and O_2 needed by the living organisms. These add up to ~1 kPa—only slightly more than the current pressure on Mars. However, to make Mars warm with the greenhouse effect of CO_2 requires that the total amount of CO_2 on Mars be ~200 kPa. Lower levels of CO_2 can be compensated for by artificial greenhouse gases such as PFCs or by biologically produced methane.

Oxygen and CO_2 levels for algae and plants

Seckbach et al. (1970) reported on photosynthetic algae that thrive under pure CO_2. It is possible that many plants would be able to adapt to an atmosphere dominated by CO_2 with low levels of O_2. Experimental studies of plant growth under twice the present atmospheric CO_2 on Earth indicate generally increased productivity for many species (Bazzaz, 1990; Jones et al., 1998; DeLucia et al., 1999). In general, the tolerance of plants to high CO_2 and low O_2 varies between plant and among C-3, C-4, and CAM plants (Salisbury and Ross, 1985). Experimental studies have focused on doubling of CO_2, and it is not clear whether these results can be extrapolated to very high partial pressures of CO_2.

McKay et al. (1991) pointed out that some plants actually prefer O_2 levels well below the current value. The requirements vary depending on the plant, but, in general, net primary productivity increases as O_2 is reduced from the ambient level until a point is reached where the O_2 concentration is low enough (2 kPa) to cause metabolic complications (e.g., Salisbury and Ross, 1985). It may be possible to adapt plants to accept even lower O_2 levels (0.1 kPa) since the mitochondrial enzyme that requires O_2 can function at O_2 levels of 0.01 kPa (e.g., Salisbury and Ross, 1985). Some viable strategies (Fogg, 1995b) include plants that retain their own photosynthetically produced O_2 or have more efficient transfer of O_2 to the sites of O_2 utilization.

The current Mars atmosphere contains 0.1% (0.0006 kPa) O_2 (and 0.07% CO), produced by the photochemical breakup of CO_2. If this mixing ratio of O_2 and CO is assumed constant and the total atmospheric pressure was increased to 100 kPa, then the concentration of O_2 would be 0.1 kPa, close to the levels needed for plants. Unfortunately, the levels of CO would be 0.07 kPa— seven times the concentration that produces

clinical symptoms in humans; plants and microorganisms are unaffected by CO. Photochemical models of O_2 production on early Earth, with a CO_2-rich atmosphere, do not directly relate to the photochemistry on a future thick CO_2 martian atmosphere, since on the early Earth, unlike present-day Mars, the level of O_2 was kept low because of the presence of reductants in the environment and outgassing from volcanoes (Kasting, 1993; Rampino and Caldeira, 1994). On Mars, the surface is oxidizing, and there appears to be no source of reducing material (Hartman and McKay, 1995). The only photochemical models that have addressed this condition are those of Rosenqvist and Chassefière (1995). To determine the upper limit on abiotic O_2 on the early Earth, they considered models without any sinks for O_2 due to outgassing or surface reductants. They found that the O_2 partial pressure for a thick CO_2 atmosphere was ~0.2 kPa. Detailed photochemical models are capable of addressing this question directly, and such results are a good area for future research. The lower solar flux on Mars might reduce the expected O_2 concentration; however, the lower temperatures and hence lower H_2O concentration would raise the expected O_2 concentration. Models specifically addressing the photochemical state of a thick CO_2 atmosphere on Mars are still needed and would be important for understanding the progression of plants and animals that might be able to survive on Mars with the increasing atmospheric pressure.

Lower limit for nitrogen fixation

Nitrogen is required for all organisms, and the amount of atmospheric N_2 must be high enough to provide for biological nitrogen fixation. Preliminary work suggests that bacteria can fix N_2 at levels of 0.5 kPa (Klingler et al., 1989). The current pressure of N_2 on Mars is just under 0.02 kPa. A more accurate determination of the minimum required N_2 pressure is needed.

Pressure and oxygen levels needed for invertebrates

Previous studies on habitability have focused on the environmental requirements for microorganisms and plants on one end and humans on the other. These extremes are shown in Table 2. However, it is important to consider the CO_2 tolerance and O_2 requirements of invertebrates. Small animals play important roles in land ecosystems. Perhaps the two most prominent examples are the role of earth-moving animals, such as earthworms and termites, in soil processes and the role of flying insects in plant pollination. The only experiments that we are aware of are those of Cockell et al. (1999) in which a range of insects (ladybugs, beetles, termites, flies, ants, and dragonflies) were subjected to pressures of air from ambient down to <0.1 kPa. They found that all insects could tolerate pressures down to 10 kPa (O_2 partial pressure of 2 kPa) but that water loss at low pressure was an important issue. They concluded that on a terraformed Mars the total pressure would need to be 20 kPa to minimize water loss with an O_2 partial pressure of at least 1 kPa for breathing. However, their experiments used only an air gas mixture and over a short period of time; the experiment did not allow for acclimatization or adaptation of the insects, as might occur over sustained exposure. Multigeneration studies of invertebrates under a range of O_2 and CO_2 levels will be needed to determine accurately at what point invertebrates could begin to play a constructive role in a future martian ecology.

Buffer gas requirements for breathing in humans

A key uncertainty in the current understanding of the requirements for a human-breathable atmosphere is the minimum level of buffer gas needed in addition to O_2 for long-term habitation. There is general agreement that pure O_2 atmospheres are not adequate because of both the flammability hazard and long-term oxygen toxicity. However, the minimum amount of buffer gas needed (for which N_2 is the only viable solution) is not well established. Natural experiments in breathing at reduced pressures (high-altitude populations and mountain climbers) are conducted in air gas composition. The effect of buffer gas or O_2 partial pressures on flammability is also not well determined for realistic environmental conditions (cf. Watson et al., 1978 and Robinson, 1989; discussed in Berner et al., 2000).

The best available long-term studies of the effect of lowered buffer gas concentration on physiology have been space missions. The Apollo missions to the Moon were conducted with pure O_2 atmospheres at a total pressure of 34.5 kPa (5 psi). However, the longest mission was only 12 days.

Skylab astronauts lived for up to 84 days in a mixture of ~70% O_2 and 30% N_2 at a total pressure of one-third Earth-normal (34 kPa). While this gave a partial pressure of O_2 equivalent to sea level air, the reduced N_2 level required special precautions against flammability. For example, paint could not be used on surfaces, and clothing had to be made of plastic. The long-duration Mir missions as well as the Space Shuttle use standard air mixture and Earth-normal pressure (101.3 kPa). The role of gravity in the amount of buffer gas required to retard flames has not been determined. From flammability and breathing considerations, Dole (1970) and McKay et al. (1991) estimated that 30 kPa of buffer gas would be required, and Fogg (1995a) similarly suggested a minimum of 28.5 kPa. These values are much higher than the Skylab value of 10 kPa of N_2. Given the Skylab experience, one might conclude that the level of buffer gas must at a minimum be between 10 and 30 kPa.

Earth history lesson

In a general way, the two habitable states listed in Table 2 correspond to the early Earth before the rise of O_2 and the present Earth. For the present Earth, the functioning of the biosphere in terms of temperature regulation, plant and animal physiology, and biogeochemical cycles, if not completely understood, can at least be directly observed. For the early Earth this is not the case, and many aspects remain unclear. Of particular relevance to planetary ecosynthesis on Mars is how the temperature on early Earth was sustained when it appears that the level of CO_2 was not sufficient (Pavlov et al., 2000). Current models suggest that biogenic methane may have produced the needed greenhouse effect (Pavlov et al., 2000), a possibility that may be relevant to Mars as well.

THE RIGHT STUFF: CO_2, N_2, AND H_2O

Having identified two possible habitable states we must next consider if Mars has the ingredients necessary to construct these states. One might wonder if it is possible to import from Earth or from the outer solar system enough materials to construct an atmosphere. The masses involved are too large for foreseeable technology. The mass of just 0.1 Pa of atmosphere on Mars is

4×10^9 tons—much larger than the few hundred ton payload of a large rocket to low Earth orbit. Volatiles in sufficient quantities may exist in comet-like objects in the outer solar system, but there is no foreseeable technology for moving such an object onto a trajectory where it would impact Mars in a way that would contribute its volatiles to the martian atmosphere rather than cause a net removal of mass due to the impact explosion (Melosh and Vickery, 1989). Thus the only approach to planetary ecosynthesis considered here is based on compounds present on Mars.

In addition to the main volatiles discussed below, life must have sulfur, phosphorus, sodium, chlorine, potassium, and a range of trace elements (e.g., selenium). Not all of these have been directly detected on Mars but are all thought to be there based on theories of planet formation (e.g., discussed in McKay et al., 1991). Stoker et al. (1993) have prepared a complete analysis of the probable elemental composition of the martian surface based on the Viking results and analyses of the martian meteorites and concluded that the minor element composition on Mars is adequate for life.

The essential ingredients needed to build a biosphere are the volatile compounds: CO_2, N_2, and H_2O. There are only trivial quantities of these in the present martian atmosphere, but theoretical considerations and observations of past fluvial activity suggest that Mars must have had much larger quantities of all three compounds. Unfortunately, we do not yet know how much of each of these key ingredients Mars has located in the subsurface in nonvolatile form: H_2O frozen as ground ice, nitrogen in the form of nitrate, and CO_2 in the polar caps and absorbed in the regolith and as carbonates.

There are a variety of ways to estimate how much thicker the early martian atmosphere was. Estimates have been made based on the abundance of the rare gases, theories of atmospheric evolution, the size of the fluvial channels on Mars, and simply by scaling from Earth. Not surprisingly, the various estimates do not agree on how much of each of the volatiles were, or are still, present on Mars. Table 3 shows a comparison of the amount of material needed to make Mars habitable compared with the range of estimates of the initial abundances for CO_2, N_2, and H_2O. For CO_2 and N_2 the partial pressure of the gas is given, while for H_2O the thickness of a planetary-wide layer is given.

TABLE 3. INVENTORY OF IMPORTANT VOLATILES ON MARS

	CO_2 (kPa)	N_2 (kPa)	H_2O (m)
Required for plants	>200 (for warming)	>1	>500
Required for humans	>20 (for oxygen)	>30	>500
Present Mars atmosphere	1	0.02	7×10^{-6}
Earth scaling	270	30	1,200
Range of current estimates	20–200	0.2–30	6–1,000

Adapted from McKay and Stoker (1989).

As discussed above in the context of Table 2, creating a habitable state only for plants and microorganisms requires a minimal amount of gases. However, the amount of CO_2 needed in this case is set not by the physiological requirements of plants, but by the need to warm Mars enough to raise the average temperature above freezing. The amount listed in Table 3, 200 kPa, is enough CO_2 that augmentation of the greenhouse effect by other greenhouse gases is not necessary (McKay et al., 1991). If the total available inventory of CO_2 was less than this amount, then additional greenhouse warming from artificial greenhouse gases such as PFCs or from biogenic greenhouse gases such as CH_4 would be required. The amount of nitrogen needed is set by the ability of organisms to fix atmospheric N_2 (1 kPa). This total amount of nitrogen would not limit the mass of a global biosphere. If all the nitrogen in the current martian atmosphere were converted to biomass with the typical nitrogen concentration of 5% by weight (Davies and Koch, 1991), then the amount of biomass per unit area would be 87 kg m^{-2}, or ~25 times the average biomass per unit area on the Earth [3.6 kg m^{-2} (Krebs, 1985)].

For a breathable atmosphere the requirements are much different. Here the main need for CO_2 is as a source of O_2, and thus only 20 kPa is required. Nitrogen is needed not just to provide for nitrogen fixation, but also as a buffer gas in breathing. The upper limit on CO_2 consistent with a breathable mixture ensures that the greenhouse effect of CO_2 and H_2O in such an atmosphere would be insufficient to warm the surface, and significant amounts of additional greenhouse gases (PFCs and CH_4) would be needed (McKay et al., 1991).

For all habitable states a hydrological cycle is required, and we estimate that this implies enough water to create large bodies of water. If Mars had a layer of water 500 m thick over the entire surface and if this water were to collect into the current topographic shape of Mars, then about one-third of the planet would be covered with water.

Interestingly, the estimates of the amount of volatiles initially present on Mars overlaps the range needed for habitability (McKay and Stoker, 1989). However, it is not clear whether these volatiles are still present on Mars and present in forms that are accessible, even if the initial quantities were large.

Present reservoirs of CO_2

It is believed that the primary loss mechanism for the early dense CO_2 atmosphere was the formation of carbonate rocks (e.g., Fanale, 1976; Kahn, 1985; Pollack et al., 1987; McKay and Nedell, 1988). Other processes, such as CO_2 loss from the top of the atmosphere by solar wind and nonthermal escape mechanisms, do not seem able to explain the loss of a putative thick early atmosphere (Jakosky et al., 1994). Models of carbonate formation can account for the coincidence of the observed atmospheric pressure on Mars and the triple point pressure of water (Kahn, 1985). Carbonate formation would have proceeded on Mars as long as liquid water was present and ceased once the pressure dropped low enough to render liquid water unstable (Kahn, 1985). The timescale for decreasing atmospheric CO_2 from 100 kPa (1 bar) to its present value by carbonate formation is estimated to be as short as 10^7 years (Fanale, 1976; Pollack et al., 1987). More complex models (Schaefer, 1993), however, give longer timescales. Thus, in the absence of CO_2 recycling, the lifetime of a warm early atmosphere would have been limited. On an active planet like the Earth, subduction of ocean sediments at plate boundaries followed by thermal decomposition of carbonates deep below the surface is the primary mechanism for completing the long-term

geochemical CO_2 cycle (Walker et al., 1981). Mars does not have, nor is there any sign that Mars ever had, crustal dynamics akin to plate tectonics; rather, Mars's features are consistent with a one-plate planet (Solomon, 1978; Head and Solomon, 1981; but cf. Sleep, 1994). Without these processes there appears to be no long-term geological mechanism on Mars to recycle CO_2-sink materials back into the atmosphere.

If the early martian atmosphere were thick enough to warm the surface above freezing and if this atmosphere were primarily converted to carbonate, then massive carbonate deposits should cover much of the martian surface. One atmosphere of CO_2 on Mars converted to carbonates with a specific density of 3 would form a layer 20 m thick over the entire planet. Surprisingly, carbonate has not been clearly detected on Mars either from Earth-based telescopes or from spacecraft in orbit over Mars (e.g., Bandfield et al., 2000). Carbonates are not expected to have uniformly precipitated over the planet but would form in lake basins and drainage areas. One interesting suggestion is that the intracanyon layered deposits in the Valles Marineris system are carbonates (McKay and Nedell, 1988). Figure 2 shows Hebes Chasma and the central plateau within that canyon, which appears to have been deposited when the canyon contained a lake generated by regional groundwater flow. Because the canyon has no inflow or outflow channels, chemical precipitation is a likely explanation for the sediments. McKay and Nedell (1988) estimated the mass of the plateau corresponds to 3 kPa of atmospheric CO_2.

The fact that massive carbonate deposits have not yet been detected on Mars may be an indication that our understanding of the composition and fate of the early martian atmosphere is incorrect. On the other hand, there may be factors that obscure carbonates from remote viewing. For example, even a thin layer of dust would hide the carbonate spectral features. In addition, Mukhin et al. (1996) have conducted experiments in which they determined that calcite was not stable under UV irradiation at wavelengths between 200 and 400 nm in vacuum. This result appears to be inconsistent with previous work (Booth and Kieffer, 1978), which showed that carbonates form under conditions similar to those on the surface of Mars (0.6 kPa of CO_2) even with UV light present. A more promising way to destroy exposed carbonates may be by acid weathering. Banin et

al. (1997) has proposed that acid fog composed of chlorine and sulfur gases produced by volcanoes could be the primary weathering agent on Mars. If so, any carbonate exposed at the surface would be destroyed. Thus the absence of spectral evidence for carbonates is troublesome but not a decisive argument against the presence of massive carbonate deposits on Mars.

Even given ample carbonates on Mars, releasing CO_2 from this source is difficult (e.g. Fogg, 1989). Carbonate decomposes to form CO_2 at high temperatures (1,000°C) or low pH (<5). On Earth, carbonates are exposed to high temperature when they are carried deep below the surface at subduction zones. On Mars, the only feasible way to generate CO_2 from carbonates appears to be by acidification. Fortunately, there are some known microorganisms that seem to be able to decompose carbonates (Friedmann et al., 1993). However, while this biological source of CO_2 may be of importance in the ultimate functioning of a martian biosphere, it cannot be a source of CO_2 as Mars is warmed from its present cold state, which is too dry and cold to support the growth of microorganisms.

The sources of CO_2 that would contribute to the warming of the present Mars are the exchangeable reservoirs, that is, the CO_2 that is in the atmosphere, frozen on the polar caps, or absorbed in the regolith. The CO_2 in these sources is in equilibrium with the surface temperature, and if the surface temperature were raised, then CO_2 would move from the condensed reservoirs (polar caps and the regolith reservoirs) to the atmosphere, thereby abetting the warming. The positive feedback of this CO_2 degassing, triggered by artificial greenhouse gases, is essential to warming Mars (McKay et al., 1991; Marinova et al., 2000).

Theoretical studies of climate evolution on Mars (McKay and Davis, 1991; Haberle et al., 1994) suggest that up to 50 kPa of CO_2 may have remained after the main phase of carbonate formation. Presumably this CO_2 would have been mostly stored in the polar caps and regolith reservoirs. It was once thought that the polar caps on Mars were composed of massive amounts of CO_2 in equilibrium with the atmosphere. However, the existence of a permanent CO_2 cap can be ruled out for the North Pole (e.g., Fanale et al., 1974), and there is unlikely to be significant CO_2 in the layered deposits (Mellon, 1996). In the southern hemisphere there is evidence for a year-round
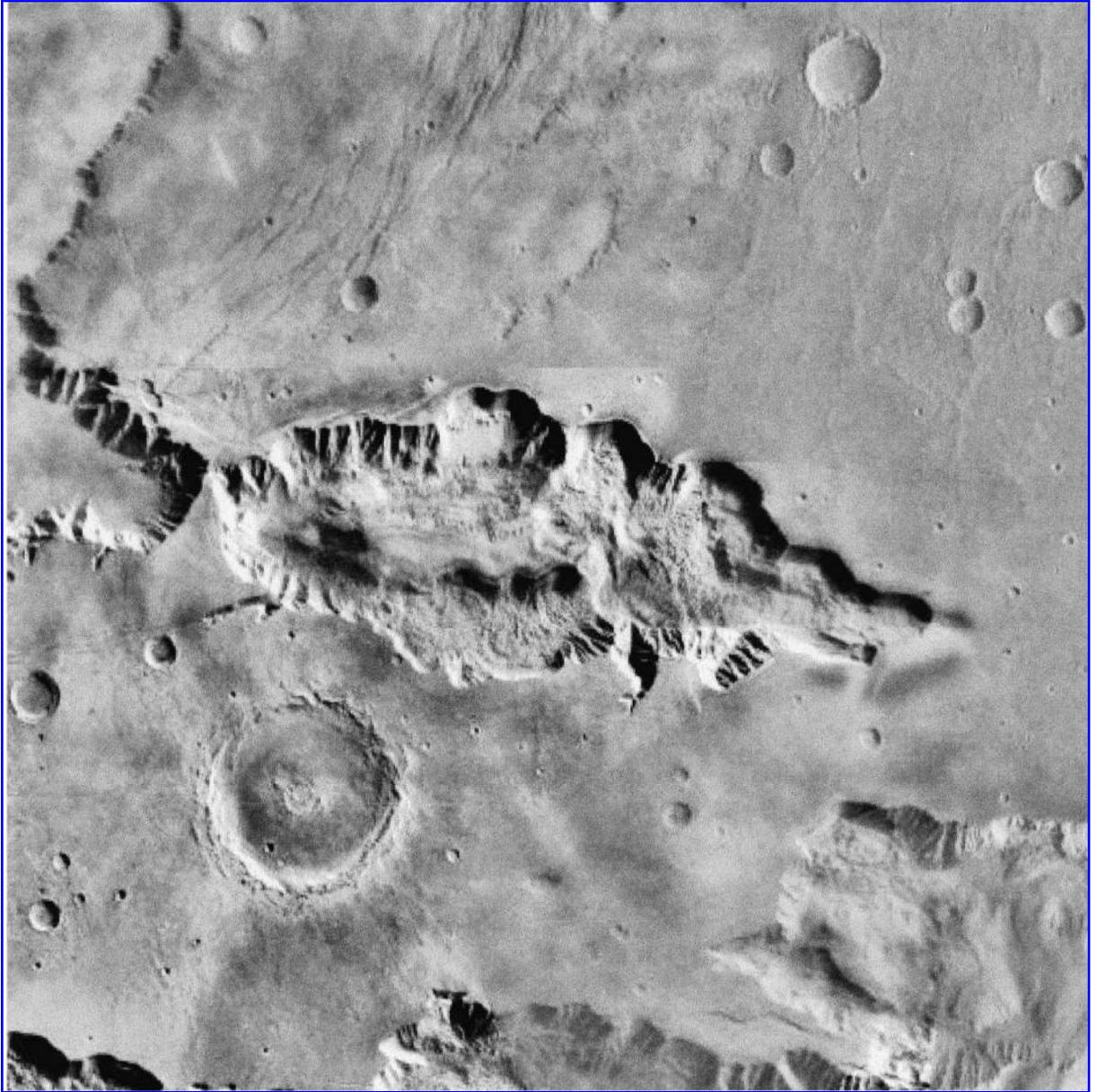
FIG. 2. Viking orbiter image of Hebes Chasma (0°S, 75°W). This canyon is a box canyon ~280 km long. The mesa in the center of the canyon shows layered sediments that may be carbonates (McKay and Nedell, 1988) illustrating what is thought to have been, and would be, the fate of martian CO_2. Decomposing these carbonates to create atmospheric CO_2 requires either high temperatures or low pH. Microorganisms are capable of lowering pH sufficiently to release CO_2 from carbonate and could complete the carbon cycle on Mars (Friedmann et al., 1993).

CO_2 reservoir at the South Pole (Fanale and Cannon, 1974). The size of this reservoir is not determined, but the residual cap is small—only ~350 km in diameter—and basal melting should limit the thickness of CO_2 it could contain. A 1-km-thick cap of this size could provide ~10 kPa of CO_2; hence a more detailed assessment of the existence and stability of a permanent CO_2 South Polar Cap on Mars would be of interest. Thus the

potential release of the 10 kPa of CO_2 from the South Polar Cap may be a key first step in the warming of Mars (McKay et al., 1991).

Another possible source of CO_2 is the martian regolith. Various studies have estimated there to be from five to 50 times as much CO_2 absorbed in the regolith as is present in the atmosphere (e.g., Zent et al., 1987; Kieffer and Zent, 1992; Zent and Quinn, 1995). McKay et al. (1991) modeled

the desorption of the regolith CO_2 upon heating and found that it may be an important positive feedback in the warming of Mars, but because the CO_2 may be tightly absorbed onto the regolith, it would not vent to the atmosphere as readily as the polar cap CO_2.

Present reservoirs of H_2O

The initial inventory of water on Mars is uncertain, with estimates ranging from only a few meters thick to almost a kilometer, in terms of a layer covering the entire planet (Table 3). In general, estimates based on geological features, such as the fluvial features, imply higher levels of water—up to 1 km. Estimates based on scaling from observed abundances of noble gases or based on isotopic data suggest lower levels—closer to a few meters. Some water might have been lost to space from Mars, but the current loss rate is insufficient to deplete any significant initial reservoirs. If the current rate of atmospheric escape has remained constant for water (as 2H and O) at 6×10^7 cm^{-2} s^{-1} (Liu and Donahue, 1976; McElroy et al., 1977), the total loss over the past 4.5 billion years would be 2.5 m of water. Recently the debate on water levels has focused on the D/H ratio on Mars; it is a factor of 5 more enriched in D than the terrestrial standard (e.g., Owen et al., 1977; Yung et al., 1988; Donahue, 1995; Jakosky and Jones, 1997). Initially, this was interpreted to imply that Mars had lost most of its water and had an initial inventory of only a few meters. However, the D/H ratio in the martian meteorites has shown that the current amount of crustal water on Mars must be large and that the initial inventory must have been more than several hundred meters deep (Donahue, 1995). Geochemical evidence from the martian meteorites also implies significant quantities of martian water $<200 \times 10^6$ years ago (McSween et al., 2001). The D/H in the atmosphere appears to correspond to fractionation by escape of just the atmospheric and near surface reservoirs.

Most current models suggest that the bulk of the martian water is tied up in the subsurface, either as permafrost or as deep aquifers. The evidence for permafrost is from craters in polar latitudes, which show a morphology that indicates ground ice (Squyres and Carr, 1986). The arguments for an extensive subsurface aquifer system are more indirect, but this could also be a significant reservoir of H_2O on Mars (Clifford, 1993).

Fogg (1995a) tallied up the polar cap and ground ice reservoirs on Mars and concluded that ~25 and 500 m of water, respectively, could be expected from these two sources. Mars thus appears to have sufficient water, if warmed, to form large bodies of liquid water and therefore once again be capable of harboring life.

Present reservoirs of N_2

Perhaps the key issue in assessing the potential of Mars for long-term human habitability is the abundance of nitrogen. As seen in Table 3 the amount of nitrogen needed to make a breathable atmosphere is at the upper limit of the range of estimates of the total initial inventory of nitrogen on Mars. If Mars did start out with that much nitrogen and it is still on the planet, the only possibility is that it is tied up as nitrate in the regolith and subsurface. On Earth nitrate does not usually accumulate in the soil because it is a very soluble salt easily removed by water and it is readily converted by microorganisms into N_2. The only significant accumulations of nitrate on Earth occur in the Atacama Desert. The nitrate in the Atacama is of atmospheric (lightning) origin based on the stable isotope work (e.g., Böhlke et al., 1997), and the implied production rates are not unusually high. What is unusual is that there are no removal mechanisms due to the lack of water activity and resultant lack of microbial denitrification. Over the age of the Atacama Desert ($10–15 \times 10^6$ years) the accumulation has resulted in large concentrated deposits. Mars has less water and, likely, less microbiological activity than the Atacama Desert, and consequently nitrogen may have been slowly converted to nitrate by lightning, volcanic-induced electric discharge, or meteors. The nitrates would have accumulated in sediments with no recycling mechanism. Following this scenario, most of Mars's initial nitrogen may be nitrate in the sediments, possibly colocated with the carbonates. Preliminary experiments with denitrifying bacteria by Hart et al. (2000) suggest that nitrate would be rapidly metabolized to N_2 in a CO_2 atmosphere if liquid water and organic materials were present. Thus a key target for future missions will be to assess the amount and location of nitrates on Mars. Ferrying nitrogen from Earth is clearly impractical, since the amount needed to reach a pressure of 0.3 atmospheres is $>10^{15}$ tons (compare with the Shuttle lift capability of 20 tons). Importing this amount of ni-

trates would equivalently require over several hundred thousand comets with a radius of 1 km composed of pure nitrogen. If Mars does not have the necessary nitrogen, it is not within near-term capabilities of humans to import it. Nitrogen could be the factor that prevents the creation of a human-breathable atmosphere on Mars, but is very unlikely to be limiting for a plant-dominated biosphere.

TIME AND ENERGY ANALYSIS

Assuming that Mars has adequate reservoirs of available CO_2 in the polar caps and regolith reservoirs, sufficient amounts of H_2O as ground ice in the permafrost regions, and enough nitrates in the sediments, then it is logical to next consider how much energy it would take to transform these compounds into the desired warm, high-pressure state. Table 4, modified from McKay et al. (1991), shows an energy analysis for warming Mars and altering its chemical state. We divide the process into three parts: surface warming, deep warming, and chemical alteration. The initial state refers to Mars as it is today with the volatiles locked up in the frozen state. The final state refers to the desired warmer state and, for the last row, the state with high O_2 levels.

In Table 4 the entries under Surface warming include the sublimation of 2 atmospheres of CO_2, warming the top 10 m of the surface, melting of a 10-m layer of water ice, and moistening the atmosphere. Since sunlight is the largest and only plausible large-scale energy source, the required energies are converted into equivalent years of

martian sunlight. The total energy difference between the initial and final states corresponds to ~10 years of martian sunlight; most of this energy is associated with vaporizing CO_2 from the polar cap and regolith reservoirs. Thus, if every single photon reaching Mars from the sun were used to warm Mars, it would have a warm surface in only 10 years. However, it is not possible to trap solar energy with 100% efficiency. Even with a strong greenhouse effect, a much smaller value is more probable due to two factors. First, the frozen volatiles are in the polar regions, and they receive only a fraction of the total solar energy that reaches Mars. Second, Mars continues to radiate infrared energy from the top of its atmosphere, so the heating of the planet is the absorbed solar less this radiated infrared. Without a time-dependent model of the coupled polar cap/regolith/atmosphere system we cannot evaluate the efficiency with which Mars would be warmed; however, we estimate that it would be of the order of 10%. Thus we assign the total time for warming the surface of Mars to 100 years.

To melt the deep ice layers on Mars fully would take much longer because of both the energy required and the time for heat to penetrate the deep layers below the surface. As listed in Table 4, to melt enough ice to provide a 500-m-thick layer of water over the surface of Mars requires the equivalent of 56 years of martian sunlight. The process would probably be limited by the rate of heat transport into the regolith. If thermal diffusion were the only method of warming the subsurface, this would require on the order of 10^5 years; however, as the permafrost melts, liquid water would allow for the convective transport of heat by the

TABLE 4.   ENERGY REQUIREMENTS FOR TERRAFORMING MARS

Initial state	Final state	Amount	Energy ($J\ m^{-2}$)	Solar energy (yr)[a]	Time (yr)
Surface warming					
$CO_2(s)$ at 125°C	$CO_2(g)$ at 15°C	200 kPa; 5.4×10^4 kg m^{-2}	3.7×10^{10}	7.9	
Dirt at −60°C	Dirt at 15°C	~10 m; 2×10^4 kg m^{-2}	1.2×10^9	0.3	
$H_2O(s)$ at −60°C	$H_2O(l)$ at 15°C	10 m; 1×10^4 kg m^{-2}	5.5×10^9	1.2	
$H_2O(s)$ at −60°C	$H_2O(g)$ at 15°C	2 kPa; 5.4×10^2 kg m^{-2}	1.6×10^9	0.33	
Total				10	100
Deep warming					
$H_2O(s)$ at −60°C	$H_2O(l)$ at 15°C	500 m; 5×10^5 kg m^{-2}	2.8×10^{11}	56	500
Making O_2					
$CO_2(g) + H_2O$	$CH_2O + O_2(g)$	20 kPa; 5.4×10^3 kg m^{-2}	8×10^{10}	17	100,000

Adapted from McKay et al. (1991).
[a]Energy divided by the total solar energy reaching Mars in a year, 4.68×10^9 J m^{-2} yr^{-1}.

percolating liquid. This could greatly accelerate the melting. We estimate the total time as 500 years.

The final entries in Table 4 deal with the conversion of atmospheric CO_2 to O_2. From a simple energy balance, the energy equivalent to 17 years of martian sunlight must be used to transform the CO_2 into O_2. At present, the only mechanism that can generate planetary-scale oxygen is a biosphere. McKay et al. (1991) estimated the length of time it might take to achieve this by considering a biosphere on Mars with an efficiency of 10^{-4}—the same energy efficiency as the biosphere on the present Earth. With this efficiency it would take $\geq 100,000$ years to produce a breathable atmosphere on Mars if all the organic material produced were buried and not allowed to recycle into the atmosphere as CO_2. On Earth, only a small fraction of the total productivity of the biosphere is sequestered in sediments. It would seem that the production of a breathable oxygen atmosphere on Mars is not feasible with near-term technologies. While genetic engineering could make individual plants that are more efficient at producing oxygen, these technologies are unlikely to be able to produce ecosystems that are more efficient at oxygen production. Plants produce oxygen as a direct by-product of their growth. Over millions of years there has been evolutionary selection for those plants and ecosystems that can grow and reproduce more efficiently. It seems likely that net production is limited by factors other than genetics.

However, genetic engineering may help in preventing the recycling of organic matter. It has been suggested that the development of lignin in plants during the Carboniferous age resulted in the production of a form of organic matter for which there was no metabolic pathway for degradation. This in turn resulted in the efficient burial of organic material and a sharp rise in O_2 (Berner et al., 2000). Genetically engineered plants on Mars may be needed in order to produce organic material that does not easily decompose, consuming the O_2 produced. However, we note that genetic engineering does not promise to lift the environmental limits of life. Organisms can be altered to produce desired compounds (e.g., PFCs) or for enhanced environmental protection, but they do so at a metabolic cost that will influence their survival in a natural ecosystem. The efficacy of genetic engineering in a community subject to natural selection may be vastly different than in the controlled conditions of the laboratory or bioindustrial reactors.

There may be nonbiological ways to produce an oxygen-rich atmosphere, but none is within the reach or even scope of current technology. Possibly in the long term we can hypothesize the existence of some rooftop fabric covering 1% of the martian surface that captures the incident sunlight and affects the chemical reduction of carbon dioxide to oxygen with 10% efficiency; even this approach would only reduce the time required to 10,000 years.

WARMING AND OUTGASSING

The warming of Mars is the essential ingredient to making the planet habitable. In a final state, for both a CO_2- and a breathable O_2-rich atmosphere, the planet must be capable of remaining at a stable warm temperature for a significant amount of time without continued technical intervention.

As discussed above, the basic scenario proposed for warming Mars consists of adding super greenhouse gases to the atmosphere, thereby warming the surface. This in turn will cause CO_2 to be released from the South Polar Cap and the regolith. This released CO_2 will augment the super greenhouse gases and cause further warming, causing more CO_2 release. The dynamics of this process for both a polar cap and a regolith reservoir have been analyzed by McKay et al. (1991) and Zubrin and McKay (1994).

The sublimation of the South Polar Cap in response to heating provides an example of the mechanism. Figure 3 shows the vapor pressure of a CO_2 ice cap compared with the climatic response of the polar region to atmospheric CO_2. As long as a cap of CO_2 exists, both curves must be satisfied [i.e., the lines must cross (points A and B)]. Another possible equilibrium is when all the CO_2 has evaporated into the atmosphere (point C).

Currently Mars is at a stable point, with a low pressure and a low temperature (point A in Fig. 3). A slight increase in pressure will generate a slightly warmer temperature, but that increased temperature is lower than the temperature for which the caps would be in equilibrium, and so CO_2 would condense on the caps, lowering the pressure and lowering the temperature. Similarly, a small decrease in pressure results in a tem-

perature warmer than the cap equilibrium, causing evaporation and an increase in temperature. Hence, the system returns to state A for any small perturbation about A. This behavior is shown by the arrows. Unlike point A, point B is an unstable equilibrium point. Small perturbations will grow moving the system away from point B. Hence, if the temperature and pressure are forced to rise from point A to point B, a runaway greenhouse effect will take place, and the planet's entire exchangeable CO_2 inventory (frozen on the polar caps and absorbed in the regolith) will be outgassed into the atmosphere, reaching point C.

It is important to note that once started, the runaway greenhouse effect will continue until the system reaches its own end with all the CO_2 in the atmosphere. This implies that there are two ways in which the runaway greenhouse effect on Mars might be problematic. The first problem results from there being too much CO_2, and the other from there possibly being too little. In general, point C can represent an excessively thick and warm atmosphere, giving Venus-like conditions. If there were unexpectedly large polar caps on Mars, the final climate state might be too warm. The more likely problem is the opposite—too little CO_2. If there is not enough CO_2 to push the system beyond point B it will relatively quickly return to its present state (point A). Currently we do not know how much CO_2 is available on Mars. The range of estimates are from 10 to >100 kPa. Even this lower value is probably enough to move the climate state up above point B with a little assistance from other greenhouse gases, and enough for habitability with major assistance from other greenhouse gases.

Despite the various techniques available for warming Mars, the planet's CO_2 inventory is the only viable solution for creating the required ≥60°C warming. Artificial methods are intended for use in pushing the planet's balance past point B, past which the planet can itself take over the warming process.

In addition to the super greenhouse gases discussed above, various other methods have been suggested for the warming of Mars. These include placing dark material over the poles to decrease their albedo and release CO_2, and placing large mirrors in orbit to increase the sunlight absorbed by Mars, perhaps targeted at key locations like the polar caps. However, mirrors the size of Texas (10^{12} m^2) would be required to increase the total solar energy incident on Mars by 2%.

Fogg (1992) pointed out that any specific greenhouse gas is most efficient at warming Mars in low concentrations (see also Marinova et al., 2000). This also applies to other methods of warming Mars. Thus the most efficient way to warm Mars may be a synergistic combination of techniques (Fogg, 1992). As pointed out by Zubrin and McKay (1997) the introduction of greenhouse gases other than CO_2 or the additional absorption of solar energy raises the climate curve shown in Fig. 3, effectively moving point B closer to point A and making the system more susceptible to runaway outgassing.

SUPER GREENHOUSE GASES

As discussed above, the most promising technique for warming Mars using current technology is the use of the super greenhouse gases, such as CFCs and PFCs. As seen on the Earth, super greenhouse gases are a demonstrated method for warming a planet, and the gases can be readily produced at rates that cause a noticeable warming in a short time frame. Super greenhouse gases are very potent—over an order of magnitude stronger than CO_2—and therefore are required in very small amounts, part per million level, to produce the warming required to make Mars habitable.

Greenhouse gases are transparent to visible radiation but are very effective at absorbing the infrared rays radiated from a planetary surface. Thereby, the gases form a blanket that traps heat near the planet's surface, rather than letting it escape into space.

A variety of criteria must be used when selecting the appropriate gases. The gases to be used must have a strong greenhouse effect, have a long lifetime in the martian atmosphere, not have any negative effects to a biosphere, be readily synthesized from materials available on Mars, and ultimately should be capable of being produced by microorganisms if super greenhouse gases become part of long-term warming for a thin CO_2 atmosphere or an N_2/O_2 atmosphere. In order to block the maximal amount of infrared radiation from leaving the planet and therefore cause maximal warming, a mixture of gases must be used, which, taken together, effectively cover the IR spectrum. As shown in Fig. 4, there are two adjacent regions that require the most attention. The gases used must be strong absorbers in the

200–800 cm^{-1} (50–12.5 μm) range, where Mars is currently radiating most of its thermal energy (Fig. 4). As the planet warms up and the peak shifts to higher wavenumbers, it will be important to use gases that cover the 800–1,200 cm^{-1} (12.5–8 μm) region, where CO_2 and water vapor do not absorb any thermal radiation.

While the choice of greenhouse gases to be used is strongly based on their greenhouse potential, there are a number of other properties that must be considered. To simplify production, the greenhouse gases used must have very long lifetimes in the martian atmosphere. This is especially important since Mars's thin ozone layer does not significantly block UV light, and therefore very-short-wavelength UV radiation penetrates all the way to the surface. Because of this, gases that typically have longer lifetimes on Earth will have shorter lifetimes on Mars. As an example, on Mars, NH_3 would have a short lifetime, thereby making it an impractical greenhouse gas despite its great greenhouse potential (Kuhn and Atreya, 1979). Because the reason for warming Mars is to make it habitable, the greenhouse gases chosen should not in any way be harmful to the biosphere. This means that gases with chlorine and bromine, which chemically destroy ozone, would not be used. Another crucial characteristic when choosing a greenhouse gas is the viability of producing it on Mars. While super green-

house gases are very effective, it is not viable to bring them to Mars even to create a part per billion concentration because of the prohibitively large mass that would have to be transported. Therefore, all the constituents of the proposed gases must be readily available in the martian atmosphere and regolith, and the synthesis process must require low energies. Recent work (e.g. Marinova et al., 2000; Sturges et al., 2000; Gerstell et al., 2001) has shown a large number and variety of gases that fit the above criteria, such as PFCs, SF_6, and other large molecules containing only C, F, H, S, and O. Industrial processes currently produce most of these molecules. Similar processes could be used on Mars for their production, without the need for inventing new technologies or processes. The locations and strengths of absorption bands of selected PFCs and SF_6 are shown in Fig. 5. Figure 6 shows the spectrum of one gas, C_3F_8, at three different concentrations.

The warming potentials of some PFCs and SF_6 are shown in Fig. 7 and are calculated based on the method of Marinova et al. (2000). Of these, the most effective gas with respect to a Mars temperature profile appears to be C_3F_8, which produces a warming of ~7°C for 0.1 Pa of the gas in the martian atmosphere.

To warm Mars, a suite of efficient greenhouse gases is needed that can effectively absorb across the entire IR spectrum. McKay et al. (1991) have

FIG. 3.   Equilibrium constraints for polar cap CO_2 on Mars (adapted from McKay et al., 1991). Dotted line shows the phase equilibrium of CO_2 solid and gas. Solid line shows the climatically determined temperature, including advection and greenhouse effect. Possible equilibriums are shown as points A (stable cold state with most CO_2 frozen), B (unstable equilibrium), and C (stable warm state with all CO_2 in atmosphere). To transition Mars from state A to state C it must be moved beyond point B.

FIG. 4.   Thermal balance of warm Mars. The two curves show radiative flux (Planck curve) leaving the top of the martian atmosphere (−60°C) and the radiative flux leaving the surface of a warmed Mars (15°C) as a function of wavelength. The difference must be compensated for by greenhouse forcing. The greenhouse effect for CO_2 and H_2O is shown schematically. The "window" region of 8–12 μm (1,200–800 cm^{-1}) must be filled by super greenhouse gases in order to warm Mars.

FIG. 5.   Schematic diagram of the location of absorption bands for PFCs and SF_6. The absorption strength of the bands is shown by the thickness of the line, where thick lines represent strong absorption bands and thin lines are weak absorption bands. Note the gases coverage of the 8–12 μm (1,200–800 cm^{-1}) region.

FIG. 6.   Absorption spectra for C_3F_8 at mixing rations of 10^{-7}, 10^{-3}, and 10^0. C_3F_8 appears to be the PFC with the strongest greenhouse potential.

FIG. 7.   The warming produced by PFCs and SF_6 as a function of their partial pressure in the atmosphere. All values are for current Mars; the calculations do not take into account overlap of the super greenhouse gas bands with absorption bands of CO_2.

FIG. 8.   Proposed basis vectors of environmental ethics (adapted from McKay, 1990). These are not categories but rather components. Systems of environmental ethics are composed of various mixtures of these three components. Only anti-humanism necessarily rejects making Mars habitable.
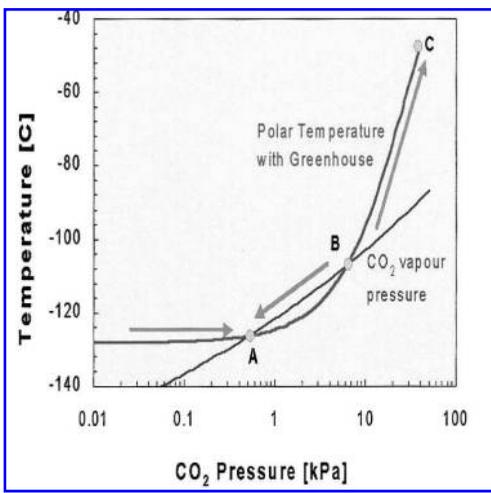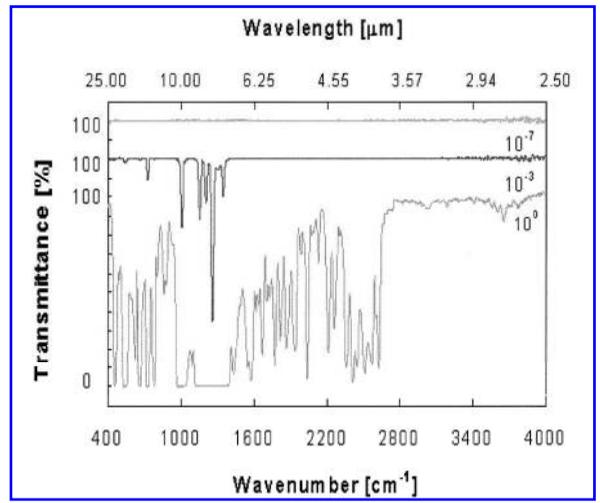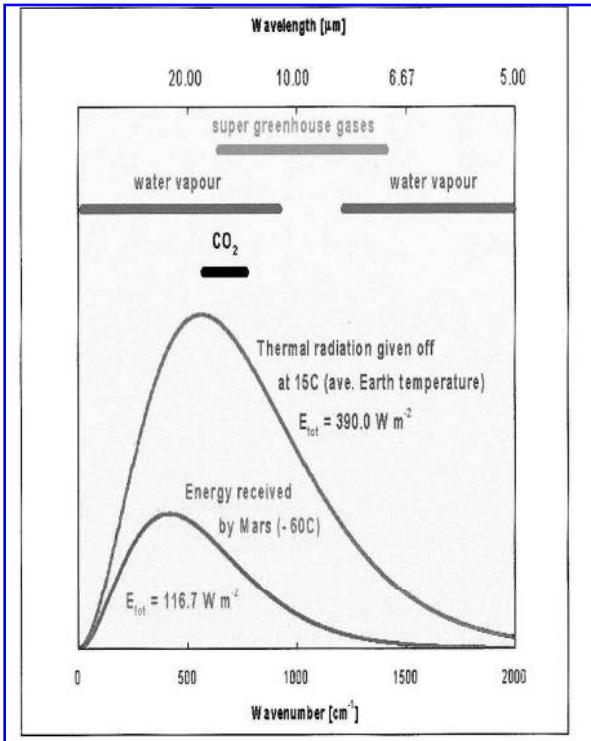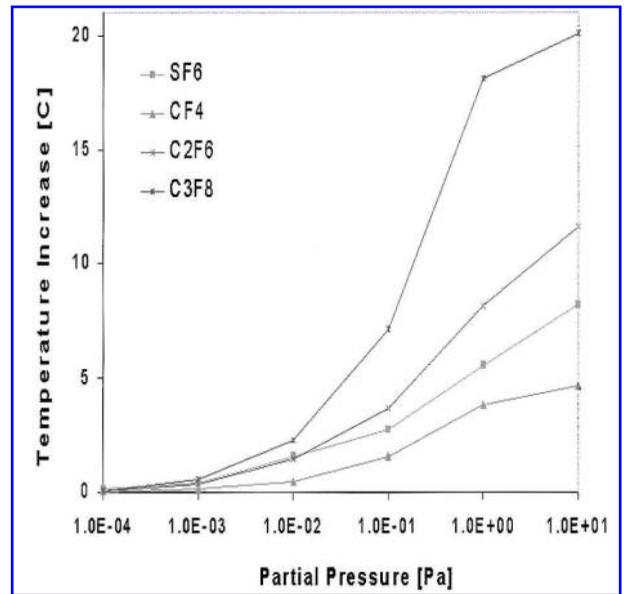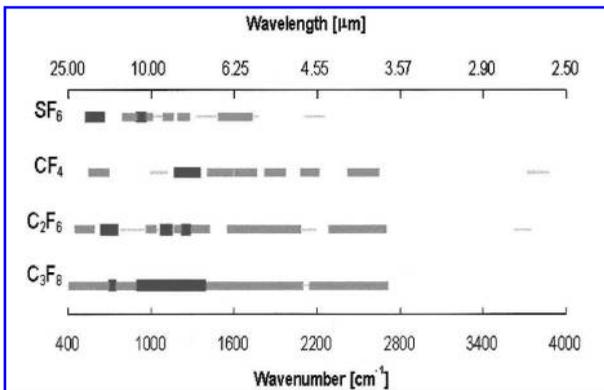
FIG. 3.

FIG. 6.
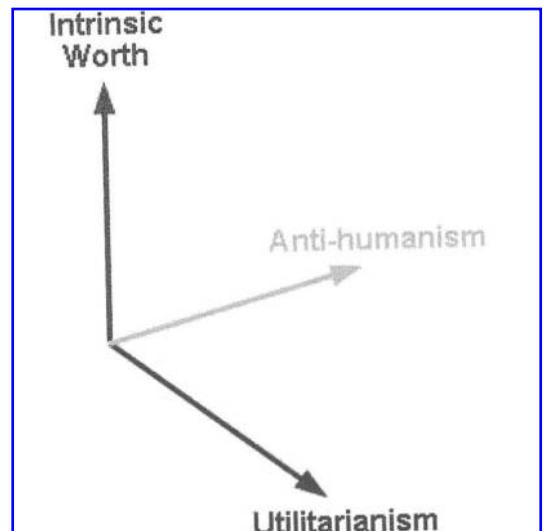

FIG. 4.

FIG. 7.

FIG. 5.

FIG. 8.

shown that just blocking the window region of 8–12 μm (800–1,200 cm^{-1}) is not sufficient. The short list of gases in Fig. 5 do not form an adequate mixture; however, these gases are those that only occur naturally. It is important that we begin to design gases that have a large greenhouse potential. Recent work by Gerstell et al. (2001) evaluated theoretical molecules that had a significant greenhouse potential. Further work in this area may discover molecules that are a factor or two more effective than C_3F_8, which would further simplify the process of warming Mars. One possible drawback to these newly discovered molecules is their size. Because of the large molecular mass, they may be more difficult to manufacture, requiring more materials and energy for their fabrication. Super greenhouse gases have an important role to play in terms of warming Mars to create a thick CO_2 atmosphere and keeping a breathable O_2/N_2 atmosphere warm.

There have not been any detailed studies looking at how PFCs and other super greenhouse gases might be produced on the present Mars. However, it is possible to use basic energy considerations to get a sense of the magnitude of the energy required for the task. If we assume that with a suitable mixture of super greenhouse gases the total concentration required to warm Mars is 1 Pa, and if we assume that the energy of formation of these gases is on average $\sim 10^7$ J/kg, then the total energy required is 4×10^{20} J—equivalent to 5 hours of martian sunlight. Consider for illustrative purposes that this power was provided by generating facilities of size 500 MW (the size of a small nuclear reactor); if we take 100 years as the production time, then 245 such facilities would be required.

ECOLOGICAL SUCCESSION ON MARS

As discussed above, the inventory of gases and the thermodynamics of changing the martian atmosphere will determine the environmental conditions in the initial stages of ecosynthesis. Within this framework the lifeforms that can be implanted on Mars can be considered. J. Graham (paper in preparation) has likened the ecological changes over time on Mars to the ecological changes moving down a mountain: from barren frozen rock at the mountain top through alpine tundra and arctic and alpine grasses and eventually to trees and forests.

Currently Mars is too cold and dry to allow for the survival of any terrestrial organism. Therefore, purely engineering mechanisms, such as chemically produced PFCs, would have to be used to warm Mars to a minimal level before any life from Earth can survive there. The ecosystem on Earth that thrives in the coldest driest, most Mars-like environment are the cryptoendolithic microbial ecosystems found in the dry valleys of Antarctica (Friedmann, 1982). The Dry Valleys are so cold and dry that they appear lifeless. However, lichens, algae, and bacteria live a few millimeters below the surface of sandstone rocks, where they find a warmer, wetter environment than on the rock's surface. Enough sunlight penetrates through the rock at these depths to allow for photosynthesis (Nienow et al., 1988). Anaerobic counterparts of these Antarctic microbial ecosystems could be the first photosynthetic lifeforms living naturally on the surface of Mars (Friedmann and Ocampo-Friedmann, 1993). Studies of the physical ecology of the Antarctic cryptoendolithic microbial ecosystems show that they survive with a growing season of only 100 h/yr (Friedmann et al., 1987; McKay et al., 1993). These organisms grow in locations where the air temperature virtually never rises above freezing. By analogy, microorganisms in a rock habitat could survive on Mars when the air temperatures reach values of $-10°C$ during the daytime for a few weeks during the warmest part of the year— presumably at the subsolar point in southern summer when Mars is at perihelion. Sunlight warming the rock would raise the temperature above freezing. Light levels in the Dry Valleys of Antarctica during summer are 600 W/m^2 at noon (Dana et al., 1998). By comparison, the subsolar point on Mars at perihelion has a sunlight level of 580 W/m^2, assuming a typical clear-sky atmospheric transparency of 0.8.

As Mars continues to warm, Arctic and alpine tundra ecosystems could survive. These systems require air temperatures above freezing during the growing season along with low levels of rain or meltwater runoff (Chapin et al., 1997). In these areas precipitation ranges between 5 and 50 cm (Chapin et al., 1997). With further warming and extension of the growing season, alpine plants might survive and cover vast regions of equatorial Mars.

A major event in the developing ecology of Mars would occur when the treeline first reaches the lower parts of the equatorial canyons on Mars.

In the temperate zone on Earth, the treeline is determined by the summer temperature. However, the equatorial regions on Mars will have only a slight seasonality because of the eccentricity of Mars's orbit. Thus tropical treelines provide a more direct example of how the first trees will grow on Mars. The highest treeline on the Earth (4,000 m) is found on Pico de Orizaba at 19°N in Mexico (Lauer, 1978; Körner, 1998) and corresponds to a ground temperature of between 3°C and 7°C (Lauer, 1978). Thus we suppose that when the equatorial regions of Mars reach a comparable temperature, trees will be possible.

On Mars, the first introduction of photosynthetic microbial ecosystems and Arctic and alpine tundra will be of biological interest. However, only with the development of ecosystems based on higher plants will the ecological development of Mars become significant in terms of the production of organic matter and O_2. Plant-based ecosystems (e.g., forests and grasslands) could be effective O_2 producers because they have very high biomass density, can produce organic material—like wood—that does not lock up phosphorus and nitrogen nutrients, and can possibly be engineered to produce lignin-like materials that are resistant to microbial decomposition.

As discussed above, a thick CO_2 atmosphere on Mars may have levels of O_2 sufficient for plant growth. Such levels would provide important UV shielding due both to the O_2 (Rosenqvist and Chassefière, 1995) and O_3 produced (Hiscox and Linder, 1997) and to scattering of UV by CO_2 (e.g., Cockell et al., 2000). In addition, the PFCs may provide direct UV absorption. Yung and DeMore (1999) suggested that one solution to the creation of a UV shield may be a polysulfur layer in the upper atmosphere like that in the atmosphere of Venus. To create the shield, carbonyl sulfide (COS) would need to be injected into the atmosphere at a rate of 10^7 tons/yr. Finally, we note that many microbial communities can survive high UV rates with strategies that include rapid repair, protective pigments, and UV-absorbing layers of dead cells or inorganic material (e.g., Averner and MacElroy, 1976; Cockell, 2000). In addition, it is not known how life on early Earth survived without an effective ozone shield (e.g., Cockell, 2000; Cockell et al., 2000), but life did survive, and perhaps similar solutions might operate on a future Mars.

While plants will be the dominant agents of ecological change on Mars—as they are on Earth—small animals could play a key role. Insects and soil invertebrates, such as earthworms, would be beneficial additions to the developing martian ecosystems. In particular, pollination by flying insects would greatly increase the diversity of plants grown on Mars at every stage of the process (J. Graham, paper in preparation). Unfortunately, the minimum O_2 requirements and maximum CO_2 and UV tolerance of flying insects at 0.38 g remain unexplored.

While lifeforms from Earth might be introduced to Mars in a controlled and prescribed way, this does not imply that the resulting ecological systems will develop as predicted. In fact, they are unlikely to do so. As life on Mars interacts with itself and the changing martian environment, it will follow an independent evolutionary trajectory that will be difficult or impossible to control. This is not a problem and, in fact, should be considered an asset. The resulting biological system is more likely to be stable and globally adapted to the altered martian environment than any preconceived ecosystems. If the *Gaia* hypothesis is correct, and life works to stabilize the biosphere, then this will be how it does so (McKay, 1982; Lovelock and Allaby, 1984).

ENVIRONMENTAL ETHICS

It is important to consider not just the physics and biology of making Mars habitable, but also the environmental ethics. This poses a challenge to the field of environmental ethics, which is a discipline that has never before looked beyond the Earth. On Earth there is no distinction between life and nature, terms often used synonymously. However, when we venture beyond the Earth, we find worlds apparently devoid of life. A distinction between life and nature, never needed before, becomes necessary in considering life on Mars. Consider, for example, Leopold's (1966) egalitarian ecosystem ethic, arguably the founding principle of modern environmental ethics: "A thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community. It is wrong if it tends to do otherwise." It is obvious how to apply this on Earth, but not clear at all on Mars where there is no "biotic community." Do we "preserve" what is there, or do we introduce a "biotic community"? To apply environmental ethics to the question of making Mars habitable, we need to generalize the topic.

McKay (1990) proposes that any system of environmental ethics is based on three basic normative axioms—each system of environmental ethics is composed of varying mixes of these three basic axioms. The basic axioms are: anti-humanism or preservationism, which holds that humans should not exercise their technological capabilities to alter the Earth, and by extension the cosmos; wise stewardship or utilitarianism, which holds that humans can use, control, and change natural systems but must do so wisely and to maximize long-term human benefit; and intrinsic worth, which holds that human use is not the ultimate value and that living systems have intrinsic worth independent of human utility.

These three axioms are not categories of systems of environmental ethics, but rather the components of these systems. All systems have some of each of these axioms but to varying extent. In that sense the three axioms are like the basis vectors of Cartesian coordinates. This is illustrated in Fig. 8, where the three normative axioms of environmental ethics are shown as a basis vector system. If systems of environmental ethics are composed of different amounts of these three basic principles, and if we examine the implications of each of these basic axioms for introducing life to Mars, we can then understand how systems of environmental ethics would address the issue.

Anti-humanism would argue against altering the martian environment either to assist any martian life or to allow for life from Earth. Wise stewardship is certainly the major part of most systems of environmental ethics, especially in the Western Tradition. Of the three axioms defined in Fig. 8 it is the only one with universal appeal. McKay (1990) argues that restoring Mars to a biological state would be consistent with wise stewardship in that such a project would help us develop a scientific understanding of how biospheres work as well as providing aesthetic and educational advantages.

The principle of intrinsic worth provides a new perspective on terraforming Mars. The notion of intrinsic worth as a principle in environmental ethics traces back to a seminal paper by Naess (1973, 1984) in which he elaborates on what has become known as "Deep Ecology." The first two tenets of Deep Ecology are particularly relevant to the question of bringing Mars back to life. They are:

1. The well-being of nonhuman life on Earth has value in itself. This value is independent of any instrumental usefulness for limited human purposes.
2. Richness and diversity in lifeforms contribute to this value and are a further value in themselves.

The implications of this are that a biologically rich and diverse Mars is of more value than the beautiful, but virtually dead, world we explore today. A further conclusion from these tenets of deep ecology is that indigenous martian life, different from Earth life, should be the first aim of restoration ecology on Mars, thereby increasing the diversity of life. Even though it is unlikely, it may be possible to find viable martian life or revive dead but frozen martian microbes. If life on Mars did experience its own separate genesis, then restoring that life to global diversity would have to be the best possible option for Mars. If life on Mars is genetically related to life on Earth (a possibility due to exchange between the planets) or if there is no life to revive on Mars, then a Mars teaming with Earth life is the next best option.

FUTURE WORK NEEDED

Our knowledge of Mars is incomplete, as is our understanding of many of the functions and interactions of life on Earth. It is no surprise therefore that there is a long list of future research needs dealing with the question of making Mars habitable. We suggest the following list as indicative and by no means inclusive:

1. Are there carbonate deposits on Mars, and what is their total mass?
2. What is the total amount of CO_2 in the South Polar Cap on Mars?
3. What is the total amount of CO_2 absorbed into the regolith on Mars?
4. What are the location and state of subsurface ice and water on Mars?
5. Are there nitrate deposits on Mars?
6. Are there subsurface organics on Mars, and are these associated with the nitrate deposits?
7. What is the expected photochemical concentration of O_2 in a thick (≥ 100 kPa) CO_2 atmosphere on Mars?
8. What is the minimum O_2 for plant growth, and how will different plants respond to very high CO_2 levels?

9. What is the minimum level of N_2 at which biological nitrogen fixation can occur?

10. Could microorganisms be genetically engineered to produce PFCs?

11. What are the lower limits of O_2 and upper limits of CO_2 for insects and soil invertebrates?

12. What are the buffer gas requirements for humans and other animals?

13. Would biogenic CH_4 produced in a CO_2 atmosphere make a significant contribution to the greenhouse warming on Mars as it is thought to have on early Earth?

14. Are there biological methods for recycling carbonates on Mars, and if not, what is the expected lifetime of the atmosphere?

15. What would be the rate of warming on Mars as PFCs are produced?

16. What would the global climate and weather on Mars be when it has an extensive body of water?

17. Can genetic engineering produce plants that produce nondecomposable organic matter, UV-resistant lifeforms, and invertebrate animals with high tolerance for CO_2 and low demand for O_2?

Astrobiology is a newly formed discipline. Of the topics examining the question of life, the expansion of life beyond its planet of origin is the area with the least heritage of previous research. Much remains to be done, but a great ecological lesson is before us.

ABBREVIATIONS

CFC, chlorofluorocarbon; PFC, perfluorocarbon.

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Address reprint requests to:
Dr. Christopher P. McKay
Space Science Division
NASA Ames Research Center
Moffett Field, CA 94035

E-mail: cmckay@arc.nasa.gov

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