**AIAA-93-2005**

# Technological Requirements for Terraforming Mars

Robert M. Zubrin† and Christopher P. McKay

Martin Marietta Astronautics
PO Box 179, Denver, CO 80201
303-971-9299 (ph) 303-977-1893 (FAX)

NASA Ames Research Center
Moffett Field, CA, 94035
415-604-6864(ph) 415-604-6779 (FAX)

## Abstract

The planet Mars, while cold and arid today, once possessed a warm and wet climate, as evidenced by extensive fluvial features observable on its surface. It is believed that the warm climate of the primitive Mars was created by a strong greenhouse effect caused by a thick $CO_2$ atmosphere. Mars lost its warm climate when most of the available volatile $CO_2$ was fixed into the form of carbonate rock due to the action of cycling water. It is believed, however, that sufficient $CO_2$ to form a 300 to 600 mb atmosphere may still exist in volatile form, either adsorbed into the regolith or frozen out at the south pole. This $CO_2$ may be released by planetary warming, and as the $CO_2$ atmosphere thickens, positive feedback is produced which can accelerate the warming trend. Thus it is conceivable, that by taking advantage of the positive feedback inherent in Mars' atmosphere/regolith $CO_2$ system, that engineering efforts can produce drastic changes in climate and pressure on a planetary scale.

In this paper we propose a mathematical model of the Martian $CO_2$ system, and use it to produce analysis which clarifies the potential of positive feedback to accelerate planetary engineering efforts. It is shown that by taking advantage of the feedback, the requirements for planetary engineering can be reduced by about 2 orders of magnitude relative to previous estimates. We examine the potential of various schemes for producing the initial warming to drive the process, including the stationing of orbiting mirrors, the importation of natural volatiles with high greenhouse capacity from the outer solar system, and the production of artificial halocarbon greenhouse gases on the Martian surface through in-situ industry.

If the orbital mirror scheme is adopted, mirrors with dimension on the order or 100 km radius are required to vaporize the $CO_2$ in the south polar cap. If manufactured of solar sail like material, such mirrors would have a mass on the order of 200,000 tonnes. If manufactured in space out of asteroidal or Martian moon material, about 120 MWe-years of energy would be needed to produce the required aluminum. This amount of power can be provided by near-term multi-megawatt nuclear power units, such as the 5 MWe modules now under consideration for NEP spacecraft.

Orbital transfer of very massive bodies from the outer solar system can be accomplished using nuclear thermal rocket engines using the asteroid's volatile material as propellant. Using major planets for gravity assists, the rocket $\Delta V$ required to move an outer solar system asteroid onto a collision trajectory with Mars can be as little as 300 m/s. If the asteroid is made of $NH_3$, specific impulses of about 400 s can be attained, and as little as 10% of the asteroid will be required for propellant. Four 5000 MWt NTR engines would require a 10 year burn time to push a 10 billion tonne asteroid through a $\Delta V$ of 300 m/s. About 4 such objects would be sufficient to greenhouse Mars.

Greenhousing Mars via the manufacture of halocarbon gases on the planet's surface may well be the most practical option. Total surface power requirements to drive planetary warming using this method are calculated and found to be on the order of 1000 MWe, and the required times scale for climate and atmosphere modification is on the order of 50 years.

It is concluded that a drastic modification of Martian conditions can be achieved using 21st century technology. The Mars so produced will closely resemble the conditions existing on the primitive Mars. Humans operating on the surface of such a Mars would require breathing gear, but pressure suits would be unnecessary. With outside atmospheric pressures raised, it will be possible to create large dwelling areas by means of very large inflatable structures. Average temperatures could be above the freezing point of water for significant regions during portions of the year, enabling the growth of plant life in the open. The spread of plants could produce enough oxygen to make Mars habitable for animals in several millennia. More rapid oxygenation would require engineering efforts supported by multi-terrawatt power sources. It is speculated that the desire to speed the terraforming of Mars will be a driver for developing such technologies, which in turn will define a leap in human power over nature as dramatic as that which accompanied the creation of post-Renaissance industrial civilization.

---

† Member AIAA

## Introduction

Many people can accept the possibility of a permanently staffed base on Mars, or even the establishment of large settlements. However the prospect of drastically changing the planet's temperature and atmosphere towards more earthlike conditions, or "terraforming" seems to most people to be either sheer fantasy or at best a technological challenge for the far distant future.

But is this pessimistic point of view correct? Despite the fact that Mars today is a cold, dry, and probably lifeless planet, it has all the elements required to support life: water carbon and oxygen (as carbon dioxide), and nitrogen. The physical aspects of Mars, its gravity, rotation rate and axial tilt are close enough to those of Earth to be acceptable and it is not too far from the Sun to be made habitable.

In fact computational studies utilizing climate models suggest that it could be possible to make Mars habitable again with foreseeable technology. The essence of the situation is that while Mars' $CO_2$ atmosphere has only about 1% the pressure of the Earth's at sea level, it is believed that there are reserves of $CO_2$ frozen in the south polar cap and adsorbed within the soil sufficient to thicken the atmosphere to the point where its pressure would be about 30% that of Earth. The way to get this gas to emerge is to heat the planet, and in fact, the warming and cooling of Mars that occurs each Martian year as the planet cycles between its nearest and furthest positions from the Sun in its slightly elliptical orbit cause the atmospheric pressure on Mars to vary by plus or minus 25% compared to its average value on a seasonal basis.

We can not, of course, move Mars to a warmer orbit. However we do know another way to heat a planet, through an artificially induced greenhouse effect that traps the Sun's heat within the atmosphere. Such an atmospheric greenhouse could be created on Mars in at least three different ways. One way would be to set up factories on Mars to produce very powerful artificial greenhouse gasses such as halocarbons ("CFC's") and release them into the atmosphere. Another way would be to use orbital mirrors or other large scale power sources to warm selected areas of the planet, such as the south polar cap, to release large reservoirs of the native greenhouse gas, $CO_2$, which may be trapped their in frozen or adsorbed form. Finally natural greenhouse gases more powerful than $CO_2$ (but much less so than halocarbons) such as ammonia or methane could be imported to Mars in large quantities if asteroidal objects rich with such volatiles in frozen form should prove to exist in the outer solar system.

Each of these methods of planetary warming would be enhanced by large amounts of $CO_2$ from polar cap and the soil that would be released as a result of the induced temperature rise. This $CO_2$ would add massively to the greenhouse effect being created directly, speeding and multiplying the warming process.

The Mars atmosphere/regolith greenhouse effect system is thus one with a built-in positive feedback. The warmer it gets, the thicker the atmosphere becomes; and the thicker the atmosphere becomes the warmer it gets. A method of modeling this system and the results of calculations based upon it are given in the sections below.

## Equations for Modeling the Martian System

An equation for estimating the mean temperature on the surface of Mars as a function of the CO2 atmospheric pressure and the solar constant is given by McKay and Davis[1] as:

$$T_{mean} = S^{0.25}T_{BB} + 20(1+S)P^{0.5} \qquad (1)$$

where Tmean is the mean planetary temperature in kelvins,S is the solar constant where the present day Sun=1, $T_{BB}$, the black body temperature of Mars at present = 213.5 K, and P is given in bar

Since the atmosphere is an effective means of heat transport from the equator to the pole,we propose (as an improvement over equation (1) in reference 2):

$$T_{pole} = T_{mean} - \Delta T/(1 + 5P) \qquad (2)$$

where $\Delta T$ is what the temperature difference between the mean value and the pole would be in the absence of an atmosphere (about 75 K for S=1).

For purposes of this analysis it is further assumed based upon a rough approximation to observed data that :

$$T_{max} = T_{equator} = 1.1T_{mean} \qquad (3)$$

and that the global temperature distribution is given by:

$$T(\theta) = T_{max} - (T_{max}-T_{pole}\}\sin^{1.5}\theta \qquad (4)$$

where θ is the latitude (north or south).

Equations (1) through (4) given the temperature on Mars as a function of $CO_2$ pressure. However, as mentioned above, the $CO_2$ pressure on Mars is itself a function of the temperature. There are three reservoirs of $CO_2$ on Mars, the atmosphere, the dry ice in the polar caps, and gas adsorbed in the soil. the interaction of the polar cap reservoirs with the atmosphere is well understood and is given simply by the relationship between the vapor pressure of $CO_2$ and the temperature at the poles. This is given by the vapor pressure curve for $CO_2$, which is approximated by:

$$P = 1.23 \times 10^7\{\exp(-3168/T_{pole})\} \qquad (5)$$

So long as there is $CO_2$ in both the atmosphere and the cap, equation (5) gives an exact answer to what the $CO_2$ atmospheric pressure will be as a function of polar temperature. However if the polar temperature should rise to a point where the vapor pressure is much greater than that which can be produced by the mass in the cap reservoir (between 50 and 150 mb) then the cap will disappear and the atmosphere will be regulated by the soil reservoir.

The relationship between the soil reservoir, the atmosphere and the temperature is not known with precision. an educated guess is given in parametric form in reference 1 as:

$$P = \{CM_a\exp(T/T_d)\}^{1/\gamma} \qquad (6)$$

where Ma is the amount of gas adsorbed in bar, $\gamma$=0.275, C is a normalization constant set so that with chosen values of the other variables equation (6) will reflect known Martian conditions, and $T_d$ is the characteristic energy required for release of gas from the soil. Equation (6) is essentially a variation on Van Hofft's law for the change in chemical equilibrium with temperature, and so there is fair confidence that its general form is correct. However the value of $T_d$ is unknown and probably will remain so until after human exploration of Mars. In reference 2 McKay et al varied parametrically $T_d$ from 10 to 60 K and produced curves using equation (6) with T set equal to either $T_{pole}$ or $T_{mean}$. In this paper we choose $T_d$=15 to 40 K (a reasonable subset of the spectrum slightly on the optimistic side; the lower the value of $T_d$ the easier things are for prospective terraformers.) Because equation (6) is so strongly temperature dependent, however, we do not simply set T to the extreme values of $T_{mean}$ or $T_{pole}$ and solve equation (6) to get a global "soil pressure" however, as was done in reference 2. Rather we use the global temperature distribution given by equation (4) to integrate equation (6) over the surface of the planet. This gives a more accurate quasi 2-Dimensional view of the atmosphere/regolith equilibrium problem in which most of the adsorbed $CO_2$ is distributed to the planet's colder regions. In this model, regional (in the sense of latitude) temperature changes, especially in the near-polar regions, can have as important a bearing on the atmosphere/regolith interaction as changes in the planet's mean temperature.

## Results of Calculations

In figure 1 we see the results of our model when applied to the situation at Mars' south polar cap, where it is believed that enough CO2 may be held frozen as dry ice to give Mars an atmosphere on the order of 50 to 100 mbar. We have plotted the polar temperature as a function of the pressure, in accord with equations (1) and (2), and the vapor pressure as a function of the polar temperature, in accord with equation (5). There are two equilibrium points, labeled A and B where the values of P and T are mutually consistent. However A is a stable equilibrium, while B is unstable. This can be seen by examining the dynamics of the system wherever the two curves do not coincide. Whenever the temperature curve lies above the vapor pressure curve, the system will move to the right, i.e. towards increased temperature and pressure; this would represent a runaway greenhouse effect. Whenever the pressure curve lies above the temperature curve, the system will move to the left, i.e. a temperatures and pressure will both drop in a runaway icebox icebox effect. Mars today is at point A, with 6 mbar of pressure and a temperature of about 147 K at the pole.

Now consider what would happen if someone artificially increased the temperature of the Martian pole by several degrees K. As the temperature is increased, points A and B would move towards each other until they met. If the temperature increase were

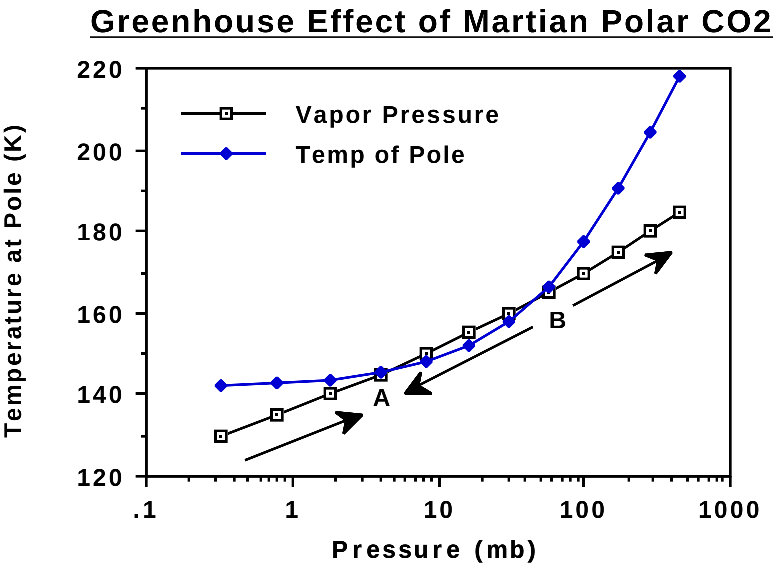

Fig. 1 Mars polar cap/atmosphere dynamics. current equilibrium is at point A. Raising polar temperatures by 4 K would drive equilibria A and B together, causing runaway heating that would lead to the elimination of the cap.

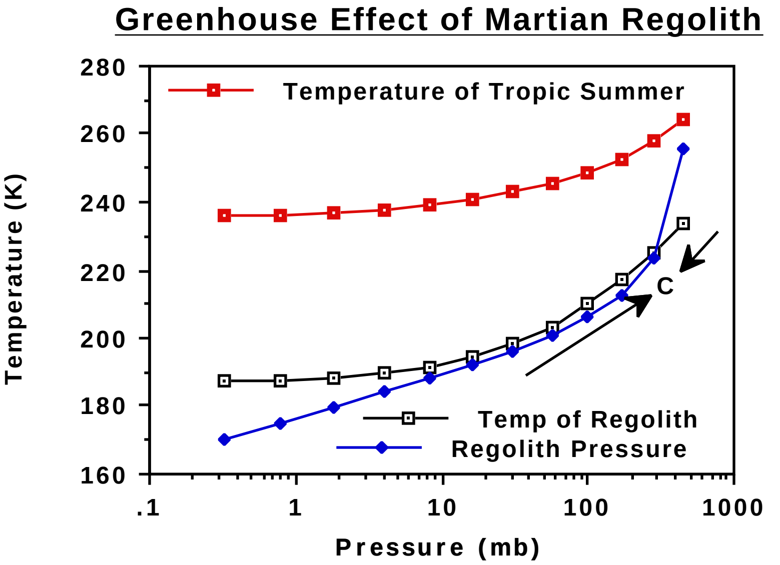

Fig. 2 Mars regolith/atmosphere dynamics under conditions of Td=20 with a volatile inventory of 500 mb of $CO_2$

4 K, the temperature curve would be moved upwards on the graph sufficiently so that it would lie above the vapor pressure curve everywhere. The result would be a runaway greenhouse effect that would cause the entire pole to evaporate, perhaps in less than a decade. Once the pressure and temperature have moved past the current location point B, Mars will be in a runaway greenhouse condition even without artificial heating, so if later the heating activity were discontinued the atmosphere will remain in place.

As the polar cap evaporates, the dynamics of the greenhouse effect caused by the reserves of CO2 held in the Martian soil come into play. These reserves exist primarily in the high latitude regions, and by themselves are estimated to be enough to give Mars a 400 mbar atmosphere. We can't get them all out however, because as they are forced out of the ground by warming, the soil becomes an increasingly effective "dry sponge" acting to hold them back. The dynamics of this system are shown in fig. 2, in which we assume Td=20, current polar reserves of 100 mb, and regolith reserves of 394 mb, and graph the pressure on the planet as a function of $T_{reg}$, where $T_{reg}$ is the weighted average of the temperature given by integrating the right hand side of equation (6) over the surface of the planet using the temperature distribution given by equation (4).

That is

$$T_{reg} = -T_d \ln\{\int_0^{90} \mathrm{Exp}(-T(\theta)/T_d)\sin\theta d\theta\} \qquad (7)$$

Since $T_{reg}$ is a function of the temperature distribution and $T_{mean}$, it is a function of P, and thus $T_{reg}(P)$ can also be graphed. The result are a set of T(P) curves and P(T) curves, whose crossing points reflect stable or unstable equilibrium, just as in the case of the polar cap analysis.

It can be seen in fig. 2 that the atmosphere soil system under the chosen assumption of $T_d$=20 K has only 1 equilibrium point, which is stable, and which will be overrun by the pressure generated by the vaporized polar cap. Thus, by the time the process is brought to a halt, an atmosphere with a total pressure of about 300 mbar, or 4.4 pounds per square inch, can be brought into being. Also shown in Fig. 2 is the day-night average temperature that will result in Mars' tropical regions ($T_{max}$) during summertime. It can be seen that the 273 K freezing point of water will be approached. With the addition of modest ongoing artificial greenhouse efforts, it can be exceeded.

The assumption of $T_d$=20 is optimistic, however, and the location of the equilibrium convergence point (point C in fig. 2) is very sensitive to the value chosen for $T_d$. In fig.3 we show what happens if values of $T_d$=25 and $T_d$=30 are assumed. In these cases, the convergence point moves from 300 mb at $T_d$=20 to 31 and 16 mb for $T_d$=25 and $T_d$=30 respectively. (The value of the $T_{reg}$ curve in fig. 3 was calculated under the assumption of $T_d$=25; it varies from this value by a degree or two for $T_d$=20 or 30.) Such extraordinary sensitivity of the final condition to the unknown value of Td may appear at first glance to put the entire viability of the terraforming concept at risk. However in fig 3 we also show (dotted line) the situation if artificial greenhouse methods are employed to maintain Treg at a temperature 10 K above those produced by the $CO_2$ outgassing itself. It can be seen that drastic improvements in the final T and P values are effected for the $T_d$=25 and 30 cases, with all three cases converging upon final states with Mars possessing atmospheres with several hundred millibars pressure.

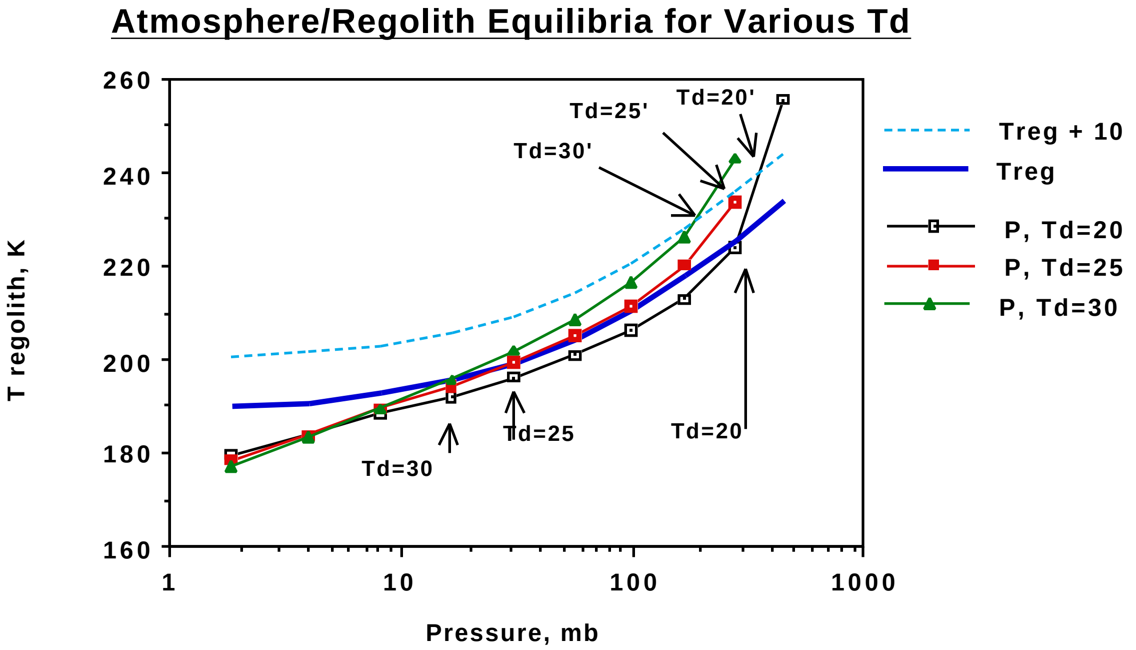

Fig. 3 An induced 10 K rise in regolith temperature can counter effect of $T_d$ variations. Data shown assumes a planetary volatile inventory of 500 mb $CO_2$.

In figs 4,5,6, and 7 we show the convergence condition pressure and maximum seasonal average temperature in the Martian tropics resulting on either a "poor" Mars, possessing a total supply of 500 mb of $CO_2$ (50 mb of $CO_2$ in the polar cap and 444 mb in the regolith), or a "rich" Mars possessing 1000 mb of $CO_2$ (100 mb in the polar cap and 894 mb in the regolith). different curves are shown under the assumptions that either no sustained greenhouse effort is mounted after the initial polar cap release, or that continued efforts are employed to maintain the planet's mean temperature 5, 10 or 20 degrees above the value produced by the $CO_2$ atmosphere alone. It can be seen that if a sustained effort is mounted to keep an artificial DT of 20 degrees in place, then a tangible atmosphere and acceptable pressures can be produced even if $T_d$ has a pessimistic value of 40 K.

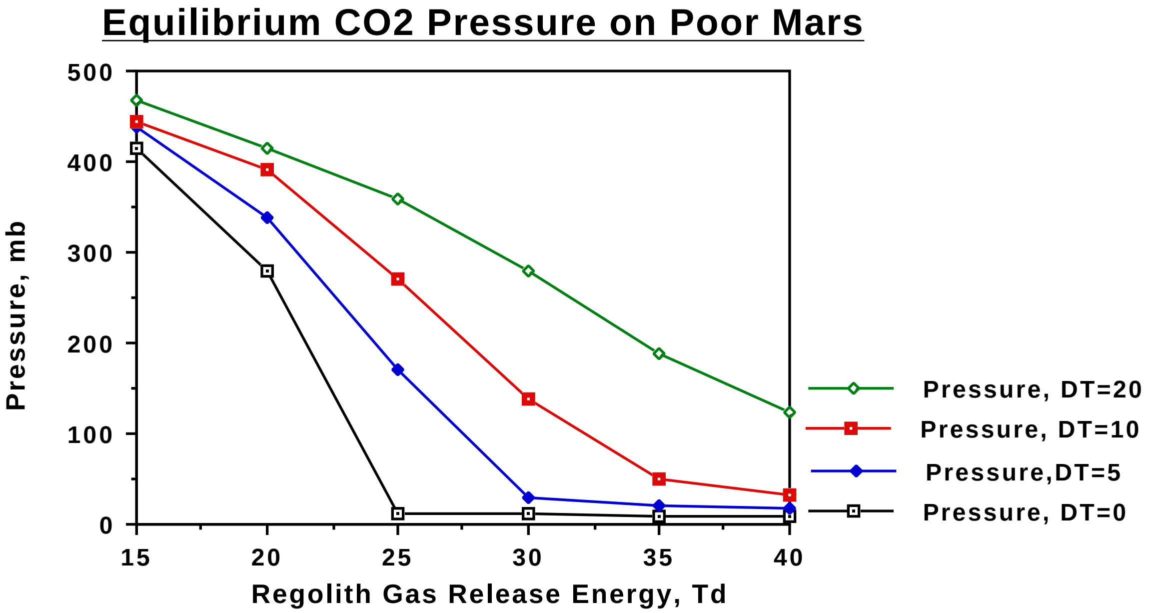

Fig .4 Equilibrium pressure reached on Mars with a planetary volatile inventory of 500 mb $CO_2$ after 50 mb polar cap has been evaporated. DT is artificially imposed sustained temperature rise.

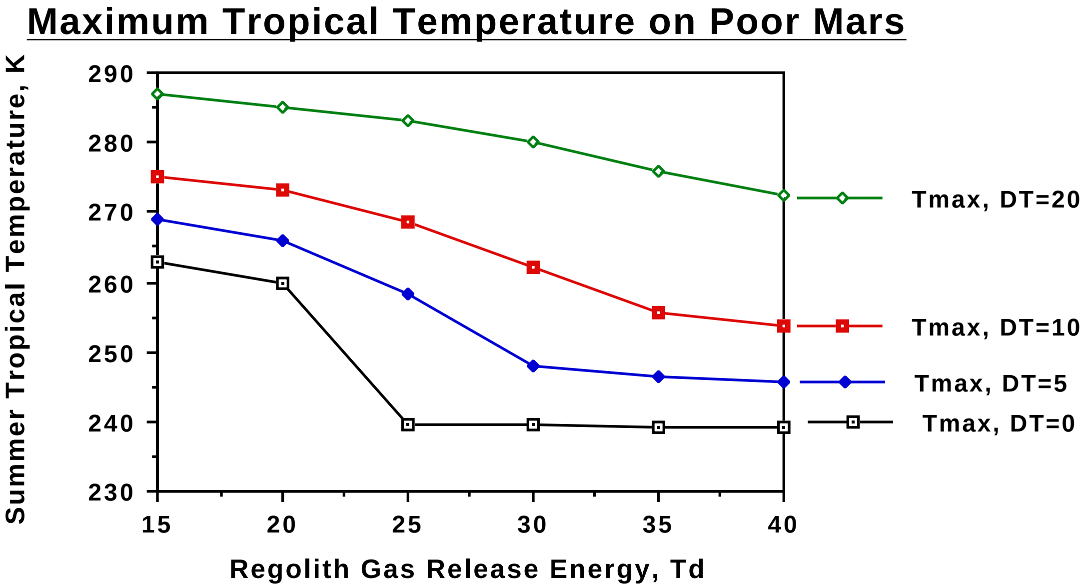

Fig. 5 Equilibrium maximum seasonal (diurnal average) temperature reached on Mars with a planetary volatile inventory of 500 mb $CO_2$ after 50 mb polar cap has been evaporated

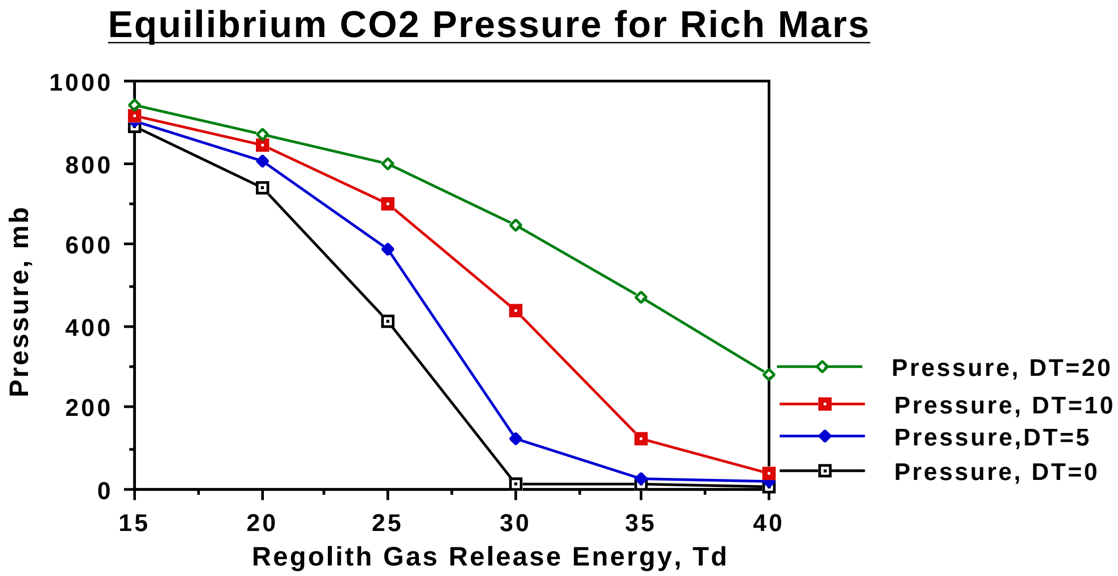

Fig. 6 Equilibrium pressure reached on Mars with a planetary volatile inventory of 1000 mb $CO_2$ after 100 mb polar cap has been evaporated

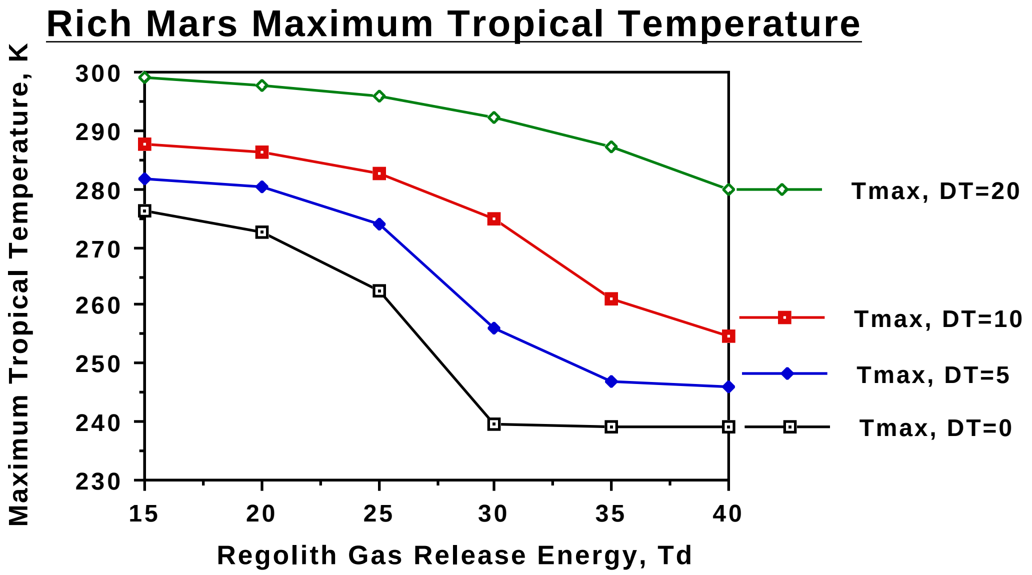

Fig. 7 Equilibrium maximum seasonal temperature (diurnal average) reached on Mars with a planetary volatile inventory of 1000 mb $CO_2$ after 100 mb polar cap has been evaporated.

The important conclusion to be drawn from this analysis is that while the final conditions on a terraformed Mars may be highly sensitive to the currently unknown value of the regoliths outgassing energy, Td, they are even more sensitive to the level of sustained artificially induced greenhousing ,DT Put simply, the final conditions of the atmosphere/regolith system on a terraformed Mars are *controllable.*

Once significant regions of Mars rise above the freezing point of water on at least a seasonal basis, the large amounts of water frozen into the soil as permafrost would begin to melt, and eventually flow out into the dry riverbeds of Mars. Water vapor is also a very effective greenhouse gas, and since the vapor pressure of water on Mars would rise enormously under such circumstances, the reappearance of liquid water on the Martian surface would add to the avalanche of self accelerating effects all contributing towards the rapid warming of Mars. The seasonal availability of liquid water is also the key factor in allowing the establishment of natural ecosystems on the surface of Mars.

The dynamics of the regolith gas-release process are only approximately understood, and the total available reserves of $CO_2$ won't be known until human explorers journey to Mars to make a detailed assessment, so these results are must be regarded as approximate and uncertain. Nevertheless, it is clear that the positive feedback generated by the Martian $CO_2$ greenhouse system greatly reduces the amount of engineering effort that would otherwise be required to transform the Red Planet. In fact, since the amount of a greenhouse gas needed to heat a planet is roughly proportional to the square of the temperature change required, driving Mars into a runaway greenhouse with an artificial 4 K temperature rise only requires about 1/200th the engineering effort that would be needed if the entire 55 K rise had to be engineered by brute force. The question we shall now examine is how such a 4 K global temperature rise could be induced.

## Methods of Accomplishing Global Warming on Mars

The three most promising options for inducing the required temperature rise to produce a runaway greenhouse on Mars appear to be the use of orbital mirrors to change the heat balance of the south polar cap (thereby causing its $CO_2$ reservoir to vaporize), the importation of ammonia rich objects from the outer solar system, and the production of artificial halocarbon ("CFC") gases on the Martian surface. We discuss each of these in turn. It should be noted, however, that synergistic[3] combination of several such methods may yield better results than any one of them used alone.

### Orbiting Mirrors

While the production of a space-based sunlight reflecting device capable of warming the entire surface of Mars to terrestrial temperatures is theoretically possible[5], the engineering challenges involved in such a task place such a project well outside the technological horizon considered in this paper. A much more practical idea would be to construct a more modest mirror capable of warming a limited area of Mars by a few degrees. As shown by the data in fig. 1, a 5 degree K temperature rise imposed at the pole should be sufficient to cause the evaporation of the $CO_2$ reservoir in the south polar cap. Based upon the total amount of solar energy required to raise the black-body temperature a given area a certain number of degrees above the polar value of 150 K, we find that a space-based mirror with a radius of 125 km could reflect enough sunlight to raise the entire area south of 70 degrees south latitude by 5 K. If made of solar sail type aluminized mylar material with a density of 4 tonnes/$km^2$, such a sail would have a mass of 200,000 tonnes. This is too large to consider launching from Earth, however if space-based manufacturing techniques are available, its constructing in space out of asteroidal or Martian moon material is a serious option. The total amount of energy required to process. the materials for such a reflector would be about 120 MWe-years, which could be readily provided by a set of 5 MWe nuclear reactors such as are now being considered for use in piloted nuclear electric spacecraft. Interestingly, if stationed near Mars, such a device would not have to orbit the planet. Rather, solar light pressure could be made to balance the planet's gravity, allowing it to hover as a "statite"[6] with its power output trained constantly at the polar region. For the sail density assumed, the required operating altitude would be 214,000 km. The statite reflector concept and the required mirror size to produce a given polar temperature rise is shown in figs 8 and 9.

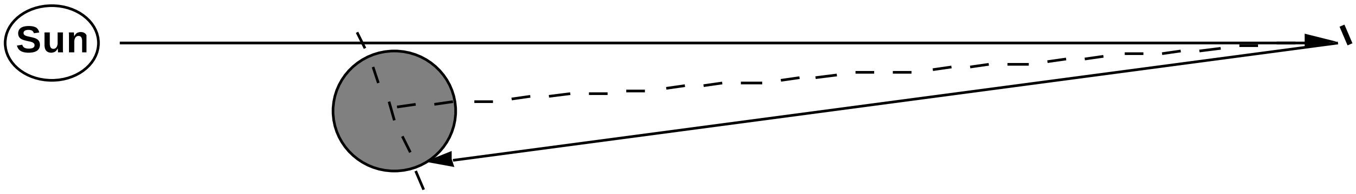

Fig.8 Solar sails of 4 tonnes/$km^2$ density can be held stationary above Mars by light pressure at an altitude of 214,000 km. Wasting a small amount of light allows shadowing to be avoided.

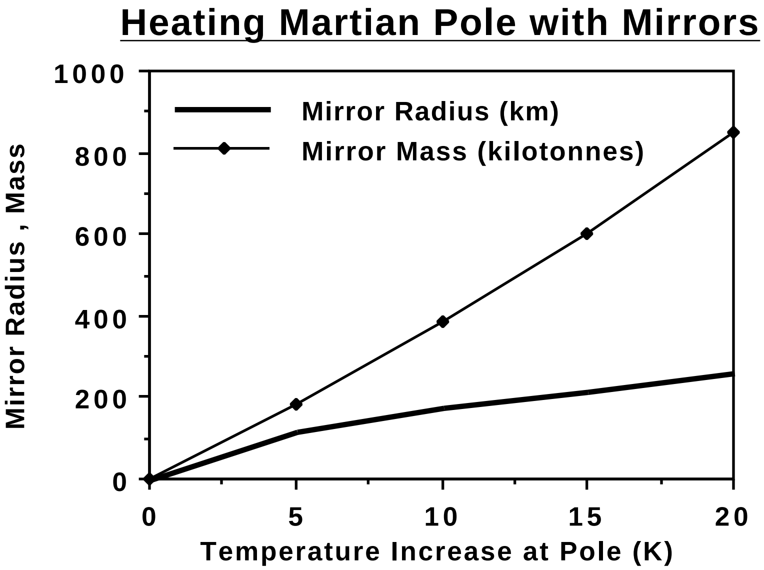

Fig.9. Solar sail mirrors with radii on the order of 100 km and masses of 200,000 tonnes can produce the 5 K temperature rise required to vaporize the $CO_2$ in Mars' south polar cap. It may be possible to construct such mirrors in space

If the value of $T_d$ is lower than 20 K, then the release of the polar $CO_2$ reserves by themselves could be enough to trigger the release of the regolith's reserves in a runaway greenhouse effect. If however, as seems probable, Td is greater than 20 K, then either the importation or production of strong greenhouse gases will be required to force a global temperature rise sufficient to create a tangible atmospheric pressure on Mars.

### Moving Ammonia Asteroids

Ammonia is a powerful greenhouse gas, and it is possible that nature has stockpiled large amounts of it in frozen form on asteroidal sized objects orbiting in the outer solar system. If moving material from such objects to Mars is envisioned, then such orbits would be quite convenient, because strange as it may seem, it is easier to move an asteroid from the outer solar system to Mars than it is to do so from the Main Belt or any other inner solar system orbit. This odd result follows from the laws of orbital mechanics, which cause an object farther away from the Sun to orbit it slower than one that is closer in. Because an object in the outer solar system moves slower, it takes a smaller $\Delta V$ to change its orbit from a circular to an ellipse. Furthermore, the orbit does not have to be so elliptical that it stretches from Mars to the outer solar system; it is sufficient to distort the objects orbit so that it intersects the path of a major planet, after which a gravity assist can do the rest. The results are shown in Fig. 10. It can be seen that moving an asteroid positioned in a circular orbit at 25 AU, by way of a Uranus gravity assist to Mars, requires a $\Delta V$ of only 0.3 km/s, compared to a 3.0 km/s $\Delta V$ to move an asteroid directly to Mars from a 2.7 AU position in the Main Belt. the time of flight required for such transfers is shown in Fig. 11.

Now we don't know for sure if there are numerous asteroid size objects in the outer solar system, but there is no reason to believe that there aren't. As of this writing, only one is known, but that one, Chiron, orbiting between Saturn and Uranus is rather large (180 km diameter,), and it may be expected that a lot of small objects can be found for every big one. In all probability, the outer solar system contains thousands of asteroids that we have yet to discover because they shine so dimly compared to those in the Main Belt (The brightness of an asteroid as seen from Earth is inversely proportional to the fourth power of its distance from the Sun.). Furthermore, because water, ammonia, and other volatiles freeze so completely in the outer solar system, it is likely that the asteroids to be found beyond Saturn are largely composed of frozen gases (such appears to be the case for Chiron). This makes it possible for us to move them.

Consider an asteroid made of frozen ammonia with a mass of 10 billion tonnes orbiting the sun at a distance of 12 AU. Such an object, if spherical, would have a diameter of about 2.6 km, and changing its orbit to intersect Saturn's (where it could get a trans-Mars gravity assist) would require a $\Delta V$ of 0.3 km/s. If a quartet of 5000 MW nuclear thermal rocket engines powered by either fission or fusion were used to heat some of its ammonia up to 2200 K (5000 MW fission NTRs operating at 2500 K were tested in the 1960s), they would produce an exhaust velocity of 4 km/s, which would allow them to move the asteroid onto its required course using only 8% of its material as propellant. Ten years of steady thrusting would be required, followed by a about a 20 year coast to impact. When the object hit Mars, the energy released would be about 10 TW-years, enough to melt 1 trillion tonnes of water (a lake 140 km on a side and 50 meters deep). In addition, the ammonia released by a single such object would raise the planet's temperature by about 3 degrees centigrade and form a shield that would effectively mask the planet's surface from ultraviolet radiation. As further missions proceeded, the planet's temperature could be increased globally in accord with the data shown in Fig. 12. Forty such missions would double the nitrogen content of Mars' atmosphere by direct importation, and could produce much more if some of the asteroids were targeted to hit beds of nitrates, which they would volatilize into nitrogen and oxygen upon impact. If one such mission were launched per year, within half a century or so most of Mars would have a temperate climate, and enough water would have been melted to cover a quarter of the planet with a layer of water 1 m deep.

While attractive in a number of respects, the feasibility of the asteroidal impact concept is uncertain because of the lack of data on outer solar system ammonia objects. Moreover, if $T_d$ is greater than 20 K, a sustained greenhousing effort will be required. as the characteristic lifetime of an ammonia molecule on Mars is likely to be less than a century, this means that even after the temperature is raised, ammonia objects would need to continue to be imported to Mars, albeit at a reduced rate. As each object will hit Mars with an energy yield equal to about 70,000 1 megaton hydrogen bombs, the continuation of such a program may be incompatible with the objective of making Mars suitable for human settlement.

A possible improvement to the ammonia asteroidal impact method is suggested by ideas given in reference 4, where it is pointed out that bacteria exist which can metabolize nitrogen and water to produce ammonia. If an initial greenhouse condition were to be created by ammonia object importation, it may be possible that a bacterial ecology could be set up on the planet's surface that would recycle the nitrogen resulting from ammonia photolysis back into the atmosphere as ammonia, thereby maintaining the system without the need for further impacts. Similar schemes might also be feasible for cycling methane, another short-lived natural greenhouse gas which might be imported to the planet.

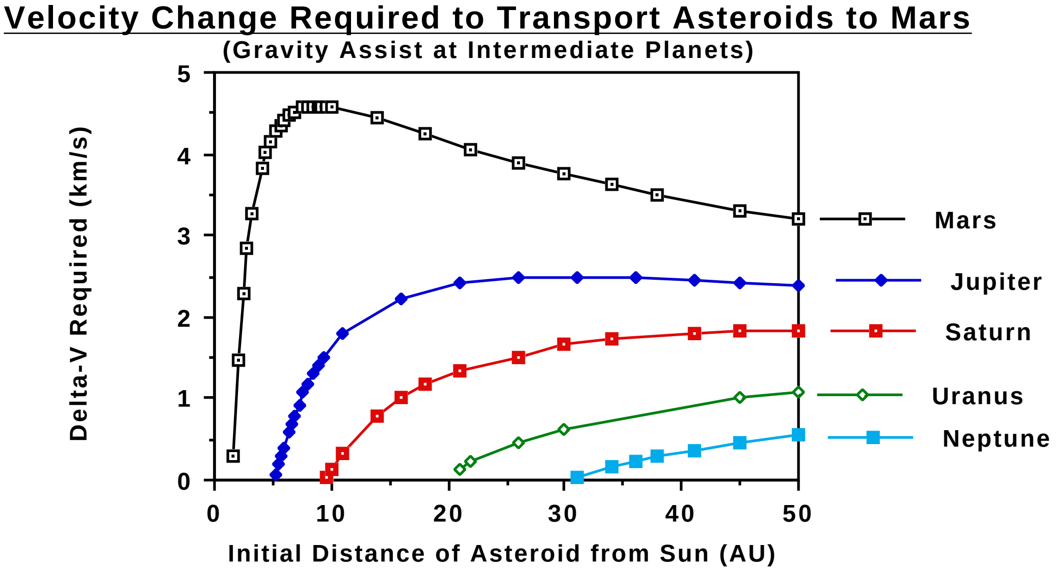

Fig.10 Using gravity assists, the $\Delta V$ required to propel an outer solar system asteroid onto a collision course with Mars can be less than 0.5 km/s. Such "falling" objects can release much more energy upon impact than was required to set them in motion.

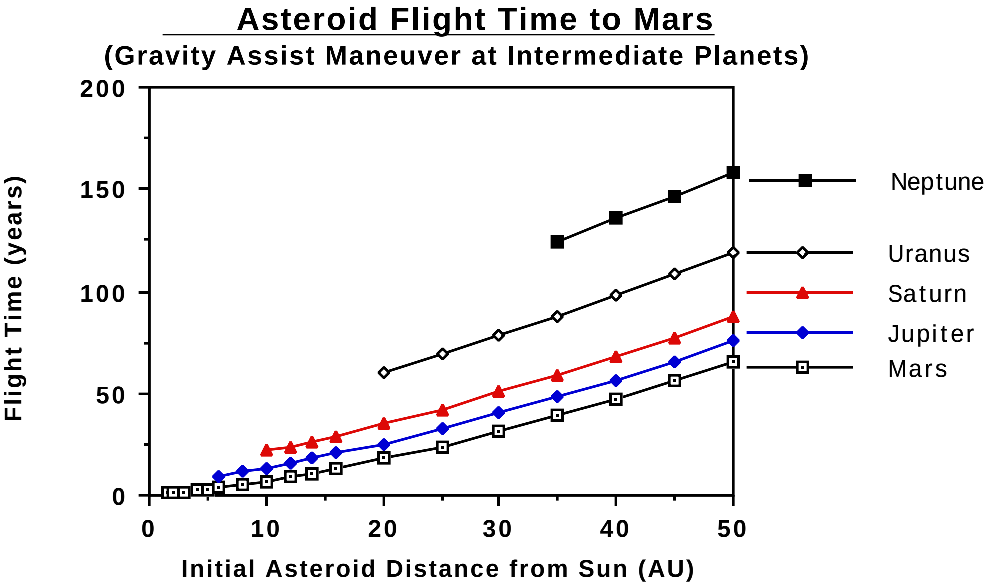

Fig.11 Ballistic flight times from the outer solar system to Mars are typically between 25 and 50 years.

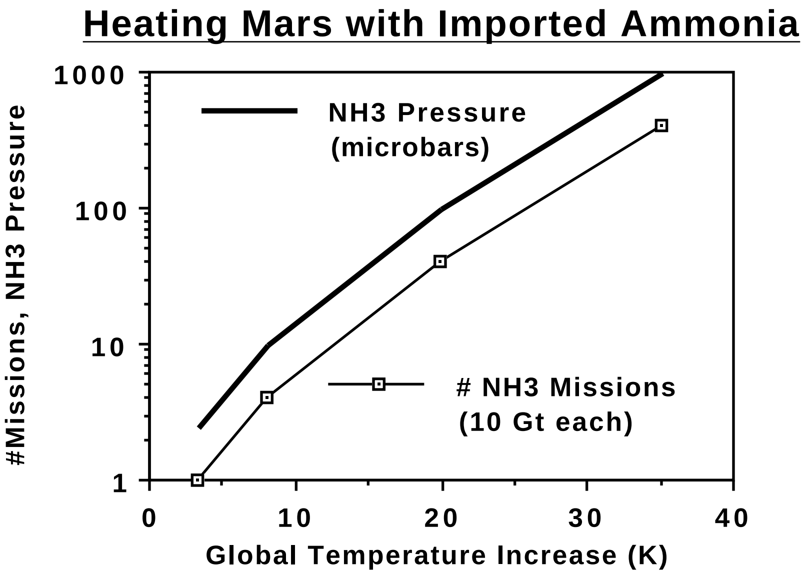

Fig. 12 Importing four 10 billion tonne ammonia asteroids to Mars would impose an 8 K temperature rise, which after amplification by $CO_2$ feedback could create drastic changes in global conditions.

### Producing Halocarbons on Mars

In Table 1 we show the amount of halocarbon gases (CFC's) needed in Mars' atmosphere to create a given temperature rise, and the power that would be needed on the Martian surface to produce the required CFC'c over a period of 20 years. If the gases have an atmospheric lifetime of 100 years, then approximately 1/5th the power levels shown in the table will be needed to maintain the CFC concentration after it has been built up. For purposes of comparison, a typical nuclear power plant used on Earth today has a power output of about 1000 $MW_e$. and provides enough energy for a medium sized (Denver) American city. The industrial effort associated with such a power level would be substantial, producing about a trainload of refined material every day and requiring the support of a work crew of several thousand people on the Martian surface. A total project budget of several hundred billion dollars might well be required. Nevertheless, all things considered, such an operation is hardly likely to be beyond the capabilities of the mid 21st Century.

**Table 1: Greenhousing Mars with CFCs**

| Induced Heating (degrees K) | CFC Pressure (micro-bar) | CFC Production (tonnes/hour) | Power Required ($MW_e$) |
|---|---|---|---|
| 5 | 0.012 | 263 | 1315 |
| 10 | 0.04 | 878 | 4490 |
| 20 | 0.11 | 2414 | 12070 |
| 30 | 0.22 | 4829 | 24145 |
| 40 | 0.80 | 17569 | 87845 |

In a matter of several decades, using such an approach Mars could be transformed from its current dry and frozen state into a warm and slightly moist planet capable of supporting life. Humans could not breath the air of the thus transformed Mars, but they would no longer require space suits and instead could travel freely in the open wearing ordinary clothes and a simple SCUBA type breathing gear. However because the outside atmospheric pressure will have been raised to human tolerable levels, it will be possible to have large habitable areas for humans under huge domelike inflatable tents containing breathable air. On the other hand, simple hardy plants could thrive in the $CO_2$ rich outside environment, and spread rapidly across the planets surface. In the course of centuries, these plants would introduce oxygen into Mars's atmosphere in increasingly breathable quantities, opening up the surface to advanced plants and increasing numbers of animal types. As this occurred, the $CO_2$ content of the atmosphere would be reduced, which would cause the planet to cool unless artificial greenhouse gases were introduced capable of blocking off those sections of the infrared spectrum previously protected by $CO_2$. The halocarbon gases employed would also have to be varieties lacking in chlorine, if an ultraviolet shielding ozone layer is to be built up. Providing these matters are attended to, however, the day would eventually come when the domed tents would no longer be necessary.

## Activating the Hydrosphere

The first steps required in the terraforming of Mars, warming the planet and thickening its atmosphere, can be accomplished with surprisingly modest means using in-situ production of halocarbon gases. However the oxygen and nitrogen levels in the atmosphere would be too low for many plants, and if left in this condition the planet would remain relatively dry, as the warmer temperatures took centuries to melt Mars' ice and deeply buried permafrost. It is in this, the second phase of terraforming Mars, during which the hydrosphere is activated, the atmosphere made breathable for advanced plants and primitive animals, and the temperature increased further, that either space based manufacturing of large solar concentrators or human activity in the outer solar system is likely to assume an important role.

Activating the Martian hydrosphere in a timely fashion will require doing some violence to the planet, and , as discussed above, one way this can be done is with targeted asteroidal impacts. Each such impact releases the energy equivalent of 10 TW-yrs. If Plowshare methods of shock treatment for Mars are desired, then the use of such projectiles is certainly to be preferred to the alternative option[3] of detonation of hundreds of thousands of thermonuclear explosives. After all, even if so much explosive could be manufactured, its use would leave the planet unacceptably radioactive.

The use of orbiting mirrors provides an alternative method for hydrosphere activation. For example, if the 125 km radius reflector discussed earlier for use in vaporizing the pole were to concentrate its power on a smaller region, 27 TW would be available to melt lakes or volatilize nitrate beds. This is triple the power available from the impact of 1 10 billion tonne asteroid per year, and in all probability would be far more controllable. A single such mirror could drive vast amounts of water out of the permafrost and into the nascent Martian ecosystem very quickly. Thus while the engineering of such mirrors may be somewhat grandiose, the benefits to terraforming of being able to wield tens of TW of power in a controllable way can hardly be overstated.

## Oxygenating the Planet

The most technologically challenging aspect of terraforming Mars will be the creation of sufficient oxygen in the planet's atmosphere to support animal life. While primitive plants can survive in an atmosphere without oxygen, advanced plants require about 1 mb and humans need 120 mb. While Mars may have super-oxides in its soil or nitrates that can be pyrolysed to release oxygen (and nitrogen) gas, the problem is the amount of energy needed: about 2200 TW-years for every mb produced. Similar amounts of energy are required for plants to release oxygen from $CO_2$. Plants, however, offer the advantage that once established they can propagate themselves. The production of an oxygen atmosphere on Mars thus breaks down into two phases. In the first phase, brute force engineering techniques are employed to produce sufficient oxygen (about 1 mb) to allow advanced plants to propagate across Mars. Assuming 3 125 km radius space mirrors active in supporting such a program and sufficient supplies of suitable target material on the ground, such a goal could be achieved in about 25 years. At that point, with a temperate climate, a thickened $CO_2$ atmosphere to supply pressure and greatly reduce the space radiation dose, and a good deal of water in circulation, plants that have been genetically engineered to tolerate Martian soils and to perform photosynthesis at high efficiency could be released together with their bacterial symbiotes. Assuming that global coverage could be achieved in a few decades and that such plants could be engineered to be 1% efficient (rather high, but not unheard of among terrestrial plants) then they would represent an equivalent oxygen producing power source of about 200 TW. By combining the efforts of such biological systems with perhaps 90 TW of space based reflectors and 10 TW of installed power on the surface (terrestrial civilization today uses about 12 TW) the required 120 mb of oxygen needed to support humans and other advanced animals in the open could be produced in about 900 years. If more powerful artificial energy sources or still more efficient plants were engineered, then this schedule could be accelerated accordingly, a fact which may well prove a driver in bringing such technologies into being. It may be noted that thermonuclear fusion power on the scale required for the acceleration of terraforming also represents the key technology for enabling piloted interstellar flight. If terraforming Mars were to produce such a spinoff, then the ultimate result of the project will be to confer upon humanity not only one new world for habitation, but myriads.

## Conclusion

We have shown that within broad tolerances of uncertainty of Martian conditions, that drastic improvements in the life-sustaining characteristics of the environment of the Red Planet may be effected by humans using early to mid 21st century technologies. While our immediate descendants cannot expect to use such near-term methods to "terraform" the planet in the full sense of the word, it at least should be possible to rejuvenate Mars, making it again as receptive to life as it once was. Moreover, in the process of modifying Mars, they are certain to learn much more about how planets really function and evolve, enough perhaps to assure wise management for our native planet.

Beyond such near-term milestones, the tasks associated with full terraforming become more daunting and the technologies required more speculative. Yet who can doubt that if the first steps are taken, that the developments required to complete the job will not follow, for what is ultimately at stake is an infinite universe of habitable worlds.

Seen in such light, the task facing our generation, that of exploring Mars and learning enough about the planet and the methods of utilizing its resources to begin to transform it into a habitable planet, could not be more urgent, or more noble.

## References

1. C. McKay and W. Davis, "Duration of Liquid Water Habitats on Early Mars," Icarus, 90:.214-221, 1991

2. C. McKay, J. Kastings and O.Toon, "Making Mars Habitable," Nature 352:489-496, 1991.

3. M. Fogg, "A Synergistic Approach to Terraforming Mars," Journal of the British Interplanetary Society, August,1992

4. J. Pollack and C. Sagan, "Planetary Engineering," in Near Earth Resources, J. Lewis and M. Mathews, eds, Univ. of Arizona press, Tucson, Arizona, 1993.

5. P. Birch,"Terraforming Mars Quickly" Journal of the British Interplanetary Society, August 1992.

6. R. Forward, "The Statite: A Non-Orbiting Spacecraft," AIAA 89-2546, AIAA/ASME 25th Joint Propulsion Conference, Monterey, CA, July 1989.