TERRAFORMING MARS

Shaun Moss
Mars Society Australia
shaunmoss@yahoo.com.au

ABSTRACT

As humankind heads into space, one of our primary goals is to find new worlds to settle. Mars stands out as far and away the most practical choice to begin this next phase of human civilization.

Apart from its relative closeness, one of the main reasons for this is Mars's potential for terraforming. The red planet's characteristics, while representing challenges, offer an opportunity for the manifestation of a vision which has permeated human thought since the dawn of science fiction – another planet that humans can walk on without the need for a spacesuit; a planet with air, water, soil, plants and animals.

Numerous thinkers have contributed to the development of terraforming strategies. This paper expands on previous work, incorporating our current understanding of Mars as well as emerging technologies.

The result is a strategy that incorporates past ideas with several new ones. Terraforming is organised into 3 primary tasks: increasing the temperature, building the atmosphere, and implanting the biosphere. These are implemented in stages, favouring solutions that are controllable yet still fast. The use of robotics and genetic engineering are emphasized, based on the assumption that these technologies will be much more advanced, probably even commonplace, during the 21st – 22nd century.

INTRODUCTION

Goals of Terraforming

Terraforming means to "make like Earth". However, it is worthwhile clarifying what that entails. The primary mineral constituents of a world must probably remain as they are, along with its size, mass, orbital characteristics, and level of gravity. Terraforming therefore generally refers to engineering those characteristics of a planet which can substantially be changed, such as atmospheric constituents, temperature, the size of the hydrosphere, and the addition or expansion of a planet-wide biosphere. Some planets are therefore more terraformable than others.

Thus, the primary goal of terraforming is usually taken to be the creation of a planetary environment that supports the survival of humans, as well as other organisms of Earth origin, across a significant fraction of the planet’s surface without requiring substantial use of technology (beyond, say, warm clothes). This includes:

- a breathable atmosphere at suitable pressure;
- liquid water at the planet’s surface;
- livable temperatures;
- and a biosphere, which can both maintain the modified environment in equilibrium as well as provide an abundant source of food.

Traditional Approach

Traditional terraforming strategies for Mars begin by warming the planet slightly (typical estimates are 4-10 degrees Kelvin) in order to initiate a runaway greenhouse effect. A slight temperature increase encourages sublimation of carbon dioxide and water vapour (both greenhouse gases) from the polar caps and regolith. The increased levels of these gases in the atmosphere trap more of the Sun’s heat, causing more sublimation, and so on, until a new equilibrium is reached at a higher temperature and atmospheric pressure.

Mars is known to hold significant reserves of water, primarily in the form of ice at the polar caps and frozen in the regolith. There is also evidence on the Martian surface of recent liquid water flows, such as seepage from crater walls; however, water cannot remain in liquid form on the surface of Mars for very long, and will rapidly freeze or boil. Solid ice lakes have been discovered in the bottom of craters.

As the atmosphere is thickened and warmed, this increases the duration that water can remain in liquid form on the surface of the planet. As water is a primary requisite for DNA-based life, this greatly improves the habitability of the planet’s surface. Eventually it becomes possible to introduce organisms from Earth, and thereby gradually construct a global biosphere. Through the selection, engineering and nurturing of appropriate organisms, Mars is incrementally shifted towards the desired terraformed state.

Basic Strategy

It is possible that mechanical methods could be employed to keep Mars in a terraformed state. However, a well-designed, self-regulating global biosphere will be much more preferable and effective, as it will not require constant maintenance.

Taking this as our eventual goal and working backwards, a basic series of steps can be determined (Figure 1). Note the inclusion of a step that is frequently ignored or glossed over in terraforming discussions, namely nitrogen importation.

Temperature increase and importation of nitrogen (as well as other techniques to manage atmospheric pressure and composition) will develop the necessary hydrosphere and atmosphere for biosphere construction. Terraforming can thus be simplified to 3 primary engineering tasks:

1. **Increasing Temperature**
2. **Atmospheric Engineering**
3. **Biosphere Construction**

1. INCREASING TEMPERATURE

The bulk of the required temperature increase may indeed come as a result of increased levels of carbon dioxide and water vapour in the atmosphere, and the well-known runaway greenhouse effect. However, some initial warming is still required to initiate this process. The methods most often proposed include large mirrors in space, either in orbit around the planet (Oberg, 1981) or positioned beyond Mars in such a way that sunlight is reflected back onto one of the poles (Zubrin & McKay, 1997). Other popular techniques include the addition of other greenhouse gases to the atmosphere such as chlorofluorocarbons (Lovelock & Allaby, 1984) or ammonia (Zubrin & McKay, 1997).

Phobos Mirror

A variation on the space mirror concept is to use Phobos as a platform for an orbiting mirror array.

Phobos is currently in a decaying orbit, and, left uncorrected, will either collide with Mars or break up into a planetary ring in about 50 million years. Although not an especially urgent problem, the easiest way to prevent this is to move Phobos into a higher, stable orbit. This can be achieved using currently understood technology, and in fact the problem of modifying the orbits of minor planets has already been addressed in the context of Near Earth Objects (Zubrin, 2000). For example, rocket engines can be attached to the object and its own material used as reaction mass.

One way to solve this problem, while simultaneously contributing to terraforming, is to move the moon into a polar orbit and use it as a foundation for an orbiting mirror or mirror array (Figure 2). In a polar orbit, Phobos would pass over each of Mars's poles approximately three times per sol (depending on its new altitude), reflecting sunlight directly onto them even during the winter months when they would normally receive no light or heat at all. Despite the small size of the moon, the impact of regular direct sunlight on the poles should still noticeably encourage sublimation. Phobos's path would also pass over every other part of Mars, adding heat and encouraging sublimation from regolith reservoirs.

Although the moon could be turned into a single large mirror, the question remains as to how it would remain optimally oriented throughout its orbit. A better approach would be to cover the moon's near side with an array of large, independently positionable mirrors mounted on motor-driven shafts. A computer would adjust the angle of each mirror to continually track the Sun and maximize the amount of energy being reflected down onto Mars. The system would be solar-powered.

While this would be the more complex and maintenance-intensive option, it allows a greater degree of control. If needed, the solar energy from Phobos could be tightly focused into a narrow beam cutting across the planet's surface, as a method for dislodging carbon dioxide and water bound in regolith minerals. Or, if preferable, the mirrors could be angled to send a divergent beam of light that spread across a wide area of the planet.

Although space-based mirrors have been suggested before, the advantage of using Phobos in this way is that material for the mirrors can be obtained directly from the small moon itself. Since Phobos is made from rock and ice, its material could be used to make mirrors of glass, pure ice, or polished iron.

As Phobos's average diameter is only 22 kilometres, it is not certain whether a Phobos mirror alone would be sufficient to trigger a runaway greenhouse. However, it need not be the complete solution to temperature increase. Also, a framework could be extended outwards from the satellite in order to support a larger mirror array if needed.

Phobos's apparent diameter from the surface of Mars ranges between 0.14º and 0.20º, whereas the Sun's is 0.35º. Therefore Phobos would appear something like a second sun, with about half the diameter of Sol, and crossing the sky from north to south rather than east to west.

Greenhouse Gases

Although atmospheric chlorofluorocarbons (CFCs) are known to be highly effective greenhouse gases, due to high levels of UV radiation in the absence of an ozone layer they would only last a few hours in the Martian atmosphere. The most popular alternative is perfluorocarbons (PFCs), which would last much longer due to the stronger fluorine-carbon bond. Another suggestion has been to add ammonia to the Martian atmosphere by throwing ammonia-rich asteroids at it (Zubrin & McKay, 1997), although this seems a very uncontrolled approach and the overall effect on the Martian climate would be hard to predict.

An excellent greenhouse gas already present on Mars in trace amounts (approximately 10 ppb) is methane. Since methane is not especially long-lived in a high-UV environment, its presence in Mars's air could be indicative of a replenishing source, which may be biological. If Mars does have extant life then it would make sense for it to be methanogenic, since methanogens generally thrive in low oxygen environments and are usually found underground, where any Martian life is likely to be found due to the higher temperatures and higher potential for liquid water.

Regardless of whether or not Mars has extant life, it may be possible to implant a methanogenic ecosystem as an early stage of biosphere development. In the long-term, methanogens would be unlikely to survive the terraforming process since they die in the presence of oxygen. However, as a means of adding methane to the atmosphere to serve as a greenhouse gas, the large-scale culture of a methanogenic ecosystem may still be worthwhile, especially if the organisms can be engineered to serve other purposes such as production of organics or nitrogen compounds.

Although a biological approach is preferable, methane could also be manufactured industrially and released into the atmosphere. Manufacturing methane from locally sourced water and CO_2 has already been examined in detail, and demonstrated in the laboratory, in the context of ISPP (In-Situ Propellant Production) (Zubrin, 1996).

Albedo Reduction

Yet a third frequently-suggested approach to warming Mars is by decreasing the planet's albedo, usually through such techniques as spreading black dust on polar ice caps, or by the widespread growth of dark-coloured algae or lichen.

In view of the difficulty of maintaining a dust layer in Martian winds, the second idea probably has greater merit, although the planet must already be capable of supporting life.

The idea can be extended to include specially engineered Martian plants with especially dark-coloured leaves. As the biosphere spreads across the planet, most of the atmospheric carbon dioxide will be consumed. While this is desired, it will also cause unwanted cooling due to reduction in the CO_2-induced greenhouse effect. This may be partially offset by dark-green plants. Once atmospheric CO_2 has been substantially replaced by O_2, and the methanogens have died off, this may be the most effective way to maintain higher temperatures in the long term.

2. ATMOSPHERE ENGINEERING

Mars's current atmosphere is primarily composed of carbon dioxide along with small amounts of nitrogen and argon, and trace elements of other gases such as oxygen, carbon monoxide and water vapour. The atmospheric pressure is rather low, however, at approximately 0.8 kilopascals (c.f. Earth's 101kPa).

The ideal atmosphere on a terraformed Mars would have the same pressure and composition as Earth, because a lower pressure would present a problem for some newcomers to the planet, in the form of altitude sickness. However, this is not a requirement for terraforming, and a thinner atmosphere may suffice. It is worthwhile to specify the minimum requirements.

Oxygen

The minimum safe breathable partial pressure of oxygen is 16kPa, somewhat less than the partial pressure of oxygen on Earth (21kPa). As this will be manufactured from carbon dioxide, and CO_2 reserves at the poles and in the regolith are estimated to be approximately 50kPa (Zubrin & McKay, 1997), this seems achievable using local ingredients.

Nitrogen

The importance of nitrogen seems to be frequently overlooked by terraformers. Aside from being an essential element of proteins, nucleic acids, and therefore DNA-based life, atmospheric nitrogen acts as a buffer gas, diluting oxygen and thereby preventing the rapid oxidative and combustive processes that would otherwise occur. On Earth, it is estimated that spontaneous combustion of the biosphere would commence if O_2 levels reached 35%. This limit may be higher or lower on Mars due to differences in temperature, pressure and humidity, but serves as useful starting point for engineering purposes.

For safety, whatever amount of oxygen is contained in the atmosphere must be combined with at least twice as much buffer gas, and ideally four times as much. For breathable air this need not necessarily be nitrogen, and a noble gas such as helium or argon may also serve. However, in view of the quantities required, nitrogen is by far the easiest to source, plus there are the benefits of our familiarity with nitrogen chemistry, and, of course, its requirement by the biosphere.

A bare-minimum atmosphere for a terraformed Mars may therefore be specified as follows:

O_2	16kPa	$6.85\text{x}10^{17}$kg
N_2	32kPa	**$1.2\text{x}10^{18}$kg**

Mars has relatively minimal supplies of N_2 in its atmosphere, and although there may also be nitrogen contained in the regolith in the form of nitrates and other compounds, it seems very unlikely that there would be enough for the above requirement. Therefore most, if not virtually all, of the above quantity will need to be obtained off-Mars.

There are three potential sources that could provide this quantity of nitrogen (Fogg, 1995):

- Earth's atmosphere
- Venus's atmosphere
- Titan's atmosphere

Despite the closeness of Earth, it is unlikely that the removal of this much of Earth's atmosphere would ever be permitted in view of the resulting climate change.

Of the other two options, Venus has the advantage of being significantly closer to Mars. However, Venus's atmosphere is only 3.5% N_2, which would need to be separated from the remaining CO_2. While this would be possible, the energy costs would be significant in view of the quantities required. Titan, on the other hand, has an atmosphere of 98% nitrogen. The remainder is mostly methane, which, as discussed, is an excellent greenhouse gas and would be welcome on Mars. As no separation of gases would be required, mining the atmosphere of Titan would thus be considerably easier.

Titan has approximately $9\text{x}10^{18}$kg of atmosphere, so this idea entails transplanting at least 13% of it to Mars. While this may at first seem a formidable task, in view of the technologies likely to be available to us at the time it may be achievable in a matter of decades.

For example, imagine that in our first year just 5 spherical robotic tankers are constructed, each with a radius of 100 metres, and each requiring 10 years to make a round-trip from Mars to Titan and back. Every subsequent year our technology improves and, on average, 10% more ships are constructed, each with a 10% larger radius and each taking 10% less time to complete a round-trip. The required quantity of N_2 would be obtained in just 4 decades. This is comparable to the lifetime of a small mine or quarry, and considerably less than the estimated timeframes of other aspects of terraforming. Even if it takes 2 or 3 times this long, this is still not excessive.

Although Titan presents a simpler solution technologically, it is still worth giving serious consideration to the option of mining Venus's atmosphere for N_2, which may actually be preferable if Venus is terraformed simultaneously. One strategy for terraforming Venus could include converting its CO_2 atmosphere into liquid water oceans via the Bosch reaction, whereby H_2 (obtained from Jupiter) is reacted with Venus's CO_2 to form water and solid carbon. The method would require separation of the carbon dioxide and nitrogen, and in light of the fact that Venus has approximately 4 times too much N_2 for a terraformed Venus, some of it could be transported to Mars.

Carbon Dioxide

The bounds on our O_2 requirements set approximately equal bounds on the amount of atmospheric CO_2 that precedes it, say, between 16kPa and 21kPa (this upper bound is somewhat nominal, but the higher the O_2 levels, the more N_2 must be imported). Some researchers estimate that as much as 80kPa of carbon dioxide could potentially be released into the atmosphere. This would probably be too much, although the level would drop once Mars has oceans.

This is because carbon dioxide dissolves in water, and the colder the water, the better. As liquid water becomes increasingly prevalent on the surface, CO_2 will dissolve in the new ice-cold water bodies. As occurs on Earth, it may then combine with crustal minerals to form carbonates (although, the lack of carbonates on Mars has led to the suggestion that Mars's past oceans may have been too acidic for carbonates to form, and this may again be the case during terraforming). If too much carbon dioxide is being lost to new lakes and seas, the best way to combat this is to maximise the size and effectiveness of the photosynthetic biomass, especially within the water bodies themselves, thereby converting as much CO_2 to O_2 as possible before it can form carbonates.

If carbon dioxide is chemically bound to regolith minerals, it may resist sublimation into the atmosphere and there may be a shortage. If so, one solution is to import more CO_2 from Venus.

Atmosphere Construction Strategy

Most atmosphere-building strategies for Mars focus on increasing carbon dioxide levels, then converting it to oxygen via photosynthesis. Nitrogen is usually overlooked, but even if it's added afterwards, this still leaves a long period of fire danger (Figure 3).

The safest option is to import all necessary nitrogen first, before warming the planet and building up the CO_2 fraction (Figure 4). One advantage of this strategy is that it permits a long period of Mars research before the climate is substantially altered. The increased atmospheric pressure will also improve the stability of liquid water on the surface.

However, the likely approach will balance expedience and safety by building the components of the atmosphere concurrently, importing N_2 while CO_2 levels are increasing, and even beginning the CO_2-to-O_2 conversion before all the required CO_2 is sublimed (Figure 5). This requires a significant degree of preparation. A highly reliable N_2 supply system must be constructed before the warming process is commenced.

The benefits of early nitrogen importation are manifold:

1. The atmosphere is thicker sooner, which aids construction and improves stability of liquid water.
2. A buffer gas is in place early, reducing combustive and oxidative processes.
3. The earliest organisms can make use of atmospheric nitrogen, adding nitrogen compounds to the soil sooner to prepare the way for plants.

3. BIOSPHERE CONSTRUCTION

Biological elements can be added to Mars as soon as liquid water is available, which may be right from the start. There may be pools, streams or aquifers below the Martian surface where temperatures are higher, and if these places can be accessed, new organisms can be introduced as soon as we decide to begin terraforming.

No new species should ever be introduced to Mars without first carefully evaluating, including computer modeling, its overall effect on the ecosystem and environment.

The Martian biosphere will be built by starting at the bottom of the food chain and working up. This suggests a 3-phase approach:
1. **Microbes.** With the basic nutrients available, a microbial ecosystem can be designed and implanted. Its primary role is to prepare the regolith for global introduction of photosynthetic organisms.
2. **Plants.** These serve the important function of converting the atmosphere from carbon dioxide to oxygen.
3. **Animals.** Most animals will not be added until terraforming is complete, although worms, fish and perhaps others may be introduced earlier.

These phases will overlap, with new organisms regularly added to the mix in response to Mars's changing environment and our improving technology. Less genetic modification will be required as the environment becomes progressively more Earth-like.

Microbial Martians

Genetics will be much more advanced at the time of terraforming. Although some terraformers have sought to identify terran extremophiles that can potentially survive on the Martian surface, mere survival is not enough. What is really necessary is to design organisms that will create a specific required effect.

The primary role of the "first wave" of aquatic microbes will be to photosynthesize. For non-aquatic microbes, it will be the addition of nitrogen compounds to the soil in order to prepare the ground for plants. As mentioned earlier, one possible secondary role for terrestrial microbes could be to produce methane, a useful greenhouse gas.

New microbes to fulfill this role can be created using genetic material from a variety of sources, including:
a) organisms that perform these roles on Earth

b) extremophiles with traits suited to Mars
c) extant Martian life

Beginning with engineered organisms, a program of ‘managed evolution’ combining genetic engineering methodologies with natural evolutionary processes, will produce a multitude of new organisms well-suited to Mars’s environment, which would perform a key role in the terraforming process.

Extremophiles

Extremophiles are often cited as being a good choice for early Martians. There are several categories with genetic traits that would be useful on Mars:

- halophiles (salt-loving)
- acidophiles (acid-loving)
- cryophiles (aka psychrophiles – cold-loving)
- xerophiles (dryness-loving)
- oligotrophs (adapted to lack of nutrients)
- radioresistant (adapted to high radiation levels)

Some of the most popular extremophiles discussed (Hiscox & Thomas, 1995; Budzik, 2000; Slotnick, 2000) in the context of terraforming are:

1. *Deinococcus radiodurans*. This is a polyextremophile with excellent DNA-repair mechanisms, capable of surviving in high radiation levels, and also resistant to peroxides and other oxidisers, desiccation and cold.

2. *Chroococcidiopsis sp*. A polyextremophilic cyanobacterium adapted to salty, arid conditions and capable of withstanding extremes of temperature.

3. *Matteia sp*. This is a desiccation-resistant cyanobacterium that can dissolve through carbonate rock, able to liberate carbon dioxide as well as fix nitrogen.

Nitrogen processors

Azotobacter is a type of soil bacteria that fixes nitrogen. Present Terran versions would not survive on the Martian surface, but combined with radioresistant, cryophilic and other genetic traits, *Azotobacter radiodurans* (for example) may perform the important task of adding ammonia to the soil. Other new species could be created from bacterial families such as *Nitrosomonas* (which convert ammonia to nitrites) and *Nitrobacter* (which convert nitrites to nitrates).

Methanogens

Another useful category could be methanogens, if we decide that biological methane production would be a safe and useful method of warming the planet. On Earth, methanogens are typically found underground, possibly because of the high oxygen levels on Earth’s surface. Perhaps on Mars, while O_2 levels are low, some extremophilic methanogens could thrive on the surface. It may be possible to engineer methanogens that do not die in the presence of oxygen, and which can remain on Mars in the long term – one possible way to maintain higher temperatures after CO_2 levels have dropped.

Extant Martian Life

If Mars harbours DNA-based life, we can make some educated guesses as to its nature. The presence of trace amounts of methane in the atmosphere indicates it may be methanogenic, which is congruous with the low oxygen levels. It probably lives underground, where temperatures are higher and liquid water is more likely to be prevalent, and therefore is probably chemotrophic. It could also be endolithic, or aquatic, living in subsurface pools or aquifers, or in ice.

Mars's life forms, if any, would be a useful source of genetic material. Martian organisms will have extremophilic traits which may be incorporated into new organisms to improve their compatibility with Mars. This may also be a way to address the moral issue associated with selfish displacement of existing residents. If their DNA is used to create new species, perhaps this can be seen as a form of assisted evolution.

Aquatic Ecosystems

Just as life on Earth first appeared in the oceans, development of aquatic ecosystems on Mars will occur far in advance of non-aquatic ones. In polar regions on Earth, the non-aquatic biomass is much smaller than in temperate or tropical zones, but in contrast, the aquatic biomass is significantly larger. This is due to the increased capacity of colder water to dissolve CO_2, which in turn improves conditions for phytoplankton, and thus providing an abundance of food for higher species. Nutrients such as sulphates, phosphates and other minerals are also more available in aqueous environments.

Furthermore, in the absence of an ozone layer, water provides shielding from UV radiation if it contains UV-absorbing ions such as Cl^-, Br^-, Mg^{2+}, or Fe^{2+}, which it will on Mars. As on the early Earth, aquatic ecosystems may totally predominate on Mars until photosynthesis has produced enough oxygen for the ozone layer to thicken, providing UV protection on land.

With liquid water available, it will become possible to introduce organisms into water bodies, mainly ponds and lakes in crater floors. Phytoplankton, especially diatoms, dinoflagellates and cyanobacteria, could be modified with the necessary halophilic, acidophilic and other traits in order to flourish in these environments. Ideally they will be designed to improve conditions for new organisms.

These may be followed up with zooplankton, krill, squid, and cold-water fish such as cod, herring, salmon, etc., and macroscopic algae such as kelp.

On Earth, algal blooms can cause eutrophication, whereby sunlight is blocked from reaching to deeper water, limiting fish growth. Although usually unwelcome, this may be an advantage during terraforming. If ultra-successful phytoplankton are desired in order to maximize O_2 production, then aquatic animals could be postponed until the atmosphere is appreciably changed.

Non-aquatic Ecosystems

Eventually it will become possible to add plants to the surface of Mars.

Tundral species, those found in Arctic, Antarctic and alpine ecosystems, are likely to be the most successful during the early years. These mainly include lichen, algae and bryophytes (mosses and liverworts), followed by cryophilic grasses and flowers (e.g. arctic poppy), and woody plants like the arctic willow and birch. In the absence of pollinating insects in these environments, many of these plants have evolved vegetative methods of propagation, including underground runners, bilbuls, and viviparous flowers.

Some xerophilic desert species, such as cacti, may also be viable.

Earthworms can be introduced as soon as practical, to process organic matter and mineral grains into soil. Bubbles of oxygen can become trapped in soil and therefore support the survival of earthworms even while O_2 levels are still too low for surface animals.

When the planet has warmed sufficiently and oxygen levels are high enough (or as soon as species can be engineered), bees and granivorous birds can be added to the ecosystem to perform pollination and propagation tasks. This will permit the introduction of more types of plants as well as greatly assist in the expansion of the biosphere. Stingless bees are likely to already be employed within enclosed bases for this purpose.

As plants spread across Mars, herbivores can be introduced. Again, these may be tundral species, such as arctic hares, muskoxen, caribou, llamas or mountain goats. These may be followed by carnivores: mammals such as arctic foxes, wolverines or snow leopards, and birds like snowy owls and arctic terns. (It seems unlikely that large carnivores like polar bears would be deliberately introduced if our goal is to make Mars safe for humans.)

Robotic Gardeners

Left to the usual processes of nature, it may be thousands of years before a biosphere encompasses Mars. However, this period may be significantly reduced by employing robotic gardeners to distribute soil, seeds and spores. Robotics and AI will be much more advanced by the time they are needed for this task, and likely to already be in widespread use on Mars for mining, construction and other purposes.

Bases may incorporate farms where algae, worms or bacteria are grown, and factories that produce fertile soil from Martian regolith, vegetable waste, manufactured ammonia, seeds and bacteria. Robots can obtain containers of organic material from these locations for distribution on the planet’s surface. Many of these could be aerial robots, such as helicopters or balloons, whereas others could be rovers that can operate at ground level.

Satellites in martian orbit would identify those areas most receptive to biology (such as ponds or streams), and the data used to direct robots. Growth rates, oxygen and heat production, and other factors can also be measured from space, the data providing valuable information about the success of certain organisms or strategies, and areas of interest.

Radiation Protection

The biosphere must be protected from the high levels of radiation on Mars. A thicker atmosphere will provide greater protection from charged particles, and increasing oxygen levels increase will cause an ozone layer to form, which will shield the surface from UV.

It has also been suggested that a magnetosphere could be created by building a huge conductor around the planet's equator, which would double as the backbone of the planet's electricity grid.

CONCLUSION

Terraforming Mars is a formidable project, but one that Martian colonists will surely tackle. Some of the associated challenges have been overlooked in the past, most notably Mars's lack of nitrogen, but even seemingly difficult problems like this can be overcome with ingenuity, technology and resourcefulness.

Past estimates of the time required for terraforming Mars have probably been unnecessarily conservative, being based on current or near-term technologies. However, future Martians will have highly advanced genetics, robotics and spacecraft available to them during the terraforming period. The result will be a relatively speedy planetary engineering process.

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FIGURES

Figure 1. Steps in the Terraforming Process

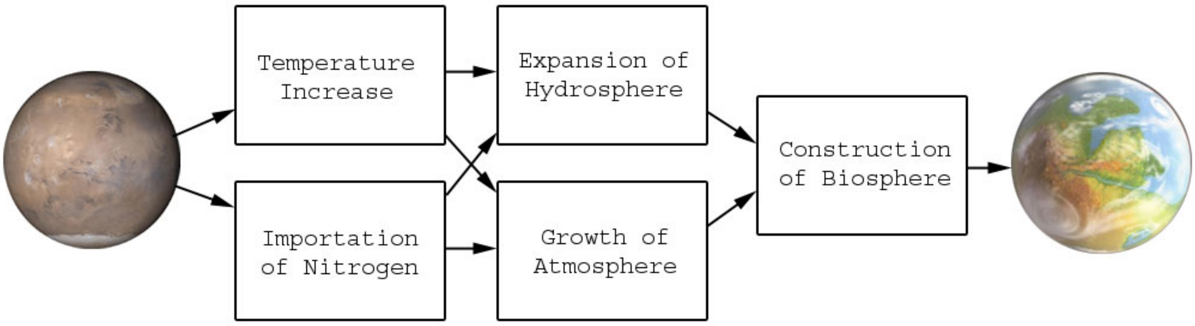

Figure 2. Phobos Orbiting Mirror Platform

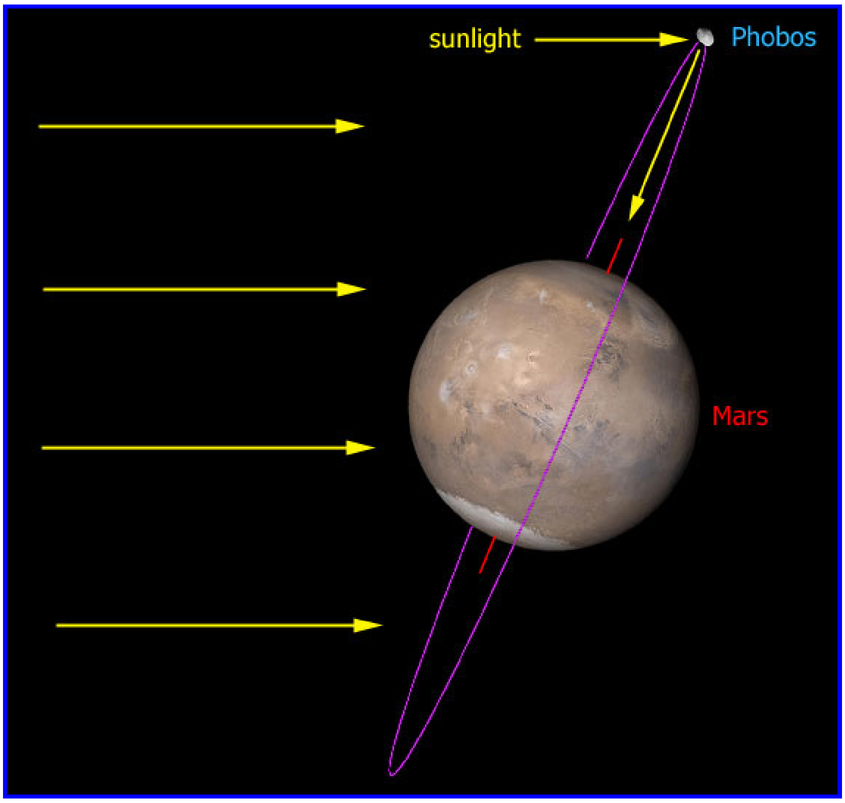

Figure 3. Late Nitrogen Importation

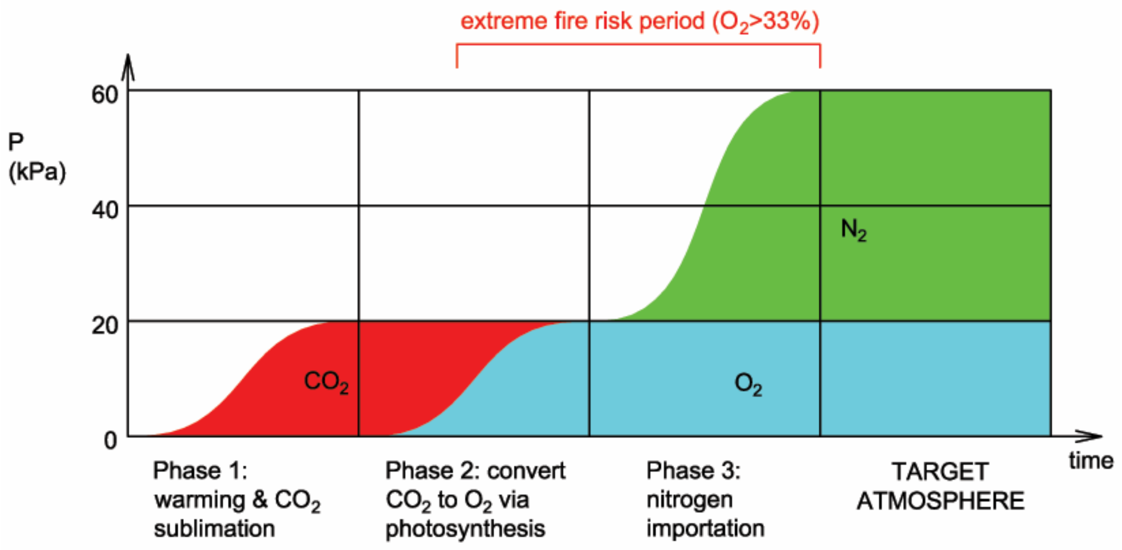

Figure 4. Early Nitrogen Importation

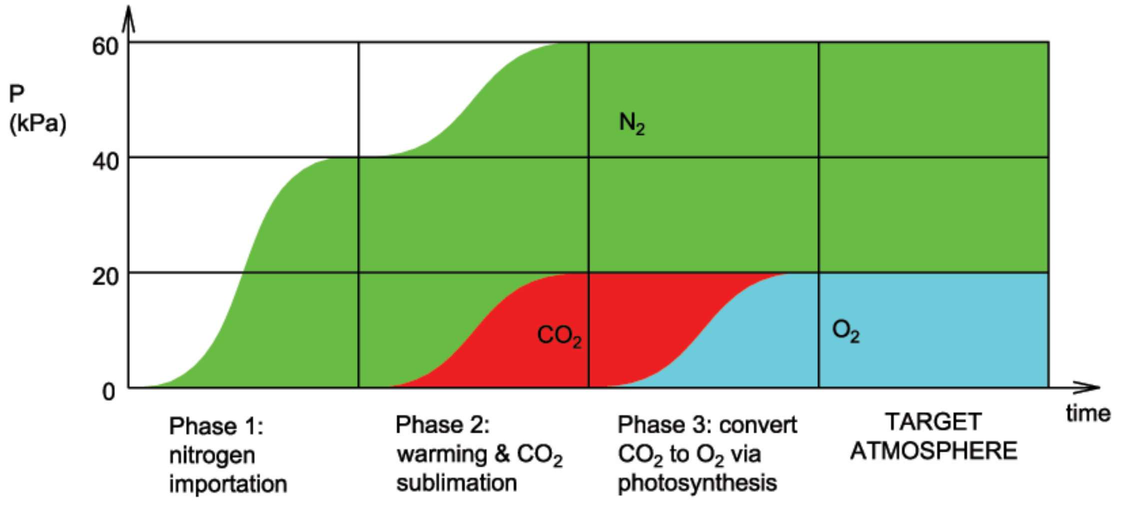

Figure 5. Concurrent Atmosphere Building Processes