TERRAFORMATION OF MARS

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TERRAFORMATION DEFINED

The literal meaning of terraformation can be described by dividing the word into parts: *terra*—the earth, and *formation*—the process of giving form or shape (Fogg 9). There is not as of yet a universal definition for terraformation, but it can be described most generally by the following definition (Fogg 9):

Terraforming is a process of planetary engineering, specifically directed at enhancing the capacity of an extraterrestrial planetary environment to support life. The ultimate in terraforming would be to create an unconstrained planetary biosphere emulating all the functions of the biosphere of the earth—one that would be fully habitable for human beings.

The major steps to fully complete terraforming Mars consist of the following: raise planet surface temperature, raise atmospheric pressure, make the surface wet, change atmospheric chemical composition, and reduce the surface flux of UV radiation (Fogg 219).

Clarity of Terminology

To prevent any misunderstanding of terminology, distinction between, ecopoiesis, and planetary engineering is necessary:

**Ecopoiesis.** The fabrication of an uncontained, anaerobic, biosphere on the surface of a sterile planet is called ecopoiesis. Ecopoiesis can represent an end in itself or be the initial stage in a more lengthy process of terraforming.

**Planetary engineering.** The application of technology for the purpose of influencing the global properties of a planet is called planetary engineering (Fogg 122). These former definitions imply the following: Ecopoiesis Í Terraforming Í Planetary Engineering.

Terraforming Mars will comprise a mission of enormous magnitude and will face major obstacles such as time and population requirements, attention span, working in a hostile environment, energy derivation, cost, budget constraints, vegetation implantation, terraformer health, environmental space law, conservation, ethics, and morality. Generally, a celestial body has the potential to be successfully terraformed if the gravitational well of the body is strong enough, and if resources for the terraformation are present. With these qualities, the planet
holds promise to accommodate a global biosphere—the most secure and efficient life-support system for living apart from our home planet (Fogg 82).

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HISTORY OF TERRAFORMATION

The scientific debut of terraformation made an effort to emerge with the annual Lunar and Planetary Science Conference scheduled for March of 1979. The conference management decided not to give the terraformation session official status, but allowed the participating scientists to use the conference facilities. The management’s decision was based on the belief that terraformation is “highly speculative and not closely linked to exploration of the planets…” (Oberg 29)” Nevertheless, The First Terraforming Colloquium took place in Houston, Texas on March 16, 1979, almost 18 years ago (Oberg 29). Over 100 scientists met for 4 hours to discuss the preposterous idea of terraformation. Since then, the concept of terraforming other worlds like Mars has gained remarkable popularity and significant scientific respectability.

PURPOSE OF TERRAFORMING MARS

The purpose and long-term goal of space exploration should be to permanently establish the human presence into space and to make the conditions necessary to permit new civilizations to grow and prosper independently from Earth. Migration and colonization to hostile environments has been a trait of biological evolution for billions of years. A recent letter sent to the editor of *Space News* titled “Meaning of Life” expresses one reader’s point of view: “We should be going to Mars not mainly as paleontologists, but as pioneers. We should be going to Mars not to learn about its past, but to understand its prospects for our future (Liss 14).” The utmost treasure with a terraformed Mars is the birth of an independent spacefaring civilization. The proposal to implant life on Mars as a long-range goal of human accomplishment poses several ethical, political, and legal questions. The time required to successfully terraform Mars must first be put into perspective before introducing obstacles that may challenge courageous pioneers of the future.

TIME REQUIREMENT

Aggressive Approach

How long the terraformation process will take is a controversial issue between two schools of thought. The first consists of an *aggressive* approach. Scientists supporting this direct approach believe the process will take 150-160 years to complete. This fast-paced bold process systematically has six steps: exploration and evaluation, initiation of the warming process, manipulation of the atmosphere, development of industries, expansion of the Martian economy, and intensification of oxygen production (Darrach, Patranek, Hollister 32-35).

Incremental Approach

The second school of thought advocates a much slower, *incremental* approach using two
phases with more natural processes: first raise surface temperature, then introduce organisms that will live off water, trace elements, and sunlight to remove the 95% concentration of carbon dioxide in the atmosphere (Nadis 28). Fogg and other scientists believe terraforming Mars would be a much more involved process and to “shake and bake” Mars into a terraformed world in less than 200 years would be unattainable, or the fait accompli of some science fiction (Fogg 325). Zubrin asserts in his essay “A New Frontier: Recapturing the Soul of America” that this gradual procedure will take close to 100,000 years to complete. This second school of thought suggests microbial ecosystems may be implanted no earlier than 200 years from now (McKay, Haynes 144).

The terraforming of Mars could be initiated by the twenty-second century with sufficient justification (Sagan 346). The long terraformation operation sounds discouraging for two predominant reasons: First, most people naturally set their activities and plan personal goals so that they are achievable during their lifetimes, and secondly, most governments usually cannot set budgetary expenditures beyond a year in advance.

**POPULATION REQUIREMENT**

After first colonizing the planet, and assuming the population of the colonists doubled every twenty years, it would be then possible for a colony of 1000 people on Mars to reach a population of one billion in four centuries (Allen 298). After the population achieves the census of one billion, then a genuine terraformation program could be initiated (Allen 298). Ben Bova asserts in his book *Welcome to Moonbase* that the immigration of people to an eventual base on the moon will allow only the most motivated and intelligent immigrants from Earth and that the movement will be very different from the migrations of early Earth history (Bova 217, 218):

In direct contrast to the immigration policies of an earlier century on Earth, Moonbase does not seek ‘your tired, your weak, your poor.’ The men and women who come to Moonbase are the best and brightest of our home world. They come from every nation, and they are allowed to work at Moonbase only after psychological screening tests have assured that they are not hampered by racial or religious prejudices. It is from this stock that our permanent residents are drawn.

We can assume the prerequisites for Martian terraformers will be no different if not more stringent. The colonists of Mars will most likely see steady rotations of scientists and engineers, while terraformers will probably be a group of people that wish to seldom return to Earth if ever.

**ATTENTION SPAN**

A critical problem with terraforming Mars will not be the capabilities of engineering or science, but the attention span of the societies which partake in it. The incredibly long duration of the Mars terraformation will test procedure thoroughness, attitudes, and diligence of the terraformers involved. Weak attention span will be due to lack of immediate return on initial investments. Perhaps part of the reason why there is no motivation to begin terraforming Mars today is because people are more concerned about immediate returns from their investments, at
least within their lifetime, for their children, or their grandchildren. The awards of terraforming Mars will not be recognized by the pioneers, but by their descendants 100s or perhaps 1000s of years after the terraformation process begins. For this reason, there is weak motivation to undertake the Mars terraformation. (Fogg 325). Gerald A. Soffen, Director of University Programs at NASA’s Goddard Space Flight Center states in an interview with Ben Iannotta of Space News that “We are focusing on smaller, faster, cheaper, not mission success (Iannotta 22).” Before an incredibly complex mission such as terraforming Mars will be considered, a paradigm shift will have to occur from an incremental to a revolutionary way of conducting space exploration.

Proposal

The huge responsibility of terraforming Mars could be broken down into 20 year segments so each generation could contribute to the endeavor (Fogg 326). Just as a family, country, or society manages their future, perhaps the human species should consider managing their future on a much wider scale. A paradigm shift will also have to take place in how human beings contemplate their futures: not just for 60-90 years of life, but hundreds of years into the future. Until the societies of the world grapple such a paradigm, the terraformation of Mars will remain an untried science. If people could be enticed by seeing a noticeable improvement of the Martian environment from their generation’s contribution, there may be some hope to maintain attention span.

RAISE TEMPERATURE: THE GREENHOUSE MODEL

Temperature Extremes

There is not enough greenhouse effect in the Martian atmosphere to warm the surface—the planet is essentially a frozen desert (Sagan 343). Mars’ average temperature is about -81°F. Fahrenheit (F) and the polar regions can plummet to –220°F. The diurnal temperature varies from 170°K to 268°K (Hiscox 1). The entire terraformation process will be integrated with a persistent attempt to raise the average surface temperature. Organisms cannot survive on Mars due to the temperature extremes predominantly for the following reasons (Hiscox 1):

1. formation of ice crystals from the freezing process would cause cellular damage in any organism

2. inhibited biochemical /metabolic reactions from extremely low temperatures raise the activation
energy for enzyme catalyzed processes

3.

efficient transport of metabolites would not occur in ice crystals, biochemical reactions need solution for transport.

Despite its frigid appeal, Mars resembles the Earth’s temperatures more than any other planet in the solar system.

Greenhouse Model

The most profound natural cycle on Mars is the CO$_2$ cycle and there are three reservoirs of the compound on Mars: the atmosphere, the dry ice in the polar caps, and as a gas adsorbed in the regolith (Zubrin, McKay 3). The greenhouse model is perhaps the most widely known and discussed method of terraforming Mars. This standard to alter the Martian climate to its former state appears to support a less expensive approach to terraform Mars and avoids the use of more costly planetary engineering inputs. Assuming that there is a reservoir of water buried deep beneath the surface of Mars, Zubrin believes it could take as little as 40 years to create enough greenhouse heat to melt the frozen H$_2$O on and near the equator (Hansson 94). The goal of the greenhouse model is to have positive feedback built-in: the warmer the surface gets, the thicker the atmosphere becomes (Zubrin, McKay 2).

Positive Feedback

Atmospheric thickening will be a continuous process as more solar energy will be absorbed. Warming subsurface porous rocks, regolith, and outer surface crust will subsequently proliferate more carbon dioxide and volatiles into the atmosphere. Raising the average surface temperature and boosting atmospheric density are objectives where results obtained for one task will likewise benefit the other. As the atmosphere thickens it will act as a blanket therefore retaining more solar heat. The polar ice caps reflect much of the solar energy received by Mars back into space.

Burial of Polar Ice Caps

Approximately 16 percent of the sunlight received by Mars is reflected back to space, mostly due to the polar regions of the planet (Clarke 94). The albedo of Mars could be lowered by covering the polar regions with a few million tons of black-colored soot or carbon. There is a two fold benefit for this action: it raises the average surface temperature and will help set free an immense abundance of frozen H$_2$O and CO$_2$ into the atmosphere (Clarke 94). Carbonate minerals and dry ice from one of the polar caps could be used to generate CO$_2$, a major
Carbon from Phobos. Phobos could be a terrific source of carbon as it has a very low albedo and is relatively close, but terraformers would benefit more if they initially derived their source of a darker soot from the carbonates found on the Mars surface. This will also help proliferate more oxygen into the atmosphere.

Martian soil and regolith. Terraformers could bury polar caps with Martian soil and regolith so the darker material absorbs solar radiation. Since approximately 100 million tons of material will be needed to alter the albedo of the poles, a dark regolith with an albedo of less than 9 percent can be used from the Syrtis Major region of Mars (Fogg 228). To produce comfortable temperatures on Mars would require the carbonate minerals within entire surface of the planet to be tilled and processed several kilometers deep to eventually trap the greenhouse effect of CO₂ (Sagan 344). To lower the net albedo of the polar ice caps to a few percent, terraformers could deposit a layer carbon black material which covers 6 percent of the polar caps (Fogg 228). This would relieve the amount of material needing to be transported from another source.

Vegetation. Sagan has proposed that terraformers could activate a Martian “spring” by darkening the polar ice caps’ albedos with layers of black dust or plant growth (Fogg 226). The result would be absorption of solar radiation, heat up the polar ice caps and release CO₂ into the Martian atmosphere. A thicker atmosphere will enable warmer air from the equatorial region to move toward the poles thus enabling a greater greenhouse effect and runaway growth of the atmosphere. The vegetation needed for this frigid region of Mars will require advances in genetic engineering in order for plant life to sustain itself.

Problem: aeolian activity. The problem with this burial idea is that Mars has aeolian activity, sometimes very distinguishable and enduring. The wind is so strong it may gust an initial 1-mm thick deposit of material downwind or carry it aloft into the atmosphere. A thicker deposit on the polar ice caps will be a necessity, at least 10-100 times more than the original amount of 1-mm (Fogg 228). Vegetation with a darker albedo could be imported to the surface of Mars to counteract the erosional effect of aeolian activity. As the vegetation grows on the polar ice caps, it would be able to anchor itself, thus preventing erosion.

Benefits of altering the polar caps. The transition created by the altered polar ice caps and subsequent greenhouse effect will yield a warm, moist surface, but Mars would not be habitable at this point of the terraformation. The CO₂ density of the planet will be similar to that of the Earth in a time scale as short as 100 years (Fogg 226). The artificial instability induced by polar cap alteration will increase warmth and subsequently cause devolatilization of the regolith on the planet’s surface, thus contributing to the greenhouse effect. The runaway greenhouse input for the terraformation of Mars is a powerful tool due to huge returns in comparison to the amount of effort involved. After the albedo of the polar ice caps are altered, the solar energy is the only other input needed to stimulate the runaway greenhouse effect. This concept was principally conceived by Carl Sagan and has become the basis for several terraforming models (Fogg 226).
Mirrors

If frozen water exists in the poles, the melting process may release water vapor into the atmosphere thus thickening the thin Martian air and increasing heat capacity. Zubrin claims in his essay “A New Frontier: Recapturing the Soul of America” that although the status of Martian water is in the form of permafrost, if it were all melted and the entire surface was flat, the entire planet would be covered with an ocean several hundred meters deep. Melting the polar caps of permafrost by precise aiming of Mylar mirrors, each several square miles across in sun-synchronous orbit, may raise temperature (Darrach, Patranek, Hollister 32).

Mirror dimensions. To vaporize the CO$_2$ of the southern polar cap, mirrors will need to have a radius of 100 km, and once the pole temperature is raised 5°C, the CO$_2$ reservoir should begin to evaporate (Zubrin, McKay 1, 8). The entire area of Mars south of 70° south latitude could be warmed by 5°C with the use of a mirror having a radius of 125 km (Zubrin, McKay 8). Zubrin and McKay assert that if a 125 km radius mirror were used to concentrate its power on a specific area, 27 TW of power would be accessible to melt lakes and induce nitrate beds to devolatize (Zubrin, McKay 12). Future construction of mirrors like this seems to be arrogant presumption, but the yield of these powerful, more manageable tools of terraforming are far more appealing than the asteroid impact concept. Other scientists recommend mirrors much larger in size.

Orbiting mirrors as proposed by Clarke suggest that the objective of the mirrors will be to increase the level of solar radiation received by a factor of 2 (Clarke 94). The area size of the mirror would have to be equivalent to the area of Mars, approximately 10 million km$^2$ (Clarke 94). Despite the vast area needed, the mirror need only be a few atoms thick to provide the reflectivity needed. This very tenuous mirror would be subject to space debris damage and seems to be a far-fetched idea to warm the planet with today’s technology, but advances in solar sail development may benefit the orbiting mirror concepts.

Mylar mirrors. Pending on the manufacturing abilities of the future, if solar sail-type aluminized Mylar mirrors could be built using materials from either Deimos, Phobos, or an asteroid. This type of mirror with a density of 4 tonnes/km$^2$ and a mass of 200,000 tonnes would require 120 MW-years worth of energy to process and could be facilitated by 5 MW nuclear reactors (Zubrin, McKay 8). The altitude for this type of mirror would be 214,000 km and its power output should be concentrated at the polar region (Zubrin, McKay 8).

Magnifying Soleta

Another design to provide Mars with Earth-like insolation is to employ focused sunlight with a magnifying soleta inserted between Mars and the Sun (Fogg 285). The soleta has huge dimensions: 10,600 km across, consisting of a 1300-km-wide reflective inner cone with annular slats made from solar sail material (Fogg 286). The soleta can be used either as a heat beam for vaporizing regolith and devolatilization or it can be used to increase global insolation by defocusing the return of solar energy to cover the entire diameter of Mars. If the soleta is
positioned 100,000 km away from the planet, the smallest target area of 600 km would receive
80 KW/m$^2$ of energy. If the soletta was set up to return its energy with the widest possible
diameter, the returned solar energy would multiply Mars’ insolation by a factor of 2.4, equal to
Earth’s global insolation (Fogg 286, 287).

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**Problem: frail design.** The mass of the soletta would approach 50 million tons of aluminum
and the design calls for a density of $r_a = 0.3$ g/m$^2$ or approximately 0.1 mm-thick aluminum
(Fogg 287). This would make the structure very susceptible to impact damage from space
debris. The soletta will probably be too fragile and may have many handling and stability
problems. The flux passing through the focus of the soletta is insufficient and will need more
concentration. An extremely lightweight lens will need to be suspended in the atmosphere of
Mars to assist in focusing the devolatizing return of solar energy from the soletta to
approximately 30-80 km (Fogg 287-288). Although this concept may seem impractical and
beyond our capabilities today, it has been widely supported that solar power should be the
primary source of energy for the terraformation of Mars. Despite the fact that we as a
civilization cannot construct something of this magnitude with today’s technology, it would be
precarious to assume that planetary engineers of the future will not be capable or motivated
enough to attempt such feats.

**Chlorofluorocarbons (CFCs)**

CFCs can augment the greenhouse model significantly by importing them via rocket impact, or
by constructing factories on the surface of Mars to manufacture the CFCs in-situ. CFCs are
1000 times more efficient over CO$_2$ in stimulating the greenhouse effect (Smith 126).

**Factories.** Martian chemical factories eventually constructed by pioneers may generate CFCs
(Nadis 29). These constructed factories would require approximately 5000 megawatts of power
to produce the CFCs needed to boost surface temperature (Hansson 94). Instead of importing
the supplies to manufacture the CFCs, the surface of Mars can facilitate fluorine-containing
minerals as a source (Sagan 344).

**Importation.** Manufacturing CFCs or Chlorofluoromethanes (CFMs) on Earth and
transporting these artificial chemicals to Mars may be possible. We now create about 650,000
tons of CFCs yearly, which equates to nearly 65 percent of the CFCs needed to catalyze the
greenhouse effect on Mars (Hansson 94).

Transporting the CFCs and CFMs to Mars would be expensive. Using the Saturn V- or
Energiya-class boosters would require at least a launch per day for 100 years (Sagan 344). It
would be cheaper to launch the payloads every two years as this would require less fuel and
time to reach Mars.

The Allaby-Lovelock proposal advocates using Poseidon, Polaris and Trident solid-fueled
missiles after strategic arms limitations have been signed (Smith 126). This proposal predicts
the warming process could be expedited if the rockets were placed on trajectories so that they impact the surface of the planet and crash the CFC payloads onto the surface (Smith 126).

Problems with importation model. There are several flaws with the importation model. Trident missiles cannot achieve escape velocity from Earth and would require modification along with lighter payload requirements. Some of the rockets that do achieve escape velocity would still not be powerful enough to reach Mars due to the planet’s opposition in its orbit. Most importantly, if a launch of one of the missiles fail before reaching space, the CFC payload could explode in our atmosphere. Even if the launches were placed on reserve for only when Mars is at closest approach to Earth, launching hundreds of these high-risk rockets at a time for Mars does not seem worth the risk nor the expense.

Threat to ozone. An ozone layer will most certainly never have a chance to develop due to the ever prominent population of chlorine in the atmosphere of Mars. The intent of CFC introduction is to create positive feedback with vicious cycle implications, but this positive feedback would be detrimental to Mars’ bleak ozone in its atmosphere. The warmer temperatures via CFC introduction would prevent Martian inhabitants protection from extremely serious solar ultraviolet hazards (Sagan 345). An alternative is to use halogens which do not contain chlorine. Careful combinations of CO$_2$, CFC, and NH$_3$ greenhouse gases on Mars might be able to warm surface temperatures close to the freezing point of water (Sagan 346).

Violent Bolide Impacts

Terraformation can be augmented by importation of volatiles from elsewhere in the solar system. Huge chunks of carefully selected, volatile rich asteroids, comets, or moons may be retrieved from space and forced into a trajectory so that they impact the surface of Mars. If the bolide impact model is to be used for importation of volatiles, there are 5 parameters which must be followed: the bolide must be rich in volatiles, especially N$_2$, the bolide should be close to a giant planet to reduce the DV needed to conduct a gravity-assist maneuver, the bolide must have an impact less than 10 km/s, the bolide should be small, and the desired target area should be an area volatile rich (Fogg 299).

Nitrogen significance. Only a small amount of ammonia (NH$_3$) would be needed to raise the temperature of Mars above 0°C, the freezing point of water. Since ultraviolet light converts NH$_3$ back into N$_2$ in about 30 years, there will have to be a continuous resupply of NH$_3$ (Sagan 345). The N$_2$ required for more greenhouse NH$_3$ could be delivered from elsewhere in the solar system, as N$_2$ is the principal constituent of Earth and Titan’s atmospheres (Sagan 345). Volatile derivation could be retrieved from nearby asteroids, comets, or moons.

Asteroids. The objective is to retrieve a volatile rich asteroid and cause it to violently impact Mars, preferably in a bed of nitrates on the surface. An ammonia-rich asteroid with a diameter
of 2.5 kilometers may be retrieved and fired via rockets into the Martian surface causing an explosion equal to 70,000 megatons, releasing ammonia’s greenhouse potential into the atmosphere, creating more heat capacity (Nadis 30). Between 3 to 40 meters deep into the surface or perhaps in the polar regions, there may be organic material either deposited there by meteorites or the remains of the ancient biosphere (Hiscox 2).

Zubrin and McKay claim a temperate climate on Mars would be achieved in 40 years if an annual impactor bombarded the surface of Mars, providing the bolide is a frozen ammonia asteroid with a diameter of 2.6 km, 12 AU distant from the Sun, and has a mass of 10 billion tonnes (Zubrin, McKay 9, 10). McCay and Zubrin also claim that the 40 impacts would double the nitrogen content of the atmosphere, even more if the target area contained high nitrate concentrations, thus causing nitrogen and oxygen to volatize upon impact (Fogg 298-299). This approach may not be fully controllable and could become anti-productive to terraformers performing other duties on the surface of the planet.

**Retrieval locations.** Asteroids from the outer solar system instead of from the “main belt” for two reasons. First, asteroids further away from the Sun are known to be more volatile rich due to less devolatilization caused by the solar wind. Secondly, an asteroid further out in the solar system will require less fuel to redirect it to Mars. An asteroid in a circular orbit approximately 25 AU out from the Sun would require first a 0.3 km/sec \(DV\) to perturb the orbit of the asteroid toward Mars, then boosts from gravity assists could fulfill the transfer (Zubrin, McKay 9). A concept supported by McKay and Zubrin is to use a bombardment campaign with 2.6-km-diameter ammonia asteroids that are in orbit beyond Saturn. Time of flight for asteroids retrieved from the outer solar system would require 25-50 years to collide with Mars (Zubrin, McKay 11).

**Large impactors.** Dr. A. W. G. Kunze of the University of Akron suggests asteroid impacts for another interesting purpose. If a large, dense bolide were to impact the surface with enough force, the excavation phase of impact may produce a crater deep enough to cause the Martian atmosphere to fill in the void, thus giving the crater a denser atmosphere than at ground level. An asteroid with a diameter of 67 km and a density of 3 g cm\(^{-3}\), traveling at a velocity of 5.1 kms\(^{-1}\) would create a 41 km-deep crater (Smith 131). The atmospheric pressure at the bottom of the crater would rise up to 500 mb (Smith 131). But this concept can only serve as an incremental approach to terraformation since only a portion of the surface could benefit from the rise in atmospheric pressure.

**Comets.** Another source for volatiles may be comets since their constituents are rich in frozen water and many are loaded with useful volatiles and carbon compounds. According to Clarke, only a moderate amount of energy would be needed to redirect the comet’s orbit toward Mars (Clarke 94). If rocket thrust were applied to the comet’s aphelion point of orbit, less energy would be needed to guide it into the proper trajectory. The comet selected should have a slower terminal velocity and smaller mass so as to facilitate a harmless burn-in and enable its volatiles to shower the atmosphere. Engineers may be able to adjust the comet’s trajectory so that it
either impacts the surface or breaks up in the sky. The asteroid and comet impact methods to boost the greenhouse effect summons caution as larger comet or asteroid bolides may be as destructive to the local strata as thermonuclear mining (Clarke 95).

**Satellite fractionation.** A similar concept to boost the greenhouse of Mars involves the disassembly of a small moon such as Enceladus by streaming small chunks of volatiles from this moon toward Mars (Fogg 299). The stream shower effect would resemble the Shoemaker-Levy 9 comet which was broken up into several pieces forming a chain to eventually collide with Jupiter. The same effect would be involved in this case, but here a total mass of $6.5 \times 10^{19}$ kg is to be moved with a power of approximately $2.8 \times 10^{12}$ W (Fogg 299). The propulsion needed to send Enceladus on its way toward Mars would be a DV of 187 m/s (the escape velocity of Enceladus), and then solar sail propulsion combined with gravity assists to escape from the Saturn system, thus requiring a total energy of $1.1 \times 10^{24}$ J (Fogg 299). The period required to complete the operation is very long, about 13,000 years, as the moon breaks-up piece by piece, into a $1.6 \times 10^8$ kg/s stream that would spiral into the surface of Mars (Fogg 299). Approximately 2000 TW of power would be dissipated into the atmosphere of the planet, amounting to 9 percent of the entire insolation of Mars (Fogg 299).

**Disadvantages of bolide impact models.**

*Violent nature.* There are some down sides to using the impactor method to boost the temperature and increase atmospheric pressure. Zubrin asserts that the practicality of corralling enough comets to do the job is questionable: it will take 200,000 impactors the size of Halleys Comet to transfer one bar of CO$_2$ (Hansson 96). The violent nature of using large bodies such as asteroids, fragmented satellites, or nuclear explosions could be contradictory to the goal of making Mars habitable for humans.

*Bolide population depletion.* The asteroid belt would be depleted somewhat and the operation would use up many of the small, icy asteroids between Saturn and Uranus. These asteroids may serve a better purpose later on, such as being sources of water and resource mining for future deep space excursions.

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*Too much energy required.* The asteroids in the main belt are moving much more quickly than asteroids beyond Saturn, such as Chiron. Asteroids in the main belt approximately 2.7 AU out will require 3.0 km/sec DV to inject them into a trajectory toward Mars, a significant amount of energy (Zubrin, McKay 9). Fogg believes asteroid impacts will not achieve major results in the terraformation of Mars (Fogg 298).

**Thermonuclear Explosions**

A very aggressive and controversial method to increase the mean surface temperature of Mars and boost the greenhouse effect would be to use thermonuclear explosions on the surface. Thermonuclear explosions used as shock wave perturbations and violent impacts may penetrate
accumulations of trapped volatiles. Massive quantities of carbon and oxygen are believed to be locked into minerals such as calcite (CaCO$_3$). Water aquifers believed to exist in a frozen state beneath the crust would be released to the surface thus contributing to the atmosphere and eventually to help warm the planet with induced greenhouse effects (Taylor 301).

**Controversial model.** Enormous amounts of energy, comparable to tens of millions of high-yield nuclear bombs, would be required to release the volatiles from the minerals on a global scale (Clarke 95). Nuclear explosions may be detrimental to the effort of raising Mars’ surface temperature. Radioactive contamination will pollute the surface for several years and will be detrimental to any advances the colonists and terraformers attempt while working on the surface. The suggestion to use this thermonuclear mining approach to aggressively supplement the greenhouse model may not be the best choice due to the negative result of long lasting radiation. Zubrin and McKay believe a mixture of all methods to warm Mars would yield better results instead of using a solitary approach (Zubrin, McKay 8).

**RAISE ATMOSPHERIC PRESSURE**

The average atmospheric pressure (AP) is roughly 8 millibars (mb). The AP of Mars varies by +25 percent to -25 percent of the average AP due to the planet’s orbit from aphelion to perihelion (Zubrin, McKay 2). This extremely low AP would damage organisms and can affect efficient DNA repair (Hiscox 1).

The main reservoirs of CO$_2$ are believed to exchange between 10 and 100 times the AP of CO$_2$ by way of the atmosphere and probably regulate climate change on Mars (Hiscox 2). Artificially induced warming of Mars by terraformers will force the porous rocks on the surface to release trapped volatiles to the atmosphere, and concurrently AP should begin rising from its present state to the goal of 24 mb of AP, the partial pressure of water (Allen 297).

Water on the surface of Mars does not exist in a liquid state due to the low AP. Once the AP matches half that of the Earth’s, water will no longer boil on the surface and may begin to pool. Allen asserts that after the AP reaches 24 mb, dendritic systems and river deltas will again flow with liquid water (Allen 298). The presence of liquid water will increase heat capacity and permit genetically altered vegetation to be introduced which would also accelerate terraformation (Allen 299). As more oxygen and pressurization is achieved, rebreathers may be substituted for pressure suits, granted a sufficient ozone layer substitute provides effective protection against harmful solar flares and galactic cosmic radiation (GCR). Oxygen may also be derived from the carbon dioxide in the Martian air and tons from the carbonate rocks and deposits of iron oxide (Darrach, Patranek, Hollister 34).

Collectively these steps may change the atmospheric pressure and enable liquid water to be stable on the surface. Mars has the capability to maintain an AP twice that of the Earth’s with invariable, warm temperatures above the 0°C mark, according to McKay (Hansson 94).
MAKE SURFACE WET

Despite Mars’ smaller size, the planet has roughly the same amount of land area as that of the Earth (Allen 298). Water on Mars may have been lost by hydrodynamic escape, atmospheric sputtering, and other mechanisms and Mars may not be able to return to its once climatic state (Hiscox 2). Mars has a vivid history of full-born outburst flooding of water as chaotic terrain and outflow channels are evident on the planet’s surface. These features of Mars give evidence that the surface of the planet had large bodies of standing water many times over where the surface was dry. The morphology of these regions of Mars imply that the enormous flow rates could have immersed the northern plains in a few months to a couple of years (Fogg 308).

Create Hydrologic Cycle

The repeat of such floods would greatly enhance terraformation efforts and expedite the new hydrological cycle that is needed. Artificial melting and draining of Martian aquifers may accelerate the terraformation process (Fogg 311). From his article “The Case For Colonizing Mars,” Zubrin believes that if Mars were as smooth as a ball and all its ice and permafrost melted to liquid form, Mars would be immersed by an ocean of water 100 meters deep (Zubrin 36).

Northern Ocean

A goal for terraformers would be to create a small polar ocean north of the line of dichotomy. An ocean located in this region would cover about 10 percent of the surface and have an average depth of about 70 meters. These parameters would enable Mars to become about 80 times more wet in terms of the average mass of moisture per unit area in comparison to the arid Mars of today (Fogg 310). This northern sea would benefit the hydrologic cycle and would be crucial for the continuous supply of fresh water. Evaporation from the northern sea of Mars will also stimulate the hydrologic cycle, moisten the Southern Uplands with precipitation, and pool lakes in craters. Ancient runoff channels will provide transport back northward to the reservoir (Fogg 310).

Heat reservoir. Liquid water will serve as an enormous heat reservoir therefore contributing to the terraformation process. As the AP rises on Mars, the emergence of liquid water on the surface will greatly assist with positive feedback since water vapor is a very effective greenhouse gas (Zubrin, McKay 7). Approximately 0.25 meters of water and 100 ~?bar of ammonia would be adequate to produce a greenhouse warming effect of about 20°C (Fogg 298).

Canals to Arid Regions

Since 80 percent of the precipitation of the Earth occurs over the oceans, there may be a problem on Mars in getting the much needed rain to the arid regions of the planet after the northern ocean forms. Canals will be needed to irrigate the water from the northern ocean south, beyond the line of dichotomy.
Buried Explosions

The Martian aquifers are probably frozen at the average surface temperature and the terraformers will need to raise the temperature of the rock and ice by about 60°C (Fogg 310). Nuclear explosions are a more violent approach to augment the melting of ice deep inside the crust of Mars, but they could be effective. The explosions would be more contained than a surface explosion and venting to the surface would not be desired (Fogg 312).

Pros and cons of buried explosions. In comparison with the method of impacting guided asteroids or comets to the surface, buried explosions will not leave as many scars on the surface of the planet as would the impactor method. The buried explosions would cause less damage to surface strata in comparison to the impactor method, except for the morphology of chaotic terrain and full-born outburst runoff, which are already natural features of the planet (Fogg 312). The negative impact of using buried nuclear explosions is radiation: terraformers and colonists may have to evacuate entirely from the surface depending on how widespread the activity is used.

OZONE

Based on O₃ estimates from the Precambrian atmosphere, the minimum O₃ thickness of the ozone layer to permit unprotected bacteria to live is between 1 x 10¹⁸ and 4 x 10¹⁸ cm² (Hiscox 6). Since oxygen is not required to form an ozone layer, the photodissociation of CO₂ could be used to generate enough O₃ to provide an O₃ layer in the Martian atmosphere (Hiscox 6). There still will be a threat to organisms on the surface during the initial formation of the O₃ layer.

Ozone’s companion: dust. Depending on the season and location of latitude, as much as a 40 percent variation in O₃ occurs due to dust and cloud opacities in Mars’ atmosphere (Hiscox 6). Since photodissociation of O₃ is greatly reduced by dust, an increase of 10 to 50 percent of O₃ can occur simply from the present amount of dust in the atmosphere (Hiscox 6).

Dust storms. Terraformers could create dust storms to augment additional protection from the harmful electromagnetic radiation penetrating through voids in weaker parts of the thickening O₃ layer (Hiscox 6). Heating one of the polar regions with mirrors may spawn global dust storms, thus causing a pressure differential as winds would carry the dust aloft (Hiscox 6). The remote sensing spacecraft which are used for Mission to Planet Earth to observe O₃ holes could be sent to Mars to forewarn terraformers of weaker areas of the developing O₃ layer.

Pulverized asteroids or surface debris injected into the atmosphere above the altitude of CFCs may prevent ultraviolet bombardment to an extent (Sagan 345).

VEGETATION

Vegetation will play an important role in terraformation due to plant life’s ability to absorb
carbon dioxide and expel oxygen. Director of the Institute of Ecology at the University of Georgia Frank B. Golley asserts that terraformation of Mars would best be achieved by forward contamination with lower life forms such as bacteria, algae, or protozoa (Golley 220).

One of the most difficult stages of terraformation is the production of microorganisms through photosynthesis by biological engineering. Specially engineered microorganisms would convert N\textsubscript{2} of the Martian atmosphere to NH\textsubscript{3}, or Martian factories might be able to produce the desired result (Sagan 344).

Introduction of genetically modified plant life would be possible with the presence of liquid water, and then plant life would directly contribute to the terraformation effort (Allen 298). Carbon dioxide will descend to a low amount and hardy tundra vegetation will be able to be planted in Mars’ warmest climates.

Temperature Extremes

Psychrophilic lifeforms, organisms which grow best in low temperatures (normally from 288-293°K), will be required during the initial stages of terraforming (Hiscox 7). The Ross Desert in Antarctica most closely resembles the Martian environment, disregarding the greater AP and less ultraviolet radiation (Hiscox 7). Endolithic microorganisms are lifeforms which live under the surface of rocks there and are extremely hardy critters as they endure temperature extremes of 258°K to 273°K in the summer and as low as 213°K in the winter (Hiscox 7). This persuades many scientists to believe these types of hardy organisms can be used to start the initial phases of vegetation growth on Mars.

Bacteria

The metabolization of nitrogen and oxygen to produce ammonia can be produced by bacteria (Zubrin, McKay 10). Terraformers could set up a bacterial ecology on the surface of Mars which would metabolize the nitrogen and oxygen in the atmosphere into ammonia, thus contributing to the greenhouse effect (Zubrin, McKay 10). Methane can be produced from bacterium that ingest hydrogen therefore supporting the greenhouse effect.

Reproducibility. Bacterial colonies can be grown from a single individual since sexual reproduction is not necessary to breed, and under favorable conditions, an entire ocean can be infected by a single bacterium (Crick 127, 128). Bacteria can grow very far apart from each other since they do not require a mate to reproduce.

Adaptability to extremes. Considering the harsh climatic and radiological conditions of the surface early in the terraformation process, bacteria is a hopeful candidate to survive the trials of life. Many different kinds of bacteria live in severe environments on Earth such as in deserts and hot springs—some have adapted themselves to withstand radiation in nuclear reactors (Crick 127). Stalwart single-celled organisms called archeabacteria occupy volcanic vents of
Oceans and geysers of Yellowstone, capable of sustaining themselves in extremely hot environments. They exist in oil wells and in cracks of basalt deep within the Earth (Myrhvold 64).

Some bacteria are capable of carrying out photosynthesis without the use of oxygen, and many other kinds of bacteria get their energy from sunlight which enables them to carry out several other types of photosynthesis (Crick 127). This type of microorganism may be the best choice of organisms to send to Mars to have the greatest chance of survival during the inhospitable beginning of terraformation.

*Escherichia coli* is a form of bacteria that is one micron wide and two microns long, therefore enabling a billion of these to be packed into a volume of only a few cm$^3$ (Crick 128). These bacteria can be frozen alive and if the temperature is cold enough, they could survive for over ten thousand years (Crick 128). Bacteria only sustains minimum cell damage when freeze-dried (Crick 127) therefore enabling multitudes of bacteria to be shipped with less mass for less cost. Due to their hardy nature and need for little or no oxygen, they would be nearly immune to impact shock and if they fell into a prebiotic ocean, they would probably thrive (Crick 128, 129).

**Algae**

Most of the major functions of a life-support system such as the production of food, oxygen, potable water, and the removal of CO$_2$ can be carried out by photosynthesis (Averner *et al.* 1). Green algae *Chlorophyta* and blue-green algae *Cyanophyta* are microorganisms capable of photosynthesis (Averner *et al.* 1). These algae grow quickly, their metabolisms can be controlled, and their gas-exchange characteristics are compatible with human requirements (Averner *et al.* 1). These type of algae could become candidates to assist terraformers in food production, the depletion of CO$_2$, and the generation of oxygen for the Martian atmosphere.

The green algae species *Chlorella* and *Scenedesmus* with the blue-green algae species *Anacystis* and *Spirulina* are currently under consideration for space related activities (Averner *et al.* 2) and may later assist in the colonization and terraformation of Mars. Prokaryotic N$_2$-fixing cyanobacteria species deserve the most consideration for the following reasons (Averner *et al.* 2):

1. no class of organisms exist in nature with simpler nutrient requirements
2.
they grow well in a broad range of light intensities between 600 and 650 nm - a range in which most other photosynthetic organisms will not grow well

3.

cyanobacteria species can be selected that exhibit short generation times and can endure a wide tolerance for environmental stresses

4.

most cyanobacteria produce a high content of proteins, in some cases a much as 70 percent of the total dry weight.

Long term exposure in the early stages of Martian terraformation may expose algae cultures to ionizing radiation where there is the risk of mutation.

**Cyanobacterium.** In several parts of the world, cyanobacteria have already been widely used as a food source for animals and people, as in China where it has been used for hundreds of years (Averner *et al.* 9). E. Imre Friedmann and colleagues from the University of Florida proposed an ideal pioneer Martian organism to be cyanobacterium, *Chroococcidiopsis*, a large and heterogeneous group of oxygenic phototrophic bacteria that used to be called “blue-green algae.” They are widespread in nature and due to their extreme hardiness, they are found in the remote areas of Antarctica (Fogg 2, 30). Since the atmosphere is rich in CO$_2$, the spread of simple hardy vegetation could react vigorously and spread rapidly across Mars’ surface. After centuries of propagation, Mars’ atmosphere could be increased with more oxygen and later opening up the possibility for more complex plants and animals (Zubrin, McKay 12). As the CO$_2$ content drops, halocarbon gases without chlorine should be used to maintain the greenhouse effect. Halocarbons with chlorine would cause a vicious cycle in the upper atmosphere of Mars, destroying whatever O$_3$ has been created, and should be avoided. The new O$_3$ cycle on Mars must reach equilibrium if so that vegetation populations may flourish.

According to Hansson, the hardiest of all microbial life will require more temperate conditions on the surface and will have to wait at least 200 years through the artificial warming process before introduction (Hansson 95). As the atmosphere thickens, specially bred crops will be able to be grown outside their habitation domes. After the temperature achieves 32°F, the air will be almost twice as heavy as Earth’s. Advanced plants require roughly 8 mb of oxygen to survive and humans need 120 mb (Zubrin, McKay 13). Terraforming Mars will require expert gardeners on-hand to plant aerobic life and evergreen trees (Darrach, Patranek, Hollister 34).
Energy has strong economic worth and there is a striking resemblance between the standard of living on the Earth and the per capita of energy use (Fogg 81). Many sources of energy will be necessary for terraformers.

**Solar and Wind**

Zubrin claims in “The Case For Colonizing Mars” that the vast quantities of carbon and hydrogen on Mars will be able to provide for the manufacturing of silicon needed for solar panel construction, and wind-generated power holds certain promise (Zubrin 36). Zubrin asserts in the article that the solar panels and the wind collected power will only support modest power production, 10s or at the most 100s of kilowatts (Zubrin 36).

**Geothermal and Hydrothermal Sources**

Hot underground hydrothermal reservoirs may exist on Mars even though the planet does not have active volcanism. Zubrin claims a more generous supply of power could be found with geothermal power producing outputs of up to 10 MW (Zubrin 36). He also asserts in his article “The Promise of Mars” that if reservoirs could be found, they could support colonists with both water and geothermal power (Zubrin 35). If the hydrothermal reservoir supply is abundant enough, it could be used in the terraformation effort.

**Indigenous Deuterium**

The economy of the initial settlers of Mars will be powered by an energy resource called deuterium. Deuterium may be used in thermonuclear fusion reactors that are nearly waste free. This heavy isotope of hydrogen is 5 times more plentiful on Mars than on Earth and it is the key fuel for fusion reactors (Zubrin 37-38). Deuterium occurs as 166 out of every million hydrogen atoms on Earth, but on Mars it occurs 833 out of every hydrogen atom (Zubrin 38). Its current market value on Earth is $10,000 per kilogram, or 50 times more valuable than silver or 70 percent as valuable as gold (Zubrin 38).

Current treaties such as the Outer Space Treaty, Moon Treaty, and the Test Ban Treaty do not permit the use of fusion reactors on celestial bodies. If treaties are eventually amended, Mars’ terraformation will not suffer from a power base problem, but the risks posed by contamination, nuclear waste, and melt-down will certainly endure.

**Importation of Weapons-Grade Plutonium (WGPu)**

The United States’ surplus of weapons-grade plutonium (WGPu) in excess of 100 metric tons (MT) could be used for energy purposes while terraforming Mars (Muscatello, Houts 1). Terraformers could use the plutonium as fuel in nuclear reactors which may someday be constructed on the surface of Mars. Muscatello and Houts claim that the United States generates 10 billion KW hours of power a day. Roughly 500 billion KW hours of energy could be produced from only 75 percent burnup of the >100 MT of WGPu available. This is an impressive amount of power which could be made available to colonists and terraformers, pending the successful launch and delivery of the payloads.

Since current space treaties and policies concerning nuclear materials in space prohibit any such
launch, any such attempt in the immediate future is not conceivable. There is not enough confidence for successful launches carrying payloads of this nature, and even if launches are successful, there is still the risk the main payload may fail to achieve escape velocity from Earth. The same risks are at stake for the Martian side of the transfer. There will be the problem of disposing nuclear waste if WGPu is used on the surface of Mars during terraformation.

Imports from Jupiter and the Moon

Isotopes which do not exist on Earth such as tritium and helium 3 can be derived from the clouds of Jupiter to be used by terraformers in advanced fusion reactors for energy production (Bova 219). Bova asserts that automated spacecraft may be able to retrieve these isotopes from grazing the outermost part of the Jovian atmosphere, analogous to aircraft used to skim across the surface of lakes to collect water and assist with dousing fires. The import of helium 3 might also be possible from the surface of the Moon.

NANOTECHNOLOGY: THE VON NEUMANN SYSTEM

A von Neumann system or machine is a device “which can collect energy and material from its surrounding environment and use them to manufacture a working copy of itself (Clarke 96).” An analogous, natural example of a von Neumann operation is bacteria. Eventually in the future, the von Neumann principle will be synthesized to mechanical systems enabling submicroengineering techniques to manufacture machines on the nanometer scale.

K. E. Drexler, a computer scientist at the Artificial Intelligence Laboratory of the Massachusetts Institute of Technology in Boston predicts nanotechnology will enable a billion bytes of data will be stored in a storage space equivalent to the size of a bacterium or smaller (Smith 130). Nanomachines could be used as either assemblers or disassemblers depending the program of the communication network being used. Assembler nanomachinery will be able to construct objects while the disassemblers will displace an object atom by atom. Mechanical action of the nanocomputers will not be as rapid as electronic action, but the nanocomputers would be very fast. Producing rocket propellant on the surface is an arena where nanotechnology may be used since H$_2$O$_2$ and HNO$_3$ could be derived from the surface (Smith 130).

Enterprises such as chemical engineering, agriculture, and mining will be transformed to conduct nearly any task imagined, at incredible speeds due to their capacity of self-reproduction (Clarke 96). The von Neumann machines which may be derived for the terraformation of Mars will need to be the most advanced of submicroengineering technology. The von Neumann system may be an important mechanism to help future engineers to terraform Mars more expeditiously. There would be less risk and loss of life may be prevented due to no human intervention. The von Neumann machines could provide support by exploring low-gravity asteroids and satellites for volatiles and raw materials. They could be used to mine asteroids and comets for volatiles and they may be able to build solar sails to deliver valuable excavations
from afar (Clarke 98).

If the nanomachines are used for the terraformation operation, the assemblers could be programmed to reproduce themselves, and once enough assemblers are on-hand, they could help change the environment of Mars. If a multitude of assemblers can be produced and if they are spread over enough of the surface, they could be programmed to generate organic molecules thus making the regolith into a fertile soil.

The emplacement of a von Neumann robotic factory on the surface of Enceladus would be instrumental to the terraformation of Mars (Hansson 96, 97). The system on Enceladus would be able to fragment the volatile rich satellite, furnish each bolide with a solar sail and project it on a trajectory for Mars.

Nanotechnology is certainly a bizarre suggestion, but staggering advances in technology may bring forth what today seems impossible. We already have the capability to manipulate single atoms through submicroengineering technology, but the von Neumann concept for advanced mechanical systems is dependent on future technology and is for now only conjecture.

COST

The Price Tag

The cost for terraforming Mars is incredible and will surely be a long term investment if ever approved. Each stage of the six step aggressive approach to terraform Mars would require distinct dollar amounts, successively: several $100 billion for stage one, $15 for stage two, $45 for stage three, $2-3 billion for stage four, Stage five would require only minimal support as Mars should be able to pay for most of what it imports, and lastly stage six, Mars will begin to repay the money invested. According to Hollister, “Before the end of the 22nd century, Mars could well be the richest colony in human history—Thousands of immigrants and billions of dollars will inundate the planet…” within a 155-year time frame (Darrach, Patranek, Hollister 34). Opponents to manned space exploration have quoted prices in excess of $500 billion for only establishing a colony on Mars (Allen 299).

Solution to the Cost: International Commitment

The only possible solution is international commitment. The tallest hurdle for the advocates of terraforming Mars will undoubtedly be to convince the governments of the world with a justifiable purpose and sensible economical plan which can follow through to a successful terraformation. If the people of the world are behind it, the world’s governments and societies should have a fair chance to support the operation. The only way to get support for such an expensive on-going operation is with public support. People will want to know that the terraformation of Mars will render to our ancestry another Earth as the operation eventually unfolds. Representative Robert Walker (R-Pa.), chairman of the Science Committee stated that
“a manned mission to Mars almost certainly will require international cooperation, perhaps a consortia similar to the international space station partnership (Eisele 19).” We can assume that the near-permanent operations of terraforming Mars will deserve the same type of consortia.

The Case for Mars Workshop II suggests Space Shuttles may be used to transport necessary vehicles and supplies to a space station in low-Earth orbit. Therefore the International Space Station (ISS) may serve as a platform for departing and returning crews (Case For Mars Workshop II 1). A University of Stanford study supports the aggressive approach to a manned Mars mission instead of debilitating budgets with ISS and a prospective Moon base (Hardie 295).

**Propulsion Requirements**

Retired USAF Lt. General Thomas Stafford claims that a minimum payload of 500 metric tons from low earth orbit is required to send a single manned mission to Mars (Eisele 19). The Russians’ heavy lift launch vehicle Energiya can lift up to 100 tons into low-Earth orbit; in comparison, the Titan IV can lift about 18 tons (Hardie 296) and has a launch cost of roughly $350 million (Grondine 32). Space News staff writer Anne Eisele reported in her recent article “Officials List Requirements For Mars Exploration” that future Mars missions will require “restoration of the U.S. heavy-lift launch capability of the 1970s, redevelopment of a nuclear thermal rocket and stabilization of NASA’s space science budget...(Eisele 19)”

NASA and the USAF estimate the cost to develop a US equivalent to Energiya would be $12 billion (Hardie 296). Money may be saved if Mars missions use Energiya and Space Shuttles instead of developing new heavy lift launch vehicles. Ariane 5 of the European Space Agency and the H2 of Japan have launch costs of roughly $150 million (Grondine 32). These heavy launchers can augment the more costly Titan 4 and the risky Energiya.

Terraforming Mars is very expensive by present standards, and environmentally destructive as well (Sagan 346). The terraformation of Mars must somehow reflect a balance between yield and cost, but before terraformation can begin, critical scientific information and knowledge of Mars must be obtained.

**BUDGET**

In order to amass the funding needed for such a huge project such as terraforming Mars, a major paradigm shift will have to occur in how governments financially support the scientific community. President Clinton’s long-range budget projects NASA’s purse to plummet to $11 billion by 2000 in effort to balance the budget (David 22). Six years ago, NASA’s budget outlook for 2000 was roughly $35 billion a year, but now the projected purchasing power of 2000 for NASA will be less than $10 billion per year...(Rogers 15)” According to T. F. Rogers, commentator for Space News, the federal civil space program “has lost 15 percent in purchasing power and the U.S. President Bill Clinton has just projected a further decrease of
The combined funding for Pathfinder, Sojourner, and the Delta 2 launch vehicle will cost about the same as the production of the movie “Waterworld” (Shirley 14). From November 6, 1996 until 2005, NASA will be launching a lander and an orbiter together every 26 months and will have an annual budget of $150 million - all in stride of the new NASA paradigm of smaller, cheaper, faster (Burns, Smith 15). Although these missions are constrained to tight budgets, the success of these smaller missions are key to eventually having the opportunity to terraform Mars.

**YIELD**

Terraformation will not yield any *short term* economic productivity for Earth. This huge project can only deliver a yield in the extreme long term for the investors’ ancestors. Metals, silicon, sulfur, phosphorous, inert gases and other raw materials are available on Mars and will help support a future advanced technological civilization on the planet. As increased knowledge and understanding of the Martian environment improve, resources from Mars will be able to supplement Earth’s exhausted supplies thus improving the quality of life.

**Mining**

Several precious elements may have been consolidated into local concentrations of high-grade mineral ores by hydrologic and volcanic activity of Mars’ past. In the same article, Zubrin foresees the possibility of mining highly concentrated metals from readily available ores, consolidated from Mars’ complex geologic history. If concentrated supplies of metals as precious or more valuable than silver could be excavated, there is a possibility that these metals could be transported back to Earth for profit (Zubrin 38). Zubrin asserts in “The Case For Colonizing Mars” that the planet has every element required for industrial purposes (Zubrin 36).

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**Ecological Economics: The Importance of Natural Cycles**

Potential extraterrestrial societies of the future may be tempted with terraformation interests for its economical value. There are several cycles on Earth which some people take for granted such as the hydrological cycle, the ozone cycle, the nitrogen cycle, the carbon cycle, and wilderness ecosystems to just name a few. These cycles are contributors to the equilibrium of a biosphere and each have a huge price tag. Space pioneers will have to contribute costly, technologically acquired energy to provide life support systems. Mars will require these biospheric matter cycles that are active on Earth, and as soon as Mars becomes unfrozen, the cycles may occur spontaneously (Fogg 219).

The driving force of cycling systems in the atmosphere and hydrosphere of Mars is the unrestricted nature of the Martian biosphere. With the participation of ecosystems, the
biosphere of a planet has a continuous capability to disperse enormous quantities of solar energy (Fogg 219). The resources that are free can either cost the same or go up in amount if they are mismanaged. Efficient use of expensive resources will lower their cost. One of the best attributes of terraforming in general is that it will provide a low cost method of living in space once it is in place (Fogg 81). The driver of the hydrological cycle, the provision of fresh air, clean water, and the recycling of most wastes will be natural weather and will receive help from the “wilderness” biota (Fogg 81).

In comparison to a closed biosphere habitat such as a domed city, nearly all of these processes will need to be critically monitored and manned. This closed model will require human feedback in agriculture and cultural infrastructures (Fogg 81,82).

Mars’ Positional Advantage

Mars’ close proximity to asteroids will allow terraformers to mine them for their mineral and volatile content, including water. Certain asteroids could be used to impact the surface of Mars. In the main belt between Mars and Jupiter, there are more than 5,000 asteroids in this zone, accountable for 98 percent of the solar system’s asteroid population. Some of the asteroids contain rich minerals and volatiles which could be useful during the Mars terraformation. Zubrin claims in the article “The Case For Colonizing Mars” of all the known near-Earth asteroids, 90 percent of them orbit closer to Mars than they do Earth (Zubrin 38).

A New Industrial Revolution

There very well could be another industrial revolution spawned by the terraformation of Mars. The primary reason to expect a huge boost in resourcefulness and inventions will be due to the extreme labor shortage. The best paid, most valued and essential staple product from terraforming Mars will be human labor. New and more powerful sources of energy will be made available, along with more efficient methods of space transportation and communication (Zubrin 5). Advances in energy production, automation and robotics, and biotechnology will result from human ingenuity brought about by budgetary constraints, remote location, and lack of individuals to support a work force (Zubrin 38).

Donna Shirley, Manager of the Mars Exploration Program at the Jet Propulsion Laboratory in Pasadena, California, claims that in-situ production of propellant from Mars’ atmosphere is possible to augment trips going back and forth to Earth: “on-site propellant production is a technology which will enable mass savings and use of an even smaller launch vehicle. However, that technology requires a long surface stay time - about 2 Earth years or one Mars year (Shirley 14).”

HEALTH

The hazardous duty of space and the hostile environment of Mars will always be a part of the
terraformer’s life. It would be beyond the scope of this paper to include all possible ailments which could impair terraformers. For this reason some of the more impacting health issues that could compromise mission integrity will be addressed such as radiation exposure, bone deterioration, orthostatic intolerance, space anemia, and food requirements. The threat from ionized radiation will be a recurring barrier for terraformers during their daily routines.

**Radiation Exposure**

Terraforming pioneers will face the threat of ionizing radiation such as galactic cosmic radiation, solar particle radiation, and solar flares. Sagan recently commented in an article titled “Why Mars?” from *The Planetary Report* that Mars has a planet-wide ozone hole which allows the Sun’s ultraviolet light to bombard its surface every day unobstructed (Sagan 10). Ozone in Mars’ atmosphere is proportional to 0.03 p.p.m. presently, so attempting to boost this bleak amount is a major terraforming objective.

**Exposure limits.** There is a certain amount of radiation a human being can absorb before problems in health begin. This limit depends on two factors: the amount of radiation present, and the medium the radiation is penetrating. The roentgen is the basic unit of measurement for the amount of radiation. Radiation exposure to humans can be measured in units of “rem” (roentgen equivalent, man). More modern measurements of radiation exposure to humans may use a different unit called the sievert (Sv) where 1 Sv = 100 rem. A human that receives more than 5 rem a year or more than 50 rem for an entire career is considered not safe. It will be a continuous responsibility for terraformers to monitor their amount of radiation exposure.

**Countermeasures.** Construction of safehavens for shielding from solar flares and solar particle events will probably be one of the first objectives of terraforming pioneers. Countermeasures to prevent overexposure to radiation include safehavens made of high density shielding, brief exposure intervals, and avoidance of predicted exposure. We need to improve our spacecraft designs to ensure terraformers enroute to, returning from, and on Mars’ surface have sufficient safehavens. These structures will need to be made with lightweight materials which are also easily accessible. If ozone cannot be produced in sufficient quantities in the upper atmosphere, a long-term terraforming project will be necessary to derive a substitute buffer on the surface and then pumped high into the atmosphere for shielding to buffer GCR and solar flares.

**Bone deterioration.** One of the most critical problems terraformers will face is the problem with loss of bone mass in their bodies. Bone activity will decrease the most in the slow twitch muscles which are the weightbearing muscles and bones. This would include primarily the bones of the legs, feet, and back. The calcium balance for a normal person on Earth over a period of time is stable. People with abnormal calcium balances suffer losses of calcium, but eventually their calcium content levels off to a steady equilibrium. When a human is exposed to space, severe calcium loss begins and does not compensate which can cause serious side effects in a space environment.

One example of a side effect from calcium rejection is kidney stones. Imagine how drastic the situation would be if a crewperson eight to nine months into a mission suffers so much bone
loss and contracts kidney stones. The medical procedure for this type of ailment would be quite
difficult to treat in space.

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Countermeasures. Terraformers will need to follow certain protocols to ensure they are able
to smoothly enter the labor force of the Martian civilization. Countermeasures used today in
space to avoid calcium loss is exercise. Stationary bikes, rowing machines, and treadmills are
helpful in attempting to maintain bone mass, but this can interfere with other crew members
trying to sleep or perform certain experiments. If the body senses a need for calcium it will
retain it. Very rigorous exercise protocols are needed to stimulate the muscles and bones of the
body which will then convince the necessity for more calcium and muscle mass.

Other countermeasures which may be of use in the future are spacecraft with modules capable
of artificial gravity, electrostimulation, and improvisations of lower body negative pressure.
Before we attempt terraforming Mars, a method needs to be devised by physicians to make
bones more receptive to calcium in microgravity and prevent the body from expelling it.

Orthostatic Intolerance

Orthostatic intolerance upon arrival to the Martian surface may be a big problem for some
terraformers. This occurs when the body cannot maintain an adequate blood pressure in a
gravity environment. The severity of orthostatic intolerance will depend on how long the
terraformers where traveling from Earth. Terraformers will need to augment current-day
protocols such as fluid loading with isotonic saline and lower body negative pressure units to
alleviate symptoms of orthostatic intolerance upon arrival at Mars.

Space Anemia

Space anemia can result due to low hemoglobin in the blood. This will occur when there is a
decreased production of red blood cells from the bone marrow.

Food

Proteins, carbohydrates, fats, minerals, vitamins, trace elements, and the assimilation of CO\textsubscript{2}
and excretion of O\textsubscript{2} will be provided by legumes and cereals initially (Smith 131). Inflatable,
ultra lightweight greenhouses will be used to provide growing areas for food production in the
early stages (Zubrin: Case for Mars Workshop II 4). Terraformers need to be the healthiest,
most invigorated, physically adept people.

Mission Integrity

It will be absolutely imperative that groups selected for terraforming are compatible.
Communications will be a very important part of missions to preserve well-being, mission
effectiveness, and esprit de corps. Integrity of the 6 to 8 month-long trips (Zubrin: Case For
Mars Workshop II 2) to and from Mars may be jeopardized due to friction between crew
members resulting from isolation, confinement, low morale, boredom, sex, depression, and cultural and religious differences from multinational crew members.

**TERRAFORMATION AND SPACE LAW**

If Mars is to be considered for terraformation, responsibility for preserving Martian terrain will most certainly be an important issue. Terraforming Mars would destroy Martian landforms which contain the ancient data of Martian past, most particularly the laminated polar terrain (Sagan 343). The processes of terraformation may disturb the niche of an indigenous life and impose extinction. For these and other reasons, there are laws which protect celestial bodies from certain activities conducted by nations whom are party to the treaties. Among the legislation which would have a direct impact on the possibilities of terraforming Mars, three of the most powerful treaties are the Outer Space Treaty, Moon Treaty, and the Test Ban Treaty.

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**Outer Space Treaty**

The cornerstone of space law comes from the Multilateral Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, 18 U.S.T. 2410; T.I.A.S. 6347 [Outer Space Treaty]. The Outer Space Treaty specifically points out that the use of nuclear weapons is not authorized by any one party to the treaty, as stated in Article IV (Reynolds, Merges 64):

States Parties to the Treaty undertake not to place in orbit around the Earth any objects carrying nuclear weapons or any other kinds of weapons of mass destruction, install such weapons on celestial bodies, or station such weapons in outer space in any other manner.

Article IX of the Outer Space Treaty elaborates more on the concerns of harmful contamination of another celestial body (Reynolds, Merges 66):

States Parties to the Treaty shall pursue studies of outer space, including the moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination…

**Searching for Identity.** A nation or group of nations cannot terraform Mars and then claim sovereignty over the planet or portions thereof, as stated in Article II of the Outer Space Treaty, “Outer space, including the moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means (Reynolds, Merges 64).”

After successful colonization and eventual terraformation of Mars, the people of this new world may possibly seek their own identity. This type of situation may become analogous to the colonies of the United States seeking their own unity and freedom over England. It is conceivable that Mars may someday become the melting pot of the human race. The natural resources available there may become so marketable and profitable that the natives in control of exportation may become more independent and in control of their new found wealth. But according to Article I of the Outer Space Treaty states that celestial bodies “shall be the
province of all mankind (Reynolds, Merges 64).”

Moon Treaty

The Agreement on Activities of States on the Moon and Other Celestial Bodies (UN General Assembly Resolution 34/68) [Moon Treaty] clearly states in Article 1 that “The provisions of this Agreement relating to the moon shall also apply to other celestial bodies within the solar system…” (Reynolds, Merges 102).” Therefore the Moon represents all celestial bodies in the literature of the Moon Treaty to include Mars.

Terraforming lobbyists will face major challenges such as Article 7 of the Moon Treaty, which asserts: “…states parties shall take measures to prevent the disruption of the existing balance of its environment whether by introducing adverse changes in that environment, by its harmful contamination through the introduction of extra-environmental matter or otherwise (Reynolds, Merges 104,105).” Article 11, Sections (1), (3), and (5) of the Moon Treaty reiterates the Outer Space Treaty and states (Reynolds, Merges 106):

The moon and its natural resources are the common heritage of Mankind…Neither the surface nor the subsurface of the moon, nor any part thereof or natural resources in place, shall become property of any state, international intergovernmental or nongovernmental organization, national organization or nongovernmental entity or any natural person…States parties to this Agreement hereby undertake to establish an international regime, including appropriate procedures, to govern the exploitation of the natural resources of the moon as such exploitation is about to become feasible.

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Test Ban Treaty


Each of the Parties to this Treaty undertakes to prohibit, to prevent, and not to carry out any nuclear weapon test explosion, or any other nuclear explosion, at any place under its jurisdiction or control: (a) in the atmosphere; beyond its limits, including outer space…

“The Partial Test Ban Treaty of 1963 prohibits nuclear explosions in the atmosphere, underwater, and in outer space, in an attempt to prevent pollution by nuclear fall-out.” (Matte 437) China, France, and India all have the capacity to produce nuclear contamination but are not parties to the Treaty, hence restricted effectiveness.

Declaration of First Principles for the Governance of Outer Space Societies

This declaration will be very important to colonists who terraform Mars in the future. Every aspect of the declaration is indispensable for human endeavors to terraform the planet, but provisions (C) and (G) of Article II of the Declaration are particularly significant (Gabrynowicz 3):

The United States shall provide for an orderly and peaceful transition to self-governance by outer space societies
under its jurisdiction at such time as their inhabitants shall manifest clearly a belief that such a transition is both necessary and appropriate… Outer space societies shall protect from abuse the environment and natural resources of earth and space.

1977 Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques

Article I of this agreement prohibits the “military or any other hostile use of environmental modification techniques having widespread, long lasting or severe effects (Matte 437).”

Consequences for Terraforming Mars

The limitations imposed by legislation and the operations essential to terraform Mars are not compatible. Parties to these treaties and agreements could not use nuclear weapons in any way for terraforming Mars. Contaminating Mars with radioactive waste from the proposed nuclear power plants and for assisting global warming would also not be tolerated. The environmental modification techniques and the introduction of extra-environmental matter necessary for terraforming Mars are not consistent with international space law. According to the Moon Treaty, appropriate procedures and establishment of an international regime will be required before resources can be exploited on Mars for any mission, to include terraformation.

CONSERVATIONAL OBJECTION AND ENVIRONMENTAL ETHICS

There are advocates who believe human expansion into the solar system is a natural part of our evolution, and that once colonization of Mars and other worlds are sustainable, terraformation will inevitably be considered. Opposition to such a radical engineering mission is already well represented.

Conservation vs. terraformation. Some people will inevitably protest the movement to terraform Mars, as this statement from Dr. David Thompson’s article “Astropollution” clearly declares (Oberg 256):

The groundwork for conservation of resources of the solar system, including space and celestial bodies, must be laid now, before exploitation begins and vested economic interests develop. Over-zealous pursuit of an economic frontier in space will undermine the development of zero-growth philosophies and economies on Earth, spark new demands for Earth’s resources, and create additional resources for environmental pollution… If the public is led to believe today that limitless resources of outer space are there to bail us out when the going gets really tough, then we may never be able to achieve zero-population…

Terraformers and conservationists will need to compromise on their doctrines since both sides will have justifiable points. The benefit terraformers will be able to sell to environmentalists is that they will be able to provide more opportunities for human beings to live in a “natural” condition, instead of living in overpopulated megalopolis surroundings. The astro-ecological pioneers will be responsible for controlling the consistent integration of natural cycles of Mars (Oberg 257). As director of NASA’s Solar System Exploration Division, Geoffrey A. Briggs has mixed feelings on the issue of terraforming Mars and perhaps speaks on behalf of
conservationists in general (Briggs 115):

…I have come to like Mars very much just as it is—a beautiful red planet with stunning geological formations and with dynamic polar caps and clouds. So, I would intuitively prefer to leave Mars alone as a pristine planetary wilderness…If it would be possible to recreate the earlier Mars (tapping water that is evidently abundant on Mars in the form of permafrost), then such terraforming might be an acceptable goal.

There is the possibility that with Mars terraformed, the undeveloped areas of Earth could be maintained and expanded (Oberg 258).

The paradigm of using a runaway greenhouse approach to make Mars habitable in a century would return Mars to a natural state of its past. Less planetary engineering would be involved due to the solar energy interaction with greenhouse gases may help calm criticism concerning human interference with nature. The goal of returning Mars to its once much more climatic state will be easier for conservationists to accept than a full-blown restructuring of the planet into a totally different environment it never has had.

Environmental Ethics

Dr. Jeffrey Warner, of NASA’s planetary science office in Washington, gave his beliefs with a speech titled “Ethical Aspects of Terraforming.” His creed is well supported amongst the environmental community and undoubtedly will be their stronghold against any lobbyists wishing to terraform Mars (Oberg 255-256): “When I first became aware of the topic I had the enthusiastic knee-jerk reaction: the concept was morally wrong and even discussing it would be a sin. Humanity has already screwed up Earth. What right does humanity now have to screw up other planets, especially elegant ones like Mars, Venus, Io, and Titan?”

Although life on Mars was not found by the Viking spacecraft, it was not ruled out. If life does exist, it may only be microbial in form. Perhaps we may find Mars to be inhabited with microorganisms in only a few areas of the planet, will we have a right to convert and modify their environment for our own aspirations? We will have to decide on whether to continue with our terraformation endeavor or scrub the entire project. Cohabitation with an indigenous life opens the same risk to ourselves. There is considerable support for the right to settle and colonize and eventually terraform Mars for the sake of our own prosperity. Preservation of a waning indigenous microbial life would be a controversial issue. A question of morality will most certainly be asked if we discover life on Mars and may interfere with any terraformation efforts in the future.

A reader of Space News contemplates the predicament the astronauts will be in if they indeed discover life on the planet: “…if a drill team or any Martian explorers find a living Martian organism, and if they become contaminated, no one is going to risk exposing the Earth’s ecosystem to this new life form by letting them return home…How can it be assured that a manned flight will be safe, that no virulent life forms exist on Mars? (Grondine 24)” The point the individual makes is valid, but hopefully quarantine methods will be established and
The terraformation of Mars will most certainly determine whether life exists or had ever existed on the planet, if not discovered sooner. Single-celled microbial organisms can prosper in harsh conditions on Earth, so there is strong possibilities that the same type exist on Mars. Suppose they do exist and Martian colonists discover them on the surface of Mars in the future. If the human race modifies the Martian environment in any way, we may be jeopardizing the existence of extraterrestrial life, or we may enhance it. It is possible to debate the issue that “rocks have rights,” but then it is as logical to insist that “Mars has a right to life (Fogg 30).”

SIGNIFICANCE OF METEORITE ALH84001

The discovery of possible evidence of ancient life on Mars is very significant to the future of terraforming Mars and deserves the highest acclaim. If the evidence becomes conclusive, the discovery would be the cornerstone of a huge beginning for unprecedented commitments for the space program, manned missions to Mars, colonization, and possibly in the long term, terraformation. Alan Hale, commentator for Space News claims that if the ALH84001 meteorite can be verified to show evidence of early Martian life, “this could well represent the greatest discovery of science (Hale 15),” possibly paving the way to the greatest scientific endeavor of all time: the terraformation of Mars. David McCay, the leader of the group of scientists who had claimed they had found possible bacteria-like organisms in meteorite ALH84001, says that if their claim of fossilized life is conclusive, “I am absolutely convinced there will still be life there. Once it gets started, you are not going to kill it off. It’s going to go to hot areas underneath Mars’ surface. If so, my guess is that Mars is teeming with life right now (David 22).”

Characteristics

The ALH84001 meteorite was found in the Allan Hills of Antarctica in 1984 and is believed to have struck the earth 13,000 years ago (David 3). The 4 - 4.5 billion year old, potato size piece of Mars was struck by an asteroid which impacted the planet 3.6 billion years ago, and may house microscopic fossils of primitive bacteria-like organisms (Dasch, Kross 28-29; David 3). The structures which were discovered on August 6, 1996 appear to be fossils and are no larger than 1/100th the diameter of a human hair, but most are 10 times smaller (Dasch, Kross 29). The organic molecules the scientists found are polycyclic aromatic hydrocarbons (PAHs). When microorganisms perish, their complex organic molecules frequently decay into “organic fingerprints” like PAHs (Dasch, Kross 28-29). The meteorite has raised significant attention from the public, scientific, and the political arenas.

Public Impact

Carl B. Pilcher, commentator for Space News, recently expressed in his article “The Human Side of Spaceflight” the seriousness of these new discoveries “have touched people who are not scientists or specialists, but just folks with families and faith, hopes and beliefs, who see in them [the discoveries] a connection to their lives (Pilcher 15).” Although the discovery is not conclusive, the attention to this incredible find is a blessing to the space program for it gives NASA a chief motivating goal to shoot for—Mars is now becoming the focal point of our
society’s space endeavors. Zubrin believes that a new revitalized Mars program will mobilize the space program, the nation’s research and development capabilities, and educational system. The significance of the meteorite has definitely stimulated more public interest in Mars, and may provoke Mars’ terraformation sooner for future generations.

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Scientific Impact

The scientific community has been invigorated by the meteorite’s possible content and initially excited public interest so much that NASA officials are sketching plans for manned missions to Mars as soon as 2011 (NASA 3). Zubrin stated in a *Space News* commentary “Time To Send Humans To Mars” that by “sending humans to Mars we would be taking the first step toward opening a new frontier in which a new and dynamic branch of human civilization can be created”, and quite possibly in the long run, another transformed world in which to live.

Missions being prepared for launch are the Mars Surveyor (November 6) and Mars Pathfinder (December 2) from the United States, Mars 96 (Nov 16) from Russia, and a Japanese commitment is planned. Since ALH84001 became such a momentous discovery, some Mars programs may be approved for acceleration. While at a press briefing on August 7, NASA Administrator Daniel Goldin said “I think we may have to accelerate some activities…Right now, we are in a very slow time scale… (David 18).”

In an effort to reassess the objectives of exploring Mars, Goldin asked Sagan to point out motives for having a strong Mars initiative. From the article “Why Mars?” in the September/October 1996 edition of *The Planetary Report*, Sagan gives his reasons to Goldin, and among them were these:

1. Mars is the prime site for self-sustaining communities on other worlds, and

2. Mars is the most readily terraformed world in the solar system.

The director of the Lunar and Planetary Institute, David Black, stated in the August 26-September 1 issue of *Space News* that “Mars is going to get all the business for the years to come (David 22).”

Political Impact

In Zubrin’s commentary “Time To Send Humans To Mars” from *Space News*, he recalls
President Bill Clinton stating that “The American space program will put its full intellectual power and technological prowess behind the search for further evidence of life on Mars…For if the discovery can be confirmed it will surely be one of the most stunning insights into the universe that science has ever encountered.”

If and when scientists can conclusively prove the meteorite houses ancient fossilized organisms from Mars, the possibility of one day terraforming Mars can only look brighter. NASA can expect more support from the President and Congress if confirmation of the fossilized organism can be obtained. Although President Clinton forecasts a slimmer NASA budget, he may be persuaded to allot more support for Mars missions in the future if ancient life can be proven to once exist on Mars: “I am determined that the American space program will put its full intellectual power and technical prowess behind the search for further evidence of life on Mars (Levin 13).” The day after President Clinton gave this announcement, NASA Administrator Daniel Goldin declared the NASA Mars program is being accelerated (Levin 13). These recent advances have direct impact on the possibilities of terraforming Mars and generally stimulates the global space program as a whole.

We can have an optimistic appraisal for future explorers of Mars and the other celestial objects of the Solar System. They will have new ideas and will look at the other worlds with totally different perspectives beyond our understanding and imagination.

Mission integrity will always need to be checked as personal greed and profit can undoubtedly either benefit or threaten the success of planetary engineers and countries involved. As in many large financial operations, the terraformation age will offer personal interest concurrently with the quest in building another planet to live on. Unfortunately with the good intentions of terraformation, there is the possibility of future crimes being committed in space.

**TERRAFORMATION SABOTAGE**

Parts of the industrialization and infrastructure needed for terraforming Mars could become powerful weapons for celestial blackmail in the next millennium. Imagine several hundred years from now the infrastructure to terraform Mars is established and Mars’ biosphere is evolving year-by-year. Crime will always be a part of human culture and the possibility of using terraformation applications for military advances would be possible.

The potential of hijacking one of the “big toys” of terraformation to rain havoc on an enemy here on Earth (or elsewhere in the solar system) will be a remote possibility. The huge mirrors which may someday be used to warm the climate of Mars, devolatize regolith, illuminate rescue attempts, control hurricanes or save crops were originally conceived to be weapons of war to burn enemy countries (Oberg 255). Consider the destructive power of an asteroid harnessed from the outer solar system to impact Mars for greenhouse purposes somehow goes off course and collides into Earth as a military war maneuver (Oberg 255). Altering planetary rainfall or manipulating O₃ and other parts of the stratosphere’s concentration over certain countries and
continents could be devastating. The more we study terraformation the more we can do to prevent, not increase the possibility of catastrophe (Oberg 255).

PUBLIC SUPPORT

Supportive

David McCay, Senior Scientist for Planetary Science and Exploration at NASA’s Johnson Space Center, believes “there is so much public interest, we should push the Mars missions. Why not keep the momentum going? That would be good for the country, rather than a 20-year program of business as usual (Leonard 22).” Another reader of the same paper claims that “People won’t care about fossils, or whether there is still life on Mars, or anything except establishing a colony and making it pay (Reynolds 12).”

Non-Supportive

There is mixed endorsement of such an immense project such as terraforming Mars. There are already people criticizing the proposed manned Mars missions to explore the surface of the planet once samples are returned from pending robotic missions. A letter received from Space News has a protesting reader expressing his opinion about possible manned Mars missions, and wishes “to remind the scientific community that we labor under a $5 trillion debt and one out of eight Americans is functionally illiterate (Longhi 12).”

The massive dedication required for a colossal project as terraforming Mars will undoubtedly spark controversy and some animosity in the public eye. Some individuals may believe as commentator Linda Billings that the space program should not be designed around exploitation, but exploration, as this passage defines: “The American people did not and will not get excited about a space exploration initiative designed to conquer and exploit, to beat the solar system into submission and pave the way toward crass commercialism in space…colonizers should turn in their space-explorer badges. They should have no place in shaping the future of space exploration (Billings 13).” Clearly this modern view would uphold strong opposition against ambitious terraformation endeavors. Unquestionably, attempting to terraform Mars will face fierce political opposition.

Ray A. Williamson, commentator for Space News states in his article “A Realistic Space Policy” that “Today, I see neither the congressional will nor the broad public interest to pursue a more extensive program of human exploration (Williamson 15).”

Moon Before Mars

Finding the support of an international commitment for long-term projects such as terraforming Mars may be difficult if other countries have their space exploration priorities with the Moon. Some support the movement for Mars but insist the Moon should be used for experience before trying to tackle Mars to prevent a disaster which would set back any attempt for Mars
even further. Another reader of Space News had written in to the editor of the paper claiming that we do not know enough about long-term space travel and we lack the capability to design complex spacecraft to pursue Mars missions. Wendell Mendell, a planetary scientist with NASA, stated in a recent Space News article that without using Moon missions as a learning experience, “Mars exploration is too big a task (Kallender 3)”. There is an international movement for moon operations, considerably with Japan. Maria Perino is an engineer working for Alenia Spazio of Rome, and he claims that the most important step for human expansion into space is not Mars but a permanently manned lunar base (Kallender 3). The general manager of the space systems division at Shimizu Corporation of Tokyo, Shinji Matsumato, says Shimizu has been correlating with McDonnell Douglas Corporation on the possibility of providing for a 15-person permanent crew presence by 2050 (Kallender 3).

Outlook

President Clinton’s space policy has a number one goal of “knowledge of the Earth, the solar system and the universe” with a new objective of the space program to support “environmental stewardship” (Williamson 15). In order for the terraformation of Mars to ever be considered, the most powerful office on Earth will have to endorse the endeavor.

Perhaps the only chance Mars will have to be terraformed will be after several incredible successes in the incremental space program, accompanied with the support of a revolutionary world leadership. In an age of “smaller, cheaper, faster” capable of only incremental progress, if a revolutionary project such as terraforming Mars were ever to be proposed to today’s society, it would probably be denounced as being too radical and impractical. This frame of mind shall not permanently engross our society since our fascination with Mars will undoubtedly increase with more knowledge.

POST TERRAFORMATION

Some scientists believe long-term habitability of a planet lacking plate tectonics is not probable. It has been predicted that within about 10 million years the inaccessible sediments will trap biogenic elements, surface strata would be eroded down to sea level, and chemical weathering would cause much of the atmosphere to become mineralized into the crust (Fogg 322). The degradation of ecosystems may be prevented by their evolution, for they can independently grow and change with biological innovations in their environments.

As Mars’ local industry becomes established, natives of Mars will be able to manufacture their own spacecraft for return visits to Earth or begin to terraform other satellites in the solar system such as Titan or Europa.

It is logical to assume that as the population of Mars expands with the terraformation process, the dependence of the terraformers and colonists will eventually subside from mother Earth. Bova claims that a future independent society on the Moon may choose to apply to the United
Nations for membership as an independent state. It is conceivable that an economically thriving civilization on Mars may similarly seek autonomy without reservation.

CONCLUSIONS

There are a number of barriers which conflict with the movement to terraform Mars. Conservation and terraformation appear to be at opposite ends of the spectrum partly due to the fact that the yield from terraforming Mars will only be felt in the long term. The planet may go through a metamorphosis that could be violent and contaminated, but in order to realize the benefits terraformation can give to society, one has to look hundreds of years into the future.

Space must be made more open to the public if there is ever to be enough support for the terraformation of Mars. The space program needs to strengthen its public appeal personally, socially, and economically by interacting with the average person so that she or he can realize how terraforming Mars would benefit them. Legislative obstacles will have to be overcome and budgets will need to meet cost requirements for each successive generation to fulfill.

The terraformation of Mars offers human ingenuity an opportunity for expansion. We should attempt to terraform Mars not for science or to expand our technology, but to open a new civilization. There may someday be a compelling reason to change other moons, asteroids, or planets of our solar system into habitable, life sustainable worlds for humans to prosper in, but Mars is our most promising prospect in the solar system. It is a planet which has the resources to make it self-sufficient and eventually independent from Earth, but to do this, the planet will require a huge work force numbering in the millions.

Domed or subsurface settlements or some other form of closed ecological system may be our only alternative to terraformation if we realize the cost or environmental penalties are too exhaustive. We may decide in the future not to convert the surface of Mars to resemble something we have on Earth. Instead there may be some graceful, frugal, and environmentally sound method of terraforming that we have not yet thought of.

There is a great amount of risk involved with such a huge planetary engineering mission as terraforming Mars. There is the risk of the terraformation infrastructure of getting into the wrong hands and being exploited in a harmful way. Only when we have a much better understanding of Mars should a massive alteration of the Martian environment be conducted with competence and responsibility (Sagan 346-347).

If our posterity is ever to terraform Mars, they will indeed learn more on how planets evolve and function and the endeavor will be a constant reminder of how unique our precious Earth really is. Before the terraformation of Mars is to be initiated, there will need to be one purposeful decision to entrust large resources for the project to enable each successive generation the ability to continue. Since human political institutions are temporary and consist of so many transitions, it would be very difficult to guarantee the needed maintenance and
replenishment to continually terraform Mars. When will we be ready to terraform Mars? In Carl Sagan’s words (Sagan 348):

…a useful indication of when the human species is ready to consider terraforming seriously is when we have put our own world right. We can consider it [terraformation] a test of the depth of our understanding and our commitment. The first step in engineering the Solar System is to guarantee the habitability of the Earth.

Generous harvests of technological breakthroughs, inventions, knowledge, and educational prosperity lie within our grasp. In the wake of creating another world, we may be saving another.

REFERENCES


Gabrynowicz, Joanne I., ed. Declaration of First Principles for the Governance of Outer Space Societies.


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