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Terraforming Venus: A Challenging Project for Future Colonization

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Venus is in many ways similar to the Earth, but the thick atmosphere and high surface temperature presents a tough challenge to human habitation. Several proposals have been made that it may be possible to terraform Venus, modifying the environment to make the surface more earthlike. This project would require removing or sequestering the main portion of atmosphere, to eliminate most of the "greenhouse effect" that keeps the surface temperature high. A review of several methods proposed to do this shows that this would be a difficult project; requiring an unreasonable amount of energy, or the use of highly advanced technologies. At altitudes above the main cloud layer, the atmosphere of Venus reaches a temperature and pressure comparable to terrestrial conditions, and an alternate concept would be to engineer a habitable environment at this altitude; either by floating at about 55 km above the surface, or building up structures from the surface to reach these altitudes.

I. Introduction

The surface of Venus is a hostile environment, with a surface temperature averaging 452°C, and atmospheric pressure of 92 bars of unbreathable carbon dioxide, as well as a slow rotation period, with a solar day of 117 Earth days[1-2]. Nevertheless, in many ways Venus is the Earth's closest analogue in the solar system, with a size and surface gravity similar to that of Earth, and incident solar radiation ("insolation") slightly higher than that of Earth.

Serious calculations about the feasibility of terraforming have a fifty-year history, dating back to Sagan's 1961 proposal to terraform Venus[3], and 1973 proposal to terraform Mars[4]. The term "terraforming" refers to the concept of altering a planet's environment to make it suitable for human habitat. The word was coined by SF author Jack Williamson in 1942[5]. The more general term "planetary engineering" allows for the case of engineering the environment of a planet to change it, without specifically making the final environment a replica of the Earth[6].

The standard hypothesis about the history of Venus suggests that, in the early solar system, Venus was much a more habitable planet, with a surface temperature low enough for the planet to have an ocean[7]. As the brightness of the sun increased, the amount of water vapor in the Venus atmosphere also increased, eventually culminating in a runaway greenhouse effect, in which the oceans boiled, and the surface temperature increased to the point where carbonate rocks decomposed, returning their carbon dioxide content to the atmosphere, resulting in a stable equilibrium of a high-temperature planetary surface. In a sense, then, proposals to terraform Venus are thus simply engineering attempts to return Venus to its early state.

II. Early Concepts

Sagan proposed eliminating the strong greenhouse effect at the surface by use of floating photosynthetic bacteria to reduce the infrared-absorbing carbon dioxide atmosphere to an infrared-transparent oxygen atmosphere, in order

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to produce a cooler planet that would be similar to the Earth in climate. This is possible because, although the temperature of Venus at the surface level is well above the boiling point of water, at altitudes sufficiently high in the atmosphere, the temperature moderates to a level low enough that bacteria would be able to survive. Unfortunately, this proposal, although audacious, would not work in the real world due to the thickness of atmosphere.

A review by Martyn Fogg[6] discusses the difficulties with such a simple proposal for terraforming Venus. When Sagan first proposed terraforming Venus by "seeding" algae into the clouds in 1961, Venus was though to be much more Earthlike than it is now known to be. We now know that the temperature of Venus is significantly hotter, the atmospheric pressure tremendously higher, and the chemical environment a lot harsher, than was thought in the pre-Pioneer days. Venus has simply too much atmosphere. Three decades after his original proposal, Sagan conceded that his concept for terraforming Venus with atmospheric microbes was naïve. In *Pale Blue Dot*[8] he wrote:

> *"Here's the fatal flaw: In 1961, I thought the atmospheric pressure at the surface of Venus was a few bars ... We now know it to be 90 bars, so if the scheme worked, the result would be a surface buried in hundreds of meters of fine graphite, and an atmosphere made of 65 bars of almost pure molecular oxygen. Whether we would first implode under the atmospheric pressure or spontaneously burst into flames in all that oxygen is open to question. However, long before so much oxygen could build up, the graphite would spontaneously burn back into* CO_2*, short-circuiting the process."*

Fogg also points out that, even if it were possible to engineer organisms to sequester the carbon dioxide from the Venus atmosphere, the process would take between eleven thousand and 1.1 million years, depending on how optimistic one is about how efficient photosynthesis could be made to become[6].

III. Terraforming Concepts

In the fifty years since Sagan's original concept, many other proposals for terraforming Venus have been analyzed[6,9,10]. These terraforming concepts require removal of the majority (99%) of the Venus atmosphere (and conversion of the remainder to an infrared-transparent gas).

The amount of atmosphere that must be removed is large: terraforming would require removal of about 500 quintillion kilograms of excess carbon dioxide. Proposed ways to do this include chemically combining or sequestering the atmosphere, or by physical removal technologies. The energies, and the amount of gas to be processed, are daunting, but may be achievable by an advanced civilization.

A. Chemical Sequestering

Chemically sequestering the atmosphere could be done if the carbon dioxide is combined with surface rock to form carbonate rock such as dolomite ($CaMg(CO_3)_2$), by reactions such as $CaMgO_2 + 2CO_2 \dashrightarrow CaMg(CO_3)_2$

The reaction shown requires slightly over one kilogram of $CaMgO_2$ to sequester one kilogram of carbon dioxide, and not all of the surface rocks of Venus will comprise minerals suitable for forming carbonates. It would require pulverizing the surface to a depth of at least 1 km, and possibly more, to produce enough rock surface area to convert enough of the atmosphere. It will also require a technique for producing carbonates. On Earth, this process is mediated by water. Finally, carbonates are not stable at Venus surface temperature: they decompose rapidly back to rock and carbon dioxide. Even if a method can be found to produce carbonates, it is unclear what can be done with the carbonates such that they will not decompose and release the carbon dioxide back into the atmosphere.

Alternately, the atmosphere could be converted into some other material sequestering carbon dioxide. One possibility would be to convert the carbon dioxide atmosphere into carbon and oxygen, sequester the carbon in the form of elemental carbon (in the form of graphite or "coal"), and use the oxygen to oxidize surface rocks. The mineralogy of the Venus surface includes primarily rock with iron in its +2 oxidation state, in the form of FeO. According to Venera data, FeO comprises between 7.7 and 9.3 percent of the crust of the Venus surface[11]. This could be oxidized into the higher oxidation state of Fe_2O_3, *e.g.,* $2\ FeO + O_2 \dashrightarrow Fe_2O_3$. Again, this would require pulverizing a large amount of the surface.

B. Physical Removal

An alternative concept would be to blast away the atmosphere. At the escape velocity of Venus, the minimum energy needed to remove atmosphere is about 50 MJ/kg. The energy required would be on the order of 2.5E28 Joules: equal to a terawatt of power applied continuously for 850 million years. This number is very large.

The atmosphere could conceivably be ablated away by a sufficient number of asteroid impacts. There are a number of difficulties with this proposal, however. I will assume an asteroid impact would, at best, remove the atmosphere over the region of the atmosphere for which the blast site is not below the horizon. Taking 16 kilometers as the effective scale height, this is a distance of about 440 km, or an area about 1/750th of the surface area of Venus. Thus, it would take on the average at least 750 impacts to reduce the atmosphere by a factor of e. Reducing the pressure from 92 bar to 1 bar would, by this calculation, require a minimum of 2000 impacts, even if the efficiency of atmosphere removal was perfect.

(2) Coupling of energy from the impact to kinetic energy of the atmosphere is not expected to be efficient. Most of the energy is likely to go into vaporizing the impactor, and a significant amount will be released as heat and thermal radiation. Of the energy reaching the atmosphere, some of it will heat the atmosphere, but by an amount less than the escape energy; while on the other hand, some of the atmosphere that is ejected will be ejected with more than the minimum escape energy. Hence only a small fraction of the impact energy will result in removal of atmosphere. If ten percent of the impact energy is assumed to be effective in removing atmosphere, and on the average the impactors arrive at Venus orbital velocity, which is about ten times escape energy, then each impacting asteroid will ablate away an amount of atmosphere equal to its own mass. Thus, the impact of about two million 1-km diameter asteroids, or two thousand 10-km asteroids, would be required to ablate the required amount of atmosphere. The asteroid belt is believed to contain about 10,000 asteroids of diameter greater than 10 kilometers, and the Kuiper belt and the Oort cloud many times more. Nevertheless, it is likely that a spacefaring civilization with the technology to redirect the orbits of asteroids will most likely have other uses for asteroids, and not be interested in using the asteroids as impactors.

Thus, removal of atmosphere by asteroidal impacts does not seem to be a reasonable method of terraforming Venus.

It is also reasonable to envision a several of these methods used in combination. Impacting the surface with asteroids, for example, could not only remove atmosphere directly, but would pulverize some amount of the surface, increasing the surface area available for reaction of the atmosphere to form carbonates or oxides; if the impactors contained ice, they could also add water which may enhance the formation of oxides or carbonates.

C. Condensing the Atmosphere

A final possible proposal would be to use a large shadow-shield, placed between Venus and the sun, to reduce the solar input and so cool the planet sufficiently that the carbon dioxide would condense into liquid, and then (as the pressure reduces further) freeze out in the form of carbon dioxide ice. The shield would have to be extremely light weight; presumably a technology similar to a solar sail, although much larger. It could be made of reflective material, or alternately could be diffractive or refractive, serving to scatter light away from the planet. The shield would be located at Venus/Sun L1 point (with the orbit suitably adjusted to account for solar photon pressure), or could consist of a larger number of smaller shields in a lower Venus orbit.

This proposal also has a number of problems. It takes a planet like Venus an extremely very long time to cool. The Venus atmosphere has a large heat capacity, and the Venus rocks and soil also have a very large heat capacity. It is also unclear to what extent a planet covered with carbon dioxide snow can be called "terraformed." The desired final state would be to have the CO_2 snow concentrated in some places (*e.g.*, "polar caps"), allowing other regions of planet to be temperate.

Again, the proposal to freeze part of the atmosphere could be used in combination with other techniques to reduce the amount of atmosphere; either first removing atmosphere before implementing the sunshield, or alternately implementing a sunshield to reduce the temperature in order to prevent atmosphere that is sequestered by chemical means from returning to the atmosphere.

IV. Alternate proposals

A. Floating colonies

Like earth, the temperature of the Venus atmosphere decreases with altitude above the surface, with an adiabatic lapse of roughly 7.7 °C/km. If "sea level" is defined as the altitude at which the atmospheric density is roughly that of terrestrial sea level, the problem with Venus is not that it's too hot and the pressure is too high-- the problem is the surface is too far below sea level.

A "sweet spot" exists in the atmosphere of Venus, at an altitude at which the temperature is roughly similar to that of Earth, and the atmospheric pressure is also similar to that of Earth. Figure 1 shows the atmospheric pressure and temperature in the atmosphere of Venus as a function of altitude above the surface. The atmospheric pressure is roughly equal to that of Earth sea level at slightly over 54 km above the mean surface, and the temperature is 20°C at slightly under 56 km altitude. Near and slightly above these altitudes, the atmospheric pressure and the atmospheric temperature approach those of the surface environment of Earth.

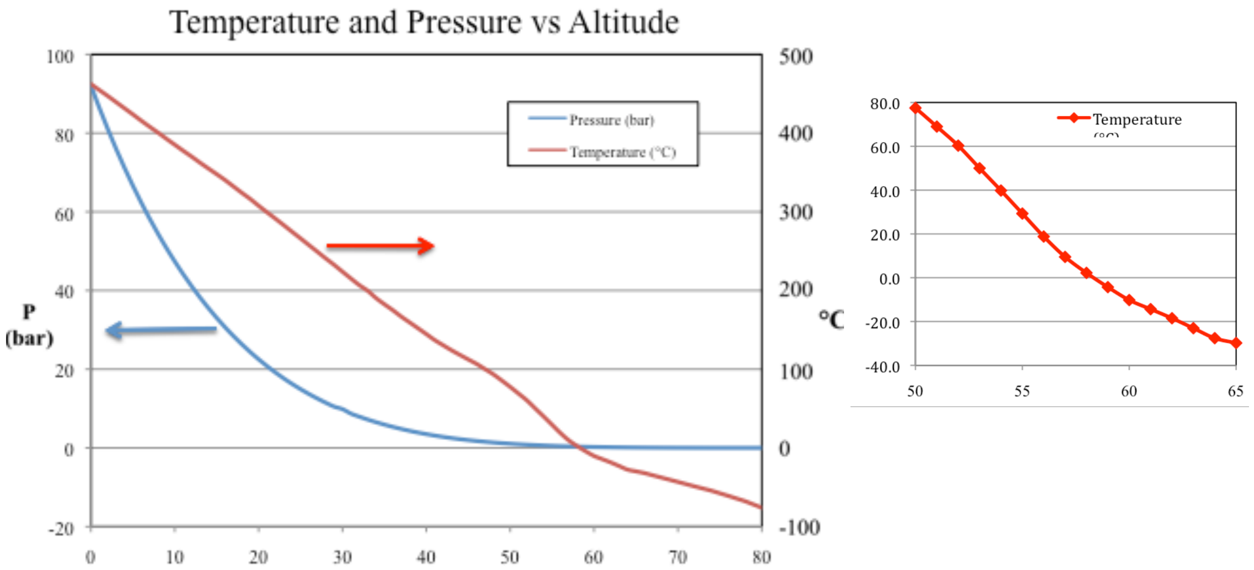

Figure 1: Pressure and temperature in the Venus atmosphere as a function of altitude above the mean surface. The inset figure on the right shows the detail of temperature (in °C) over the region from 50 to 65 km altitude.

An alternate technology for colonizing Venus is to leave the atmosphere in place, and to envision colonization at a level in the atmosphere that is above the dense lower atmosphere, and hence above the greenhouse effect.

A "near-term solution" would be to envision colonies in the form of floating habitats[7,12], taking advantage of the fact that the carbon-dioxide atmosphere of Venus is denser than the oxygen-nitrogen mixture of the Earth's environment, and hence breathable air is a gas that could be used as the primary lifting gas of balloons or aerostats, allowing the entire envelope to be used as habitat volume requiring no pressurization. Conventional proposals for "space colony" habitats have significant difficulties: gravity must be provided by engineering solutions (involving centrifugal force), and hence require significant structure, and the habitats also have to hold pressure, again requiring significant structure. Space is subject to significant amounts of ionizing radiation, including solar radiation, galactic cosmic radiation, and (for low orbits) trapped Van-Allen belt radiation, all of which require shielding consisting of many meters of regolith. Finally, all the material for a space colony must be transported in from another location, and some, the volatile resources, are relatively scarce in near-Earth space.

In this respect Venus has great advantages over conventional space colony concepts, in that the gravity is provided by the planet, radiation protection is provided by the atmosphere, and no pressurization is needed (the habitats can float at or near the one-bar level). In addition, the atmosphere contains major volatiles needed for life (carbon, hydrogen, oxygen, nitrogen, sulfur), and above the clouds the environment has an abundance of solar energy.

B. A Built-up surface

In a longer-term solution, structures could be built up from the surface to the earthlike level. A mesa extending up 55 km above the surface would reach to the point where the atmosphere is Earthlike. This could be done by "artificial mountains," built using the existing surface rocks. A difficulty here is the compressive strength-to-weight ratio of rock. For a structure made of rock that is higher than about 10 km, the weight of rock pressing down on the base will result in plastic deformation of the base.

Assuming that the rock is basalt, the possible altitude of a mountain can be calculated. The density of basalt is about 2650 kg/m^3, and the ultimate compressive strength of dry basalt is about 250 MPa[13]. From these figures, at Venus gravity of 8.87 m/sec^2, a mountain of rectangular cross-section 10.6 km high would reach its compressive strength limit at the bottom.

Higher mountains could be built if the mountain is tapered, however. An optimum area taper would result in constant stress at all points. For such a mountain, assuming 10 km as the characteristic compressive strength to weight ratio, the area of the base would have to be greater than the area of the mesa on top by a factor of $e^{5.5}$, or about 250. Thus, about 1/400th of the surface area of Venus could be made habitable by this method. Since the surface area of Venus is about 460 million square kilometers, this results in an area of about 1.9 million square kilometers available for terraforming, about twice the area of the original 13 colonies of the United States.

Schlultz[14,15] estimates the compressive strength of basalt at 450°C at 210 MPa, only slightly lower than that at 20°C. However, he points out that the actual rock structures will consist of both the intact rock and the associated fracture, faults, lithologic contacts, and other discontinuous surfaces, with effective strength less than that of intact material of the same composition, and hence intact failure strength numbers underestimate the extent and magnitude of brittle deformation. He calculates that that the weakening effects of scale will plausibly decrease the effective compressive strength to 12–63 MPa[15]. This would significantly reduce the possible mountain height, and, correspondingly, reduce the area that could be terraformed by this method to an unreasonably low number.

In the longer term, this could be done by use of technological structures, for example, a platform built up out of a truss structure. Essentially, this would be building a "shelf" at the appropriate level in the atmosphere. Iron has a ultimate compressive strength of 1.2 GPa, and a density of 7446 kg/m^3, resulting in a characteristic height of 18 km on Venus. This strength must be derated by about 15% to account for the high temperature at the Venus surface. A structure built of iron would have to have an area ratio of about $e^{3.6}$, or 37. Thus, the support beams must be 37 times greater cross-sectional area at the bottom of the structure than that at the top. This is not an implausible ratio. However, at Venus temperatures, iron (or steel) structures will be subject to materials creep at stresses well below the compressive failure limit; this would probably make iron or steel a poor material for the application.

More plausible would be high temperature composite materials, such as graphite ("carbon carbon") composite or, further in the future, carbon nanotubes, potentially manufactured from the available carbon-dioxide atmosphere.

The structural methods could be combined, with a manufactured structure emplaced on top of mountains. Emplacing a built structure on top of Maxwell Montes, at 10.4 km altitude, would be a significant help to the amount of material needed for an initial structure. In the longer term, built structure could be built on top of manufactured mountains.

C. Ecopoiesis Without Terraforming

While Venus may not be home to life in the present day, it may yet, in the future, have an atmospheric ecosystem: Venus could potentially be a habitat for life bio-engineered by humans. Although the environment would be nothing like Earth, nevertheless it could sustain an ecology of earth-derived life.

Sagan's originally proposed method was for photosynthetic bacteria that would float in the atmosphere of Venus by the technique of reproducing fast enough that vertical mixing of the atmosphere keeps a population airborne faster than Stokes settling makes them settle toward the surface. Unfortunately, some fraction of the organisms will settle or be moved by vertical convection to the lower atmosphere[16], encountering temperatures at which they will be pyrolized; if the atmosphere contains significant amounts of oxygen, they will then be oxidized, returning any sequestered carbon dioxide to the atmosphere.

Since in any case genetic engineering is required, a more reasonable solution would be to further genetically engineer plants to incorporate oxygen or hydrogen containing gas bladders, to allow them to float reliably above the high temperature lower atmosphere. This concept was originally suggested by Morowitz and Sagan[16,17] in 1967, and analyzed in more detail by Cockell[18] in 1999. Kelp, for example, is a common ocean plant that uses atmosphere-filled bladders to float in the atmosphere on Venus; the same gas would be lighter than the carbon-dioxide atmosphere.

In addition to simply producing an airborne ecology away from the Earth, for long-term habitation it is desirable that the atmosphere should contain oxygen as well as carbon dioxide. A plausible target for such terraforming would be an atmosphere composition of mixed carbon dioxide and oxygen. This would allow humans to survive outside the habitat at the earth-analogue altitude without the requirement for a pressure suit, and without carrying an oxygen supply, but only a breathing apparatus with the capability to separate the oxygen from carbon dioxide.

V. Terraforming: Additional Challenges

There are a number of additional challenges in the process of terraforming, which are of less difficulty than the main problem of reducing the temperature, but still important enough to mention.

A. Not enough water

For the terraformed Venus to not be an arid surface, we will want to import water. This is not a problem in principle– there are many icy objects in the outer solar system (and likely as close as the asteroid belt). The objective would be not to mimic the Earth, in which most of the water is in the deep ocean, but make fewer, shallower seas.

However, it must also be noted that water is a potent greenhouse gas, and the runaway greenhouse effect that is believed to be primarily responsible for the high temperature of Venus was originally triggered by water vapor in the atmosphere. It will be a delicate problem to balance the instability of the greenhouse effect of water in the atmosphere with the desire for water in the ecosystem.

B. Sulfuric acid clouds

Today's Venus has clouds of sulfuric acid, which is both corrosive and hazardous.

This, however, is not likely to be as much of a problem as it appears, since sulfuric acid reacts with rocks much more readily than carbon dioxide. It should be possible to sequester the sulfuric acid by reacting it with the rocks and soil to form sulfate rocks (*e.g.*, gypsum). This will be a far lesser problem than that of reacting the atmosphere.

C. Moderating the temperature

Venus today is reflective: the clouds reject most of the sunlight. If the clouds were removed, even with the density of the atmosphere reduced, the surface of Venus will still be very hot (about 65°C, assuming that the greenhouse effect is ameliorated, and that terraforming resulted in the same albedo and emissivity characteristics as the Earth.) In itself, this could lead to a runaway greenhouse effect due to water vapor, and in any case would be too hot to be habitable. Thus, for terraforming systems relying on removing or sequestering atmosphere, some additional cooling in the form of adding reflectivity to the atmosphere, or orbital sun shields, will be desired.

D. Venus day is too long

The solar day is 117 Earth days, which is inconveniently long for terrestrial ecosystems.

Would it be possible to increase the spin of the planet? Although this may be possible in principle using low-angle asteroid impacts[19], the required energy is huge, and even if it could be applied, this much energy would be catastrophic to the surface.

A better solution would be to live with the 117-day day/night cycle. One possibility would be to illuminate surface with reflected sunlight from mirrors (or "soletta") in Venus orbit[20]. The minimum amount of light would be a sufficient intensity to be sufficient for human visibility, and a more desirable intensity would be a sufficient amount for plant growth, although an alternate would be to use plants adapted to growth in a 117 day cycle; either naturally existing plants or plants engineered to this specification. It would be desirable that the amount of light from such a soletta not add a large amount of power to the ecosystem, in order to avoid excess heating; the mirrors could be dichroic, to reflect only selected wavelengths to the surface.

A related problem is the day-night temperature swing that is likely with a 117-day cycle. It is desirable that these not be too large. This may be ameliorated to some extent by atmospheric convection.

VI. Long Term Goals

In the longest term, it would be desirable to fully terraform the planet, most desirably even adjusting the rotation to produce a diurnal cycle that is closer to the Earth's 24-hour day. This would require control of energies and processing of materials at levels beyond that which is reasonable using currently plausible technology. Future technological advances may change this status.

VII. Why Terraform?

Even if it is possible, why should humanity choose to engage in such an enormous and long-term project?

Classically, two reasons have been given as reasons for terraforming:

- The imperative of life to expand into new territory
- A new home for humanity could preserve life in the event of global catastrophe

Historically, the settling of new lands has always led to great cultural and economic advances. In addition, however, terraforming other planets will give us scientific knowledge about our own planet. We are inadvertently reforming the Earth by technology anyway; it would be useful to learn about what we are doing on a planet where we can afford to make mistakes. Developing terraforming technology will help us develop the understanding and the technologies to address problems we have created in the Earth's environment, and produce other valuable spin-off technologies.

In addition, a long-term project such as terraforming Venus would serve as a focus to promote world-wide teamwork for a worlds-wide goal: a peaceful project for all of humankind-- "the moral equivalent of war." It would be a major economic venture for the Earth's people. Terraforming efforts would excite the human population in planetary engineering, space exploration and colonization.

And, finally, terraforming would be worthwhile because it is a great technical challenge that appears to be possible and is within our reach.

VIII. Conclusions

Venus, Earth's sister planet, is in many ways the most Earthlike planet in the solar system-- and also very different from Earth. The surface of Venus presents a tough challenge to exploration and colonization, but the atmosphere of Venus above the main cloud layer is ideal in temperature and pressure for human life-- far better than Mars.

Many proposals have been made that it might be possible to terraform Venus, to turn the surface into an analogue of Earth, or a minimum a habitable planet, but analysis shows that this would be a difficult project; requiring considerably more modification to the environment than the initial proposal to simply add photosynthetic bacteria to the atmosphere.

A proposal is made here that it might be possible to effect many of the results of terraforming simply by addressing the problem of living in the region of the atmosphere at about 55 km above the surface, where the atmospheric density and temperature approximate that of Earth.

Let's colonize Venus!

Acknowledgements

In the fifty years since Sagan's original proposal, a large amount of analysis has been done on many terraforming concepts, far too much to reference even the high points in a brief review. The author apologizes to the many researchers whose work and ideas has not been discussed, or been only superficially discussed here, and directs the interested readers to Martyn J. Fogg's 1995 textbook, *Terraforming: Engineering Planetary Environments*, which contains a far better bibliography and list of sources, or the 2009 book *Terraforming: The Creating of Habitable Worlds* by Martin Beech, which presents a less technical review of the subject.

References

1. D. M. Hunten, L. Colin, T. M. Donahue, and V. I. Moroz, eds., *Venus*, University of Arizona Press, 1983.
2. S. Vougher, D. Hunten, and R. Phillips, eds., *Venus II,* University of Arizona Press, 1997.
3. C. Sagan, "The Planet Venus," *Science, 133,* 1961, pp. 849-858.
4. C. Sagan, "Planetary Engineering on Mars," *Icarus*, *20*, 513, 1973, pp. 514.
5. J. Williamson (Will Stewart), "Collision Orbit," *Astounding Science Fiction,* July 1942, p. 80 ff.
6. M. J. Fogg, *Terraforming: Engineering Planetary Environments*, SAE Press, ISBN 1-56091-609-5, 1995.
7. D. H. Grinspoon, *Venus Revealed,* Perseus Publishing, 1997.
8. C. Sagan, *Pale Blue Dot*, Random House, New York, ISBN 0-679-43841-6, 1994.
9. J. E. Oberg, *New Earths*, Stackpole, 1981; New American Library, 1983.
10. P. Sargent, *Venus of Dreams*, Bantam Spectra Books, New York, 1986.
11. K. Loders and B. Fegley Jr., *The Planetary Scientist's Companion*, Oxford, 1998*,* pp 108-124.
12. G. Landis, "Colonization of Venus," presented at Conference on Human Space Exploration, Space Technology & Applications International Forum, Albuquerque NM, Feb. 2-6 2003; *AIP Conference Proceedings Vol. 654,* pp. 1193-1198.
13. D. X. Gu, W. Tamblyn, I. Lamb, and N. Ramsey, "Effect of Weathering on Strength and Modulus of Basalt and Siltstone," ARMA 08-207, 42nd US Rock Mechanics Symposium and 2nd U.S.-Canada Rock Mechanics Symposium, San Francisco, June 29- July 2, 2008.
14. R. A. Schultz, "Strength and Deformation Properties of Basaltic Lava Flows on Planetary Surfaces," Twenty-Fourth Lunar and Planetary Science Conference. Part 3, March 1993, pp. 1263-1264,
15. R. A. Schultz, "Brittle Strength of Basaltic Rock Masses with Applications to Venus," *J. Geophys. Res., 98(E6)*, 1993m doi:10.1029/93JE00691, pp. 10,883–10,895.
16. C. Sagan, "The Trouble with Venus," *Planetary Atmospheres, Proceedings from 40th IAU Symposium*, International Astronomical Union Symposium No. 40, Marfa, Texas, Oct. 26-31, 1969, pp. 116-127.
17. H. Morowitz, and C. Sagan, "Life in the Clouds of Venus?" *Nature, 215*, 16 September 1967, pp. 1259-1260.
18. C. S. Cockell, "Life on Venus," *Planetary and Space Science. 47*, 1999, pp. 1487-1501
19. P. Birch, "How to Spin a Planet," *Journal of the British Interplanetary Society, 46*, 1993, pp. 311-313.
20. K. A. Ehricke, "Contributions of Space Reflector Technology to Food Production, Local Weather Manipulation and Energy Supply, 1985-2020," *Journal of the British Interplanetary Society*, *34,* 1981, pp. 511-518.