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TERRAFORMING VENUS QUICKLY

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Venus would be Earthlike if it were cooler, had a less dense O_2/N_2 atmosphere and a shorter day. Previous terraforming proposals have been incomplete or have described very slow processes. This paper addresses the problems of terraforming Venus quickly. It is shown that a sunshade can be used to cool Venus, causing the CO_2 to precipitate out of the atmosphere and gather as seas in the lowlands. A thermally insulating cover will prevent re-evaporation. Venus can then be provided with water by impact with an ice-moon, moved from its orbit with energy from solar mirrors or a light-sail windmill. A soletta can provide a 24-hour cycle of day and night, while vegetation on the land and in the sea produces a breathable atmosphere. Colonies floating at the one-atmosphere level will permit almost immediate habitation. It is claimed that terraforming could be completed in under ~200yr.

1. INTRODUCTION

Venus has long been thought of as Earth's sister planet. In size and constitution it is very similar ($R_{♀}$=6056 km, $R_{\oplus}$=6376 km). It is a rocky planet, neither a gas giant nor a ball of ice. Consequently, its surface gravity is also Earthlike ($g_{♀}$=8.88ms^{-2}; $g_{\oplus}$=9.81ms^{-2}). For these reasons it is a prime candidate for future colonisation. Unfortunately, Venus differs from Earth in a number of important ways, which appear to make immediate colonisation without terraforming impracticable.

First, Venus is very hot. The temperature at the surface is about 730 K, compared to 300 K on Earth. This is partly because Venus is so much closer the Sun (0.72 AU) and partly because of the greenhouse effect of the dense atmosphere.

Second, Venus has a dense atmosphere, primarily composed of carbon dioxide. The pressure at the surface is about 95 bars.

Third, the Venusian day is 127 Earth-days long.

Further problems arise from minor atmospheric constituents, including sulphur dioxide and carbon monoxide. The clouds are composed of hot fuming suphuric acid, one of the most corrosive substances known. There is no free oxygen, and perhaps one part in a thousand of superheated steam. There is little water.

Venus has frequently and justly been compared to Hell.

Terraforming is defined as making a planet over into an Earthlike planet. That simple definition hides some subtleties. A *planetological terraform* leaves a fully Earthlike planet, stable over geological eras without further human intervention. Few if any proposals have successfully addressed the challenge of a *full* planetological terraform. A *habitable terraform* leaves a planet adapted for human habitation, but uses artificial shortcuts and needs maintaining. It is simpler, but perhaps less satisfying.

In this paper I attempt to present a fairly complete and economically viable scenario, with emphasis on the colonisation of Venus during the next few centuries [1]. I have deliberately sought techniques that minimise the terraforming time and cost, and reach a habitable terraform as *quickly* as possible. Nonetheless, terraforming does not cease once full habitation has been accomplished and the final state is as close to the full planetological terraform as may be found in the literature.

Early terraforming proposals [2-4], in suggesting the use of photosynthetic algae as the main terraforming technique, appear to have been overly sanguine. It is now considered that merely seeding the clouds with algae is not enough.

Later proposals [5-7] have attempted to remedy some of the defects, but most deal with long timescales (thousands of years) and often do not permit colonisation until terraforming is almost complete. Despite their planetological bias, they do not entirely succeed in eliminating the need for artificial upkeep.

It has been suggested [8] that terraforming is more a scientific and engineering challenge than a basis for colonisation, and thus long timescales may not be prohibitive. There is some justice in this claim. Space colonies of considerable size can be built cheaply and quickly; they are likely to be safer, more convenient and more comfortable than natural planets [9-11]. In another paper in this issue [12] I show how even planetary-sized habitats can be constructed without long-winded conventional terraforming.

But the viability of such protracted projects must remain in doubt. Economic and practical considerations cannot wholly be neglected.

First, maintaining sympathy and funding for a terraforming project without practical benefit over thousands of years would be enormously difficult.

Second, overlong projects are apt to be overtaken by events before their completion. Where a market for habitable planets or raw materials exists, slow terraforming techniques will be replaced with colonisation by faster means. In the distant future, where such projects are often placed, the virgin planets, sun, solar system, galaxy, will long since have been drastically re-engineered.

Third, long-term projects still have to be paid for. Economic viability is seriously compromised if the initial investment is not returned within ~30 years. Delay increases the cost in the amount of interest that would have accrued had the capital been otherwise invested. Over fifteen years this about doubles the cost. Over fifteen *thousand* years the effective cost of a project would increase astronomically.

It may be argued that slow terraforming may still be carried out for scientific purposes, even if it is quite uneconomic for colonisation. However, the same arguments apply. We cannot justify a large investment of scientific effort into a project that will produce only limited scientific results a long time in the future. We can learn more by putting those resources into more fruitful fields.

Of course, this is far from suggesting that it is foolish to use such project ideas as academic exercises and thought experiments. On the contrary, they remain fascinating, informative and valuable.

Ideally, a project should not now exceed a working lifetime, should be able to fund most of its capital investment out of revenue and should have an economic breakeven well under thirty years.

This paper thus addresses the problem of terraforming Venus *quickly*, in the hope of finding solutions that are economically and psychologically sound as well as scientifically sound.

Advanced space industrialisation is surely a prerequisite to the terraforming of Venus. A Gross Space Product ≥ 1T£yr^{-1} (1980 £'s) can be assumed by the mid-21st century. However, the terraformed Venus is unlikely to be fully occupied until the population of the space colonies reaches $\sim 3\times10^{10}$ and demand is sufficiently high, perhaps ~150 years from now [12]. Costs in this paper are compatible with such a development of space industrialisation [12].

The value of a fully terraformed Venus, in today's terms, is likely to be in the region of 250T£, about the same as the Gross World Value (GWP ~ 10T£yr^{-1} × 25 yr, or £50,000 per person). In the space colony market it might be worth considerably more.

A terraformed Venus may need maintainance, but this will not be a problem on an occupied planet; the annual cost will be no more than a small fraction of the cost of terraforming.

Although we should not take such figures too seriously, they give a useful indication of the time scales and costs to be met. An important *caveat*: when dealing in amounts $\gg$100G£ we can afford enormous amounts of research and can expect fantastic economies of scale. Very cheap methods of large-scale manufacturing in space are likely to be developed; the overall costs of terraforming may be greatly reduced.

Although this proposal is justified more by the potential for colonisation than by scientific merit, it is important to realise that the planetological terraform is not obviated by the artificiality of some of the human habitats, any more than cities on Earth make Earth any less Earthlike.

2. TERRAFORMING REQUIREMENTS

To terraform Venus we need to:

1) Cool the planet to ~290K.

2) Reduce the atmospheric pressure to ~1 bar, removing the excess CO_2 (~93 bar) and other poisonous atmospheric constituents, and providing ~0.24 bar of breathable oxygen.

3) Reduce the length of the day to ~24 hour.

4) Provide sufficient water for a water-table and seas.

A variety of techniques for fulfilling these requirements will be considered, and then combined into a single scenario.

TABLE 1: *Time taken for Venusian Atmosphere to cool.*

STAGE	CONDITIONS	TIME TAKEN
1	730K→304K;95bar	5.6yr/ε(1) or 58yr(2)
2	304K;95bar→76bar	7.4yr/ε or 22yr
3	304K;76bar→217K;7bar	48yr/ε or 94yr
4	217K;88bar liquid→solid	17yr/ε or 17yr(3)
5	217K;7bar→192K;2.8bar	9.2yr/ε or 9yr(4)
6	192K;800mb→142K;3mb(6)	3.7yr/ε or 4yr(5)
TOTAL OF STAGES 1 TO 5 :		87.2yr/ε or 200yr

(1) At constant emissivity (2,3,4) At ~160, 126, 100 Wm^{-2} (5) At ~50Wm^{-2} (6) Optional stage to reduce CO_2 to ~3mbar

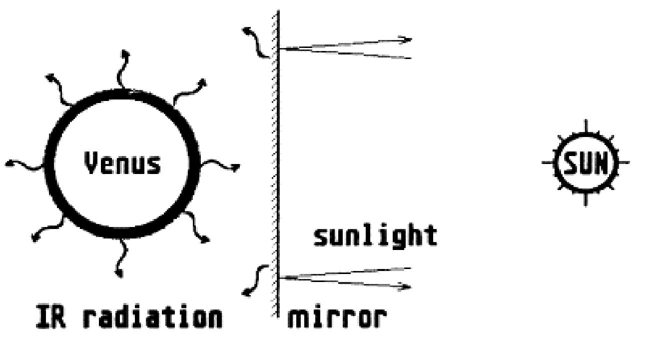

Fig. 1. Sunshade mirror to cool Venus.

3. COOLING VENUS

3.1 Use of a Sunshade

If one positions a large mirror between Venus and the Sun the planet will radiate to deep space and cool down (Fig. 1). Such a mirror, although large, can be very light and flimsy; because it merely reflects light away from the planet it does not need to be optically flat.

Solar sail material, an aluminised film of $\sim 3\times10^{-4}\,\mathrm{kg\,m^{-2}}$, would be suitable. It would have to cover an area $\sim 2.2\pi R_♀^2$ $\sim 2.5\times10^{14}\,\mathrm{m}^2$ and would have a total mass $\sim 7.6\times10^{10}$ kg. It would be manufactured in space, using lunar or asteroidal materials and cost about as much as the Apollo programme (Section 9 goes into more detail).

Similar suggestions have been mooted elsewhere [6, 13-16].

After the deployment of the sunshade one must wait rather a long time for Venus to cool down. However, other terraforming tasks may be carried out at the same time.

3.2 Simplified Cooling Scenario

A simplified scenario for the cooling process after sunshade deployment is as follows:

The temperature of the atmosphere falls to the critical temperature of CO_2 (304 K). It then starts to rain liquid CO_2; and ~20 bar precipitate until the CO_2 pressure reaches 74 bar, the critical pressure, when the temperature can fall again.

The CO_2 rain continues as both temperature and pressure fall. It drains into the lowlands and forms CO_2 seas. At the triple point (217 K and 5 bar CO_2) the seas begin to freeze.

Once the seas have frozen over the temperature falls again, and the rest of the CO_2 precipitates as snow. At a temperature of about 192K only ~0.8 bar of CO_2 and the inert gases—principally ~2 bar of nitrogen—are left in the atmosphere.

Now the frozen carbon dioxide oceans can be covered over and the temperature brought back up to ~290K.

Table 1 gives the length of time taken for each phase of the cooling process. The calculations are given in the Appendix. The most uncertain value is that for stage 1. Initially the planet radiates at only 160Wm^{-2}, due to the sulphuric acid clouds and the greenhouse effect of the dense CO_2. But convection currents and the precipitation of aerosols during cooling will reduce the atmosphere's opacity, so radiation rates may increase. Clearly, the emissivity should be as high as possible and the heat should come from as deep in the atmosphere as possible.

The maximum cooling time obtains when radiation from the cool top of the atmosphere dominates, corresponding to ~160Wm^{-2}. The minimum time obtains when the emissivity is unity at each stage. We have:

$$90\ \mathrm{yr} \lesssim \text{'total cooling time'} \lesssim 200\,\mathrm{yr}$$

Relief on Venus is hydrostatically compensated, a thin crust in equilibrium on a molten interior. Any extra weight on the sea-floors will immediately cause them to sink and push the continents upwards. This is a rapid process, which will cause widespread earthquakes, and may trigger volcanic eruptions, during the rain-out of the CO_2. Some additional outgassing is possible. Because the seas are deepened under their own weight, they will cover a smaller area than one would otherwise expect. For some time afterwards, minor earthquakes may occur, as the residual strains of this process are released.

Stage 4 can be eliminated if the CO_2 ocean freezes over from the top, due to the presence of a layer of water-ice floating on the surface, and traces of water in the CO_2 snow.

During stage 5, CO_2 snow that falls on the land will no longer drain into the oceans, where it is wanted. Although the residual warmth of the surface rocks will cause some of it to resublime, it will be necessary to warm the land slightly throughout this phase, using $\sim 10^{12} m^2$ of solettas.

It has been assumed that the heat of the Venusian crust will not substantially increase the cooling time. This is justified by the limited thermal conductivity of rock, which restricts crustal cooling to a relatively thin surface layer ~30m thick, increasing the atmospheric cooling time by ≤3%. This will be true unless intensive fissuring or soil permeability permits liquid CO_2 to percolate to greater depths over a large fraction of the planet's surface, which on present evidence seems unlikely.

Some CO_2 will be absorbed by the surface rocks through reactions like $CaSiO_3 + CO_2 + H_2O \rightarrow CaCO_3.H_2O + SiO_2$, but it is not anticipated that this will significantly reduce the quantity of atmospheric CO_2 over the short timespan of this scenario.

After cooling the atmosphere will consist of about 2 bar of N_2, about 0.8 bar of CO_2, about 0.5 mbar of CO (~250 ppm), and traces of argon and other inert gases. The CO_2 will in due course be converted into oxygen, and the carbon monoxide must be removed, in order to produce a breathable atmosphere.

3.3 Heat Pipes to Speed Cooling

To cool the planet more quickly high temperature heat must be brought up to the radiating regions, at about the 1 bar level, using heat pipes (Fig. 2).

A working fluid condenses from vapour at the top end, releasing heat to the ambient atmosphere. The condensed liquid runs down channels leading back to the base of the heat pipe, where it is passes through nozzles, boils and is warmed by the ambient atmosphere. The vapour then expands through a jet nozzle and streams at high speed up the pipe.

At the base and the head the pipe spreads out into a complex fluted surface, to permit efficient heat exchange with the atmosphere by convection.

The working fluid should have a high latent heat and change state under high pressure at the temperatures of interest. Water is suitable at high temperatures ≥400K, but at lower temperatures its vapour pressure is rather too low. The temperature range for ammonia is much lower, ~240K to ~400K. Ammonia-water mixtures, shifting from 100% water at ~600K to 100% ammonia at ~400K, can maintain the efficiency of the heat pipe as the atmosphere cools, although below 400K the heat flow will fall, due to the drop in vapour pressure.

An initial throughput of $\sim 10^{11} kg\,s^{-1}$ of water is required to increase planetary heat loss by a factor of four. At an average flow speed $\sim 500\,m\,s^{-1}$ the working fluid can cycle in ~250 s. The total mass of water required is therefore $\sim 2.5 \times 10^{13}$ kg, which at $\sim 10p/m^3$ costs ~2.5G£. The walls of the pipe must withstand the difference in pressure between the working fluid and the ambient atmosphere. This is equivalent to constructing

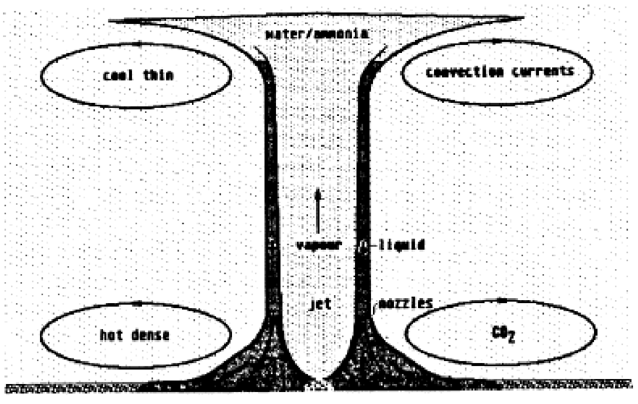

Fig. 2 Heat pipes to speed cooling

an empty volume of up to $\sim 2.5 \times 10^{10} m^3$ within the ~95 bar lower atmosphere, which can be achieved with $\sim 2.5 \times 10^9 m^3$ of fused rock, costing ~5G£. Thus the cost of the heat pipes may be ~10G£ initially, increasing to ~100G£ at ~270K, below which temperature they cease to have a major effect.

4. WATER FOR VENUS

4.1 The Need for Water

The amount of water present on Venus is not well established. The data available are contradictory, or indicative of wide variations from place to place, ranging from the equivalent of ~1 cm of liquid water to ~1 m. It is not known how much of this would be soaked up by the soil, nor whether a true water-table and open water could form. An Earthlike atmosphere would by itself need to contain some 10 cm equivalent.

Clearly, if Venus is to become pleasantly Earthlike, more water will be needed.

4.2 Water from other Venusian Sources

Sulphuric acid from the clouds will provide water by reactions like $H_2SO_4 + MgSiO_3 \rightarrow MgSO_4 + SiO_2 + H_2O$. However, there is probably only about 1 mm of water locked up in sulphuric acid, so these reactions, and similar ones for other acids such as HF and HCl, will be important only as mechanisms for removing these corrosives from the atmosphere.

Outgassing from the crust, induced by the hydrostatic loading as CO_2 drains into the seas, may lead to an increased availability of water, though at present this is hard to quantify.

4.3 Water from Imported Hydrogen

The outer planets have an abundance of hydrogen which could be brought to Venus and combined with oxygen from the indigenous CO_2 to make water.

The technique of mining planetary seas and atmospheres by means of Orbital Rings [17-19] is addressed in Ref. 12. Here we simply note that sleds on an eccentric orbital ring, dipping into the atmosphere of a gas-giant like Uranus, could scoop up quantities of its atmosphere—principally hydrogen—and dispatch them to Venus for an energy cost $\sim 2.5 \times 10^8 J kg^{-1}$. The energy could be obtained by dumping material from nearby moons onto the planet via the Orbital Ring [19].

A mass throughput $\sim 10^{-5} kg\,s^{-1} kg^{-1}$ could be achieved. Thus the cost of H_2 throughput might be $\sim 5 \times 10^5$ £/kgs^{-1}. Over a lifetime of 30 years, the cost of delivered hydrogen becomes $\sim 5 \times 10^{-4}$ £kg^{-1} and the cost of water around one tenth as much. Thus over Venus' surface water would cost $\sim 25\,T£\,m^{-1}$.

Water sent directly from the moons by a similar method might cost several times as much.

This technique would be obviously be useful for the provision of water to colony sites on Venus—as for space colonies—for local consumption and irrigation, at a very acceptable cost ~10p/m^3. But it seems to be too slow and too expensive for the full provision of oceans and water tables for the whole planet *prior* to colonisation.

The same methods can be used to *export* excess nitrogen and CO_2 from Venus, at a delivered cost under 10p/tonne or 250T£ bar^{-1}. Water arriving from the outer system will have enough energy to launch up to ten times its own mass, in exchange, from Venus to space habitats throughout the inner system. Both during and after terraforming this can be expected to be a profitable trade for Venus.

4.4 Water from an Ice-Moon

Ice-moons and comets in the outer system have an abundance of water. If we crash a large enough ice-body onto Venus we can provide sufficient water for terraforming in one go.

4.4.1 Gravity-assisted Rapture of Ice-Moon

We consider ejecting one of Saturn's moons—Enceladus or Hyperion—from the Saturnian system by gravity assists from the neighbouring moons towards Jupiter, which can swing its trajectory towards the planets of the inner system. The moon could be dispatched from Jupiter to Venus directly, or *via* Mars or Earth encounters to reduce the impact velocity. The journey time after leaving Saturn would be about 15-20 years, and times of best opportunity will occur every 20 years.

To begin the gravity assist manoeuvres the moon must be brought near to another massive body (Enceladus to Tethys, Hyperion to Titan). The velocity change for a semi-adiabatic manoeuvre (circular orbit at r_1 → elliptical orbit between r_1 and r_2) is about the same as a ballistic transfer without circularisation, provided that the initial and final radii are not too different:

$$\Delta V = \tfrac{1}{2} V_1 \times (1-(r_1/r_2)^{\frac{1}{2}})$$

For the cases considered here $\Delta V/V_1 \approx 0.050$. We can summarise the choices as:

Enceladus: Diameter 500km → 140m water over Venus
$v_{orbital} = 12.6\,\mathrm{km\,s^{-1}}$
$\Delta V_{\rightarrow Tethys} = 0.63\,\mathrm{km\,s^{-1}}$ $(r_1/r_2 = 0.808)$

Hyperion : Diameter 310km → 34m water over Venus
$v_{orbital} = 5.06\,\mathrm{km\,s^{-1}}$;
$\Delta V_{\rightarrow Titan} = 0.25\,\mathrm{km\,s^{-1}}$ $(r_1/r_2 = 1.214)$.

4.4.2 Steam Rocket Powered by Solar Furnace

To give an ice-moon a velocity change of 250ms^{-1}—630ms^{-1} we may use solar power to drive a steam rocket. A solar furnace (mirrors concentrating the Sun's rays) will vaporise water-ice and can heat the steam up to ~6000K, at which temperature the jet velocity can be up to ~3.7kms^{-1}.

Suppose we ask for 90% of Hyperion to be delivered to Venus. We let the jet velocity be 2.5kms^{-1} and require that $\Delta V = 250\,\mathrm{ms^{-1}}$ be built up in 30 years. Then the acceleration $a = 2.5\times10^{-7}\,\mathrm{ms^{-2}}$. Since the mass of Hyperion $\approx 1.5\times10^{19}$kg, this requires 10^{16}W of heat, supplied over half of each orbit. During the other half orbit the heat is used to vaporise water (2MJkg^{-1}, equivalent to a speed of 2kms^{-1}) and store the low pressure steam in a chamber at the heart of the ice-moon.

For navigational manoeuvres during fly-bys the acceleration can be increased markedly by storing steam under pressure at the moon's core, then releasing it instantaneously at perigee.

At Saturn the solar flux is only 15Wm^{-2}, so the mirror area required is about 6.5×10^{14} m^2, several times the area of the sunshade mirror. This means a cost ~200G£, but the mirror could be reused at Venus, or for space colonies elsewhere.

To reduce the mirror area one might consider using subsidiary mirrors near the Sun to send more power outwards. But the total mirror requirements are only reduced this way if the power exceeds $L_\odot(R_\odot/4d)^2$, which at the distance of Saturn (1.43×10^{12}m) is 6×10^{18}W, rather more than is needed.

4.4.3 Steam Rocket Powered by Light-Sail Windmill

Instead of a solar furnace we could use power from a light-sail windmill [19] close to the Sun. Such a windmill would be used to launch pellets outwards at high speeds; the pellet stream would supply power throughout the solar system, and be used to propel interplanetary and interstellar spacecraft. If such a pellet stream is used to power the steam rocket, jet velocities considerably in excess of 3.7kms^{-1} are possible, though perhaps not desirable for small velocity changes.

A power capability of ~10^{18}W could probably be provided for ~200G£ (a light-sail windmill with $\rho_a = 3\times10^{-4}\,\mathrm{kgm^{-2}}$ at 1£kg^{-1} will give about 2×10^{7}W£$^{-1}$) and could produce the required $\Delta V = 630\,\mathrm{ms^{-1}}$ for Enceladus in about a year.

Since the windmill system would be used principally for other projects the cost to the Venus terraforming project might be ~20G£, a rather small amount. Other works on the ice-moon, including cutting and lining ducts, chambers and rocket nozzles, and a ~100km^2 colony for the work-force of ~10^5, might come to ~100G£.

4.4.4 Other Gravity-assist Possibilities

There are many other gravity-assist possibilities, which have not been investigated in detail.

Before the Voyager fly-bys, the diameter of Hyperion was believed to be an ideal 500km. Now, at only a quarter the volume, it may no longer be enough for terraforming Venus, though one might still consider using it to increase the water inventory of Mars.

The Uranian moon Miranda is a good alternative, although the transfer from Uranus to Jupiter via Saturn would of course take longer. Other moons are too big or too small.

At the expense of additional transfer times, more complex gravity-assist scenarios are available which could reduce the propulsion requirements further. For example, if one moves a smaller moon into the orbit of the desired moon, it can with multiple passes extract the latter from its orbit. And an even smaller moon can extract the first. In fact, a cascade of gravity-assist manoeuvres with bodies of progressively larger mass can amplify an initiating manoeuvre by an arbitrarily large factor. Theoretically, one could flick a pebble out in the asteroid belt and end up dumping Mars into the Sun—or moving Venus away from the Sun for complete planetological terraforming.

4.4.5 Impact of the Ice-Moon

If the ice-moon were delivered to Venus before the planet was cooled or colonised it could be allowed to impact at ~30kms^{-1} on a direct trajectory from Jupiter. It would heat the 95 bar atmosphere to ~10^4K and ionise it. After ~4 days, it would cool quickly; in a week to ~5000K; in a year to ~600K, when rain-water would wash the atmosphere clean.

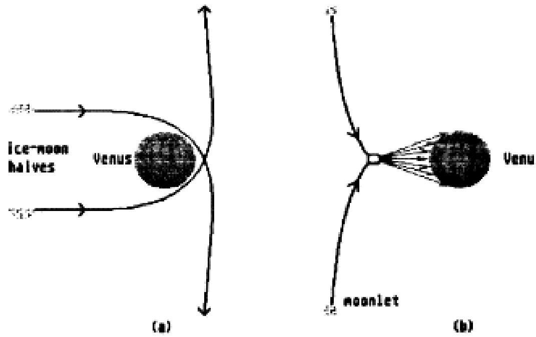

Fig. 3. Ice-moon trajectories near Venus

A problem with adding water at this stage is that it would rain out first and form water oceans *under* most of the carbon dioxide. After covering the CO_2 it would then be necessary to drill holes through down to the aquasphere to release the water. Also, the full time taken to transport the moon would have to be added to the total terraforming time.

However, if the ice-moon were delivered just after the atmosphere had been cooled and the CO_2 oceans covered no time would be lost.

If the ice-moon then hit at $\sim 30 \mathrm{kms}^{-1}$ far too much energy would go into the much thinner atmosphere. But additional gravity-assist passes of the inner planets could reduce the impact velocity to around $12\,\mathrm{kms}^{-1}$, when a temperature of $\sim 10\,000$K would again result.

Trajectories near Venus (Fig. 3) could be chosen to mitigate the effects of icefall. Prior to encounter, the ice-moon would be split in half. Each half would swing by the planet over either pole, into an orbit around the Sun, like that of the planet, but inclined out of the ecliptic (Fig. 3a). They would return to the vicinity of Venus every 112 days—half a Venus year. If the ice-moon were further divided, icefall could be extended, with a pair of moonlets colliding just short of the planet every 112 days (Fig.3b). The hot gas and debris would spread out in a jet and cool, most of it hitting the planet directly. Only a small fraction of the rest would have enough energy to escape Venus altogether.

The impact of the whole ice-moon Enceladus would be equivalent to an explosion $\sim 10^{12}$MT. Nevertheless, the blast overpressure with these trajectories would only be ~2 bar at the planet's surface. If there are more than ~10 moonlet pairs the blast should not be a problem, even on an inhabited Venus.

Shielding the planet from the flash is more important. If the planet is enclosed in a reflecting canopy the thermal radiation will be effectively excluded. A simple solar sail mirror would be vaporised and rendered ineffective; but a carbon-backed high-temperature film, cooled by the evaporation of a bed of water, could survive. Air trapped beneath the canopy will insulate the surface from the hot atmosphere, because it is stable against convection and the thermal conductivity of air is low.

After the flash, the atmosphere will cool quickly until the rain begins. Calculations are presented in the Appendix.

Now if the entire ice-moon were deposited at once the atmosphere would contain ~10 bar of water vapour, starting to condense at ~600K. With heat pipes to maintain the radiating temperature, the precipitation of ~100m of water would take as little as 2 years. The climate would not be hospitable.

But if only ~1% of the ice-moon were deposited at a time, condensation would commence at only ~320K, with ~1 m of water precipitating in ~70 days. Although the climate might be very hot and humid, it would not be unbearable. If the canopy is set high in the sky, the climate below may remain comfortable throughout icefall and the subsequent rains.

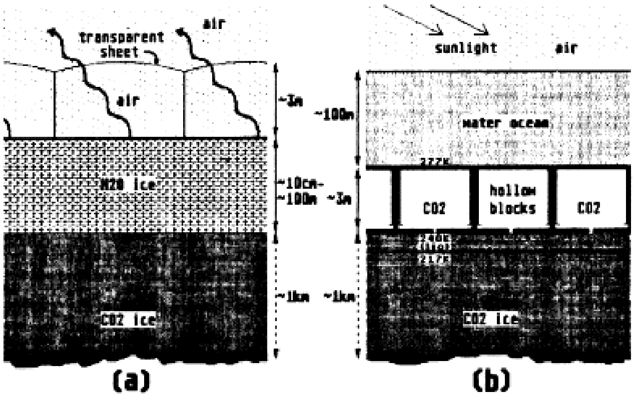

Fig. 4. Thermally-insulating covers for carbon dioxide oceans (a) Cheap short term; (b) Longer term.

5. COVERING THE OCEANS

Carbon dioxide, precipitating out of the Venusian atmosphere, forms oceans over ~70% of the planet's surface. This CO_2 must be covered and thermally insulated to prevent re-evaporation, before the planetary temperature can be allowed to rise again to ~290K, or warm water allowed to drain onto it.

Figure 4 shows two possibilities. If the full Sun shines only on the land or inhabited colonies, the air above the oceans will be cold and thermal radiation to space from the surface will keep the temperature below 200K. No cover would then be needed. If the air is warmer a cover of inexpensive transparent silica or plastic sheeting $\sim 100\,\mathrm{g\,m}^{-2}$ could be used, costing only ~5T£ over the entire planet. But deposition of water would have to be carefully controlled, especially after icefall.

The second type of cover might be expected to cost ten or twenty times as much and would be difficult to fund prior to colonisation. As a semi-permanent cover, using a stable base of very light hollow blocks or foamed rock (density $\sim 20\,\mathrm{kg\,m}^{-3}$), it would permit sunlit seas of liquid water for photosynthesis.

A mosaic of linked hollow blocks could be laid down directly on frozen CO_2 or on a layer of water-ice above the CO_2. In the latter case the ice would melt and the blocks would fill with water and slowly sink to the CO_2. The blocks would then fill with CO_2 gas, cutting the heat flow down to $\sim 0.2\,\mathrm{Wm}^{-2}$. At an evaporation rate ≤ 1mb/yr, CO_2 might be allowed to bubble up freely from the vents. Alternatively, it could be ducted away or kept cool by heat pumps in the blocks.

Residual leakage of heat from the crust below will gradually melt the frozen CO_2, initially at a rate of ~1 m/yr. Eventually, the ocean would need refridgeration. In practice, CO_2 will be removed for export faster than its natural melting rate, and warm water may be fed through the blocks to melt more.

Mean volcanic heat flow into Earth's oceans is a negligible $\sim 4 \times 10^{-4}\,\mathrm{Wm}^{-2}$; recent evidence suggests that Venus is only ~5% as volcanically active, producing $\sim 1\,\mathrm{km}^3$ of lava per year. Although violent volcanic eruptions, on a par with Krakatoa, could burst through the cover and hurl up to $\sim 30\mathrm{km}^3$ or $\sim 10^{-5}$ bar of CO_2 into the atmosphere, such events would be very rare and significant only locally. Smaller eruptions, releasing only $\sim 1\mathrm{km}^3$, might occur more frequently.

During icefall, an ocean canopy is needed for protection. Unless the entire icemoon is deposited in a single icefall, the CO_2 cover will not be enough, because successive icefalls would evaporate the water already precipitated; this would not only retard cooling and condensation, but would destroy the photosynthetic algae at work in the water. On an inhabited Venus, a separate high-level canopy is desirable, with shades drawn across during icefall and drawn back afterwards.

6. PROVISION OF AN OXYGEN ATMOSPHERE

Carbon dioxide, over-plentiful on Venus, can be converted into oxygen by photosynthesis. Many authors [2-7] have suggested seeding the clouds with blue-green algae. This would reduce the greenhouse effect and improve the atmospheric composition, but it would not by itself produce an Earthlike planet; it would remain far too hot and the atmosphere far too dense.

6.1 Pre-cooling Photosynthesis

If a strain able to live and multiply in the clouds can be found, and if the cloud particles contain enough magnesium, phosphorus and other nutrients to support photosynthesis, then a *single* cell placed within the cloud layers could multiply rapidly enough to cover Venus in days or weeks. The cost of seeding, which could be performed at the start of terraforming, before the arrival of the ice-moon or the sunshade, would be very low indeed.

In pure CO_2 and a light flux of $670\,Wm^{-2}$ carbon fixation rates of up to $\sim 100\,kgm^{-2}yr^{-1}$ are possible, so ~0.24 bar of oxygen could theoretically be produced in as little as a decade. However, it is not clear what rate could be sustained in practice, nor whether enough dust could be entrained in the atmosphere to replace all the nutrients lost to precipitating cells. Furthermore, some carbon dioxide may still remain in the atmosphere after cooling and would have to be removed at that time.

Pre-cooling photosynthesis is thus seen to require unproven bio-technology (cloud-living algae) and additional photosynthetic transformation of the atmosphere after cooling. Photosynthesis will of course be encouraged within any aerial habitats.

6.2 Post-cooling Photosynthesis

After cooling, the residual atmospheric CO_2 can be converted to oxygen using algae or ground vegetation. Certain grains are known to fix $50\,g\,m^{-2}day^{-1}$ under optimum field conditions [10, 20]. On Venus, in a CO_2-rich environment, considerably faster rates of $\sim 100\,g\,m^{-2}day^{-1}$ are probable, especially in the shallow eutrophic seas, enriched with nutrients after every icefall. It would then take about 28 years to replace 0.33 bar of CO_2 by 0.24 bar of oxygen. Twenty-four hour IR-filtered sunlight can double the mean photosynthetic rate [12], giving a greater margin for the inevitable inefficiencies.

In CO_2 and under continuous illumination, reverse reactions in the plant (sugar-burning) will be minimised. Buried in mud and silt, plant remains will not then undergo significant oxidative decomposition, especially in the absence of decay bacteria.

Sugar beet is an example of a good crop for the land, yielding edible foodstuffs and commercially useful products like ethanol. Upon heating sugar in the absence of air, water is driven off and carbon left behind. This is a valuable industrial feedstock for the production of organics, carbon-fibre and diamond.

6.3 Removal of Carbon Monoxide

The residual Venusian atmosphere will contain a lethal concentration of carbon monoxide ($[CO]/[CO_2] \sim 10^{-3}$), which will also be removed by photosynthesis.

On Earth, carbon monoxide levels in cities are reduced appreciably by the presence of trees and grass—they seem to be able to use CO as readily as CO_2. It seems probable that oxidation of CO to CO_2 in the plant is rapid, and that photosynthesis is the rate-determining step.

The concentration ratio $[CO]/[CO_2]$ will then remain constant as photosynthesis progresses. Once the CO_2 has been reduced to ~0.1%, the level of CO will have fallen to a safe ~1ppm.

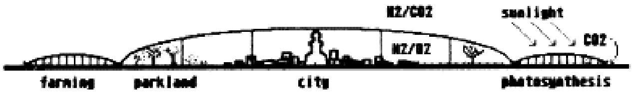

Fig. 5. Colony on Venus after cooling.

7. COLONIES ON VENUS AFTER COOLING

Colonisation of the land could perhaps commence at stage 4. Initially, the full 0.24 bar of oxygen is unnecessary. It would be quite simple to place cities, farms and parkland under large transparent tents (Fig. 5).

Supported by the buoyancy of O_2/N_2 in CO_2/N_2 and their internal warmth, these tents could be held in place by soil heaped around the periphery and by guy-ropes inside. With an average height ~10m—more above the cities, less above the peripheral farmlands—the internal air would contain $\sim 5\,kg\,m^{-2}$ of oxygen, which could be replaced by photosynthesis in ~20 days.

The outer region contains perhaps half the total area. This is where most crops are grown and where the CO_2 of the external air is replaced by oxygen by photosynthesis. The region is divided by a spiral wall with windbreaks, lengthening the air path between inside and outside. Atmospheric pressures at the periphery are equalised. Climatic changes may cause the CO_2/O_2 boundary to move back and forth, but vegetation will keep it near the outer perimeter and diffusion inwards of the CO_2 will occur only over a distance of a few hundred metres.

The concentration of CO_2 will be maintained relatively high in the peripheral farming regions, where it will encourage high yields and rapid photosynthesis, but in the inhabited central regions the concentration will be low, ~1000ppm. In the absence of any internal source of carbon monoxide, its concentration will be also be low, ≤0.1ppm.

Minor leaks in the tent are not critical, because the pressure differentials are small and a slow (>20 day) mixing of internal and external atmospheres is beneficial. Damaged panels can easily be patched. Moreover, the volume of the tent could be very great, and its height could be allowed to increase as more and more oxygen was produced.

The cost of such tents would be very small, perhaps $\sim 1p/m^2$ over large enough areas—only ~£40 per person at the current population density of the UK. Water for these colonies may be imported by Orbital Ring, at a cost of $\sim 10p/m^2$ or ~£400 per person for ~1m, enough to moisten the soil and leave some open water. About $1\,mm\,yr^{-1}$ will be lost to the atmosphere, and another $100\,m^3yr^{-1}person^{-1}$ may be used.

During icefall it will be necessary to protect these colonies from the heat. The tents themselves would be adequate if the perimeters were sealed and cooled reflective shades drawn across the canopy. But the need for a similar canopy over the oceans suggests that the two could readily be combined. A high-level canopy for the whole planet, floating above the lower atmosphere at ~25km, would cost ~5T£.

Between icefalls, bright sunlight would be re-admitted to the land and sea below, both to illuminate the colonies and to provide energy for photosynthesis.

The continued release of oxygen would permit low or medium level tents, sheltering the vegetation spreading out across the land, to be raised at a rate of up to ~250m/yr, while maintaining a breathable atmosphere within.

Finally, when the planetary CO_2 level drops below ~1%, the tents could be abolished completely. Although by then the colonists might not always want to: what, live out in all that nasty *weather?*

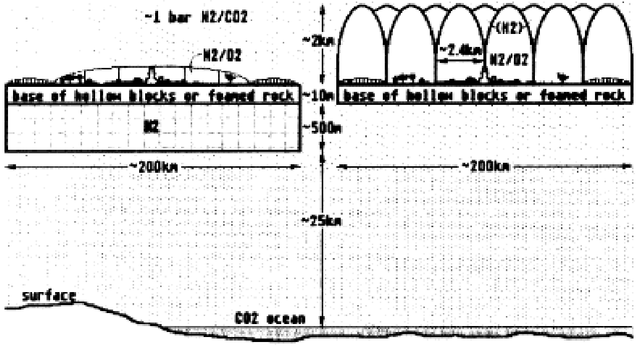

Fig. 6. Two kinds of floating colony.

8. FLOATING COLONIES

Colonisation of the surface of Venus before cooling would seem to be impracticable. But conditions in the upper atmosphere, around the 1 bar level, are much more amenable. Even before the deployment of the sunshade, temperatures are only ~290K.

Floating colonies (Fig. 6) can make immediate habitation practicable, greatly improving the economics of the terraforming process.

Two kinds of floating colony are shown. In both, the geosphere [12] is supported on a light base constructed from hollow blocks or foamed rock. The mean areal density is $\sim 1000\,\mathrm{kg\,m^{-2}}$, the base structure coming to $\sim 200\,\mathrm{kg\,m^{-2}}$.

In the first design, the colony is placed under a low tent (*cf.* Fig. 5) and supported by compartmentalised hydrogen-filled chambers underneath. Only $\sim 50\,\mathrm{kg\,m^{-2}}$ of H_2 are required; the chamber structure could be far lighter, but a further $\sim 50\,\mathrm{kg\,m^{-2}}$ leaves a large safety margin.

In the second design, the buoyancy of the N_2/O_2 internal air in the N_2/CO_2 external atmosphere is used to support the colony. The roof is much heavier than a tent, ~1cm thick, coming to $\sim 50\,\mathrm{kg\,m^{-2}}$.

In both versions $\sim 750\,\mathrm{kg\,m^{-2}}$ is left over for the geosphere, enough for ~0.5m of soil or ~0.75m depth of water over the surface. One might consider using platforms of the first kind as manufacturing bases on which to build colonies of the second kind, which could float away once completed.

Colonies of various shapes and sizes are possible. A suggested standard is a fractal hexagon [22] ~100km on a side, built up of 19^3 unit hexagons ~1.2km on a side. Its $26\,000\,\mathrm{km}^2$ could hold ~ 6 million people at the population density of the UK. Such shapes are self-similar and pertiling, permitting colonies of various sizes to be linked together into larger ones.

The internal layout of the colonies is optional, though there are some restrictions on loading. One exciting idea is to build most of the homes on a steep slope around the periphery, looking out and down to the planet far below.

Large buoyant colonies are very different from ordinary airships. They behave more like rafts on water, rigid on scales ≤100m, highly flexible on scales ≥1km. Their areal density of $\sim 1000\,\mathrm{kg\,m^{-2}}$, twice the wing loading of a heavy military jet, enables them to withstand extreme turbulence and differential winds $\gtrsim 140\,\mathrm{ms^{-1}}$ without hazard. One threat to the stability of such colonies is the liquid water in the lakes and rivers, which must not slosh too much from side to side; we are safe if the rms diameter of lakes is $\lesssim D_{colony}(\rho_{ambient}/\rho_{water})^{\frac{1}{2}} \sim 7\,\mathrm{km}$ and major rivers are provided with weirs at similar intervals.

As the CO_2 cools and rains out of the atmosphere, the floating colonies will gradually descend. Once terraforming is complete they will touch down onto the water, rearranging their coastlines and their terrain as they choose. Except over cities, the roof-domes will probably be dismantled. Archipelagos of floating islands may then cover much of the oceans.

The buoyancy of the colonies can be increased by filling the secondary roof spaces with hydrogen (Fig. 6), separated from the internal air by the double roof structure. This will permit the colonies to float in the warm water-laden atmosphere after icefall, protected by their own reflecting shield or the sky-canopy. They could survive on the surface, but the sky might be more pleasant.

While the cooling of the atmosphere and ocean is proceeding, CO_2 ocean cover disks—very similar to the colony bases—could be assembled upon manufacturing floaters or suspended beneath the colonies, then stacked on the ocean surface below. They would be moved quickly into place at the end of stage 5.

Floating colonies can be illuminated by orbiting solettas. To avoid light spilling over onto the planet's surface—which we are trying to cool—we can use mirrors lower than the 24-hour orbit. A soletta $1.0\times10^7\,\mathrm{m}$ from the centre of Venus orbits once every 3 hours; so a sequence of six could illuminate a colony continuously, with a spot diameter down to ~150km. During the day-time the "sun" would then sweep across the sky every half hour. More complex multiple-mirror arrangements could cut down the apparent angular size of the Sun and the minimum spot size, and reproduce Section 10's diurnal cycle.

The presence of colonies floating in the upper atmosphere need not slow the cooling process; they could even cool their undersides with heat pumps and radiate into space more efficiently than the surrounding atmosphere. They could also be anchored above the upper ends of heat pipes.

Floating colonies will therefore provide safe, robust and pleasing environments at modest cost, ideal for general habitation on Venus throughout the process of terraforming.

8.1 An Artificial Planetary Surface

Since floating colonies can be aggregated into large rafts of any size, there is nothing in principle to preclude covering the whole planet with them. The artificial surface thus formed would obviate all need for further terraforming. A complete planet could be built on this foundation, including its own seas and mountains. However heavily laden, it would be supported by the atmosphere compressed beneath it, the heat and density of which would no longer matter.

This extreme form of 'terraforming' essentially entails the construction of a *supramundane planet* [12], except that as described it uses gas pressure for support rather than Orbital Rings. The distinction is less than it appears, for—analysed microscopically—gas pressure is no more than the resultant of numerous ephemeral dynamic compression members [21].

It is apparent that the colonies, instead of floating on air, could be supported at any altitude by Orbital Rings or dynamic compression members. The nature and construction of such colonies and artificial planets is examined in detail elsewhere [12]. But in the case of Venus, buoyant support would seem to be more convenient.

We may argue that in terraforming Venus we wish to create and colonise a planet with a natural geosphere, solid mountains and deep oceans. A rough world, neither completely tamed nor fully landscaped. A new Earth. Not identical to the old, but similar. An artificial planet would not really meet these desires. There are also many other bodies—the giant planets especially—which are not suitable for conventional terraforming, but which would be ideal locations for supramundane planets. So, having noted the possibility of giving Venus a completely artificial floating surface, we put it on one side.

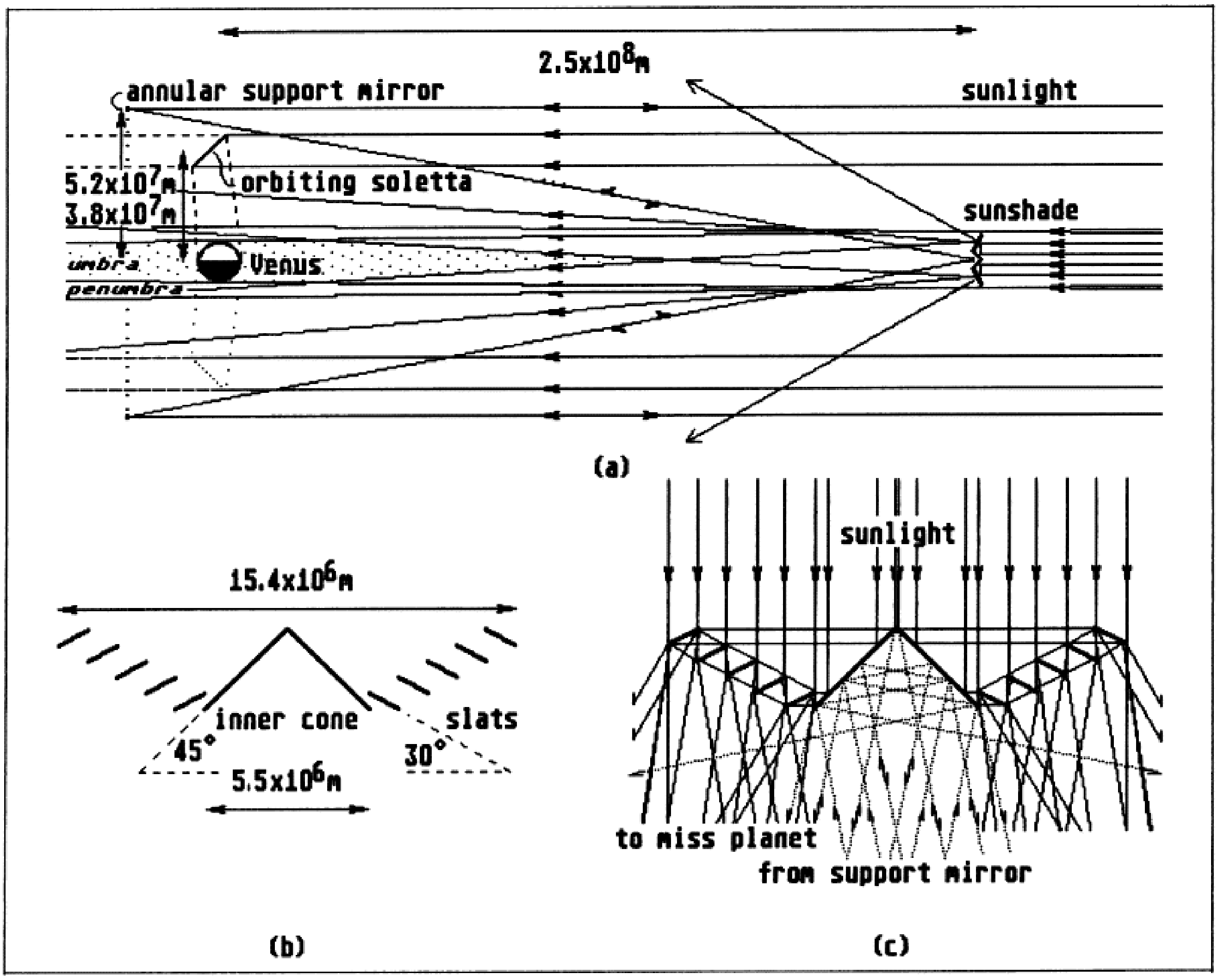

Fig. 7. Venus mirror system (a) Layout (b) Sunshade geometry (c) Light paths through sunshade

9. VENUS SUNSHADE

The sunshade or cooling mirror can be placed near the Lagrangian point L1 of the Venus-Sun system. This is 1.0×10^{9} m away from Venus; at this distance, the sunshade must be about twice the diameter of the planet.

Photon thrust on the mirror requires us to place it nearer the Sun, or to support it in some other fashion. The mirror can also be loaded with extra mass, to increase the effect of the Sun's gravity, or the mirror can be angled away from the Sun, to reduce the photon thrust.

A variety of solutions involving angled and loaded mirrors, sometimes supported by Orbital Rings, have been considered and found viable.

The solution presented here is the best found to date. It is not necessarily the best possible solution.

The sunshade is positioned (Fig. 7) at about a quarter the distance to the L1 point. It is constructed of solar sail material, reflective on both sides. It comprises an inner cone of half-angle 45° and a series of annular slats tilted at approximately 30°. Only five slats are shown; it will be best if there are rather more, but the exact number is not critical.

The light paths through the sunshade are complex. First consider the sunlight striking the inner cone. Reflected to the side, it is intercepted by the slats and redirected out along a cone of half-angle 30°, missing Venus by a wide margin. The net photon thrust from this light, referred to the frontal area of the sunshade, is only 0.017 units, where a mirror normal to the light would receive 2 units of thrust.

Sunlight striking a slat is reflected back to the next slat outwards, and then onwards, almost along its original path. Here, alternate slats are angled ±1° to either side of the nominal 30°; this deflects the sunlight alternately by ±4°, which is sufficient just to clear Venus on either side. For clarity these angles are exaggerated in the diagram (Fig. 7c). The net photon thrust from this deflection is negligible (0.002 units).

Because the mirrors are imperfect and absorb some of the incident light, an additional photon thrust of about 0.08 units is generated. In all about 0.1 units of photon thrust must be countered.

At an areal density of $3\times10^{-4}\,\mathrm{kg\,m^{-1}}$, the weight of the sunshade in a gravitational field of $5\times10^{-3}\,\mathrm{m\,s^{-2}}$ is equivalent to another 0.2 units of thrust. Thus the sunshade must be supported against a total of ~0.3 units of thrust (~1.6 GN).

The sunshade is supported by a *dynamic compression member* [21], utilising light directed from an annular mirror on the other side of Venus. The light from the support mirror strikes the reverse side of the inner cone. If the cone then behaved as a simple corner reflector the sunshade could be supported by the light from a mirror only a sixth of its frontal area.

However, a slightly larger support mirror area allows greater subtlety. As shown in Fig. 7c, the incoming support light is

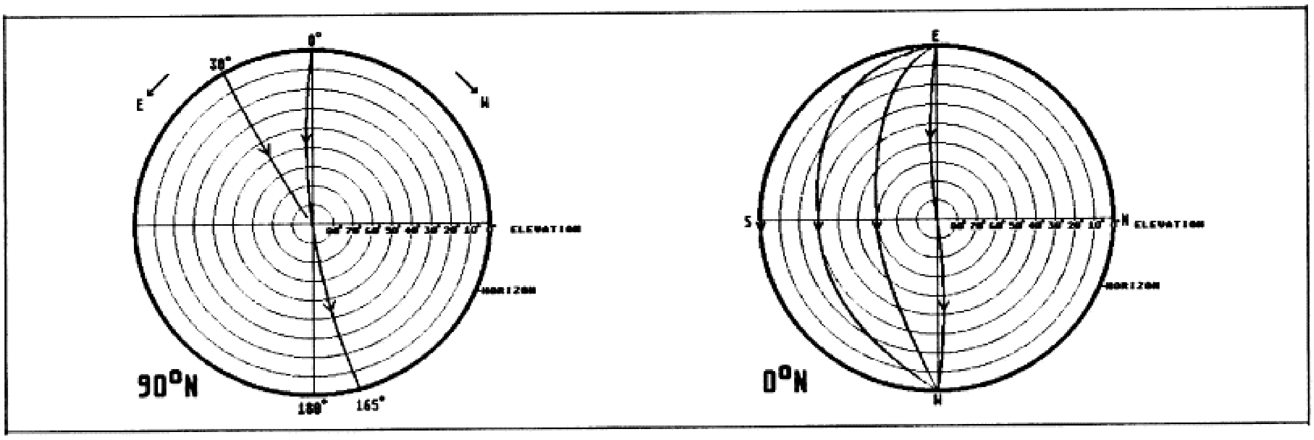

Fig. 8. Track of reflected Sun across Venus' sky. For clarity, the rotation of the planet has been exaggerated by a factor of ten.

directed more towards the far side of the cone. On reflection, some of it misses the other side of the cone and is lost to the side. This makes the support mechanism stable: if the shade moves in towards the planet, more of the support light is reversed and the thrust increases; if the shade moves away, more is deflected and the thrust decreases. Likewise, if the shade moves to the left, a net sideways thrust to the right develops, and *vice versa*. The flux of direct sunlight also leaves the shade stable against tilting.

The light from the support mirror then produces a net thrust of $\sim$1.75 units. The area of the annular support mirror is then 0.18 times the frontal area of the sunshade.

The annular support mirror is in a stable orbit 6×10^7m from the centre of Venus. The orbit is circular, but its plane is pushed back by light pressure through an angle of $\sim30^\circ$. The orbital plane must precess once a Venusian year; light pressure can be used for this too. A couple is set up if somewhat more of the light reflected back from the sunshade to the support mirror reaches the north side or the south side. If the cone half-angle is increased to 46° most of the reversed support light will not hit the support mirror again.

The finite angular size of the Sun has been taken into consideration. At a distance of 2.5×10^8m, it requires the diameter of the sunshade to be 1.27 times the diameter of Venus so that the planet remains wholly within the umbra.

The total mirror area—including both sunshade and support—is thus $\sim2.2\pi R_{♀}^2 \sim 2.5\times10^{14}\mathrm{m}^2$. The mass is $\sim7.6\times10^{10}$kg and at $\sim1\,£\mathrm{kg}^{-1}$ the cost may be $\sim$75 G£.

10. VENUS SOLETTA

After the cooling of the atmosphere and the covering of the CO_2 oceans, sunlight is needed once again. The Venusian solar day or 'sol' of 117 Earth-days is far too long and must be shortened—preferably to 24 hours.

Increasing the planet's spin is the "brute force" method, but the mass is too great for it to be easy. Various techniques for accumulating the necessary angular momentum have been considered [5,6] without proving economic for rapid terraforming projects. The author has recently devised a technique, using dynamic compression members, that may enable us to spin-up the planet in $\sim$30yr at an acceptable cost [23].

Icefall can cause a change in the spin rate of up to $\sim10^{-7}$ rad/s, leading to a sol in the range 80 to 150 days. With care, we may adjust the length of the sol to 120 days, or perhaps 121.75 days (four months).

A more elegant approach is to use a soletta, orbiting in a 24 hour polar orbit, to provide a day exactly 24 hours long (Fig. 7a). The sunshade is retained and the soletta mirror given a filling factor of 50%, cutting the sunlight down from a full $2650\mathrm{Wm}^{-2}$ to about half as much, equivalent to the sunlight on Earth. The soletta orbits at a distance of 3.8×10^7m (in the absence of photon pressure it would be 4.0×10^7m), inclined at about 45° to the Sun. To stabilise the aspect of an elliptical mirror, 12600km × 17800km, an additional area of mirror would be needed. A circular mirror of radius 8900km, rotating once an orbit, is probably better; it needs relatively little control, because each part of it is very nearly in a free orbit of itself.

The main soletta will therefore use $\sim1.1\pi R_{♀}^2 \sim 1.3\times10^{14}\mathrm{m}^2$ of solar sail material, or $\sim4\times10^9$kg, costing $\sim$40G£.

On the planet below, the image of the Sun is seen in the sky at right angles to its true position. The disk is full-sized; it has an angular diameter 40% greater than the Sun seen from Earth, but is weakened so as to appear no brighter.

The track of the Sun, for observers at the pole and the equator, is shown in Fig 8. The sol has been taken to be 120 days—the drawing is exaggerated for clarity, as if for a twelve-day sol. The effects of orbital eccentricity (which at 0.007 is small) and axial tilt (3°), the shift of the plane of the polar orbit due to photon pressure, and the possibilities of eccentric or tilted 24-hour orbits have been ignored.

The pole is tropical, with the Sun's track always passing overhead. The Sun rises and sets on opposite sides of the sky, but every day it rises 3° further east, taking 120 days to work all the way round the horizon. Day and night are each twelve hours long. When it is day at the north pole it is night at the south pole.

The equatorial region is also partly tropical, the Sun passing overhead, and partly arctic, the Sun resting on the horizon. These parts are separated by 90° in longitude and alternate twice a solar day. On the equator, the Sun rises in the east and sets in the west for half a sol, *vice versa* for the other half. Except in "mid-winter", every two months, when the Sun tracks around the horizon, day and night are each twelve hours long.

At other latitudes, intermediate paths are described, combining the march of the azimuth of sunrise and sunset around the horizon with the cyclic variation of the elevation of the noonday Sun. Axial tilt and other orbital effects add further complexity.

It is apparent that seasons on Venus will not be quite the same as on Earth. Unlike on Earth, where the Sun's track is confined to a band, on Venus it will at various times cover the whole sky. In general, a more uniform climate and gentler weather is to be expected.

A pair of modified solettas, with IR-filters, could be deployed temporarily in diametrically-opposite orbits during terraforming to speed photosynthesis through cold 24-hour lighting [12].

11. FINAL SCENARIO

A complete scenario for the terraforming of Venus can now be put together, choosing the fastest and most economical of the techniques investigated above. For definiteness I insert actual dates into the scenario, assuming that terraforming commences in 2040. The technology, costs and space populations are compatible with those achievable by that time and through the duration of the project [12]. Within ~5yr, the project is funded from its own revenues and most of the work is accomplished by ~2200.

2030 Planning, design and research phase. Scientific work on the pre-terraformed Venus must be concluded during this period.

2040 Terraforming begins. Several small space colonies are placed in orbit, and a heavy Orbital Ring is constructed, around Venus. Heat pipes using water are emplaced to cool the lower atmosphere. A $\frac{3}{19}$th size manufacturing floater is assembled at the 1 bar level and a $\frac{3}{19}$th size floating colony built on it.

2045 The first aerial colony floats free and can be sold and inhabited. The next colony is started. Six small solettas, each ~10^{10}m^2, the annular support mirror and the sunshade are deployed. A small space habitat is positioned at the centre of the sunshade. Ammonia replaces water in the heat pipes, more of which are emplaced to maintain heat flow as the temperature of the lower atmosphere falls. *Economic break-even.*

2050 The second aerial colony is completed. A second manufacturing floater is assembled. Further solettas are deployed as required. Emplacement of heat pipes continues.

2055 Stage 1 cooling is complete; heat pipes have saved ~45 years. Emplacement of heat pipes continues. Production of aerial colonies and manufacturing floaters, full-size hereafter, grows at ~7%*pa* to 2135, when there will be ~640 floating colonies. Their numbers will finally reach ~4800 by 2190.

2060 Carbon dioxide is now raining down upon the Venusian surface at ~2mm/hr and the oceans are beginning to fill.

2065 Stage 2 condensation is complete; heat pipes have saved about 15 years. Emplacement of heat pipes continues.

TABLE 2: *Summary of Costs and Benefits*

DATE	EXPENDITURE	INCOME	POPULATION
2030	≤1G£	—	~ 10^3 (1)
2040	~ 35G£	~ 2G£	~2.0×10^5 (1)
2045(2)	~115G£	~150G£	~1.6×10^6
2050	~170G£	~510G£	~3.4×10^6
2065	~474G£	~ 2.0T£	~1.8×10^7
2080	~ 1.2T£	~ 4.8T£	~5.4×10^7
2095	~ 3.0T£	~ 9.9T£	~1.3×10^8
2110	~ 7.4T£	~ 21T£	~3.0×10^8
2125	~ 20T£	~ 45T£	~6.5×10^8
2140	~ 67T£	~ 93T£	~1.4×10^9
2155	~ 90T£	~151T£	~2.7×10^9
2170	~ 53T£	~207T£	~4.6×10^9
2185	~ 48T£	~261T£	~7.0×10^9
2200	~ 10T£	~204T£	~1.0×10^{10}
TOTAL	*− 300T£*	*+ 1000T£*	*= 700T£ net.*
TOTAL(3)	*−4800T£*	*+ 11600T£*	*= 6800T£ net.*

(1) In orbit and temporary accomodation. (2) Break-even.
(3) Effective total with interest at 4.8% per annum.

2095 The colonies are now floating at a height of around 15km above ~1km deep oceans of CO_2. In stage 3 so far (273K; 26 bar) heat pipes have saved about 30 years, but now the temperature is becoming too low for them to help. Ground stations for limited occupancy are established.

2125 Sand and rocks are scooped up from fresh ocean silts. Some is stockpiled for the construction of the permanent ocean cover plates. A 100km^2 space colony, population ~10^5, is sent out to Saturn to commence work at Enceladus.

2130 Stage 3 cooling and condensation is now complete. The aerial colonies are floating at an altitude of only ~8km. The first tent colonies on the land are established. Orbital solettas are programmed to keep the land moderately warm and clear of CO_2 snowdrifts. The output of a light sail windmill is leased for a year to commence the transfer of the ice-moon Enceladus. Additional bursts of power will be required for navigational manoeuvres during the gravity-assist flybys.

2135 Manufacture of the ocean cover disks commences. Suspended from the underside of a colony for assembly, they are lowered to the ocean surface and stacked there on completion. The floating colonies produce one cover disk each every 2¼yr until 2160, making ~12000 in all.

2150 Stage 4, the freezing of the oceans, is completed. Tent colonies are spreading out on the land. Water vapour escaping from the colonies is freezing onto the oceans along with the rest of the excess atmospheric CO_2. Localised soletta heating keeps the land clear of drifts and tidies up the margins.

2160 Stage 5, freezing out the remaining CO_2 gas onto the oceans, is completed and the ocean cover fitted in place. Export of the excess 60% of the N_2/CO_2 atmosphere commences; only ~1 bar is left. A sky-canopy is deployed at ~25km altitude, and two IR-filtered full-sized solettas in diametrically opposite orbits. Power from the light sail windmill splits Enceladus into halves, which swing into contrary out-of-ecliptic orbits. Each half splits again into ~100 moonlets. Icefall occurs every 112 days for ~30yr. Above the canopy the atmosphere cools for ~5 days. It rains for ~70 days. Before each icefall, the sunshade, support mirror and solettas are flown out of the way beyond the L1 point, and the canopy shades drawn. Between icefalls, 24-hour sunlight induces rapid photosynthesis.

2190 End of ice-fall. The mirrors are flown back to their normal positions and a permanent main soletta deployed in 24-hour orbit. The sky-canopy, land canopies and old solettas are cleared away. Aerial colonies settle upon the ~120m deep water oceans and convert themselves into floating islands; a few stay airborne for fun. Land and sea are seeded with diverse lifeforms. CO_2 falls below 1%, O_2 rises to ~23%, N_2 is ~77%. The warm seas cool, climate and ecosystem begin to stabilise.

2200 The atmosphere and climate are Earthlike. The last tents are folded up. The export of unwanted CO_2 to space by orbital ring continues for ~50yr, supplying ~250$A_\oplus$ of space habitats [12], replacing it with permanent deep-water oceans.

2250 Terraforming is complete.

12. CONCLUSIONS

We have seen that by combining a variety of techniques it is possible to terraform Venus quickly and economically.

APPENDIX

The cooling process, from an atmosphere of 93 bar CO_2 and 2 bar N_2 at a mean temperature of 630 K, to an atmosphere of only 0.8 bar CO_2 and 2 bar N_2 at a temperature of 192 K, is analysed as follows:

Stage 1   730 K (mean 630 K) → 304 K; 95 bar
$\tau_1 = \Delta T\, C_p\, P/(\hbar g_♀)$
$\tau_1 = 326\text{K}\times 840\text{Jkg}^{-1}\text{K}^{-1}\times 95\times 10^5\text{Nm}^{-2}/(160\text{Wm}^{-2}\times 8.88\text{ms}^{-2})$
$\tau_1 = 1.8\times 10^9\text{s} = 58$ yr.
or at constant emissivity ε,
$\tau_1 = \frac{1}{3}(T_2^{-3} - T_1^{-3})\, C_p\, P/(\varepsilon\sigma g_♀) = 5.6$ yr / ε.

Stage 2   304 K; 95 bar → 76 bar
$\tau_2 = \Delta H_{vap}\, \Delta P/(T^4 \varepsilon\sigma g_♀) = 530\,\text{kJ kg}^{-1}\times\ldots = 7.4$ yr / ε.

Stage 3   (304 K; 76 bar) → (217 K; 7 bar)
In this range the vapour pressure is approximately exponential:
$P = P_{N_2} + P_0 \exp(T/T_0) = 2\text{ bar} + (604\text{Nm}^{-2})\exp(T/32.3\text{K})$
$\partial\hbar/\partial T = -(C_v P + \Delta H_{vap}\partial P/\partial T)/g_♀$
As the lower parts of the atmosphere condense out we have:

$$\tau_3 = \frac{C_v P_1(T_2^{-3} - T_1^{-3})}{3\varepsilon\sigma g_♀} + \frac{P_0 \Delta H_{vap}}{T_0^4 \varepsilon\sigma g_♀}\int_{T_2/T_0}^{T_1/T_0} \frac{\exp(T/T_0)}{(T/T_0)^4}\, d(T/T_0)$$

Evaluated, the integral comes to 2.22, and $C_v = 650\,\text{Jkg}^{-1}\text{K}^{-1}$, so:
$\tau_3 = 47.6$ yr / ε.

Stage 4   (217 K; 7 bar); 88 bar liquid → solid
$\tau_4 = \Delta H_{fus}\, P_{sea}/(T^4 \varepsilon\sigma g_♀) = 70\,\text{kJ kg}^{-1}\times\ldots = 17.4$ yr / ε.

Stage 5   (217 K; 7 bar) → (192 K; 2.8 bar)
Then the vapour pressure of dry ice leads to a pressure:
$P = P_{N_2} + P_0 \exp(T/T_0) = 2\text{ bar} + (.060\text{Nm}^{-2})\exp(T/13.6\text{K})$
Now τ_5 is calculated like τ_3 in stage 3, except that we use $\Delta H = \Delta H_{vap} + \Delta H_{fus}$ and $C_v = 690\,\text{J kg}^{-1}\text{K}^{-1}$, adjusted for the presence of the nitrogen. The integral now comes to 132, so:
$\tau_5 = 9.2$ yr / ε.

Stages 1-5
The total cooling time for constant emissivity is:
$\tau = 87.2$ yr / ε.

The above analysis effectively assumes that radiation occurs at the temperature of the bottom of the atmosphere. In reality, the atmosphere will tend to radiate predominantly from the cooler upper regions, where the optical depth is of order unity and the temperature is ~230K. This temperature is determined by the opacity and vapour pressure of CO_2; for if it became colder, latent heat would be released, H_2O and CO_2 snow would fall, and the temperature would stabilise. So at the pressure level from which the radiation escapes, the temperature and heat loss will tend to remain fairly constant, throughout the cooling process, except during stages 4 & 5.

Thus, in the absence of specific measures to increase the radiating temperature of the atmosphere, the total cooling time can be expected to be:
$\tau = 935\text{kJ kg}^{-1}\times 95\times 10^5\text{Nm}^{-2}/(160\text{Wm}^{-2}\times 8.88\text{ms}^{-2})$
$\tau = 6.3\times 10^9\text{s} = 200$ yr.

The minimum cooling time obtains when $\varepsilon = 1$ throughout, so:

$90\text{ yr} \lesssim \tau \lesssim 200\text{ yr}.$

Cooling after icefall may be analysed thus, for representative cases of icefalls of (a) 10 bar and (b) 0.1 bar, into 1 bar atmospheres:

Stage 6   ~20 000K → (a) 600K; 11 bar (b) 320K; 1.1 bar
This is the cooling of the very hot gas down to the dew point, at which it begins to to rain. We have:
$\tau_6 = \frac{1}{3}(T_2^{-3} - T_1^{-3})\, C_p\, P/(\varepsilon\sigma g_♀) = 80$ days / ε (a)
$= 26$ days / ε (b).

Stage 7a   600K; 11 bar → 320K; 1.1 bar
The vapour pressure of water falls rapidly with temperature. We may therefore estimate the cooling time as:
$\tau_{7a} \approx (\Delta H_{vap}\Delta P + C_v P \Delta T)/(T_{rad}^4 \varepsilon\sigma g_♀)$
$\tau_{7a} \approx 2$ yr/ε, T_{rad} ~550K, when maintained by heat pipes;
$\tau_{7a} \approx 8$ yr, T_{rad} ~400K, when radiating from 1 bar level.

Stage 7b   320K; 1.1 bar → 290K; 1 bar
Calculated as for τ_{7a} with ΔH_{vap}=2.2 MJkg^{-1} and T_{rad}=300K:
$\tau_{7b} \approx 250\text{kJ kg}^{-1}\times 10^5\text{Nm}^{-2}/(460\text{Wm}^{-2}\times 8.88\text{ms}^{-2})$
$\tau_{7b} \approx 6.1\times 10^6\text{s} \approx 71$ days.

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