Chapter 1

Introduction

Scientists study the world as it is, engineers create the world that never has been.

Theodore von Karman

1.1 What is Terraforming?

Before we answer this question, let us pose another: what should be the long-term aim of space exploration? Should it concentrate primarily on the acquisition of knowledge or on the satisfaction of our sense of adventure? Of course, space exploration already encompasses both of these aspects of experience, but perhaps there is only one long-term aim that truly integrates them both and measures up to the full potential of human imagination and creativity: the ultimate goal of space exploration should be to permanently extend the human presence into space; to create the conditions that allow new civilizations to be born and to grow, independent of the Earth.

Such a view, whilst far from being universally held, is sufficiently widespread within the space exploration community that it sometimes finds overt and collective expression in official documents, such as in 1986 when the US National Commission on Space [1] stated its conclusion that the proper long-range ambition of the US civilian space programme should be to establish free societies on new worlds: *"... from the highlands of the Moon, to the plains of Mars."* Behind such aspirations however lies something more fundamental. Since human beings cannot survive long in biological isolation, it follows that the long-term aims of space exploration should be concerned with taking out into space and establishing terrestrial life in all its great diversity.

If we accept this view, or at least take it as an assumption to work with, then it is proper to consider the issues of manned space exploration over much longer timescales than those characteristic of visiting or pioneering missions. If people are to start living in space permanently, then cultural and historical timescales inevitably come within the remit of discussion. Whilst nothing specific can be planned that far ahead, such a change in focus from a temporary stay in space to an indefinite one completely changes the scientific dimensions of the problem. Getting to Mars is one thing, but what will people do when they arrive? How will they, and the ecosystems they bring with them, survive and persist when there is an unbounded future ahead? The fundamental question that arises from this issue of space settlement is therefore: *what will be the optimum system for the support of terrestrial life beyond the bounds of the Earth?*

This question has been addressed on a number of occasions and designs for space habitats, ranging in size from smaller than a London bus to larger than a city, can be found within a variety of technical journals and books. *Terraforming* however represents the most ambitious of such speculations — no less than the concept of making entire planets habitable. Whilst daunting, such an ambition is seen as worthwhile by some of those interested in the colonization of space and has been attracting the interest of an increasing number of researchers. This is because of one simple observation: the only life-support system of which we know, or can conceive, which is stable over geological time in the absence of all-encompassing technological management, is the biosphere of the Earth. In other words, it may be that planetary biospheres are sufficiently large and complex that they can be left to "run themselves" (or nearly so) once made, being truly robust and near-permanent living systems. It is this prospect therefore that motivates scientists interested in terraforming: the possibility of the engineered creation of habitable planets from lifeless worlds such as Mars and Venus.

Whilst the notion of engineering planetary environments may be startling, its practise is very ancient indeed. Since prehistory, *Homo sapiens* has used a level of inventiveness unique in the Animal Kingdom to purposefully alter the environment to improve his chances of survival. It is an activity that has kept pace with technological and cultural development to the point that now a large fraction of the population of the Earth exists in material comfort and sheltered from extremes of climate. Not only are people to be found dwelling in every region where the planet's crust rises above the sea, but also, in small numbers and for short periods, within the oceans and in space. Clearly, engineering in its broadest terms, *the application of science and mathematics to "useful ends"*, is an extremely important pursuit — in fact it is crucial, for the infrastructure of civilization is an engineered creation, without which all but the most primitive of hunter-gatherer societies could not exist.

Recent technology has ensured that many aspects of modern civilization are now globally integrated. Entirely new flows of matter and energy have sprung from the world economy that simply didn't exist mere centuries, or even decades ago. Some of the fundamental parameters determining the climate of the Earth, such as the mean surface temperature, atmospheric composition and albedo are now suspected to be partially under human influence. People are becoming increasingly aware that anthropogenic environmental change is occurring on a global scale. Terms such as the "greenhouse effect" and the "ozone hole" are in common parlance, if often misunderstood. Whilst the rights and wrongs of the human influence on the Earth's environment are not all clear cut, the issues are being widely aired and are debated in an extensive literature. However, rising above all these arguments concerned with human nature or environmental ethics is one plain fact — humanity now has the capacity to reshape an entire world, and is changing the face of the Earth in less than the geological twinkling of an eye.

Strictly speaking, civilization's alteration of the global environmental parameters of the Earth cannot be called engineering since these alterations themselves are unintentional and have not been done for any useful purpose. They are rather the consequence of numerous smaller-scale activities, which together rival the processes of nature. Engineering of the environment on a regional scale has been possible since even before the industrial revolution, as evidenced by the dyke systems of Holland that have reclaimed half the land surface of the country from the North Sea. Thus, it does not require much extrapolation, or an enormous leap of faith, to postulate that civilization might soon embark on the first projects of global-scale modification, possibly to offset or repair the inadvertent damage that has been done thus far. This *planetary engineering* (or in the specific case of the Earth, *geoengineering*) will become possible by adding intention and design to a capacity, which already exists. Planetary engineering might therefore be defined as: *the application of technology for the purpose of influencing the global properties of a planet.* The main subject of this book however is to look further into the future, one where technological civilization expands off the Earth to take permanent residence in space. In such an event, it is possible to foresee planetary engineering being employed on other worlds to render them habitable.

Terraforming is a word, which has been in increasing use for about fifty years since it was first used in a science fiction novella by author Jack Williamson. It is a concept that has long been familiar to planetary scientists and readers of space-related and science fiction literature, but has gradually gained a wider public exposure. Only very recently, following a campaign by the American geographer Richard Cathcart, has the verb "to terraform" received formal recognition by inclusion in the New Shorter Oxford English Dictionary [2]. The literal meaning of terraforming can be gleaned from its two components: *terra* — the Earth and *forming* — the process of giving form or shape. Although there is not yet any officially agreed definition of terraforming, few would quibble with the one adopted for this book: *Terraforming is a process of planetary engineering, specifically directed at enhancing the capacity of an extra-terrestrial planetary environment to support life. The ultimate in terraforming would be to create an unconstrained planetary biosphere emulating all the functions of the biosphere of the Earth — one that would be fully habitable for human beings.*

Having defined terraforming, and noted its precedent in the analogy of humanity as global agents on the Earth, what can we say about its realism? If trends in scientific interest provide any clue, then terraforming, and planetary engineering in general, appear to be feasible future activities. Larger numbers of researchers than ever before are examining such questions (especially in relation to geoengineering and the terraforming of Mars) and no study has concluded such exercises to be essentially impossible. On the contrary, there is discernible at conferences and in the literature an increasing boldness in plainly stating the goal of a life bearing — terraformed — Mars as a worthy long-term aim of settlement. Naturally, opinions differ greatly as to the scientific, technological, industrial and ethical pre-requisites for a given planetary engineering project to become practical, but it is now commonplace to conduct such debates in the pages of technical journals, rather than those of science fiction.

The concept of colonizing other worlds, stocking them with breathable air, oceans and ecosystems — remaking them for life — is not new, but it is only quite recently that relevant research has accrued into a substantial body of published work. It is the purpose of this book to review this work in some detail; but first, to set the scene for the following chapters, we trace the historical roots of terraforming through to the present day.

1.2 A Concise History of Terraforming

Ideas do not spring out of an intellectual void, but normally when the time is right. Until comparatively recently, the idea of terraforming could have been nothing but nonsense. Gods made worlds — not mortals, and human beings were merely stewards of a creation with uncertain boundaries and superstitious rules, ordered and run by divine powers. For terraforming to make any sense at all, and therefore to arise as a valid concept, required the demythologizing of nature and a scientific appreciation of both the planetary nature of the Earth and the possibility of visiting other worlds.

Increasing evidence of man's influence on the environment prompted a re-assessment of ancient wisdom by thinkers in the seventeenth and eighteenth centuries. Men like John Ray and Count Buffon looked upon the Earth as unfinished, with man taking on the role of a junior partner in creation, taming the wilderness as part of a historical progression towards "perfection." In the nineteenth century, the deleterious effects of man's activities, over large geographical scales, were being recognised and were first explored in detail by George

Perkins Marsh in his book Man and Nature, or Physical Geography as Modified by Human Action [3]. Not only did Marsh catalogue many cases of deforestation, soil erosion and changes in the course and volume of rivers, but he also glimpsed much of the interconnection between natural processes that tend to amplify and ramify human actions. Often named as one of the founding fathers of environmentalism, Marsh did not consider all human activities to be negative and praised restorative efforts such as re-plantation of forests, regulation of water courses and reclamation of deserts, saying of them, *"These achievements are far more glorious than the proudest triumphs of war..."*

The role of civilization in transforming the environment of the Earth is now well known, if not fully understood. Yet it needed to be recognised that the Earth is more than a jigsaw of landscapes separately modified from a pre-existing, hypothetical, pristine state. Early this century, the Russian natural scientist Vladimir Vernadsky was one of the first to emphasize that atmosphere, water and nutrients are cycled globally and ecosystems are not just internally connected, but continuously import and export vital material — a change in one place might influence another far away [4,5]. Thus, there exists a higher level in the geographical hierarchy than the regions often studied for evidence of environmental change, and that is the planet itself. Vernadsky pioneered the study of the unit in this hierarchy corresponding to the top level of organization of life — the *biosphere*. Also much admired by environmentalists, Vernadsky thought of life as a global phenomenon, involving integrated flows of energy and cycling of matter that could be considered distinct from purely local processes. A man with a strong visionary outlook, who co-developed some of his more radical concepts with the Jesuit palaeontologist Pierre Teilhard de Chardin, he also appreciated the increasing human involvement in the functioning of the planet, characterising the powers of mankind as being, *"... a mighty geological force."* Vernadsky however was positive about collective human ability and thought it imperative for humanity to become consciously involved in biogeochemical cycles — to become planetary engineers — to, *"... rebuild the province of his life by his work and thought."* He believed the biosphere to be currently undergoing a transition to such a consciously engineered state, an intelligent and synergistic synthesis of ecology and technology, an envelope of mind sustaining an ever more ordered and information-rich system — a state he called the *noosphere*. Since Vernadsky stated his belief in the future probability of the manned exploration of space, it seems likely that he may have considered the eventual possibilities of creating noospheres on other planets. In practise however, he confined his published reflections on planetary engineering to the Earth.

1.2.1. Lowell and the First Planetary Engineers.

The astronomer Percival Lowell, writing at the turn of the century, was the first to speculate in detail over planetary engineering on another world [6-8]; however his engineers were not human, rather they were intelligent Martians whose works he and others claimed to have observed. The canals of Mars, fleetingly visible through the telescope only during the most exceptional viewing conditions, are famous and gripped the imagination of the public for decades (see Plate 1.1). Their geometric appearance seemed unmistakably artificial; as Lowell put it [8]:

"They join all the salient points of the surface to one another... That they are so regardant of topography on the one hand, and so regardless of terrain on the other, gives a most telltale insight into their character; it shows that they are of later origin than the main markings themselves... Their characteristics and their atti-

tudes, in short, betray that at some time subsequent to the fashioning of the planet's general features the lines were superposed upon them."

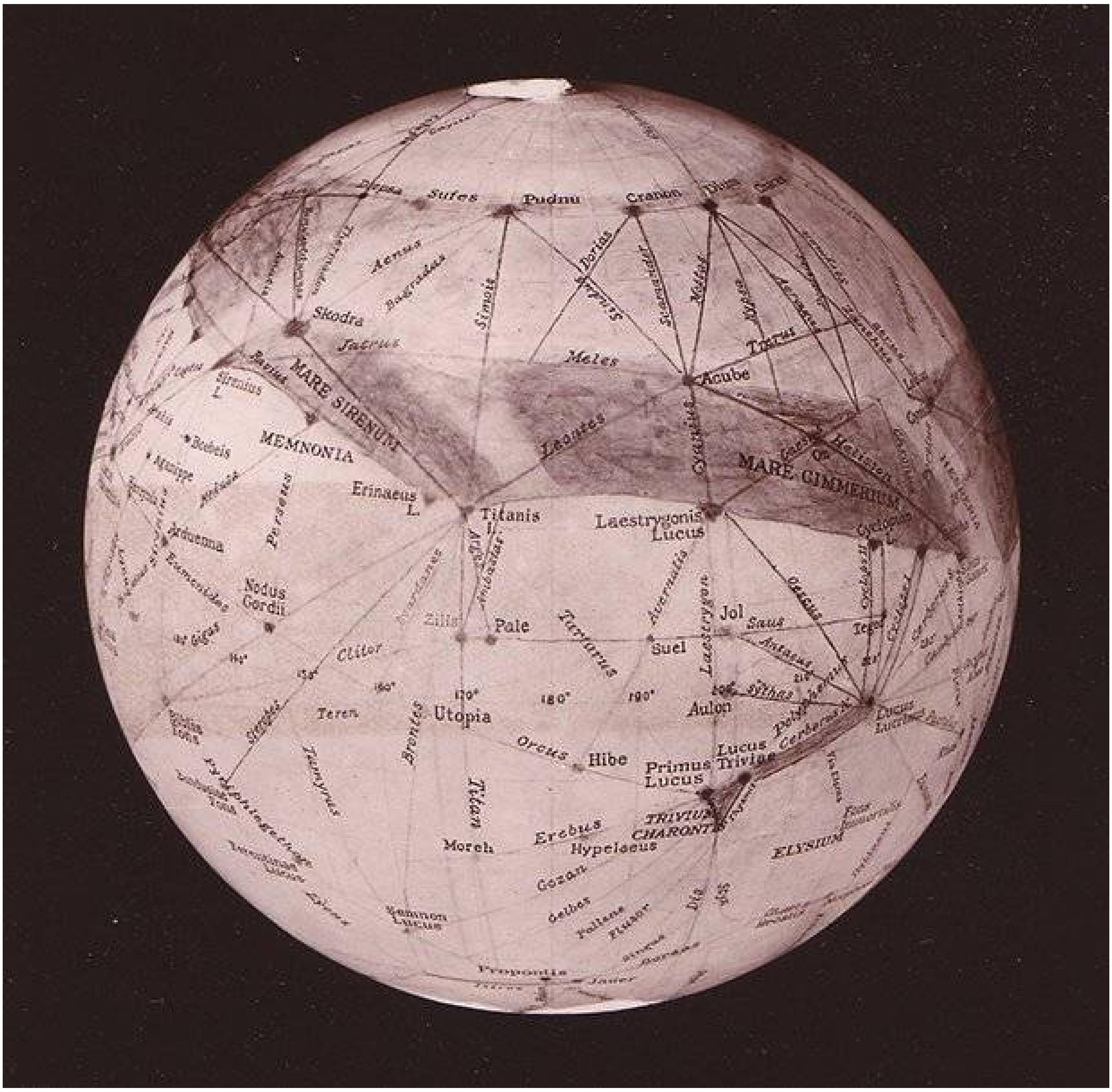

Plate 1.1 *Mars as interpreted around 1900 by Percival Lowell: a "terraformed" planet maintained in a habitable state by a globally integrated canal system. (Photo courtesy of the Lowell Observatory.)*

The connection of many canals with the planet's polar caps and their appearance in local Spring led to the conjecture that their function was to capture polar meltwater to transport it into the arid equatorial regions.

As the water flowed, it irrigated a swathe of vegetation adjacent to each bank, making the watercourse visible across space. To Lowell, who believed Mars had lost most of its original supply of water, these observations were an indication of a civilization, a dying race of planetary engineers, consciously directing their hydrological cycle in a battle to preserve life on their desiccating world:

"It becomes apparent to any one capable of weighing evidence that these things which so palpably imply artificiality on their face cannot be natural products at all, but that the observer apparently stands confronted with the workings of an intelligence akin and therefore appealing to his own. What he is gazing on typifies not the outcome of natural forces of an elemental kind, but the artificial product of a mind directing it to a purposeful and definite end.

"Now such is precisely what appears in the world spread system of canals. That it joins the surface from pole to pole and girdles it at the equator betrays a single purpose there at work. Not only does one species possess the planet but also even its subdivisions must labour harmoniously to a common aim. Nations must have sunk their local patriotisms in a wider breadth of view and the planet be a unit to the general good... Both polar caps would be pressed into service in order to utilize the whole available [water] *supply and also to accommodate most easily the inhabitants of each hemisphere. We would thus expect to find a system of conduits of some sort worldwide in its distribution and running at its northern and southern ends to the termini in the caps. This is precisely what the telescope reveals."*

In fact the telescope, and those astronomers who subscribed to Lowell's model, were wrong. His civilised Red Planet is now no more, its canals and oases finally proved beyond all doubt to have been an illusion after the successful flyby of the probe Mariner 4 in 1965. No spacecraft can ever bring us back pictures of Lowell's Mars, however it has been possible to explore many exotic variants of his world within the science fiction that it inspired. This therefore has been the enduring legacy of Lowell's work — he gave us a scientifically based model that, though it was incorrect, illustrated the richness of possibility in the universe and provided a tonic to the imagination. He conjured up a vision of a *living* Mars and an *engineered* Mars, a noosphere of austere beauty, peopled by noble and altruistic beings. It was a world that perhaps could have been, and thus was of wide appeal. The only radically new ingredient writers needed to convert this view of Mars for their fantasy stories was human interest and so sooner or later the idea of *human* planetary engineers was bound to catch on. It is not surprising therefore that soon after Lowell's Mars was being turned into a locale for adventure stories by authors like Edgar Rice Burroughs, the first developments in terraforming were also appearing in science fiction.

1.2.2 Terraforming and Science Fiction

Science fiction gave terraforming its name and helped to explore its vision, much in the same way it has done for other imaginative ideas that have since made it into actuality, or into the province of theoretical science. Thus, whilst this book is about the science of terraforming, it is fair and proper in this introductory Chapter to acknowledge the subject's fictional roots. However, a scientifically based review must be selective, ignoring the majority of novels that have not added to the idea but which merely used it as a futuristic stage set for an otherwise irrelevant plot. Below, we concentrate on the few SF writers who, in the present author's opinion, have made genuine historical contributions to the subject.

Introduction

The first detailed description of terraforming, and still one of the best, occurred in Olaf Stapledon's future history Last and First Men, published in 1930. It had as its precursor an essay "The Last Judgment" [9] by the biochemist J.B.S. Haldane, which appeared in 1927 and was later reprinted in a volume of such pieces called Possible Worlds. Haldane is best remembered today for his work on the origin of life, but he was also a noted populariser of science and not afraid to stick his neck out over speculative issues. In "The Last Judgement" Haldane considered a number of ways the world might end and then, choosing a cosmic accident that makes the Earth uninhabitable, embarked on a discussion of the future evolution of the human species, migrating to other worlds and adapting to cope with other conditions. Man's first port of call, he suggested, might be Venus. By fleshing out the bones of Haldane's scheme with his own rich imagination, Stapledon created Last and First Men.

Olaf Stapledon, as well as being a writer, was a part time teacher and lecturer in philosophy associated with Liverpool University, and is considered the second great name in English science fiction after H.G. Wells. In Last and First Men [10] he produced less of a novel than a philosophical meditation over a two billion year career for a succession of human species — a *tour de force*, all the more extraordinary when one considers when it was written. The book still retains much of its power to evoke wonder sixty years on; although Stapledon's depiction of the remainder of the 20th Century now appears naive, and much of his science was either wrong or missing, the dispassionate and impartial nature of his narrative ensures that the visionary quality of Last and First Men remains unimpaired, and some would say unsurpassed. Quotes from his relevant Chapter are therefore appropriate to illustrate the depth of his thinking.

It was Stapledon's “Fifth Men,” a highly evolved, near-immortal race who predicted an oncoming and unpreventable cosmic catastrophe that would force them to leave the Earth. But where to? He set out the problem so:

"Clearly humanity must leave its native planet. Research was therefore concentrated on the possibility of flight through empty space, and the suitability of neighbouring worlds. The only alternatives were Mars and Venus. The former was by now without water and without atmosphere. The latter had a dense moist atmosphere, but one which lacked oxygen. The surface of Venus, moreover, was known to be completely covered with a shallow ocean. Further the planet was so hot by day that, even at the poles, man in his present state would scarcely survive."

The initial problems facing the Fifth Men were therefore those of engineering a habitable environment on Venus. In particular they had to do something about the excessive surface temperatures and the poisonous air:

"The polar surfaces..., shielded by impenetrable depths of cloud, proved after all not unendurably hot. Subsequent generations might perhaps be modified so as to withstand even the sub-arctic and 'temperate' climates. Oxygen was plentiful, but it was all tied up in chemical combination. Inevitably so, since oxygen combines very readily, and on Venus there was no vegetable life to exhale the free gas and replenish the ever-vanishing supply. It was necessary, then, to equip Venus with an appropriate vegetation, which in the course of ages should render the planet's atmosphere hospitable to man."

Stapledon thus had a creditable grasp of biogeochemical cycles, and how they might be manipulated to change a planetary environment. Moreover, throughout the book he also demonstrated foresight of what we would now call “genetic engineering” — artificial alteration of the genome, which might be used to adapt life for unusual or alien climates. However, he also recognised that biological methods of planetary engineering were likely to be slow. The Fifth Men found that the Earth would need to be evacuated faster than originally thought and thus a technological “quick-fix” had to be found to speed up terraforming:

"... Venus could not be made ready soon enough unless some more rapid change was set on foot. It was therefore decided to split up some of the ocean by a vast process of electrolysis... The oxygen thus formed would be allowed to mix with the atmosphere. The hydrogen had to be got rid of somehow, and an ingenious method was devised by which it should be ejected beyond the limits of the atmosphere at so great a speed that it would never return. Once sufficient free oxygen had been produced, the new vegetation would replenish the loss due to oxidation. This work was duly set on foot. Great automatic electrolysing stations were founded on several of the islands; and biological research produced at length a whole flora of specialised vegetable types to cover the land surface of the planet. It was hoped that in less than a million years Venus would be fit to receive the human race..."

A mere million years represented only a few generations for the Fifth Men and so they pressed on with this faster terraforming method. However, after initial progress, the project began to be interrupted by acts of sabotage — a hitherto unsuspected civilization of Venusians, living on the ocean floor, resented the tampering with their world and had declared war on the human invaders. Stapledon therefore had one final obstacle to place in the way of his protagonists — an ethical dilemma:

"The Fifth Men were thus faced with a grave moral problem. What right had man to interfere in a world already possessed by beings who were obviously intelligent, even though their mental life was incomprehensible to man? Long ago, man himself had suffered at the hands of the Martian invaders, who doubtless considered themselves as more noble than the human race. And now man was committing a similar crime. On the other hand, either the migration to Venus must go forward, or humanity must be destroyed.."

The planetary engineering went ahead in the hope that mankind might accommodate itself with minimal interference with the native population. But this proved impossible; not only did any attempt to negotiate with the Venusians come to nothing, but the terraforming process itself was gradually polluting and poisoning indigenous habitats:

"... it was found that, as electrolysis poured more free oxygen into the atmosphere, the ocean absorbed some of the potent element back into itself by solution; and this dissolved oxygen had a disastrous effect on the oceanic organisms [which were anaerobic]. *Their tissues began to oxidise. They were burnt up, internally and externally, by a slow fire. Man dared not stop the process of electrolysis until the atmosphere had become as rich in oxygen as his native air."*

Both races therefore were locked in a battle that the Fifth Men, by virtue of their more sophisticated technology, were bound to win. The indigenous life was therefore condemned to a slow and unpleasant extinction. Rather than permit this the Fifth Men decided to wage a campaign to rapidly exterminate the native fauna, *"... without hate; indeed, rather out of love."* The consequences of this action however could not be escaped lightly:

"This vast slaughter influenced the mind of the fifth human species in two opposite directions, now flinging it into despair, now raising it to grave elation. For on the one hand the horror of the slaughter produced a haunting guiltiness in men's minds, an unreasoning disgust with humanity for having been driven to murder to save itself. ... Together... these influences tended toward racial neurosis."

The genocide complete, the section ends with a description of the seeding of Venus with terrestrial life and its inheritance by a deranged and mentally impoverished humanity, struggling with the less than ideal environment they had managed to create. Civilization eventually collapses into barbarism and it is left to natural evolution over succeeding millions of years to fashion a human species suited to the planet.

This first account of a terraforming project therefore cannot be described as an entirely uplifting one! Yet Stapledon's story is clearly not meant as a prediction or a prophecy, but a device by which to question the values of the day. The moral question of man's increasing dominion over terrestrial life may be what underlay his parable of a future Venus. The turning of a Promethian dream into a nightmare was probably motivated by his evident fascination with the paradox of the simultaneous greatness and insignificance of man. Stapledon correctly identified the terraforming thought experiment as having two fundamental dimensions — problems in engineering and ethics. The latter dilemma was illustrated in its most extreme form — probably one which will not trouble future planetary engineers, as none of the planets in our solar system now seem likely to host any form of life, let alone an indigenous civilization. Neither is the population of the Earth likely to be faced with such an urgent need to escape total extinction on its home planet, making terraforming into an issue of the survival of the species. Nevertheless, Stapledon, doubtless because of his background in philosophy, was way ahead of his time in considering the ethical dimensions of planetary colonization and terraforming. The first academic papers to tackle this issue came over fifty years later.

It is unlikely however that Stapledon ever heard the actual word “terraforming” since this was first invented by Jack Williamson (see Plate 1.2), using the pseudonym Will Stewart, in a novelette, "Collision Orbit", published in the July 1942 issue of *Astounding Science Fiction* magazine [11]. It was the first of a series of stories later revised and published as the novels Seetee Ship (1951) and Seetee Shock (1949) [12]. Their main theme was not terraforming itself, but the problems of manipulating antimatter and, like many SF stories, it mixed real science with the purely imaginary — such as, in this case, the fictional force of “paragravity.” Nonetheless, Williamson is rightly credited for having coined what has become a standard word in the lexicon of SF terminology and one that, despite competition from other contenders is also favoured by many scientists. Here, we reprint the first published use of the term:

"He had been the original claimant of Obania, forty years ago; and Drake was the young spatial engineer he employed to terraform the little rock, only two kilometres through—by sinking a shaft straight to its heart for the paragravity installation, generating oxygen and water from mineral oxides, releasing absorptive gases to trap the feeble heat of the far-off Sun."

After filtering out the fantasy, this paragraph gives us volatiles mining, the greenhouse effect and an elegant and descriptive neologism for the concept of engineering a global Earth-like environment.

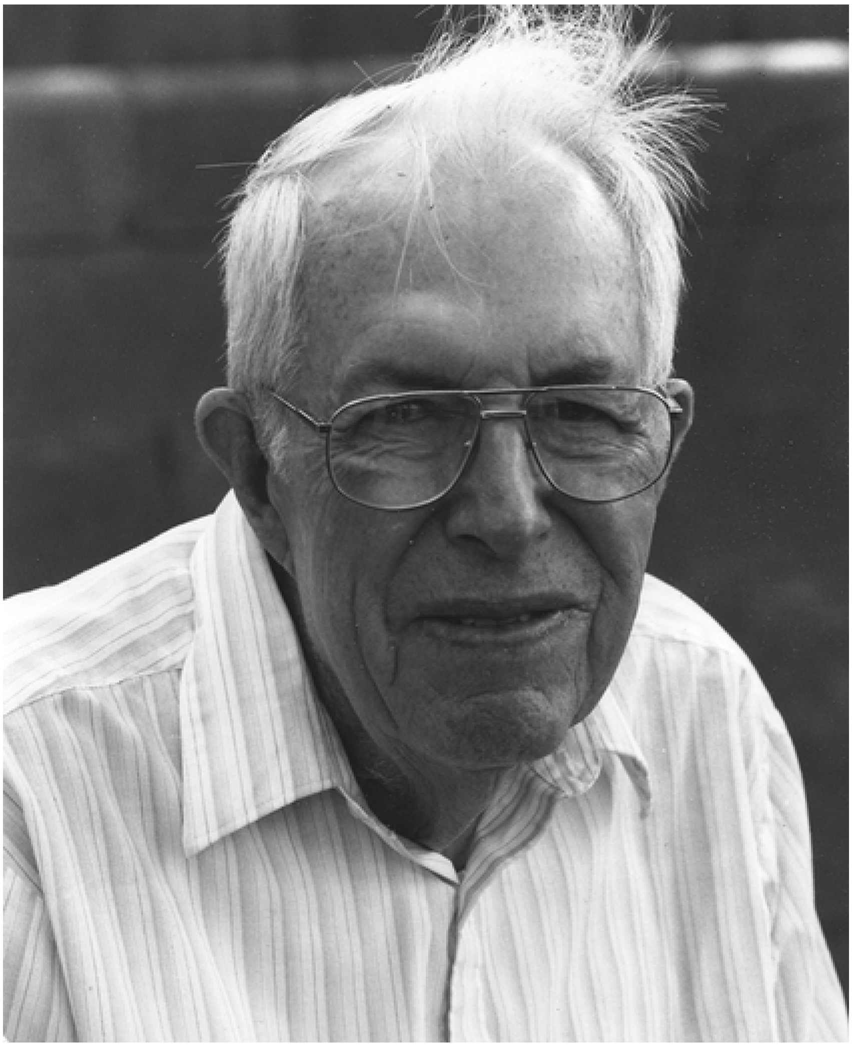

***Plate 1.2** Jack Williamson: science fiction author and inventor of the word "terraforming."*
(Photo by Betty Williamson.)

The next fictional landmark in the history of terraforming was Farmer in the Sky [13] by Robert Heinlein. Published in 1950, it depicts the challenges and hardships faced by settlers terraforming and making a home out of the Jovian satellite Ganymede. Although modern planetological knowledge undermines the bases for some of Heinlein's proposals, the novel remains an effective and entertaining read. He did have to invoke a couple of gimmicks to permit his scheme to work — a "heat trap", effectively a very powerful artificial greenhouse effect, and an abundance of nuclear power based upon matter annihilation — however, the book is sufficiently well written as to allow all but the most critical readers to suspend their disbelief. As far as terraforming is concerned, Farmer in the Sky is historically important for five reasons: a) terraforming is for the first time the central theme of an entire novel; b) the subject is made more approachable by intertwining it with an individual human story; c) terraforming is made relevant to the *near-future*; d) planetary engineering processes are described *quantitatively*; and e) the novel stressed many of the complex problems involved in life-support and ecosystem design years before ecology became a fashionable science.

Heinlein thus thought through the basis for his novel quite meticulously and he must have been one of the first to consider terraforming, not just scientifically, but *mathematically* as well. Here, Bill, the central character of the novel, does his homework:

"This takes us into the engineering side of ecology. Ganymede was bare rock and ice before we came along, as cold as could be, and no atmosphere to speak of—just traces of ammonia and methane. So the first thing to do was to give it an atmosphere men could breathe.

"The material was there—ice. Apply enough power, bust up the water molecule into hydrogen and oxygen. The hydrogen goes up—naturally— and the oxygen sits on the surface where you can breathe it. That went on for more than fifty years.

"Any idea how much power it takes to give a planet the size of Ganymede three pressure-pounds of oxygen all over its surface?

"Three pressure-pounds per square inch means nine mass pounds, because Ganymede has only one third the surface gravitation of Earth. That means you have to start with nine pounds of ice for every square inch of Ganymede—and that ice is cold to start with, better than two hundred degrees below zero Fahrenheit.

"... to carry out this breakdown takes power and plenty of it—65,000 Btus for each square inch of surface, or for each nine pounds of ice, whichever way you like it. That adds up; Ganymede may be a small planet but it has 135,000,000,000,000,000 square inches of surface. Multiply that by 65,000 Btus for each square inch, then convert British thermal units to ergs and you get: 92,500,000,000,000,000,000,000,000,000,000 ergs.

"Ninety-two-and-a-half million billion quadrillion ergs! That figure is such a beauty that I wrote it down in my diary and showed it to George.

"He wasn't impressed."

Thus, Heinlein had to assume his Ganymede colonists had routine access to a lot of power to get his terraforming timescale down to fifty years (in SI units the power requirement is about 6000 TW, or about 600 times the primary power production of modern terrestrial civilization). A realistic project would probably take a good deal longer. However, the fact that he did his back-of-envelope calculations and presented them for scrutiny is a rare treat in SF. Heinlein also showed evidence of having considered in detail many of the ecological issues inherent in bringing life to a formerly sterile planet. There are extensive passages in which he deals with the nitrogen cycle, biotic diversity, interactions within ecosystems and the growing of crops. He felt the rapid production of fertile soil to be a particular problem:

"Not that you can start farming with oxygen, carbon dioxide and a stretch of land. That land was dead... Bare rock, sterile, no life of any sort—and there had never been any life in it. It's a far piece from dead rock to rich, warm, black soil crawling with bacteria and earthworms, to the sort of soil you have to have to make a crop...

"That meant taking whatever you came to—granite boulders melted out of the ice, frozen lava flows, pumice, sand, ancient hard rock—and busting it up into little pieces, grinding the top layers to sand, pulverizing the top few inches to flour, and finally infecting the topmost part with a bit of mother Earth herself—then nursing what you had to keep it alive and make it spread. It wasn't easy."

On the Earth now we are finding in many regions that topsoil, once lost, takes decades to regenerate; substantial human effort is needed to replace it more quickly. Thus many of Heinlein's ideas in Farmer in the Sky have not dated and in some ways the book has gained an even greater relevance. It is also stimulating in a different, but complimentary, way to Last and First Men. It brought terraforming into the arena of tomorrow, rather than the next geological age — into the lifetime of the individual, rather than the species. It made the point that *ordinary people are planetary engineers too*; like on Earth, enough individuals, equipped with not much more than a pick and shovel, can change the face of a planet.

Many other SF authors, some of them well known, have written pieces containing an element of terraforming. Terraforming Mars was first addressed at the end of the novel The Sands of Mars (1951) by Arthur C. Clarke [14]. The planet he depicted was a ground-breaking departure from the Lowellian norm and was much more similar to the Mars we know today. However, his terraforming methods — turning the satellite Phobos into an artificial sun with a nuclear explosion and using a plant that can break down the Martian sands to release oxygen — are doubtful. Poul Anderson tackled the terraforming of Venus in two short novels, The Big Rain in 1954 and Sister Planet in 1959 [15]. In the former he considered some of the sociological implications posed by the long timescales inherent in planetary engineering projects, but it became most well known for its title, which later became associated with a scientifically based terraforming model. The latter story is set on a Venus much like Stapledon's — ocean covered and host to a diverse biota and primitive intelligence. Human visitors discover that the core of the planet is metastable and could be triggered to switch into a less dense phase by setting off several thousand nuclear explosives under the ocean floor (again an extremely dubious notion). An expanded core would compress the planetary layers above and, after the upheaval, landmasses would be present above sea level. The native fauna would of course be wiped out, recapitulating Stapledon's moral dilemma. This time, Anderson comes down on the side of indigenous life — the piece ends with an outraged crewmember destroying the human research outpost and all the evidence it had gathered.

Thus, not long after terraforming became widely exposed in science fiction literature, its future pattern of use in the genre was becoming established. Terraforming became part of a writers toolkit of ideas, rarely developed further in its own right, but used either as a device to highlight other concerns (as in Sister Planet), or more often as high-tech wallpaper, a *fait accompli* background against which to set futuristic entertainment. Notable exceptions to this trend include Gregory Benford's Jupiter Project (1975) and Against Infinity (1983) [16]. The former has been called a spiritual sequel to Farmer in the Sky and both are set on a Ganymede being terraformed in an updated and plausible way; (Benford is a Professor of Physics at the University of California at Irvine). Other important recent novels are The Greening of Mars (1984) by James Lovelock and Michael Allaby [17], Venus of Dreams (1986) and Venus of Shadows (1988) by Pamela Sargent [18] and Red Mars (1992) and Green Mars (1993) by Kim Stanley Robinson [19]. These latter books by Robinson have kept up with current scientific and ethical developments in the field and are deserved award winners, the former having won the 1994 Nebula Award and the latter the 1994 Hugo Award (the most prestigious accolades in the SF world). They are the first two novels of a trilogy and consider in unprecedented detail, and with great skill, how a civilization might develop in concert with the planet it is terraforming.

Of all these novels however, The Greening of Mars [17] has been the most influential on the scientific community engaged in terraforming research. In fact, it is largely forgotten as a piece of science fiction and has been treated more as an academic work, having been cited in almost every paper written on the terraforming of Mars since 1984. There are two reasons for this. The first is that the writers of The Greening of Mars are well-respected scientists, especially the principal author, James Lovelock, who is famous for having invented the "Gaia Hypothesis" of the Earth's biosphere and for having published many papers and a number of influential books on environmental science. The second reason is that the format of the book is totally different from that of a conventional science fiction novel: rather than being an adventure story in a scientific setting, the reader is presented with an exploration of science assisted by fiction. The narrator is a second-generation Martian settler in the year 2245 AD, looking back and telling the story of the colonization and terraforming of what is his native planet. From this viewpoint, the authors are able to convincingly explore a whole range of interesting scientific questions raised by their scenario — to get back to the basics by looking at fundamentals first and progressing from there. In this way The Greening of Mars takes much less for granted than the traditional offerings of the genre, with their principal emphasis on human drama. Not that it is at all dull, but its appeal to the space-orientated scientific community was understandable. It discusses planetary formation and evolution; the origin of life; and, from the position of Lovelock's own hypothesis, the development and operation of the Earth's biosphere. It depicts realistic interplanetary spacecraft, expending detail on both their hardware and living conditions. It describes the terraforming itself and the kind of life-style the transformed Mars imposes on its inhabitants.

The main issue for Lovelock and Allaby was that of a suitable life-support system for a long-term human presence away from Earth. They made the point that, since Mars does not possess a biosphere, colonising the planet will involve much more than "taming" and "domesticating" its environment, as was done in the colonising of the Americas and the Antipodes. Conversely, living within hermetically sealed artificial habitats, such as would be needed on the Moon, is a less than attractive permanent solution. Mars, they suggested, permits a third approach:

"The newer view of the relationship between living organisms and their environment suggested a quite different way to approach the problem. If the planet could be 'seeded' in some way, if the conditions needed for life to begin could be supplied and then living organisms could be introduced, in time Mars would turn itself into a place where humans could live in the open, without special protection. With a little help, and it might be a very little help indeed, Mars might be transformed into a living planet."

The terraforming model they chose for their scenario was one worked on by planetary scientists in the 1970's and is described in detail later in this book. It relies on the assumption that the planet can be freed from its present "ice age" by thickening its atmosphere which is mostly frozen and locked up in the surface. Modest warming of the surface, releases some of the gas, which further warms the surface, eventually causing a runaway outgassing and a climatic transition to more habitable conditions. The new idea added by Lovelock and Allaby was a proposal for how the initial warming might be put into effect. They suggested adding chlorofluorocarbon gases (CFCs) to the atmosphere of Mars because:

"CFCs are 'super-greenhouse' gases. Like carbon dioxide and water vapour, they are transparent to short-wave radiation and fairly opaque to long-wave radiation, but they trap heat about a thousand times more ef-

fectively than does carbon dioxide. Turn that statement around and you will see you need one thousand times more carbon dioxide than CFC to produce the same warming effect."

Their estimate as to how much CFC would be needed to significantly warm Mars was far too low and so their tale of an entrepreneur using cast-off ICBMs to send unwanted CFCs from Earth to Mars would never have worked. (However, there would be nothing to stop the requisite quantity being manufactured on Mars itself.) After the climatic transition, anaerobic life is spread over the surface of the planet to set in motion biogeochemical cycles and to start making soil. In addition, in line with Lovelock's “Gaia Hypothesis”, the biota were also expected to regulate the new Precambrian-like environment:

"On a planet that supports life, conditions are maintained to a very large extent by the living organisms themselves. Provided conditions are produced in which life can begin and become firmly established, and provided there is no major interference from outside, microorganisms, plants and small invertebrate animals are capable of 'taking over' an entire planet and altering it to suit themselves. After all, that is what they did to Earth."

Lovelock and Allaby thus presaged a debate within the present day terraforming community as to whether the goal of planetary engineering should be to create as near an exact duplicate of Earth as possible, or instead might be seeded with a minimum inventory of life and left to develop in its own way. They supported the latter approach, content to envisage an anaerobic Mars, where humans no longer require pressure suits to venture outside their habitats, but still need breathing gear. Nonetheless, the hushed serenity of their transformed Martian landscape is described with great feeling:

"There are rivers on modern Mars, a few marshy areas, some lakes, but to experience our world, to feel the planet as it were, you must stand alone, quite still, and absorb its atmosphere. The green hills rise away, with patches of bright lichen colour where large rocks crop through the thin soil, to the red Martian soil on the higher, more exposed ground. Here and there, trees murmur quietly in the thin Martian wind. Perhaps a stream splashes over loose stones, rattling them, or a small waterfall utters a steady but muted roar, but the sounds are of inanimate things. No bird sings, no insect buzzes, no cow or sheep cries its presence. And above the scene, white clouds move at a leisurely pace across the palest of pink skies. The landscape is at peace. It rests. It awaits its future as it waited billions of years for the arrival of this much life. It is patient, as it has always been patient."

The Greening of Mars therefore achieved two significant things: its “big idea” of CFCs has stimulated serious research into the use of super-greenhouse gases as terraforming tools and its concept of a 'Gaian' Mars has become one followed by a large fraction of the terraforming research community.

The final entry in this review of the fictional contributions to terraforming is without doubt the most extraordinary. Yet the work is not a novel, or short story at all: it is an epic poem, Genesis by Frederick Turner (1988) [20]. Turner is Professor of arts and humanities at the University of Texas at Dallas (see Plate 1.3) and, amongst all his other activities, is a well known for his philosophical contributions to restoration ecology. His interest in terraforming is long-standing. He published a novel, A Double Shadow in 1978, set on a terraformed Mars, and has been a participant at terraforming-related scientific meetings. Genesis is partially set on a Mars in the process of being terraformed, however its ambition is of a higher order than mere story telling. What Turner sets out to create, by using the construction of the epic poem (exactly 10,000 lines of iambic pentameter), is no less than a prototypical foundation myth for a future planetary civilization.

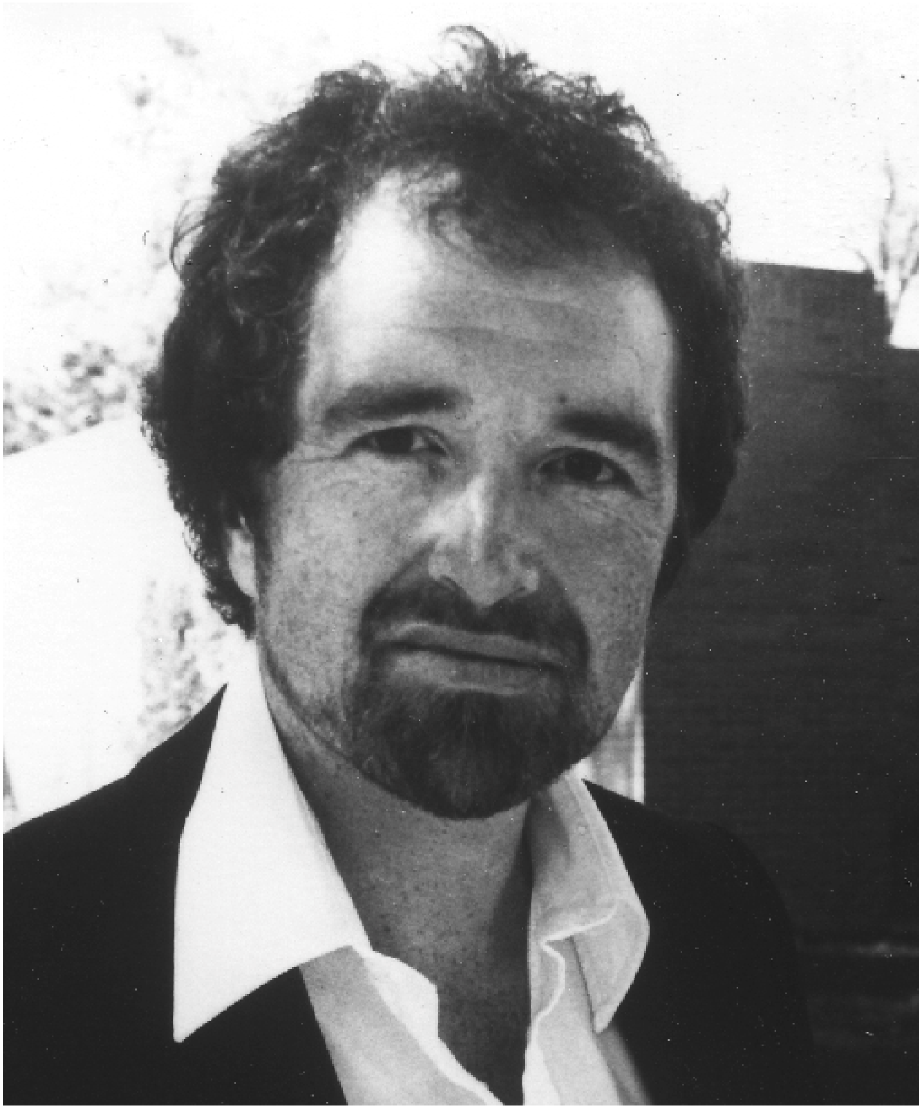

Plate 1.3 *Frederick Turner: Professor of Arts and Humanities of the University of Texas at Dallas; author of much philosophical comment on restoration ecology and terraforming and author of the epic poem Genesis.*

Joseph Campbell, the American scholar of myth, ancient and modern, one wrote, *"It would not be too much to say that myth is the secret opening through which the inexhaustible energies of the cosmos pour into the human imagination."* So it feels after reading Genesis — a work that is moving, profound, and rich with comment and detail. Its poetic expression, evocation of the glories of history, and cast of Homeric-style protagonists anchors the work within that past which, because it is so ancient, is properly the stage of legendary heroes. From these roots, the poem branches into a hard-won future on a world where biosphere and civilization are wrought together by characters in the true epic tradition — both larger than life and flawed — victors and victims of dreams actively forged into reality. Through tragedy and triumph, the subject matter of the poem ramifies through science, philosophy and religion. Among the scenes it visits, there are places that have permeated man's utopian dreams for thousands of years — from the Fields of Elysium to, *"... piny, muslin-lighted, poppied Mars."*

An example of Turner's expression is given in this passage describing the Mars of today:

A numb plain spread with stone. A weary steppe
All bleached to tired red with ultraviolet.
Soil crusted, sere; limonite, siderite.
Hard radiation in a waste of cold.
Rocks sucked dry by the near vacuum.
Stunned with the blank math of the albedo
The eye tries to make order of it, fails.
Whatever's here once fell from someplace else.
Sometimes a crag a foot high, or a mile;
Always the sagging tables of the craters,
The precise record of a mere collision.
And yet a stunted and abortive chemistry,
A backward travesty of life, proceeds:
Parched cirrus clouds move over the ejecta;
A hoarfrost forms upon the shadow sides;
Dark patches colonize the regolith;
Sometimes with a thin violence a sandstorm
Briefly makes shrieks of sound between the stones;
Rasps off their waists and edges, and falls silent.
Time here is cheap. A billion years can pass
Almost without a marker; if you bought
A century of Marstime in the scrip
And currency of Earth, you'd pay an hour
Or half an hour of cashable event.

Turner's appreciation of Mars as it is, is more than matched by his feeling for the living Mars that terraformers would create:

This garden: let it propagate itself,
Sustain itself, an arch-oeconomy
Dynamically balanced by the pull
Of matched antagonists, controlled and led
By a fine dance of feedbacks, asymptotic,
Cyclical, damping, even catastrophic.
Let there be forest fires to purge the ridges;
Let there be herbivores to mow the parkland,

And predators to cull their gene pools clean
And viruses to kill the carnivores
That sheep may safely graze. Each form of life
Shall feed upon the wastes of its convivors;
Let there be beetles and bacteria
And moulds and saprophytes to spin the wheel
Of nitrogen, corals and shells to turn
The great ratcheted cycle of the carbons;
Each biome—grassland, forest, littoral;
Benthic, pelagic; arctic, desert, alp—
Shall keep appointed bounds and yet be free.

As an exercise in myth creation, Genesis works superbly. As an exponent of terraforming (in this author's opinion) Turner has succeeded beyond the efforts of other fiction writers — the reader finds himself, his way of thinking, being changed in concert with Mars itself. That few people have come across Genesis is perhaps because epic poems are too esoteric for the tastes of most readers and require to be studied as well as read. This is as it should be — its function is to serve as an illustration of a future cultural document. It may be that if the terraforming of Mars ever happens, something like Genesis will be compiled from the drama of the times and, as future history progresses, will become as much a part of Martian culture as the Iliad and Odyssey are Greek.

1.2.3 A Chronology of Science and Terraforming

The detail of the history of scientific terraforming studies will emerge in the following Chapters. Here, it suffices to provide a brief account of events to provide a context for the rest of the book.

Before proceeding however, the remit of this book must be more precisely defined. We are primarily interested here in the subset of planetary engineering that is terraforming. However, geoengineering, that subset dealing with planetary engineering on the Earth, is undoubtedly relevant and cannot be ignored in any comprehensive survey of terraforming concepts. However, the coverage of geoengineering has here been restricted purely to its technical aspects and can be found in Chapter 4. This is to reflect an underlying and practical difference between the two topics: terraforming is concerned with the *creation* of biospheres on *lifeless* worlds, whereas geoengineering is largely concerned with the *repair* of a stressed biosphere on an *already inhabited* planet. Terraforming therefore allows us to consider the fundamentals of planetary engineering without such an urgent need to be drawn into posturing over the sort of environmental, political, legal and ethical complexities inherent in modifying the Earth.

Scientists have shown a sporadic interest in the notion of planetary engineering throughout the century. The speculations of Lowell and Haldane have already been described and through much of his career the astronomer and galaxy specialist, Fritz Zwicky, often alluded to terraforming-related ideas as part of what he saw as a challenge for humanity to reconstruct the Universe [21]. The first paper to examine the possibility of some specific terraforming operations appears to have been written by the British civil engineer Edward Hope-Jones in 1953. Based on a lecture given that year to the British Interplanetary Society, and later published in the Society's journal [22], it had the curiously modern title of "Planetary Engineering." In the paper, Hope-Jones briefly speculated over two opposite extremes in scale of engineering activities that might be necessary for human survival on other planets. On the one hand he examined construction techniques and the harnessing of power for small settlements, and on the other, enormous engineering feats such as changing planetary orbits and periods of rotation. Not surprisingly, he characterized these latter operations as requiring such titanic forces as to be impractical. Hope-Jones did not raise the possibilities of environmental modifications of a lesser magnitude (the body of what comprises terraforming studies today) probably because of how little was known about the planets at that time.

This credibility gap started to narrow in 1961 when the first serious proposal of a terraforming method, based on almost modern data, appeared at the end of a paper published in the journal *Science* [23]. The author was Carl Sagan (see Plate 1.4), then a research fellow in astronomy at the University of California at Berkeley, and the paper was on the new views being formulated about Venus. Gone were those visions of Venus as a Carboniferous swamp, or an ocean-world, and in their place, was described a picture close to that of today — a planet with a sterile, baking, surface, heated by the greenhouse effect of a dense carbon dioxide atmosphere. However, since Sagan assumed the composition of the Venusian clouds to be water vapour, he felt that an ecological niche for aerial life was possible. Furthermore, since he underestimated the surface pressure of this atmosphere to be only four times that of Earth (no space probes had yet reached the planet), he proposed that seeding the clouds with microbial life might be a first step in preparing Venus for comfortable human habitation. Fixation of carbon dioxide by photosynthesis and the deposition of charred biomass at the surface would have the net effect of enriching the atmosphere with oxygen and reducing the greenhouse effect. Eventually surface temperatures would fall sufficiently to allow water to collect at the surface and to permit chemical weathering of rocks by carbon dioxide, further reducing its abundance... Thus, *"microbiological planetary engineering"*, as Sagan called the process, seemed to hold out the prospect of almost cost-free, effortless, terraforming — the simple exportation to Venus of a suitable biota, rapidly transforming the planet in a cascade of positive feedbacks.

For a number of reasons, the Sagan scenario for terraforming Venus, in its original form, has not stood the test of time, although it has been much hyped by popular science writers since. New models of the environment of Mars were devised after its preliminary exploration by the Mariner spacecraft and this prompted the publication of the first papers on terraforming Mars in 1973. Once again, one of the first contributors was Carl Sagan (now at Cornell University) who proposed a “Long Winter Model” of the Martian climate [24] to account for the presence of what appear to be dried up riverbeds on the planet's surface. According to the model, the planet oscillates between warm, moist, phases, where the atmosphere is many times as dense as today, and cold “winters”, such as now, where everything is frozen, including most of the atmosphere as CO_2 ice in the polar caps. Since the whole process was supposed to be controlled by the precession of the Martian equinoxes (a period of ~ 51,000 years), the natural occurrence of epochal spring would involve a long wait. However, Sagan noted that the model predicted that spring might be triggered prematurely by destabilising the polar caps. His idea was [25] to reduce the albedo of the caps with a layer of dust or plant growth, thereby increasing their absorption of solar radiation and heating them. Some of the CO_2 would sublime, increasing the greenhouse effect of the atmosphere, further heating the caps, releasing more CO_2, and so on... Within a century or so, Mars would be transformed, *"... into a world with much higher pressures and temperatures, and much larger abundances of liquid water than are now available on the planet."*

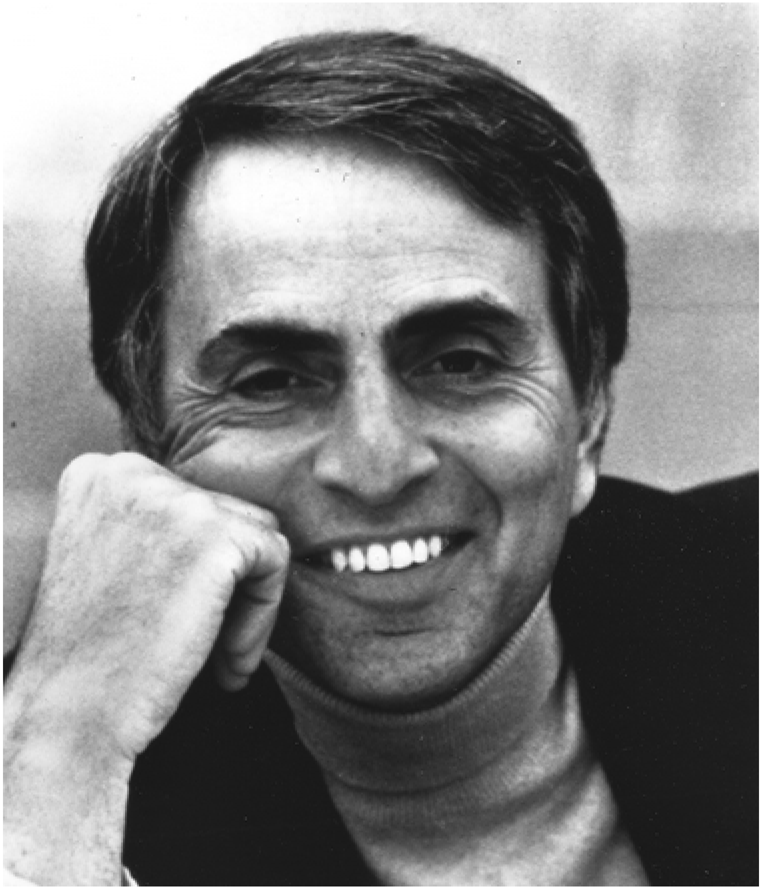

*Plate **1.4** Carl Sagan: Professor of Astronomy and Space Sciences at Cornell University, and noted writer and broadcaster; the first scientist to seriously discuss the possibility of terraforming in the technical literature.*

In his papers, Sagan took care to express the opinion that it would be unwise to commence any form of planetary engineering before the planet in question is thoroughly explored. However, what sticks in the mind most about his proposals for both Venus and Mars is just how little planetary engineering seems to be required to effect massive changes. He held out the hope of future civilization being able to wield a very powerful, self-amplifying, but gentle lever — biological systems — which, when applied to an intrinsically unstable planetary environment, would rapidly transform that environment into a more habitable state. Sagan's original concept for Martian terraforming has also fallen foul of updated knowledge; however, some of its modern successors still rely on similar “leverage” to minimize engineering input and maximize the result. His pioneering scenarios therefore remain influential on current thinking, and have stimulated a great deal of further work.

The results of the first large multi-authored study on terraforming were published by NASA in 1976 in a report entitled, "On the Habitability of Mars: An Approach to Planetary Ecosynthesis" [26]. Seven scientists contributed to the work, two of them, Melvin Averner of Southern Oregon College and Robert MacElroy of the NASA Ames Research Centre, also acting as Editors. It adopted a planetary engineering model similar to that proposed by Sagan and went further to investigate pioneering Martian organisms, ecosystems and the biological generation of oxygen. They judged that, in the absence of better data, *"No fundamental, insuperable limitation to the ability of Mars to support terrestrial life has been unequivocally identified."* The species that seemed most fit to thrive on the chilly, arid and UV-irradiated Martian surface, assumed to be the aftermath of initial terraforming, were bacteria, blue-green algae and lichens. However, the time such ecosystems might take to generate a breathable partial pressure of oxygen was estimated to be ~ 100,000 years. The study team were nevertheless willing to speculate that more rapid approaches to terraforming Mars than the conservative one they had chosen might be possible, especially by genetically engineering organisms specifically for the Martian environment. Their final conclusion was, *"Altering either the Martian environment or available photosynthetic organisms, or both, would significantly decrease the time required to create an acceptable human habitat on Mars, Indeed it may be mandatory to do so. If these steps are taken, Mars may well be made into a habitable planet."*

One of the participants in the NASA study was Joel Levine, now a senior atmospheric scientist at the NASA Langley Research Centre. It was he who organized and chaired the very first conference session on terraforming in 1976 at the 13th Annual Meeting of the Society of Engineering Science, held at Hampton, Virginia. In those days, “Planetary Engineering”, the preferred title of the session, was still considered a slightly risqué phrase and so it was called “Planetary Modelling” instead. It must have been quite a modest affair, involving the presentation of just three papers which were later published in proceedings [27]. But it was a start nonetheless and larger occasions were in the offing.

The 1970's was a time when the scientific study of terraforming really took off and the fiction writers handed over the reins of the subject to the scientists. Researchers were no longer content to wave their hands over coffee and doughnuts, or to speculate in just a few daring paragraphs here and there — for the first time, entire papers were being written on the subject. However, because of its speculative, and less than fully respectable nature, and its pursuit as a spare time scientific hobby, much of the work still tended to be done in obscurity and isolation. At the end of the decade therefore, NASA engineer and author, James Oberg, thought it right to bring affairs to some kind of focus and organised a special session on terraforming to be held at the Tenth Lunar and Planetary Science Conference, in Houston in March 1979. This “First Terraforming Colloquium”, as it was called, was the first large-scale gathering of terraforming researchers and brought together a disparate group of people, many of whom had never published in the field before. In Oberg's words, *"... a wide selection of previously uncoordinated work came to my attention. ... For much of the scientific community, the colloquium served as a public announcement that yet another 'crackpot idea' was about to move closer to scientific respectability at last."* One of the students who travelled to the conference to present a paper was Christopher McKay, then at the University of Colorado.

McKay has since become the most influential figure in modern terraforming studies (see Plate 1.5).

In retrospect, the First Terraforming Colloquium was actually the high water mark of a surge of interest in terraforming. It needed a book to gather together all the threads into a coherent whole and in 1981 James Oberg published New Earths [28], the first book to review the full range of terraforming ideas for a popular readership. Chris McKay published his first paper on terraforming Mars in a 1982 issue of the *Journal of the British Interplanetary Society* (*JBIS*) [29] in which he raised the possibility of a self-regulating Martian biosphere two years before Lovelock himself raised this issue to greater prominence in "The Greening of Mars". After this, most of the overt academic interest in planetary engineering research went back into hibernation.

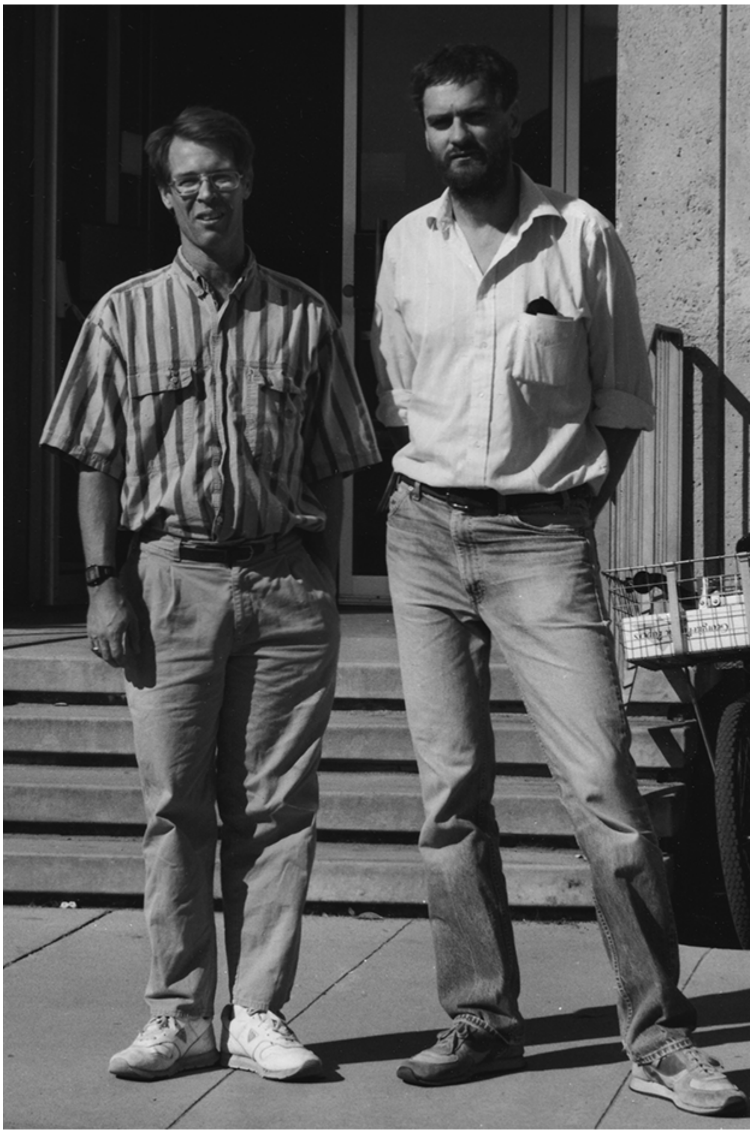

Plate 1.5 *Planetologist Dr. Christopher McKay (right) and science fiction writer Kim Stanley Robinson on the steps of the Space Sciences Building at the NASA-Ames Research Center. (Photo by Martyn Fogg.)*

It took another six years before the field acquired new vigour. Possibly a better word to describe this hiatus would be "gestation" — for interest continued "underground." Robert Haynes, a Professor of Biophysics at York University, Ontario, had his latent interest in terraforming (dating back to 1968) stimulated into activity after reading The Greening of Mars. A lengthy correspondence with James Lovelock resulted, followed by ambitious plans for a three-day terraforming workshop. Nothing came of this at the time, but Haynes' contributions to the subject, both in public and “backstage” have grown in importance since. Popular articles on terraforming did not entirely dry up during the mid-eighties and there were two excellent ones on the subject of Venus, written for *Analog* magazine by Stephen Gillett, a geologist of the Mackay School of Mines in Nevada [30,31]. However for terraforming to be academically reactivated, new papers were needed. Basically, it was a matter of the younger generation that attended the First Terraforming Colloquium (or who “were there in spirit”) finding the right time to publish. McKay describes his own position thus [32], *"Basically in 1982 I graduated* [and moved to the NASA Ames Research Centre] *and had to work on 'real' projects in order to build sufficient inertia in the planetary science field that I could afford to send time on terraforming topics and, equally importantly, have it taken seriously."*

In 1987, Oberg organised a second Terraforming Colloquium at the 18th Lunar and Planetary Science Conference and at the end of this year Martyn Fogg (the present author) published his first terraforming paper in *JBIS* [33], looking at the case of Venus. The next year, Chris McKay, now firmly established at NASA-Ames, and Robert MacElroy organised the first of the Ames workshops on terraforming Mars. It lasted a day and attracted a small group of interested scientists.

By 1989, this new momentum in terraforming studies was beginning to gather pace. Following a suggestion by Martyn Fogg to Len Carter, the Executive Secretary of the British Interplanetary Society, the BIS agreed to devote an entire issue of their journal to terraforming. Fogg was nominated as Contributing Editor and gathered together seven papers for the issue. It was published in December and, again, was another first — no issue of any academic journal had before been entirely concerned with terraforming [34]. It contained papers covering the entire range of speculation, from managing planet Earth, through terraforming Mars and Venus, to a piece on the Galilean satellites. Its importance also stemmed from the fact that it introduced some completely fresh and original thinking into the field — sorely needed as its dominant paradigms, now fifteen years old, were in danger of stagnating from lack of criticism. Examples of this included a paper by British geologist Alexander Smith which proposed a more logical method of disposing of the massive Venusian atmosphere — reacting it with crustal rocks to form carbonates, a situation that pertains naturally on Earth [35]. A paper by the present author questioned the Sagan/McKay scenario for terraforming Mars, suggesting that a much more technologically intense solution would be required [36]. Since this first *JBIS* special terraforming issue, there have been three others and its tradition of iconoclasm, originality and exploration of the limits of the field contrasts with, and compliments, the more solid, conservative approach generally adopted in the USA.

In 1990, two more ground-breaking papers [37,38] were published by Robert Haynes and Chris McKay, being the first to examine the prospects of terraforming Mars from the perspective of environmental ethics. The bottom line here seems to be that one's ethics are a matter of choice — within the limits of propriety — and although it is possible to argue that “rocks have rights”, it is equally valid to contend that, “Mars has a right to life”. Not surprisingly, the authors came down on the side of this latter point of view.

The second *JBIS* special issue appeared in 1991 [39], containing five papers, varied in subject matter and philosophical approach, which further added to terraforming's stock of ideas. The year also witnessed a number of other important events. McKay and Haynes organised a second Ames workshop on terraforming Mars that was twice the event that the last one had been, in that it lasted two days and attracted double the previous attendance. Ten short papers were presented, including one by the present author — the only European to attend the meeting. Two of the participants were senior planetary scientists, Owen Toon of NASA-Ames and

James Kasting of Pennsylvania State University who had just completed a large paper, jointly with Chris McKay, on terraforming Mars. It was published in *Nature*, under the title "Making Mars Habitable" later in the year [40]. The significance of this event cannot be understated for it conveyed upon terraforming, as a concept, a validity, respectability, and wide exposure not possible for more parochial journals like *JBIS*.

By 1992, interest in terraforming had taken root in Japan, with the appearance of a magazine-format book, The Terraforming of Planets [41]. Interviews with and translations of articles by McKay, Fogg and Smith made up a large fraction of the text. Its publisher, Kiyoshi Yazawa, the proprietor of the Yazawa Science Office, then went on to found "The Terraforming Society" — a group of Japanese enthusiasts that produce a small quarterly journal *The Terraforming Report*. In August, the third *JBIS* special issue was published [42], containing three lengthy papers on terraforming Mars: one by the present author that tackled the problem with a combination of planetary engineering techniques [43]; a radical proposal for rapid terraforming by British technical author Paul Birch [44]; and a paper introducing the novel concept of *paraterraforming* by London University astronomer Richard Taylor [45]. The possibility of bringing life to Mars was also continuing to be investigated in the USA; terraforming papers were presented at "Life on Mars: Past, Present and Future", a session held at the World Space Congress in Washington DC. A valuable contribution came from E. Imre Friedmann and colleagues from the University of Florida [46], who gave details of an extremely hardy cyanobacterium in Antarctica, *Chroococcidiopsis*, that might serve as an ideal pioneer Martian organism.

An account of 1993 brings this brief history up to date. Successful overtures to the British Broadcasting Corporation by Richard Taylor resulted in the making of a *Horizon* TV documentary Mars entitled "Mars Alive". Many of the personalities in the field were featured, along with their ideas of how the colonization of Mars might lead to the terraforming of the planet. Although the scientific merits of the programme were mixed, it was a considerable success at both spreading the terraforming message and making money. It is probable that syndication of the episode on international TV networks has more than recouped its five figure budget — a far greater sum than the total official spending on terraforming research to date!

Terraforming continued to tread the conference circuit, a session being held at "Case for Mars V" at the University of Colorado. Here, the presentation of two papers on the technical feasibility of terraforming, by Robert Zubrin (an engineer at Martin-Marrietta Astronautics) and Martyn Fogg, was followed by a debate amongst the audience concerning the ethics of settling Mars should it prove to host indigenous life. The most sizable meeting however was "Bringing Worlds to Life, organised by Richard Taylor and held at the Centre for Extra-Mural Studies, University of London and co-sponsored by the British Interplanetary Society [47]. Ten papers were presented over two days to a public audience by a wide variety of specialists, some of whom were turning their thoughts to the problems of terraforming for the first time. The concentration of intellectual debate, the fresh insights, and the active participation of the audience, made it a particularly noteworthy occasion.

As this text is being written, the fourth *JBIS* terraforming issue is being published [48], containing six papers ranging in subject matter from microbiology to orbital mechanics. These, and all the papers published since 1987, are the most up to date reference sources used for this book, but will be far from the last word on the subject.

1.3 Future Prospects for an Emerging Discipline

Terraforming research will go on, so long as the dream of settling space persists. However, whilst the quantity of this research is on the increase, it is destined to remain a "back-room" theoretical subject for some time to come — planetary engineering without a planet on which to apply the art. For a space-faring civilization however, one can foresee terraforming becoming a mainstream applied science, biosphere creation and maintenance having established principles and modes of practise.

In this light, it is easy to appreciate why modern terraforming studies are characterised by a wide diversity of views, not just about what is plausible, but what is acceptable. The co-existence of its reticent conservatives on the one hand, and its hand waving extrapolators on the other, are healthy signs of a young discipline — a practical application for planetary science — that interdisciplinary field that combines astronomy with the geological, environmental and life sciences. That topics so remote from each other in scale and practicality often share equal prominence within the pages of the same journal or on the conference platform, is a reflection of this immature character of terraforming as a subject for inquiry. Researchers are not attempting to dictate future policy, saying what should be done; or to predict some sort of future history by saying what will be done; but instead, by using boundaries constrained by science, and our understanding of the planets, and adopting assumptions of the engineering capacities if future civilizations, they are partaking in a *disciplined thought experiment of what might be possible*. Terraforming might therefore be looked upon as "applied planetology" — a new-born branch of engineering that cannot be expected to mature for a century or more.

When terraforming actually happens, it is likely that many, or most, of the proposals of today will be of historical, rather than practical interest. This is inevitable. Yet as James Oberg said in New Earths [28], *"Questions raised in these intellectual, scientific and technological pursuits will have applications elsewhere in our civilization. Detailed research into planetary engineering, into terraforming, even if it never occurs in any form remotely resembling the speculation put forth in this book, will still be useful."*

Chris McKay, in an answer to a question about the resurgence of interest in the field since 1987 said [32], *"I think that the problem is different now in that there is a 'community', albeit a small one, interested and working and publishing on the subject. In many ways this is instantly taken more seriously. One person is a nut, two people are deluded, but three or more form a research community and press for funding."* Whilst nobody is being officially funded for terraforming research, this part-time research community is bigger than ever before. Over twenty scientists have authored, or co-authored, terraforming-related papers since 1987 and have published in journals such as, *Nature*, *JBIS*, *The Environmentalist*, *Advances in Space Research* and *Speculations in Science and Technology*. If one includes those who published during the seventies and who retain an interest, the number is nearer thirty. At conferences, terraforming can attract audiences in the hundreds. The size of this group will fluctuate, but over the long-term, if mankind does have a destiny in space, it will surely grow, and grow enormously.

In New Earths Oberg made this prediction, *"I believe the time is right for such a book, and that the topic of terraforming is worth investigating right now, in the closing years of the twentieth century, and in the still infant years of the Space Age. This topic will be studied more deeply in the future, and this book will be rewritten innumerable times, but a start must be made."*

He was correct. The recent strong upsurge of interest has already produced more significant papers in the last five years than in the previous twenty five. Now is the time to bring these new threads together and merge them with the old.

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