Chapter 3

Some Guidelines for the Study of Terraforming

Everything in space obeys the laws of physics. If you know these laws, and obey them, space will treat you kindly. And don't tell me man doesn't belong out there. Man belongs wherever he wants to go—and he'll do plenty well when he gets there.

Wernher von Braun

Cap'n, I canna change the laws of physics!

Montgomery Scott

3.1 Method of Approach

In the previous two chapters, the concept of terraforming and its history have been outlined. We have also examined the possible importance of terraforming to man's space-faring future, specifically its potential to create large-scale and long-term life support systems remote from the Earth. For here onwards, this book will be considering in more detail the *process* of terraforming — its assumptions, aims, techniques and implications. Since we will be attempting to cover the entire field, the journey will be a long one through diverse and sometimes quite extreme intellectual terrain. This Chapter therefore is intended to establish some organising concepts that will provide a common foundation to the range of ideas that are to come.

Terraforming is an extremely speculative subject, which, since it deals with no less than the creation of new habitable planets, ramifies throughout many spheres of activity. Few of the scientists active in terraforming studies seriously expect to see their dreams come to fruition within their lifetimes. Perhaps a good analogy to the current situation is with the early pioneers of space travel who were able to establish much of its basic theory, but who could not have known at what pace their dreams would be realized.

Enquiry into terraforming therefore is mainly conducted within the framework of what is known as a "thought experiment." Here, one's laboratory — where all the laws of physics apply as normal — is within the mind, rather than in the "real" world. Thought experimentation allows one to apply theoretical knowledge to imaginary, but possible systems, which may currently be impractical to handle because of their expense or scale. They have an honourable place in the history of science, and one can cite many examples where they have permitted the leap-frogging of the chain of physical experimentation to predict some more profound truth. Einstein for instance was able to think through some of the consequences of his theory of Special Relativity, even though he could not experiment directly with objects at velocities close to the speed of light. Subsequent physical experiments proved him correct.

To establish a precedent for their ideas, terraforming researchers can appeal to the evidence for man's planetary engineering capabilities provided by our increasing influence on the environment of the Earth (see Chapter 4). Fieldwork can be directed towards the discovery of microorganisms that might serve as initial colonists during the early stages of terraforming and which might themselves contribute to the process (see

Section 5.6.3). The results of a wide range of past and present research, from the tolerance of organisms to environmental extremes, to the fabrication of structures in space, are of direct relevance to terraforming and can be used as factual data to be fitted within the mosaic of a larger picture. This larger picture though, the *process* of purposefully re-engineering a planet's environment along a pre-planned trajectory, is not yet practiced — it belongs to the realm of the imagination and will only emerge from it gradually once we attempt the terraforming of our first planet.

If terraforming research, even if entirely theoretical, is correctly disciplined then its science is valid. If one imagines the playground for thought experimentation as being a multi-dimensional space controlled by as many parameters as there are dimensions, it can be appreciated that, without any limits on the values of the parameters, the space can enfold an infinite number of possibilities. To reduce these to a sub-set of *real* possibilities we must accept first and foremost the constraint of physical law. This effectively separates the scientific from the purely science fictional and means, as far as terraforming is concerned, one cannot include such paraphernalia as “antigravity machines,” “matter transporters” or “warp drive” within any rational scenario. Of course, as science progresses, our understanding may change — we may discover new laws that open up undreamt of possibilities. However, anticipation of what cannot follow from physical law is not part of science and demands the impossible. Engineering limits of some kind will probably apply into the indefinite future.

Non-violation of these laws however still permits a vast array of possibilities, which could only be realized by an arbitrarily advanced civilization. The next step therefore is to make certain assumptions about the engineering capabilities of the civilizations undertaking terraforming, their access to energy and raw materials. These are of course subject to a personal interpretation of what the future will bring and can vary widely within the boundaries of what seems likely. For instance, some workers restrict their scenarios to activities on a planetary surface with a minimum of engineering and using present technology; others assume the establishment of a widely distributed space-faring civilization with access to the resources of the entire Solar System and capable of feats of engineering substantially scaled-up from what is feasible today. Uncertainties imposed on our assumptions are further increased by our incomplete understanding of the habitability of the Earth and our partial knowledge of other worlds, such as Mars and Venus, where terraforming might be applied. However, our planetological models — the way scientists think these worlds work — provide a framework for speculation that connects our thought experiments with real possibilities and therefore with science itself. Of course, the evolution and present state of various planets are often described by rival models, which are either partially or wholly incompatible. For the terraformer however, the important thing is to make what seem reasonable choices of planetological and cultural model and then to state one's assumptions clearly. Constrained in such a manner, the thought experiment can then proceed to build a picture that is plausible within the bounds of the uncertainty of present knowledge.

Thus, the control space within which terraformers can conduct legitimate thought experiments is presently a spacious one. It has permitted a variety of approaches to the problem, the full spectrum of which will emerge in the following chapters. We will criticize these mainly on grounds of science and practicality, rather than on the “'values” they appear to represent. (The implications of terraforming for environmental ethics and other issues of a non-scientific nature are reserved for Chapter 9).

Our philosophy in this book is therefore to be unashamed about the speculative nature of terraforming and to use the thought experiment as a well-tried method of creative enquiry. Physicist Dennis Gabor summed up the approach thus [1], *"The future cannot be predicted, but futures can be invented. It was man's ability to invent which has made human society what it is. The first step of an inventor is to visualise, by an act of* *imagination, a thing or state that does not yet exist and which to him appears in some way desirable. He can then start rationally arguing backwards and forwards until a way is found from one to the other."*

3.2 Another Look at Terminology

In the beginning there was terraforming... but any new field, invented in fits and starts by isolated individuals proliferates with alternative terminology. Next there follows a natural selection process where "brand names" compete for usage and losers fall by the wayside; those terms that remain are defined and ordered in their proper place. Few people for instance remember what a "frozen star" or "collapsar" is supposed to be, but everybody has heard of a black hole. Terraforming has had its share of competitive neologisms and it has only fairly recently nudged ahead in its struggle to become the term most used in science as well as science fiction.

It is appropriate here to reconsider our definition of terraforming, given in Chapter 1: *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 uncontained planetary biosphere emulating all the functions of the biosphere of the Earth — one that would be fully habitable for human beings.*

It seems to this author that this definition faithfully encapsulates the broad way in which the term has been used for over fifty years, as well as recognizing that its roots allude to an ultimate aim of rendering other planets earth-like. It specifically states that terraforming applies to other planets, since use of phrases such as "terraforming the Earth" have a ring of nonsense about them — how does one make the Earth more like itself? The definition contains the phrase *planetary engineering*, which is clearly neutral as far as any aims are concerned, since one can imagine a planet being subject to some form of global engineering for some other purpose than the establishment of a biosphere. Planetary engineering is thus defined as: *the application of technology for the purpose of influencing the global properties of a planet*. Terraforming is therefore a subset of planetary engineering. Planetary engineering activities on the Earth should be referred to as *geoengineering* and the grotesque "terraforming the Earth" should be avoided at all costs!

Terraforming, as defined above, won the vernacular war of words some time ago and few people when speaking of the subject use any other term. As a preferred term in the scientific literature however, it took far longer to become dominant, probably because of scientists' reluctance to adopt words from science fiction and their liking for inventing new words of their own. In Carl Sagan's original papers [2,3], he used the more colourless phrase of planetary engineering in place of terraforming, even though the changes he was envisaging were clearly to make Venus and Mars suitable for life (i.e. more earth-like), if not to render them perfect facsimiles of the Earth. The NASA study of 1976 [4] preferred to substitute the expression *planetary ecosynthesis*, which defines itself nicely as "the making of a home for life on a planetary scale." However, it has rarely been used since, probably because it is complete only in two words rather than one — ecosynthesis on its own possesses no scale and could just as well apply to a goldfish bowl, as well as a planet. The first paper to be published that used *terraforming* in its title was by Christopher McKay in a 1982 volume of *JBIS* [5]. Its title, "Terraforming Mars," was bold and to the point.

The only neologism to seriously rival the supremacy of terraforming was invented by Robert Haynes in 1984 (see Plate 3.1). He came up with the word *ecopoiesis*, which actually means the same thing as ecosynthesis — although it is grammatically more elegant as its roots are pure Greek, rather than mixed Greek and Latin.

Initially, Haynes's apparent purpose was to establish ecopoiesis as the standard term that would encapsulate all life-directed planetary engineering activities, relegating terraforming to describe a limited sub-set of possible outcomes.

Haynes set out his views thus [5]: *"Ecopoiesis is my neologism. The term refers to the fabrication of a sustainable ecosystem on a currently lifeless, sterile planet, thereby establishing a new arena in which biological evolution can proceed independent of further human husbandry. Terraformation is a specialized form of ecopoiesis, which refers to the development of specifically earth-like conditions culminating in the transfer of suitable Earth organisms to the target planet... The expression ecopoiesis is derived from the Greek roots* οικος*, an abode, house or dwelling place (from which we also derive 'ecology' and 'economics') and* ποιησις*, a fabrication or production (from which we derive 'poesy', as well as a variety of other biological terms such as biopoiesis, haematopoiesis, etc.)."*

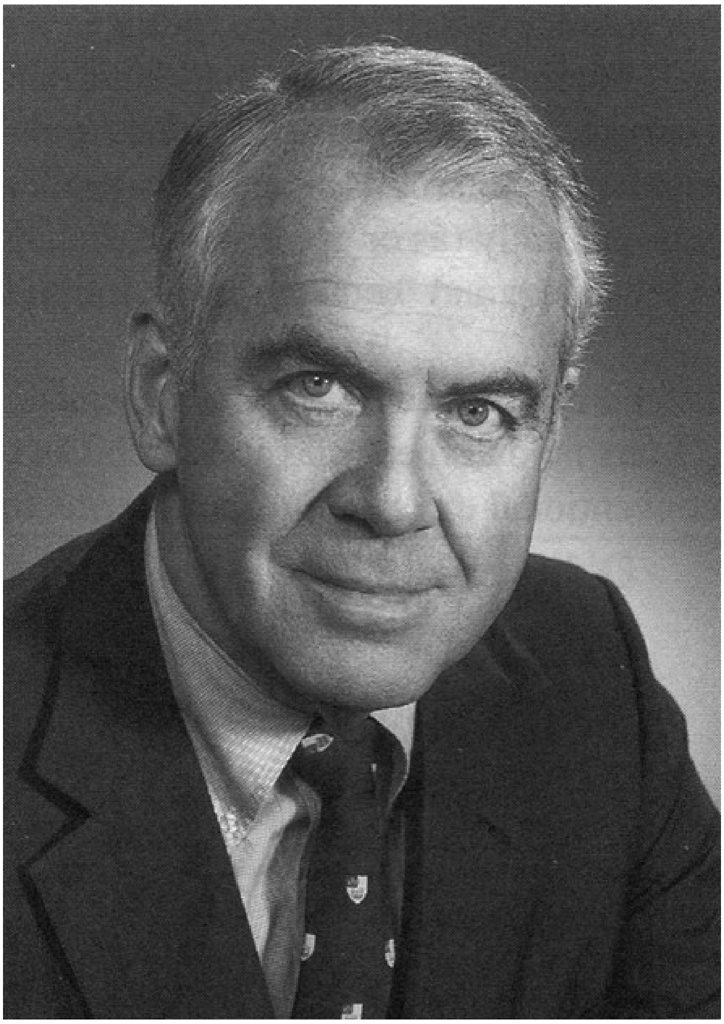

Plate 3.1 *Robert Haynes, biophysicist and Distinguished Research Professor at York University, Ontario, inventor of the term "ecopoiesis."*

As we will note in the following Section, ecopoiesis was adopted and used enthusiastically by adherents of the Gaia Hypothesis. As Lovelock wrote in 1988 [7], *"I prefer it to the word terraforming, often used when* *considering this act for planets. Ecopoiesis is more general. Terraforming has the homocentric flavour of a planetary-scale technical fix."* However, it was pointed out by Fogg [8] that since endowing a planet with life inevitably involves some sort of technological direction by man, terraforming cannot be separated from ecopoiesis on these grounds. In the end, it was the use of terraforming by authors of papers and articles and broadcasters on TV and radio who settled the issue of which word should be the generic term. The majority of papers written since the reactivation of the field in 1987 have used the word freely, in both its narrow sense and the broad meaning which ecopoiesis was supposed to replace.

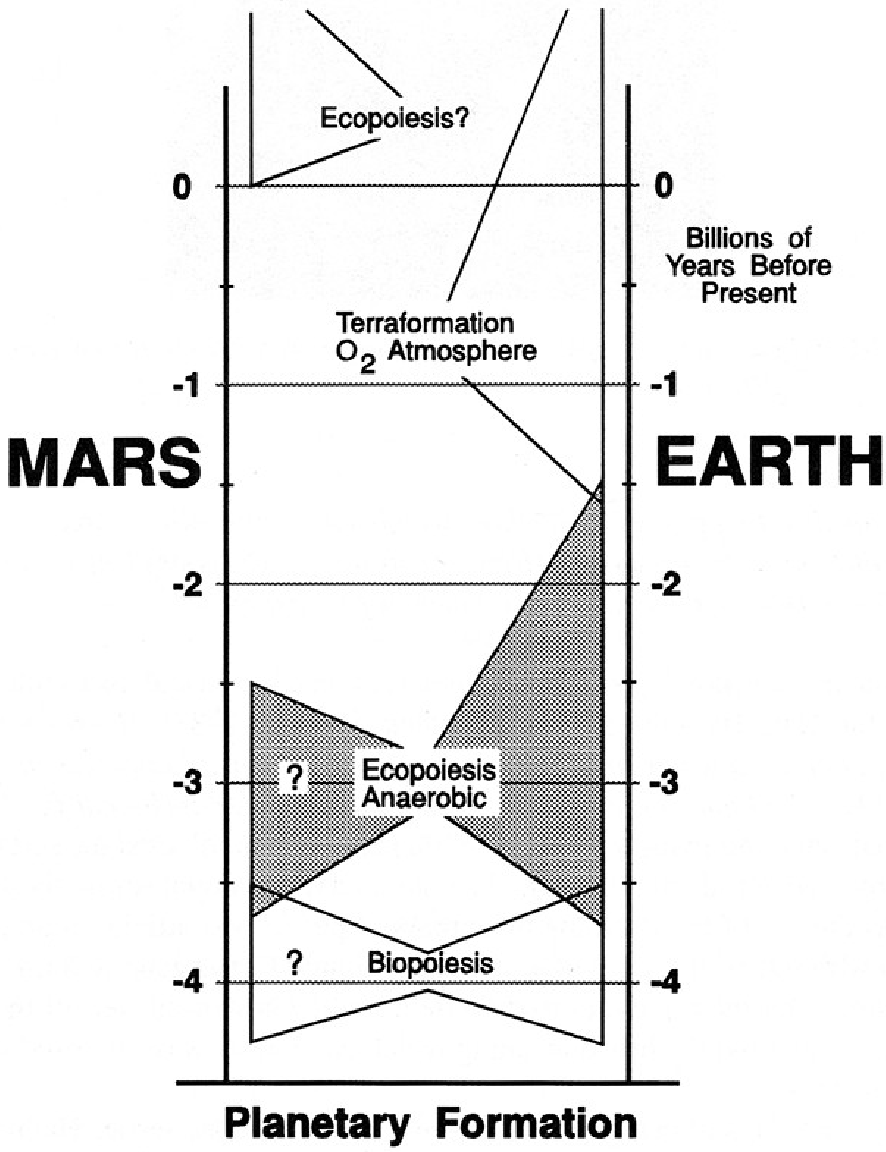

Figure 3.1 *The extension by Haynes and McKay of ecopoiesis and terraforming to natural as well as anthropogenic processes [9]. According to this use of terminology (not universally accepted), biopoiesis is the origin of the molecular building blocks of cellular life; ecopoiesis is the creation of a primordial anaerobic biosphere; and terraforming is the subsequent development of an aerobic biosphere.*

Ecopoiesis is however still in use, but mostly in a more restricted sense. Haynes and McKay [9] have pointed out that virtually any terraforming project is likely to follow a similar environmental trajectory as did the Earth, only greatly accelerated. In other words, microbial ecosystems will be seeded on a planet when its environment is still anaerobic, in order to set in motion biogeochemical cycles and to create soil. This would be an analogue to the Earth in the Precambrian Era where ecopoiesis can be said to have followed *biopoiesis* (the origin of life) and to have progressed entirely naturally. The planet could then either be left as it is or further engineered into a fully-terraformed aerobic state. Haynes and McKay therefore defined ecopoiesis and terraforming as being consecutive stages in a process of planetary engineering (see Figure 3.1), that can occur naturally (as on Earth) or artificially; the former representing the creation of an anaerobic biosphere and the latter its evolution into an aerobic biosphere.

This arrangement received some robust criticism from some of the participants at the 1991 Workshop on Terraforming Mars held at the Ames Research Centre. The principal sticking point seeming to be the unconventional extension of both terms to encompass natural, non-engineering, processes. It also ignores the reality that terraforming is now firmly established as the generic term for the whole process. We do use ecopoiesis extensively in this book however — but to make it consistent with the definitions of terraforming and planetary engineering given above, we define it thus: *Ecopoiesis is the fabrication of an uncontained, anaerobic, biosphere on the surface of a sterile planet. As such, it can represent an end in itself or be the initial stage in a more lengthy process of terraforming.*

Ecopoiesis is therefore a sub-set of terraforming as illustrated in Figure 3.2.

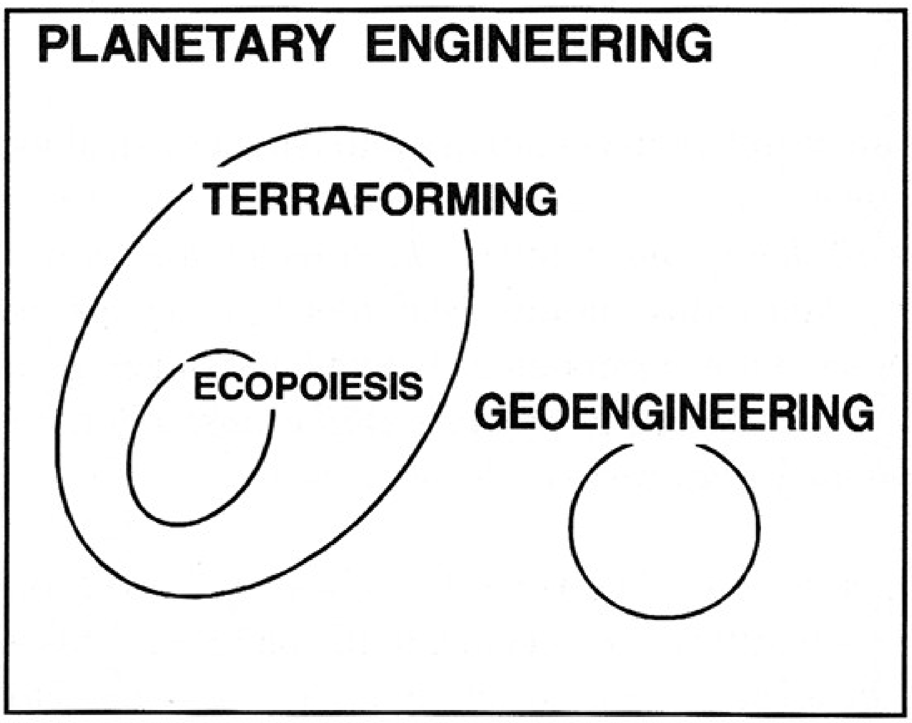

Figure 3.2 *The use of the terminology in this book: Ecopoiesis is a subset of terraforming and both terraforming and geoengineering are subsets of planetary engineering. See text for their full definitions.*

3.3 Philosophical Attitudes to Terraforming

Attitudes towards our study of and position within the Earth's biosphere inevitably influence speculation over terraforming. It is appropriate therefore to explore the prominent philosophical strands within biospheric science and how they map into terraforming studies. Whilst it is impractical to specifically distinguish all individual viewpoints, a general categorization of approaches to the subject is of use, especially in explaining the widely differing assumptions made by researchers.

The range of thinking concerning the biosphere of the Earth spans a continuum between opposite poles of *ecocentrism* (a nature-centred ethic) and *technocentrism* (a technology-centred ethic) — the *Gaia Hypothesis* being associated with the former and the concept of the *noosphere* with the latter [10]. Advances in the study of the biosphere and legitimate concern over its exploitation has led to much current opinion being attracted towards the former, "green," point of view.

The Gaia Hypothesis rightly emphasizes the role of the biota as a whole in running biogeochemical cycles and, in particular, the crucial part played by microorganisms — the sole inhabitants of the planet for > 80% of its history [7,11]. The activities of human civilization however are regarded as, at best, an irrelevance and, at worst, a planet-threatening malady. An example of this school of thought is well illustrated in a joint essay by Lynn Margulis (Professor of Biology at the University of Massachusetts and the co-founder of the Gaia Hypothesis with Lovelock) and science writer Dorian Sagan [12]. For instance they relegate the importance of consciousness with the following words, *"Gaia is synonymous with the biosphere, a sort of proper noun (derived from the Greek goddess of the Earth) we can use to address this provident entity of which our human wisdom is only a small (and perhaps ultimately insignificant) part."*

They abstract the notion of individual creativity into a hypothetical global holism by saying, *"Thus human beings are not special, apart or alone... Ours is a permutation of the wisdom of the biosphere... As with theory and intellect, high technology also is not really ours, but planetary in nature..."* And following this, Margulis and Sagan expose what they seem to regard as the futility of any human aspirations beyond that of being plain biotic citizens, *"In a deep way our economists must be shown that even the most industrious amongst us are never productive: only the photosynthesizers can harvest the sun."*

As emphasized in Chapter 2, the Gaia Hypothesis has much to recommend it as a position from which to attempt a scientific understanding of life on Earth. This is regardless of whether it ultimately proves to be an accurate description of the biosphere. However, there is a more profound reason for its wider influence and this is because it can be adapted to accord perfectly with the foreboding spirit of our age: *"...we must make up our real deficit and repay our debt to the biosphere by studying it. Otherwise it may foreclose on us."*

Both Lovelock and Margulis have expressed an interest in terraforming, although they tend to refer to ecopoiesis (see Lovelock's quote in the previous Section). A number of other terraforming researchers however, whilst not overt adherents of Gaia, approach terraforming in a generally ecocentric way (especially terraforming Mars — see Chapter 5). There are two principal elements to the ecocentric approach. The first is a strong aversion to the "technical fix," i.e. a desire to minimize as much as possible the level of planetary engineering and conscious design inherent in any scenario. This is replaced as much as possible by exploiting Gaian concepts such as the ability of life (especially microbes) to unconsciously proliferate over a planetary surface and self-organize into a global entity capable of improving and regulating the environment for its own benefit.

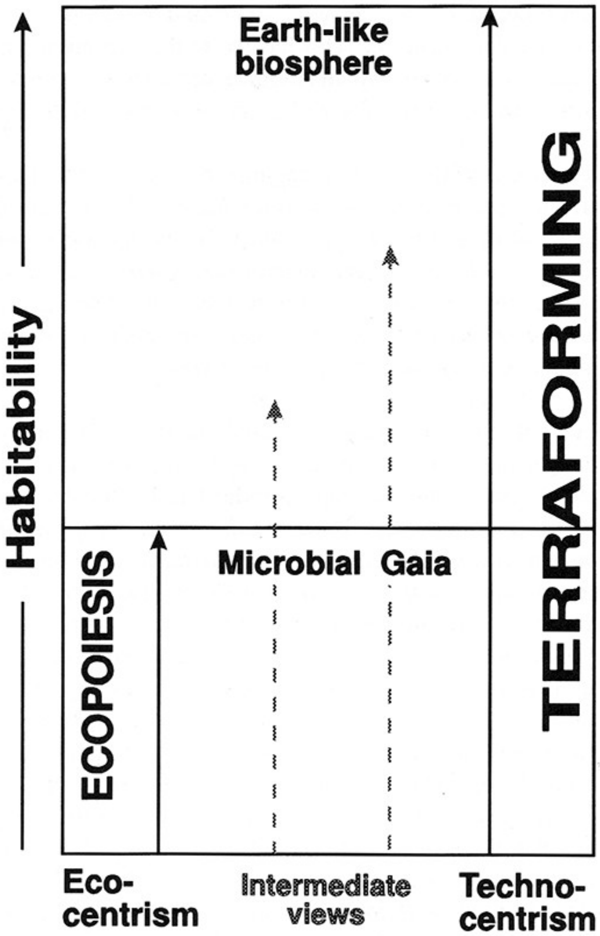

Figure 3.3 *The range of philosophical attitudes to terraforming. Ecocentrists focus their interest on the creation of an integrated biosphere and are not so concerned with the sophistication of its component organisms or with planetary engineering. Technocentrists regard human goals as paramount and therefore seek engineering solutions to create a specifically human habitable environment. Most researchers adopt intermediate views.*

The second element in the ecocentric approach is to downplay the importance of human motivations and aims in favour of Gaian ones. The emphasis is therefore placed on the birth of a new Gaia, rather than the specific goal of creating a biosphere habitable for man; (the notion of a technologically intense, anthropocentric restructuring of a planet is often regarded as impractical or ethically suspect). *The focus of ecocentrism is therefore ecopoiesis* and further terraforming to provide life-support for higher organisms is normally considered vaguely, or not at all (see Figure 3.3). The ecocentric model for terraformers is therefore often some variant of the Earth in the Precambrian, rather than the present day.

The technocentric view of the biosphere is exemplified by the concept of the noosphere (literally, the envelope of mind). In total contrast to Gaia, the evolution of human beings and their use of technology to intervene in biogeochemical cycles is seen as a progressive step in biospheric evolution — a transition from inadvertent to conscious intervention in the processes of the biosphere so as to sustain a more ordered and information-rich system. Ironically, the co-creator of the noosphere concept was none other than Vladimir Vernadsky (see Section 1.2), the founder of biospheric science. This has led to the curious situation where one can find articles by modern life-scientists which eulogise Vernadsky as a great historical antecedent and yet which disagree fundamentally with some of his more radical views [12].

Vernadsky was not only one of the first to recognise the biosphere, but also the global influence of civilization. *For him consciousness was not insignificant, it was paramount*. Human work was not futile but of evolutionary significance. In his last, and possibly greatest paper, he put it thus [13]: *"The whole of mankind put together represents an insignificant mass of the planet's matter. Its strength is not derived from its matter, but from its brain. If man understands this, and does not use his brain and his work for self-destruction, an immense future is open before him in the geological history of the biosphere."*

To Vernadsky, the advent of technological civilization on the evolutionary stage did not represent so much a danger to the status quo, as an opportunity for the biosphere to undergo a transition to a quasi-conscious state, a change as radical, as he saw it, as the Cambrian explosion. *"There arises the problem of the reconstruction of the biosphere in the interests of a freely thinking humanity as a single totality. This new state of the biosphere, which we approach without our noticing it, is the noosphere... The noosphere is a new geological phenomenon on our planet. In it for the first time man becomes a large-scale geological force. He can and must rebuild the province of his life by his work and thought, rebuild it radically in comparison with the past. Wider and wider creative possibilities open before him."*

He therefore had a faith in the pursuit of science and the advances in technological development and social organization that he expected to follow. Even in the midst of a terrible World War, which ravaged his country more than any other, he looked forward to a positive future for man, life and the biosphere — not just on the Earth, but in space. *"Fairy tale dreams appear possible in this future: man is striving to emerge beyond the boundaries of his planet into cosmic space. And he probably will do so... We are entering the noosphere... Therefore, we may face the future with confidence. It is in our hands. We will not let it go."*

The contrast between this dynamic optimism and the stern warnings of some modern environmentalists is about as total as one can imagine. Of course, the extent of our knowledge has expanded greatly since Vernadsky's pioneering syntheses. Whilst the need for some kind of intelligent management of our civilized planet is indisputable, the desirability of a wholesale anthropocentric restructuring of the biosphere is less obvious. Moreover, since civilization on Earth has evolved in a fragmented and haphazard fashion and since the processes of the biosphere do not necessarily need the guiding hand of mankind, perhaps his vision of the Earth-bound future was too sanguine and holistic. Nevertheless, Vernadsky does offer a vision of man as a species of planetary engineers, with an imperative to complexify a planetary environment, not just for himself, but for the life-support systems that support him. *It is thus in terraforming where this imperative comes into its own* [8].

The principal element of the technocentric approach are therefore the opposite of those inherent in ecocentrism. *Conscious* direction of the terraforming process is crucial. The “technical fix” is not considered suspect or unethical at all, but rather as an acceptable means to an end. There are no qualms about using whatever planetary engineering is required to achieve the desired result. Life tends to be regarded as something that is introduced into a suitable environment, deliberately created by technological or biological *engineering*. Gaian mechanisms are sometimes invoked to stabilize the post-terraformed regime, but if these appear inadequate, conscious direction of biogeochemical cycles is admissible. *Human aims are paramount and thus technocentrists focus their interest from the outset on the creation of an aerobic biosphere — ecopoiesis being just an initial stage on the road to full terraforming* (see Figure 3.3). The technocentric model for terraformers is therefore the present day Earth (see Section 2.7). On planets where self-stable earth-like biospheres are not possible, habitable conditions might be maintained by an element of conscious control — biosphere would surrender its place at the top of the ecological hierarchy to the noosphere [8].

Thus ecocentrism and technocentrism represent idealizations of ecology on the one hand and technology on the other: in reality people's views are positioned in a spectrum of possible alternatives that exists between them [10] (illustrated in Figure 3.3). However, they are of value as loose descriptions of two intellectual trends, especially in understanding approaches to terraforming Mars.

3.4 Conditions for Habitability

Although we have identified a copy of the Earth as being the ideal extraterrestrial habitat for man and terrestrial life, practical limitations in many instances may prevent terraformers from duplicating all of our planet's features. As we saw in the previous section, ecocentric terraformers may not include man at all in their speculations, preferring to focus on the requirements for ecopoiesis and, even if continuous terraforming to a human-habitable state takes place, the environment can be expected to progress though a continuum of states of improving habitability in which a progressively larger variety of organisms can survive. Thus it is essential for us to define the limits to habitability of the entire range of life, in terms of those environmental parameters directly relevant to physiology, such as gravity, temperature, pressure, atmospheric composition, illumination etc. Comparison of the envelope defined by these limits with the parameters of a given planet permits a crude appraisal of the requirements of terraforming.

3.4.1 Direct Constraints on Parameters Imposed by the Requirements of Life

3.4.1.1 Temperature

Physiological constraints on temperature, total atmospheric pressure (P_{atm}) and the partial pressures of important atmospheric constituents (pCO_2, pO_2, pN_2) are shown in Table 3.1. Three separate tolerance ranges are listed: that for microorganisms, higher plants and humans. These divisions are admittedly somewhat arbitrary, as there is great variation in each group and terraforming is expected to be a continuous, rather than a three-step process. Nevertheless, Table 3.1 aims to give a rough indication of the environment planetary engineers would need to create to achieve 1) minimal ecopoiesis; 2) widespread cover of plants; and 3) a rich inventory of animals and conditions suitable for unprotected human beings.

The quintessence of life is liquid water, and one of its determinants is temperature. The temperature range tolerable by microorganisms is remarkable and the microbial ecosystems of Antarctica typify the sort of life that can survive where extreme cold is a limiting factor. Cryptoendolithic communities (algae, cyanobacteria and fungi that live in porous rock) are perhaps the most psychrotolerant ecosystems on Earth [14,15], clinging to a sparse existence in the Ross Ice Desert where temperatures can fall as low as -48^{o}C. However, for metabolism to function in a way that will permit growth, it must be much warmer than this and it has been shown that net primary production is possible at -10^{o}C, reaching optimal values at ~ 0^{o}C. For continued survival, a certain length of time each year is required where temperatures rise into the metabolically active range (evidence has been found for extinct cryptoendolithic communities where presumably this did not happen [16]). A minimum period of > 500 hours/year at a temperature of ~ 0^{o}C has been suggested [17].

TABLE 3.1 LIMITS OF PHYSIOLOGICAL TOLERANCE. HABITABLE TEMPERATURES AND PRESSURES

Parameter	Limits/Ranges	Comments
Temperature:		
Microorganisms	< 110°C	Death of extreme thermophiles, e.g. *Pyrodictium*.
	> - 10°C	Metabolic activity of psychrophiles, e.g. Antarctic cryptoendolithic algae.
Higher Plants	< 45°C	Heat stress/death.
	> 0°C	Productive photosynthesis; cold stress in some species.
	10 - 30°C	Optimum range for germination of most seeds.
Humans	0 - 30°C	Habitable range of mean annual temperature, assuming optimum clothing.
	< 40°C	Hyperthermia in 24 hours at 50% humidity.
	> -10°C	Hypothermia in 24 hours (optimum clothing).
Pressure:		
Microorganisms		
P_{atm}	> 10 mbar	Water vapour pressure at 0°C plus minimum of CO_2 & N_2.
pCO_2	Wide range	
pO_2	Wide range	Anaerobes/Aerobes.
pN_2	> 1 - 10 mbar	Nitrogen fixation.
Higher Plants		
P_{atm}	> 90 mbar	Minimum of N_2 & O_2, plus 10 mb water vapour.
pCO_2	> 0.01 mbar	C4 photosynthesis; (> 0.1 mbar for C3 photosynthesis).
	< ? mbar	No clear upper limit, but damage to some plants at > 1 - 10 mbar.
pO_2	> 20 mbar	Root respiration.
pN_2	> 60 mbar	Buffer gas.
Humans		
P_{atm}	> 140 mbar	Pure oxygen (80 mb pO_2 (inspired) plus 60 mb lung water vapour).
	< 3700 mbar	Upper limits of N_2 & O_2.
Air mixture	440 - 2600 mbar	21% Oxygen
pCO_2	< 10 mbar	Toxicity
pO_2 (inspired)	> 80 mbar	Hypoxia
	< 530 mbar	Toxicity; could be up to 200 mbar lower
pN_2	> 285 mbar	Buffer gas, minimally breathable atmosphere, 25% O_2.
	< 3200 mbar	Nitrogen narcosis.

Thermophilic bacteria prefer scalding hot temperatures and thrive within hot springs, both on land and on the ocean floor. However, their metabolic optima are usually very close to their upper temperature limit — a few degrees above and they are killed. Various species of cyanobacteria can withstand temperatures of ~ 70°C, whilst some archaebacteria such as methanogens and extreme thermophiles can survive > 100°C under conditions where high pressure has raised the boiling point of water. One of the most thermophilic organisms known is *Pyrodictium occultum* which lives adjacent to hydrothermal vents on mid-ocean spreading ridges [18]. Its upper temperature limit is an extraordinary 110°C (see Plate 3.2).

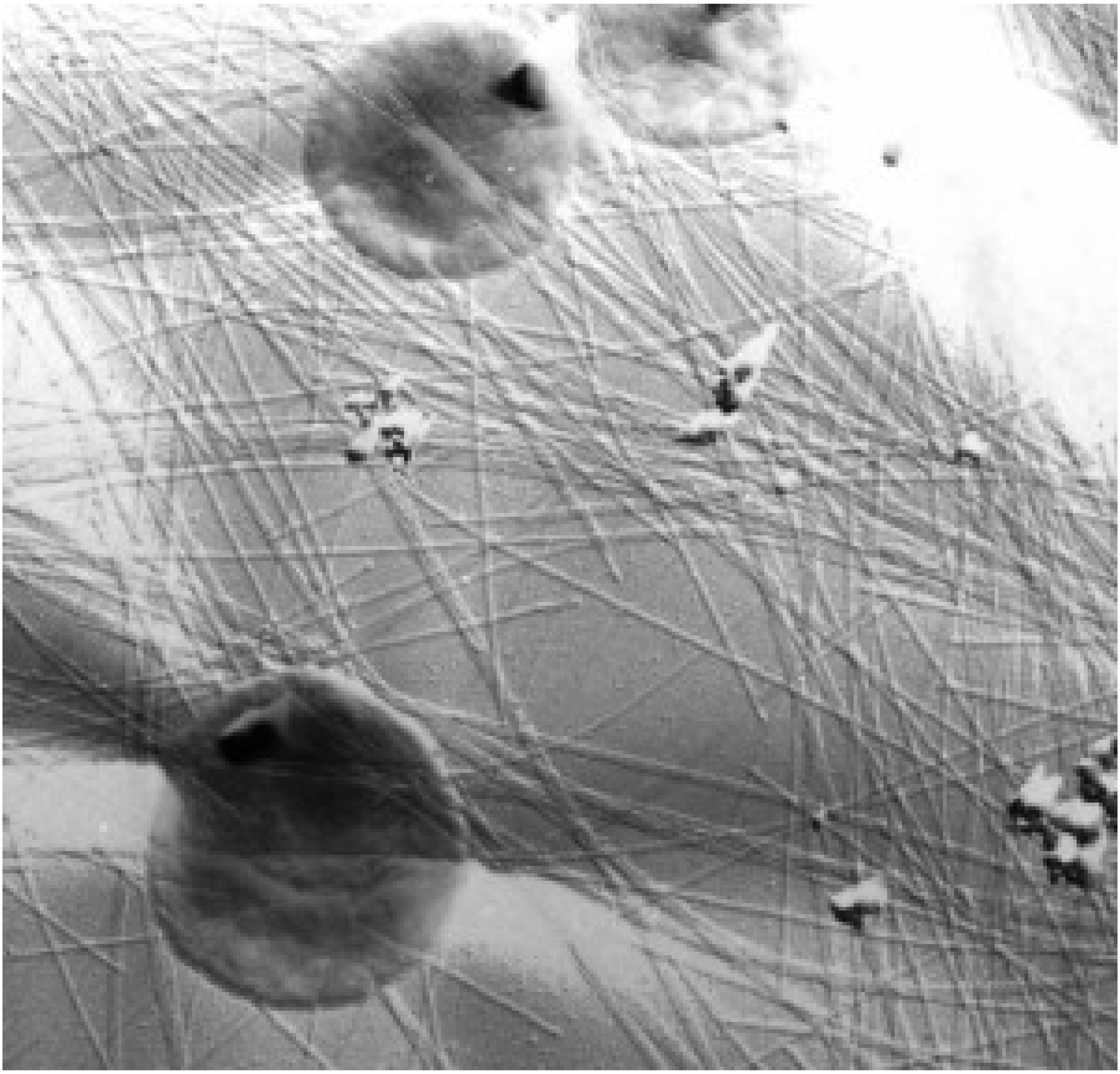

Plate 3.2 *Pyrodictium occultum: mag: 16,000X, air-dried, platinum shadowed. The most thermophilic organism known with a metabolic optimum of 105°C. Found in submarine volcanic vents, it is a strict anaerobe that gains energy for growth by oxidizing hydrogen with sulphur. Cells are irregularly disc- and dish-shaped and attached by a network of proteinaceous fibers to the rocky substratum. (micrograph courtesy of Reinhard Rachel.)*

The range of tolerable temperatures for multi-cellular organisms is much more restricted. Coniferous trees in Boreal forests can survive winter freezes of < -40°C, but require warm summers to put on growth. Many plants not specifically adapted to cold suffer fatal frost damage by one night's exposure at ~ 0°C. In general, productive photosynthesis requires temperatures of > 0°C and preferably > 10°C [19]. The optimum range for germination of most seeds and growth of most plants is 10 - 40°C. Heat stress and death occurs at > 45°C, unless specifically adapted to extremes — Death Valley cacti have a metabolic optimum of ~ 50°C and are killed only by temperatures > 65°C [19].

These temperature ranges are little different to those tolerable by animal life — which is hardly surprising, since plants are the basis of the food chain. *Homo sapiens* has shown a particular ability to cope with temperature variations and is thus found in more varied locales than any other animal species. This is of course because of one of our earliest technological inventions — clothing. However, even by varying clothing to optimize it to the environment, there are limits (by clothing we do not include artificially heated or refrigerated dress). At high temperatures, the relative humidity of the air becomes an equally important factor; above human body temperature (37°C) evaporative heat loss via perspiration must take on the entire burden of thermostasis and this cannot occur if the air is already saturated with water vapour (100% relative humidity). As temperature increases, relative humidity must be reduced and the time of exposure lessened to avoid hyperthermia. For instance, people can just about withstand 50% humidity at 40°C for 24 hours, but any longer than this would require lowering the temperature, humidity, or both [20].

At the other end of the scale, tolerance limits to cold are not easy to define. Humans live and work in Antarctica for instance, but only with the benefit of cold-weather attire and heated habitats. Even with optimum clothing however, prolonged exposure to < 0°C runs the risk of hypothermia as is demonstrated by the occasional deaths of well equipped, but inexperienced, mountain climbers trapped by freak weather conditions. Humans however cannot exist remote from the ecosystems that provide life support. Taking this into account therefore, a mean average temperature range of 0 - 30°C seems reasonable for sustainable human habitability, so long as the most extreme of seasonal variations do not take daily average temperatures much in excess of 40°C or far below -10°C [20].

3.4.1.2 Atmospheric Pressures and Chemical Composition

There is expected to be a wide range of atmospheric pressure consistent with habitability; the total barometric pressure consisting of tolerable partial pressures of essential constituents, such as nitrogen, oxygen, carbon dioxide and water vapour. This is especially so for microorganisms, with their extraordinary adaptability and metabolic variety. For instance strict anaerobes find oxygen lethal and some species of algae have been grown under pure CO_2 [21]. Conversely, aerobic bacteria have an absolute requirement for oxygen and can successfully assimilate CO_2 at partial pressures lower than the current pCO_2 of ~ 0.35 mbar. Between these two poles there are organisms capable of coping at lower oxygen tensions, or of switching between aerobic and anaerobic metabolism. Bacteria have also demonstrated the ability to tolerate and metabolize gaseous compounds that would be dangerous to higher organisms such as hydrogen, ammonia, methane and hydrogen sulphide. For a sustainable bacterial ecology, nitrogen fixation will be required at it has been estimated that the organisms responsible could carry out this process at pN_2 between 1 - 10 mbar, much less than the 790 mbar in the Earth's present atmosphere [22]. The minimum total atmospheric pressure that might be consistent with bacterial habitability would therefore be made up from water vapour pressure in equilibrium with an average planetary temperature of ~ 0°C (~6 mbar) plus essential amounts of N_2, O_2 and CO_2. McKay et al have estimated that ecopoiesis could proceed therefore with a total atmospheric pressure as low as $P_{atm} \approx 10$ mbar [23].

Higher plants are complex *aerobic* organisms which evolved in concert with animals and need more salubrious conditions. They are thus limited in their function by both pCO_2 for photosynthesis and pO_2 for respiration — the necessity for the latter is sometimes overlooked as it is easy to assume (wrongly) that since plants evolve O_2 as they grow, they are never limited by oxygen deficiency. The responses of plants to wide ranges of pCO_2 and pO_2 are however quite complex and vary not just between species, but in the way the data has been gathered. For practical purposes many experiments have been conducted in the laboratory and not in the field, and have been conducted in vitro, rather than in vivo. The discussion below therefore attempts no more than to define general limits on the large majority of plant life.

There are two types of autotrophic metabolism that must be considered. The majority of plants (~ 300,000 species) operate what is called C3 metabolism, whilst a much smaller group (~ 3000 species, but with important members such as sugar cane and maize) function with C4 metabolism [19,24]. For productive photosynthesis plants require light, water, carbon dioxide, mineral nutrients and a suitable temperature and a restriction in any of these essentials can be limiting (cf Equation 2.1). C3 plants are limited in their growth rates by the characteristics of the present environment in two ways. The low ambient pCO_2 limits the CO_2 assimilation rate so that at some level of irradiation, growth reaches a plateau. This *light saturation* begins at irradiation levels of > 200 μmol photons/m^2/s of photosynthetically active radiation (PAR) and is complete at ~ 1000 μmol photons/m^2/s. At > 1500 μmol photons/m^2/s, photoinhibition (a process whereby the chloroplast can become overloaded with energy) can cause the CO_2 assimilation rate to fall. (Full sunlight can peak at ~ 2000 μmol photons/m^2/s PAR). The other limitation is that high pO_2 stimulates high levels of photorespiration in C3 plants, which is the light-stimulated release of CO_2 from the leaves. It is completely different from mitochondrial respiration and therefore competes with photosynthesis, reducing its photochemical efficiency (mol fixed CO_2/mol photons). A lowering of pCO_2 eventually drives a plant to its *CO_2 compensation point* where net CO_2 assimilation is zero (photosynthesis = respiration) and growth ceases. Published values of the CO_2 compensation point vary, but there is general agreement that it lies not far below ~ 0.1 mbar. These points are illustrated schematically in Figures 3.4 and 3.5 which plot CO_2 assimilation rate vs. intensity of PAR and photochemical efficiency vs. CO_2 concentration respectively. The effects of light saturation and lowering pCO_2 on C3 metabolism (the solid lines) are quite evident.

Also shown on the Figures are the results of relaxing these constraints on C3 metabolism. Increasing pCO_2 increases the efficiency of photosynthesis and the CO_2 assimilation rate at which light saturation occurs. Doubling pCO_2 from its present value can increase the growth of many plants by ~ 30-60% and CO_2 enrichment in greenhouses is thus used commercially the increase productivity of many crops [24]. Prolonged exposure to ~ 1 - 10 mb of carbon dioxide can however damage some plants, although there is no clear upper limit of pCO_2 for plant life as a whole. It may be possible to adapt plants for existence at high concentrations of carbon dioxide, especially in view of the likelihood that pCO_2 may have been considerably elevated over the present value at times even in the recent geological past. C3 plants also respond well to a decrease in the partial pressure of oxygen since this reduces the rate of photorespiration. At low pO_2 photochemical efficiencies are increased.

The metabolism of C4 plants endows them with certain advantages over C3 in certain contemporary environments. C4 metabolism has additional mechanisms for concentrating CO_2 which reduces the CO_2 compensation point down to vanishingly low levels (~ 0.01 mbar) and renders the plant insensitive to pCO_2 over a wide range [19,24]. Photorespiration is much reduced so C4 plants are more efficient and are also largely insensitive to pO_2 (see Figure 3.5). Figure 3.4 shows that the rate of CO_2 assimilation continues to increase with irradiation and overtakes the yield of C3 metabolism at > 200 μmol photons m^2/s. There is no light saturation and photosynthesis can take advantage of full sunlight. C4 plants are therefore optimized for warm, sunny climates and low pCO_2.

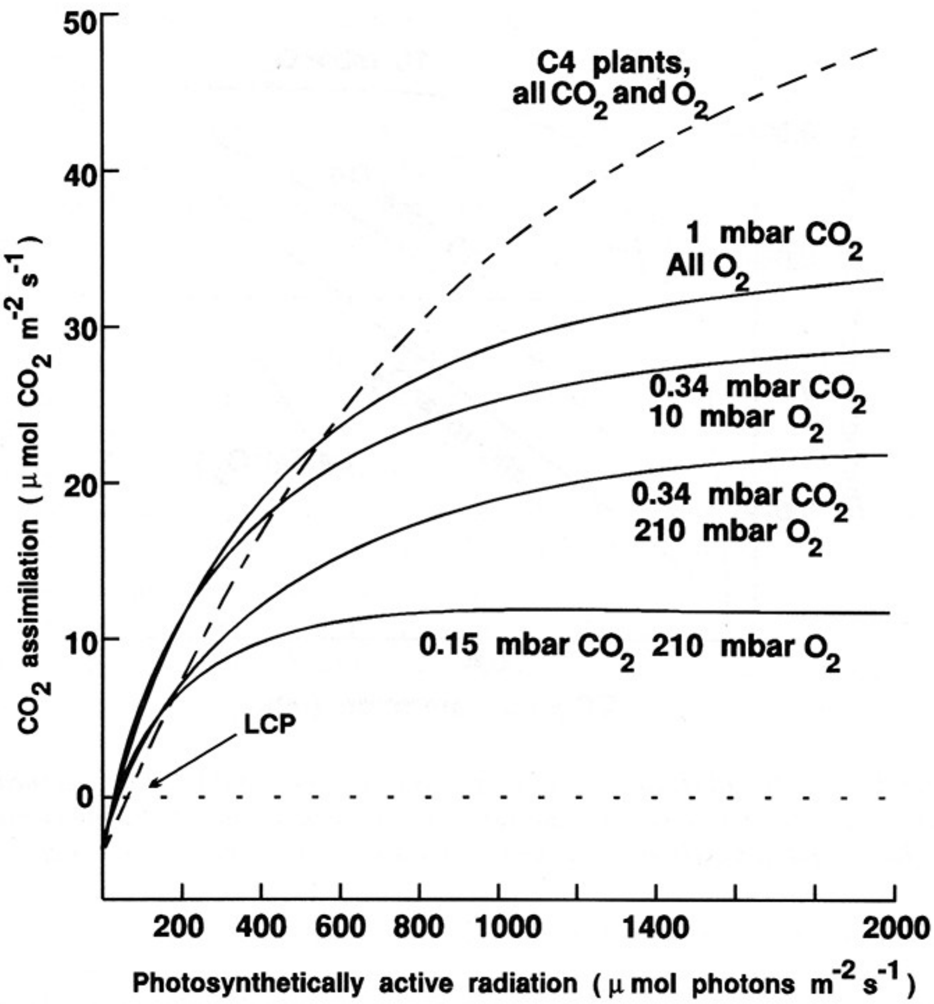

Figure 3.4 *The rate of net photosynthesis plotted against the intensity of photosynthetically active radiation. The effect of light saturation on C3 plants is seen by the flattening of the solid curves, as are the improvements in performance with increased CO_2 and reduced O_2. The light compensation point (LCP) is shown where the curves intersect the zero net CO_2 assimilation line. (A schematic compilation of data: reproduced with permission from Ref. [24].)*

Although reducing the partial pressure of oxygen can improve the performance of C3 photosynthesis, a certain level of oxygen is nevertheless required for respiration, particularly in tissues where there is high metabolic activity [19]. Isolated mitochondria are unaffected by $pO_2 < 1$ mbar; however oxygen must pass through tissues by diffusion which is driven by a concentration gradient. Substantially higher values of ambient pO_2 are therefore required to permit adequate oxygenation of interior tissues. The oxygen level below which respiration is impaired is known as the *critical oxygen pressure* (COP) and varies greatly for different tissues [25]. One of the organs of a plant where oxygen is in most demand is the root, especially the apical meristem which needs energy for growth and uptake of mineral nutrients from the soil against an osmotic gradient. Since the roots are isolated from an unrestricted flow of air and since they must compete with the soil microbiota for oxygen, it is reasonable to consider the high COP of this vital organ as limiting the whole plant. Even though the Earth's atmosphere is rich in oxygen, there are many land habitats (especially those prone to flooding) where plant roots suffer hypoxia, or even anoxia [26]. The former reduces growth and prolonged exposure to the latter normally results in death. Reduction of pO_2 from present levels, although initially beneficial for C3 plants, can be expected to increase the surface area of oxygen deficient habitats, until a point is reached where even well aerated soils become hypoxic and a varied, vigorous and widespread inventory of higher plants is not possible.

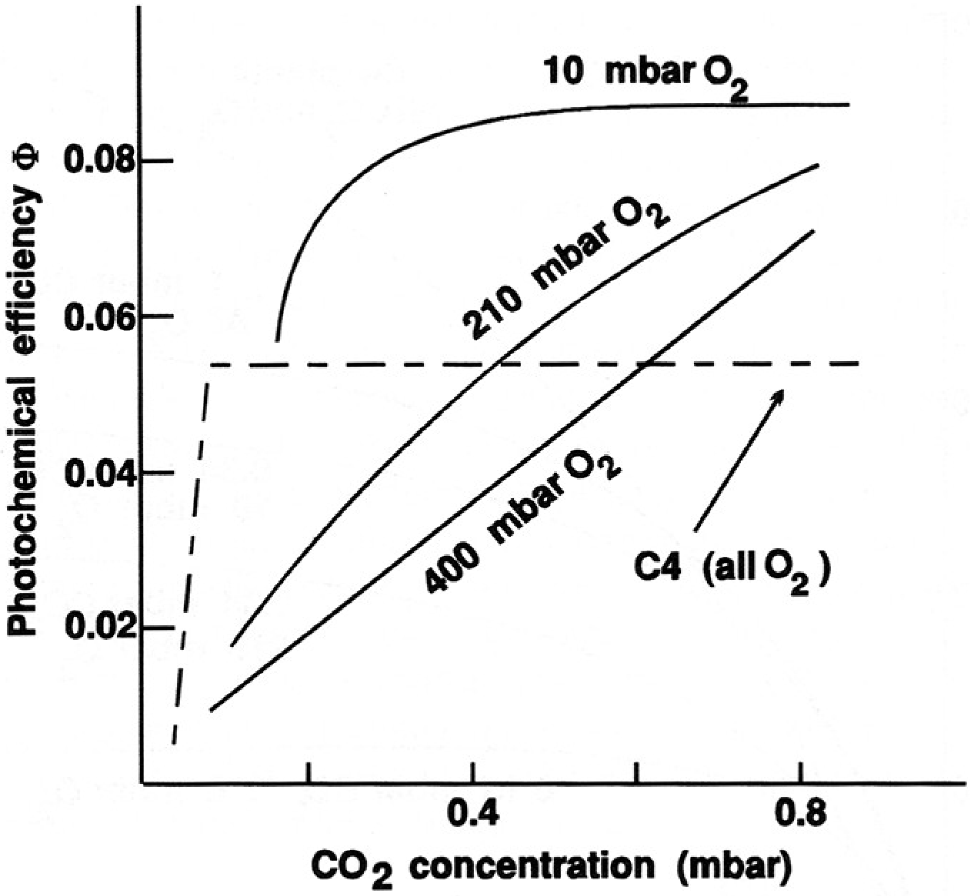

Figure 3.5 *Photochemical efficiencies for C3 plants (solid lines) and C4 plants (dashed line), plotted against CO_2 concentration. C3 plants are seen to be significantly limited under present-day atmospheric conditions. (Highly schematic: reproduced with permission from Ref. [24].)*

Experimentally determined root COPs vary widely and values of $pO_2 > 100$ mbar are usually reported for excised root tips. In vivo experiments however report lower values of ~ 20 - 60 mbar; this reduction has been attributed to the fact that intact plants contain aerenchyma — air spaces that allow the internal transfer of gas from above ground to below [25,27]. A high proportion of gas space characterizes wetland plants that are specifically adapted to cope with hypoxia and temporary bouts of anoxia. For unrestricted respiration in species such as rice, it has been estimated that this ventilating system must be such as to maintain $pO_2 > 20$ mbar in the region of the roots [25]. Prolonged anoxia, affecting all parts of a plant, appears not to be tolerable. However, since photosynthesis outstrips respiration during active growth, plants actually produce more oxygen than they require for respiration. In principle therefore, it would seem that some sort of internal recycling and ventilation mechanism could allow plants to survive in completely anoxic environments. Whether plants can be adapted, or genetically engineered to survive in an ambient $pO_2 \rightarrow 0$ is an open question. At the present time, terraformers cannot realistically rely upon this being possible.

Thus, we might choose pO_2 = 20 mb as a rough ballpark figure of the lower threshold at which a satisfactory plant biosphere can be established. Some plants may well be able to survive at lower concentrations and others, especially rapidly growing species with a need for vigorous root respiration, will undoubtedly be limited in performance or viability until higher values are reached.

The only other gas to limit plant habitability is nitrogen. Plants obtain nitrogen for growth from the soil as the mineral salts ammonium and nitrate, forms that are made available by microorganisms (cf Chapter 2.5.2). However, it, or some other inert gas, must be present in much larger quantities in the atmosphere than that required by nitrogen fixation so as to inhibit the spread of fire. Flammability is more a function of the volume proportion of oxygen rather than partial pressure. A fraction of > 25% oxygen in an atmosphere apparently runs the risk of even damp vegetation catching fire [28] (a not undisputed figure [29]) and so we require a minimum of 75% of the mixture to be of some inert buffer gas, or gases. The only reasonable candidate for the bulk of this requirement is nitrogen. So our minimum pN_2 is ~ 60 mb; combining this with a fraction of a mbar CO_2, 20 mb pO_2, and 10 mb pH_2O (vapour pressure in equilibrium with T_{surf} = 10°C) gives a minimum total atmospheric pressure for "plant world" as $P_{atm} \approx$ 90 mb.

We can assess human tolerance to variations in atmospheric pressure and composition perhaps a little better than for plants since there is a wealth of data to draw on provided by populations acclimatized to different altitudes. Atmospheric pressure falls with altitude according to the barometric law:

$$P_{atm} = P_0 e^{-z/h} \tag{3.1}$$

where P_0 is the sea level pressure (1013 mbar), z is the height above P_0 and h is the scale height, the vertical distance through which P_{atm} is reduced by a factor of 1/e. The formula for the scale height is:

$$h = \frac{RT}{M_m g} \tag{3.2}$$

where R is the Gas Constant (8.314 J/K/mol), T is the temperature, M_m is the average molar mass of the atmosphere and g is the acceleration due to gravity. Near the surface of the Earth where T ≈ 288 K and $M_m \approx$ 0.029 kg/mol, h ≈ 8400 m. Temperature falls with altitude which tends to decrease the scale height, but for our general purposes it is a sufficient approximation to assume h is constant at its near-surface value. When determining limits on breathable oxygen, we must take into account that air in the lungs is humidified and saturated with water vapour at body temperature (at 37°C, $pH_2O \approx$ 60 mbar). A correction must be made to calculate the inspired partial pressure of oxygen in millibars [20]:

$$pO_2\,(\text{inspired}) = fO_2(P_{atm} - 60) \tag{3.3}$$

where P_{atm} is in units of millibars and fO_2 is the volume fraction of oxygen. The value of pO_2 (inspired) at sea level is therefore 200 mbar.

The body can acclimatise to significantly lower oxygen pressures by such physiological adaptations as increasing the blood red cell count and thus its oxygen carrying capacity. Sea-level dwellers need to increasingly acclimatise to altitudes > 3100 m where P_{atm} < 700 mbar, pO_2 < 147 mbar and pO_2 (inspired) < 135 mbar. However, the maximum altitude for normal function is much higher than this [30]. In the Andes there are permanent human settlements as high as ~ 5000 m ($P_{atm} \approx$ 560 mbar, $pO_2 \approx$ 118 mbar, pO_2 (inspired) $\approx$ 105 mbar) and there is evidence that one can live and feel fit indefinitely at ~ 7000 m ($P_{atm} \approx$ 440 mbar, pO_2 $\approx$ 92 mbar, pO_2 (inspired) $\approx$ 80 mbar) [20,30]. We might adopt these latter values therefore as describing the lower pressure limit of an air mixture tolerable by a well acclimatized population, although superbly fit and highly trained climbers have made it to the top of Everest (8848 m) without bottled oxygen ($P_{atm} \approx$ 350 mbar, $pO_2 \approx$ 74 mbar, pO_2 (inspired) $\approx$ 62 mbar).

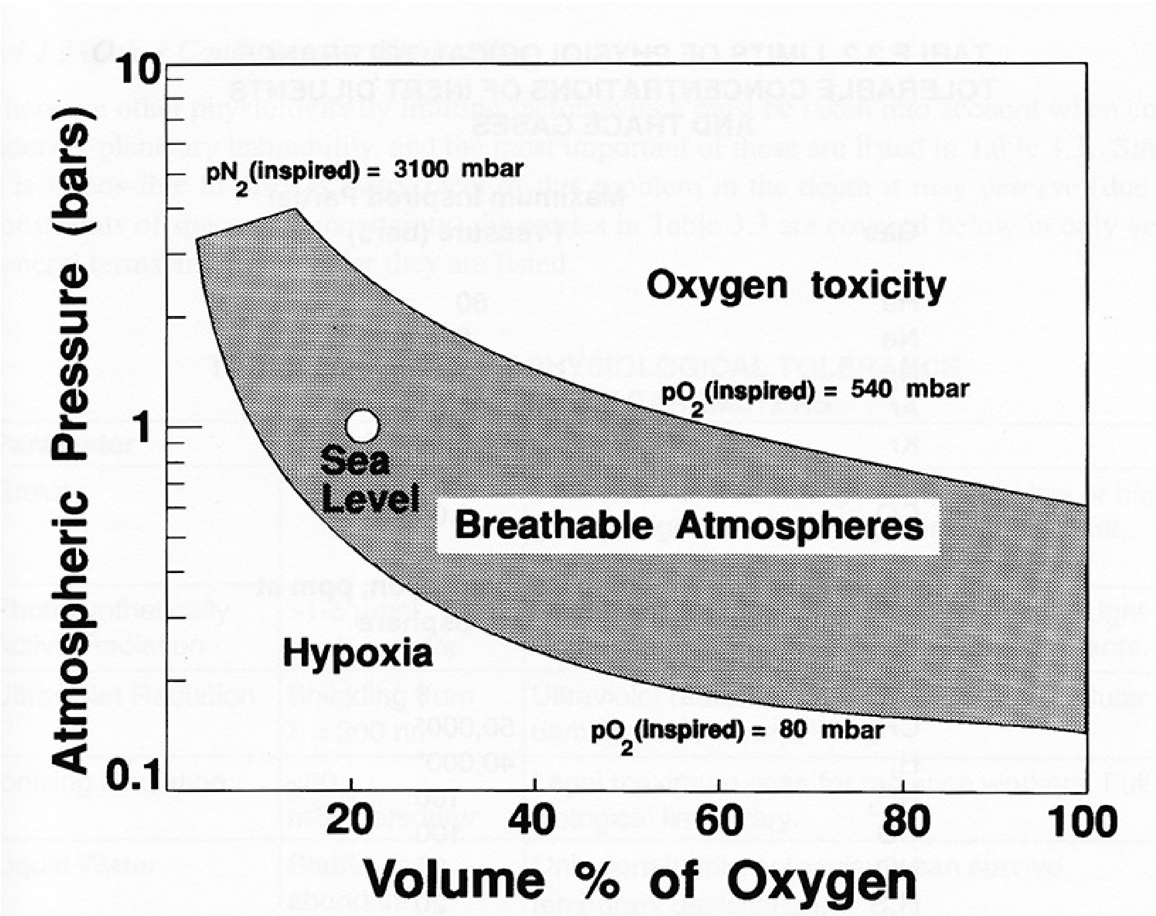

Figure 3.6 *Breathable atmosphere as defined by Eq. 3.3 and toxic or hypoxic limits of oxygen and nitrogen. Ideally, the volume percentage of oxygen should be constrained within 15-25% to support acceptable levels of flammability. (This assumes 1g: in fact, since convection depends on gravity and flames are fed by convection, this band would shift to higher percentages at lower gravities and vice versa.)*

The lowest pressure breathable atmosphere is one of pure oxygen: with a pO_2 (inspired) of 80 mbar and fO_2 = 1, P_{atm} = 140 mbar; below this, people will require pressure suits to survive [20]. However, as mentioned above when discussing plants, pure oxygen atmospheres are not practical due to fire risk and so ideally, a > 75% mole fraction of buffer gases is required. Realistically therefore our minimum pressure habitable atmosphere at pO_2 (inspired) = 80 mbar and fO_2 = 0.25 will be of total pressure P_{atm} = 380 mbar with some 285 mbar of buffer gases, the great bulk of which will be nitrogen.

TABLE 3.2 LIMITS OF PHYSIOLOGICAL TOLERANCE.
TOLERABLE CONCENTRATIONS OF INERT DILUENTS AND TRACE GASES.

Gas	Maximum Inspired Partial Pressure (bars).
He	80
Ne	5
N_2	3.1
Ar	1.6
Kr	0.46
Xe	0.21
CO_2	0.009

	Toxic Concentration, ppm at 1 Atmosphere.
N_2O	†
CH_4	50000*
H_2	40000*
NH_3	100
CO	100
NO_2	25
H_2S	20
HCN	10
H_2CO	10
HCl	5
SO_2	5
Cl_2	1
F_2	0.1
O_3	0.1

† Analgesic effects at > 10% concentrations in air.
** Lower flammability limit in air, toxic level is at higher concentration*

Data adapted from Ref. 20.

Characteristics of tolerable high-pressure atmospheres are controlled by the maximum permissible inspired partial pressures of oxygen and nitrogen. Whilst pure oxygen at sea-level pressure can be tolerated for a while, it is toxic at prolonged exposures at pO_2 (inspired) > 530 mbar; nitrogen becomes narcotic at pN_2 (inspired) > 3100 mbar (both these values are approximate and would be subject to individual variation) [20]. The highest-pressure air mixture consistent with prolonged habitability is therefore $P_{atm} \approx$ 2600 mbar. Greater pressures than this are attainable by lowering the percentage of oxygen so that nitrogen becomes the limiting factor instead — survivable pressures up to $P_{atm} \approx$ 3700 mbar are then possible. Equation 3.3 and the limits discussed above thus define an envelope of possible breathable nitrogen/oxygen atmospheres, which is illustrated in Figure 3.6. Full terraforming will aim to create an atmosphere somewhere in this envelope, preferably between $fO_2 = 0.15 - 0.25$ to permit an acceptable rate of combustion.

There are other gases that might comprise a habitable atmosphere, both in bulk and trace amounts and are listed in Table 3.2. Naturally occurring inert gases have the potential to supplement nitrogen in the role of a fire suppressant and the choice is shown in the top half of the Table, alongside an estimate of its maximum tolerable inspired partial pressure. Helium and neon are tolerable at greater pressures than nitrogen and helium is therefore used to buffer oxygen against oxidation in breathing mixtures for deep sea diving. However, both are rare, except in gas giant planet atmospheres and helium is especially prone to escape from small planets due to its small atomic mass. Argon is relatively common (~ 1% of the Earth's atmosphere), heavy, and is tolerable up to pAr (inspired) ≈ 1600 mbar; however the likelihood is that, on any planet one could conceive of terraforming, it would not be common enough. Substantial (and perhaps impractical) importation of Argon from elsewhere would be needed to make up a significant proportion of a habitable atmosphere. Table 3.2 shows that carbon dioxide becomes toxic at pCO_2 (inspired) > 9 mbar, ~ 1% CO_2 in sea-level air. As will be shown in Chapter 7, terraforming Venus will entail having to *remove* ~ 90000 mbar of carbon dioxide.

Other highly reactive gases must be restricted to trace levels and, for human tolerance, below the part per million thresholds shown in Table 3.2. Some of these species occur naturally at lesser concentrations in the atmosphere of the Earth and are of biological origin (N_2O, H_2, CH_4, NH_3, H_2S). On a terraformed planet with a tendency towards cold temperatures it might be desirable to increase their concentration because of their greenhouse effect. A suitable microbial biota could withstand much higher limits than shown in the Table, especially as the latter four compounds are of use to lithotropic metabolism and are 'food' for many bacteria.

3.4.1.3 Other Conditions for Habitability

There are other physiologically limiting factors which must be taken into account when considering planetary habitability and the most important of these are listed in Table 3.3. Since it is impossible to discuss every facet of this problem in the depth it may deserve (due to constraints of space and uncertainty) the entries in Table 3.3 are only covered below in very general terms and in the order they are listed.

For humans to be able to settle other planets, it will first be essential to establish the range of gravitational acceleration consistent with normal development and a healthy life. This is especially important to terraformers as the gravity of other worlds will probably be an impracticable parameter to alter. If gravity is too low or too high to allow people to make a permanent home of a planet then terraformers will have to content themselves with some sort of ecopoiesis and may decide not to bother at all. Unfortunately, we have very little evidence to go on. Terrestrial life has evolved under the uniform and constant gravitational acceleration of 9.8 m/s^2; astronauts and other laboratory organisms have spent extended times in orbit subject to ~ 0 m/s^2 — there is unfortunately no data of *long-term* survival at other accelerations and the only experience we have at all comes from experiments in aircraft and centrifuges. It does appear that there are serious problems with prolonged human life at zero gravity, especially with decalcification of the bones; whether people can be adapted for an indefinite life in free fall with a regime of drugs and exercise is an open question. The lower gravity threshold at which these problems start to become serious is not known [31]. Could children grow up healthily on the Moon (1.62 m/s^2) or Mars (3.72 m/s^2)? We would hope so, but cannot be sure. A terraformed Venus perhaps, with its earth like gravity of 8.60 m/s^2 inspires more confidence. Terraformers therefore have no choice but to wave their hands when somebody mentions gravity — there is presently no answer to our questions and will not be until it is possible to build habitats in space where gravity can be varied and the habitable threshold found by experiment. We can be fairly sure however that microorganisms could survive in just about any realistic planetary gravity field one can imagine.

TABLE 3.3 LIMITS OF PHYSIOLOGICAL TOLERANCE. OTHER HABITABLE PARAMETERS.

Parameter	Criterion/Range	Comments.
Gravity	?	Unlikely to limit microorganisms. Very low or high gravity might affect development of terrestrial, multicellular organisms. Limits unknown.
Photosynthetically Active Radiation.	> 1 - 5 μmol photons/m^2/s	Lower limit for productive photosynthesis (Light Compensation Point) for shade adapted plants.
Ultraviolet Radiation	Shielding from λ < 300 nm	Ultraviolet radiation causes genetic and cellular damage. Limits vary.
Ionizing Radiation	< 50 mSv/person/yr	Legal maximum dose for radiation workers. Full biological limits vary.
Liquid Water	Stable and abundant	Only certain microorganisms can survive temporary desiccation.
Salinity	< 0.1% NaCl < 32% NaCl	Quality irrigation water for most crops. Extreme halophilic bacteria.
pH	5 - 9 > 1 ; < 11	Most terrestrial environments. Acidophilic; alkalinophilic bacteria.
Mineral Nutrients	Present in accessible form	Macronutrients (see Table 2.1) and micronutrients, e.g. Se, Cu, Mo, I, Zn, Ni.

There is a minimum level of irradiation at which the net assimilation of CO_2 by plants falls to zero (photosynthesis = respiration). This is known as the *light compensation point* and is marked by the arrow on Figure 3.4. The LCP is generally lower for C3 metabolism than for C4. Plants used to growing in full sunlight cannot grow below a flux of ~ 20 μmol photons/m^2/s PAR whereas those adapted for shady conditions (such as under the canopy of a forest) can grow — very slowly — down to ~ 1 - 5 μmol photons/m^2/s PAR [19]. Undiluted sunlight is therefore adequate for some degree of photosynthesis as far from the Sun as ~ 50 astronomical units (AU — the distance of the Earth from the Sun). However, for reasonable rates of biomass production, some concentration or supplementation of natural sunlight will perhaps be required from the orbit of Jupiter outwards.

Other forms of radiation that are damaging to living tissue must be reduced to safe levels. These include ultraviolet light and ionizing radiation such as X rays, γ rays and high-energy particles emitted by radioisotopes and originating from space. UV radiation is removed in the atmosphere by photoionization and photodissociation. Absorption by oxygen removes radiation of wavelength < 200 nm as do other gases of greater abundance in other atmospheres, such as carbon dioxide. The surface however must also be shielded from UV of 200 - 300 nm which is especially lethal to living tissue in the range 250 - 270 nm where it damages DNA and RNA. On Earth, these wavelengths are absorbed by ozone (O_3) in the Stratosphere at a height of ~ 25 km and since ozone is a form of oxygen, it raises the question of how much oxygen is needed in an atmosphere to generate a sufficient ozone screen. (This question is pertinent to the habitability of the anoxic Earth in the early Precambrian as well as to hypothetical terraformed atmospheres). Joel Levine and colleagues [32] and a group headed by James Kasting [33] have modelled the problem and their calculations suggest that a functional ozone layer could exist at 10% the present atmospheric level of oxygen (0.1 PAL). However, they calculated the maximum ozone concentration would be lower down and the surface concentration would be considerably elevated, possibly to a dangerous concentration (ozone is damaging in very low doses — see Table 3.3). At 0.01 PAL, the ozone layer would still shield effectively between 220 - 300 nm, but would leave a 'window' open between 200 - 220 nm, where the ultraviolet is only attenuated to ~ 1 - 10% of its flux at the top of the atmosphere. Concentrations of oxygen at 10^{-3} PAL produce enough ozone to provide some attenuation around ~ 250 nm, especially at high latitudes, but no satisfactory shielding anywhere in the range. A reduction to 10^{-4} PAL results in almost no protective effect at all. Thus, we might assume that complete protection from ultraviolet radiation requires a column mass of oxygen equivalent to ~ 20 mbar on the Earth (0.1 PAL); satisfactory protection from most wavelengths is possible down to a terrestrial column mass of oxygen equivalent to ~ 2 mbar (0.01 PAL). Ecosystems protected from UV (for example under rocks, soil or water) could survive without a complete ozone screen — in fact they must have done this possibly for half the Earth's history. Once again however, such an existence would suit bacteria better than multicellular land dwelling organisms.

Plate 3.3 *Deinococcus radiodurans: mag: 35,000X. An aerobic , heterotrophic bacterium with impressive resistance to ultraviolet and ionizing radiation which appears to be due to a multilayered cell wall, carotenoid pigments, and efficient DNA repair mechanisms. Viable cells have been isolated from the cooling waters of nuclear reactors. Many strains of deinococci are also known to resist desiccation. (Micrograph courtesy of R.G.E. Murray.)*

Charged particles from the solar wind and deep space can be deflected away from the Earth by the planet's magnetic field. The flux that reaches the top of the atmosphere, including high-energy cosmic rays, is greatly attenuated in its passage to the surface by interaction with the column mass of air. The average annual dose of cosmic rays received by an inhabitant of the UK is estimated to be ~ 300 μSv [34] and, as one would expect, this increases with altitude: for instance, an airline flight from the UK to Spain exposes passengers to an extra ~ 10 μSv. The average annual dose from natural terrestrial radiation (γ rays, radon products, and isotopes in food such as ^{14}C and ^{40}K) is much higher at ~ 1570 μSv; whilst the additional annual increment from artificial sources (mainly medical procedures) averages at ~ 280 μSv. The estimated risk factor for serious hereditary defects in the first two generations and of fatal radiation-induced cancers is 1.65×10^{-2}/Sv; assuming a linear relationship between exposure and risk gives an illness probability ~ 3.5×10^{-5}/person/year (much less than the risk inherent in cigarette smoking or bad diet) [34]. The legal upper limit of annual exposure for workers in the radiation industry (very rarely reached) is > 100 times the background rate at 50mSv — this increases the illness probability to ~ 8.25×10^{-4}/person/year (of a similar order to smoking-related diseases). It does not seem likely that natural ionizing radiation doses higher than this will be acceptable for a permanently established population. Terraforming therefore must create atmospheres of sufficient column depth to provide adequate shielding and must not leave behind dangerous quantities of radioactive waste. Dose limits for other organisms could of course be considerably higher. Again, certain bacteria seem to be the most resistant to this kind of environmental stress (see Plate 3.3) — viable populations of *Deinococcus radiodurans* having been found in the cooling waters of nuclear reactors [18,35]!

It scarcely needs emphasising that the presence of liquid water is a fundamental pre-requisite for life. Whilst there are drought-adapted plants and bacteria that can survive temporary desiccation, biochemistry out of aqueous solution is not possible. On a terraformed planet therefore, liquid water must be stable and plentiful. There must not just be enough to episodically fill living cells and to provide an external aqueous medium but, for a rich biosphere, there must be sufficient for a bulk hydrological cycle capable of water purification and heat transfer on a global scale. The quality of the water is also important: most crops on which humanity depends require irrigation by water of salinity < 0.1% [19]. However, in localities where high salinity is an unavoidable environmental factor, terraformers may be able to introduce salt-tolerant plants (halophytes) and salt marsh fauna that can cope with inundation by sea water (3.2 % salinity) — plus, in areas of deep water, the entire gamut of oceanic organisms. The range of life possible at higher salinities becomes more restricted (see Plate 3.4): algae, halophilic bacteria and brine shrimps thrive at ~ 20% salinity and extreme halophiles can survive in saturated NaCl solution (32% salinity) [18]. Then there is the pH of the solutions to take into account. Most terrestrial environments have a pH range of 5 - 9, (sea water has a pH of 8). Root growth is best at a pH of 5.5 - 6.5 since this helps release mineral nutrients from the soil [19]. Bacteria can tolerate much more extreme pH values. Alkalinophiles can survive in basic fluids of pH ~ 11 (as high as ammonia solution) and acidophiles can tolerate sulphuric acid. Many acidophiles are also thermophiles (see Plate 3.5), such as *Sulfolobus* and *Metallosphaera* which are adapted to life in hot springs at temperatures of ~ 80^0C and a pH range of 1 - 5 [18,36].

Lastly, Table 3.3 reminds us that terrestrial life requires mineral nutrients to be present in accessible form. This does not just include *macronutrients* that are required in large amounts (cf Table 2.1) but also *micronutrients*, trace elements needed in minute, but critical concentrations. These include elements such as cobalt, zinc, molybdenum, copper, manganese, selenium and several others. Since rocks analysed on the Moon, Mars and Venus appear to be similar to terrestrial basalts we might expect them to weather into fertile soils. However, as will be noted later, nutrient limitations probably preclude at least one favoured scenario for terraforming Venus.

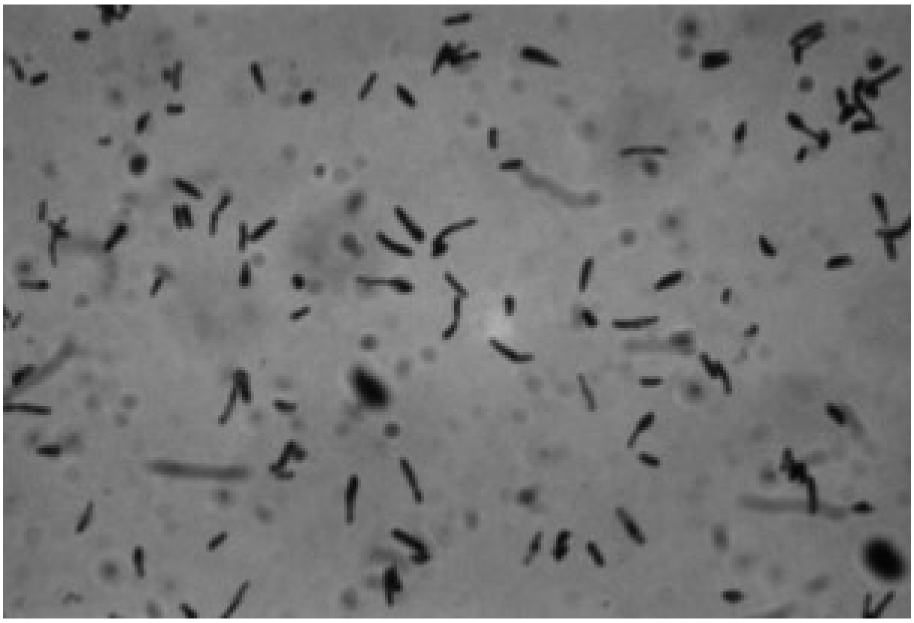

Plate 3.4 *Halobacterium salinarum: mag: 100X. An aerobic, heterotrophic inhabitant of hyper saline environments. Pigments embedded in its cell walls have the special property of being able to use light energy to augment its metabolism. (Micrograph courtesy of Renia Gemmel and W.D. Grant.)*

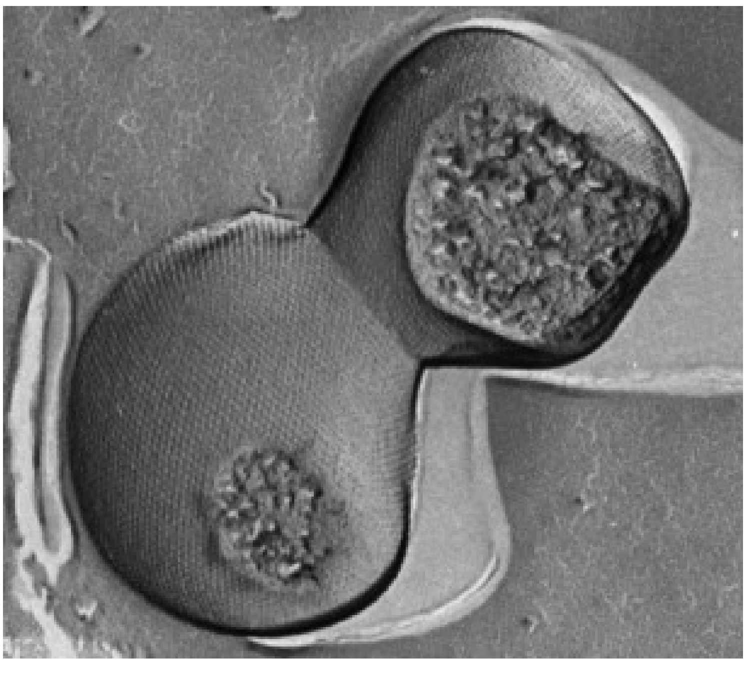

Plate 3.5 *Metallosphaera sedula: mag: 57,000X, freeze-etched, platinum shadowed. A thermoacidophilic bacterium, isolated from acidic hot springs that grows between pH 1.0-4.5 and at an optimum temperature of 75°C. It can grow aerobically by oxidizing sulfidic ores or elemental sulphur to sulphuric acid. (Micrograph courtesy of Reinhard Rachel.)*

3.4.2. Indirect Constraints on Planetary Parameters

Planetary habitability is a complex problem that is far from fully understood. It is being grappled with on three fronts. The great bulk of the research concentrates on quantifying and comprehending the processes of the Earth — in fact a large chunk of all of scientific endeavour is ultimately to do with explaining how life originated, why it persists and how it operates. The other two fields to which scientists turn their attention, mostly in their spare time, are *exobiology* and terraforming. Part of the former is to consider the natural occurrence of habitable planets elsewhere in the Universe, whereas the latter deals with the conscious design and engineering of life-bearing worlds. Both of these differing extraterrestrial perspectives are of value in the overall debate.

In defining a habitable environment above, we have set limits on those planetary parameters *directly* relevant to life. Yet it is not difficult to appreciate that since we are dealing with a system, any constraint we care to define will also set limits on that system as a whole. This is shown in Figure 3.7 which is a pictorial representation of a simple model of a terrestrial planet. Each parameter in the oval balloons can interact with those others with which it is connected and can exert a positive influence (increasing the value of the downstream parameter), a negative influence (decreasing downstream), or both (depending on circumstance or some more complex interaction). It can be seen that the presence of life potentially limits every parameter upstream, not just those that we have already discussed, such as temperature and atmospheric composition, *but all of them*. Thus, only a small subset of possible worlds are habitable. For our purposes, we can approach a complete definition of a habitable planet by considering the constraints imposed by a habitable environment on the whole system. By its very nature, the *natural* phenomenon of planetary habitability cannot be ephemeral or short lived (at least in terms of human history) because of its inherent biological and geological processes. The creation of a planet with such properties would obviously be the preferred goal of terraforming, especially from the ecocentric point of view. However, this is not the only possible goal since one can imagine terraforming creating and maintaining a habitable environment, whilst not addressing the full task of emulating a naturally habitable planet. An example might be where a planet's insolation is too low to raise its surface temperature above freezing: altering its orbit closer to the Sun would be the best solution, but extremely difficult; reflecting extra sunlight onto the planet using orbiting mirrors would be much easier, but represents an ongoing technological alternative [8].

The theoretical study of extraterrestrial habitable planets can therefore tell us something about the ultimate demands of terraforming, especially the habitable ranges of those parameters *indirectly* constrained by the preconditions for life. The most important of these are listed in Table 3.4 and mostly apply only if terraformers choose not to adopt long-term engineering solutions. Now it must be admitted that the habitable bands of many of these parameters are uncertain and so any definition must be, to a greater or lesser extent, arbitrary. A good example is a planet's rotation period: we can calculate that if the Earth were rotating in less than ~ 1.5 hours it would be in danger of breaking up and so this sets a fundamental lower limit — but what would determine the upper limit to the length of the day? As the rotation period of an earth like planet increases from the 24 hours with which we are familiar, diurnal temperature variations and the vigour of its weather would become more extreme. A point would eventually be reached where conditions became too hostile for life and would be further complicated by such factors as the obliquity and the density of the atmosphere. Stephen Dole, a researcher at the RAND Corporation, published an influential study of the prevalence of habitable planets in 1964 [20] and looked at the constraints of many of these parameters for the first time. His choice of upper limit of rotation period consistent with comfortable human habitability was 96 hours; it is probable that hardier forms of life could withstand the climatic consequences of considerably longer days than this.

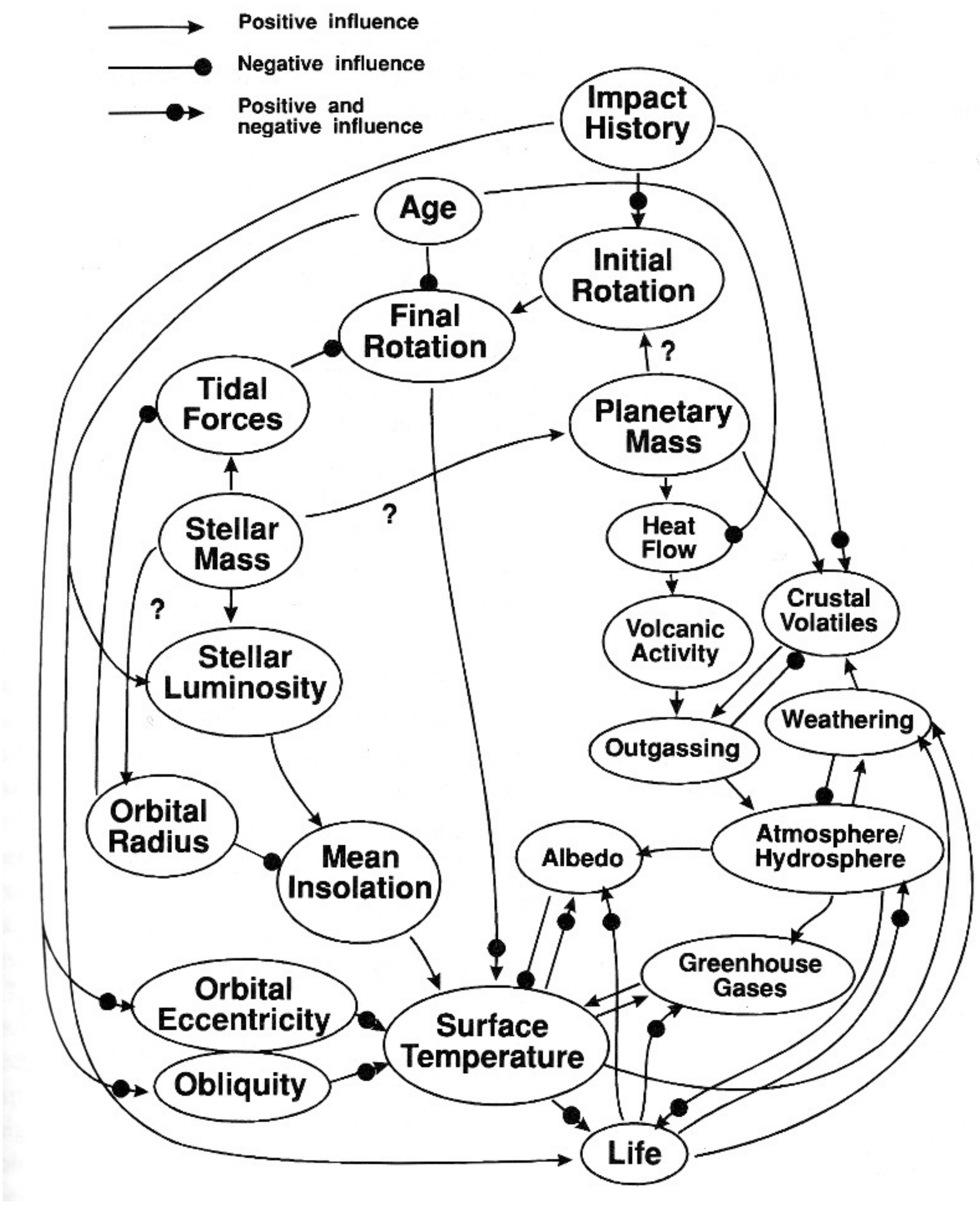

Figure 3.7 *Schematic model of a terrestrial planet. Items in oval balloons interact and influence those "downstream" to either increase or decrease their value. Question marks signify particularly speculative linkages. Both positive and negative feedbacks are shown. Adapted from the algorithm in Ref. [37].)*

Some Guidelines for the Study of Terraforming

Detailed discussion of every entry in Table 3.4 is not appropriate here and in most cases the level of uncertainty makes it sufficient to accept arbitrary, but reasonable criteria. We confine ourselves therefore to briefly looking at one parameter that has been subject to substantial investigation — the insolation at which a terrestrial planet may be naturally habitable. The upper and lower limits of insolation define inner and outer orbital distances from the Sun within which a planet can be thermally compatible with life. This region is known as the *ecosphere*. There is a long history of scientist's attempts to define the ecosphere [37], the most modern work having been done by Kasting and co-workers [38-40].

TABLE 3.4 APPROXIMATE CONSTRAINTS ON ADDITIONAL PLANETARY PARAMETERS IMPOSED BY THE REQUIREMENTS OF A HABITABLE ENVIRONMENT (IN THE ABSENCE OF PLANETARY ENGINEERING).

Parameter	Limits/Range	Comments
Insolation	$< 1.1\ S_\oplus$ $> 0.36 - 0.53\ S_\oplus$ $0.85 - 1.1\ S_\oplus$	'Moist Greenhouse' effect Maximum CO_2 greenhouse Potentially breathable atmospheres ($T_{surf} > 273$ K, $P_{CO2} < 10$ mbar)*
Orbital Eccentricity	< 0.2	Excessive annual temperature variations (arbitrary criterion due to Dole [20])*
Rotation Period	< 96 hours	Excessive diurnal temperature variations (arbitrary criterion due to Dole [20])*
Obliquity	$< 54^o$	Average annual insolation greater at poles than equator. Excessive seasonal temperature variations (arbitrary)*
Mass	$< 3\ m_\oplus$ $> 0.2\ m_\oplus$	Formation of giant planet during accretion? Excessive gravity?* Long-term retention of nitrogen atom at exosphere temperature of ~ 1000 K.
Rock Cycle	Active	Essential geochemical cycles
Age	> several billion years	Time to evolve an aerobic atmosphere? Natural 'terraforming' timescale?*
Hydrosphere	Present	Climate stability, greenhouse effect, biochemistry, biogeochemical cycles etc.
Life	Present	Biological influence on habitable parameters; e.g. atmospheric composition, planetary homoeostasis etc.
Magnetic Field	?	Necessity not clear
Large Satellite	?	Stabilization of chaotic obliquity variations?

* Requirements for a human-tolerable environment; less complex forms of life could survive greater extremes.
$\oplus$ = the Earth.

The inner edge of the ecosphere is influenced by the fact that the partial pressure of water vapour in a planetary atmosphere is strongly influenced by temperature and that water vapour is a powerful greenhouse gas. Increasing the insolation of the Earth would therefore be expected to raise the surface temperature by a greater amount than if the atmosphere was optically thin, because of an additional warming increment provided by the positive feedback of the water vapour greenhouse effect. Kasting *et al.* have estimated a value for the inner edge by studying the response of a model terrestrial atmosphere with fully saturated, cloud free, conditions to increases in solar flux [38]. At an insolation of 1.4 $S_\oplus$ (where $S_\oplus$ is the present insolation of the Earth), the oceans evaporate entirely, producing the classical *runaway greenhouse effect*. However, at a lesser insolation of 1.1 $S_\oplus$ they identified another possible planetary environment, the *moist greenhouse*. It appears that between 1.1 - 1.4 $S_\oplus$ the increase in water vapour pressure elevates the boiling point sufficiently to keep it above the surface temperature. A moist greenhouse world is one of scalding oceans, overlain by water-laden atmospheres of several bars pressure. In both greenhouse states the "cold trap" at the tropopause (see Section 2.7.1) is undone and water vapour rises high in the atmosphere where is it subject to photodissociation by UV radiation. If this was the original fate of Venus, then it could have lost an ocean's worth of water by the escape of hydrogen to space in just a few hundred million years, explaining its present desiccated state. A planet in the early stages of the moist greenhouse might suit some extreme thermophiles such as *Pyrodictium*, but cannot be described as habitable in any further sense. Kasting's model may be conservative in the sense that it does not include any negative feedback from increased cloud cover that would reduce the Earth's albedo. However, the sign of the feedback of clouds with surface temperature is not known, especially at these warm temperatures, and is one of the outstanding unsolved problems of climatology. His value of 1.1 $S_\oplus$ as the insolation at which moist greenhouse conditions commence (pertaining at present at an orbital radius of 0.95 AU) is therefore a reasonable approximation to the upper limit of insolation at which a planet can remain naturally habitable; above this, terraformers will have to maintain habitability with an engineering solution.

Kasting and co-workers have also studied the position of the outer edge of the ecosphere and propose, in contrast to the inner edge, that it is controlled by a negative feedback — the geochemical carbon cycle [40]. It was explained in Section 2.7.3 how this process may have maintained the surface temperature of the Earth within habitable bounds, as solar luminosity increased, by cybernetically controlling the carbon dioxide greenhouse effect. Thus, if our views on the changing luminosity of the Sun are correct, we can say that the lower level of insolation consistent with habitability must be ~ 0.7 $S_\oplus$ or less (the estimated insolation of > 4 billion years ago). However, there is evidence on the older surfaces of Mars, in the form of dry rivers and lakebeds, that in the first billion years of this planet's history it too had a warm, moist climate. It may therefore be that the youthful Mars had sufficient volcanic and tectonic activity to sustain an active geochemical carbon cycle. This would then naturally have maintained a sufficient mass of atmospheric CO_2 (in terms of pressure, equivalent to ~ 5 bars) to keep surface temperatures above freezing [41]. Thus, geological evidence is suggesting that, at the distance of Mars from the Sun (1.52 AU) and at conditions of ~ 70% solar luminosity, an active geochemical carbon cycle can sustain conditions suitable for life. The lower level of insolation consistent with this would be ~ 0.3 $S_\oplus$. Kasting *et al.* [40] have since revised this estimate and have raised it to between 0.36 - 0.53 $S_\oplus$, because of the realization that the formation of CO_2 clouds in their model atmospheres can raise the planetary albedo, counteracting some of their greenhouse effect [42]. Where this leaves Mars is uncertain — either the planet had other greenhouse gases in its early atmosphere, or planetologists are mistaken about its "early Eden."

Even if both young Earth and Mars were compatible for life, they would have been uninhabitable for human beings due to their high atmospheric quantities of carbon dioxide. If we constrain the pCO_2 to the toxic limit for humans (~ 10 mbar) then the minimum insolation required to bring the average planetary temperature up to 0^oC is ~ 0.85 $S_\oplus$ and to raise it to 15^oC (the present value) would demand ~ 0.9 $S_\oplus$ [43]. These estimates are bound to vary with other factors such as the presence of other greenhouse gases and the atmospheric scale height; however it permits us to define 0.85 - 1.1 $S_\oplus$ as the approximate range of insolation consistent with a non-engineered, human-habitable, planetary environment.

3.5 The Rudiments of Planetary Engineering

Terraforming a planet will therefore be a task rivalling the complexity of understanding the phenomenon of planetary habitability. However, it is possible to address the subject at a more fundamental level that is better understood. In Chapter 2, we defined a life-support system so: *"A life-support system involves a flow of energy though a space that drives internal cycling of matter into which the specific cycles of life can be integrated."* Terraforming therefore will involve no less than altering the energy and chemical balances of a planet to within the tolerance range of life so that living systems can integrate themselves within (and possibly take control of) global matter cycling. *Energy flow* and *matter cycling* are therefore at the heart of planetary engineering and we shall constantly refer back to this theme throughout the book.

An equation that illustrates well how a planet's energy flow might be manipulated is that determining the average global surface temperature (a combination of equations 2.15 and 2.16):

$$T_{surf} = \left(\frac{S(1-A)}{4\sigma} \right)^{1/4} + \Delta T_{\text{green}} \tag{3.4}$$

This gives us three parameters planetary engineers might directly manipulate to change surface temperature: S, the insolation; A, the albedo; and ΔT_{green}, the greenhouse effect. This latter parameter also alludes to an altered atmospheric chemistry.

However, planetary engineers might be able to exploit *feedbacks* inherent in a planet's climatic sub-systems to amplify or damp down any perturbation. In the case of surface temperature we can write:

$$\Delta T_{surf} = f\Delta T \tag{3.5}$$

where ΔT is the initial temperature increment, f is the feedback factor and ΔT_{surf} is the final temperature increment. For instance if we have a feedback factor of f = 1.5, and a temperature increment (in the absence of feedback) of $\Delta T = + 2^{o}C$, then the observed rise in temperature will be $\Delta T_{surf} = + 3^{o}C$.

Any planetary environment will contain a multitude of processes with potential feedback effects (cf Figure 3.7). To appreciate their cumulative impact, is useful to characterize their *gain*, a term that is derived by analogy with the behaviour of an electronic amplifier [44]:

$$g = (\omega - \iota) / \omega \tag{3.6}$$

where g is the gain, ω is the output signal and ι is the input signal. Feedback is related to gain by the following equation:

$$f = \omega / \iota = 1 / (1 - g) \tag{3.7}$$

Gains are additive and so we obtain the following equation for the final temperature increment:

$$\Delta T_{surf} = \frac{\Delta T}{1 - \sum_{i=1}^{n} g_{\mathrm{i}}} \tag{3.8}$$

where n is the number of gains. Equation 3.8 is therefore equivalent to equation 3.5, where f has been calculated as a combination of all relevant feedbacks. The meaningful ranges of g and f are listed in Table 3.5 and show the values at which there is positive feedback (amplification of ΔT), negative feedack (diminution of ΔT) or no feedback at all ($\Delta T_{surf} = \Delta T$). Also listed are the values where there is no stable solution and some form of runaway occurs which would presumably become self-limiting within the context of some significantly different climatic regime.

TABLE 3.5 GAINS AND FEEDBACKS IN CLIMATE CHANGE.*

	g	f
Unstable	1	∞
Positive Feedback	$0 < g < 1$	$1 < f < \infty$
No Feedback	0	1
Negative Feedback	< 0	$0 \leq f < 1$

* *Study in conjunction with Equations 3.5 - 3.8.*

It is true to say that values of g and f are only usually valid over small ranges of ΔT. However, the implications for planetary engineers are clear. If the aim is to rapidly and cheaply transform a planetary regime to some entirely new steady state (e.g. Mars at a much higher T_{surf}), then the exploitation of climatic instability (natural or engineered) would be desirable ($g \rightarrow 1$, $f \rightarrow \infty$). In this case, a minimum of planetary engineering is needed to initiate wholesale change — amplifications inherent in the system running away with the process ($\Delta T_{surf} >> \Delta T$) . Alternatively, the aim might be to stabilize a planetary climate ($\Delta T_{surf} << \Delta T$), such as after terraforming is complete. In this case we would need to maximize negative feedback ($g << 0$, $f \rightarrow 0$).

Thus planetary engineers may conceive of modifying planetary parameters by either *direct* manipulation, *indirect* means, or by some sort of combined approach. Each parameter therefore may be expected to be potentially subject to manipulation by a variety of methods. In order to help clarify forthcoming discussions, we define three terms here that will be used consistently throughout the rest of this book.

1) *Planetary engineering technique*: a method of achieving a desired planetary engineering aim.
2) *Planetary engineering tool*: something, whether mechanical or biological, that serves as a means for accomplishing planetary engineering.
3) *Planetary engineering application*: the use to which planetary engineering techniques and tools are put.

In all of the above, the word terraforming can be substituted for planetary engineering if relevant. A terraforming technique that exploits a large positive feedback, or climate instability, is often said to possess high *leverage*.

Various energy sources that might be exploited for planetary engineering are cross-referenced with techniques, tools and applications in Table 3.6. It sums up many of the most popular terraforming concepts, although is *not* comprehensive. Generalizing the range of planetary engineering possibilities into a small set of standard paradigms is not easy.

TABLE 3.6 A SUMMARY OF PLANETARY ENGINEERING CONCEPTS

Energy Flow	Source	Technique	Tools	Application
Extrinsic				
Electromagnetic radiation (EMR)	Sun/Stars	Reflect/redirect radiation	Mirrors	Increase $S \rightarrow T_{eff} \rightarrow T_{surf}$; global or local climate modification; release of surface volatiles; change nature of diurnal or seasonal cycles.
		Interrupt radiation	Parasols Dust Clouds Rings	Reduce $S \rightarrow T_{eff} \rightarrow T_{surf}$; global or local climate modification; condensation of surface volatiles change nature of diurnal or seasonal cycles.
		Change planetary orbit Alter properties of primary star	? ?	Increase or reduce $S \rightarrow T_{eff} \rightarrow T_{surf}$; global only.
Kinetic Energy	Orbital energy of celestial bodies, e.g. asteroids and comets	Alter orbit to collision course, possibly including planet flybys.	Asteroid or comet propelled by, rocket motors, nuclear explosions, or mass drivers.	Release of indigenous volatiles; addition of extrinsic volatiles; atmospheric erosion; surface cratering; stimulation of geological activity; alteration of rotation rate and obliquity; protection from impacts.
Tidal Energy	Gravitational influence of other celestial bodies	Alter configuration of celestial bodies	?	Modify precession and obliquity variations; generation of internal heat?
Intrinsic				
Solar spectrum EMR	Sun/Stars	Modify albedo of illuminated surfaces	Aerosols Dust Plant cover	Change $A \rightarrow T_{eff} \rightarrow T_{surf}$; global or local climate modification; release of surface volatiles.
		Absorption by living systems	Photoautotrophs and dependant ecosystems	Change atmospheric and surface composition; life support etc.
Infrared EMR	Absorption and re-radiation in atmosphere	Manipulate atmospheric greenhouse effect	Bulk and trace greenhouse gases	Increase or reduce $\Delta T_{green} \rightarrow T_{surf}$.
Geothermal heat	Radioactive decay of naturally occurring isotopes	?	?	Geochemical cycles
Nuclear Energy	Appropriate naturally occurring isotopes	Fission/fusion	Nuclear explosives Nuclear reactors	Release of volatiles; surface cratering; stimulation of geological activity; waste heat - increase T_{surf}

$\rightarrow$ indicates a change in one parameter feeding into another.

Any particular technique may be associated with a number of different tools and these may conceivably be used for a variety of applications. Since the entries in Table 3.6 are of a diverse speculative content (some are possible at the present time, others not), its form is also influenced by the assumptions inherent in any particular scenario — the planet that is being terraformed, the level of technological input that is considered feasible, ethical and so on. Thus, we make no attempt here to discuss planetary engineering in detail outside the specific contexts in which it is proposed. The techniques, tools and applications generalized in Table 3.6 will therefore be endowed with more detail later in this book when we consider the individual cases of geoengineering of the Earth and terraforming of Mars, Venus and other bodies

One important dichotomy however does arise from Table 3.6: the division of planetary energy flow into *extrinsic* and *intrinsic* parts that was discussed in Chapter 2 can be used to classify planetary engineering into two categories. Extrinsic flow is that entering or leaving at the top of a planet's atmosphere and its manipulation will require space-based techniques and industry. *Extrinsic planetary engineering* therefore is fundamentally technocentric in its approach. Intrinsic flow comes from sources inherent to the planet itself, or being processed within its sub-systems; in this case, *intrinsic planetary engineering* can be kept to the planet itself and accommodates both technocentric and ecocentric viewpoints.

3.6 Summary

- If constrained by the laws of physics and plausible assumptions of future advances in technology and engineering, research into terraforming represents valid scientific enquiry.
- Planetary engineering can be defined as: the application of technology for the purpose of influencing the global properties of a planet.
- Terraforming can be defined as: 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 uncontained planetary biosphere emulating all the functions of the biosphere of the Earth — one that would be fully habitable for human beings.
- Ecopoiesis can be defined as: the fabrication of an uncontained, anaerobic, biosphere on the surface of a sterile planet. As such, it can represent an end in itself or be the initial stage in a more lengthy process of terraforming.
- These definitions imply that Ecopoiesis $\subseteq$ Terraforming $\subseteq$ Planetary Engineering.
- Geoengineering is planetary engineering applied specifically to the Earth.
- Philosophical attitudes to terraforming, that influence the subjective assumptions of researchers, can be categorized as existing between opposite poles of environmental opinion. Ecocentrism minimizes the human role in planetary engineering, preferring to invoke instead the unconscious processes of life as a whole. The principal goal of ecocentrism is ecopoiesis. Technocentrism emphasizes technology and conscious design as means to overcome obstacles that biology cannot tackle and to attain specifically human aims. The principal goal of technocentrism is complete terraforming.
- The boundaries of a habitable environment are defined by a multitude of parameters which vary for different categories of organisms. The common pre-requisite for all life is the availability of liquid water. Multicellular life is much less tolerant of environmental extremes than more primitive unicellular life. Microbes will therefore be the pioneers of terraforming — the first organisms to thrive on a planet awakening to life.
- The concept of a consciously designed (terraformed) biosphere is a useful contrast to a naturally evolved biosphere as it can provide a novel perspective on the general, and not fully understood phenomenon of planetary habitability. The best outcome of a terraforming project is to create a biosphere that emulates a stable, natural counterpart.
- Purposeful manipulation of energy flow and matter cycling are fundamental to any planetary engineering process. Extrinsic planetary engineering manipulates energy or mass flow entering or leaving

the top of the atmosphere. Intrinsic planetary engineering manipulates flows inherent to the planet itself. Exploitation of natural feedbacks within a planetary environment could be used to amplify and accelerate the effects of terraforming.

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