CHAPTER 2

Contained, Uncontained and Terraformed Biospheres

Hamlet: To what base uses we may return Horatio! Why may not imagination trace the noble dust of Alexander till he find it stopping a bunghole?

Horatio: 'Twere to consider too curiously to consider so.

Hamlet: No, faith, not a jot; but to follow him thither with modesty enough, and likelihood to lead it: as thus; Alexander died, Alexander was buried, Alexander returneth into dust; the dust is earth; of earth we make loam; and why of that loam whereto he was converted might they not stop a beer barrel?
Imperious Caesar, dead and turn'd to clay,
Might stop a hole to keep the wind away:
O, that such earth which kept the world in awe
Should patch a wall to expel the winter's flaw!—

William Shakespeare

2.1 The Issue

Without a life-support system, there can be no life.

Such a statement would strike the occupant of a submarine or space capsule as obvious. When challenged to indicate the systems keeping him alive, he could point to stores of food and water; air conditioners to circulate and dehumidify the atmosphere; bottles of liquid oxygen and adsorbers for scrubbing carbon dioxide; and batteries and fuel cells to provide the power to keep everything running. He would also be only too aware that this technology only provides a limited period of habitability before requiring recharge and maintenance.

The statement is less obvious to someone sitting in his living room or walking in the street. The question as to how air is revitalized — how it stays breathable and what prevents it running out, where the energy in food comes from, and how wastes are recycled, is rarely thought of. It just happens — life goes on. The sheer ordinariness of it means that we sometimes cannot see the wood for the trees. It obscures the fact that we live *within* a biological, self-maintaining, autonomous, life-support system — the biosphere of the Earth — where life and life-support are a unified process.

This returns us to the question floated in the introductory Chapter and the fundamental issue of this book. *What is the life-support system, of which we can presently conceive, that will be the best suited for the long-term, indefinite, sustenance of terrestrial life away from the Earth?* To answer this problem, and to highlight the possible significance of terraformed planets, we must first define a life-support system and critically examine the choices that will be available to a space-faring civilization.

2.2 What is a Life-Support System?

Patterns of order are imposed on many systems by a flow of energy [1]. An obvious example is the sunlight-driven circulation of the Earth's atmosphere and oceans, which are characterized by a matter cycling steady state, rather than by thermodynamic equilibrium. Life itself represents a highly sophisticated and ordered phenomenon, maintained in the same way by continually dissipating energy from low to high entropy states. Solar energy is captured by plants, which convert a small fraction of it to chemical energy, using this to synthesize organic matter from inorganic molecules (see Fig. 2.1). They are *producers*, using the energy of sunlight and the process of photosynthesis to grow:

$$CO_2 + H_2O \rightarrow \underset{\text{Carbohydrate}}{(CH_2O)} + O_2 \tag{2.1}$$

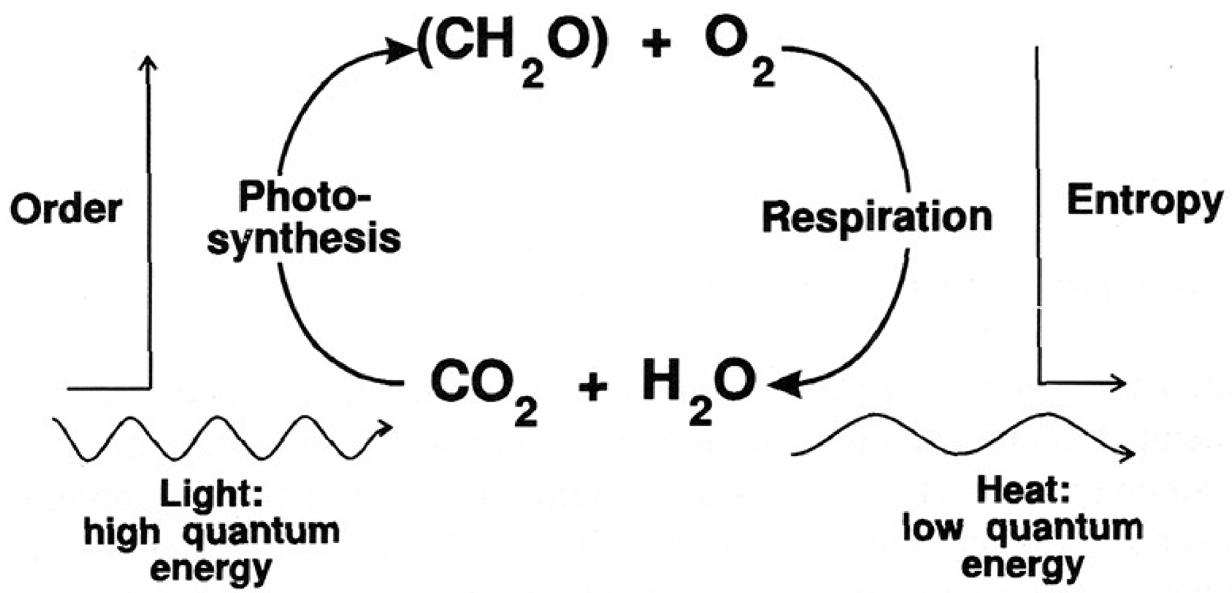

Figure 2.1 *The dynamics of a life support system. Matter cycling and organic molecules (ordered phenomena) are maintained by dissipating sunlight into heat.*

Growth therefore involves the embodiment of a concentrated form of energy in a low entropy material — organic matter or biomass. (The second law of thermodynamics, that the entropy of a system increases with time, is not violated as most of the sunlight involved in photosynthesis is converted to and rejected as heat which is high in entropy.) Animals and other *consumers* take advantage of this by eating organic matter to obtain energy and material for their own growth. Ultimately, through the processes of respiration and decay, organic matter is broken down back into inorganic matter and returned to the environment in a form usable again by plants:

$$(CH_2O) + O_2 \rightarrow CO_2 + H_2O \tag{2.2}$$

The matter cycle is complete and sunlight — the low entropy energy used to power it — is completely dissipated into heat. Similar closed cycles operate for other elements that are vital for the make-up of living systems (these major elements are listed in Table 2.1). Thus, so long as energy continues to flow and matter to cycle, the structural patterns that characterize life can persist; however, if we include outer space within our system, then we see that overall entropy has increased, in accord with the second law of thermodynamics. The only net change is that sunlight enters the biosphere from space and returns as heat.

TABLE 2.1 COMMON FORMS OF THE MAJOR ELEMENTS NEEDED FOR BIOSYNTHESIS OF CELL COMPONENTS

Element	Usual Form in the Environment
C	Carbon dioxide (CO_2)
	Organic compounds
H	Water (H_2O)
	Organic compounds
O	Water (H_2O)
	Oxygen gas (O_2)
N	Ammonia (NH_3)
	Nitrate (NO_3^-)
	Organic compounds (e.g. amino acids)
P	Phosphate (PO_4^{3-})
S	Hydrogen sulphide (H_2S)
	Sulphate (SO_4^{2-})
	Organic compounds (e.g. cysteine)
K	K^+
Mg	Mg^{2+}
Ca	Ca^{2+}
Na	Na^+
Fe	Fe^{3+}
	Organic iron complexes

At is most fundamental therefore, *a life-support system involves a flow of energy through a space that drives internal cycling of matter into which the specific cycles of life can be integrated*. In the case of the biosphere of the Earth: this comprises an integrated living and life-supporting system englobing the planetary surface and extending as far up into the atmosphere and as far down into the crust as life naturally exists. Physically, it is a region permeable to the flow of solar and geothermal energy and characterized by the stability of liquid water.

2.3 Requirements and Choices

The permanent habitation of space requires self-sufficiency in all the requisites of life. Whilst the initial stages of exploration and settlement will be supported by a supply of life-support components from Earth, there will inevitably come a time when both economics and the desire for independence in basic necessities dictate that the umbilical cord to the biosphere of the mother planet be cut. *The issue of a long-term, self-sufficient life-support system will then become paramount* — there being an obvious preference for one which is safe, stable, reliable and inexpensive in terms of energy and conscious effort to maintain. More explicitly, the following attributes are most desirable:

1) It must rely principally on utilization of *gratis* energy, such as that in sunlight and natural, solar-powered, matter cycles. Thus it must minimise dependence on technologically processed energy, such as electrical power and the energy embodied in manufactured life-support infrastructure.

2) It must be *self-contained*, ideally not requiring continued supplementation of energy and matter in excess of its natural endowment. Its internal matter cycling should be *regenerative*, the system having a high degree of *closure*, production and consumption must either be balanced or capable of easy compensation from the exterior.

3) Its components should have the properties of *self-replication* and *self-maintenance*, so as to reduce the human role in manufacture and repair.

4) Its internal dynamics must be *self-stabilizing* and *autonomous* — as safe as possible from dangerous perturbations and keeping essential human monitoring and control to a minimum.

5) The habitable environment provided must be pleasant to live in, having a variety of *aesthetic* and *challenging* qualities.

The categories of life-support system (LSS) from which to match with the ideal as defined above are shown in Table 2.2. Only two of these are in reliable operation today, namely the “open-loop” LSS of spacecraft and the biosphere of the present-day Earth. The fully autonomous, pre-agricultural, biosphere of Earth is now no more and the others remain either unperfected or conjectural. It may seem obvious to some that the Earth — by its very nature, since we evolved within its biosphere — represents the “best of all possible worlds” for man and that a terraformed duplicate of Earth will therefore be the ideal extraterrestrial habitat. However, it would be remiss not to contrast what other solutions might be on offer and to line the competitors up on a level playing field so as to learn by the comparison. The sum-total of experience, data, and theory concerning the entries in Table 2.2 allows us to at least attempt an impartial appraisal of each system.

It is apparent that all the systems in Table 2.2 vary in their degree of closure, their balance of mechanical and biological subsystems, the presence or absence of a containing structure and their degree of autonomy. In order to clearly illustrate such differences, we shall use the pictorial 'energy circuit language' developed by Howard Odum of the University of North Carolina [2,3]. As a method of clarifying the qualitative nature of ecological dynamics, it is both adaptable and easy to understand. A key to its symbols is given in Fig. 2.2.

TABLE 2.2 CATEGORIES OF LIFE-SUPPORT SYSTEM

	Open Loop	EC/LSS	Small Contained Biosphere	Large Contained Biosphere	Present-day Earth or Terraformed Planet	Pre-civilized Earth
Air revitalization	Stored supply & waste	Mechanically recycled	Biologically recycled	Biologically recycled	Biologically recycled	Biologically recycled
Water reclamation	Stored supply & waste	Mechanically recycled	Biologically & mechanically recycled	Quasi bio-hydrological cycle	Natural bio-hydrological cycle	Natural bio-hydrological cycle
Solid waste management	Treated & stored	Treated & stored	Biologically & mechanically recycled	Biologically recycled?	Biologically recycled	Biologically recycled
Food service	Stored	Stored	Horticulture	Agro-ecosystems	Agro-ecosystems	Natural ecosystems
Essential monitoring and control	Continuous	Continuous	Continuous	Continuous	Partial	Unnecessary
Containing structure	Present	Present	Present	Present	None	None
External resupply requirements	Total	Partial	Minimal	Minimal	None	None

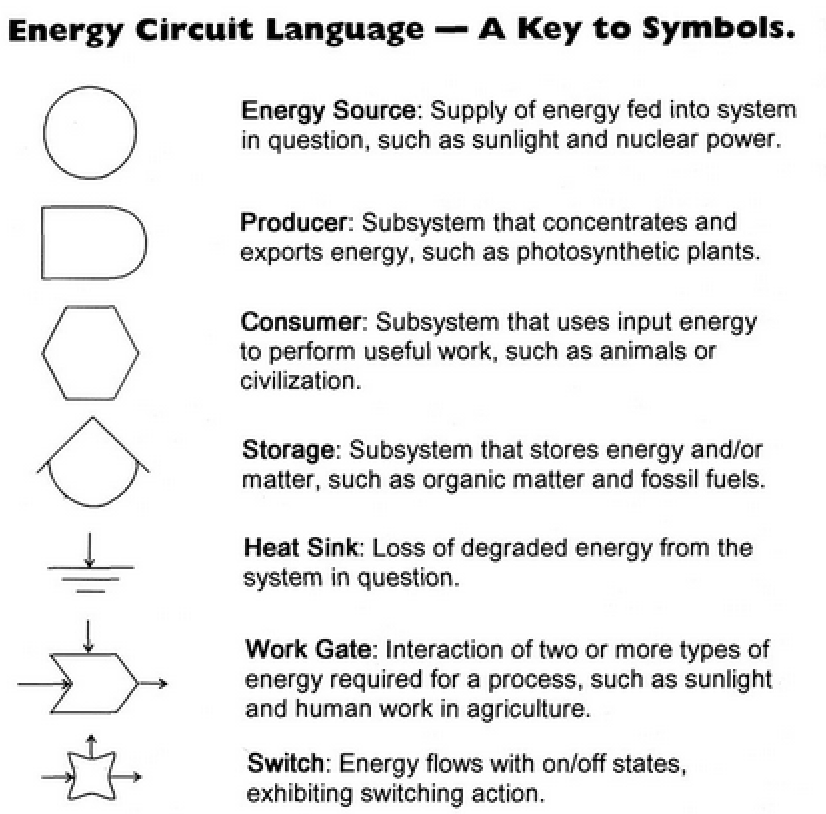

Figure 2.2 *The symbolic convention of H.T. Odum's energy circuit language [2].*

2.4 Open or Partially Closed Life-Support Systems

It is not difficult to see why the “open loop2' LSS of present day spacecraft will be of no use for permanent space settlement. Fig. 2.3 shows the nature of energy and matter flow in such systems. All the essentials for life are taken on board before a journey and are treated as expendable. To maintain a breathable atmosphere, oxygen is provided from liquid oxygen cylinders; carbon dioxide is removed by passing the air through LiOH canisters and trace contaminants are mopped up by canisters of activated charcoal (see Plate 2.1). A supply of water is provided for drinking and washing; food is provided in freeze-dehydrated form; wash water, urine and faeces are collected, treated and either stored or dumped overboard. Nothing is internally regenerated — continued habitability is thus dependent on an external regenerative loop passing through the Earth's biosphere which re-supplies victuals before launch and recycles wastes upon return.

Partially regenerative, mechanical, life-support systems are under design for the *Alpha* space station and for applications in long-duration missions, such as to Mars [4,5]. There are a number of variant designs of what is generically known as the Environmental Control/Life -Support System (EC/LSS); a common objective however, to cut down on the mass of consumables required, is to mechanically regenerate air and water — but still to rely on stored food. Fig. 2.4 describes these basic operations.

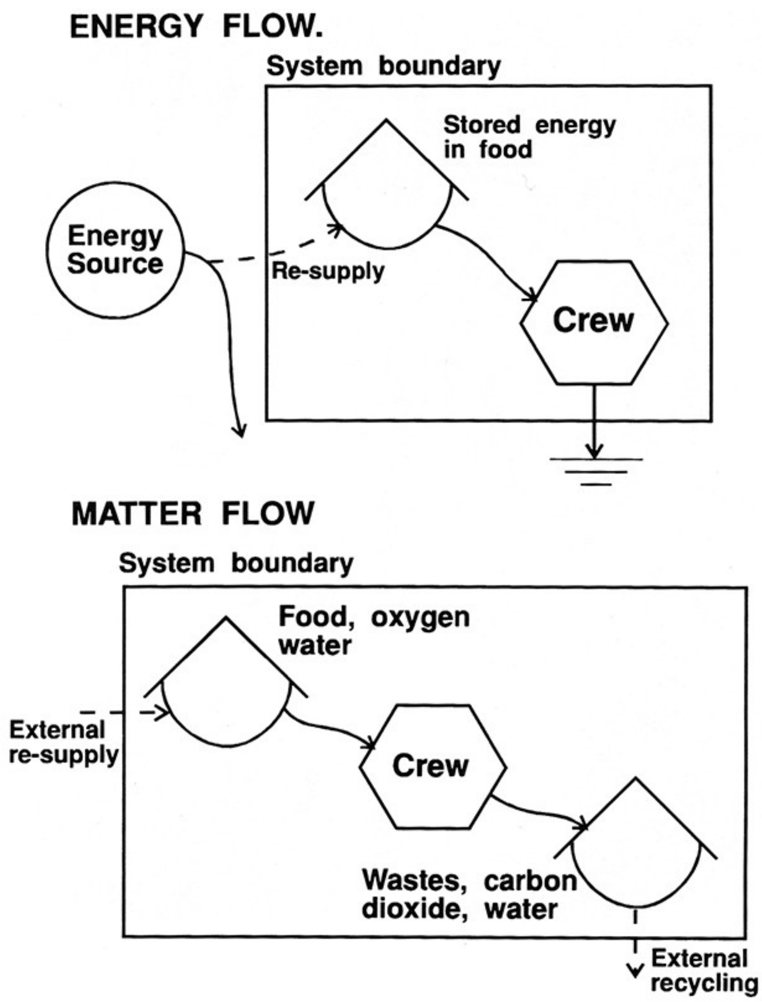

Figure 2.3 *Energy flow and matter flow in a non-regenerative (open-loop) life support system.*

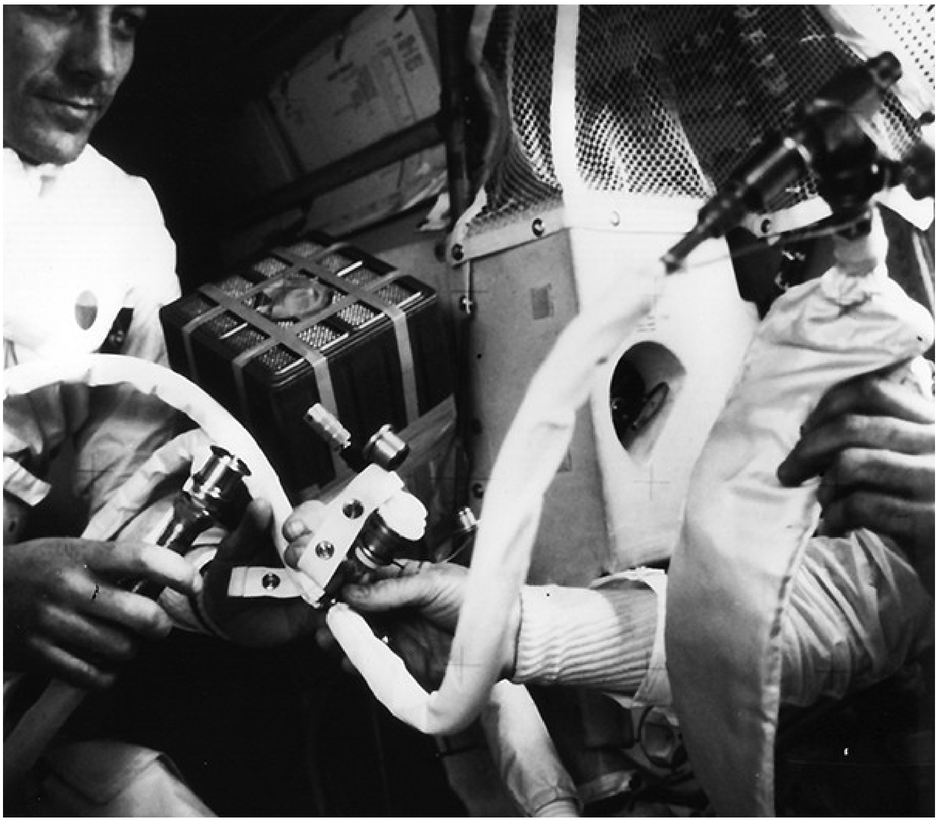

Plate 2.1 *On a spacecraft, life-support equipment is omnipresent. Shown is a lithium hydroxide canister on board Apollo 13 being used to remove carbon dioxide from the atmosphere of both the command module and lunar excursion module. (Photo courtesy of NASA).*

Air revitalization involves a loop for removal of CO_2 and regeneration of oxygen, removal of trace contaminants, and replacement (from storage) of leaked gases, including nitrogen. Water reclamation would use a variety of techniques to recover fuel cell water, cabin humidity condensate, wash water and urine (in order of difficulty). The degree of closure achievable by the EC/LSS can be well appreciated by considering the coupled process of food consumption and air revitalization. Oxygen is produced from water by simple electrolysis:

$$2\,H_2O \rightarrow 2\,H_2 + O_2 \tag{2.3}$$

After being removed from air, carbon dioxide is then reduced by either of two ways. The Sabatier process converts CO_2 to methane at 370 °C in the presence of a catalyst:

$$4\,H_2 + CO_2 \rightarrow 2\,H_2O + CH_4 \tag{2.4}$$

Combining respiration, electrolysis, and the Sabatier process (equations 2.2, 2.3, and 2.4), we obtain the overall reaction:

$$(CH_2O) + H_2O \rightarrow CH_4 + O_2 \tag{2.5}$$

Food and water are consumed, producing an oxygen excess and waste methane.

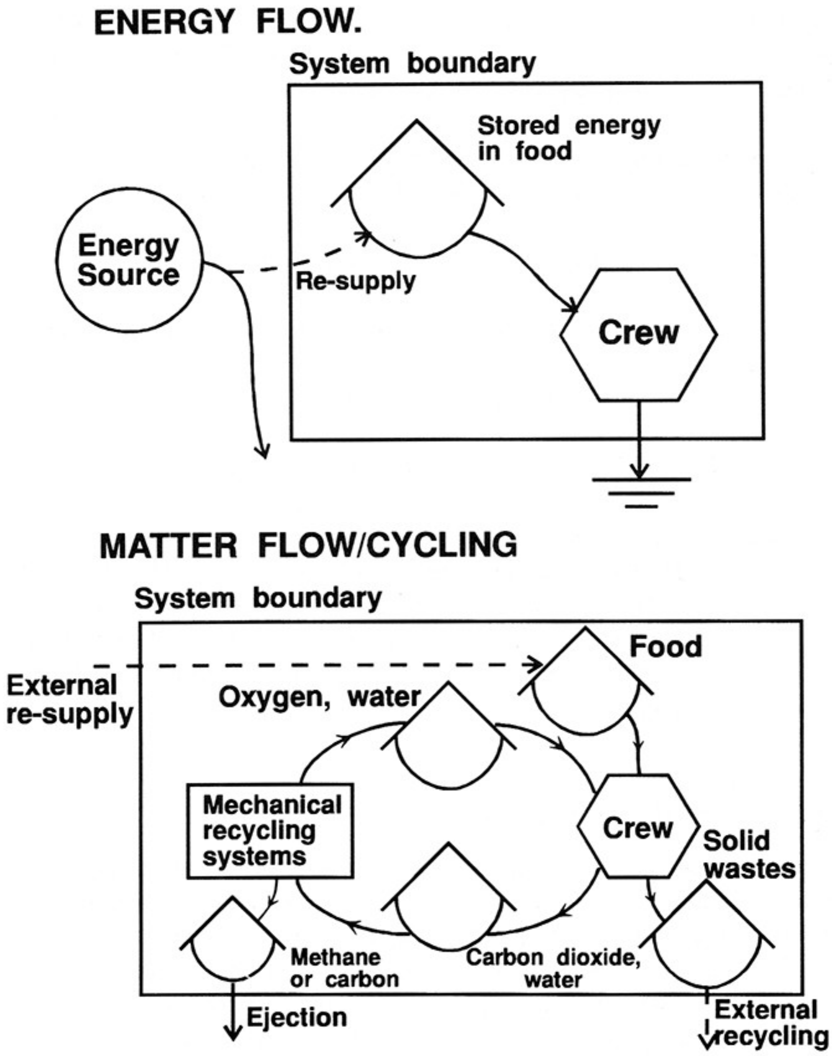

Figure 2.4 *Energy flow and matter flow/cycling in a partially regenerative, mechanically based life-support system.*

When combining the Sabatier process with a hydrazine-based nitrogen generation sub-system for maintenance of cabin pressure:

$$N_2H_4 \rightarrow N_2 + 2\,H_2 \qquad (2.6)$$

hydrogen is provided for CO_2 reduction, conserving water. The expendable atoms therefore are carbon and hydrogen. The advantage of the Sabatier process is that the machinery is quite lightweight and the reduction of carbon dioxide occurs at high efficiency.

When it is desired to minimise the loss of hydrogen, the Bosch process can substitute for the reduction of CO_2. Between 500 - 700 ^oC, over an iron catalyst, solid carbon is produced:

$$CO_2 + 2\,H_2 \rightarrow C + 2\,H_2O \tag{2.7}$$

Combining equations 2.2, 2.3 and 2.7 stoichiometrically, we find the following overall reaction:

$$(CH_2O) \rightarrow C + H_2O \tag{2.8}$$

Only food is expended, producing waste carbon and excess water.

Partially regenerative life-support systems therefore hold out the prospect of extending residence time in space and reducing launch weights for long missions. However, the EC/LSS is far from what is required for the indefinite support of life. They are not fully closed, requiring intermittent connection to a system that can provide food and replace leaked gases; they rely on machinery that requires electrical energy to operate and which need human monitoring, control and maintenance.

2.5 Closed Life-Support Systems

The above, purely mechanical life-support systems replace the terrestrial ecosystems of which humans are a part with machinery. It is evident that what is required for long-term habitability is a LSS where energy flow and matter cycling are handled biologically. The processes at the disposal of such a *bioregenerative* system would have a number of advantages. Photosynthetic biomass production could regenerate oxygen and manufacture plant matter, to be used as human food in its own right, or as the basis for a food chain (see Equations 2.1 & 2.2). The parallel process of evapotranspiration would produce a supply of pure water. Bacterial digestion might be exploited to break down inedible material, solid wastes and toxic contaminants. In an ideal case, complete closure would be attainable, production and consumption being balanced, the system operating on little more than sunlight. Other advantages are the prospect of exploiting the self-reproducing and self-maintaining properties of life and the self-stabilising properties of ecosystems, allowing life-support to become an effortless and automatic background process.

This idealized situation is illustrated in Fig. 2.5 and fits a very simple description of the Earth's biosphere. The system boundary is open to a steady, gratis, energy flow (rather than to intermittent recharge) but is closed to matter. It is true that specific *internal* ecosystems are open to imports and exports of material, but the biosphere as a whole is fully bioregenerative. Such a description matches our list of ideal requirements for an extraterrestrial LSS set out above. However, since there are no exact duplicates of Earth that we know of, future space settlers will have to create their own anthropogenic biospheres. The choices in Table 2.2 fall into two basic categories — those that are *uncontained* (except by virtue of being in a gravitational well) such as the biosphere of a terraformed planet (column 5) and those, which are *contained* within an artificial structure (columns 3 & 4). Obviously, people will be living in space long before a terraformed planet becomes available and so habitation within some kind of *contained biosphere* will be mandatory. An important question thus arises — *how well might contained bioregenerative LSS match the ideal requirements for indefinite habitability?* Can they compete in providing all the benefits of a planetary biosphere? If the answer is *yes*, then there would be less of an incentive for future space-faring civilizations to proceed with terraforming.

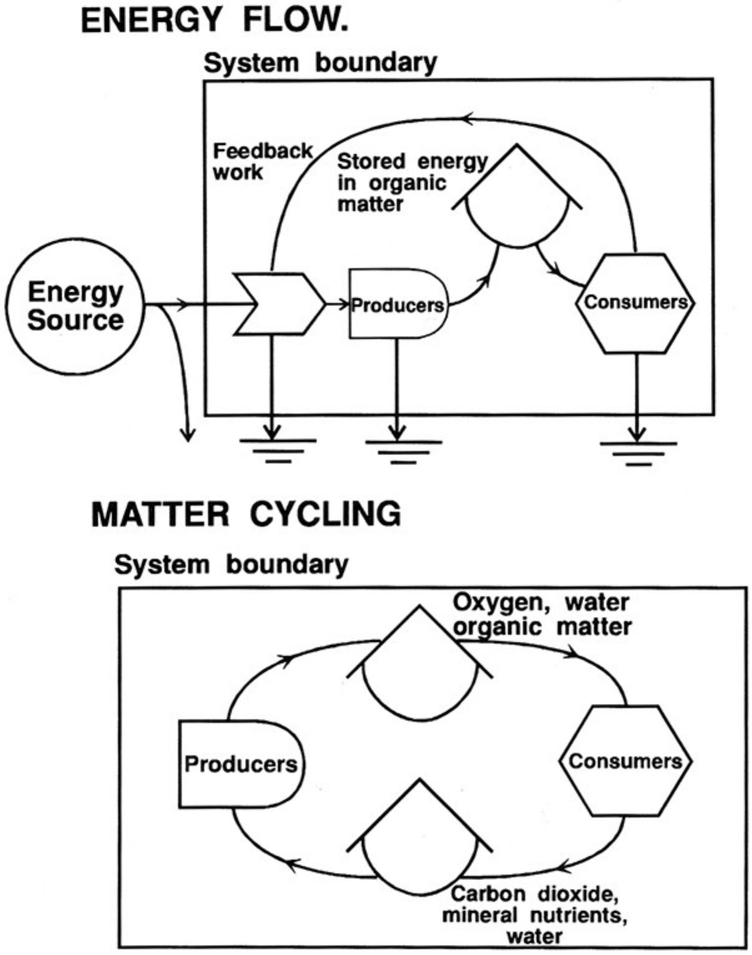

Figure 2.5 *Energy flow and matter cycling in a bioregenerative life-support system.*

2.6 Contained Biospheres

Designs for contained biopheres have been proposed in varying detail, over an extensive range of sizes. Here we do not distinguish between their finer differences in detail, referring to such systems designed for planetary surfaces as *biosphere habitats* and for freely floating in space as *space settlements*. Six examples are illustrated in Fig. 2.6 and are compared to scale with two terrestrial buildings, the World Trade Centre in Manhattan and the Vertical Assembly Building at the Kennedy Space Centre.

The first two are biosphere habitats: Biosphere 2 — a working closed bioregenerative LSS in Arizona [6]; and 'Hyperion' — a theme park patterned on a concept for a Martian domed-city to be built in Japan [7].

The next three concepts for space settlements, all designed to a size to generate earth-normal artificial gravity within by rotating the habitat once a minute. The 'Stanford Torus' is a low-volume NASA design that could accommodate 10,000 people; the 'Bernal Sphere' could hold 75,000; whilst the cylinder (see also Plate 2.2), one of a range of space colony designs by Princeton physicist Gerard O'Neill, could support a population of

820,000 [8]. The bottom illustration represents a small section of a 3 km high 'Worldhouse' designed for Mars — an enormous planet-wide biosphere habitat and one of the most grandiose designs for a contained biosphere to have appeared in the literature [9]. (The Worldhouse and the most general concept of p*araterraforming* are covered in Chapter 8.)

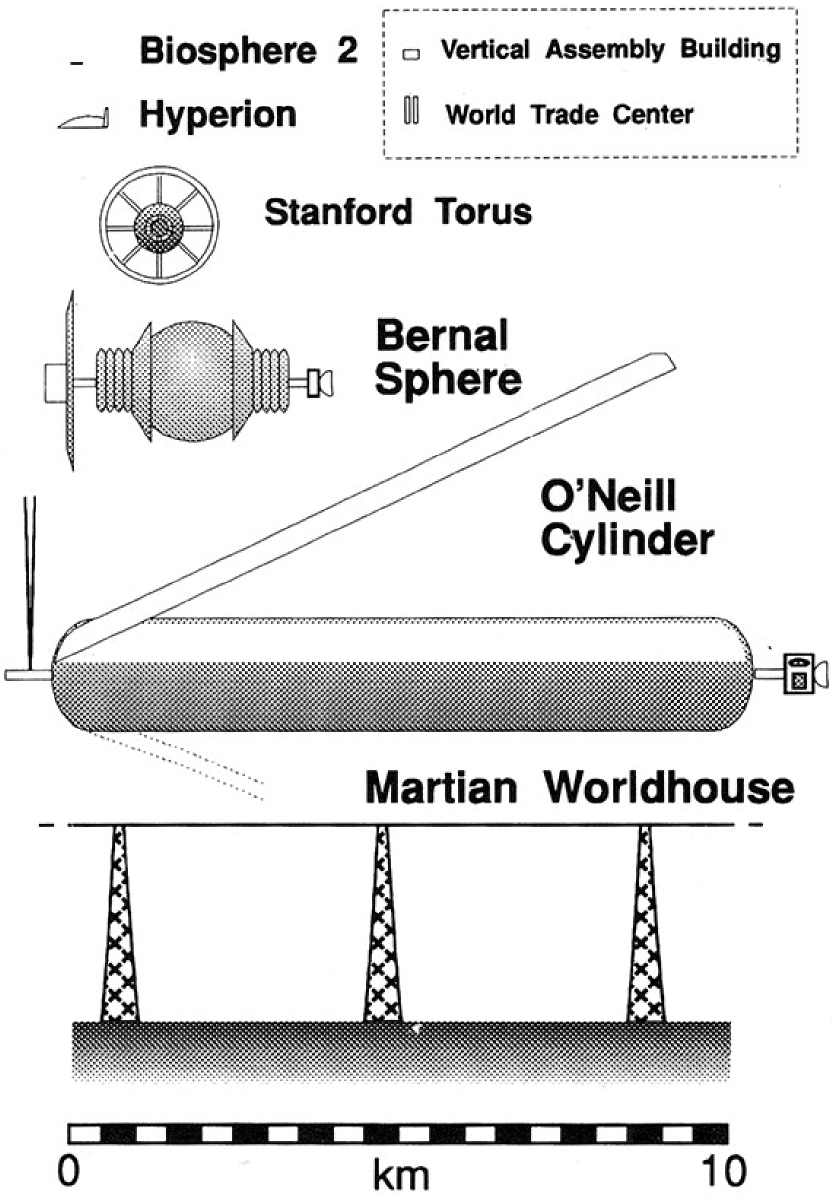

Figure 2.6 *Six different sizes of contained biospheres compared in size to two of the 20th century's largest buildings. All are theoretical except for the smallest, Biosphere 2.*

The main distinction made within these two classes of contained biosphere is simply between *small* and *large* — the somewhat vague dividing line between them being the volume at which quasi-natural weather, involving wind and rain, can spontaneously occur. The world's largest hollow building, Vertical Assembly Building (160 m high, 218 m long and 179 m wide, shown in Fig. 2.6), is known for 'having is own micro-climate' and for occasionally forming thin mists. However, judging from terrestrial cloud formation, a bare minimum of several hundred metres of overhead clearance seems to be indicated for some sort of precipitation to be possible. By this rough criterion, we might assign the label 'small' to the upper three designs in Fig. 2.6 and 'large' to the lower three. Space settlements kilometres in size are only going to be built well into a colonization programme. Early space settlers therefore will be living in small contained biospheres.

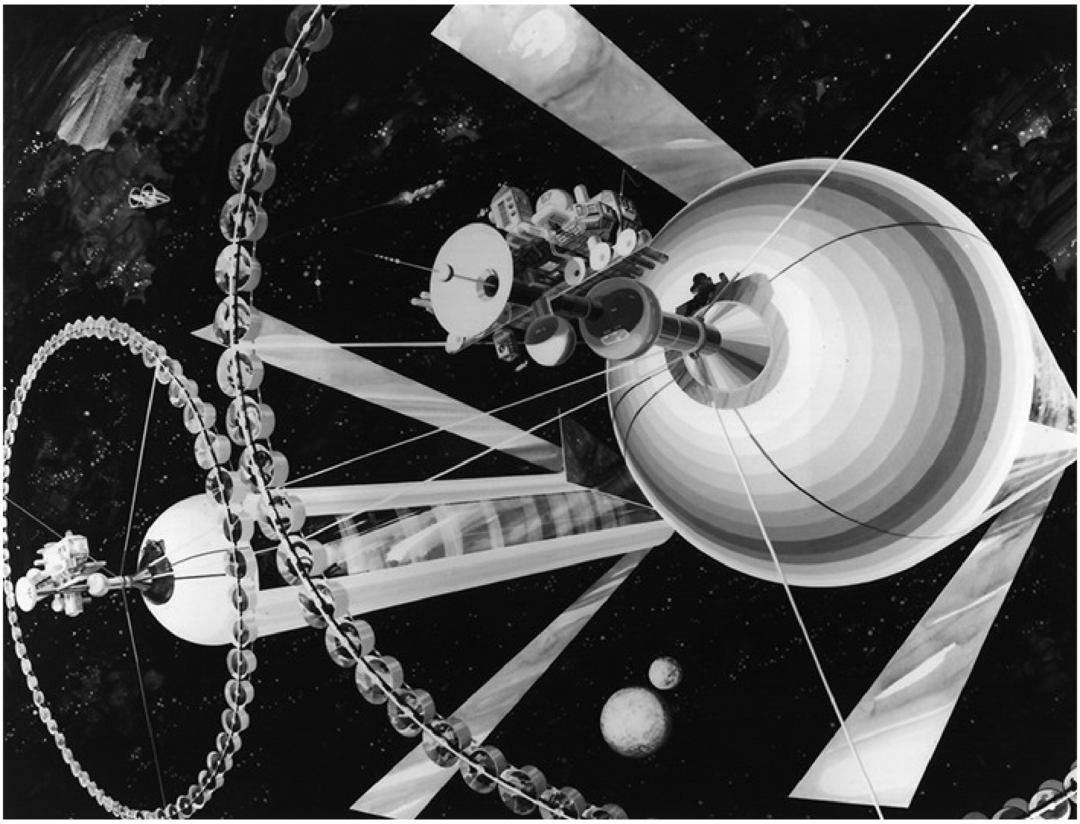

Plate 2.2 *The cylindrical space colony concept of G.K. O'Neill. This painting illustrates the largest of four similar designs, being 32 km long and 6.4 km wide. The habitat is spun about its long axis every 114 seconds to provide Earth like gravity on the interior surface. The teacup shaped containers ringing the cylinder are agricultural stations and the cylinder is capped by a manufacturing and power station. Large moveable rectangular mirrors on the sides of the cylinders, hinged at the far end, direct sunlight into the interior, regulate the seasons and control the diurnal cycle. Habitats are paired and spun in the opposite sense to cancel their net angular momentum, making it simpler to precess the overall assembly in order to maintain its facing with respect to the Sun. (Artist: Don Davis; photo courtesy of NASA).*

A considerable amount of theoretical modelling of small bioregenerative life-support systems has been done, many of the studies working roughly along the lines of attaching a horticultural greenhouse to a human habitat to create an artificial ecosystem — the greenhouse exports food, oxygen, clean air and water to the habitat which returns carbon dioxide, nutrient-rich wastes, and contaminated air and water [e.g. 10]. Such "on paper" studies are essential as a first stage in design, to calculate the energy and matter fluxes the system must handle, but are no substitute for proper experimental test-beds, which tend to throw up the unexpected problems of real life. Many of the early practical attempts to integrate human beings into such systems were done in the Soviet Union. In 1961, Yevgeny Shepelev at the Institute of Biomedical Problems in Moscow was enclosed in a small chamber with 30 litres of *Chlorella* algae and walked out, a day later, fit and well. The algae had supplied all his oxygen and water, but had not been able to prevent the build up of foul-smelling trace contaminants in the air.

An advance on algal systems, to those based on higher plants was made using the Bios 3 test bed at the Institute of Biophysics, Krasnoyarsk in Siberia [11]. Bios 3 consisted of an airtight stainless steel hull, with a volume of about 315 m^3 containing a hydroponic crop growing area of 40 m^2, an algae compartment, and room for three crew. Illumination was provided by artificial lighting and the crops produced 30-70% of the crew's food; meat products had to be imported to provide amino acids missing from their vegetarian diet. Photosynthesis provided enough oxygen for the crew and the water cycle was almost completely closed. Cabin water vapour was precipitated in condensers, urine was processed in the algae tanks and the water in solid wastes was extracted externally and returned to the system. Solid wastes were not recycled and inedible plant biomass was burned to free its inventory of CO_2. Trace contaminants had to be removed by passing air through a catalytic burner. Closure periods of up to six months were achieved, before the gradual loss of essential trace elements, due to the partially regenerative nature of the system, became a serious problem.

A similar reductionist approach to bioregenerative life-support was taken in the USA with the NASA CELSS (Controlled Ecological Life-Support System) program [12-14], which started in 1977. Its aim is to keep ecosystems simple, comprising just a few species and to reduce size and weight so that the whole system will be compact enough to be used on spacecraft. CELSS research is divided amongst various institutions studying particular aspects of the problem, such as choice of plant species and optimization of their yield, aquaculture, food preparation and waste recycling. This laboratory research is being scaled up and integrated as part of the CELSS 'Breadboard Project', the centrepiece of which is the Biomass Production Chamber at the Kennedy Space Centre, a cylindrical pod, 3.5 m diameter and 7.5 m high, containing racks of plants, high pressure sodium lamps and ventilation and water systems. Precise control of lighting and nutrient flows has produced yields of wheat several times greater than the world field record. It is hoped that the experience gained by the Breadboard Project will clarify the way forward to a further scaling up of the system and eventual human integration.

By far the most ambitious and well known attempt at constructing a biosphere habitat is the Biosphere 2 project, set up and run by the private company Space Biospheres Ventures (SBV), financed by Texas millionaire Edward Perry Bass [6,15,16]. Here, the philosophy behind LSS design is the complete opposite to that of CELSS or Bios 3. The problem is tackled instead by a 'top down' approach where the building blocks of life-support are ecosystems, rather than individual species. Biosphere 2 is therefore a substantial structure, the world's largest airtight building, with a steel and glass space frame shell above ground and a steel and concrete lining below. It has an airtight footprint of 12,766 m^2 and a volume of 204,045 m^3. Plants are grown in soil, rather than hydroponically and the system comprises seven biomes — intensive agriculture, human habitat, rainforest, ocean, marshland, savannah and desert; each of these is stocked with appropriate ecosystems, resulting in a total inventory of over 3000 species. The ambition of Biosphere 2 is to demonstrate fully closed, bioregenerative, life-support for a crew of eight, over a two year period, using sunlight for biomass production. Agriculture provides food and oxygen; wilderness biomes also partake in atmospheric revitalization, add to the aesthetics of the surroundings and, because of their supposed ability to regulate their environment, are included to help in stabilizing the system. Wastes are recycled by aquatic and microbial ecosystems and trace contaminants are dealt with either by absorption by the mass of the biota or by bacterial decomposition in soil-bed reactor systems.

Obviously, such a large structure as Biosphere 2 (although still the smallest in Fig. 2.6) cannot be considered as a first generation bioregenerative space life-support system. However it has been widely touted by SBV as a prototype solution for the long-term habitation of an extraterrestrial planetary surface, such as Mars. As this text is being written, the first two-year mission of Biosphere 2 is approaching its conclusion. Not all the results have been good, although since enclosed bioregenerative life-support is such a new field it would have been a surprise if every facet of the operation had worked perfectly first time. Among the crew's problems was the fact that their agriculture produced much less food than expected because the amount of sunlight entering the structure had been overestimated and because of abnormally cloudy weather outside. In winters especially, consumption outstripped production resulting in the partial pressure of carbon dioxide soaring to over ten times that of the outside air. A CO_2 scrubber had to be installed, precipitating calcium carbonate in a two step process:

$$CO_2 + 2\,NaOH \rightarrow Na_2CO_3 + H_2O \tag{2.9}$$

$$Na_2CO_3 + CaO + H_2O \rightarrow CaCO_3 + 2\,NaOH \tag{2.10}$$

Should more CO_2 be needed later then the solid inventory could be restored to the atmosphere by heating at $> 1000\ ^{o}C$ in a furnace:

$$CaCO_3 \rightarrow CaO + CO_2 \tag{2.11}$$

Another problem was that ecosystems proved less stable than was hoped and had to be protected from deterioration by the crew taking on the time-consuming role of so-called “keystone predators,” culling pathological species that threatened to get out of hand. For instance, an unfortunate plague of broad mites that attacked their crops further reduced agricultural productivity. Most seriously however was that Biosphere 2 suffered a totally unexpected steady decline in the partial pressure of oxygen, which eventually became life-threatening. This deficit took time to trace, but was eventually understood to have been caused by the oxidation of organic matter in the soil. The reason why CO_2 didn't build up more than it did was because the building’s concrete liner was absorbing it. Since no back-up systems for the regeneration of oxygen (such as those described for the EC/LSS above) had been installed, closure was broken in January 1993 to inject a large quantity of liquid oxygen to raise the quantity in the atmosphere from 14% to 19%. Adequate Bioregeneration and balance within Biosphere 2 has therefore not been achieved.

2.6.1 Intrinsic Problems with Small Contained Biospheres

The structure of Biosphere 2 is designed to last for 100 years and it is likely that future experiments will iron out many of its current failures. Small contained biospheres are undoubtedly the future choice of habitat for at least the initial foundation and growth of an extraterrestrial civilization. But what about our original question about indefinite habitability? What can we deduce about the fundamental capabilities of such habitats to match our requirements of a truly long-term life-support system?

Realistically, it seems that such systems may always fall short of the ideal, simply because it may be impossible to scale down the volume of the Earth's biosphere by a factor of $> 10^{13}$ and adequately maintain all its functions. Perusal of the life-support literature and experience gained by the experiments that have been done so far reveal a substantial list of aspects of bioregenerative life support that will need assistance from technology. This list is shown in Table 2.3 and arises because of two inevitabilities — the containment itself and the system's low volume.

TABLE 2.3 SMALL CONTAINED BIOSPHERES: ASPECTS REQUIRING A TECHNOLOGICAL SOLUTION

- Maintenance of habitable enclosure
- Replacement of leaked gases
- Radiation protection
- Temperature regulation
- Hydrological cycle
- Trace contaminant control
- System stabilization
- Solid waste recycling
- Management of horticulture
- Pest and disease control
- Emergency life-support

In space, or on the surface of bodies such as the Moon or Mars, the containing structure of a life-support system literally demarcates where life can and cannot exist. Its integrity is therefore essential and will require continuous monitoring and maintenance. Comparing the drama involved in coping with a broken greenhouse window on Mars with a similar incident on Earth gives some idea of the extra day to day work occupants will have to put into offsetting the fragility of their habitable surroundings. Loss of atmosphere will inevitably occur, whether suddenly through meteorite impact or human error, or gradually through losses accumulated from the entry and exit of inhabitants or tiny leakages inherent in the container. The current state of the art in making resilient, gas-tight, buildings will have to be greatly improved upon. Biosphere 2 *is* the current state of the art and has an exchange rate with the outside air of ~ 6% per year, much less than previous US and Russian facilities [16]. However in space this would become a loss that would add up to a need to replace a substantial fraction of the atmosphere after just a few years. This would not be a severe problem on Mars, which has an atmosphere (albeit thin) of its own to re-supply the habitat; many other locales in the solar system however possess no such convenient reservoir. There will therefore be no buildings in space that are allowed to lapse into picturesque dilapidation — none that remain habitable anyway.

Then there is the problem of ionizing radiation from galactic cosmic rays and solar flares. Habitat design must take into account the fact that there is no natural protection from these hazards beyond the atmosphere of the Earth which due to its column mass of ~ 10^4 kg/m^2 provides shielding equivalent to a ~ 10 m thickness of water. Not surprisingly therefore designs for extraterrestrial habitats include substantial masses of radiation shielding: concepts for space settlements speak of sheathing the habitat with several metres thickness of rocky material left over from mining [8]; bases on the Moon and Mars are often shown buried under a layer of bulldozed soil, with many, or all, plant growing areas being illuminated by electric lighting, or reflected, rather than direct sunlight [17]. Cities on Mars resembling the elegant glasshouse design of Biosphere 2 therefore are only going to be possible after the planet is partially terraformed and its atmosphere is thick enough to provide natural shielding.

The low volumes of such life-support systems and the presence of a roof a few metres above results in an inevitable absence of natural weather to circulate fresh air, and ameliorate temperature differences. Small contained biospheres must therefore be provided with air conditioning and temperature regulation systems. The need to cool Biosphere 2 in the summer and to heat it in the winter consumes a great deal of power. It has been estimated that if its cooling system were to fail on a sunny day, temperatures would soar within an hour to > 60^{o}C, rapidly killing off most of the biota [6]. An inability to form clouds and rain also requires that the hydrological system be operated artificially. After transpiration by plants, water must be condensed from the air and then piped back into watering systems and sprinklers. All experimental bioregenerative life-support systems have worked this way and even concepts for quite large ones, such as the Stanford Torus space colony, incorporate dehumidification systems as essential recycling infrastructure [8].

Another consequence of low volume is that the dynamics of the contained biosphere are poorly buffered. By this, it is meant that the biota is connected with a much smaller inorganic reservoir of biogenic materials than on the Earth. Such materials therefore, as a proportion of their abundance, have to be cycled through the biota at a much faster rate. For instance, Biosphere 2, which has a ratio of biomass to atmosphere mass several hundred times that of Earth, has to recycle all the CO_2 in its atmosphere *in just a few days*, as opposed to the Earth's several years [15,16]. Substantial fluctuations in the CO_2 concentration are seen on a daily basis — as much as 600 ppm, nearly double the concentration in the outside air — cycling between production and consumption with day and night. This faster pace of change has the effect of making the system *intrinsically* less stable. Minor imbalances significantly affect the composition of the buffer in a short period of time. Any habitable equilibrium must therefore be extremely precise as these imbalances could run away very rapidly. The less-than-total predictability of the dynamics of ecological systems may make achievement of such a fine balance very difficult, especially as natural stabilizing biotic responses that function within the vast and massive biosphere of the Earth may be too slow or inoperable in a confined space. Once the composition of the buffer has changed to the extent that biological function is endangered (by for instance levels of CO_2 falling too low or rising too high) the system is in danger of crashing completely.

Thus, small contained biospheres will be sensitive to destabilization by minor perturbations, the speed of subsequent environmental change possibly overwhelming the ability of ecosystems to compensate. Examples of events that could trigger a sudden environmental crisis include: a reduction in the amount of sunlight due to season or exterior meteorology in a locality such as Mars; a sudden influx of immigrants due to an emergency elsewhere; and an attack of pests or disease that disables some crucial aspect of Bioregeneration. We might conjecture that this tendency to instability is proportional to the biomass to atmospheric mass ratio. Rough estimates of these ratios, for the systems mentioned in the text, or illustrated in Figure 2.6, are shown in Table 2.4; each case assumes an atmospheric pressure of 1 bar, an identical areal density of biomass and is normalized to a 1:1 value for the Earth. The differences between small and large contained biospheres and natural or terraformed planets are easy to spot — there being an order of magnitude reduction in biomass / atmospheric mass and a corresponding increase in buffering between each category.

Consequently, some of the problems experienced by Bios 3 and Biosphere 2 come from fundamental difficulties stemming from their containment and low volume. *The inevitable solution to the problem of the viability of contained biospheres therefore seems to entail the back-up of ecological life support with* *technology and conscious monitoring and control of the whole system* [14]. Comfortable living conditions would have to be maintained by artificial air and water cycling. Machinery capable of manufacturing precise amounts of O_2 and CO_2 could compensate for unwanted deviations in the balance of these gases. The most indigestible of solid wastes might be more reliably broken down mechanically, as would trace contaminants that are not reabsorbed by the biota. Uncertainties in agricultural production could also be reduced by exploiting the wide range of technologies available to horticulture to deliver precise fluxes of light and flows of air, water, nutrients and pesticides.

TABLE 2.4 APPROXIMATE BIOMASS : ATMOSPHERIC MASS RATIO FOR VARIOUS BIOSPHERES. (NORMALIZED TO 1:1 RATIO FOR THE EARTH)

CELSS 'Breadboard'	2000 : 1
Bios 3	1000 : 1
Biosphere 2	350 : 1
Stanford Torus	250 : 1
O'Neill Island 2	20 : 1
Bernal Sphere	13 : 1
Martian 'Worldhouse'	7 : 1
Earth	1 : 1
Terraformed Mars	1 : 2.7

Protection from complete failure of the habitat's ecological LSS would require a comprehensive back-up mechanical LSS (of the type described earlier in this Chapter) capable of functioning in a last resort and for some considerable time following a serious emergency. *Intimate integration of ecosystems with machinery is therefore the key to continued survival within contained biospheres*. Whilst this has been recognized by the designers of Biosphere 2, the fact that the project's publicity has fostered a “new age” image, emphasizing the role of its “green” components, has tended to overshadow just how much it is reliant on technology and fossil fuel. Table 2.5 shows a list of Biosphere 2's mechanical life-support sub-systems (or in the terminology of SBV — *bioregenerative technology*). It is interesting to note the similarities between Tables 2.3 and 2.5.

A small contained biosphere will therefore require electrical energy to be expended on operating its bioregenerative technology. These energy flows, for the case of a biosphere habitat on Mars, are shown in Fig. 2.7. Circuits combining human work and electrical power are shown being fed back into the technological sub-systems that enable energy to flow into the base of the food chain. Without this feedback, the habitability of the enclosure would rapidly degrade. It is fair to point out that terrestrial civilization also sustains itself by feeding back energy into flow and maintenance systems — however, much of this is for human cultural activity. Most basic life-support on Earth comes for 'free', in space it will represent an additional power requirement. How much more?

TABLE 2.5 BIOSPHERE 2: BIOREGENERATIVE TECHNOLOGY. [LIST COMPILED FROM REF [6] — MAY NOT BE EXHAUSTIVE.]

- External structural maintenance teams
- Fans to circulate air
- Temperature regulation system
- Dehumidifiers in basement air coolers
- Pumps to circulate water
- Misting machine for "rainforest" cloud
- Desalination systems to maintain fresh water reservoir
- Algae scrubbers to transfer water between "salt marsh" and "ocean"
- Wave machine to oxygenate "ocean"
- Soil bed reactor to neutralize trace contaminants in air
- CO_2 scrubbers (not included in Ref [6])
- Emergency oxygen injection system (not included in Ref [6])
- Compost machine for rapid recycling of inedible plant waste
- Monitoring systems

Some relevant comparisons of power consumption are shown in Table 2.6, which compares the needs of terrestrial civilization with habitats proposed for space. On Earth, the per capita use of primary energy, such as embodied in fossil fuels, averages at ~ 2 kW/person world-wide, with consumption of electrical power averaging at ~ 0.2 kW_e/person. For the industrial countries, these averages rise to ~ 6 kW/person and ~ 0.7 kW_e/person respectively [18]. Estimates of power consumption to sustain life in space are variable, often because they represent rough and incomplete calculations of the properties of differing complex systems. The range of values in Table 2.6 is reasonably representative of what estimates can be found in the literature.

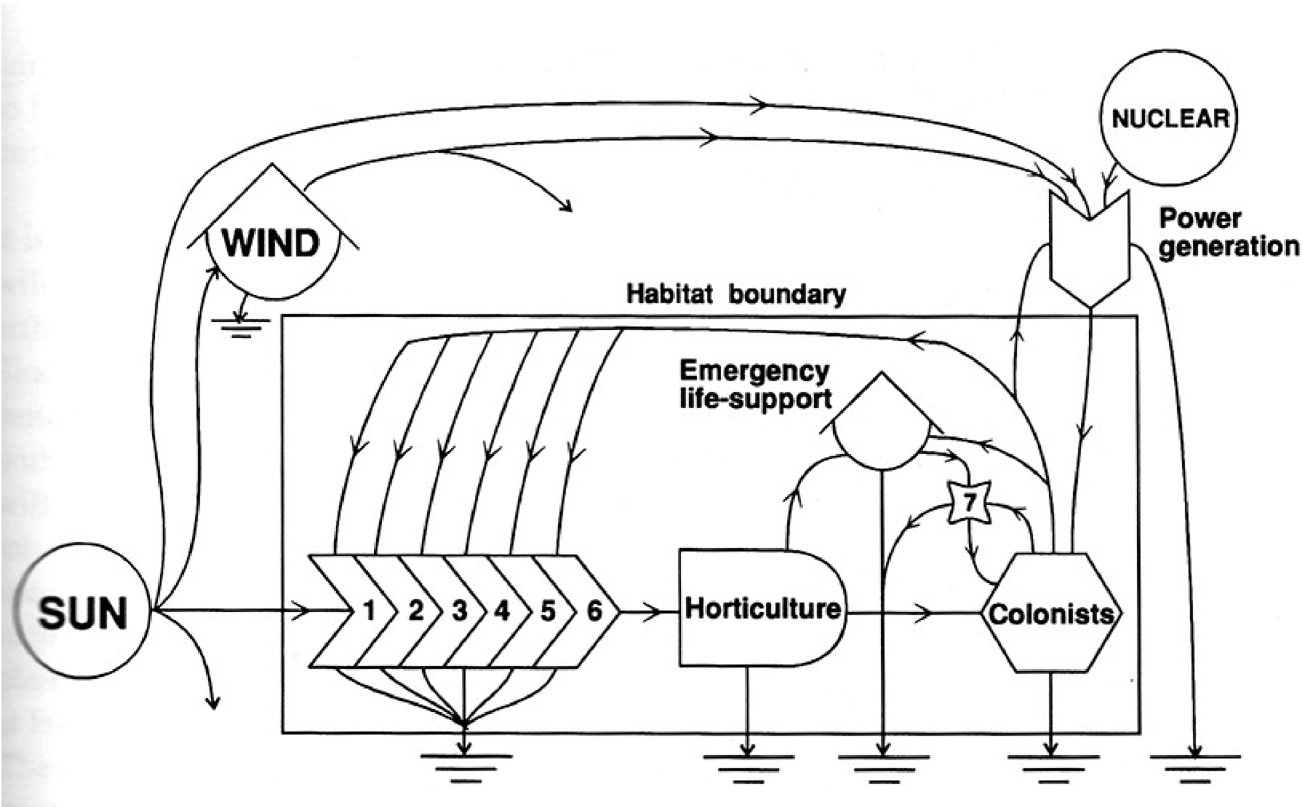

Figure 2.7 *Energy flows of a small contained biosphere on Mars. Life support must be extensively subsidized by electrical power and human work. Key: 1) habitat maintenance; 2) temperature regulation; 3) water recycling; 4) waste recycling; 5) environmental monitoring and control; 6) horticultural work; 7) emergency life support flow switch.*

Operation of the partially regenerative, fully mechanical, EC/LSS is calculated to require ~ 2kW$_e$/person [5]; this however does not take into account the outside energy subsidy in resupplying food and spare parts. An estimated power demand of a CELSS growing crops under artificial lighting is ~ 10 - 15 kW$_e$/person, dropping to < 5 kW$_e$/person if sunlight is used for photosynthesis and power is only needed for support machinery [19]. Space settlements such as the Stanford Torus, which admit sunlight into their interior, have a similar calculated power demand (~ 3 kW$_e$/person), but this includes power for both life-support and human activities and so may be underestimated [8]. (Space settlement designers normally focus on details of structural engineering, rather than bioregenerative life-support systems.) Theoretical studies therefore seem to indicate that the electrical power requirements of contained biospheres, *for life-support alone*, are going to be in excess of ten times the per capita electrical power consumption of terrestrial civilization. In terms of primary energy use, the requirements for *overall* human activities (life-support and culture) appear to be a minimum of double that on Earth and may be much greater. For instance, a 150-person Mars settlement designed by the Japanese Ohbayashi corporation has an estimated power demand of ~ 50 kW$_e$/person [20]. This includes not just life-support and routine use, but energy for mobility, expansion and emergencies.

A particularly worrying feature about Table 2.6 however is the power consumption of the one working model of a biosphere habitat — Biosphere 2, which requires a huge ~ 100 kW$_e$/person to operate [15], being supplied by an on-site natural gas power station.

**TABLE 2.6 HUMAN POWER CONSUMPTION:
COMPARISON OF EARTH AND CONTAINED BIOSPHERES**

Earth (Gratis Life-Support)	
World Average Primary Power	~ 2 kW / person
World Average Electrical Power	~ 0.2 kW_e / person
Industrial Nations Primary Power	~ 6 kW / person
Industrial Nations Electrical Power	~ 0.7 kW_e / person
Extraterrestrial Estimates	
EC/LSS only (stored food)	~ 2 kW_e / person
Stanford Torus Space Settlement	~ 3 kW_e / person
CELSS only (fluorescent lighting)	~ 15 kW_e / person
Ohbayashi Mars Colony 2057 (total power for all activities)	~ 50 kW_e / person
Biosphere 2	~ 100 kW_e / person

This energy subsidy needed to operate its mechanical subsystems is so large, it is actually equivalent to half of the average solar flux intercepted by Biosphere 2 and greatly exceeds the power flowing though its ecosystems. An idea that has been raised to install artificial lighting in the agricultural area to boost flagging production would increase the fossil fuel bill even more [21]. In addition to its voracious appetite for electricity, the up-keep of Biosphere 2 also requires substantial human labour. Two thirds of crew time is spent on agricultural activities, preparing food and maintaining the health of ecosystems in the "'keystone predator" role [21]. In space, if all this time has to be devoted to just staying alive, there will be precious little left in which to explore the universe!

It is clear therefore that substantial advances in design and efficiency of working contained biospheres will be needed before they can match the theoretical performance of on-paper concepts. Nevertheless, they undoubtedly represent the way to proceed from visiting to *living* in space. Since they will recycle food, as well as air, they offer the prospect of near, or complete, independence from Earth. The initial settlement of space will be done with such systems and, with the growth of a space-based economy, utilizing extraterrestrial resources, populations will expand. Bigger and better habitats will be built and will be occupied as long as the inhabitants are prepared to maintain them [22]. However, as an indefinite solution to life in space, they still fall short of our ideal requirements on every count: life-support systems will require subsidy from electric power and manufactured materials and therefore cannot be completely bioregenerative, self-replicating, self-maintaining, self-stabilizing and autonomous — at least, not without being made from some far-future technology with quasi-living properties. The aesthetic qualities of the surroundings within something like a cross between an ocean-going liner and large greenhouse will also have trouble matching the variety and freedom of the environment we are traditionally familiar with.

2.6.2 Large Contained Biospheres

It has been claimed that scaling up the size of habitats into the 'large' category would reduce many of these drawbacks. This is true. Quasi-natural weather would replace the need for fans, pumps, and rain-making machines. Biomass to atmospheric mass ratios would be reduced to only about an order of magnitude greater than Earth (Table 2.4). Environmental buffering would therefore be improved and the characteristic time for imbalances to translate into serious environmental change is increased. By analogy with the Earth, better buffered ecosystems, kilometres in extent, with not just internal flows of matter, but imports to and exports from neighbouring ecosystems of similar size are more likely to exhibit the self-stable, autonomous qualities desired, allowing humans to settle down to human life, rather than hanging on to ludicrous survival as “'keystone predators.” The aesthetics of life within a space that might take a day to cross on foot would also be a big improvement (see Plate 2.3), there being room for cities and wildernesses, even a modicum of landscaping to provide 'hills' and 'seas' [22].

Plate 2.3 *Artist's impression of the interior of the O'Neill cylinder illustrated in Plate 2.2. Habitats on this very large scale would be the size of counties or city states and, whilst still controlled and noticeably artificial, might provide largely unobtrusive life-support to the average citizen. (Artist: Don Davis; photo courtesy of NASA).*

However, such large contained biospheres will still be ~ 10^6 - 10^9 times smaller than the Earth's biosphere and will still be palpably artificial. Although ecologically more autonomous, they will still require conscious control and maintenance to tie up any loose ends in matter cycles and to operate technological sub-systems. Space settlements for instance will require a station keeping mechanism to keep their mirrors correctly orientated toward the Sun and these mirrors will have to be angled in a regular cycle to simulate day and night. Vigilance against the dangers of the exterior vacuum must be continuous and replacement for leaked gases will be needed at intervals. On Earth, perhaps two of the things we take for granted most of all, as much as sleeping and breathing, are the constancy of day and night and the permanence of the air about us.

This is perhaps the best that can be achievable with contained biospheres — habitability will last as long as habitation by humans, or some other form of consciousness, who know and care about maintaining the system. Integration of non-self-renewing hardware within fundamental systems of life-support leaves life vulnerable and intolerant to historical inevitabilities, such as conflict, cultural change and the rise and fall of civilizations. Even the largest contained biospheres cannot be expected to withstand more than a few years of neglect — let alone run themselves autonomously for geologic periods of time.

The most tenable long-range view for a system to support terrestrial life in space requires an option only available to settlers on a planetary surface (see Plate 2.4). Should the parameters of the planet in question be favourable, then they might terraform it to create a life-support system emulating all the functions of that on Earth [23].

Plate 2.4 *The rising Earth, as seen by Apollo 8 from the Moon. An uncontained planetary biosphere, contrasted against the surface of an airless and dead world. (Photo courtesy of NASA).*

2.7 Uncontained Biospheres — or the Earth as a Model for Planetary Engineers

A planetary biosphere has no artificial container and is merely restricted in its extent by gravity; it would naturally encompass the entire planet on which it is situated, filling all its interstices. By analogy with the Earth, such a life-support system might match our ideal attributes for a comfortable, perpetually renewing, habitat. Terraforming therefore is an exercise in recreating the Earth's biosphere elsewhere, *reproducing its scale*, as well as its internal dynamics. In this section, we attempt a concise appraisal of the Earth's basic parameters and processes that are responsible for and maintain its habitability. In short, we outline the Earth as a model planetary life-support system that can serve as a guide to the requirements of terraforming activities.

A compressed description of the Earth is given in Table 2.7, which lists a wide range of relevant numerical data. The following text makes comments on items in this Table, expanding into detail where necessary.

TABLE 2.7 PHYSICAL PARAMETERS OF THE EARTH

Parameter	Value.
Age	$4.6\text{x}10^9$ years
Mean Distance from Sun	$1.496\text{x}10^8$ km
Sidereal Period	365.256 days
Mean Orbital Velocity	29.79 km/s
Eccentricity	0.0167
Insolation	1370 W/m^2
Mass	$5.974\text{x}10^{24}$ kg
Equatorial Radius	6378.14 km
Mean Density	5520 kg/m^3
Surface Gravity	9.78 m/s^2
Escape Velocity	11.2 km/s
Sidereal Rotation Period	23.9345 hr
Obliquity	23.45^o
Albedo	0.3
Atmospheric Mass	$5.3\text{x}10^{18}$ kg
Atmospheric Pressure	1.013 bars
Atmospheric Scale Height	8.4 km
Effective Temperature	-18 ^oC
Mean Surface Temperature	15 ^oC
Magnetic Dipole Moment	$8\text{x}10^{15}$ $T\text{-}m^3$
Land Area (29.22%)	$1.49\text{x}10^8$ km^2
Ocean/Sea Area (70.78%)	$3.61\text{x}10^8$ km^2
Mass of Oceans/Seas	$1.41\text{x}10^{21}$ kg
Mass of Ice Sheets/Glaciers	$2.30\text{x}10^{19}$ kg
Biomass on Land	$1.8\text{x}10^{15}$ kg
Biomass in Oceans/Seas	$3.9\text{x}10^{12}$ kg

(Data from Various sources)

2.7.1 The Earth's Container

The fact that the Earth does not need a container to retain its atmosphere is because of the value of its escape velocity, v_{esc}, which is a function of its gravity, g, and radius, R:

$$V_{esc} = \sqrt{2gR} \tag{2.12}$$

These parameters themselves are dependant on the planetary mass and mean density. Escape of volatile material occurs from the exosphere — the topmost layer of the atmosphere above ~ 500 km, where gases are so tenuous and particle collisions so rare, atoms moving fast enough can fly away into space unimpeded. The criterion for the retention of a gas [24], over geologic time, is that the most probable velocity, v_0, of its constituent particles at the temperature of the exosphere must be less than six times the escape velocity ($v_{esc}/v_0 > 6$). This means that the fraction of particles in the high velocity tail of the Boltzmann distribution where $v_0 > v_{esc}$ is extremely small and negligible loss occurs.

The most probable velocity of the particles in a gas is:

$$V_0 = \sqrt{\frac{2kT}{m}} \tag{2.13}$$

where T is the temperature, m is the particle mass and k is the Boltzmann constant (1.38×10^{-23} J/K). Thus, the criterion for the long-term retention of a gas is:

$$\sqrt{\frac{gRm}{kT}} > 6 \tag{2.14}$$

Thermal escape parameters for common volatile species on the Earth are shown in Table 2.8, assuming a temperature of 1500 K (the exosphere is heated very strongly by extreme ultra-violet radiation). It is seen that only hydrogen and helium are ephemeral; other elements, even in their atomic forms, are retained.

TABLE 2.8 THERMAL ESCAPE OF ATMOSPHERIC GASES

Atom	**V_o - Most Probable Velocity at 1500 K**	**V_{esc}/V_o**	**Escape Over Geologic Time?**
H	5.0 km/s	2.2	Yes
He	3.5 km/s	3.2	Yes
N	1.3 km/s	8.6	No
O	1.2 km/s	9.3	No
Ar	0.8 km/s	14	No

There are other ways that particles can be accelerated to escape velocity — via energy imparted by photochemical reactions for instance — however, the Earth is too massive a planet for these processes to have been important over its history [24]. The greatest risk to the Earth's volatile endowment is a gradual loss of water, not by direct escape of the water molecule, but via its photodissociation by UV radiation and the subsequent escape of hydrogen. However, most water is confined to the troposphere, the lowest ~ 12 km of the atmosphere (see Fig. 2.8) — the negative temperature gradient of this region causing water to freeze out under the tropopause and the positive gradient in the overlying stratosphere preventing convection carrying it any higher. Thus, the Earth's 'container', so to speak, is a combination of the solid crust of the planet, its gravity well and its atmospheric 'cold trap'. Not only are the losses of volatiles effectively prevented, but also the large thickness of the 'container' and the large column mass of the atmosphere required to fill it, protects the surface from dangerous doses of ionizing radiation and small meteoroids.

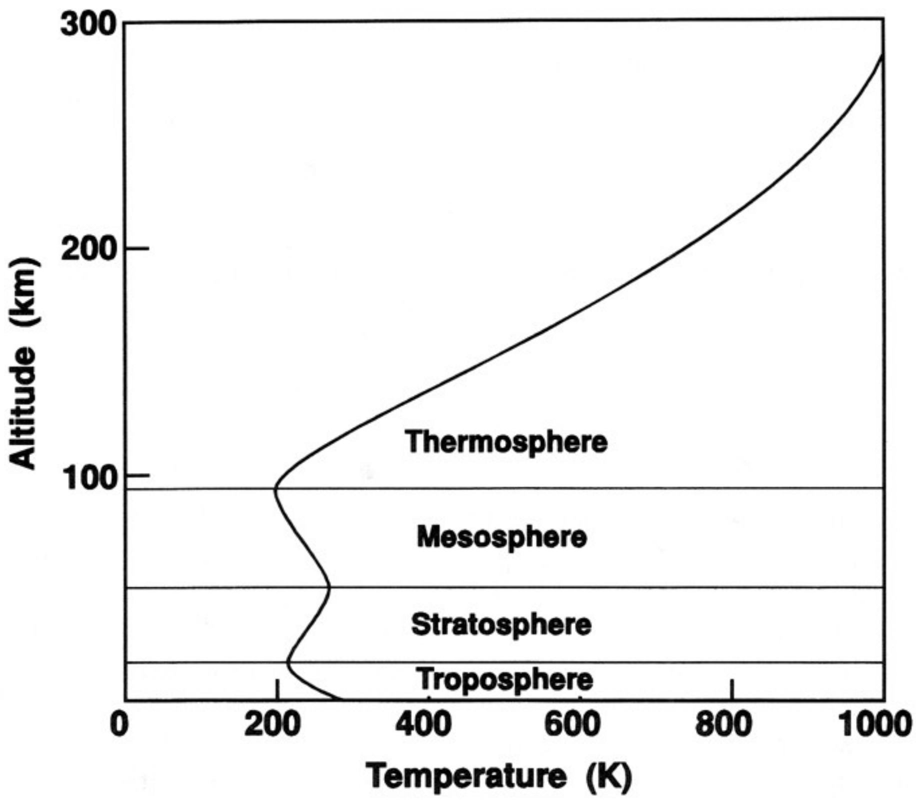

Figure 2.8 *Temperature profile of the atmosphere of the Earth. The temperature inversion at the boundary between the troposphere and the stratosphere (the tropopause) prevents large quantities of water from rising to higher altitudes.*

2.7.2 The Earth's Energy Flow

The energy flow of the Earth can be divided into two components: an *extrinsic* flow, i.e. energy entering or leaving the top of the atmosphere, and an *intrinsic* flow, representing energy emanating from the planet's interior, or temporarily processed within its systems. A body the size of the Earth needs a powerful extrinsic source of energy to be habitable and this is provided by the Sun. The crucial nature of this flow depends on the planet's astronomical parameters: orbital radius and eccentricity determine the average insolation and the annual extremes respectively; whilst its obliquity and rotation period determine the spatial and temporal distribution of radiation over the planet's surface, the character of the seasons and the variations between day and night.

The effective temperature of the planet — that at which it radiates back into space is given by [24]:

$$T_{eff} = \left(\frac{S(1-A)}{4\sigma}\right)^{1/4} \qquad (2.15)$$

where S is the average insolation, σ is the Stefan-Boltzmann constant (5.67×10^{-8} W/m^2/K^4), and A is the albedo (the fraction of incident radiation reflected back into space without being turned into heat — an intrinsic flow of energy). If we insert the values for S and A for Earth (Table 2.7) into the above equation, we find that $T_{eff} \approx 255$ K, or -18 ^{o}C.

The mean surface temperature of the Earth, T_{surf} is significantly higher than this since T_{eff} is augmented by the greenhouse effect ΔT_{green}:

$$T_{surf} = T_{eff} + \Delta T_{green} \qquad (2.16)$$

The temperature increment provided by the greenhouse effect is another intrinsic flow of energy, resulting from infrared absorbing gases in the atmosphere trapping some of the planet's heat and re-radiating it back to the surface. The main gases responsible are water vapour and CO_2 ($\Delta T_{green} \approx 33$ K); other gases such as CH_4 and N_2O also play a minor role [25]. The mean surface temperature of the Earth is therefore ~ 288 K, or 15 ^{o}C. Taken together, equations 15 and 16 show that T_{surf} is a function of a large set of explicit and implicit parameters. These large-scale terrestrial energy flows are summarized in Figure 2.9, showing the total flux of sunlight entering the system (visible radiation at ~ 6000 K — the temperature of the surface of the Sun), the flux of heat leaving (infrared radiation at ~ 255 K), and the fluxes trapped within various temporary storages and cycles in the process of being dissipated into heat. It is this massive capacity of the Earth to store energy within mobile materials that not only gives rise to the greenhouse effect (clearly shown in Fig. 2.9 as supplementing the direct insolation of the surface), but also allows for the natural matter cycling essential for an autonomous life-support system.

Numerical estimates of the power of terrestrial energy flows are given in Table 2.9 and also includes some smaller-scale fluxes than those illustrated in Fig. 2.9. Of particular interest is the power embodied in net primary production (NPP), the amount of organic matter fixed by plants in excess of their respiratory needs and therefore available as a basis for the food chain. NPP is also linked to essential regenerative processes and thus is one measure of the biologically useful work being generated within a biosphere (cf Figure 2.4). On Earth, NPP is responsible for ~ 90 TW of energy flow, ~ 20 TW of this through ecosystems subject to some sort of human management [27]; a detailed breakdown of NPP and quantity of biomass for various types of ecosystem is given in Table 2.10. Now, 90 TW represents an efficiency of conversion of the entire Earth's insolation into biochemical energy of ~ 0.05% and an efficiency of conversion of the radiation incident at the surface of ~ 0.1% — the maximum efficiency of leaf-incident radiation is ~ 5% [18]. This may seem quite low compared to man-made energy conversion devices, such as solar cells with efficiencies of ~ 10%; however, such a superficial comparison is not valid without taking into account the self-renewing properties of living systems. Solar cells do not reproduce and repair themselves and require subsidy from other sources of energy for their manufacture — neither do they contribute to matter cycling. The Earth's biosphere is therefore a very efficient, abundant and self-sustaining provider of life-support.

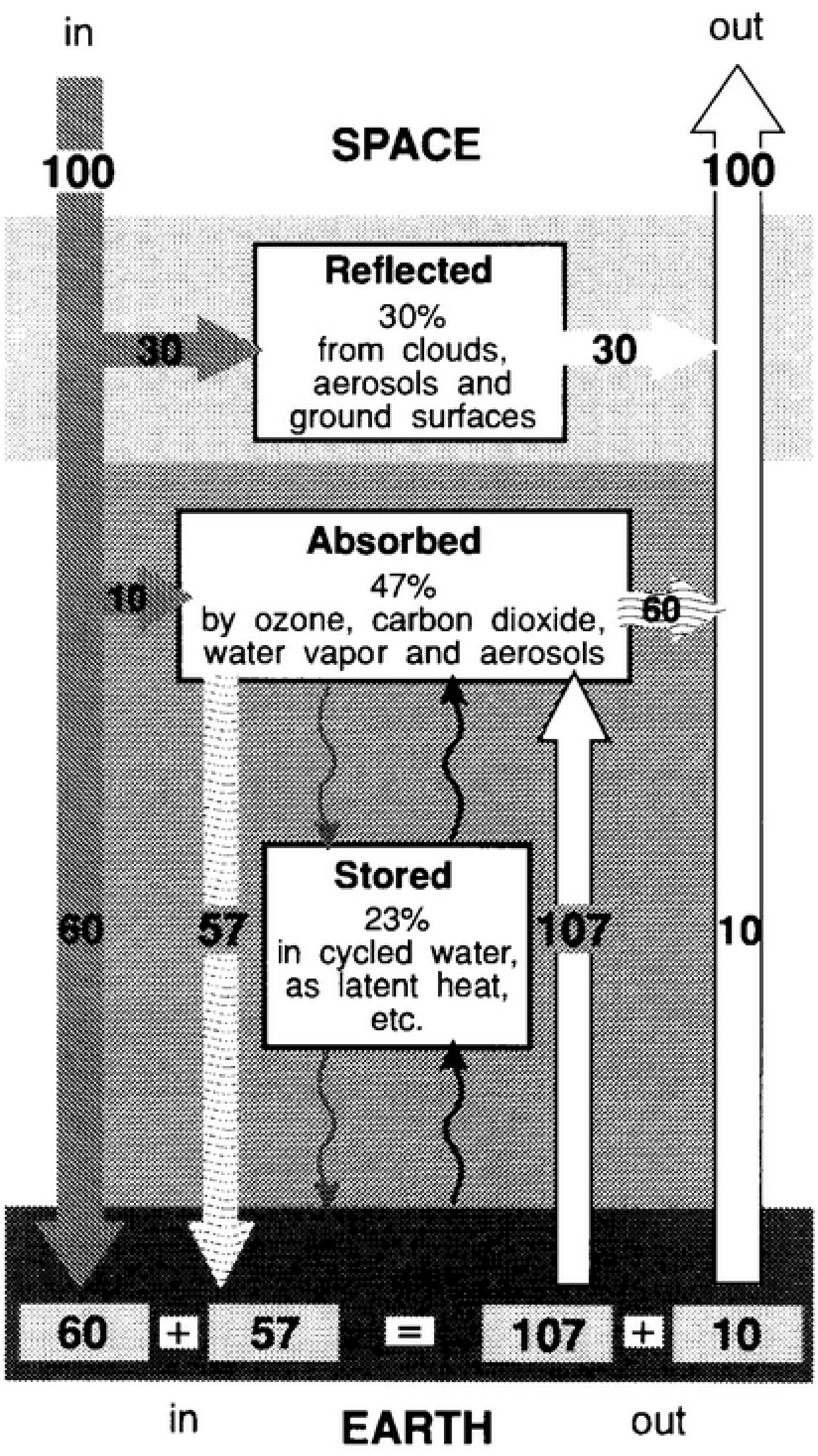

Figure 2.9 *Extrinsic and intrinsic energy fluxes of the Earth (arbitrary units). Sunlight enters, reflected light and heat exit. Temporary storages of energy drive atmospheric and oceanic cycling and give rise to the greenhouse effect. (Modified from Ref. [26].)*

TABLE 2.9 TERRESTRIAL ENERGY FLOWS

Natural.	
Total Insolation (top of atmosphere)	~ 175 000 TW.
Absorbed by Atmosphere and Converted to Heat	~ 82000 TW.
Stored in Hydrological Cycle, Oceans and Ice	~ 40000 TW.
Driving Circulation of Winds, Waves, etc.	~ 370 TW.
Net Primary Productivity (NPP)	~ 90 TW.
Geothermal Heat Flow	~ 40 TW.
Tidal Power from Moon's Gravity	~ 3 TW.
Anthropogenic.	
Human 'Control' of NPP	~ 20 TW.
Primary Energy Production	~ 10 TW.
Food Consumption	~ 0.5 TW.
Hypothetical (hopefully).	
Twelve Hour Nuclear War	~ 1000 TW.

TABLE 2.10 NET PRIMARY PRODUCTION AND PLANT BIOMASS FOR THE EARTH

Ecosystem Type	Area (million km^2)	Net Primary Productivity per Unit Area ($g/m^2/yr$)		World Net Primary Production (billion t/yr)	Biomass or Standing Crop (kg/m^2)		World Biomass (billion t)
		Normal Range	Mean		Normal Range	Mean	
Tropical rain forest	17.0	1000-3500	2200	37.4	6-80	45	765
Tropical seasonal forest	7.5	1000-2500	1600	12.0	6-60	35	260
Temperate evergreen forest	5.0	600-2500	1300	6.5	6-200	35	175
Temperate deciduous forest	7.0	600-2500	1200	8.4	6-60	30	210
Boreal forest	12.0	400-2000	800	9.6	6-40	20	240
Woodland and shrub land	8.5	250-1200	700	6.0	2-20	6	50
Savannah	15.0	200-2000	900	13.5	0.2-15	4	60
Temperate grassland	9.0	200-1500	600	5.4	0.2-5	1.6	14
Tundra and alpine	8.0	10-400	140	1.1	0.1-3	0.6	5
Desert and Semi desert scrub	18.0	10-250	90	1.6	0.1-4	0.7	13
Extreme desert, rock, sand, ice	24.0	0-10	3	0.07	0-0.2	0.02	0.5
Cultivated land	14.0	100-3500	650	9.1	0.4-12	1	14
Swamp and marsh	2.0	800-3500	2000	4.0	3-50	15	30
Lake and stream	2.0	100-1500	250	0.5	0-0.1	0.02	0.05
Total continental	149		773	115		12.3	1837
Open ocean	332.0	2-400	125	41.5	0-0.005	0.003	1.0
Up welling zones	0.4	400-1000	500	0.2	0.005-0.1	0.02	0.008
Continental shelf	26.6	200-600	360	9.6	0.001-0.04	0.01	0.27
Algal beds and reefs	0.6	500-4000	2500	1.6	0.04-4	2	1.2
Estuaries	1.4	200-3500	1500	2.1	0.01-6	1	1.4
Full marine	361		152	55.0		0.01	3.9
Full total	510		333	170		3.6	1841

To convert $g/m^2/yr$ to t/ha/yr, multiply by 0.01. After Whittaker, R.H., Communities and Ecosystems, Macmillan, New York (1975). Reproduced from Ref [28].

2.7.3 The Earth's Matter Cycles.

As a whole, it can be said that the Earth's biosphere is at a state of *ecological climax*, production and consumption being balanced on a global scale. The bioregenerative loop in Fig. 2.5 between the biota and their reservoirs of biogenic materials is therefore closed, or nearly so, as exchanges of matter with the planet's crust do occur, but are influential over geological, rather than biological timescales. The large 'inertia' of the biosphere, with its massive atmospheric buffer, its low biomass to atmosphere mass ratio compared to a contained system (see Table 2.4), results in environmental perturbations being resisted more strongly and taking longer to translate into significant shifts of climate or chemical balance. Restorative feedbacks that act to maintain the status quo, whether physical or biological, therefore have a better chance of stabilizing an environment damped by its own enormous mass and volume.

TABLE 2.11 COMPOSITION OF TROPOSHERIC AIR

Constituent	**Formula**	**Volume Proportion**
Nitrogen	N_2	78.08%
Oxygen	O_2	20.95%
Argon	Ar	0.93%
Water Vapour	H_2O	≤ 4%
Carbon Dioxide	CO_2	353 ppm
Neon	Ne	18 ppm
Helium	He	5.2 ppm
Methane	CH_4	1.7 ppm
Krypton	Kr	1.1 ppm
Hydrogen	H_2	0.4 - 1 ppm
Nitrous Oxide	N_2O	0.3 ppm
Xenon	Xe	0.08 ppm
Carbon Monoxide	CO	0.01 - 0.2 ppm
Ozone	O_3	≤ 50 ppb
Ammonia	NH_3	≤ 20 ppb
Sulphur Dioxide	SO_2	≤ 20 ppb
Hydrogen Sulphide	H_2S	2 -20 ppb
Formaldehyde	CH_2O	≤ 10 ppb
Nitrogen Dioxide	NO_2	≤ 3 ppb
Nitric Oxide	NO	≤ 3 ppb
Industrial Halocarbons	$C_mH_nCl_xF_yBr_z$	> 1 ppb
Hydrochloric Acid	HCl	≤ 1.5 ppb
Hydrogen Peroxide	H_2O_2	~ 1 ppb
Nitric Acid	HNO_3	≤ 1 ppb
Methyl Chloride	CH_3Cl	~ 0.6 ppb
Carbonyl Sulphide	COS	~ 0.5 ppb
Sulphuric Acid	H_2SO_4	~ 0.1 ppb
Methyl Iodide	CH_3I	~ 10 ppt
Methyl Bromide	CH_3Br	~ 5 ppt

(Data from Ref [29] and other sources).

The detailed composition of the lower atmosphere is shown in Table 2.11. The two bulk gases , nitrogen and oxygen are essential for biochemistry, as are carbon dioxide and water vapour. Nitrogen also fulfils another important role as a fire suppressant — in an atmosphere with more than 25% O_2, there is a suggestion that even damp vegetation becomes inflammable and so the presence of an inert gas to interfere with rapid oxidation is essential [30]. Traces of another variety of oxygen, ozone, are also present and are concentrated mostly in the stratosphere, between 12-30 km high. Ozone is manufactured and destroyed by photochemical processes and, as part of this, absorbs UV radiation between 200-300 nm, an essential factor in permitting the habitability of the land. The presence of both oxidized and reduced molecules in the same mixture demonstrates that the atmosphere is actively exchanging material with living systems. On an Earth with no life, the atmosphere would be much more like that on Mars and Venus — mostly CO_2, with no photosynthesis to supply oxygen; no denitrification to regenerate nitrogen and no anaerobic respiration to produce methane and other reduced species. It was James Lovelock who first pointed to the out-of-equilibrium composition of the atmosphere of Earth as being the unmistakeable 'fingerprint' of a planet with indigenous life [31].

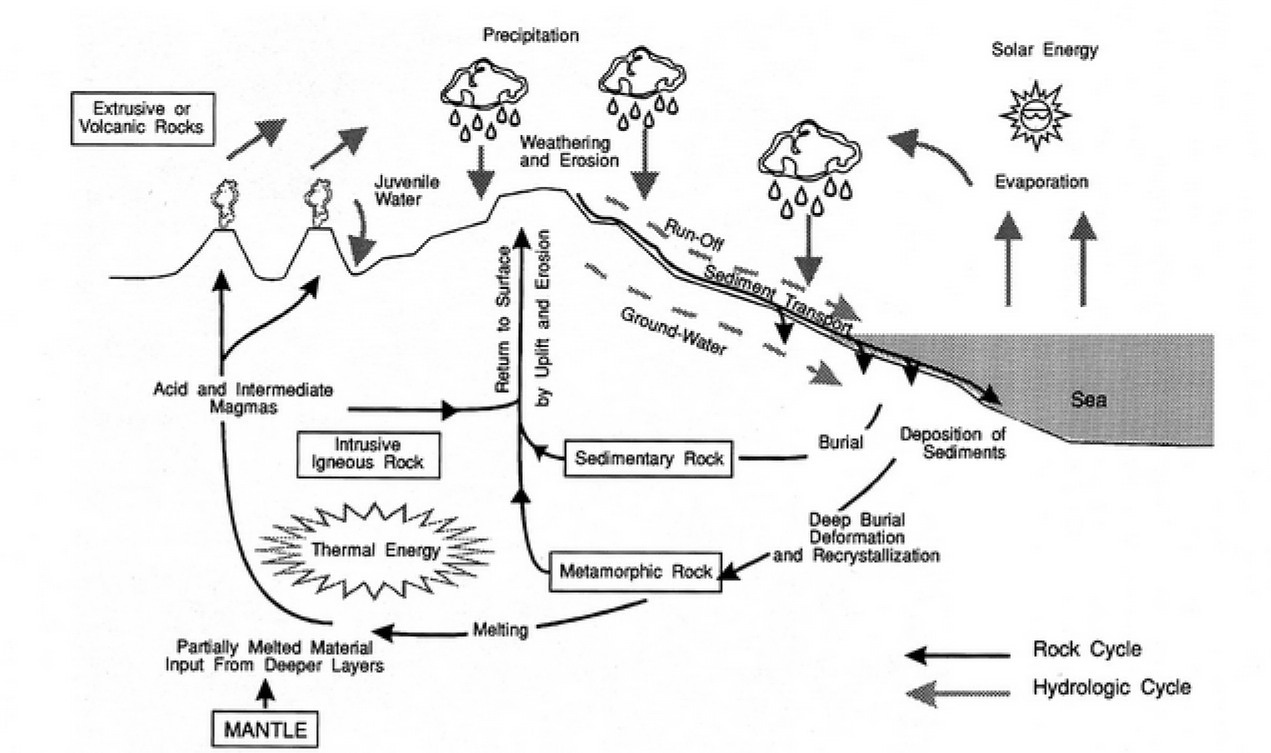

Figure 2.10 *The rock and hydrologic cycles. The land surfaces are worn down by weathering and erosion and are rejuvenated by volcanic and tectonic processes. (Reproduced with permission from Ref. [33].)*

The carbon dioxide in the Earth's atmosphere cycles through the biota in ~ 10 years and the oxygen in ~ 6000 years. However, exchanges of these molecules and other essential mineral nutrients (cf Table 2.1) with surface reservoirs also occurs, but at a much slower rate. Thus, some cycling of crustal rocks to release biogenic materials back into the biosphere is necessary to sustain habitability over million year periods or more. The Earth's active geology and plate tectonics, driven by its intrinsic geothermal energy (generated by the decay of radioactive isotopes), makes this longer-term cycling possible and is illustrated in Fig. 2.10, which combines both the hydrological cycle and the rock cycle. Continuous weathering and erosion releases nutrient elements from rocks into the environment and produces sediments that wash into basins where they consolidate into sedimentary rocks. These rocks however can become sinks for biogenic materials, trapping essential elements like carbon, sulphur and phosphorous in mineralized form and isolating them from living processes. If this were to go on for a few million years, much of the land would become worn down close to sea level and the ocean basins would become clogged with salts and sediments — causing chronic nutrient shortages that would drive the biosphere into a terminal decline. However, these sediments are not always buried in perpetuity, but are thrust back to the surface in mountain-building episodes and re-exposed to weathering and erosion (see Plate 2.5). Deposits on the ocean floor can be dragged to great depths under subduction zones and subjected to high temperatures and pressures to form metamorphic rocks, releasing volatiles from chemical combination so that they can escape back to the atmosphere in volcanic gases (see Table 2.12 and Plate 2.6). These *geochemical cycles* therefore compliment biochemical cycles, rejuvenating the planet over evolutionary and geological timescales. They make of the Earth an autonomous *biogeoregenerative* life-support system, with a life span of billions of years.

Plate 2.5 *A rejuvenated part of the Earth. The South face of the Himalayan range in India, Kashmir and Punjab; mountains made of sea-floor sediments thrust upwards by plate tectonic motions. (Photo courtesy of NASA).*

This extra dimension to matter cycling on a geologically active planet is shown in Fig. 2.11, which illustrates the biogeochemical carbon cycle. The central loop connecting the biota and CO_2 is the familiar biochemical carbon cycle depicted in Figure 2.4. It is largely balanced and at ecological climax, the rate of photosynthesis equalling that of respiration and decay. The outermost, geochemical, loop operates with fluxes of carbon > 1000 times less but which could still add up over periods of > 10^6 years to significant deficits within the system. Burial of unconsumed biomass removes organic carbon from the biosphere and the chemical weathering of silicate rocks removes CO_2 directly.

TABLE 2.12 THE COMPOSITION OF TYPICAL HAWAIIAN VOLCANIC GASES.

Constituent	Volume (%)
H_2O	77.0
CO_2	11.7
SO_2	6.5
N_2	3.0
H_2	0.5
CO	0.5
S_2	0.3
Cl_2	0.05
Ar	0.05

(Data from Ref [32]).

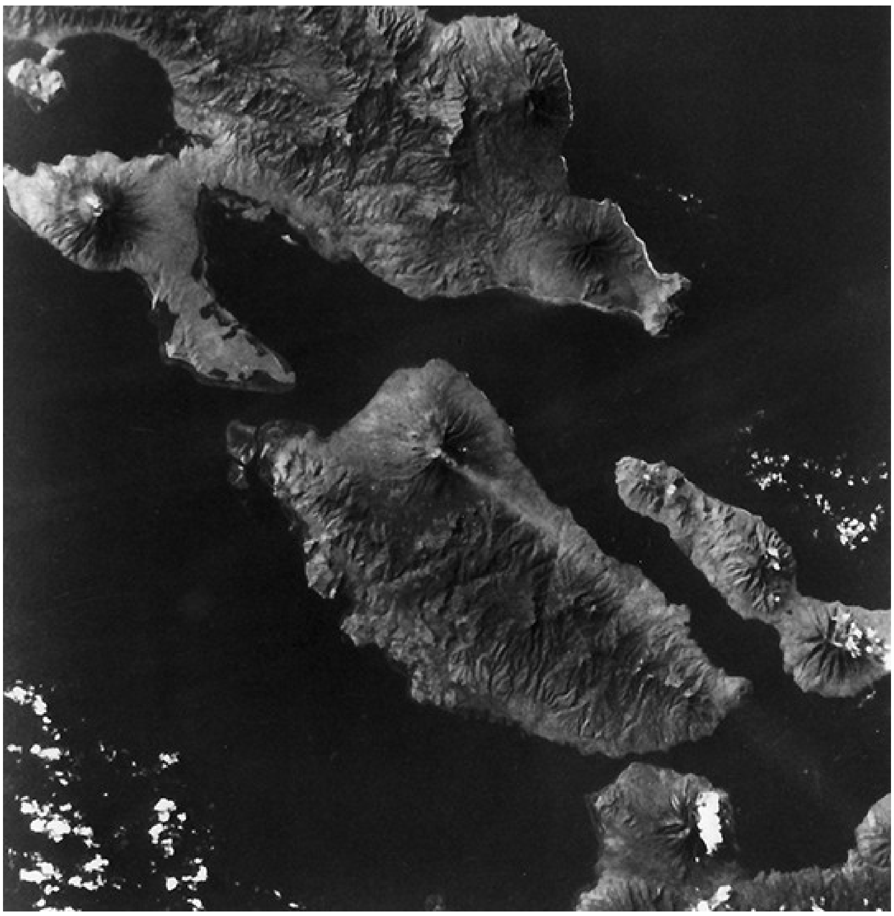

Plate 2.6 *Recycling of the Earth's volatiles. An active 1700 m volcano on Adonara Island in Indonesia leaves a 50 km visible trail of smoke. (Photo courtesy of NASA).*

An example of the latter process is where dissolved carbon dioxide (carbonic acid) replaces the silicate mineral wollastonite, releasing calcium ions and bicarbonate:

$$CaSiO_3 + 2\,CO_2 + H_2O \rightarrow Ca^{2+} + 2\,HCO_3^- + SiO_2 \qquad (2.17)$$

In the oceans, calcium combines with bicarbonate to form calcium carbonate:

$$Ca^{2+} + 2\,HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O \qquad (2.18)$$

For every two moles of carbon taking part in weathering, only one remains in volatile form. Without the return of this carbon to the biosphere, the partial pressure of CO_2 in the atmosphere would eventually fall too low for photosynthesis. The same rock-cycle process as in Figure 2.10 accomplishes this return. Tectonic uplift returns fossil organic carbon deposits (kerogen) to the surface, where they are oxidized back to CO_2. Deeper burial and heating bakes CO_2 out of carbonate rocks in a reverse of the two equations above:

$$CaCO_3 + SiO_2 \rightarrow CaSiO_3 + CO_2 \qquad (2.19)$$

where it is returned to the atmosphere by volcanic degassing.

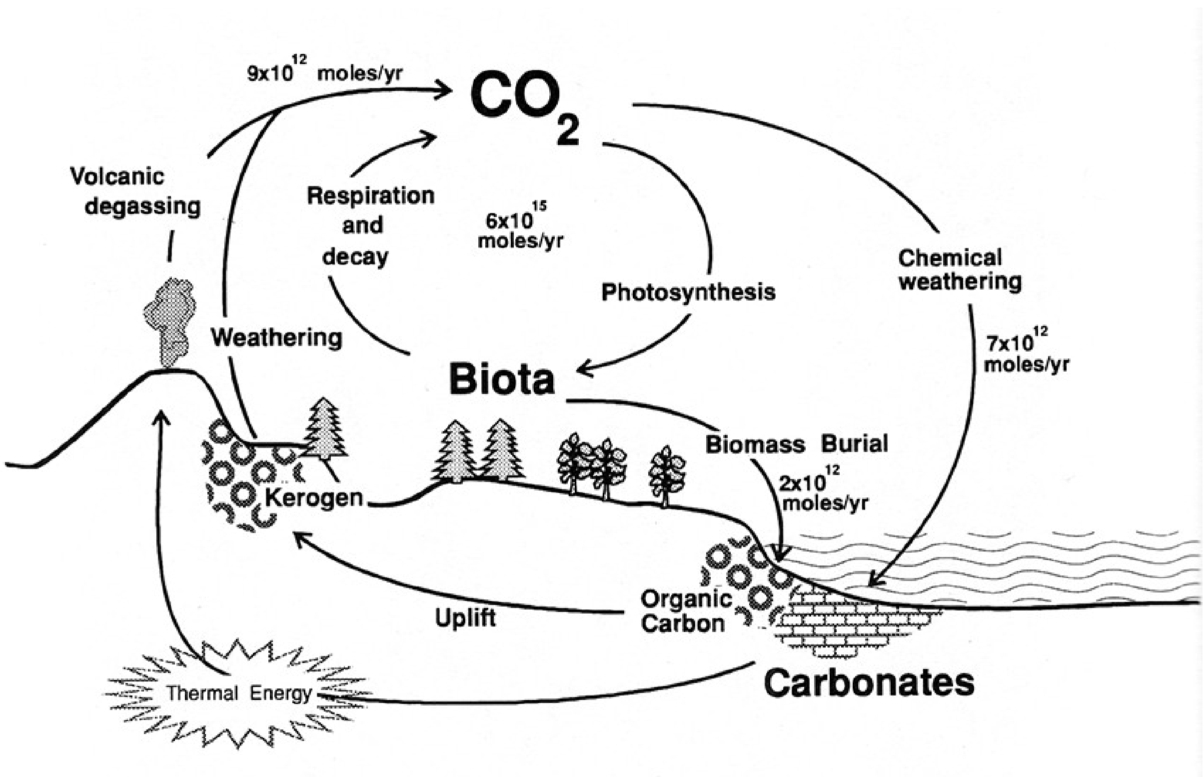

Figure 2.11 *Biogeochemical carbon cycles. The central biochemical loop is driven by solar energy; the external geochemical loop involves a contribution from geothermal energy.*

This basic principle of the long-term habitability of a planet relying on both biochemical and geochemical cycling applies to all other essential biogenic elements. Oxygen, for instance, essentially moves in flows opposite to carbon in Fig. 2.11. Photosynthesis liberates oxygen, respiration consumes it; burial of organic carbon allows it to accumulate in the atmosphere (since the biomass is escaping oxidation), whereas the weathering of kerogen soaks up oxygen. These interdependent flows of carbon and oxygen are also connected to the biogeochemical sulphur cycle, since the use of the sulphate anion for respiration in anoxic conditions and the burial of sedimentary pyrite (FeS_2) results in a net release of oxygen. The overall reaction is:

$$2\,Fe_2O_3 + 16\,Ca^{2+} + 16\,HCO_3^- + 8\,SO_4^{2-} \rightarrow 4\,FeS_2 + 16\,CaCO_3 + 8\,H_2O + 15\,O_2 \qquad (2.20)$$

The reverse of this occurs when the rock cycle returns pyrite deposits to the surface where they can be oxidized. The sulphur cycle itself influences the phosphorous cycle (shown in Fig. 2.12), since the chemical reactions that produce pyrite liberate phosphorous from sediments by converting it from insoluble to soluble form [34].

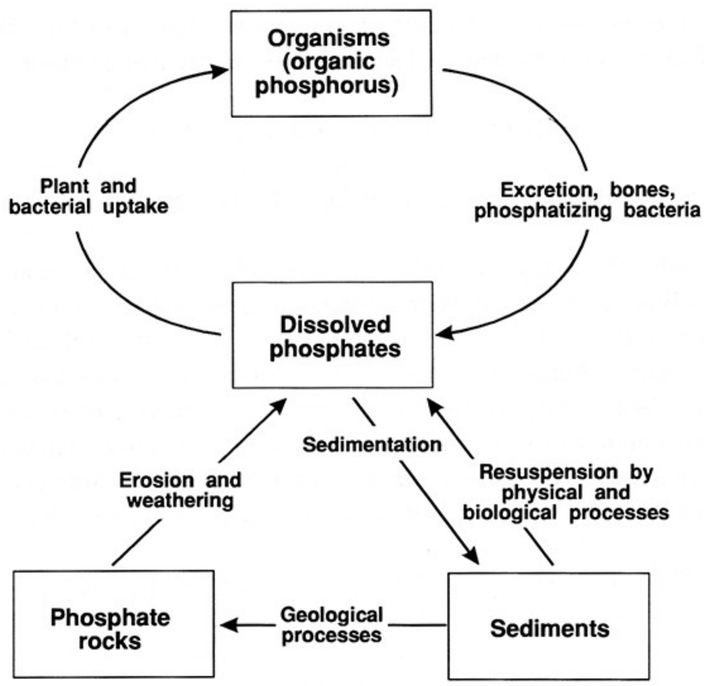

Figure 2.12 *The phosphorous cycle. (Reproduced with permission from Ref. [34].)*

Not even the briefest account of biogeochemical cycles would be complete without a mention of the nitrogen cycle, illustrated in Figure 2.13. On a dead Earth, at chemical equilibrium, the production of nitrogen oxides in the atmosphere by lightning discharges would ensure that much more nitrogen would exist as sodium nitrate in sediments or dissolved in hyper saline oceans. Our massive nitrogen-dominated atmosphere is however maintained by *denitrifying* bacteria which use nitrate, NO_3^-, for respiration in anaerobic conditions as a replacement for oxygen. Nitrogen is an essential component of proteins and terrestrial life is impossible without it. However, abiotic fixation of nitrogen from the atmospheric reservoir is too slow to sustain abundant life, so some micro organisms, such as cyanobacteria, have evolved the ability to fix nitrogen by synthesizing ammonia, which can then be bio chemically assimilated. Such organisms are often the first to colonize barren areas since they are not limited by lack of nitrogen. Their capacity to build up nitrogen in soils permits other species to move in later. Ammonia liberated into an aerobic environment is consumed by other specialized *nitrifying* bacteria that use it as an energy source, oxidising it via nitrite, NO_2^-, to nitrate. It is as nitrate and ammonium ions that plants most commonly assimilate nitrogen. As with other mineral cycles, nitrogen is gradually lost to deep sediments, mostly incorporated within buried organic matter. The rock cycle ensures that this is eventually returned to the biosphere, either by surface weathering or in volcanic gases (see Table 2.12).

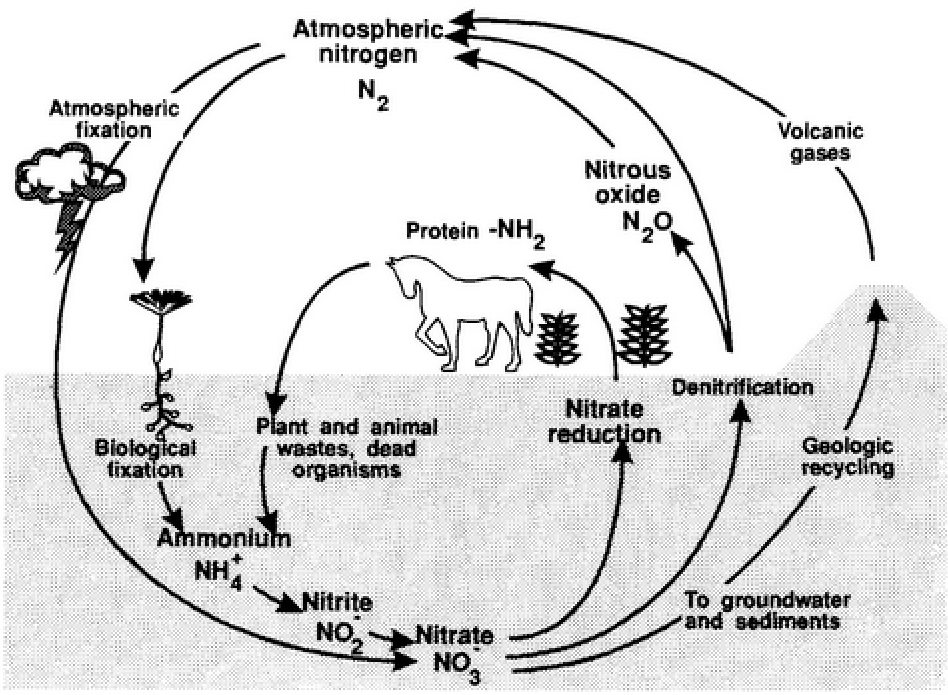

Figure 2.13 *The nitrogen cycle.*

It is plain therefore that the matter cycles of the Earth that are crucial for biology are inextricably bound together, like meshing cogs within a larger machine. Their biochemical aspect is powered by the ~ 90 TW of solar energy fluxing through the biota, plus subsidies from tidal energy and the much greater power embodied within the circulation of the atmosphere and hydrosphere. Their geological aspect is made possible by the ~ 40 TW of geothermal heat flow that keeps the Earth's crust mobile.

2.7.4 The Earth's Control Systems

Even so, we might still expect even such a massively buffered life-support system to drift away from a habitable state over the huge expanse of geological time. We know that there have been significant excursions in the chemical state of the biosphere since the origin of life ~ 3.5 billion years ago. Up until ~ 1.8

billion years ago, it is thought that the atmosphere contained very little oxygen and that this reactive gas only started to accumulate in large quantities after the crust itself had become sufficiently oxidized it could no longer mop up free oxygen at a faster rate than the burial of biomass could release it. However, the Earth has nonetheless remained invariably hospitable to life whilst gradually evolving and complicating both its biota and chemical state. Over the "recent" history of our planet, since the beginning of the Phanerozoic Aeon ~ 600 million years ago, the closure of biogeochemical cycles has been precise enough to ensure that the Earth has remained constantly habitable for complex, multi-cellular organisms.

Thus, we have to pose the question — is the habitability of the Earth a fluke? Did our life-support system just "muddle through" by chance? — Or, have there been self-regulatory processes at work that have maintained our planet as a warm, wet, hospitable place over geological time? The answer is an almost certain *yes* — that there exist restorative feedback processes that operate over all scales of the ecological hierarchy and over a range of timescales. What is more in dispute is the significance of the participation of the biota in planetary self-regulation. There is no doubt that life influences the state of its environment (see Table 2.11), but there is a school of thought that takes this further to postulate that the global biota has the capacity to *actively* maintain the planet's climate and chemical condition within narrow, habitable, bands. Regulation of parameters by internal feedback loops to optimise that system for the benefit of the system — the analogy with the homoeostatic mechanisms of individual organisms is appropriate and has been pointed out by James Lovelock, the originator of the *Gaia Hypothesis* [30,35,36]. He and his supporters (such as Lynn Margulis of the University of Massachusetts [37]) believe life, when viewed on a global scale, to have emergent properties — "the whole is more than the sum of its parts" — and that the biosphere is endowed with many of the qualities of a single living entity, a "super-organism" with its own "geophysiology." Lovelock has named this tightly coupled system of planet and life *Gaia*, after the Earth goddess of Greek myth. The Gaia Hypothesis is not universally accepted and has been subject to much attack and alternative interpretation; however, as a method of stimulating fresh debate over the phenomenon of planetary habitability, from a fresh overarching perspective, it has been extremely valuable.

Many control systems for regulating the Earth's environment have been proposed which rely on manipulation of parameters such as the albedo or greenhouse effect so as to resist climatic change. None are unequivocally proven and all gain in complexity when examined in detail. To do this topic justice here is not possible and so we choose to illustrate the concept by discussing one particularly important postulated control system that is claimed to be capable of planetary homoeostasis over geological time and which has both non-living and Gaian elements. This is the *geochemical carbon cycle* — the outermost loop illustrated in Fig. 2.11. However, before considering its homoeostatic properties, it is appropriate to consider the scale of the task it has had to fulfil.

There is a problem planetologists have to face when attempting to understand the long-term habitability of the Earth and that is what has become known as the "Faint Young Sun Paradox." One of the near-certainties of astrophysics is that main-sequence stars gradually brighten with age due to the gradual contraction and heating of their cores. It appears that the luminosity of the Sun at the time of the Earth's earliest history was only ~ 70% of its current value [38]. If all the other parameters of the Earth apart from its insolation were the same then as they are now, the planet would have been completely frozen and would have remained so for a couple of billion years. However, as far back in the geological record as it is possible to look, we find evidence of sedimentary rocks deposited in liquid water. There is evidence too for episodes of glaciation during the Precambrian, but at no time does the Earth seem to have completely frozen over. Some mechanism appears to have continuously maintained the mean surface temperature of the Earth, not just within the stability field of liquid water, but in the range comfortable for life.

The probable answer to this paradox is that the Earth's lower insolation was counteracted by a lower albedo and a more powerful greenhouse effect that would have been much more effective at trapping the heat of the dimmer Sun (see Equations 2.15 & 2.16). Current thinking therefore postulates that the original atmosphere of the Earth was denser than it is now with greatly elevated levels of carbon dioxide. As the Sun gradually became brighter, the tendency for the planet to overheat would have been neutralized by a systematic reduction in the partial pressure of CO_2: Fig. 2.14 illustrates the results of a model due to James Kasting of Pennsylvania State University which shows CO_2 levels declining from ~ 1 bar at 4.5 billion years ago to the ~ 350 ppm of today, the Earth remaining habitable throughout [39]. Obviously, such precision indicates some regulatory process at work that links the partial pressure of CO_2 into some inverse relationship with insolation. A possible solution was proposed by James Walker of the University of Michigan and colleagues who identified the geochemical carbon cycle as having thermostatic properties [40,41].

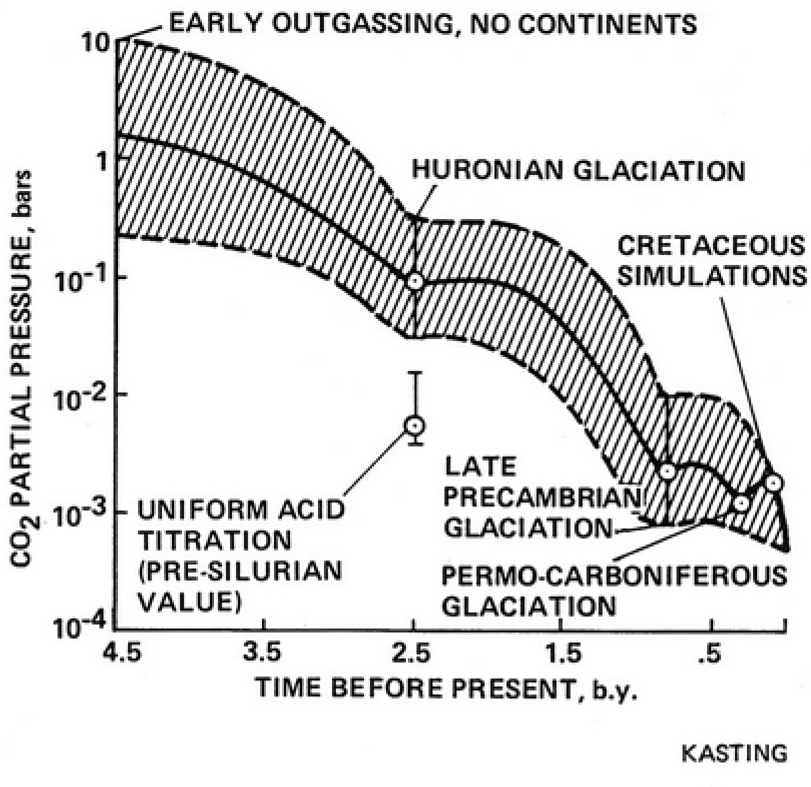

Figure 2.14 *Estimated change in the partial pressure of CO_2 over geological time, according to the modelling of Kasting. The solid curve is a "best guess" based on climate model simulations and the shaded area represents the climatically reasonable range. (Reproduced with permission from Ref. [39].)*

The key to the cycle acting as a control system lies in the fact that the rate of chemical weathering is sensitive to temperature and responds to changes almost immediately. In contrast, the delays inherent in the sub-surface part of the cycle maintain a constant outgassing rate — at least over the timescale of climatic change. So, if there is a climatic perturbation that raises surface temperature, the weathering rate increases, drawing carbon dioxide out of the atmosphere at a faster rate than volcanic out gassing can replace it (see Equations 2.17 & 2.18). Thus the greenhouse effect falls causing a climatic cooling — negating the original warming trend. A similar restoration occurs if the Earth becomes colder: chemical weathering now slows down, whilst the rate of volcanic re-supply stays the same. Carbon dioxide builds up in the atmosphere, increasing the greenhouse effect and boosting surface temperature. Thus, since the rapid weathering of silicates occurs in the aqueous phase, the system is automatically maintained at a state warm enough to permit the existence of plentiful liquid water, but not so warm that the rate of CO_2 removal exceeds the rate of replenishment. This means that *for any particular combination of solar luminosity, out gassing rate, land area etc., there is an equilibrium level of atmospheric CO_2 at which the system is stable* — hence the remarkable appearance of Fig. 2.14.

Although the geochemical carbon cycle can operate abiotically, some workers have pointed out that it works as a much better thermostat when assisted by biology [42]. The respiration of soil micro organisms and plant roots produces a level of CO_2 in gases between soil particles of 10-100 times that in the overlying atmosphere. Thus chemical weathering of mineral particles in biologically active soils is greatly enhanced when compared with bare rock. A "living" planet therefore will have a consistently lower level of atmospheric CO_2 and will be cooler; but since biological activity is also dependant on temperature, the negative feedback into the planetary thermostat will be stronger. The homoeostasis on a living world is more robust and constrained within tighter limits.

A number of other methods of biogeochemical climate regulation have been proposed and are detailed in a recent conference proceedings which well reviews both the science of Gaia and the controversy surrounding it [43]. Basically, the Gaia hypothesis states that life on a planetary scale has the ability to actively control its environment, rather than passively adapting to change. This notion that life can "take over" a planet (explicitly stated by Lovelock in The Greening of Mars — see Chapter 1) and make a stable home for itself is of obvious interest to would-be terraformers. It promises an ultimate dividend of not just a voluminous and well-buffered life-support system, but a strongly self-regulating one too. For some, it seems to offer a way to avoid what they see as inelegant planetary engineering and subsequent planetary maintenance — to implant planets with life and then to leave them to eke out their own evolutionary destiny. However, it cannot be assumed that such an action on another world, should it be possible at all, will necessarily result in an analogue of Gaia that climaxes and maintains itself at a state suitable for man. The level of researcher's regard for the Gaia hypothesis therefore influences their approach to terraforming and their view of whether it should be directed towards "Gaian" or anthropocentric aims.

The Earth's biosphere (or Gaia, depending on one's opinion) has existed for > 3.5 billion years. How much longer will it survive? Astrophysicists calculate that the Sun will last another ~ 5 billion years on the main-sequence before old age brings about drastic changes in its structure, swelling it into a Red Giant that will engulf the inner solar system [44]. However, long before this, the equilibrium level of CO_2 in the atmosphere, steadily falling due to the gradual brightening of the Sun, is expected to become too low for photosynthesis, cutting off primary production and causing the demise of the biosphere. This however is not expected for another ~ 0.9 - 1.5 billion years [45] and so it appears that life on a planet such as Earth can persist unaided for ~ 5 billion years and multicellular life for ~ 2 billion years. As will be shown in Chapter 8, a modicum of planetary engineering — much less than would be required for terraforming Mars or Venus — could extend the life of the biosphere right up to the Red Giant catastrophe.

2.7.5 Ecological Economics of Uncontained Biospheres

We have noted above that the Earth is an efficient, abundant and autonomous provider of life-support compared to what is expected from contained biospheres. This raises the possibility of there being a long-term *economic* argument in support of terraforming.

It is probably safe to assume that space colonization will occur for a variety of reasons and not just for the purpose of terraforming planets. Thus, it is likely to be extraterrestrial societies that are faced with the economic issues of terraforming, rather than the people of Earth. It is difficult to predict what the economics of a space-based society, a century or more in the future will be like and so, rather than examine the problem in terms of some extrapolated version of a present-day monetary unit, we choose to use a more basic unit of currency — that of energy. Energy has a strong economic function, flowing in an opposite direction to flows of money and being the prime mover of economic activity in much the same way as it drives ecosystems [2,3]. Not surprisingly, the standard of living on the Earth is a close function of per capita energy use. Moreover, many benefits of the Earth's biosphere that are normally taken for granted — such as wilderness ecosystems, for instance — can be assigned an economic value for the *gratis* life-support services they provide. This can be estimated in terms of the energy flow through the ecosystem and converted to a cash equivalent on the basis between energy and money in the production of market goods [34]. This *ecological economics* is likely to be particularly important to space settlers since they will have to pay in expensive, technologically processed, energy for their life-support systems from the very start (see Fig. 2.7, Table 2.6). If a resource comes for free, then the price can either stay the same or increase if that resource is mishandled. (We face this prospect on the Earth soon with our over-exploitation of the biosphere). If a resource is expensive, then a more efficient usage will lower the cost. This is what terraforming is about — *a low-cost method of living in space*.

The energy flow that would be characteristic of a fully terraformed Mars is shown in Fig. 2.15 and comparison with the dynamics of a biosphere habitat in Fig. 2.7 is most interesting. We see now that the solar energy intercepted by *the entire planet* is now available for diversion into useful work. Figs. 2.9 and 2.15 show that civilization would benefit from two powerful and *gratis* energy flows. Natural weather now drives the circulation of air and the hydrological cycle and the provision of fresh air, clean water and the recycling of most wastes are services also provided for free by the "'wilderness" biota. Feedback of human work will be needed for agriculture, but not in the quantity needed by the intensive, sealed, horticulture of a biosphere habitat. Expenditure of energy on those aspects of life support listed in Table 2.3 will either be zero, or much reduced. *For a given per capita consumption of primary energy. those living on terraformed planets will have more to spend on cultural activity and the general standard of life*.

The magnitude of these gratis life-support subsidies from a planetary biosphere can be estimated by comparing those that benefit terrestrial civilization (Table 2.9). The present world commercial power production is ~ 10 TW and human control of net primary productivity, because of the large areas under human management, amounts to ~ 20 TW. Of this ~ 0.5 TW is consumed as nutrient energy by mankind. The NPP of the global biota is however ~ 90 TW and the power embodied in weather and the hydrological cycle is > 10^4 TW. Since we cannot sub-divide the biosphere into smaller units with the same properties, one can reason that humanity, being part of the biosphere and a consumer at the top of the ecological hierarchy receives > 10,000 TW of *gratis* life-support subsidy, equivalent to > 2 MW/person. This is of course quite a crude argument, but it does make the 100 kW_e/person of Biosphere 2 appear more reasonable, except for the fact it has to be paid for in fossil fuel and electric generators.

To conclude therefore — as well as the concept being attractive from the viewpoint of life-support system function and aesthetics, *terraforming is also supported by a long-term economic argument*. Pioneers who choose to settle interplanetary space will have no choice but to live in contained biospheres — permanently; *but this will be the wrong way to go about living on a planetary surface*, treating it as if it is no more than a very large asteroid [23]. If the gravitational well of a planet is deep enough, and resources for terraforming

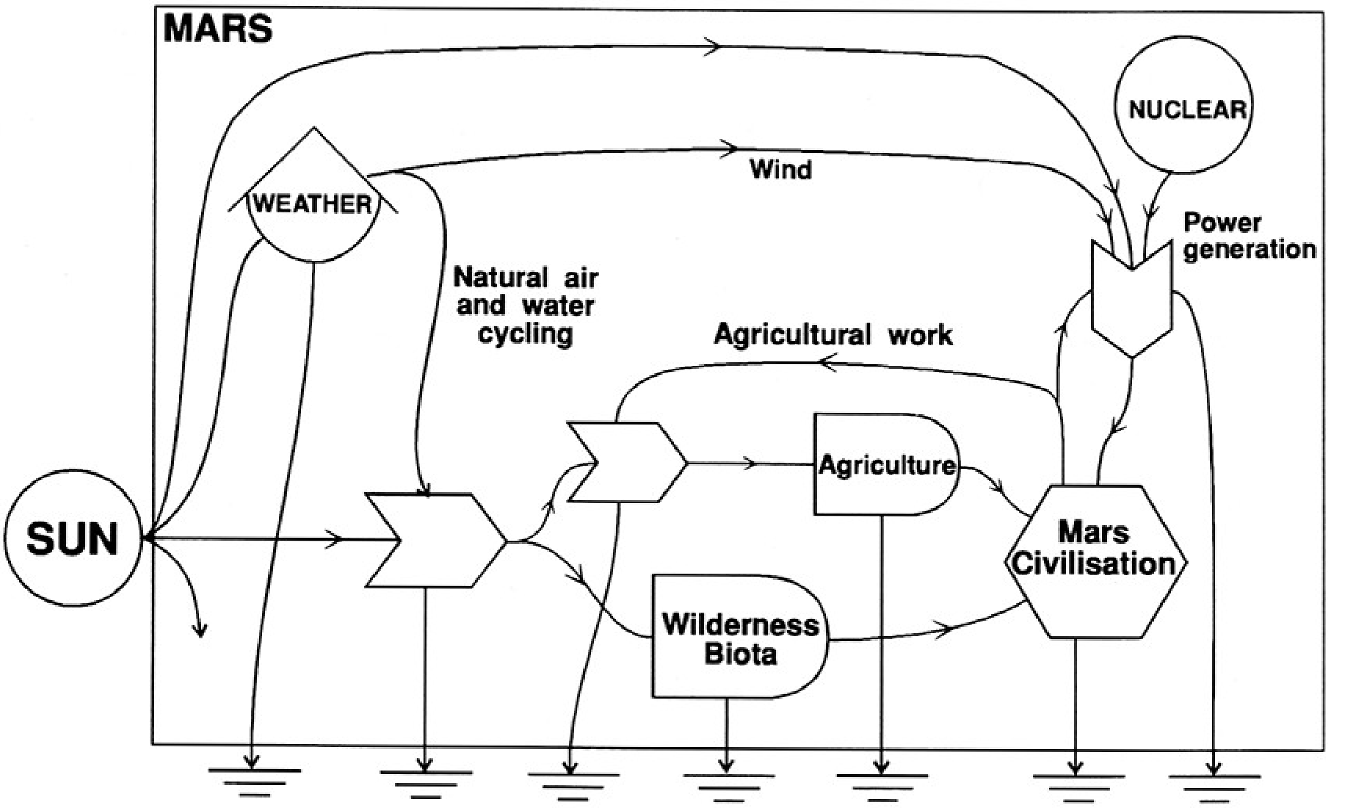

Figure 2.15 *Energy flow on a fully terraformed Mars. Civilization now receives huge subsidies from weather and wilderness biota and has to feed back work only into agriculture and cultural infrastructure. Compare with Fig. 2.7.*

are present, then it has the *potential* to host a global biosphere — the most efficient and secure life-support system for living away from Earth.

Irrespective of the extent to which the Gaia Hypothesis is true, it seems unlikely that any contained biosphere can match the performance of a habitable planet. Of course, we do not yet have anything like a full understanding of the functioning of the Earth's biosphere; but what we do know is that, as a life-support system, *it works* and will continue to do so for a long time. A habitable planet, with its variety of biogeographical regions, multiplicity of landscapes, diversity of natural processes and — even its ability to gradually absorb, clean up, or cover over garbage, has obvious aesthetic advantages over canned or greenhouse habitats. Other life-bearing planets in the Universe are expected to have these properties and to persist, unconsciously, for billions of years. Such worlds are therefore places where one can appreciate both the ordinariness of life and wonder at its profusion of forms, where one can escape the reliance on nearby machinery for the basic essentials of survival and where there is time enough for biological evolution — that gentle plasticity of form and function that gives rise to a progression of endless possibilities.

Artificial life-support systems must and will be built if mankind is to leave Earth; however, the benefits of terraformed planets are likely to impress themselves on at least some of our space-faring descendants, not just as a home for life as a whole, but also for their civilization.

2.8 Summary.

- If life is to have an extraterrestrial future, then the issue of a long-term life support system becomes important. Such a system should have the properties of utilizing sunlight for its energy source and regenerating its supply of biogenic elements. It should be as autonomous as possible, so its components should be self-reproducing and self-maintaining, and the environment as a whole stable and buffered against perturbations.
- Life-support systems, where the energy source is electrical power and matter recycling is carried out by machinery, do not fulfil these criteria and are suitable only for temporary residence in space.
- Artificially contained bioregenerative life-support systems produce food, recycle wastes and revitalize air and are thus more suited for long-term habitation. However, the level of their autonomy is poor as their limited volume entails technological assistance in matter cycling and environmental stabilization. The basic requisites of life therefore must remain subsidized by electrical power and machinery and be subject to constant conscious monitoring and control.
- The only long lasting and reliable life-support system which is currently known is the biosphere of the Earth. This functions almost entirely on its supply of solar energy and is voluminous enough to automatically exhibit weather, a hydrological cycle and to resist rapid and dramatic change. Its physical and biogeochemical dynamics are autonomous, except for those involved in agriculture and other cultural activities.
- Terraforming aims to create uncontained biospheres on other planets, which emulate the properties of Earth. In other words, the intention is to create a life-support system as beneficent, reliable, unobtrusive and long lasting as our planet's history shows is possible and to allow life not just to settle in space, but also to persist.

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