MAR 98-092

AN ECOLOGICAL APPROACH TO TERRAFORMING, MAPPING THE DREAM

Richard W. Miller

Department of Independent Studies, University of Waterloo, Waterloo, Ontario, Canada. E-mail: mars@kw.igs.net.

James Lovelock's Gaia hypothesis, suggests that Earth's biosphere is a self-regulating entity with the capacity to keep our planet healthy by controlling the physical and chemical environment. Central to Lovelock's model are the ideas of interconnectivity and feedback between components of the biosphere, and that life, when viewed on a global scale, has emergent properties. In effect, the Earth, its atmosphere, oceans, rocks and life comprise one entire ecosystem.

According to Eric D. Schneider, Hawkwood Institute and James J. Kay, University of Waterloo, ecosystems are systems of organisms, interacting with one another, within spatial and temporal boundaries, and consist of processes which bind organisms together and influence the development, structure and function of the ecosystem. They view ecosystems as "evolving complex systems that are held away from thermodynamic decay by imposed physical or chemical gradients." The Earth, as far as we know, is the only existing planetary ecosystem.

The physiognomy of planetary engineering is generally considered to have two aspects: ecopoiesis and terraforming. The goal of terraforming Mars would be to create an uncontained planetary biosphere emulating all the functions of the biosphere of Earth, one that would be fully habitable by humans.

So far, much of the speculation on planetary engineering has concentrated on the physical and chemical modifications required for terraforming Mars. This work has been based on traditional analytic and reductionist approaches to scientific inquiry. Silvio Funtowicz, Institute for Systems, Informatics and Safety, and Jerry Ravetz, Research Methods Consultancy, Ltd. claim that these methods are inadequate to cope with dynamic, complex systems, such as ecopoiesis and terraforming, which are characterized by unpredictability, incomplete control, and a plurality of legitimate perspectives. Terraforming, in which humans are an integral component, is an 'emergent' complex system which includes properties of reflection and contradiction. In this paper, I examine methods for describing complex systems, the tools which can be employed to manage them, and then suggest how these ideas can be applied to terraforming.

INTRODUCTION

In 1979, James Lovelock, published his theory that living organisms do not simply adapt to their physical conditions, but actively interact to modify and control the chemical and physical environment of Earth. Lovelock's theory, the Gaia hypothesis, states that, " the biosphere is a self-regulating entity with the capacity to keep our planet healthy by controlling the physical and chemical environment" (Odum, 1993:61). Central to Lovelock's model are the ideas of interconnectivity and feedback between components of the biosphere and that life, when viewed on a global scale, has emergent properties (the whole is greater than the sum of its parts), (Fogg, 1995: 77). In effect, the Earth, its atmosphere, oceans, rocks and life comprise one entire ecosystem.

According to Schneider and Kay (1994: 627), ecosystems are systems of organisms, interacting with one another, within spatial and temporal boundaries, and consist of processes which bind the organisms together and influence the development, structure and function of the ecosystem. Schneider and Kay view ecosystems as “evolving complex systems that are held away from thermodynamic decay by imposed physical or chemical gradients” (*ibid.*: 630). The Earth, as far as we know, is the only existing planetary ecosystem.

However, in their fictitious work, *The Greening of Mars*, Lovelock and Allaby (1984) speculated on the possibility of employing technology to change the physical environment of Mars into a self-sustaining living system. The physiognomy of planetary engineering is generally considered to have two aspects: ecopoiesis and terraforming. In 1984, Robert Haynes, biophysicist and Distinguished Research Professor at York University, invented the neologism, ecopoiesis, derived from the Greek roots *oikos* - an abode, house or dwelling place + *poiesis* - a fabrication or production. Ecopoiesis refers to “the fabrication of a sustainable ecosystem on a currently lifeless, sterile planet, thereby establishing a new arena in which biological evolution can proceed independent of further human husbandry” (Haynes, 1990:180). Martyn Fogg (1995), in Terraforming: Engineering Planetary Environments, defines terraforming as “a process of planetary engineering, specifically directed at enhancing the capacity of an extraterrestrial planetary environment to support life. The ultimate in terraforming would be to create an uncontained planetary biosphere emulating all the functions of the biosphere of Earth - one that would be fully habitable by humans”.

So far, much of the speculation on planetary engineering, as compiled in Fogg’s 1995 seminal work, *Terraforming: Engineering Planetary Environments*, has concentrated on the physical and chemical modifications, to the Martian environment, that will be required in order to set the stage for the denouement of planetary engineering, ecopoiesis and terraforming, the establishment of living organisms and eventually humans in a Martian planetary ecosystem. This work has been based on the traditional analytic and reductionist approaches to scientific inquiry. Funtowicz and Ravetz (1994) claim that these methods are inadequate to cope with dynamic, complex systems, such as ecopoiesis and terraforming, which are characterized by unpredictability, incomplete control, and a plurality of legitimate perspectives. Terraforming, in which humans are an integral component, is an ‘emergent’ complex system which includes properties of reflection and contradiction. The objective of this paper is to examine methods for describing complex systems, the tools which can be employed to manage them, and then to explore how these ideas can be applied to terraforming.

COMPLEXITY

Schneider and Kay (1994: 642) and Funtowicz and Ravetz (1994: 569) identify a continuum of complex states, Figure 1(a). The simplest state, *complication*, can be characterized by single optimizing (maximizing / minimizing) functions. Such systems are deterministic in nature and characterized by non-linear processes. *Ordinary* complex systems, exhibit simple teleology such as growth or survival and are characterized by balanced optimization. These systems consist of diverse elements, interacting both cooperatively and competitively, so as to maintain a dynamic stability, unless disturbed beyond their limit of resistance by outside perturbations (*ibid.*: 570). When perturbed beyond their limits, complex systems can exhibit catastrophic changes which may be manifest in one of several indeterminate transformations. *Emergent* complex systems, consist of symbolic information and are characterized by conflicting goals (Schneider and Kay, 1994: 642). Some elements within them possess individuality, with varying amounts of intentionality, consciousness, foresight, purpose, and morality (Funtowicz and Ravetz, 1994: 570). Continuous novelty is also characteristic of emergent complex systems. Emergent complex systems combine the mechanistic attributes (space, time, measurable properties) of complicated systems, the ordinary complex attributes of structure and function, with technical, economic, social, personal and moral attributes related to knowledge and consciousness (*ibid.*: 574). For the purposes of this discussion, abiotic systems are considered to fall into the realm of complication. biotic systems to exhibit ordinary complexity, and socio-cultural systems to be characterized by emergent complexity.

Complicated systems have been successfully understood using traditional reductionism and analytical scientific approaches. “In this ‘normal’ state of science, uncertainties are managed automatically, values are unspoken, and foundational problems unheard of.” (Funtowicz and Ravetz, 1993: 740). Understanding ordinary complex systems and emergent complex systems, requires new scientific approaches “based on the assumptions of unpredictability, incomplete control, and a plurality of legitimate perspectives” (*ibid.*). In the next section I will explore a parallel spectrum of scientific approaches which can be applied to understanding the various segments of the continuum of complexity. These approaches will be based on the level of system uncertainty, and the value of the associated decision stakes.

Figure 1 Continuum of Complexity.

Table 1

PROBLEM SOLVING STRATEGIES IN SCIENCE

PROBLEM-SOLVING STRATEGIES

Figure 1(b) illustrates a spectrum of problem solving strategies or scientific approaches that may be employed to address the various segments of the complexity spectrum. The approaches of core science, applied science, professional consultancy, and post-normal science are depicted against gradients of decision stakes and system uncertainties. According to Funtowicz and Ravetz, (1993: 744), the term decision stakes considers “all the various costs, benefits and value commitments that are involved in the issue through the various stakeholders”, and system uncertainties “conveys the principle that the problem is concerned not with the discovery of a particular fact, but with the comprehension or management of an inherently complex reality”. Table 1 tabulates the fundamental distinctions in the various problem solving strategies in science as explained by Funtowicz and Ravetz, (1993). These distinctions include **problem characteristics** - issues, values, constraints, conflicts, decision stakes, and assumptions;

problem uncertainties - level of uncertainty, characteristics of uncertainty, and methods for managing uncertainty; **actors** - legitimate community of concern, goals and focus of community members, type or style of knowledge employed, and scientific dialogue for argument; and **problem solving** - methods, strategies for addressing uncertainties in knowledge and ethical complexities, quality assurance processes, and the ultimate availability of results.

Ecopoiesis and terraforming will produce complex and dynamic natural systems. Terraforming, which involves interactions with humans, and exhibits properties of reflection and contradiction - is emergent. This perspective is consistent with Fogg's definition, and the viewpoint expressed in *Green Mars*, volume two, of Kim Stanley Robinson's fictional terraforming trilogy. "Robinson ...explore[s] the consequences of people struggling to 'yoke together impossible opposites' (Robinson, 1994:229): mind and body, spirit and matter, nature and culture, and biosphere and technoscience" (Markley, 1997: 774). Terraforming is a problem characterized by issues in which the facts are uncertain, and values are in dispute. Commercial pressures, bureaucratic regulation and activist protests are likely constraints, which will give rise to conflicting purposes. A realistic assumption, concerning terraforming, is that it will be a process with unpredictable outcomes, incomplete control, and many legitimate perspectives. The uncertainties in a terraforming project will be high, bordering on ignorance in many areas, and include an ethical perspective. An extended community of stakeholders will have a vested interest in managing these uncertainties. The legitimate community of stakeholders will include representatives from broader societal and cultural institutions. Their focus will naturally be on the purpose of the project and the bringing to bear of practical knowledge through interactive dialogue. Problem solving strategy will need to be systemic and humanistic, as the results of the project will affect the broad community of humanity, future generations, and the planetary environment of Mars. Thus post-normal science is the suggested strategy for addressing terraforming.

ASSESSMENT

Assessment is a key element in managing complex, adaptive systems which are the result of projects such as ecopoiesis and terraforming. Nelson and Serafin (1993:392) define assessment, "assessment is usually taken to refer to a process which attempts to make judgments about ecological, economic and social impacts of development proposals and activities as a basis for improved projects, programs, policies and other activities in the future". They consider two types of assessment; managerial (professionally-oriented) and civics (citizen-oriented). Managerial assessment involves combining, interpreting and judging selected findings to formulate a comprehensive overview of the project. This information is then employed as if the information and processes not considered were irrelevant and may be force-fitted to accommodate existing institutional constructs of laws, policies and guidelines, etc.. Civics assessment considers the project context and how human activities affect cultural and natural settings at present and in the future. It requires reflection on ideas, beliefs, and ways of life that people value and use to understand and adapt to changes engendered by the project (*ibid.*: 394). Citizens are involved in decision processes and understand and take responsibility for the dynamic interaction among ecosystems, human activities, and institutions. Nelson and Serafin suggest a three phase transition from managerial to civics assessment; analytical, interpretive and adaptive. These phases are depicted against gradients of degree of involvement and scope of interest in Figure 1 (c). Analytical assessment employs quantitative information, a reductionist approach and assumes a predictable result. The interpretive phase recognizes a plurality of views and requires public consultation. The adaptive phase encourages learning, understanding, and shared decision making (Dempster, 1996).This progression of phases from analytical to adaptive management, promotes consideration of contextual or background issues such as changes in ways of life, language, land use, employment and economic vitality which are usually neglected in managerial assessment processes (Serafin and Nelson, 1993).

INTEGRATION OF COMPLEXITY, SCIENTIFIC APPROACH AND ASSESSMENT METHODS

The combination of complexity, scientific approach and assessment methods shown in Figure 1, illustrates the parallel between the three conceptual maps, affirmed by Dempster (1996). She suggests that it is essential to employ the appropriate scientific approach and assessment method which corresponds to the level of complexity exhibited by a system. For systems such as ecopoiesis and terraforming it is necessary to use post-normal science and adaptive assessments.

THE APPLICATION OF POST-NORMAL SCIENCE TO TERRAFORMING

At the Bi-Annual Meeting of the International Society for Ecological Economics, Boston, 1996, James Kay, of the University of Waterloo, advocated the application of the *ecosystem approach* in the post-normal science mode for developing a landscape as a **sustainable** ecosystem. I emphasize **sustainable** here in regard to a terraformed Martian landscape. Some terraforming advocates, for example, Robert Zubrin, are not especially concerned with sustainability, “Does the settling of Mars then simply represent an opportunity to prolong, but not save, a civilization based on dynamism?.......I think not. .....The universe is vast. Its resources, if we can access them, are truly infinite (Zubrin, 1996:305). I believe, however, that sustainability will be one of the keystones of terraforming. Why? Because it makes economic, social and practical sense. As Martyn Fogg (1995: 80-81) has pointed out, space colonization will occur for a variety of reasons. However, extraterrestrial societies will be faced with the economics of terraforming. Providing the technologically processed energy and services for the life-support systems, which will by necessity be employed by early space communities, will be an extremely expensive and time consuming task. Consider the value assigned by Costanza, *et al.* (1997) to the goods and services provided gratis by Earth’s biosphere, as summarized in Table 2:

Table 2

Certainly the life of Martian settlers would be much less expensive and easier if a terraformed biosphere could be constructed, to provide the Martian equivalent of these gratuities, rather than having to rely on a technological life-support solution. Allen and Hoekstra, (1992: 275) in their discussion of management techniques for terrestrial ecosystems, emphasize this style of management, "The bottom line........is for the manager to maximize the natural contributions of energy to the functioning of the managed system, while minimizing artificial energy subsidies". To not manage such resources sustainably would be an ultimate irresponsibility. Not only that, but from our current knowledge of the operation of complex adaptive systems, "...Only by acknowledging that the essence of ecosystems is self-organization, and our responsibility for maintaining these self-organizing processes, will we ensure our species a sustainable niche in the [terraformed] biosphere" (Schneider and Kay, 1994: 644).

The goal of this section of the paper is to establish a framework for planning the terraformation of the Martian environment. This framework will be based on an ecosystem approach which can be employed to develop strategies that reflect the wholeness and interconnectedness of ecological systems. We need to recognize the patterns and processes that will drive a terraformed ecosystem and incorporate them into a management strategy. The ecosystem approach is based on the ideas of complex systems theory as advocated by Kay and Schneider (1994) and Allan and Hoekstra (1992). Complex systems theory envisions ecosystems as dynamic, constantly evolving systems which are not deterministic but inherently unpredictable. Such systems may evolve smoothly or in sudden and surprising ways, which at times may be catastrophic. The focus of management activity, employing an ecosystem approach, is illustrated in Figure 2. In developing a management plan we must consider the elements of sociology (human needs and wants), ecological possibility, technology (feasible tools and processes) and economics (available funds). Simultaneous integration of these factors will be required to develop optimal alternatives for terraforming (Jensen, *et al.*, 1994: 1).

943

Figure 2

As has been noted by Kay (1996) managing a [terraformed] ecosystem, “.....is not about managing the ecosystem, but rather about managing human influences on the landscape such that the desired ecosystems emerge and flourish”. Managing terraforming will require continuous dialogue between Martian inhabitants and the decision makers who manage the system, combined with ongoing assessment as to whether the terraforming is proceeding as envisioned. These activities will facilitate revision of the vision for terraforming based, on the learning developed as the project progresses.

THE ECOSYSTEM APPROACH

The model of the ecosystem approach, which I present here, draws heavily upon the work of the Huron Natural Area Working Group, Department of Environment and Resource Studies, University of Waterloo, This working group under the leadership of Professor James J. Kay has developed a practical ecosystem approach to environmental planning, which I have adapted to the problem of terraforming the Martian environment.

The ecosystem approach requires defining the ecosystem by linking various ecosystem concepts and their interactions at appropriate scales. With this approach, the ecosystem is viewed from a variety of perspectives, employing various system models to develop a comprehensive picture. An important activity, in beginning the work, is to delineate and define the boundaries of the components of each perspective. This is necessary to identify the structural and process components of the ecosystem.

The questions we ask about terraforming define the perspectives from which we observe the project. These perspectives in turn define the boundaries of systems and allow us to distinguish foreground from background (Burgess, *et al.*, 1995). In many instances, these systems are conceptual rather than physical and their boundaries, as a result, are dynamic and permeable. How then are we to define the scale of systems? When describing the scale of systems, we are concerned with their spatial and temporal dimensions. Grain and extent are two concepts applied to system scale. Grain determines the smallest and most ephemeral entities that can be observed. Extent is related to the scope of the system, that is the highest level of organization that can be accessed (Allan and Hoekstra, 1992:18 -19). The ultimate goal of terraforming is to engineer an uncontained biosphere over the entire planet of Mars. This is the largest extent of the project. On the other hand, we will begin the process by establishing an initial outpost on the Martian surface which will consist of sub-systems and components supplied from Earth. This lowest level of organization defines the grain of the project. The scale of a system is also constrained by the time and place of observation. Indeed, one could consider that the terraforming of Mars has already begun with the landing of the Viking and Pathfinder instrument packages on the Martian surface. The spatial and temporal, grain and extent of these initiatives could be defined by the optical and mechanical reach of the data sensors and the duration of the mission.

There are a number of important lessons to be learned from the study of complex systems and the application of the results to ecosystems. “First, such systems can only be understood from a hierarchical perspective” (Schneider and Kay, 1994: 641). The hierarchical levels within a system are not defined by the size of representative systems but by the grain and extent of the system. Systems theory conceptually views ecological systems as a group of nested sub-systems (Burgess, *et al.*, 1995). Each sub-system is placed on every level in the hierarchy. We can compare sub-systems (perspectives) horizontally across a given spatio-temporal level in the hierarchy, or we can consider one sub-system (perspective) as we move up and down the hierarchical structure (Allan and Hoekstra, 1992: 54). Four principles of hierarchy theory are necessary for understanding the patterns and dynamics of ecosystems (Jensen, *et al.*, 1996):

“1.

The whole/part duality of systems states that every component of a system, ecological or otherwise, is a whole and a part at the same time. For example, a forest (a whole) is made up of trees (the parts). However, at larger spatial scales, the forest is part of a regional landscape. In that case, the regional landscape is the whole and the forest becomes a part. The notion of whole/part duality is very important to the characterization of ecological systems.

2.

Patterns, processes, and their interactions can be defined at multiple spatial and temporal scales. These scales need to be clearly identified.

3.

There is no single scale of ecological organization that is correct for all purposes. This is an important consideration because scientists often provide information/interpretations on ecological systems at a single or limited number of scales.

4.

The definition of an ecological hierarchy (component patterns and processes) is dictated by the objectives of a study or planning endeavor."

The net result of these principles is that the behavior of components and sub-systems at lower levels are constrained, and are a consequence of, the behaviour of the system at the higher levels. "Self-organization of ecosystems, can only be understood in the context of what makes them up and the environment in which they must function." (Schneider and Kay, 1994: 641).

Another characteristic of ecosystems, as revealed by the study of complex adaptive systems, is that they exhibit dynamic emergent behavior (*ibid.*). The behavior of ecosystems is indeterminate. As environmental changes occur over time, there are a number of developmental paths that an ecosystem can follow. Ecosystems do not have one single stable structure and functional organization, and as such must be studied as dynamic, changing entities. Holling (1992) has provide a synthesis of dynamic ecosystem behavior in terms of four sequential ecosystem functions: exploitation, conservation, creative destruction and reorganization, Figure 3. As each function gains dominance at a different time, the overall stability of an ecosystem is a function of the interaction of these properties. Holling's dynamic "cycles" can be further elaborated (Gunderson, *et al.*, 1995: 22). In the course of traversing a cycle, biological time flows at an uneven rate. The cycle proceeds from the exploitation phase, slowly to conservation, more rapidly to release , rapidly to reorganization, and rapidly back to exploitation. During the traverse from exploitation to conservation, connectedness and stored capital increases. The capital within the system becomes more tightly bound until the system becomes overconnected and brittle. At this point the system is very vulnerable to external disturbances (stress) and the stored capital is released with the concomitant loss of organizational structure. This allows the released capital to be reorganized to again initiate the cycle. The dynamics of the Holling cycle have important implications for the hierarchical structure of ecosystems. The levels of the hierarchy are, at certain times in the cycle, vulnerable to small disturbances (*ibid.*: 24). The slower, larger levels in the hierarchy become vulnerable to dramatic transformation due to small fast events. When the system becomes over connected and brittle in the conservation stage, it losses its resilience, or ability to recover its stable state when perturbed. As a result, it may undergo a precipitous change. Small fast variables can also dominate during the reorganization phase. The system is underconnected and weakly organized at this point. At this stage, due to its weak organization and regulation, the system is most vulnerable to the action of change agents. This is the stage in which catastrophic changes (see cusp-catastrophe surface, Figure 3) to unexpected and more productive configurations are possible. It is the phase in a system - ecological or socio-cultural - where the individual or small groups of individuals can make the greatest structural change for the future. It is the stage of emergent properties.

Figure 3

Holling (1992) originally introduced his four phase cycle as a model of ecosystem dynamics. However, as Gunderson *et al.* (1995: 510) have pointed out, “the notion of a complex adaptive system as an entity in itself has emerged from a number of different fields and those independent insights have begun to successfully cross-fertilize each other.” In the past decade work at the Santa Fe Institute has provided grounding for the application of complex adaptive system theory to economic, social, biological, and ecological fields of inquiry (*ibid.*)

The ecosystem approach can be a valuable tool for the process of creating a terraformed biosphere on Mars. There are several considerations to keep in mind when applying the ecosystem approach to terraforming (Burgess, *et al.*, 1995):

1.

Ecosystems are inherently dynamic in space and time. Their boundaries are dynamic and permeable. The flows of energy, nutrients and species across boundaries are more significant than precise boundary definitions.

2.

Ecosystem processes operate on many levels. The scale of ecosystems, their grain and extent, must be explicitly defined to bound the problem, and at the same time, must be wide enough to capture entire processes on a variety of scales.

3.

Ecosystems are complex, dynamic systems that do not exhibit single points of stable equilibrium, but have a multitude of steady states across space and time. Each state is only one of many possible valid conditions for that ecosystem.

4.

When the disorganizing forces of the environment and the organizing forces of the ecosystem are in balance, one of its many optimum operating points is established. When stressed beyond the limit of its organizing forces, the stored capital is released and the system becomes disconnected.

5.

The reorganization phase is the stage in which the system is most vulnerable to erosion and loss of accumulated capital. However, there is the potential in this stage to jump to unexpectedly different and more productive systems. This is the stage when emergent properties, which are inherently unpredictable, develop.

The terraforming engineer must continually be aware of the current state of the terraformed system, the balance of the forces which maintain the current operating point, and the opportunities for change which arise as the system moves from the reorganization phase to the exploitation phase.

In the next section, I will show how the ecosystem approach can be applied to provide insight into the terraformation of a Martian biosphere.

THE ECOSYSTEM APPROACH APPLIED TO TERRAFORMING MARS

In applying the ecosystem approach to the terraforming of Mars, we need to be cognizant of a fundamental difference compared to the application of the ecosystem approach to managing a terrestrial ecosystem. In the case of the terrestrial ecosystem, it already exists, its hierarchies and organizing principles are there for us to examine and select. The hierarchical structure and organizing principles which we choose will depend upon the particular ecosystem and problem we wish to address. In the case of Mars, however, the terraformed biosphere does not exist, it is something that we wish to create. Borrowing then from Stephen R. Covey's second habit of highly effective people, "[let us] begin with the end in mind", namely Martyn Fogg's definition of terraforming: *"a process of planetary engineering, specifically directed at enhancing the capacity of an extraterrestrial planetary environment to support life. The ultimate in terraforming would be to create an uncontained planetary biosphere emulating all the functions of the biosphere of Earth - one that would be fully habitable by humans"*.

In this section I will define the relevant scales in space and time and the hierarchical levels associated with terraforming. The operational scale paradigm for terraforming will define the scales at which phenomena of interest can be observed. It will then be necessary to select organizing principles appropriate for resolving patterns and processes, at each spatio-temporal scale, which will be dealt with in the next section.

The spatio-temporal domains, as defined here, are derived from the hierarchical scheme developed by Delcourt and Delcourt (1988: 25). "The bounds placed on these dimensions of these domains represent a generalized overview for the purpose of illustrating relationships" (*ibid.*). The micro-scale domain (Figure 4) has a duration of from 1 to 500 years, and a spatial dimension of 1 m^2 to 10^6 m^2 (100 ha). The meso-scale domain extends in time from 500 to 10,000 years and in space from 10^6 m^2 to 10^{10} m^2 (a physical feature up to approximately 113 km in diameter). The macro-scale domain operates at temporal scales of 10,000 to 1 million years and at spatial scales ranging from 10^{10} m^2 up to 10^{12} m^2 (a physical feature up to approximately 1128 km in diameter). The mega-scale extends the temporal scale beyond 1 million years and the spatial scale beyond the entire surface area of Mars (1.4441 X 10^{14} m^2). This scale paradigm is constructed upon an implied set of hierarchical relationships as required to understand complex systems. These scales will be employed to establish a conceptual nested hierarchical frame work for terraforming.

Figure 4

A NESTED HIERARCHICAL FRAMEWORK FOR TERRAFORMING

I have defined three hierarchical levels for terraforming; outpost, colony and terraformed biosphere. The spatial and temporal extent of these hierarchical levels is suggested from current thinking regarding the energetics of Martian ecosystems (Fogg, 1995). The lowest hierarchical level is the outpost. Martian outposts will likely depend upon a form of partially regenerative life-support system which must be externally resupplied from Earth resources (Figure 5, adapted from Fogg, 1995: 45). The spatial dimensions of the outpost may be about 100 m in diameter, and its temporal dimension up to 10 years. A Martian colony (Figure 6, *ibid.*: 57) will likely be some form of contained biosphere which will require little or no support from Earth resources. However, life support will be extensively subsidized by technology and human work for habitat maintenance, temperature regulation, water recycling, waste recycling, environmental monitoring and control, horticultural work and emergency life-support. The colony may extend from the outpost scale up to a spatial area of about 113 km diameter and a temporal range up to 100 years. The final hierarchical level, the terraformed biosphere may have temporal dimensions of 100 to 10,000 years and extend to cover the entire surface of the planet. At this stage, the Martian civilization (Figure 7, *ibid.*: 82) will receive huge subsidies from the weather and wilderness biota on a fully terraformed planet. As with any uncontained biosphere, the environment and culture of the planet will require careful management to achieve a condition of sustainability. As can be noted in Figure 4, there is considerable overlap in the proposed hierarchical scales of outpost, colony and terraformed biosphere. The ultimate delineation of their boundaries will depend upon the interaction of the components, organizing criteria at each level, and the linkages which form between adjacent levels, due to the emergent properties of the components.

Figure 5

Figure 6

Figure 7

Figure 8

ORGANIZING PRINCIPLES FOR ECOSYSTEM COMPONENTS AT HIERARCHICAL LEVELS

In this section, I employ an adaptation of Dorney's ABC methodology as suggested by Kay (1994). This methodology allows the "use [of] different disciplinary perspectives without losing our sense of the whole" (*ibid.*). I have organized resource information into five categories: abiotic, biotic, energetics, social and economic.

The abiotic category consists of the non-living aspects of the ecosystem such as regolith, rocks, water and atmosphere. The biotic category includes all living organisms. Energetics refers to the nutrient flows, matter cycling and gas exchange within the system. The final two categories; economic and social refer to aspects of the ecosystem that are explicitly anthropocentric. The relationships among these components and the hierarchical structure of terraforming is shown in Figure 8. Each of the categories appears, on each of the hierarchical levels, in a somewhat different aspect. For example, the social organizing principle appears at the outpost level as *rules*, at the colony level as *policy* and at the terraform level as *culture*. These components appear at each level in the form of a Holling adaptive cycle. They are elements of a complex adaptive system nested inside one another (Gunderson, *et al.*, 1995: 518). "Periodic reshuffling within levels maintains adaptive opportunity and the interaction across levels maintains system integrity" (*ibid.*: 519). Gunderson, *et al.* have named these pillars of hierarchically nested adaptive cycles, “*panarchies*”.

Table 3

ORGANIZING PRINCIPLES

Table 3 illustrated the relationships among the panarchies (organizing principles) and the system perspectives used to describe the environment at each hierarchical level. The abiotic panarchy consists of examining the system from the perspective of the atmosphere, hydrology, and geomorphology. From an atmospheric perspective we are concerned with the present atmosphere of Mars, the atmosphere that will be required to support both plants, animals and humans in the life support systems of the outpost and colony and the eventual changes that will be required to terraform the Martian atmosphere. As well, atmospheric constituents may provide resources and fuels to support development. From the hydrological perspective, considerations focus on evidence that Mars once had a hydrologic system and whether there are remnants of the system in the form of deep aquifers, permafrost and the polar ice caps that can be tapped or reactivated. The geomorphological perspective will consider processes that formed the landscape, the formation, chemistry and mineralogy of the regolith and the potential for resource extraction to support an outpost or colony, and eventually a terraformed biosphere. The biotic panarchy will focus initially on the possibility of extinct or extant life that might be of concern in modifying the environment for building an outpost, colony and eventual terraforming. There is also the possibility of back-contamination to Earth to consider should extant microorganisms be discovered. Additional biotic considerations include the role of biological processes and systems in mechanical and controlled ecological life support systems (CELSS), and in the eventual use of biological entities in the terraforming process.

The description of the social panarchy will consist of examining the system from the perspective of the rules, institutions, policies, and controls which will evolve as the Martian colonists seek to establish their civilization. During the process of terraforming, it is likely that a new culture with ideologies, attitudes and perceptions somewhat different from Earth's civilizations will evolve.

A viable Martian civilization will require an economic foundation. The economic panarchy will examine the possibility of the eventual development of Martian and interplanetary commerce. The development of an economic structure will have complex interactions with the abiotic, biotic, social and energy panarchies. Such linked ecological-economic systems are extremely complex.

The energetic flows panarchy refers to the nutrient flows, biomass production and food webs that must exist at every hierarchical level. This is the description of the overall energy balance, and cycling within initial open-loop mechanical life support systems, CELSS and eventually the terraformed biosphere.

The abiotic, biotic, economic ,social and energetic panarchies allow us to describe terraforming from a variety of perspectives. Each perspective considers processes which are relevant within each hierarchical level. The next section provides an overview of the hierarchical levels of outpost, colony and terraformed biosphere and a detailed analysis of each panarchy and their system perspectives at each hierarchical level.

SYSTEMS IDENTIFICATION AND DESCRIPTION

The Outpost

The outpost will be the site of the initial human exploration of Mars. A site will be selected as near as possible to locations which are scientifically interesting and at the same time afford safe landing zones at a low elevation to provide a thick atmospheric cover for radiation protection and aerocapture reasons (Zubrin, *et al.*, 1997: 302). An additional consideration would be the location of a reservoir of water by one of the Martian Surveyor orbiter/lander/rover space craft. Barring the location of water, a good landing site would be the southern plains of Lunae Planum (Figure 9) , just to the north of Ophir Chasma, on the equator at about 65° longitude (on Mars longitude is measured westward from 0° at the prime meridian which runs through Airy crater). This location is within reach of the seven primary geological features of Mars; northern plains, southern cratered terrain, volcanoes, lava flows, canyons, channel terrain and craters. The outpost on Lunae Planum would be located at an elevation of 5000 m in an area designated as ridged plains (Scott, *et al.*, 1986). This area is characterized by broad planar surfaces with volcanic flow lobates visible in places, and long parallel, linear to sinuous mare-type wrinkle ridges 30 to 70 km. apart. These feature are dated at an age of 3.2 By, in the early Hesperian period. The time of the emplacement of ridged plains surrounding the Tharsis region corresponds to the formation of Valles Marineris and the beginning of major Tharsis volcanism (*ibid.*).

952

Figure 9 The Outpost and Colony.

The Colony

The particulars of the colony hierarchical level are derived from Mars Habitation 2057: Concept Design of a Mars Settlement in the Year 2057 (Ishikawa, *et al.*, 1997: 309). The target population for establishing a Mars colony within this concept is 150 residents. These early colonists would command a cross-section of skills in the fields of science, engineering, agriculture, medicine, psychology, journalism and the arts. The colony would be located at 20° N, 70° W (Figure 9) in a flat plain on Lunae Planum, south of Kasei Vallis (*ibid.*: 312). Such a site would be easily accessible from equatorial orbit, in the vicinity of a possible water resource, and is located near many scientifically interesting places such as Vallis Marineris and the Tharsis volcanoes.

The colony would be located at an elevation of 3000 m. in a geologically similar region to the outpost. Kasei Vallis lies about 100 km. to the north and west. The outflow channel of Kasei Vallis "originates in a shallow, north-south-trending depression, 300 km wide and 1,500 km. long, which merges southward with the box canyon Echus Chasma" (Carr, 1981: 145). Kasei

Vallis enters Chryse Planitia to the northeast. The floor of the valley consists of older channel deposits which are longitudinally striated with teardrop shaped channel bars. The south side of the valley rises sharply as a 3000 m escarpment from 1000 m below chart datum to Lunae Planum at an elevation of 2000 m. The Kasei river channel deposits are dated in the late Hesperian, 1.8 to 3.1 Bya. (Scott and Tanaka, 1986).

The Terraformed Biosphere

The transformation of Mars has begun. Through the use of greenhouse gasses, space mirrors and geothermal venting, the surface temperature in equatorial regions has risen to 280° K. The warming atmosphere and geothermal mining has triggered the release of water from frozen aquifers, and melted much of the northern polar cap to establish a Martian hydrological cycle. A Boreal Ocean now covers the northern plains (Figure 10). Genetically engineered Martian organisms are beginning to convert the carbon dioxide, desorbed from the regolith, to oxygen, by photosynthesis. An ozone layer has begun to form, filtering out the UV radiation, allowing new biota based on Terran genetic templates to take hold. As the new biosphere emerges and cities are established across the planet, a new planetary and interplanetary commerce is developing. Mars is a powerful force shaping not only the biology of the planet, but also its culture and institutions. Terraforming Mars has produced the ultimate complex adaptive system. “This process, no matter how much we intervene.....is essentially out of our control. Genes mutate, creatures evolve: a new biosphere emerges, and with it a new noosphere. And eventually the designers’ minds, along with everything else, have been changed forever.” (Robinson, 1994: 3). But this is exactly the point. “The point is not to make another Earth. Not another Alaska or Tibet, not a Vermont nor a Venice, not even an Antarctica. The point is to make something new and strange, something Martian (*ibid.*: 2).

Figure 10 Terraformed Martian Biosphere.

THE ECOSYSTEM APPROACH APPLIED TO THE OUTPOST

The outpost on the southern plains of Lunae Planum will be the location of the first human presence on Mars. Future Martians will remember this outpost as an historical site, commemorating the birth of their civilization. Whether or not a successful new branch of humanity develops on Mars will depend upon the human choices made in the adaptive cycles of the abiotic, biotic, economic, social and energetic flow panarchies at the outpost level in the terraforming hierarchy.

Abiotic Panarchy - Resupply, Local Resources

When the first humans land on Mars, they will encounter a harsh environment that is not conducive to life. The basic abiotic conditions of Mars are listed in Table 4. However, many of the materials required to support a Martian outpost and eventually a settlement are to be found on Mars. In situ resource utilization (ISRU) (Meyer and McKay, 1996) will be the cornerstone of a viable Martian outpost. ISRU technology can be used to produce consumables such as air, water, and fuel from Martian resources. Oxygen and buffer gasses such as nitrogen and argon can be extracted from the atmosphere. Water can be obtained from the atmosphere, regolith, and ground ice. The regolith also contains the essential nutrient elements for agriculture, although it may have to be washed of salts, oxides and toxins before being adjusted for pH and fertilized. Ammonia can be obtained from atmospheric nitrogen to produce fertilizers. It is highly unlikely that any sort of fossil fuels will be found on Mars. However, given a source of hydrogen, methane can be produced from the Martian CO_2 atmosphere using the Sabatier process. For building materials a substance called “duricrete” which is similar to concrete can be produced from the Martian regolith. It may be possible to manufacture ceramic and glass from Martian silicates, although transparent glass will be difficult to produce, due to the high iron content of the silicates. Source minerals in the Martian regolith, iron, aluminum, titanium and magnesium, can be used for metals fabrication. As well, the Martian regolith can be employed to provide additional habitat shielding against primary cosmic radiation and the high radiation flux from solar flares.

Table 4

MARTIAN OUTPOST CONDITIONS
(Fogg, 1995: 220)

The mining of the Martian atmosphere for essential consumables, including fuel, compared to the expense of having to ship these materials from Earth, will make the establishment of an outpost an economical proposition. In the longer term the development of ISRU technology will be essential for establishing a permanent human presence on the planet.

Biotic Panarchy - Indigenous Life: Extinct, Extant

The possibility of destroying evidence of extinct Martian life forms, or an even more disturbing concern, that of eradicating any possible extant life forms, has been a topic of much controversy in discussions of establishing a human presence on Mars (Fogg, 1995: 494). In the early stages of its development, billions of years ago, there is evidence that Mars had a warm and wet environment with conditions suitable for the formation of life (Banin and Mancinelli, 1995, Mancinelli and Banin, 1995). It has been speculated, by exopaleontologists such as Jack Farmer and David Des Marais of NASA Ames Research Center, that geological features which show evidence of prolonged liquid water activity and which have sedimentary deposits may harbor fossilized evidence of extinct life (Farmer *et al.*, 1993). More recently, McKay, *et al.*, (1996) reported evidence of abundant polycyclic aromatic hydrocarbons (PAHs) found in Martian Meteorite ALH84001, and suggested that the PAHs and associated carbonate globules and their secondary mineral phases and textures could possibly be fossilized remains of past Martian biota. These findings remain highly controversial and work continues along this line of investigation.

In 1977, two Viking landers set down on the surface of Mars. Each lander contained a miniaturized biological laboratory designed to detect the presence of extant life. Included in the array of Viking experiments, were a gas chromatograph-mass spectrometer to detect organic compounds, and three biology experiments; the gas exchange experiment (GEX), the pyrolytic release experiment (PR) and the labeled release experiment (LR) (Klein, *et al.*, 1992: 1225). Details of these experiments can be found in Journal of Geophysical Research, Vol. 82, No. 28, 1977. The general conclusion of the analysis of the Viking biology experiments has, for the most part, been, that the data essentially rule out the possibility of living organisms anywhere on Mars (Horowitz, 1986). However, there are those who feel that there may well be active biology on Mars and that it was detected by the LR experiment (Levin, 1997).

Other workers have considered the possibility of specialized microhabitats, such as have been found on Earth. Friedmann and Ocampo-Friedmann (1984) discuss Antarctic cryptoendolithic ecosystems (in which microorganisms live inside porous sandstone rocks in a comparatively mild microclimate protected by a thin rock crust) and speculate on the possibility that such microbial niches on Mars cannot be entirely excluded. Additional microhabitats considered, may be inhabited by a group of microorganisms known as extremophiles (Madigan and Marrs, 1997: 82). Such organisms include thermophiles which may exist far below the Martian surface in association with geothermal vents. Other microhabitats suggested are unfrozen microvolumes in the Martian permafrost (Ostroumov, 1995) and cryptic microbial mat communities of endovaporites and acidophiles (Rothschild, 1995). Confirmation of either extinct or extant Martian life forms would be a discovery of considerable scientific importance. The effect of outpost, colonization and terraforming on these organisms would need to be considered before undertaking such activities. In addition, the possibility of back-contamination to Earth by extant organisms from sample return missions and returning astronauts, is considered to have societal and international legal implications that require discussion (Task Group on Planetary Protection, National Research Council, 1992: 55).

Economic Panarchy - Exchange, Barter

The purpose of the outpost stage is to conduct research on techniques such as agriculture, industrial, chemical, and civil engineering which will be required to produce materials for the development of colonies and eventual terraforming of Mars (Zubrin, 1995: 407). A division of labor and associated skills of a large number of people will be required. During this stage, there will likely be little economic activity other than barter and exchange amongst individuals. This could take the form of the exchange of skills or the few personal items allowed to crew members. Outposts are most likely to be funded by consortiums of international governments. However, the possibility of private economic involvement in establishing a human presence on Mars has been suggested (Zubrin, 1996). One proposal involves selling Martian real estate to those interested in speculating on its future value (*ibid.*: 237). Another proposal considers a graduated succession of challenges based on a series of prizes to be awarded for specific accomplishments ranging from imaging missions, to sample return missions, to an eventual human landing on the red planet (*ibid.*: 286). Zubrin feels that such a prize challenge would substantially reduce the cost of these endeavors as companies could no longer rely on "cost plus" contracts would be forced to control costs and remove expensive overhead structures.

Social Panarchy - Rules

Miller (1997) has discussed the sociological aspects of space communities using a structural functionalist paradigm. The social structure at the outpost level will be similar to that of a total institution as defined by Goffman (1961) - "a place of residence and work where a large number of like-situated individuals cut off from wider society for an appropriate period of time, together lead an enclosed formally administered round of life". Zurcher, (1965: 53-56) delineates the characteristics of the outpost:

1.

All aspects of life are conducted in the same place under a single authority.

2.

Every member of a given category carries out his activities in the company of others and is treated exactly like all the others.

3.

Activities are completely scheduled, with each activity leading at a certain time into the next and the whole sequence is decided by a hierarchical chain of authority.

4.

Members of the community live on site for twenty-four hours a day and work is undertaken for motives other than those in more conventional communities.

5.

There is a clear division between the supervisors and others in the community and social contacts between the two groups may be limited.

6.

In such a community, the individual may have no information about what will happen to him next.

7.

There is a real, if not symbolic, barrier between the community and the remainder of society.

8.

All the various enforced activities contribute to the achievement of the official goal of the community.

A space community will likely be similar to a “total institution”, albeit with some significant differences. The differences may well center around the requirement for a more egalitarian approach to community functioning, since many members of the community will be highly trained specialists whose functions are required for the survival of the community, and who are not used to functioning around the clock in formal hierarchical structures (Conners *et al.*, 1985:262).

957

In the outpost, formal rules and standard operating procedures will necessarily dominate early in its existence. Uncertainty will be decreased as much as possible in order to provide consistency and efficiency, and build competency (Gunderson, *et al.*, 1995: 524). However, outpost leaders will need to be aware of the social/institutional adaptive cycle (Figure 11), operating at the outpost level, in order to effectively manage the change which will inevitably occur as the outpost develops. They need to be aware that as the social structure is in transition from the exploitation G phase to the K conservation phase, the very rules which were initially designed to make the outpost society successful, will make the social structure more rigid and vulnerable to destruction. In the context of the outpost, destruction may appear as a form of social unrest such as the challenge to leadership or reduced attention to safety issues. This may lead to a situation in which rules and procedures are no longer sufficient to successfully manage the outpost community. During the release phase a, which may involve small tightly organized groups or a charismatic leader with a strong ideology, minor activities and small scale movements will be agents of change. The system may then move into the reorganization phase W, in which change agents can be most effective, provided they are aware of the limited window of opportunity for profound change and learning, that presents itself during this phase. It is during reorganization that cross-scale linkages to higher hierarchical scales, such as the colony, are possible under the influence of micro processes at the outpost. At this point, the system will return to the exploitation phase and begin the cycle once again.

Figure 11 Social System.

Energy Panarchy - Open-loop Mechanical Systems

There is no system currently operating on Mars that can support human life. Without a life-support system there can be no life (Fogg, 1995: 37). The first humans to land on Mars must take some form of life-support system with them. Fogg (*ibid.*: 39) has defined a life support-system, “a life-support system involves a flow of energy through space that drives internal cycling of matter into which the specific cycles of life can be integrated”. The Earth’s biosphere provides our life support through the sunlight-driven circulations of the atmosphere and oceans, characterized by a matter-cycling steady state. In fact, “life itself, represents a highly sophisticated and ordered phenomenon, maintained in the same way by continually dissipating energy from low to high entropy states” (*ibid.*: 38). Kay (1983) has developed a paradigm for the self-organization and thermodynamics of living systems. There are only two types of life-support systems (LSS) that currently operate in a reliable fashion, the open-loop LSS of space craft such as the space shuttle and the Earth’s biosphere. The functions performed by each of these LSS and the mode of operation is shown in Table 5, adapted from Fogg (1995: 41). As well, the mode of operation of an Environmental Control/Life-Support System (EC/LSS) that will be used in the outpost is shown.

Table 5

LIFE-SUPPORT SYSTEMS AND FUNCTIONAL MODES

The purpose of the EC/LSS in the outpost is to reduce the mass of consumables by mechanically regenerating air and water. The food supply is still stored. The operation of the outpost EC/LSS is shown in Figure 5. A partially regenerative LSS will extend residence time on the surface of Mars and reduce launch weights. The EC/LSS is not fully closed and will still require intermittent re-supply either from Earth or ISRU technology to provide food and gasses. It requires considerable technology, electrical energy and human monitoring, control and maintenance. Such systems are suitable for the operation of an outpost, but insufficient for the sustaining a long term colony.

THE ECOSYSTEM APPROACH APPLIED TO THE COLONY

By the year 2050-2057, there should be sufficient population, infrastructure and ISRU technology developed to begin a Martian colony. We define the beginning of the colonial period when conditions are such that ordinary residents can begin their immigration to Mars. The concept of the Mars colony developed here is based on the design of Mars Habitation 2057: as suggested by Ishikawa, Ohkita, and Amemiya, (1997; 309).

Abiotic Panarchy - Aeroworks, Atmosphere

At the colony hierarchy, the basic abiotic conditions of the planet will not have changed from those listed in Table 4. Understanding and developing the potential for extracting, manufacturing and using construction and life support materials derived from the Martian abiotic environment will have matured to the point of being an operational component of life on Mars. In situ resource utilization (ISRU) will have advanced to the phase which I have called “areoworks”. In the “areoworks” phase, the Martian abiotic environment and native materials are employed, to an extent similar to resources on Earth, in support of a blooming Martian civilization. Meyer and McKay (1996: 421) have suggested materials which can be made from Martian atmospheric and regolith resources and associated manufacturing process, (Table 6).

Table 6

MANUFACTURING PROCESSES AND MATERIALS
WHICH CAN BE MADE FROM MARTIAN RESOURCES

The aeroworks will begin by building an initial habitat domicile tunnel in the hillside at the north end of the colony complex Ishikawa, Ohkita, and Amemiya, (1997; 311). The base will expand in a southward direction with four basic lines, habitat - residence domiciles, water/gas/ utilities lines, greenhouse line, auxiliary facilities line - research, rover stations, and storage facilities (Figure 12). The abiotic components of the colony will consist of habitat modules, greenhouses, Terraria, a control center, rectenna and launch pads listed in Table 7.

Figure 12

Table 7

COLONY COMPONENTS

961

Habitat Modules

The habitat modules will be private living space for the colonists. Designs will include. living rooms, bed rooms, kitchens hygiene facilities and personal storage. There will be two residents per module. The module area will be covered with three meters of regolith to reduce radiation exposure.

Greenhouses

Hundreds of greenhouses will be used to raise vegetables and algae.

Terraria Type 1

These terraria will initially contain a native Martian atmosphere, and sunlight and cosmic radiation will be allowed to enter. In other words, Terraria Type 1 will be self-contained experimental test beds used to prototype ecopoiesis and terraforming experiments. They will be self-contained units which are isolated from the outside Martian atmosphere, and to sufficient depth from the surface regolith, while retaining regolith features such as permafrost and thermal vents.

Terraria Type 2

These terraria will be structures which will significantly enhance the physical and psychological quality of life for the colonists. They will be pressurized at one Earth atmosphere and be park-like in nature with trees, ponds, insects, plants and animals such as goats, poultry and fish. The ecosystem contained within the type 2 terraria will be as closely as possible a replica of a terrestrial ecosystem.

Potential water sources include melted ground ice, deep ground water reservoirs and extraction from the atmosphere by dehumidification. Power may be supplied by small nuclear generators, wind , solar panels or via microwave energy from a solar power satellite. Facilities will also be constructed for Martian aircraft and interplanetary transportation.

Biotic Panarchy - Ecosystem

As mentioned in the previous section, there will be three basic forms of “ecosystems” in the biotic panarchy of the colony; greenhouses (Figure 13) and terraria types 1 and 2 (Figure 14). Each of these biosystems will be some form of controlled environment life support system (CELSS).

Figures 13 and 14

The Martian colony will be too far from Earth for food supply from Earth to be a viable option. Thus the ability to produce food locally will be necessary for a viable colony. For the most part, food production will be done in the greenhouse modules. Fortunately, Mars does have some amenities for agricultural purposes. Sunlight on Mars is 43% of that on Earth and is sufficient for photosynthesis. The day/night cycle is similar to Earth (length of Mars day 24 hours, 39 minutes). However, the average temperature is -60°C and additional heating will be required to make farming feasible. Based on the limited chemical and mineralogical information from the Viking data, Banin (1989: 568), has cautiously suggested that from a physical and chemical viewpoint, the Martian regolith may provide an appropriate medium for plant growth in a CELSS environment. Since the greenhouse environment will be restricted to plant growth, it will not require as extensive an atmospheric modification as a human habitable area such as the type 2 terraria. Total atmospheric pressure will be maintained at about 90 mb in an atmosphere of pO_2 ~20 mb, pN ~60 mb, H_2O ~10 mb, and CO_2 <1 mb which is sufficient for plants

(Fogg, 1995:101-105). Human workers will be required to wear scuba type gear within the greenhouse. Heating equipment will be required to maintain growth temperatures and prevent conductive heat loss through the regolith. Heat may be obtained from sunlight and hot water from underground thermal vents. The greenhouses will need to supply sufficient carbohydrates, proteins, fats, vitamins and minerals and approximately 2800 cal. per inhabitant per day. Ishikawa, Ohkita, and Amemiya, (1997; 314) suggest the following crops for greenhouse growth (Table 8).

Table 8

Terraria Type 1 will be the test-bed for ecopoeis and finally terraforming. They will be microcosms of the Martian environment in which adaptive management techniques can be employed to perform experiments in ecopoiesis and terraforming. “Adaptive management applies the concepts of experimentation to the design and implementation of natural resource and environmental policies”, (Lee, 1993:53). I will discuss adaptive management techniques in some detail later in this paper. Thomas (1995: 415) has examined the biological aspects of ecopoiesis and terraforming. Suggested problems and potential solutions are listed in Table 9 (*ibid.*: 417). The introduction of microorganisms into the type 1 terraria will greatly facilitate ecopoiesis and terraforming. Initial conditions will be too severe for most terrestrial species. However, genetic modification and directed selection may be employed to increase the utility of microorganisms for ecopoiesis and terraforming. The utility, possibilities and problems of producing and employing genetically engineered Martian microorganisms (GEMO’s) have been the subject of speculation by Hiscox (1995) and Hiscox and Thomas (1995).

The type 2 terraria which will result from the successful completion of the terraria type 1 experiment, will provide amenity space for the Martian colonists. It is expected that the relatively small size of the terraria compared to the entire red planet will permit the production of a terraformed environment in significantly less time than would be required for the entire planet (500-10,000 years) as indicated in Figure 4.

Table 9

ECOPOIESIS AND TERRAFORMING

BIOLOGICAL PROBLEMS AND POTENTIAL SOLUTIONS

Type 2 terraria will feature a breathable atmosphere of about 1000 mb, insect pollinated plants, trees, ponds, goats, poultry and fish (tilapia). The type 2 terraria will be as close as possible a replica of the Earth's biosphere within an enclosed space. It is expected that the lessons learned from the adaptive management of this project will enhance the capability to terraform the entire planet.

The manager of the type 1 and 2 terraria will need to be cognizant and skilled in the operation of biotic Holling cycles (Holling, 1992: 481). The dynamics of a biotic Holling cycle of ecosystem succession are shown in Figure 15. The process of ecosystem succession proceeds from the exploitation phase G, in which conditions are exploited by G strategists, pioneers and opportunists, to the conservation phase K (the climax phase) in which resilience is reduce, controls are intensified and the system becomes brittle and sensitive to agents of disturbance. Effective competitors (K - strategists) are most successful during this phase. In its over-connected state the system is vulnerable to change from external events which may include fire, storm and insect pests in an open biosphere. The exact form that destructive disturbances may take in a CELSS is unknown at this time. When such a disturbance occurs, the system moves quickly to the release phase W. Stored capital is released in this phase and the system loses its tight organization. Slow variables lose control and fast variables assume the upper hand. "Resilience and recovery are determined by the release and reorganization sequence, whereas stability and productivity are determined by the exploitation and conservation phase" (*ibid.*: 481).

964

Another key phase where small, fast variables may control the ecosystem cycle is during the reorganization phase a. In this phase, the system is weakly organized and regulated. Variable processes and random events may allow a diversity of exotic invaders to become established. The system is most vulnerable to erosion and loss of capital (*ibid.*: 482). However, it is during this stage that the system can jump to an unexpectedly different and possibly more productive G form rather than return to its previous exploitive stage. The task of the terrarium manager is to manage this cycle and take advantage of his/her understanding of the cycle dynamics. Special care must be taken during the a phase since the cycle exhibits emergent, self-organizing properties which cannot be explicitly predicted. Hence the requirement to employ adaptive management principles.

Figure 15 Biotic System.

Economic Panarchy - Corporate Structures

In order for the colony on Mars to survive , it must become self-sufficient. Indeed, one of the goals of terraforming is to increase the self-sufficiency of a Martian civilization by reducing its dependence upon technological life -support and by moving towards a planetary-wide, biological, ecosystem. In order to function, all living creatures, including humans, require energy, natural resources and sustenance, on a daily basis, from the ecosystem in which they live (Andersson, *et al.*, 1995). It is through economic systems that humans exert a willful effort to extract useful things from natural systems (abiotic and biotic) to satisfy their biological and psychological needs and wants (Farber and Bradley, 1996). The role of the economic system in this process is shown in Figure 16, as adapted from (Andersson, *et al.*, 1995). Our ability to operate the economic system is modulated by the dynamics of social (values) and biological (population) behavior. Since Mars will take a long time to obtain sufficient population and infra-structure to become self-sufficient, it will need to import specialized manufactured goods from Earth (Zubrin, 1995:409). Mars must be able to export something back to Earth in order to pay for these goods. Zubrin (*ibid.*) has suggested several possibilities including precious metals and ideas and inventions (fostered by frontier necessity) in energy production, automation, and biotechnology. Another possibility for trade includes metal ore extraction from the asteroid belt (*ibid.*: 410).

This endeavor becomes an attractive option, since orbit mechanics favorably dictate the energy requirements for “a ‘trade triangle’ with Earth supplying high technology manufactured goods to Mars, Mars supplying low technology and food staples to the asteroid belt and possibly the Moon, ...and the asteroids and Moon sending metals and possibly helium-3 to Earth” (*ibid.*).

Figure 16 Socio-Economic Dependence on the Life-Support Environment.

One would expect that as the Martian economy develops, corporate structures will play an increasingly dominant role as the needs and wants of both Terrans and Martians are increasingly influenced by the quest for profit. Economies at any hierarchical level possess general ecosystem properties such as dynamism, evolution, and exchange flows of materials and energy with natural systems (Farber and Bradley, 1996). Costanza *et al.* (1993: 552) have suggested that the Holling cycle model may provide a general-level conceptual model for understanding the dynamics of economic systems. A schematic of a dynamic economic system based on the Holling cycle is shown in Figure 17. During the exploitation phase G conditions are set for entrepreneurial application of market forces and innovation (Gunderson, *et al.*, 1995:513). As the system moves into the conservation phase K, institutional bureaucracies, monopolies and social rigidity control the functioning of the system. During this phase, the system becomes vulnerable to external events such as social and political unrest, new technologies, or the collapse of corporate structures which trigger the W or release phase. The release phase is often dominated by "small tightly organized groups [bound] .... to a charismatic leader with a strong, singular ideological purpose" (*ibid.*: 514).Capital is released; money, skills and knowledge, contacts and experience previously bound up in rigid corporate structures become available for reorganization in the a phase. This phase is the most unpredictable. Only slight changes in initial conditions can produce emergent complex behavior and unpredictable outcomes. It is during the a phase that individuals are capable of exerting significant influence in the development of new economic strategies, power, and alignments between previously independent variables. Astute individuals who understand the dynamics of such economic cycles can, by employing adaptive management techniques, create unique opportunities for change and novelty (*ibid.*: 517).

Figure 17 Economic System.

Social Panarchy - Policy, Controls, Institutions

At the colony level, the social panarchy is controlled by policy-making and politically motivated management processes (Gunderson, *et al.*, 1995:524). “A policy defines, in general terms, how an organization is likely to act in various sets of hypothetical or future circumstances” (Thompson, 1997). Policy decisions are incorporated into a strategies for action. Institutions will be formed at the colony level to take collective action on social, economic, and resource management matters. Gunderson *et al.* (1995,496) define institutions, “as including the sets of rules or conventions that govern the process of decision making, the people that make and execute these decisions, and the edifices created to carry out the results.” Gunderson, *et al.* have described the dynamics of the social Holling cycle (Figure 18) at the colony level. Implementation of policy takes place in the shift between the G exploitation phase and the K conservation phase. Hierarchical bureaucracies are established to implement policies. As time goes by, the bureaucrats who are charged with policy implementation focus on performing their tasks with increasing efficiency. The result is that the institutions turn inward, and become obsessed with perpetuating themselves for their own sake, rather than serving the colony and the objectives for which they were instituted. Policies begin to fail. The institution becomes brittle and open for activists to create crises. The activists become the external trigger that moves the cycle from the conservation phase to the W release phase. Activists concentrate on single issues which they believe are being mismanaged by the institution. Public exposure of these issues usually creates the conditions for the release phase. In the release phase, individuals who are capable of creating new approaches and ideas become important catalysts for action. They identify alternative policies and new possible futures which set up the conditions for the cycle to move into the reorganization a phase. In this phase, individuals and groups who can create credible futures and resolve past issues come to the fore. In the reorganization phase, the people of the colony have to be engaged, informed and educated. This is the realm of post-normal science which demands an expanded peer group for effective decision making.

Figure 18

At this point, the emergent nature of the transition from the a stage to the G exploitation phase produces the inherent uncertainty in managing complex adaptive systems. Policy decisions in the a phase, and pursuit of their resultant strategies require selective risk taking (*ibid.*: 341). Managing these risks requires engaging in a form of adaptive management; in which learning, error correction and infusion of new knowledge into action practices, are central components of the process.

Energy Panarchy - Controlled Ecological Life-Support System

The colonists on Mars will eventually wish to become independent from Earth. To achieve this goal, as well as developing their own social and economic structures, they will have to construct a habitat in which energy flows and matter cycling are handled biologically. Indeed, this is the purpose of the terraria as described in section on the colony biotic panarchy. The energy/matter flow/cycling of a contained Martian biosphere is illustrated in Figure 6. This type of life-support system is known as a controlled ecological life-support system (CELSS). Table

10 (adapted from Fogg, 1995: 41) compares the functions and mode of operation of a CELSS to the Earth's biosphere. An open question, today, is whether or not it is possible to scale down the volume of the Earth's biosphere by greater than 10^{13} and still maintain its functions (*ibid.*: 52). Fogg (*ibid.*: 53) lists the aspects of CELSS that may require a technological solution: maintenance of the enclosure, supplement to leaked gasses, radiation protection, temperature regulation, hydrological cycle, trace contaminant control, system stabilization, solid waste recycling, horticultural management, pest and disease control and emergency life-support. These technology supplements are shown in Figure 6. The small volume of the CELSS presents additional difficulties in that the dynamics of the biosphere are not well buffered. This results in the system being much less stable than the Earth's biosphere, and being susceptible to unpredictable chaotic excursions of its operating parameters, due to minor perturbations in its sub-systems.

Table 10

Life-Support Systems and Functional Modes

Such disturbances might include, reduced sunlight due to dust storms, a sudden increase in population due to an emergency in another colony, or pests and diseases in the CELSS ecosystems. Maintenance of CELSS operation will require considerable use of technology, time and effort in conscious monitoring of system parameters. Thus, maintenance of a CELSS becomes a management as well as a technical problem. The necessity for a substantial technological component, to supplement the CELSS operation, will require electrical and human energy in addition to ambient solar energy to maintain energy/matter flows. It is estimated that the 150 colonists will require 7 MW of electrical energy for life-support (Ishikawa, *et al.*, 1997: 316). Potential Martian energy sources are solar, wind, and nuclear energy (*ibid.*). Generation of electricity from ground-based solar cells is feasible (Geels, *et al.*, 1989:516) but dust storms may create problems at times. The use of wind energy on Mars has been evaluated by Haslach (1989: 171). However, due to the low wind density, generation will be of the order of 10 kW, and thus only suitable as an auxiliary power source. An SP-100 nuclear power source would produce 100 kW, but was not considered for the colony because of safety concerns. Instead, a solar power satellite (SPS) will be employed (Ishikawa, *et al.*, 1997: 317). An SPS, operating at 20% efficiency, with an area of 13,000 m^2 solar cell area, in an aerosynchronous orbit, would be capable of beaming 10 MW of microwave energy to a surface rectenna (Figure 12) (*ibid.*).

THE ECOSYSTEM APPROACH APPLIED TO A TERRAFORMED BIOSPHERE

Early in the next millennium, many Martian colonies will have been successfully established across the planet. The new Martians will have a basic understanding of the possibilities of planetary engineering. The greening of Mars can now begin on a grand scale. Planetary engineering concerns much more than the manipulation and management of the abiotic, biotic and energy environments. As we have seen, understanding and managing the social and economic environments and the linkages among all of these organizing principles is essential for this enterprise to succeed. As time goes by, there will be successes and failures, lessons learned and unlearned. On Mars, “we will be cultivating a planet and ourselves......the gardening of Mars will be an essential part of our philosophical education that we desperately need” (Turner, 1989: 33, 35). What will it be like to live on a terraformed Mars? Will we take “the road less traveled”? For two fictional and imaginative perspectives, achieved by substantially different paths, I recommend to the reader the *Red Mars*, *Green Mars*, *Blue Mars* trilogy by Kim Stanley Robinson and *Genesis: An Epic Poem* by Frederick Turner. In this paper, we can only speculate in a minimal way.

Abiotic Panarchy - Aerology, Atmosphere, Hydrology

Planetary engineering of the abiotic environment will likely be achieved in two integrated, braided processes; ecopoiesis and terraforming. Five main alterations will be required: the surface temperature must be raised, the atmospheric pressure must be increased, the chemical composition of the atmosphere must be changed, the surface must be made wet, and the surface flux of UV radiation must be reduced (Fogg, 1995: 219). These changes in the areology, atmosphere and hydrology of Mars which will likely be achieved by a synergetic technological process similar to that suggested by Fogg (*ibid.*: 300-324). This combination of technologies was put forward since no one process, by itself, appears sufficient for the task. A summary of this plan is presented in Table 11 (taken from Miller (1996)).

Table 11

TECHNOLOGIES FOR SYNERGIC PLANETARY ENGINEERING

Biotic Panarchy - Biotechnology

Biotechnology will play a major role in planetary engineering. Proposals for the use of biotic organisms in planetary engineering have been suggested by several researchers: primitive cyanobacteria (Friedmann, Hua, and Ocampo-Friedmann, 1993: Friedmann and Ocampo-Friedmann, 1995), genetically engineered microorganisms (Hiscox, 1997; Hiscox and Thomas, 1995), and genetically engineered plants (Fogg, 1995).

In the Antarctic, Friedmann has investigated cryptoendolithic habitats which are a refuge for microorganisms. These habitats which occur at altitudes of 1500 m and average annual temperatures of ~ 10°C exist in the pores of sedimentary rocks. Typical microclimates under summer sunlight conditions exhibit temperatures 15 degrees C above ambient and liquid water. Antarctic cryptoendolythic ecosystems consist of algae, cyanobacteria, fungi in lichen associations, yeasts and heterotrophic bacteria (Fogg, 1995). It is not unreasonable to suppose that such organisms could survive in similar microhabitats on Mars. Julian Hiscox, a microbiologist, has suggested the production of genetically engineered or adapted Martian organisms (GEMO's) specifically designed to survive in the Martian environment, and provide assistance in achieving the abiotic alterations required for planetary engineering. Such pioneer microorganisms, which might be engineered or selected for Mars, must be photoautotrophs and anaerobic with survival characteristics such as osmotic tolerance, resistance to UV radiation, cold tolerant, tolerant to limited nutrients and water, resistant to oxides and adapted to increased intracellular pH due to the CO_2 atmosphere. In addition, they must be able to withstand periods of intolerable conditions and be capable of preserving their genetic heritage (Hiscox and Thomas, 1995: 420). A mechanism for achieving these latter characteristics is the formation of endospores. Figure 19 (taken from Hiscox (1997)) illustrates a process for selecting organisms for survival on Mars. Such organisms will not only be part of the final biosphere but will play an integral role in the planetary engineering process itself (Averner and MacElroy, 1976, as cited in Hiscox, 1997). As noted by Haynes (1990: 170), “The introduction of microorganisms will be a substantial task, ”the optimal nature, number , relative population sizes, arrival sequence, and geographic distribution [of organisms] are some of the factors which would have to be considered".

Figure 19 Selecting Microorganisms for Ecopoiesis and Terraforming.

Following ecopoiesis, higher plants must be introduced to generate atmospheric oxygen. However, terrestrial plants do not survive easily in a low oxygen atmosphere (Fogg, 1995: 427). Fogg (*ibid.*) has suggested several physiological strategies that could be implemented in a genetically engineered plant which might over come this problem. Features which are suggested to promote plant survival in an atmosphere of low O_2 partial pressure are listed by Fogg:

- small size (less tendency to form anaerobic core)
- small surface/volume ratio (facilities self-oxygenation)
- shallow roots (pO_2 decrease with soil depth)
- high internal porosity (lowers COP; cells closer to gas phase)
- internal ventilation (facilitates self oxygenation and removal of volatile toxins)
- diffusely resistant epidermis (facilitates self-oxygenation)
- nitrate respiration (more ATP than fermentation)
- oxygen translocation in phloem (facilitates self-oxygenation)
- ethanol translocation to leaves (rectifies energy deficit of fermentation)
- translucent tissues (allows deeper photosynthesis)
- starch seeds (germinate at low pO_2)
- pollination by self, wind, or water (no insects or animals present).

In order to modify the Martian environment with biotic agents and processes, it will likely be necessary to modify life itself to suit that environment. Undoubtedly this work will require the discipline of adaptive learning.

Economic Panarchy - Ecological Economics

Development of a successful economic organizing principle for terraforming is a central theme of Robinson's *Red Mars*, *Green Mars*, *Blue Mars* trilogy (Markley, 1997: 774). Robinson's trilogy is "a theoretical intervention in the late-twentieth century debates about ecology, economics, and technology" (*ibid.*). Markely offers an analysis of Robinson's thought experiment in imagining the greening of science, economics and politics. "Imagining terraformation gives Robinson the opportunity to rethink the complex relationships between planetary ecology, the interlocking systems that create and sustain the tenuous, seeming miraculous conditions that allow life to flourish, and political economy, the distribution of scarce resources among competing populations and interests" (*ibid.*: 775). Whether Robinson's "eco-economic" paradigm is an answer remains to be seen. There is little question, however, that if we are to succeed as a species either on Earth or on Mars, we must somehow resolve the questions associated with these issues. The focus of the ecological economic organizing principle as described by Farber and Bradley (1996), is the ability of humans to choose, “to dramatically restructure and reform processes in ecosystems, of which they are a part, to such a magnitude that human [and ecosystem] welfare can be diminished or enhanced by their actions”. With terraforming, while our attention is on the latter, through either ignorance or greed we may accomplish the former. This is why it is imperative to address the interdependence and coevolution between human economies and ecosystems; natural or designed. At the end of the twentieth century, we are just beginning to recognize this fact. and to address these issues and relationships though the emerging, interdisciplinary perspective of ecological economics. Farber and Bradley have described the essential characteristics of ecological economics (Table 12). Like Robinson, we must challenge, “the conventional notion that economics means the exploitation, degradation, and exhaustion of natural resources. On a world where the biosphere itself is being manufactured, notions of value make sense only to the extent that they erase distinctions between quantitative measures of labor and capital and qualitative contributions to social and ecological balance” (Markley, 1997: 775). If we are not up to this challenge, and we venture forth across the solar system, I fear we will leave a Terran trail of rubble in our wake. Fortunately, it is doubtful that such a future for the human species would succeed in the long run.

Table 12

CHARACTERISTICS OF ECOLOGICAL ECONOMICS

Social Panarchy - Culture, Ideologies, Attitudes, Perceptions

With the terraforming of Mars, a permanent extension of human civilization beyond Earth will exist. A new culture will emerge which will be quite different from that on the home plant. Markley (1997: 787) comments on the emergent culture in Robinson’s terraforming trilogy,

> "....the changes that Mars works on its colonists. The terrain itself suggests the inadequacy of the frontier metaphor and the economic rationalizations to describe aeroformation, the changes wrought by the planet on humans as well as by humans on the planet....the impossibility of fitting Mars into paradigms imported from Earth forces characters [colonists] to move beyond false historical analogies and, consequently take moral responsibility for the complex changes - social as well as biospheric - initiated by terraformation."

In *Living and Working in Space*, Philip Harris (1996: 100) suggests that space communities will "promote peaceful synergistic societies with cultural norms that support cooperation instead of competition, group development over excessive individualism, mutual help in place of aggressive behavior". What reason do we have to believe this utopian scenario? Simply put, such a space culture will have a the best chance for survival. Mars will be a harsh mistress and will not countenance human intransigence. Harris (*ibid.*) suggests ten characteristics of space culture, which are listed in Table 13.

Table 13

CHARACTERISTICS OF SPACE CULTURE

These characteristics as defined and developed by Harris for a lunar culture can be adapted to the Martian situation:

1.

Sense of self on Mars
Culture provides a sense of self-identity, of life-space and comfort within one's group. The terraformation of Mars will provide colonists with a vastly different view of their life-space than the environment of Earth. Even as Mars is changed so too will its people change.

2.

Communication and language
Mars settlers will develop their own verbal and non-verbal communication systems. Computers, satellites, and new forms of communication/information technology will shape and

control communications at all levels of the society; work, family, education and recreation. Time delays communicating with Earth will encourage early autonomy. Terminology will change; new words and words with new meaning will enter the language. Mars will create its own linguistic heritage.

3.

Dress and appearance

Clothing will be more than fashion. It will function for survival and well as expression of culture. Culture has always been expressed in apparel, adornment and decoration. Even today the mission patch is an integral part of the spacesuit. For Martian settlers, prior to full terraforming, their garments will be their life-support system when they venture forth on fieldexcursions. The environment of Mars will have a significant influence, over time, on the manner in which Martians dress.

4.

Food and eating habits

Food preparation, diet and eating habits differentiate groups of people. Food grown in CELSS and eventually on the Martian surface will have different tastes than Earth grown food. From our short excursions into space we already know that gravity affects taste buds (*ibid.*: 102). Martian civilization will produce new foods, packaging, preservation techniques, changes in diet, food preparation and fashions of eating.

5.

Time change and time consciousness

One's sense and method of tracking time influence culture. Mars solar day is 39.6 minutes longer than the 24 hour day on Earth. The Martian environment will affect our circadian rhythm. Time schedules affect performance and productivity. How will Martians ultimately handle the question of time? Will they change the length of the second to fit a Martian 24 hour day? Will they introduce a metric system of time (Mackenzie, 1989:539)? Will they maintain the terrestrial second and twenty four hour day, and introduce the concept of the 39 minute time-slip as in Robinson's *Red Mars*, in which this period is unaccounted time. A Martian year is 669.6 Martian solar days, its seasons are of unequal length. Gangle (1986: 282) has suggested a Martian year of 24 months of 27 and 28 days. All of these temporal aspects will influence the Martian culture.

6.

Relations and families

Human cultures are fixed by organizational relationships; age, sex, status, kinship relations, wealth, power and wisdom. Martian settlers will be highly trained and knowledgeable in many technologies and disciplines. Professional relationships will be important, as will team relations and group dynamics. Martians' understanding of marriage, sexual partnerships, families, and the role of children in society will be significantly different than the corresponding terrestrial institutions and relationships. As the culture moves farther from the outpost and colony phases, linkages and communication with terrestrial family and friends will dwindle. Eventually, a completely separate and distinct human culture will form.

7.

Values and norms

Until a Martian infrastructure is in place, basic societal needs and norms will concentrate on safety and survival. In this high risk environment, competence may become the norm. Gender, race color, creed, sexual preference or national origin may become irrelevant in the face of experience, expertise and proficiency. To succeed on Mars will likely require a commitment to shared values. These values may include minimizing violence, psychological and physical well-being, social and political justice, and sustainable ecological quality and environment. Definitions and practice of ethics, law and governance will emerge based upon consensus, harmony and nurturing.

8.

Beliefs, customs, traditions

Culture is an expression of attitudes, and life-view. It motivates behavior through spiritual themes, philosophies and convictions. A Martian civilization will be formed from diverse belief systems due to the international composition of the settlers. From this diversity a new 'cosmic conscienceless' may develop which is suited to the practical realities of a terraformed biosphere.

9.

Mental processes and learning

Culture influences the manner in which people think and learn. On Mars, the essential world-view will require a diversity of perspectives for terraforming to succeed. This world-view is in many ways exemplified by the ecological approach presented in this paper. Martians will be well educated from the beginning. Sharing information and knowledge development will be facilitated by necessity. Cross training in multiple disciplines will be advantageous. While the level of education will be substantial across the population, there will also be a requirement for individuals with a practical bent who can construct, build and get the job done. All manner of skills will be valuable and everyone will have a contribution to make.

10.

Work habits and processes

A significant facet of any culture is how a society produces its goods and services and conducts its economic affairs. New career and work opportunities will emerge. Extensive use of robotics, biotechnology and nanotechnology will contribute to the creation of a new meaning of work. Tourism may eventually become a major feature of the economic base. The process of creating a new biosphere will result in new work styles, life styles and social structure.

Culture contributes to the setting of objectives, missions, roles, expectations, obligations, and boundaries which affect personnel [civilization], morale and performance (*ibid.*: 106). In their book *In Search of Excellence*, Thomas Peters and Robert Waterman (1982: 105) bespeak the importance of culture to all human enterprise, *In the very institutions in which culture is so dominant, the highest levels of true autonomy occur. The culture regulates vigorously the few variables that do count, and provide meaning. But within those qualitative values (and in almost all the other dimensions), people are encouraged to stick out, to innovate.*

Energy Panarchy - Uncontained Biosphere

A planetary biosphere is uncontained. That is, it has no artificial container. Its components are restrained by gravity. The Earth has such a biosphere. Terraforming Mars, then, is an exercise in recreating a biosphere similar to the Earth's on another planet (Fogg, 1995:61). The energy/matter flows/cycles of a terraformed Martian biosphere are shown in Figure 7. It can be seen how a Martian civilization would benefit from the energy/matter flows of a terraformed Mars. The circulation of the atmosphere, driven by the weather, would provide fresh, clean air. A hydrological cycle coupled with *wilderness* biota would provide clean water and recycling of wastes. Human labor, spent on the energy and time expenditures required for monitoring and managing technology based life-support systems, would be substantially reduced (Fogg, 1995: 81). A comparison of the functions and modes of operation of a terraformed Martian biosphere and Earth's biosphere is shown in Table 14 (adapted from Fogg, 1995:41). Human labor would still be required for agriculture but there would be more time to spend on developing culture and the standard of life. As Fogg (*ibid.*: 82) concludes, *Such worlds [natural or terraformed] are places where we 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.*

Table 14

LIFE-SUPPORT SYSTEMS AND FUNCTIONAL MODES

DEALING WITH TERRAFORMING

At the beginning of this paper, I suggested that terraforming, in which humans are an integral component, is an 'emergent' complex system which includes properties of reflection and contradiction. We have applied the ecosystem approach in the post -normal science mode to develop a framework for planning the terraformation of Mars. Still a question remains. How can we possibly accomplish all of this? To my mind, the technology is not the issue, given time, that will come. But what of the social, ethical, political and economic issues? As the millennium approaches, we are just starting to understand and put into practice the beginnings of the thinking and processes which we must master for dealing with complex adaptive systems. Assessment is a key element in managing systems such as ecopoiesis and terraforming. Nelson and Serafin (1993:392) define assessment, "assessment is usually taken to refer to a process which attempts to make judgments about ecological, economic and social impacts of development proposals and activities as a basis for improved projects, programs, policies and other activities in the future". An adaptive mode of assessment has been suggested for managing complex adaptive systems (Dempster, 1996) This mode encourages learning, understanding, and shared decision making. It promotes consideration of contextual issues such as changes in ways of life, language, land use, employment and economic vitality (Serafin and Nelson, 1993). In this section I will examine use of the of adaptive management and soft systems methodology in a synergetic approach for the management and analysis of terraforming. Borrowing Kai Lee's words concerning adaptive management in the preface of *Compass and Gyroscope*, "The obstacles to a sustainable society [terraformed planet] are hard and heavy, and the levers are short and frail. Learning how to move those obstacles is the first step."

Adaptive Management

Ecopoiesis and terraforming are complex systems which exhibit emergent properties. As a result, our ability to understand and manage these processes is limited. Such limited abilities can lead to either "charging ahead blindly" or "being paralyzed by indecision" (Taylor, 1996). Neither of these approaches will allow us to move ahead. Both can have negative social, economic and ecological impacts. Adaptive management has been describe and suggested by several researchers (Holling, 1978, Lee, 1993, Taylor, 1996) as a responsible alternative approach to such uncertain endeavors. "Adaptive management is a formal, systematic, and rigorous approach to learning from the outcomes of management actions, accommodating change and improving management," (Taylor, 1996). We can paraphrase Kai Lee's definition of adaptive management (Lee, 1993:9) to accommodate ecopoiesis and terraforming:

> Adaptive management is an approach to ecopoiesis and terraforming that embodies a simple imperative: policies are experiments; learn from them. In order to live on Mars, we must use its resources, but we do not understand the nature of Mars well enough to work within its constraints. Adaptive management takes that uncertainty seriously, treating human interventions [ecopoiesis and terraforming] as experimental probes. Its practitioners take special care with information. First they are explicit about what they expect, so that they can design methods to make measurements. Second, they collect and analyze information so that expectations can be compared with actuality. Finally, they transform comparison into learning- they correct errors, improve their imperfect understanding, and change action and plans.

This process of adaptive management is fundamentally different from the trial and error method that has traditionally been used for learning. With trial and error methods, unforeseen results are usually a surprise and people are not prepared to understand the lessons that present themselves. Accumulation of knowledge from unexamined error is slow and random. Adaptive management produces reliable knowledge from experience. "A wide range of outcomes is valuable, and unexpected results produce understanding as well as surprise" (*ibid.*). Brenda Taylor, Ministry of Forests, Forest Practices Branch, (1996) has produced, "An Introductory Guide to Adaptive Management". The essential elements of adaptive management taken from Taylor's guide are illustrated in Figure 20, along with brief explanations of each step.

Soft Systems Methodology

Post-normal science, as a problem solving strategy, requires consideration of decision stakes and system uncertainties, as indicated in this paper, in the section on problem solving strategies. Decision stakes and system uncertainties must be included as we work through the adaptive management approach to terraforming. This can only be accomplished by including a diverse set of stakeholders in the planning process. The learning component of the ecosystem approach and adaptive management is more than simply educating the public There must be an open dialogue with scientists, policy makers, and terraforming managers and colonists (stakeholders). Allen and Hoekstra, (1992:308) recommend that soft systems methodology, a protocol designed by Peter Checkland, (1979, a, b), be employed to define the decision stakes and system uncertainties involved in the operationalization of the ecosystem approach. "It is a scheme for problem solving in 'messy' situations [multiple uses of a terraformed ecosystem is a mess with many conflicting interests, and management subdisciplines] where there are too many competing points of view for simple trial and error to prevail." (Allan and Hoekstra, *ibid.*).

Figure 20

Figure 21 illustrates Checkland's soft system methodology as applied to terraforming. Stage 1 and 2 are employed to build a rich picture of the terraforming situation, without imposing a particular structure of components. Stage 3 involves selecting some systems (organizing principles from the ecosystem approach) and preparing concise definitions of what these systems are. These are termed root definitions. The components of the root definitions can be remembered by the acronym CATWOE (Allan and Hoekstra, 1992: 315).

> CATWOE's can tease apart those conflicting views to allow development of pertinent models so that a plan can be made without ambiguity. With the scale, structure and function of the [panarchy organizing principle] defined, compromise can be sought in a meaningful way, and management action will be enlightened by an understanding of what is intended, and how it is to be achieved. Rhetoric and hidden agendas can be exposed and those disingenuous can be rejected.

The next stage 4, is the process of building a model for each of the root definitions. Stage 5 involves checking the model results against observations of what actually happens in the real world. Stage 6 identifies desirable and feasible changes for the system. If these conditions cannot be met, one can return to stage 3 to look for new root definitions. The final stage 7, is the implementation of changes.

Figure 21

A Synergetic Approach to Management and Analysis of Terraforming

I have suggested the use of the ecosystem approach as a framework for the ecopoiesis and terraforming of Mars. The ecosystem approach provides a variety of perspectives to develop a comprehensive picture of the project. The ecosystem approach can be operationalized as using Checkland's soft system methodology as proposed by Allen and Hoekstra. The remaining task is to integrate these two processes into the adaptive management approach to ensure that we neither "charge blindly ahead" nor become "paralyzed with indecision", and that we maximize our learning of Mars' functions and processes, as we proceed with ecopoiesis and terraforming. Figure 22 illustrates a synergetic approach to the management and analysis of terraforming. The first step in the adaptive management stream (AM) is to assess the problem (AM - 1). This can be accomplished by entering the soft systems methodology stream (SSM) and developing a rich picture of the problem by recognizing that it is a “messy” problem (SSM -1) and considering the many points of view of the stake holders (SSM - 2). We then develop root definitions for various organizing principles, described in the ecosystem approach, using CATWOE (SSM -3), The management plan then moves back to the AM stream to step 2, design the management plan (AM - 2). By employing the results compiled from the process thus far, we can build a model for each set of root definitions (SSM - 4), checking the model against the real world (SSM - 5), and selecting desirable and feasible changes (SSM - 6). The final stage of the synergetic approach is to implement the changes (SSM - 7) though the management plan, (AM -3), monitor results (AM -4), evaluate the results against the originally predicted outcomes (AM - 5) and finally to make any necessary adjustments to the plan, as a result of learning gleaned in the adaptive management process (AM -6).

979

Figure 22 A Synergetic Approach to Managment and Analysis for Terraforming.

CONCLUSION

In Pale Blue Dot, Carl Sagan (1994,81) commented, “ The visions we offer our children shape the future. It matters what those visions are. Often they become self-fulfilling prophesies. Dreams are maps.” The many workers in the field of terraforming, who come immediately to mind, such as Martyn Fogg, Robert Haynes, Julian Hiscox, Chris McKay, Robert Zubrin and others (forgive me if I have omitted anyone’s name) have described some of the stops along the way. In this paper, I have attempted to draw the map which will show the path to fulfilling the dream, and in the words of Jean-Luc Picard, **Make it so!**

As evening approaches on a terraformed Mars, a family is out for an evening stroll along the Grand Canal, which connects the Hellas Sea to the Oceanus Borealis to the northwest, between Isidis Bay and The Narrows. In The Martian Chronicles, Ray Bradbury (1982, 181), might have been describing the scene.

> On reaching the canal, it was long and straight and cool and wet and reflective in the night. “I’ve always wanted to see a Martian,” said Michael. “where are they, Dad? You promised.”
> “There they are,” said Dad, and he shifted Michael on his shoulders and pointed straight down. The Martians were there, Timothy began to shiver. The Martians were there ....in the canal...reflected in the water. Timothy and Michael and Robert and Mom and Dad. The Martians stared back at them for a long, long silent time from the rippling water.....

.........We are the Martians now.

BIBLIOGRAPHY

Allan, T. F. H. and T. W. Hoekstra, 1992, *Toward A Unifying Ecology*, Columbia University Press, New York.

Andersson, T., Folke, C. and S. Nyström, 1995, *Trading with the Environment: Ecology, Economics, Institutions and Policy*, Earthscan Publications Ltd., London.

Averner, M. M. and R. D. MacElroy, (eds.), 1976, On the Habitability of Mars: An Approach to Planetary Ecosynthesis, National Aeronautics and Space Administration, NASA SP-414, U. S. Government Printing Office, Washington, D. C. as cited in J. A. Hiscox, 1997, *Selecting Pioneer Microorganisms for Mars*, privately circulated.

Banin, A., 1989, Mars Soil - A Sterile Regolith or Medium for Plant Growth, AAS 87-215, in C. Stoker , (ed.) *The Case for Mars III, Strategies for Exploration, General Interest and Overview*, Vol. 74, *Science and Technology Series*, American Astronautical Society, Univelt, San Diego, CA, pp. 559-571.

Banin A. and R. L. Mancinelli, 1995, Life On Mars? I: The Chemical Environment, *Advances in Space Research*, Vol. 15(3), COSPAR, pp. 163-170.

Bradbury, R., 1882, *The Martian Chronicles*, 60th Ed., Bantam, New York.

Burgess, C., Conrad, M., Eggen, M., , Green, R., Johnson, C., Metcalfe, R. and I. Thomson, 1995, *The Huron Park Natural Area, An Application of the Ecosystem Approach*, The Huron Natural Area Working Group, ERS 490, University of Waterloo, Waterloo, ON, [Online]. Available: http://www.fes.uwaterloo.ca/u/jjkay/HNA/EcoIntro.html [1997, October 30].

Carr, M. H., 1981, *The Surface of Mars*, Yale University Press, New Haven, CT.

Checkland, P. B., 1979 a, Techniques in ‘Soft’ Systems Practice, Part 1: Systems Diagrams - Some Tentative

Guidelines, *Journal of Applied Systems Analysis* (6), pp. 33-40.

Checkland, P. B., 1979 b, Techniques in 'Soft' Systems Practice, Part 2: Building Conceptual Models, *Journal of Applied Systems Analysis* (6), pp. 41-49.

Connors, M. M., Harrison, A. A. and F. R. Akins, 1985, *Living Aloft: Human Requirements for Extended Space Flight*, National Aeronautics and Space Administration, NASA SP-483, Washington, D. C.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Shahid, N., O'Neill,. R. V., Paruelo, J., Raskin, R. G., Sutton, P. and M. van den Belt, 1997, The Value of the world's ecosystem services and natural capital, *Nature*, May 15, Vol. 387 (6230).

Costanza, R., Wainger, L., Folke, C. and K-G. Mäler, 1993, Modeling Complex Ecological systems: Toward an evolutionary, dynamic understanding of people and nature, *BioScience*, 43(8), pp. 545-555.

Delcourt, H. R. and P. A. Delcourt, 1988, Quartenary Landscape Ecology: Relevant scales in space and time, *Landscape Ecology* 2(1), pp. 23-44.

Dempster, B., 1996, Self-Organizing Systems, *Post-normal Science and Adaptive Assessment: Conceptual Links for Practical Applications*, International Society for Ecological Economics Conference: Designing Sustainability, August, 1996, [Online]. Available: http://www.fes.uwaterloo.ca/u/mbldemps/ISEE-4B.html#RTFTo C1 [1997, August 22].

Farber, S. and D. Bradley, 1996, *Ecological Economics*, [Online]. Available: http://www.fs.fed.us/eco/s21pre.htm [1997, June 27].

Farmer, J., Des Marais, D., Greeley, R., Landheim, R. and H. Klein, 1993, Site Selection for Mars Exobiology, *Advances in Space Research* 13(14), COSPAR, pp. 157-162.

Fogg, M. J., 1995, *Terraforming: Engineering Planetary Environments*, Society of Automotive Engineers Inc., Warrendale. PA.

Fogg, M. J., 1995 a, Terraforming Mars: Conceptual Solutions to the Problem of Plant Growth in Low Concentrations of Oxygen, *Journal of the British Interplanetary Society*, 48(10), London, pp. 427-434. Also published as paper AAS 97-388, in *From Imagination to Reality: Mars Exploration Studies of the Journal of the British Interplanetary Society* (Part II: Base Building, Colonization and Terraformation), R. M. Zubrin, ed., AAS *Science and Technology Series*, Vol. 92, 1997, pp. 283-301.

Friedmann, E. I., Hua, M. and R. Ocampo-Friedmann, 1993, Terraforming Mars: Dissolution of Carbonate Rocks by Cyanobacteria, *Journal of the British Interplanetary Society*, 46, London, pp. 291-292.

Friedmann, E. I. and R. Ocampo-Friedmann, 1984, The Antarctic Cryptoendolithic Ecosystem: Relevance to Exobiology, *Origins of Life*, (14), pp. 771-776.

Funtowicz, S. O. and J. R., Ravetz, 1994, Emergent Complex Systems, *Futures*, 26(6), pp. 568-582.

Funtowicz, S. O. and J. R., Ravetz, 1993, Science for the post-normal age, *Futures*, September, pp. 739-755.

Gangle, T., 1986, Martian Standard Time, *Journal of the British Interplanetary Society*, June, (39), London, pp. 282-288.

Geels, S., Miller, J. B. and B. C. Clark, 1989, Feasibility of Using Solar Power on Mars: Effects of Dust Storms on Incident Solar Radiation, AAS 87-266, in C. Stoker , (ed.) *The Case for Mars III, Strategies for Exploration, General Interest and Overview*, Vol. 75, *Science and Technology Series*, American Astronautical Society, Univelt, San Diego, CA, pp. 505-516.

Goffman, E., 1961, *Asylums: Essays on the Social Situation of Mental Patients and Other Inmates*, Doubleday Anchor, Garden City, New York.

Gunderson, L. H., Holling, C. S. and S. S. Light (Eds.), 1995, *Barriers and Bridges to the Renewal of Ecosystems and Institutions*, Columbia University Press, New York.

Harris, P. R., 1996, *Living and Working in Space: Human Behaviour, Culture and Organisation*, (2nd Ed.), John Wiley & Sons, Chichester.

Haslach, H. W., 1989, Wind Energy: A Resource For A human Mission to Mars, *Journal of the British Interplanetary Society*, (42), London, pp. 171-178. Also published as paper AAS 97-376, in *From Imagination to Reality: Mars Exploration Studies of the Journal of the British Interplanetary Society* (Part II: Base Building, Colonization and Terraformation), R. M. Zubrin, ed., AAS *Science and Technology Series*, Vol. 92, 1997, pp. 53-70.

Haynes, R. H., 1990, Ecce Ecopoiesis: Playing God on Mars in D. MacNiven, (Ed.), *Moral Expertise*, Routledge, New York, pp. 161-183.

Hiscox, J. A., 1997, Selecting Microorganisms for Mars, privately circulated, pp. 16. See also paper AAS 96-345, in *The Case for Mars VI*, K. R. McMillen, ed., AAS *Science and Technology Series*, Vol. 98, 1999, pp. 491-503.

Hiscox, J. A., 1995, Biology and Planetary Engineering of Mars, submitted to *The Terraforming Report*. See also paper AAS 96-343, in *The Case for Mars VI*, K. R. McMillen, ed., AAS *Science and Technology Series*, Vol. 98, 1999, pp. 453-481.

Hiscox, J. A. and D. J. Thomas, 1995, Genetic Modification and Selection of Microorganisms for Growth on Mars, *Journal of the British Interplanetary Society*, 48(10), London, pp. 419-426. Also published as paper AAS 97-387, in *From Imagination to Reality: Mars Exploration Studies of the Journal of the British Interplanetary Society* (Part II: Base Building, Colonization and Terraformation), R. M. Zubrin, ed., AAS *Science and Technology Series*, Vol. 92, 1997, pp. 265-281.

Holling, C. S., 1992, Cross-scale Morphology, Geometry and Dynamics of Ecosystems, *Ecological Monographs*, 62(4), pp. 447-502.

Holling, C. S. (Ed.), 1978, *Adaptive Environmental Assessment and Management*, John Wiley & Sons, New York.

Horowitz, N. H., 1986, *To Utopia and Back: The Search for Life in the Solar System*, W. H. Freeman & Co., New York.

Ishikawa, Y., Ohkita, T. and Y. Amemiya, 1997, Constructing a Mars Base - Mars Habitation 2057 Concept, in T. Meyer, (ed.) *The Case for Mars IV, The International Exploration of Mars - Considerations for Sending Humans*, Vol. 90, *Science and Technology Series*, American Astronautical Society, Univelt, San Diego, CA, pp. 309-326.

Jensen, M. E., Bourgeron P., Everett, R. and I. Goodman, 1996, Ecosystem Management: A Landscape Ecology Perspective, Paper No. 95102, *Water Resources Bulletin*, 32(2), American Water Resources Association, pp. 203-216.

Jensen, M. E., Bourgeron, A. S., Hessburg, P. F., Everett, R., and B. T. Bormann, 1994, The process to generate and evaluate alternative sustainable ecosystem management scenarios, in Everett, R., Hessburg, P., Jensen, M., and B. T. Bormann, (Eds.), *Volume I, Executive Summary, Eastside Forest Ecosystem Health Assessment*, U. S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Report PNW - GTR - 317.

Kay, J. J., 1996, The Ecosystem Approach to cooperative decision making; PNS applied, Bi Annual Meeting of the International Society for Ecological Economics, August, [Online]. Available: http://www.fes.uwaterloo.ca/u/jjkay/pns/Boston/jk2.html [1997, August, 25].

Kay. J. J., 1994, The Huron Park Natural Area: An Ecosystem Approach, [Online]. Available: http://www.fes.uwaterloo.ca/u/jjkay/pubs/hna/index.html [1997, June 16].

Kay, J. J., 1983, Self-Organization and The Thermodynamics of Living Systems: A Paradigm, Chapter 2, Ph.D. Thesis, Department of Systems Design Engineering, University of Waterloo, Waterloo, [Online]. Available: http://www.fes.uwaterloo.ca/u/jjkay/pubs/thesis/2.html [1997, June 12].

Klein, H. P., Horowitz, N. M. and K. Biemann, 1992, The Search for Extant Life On Mars, in Kieffer, H. H., Jakosky, B. M., Snyder, C. W. and M. S. Matthews, (Eds.), *Mars*, The University of Arizona Press, Tucson, AZ.

Lee, K. N., 1993, *Compass and Gyroscope: Integrating Science and Politics for the Environment*, Island Press, Washington, D. C.

Levin, G. V., 1997, The Viking Labeled Release Experiment and Life On Mars, SPIE International Society for Optical Engineers, *Proceedings of SPIE "Instruments, Methods and Missions for the Investigation of Extraterrestrial Microorganisms*, July, 29 -August 1, 1997, San Diego , CA.

Lovelock, J. and M. Allaby, 1984, *The Greening of Mars*, St. Martin's Press, New York.

Mackenzie, B. A., 1989, Metric Time for Mars, AAS 87-269, in C. Stoker, (ed.) *The Case for Mars III, Strategies for Exploration, General Interest and Overview*, Vol. 75, *Science and Technology Series*, American Astronautical Society, Univelt, San Diego, CA, pp. 539-543.

Madigan, M. T. and B. L. Marrs, 1997, Extremophiles, *Scientific American*, April, pp. 82-87.

Mancinelli, R. L. and A. Banin, 1995, Life On Mars? II: The Physical Environment, *Advances in Space Research*, Vol. 15(3), COSPAR, pp. 171-176.

Markely, R. M., 1997, Falling Into Theory: Simulation, Terraforming and Eco-Economics in Kim Stanley Robinson's Martian Trilogy, *Modern Fiction Studies*, Fall, 43(3), pp. 771-799.

McKay, D. S., Gibson, E. K., Thomas-Keptra, K. L., Vali, H., Romanek, S., Clemett, S. J., Chiller, X. D. F., Maechling, C. R. and N. Zare, 1996, Search for Past Life on Mars: Possible Relic Biogenic Activity in Martian Meteorite ALH84001, *Science*, 273, pp. 924-930.

Meyer, T. R. and C. P. McKay, 1996, Using The Resources of Mars for Human Settlement, AAS 95-489, in Stoker, C. R. and C. Emmart, (Eds.), *Strategies for Mars: A Guide to Human Exploration*, Vol. 86, *Science and Technology Series*, American Astronautical Society, Univelt, San Diego, CA, pp. 393-442.

Miller, R. W., 1997, Space Communities, in R. W. Miller, *The Greening of Mars: Ethics, Environment and Society*, unpublished manuscript, Department of Independent Studies, University of Waterloo, Waterloo, ON.

Miller, R. W., 1996, Technology, Society and Terraforming, in R. W. Miller, *The Greening of Mars: Ethics, Environment and Society*, unpublished manuscript, Department of Independent Studies, University of Waterloo, Waterloo, ON.

Nelson, J. G. and R. Serafin, 1993, Improving Monitoring and Assessment for Environmental Decision-Making, in Audrey, J. and J. G. Nelson, (Eds.), *Public Issues: A Geographic Perspective*, University of Waterloo, pp. 391-414.

Odum, E. P., 1993, *Ecology and Our Endangered Life-Support System*, (2nd Ed.), Sinauer Associates, Sunderland, Mass.

Ostroumov, V., 1995, A Physical and Chemical Characterization of Martian Permafrost as A Possible Habitat for Viable Microorganisms, *Advances in Space Research* (3), COSPAR, pp. 229-236.

Peters, T. J. and R. H. Waterman, Jr., 1982, *In Search of Excellence: Lessons from America's Best-Run Companies*, Harper and Row Publishers, New York.

Robinson, K. S., 1994, *Green Mars*, Harper Collins, London.

Rothschild, L. S., 1995, A "Crypto" Microbial Mat: A New Model Ecosystem for Extant Life On Mars, *Advances in Space Research* (3), pp. 223-228.

Sagan, C., 1994, *Pale Blue Dot: A Vision of The Human Future In Space*, Random House, New York.

Schneider, E. D. and J. J. Kay, 1994, Complexity and Thermodynamics: Towards A New Ecology, *Futures*, 26(6), pp. 626-647.

Scott, D. H., Tanaka, K. L., Greeley, R. and J. E. Guest, 1986, *Geological Maps of the Western Equatorial, Eastern Equatorial and Polar Regions of Mars*, Misc. Investigation Series USGS, Maps I-1802 A, B, C & D, National Aeronautics and Space Administration.

Taylor, B., 1996, *An Introductory Guide to Adaptive Management for Project Leaders and Participants*, Ministry of Forests, Forest Practices Branch, British Columbia, Victoria, BC, [Online]. Available: http://www.for.gov.bc.ca/hfp/amhome/introgd/toc.htm [1997, July 23].

Task Group On Planetary Protection, 1992, *Biological Contamination of Mars: Issues and Recommendations*, Space Studies Board, National Research Council, Washington, D. C.

Thomas, D. J., 1995, Biological Aspects of The Ecopoiesis and Terraformation of Mars: Current Perspectives of Research, *Journal of the British Interplanetary Society*, 48(10), London, pp. 415-418. Also published as paper AAS 97-386, in *From Imagination to Reality: Mars Exploration Studies of the Journal of the British Interplanetary Society* (Part II: Base Building, Colonization and Terraformation), R. M. Zubrin, ed., AAS *Science and Technology Series*, Vol. 92, 1997, pp. 257-264.

Thompson, S., 1997, What Is Policy?, in R. Wilson, *Social Values in Forest Management*, Course FOR 4005, University of New Brunswick Department of Forestry and Environment, Fredericton, NB, [Online]. Available: http://www.unb.ca/enviro/4005/5policy.htm [1997, November, 19].

Turner, F., 1989, Life On Mars: Cultivating a planet and ourselves, *Harper's Magazine*, August, 1989.

Zonneveld, I. S., 1988, Basic Principles of Land Evaluation Using Vegetation and Other Land Attributes, in Kuchler, A. W. and I. S. Zonneveld, (Eds.), *Vegetation Mapping*, Kluwer Academic Publishers, Dortrecht, The Netherlands.

Zurcher, L., 1965, The Sailor Aboard Ship: A Study of Role Behaviour In a Total Institution, *Social Forces* (43), March, 389-400.

Zubrin, R. M., Baker, D. A. and O. Gwynne, 1997, Mars Direct: A Simple Robust and Cost Effective Architecture for the Space Exploration Initiative, in T. Meyer, (ed.) *The Case for Mars IV, The International Exploration of Mars - Considerations for Sending Humans*, Vol. 89, *Science and Technology Series*, American Astronautical Society, Univelt, San Diego, CA, pp. 275-314.

Zubrin, R. M., 1996, *The Case for Mars: The Plan to settle The Red Planet and Why We Must*, The Free Press, New York.

Zubrin, R. H., 1995, The Economic Viability of Mars Colonization, *Journal of the British Interplanetary Society* 48(10), London, pp. 407-414. Also published as paper AAS 97-385, in *From Imagination to Reality: Mars Exploration Studies of the Journal of the British Interplanetary Society* (Part II: Base Building, Colonization and Terraformation), R. M. Zubrin, ed., AAS *Science and Technology Series*, Vol. 92, 1997, pp. 239-256.