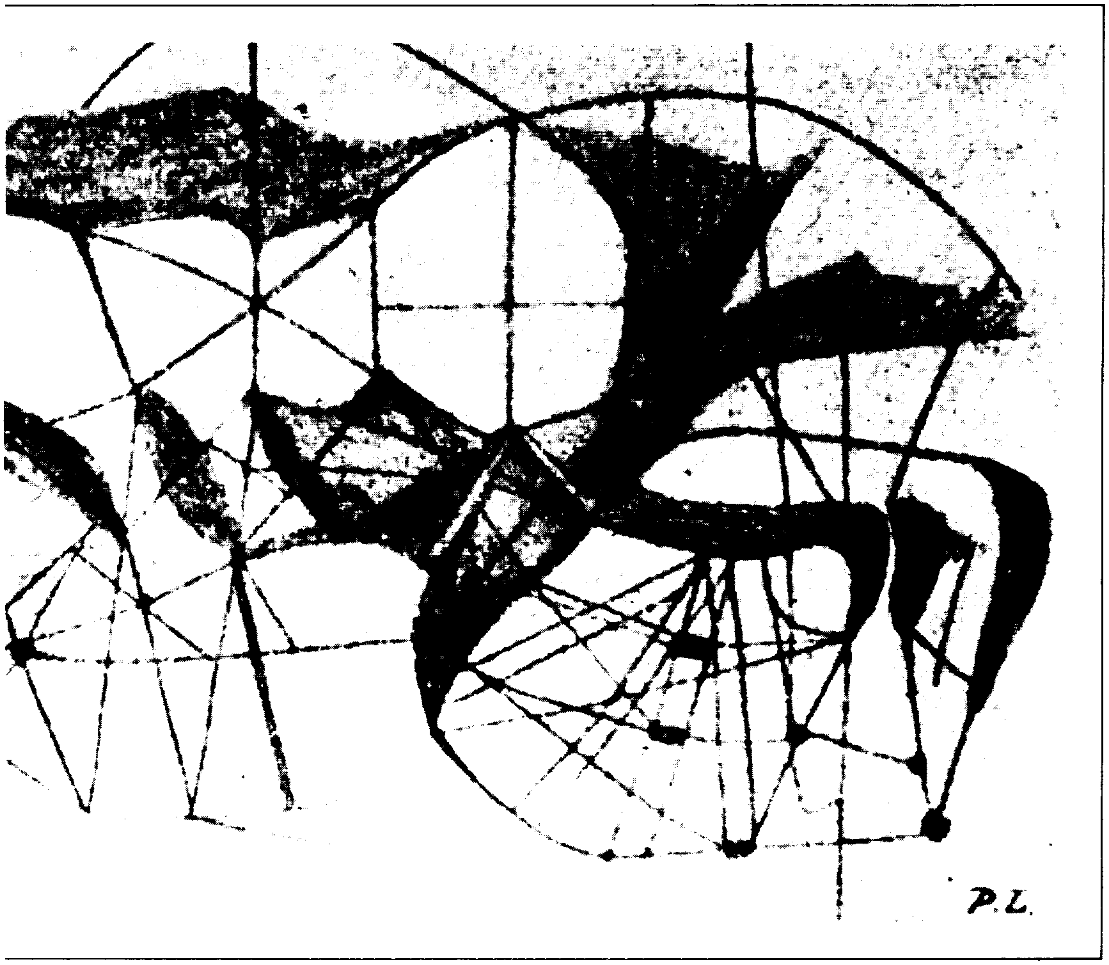
NASA SP 414

ON THE HABITABILITY OF MARS

approach to planetary ecosynthesis



ONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA SP-414

ON THE HABITABILITY OF MARS

an approach to planetary ecosynthesis

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Prepared by Ames Research Center

Scientific and Technical Information Office 1976
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C.

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PREFACE

This study was conducted at NASA-Ames Research Center, under the auspices of the Planetary Biology Division with the financial support of the Stanford-Ames Faculty Fellowship Program and NASA. The report is a compilation of individually authored contributions which have been assembled and integrated by the editors.

ACKNOWLEDGMENTS

The development of this study was stimulated by conversations with Joshua Lederberg and Hans Mark. Later, extensive discussions with James Danielli, and proddings by Ichtiaque Rasool crystallized the concept. Harold Klein, Donald DeVincenzi and Richard Young were responsible for making the study possible. Before and during the study, discussions with Martin Alexander, Edward Leadbetter, and Richard Vondrak focussed certain problems. Joel Levine's enthusiasm, willing participation, and criticism carried us over many hurdles encountered in the physical sciences. Many people have contributed their ideas and criticism to the study: Edward Griffith, Richard Vondrak, Bruce White, Robert Whitten, James Pollack, Joel Levine, Von Eshelman, Leslie Orgel, Michael Anbar, Robert Rein, Joshua Lederberg, John Oro, J. R. Garrels, H. Lettau, and John Billingham. We are particularly indebted to Carl Sagan, whose published work has previously examined several of the ideas incorporated in this study. We are very grateful to all these people for helping us into the beginnings of Planetary Engineering.

R. D. MacElroy

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1. SUMMARY

The possibility of utilizing Mars as a habitat for terrestrial life, including man, is examined. Available data, assumptions, and speculations on the climate, physical state, and chemical inventory of Mars are reviewed and compared with the known requirements and environmental limits of terrestrial life. While accurate data on several points, particularly the amount of Martian water and nitrogen reserves, are still lacking, no fundamental, insuperable limitation of the ability of Mars to support a terrestrial ecology is identified. The lack of an oxygen-containing atmosphere would prevent the unaided habitation of Mars by man. The present strong ultraviolet surface irradiation is an additional major barrier. The creation of an adequate oxygen and ozone-containing atmosphere on Mars may be feasible through the use of photosynthetic organisms. The time needed to generate such an atmosphere, however, might be several millions of years. This period might be drastically reduced by (1) the synthesis of novel, Mars-adapted, oxygen producing photosynthetic strains by techniques of genetic engineering, and (2) modifying the present Martian climate by techniques of planetary engineering. Such climatic modification would rely upon the melting of the Martian polar caps and concomitant advective and greenhouse heating effects. Melting the polar caps, however, would require the investment of very large amounts of energy over a relatively long period.

2. REPORT DIGEST

PRESENT MARTIAN CONDITIONS

Of all the planets in the solar system the Martian environment is closest to that of Earth. The diurnal variation of sunlight is about the same on Mars as on Earth, although the intensity of solar radiation at the surface of Mars is only about 60% of that at Earth's surface. The Martian day is 24.6 hr, and the year and seasons are twice as long as those of Earth. The atmosphere is only 1/200 as dense as that of Earth and is primarily carbon dioxide. Oxygen comprises only 0.1% or less of the mass of the atmosphere. Ozone is present in very small amounts and, other than at the poles, provides essentially no shielding to solar ultraviolet radiation which at the equator averages 7×10^3 ergs/cm^2/sec.

Of critical importance to habitability is the amount of water on or in the planet. The atmosphere contains less than 0.1% water vapor. While recent studies indicate that there may be as much as 10^{19} kg of water ice in the polar caps and the regolith, other estimates suggest that only 1%, or less, of this amount may be present. The assumption is made in this study that enough water is available on Mars to support the growth of terrestrial types of organisms.

The average temperature of the planet is about 60 K lower than that of Earth. However, in low- and mid-latitudes the temperature rises above freezing for about 7 hr a day in the summer. While the daytime temperature may reach a maximum of 300 K, at night it falls to a low of 170 K. Although little is known about surface winds on Mars, studies indicate their speed could approach 100 m/sec. Such winds generate dust-carrying storms that could cause severe mechanical stress to an unsheltered organism.

The surface temperature is, of course, very important to any discussion of a Martian ecology. Temperature ranges for annual and diurnal heating cycles for the Martian surface were calculated by using the method of "climatonomy," a quantitative approach developed by H. H. Lettau at the University of Wisconsin in which energy fluxes are expressed as Fourier time series. The mean annual temperature difference from summer to winter is calculated to be about 45 K in mid- and polar-latitudes, and half this value at the equator. The diurnal range is slightly over 100 K at the equator all year, and is the same for mid-latitudes, except during winter solstice when the range is 20 K. At the poles the diurnal range is zero. This technique allows estimation of the number of hours that surface temperature exceeds 270 K, a typical lower limit for growth of most terrestrial organisms. This number is roughly 2000 hr per Martin year in a region around the planet extending from the equator to 45° S.

BIOLOGICAL CONSIDERATIONS

Limits to Life

Life can exist only in certain environments. Such factors as temperature, light, water availability, and the chemical constituents of soil, water, and air impose limits on life; a certain minimum must be obtained and a certain maximum not exceeded for each factor. The ability of an environment to support life can be determined by comparing parameters of the environment with the known limits to life. A comparison for Mars is provided in table 1.

TABLE 1.– COMPARISON OF LIMITS TO LIFE WITH SELECTED MARTIAN ENVIRONMENTAL PARAMETERS

Parameter	Range compatible with life	Mars
Temperature	Growth: 255 K–377 K Survival: <79 K–377 K	140 K–300 K
Ultraviolet irradiation	3×10^5 ergs/cm^2	7×10^3 ergs/cm^2/sec
Oxygen (pO_2)	0 – 100%	≅ 0
Liquid H_2O	10% – 100% (w/w)	Present, amount unknown
Salinity	0% – 35% NaCl	?
pH	0 – 13	?
Mechanical abrasion	Abrasive particles ⩾ cell size will cause mechanical damage	Dust in storms ≅ 10–50 µM in size range of many microorganisms
Nitrogen	Absolute requirement	Not yet found
Sulfur	↓	Not yet found
Phosphorus		Not yet found
Carbon		CO, CO_2, 5 mbar
Oxygen		H_2O
Hydrogen		H_2O

When those factors whose values can be measured or estimated are considered, Mars is an environment hostile to biology. The lack of atmospheric oxygen would allow growth only of those organisms not dependent upon oxygen, the anaerobes; generally, single-celled simple organisms. Ultraviolet light, particularly in the range of 2000Å–3000Å, is lethal. Organisms on the Martian surface would be exposed to a mean flux of ultraviolet light in this range which would decrease their mean survival times to a few minutes at most.

The Martian surface temperature range would allow seasonal growth for only 7 hr a day at the equator and mid-latitudes. The low temperatures and atmospheric pressures would allow surface water to exist in a liquid state only in restricted areas of the planet, and the total amount of water can only be guessed. Other important chemical elements for life, such as nitrogen and phosphorus, have yet to be identified on Mars. Even a most optimistic appraisal suggests that the kinds of terrestrial organisms able to survive in the present Martian environment are quite limited, and the growth of even these forms would be quite restricted in vigor and extent. There have been many attempts to determine the response of microorganisms to simulated Martian environments. While conclusions have varied, in part a reflection of the experimenters' choice of organisms and environmental conditions, investigators feel that there is a definite possibility for growth of certain anaerobic, cold-adapted terrestrial bacteria on Mars.

Photosynthesis

For higher life forms, an oxygen-containing environment is mandatory. The need for an oxygen atmosphere derives from two functions of oxygen: it is required environmentally for the formation of ozone which on Earth provides an ultraviolet-absorbing shield under which life exists, and biologically for metabolism in higher organisms which are absolutely dependent upon oxygen for this purpose. There are, in principle, two ways by which gaseous oxygen can be produced: chemically, from water or other oxygen-containing compounds, or biologically, from water. The general consensus is that the present mass of terrestrial atmospheric oxygen was biologically produced and the bulk of the oxygen in the ancient primitive atmosphere was produced by green plant or algal photosynthesis. Thus photosynthesis is expected to have the *capability* of generating oxygen in the amounts necessary to make Mars habitable.

Photosynthesis can be considered as the fixing of carbon dioxide and water into a carbohydrate (starch) by chlorophyll-containing organisms in the presence of visible light. As a by-product of photosynthesis, oxygen, derived from water, is produced. In principle, all the necessary physical (light) and chemical (CO_2, H_2O) elements are available on Mars. The question then is: which of the available terrestrial photosynthetic organisms might be best fitted to survive, grow and generate oxygen on Mars? Although no Earth environment exactly resembles available Martian eco-niches, it is likely that the Antarctic dry valleys come closest. In these valleys there are four major photosynthetic groups. Comparing their properties with those required by a hypothetical "ideal" oxygen-evoloving Martian organism suggests that none are ideal, although lichens and blue-green algae are the "best" – as shown in table 2.

All groups except the blue-green algae have an absolute requirement for oxygen. All groups except the lichens are sensitive to ultraviolet light, so that survival times unprotected on the surface would be quite short. The blue-green algae, however, can occupy subsurface eco-niches and thus might be shielded from the full intensity of ultraviolet light. The very slow rate of growth of lichens is not consistent with the goal of rapid oxygen evolution.

TABLE 2.– BIOLOGICAL AND GROWTH CHARACTERISTICS OF SOME TERRESTRIAL ORGANISMS AND OF AN IDEAL MARTIAN ORGANISM

Organism	Requires oxygen	Extreme resistance to ultraviolet radiation	Extreme resistance to drying	Growth rate	Growth habitat
Green algae	Yes	No	No	Fast (hr)	Soil (surface and subsurface), Snow (surface), water
Lichen	Yes	Yes	Yes	Very slow (yr)	Surfaces (rock, tree)
Moss	Yes	No	No	Slow (wk)	Moist surfaces
Blue-green algae	No	No	Yes	Fast (hr)	Soil (surface and subsurface), water
Ideal Martian organism	No	Yes	Yes	Very fast (min)	Soil (surface and subsurface), water

Survival of Terrestrial Organisms on Mars: Computer Simulations

From a biological standpoint several questions concerning the interaction of an organism with its environment need to be examined. For example, how would the temperature of a hypothetical organism vary during a diurnal cycle, and how closely would it be coupled to the ground and atmospheric temperatures? How severe would be the water loss resulting from the lack of atmospheric water, low pressures, and strong winds characteristic of Mars? Can desiccation be significantly limited by varying the resistance properties of the structural components of the organism within reasonable limits? How might these various environmental parameters affect photosynthesis, and can estimates of photosynthetic production be made? Is it likely that any present-day terrestrial organisms could survive the envisioned Martian conditions without extensive genetic engineering?

Taking into consideration such parameters as photosynthetic rates, resistance to water movement, ultraviolet sensitivity, and the like, computer models were formulated to yield estimates of such factors as water flux, oxygen production, and organism temperature. These models incorporated two organisms which might be candidates for growth on Mars: a mat of blue-green algae and a mat of lichens. The models predict:

1. The organism's temperature would be closely coupled to the surface temperature rather than the atmospheric temperature.
2. The organism's temperature would decrease with increasing wind speed because of convective heat loss.
3. A layer of desiccated cells on the upper surface of the algal mat would control water loss. The lack of such a layer would permit large water losses from the lichen. The losses would, in turn, be affected by such factors as lichen thickness and wind speed.
4. Temperature and water loss would limit photosynthesis to only 3 to 5 hr/day. Allowing a 25% coverage of the surface of Mars, blue-green algae could generate an amount of oxygen equivalent to the present amount of carbon dioxide in the Martian atmosphere (approximately 5 mbar) in 7000 yr. To produce an amount equivalent to the minimum necessary for human breathing (approximately 100 mbar) would take 140,000 yr. The lichens would take approximately 10 times longer.

MODIFICATION OF THE MARTIAN ENVIRONMENT

Greenhouse Effects

Many of the environmental factors which are unfavorable for the establishment of life on Mars would be ameliorated by modifying the planet's temperature. The surface temperatures of Mars could be increased, and the diurnal temperature variations reduced, if a means could be found for increasing the atmospheric mass by vaporizing the polar caps. The mass and composition of the sublimate in the caps is not known, however, and although the portion of the caps which seasonally grows and recedes may be carbon dioxide, the summertime cap remnant may be carbon dioxide, water, or both.

Increasing the amount of carbon dioxide or water vapor in the atmosphere will increase the surface temperature. This warming, known as "the greenhouse effect," occurs because certain gases, carbon dioxide and water vapor among them, absorb some of the thermal radiation (heat) from the surface of the planet so that not all of the radiation is lost to space, but is re-emitted down from the atmosphere and heats the surface. The increase in surface temperature due to the injection of various amounts of carbon dioxide and water was calculated.

The greenhouse effect from carbon dioxide is small. If the remnant north polar cap were entirely carbon dioxide, then the maximum amount of carbon dioxide it might contain would only increase the mean surface temperature by 7 K, although the atmospheric pressure would increase some 100-fold.

Water vapor provides a much larger greenhouse effect; for example, if enough water vapor could be added to the atmosphere to increase the total pressure by only 10%, the resulting average temperature rise would be 10 K. If the remnant caps contain water ice which could be released to the atmosphere as water vapor and carried by advection to lower latitudes where the atmosphere could support appreciable vapor, then a substantial greenhouse effect could be induced.

The possibility of a "runaway" greenhouse effect has also been investigated; that is, could an initial injection of sublimate so increase the temperature that continued sublimation and greenhouse heating would spontaneously occur? This appears less likely for water vapor than for carbon dioxide. The latter could be maintained over the summer pole until the temperature rose several degrees; however, continued maintenance of the carbon dioxide in the global atmosphere for sufficient time to allow a new temperature steady-state to be established would be difficult.

Advective Heating

An additional factor which must be considered is advective heating; as the atmospheric mass increases, the amount of heat transported from low to high latitudes increases. The mean global temperature does not change but polar temperatures increase while equatorial temperatures decrease. In brief, there are two stable climatic regimes possible on Mars, given a carbon dioxide polar cap during the winter season. The present climate represents one of the stable regimes. The second stable regime exists at a polar surface winter temperature of 190 K and at a surface air pressure of approximately 1 bar. To attain this high temperature regime the surface pressure must be increased ten times. This might be brought about in a number of ways: by volatilizing gases bound in the regolith, by importing an atmosphere from outside the planet, or by increasing the effective solar flux over the polar cap by 20%. This last possibility could be realized if the polar cap albedo were reduced from the present 0.77 to 0.73. A relatively small admixture of sand or dust (albedo 0.25) spread over the cap would lower the cap's albedo by the required amount. If such increased solar absorbance were maintained for approximately a hundred years, advective instability could be triggered and a new high temperature climatic regime established. Carbon dioxide, although not efficient in increasing the global temperature by a greenhouse effect may provide polar heating by advection. Polar heating could cause the injection of increased amounts of water vapor into the atmosphere, which would provide for a stronger greenhouse effect. Thus the combined mechanisms of advective and greenhouse heating could be used to modify the Martian climate.

PROSPECTS FOR GENETIC ENGINEERING

Modification of the Martian climate by means of advective and greenhouse heating would increase enormously the area of the planet available for growth and would optimize the conditions under which such growth would occur. It is interesting to speculate upon the possibility of creating novel species of photosynthetic organisms far better adapted to growth in the present or modified Martian environment: in effect, transforming currently available "best fit" organisms into "ideal" organisms. Such genetic engineering is possible, utilizing methods of gene manipulation currently known or under development.

Research on bacteria and their viruses has yielded powerful tools for the manipulation of the genetic apparatus of cells. Genes determine the protein enzymes of cells and these (to a great extent) determine the physical characteristics of cells. Thus if a cell has a certain characteristic, for example, capability of rapid repair of ultraviolet radiation damage, it is due to the presence of a certain gene or of several genes. A cell which lacks such a rapid repair mechanism would lack this gene or genes. Today there are techniques for moving genes from donor organisms and inserting them into recipient organisms. Several of these techniques, that is, sexual recombination and DNA transformation, have been successfully applied in species of blue-green algae. Thus while no single species of blue-green algae may have all those characteristics defining an ideal Martian organism, they well might be found in several different species of algae – all utilizable as gene donors. Indeed, in principle, the entire gene pool of the Earth might be available for the construction of an ideally adapted oxygen-producing photosynthetic Martian organism. Continued advances in our understanding of gene structure and of methods for the synthesis of genes may lead to a potential for creating novel genes. These synthetic genes could then be integrated into a recipient "best fit" organism.

CONCLUSIONS

On the basis of currently available information the study concludes that:

1. No fundamental, insuperable limitation to the ability of Mars to support terrestrial life has been unequivocally identified. However, important data are not available, for example, the extent of water reserves and the composition of the polar caps. These data must be acquired before a more accurate assessment of the habitability of Mars can be made.
2. For human life to exist, the creation of an oxygen atmosphere is mandatory. Such an atmosphere might be generated by present terrestrial photosynthetic forms, but the time required may be in hundreds of thousands of years.
3. Climate modification leading to an increase in surface temperature might be carried out by a combination of advective and greenhouse effects initiated by the injection of polar cap sublimate into the atmosphere. This injection would need to be carried out for a long period of time at the total expenditure of amounts of energy equivalent to the total amount of solar energy incident on Mars over several years.
4. Mechanisms of genetic engineering currently available or under development could be used to construct organisms far better adapted to grow on Mars than any present terrestrial organisms.
5. Altering either the Martian environment or available photosynthetic organisms, or both, would significantly decrease the time required to create an acceptable human habitat on Mars. Indeed it may be mandatory to take these steps if Mars is to be made into a habitable planet.

3. STUDY APPROACH

The technological advances which have been achieved over the last three decades leave little doubt as to the feasibility of future planetary exploration within our solar system. While exploitation of the planets by man may seem remote, there is a distinct possibility that technological developments or the needs of society may make the utilization of Martian resources economically feasible or socially desirable. To exploit Mars more efficiently it may be necessary to establish permanent human communities on the planet. The question thus arises as to whether Mars is a habitable planet or can be made into one. This has been investigated by our group. Current data, assumptions, and speculations have been reviewed to determine whether there exists a fundamental, insuperable limitation to the prospect of Mars being inhabited by man. Examples of such a limitation would be: the absence of sufficient water or nitrogen reserves, an inability to increase intolerably low surface temperatures, or the presence of toxic chemicals in the atmosphere or soil. Failure to identify such factors may only reflect the present lack of sufficient information. The continued acquisition of data on the physics and chemistry of Mars will be necessary to clarify these and other crucial aspects of habitability. To assess the habitability of Mars the study participants posed and attempted to answer a series of questions:

1. Can contemporary terrestrial life grow on the present Martian surface?
2. If not, what are the constraints to growth and can these constraints be removed?
3. Can the Martian climate be modified to be more conducive to the growth of terrestrial organisms?
4. Can terrestrial organisms be genetically modified to be better adapted to the present or a modified Martian environment?

These questions have been arranged in a flow chart (fig. 1). This particular logic is only one of many that might be considered and, often, a clear-cut yes or no decision is impossible at this time. The study group's answers to these questions are based upon speculation, mathematical models and data generated by extensive literature review, group discussion, and conversations with invited speakers (chs. 4–8). These answers have, in turn, led to a number of conclusions (ch. 9).

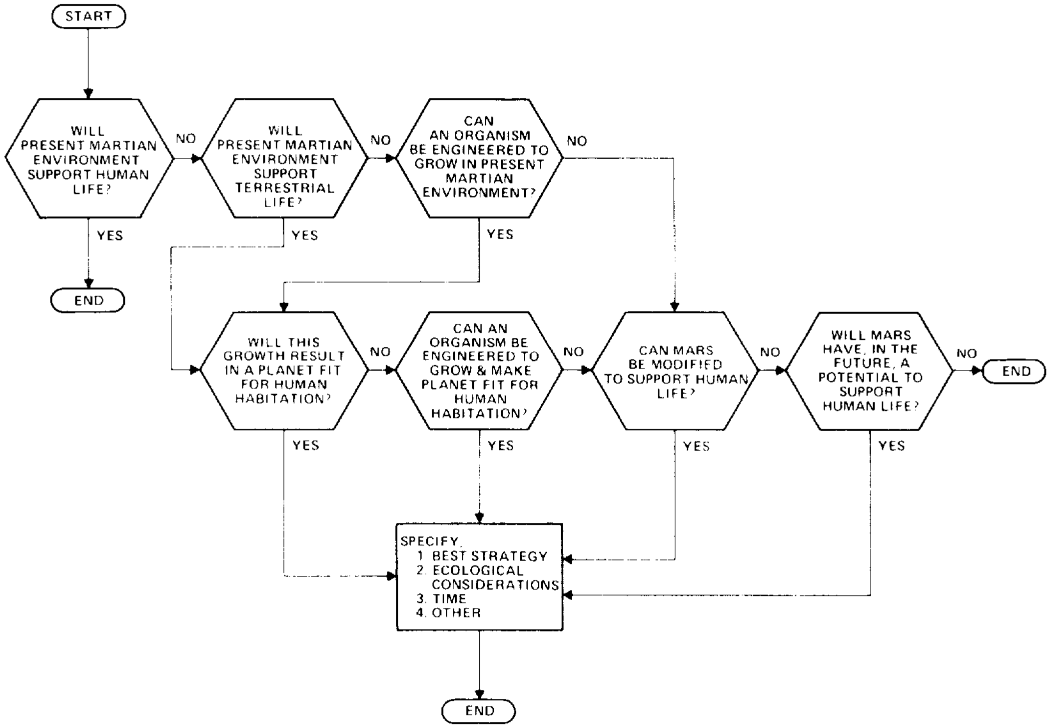


Figure 1.– Logic diagram of study.

4. PHYSICAL CHARACTERISTICS OF MARS

PHYSICAL AND CHEMICAL INVENTORY

To assess the potential of Mars for supporting life, an accurate idea of present conditions on the planet is needed. Table 3 provides an up-to-date summary of the major planetary, atmospheric, and surface parameters for both Earth and Mars. The data have been extracted from a variety of sources, both published and unpublished. The references are indicated beneath each table.

Table 3 reveals that Mars is a small, cold, dry planet with a thin atmosphere. The lack of an appreciable atmosphere with its shielding and moderating effects has led to a number of harsh surface features. These include a rough, cratered surface, strong winds organizing occasionally into global-scale duststorms, high ultraviolet flux at the ground, and large diurnal temperature excursions of the order of 100 K

TABLE 3.– PHYSICAL CHARACTERISTICS OF EARTH AND MARS

(a) Planetary and Orbital Parameters

Parameter	Earth	Mars
Mass, g	5.98×10^{27}	6.43×10^{26}
Mean density, g/cm^3	5.52	3.94
Mean radius, km	6371	3394
Surface gravity, cm/sec^2	981	373
Length of day, Earth-days	1	1.026
Length of year, Earth-days	365	687
Obliquity, deg	23.5	23.9
Orbital eccentricity	0.017	0.093
Mean distance from Sun, km	150×10^6	228×10^6
Solar constant, cal/cm^2/min	2.00	0.866
Planetary albedo	0.30–0.35	0.15–0.25
Effective temperature, K	253	216

Source of data: Goody and Walker (1972).

TABLE 3.– CONTINUED

(b) Atmospheric Parameters

Parameter	Earth	Mars
Atmospheric mass, g	5.3×10^{21}	2.4×10^{19}
Surface air pressure, mbar	1000	5
Surface air density, g/cm^3	1.2×10^{-3}	1.2×10^{-5}
Scale height, km	8.4	10.6
Adiabatic lapse rate, K/km	9.8	4.5
Average optical thickness	2	0.1[a]
Tropopause height, km	10	30?
Turbopause height, km	80	150

Sources of data: Goody and Walker (1972); Noll and McElroy (1974).

[a] Much higher in duststorms.

(c) Atmospheric Composition [% by volume]

Gas	Earth	Mars	
N_2	78	?	
O_2	20	0.1	
H_2O	1[a]	<0.1[a]	
Ar	0.93	1–25	} 99
CO_2	0.03	98–74	
CO	10^{-5}	0.1	
O_3	$< 10^{-5}$	$< 6 \times 10^{-5}$ [a]	

[a] Displays large variations with latitude and season.

Sources of data: McCormac (1971); Noll and McElroy (1974); Barth (1974); Levine (1975).

(d) Surface Winds

Typical wind speeds	Earth	Mars
2 cm above the surface,mps	0.5	5
2 cm above the surface,mps	5	50

Sources of data: Barth (1974); Noll and McElroy (1974); B. White (Univ. of Calif., Davis) (personal communication).

TABLE 3.– CONTINUED

(e) Average Solar Radiation Incident at the Surface (cal/cm^2/day)

Latitude, deg	Earth[a] Northern Hemisphere		Mars Northern Hemisphere	
	Summer	Winter	Summer	Winter
90 N	327?	0	320	0
45 N	520	112	315	100
0	380	419	250	365
45 S	99	513	100	450
90 S	0	341?	0	450

[a] Includes attenuation due to atmospheric turbidity and cloudiness.

Sources of data: Unpublished notes of H. H. Lettau (Univ. of Wisconsin) (Earth values); Levine, Kraemer, and Kuhn (1974) (Martian values).

(f) Average Ultraviolet Radiation Incident at the Surface (cal/cm^2/day)

UV Band	Earth	Mars
2000–3000 Å	≈ 0	10.6[a]

[a] This figure is equal to 6×10^3 erg/cm^2/sec.

Source of data: Nawrocki and Papa (1963).

(g) Average Surface Temperature, K

Latitude, deg	Earth[a] Northern Hemisphere		Mars Northern Hemisphere	
	Summer	Winter	Summer	Winter
90 N	279	235	185	145
45 N	289	261	220	175
0	297	297	200	240
45 S	279	287	162	265
90 S	226	263	145	200

Source of data: Crutcher (1969) (Earth values); Woiceshyn (1974); Conrath *et al.* (1973); Kliore *et al.* (1973); Hanel *et al.* (1972); (Mars values).

TABLE 3.– CONCLUDED

(h) Polar Cap Parameters

Parameter	Earth		Mars	
	NPC (Greenland)	SPC (Antarctica)	NPC	SPC
Latitudinal extent from pole:				
1. Northern Hemisphere winter, deg	---	---	60–90	88–90
2. Southern Hemisphere winter, deg	---	---	85–90	60–90
Percent of globe covered by cap:				
1. Northern Hemisphere winter, %	2.7	0.9	6.7	0.03
2. Southern Hemisphere summer, %	1.7	2.2	0.19	6.7
Average cap thickness, km:	1.5	2.5	1?	0.01?
Composition:	H_2O	H_2O	H_2O, CO_2?	H_2O, CO_2?

Sources of data: Bates (1964) (Earth); Woiceshyn (1974) (Mars).

(i) A Chemical Inventory (g/cm^2)

Species	Earth	Mars
CO_2 atmosphere:	0.3	15
crust:	10^5	$10-10^3$?
H_2O atmosphere:	2	0.01
crust:	10^6	$1-10^3$?
O_2 atmosphere:	200	0.01
crust:	10^7	?
N_2 atmosphere:	780	0.5 ?
crust:	10^2?	1–4 ?
O_3 atmosphere:	10^{-3}	2×10^{-7}

Sources of data: Barth (1974); Noll and McElroy (1974); Fanale and Cannon (1974); Sagan (1971); Ingersoll (1974).

(fig. 2). The Martian polar caps are intriguing surface features. They are believed to be mostly water ice with a thin carbon dioxide ice layer which sublimates during summer and redeposits during winter. The actual amount of water in the frozen remnants is unknown. The polar caps have been speculated to be an atmosphere in deep freeze which needs only to be thawed to initiate substantial greenhouse and advective effects. Because of this possibility, the polar regions have come under close scrutiny in recent years.

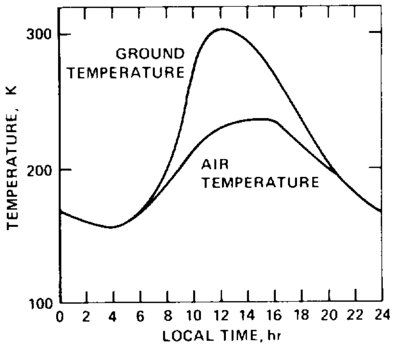


Figure 2.– Diurnal surface temperature for Mars; at the equator at equinox.

Although it is generally agreed that little water vapor exists in the Martian atmosphere, estimates of subsurface water vary widely. Based on assumed outgassing ratios, Levine (1975) suggests that as much as 3.5×10^{23} g may have been released from the planet's interior. The question of what happened to all this water remains unanswered. Fanale's suggestion (Fanale, 1975) that there may be huge underground lenses of ice or hard-frozen permafrost at high latitudes accounts for only 10–30% of Levine's estimate of water outgassed. Physical adsorption to the surface, chemically bound water, and polar cap remnants probably contain altogether no more than a few percent. The unsettled nature of the question of water on Mars reveals a serious gap in current knowledge, a gap that is especially significant when trying to project the fate of living terrestrial organisms implanted on the Martian surface.

SURFACE TEMPERATURE CLIMATOLOGY

Surface temperature is one of the crucial variables in determining success or failure of terrestrial organisms on Mars. Environmental temperatures outside a relatively narrow range, from approximately 273 K to 373 K, are detrimental to most known terrestrial organisms.

It is important to note that surface temperatures are of more concern than air temperatures, since oxygen-generating microorganisms, whose role in making Mars habitable is discussed more fully in later sections, will be in contact with, and thus controlled by, the environmental parameters at the surface. The surface temperature not only varies with latitude and season but has large diurnal variations because of the thin atmosphere. There is also a significant temperature discontinuity at the ground-air interface.

An insight to the magnitude of this discontinuity and the diurnal variations can be derived from figure 2 which is constructed from the data of Gierasch and Goody (1968), who developed a theoretical model of the Martian lower atmosphere consistent with the ground based observations of Martian surface temperatures by Sinton and Strong (1960) and Gifford (1956). Note that the air temperature variation is about 80 K, the maximum temperature being reached several hours after local noon, and the minimum in the early morning. The surface temperature variation is even larger, being some 140 K. The largest temperature discontinuity occurs at about local noon, the surface temperature being some 70 K higher than the adjacent air temperature. The size of the discontinuity depends directly on the amount of solar radiation reaching the surface. Thus, at latitude 45° N, during the winter, the difference between air and surface temperature is only about one-half the difference at the equator during equinox conditions. As one would expect, the difference between the surface temperature and the air temperature is greatest in low- and mid-latitude southern hemisphere summer when the amount of solar radiation reaching the surface is greatest.

The maximum and minimum daily temperatures as well as the number of hours per day above 273 K for several latitudes and seasons is shown in table 4. From these data one can estimate that during the Martian summer, and probably for about one-half the fall and spring seasons, the predicted temperatures would be above freezing about 25% of the time.

Despite certain ambiguities, the Mariner experiments have provided a wealth of data on the temperature structure of the Martian atmosphere. They also supply important data to check numerical models. The radio occultation experiments yield atmospheric temperatures near the surface but do not give actual surface temperatures. However, these can be determined from radiometer results. For example, the near-surface temperature determined from the Mariner 6 entry into occultation was 250 K at $15^{h}45^{m}$ Martian local time at 3.7° N. This measurement corresponds to northern hemisphere Martian fall, about one Earth-month after equinox passage. The radiometer reported a surface temperature of 269 to 279 K; a discontinuity of

TABLE 4.– DIURNAL TEMPERATURE EXTREMES ON MARS AND HOURS PER DAY ABOVE FREEZING FOR SELECTED LATITUDES AND SEASONS

[Temperatures in parentheses refer to a snow or frost covered surface]

Location (Northern Hemisphere)	Season	Maximum surface temperature, K	Minimum surface temperature, K	Hours above freezing
Equator	Equinox	295	155	6
Polar (75°)	Equinox	205 (175)	130 (145)	0
Mid-latitude	Summer	290	170	7
Mid-latitude	Winter	210 (183)	140 (145)	0

Source of data: Gierasch and Goody (1968).

about 25 K, which is reasonably close to the theoretical value of 35 K estimated from the study of Gierasch and Goody. Their calculated ground temperature corresponding to 15^h45^m local time is 270 K, very close to the radiometer results. During the exit of Mariner 6 from occultation, a near surface air temperature of 164 K was reported at latitude 79.3° N at 22^h10^m local time. A large temperature discontinuity would not be expected at the surface during this time and, indeed, Gierasch and Goody show a surface temperature of about 150 K. Thus, the surface and near-surface temperature data from Mariners 6 and 7 agree well with the modeling studies of Gierasch and Goody.

The Mariner 9 mission provided temperature data over a significant portion of the Martian year, from early northern hemisphere winter into the summer season. Unfortunately, the planet was obscured by dust during the early part of the mission so that temperature data during northern hemisphere winter may be atypical. For example, the surface temperature as deduced from radiometer data in the 10 μm region is some 30 K lower than predicted from the Mariner 6 and 7 thermal model. After apparent clearing of the dust, during late winter, the surface temperatures increased, but were still somewhat lower overall than predicted from the early Mariner data (Kieffer *et al.*, 1973). A comparison with the model of Gierasch and Goody is difficult since their results are not given for a late winter season. However, it is obvious that the Mariner 9 data are somewhat lower than those predicted in the modeling study and also lower than those obtained during the previous Mariner missions, especially in mid- and high-latitudes in the southern hemisphere (Kieffer *et al.*, 1973).

SURFACE ENERGY BUDGETS

As a result of the low Martian surface temperature reported from Mariner missions, it is natural to think of the possibility of increasing temperatures on the planet by changing the surface and atmospheric energy fluxes. For example, increasing the greenhouse effect (see footnote 1, page 63) might raise surface temperature by enhancing the atmosphere's emission of infrared radiation to the ground. Another proposal suggests augmenting the advective transfer of heat from equator to poles. Both suggestions would alter the planet's current energy balance. Before such proposals can be evaluated the nature of the surface energy balance must be understood.

Physically, temperature may be viewed as the thermal response of a given system to the net energy absorbed by (and net work done on) the system. An inventory of all energy inflows and outflows is called an energy budget. A schematic energy budget for the Martian surface is illustrated in figure 3. During the daytime, heat conduction and convection (G, H, and E) are usually flowing away from the

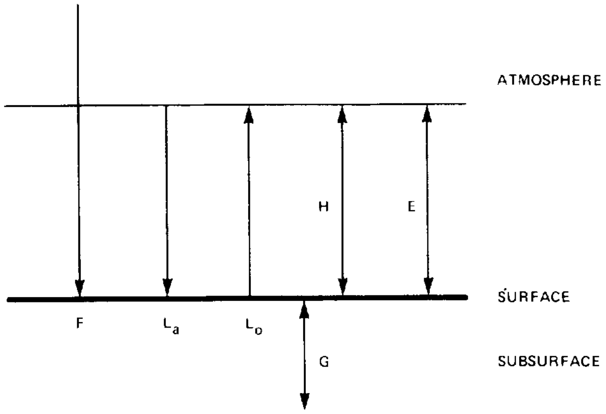


Figure 3.– Schematic energy budget for Martian surface; F = solar radiation from sun and sky absorbed by the surface; L_a = infrared (longwave) radiation from the atmosphere absorbed by the surface; L_o = infrared (longwave) radiation lost by the surface; $\pm G$ = subsurface heat conduction; $\pm H$ = sensible heat convection; $\pm E$ = latent heat convection.

surface (+). At night they usually flow toward the surface, but with less intensity (–). There are other minor components of the energy budget which have been neglected, such as geothermal heat from the planet's interior, heat released in volcanic action and marsquakes (if any), and heat lost at the surface in frictional dissipation by surface winds. All these energy sources are believed to be small enough to be neglected.

Assuming that the mean surface temperature remains constant for a year, conservation of energy requires that energy absorbed by the surface is equal to energy lost by the surface. Hence,

$$F + L_a - L_o = \pm G \pm H \pm E \tag{1}$$

To make use of (1) the terms must be estimated. The following relationships are used:

$$F = (1 - A)\,Q \tag{2}$$

where A = surface albedo, and Q = solar radiation (direct + diffuse) incident on the surface after having been attenuated by the atmosphere; values of Q for Earth and Mars are provided in table 3(e).

$$L_o = \epsilon \sigma T_o^{\,4} \tag{3}$$

where ϵ = surface emissivity (usually 0.9–1.0); σ = Stefan-Boltzmann constant ($=1.357 \times 10^{-12}$ ly/sec/K^4 = 5.67×10^{-5} erg/cm^2/sec/K^4) (1 Langley, ly = 1 cal/cm^2); and T_o = surface temperature (K). This is simply the Stefan-Boltzmann radiation law for a gray body.

$$L_a \approx KL \,, \tag{4}$$

where K is an empirically derived constant. This relation with a value of 0.73 holds remarkably well on Earth for annual averages. Table 5 shows the derivation of this value. Only near the equator, where water vapor emission becomes significant, does K deviate significantly from 0.73. But even there the percentage error is only 12%. Table 6 provides similar data for the Martian atmosphere based on radiation computations for a pure carbon dioxide atmosphere. A value of 0.12 to 0.15 seems appropriate for K for current Martian conditions; K is a measure of the strength of the greenhouse effect.

$$G = 0 \,, \tag{5}$$

over an annual period, and approximately zero over a diurnal period. This may not be true over oceans and large water bodies where currents can transport considerable heat energy from one region to another. However, this does not apply on Mars.

TABLE 5.– ESTIMATION OF K FOR EARTH, BASED ON OBSERVED RADIATION FLUXES

Latitude, deg (Northern Hemisphere)	L_a, kly[a]/yr	L_o, kly/yr	K, $=L_a/L_o$
80–90	117	160	0.73
70–80	135	190	.71
60–70	145	205	.71
50–60	155	220	.70
40–50	175	250	.70
30–40	185	260	.71
20–30	210	285	.74
10–20	245	310	.79
0–10	250	300	.83
			0.733 mean

[a] 1 langley, ly = 1 cal/cm^2

Source of data: Sellers (1965), figure 14, page 42.

TABLE 6.– ESTIMATION OF K FOR MARS, BASED ON THEORETICAL RADIATION MODEL

CO_2 partial pressure, mbar	L_a, ly/day	L_O, ly/day	K, $= L_a/L_O$
3.75	33.8	279	0.12
5.1	43.3	283	.15
9.0	48.2	286	.17
12.8	51.9	288	.18
16.7	54.8	290	.19
36.0	61.2	294	.21
159	79.4	303	.26
278	86.0	307	.28
397	90.8	309	.29

Source of data: Computer model developed by W. Kuhn (Univ. of Michigan).

H and E

are difficult to evaluate since both require knowledge of fine-scale atmospheric turbulence structure, or of bulk eddy transfer coefficients, neither of which is well determined in a simple way. Except possibly in polar regions, it is safe to set $E = 0$ for Mars on an annual basis. H can then be estimated as a residual, since all other terms in the energy budget can now be estimated with the above parameterizations.

As an application of the energy budget, annual energy fluxes on Mars are calculated for current conditions at three different latitudes. The results are presented in table 7 together with comparable data for Earth.

Table 7 reveals some interesting features. First, subsurface heat flux, while assumed zero on Mars, reaches appreciable values on Earth, particularly at the equator. Second, heat convection plays a small role in the energy balance of Mars, except at the pole where it reaches −36 ly/day, that is, transferred downward from atmosphere to surface. This is a large value, exceeding even the Earth's polar value by a factor of 1.3. Being the residual term, however, H is subject to large cumulative errors, and may only be qualitatively correct. Third, the magnitude of atmospheric radiation absorbed by the surface (L_a) is 17 to 26 times larger on Earth than Mars, and is an indication of the vastly more powerful greenhouse effect of Earth. Finally, the latent heat flux (E) term contributes significantly at lower and middle terrestrial latitudes, although assumed zero for Mars.

TABLE 7.– ANNUAL SURFACE ENERGY BUDGETS FOR EARTH AND MARS

Heat flux	Equator, ly/day		45° N, ly/day		North Pole, ly/day	
	Earth	Mars	Earth	Mars	Earth	Mars
F	427	248	337	168	93	40
L_a	682	39	479	27	320	12
L_o	821	281	685	192	438	88
G	60	0	−19	0	−6	0
H	30	6	46	3	−27	−36
E	198	0	104	0	8	0

Sources of data for Earth: Sellers (1965), table 16, page 103; figure 14, page 42.

Constants used in Mars energy budgets: $A = 0.25$ (for latitude 0° and 45°); $A = 0.75$ for North Pole; $\epsilon = 1.0$; $T_O = 220$ K, 200 K, 165 K for 0°, 45°, and North Pole, respectively; $K = 0.14$ for all latitudes.

This energy balance approach provides estimates of average fluxes. Flux variations with time can be explored by the method of "climatonomy" developed by H. Lettau at the University of Wisconsin and described in preliminary form by Lettau and Lettau (1969). The term "climatonomy" was coined to emphasize the quantitative approach to climatological problems.

The basic goal of thermal climatonomy is to predict surface temperature variations with time, $T_O(t)$, given the absorbed radiation at the surface as a function of time, $F(t)$. The method expresses $T_O(t)$ and the heat fluxes in the energy budget as Fourier cosine series with unspecified amplitudes and phase angles. By suitable parameterizations these constants can be determined and related to the unknown constants of $T_O(t)$. Full elaboration of the technique is lengthy and does not warrant a detailed account here. (The theory will be the subject of a forthcoming paper by C. R. Stearns of the University of Wisconsin.)

The following variables need to be specified for complete parameterization of the energy fluxes in the most general case:

A = surface albedo

B = Bowen ratio = H/E, if $E \neq 0$

c_p = specific heat of air

$\overline{F}$ = mean solar radiation absorbed on the surface for a given heating cycle

$\Delta \bar{F}$ = amplitude of $\bar{F}$

K = L_a/L_o

n = heating cycle frequency (e.g., annual or diurnal)

T_o = mean surface temperature over the heating cycle (this, however, can be generated by an iterated process starting with an initial guess of T_o)

$u*$ = surface friction velocity

z_o = surface roughness length

δ = phase angle of the heating cycle

ϵ = surface emissivity

μ = surface thermal admittance = $(\lambda C)^{1/2}$ (λ = molecular heat conductivity, and C = volumetric heat capacity of the submedium)

ρ = air density

The climatonomic approach has been used to derive annual surface temperatures and ranges for Mars. Two solutions were obtained. The first (solution I) was based on a machine computation for a planet without atmosphere, performed by C. R. Stearns at the University of Wisconsin, in which heat fluxes L_a, H, and E were all set equal to zero, and $\bar{T}_o$ was generated iteratively. The second (solution II) consisted of a first-order hand calculation carried out at Ames Research Center by S. Berman. Three selected latitudes in the northern hemisphere were analyzed using observed values of $\bar{T}_o$ taken from Mariner flybys and summarized in table 1(g). Also, a dry atmosphere was assumed, so that L_a and H were not zero quantities. In addition, the following variables were specified: $\mu = 0.014$ ly/deg/sec$^{1/2}$ for sand surface (assumed equatorward of 75° N and 75° S) and 0.007 ly/deg/sec$^{1/2}$ for snow surface (assumed poleward of 75° N and 75° S), $\rho = 1.26 \times 10^{-5}$ g/cm^3, $c_p = 0.822$ erg/g/K (for pure CO_2), $u* = 250$ cm/sec, and $z_o = 1$ cm.

Both solutions are summarized in table 8 below. A comparison of the two solutions shows good agreement at low and middle latitudes, considering the nature of the assumptions, but poor agreement at high latitudes. This is not surprising since strong radiative losses at the poles must be offset by equally strong atmospheric

TABLE 8.– ANNUAL SURFACE TEMPERATURES AND RANGES FOR MARS FROM CLIMATONOMY

Latitude, deg	Surface albedo	Solution I – (Stearns' program) (No atmosphere)		Solution II – (Berman) (Dry atmosphere)	
		T_O, K	Annual range, K	T_O, K	Annual range, K
90 N	0.75	103	149	165	44
75 N	.75	119	107	---	---
60 N	.20	184	111	---	---
45 N	.20	206	60	198	45
30 N	.20	219	30	---	---
15 N	.20	226	11	---	---
0	.20	228	22	220	19
15 S	.20	226	41	---	---
30 S	.20	220	64	---	---
45 S	.20	208	93	214	---
60 S	.20	188	141	---	---
75 S	.75	123	152	---	---
90 S	.75	108	186	173	---

fluxes (advection) to the surface. Consequently, solution II results appear to be more realistic in the polar regions. Solution I would be correct without an atmosphere.

First-order diurnal variations were also hand-calculated for three latitudes in the southern hemisphere in a manner similar to solution II above. No solution I diurnal variation results are available at the time of writing. The data are displayed below in table 9. The daily temperature range in table 9 is interpreted as the maximum minus the minimum. Thus, at 45° S on the day of the summer solstice, climatonomy predicts a high of 324 K and a low of 207 K. The upper value is about 20 K higher than reported from Mariner occultation experiments, and may be erroneous. The number of hours during the day that the surface temperature exceeds 270 K, a rough lower threshold for survival of terrestrial life, has been estimated assuming a sinusoidal temperature wave. Finally, these numbers have been extrapolated over a full Martian year by making the crude assumption that the equinox value applies for half the time and each solstice value applies for one-fourth the time. This yields 2164 annual hours in excess of 270 K at the equator and 1938 hr at 45° S.

In summary, surface temperature climatonomy predicts a difference in mean *annual* temperature from summer to winter of about 45 K in middle and polar

TABLE 9.– MARTIAN DIURNAL SURFACE TEMPERATURE VARIATIONS FROM CLIMATONOMY, ASSUMING A DRY ATMOSPHERE

Latitude, deg	Surface albedo	Observed T_0, K	Daily temperature range, K	Hours above 270 K
Case 1: Equinox				
0	0.2	220	117	4.2
45 S	.2	214	81	0
90 S	.75	173	0	0
Case 2: Southern hemisphere summer solstice				
0	.2	240	125	8.2
45 S	.2	265	117	11.3
90 S	.75	200	0	0
Case 3: Southern hemisphere winter solstice				
0	.2	200	97	0
45 S	.2	162	20	0
90 S	.75	145	0	0

latitudes, and about half this number at the equator. The *diurnal* range would be slightly over 100 K at the equator all year, and about the same for mid latitudes, except during winter solstice when the range would drop to 20 K. At the poles the diurnal range is always zero. About 2000 hr per Martian year were estimated to be above 270 K in the region from the equator to 45° S. There is general agreement when these results are compared with those of Gierasch and Goody (fig. 2). The major point of disagreement is the predicted summer temperature at latitude 45° S and the corresponding number of hours above freezing.

ULTRAVIOLET RADIATION

Electromagnetic radiation in the ultraviolet ($2000 < \lambda < 3000$Å) and vacuum ultraviolet ($\lambda < 2000$Å) portion of the spectrum constitutes a severe threat to living organisms. Nucleic acids and proteins strongly absorb ultraviolet radiation, particularly in the region of 2500–2900Å (Giese, 1964). Radiation in the vacuum ultraviolet generally produces energetic secondary photo electrons which transfer damaging energy to cells by collisions with molecular constituents (Alexander and Lett, 1967). Life on Earth is protected by atmospheric attenuation from the solar ultraviolet light incident upon the planet.

Attenuation of this radiation by the Martian atmosphere can be expressed in the form

$$I(\lambda,\Gamma) = I_s(\lambda)F_g(\Gamma)T(\lambda) \qquad (6)$$

Here $I_s(\lambda)$ is the spectral distribution of solar radiation incident upon the Martian atmosphere at mean distance from the Sun ($\bar{R}_M = 1.52\, AU = 1.52\, \bar{R}_E$); $F_g(\Gamma)$ is a geometrical factor ($\leqslant 1$) which is determined by the variables Γ (the instantaneous distance from the Sun R, the instantaneous latitude and longitude of the site θ, ϕ, and the Sun's instantaneous latitude and longitude, α, β, measured in a Martian coordinate system), and $T(\lambda)$ is the atmospheric transmission coefficient ($\leqslant 1$). Both $T(\lambda)$ and $F_g(\Gamma)$ are dimensionless, and $I_s(\lambda)$ is measured in units of ergs/cm^2/sec/Å, or in terms of ergs/cm^2/sec in a bandpass of a certain number of Ångstroms. A 50Å bandpass is used in the analysis when considered appropriate.

In the following sections, the spectral function $I_s(\lambda)$, the geometrical factor $F_g(\Gamma)$, and the transmission coefficient $T(\lambda)$, are described. It is concluded that while there is sufficient carbon dioxide (~80 μm atm) (Barth, 1974) in the Martian atmosphere to screen vacuum ultraviolet radiation effectively, the measured mean amount of ozone (5 μm atm) is about one order of magnitude too small to screen effectively the ultraviolet portion of the spectrum. Consequently, ultraviolet radiation constitutes a serious threat to terrestrial life forms.

Spectral Distribution of the Martian Solar Constant

The sun radiates with a spectral distribution similar to that of a black body at about 6000 K. However, in the ultraviolet and vacuum ultraviolet portion of the spectrum there are deviations from this behavior, and more precise data are required. The spectral distribution of solar intensity incident upon the Earth's atmosphere at mean distance from the Sun has been determined (Berkner and Marshall, 1965). These density values must be multiplied by:

$$\left(\frac{R_E}{R_M}\right)^2 = \left(\frac{1}{1.52}\right)^2 = 0.433 \qquad (7)$$

to be appropriate for mean Martian distance from the Sun.

These data have been used in constructing the mean values of solar intensities incident upon the Martian atmosphere in a 50Å bandpass as a function of wavelength (tables 10 and 11). In the vacuum ultraviolet portion of the spectrum the spectral distribution is not well approximated by a blackbody curve.

Estimates for the vacuum ultraviolet and ultraviolet solar constants for Mars are obtained from tables 10 and 11 in the forms

$$S_{\nu UV} \cong 80 \text{ ergs/cm}^2\text{/sec}, (1000\text{Å} < \lambda < 2000\text{Å})$$

$$S_{UV} \cong 7 \times 10^3 \text{ ergs/cm}^2\text{/sec}, (2000\text{Å} < \lambda < 3000\text{Å})$$

TABLE 10.– SOLAR VACUUM ULTRAVIOLET SPECTRAL DISTRIBUTION[a]

λ(Å)	$\bar{I}(\lambda)$	λ(Å)	$\bar{I}(\lambda)$
700	0.024	1350	0.11
750	.024	1400	.11
800	.026	1450	.22
850	.048	1500	.41
900	.11	1550	.74
950	.065	1600	1.40
1000	.078	1650	2.17
1050	.043	1700	3.55
1100	.026	1750	5.20
1150	.035	1800	8.23
1200	2.47	1850	12.1
1250	.065	1900	17.8
1300	.078	1950	23.8

[a] Values of $\bar{I}(\lambda)$ shown give the number of ergs/cm^2/sec in a 50Å bandpass centered at the indicated wavelength incident upon the Martian atmosphere at mean distance (1.52 AU) from the Sun.

TABLE 11.– SOLAR ULTRAVIOLET SPECTRAL DISTRIBUTION[a]

λ(Å)	$\bar{I}(\lambda)$	λ(Å)	$\bar{I}(\lambda)$
2000	30.3	2500	165
2050	39.0	2550	242
2100	62.8	2600	303
2150	104	2650	390
2200	134	2700	450
2250	152	2750	480
2300	156	2800	650
2350	139	2850	870
2400	147	2900	1080
2450	169	2950	1300

[a] See footnote (a) of table 8.

Since the total integrated Martian solar constant is

$$S_{\text{total}} \cong 6 \times 10^5 \text{ ergs/cm}^2\text{/sec}$$

only about 0.01% of the Sun's energy is in vacuum ultraviolet and about 1.0% in the ultraviolet region.

It is of considerable interest to note the relatively large spectral feature at about 1200Å in table 10, and to recognize that the intensity of radiation increases rapidly with increasing wavelength in the near ultraviolet spectrum, as indicated in table 11.

Geometrical Considerations

The geometrical factor $F_g(\Gamma)$ appearing in equation (6) can be written in the form

$$F_g(\Gamma) = (R_M/R_M)^2 \cos \Omega \tag{8}$$

where

$$(R_M/R_M) = (1 + e \cos \nu)/(1 - e^2) \tag{9}$$

with ν the true solar anomaly of the Sun (0–360°), $e = 0.093$ is the Martian orbital eccentricity, and Ω is the angle between the Sun's angular direction (α,β) and the site latitude and longitude (θ,ϕ).

Maximum and minimum values of $(\bar{R}_M/R_M)^2$ are obtained in the forms

$$(\bar{R}_M/R_M)^2{}_{\text{max}} = 1.22, \nu=0^\circ \qquad \text{(Northern winter)}$$

$$(\bar{R}_M/R_M)^2{}_{\text{min}} = 0.84, \nu= 180^\circ \quad \text{(Northern summer)}$$

Evidently, intensity variations of ∓20% about the mean are obtained as a consequence of the orbital eccentricity of Mars which produces significant variation in the Mars-Sun distance.

The factor $\cos \Omega$ varies from zero to one, and can be expressed in terms of site latitude and longitude and the Sun's angular position using the spherical harmonic addition theorem. It is perhaps more convenient to average the geometrical factor over a Martian day, so that it is a function of latitude and true anomaly only. This average geometrical factor $F_g(\theta,\nu)$ at the equator is approximately constant at $\cong 0.3$, whereas significant yearly variation is observed with increasing latitude in both hemispheres. It is only for latitudes greater than about 40° that the geometrical factor is less than approximately 0.1. A latitude of about 50° in the northern hemisphere is particularly favorable with respect to reduction in mean solar intensity.

Atmospheric Transmission

The transmission function can be written in the form

$$T(\lambda) = \prod_{i=1}^{\mu} T_i(\lambda) \tag{10}$$

where

$$T_i(\lambda) = \exp(-\sigma_i N_i) \tag{11}$$

and is the transmission function for the i^{th} molecular species, $\sigma(\lambda)$ is the molecular absorption cross section (cm^2), and N_i is the column density of the i^{th} species (cm^{-2}).

The absorption coefficient $k_i(\lambda)$(cm^{-1}) for O_2, H_2O, O_3, and CO_2, for $\lambda > 2200$Å, and the O_3 absorption coefficient in the 1800Å to 3000Å interval have been determined (Berkner and Marshall, 1965). These data can be converted to cross sections using

$$\sigma_i(\lambda) = k_i(\lambda)/N_o \tag{12}$$

where $N_o = 2.69 \mathrm{X} 10^{19}/\mathrm{cm}^3$ (Loschmidt's number).

The cross section $\sigma(\lambda)$ for molecular ozone has been constructed from these and additional available data (Griggs, 1968), and is tabulated in table 12. These data were used in constructing transmission functions for 1, 10, and 100 μm atm of ozone (tables 13 and 14). Evidently, at least 100 μm atm of ozone are needed to obtain significant absorption of vacuum ultraviolet and ultraviolet radiation.

TABLE 12.– MOLECULAR OZONE PHOTOABSORPTION CROSS SECTION[a]

λ(Å)	$\sigma(\lambda)$	λ(Å)	$\sigma(\lambda)$
1000	0.93	2000	0.030
1050	1.10	2050	.041
1100	1.30	2100	.052
1150	.75	2150	.12
1200	1.12	2200	.19
1250	.74	2250	.29
1300	1.50	2300	.42
1350	1.50	2350	.59
1400	.74	2400	.75
1450	.60	2450	.97
1500	.45	2500	1.02
1550	.30	2550	1.10
1600	.15	2600	.97
1650	.12	2650	.94
1700	.10	2700	.76
1750	.10	2750	.57
1800	.082	2800	.37
1850	.065	2850	.22
1900	.048	2900	.13
1950	.038	2950	.08

[a] $\delta(\lambda)\mathrm{X}10^{17}$ cm^2

TABLE 13.– VACUUM ULTRAVIOLET MOLECULAR OZONE TRANSMISSION FUNCTION

λ(Å)	1 μm atm	10 μm atm	100 μm atm
1000	0.98	0.78	0.082
1050	.97	.74	.052
1100	.97	.71	.030
1150	.98	.82	.13
1200	.97	.74	.049
1250	.98	.82	.14
1300	.96	.67	.018
1350	.96	.67	.018
1400	.98	.82	.14
1450	.98	.85	.20
1500	.49	.89	.30
1550	.99	.92	.45
1600	1.00	.96	.67
1650	1.00	.97	.72
1700	1.00	.97	.76
1750	1.00	.97	.76
1800	1.00	.98	.80
1850	1.00	.98	.84
1900	1.00	.99	.88
1950	1.00	.99	.90

TABLE 14.– ULTRAVIOLET MOLECULAR OZONE TRANSMISSION FUNCTION

λ(Å)	1 μm atm	10 μm atm	100 μm atm
2000	1.00	0.99	0.92
2050	1.00	.99	.90
2100	1.00	.99	.87
2150	1.00	.97	.72
2200	.99	.95	.60
2250	.99	.92	.46
2300	.99	.89	.32
2350	.98	.85	.21
2400	.98	.82	.13
2450	.97	.77	.074
2500	.97	.76	.064
2550	.97	.74	.052
2600	.97	.77	.074
2650	.98	.78	.080
2700	.98	.82	.13
2750	.98	.86	.22
2800	.99	.91	.37
2850	.99	.94	.55
2900	1.00	.97	.70
2950	1.00	.98	.81

Molecular carbon dioxide is completely transparent in the visible and near ultraviolet portion of the spectrum (Banks and Kockerts, 1973); the threshhold for photoabsorption occurs at about 2150Å. In table 15 the carbon dioxide photoabsorption cross section is tabulated for vacuum ultraviolet wavelengths. Since there are 80 m atm of carbon dioxide in the Martian atmosphere, the data of Table 15 and the absorption spectrum of CO_2 show that the carbon dioxide transmission function satisfies

$$T_{CO_2}(\lambda) = 0 \qquad \lambda \leqslant 1900Å$$

$$T_{CO_2}(\lambda) = 0.1 \qquad \lambda \cong 2000Å$$

$$T_{CO^2}(\lambda) = 1.0 \qquad \lambda \geqslant 2000Å$$

Consequently, the carbon dioxide in the Martian atmosphere is opaque to vacuum ultraviolet, but is transparent to ultraviolet radiation.

Upper limits on the amounts of various minor constituents in the Martian atmosphere have been determined (Owen and Sagan, 1972, Pimental *et al.*, 1972). These species generally have ultraviolet absorption cross sections much smaller than that of ozone, although a detailed search is recommended.

TABLE 15.– MOLECULAR CARBON DIOXIDE PHOTOABSORPTION CROSS SECTION[a]

λ(Å)	$\sigma(\lambda)$	λ(Å)	$\sigma(\lambda)$
1000	0.75	1500	0.050
1050	.74	1550	.075
1100	.74	1600	.069
1150	.74	1650	.036
1200	.0074	1700	.0022
1250	.010	1750	.00093
1300	.048	1800	10^{-4}
1350	.093	1850	10^{-4}
1400	.052	1900	10^{-5}
1450	.060	1950	10^{-6}

[a] $\sigma(\lambda) \times 10^{17}$ cm^2

Ultraviolet Intensity Estimates for the Martian Surface

It is evident from the previous data that the Martian atmosphere is opaque in the 1000Å to 2000Å region due to carbon dioxide photoabsorption. To estimate the intensity of ultraviolet on the Martian surface, the data of tables 11 and 14 have been combined with a geometrical factor of $\cong 0.3$ to obtain the data of table 16. Evidently, 100 μm atm of ozone is sufficient to attenuate the solar ultraviolet by approximately one order of magnitude in the 2400Å to 2700Å interval. The attenuation is significantly less in the 2700Å to 3000Å interval, and detailed action spectra for biological processes of interest will have to be employed in estimating ultraviolet damage. The total integrated intensity in the 2400Å to 2700Å interval is about 50 ergs/cm^2/sec. The total ultraviolet radiation intensity is 10^3 ergs/cm^2/sec, in the presence of 100 μm atm of ozone. Inasmuch as the maximum measured amount of Martian ozone is approximately 60 μm atm (Barth *et al.*, 1973), observed in the winter season at the polar cap, and in light of the fact that significant damage is observed in terrestrial organisms for an ultraviolet flux $> 10^3 - 10^4$/ergs/cm^2/sec, it is clear that useful radiation protection is presently afforded in the Martian polar

TABLE 16.– ULTRAVIOLET INTENSITY AT THE MARTIAN SURFACE

λ(Å)	1 μm atm O_3	10 μm atm O_3	100 μm atm O_3
2000	9.10	9.00	8.37
2050	11.7	11.6	10.5
2100	18.8	18.7	16.3
2150	31.2	30.3	22.5
2200	39.8	38.2	24.1
2250	45.1	42.0	20.9
2300	46.3	41.7	15.0
2350	40.9	35.4	8.76
2400	43.2	36.2	5.73
2450	49.2	39.0	3.75
2500	48.0	37.6	3.17
2550	70.4	53.7	3.78
2600	88.2	70.0	6.73
2650	115	91.3	9.36
2700	132	114	17.6
2750	141	124	31.7
2800	193	178	72.2
2850	258	245	144
2900	324	314	227
2950	390	382	316

[a] Values of ergs/cm^2/sec in 50Å band pass at indicated wavelength.

regions. However, a maximum value of 5 μm atm of ozone is more appropriate for lower latitudes, in which regions the radiation shielding provided is negligible.

A more detailed study of the ultraviolet absorption spectra of trace atmospheric species possibly present on Mars is recommended, as is a more careful study of the chemistry of the Martian atmosphere in order to provide estimates of abundance of trace compounds.

5. THE TRANSPLANTATION OF TERRESTRIAL ORGANISMS TO MARS

A MARTIAN ECOLOGY

Even a most optimistic appraisal suggests that the kinds of terrestrial organisms able to survive in the present Martian environment are quite limited, and the growth of even these forms would be quite restricted in vigor and extent (table 17). There have been many attempts to determine the response of microorganisms to simulated Martian environments. While conclusions have varied, in part a reflection of the experimenters' choice of organisms and environmental conditions, investigators feel

TABLE 17.– COMPARISON OF LIMITS TO LIFE WITH SELECTED MARTIAN ENVIRONMENTAL PARAMETERS

Parameter	Range compatible with life	Mars
Temperature	Growth: 255 K–377 K Survival: < 79 K–377 K	140 K–300 K
Ultraviolet irradiation	3×10^5 ergs/cm^2	7×10^3 ergs/cm^2/sec
Oxygen (pO_2)	0–100%	$\cong 0$
Liquid H_2O	10%–100% (w/w)	Present, amount unknown
Salinity	0%–35% NaCl	?
pH	0–13	?
Mechanical abrasion	Abrasive particles $\geqslant$ cell size will cause mechanical damage	Dust in storms $\cong$ 10–50 μm in size range of many microorganisms
Nitrogen	Absolute requirement	Not yet found
Sulfur	↓	Not yet found
Phosphorus		Not yet found
Carbon		CO, CO_2, 5 mbar
Oxygen		H_2O
Hydrogen		H_2O

that there is a possibility for growth on Mars of certain anaerobic, cold-adapted, terrestrial bacteria.

For the growth of higher terrestrial life forms, an oxygen-containing environment is mandatory. The need for an oxygen atmosphere derives from two functions of oxygen: it is required for the formation of ozone, the ultraviolet absorbing shield under which life exists, and for the metabolism of higher organisms which is absolutely dependent upon oxygen. There are in principle two ways by which gaseous oxygen can be produced: chemically, from water or other oxygen-containing compounds, or biologically, from water. It is generally believed that the present mass of terrestrial atmospheric oxygen was produced biologically, and that the bulk of the oxygen in the ancient primitive atmosphere was produced by green plant or algal photosynthesis as a later event after life had evolved. Thus photosynthesis is believed to have the capability of generating oxygen in amounts necessary to make Mars habitable for higher terrestrial organisms.

Photosynthesis can be considered as the fixing of carbon dioxide and water into a carbohydrate (starch) in the presence of visible light and living, chlorophyll-containing organisms. As a by-product of photosynthesis oxygen, derived from water, is produced. In principle, all the necessary physical (light) and chemical (carbon dioxide, water) elements for photosynthesis are available on Mars.

The major known barrier to the establishment of higher terrestrial life on Mars is the lack of an atmosphere containing usable levels of oxygen. A critical question is: "can terrestrial photosynthetic organisms be seeded on Mars, survive, grow and generate oxygen?"

Any attempt to establish terrestrial organisms on Mars raises many questions. Among them are:

What characteristics would be required of organisms in order for them to grow on Mars? Do any microorganisms which occur in terrestrial environments possess these characteristics? If so, do they have the metabolic capabilities to bring about desirable alterations in the Martian environment, for example, oxygen generation? Over how large an area on the Martian surface could useful microorganisms grow? Can the Martian environment be altered in order to permit the introduction of desirable microorganisms if the present environment is too hostile? What interval of time might be required before humans could inhabit the planet?

As noted earlier a number of experiments have been performed in which the growth of microorganisms in simulated Martian environments has been attempted. The most recent study of this type was performed by Foster (1973) using data obtained from Mariner 9. His results indicate that certain bacteria are capable of growing in the Martian environment if sufficient nutrients are provided. Such studies are valuable inasmuch as they indicate whether or not terrestrial forms of life can grow under a particular set of extreme conditions. However, in order to obtain some indication as to how terrestrial life might fare on Mars it is also desirable to study natural terrestrial environments which simulate the Martian environment as closely as possible. The terrestrial environments which appear most nearly to resemble the general Martian environment are the cold, dry valleys of Antarctica. These valleys, an area of several thousand square kilometers, have a mean annual air temperature of 248 K to 253 K. In summer the air temperature does not rise much higher than 273 K; however, the ground surface can reach 288 K or higher for a short period during the day. Liquid water is scarce and is the principal limiting factor for the growth of microorganisms. The relative humidity can be less than 45% and the water activity of the soil 0.45 or less.

There is a concentration of microorganisms around sources of water and a rapid thinning out in the locales of highest aridity (Horowitz *et al.*, 1972). According to Ugolini (1970) the most reliable source of soil moisture is the ice-cemented permafrost, provided it is within the maximum depth of thawing. This hard permafrost lies beneath the ground surface at depths ranging from a few centimeters to more than a meter. The moisture content of soils not covered by snow depends on the depth of the topmost permafrost below the soil surface. In areas where the ice-cemented layer is within 15 cm of the surface, some melting of the ice occurs in summer and moistens the overlaying soil. Liquid water moves upwards due to a high rate of evaporation and eventually enters the atmosphere. This loss of water to the atmosphere causes the permafrost to recede from the surface. Ugolini (1970) has shown that sodium chloride ions move upward in the soil even at temperatures which are continuously below freezing. The climatologic and pedologic factors are related to the amount of moisture in the Antarctic soils, which in turn determines the amount of life in the soils.

The dry valleys of Antarctica are extremely severe environments which appear to resemble the Martian environment in many respects. The Martian environment, however, is even more hostile. Although Mars presents serious constraints to the growth of terrestrial organisms, certain types might be capable of growth over a limited area of the planet's surface. The major obstacles to the growth of terrestrial organisms on Mars appear to be paucity of water, high flux of ultraviolet radiation, and rapid, extreme diurnal temperature variations. Factors as yet undetermined might also make dissemination of terrestrial organisms on Mars unsuccessful. The lack of subsurface ice fields close enough to the surface to be easily melted, a deficiency of elements essential to terrestrial life, or the presence of toxic compounds would further encumber attempts to establish terrestrial organisms on the planet.

The single most important limiting factor appears to be the lack of available water. At best the situation with respect to water on Mars may be analogous to that extant in the Antarctic dry valleys. As previously mentioned, certain observations have been interpreted as indicating the existence of subsurface water ice fields or permafrost on Mars (Fanale and Cannon, 1974), as is the case for the dry valleys of Antarctica. To cause melting of enough ice to moisten the soil over large areas of the planet, a general warming will have to be achieved. The amount of warming needed to melt the subsurface ice depends on the depth of the frozen water.

As previously discussed, the flux of ultraviolet light incident on Mars would be lethal to exposed terrestrial organisms. Cyanophytes (blue-green algae) seeded on Mars will need protection from this radiation until a sufficient amount of shielding ozone is produced from the oxygen they generate. Protection of the organisms against ultraviolet radiation might be afforded by various endogenous or exogenous mechanisms. The former might be accomplished by means of more efficient mechanisms of repairing genetic damage, "overproduction" of purine or pyrimidine bases, or other ultraviolet absorbing pigments. If purines or pyrimidines were excreted and entrapped by the sheaths of the organisms, considerable reduction of the ≅2600Å radiation could occur. Exogenous protection might be achieved by the growth of algal populations under thin layers of translucent soil. The overlying soil would not only protect the cyanophytes from ultraviolet radiation, but probably also would retard desiccation. The thickness of the soil layer would be critical; sufficient visible radiation must be transmitted to permit photosynthesis, but at the same time the intensity of 2600Å radiation must be greatly reduced.

Sagan and Pollack (1974) suggest that the ultraviolet flux about 0.8 cm below the Martian surface has been reduced to 1.7×10^{-3} ergs/cm^2/sec while the flux of visible light is 3.8×10^2 ergs/cm^2/sec. Thus subsoil growth might provide adequate protection from ultraviolet radiation while still supporting photosynthesis. While the organisms introduced on Mars must have highly efficient DNA repair mechanisms, the importance of effective shielding, either exogenous or endogenous is emphasized.

LICHENS AS POSSIBLE MARTIAN BIOTA

Lichens must be examined as possible candidates for "seeding" of Mars because they possess certain attributes which are requisite to the survival of any terrestrial life under the currently envisioned Martian environmental conditions. Consequently, certain of their characteristics with respect to these extreme requirements are examined. Lichens are, in essence, composites of fungal- (mycobiont) and algal- (phycobiont) cells, which live in a symbiotic relationship. The two types of cells growing together develop a "body" or thallus, which is not characteristic of the independent growth of either component separately.

Terrestrial lichen genera are classed under three broad categories on the basis of their general morphologies (Jahns, 1973).

The crustose lichens may be considered the most "primitive" or the least differentiated form. They grow in intimate contact with their substrates and are often "inseparable" from them. The mycilia of the mycobiont spread over the colonized surface in a thin filamentous mat which encloses the algae. The algal cells generally occupy the upper part of the thallus, the surface layers of which form a cortex, composed of necrotic, gelatinized cells. This type of lichen can grow completely within the substrate as, for example, the endolithic lichens which grow inside rocks. The fungal hyphae of these organisms excrete "lichen substances" which can dissolve stone and allow the penetration of the fungi and algae to depths of several millimeters (Sayers and Iskander, 1973).

An intermediate, more differentiated lichen is termed folicose. Folicose lichens consist of thalli which are formed by flattened lobes. They may be platelike, and are attached by a central discoid holdfast or umbilicus.

The fructicose group is the most highly differentiated lichen-type. They consist of strap-shaped or threadlike lobes with a radial thallus. Some fructicose lichens may degenerate at the base and become completely free. They may also be dislodged by the wind and blown over the ground.

All three types, as well as gradations between types, are found intermixed in the terrestrial environment. Furthermore, the properties which are subsequently discussed are common to most lichens regardless of their growth form.

The mechanisms which regulate and control growth in lichens are mostly unknown (Jahns, 1973). Growth is usually restricted to the tip of the thallus and rarely exceeds a few centimeters radial increase per year (Richardson, 1973). There is negligible intercalary growth, and the inner parts of the thallus have no means of transporting photosynthetic products to the growing outer portions (unlike higher vascular plants). Therefore, only the photosynthetic products of the marginal parts of the lichen thallus can be used for the growth process.

Lichens are extremely tolerant to a lack of water. The minimum water contents which lichen thalli can sustain and still remain viable after rehydration is between 2 and 9% of the dry weight. Water seems to be tightly bound to the cytoplasm (Kappen, 1973). The ability of lichens to withstand desiccation is not indicative of a capability to resist the effects of drastic water loss. Lichens tend to rapidly achieve water potential equilibrium with their surroundings.

A number of isolated observations serve to illustrate the ability of these organisms to tolerate drought. Several species were kept dry for 1.5 years in permanent light and then for another 1.5 years in permanent darkness. After 8 days of cultivation on agar medium, these specimens produced aplanospores (reproductive spores) (Rao and LeBlanc, 1966). Investigations indicate, however, that there can be a loss of drought tolerance in several species due to long periods of moist cultivation. The measurement of photosynthesis in lichens under desiccation stress has been shown to be variable among species. There is a general tendancy toward depression of photosynthetic rates with drought (Kappen, 1973). Various species have been observed to adapt themselves to extended periods of desiccation. Antarctic lichens, for example, have regained full photosynthetic capacity after several weeks of drying. The ability to regain viability upon rehydration is enhanced by storage at lower humidities (Bacquerel, 1948). There seem to be several observable effects of desiccation upon metabolic processes; many lichens metabolize actively with low water contents; most show active growth without the uptake (imbibition) of liquid water (Butin, 1954). Photosynthesis is generally active at higher water potentials (higher water contents) but has a steeper gradient of increase than does respiration as the air humidity increases (Lange, 1969). For some species water vapor uptake may be more profitable for photosynthetic gain than is strong uptake of liquid water because respiration seems to be higher than photosynthesis in the latter case (Buttner, 1971). Many lichens are thus able to photosynthesize by means of dew-water condensation in the thallus and by vapor water intake. Many lichens are also halophilic, since very low osmotic potentials (−115 atm), induced by salt incrustation, do not drastically reduce the viability of coastal species.

These observations demonstrate that lichens can be resistant to long periods of desiccation; they can fully regain their ability to photosynthesize and respire upon rehydration. There is, however, a caveat to the use of present terrestrial forms for Martian colonization. Even the most drought-tolerant lichens appear to need a relatively high water potential in order to reactivate their photosynthesis. Areas where air moisture rarely exceeds 75% may be hostile for lichens (Kappen, 1973).

A number of lichens have shown favorable responses to extremely low temperatures and freezing. The tolerance appears to increase with drying. For example, three species, after cooling to 77 K, showed normal carbon dioxide uptake almost immediately after rewetting at 283 K, and remained active for several weeks thereafter (Kappen, 1973). They have been shown to photosynthesize well, below 273 K. Lange (1969), for example, recorded photosynthesis at 268 K proceeding at 50% of the maximum rate. Lange and Metzner (1965) observed photosynthetic fixation of 14 carbon dioxide at 262 K in several species. Biosynthesis of chlorophylls and β-carotenes at 266 K have been observed (Godnev *et al.*, 1966).

The response of lichens to visible and ultraviolet radiation is also an important environmental parameter to be considered; lichens show some favorable characteristics. The exposure of various terrestrial lichens to high intensity visible radiation results in variable effects. A common observation is that the phycobionts have a tendency to "bleach," or lose color, when exposed to full summer sunlight. It has also been suggested that illumination may be a factor in determining the endolithic habitats of certain lichens. Pigmentation of the lichen thallus has been observed, and is suggested as a possible response (defense) of lichens to strong illumination. For example, different colored thalli were observed in the same lichen species in response to a variation in light intensity within the habitat. The observed high tolerance of several species to ultraviolet radiation is of particular interest. Lichens have been reported as having an extraordinary ability to withstand intensive ultraviolet radiation. The continuous exposure of at least one species to radiation of 2537Å at 2.5×10^6 ergs/cm^2/min for 24 hr resulted in no observable effect upon respiration (Siegel and Daly, 1968). The basis for this resistance was not explained. Although molecular repair mechanisms for damage by ultraviolet radiation, such as those present in some bacteria, have not been investigated, it is possible that lichens may derive all or most of their increased tolerance from morphological adaptations. A thickened cortex (upper layer), for example, has been observed in organisms which were exposed to intense visible and ultraviolet illumination.

Additionally, certain species live on quartz blocks and sand where the medulla (normally the middle or central region of the lichen thallus) forms the upper surface (usually formed by the cortex layer). This surface consists of black, short, filamentous hyphae which become interspersed with grains of quartz, lime, or the like. The phycobiont layer remains underneath and pressed closely to this quartz surface, which in turn acts in place of a cortex layer. Such a protective device could easily screen out harmful wavelengths and provide the lichen with an excellent defense against excessive ultraviolet radiation.

In view of the fact that the lack of water may impose a severe limitation upon terrestrial organisms on Mars, it is instructive to summarize some of the absorptive water relation properties of lichens. As was stated, water loss is a rapid and relatively uncontrolled process under environmental conditions of extreme drought. On the other hand, water adsorption by a dry thallus is also rapid being similar to water uptake by a hydrophilic gel. Lichens can function by absorbing water vapor, although a major portion of water is probably only gained in this fashion from atmospheres in which the relative humidity exceeds 90% (Blum, 1973). It has been demonstrated that air-dried thalli in a latent state can become reactivated and reach photosynthetic rates close to optimal values. It appears that the algal member of the symbiosis derives protection from its fungal partner, which provides a buffer to rapid changes in humidity (Quispel, 1959). It is known that blue-green algal phycobionts can hold large amounts of water in their thick gelatinous sheaths. Furthermore, some lichen forms have "xeromorphous" structures such as a thick and solid cortex or cortical hairs (Blum, 1973). The final determination of viability is made by the resistance to irreversible damage of cell structures, which are associated with vital biochemical functions during the desiccation-rehydration cycle.

The principal task of any organism used to colonize Mars is to enrich the atmosphere in oxygen. It is therefore necessary to examine some of the important factors which might influence photosynthetic production in lichens, as well as to elucidate some quantitative aspects of the process. Various maximum net rates of carbon dioxide fixation have been noted by different investigators. Reid (1960) gave a range for the maximum net photosynthetic rate as 0.34–3.2 mg $CO_2/50\ cm^2$ surface area covered/hr. Similarly, optimal rates for some alpine species are listed as 0.30–0.38 mg CO_2/gm dry wt/hr (Bliss & Handley, 1964).

The moisture content may have an appreciable influence upon photosynthesis. Lange (1969) found that net photosynthesis of desiccated thalli increased rapidly with hydration up to about 60% saturation (i.e., 60 mg water per 100 mg dry wt) in one species. The hydration compensation point occurred at 20% of the water holding capacity at 283 K and 10,000 lux (~2.5 ly/min). Adaptive responses to environmental conditions which limit the process have been observed. Lichens isolated from open habitats in the Canadian Arctic, for example, had a maximum net photosynthetic rate at 30% saturation, which fell slowly as the water content dropped to 10% (Kershaw and Rouse, 1971). Below a critical moisture content lichens assume a state of suspended animation during which there is no measurable carbon assimilation and respiration is extremely low.

The amount of water required for minimum photosynthesis varies considerably among species. Lange (1969) found that two lichen species, which were moistened nightly by dew condensation, photosynthesized for 3 hr after sunrise, and then dried, crossing the compensation point (carbon dioxide emitted for a short period). No carbon dioxide was detected for the rest of the day until the thalli became moistened again at night. The carbon dioxide balance averaged 0.54 mg CO_2/g dry wt fixed over 24 hr. Lange (1970) emphasized the fact that the annual photosynthetic gain in certain lichens would allow for a thallus growth of 5–10%, which could be attributed almost exclusively to dewfall.

The effect of light intensity upon photosynthetic rate, although obvious, seems to be variable with species. Light saturation values tend to be relatively high. Lange (1969) found that a desert lichen reached light saturation at 20,000 lux (~5 ly/min) at 275 K. Despite the fact that the light compensation point of lichens is a function of temperature, the variation and the magnitude of these points at temperatures near 273 K are small. Light compensation points have been shown to remain in the range of 200–300 lux (~0.05–0.075 ly/min) between 268 and 275 K. These effects are most probably due to an increase in the respiration rate of the fungus at higher temperatures.

In summary, some of the important features of lichens which are pertinent to their evaluation for Martian colonization or planetary engineering are summarized.

1. Resistance to long periods and cycles of desiccation, particularly at low temperatures (shows dormancy).
2. Relative ease of both water loss and water imbibition by the thallus.

3. Requirement for liquid water or an atmosphere of high relative humitidy (>90%) for rehydration of the desiccated thallus.
4. Ability to retain a near maximum photosynthetic activity in the hydration phase of the desiccation-rehydration cycle, and adaptation to such conditions.
5. Ability to show net photosynthesis while sustaining a major water loss, although rates decrease with increased desiccation.
6. Ability to sustain net photosynthesis at temperatures as low as 260 K.
7. Reproduction by means of spores which are resistant to environmental extremes and are disseminated easily.
8. Tolerance to high levels of ultraviolet radiation.
9. Extremely slow growth rates.
10. Low photosynthetic light compensation points at low temperatures.
11. Ability to degrade or weather stone substrates.
12. Low rate of respiration under conditions which prohibit photosynthesis.
13. Existence of halophilic forms.

A major omission in experiments dealing with the adaptation of lichens to environmental extremes is concerning the ability of these organisms to survive and grow under anaerobic conditions. Data on this property are most important to the evaluation of lichens for use in Martian atmospheric alteration programs.

CYANOPHYTES AS POSSIBLE MARTIAN BIOTA

The group of organisms which appear to have the greatest potential as oxygenic photosynthesizers on Mars are the cyanophytes (blue-green algae). As a group they are versatile in their physiology and display considerable latitude in their environmental tolerances. Table 18 summarizes the observed environmental extremes for growth and survival of the cyanophytes (also see pages 77 and 78). Their ability to grow or survive in hostile environments and carry out oxygen-evolving photosynthesis suggests that this group of microorganisms should be considered for primary dissemination on Mars. The wide distribution of cyanophytes on the Earth is a reflection of their ecological tolerance and versatile physiology. Cyanophytes are important as primary colonizers on Earth because they are able to grow in environments which are too austere for other organisms, and because their physiological activities bring about conditions which are conducive to the growth of other soil organisms. These activities result in an increase in the humus and combined nitrogen of the soil. A gelatinous sheath aids in binding soil particles which helps to maintain soil moisture and prevent erosion. Cyanophytes also produce substances which stimulate the growth of vascular plants. Several genera of cyanophytes have been identified in polar regions. Holm-Hansen (1963) described mats of *Nostoc* 10–15 cm in depth on top of alkaline marble areas on Ross Island, South Victoria

TABLE 18.– OBSERVED ENVIRONMENTAL EXTREMES FOR GROWTH AND SURVIVAL OF BLUE-GREEN ALGAE

	Lower limit	Upper limit
Temperature (survival)	4 K[e]	373 K (dry soil)[g] 363 K (wet soil)[g]
Phototrophic metabolism	264 K (Saline Lake, U.S.S.R.) 243 K (lichens)[d]	346 K (neutral and alkaline hot springs)[c]
Hydrogen-ion concentration (growth)	pH 4.0[c]	pH 10-11 pH 13 (*plectonema* on silica)[h]
Oxidation potential (growth)	Eh: −200 mv (pH 6) −184 mv (*aphanocapsa thermalis*) (pH range 1.2–6.6)	Eh: +700 mv (pH 4) +670 mv
Total salinity (growth)	Freshwater (0.001%)	27.5% (Great Salt Lake)[b] 31.5% (Dead Sea)[b]
Altitude (growth)	0.396 km below sea level (Dead Sea)[b]	>5.2 km above sea level (Himalaya Mts.)
Resistance to aridity and desiccation	*Schizothrix* and *Anacystis* found at Atacama Desert, Chile Nostoc revived after 107 years of storage as a dried herbarium specimen[e]	
Resistance to ionizing radiation	Some blue-green algae survived more than 10^6 rads of γ-irradiation when administered at dose rates of about $2X10^5$ r hr^{-1}[f] *Microcoleus* survived 2560 kr γ-irradiation from Co^{60} source	

[a] Table modified from Schopf (1974). Data adopted directly from Schopf unless otherwise indicated

[b] Brock, T. D. (1969)

[c] Brock, T. D. (1973)

[d] James, P. F. (1955)

[e] Cameron, R. E. (1963)

[f] Godward, M. B. E. (1962)

[g] Lund, J. W. G. (1962)

[h] Vallentyne, J. R. (1963)

[i] Stewart, W. D. P. and H. W. Pearson (1970)

Land. Fogg (1973) found that a distinct zone of cyanophytes was often present about 2 mm below the surface of white quartzite sands on the coasts of the Falkland Islands. He also reports that abundant and healthy growths of cyanophytes have been observed just below the sand surface on areas of the west coast of Scotland. Apparently enough light penetrates between the sand particles to allow photosynthetic growth.

Cyanophytes are able to survive desiccation for long periods of time. In some regions where arid conditions alternate with moist conditions the algae are inactive while water is unavailable, but when the soil again becomes moist, extensive growth appears in a short time. Cyanophytes readily become established on lava which is devoid of other growing organisms, those species which are able to fix elemental nitrogen being especially suited for growth on such material. The ability to fix elemental nitrogen coupled with photolithotrophy confers on these latter species extremely simple nutritional requirements.

All of the cyanophytes are phototrophs which utilize carbon dioxide either exclusively or almost exclusively as their source of cellular carbon. An absolute requirement for organic carbon has been demonstrated in only a small number of marine cyanophytes, and these species all appear to require vitamin B_{12} (Pinter and Provasoli, 1958; Van Baalen, 1961). Many cyanophytes are able to assimilate organic compounds, and in some cases to grow in the dark. Van Baalen *et al.* (1971) have shown that certain organic compounds are able to stimulate growth at light intensities which barely support photosynthetic growth (1.4×10^4 ergs/cm^2/sec). Although cyanophytes are capable of photosynthesis in the presence of oxygen, a reduction in oxygen concentration stimulates carbon dioxide fixation. Stewart and Pearson (1970) demonstrated the photosynthetic growth of *Anabaena flos-aquae* under conditions of anaerobiosis (see also Weller *et al.*, 1975). Notwithstanding the tolerance of blue-green algae to diversified environments, it does not appear likely that they could grow extensively even in the areas on Mars where the most moderate climatic conditions prevail. This conclusion is supported by the observations of Horowitz *et al.*, on the soil biology of the dry valleys of Antarctica (Horowitz *et al.*, 1972). These investigators express the view that the viable organisms, including cyanophytes, isolated from the most arid parts of these valleys do not constitute a population attuned to growth in the prevailing environment. Furthermore, they present data indicating that much of the soil in the valleys is sterile (20% of 328 soil samples were sterile as examined by plate count). It should again be emphasized that the dry valleys represent a much less hostile environment than appears to exist in even the most temperate regions of Mars.

The subsurface habitat assumes a movement of liquid water from the melting permafrost into the overlying soil. This movement of water would carry water-soluble salts toward the surface. Moistening of the soil would also reduce the amount of dust entering the air due to wind action, thereby permitting more radiant energy to reach the surface of the planet.

BIOLOGICAL CYCLING OF ELEMENTS ON MARS

In a closed system, recycling of the chemical elements essential to life must occur. On Earth, biogeochemical cycles circulate these elements from the inorganic, inanimate form into organic, protoplasmic combinations and then back again. The net result of these cycles is to maintain a steady-state equilibrium for such biologically important molecules as nitrogen, sulfur, oxygen, and carbon (figs. 4 and 5).

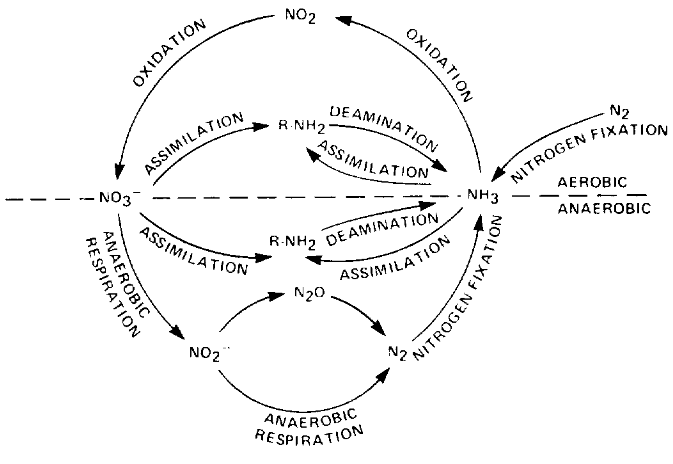


Figure 4.– The biological nitrogen cycle.

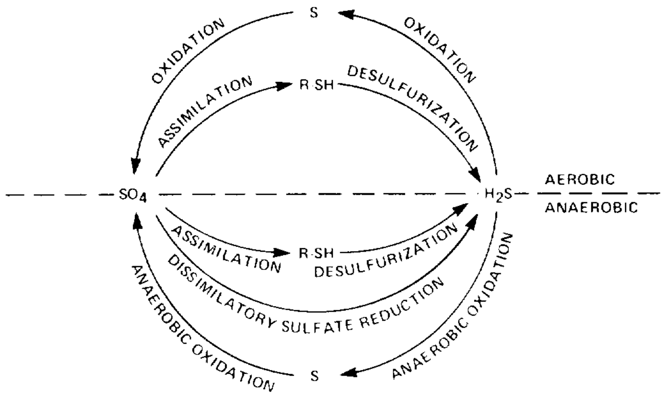


Figure 5.– The biological sulfur cycle.

For example, the removal of carbon dioxide from the atmosphere by photosynthesis is balanced by the efflux of carbon dioxide produced by respiration:

$$\begin{tikzcd}
CO_2 + H_2O \arrow[r, bend left, "\text{Photosynthesis}"] & C(H_2O) + O_2 \arrow[l, bend left, "\text{Respiration}"]
\end{tikzcd}$$

Key to the transformation of these elements from one form to another are microbes. On the Earth most soils contain a large number of microorganisms (bacteria, protozoa, and fungi). Their metabolic activity results in the modification of organic and inorganic compounds which is essential for making biologically important elements available. It is through the complex interaction of numerous higher and lower life forms, guided by many environmental factors, that raw materials do not continually flow into reservoirs of unusable compounds, but are broken down to simpler inorganic forms and thus made available for the continued growth of organisms.

If cyanophytes alone were to be introduced to Mars, their metabolic activity would cause the accumulation of organic matter containing carbon, nitrogen, sulfur, phosphorus, oxygen, and hydrogen. It would be most desirable to prevent such a one-way flow of these elements into nonusable, high molecular weight organic compounds by establishing biogeochemical cycles. The biological cycling of elements on Earth depends upon the presence of oxygen (figs. 4 and 5). The lack of oxygen on Mars, as well as the goal of building an oxygen-containing atmosphere as quickly as possible, demands the creation of biological cycles which *do not* utilize free molecular oxygen. Such cycles do not appear to occur on Earth, probably because of the physiological limitations of the numerous organisms involved in the cycling of elements.

While not minimizing the enormous complexity of designing a planet-wide, efficient, steady-state microbial ecology, particularly one not requiring oxygen, this task does not seem to be insuperable. Reasonable recycling schemes do exist, at least in principle. The overall effect of the massive anaerobic growth of a photosynthetic organism, such as a cyanophyte, on Mars would result in the generation of large amounts of nitrogen, sulfur, and phosphorus-containing organic compounds at the expense of carbon dioxide, inorganic nitrogen, sulfur, phosphorus and water:

$$CO_2 + NO_3^- + SO_4^= + PO_4^\equiv + H_2O \xrightarrow{h\nu} C(H_2O) + R\text{-}NH_2 + R\text{-}SH + R\text{-}PO_4 + O_2$$

where $C(H_2O)$ represents carbohydrate, $R\text{-}NH_2$ represents nitrogen-containing organic compounds, etc. The task is to reverse this flow *without* utilizing molecular oxygen:

$$C(H_2O) + R\text{-}NH_2 + R\text{-}SH + R\text{-}PO_4 \rightarrow CO_2 + H_2O + NO_3^- + SO_4^= + PO_4^\equiv$$

The complete cycling of carbohydrate on Earth depends upon a series of oxygen utilizing reactions called aerobic respiration. As a consequence of these reactions carbon dioxide and water are liberated. In anaerobic environments, much of the organic material remains and is not oxidized to carbon dioxide. There are, however, microorganisms that can oxidize carbohydrates to CO_2 utilizing nitrate instead of O_2:

$$C(H_2O) + NO_3^- \rightarrow CO_2 + H_2O + (NO_2^-, N_2O, N_2).$$

Most of the organisms that can carry out NO_3^--mediated anaerobic respiration *will* utilize oxygen if it is present. Thus the recycling of carbohydrate on Mars by anaerobic respiration would necessitate the synthesis or discovery of strains unable to use oxygen for respiration but still capable of using NO_3^-.

The movement of nitrogen through the biosphere is quite complex (fig. 4). Inorganic nitrogen either in the form of NH_4^+, derived from atmospheric nitrogen by the biochemical process of nitrogen fixation, or NO_3^- is assimilated by organisms into organic nitrogen compounds. The organic nitrogen is released in the form of NH_4^+ by the biochemical process of deamination. The released NH_4^+ is transformed into NO_3^- by various aerobic microbes and re-utilized in the synthesis of cell materials. As mentioned above, NO_3^- is transformed into N_2 by anaerobic respiration. The release of nitrogen from the organic compounds produced by cyanophytes on Mars could be carried out by enzymes released by the dead cyanophytes themselves (autolysis), or by a second, nonphotosynthetic deaminating organism seeded for this purpose. On Earth deamination is accomplished biologically in anaerobic environments by bacteria such as the Clostridia. The microbial transformation of NH_4^+ to NO_3^- is, on Earth, an aerobic process. The constraints to the use of aerobic processes referred to in the discussion of carbohydrate recycling suggest that alternate mechanisms must be found; NH_4^+ at high concentrations can be toxic. The utilization of NH_4^+ for cyanophyte growth, however, might maintain tolerable NH_4^+ concentrations. The residual nitrogen-free organic compounds could be further decomposed to carbon dioxide by either the anaerobic respiring organisms or the deaminating organisms (fermentation). Some cyanophytes have been shown to assimilate certain organic compounds under conditions of low light intensity. Although such assimilation generally does not lead to growth, it would help in cycling organic compounds and in supporting growth at very low light intensities.

The biological cycling of sulfur on Earth is outlined in figure 5. Sulfate, the form of sulfur that cells assimilate, is incorporated into organic compounds. Upon the death of the cell, the sulfur is released by various putrefactive decomposing organisms in the form of hydrogen sulfide, a toxic gas. Under aerobic conditions the $S^=$ is spontaneously oxidized back to $SO_4^=$. Under anaerobic conditions the hydrogen sulfide will accumulate. However, if light is available photosynthetic anaerobic bacteria can oxidize $S^=$ to $SO_4^=$. It is possible that these anaerobic, sulfur oxidizing bacteria might be adapted for growth on Mars. Alternatively, the anaerobic oxidation of $S^=$ can be accomplished by *Thiobacillus denitrificans*; this bacterium couples the oxidation of $S^=$ to $SO_4^=$ with the reduction of NO_3^- to nitrogen. The nitrogen would then enter the atmosphere, increasing its mass, or could undergo biological fixation by cyanophytes or *Clostridium* sp. to form NH_4^+. The overall flow of carbon, nitrogen, and sulfur on Mars, as discussed above, is diagrammed in figure 6.

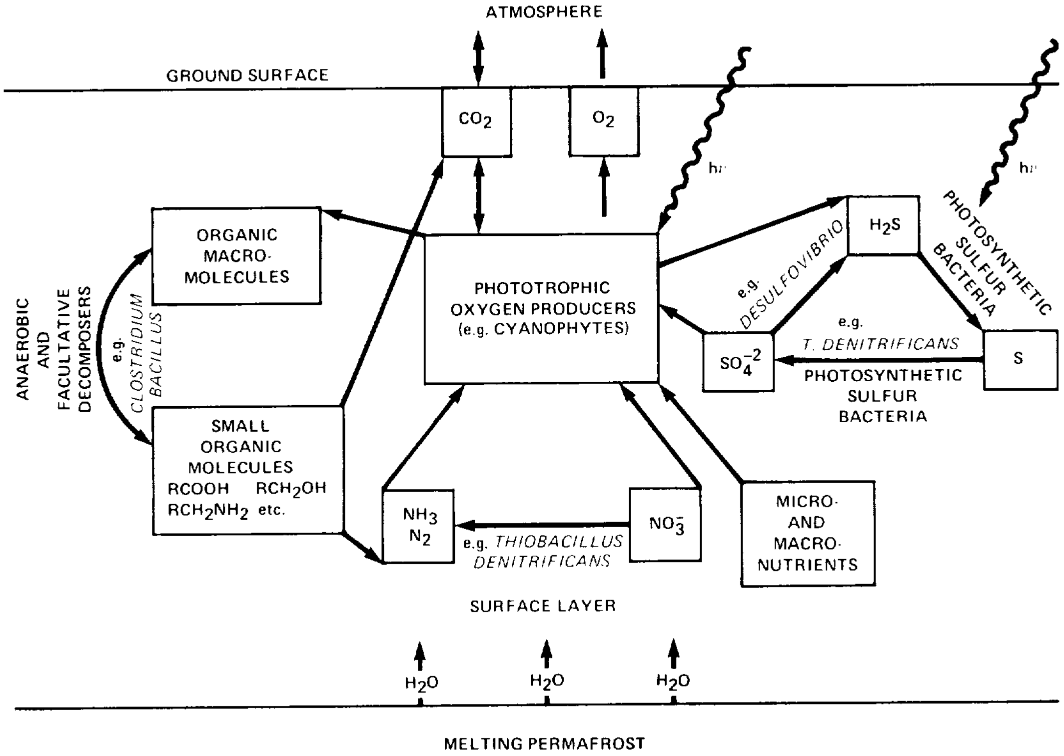


Figure 6.– Biological recycling of carbon, nitrogen, and sulfur on Mars.

6. SURVIVAL AND PHOTOSYNTHESIS OF TERRESTRIAL ORGANISMS ON MARS: COMPUTER MODELS FOR LICHENS AND CYANOPHYTES

From the biological standpoint the study group was interested in examining several questions concerning the interaction of a terrestrial organism with the Martian environment. For example, how does the temperature of a hypothetical organism vary during a diurnal cycle, and how closely is it coupled to the ground and/or atmospheric temperatures? How severe is the water loss by the organism which would result from the lack of atmospheric water, low pressures, and winds characteristic of Mars? Can desiccation be significantly limited by varying the resistance properties of the structural components of the organism within reasonable limits? How might these various environmental factors affect photosynthesis, and can estimates of photosynthetic production be made? Is it likely that any present day terrestrial organisms could survive under the envisioned Martian conditions without extensive genetic engineering?

Definitive answers to these questions require an extremely complex treatment, for which there is presently limited information. It was felt, however, that even a simplistic model for such processes could yield significant indications of important trends, and could also serve as a starting point for future, more complex treatments.

Two similar computer models were formulated to predict certain aspects of the biological behavior of lichens and cyanophytes placed on the surface of Mars.

When variables such as solar flux, wind speed, diurnal surface and atmosphere temperatures, resistance to water and carbon dioxide movement, and equilibrium constants for photosynthesis, are considered, factors such as organism temperature, rates of water loss and rates of photosynthesis (oxygen evolution) can be predicted.

The quantitative aspects of the derivation and description of the model are presented in appendix A.

GENERAL CONSIDERATIONS

Organism Temperature

To determine the coupling between organisms and the Martian environment, an energy balance model representing two terrestrial organisms – blue-green algae and lichens – has been developed. Given certain environmental parameters, the temperature of the organism can be determined assuming that the organism is in energy balance. The transpiration rate can then be determined as well as the rate of photosynthesis.

The major physical processes controlling the temperature of the organism are: (1) solar and thermal radiation, (2) convective and conductive energy transport and (3) evaporative cooling. Solar and thermal radiation from the atmosphere provide an energy source for the organism; the solar radiation reaching the organism depends upon the transparency of the atmosphere and varies with the Martian latitude, season and time of day. The planetary or thermal radiation depends upon the atmospheric temperature, primarily the lowest few kilometers, and the amount of gas which can absorb this thermal radiation. For all practical purposes, the organism absorbs all of the planetary radiation incident upon it.

Heat transport either to or from the organism occurs at the upper and lower surfaces if there is a difference in temperature between the organism and the air and/or ground. At the upper surface molecular conduction transports heat down the temperature gradient and across a laminar boundary layer. If the air temperature near the surface is lower than the temperature of the organism, then heat is conducted from the organism through the boundary layer and rapidly diffused by eddy transport into the atmosphere. The opposite occurs if the organism's temperature is lower than the air temperature. Heat transport by conduction occurs if the organism is in contact with the surface. Molecular conduction with the surface strongly influences the temperature of the organism. Two processes which allow the organism to rid itself of energy are thermal emission and evaporative cooling (transpiration). Every body radiates energy according to its temperature; solid and liquid bodies radiate nearly as much as black bodies.

Photosynthesis

Of critical importance is the potential for photosynthesis of any terrestrial organism on the Martian surface. It is acknowledged that photosynthesis involves a complex set of metabolic interactions, which are subject to numerous controlling elements. The consideration of photosynthesis on this level, although perhaps more complete, is far beyond the scope of the present model. The study group chose to represent the organism's photosynthetic rate as a function of several major limiting variables, which include temperature, light intensity, carbon dioxide concentration, and water vapor concentration or saturation of the organism. The temperature range over which the hypothetical organism may carry out photosynthesis is limited to that of approximately 260–285 K. Photosynthesis, like all cellular metabolic processes, is sensitive to freezing; temperature and water loss generally provide the controlling influences on photosynthesis in the model.

Resistance to Water Transpiration and Carbon Dioxide Diffusion

The diffusive resistance of the organism to water vapor and carbon dioxide are critical model parameters since they influence water flux, photosynthetic rate, and the temperature of the organism. The total resistance to water vapor diffusion is equivalent to the sum of the resistance of the cell wall covering, the intercellular air space and the desiccated cell layer (for cyanophytes). The carbon dioxide diffusion resistance includes all of the above and, in addition, the water-saturated cell wall, the cell membrane and the cytoplasm. All of these values have been empirically determined or estimated.

LICHEN SCHEMATIC

The schematic representation of the lichen model is presented in figure 7. As the diagram indicates, the lichen is envisioned as growing on the Martian surface, and is fully exposed to solar radiation. It could also be buried just beneath the surface, covered with sand. The segment of the lichen which is modelled is a rectangular parallelepiped of square upper surface, with an edge length of 1 cm. The thickness of this segment is T cm, including the layer of active algal and fungal symbionts in a homogeneous matrix (25% cells by volume), and a very thin "cuticose" protective layer over the top surface. Its total thickness can vary from 0.05 to 0.3 cm. A non-turbulent air layer presents an additional boundary to diffusion, and is a function of the wind speed. Inputs to and outputs from the system are the same as those in the cyanophyte model. The basic general assumptions are also the same as in the cyanophyte model, except that the minimum temperature at which the organism is photosynthetically active is set at 260 K (as opposed to 273 K). This cut-off temperature is reasonable in light of published observations (e.g., Lange and Kappen, 1972).

CYANOPHYTE SCHEMATIC

Figure 8 shows the proposed schematic for the blue-green algal model. The organisms are envisioned as existing in a thin layer of interdigitating filaments. They may be surrounded by a gelatinous covering and can reside at or just below the surface of the planet. Since such algal mats are commonly crusty or "cuticose" in

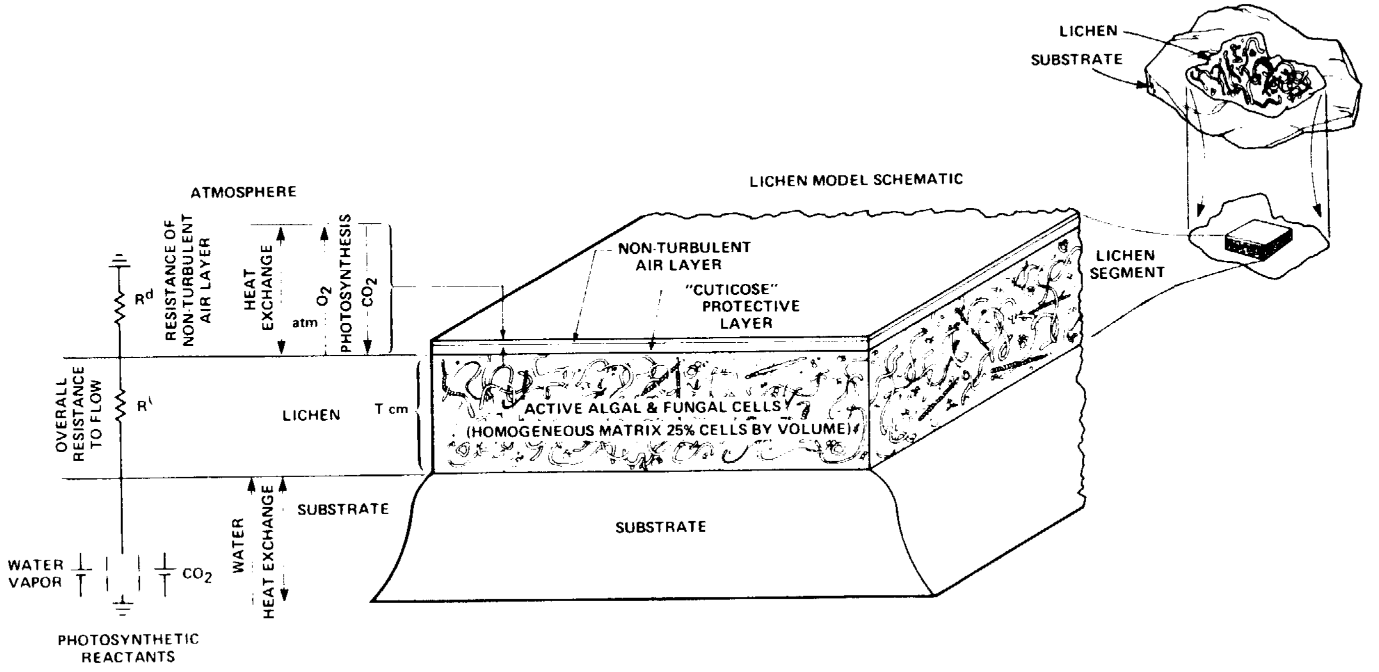


Figure 7.– Pictorial representation of the lichen computer model; left portion indicates appropriate input and output, and electrical analog. Further description is included in the text.

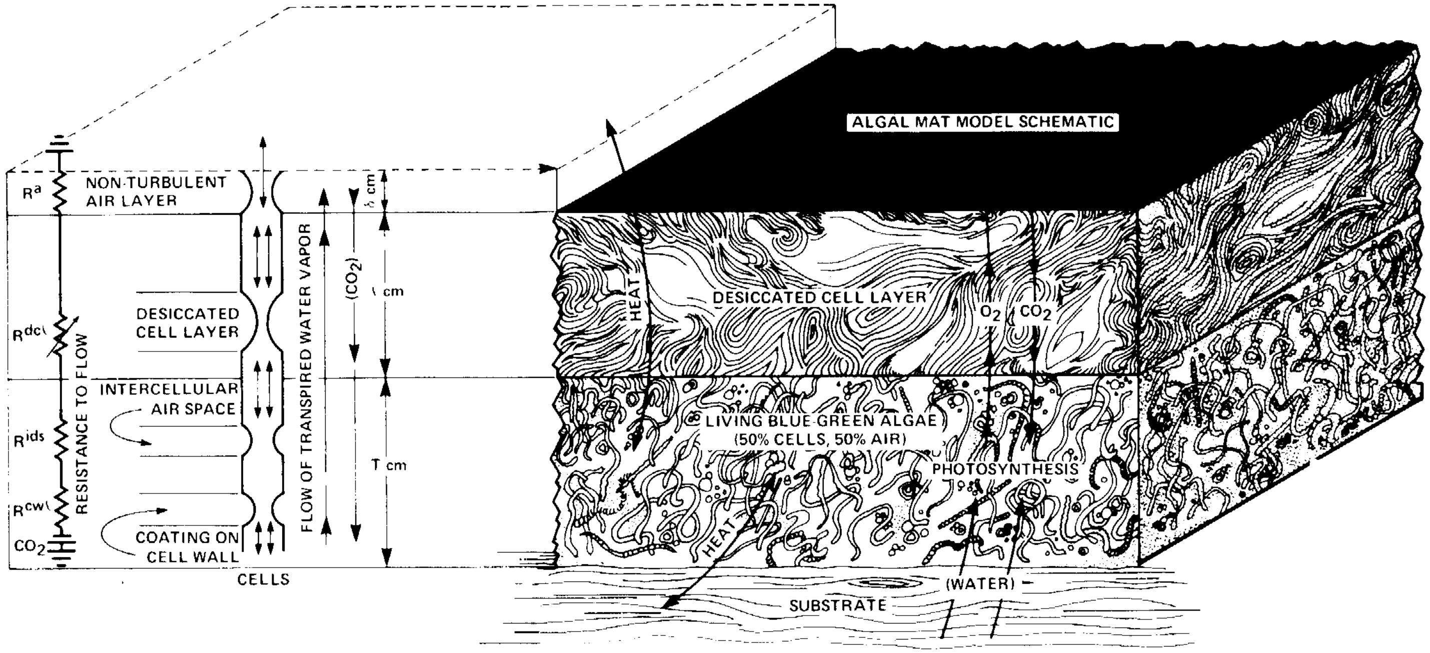


Figure 8.– Schematic representation of the proposed cyanophyte model shows volume segment along with the important photosynthetic input/output. The left portion indicates the electrical analog to the scheme [see text].

their upper segments, a desiccated layer is assumed to overlie the "active" cells. This desiccated layer may initially result from exposure of cells to the rapid moisture loss which would be characteristic of the Martian environment. It is assumed that this layer may attain a thickness equivalent to that of the active cell layer, and that this desiccated matrix provides an additional barrier to water loss by the underlying cells and probably protects from ultraviolet radiation. The resistance property of the desiccated layer is an important variable in the model. The thickness of the active cells has arbitrarily been chosen at 500 μm. By terrestrial standards this is relatively thin, however, it is assumed that the severe Martian environmental conditions would not permit luxurient growth. This layer is in intimate contact with the surface or immediate subsurface of Mars and consists arbitrarily of 50% cells by volume. The remainder is proposed to be water-saturated air. In view of the extremely low atmospheric pressures on Mars, it was thought unreasonable to postulate a liquid water layer, although its presence would be of little consequence to this model. As stated earlier, the thickness and resistivity (resistance per unit thickness) was varied to establish the influence of this property upon certain of the other parameters.

RESULTS

The environmental models of blue-green algae and lichen discussed in the previous section have been applied to Martian conditions to determine if these terrestrial organisms could survive the harsh Martian environment, and if so, whether they could bring about any appreciable change in atmospheric composition by photosynthesis.

The two crucial assumptions made are that water is available to the organism and that the organism can withstand the intense ultraviolet radiation. As discussed earlier there may well be large amounts of water ice locked in the regolith and remnant polar caps. If so, then the possibility exists that this ice could be released and utilized, at least on a local scale, for the growth of the organism; clearly if water is not available then any biological modification of Mars appears impossible. Regarding ultraviolet radiation, the desiccated layer could provide adequate shielding for the algal matt; the lichens have a high tolerance to ultraviolet radiation, as previously discussed.

The model study has not been compared with laboratory or field situations; in most cases these data are not available. Nevertheless, the results for these models are presented since they provide insight to the importance of various physical processes coupling the organism to the environment and may suggest future laboratory studies which will allow the model to be refined and used for predictions.

The particular Martian environment chosen for the model corresponds to an equatorial equinox situation which should be most conducive to terrestrial organisms in terms of temperature and radiation. The maximum solar flux at local noon is 0.86 ly/min. The back radiation from the atmosphere incident on the organism was determined from the calculations for the carbon dioxide greenhouse effect and is considered to be a constant 0.023 ly/min.

Three different values for near-surface wind speed have been used: 1, 500, and 1000 cm/sec. Martian surface wind velocities are uncertain, but low values might well represent sheltered regions as opposed to the highest velocities at surfaces with little irregularity.

The ground and air temperatures are given in figure 9 by the upper and lower curves respectively, while the numbered curves correspond to the calculated algal temperature for different wind speeds, desiccated layer thickness (*a*, cm) and their corresponding resistivities (*b*, min/cm^2). Note that for all conditions considered, the thermal conduction with the surface is the most important factor, and the plant temperature is within seven degrees of the surface temperature, even though the air temperature near the ground is some 65 K less than that of the surface; if there is no desiccated layer (profile I) then the temperature of the organism is that of the surface. The thicker the desiccated layer, the lower the mean thermal conductivity and the lower the temperature will be. The temperature also decreases with increased wind speed because of convective heat transport to the atmosphere. Also note that regardless of wind speed and the condition of the desiccated layer, the organism will be above 273 K about 6 hr during the day. Thus a knowledge of the diurnal surface temperatures on Mars can be used to predict the time the blue-green algae will be above freezing.

WIND SPEED		a	b
I	1 cm/sec	0 cm	0 min/cm^2
II	500 cm/sec	0.03 cm	3 min/cm^2
III	1000 cm/sec	0.03 cm	3 min/cm^2
IV	500 cm/sec	0.05 cm	333 min/cm^2
V	1000 cm/sec	0.05 cm	333 min/cm^2

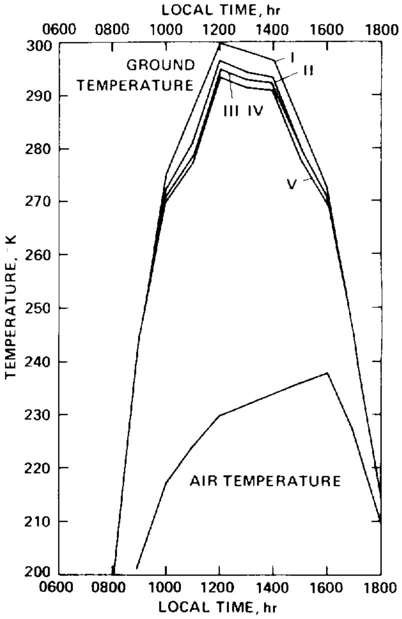


Figure 9.– Diurnal variation of blue-green algae temperature for Martian equatorial equinox conditions. Algae thickness is 0.5 mm, *a* is the thickness of the desiccated layer, and *b* is the corresponding resistivity. Profile I overlies the ground temperature profile.

The variation in the water loss for an algal mat during the day is shown in figure 10. The numbers in parentheses refer to the desiccated layer, the first being the thickness of the layer and the second the resistivity; the resistance of the layer is the product of these two numbers. Each desiccated layer thickness and resistivity has been combined with the three wind speeds; the resulting ranges correspond to the width of each

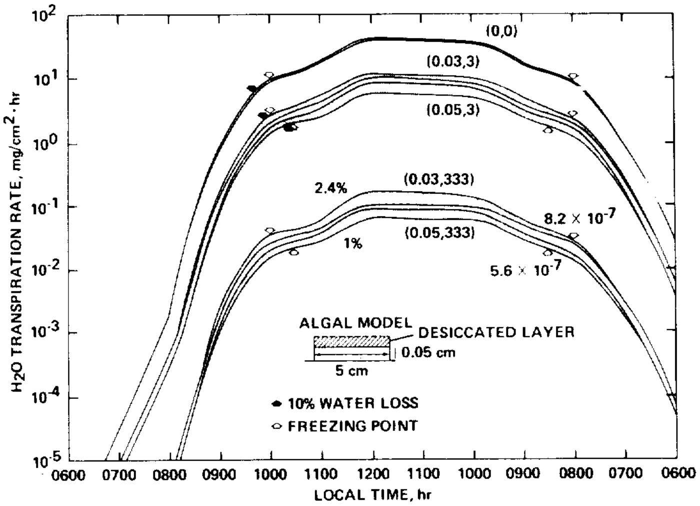


Figure 10.– Diurnal variation of transpiration rate for blue-green algae. Symbols are explained in text.

shaded region. The upper boundary of each shaded region refers to a wind speed of 1 cm/sec, and the lower boundary a speed of 1000 cm/sec. The solid arrows on the uppermost three curves are the times for which the organism has reached a 10% water loss, the total amount of water in the organism being 25 mg/cm². For the lowermost two curves which represent the largest resistivity, the water loss does not reach 10% but is either 1 or 2-1/2%, as indicated. The open arrows are the times for which the organism reaches 273 K. Photosynthesis is assumed to occur only when an organism's temperature has reached 273 K and ceases when the water content is reduced by 10%. Notice that if the resistance is less than about 0.15 (uppermost three curves), a 10% water loss is reached through sublimation before the freezing point is reached, so that photosynthesis does not occur even after subsequent warming. If no desiccated layer is present water loss would be complete and the algal mat could not survive. A desiccated layer, with resistance greater than about ten, appears necessary for survival of the organism.

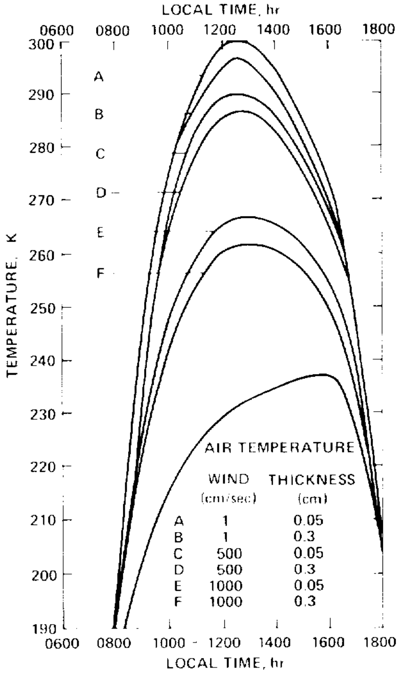
The influence of wind speed on the transpiration rate is small, the major factor being the resistance of the desiccated layer. Contrary to expectation, the larger the wind speed, the lower the transpiration rate for each resistance (each shaded region). While the larger wind speed does produce a smaller resistance for evaporative cooling and water loss, nevertheless the lower organism temperature reduces the water vapor saturation pressure within the algal system which overcompensates for the smaller resistance and gives a lower water loss (appendix A, eq. (A14)). Note that the wind speed is not a major factor in water loss; the diurnal variation in water loss, primarily controlled by surface temperature, is several orders of magnitude, while a change in wind speed changes the water loss by less than a factor of two.

The rate of photosynthesis is essentially constant over the day for all models considered. The reason for this is that the rate coefficient for radiation is very small, being 1.2×10^{-3} ly/min, so that even at 0700 hours local time, when the solar radiation is 0.2, the ratio $1.2 \times 10^{-3}/0.2 \ll 1$, and the photosynthesis rate is independent of light intensity. The numbers by the open arrows of the lower two curves of figure 10 refer to the moles of carbon dioxide fixed/cm^2/day, and organisms with desiccated layers of resistances greater than about ten would yield about 10^{-6} moles of oxygen/cm^2/day. If, for example, one-fourth of the planetary surface were covered by blue-green algae, and if they were able to photosynthesize for about half a Martian year, then in seven thousand Earth years, an amount of oxygen would have been produced equivalent to the present amount of carbon dioxide in the Martian atmosphere, that is, 5 mb.

Similar calculations have been carried out for the lichen model. The same atmospheric model has been assumed, that is, equatorial equinox conditions and three different wind speeds; 1, 500, and 1000 cm/sec. Three different lichen thicknesses were used: 3 mm, 1.5 mm, and 0.5 mm.

Diurnal variations in the lichen temperatures for different thicknesses and wind speeds are shown in figure 11. For sheltered conditions, that is, very low wind speeds, the lichen temperature is closely coupled to the surface temperature, even for a thickness of 3 mm. This occurs because the thermal conduction to the atmosphere is small. As the wind speed increases, the heat loss to the atmosphere becomes larger; also the thicker the organism, the smaller is the heat transport from the surface. Both effects tend to decrease the organism temperature. For example, for a lichen thickness of 3 mm, and wind speed of 1000 cm/sec, the maximum temperature of the lichen is only 262 K, although the ground temperature is 300 K. Thus it is apparent from figure 11 that wind speed is closely coupled to the organism and influences both transpiration and photosynthesis.

For sheltered conditions, that is, with a wind of 1 cm/sec, the water loss is large and is not strongly dependent on the lichen thickness (fig. 12). Note that for a given wind speed, the greater the thickness of the lichen, the smaller is the water loss. This is a result of the lower organism temperature associated with the larger lichen thickness. It is also apparent from figure 12 that for a given lichen thickness, the water loss decreases with increasing wind speed. The explanation for this is the same as that for the algal model (fig. 10), that is, the larger wind speed produces a lower organism temperature which lowers the saturation water vapor pressure and thus the water loss; this process is more important than the decrease in air boundary layer thickenss which decreases the resistance to water loss.



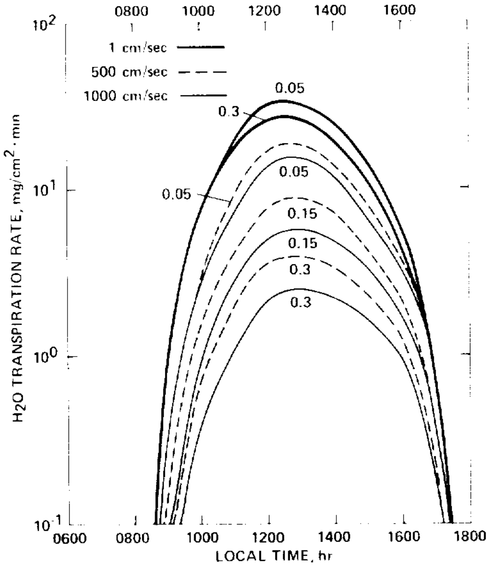


Figure 11.– Diurnal variation of lichen temperature for Martian equatorial equinox conditions.

Figure 12.– Diurnal variation of transpiration rate for lichen. Numbers refer to the thicknesses of the lichen layers.

Figure 13 shows the rate of photosynthesis (moles CO_2 fixed) for various wind speeds and lichen thicknesses. The photosynthetic rate is less than half that of the blue green algae due to the larger rate coefficient ($K2$). Note that the diurnal variation of photosynthesis exhibits the same relationship to wind speed and lichen thickness as does the transpiration rate; that is, as the wind speed or lichen thickness increases, the transpiration decreases while a corresponding increase in photosynthesis occurs. This can most easily be explained by referring to the equation for photosynthetic rate (appendix A, eq. (A12)) and noting that photosynthesis increases as the product $A\tau'$ decreases, where,

$$A\tau' \equiv (1 + K2/I)(1 + K3)/(S - 20)[r_i(D_{H_2O}/D_{CO_2}) + \delta]$$

and $\delta \propto V^{-1/2}$. The terms are explained in appendix A. As the wind speed increases, δ decreases. Also a larger wind speed means a lower water loss and thus a larger water retention S. Both parameters therefore tend to reduce $A\tau'$ and increase the photosynthetic rate.

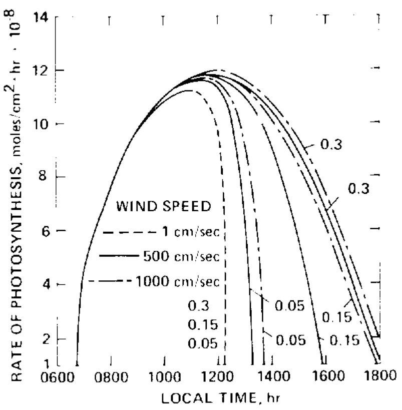


Figure 13.– Diurnal variation of photosynthetic rate for lichen. Numbers refer to the thicknesses of the lichen layers.

An additional factor which must be taken into account to determine the daily photosynthesis is the time the temperature is above the freezing point of the lichen; a temperature of 260 K is assumed and the number of moles of carbon dioxide fixed or oxygen released per square centimeter per day is calculated for various wind speeds and thicknesses. The results are shown in table 19. Note that the organism is able to photosynthesize several hours per day yielding an oxygen production of about 10^{-7} moles/cm^2, approximately one order of magnitude less than that for blue-green algae. At this rate, if one-fourth of the Martian surface were covered by lichens, about 70,000 Earth years would be required to produce an amount of oxygen equivalent to the present amount of carbon dioxide. Clearly, lichens are very slow growing and such a coverage is unrealistic. Thus it does not appear that lichens could produce any significant change in the oxygen concentration on Mars. However, because of their tolerance to ultraviolet radiation, they might be effective in generating an ozone shield.

TABLE 19.– OXYGEN PRODUCTION BY LICHEN FOR VARIOUS LICHEN THICKNESSES AND WIND SPEEDS

Thickness (cm)	Wind speed (cm/sec)	Time above 260 K (local time)	Local time when water loss reaches 80%	Hours available for photosynthesis	Oxygen released (moles/cm^2)
0.3	1.	0925–1623	1300	$3^h\,35^m$	3×10^{-7}
0.3	500.	1124–1500	---	$3^h\,36^m$	4×10^{-7}
0.3	1000.	1200–1413	---	$2^h\,13^m$	3×10^{-7}
0.15	1.	0927–1625	1300	$3^h\,33^m$	3×10^{-7}
0.15	500.	1030–1600	1700	$5^h\,30^m$	5×10^{-7}
0.15	1000.	1100–1530	---	$4^h\,30^m$	5×10^{-7}
0.05	1.	0930–1628	1300	$3^h\,30^m$	3×10^{-7}
0.05	500.	0947–1618	1400	$4^h\,13^m$	3×10^{-7}
0.05	1000.	0953–1613	1400	$4^h\;\;7^m$	4×10^{-7}

Note: Martian temperatures and radiation field correspond to equatorial equinox conditions.

7. PLANETARY ENGINEERING: MODIFICATION OF THE MARTIAN ENVIRONMENT

From previous considerations it is clear that modification of the Martian environment is necessary if extensive growth of terrestrial organisms is to occur in a reasonable time. A consideration of the evolution of the terrestrial planets indicates that the modification of the Martian environment to similarity with that of Earth is possible.

Although the evolution of planetary atmospheres is still a controversial topic (Cloud, 1965), it is generally agreed that the Earth's atmosphere is a secondary one, having outgassed from the lithosphere over a period of approximately 4 billion years (Berkner and Marshall, 1965). In view of the similarity in the material from which the terrestrial planets were formed (Pollack, 1975), it is reasonable to assume that their atmospheres are also secondary in nature. With this essential point assumed, it is possible to construct a hypothetical but plausible history of atmospheric evolution for Venus, Earth, and Mars (Rasool, 1971), and to demonstrate that Mars is presently in a state appropriate for atmospheric modification.

Calculation of the initial, mean planetary surface temperature of the three terrestrial planets, Venus, Earth, and Mars, prior to an outgassed secondary atmosphere, yields temperatures of 350 K, 270 K, and 220 K respectively. As volcanic gas, primarily carbon dioxide and water, accumulated on Venus and Earth, which were initially warm, a substantial greenhouse effect[1] developed. In the case of Venus the temperature increment of the greenhouse effect was enormous (presently $\cong$500 K), since water vapor never condensed into liquid form due to the high initial temperature. On Earth water vapor condensed, forming the oceans and limiting the incremental greenhouse effect (presently $\cong$37 K). Moreover, water in liquid form

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[1] Atmospheric greenhouse effect refers to a condition of increased warming caused by the presence of certain gases in the atmosphere. These gases, carbon dioxide and water vapor among them, absorb some of the thermal radiation (heat) rising from the surface of a planet, so that not all of the radiation is lost to space but is re-emitted down from the atmosphere thereby heating the planet's surface.

aided in the reaction of carbon dioxide with silicates in the lithosphere to form carbonates. Significant amounts of carbon dioxide also dissolved in the oceans in the form of bicarbonates. On Venus, the carbon dioxide atmosphere is still present due to the absence of liquid water. In order to guide Venus down the path of the Earth's evolution it would be necessary to cool the planet significantly.

On Mars the situation was entirely different. The low initial surface temperature caused the water vapor and carbon dioxide to crystalize into ice after volcanic outgassing. Presently, large amounts of carbon dioxide and water are present as ice and permafrost, and hence the present amount of atmospheric carbon dioxide and water is insufficient for a measurable incremental greenhouse effect (presently $\cong$4 K). Moreover, the lack of liquid water prevented the formation of carbonates from carbon dioxide and silicates.

Evidently, Mars has yet to follow the path of Earth's evolution. Unlike on Venus, only moderate temperature increases on Mars would be required to provide water in liquid form, the necessary catalyst for Earth-like planetary evolution.

INCREASING MARTIAN SURFACE TEMPERATURE

It is obvious that an increase in the surface temperature of Mars is necessary if extensive biological processes are to occur, and, indeed, even their mere existence may require a temperature modification.

An insight to the various mechanisms which might affect a temperature change can be gained by reviewing the several papers concerning long term Martian climate changes (Ward *et al.*, 1974; Gierasch and Toon, 1973; Sagan *et al.*, 1973). These mechanisms rely on a sublimation of the polar cap with the resulting substantial increase in atmospheric mass ranging up to about one bar. The sublimation of the cap could be brought about by an increase in available solar energy absorbed by the poles. This increased absorbance could be caused by increasing the amount of solar energy incident on the polar cap, for example, by modifying the obliquity or orbital parameters of Mars, by an increased solar output, or by decreasing the albedo of the caps. As additional carbon dioxide is added to the atmosphere, a warming of the planet would result both from advective (see the next section) and greenhouse effects. This warming would accelerate the sublimation of carbon dioxide until the supply in the cap is exhausted.

The possible significance of a remnant carbon dioxide ice cap to the control of the atmospheric carbon dioxide mass was initially investigated by Leighton and Murray (1966). They concluded that the polar CO_2 ice cap controlled the atmospheric CO_2. Based on this assumption Ward *et al.* (1974) determined the variations in total atmospheric pressure and polar cap temperature for various obliquity oscillations. They find that the climatic extremes corresponding to maximum and minimum obliquity would cause the remnant polar cap temperatures to range from 130 K to 160 K with a corresponding pressure variation of a few tenths of ambient to about 30 mb. Their analysis also indicates that the south residual cap should be water ice.

Ingersoll (1974) has argued against the assumption that there is a permanent carbon dioxide reservoir in the polar caps of Mars which controls the atmospheric partial pressure. Recent observations indicate the residual polar cap is water ice. Also, the increased poleward heat transport due to increasing pressure might lead to an instability, that is, a continued sublimation of the cap.

It appears therefore that the only plausible way to change the surface temperature and pressure is by a mechanically induced reduction in the sublimate of the polar caps which might initiate a "runaway effect"; advective, greenhouse, or both. Of major concern is both the composition of the cap remnants and the amount of ice available. If the remnant were carbon dioxide ice, then its thickness can be no more than a few kilometers, otherwise the buried carbon dioxide would liquify, and no evidence for this has been found. If a polar cap semidiameter of about eight degrees, with an average thickness of three kilometers, is assumed, then the amount of carbon dioxide available to the atmosphere is about 3×10^{18} kg, enough to increase the surface atmospheric pressure one hundred fold. There is also the possibility of a buried, more extensive carbon dioxide reservoir, and recent estimates of the total carbon dioxide in both the atmosphere and crust suggest about 10^{19} kg, which would yield a surface pressure of several bars if all could be released.

The relationship between a water ice cap and a runaway greenhouse effect has not been discussed in the literature although recent evidence suggests there may be as much as 10^{19} kg of water ice in the regolith. In order to have an equilibrium with liquid-water, the surface temperature and partial pressure of water vapor must be at least 273 K and 6.1 mb respectively. Approximately 10^{16} kg of water, or about one-thousandth of that thought possibly to be present, must be in the form of atmospheric vapor. A remnant cap with semi-diameter of eight degrees would need to be only 300 m thick to provide this quantity of vapor.

The increase in mean global surface temperature which might be expected from a carbon dioxide greenhouse effect is shown in figure 14. The uppermost line is the greenhouse effect if the temperature lapse rate corresponding to the mean temperature profile (Noll and McElroy, 1974) is maintained as additional carbon dioxide is added to the atmosphere. The most rapidly varying temperature, given by a dry adiabatic rate, represents a maximum greenhouse effect and corresponds to the lower curve. The dashed line shows the influence of the discontinuity at the surface; the ground temperature averaging about twelve degrees above the air temperature at the ground. Details of the calculations are given in appendix B.

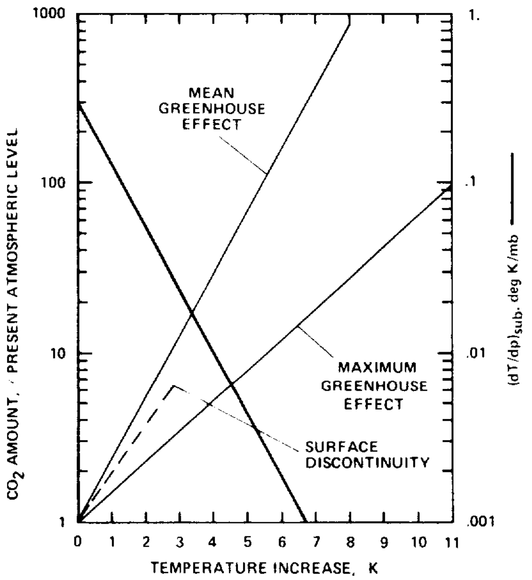


Figure 14.– Carbon dioxide greenhouse effect. Uppermost line refers to a mean temperature profile while the lower line is for an adiabatic lapse rate. Heavy line refers to the slope of the sublimation equilibrium surface for carbon dioxide.

If all the estimated carbon dioxide on Mars could be volatilized, the resulting atmospheric pressure of approximately three bars would increase the mean surface temperature between 10 and 20 K. To release such an amount of gas, if it were all carbon dioxide ice, would require 10^{21} kcal; an amount of energy equivalent to the total radiation incident on Mars for three Martian years.

It is possible that a runaway effect could be induced; that is, a mechanically generated and uniformly distributed small increase in carbon dioxide which would increase the temperature and partial pressure sufficiently to allow continued sublimation to occur. Such a process requires that

$$\frac{\Delta T}{\Delta p_{\text{gh.}}} > \frac{dT}{dp_{\text{equil.}}}$$

that is, the slope of the equilibrium curve for carbon dioxide ice and vapor should be less than the ratio of the temperature increase produced by the greenhouse effect to the corresponding increase in carbon dioxide partial pressure. The slope of the equilibrium curve for various temperatures and pressures is shown in table 20, while the $\Delta T/\Delta p$ slope from the greenhouse effect is given in figure 14. For an instability

TABLE 20.– TEMPERATURE, PRESSURE, AND SLOPE FOR EQUILIBRIUM BETWEEN CARBON DIOXIDE ICE AND VAPOR

Temperature, K	Pressure, mbar	dT/dp_{equil}, K/mbar
140	1.14	5.6
160	18.1	.46
165	32.3	.27
170	56.4	.17
180	156.	.067
200	873.	.0147
217	5180.	.0029

to develop, $\Delta T/\Delta p_{\mathrm{gh.}} > dT/dp_{\mathrm{equil.}}$ so that, initially, sublimation would proceed over the planet where surface temperatures are greater than about 165 K. The winter pole would be excluded and act as a carbon dioxide vapor sink. Even if the above inequality is not obeyed, the carbon dioxide added to the atmosphere will remain if the carbon dioxide vapor pressure is less than the equilibrium vapor pressure for the temperature induced by the greenhouse effect. Figure 15 shows this to be true except over the winter pole.

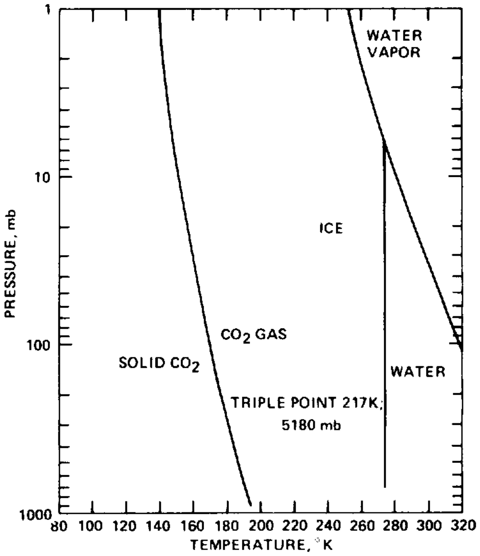


Figure 15.– Pressure-temperature cross section of the thermodynamic surface for carbon dioxide and water.

As carbon dioxide is continuously supplied to the atmosphere the carbon dioxide equilibrium partial pressure increases more slowly than the corresponding pressure increase from the greenhouse effect, and continued sublimation would only occur from increasingly higher surface temperatures. For example, if the entire polar cap remnant were carbon dioxide (which is doubtful; the carbon dioxide vapor pressure is about 5 mb over the summer pole even though an equilibrium vapor pressure of about a bar could be maintained) and could be released to the atmosphere – an increase of about two hundred fold – then the mean global temperature would increase about 7 K and the pressure would be about 500 mb. Continued sublimation could only occur when temperatures were above about 210 K, however, redeposition would not take place since the atmosphere could support more than one bar of carbon dioxide. Such analysis also suggests strongly that the residual caps are not carbon dioxide but water ice (fig. 15).

An analysis similar to that for carbon dioxide has been carried out for water vapor (fig. 16). The temperature increase is significantly greater than that for an equivalent amount of carbon dioxide. For example, if enough water vapor could be added to the atmosphere to increase the total pressure by 10%, the greenhouse effect would increase the temperature about 10 K, whereas an equivalent amount of carbon dioxide would change the temperature by only about one-tenth of a degree. The reasons that the water vapor greenhouse effect is greater than that for carbon dioxide are twofold: while the carbon dioxide absorbs planetary radiation primarily in the 15 μm spectral region, water vapor absorbs strongly in two spectral regions, one centered near 6.3 μm and the other centered about 80 μm with significant absorption down to about 18 μm. Water vapor also absorbs solar radiation in the

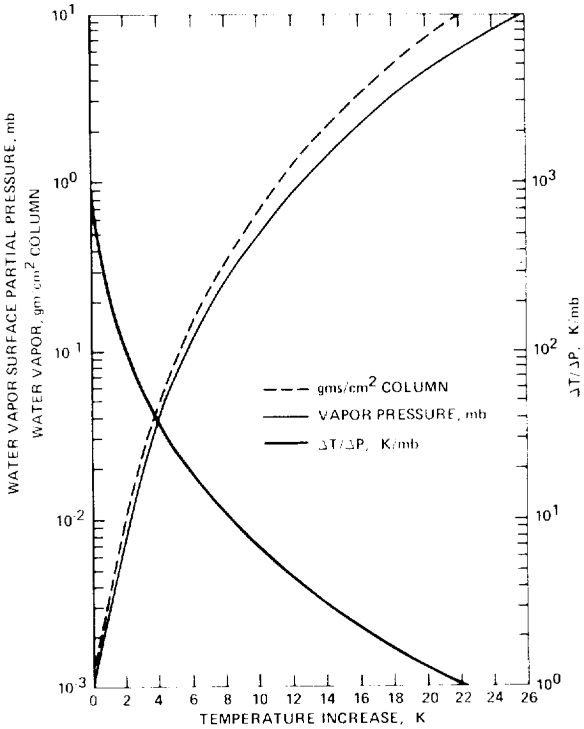


Figure 16.— Water vapor greenhouse effect. The dashed and solid curves refer to the water vapor amount in units of partial pressure (mb) and column density (g/cm^2) respectively. Heavy curve is the slope of the sublimation equilibrium surface for water vapor.

near infrared, between about 0.8 μm and 6 μm. With increasing water vapor, more solar radiation will be absorbed and must be balanced by a greater planetary emission to space and thus a higher atmospheric temperature. The details of this calculation are also given in appendix B.

The slopes of the ice-water vapor equilibrium surface for several values of pressure and temperature are shown in table 21. These values, when compared with the $\Delta T/\Delta p$ profile in figure 16 give some insight into the instability of a forced greenhouse effect. For example, if water vapor could initially be distributed into the atmosphere ($\Delta T/\Delta p_{gh.}$ = 500 K/mb), then an instability would result only for those regions where the surface temperature is greater than about 220 K (see table 21), that is, sublimation would continue until a new equilibrium is established, which would occur for that surface temperature where the slope of the sublimation curve equals that $\Delta T/\Delta p_{gh.}$ induced by the greenhouse effect. If $\Delta T/\Delta p_{gh.}$ is less than the

TABLE 21.– TEMPERATURE, PRESSURE, AND CORRESPONDING SLOPE OF ICE-WATER VAPOR SUBLIMATION SURFACE

Temperature, K	Pressure, mbar	dT/dp_{Equil}, K/mbar
125	1.66×10^{-11}	1.54×10^{11}
150	5.96×10^{-8}	6.13×10^{7}
175	2.07×10^{-5}	2.42×10^{5}
200	1.66×10^{-3}	3.92×10^{3}
225	5.03×10^{-2}	164.
250	7.71×10^{-1}	13.
273	6.11	2.

ice-vapor equilibrium slope, and if the water vapor pressure is initially in equilibrium with the surface temperature, then any water vapor mechanically released would be redeposited.

Results from a "mean global model" are of limited value, and are primarily useful in that they give insight to physical processes. However, one might imagine, based on the above analysis, that water vapor in equilibrium with the polar surface temperature could be mechanically ejected from a remnant water ice cap and because of the large wind systems, distributed throughout the atmosphere. Some deposition would likely occur over the winter pole and continued ejection to the atmosphere would be necessary. With a greenhouse-induced temperature increase, additional sublimation through instabilities, as well as a decrease in the albedo, a permanent climate change might occur. Two-dimensional models are necessary to investigate further this effect as well as probable cloud formation.

ADVECTIVE TRANSPORT

"Advection" is the term used by meteorologists to denote horizontal transport of air. "Convection," on the other hand, is usually reserved for vertical transport. The present Earth's atmosphere is particularly efficient in transferring heat from the tropics to the poles by these two processes. Warm equatorial air, rising in buoyant, turbulent, air bubbles (convection), is carried poleward by mid-latitude synoptic disturbances (advection), and is finally brought down to the polar surface by radiation and turbulent mixing (convection). Poleward heat advection reaches its peak strength between latitudes 40° and 50° in each hemisphere during winter when baroclinic weather disturbances are most intense. Such a redistribution of energy from equator to pole tends to reduce meridional temperature gradients without changing the planet's mean temperature. Because of a thin atmosphere, atmospheric heat transfer on Mars is minimal at present, but it would be of increasing significance if the atmospheric density increased.

Using an energy balance approach a crude estimate can be derived of annual heat advection at the Martian poles. Figure 17 illustrates the average annual energy fluxes at the NPC (north polar cap). To facilitate writing the mean annual energy balance equations, it is assumed that:

(a) the atmosphere is transparent to solar radiation,

(b) surface emissivity and absorptivity for infrared radiation are both unity,

(c) $G = 0$ over an annual cycle,

(d) mean annual polar atmosphere may be characterized by a single temperature, T_a, and,

(e) the system is in a steady-state equilibrium so that T_a and T_o (mean annual polar surface temperature) remain fixed.

With these simplifications the annual energy balance equations over the pole may be written:

$$V + aL_o - 2L_a = \pm H \pm E \text{ (atmosphere)}$$

$$F + L_a - L_o = \mp H \mp E \text{ (surface)}$$

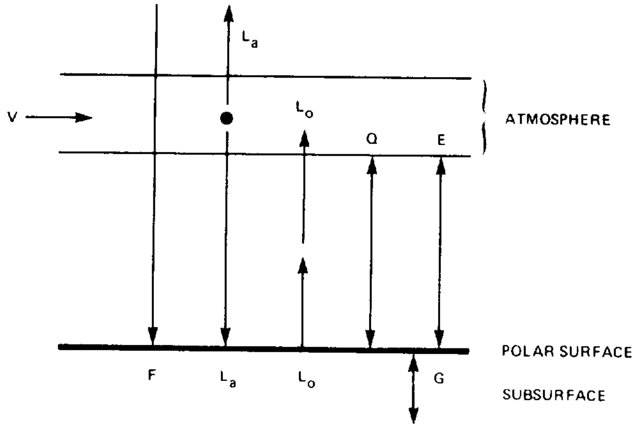


Figure 17.– Average annual energy flux diagram for north polar cap; V = poleward heat advection; F = solar radiation flux absorbed at the surface; L_a = infrared radiation lost by the atmosphere; L_o = infrared radiation lost by the surface; a = atmospheric absorptivity for infrared radiation; H = sensible heat convection; E = latent heat convection; G = subsurface heat conduction.

(see fig. 17 caption for definition of terms). Adding and rearranging terms yields for the poleward heat advection (V),

$$V = L_a + (1 - a)L_o - F \tag{13}$$

To evaluate the right-hand side of equation (14) we make the parameterizations: $L_o = \sigma T_o^4$ and $L_a = KL_o$, which together imply $a = K(T_o/T_a)^4$; σ is the Stefan-Boltzmann constant; and K is an empirically determined constant discussed in a previous section (p. 21). The factor $(T_o/T_a)^4$ is a measure of the greenhouse effect at the polar cap and has a value near unity for current conditions (i.e., no greenhouse effect). To study advective effects independent of the greenhouse effect, this ratio is maintained at unity for all calculations. By substitution, equation (13) becomes

$$V = \sigma T_o^4 - F \tag{14}$$

Equation (14) yields mean annual heat advection at the pole as a small difference between two large imperfectly known quantities. This can produce a large error in the calculated rate of advection. For example, a 5 K error in mean annual polar surface temperature will cause a 25% error in the poleward heat advection. As a result, estimates of heat advection with equation (14) must be regarded cautiously. Substituting $T_o = 160$ K and $F = 40$ ly/day (1 ly = 1 cal/cm^2), values based on table 1, $V = 39$ ly/day. Leovy and Mintz (1969) estimate atmospheric energy transport during winter solstice across 43.5° N as $19 \text{X} 20^{20}$ erg/sec. If distributed uniformly over the planet's surface poleward of 43.5° N, this is equivalent to 19 ly/day. The assumption of uniform energy distribution, however, produces values which are too low by at least a factor of 2 for the Earth's north pole where extensive radiational cooling is offset by strong advective flux from lower latitudes. If the same situation occurs on Mars, Leovy and Mintz' estimate will also be too low, perhaps also by a factor of two.

Gierasch and Toon (1973) explored the effects of heat advection on the Martian north polar cap. They suggested that a 20% increase in absorbed solar radiation at the cap, if maintained for about 100 yr, might lead to a 1 bar atmosphere and a significantly warmer climate. The physical mechanism is straightforward. The winter pole has a surface temperature very close to the frost point of carbon dioxide. Increasing solar flux at the north pole will sublime more carbon dioxide from the cap, resulting in a slightly denser atmosphere. The denser air will, in turn, have a larger heat capacity and be more efficient in advecting heat from the equator to the pole. Increased polar heating leads to further carbon dioxide sublimation, and so on. This feedback process continues until the entire polar cap has been sublimated to vapor. If the carbon dioxide supply is large enough, a 1 bar atmosphere could result. There is considerable doubt whether the quantity of carbon dioxide contained in the polar cap is sufficient to produce this large a change. Nevertheless, the advective process may still yield significant temperature changes.

Using Stone's (1972) parameterization of advective heat flux by midlatitude baroclinic waves, Gierasch and Toon obtain

$$V = \alpha P(T_e - T_a)^2 \tag{15}$$

for polar winter heat advection, where $\alpha = 1.5 \times 10^{-4}$ cm/sec/K^2; P = surface pressure, and T_e, T_a are the equatorial and polar atmospheric temperatures, respectively. Following this assumption, equatorial atmospheric temperature is taken as being constant because it is primarily determined by radiative and convective processes which should be little modified by climatic changes. It is also assumed that $T_a = T_o$ for equilibrium conditions in the absence of a greenhouse effect. Table 22 is based on figure 1 in the paper by Gierasch and Toon (1973) for a mean annual solar flux absorbed at the polar surface of 1.8×10^4 erg/cm^2/sec (= 38 ly/day), and T_e = 200 K. The advection value found for the 5 mb pressure of table 22 is smaller than that given by either Leovy and Mintz (1972) or the value discussed earlier in this section. This may, in part, be due to the fact that equation (15) includes only eddy heat flux which comprises about 65% of the total heat flux at the pole. Also,

TABLE 22.– RELATIONSHIP BETWEEN AIR PRESSURE, POLAR TEMPERATURE, AND ADVECTIVE FLUX

Air pressure, P, mbar	Temperature T_o, K	Advective flux V, ly/day	
5	146	4.6	Low temperature Stable climate
10	150	7.9	
25	155	16	
50	162	23	Transition
100	171	27	
250	183	23	
500	188	23	High temperature Stable climate
1000	190	32	

Source of data: Gierasch and Toon (1973), figure 1.

the assumption of uniform flux distribution poleward of 45° N has been made. Thus, these figures could easily be low by a factor of three.

To move from the present low temperature stable climate to the high temperature stable climate as indicated in table 22, requires an order of magnitude increase in pressure. This might be brought about by importing an atmosphere from outside the planet, volatilizing gases bound in the regolith, or somehow increasing the solar energy absorbed by the polar caps. Gierasch and Toon (1973) indicate that the transition from the current stable low polar temperature climate to the stable high temperature climate can occur if the absorbed annual solar flux at the pole is increased by roughly 20% to 2.2×10^4 erg/cm^2/sec (= 46.5 ly/day). If this can be achieved by some means and maintained for sufficient time, a self-perpetuating advective process (runaway advection) will continue until a 1 bar atmosphere with a polar temperature of 190 K is established, assuming there is enough carbon dioxide available for sublimation. If less than 1 bar of carbon dioxide is present, the high pressure stable climate is determined by the total quantity of frozen carbon dioxide.

Sagan, Toon, and Gierasch (1973) have speculated on how a 20% increase in absorbed solar flux may be brought about. This can be accomplished by altering one or more of the planetary parameters listed below:

Planetary parameter	Present value	Value needed for runaway advection
Distance from Sun	1.5 AU	1.4 AU
Orbital eccentricity	0.09	0.49
Orbital obliquity	23.9°	31.0°
Polar cap albedo	0.77	0.73

Only the polar cap albedo seems even remotely within the realm of possible modification. Since the average albedo of nonpolar regions is approximately 0.25, and much of these regions are believed to be composed of fine particles, a relatively small admixture of sand or dust over the polar cap could reduce the albedo to the required 0.73. If such an albedo could be maintained for about a hundred years or so, advective instability might be triggered and a stable higher temperature climate obtained.

8. GENETIC ENGINEERING

Preceding sections of this report have discussed the possibility of evolving an oxygen atmosphere on Mars by photosynthesis. The generation of such an atmosphere would, however, take quite long. It is desirable to investigate ways by which the time required for atmosphere alteration might be drastically reduced. One such approach, previously discussed, would be to change the present Martian climate to one more conducive to plant growth. Another approach might be to alter the characteristics of presently available photosynthetic organisms such that they would be far better adapted to the present or altered Martian climate. Such factors as resistance to ultraviolet light, the temperature range required for optimal growth and photosynthesis, the absolute rate of oxygen production, ecological niche selection, etc., could be selected to fit not Earth environments for which contemporary organisms have evolved, but Mars environments.

This chapter discusses strategies, goals, and prospects for constructing an "ideal" Martian oxygenic organism using techniques of genetic engineering.

STRATEGY

Organisms and environments evolve together. Most organisms are specialized for optimal growth and reproduction in a particular ecological niche and do not readily adapt to others. Earth niches do not resemble Mars niches exactly and the organisms adapted to the various Earth niches will be ill-adapted to Martian ones. Thus, if growth of transplanted terrestrial organisms occurs at all, it will in all likelihood be meager. To generate an oxygen atmosphere by photosynthesis in the least possible time, it would be very desirable to use organisms capable of using available Martian niches in the most efficient manner possible. Constructing such organisms by techniques of genetic engineering presently available or under development is quite possible. There are numerous approaches to the design of Mars adapted organisms; one strategy might be the following:

1. Describe in detail the environmental characteristics of available Martian niches by direct observation and measurement.

2. Describe in detail those biological characteristics required of an "ideal" Martian organism adapted to these niches.

3. Isolate "best" terrestrial organisms most closely resembling "ideal" Martian organisms by searching in Earth niches most closely resembling the prospective Martian niches.

4. Determine which characteristics of these "best" organisms need modification as compared to the projected "ideal" organism.

5. Modify the characteristics so identified by genetic engineering thereby transforming "best" organisms into "ideal" organisms.

The environmental parameters of the current or modified Martian climate dictate the biological characteristics of organisms best adapted to these climates.

The predominant environmental factors facing organisms seeded on the surface of Mars have been discussed previously. Briefly, they include: mean temperatures below freezing, large diurnal temperature variations, strong ultraviolet irradiation, highly desiccating conditions, and frequent abrasive dust storms. The number of niches available for occupation by contemporary photosynthetic organisms is probably quite limited and determined by factors such as: protection against ultraviolet radiation, water availability, wind protection, intensity of visible light, local temperature hot spots, etc. Such niches might include, for example, subsurface soil layers above regions of permafrost in the mid-latitudes of the southern hemisphere. It may be expected that a relatively moderate increase in the mean planetary maximum temperature (e.g., 5–10 K) would have an ameliorating effect on many harsh environmental factors. There would be a larger envelope of liquid water in the soil above ice layers and permafrost, a higher water vapor pressure in the atmosphere, more total hours per day above 273 K, and moderated diurnal variations and dust storms. More extreme temperature increases would be expected further to optimize environmental factors such that, for example, pools of liquid surface water might be present and the range of maximum temperature on a large part of the planet would approach that considered optimal for many terrestrial organisms. The net result of these changes would be to increase greatly the total space and time available for growth, reproduction, and oxygen production by transplanted organisms and reduce the requirement for extreme genetic modification.

In any event, adaptation to factors such as high levels of ultraviolet radiation, recurrent freeze-thaw cycles, extended periods of dormancy and others, would be necessary.

While no terrestrial organism is ideally adapted to Martian conditions, is there a group which is "best" fit to grow, reproduce, and produce oxygen on Mars? Of all Earth environments probably the Antarctic dry valleys most closely resemble the current Martian surface. These valleys have four major oxygenic photosynthetic groups: green algae, blue-green algae, mosses, and lichens. Comparing selected properties of these groups with a hypothetical "ideal" Martian organism, it is found that, while none are ideal, the lichens and the blue-green algae are "best" (table 23).

TABLE 23.– BIOLOGICAL CHARACTERISTICS OF SOME TERRESTRIAL ORGANISMS AND AN IDEAL MARTIAN ORGANISM

Organism	Requires oxygen	Extreme resistance to ultraviolet radiation	Extreme resistance to drying	Growth rate	Growth habitat
Green algae	Yes	No	No	Fast (hr)	Soil (surface and sub-surface, snow (surface), water
Lichen	Yes	Yes	Yes	Very slow (yr)	Surfaces (rock, tree)
Moss	Yes	No	No	Slow (wk)	Moist surfaces
Blue-green algae	No	No	Yes	Fast (hr)	Soil (surface and sub-surface), water
Ideal Martian organism	No	Yes	Yes	Very fast (min)	Soil (surface and sub-surface), water

All groups, other than that of the blue-green algae, have a mandatory requirement for oxygen. The latter organisms will use oxygen if available; however, they can grow in the absence of oxygen (Stewart and Pearson 1970). To provide for the maximum rate of accumulation of photosynthetically produced oxygen, blue-green algae must be modified so that they will not utilize oxygen. All groups other than the lichens demonstrate a sensitivity to ultraviolet radiation such that survival times on the surface of Mars would be quite short. The blue-green algae can occupy subsurface soil niches and thereby could be shielded from the full effect of incident ultraviolet radiation. The very slow growth rate of the lichens is not consistent with the goal of rapid oxygen evolution. On balance, and considering the particular suitability of the blue-green algae as experimental material, especially from the viewpoint of genetic engineering, it is concluded that the blue-green algae is the group most fitted to be modified so as to provide "ideal" Martian organisms. The general ecology of this group is summarized by Cameron (1963) and the following is quoted by permission of the author:

"In general, the blue-green algae occur in all parts of the world where light and water are available. Individual species may be distributed in the various climatic zones, but others are found at extreme limits of the environment, from cold regions such as the Antarctic or in the cryoconite of Greenland (Gerdel and Drouet, 1960), and from the low elevation of the Dead Sea to mountains over 14,000 feet in altitude. They are a part of the salt marsh flora (Chapman, 1960), occur in extremely saline Great Salt Lake (Flowers), hard and soft waters (Palmer, 1959) and hot, dry desert soils (Cameron, 1961; Killian and Fehér, 1939). Planktonic forms, frequently a single species, may grow prolifically in favorable seasons when nitrates and phosphates are high and in some cases release obnoxious toxins (Prescott, 1959). Aquatic species have also been found in the lower sublittoral zone where light intensity is low (Ruttner, 1953), and in hot springs where the temperature may reach 86° C. (Kaplan, 1956). Other aquatic habitats can include industrial wastes with a high content of metals and acids (Palmer, 1959). More exotic habitats include associations with animals such as sponges, corals, and snails. In barren, eroded soil, on wood, in sewage, on and under light transmitting rocks, and even in areas of comparatively recent volcanic activity (Treub, 1888), it has been found that blue-green algae are able to grow and survive. Furthermore, it has been determined that the Eh range of blue-green algae is from −0.200 to +0.700 volts and the *p*H from 1.5 to 11 (Baas Becking *et al.*, 1960). That they can resist desiccation for decades has been shown in the revival of species from old, stored soils (Bristol, 1919). Reproduction can be quite rapid, and oscillatoroid forms can develop macroscopic growth in a few hours on desert soil which has remained dry for a number of years. Prolonged resistance to desiccation has been found in a dried herbarium specimen of nonspore-forming *Nostoc commune* previously revived after 88 years of storage (Lipman, 1944), and later revived after an additional time period of 19 years (Cameron, in press). Resistance is also found to low temperatures. At −80° C., algae, in combination with fungi as lichens have been found to survive, and at −30° C. to even photosynthesize slowly (James, 1955)."

PROSPECTS FOR GENETIC ENGINEERING

Research on bacteria and their viruses has yielded powerful tools for the manipulation of the genetic apparatus of cells. Genes, composed of deoxyribose nucleic acid (DNA), determine the protein enzymes of cells and these, to a large extent, determine the physical characteristics of cells. Thus if a cell has a certain characteristic, for example, a capability for rapid repair of damage from ultraviolet radiation, it is due to the presence of a particular gene or several genes. A cell which lacks such a rapid repair mechanism would lack these genes. The collection of physical and chemical attributes of an organism is called its phenotype, while the collection of genes determining an organism's phenotype is called its genotype. The goal of genetic engineering is the deliberate alteration of an organism's phenotype by changing its genotype, either by causing small changes in a specific gene or, more important, by integrating one or more foreign genes into the genetic apparatus of the organism. Nature, of course, has been involved in genetic engineering as long as DNA and evolution have coexisted. Genetic engineering has been used for many years by plant and animal breeders to produce strains having particular characteristics.

The current interest in genetic engineering, however, reflects the recent discovery of powerful biological and chemical techniques for the creation of new genotypes. These techniques include ways of generating new genes from pre-existing genes, and for moving genes from donor to recipient organisms, thereby creating new combinations of pre-existing genes.

The primary way that modified genes can be generated from pre-existing genes is by the process of mutation in which small random changes in the chemical structure of a gene are brought about by exposure to certain chemical or physical agents. Recent advances in understanding of gene structure and in methods for the *in vitro* chemical *de novo* synthesis of genes, suggest an alternative, potentially extremely powerful, technique for generating new genes.

More important to the field of genetic engineering, and to the particular goal of the creation of an ideal oxygen-evolving organism for Mars, are techniques of moving about pre-existing genes among organisms, so as to create organisms having a particular phenotype. Nature has used sexual recombination to accomplish this for millenia. Other techniques have been developed in the laboratory. Transformation is a process in which DNA is extracted from donor cells and taken up by recipient cells. This foreign donor DNA (containing the genes for desirable traits) can be integrated into the genetic apparatus of the recipient cell, thereby endowing these cells and their progeny with the desired trait. Transduction is a similar process differing from transformation by the use of certain viruses as the donor vehicle by which genes, incorporated into the virus, can be moved into recipient cells. Recently a new, and potentially extremely effective, means of introducing genes from one organism into another, quite dissimilar, organism has been described (Cohen *et al.*, 1973). Referred to as plasmid engineering, it utilizes a specific small genetic element, a plasmid, as a vehicle for introducing genes into cells. It differs from the previous techniques mentioned by allowing the use, in principle, of *any* gene from *any* donor (e.g., Morrow *et al.*, 1974). By the use of certain specific enzymes the desired gene is joined to the plasmid and the gene/plasmid complex introduced into recipient cells.

Once in the cell the gene/plasmid complex can form a stable, genetically functional unit which replicates and is passed on to the progeny of the original recipient cell.

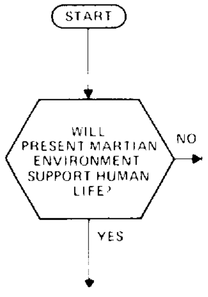
It is by judicious use of these techniques that an "ideal" oxygen-evolving Martian organism might be created.

Until recently only limited information has been gathered on the genetics of blue-green algae, a reflection of both the difficulty in obtaining appropriate mutants, and in growing the organisms in the appropriate media. Both these obstacles have been overcome and some information on the genetic systems of these organisms is becoming available and, it may be assumed, will continue to do so at an ever increasing rate. Several techniques associated with genetic engineering have been demonstrated in a few species of blue-green algae, i.e., chemical mutagenesis, sexual recombination, and transformation with DNA (Kumar, 1962; Bazin, 1968; Shestakov and Khyen, 1970; Herdman and Carr, 1971; Orkwiszewski and Kaney, 1974; and Stewart and Singh, 1975). Another technique, viral transduction, while not yet demonstrated, is quite likely (Padan and Shilo, 1973). The presence of plasmids in the blue-green algae has not been demonstrated.

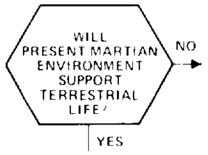
The initial description of sexual recombination in blue-green algae has been challenged; however, several recent independent reports seem to have placed this phenomenon on firm ground. Chemically extracted and purified DNA, as well as DNA released by cells in growing cultures of blue-green algae, has been used for genetic transformation experiments. Transduction is dependent upon the sensitivity of the cells to a class of viruses called "temperate" viruses. These viruses have the property of acting as carriers of genes between donor and recipient cells. Temperate viruses have been isolated which can infect blue-green algal cells. The transfer of genes between the algal cells by transduction, however, has not yet been reported. The present ability to generate new genomes in the algae by mutation and recombination, coupled with continued genetic research in these organisms and the related bacteria, suggests that the design and construction of organisms specifically adapted to the various Martian niches are quite possible. The use of these special strains would be critically important in any attempt to generate an oxygen atmosphere on Mars.

9. CONCLUSIONS

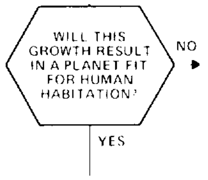
In figure 1 a series of questions was posed which would allow an assessment of the capacity of Mars to be inhabited. Answers to these questions, generated by the considerations presented in the body of this report, are outlined below.



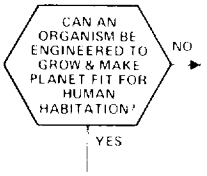
Clearly, the lack of an oxygen atmosphere by itself is enough to prevent Mars from being inhabited by man. The diurnal temperature fluctuations, intense ultraviolet radiation, and dust storms can be dealt with by adequate shielding. For Mars to be truly habitable, these environmental factors must be moderated and a breathable atmosphere generated.



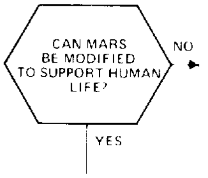
The lack of oxygen in the atmosphere will not prevent the growth of all terrestrial organisms; anaerobic bacteria particularly must be considered capable of existing in specific Martian microhabitats. Possibly, photosynthetic blue-green algae or lichens can survive also in specific microhabitats.



While the growth of bacteria is possible, such growth will not modify the Martian environment so as to allow human habitation because bacteria do not produce oxygen. However, limited growth of blue-green algae and lichens is possible and they do generate oxygen. The rate at which it would accumulate in the atmosphere would be very slow, for example, 100,000 years to produce a breathable atmosphere. This is due to a combination of environmental effects and inherent biological limitations. For example, the intense ultraviolet radiation and low temperatures are environmental factors that will limit the extent and vigor of surface growth; and biologically, the rate of lichen reproduction is also very slow.



It is possible to envision genetic modification of specific terrestrial oxygen-generating organisms in such a way that they might be far better adapted to the present martian environment with regard to survival, growth, and oxygen production. Such modification might dramatically increase the probability of generating an oxygen atmosphere and greatly decrease the time needed for its generation.



It is possible to envision modifying the Martian climate such that it might be far more conducive to the extensive biological growth necessary to produce an oxygen atmosphere. Temperature manipulation particularly seems the key to unlocking the potential of Mars for human habitation. Greenhouse effects and advective warming could bring about an increase in planetary surface temperatures. This increase could cause additional environmental changes of the kind conducive to the growth of terrestrial organisms.

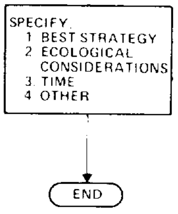


Figure 18 presents a suggested scenario for the production of an oxygen atmosphere on Mars. A key step is a moderate increase in the surface temperature to a level at which carbon dioxide would sublime and water might exist in the liquid state. It is impossible to give reliable estimates of the times required for the individual steps in the scenario, or indeed, of the scenario itself other than to suggest that time spans of 10,000 to 100,000 years might be required. Radical changes in either the climate of Mars or the organisms available would considerably reduce the time required to produce an oxygen atmosphere. Mechanisms for the concentration and storage of atmospheric oxygen would allow Mars to be inhabited by man in even shorter periods.

On the basis of information currently available the study group concluded that:

1. No fundamental, insuperable limitation to the ability of Mars to support terrestrial life has been unequivocally identified. However, important data are not available, for example, the extent of water reserves and the composition of the polar caps. These data must be acquired before a more accurate assessment of the habitability of Mars can be made.

2. For human life to exist, the creation of an oxygen atmosphere is mandatory. Such an atmosphere might be generated by present terrestrial photosynthetic forms, but the time required is on the order of tens of thousands of years.

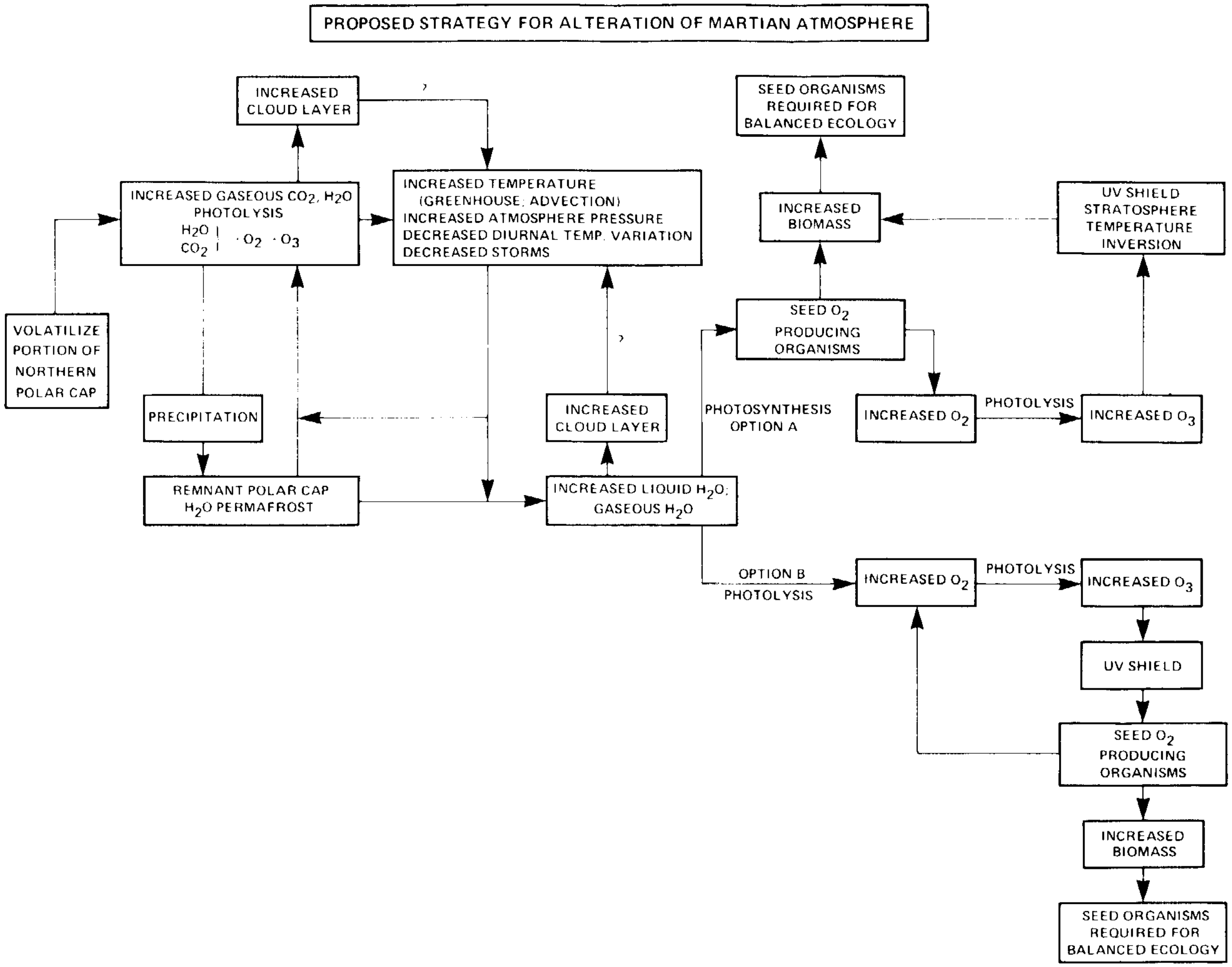


Figure 18.– Proposed strategy for the alteration of the Martian atmosphere.

3. Climate modification leading to an increase in surface temperature might be carried out by a combination of advective and greenhouse effects initiated by the injection of polar cap sublimate into the atmosphere. This injection would need to be carried out for a long time at the expenditure of amounts of energy equivalent to the amount of solar energy incident on Mars for several years.

4. Mechanisms of genetic engineering currently available or under development could be used to construct organisms far better adapted to grow on Mars than those terrestrial organisms presently available.

5. Altering either the Martian environment or available photosynthetic organisms, or both, would significantly decrease the time required to create an acceptable human habitat on Mars. Indeed, it may be mandatory to do so. If these steps are taken, Mars may well be made into a habitable planet.

10. APPENDIX A: BIOLOGICAL CHARACTERISTICS OF GROWTH OF LICHENS AND CYANOPHYTES ON MARS

GENERAL MATHEMATICAL APPROACH

To determine the coupling between organisms and the Martian environment, an energy balance model representing two terrestrial organisms – blue-green algae and lichen – has been developed. Given the environmental parameters, the temperature of the organism is determined with the assumption that it is in energy balance. The transpiration rate of the organism can then be determined as well as its ability to photosynthesize.

The major physical processes controlling the temperature of the organism are solar and thermal radiation, convective and conductive energy transport, and evaporative cooling. Solar and thermal radiation from the atmosphere provide an energy source for the organisms; the solar radiation reaching the organism depends upon the transparency of the atmosphere and, of course, varies with Martian latitude, season, and time of day. Maximum solar radiation at the surface occurs near the equator at local noon and is about 0.86 ly/min. The planetary or thermal radiation depends upon the atmospheric temperature, primarily that of the lowest few kilometers, and the amount of gas which can absorb this thermal radiation. On Mars the gas is primarily CO_2, which absorbs radiation in the 15 μm spectral region and produces an energy flux of about 0.02 ly/min at the surface. Solar radiation is coupled to the organism by the ability of the organism to absorb this radiation, which is given by an absorptivity, a. For all practical purposes, the organism absorbs all of the planetary radiation incident on it, so the radiation absorbed by the organism can be given as:

$$R = aQ_s + Q_p \qquad \text{(A1)}$$

where Q_s is the incident solar radiation and Q_p the absorbed planetary radiation.

Heat transport either to or from the organism occurs at the upper and lower surfaces if there is a difference in temperature between the organism and the air or ground or both. At the upper surface molecular conduction transports heat down the temperature gradient across a laminar boundary layer of thickness δ^a cm which is related to a mean wind speed near the surface V (cm/sec) and a characteristic organism dimension D (cm) by the expression,[2]

$$\delta^a = 0.4(D/V)^{1/2} \tag{A2}$$

If the near surface air temperature is lower than the temperature of the organism, then heat is conducted from the organism through the boundary layer and rapidly diffused by eddy transport into the atmosphere. The opposite occurs if the organism's temperature is lower than the near surface temperature. An expression for this convective-conductive energy transport C_{top} is

$$C_{\text{top}} = K_{\text{air}}(T - T_a)/\delta^a \tag{A3}$$

where T, T_a are the temperatures (K) of the organism and air; K_{air} is the thermal conductivity for CO_2, the major constituent of the Martian atmosphere; and K_{air} is approximately 35×10^{-6} cal/sec cm deg at about 273 K.

Heat transport by conduction will occur if the organism is in contact with the surface. An expression analogous to that above can be written,

$$C_{\text{bottom}} = K(T - T_g)/\Delta \tag{A4}$$

where Δ is a characteristic half thickness of the organism and K is a corresponding mean thermal conductivity. These parameters are determined by the biological model and are discussed in the next section. Molecular conduction with the surface influences strongly the temperature of the organism.

Two processes which allow the organism to rid itself of energy are thermal emission and evaporative cooling (transpiration). Every body radiates energy according to its temperature, and solid and liquid bodies radiate nearly as black bodies, that is,

$$I = \epsilon\sigma T^4 \tag{A5}$$

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[2] Recent work has shown that the coefficient is probably closer to 3 than 0.4. However, this change does not significantly influence the cyanophyte results. In the lichen model, temperatures are more closely controlled by the surface, the lichen temperature being within 10 K of the surface. Water loss is larger but photosynthetic rates are about the same.

where σ is the Stephen-Boltzmann constant and ϵ is the emissivity which is close to unity; for example, for water at room temperature, the emissivity is about 0.95. For every gram of water evaporated from an organism, about 580 cal of heat are required. This loss of heat energy can be represented as,

$$E = 580\, {}_{s}d_{t}/(r_t + r_a) \tag{A6}$$

where ${}_{s}d_{t}$ is the saturation water vapor density (g/cm^3) at the temperature of the organism, r_t is the internal resistance which the organism offers to water loss, and r_a is the air resistance across the laminar boundary layer given by

$$r_a = \delta^a / D_{H_2O\text{-}CO_2} \tag{A7}$$

where $D_{H_2O\text{-}CO_2}$ is the diffusion coefficient for H_2O near the Martian surface and is about 29.2 cm^2/sec.

The energy balance equation can now be written symbolically,

$$R = C_{\text{top}}(T) + C_{\text{bot}}(T) + I(T) + E(T) \tag{A8}$$

and for a given biological model and assumed environmental parameters, the temperature of the organism can be determined. The water loss or transpiration rate is given by equation (A6), that is, $E/580$.

GENERAL ASPECTS OF MODEL

With the exception of several individual variables, to be discussed subsequently, the general mathematical formulae for both the cyanophyte and lichen models are the same. Treatments for both models are similar to those employed in studies of energy exchanges and photosynthetic production in leaves of higher terrestrial plants (Gates, 1968; Gates, 1970; Nobel, 1970). It is assumed that the complete budget of energy exchange between the organism and its environment can be represented by the equation:

$$R = \epsilon\sigma T^4 + k(V/D)^{1/2}(T - T_a) + K(T - T_g)/\Delta + 580[{}_{s}d_{t} - (RH)({}_{s}d_{a})]/(r_t + r_a) \tag{A9}$$

The individual variables have been defined elsewhere (see pp. 85-87, 95-96). The total energy budget for a hypothetical organism, living on, or just below, the Martian surface, can therefore be summarized as the sum of three terms. The first term consists only of the organism's temperature and emissivity. The remaining three terms consider the energy flux resulting from convection (air temperature and wind speed), conduction, and transpiration (evaporative cooling), respectively. In this discussion the last term is of primary interest, since it necessarily involves the water loss the organisms will sustain in response to the other physical variables which characterize the surface microclimate. To evaluate the evaporative cooling component of the energy budget, the characteristic resistance of the organism to water loss (r_t) must be measured or calculated. Once the total resistance of the organism to water flow is evaluated (the sum of r_t and the resistance, r_a, due to the nonturbulent air layer above the organism), the flux of water vapor may be calculated from Fick's first law of diffusion:

$$J = \Delta C / R^{\text{tot}} \tag{A10}$$

where J = total water vapor flux, ΔC = the change in water vapor concentration between the inner portions of the organism and the atmosphere, and $R^{\text{tot}} = r_t + r_a$. The model can thus estimate the desiccation stress a hypothetical organism will be subjected to within the accuracy to which these parameters are known or are calculated. Estimation of the resistance values for both models is discussed for each case subsequently.

Of critical importance is the potential for photosynthesis of a terrestrial organism on the Martian surface. It is acknowledged that photosynthesis involves a complex set of metabolic interactions which are subject to numerous controlling elements. The consideration of photosynthesis on this higher level, although perhaps more complete, is far beyond the scope of the present model. The study group chose to represent the organism's photosynthetic rate as a function of several major limiting variables, which include temperature (T), light intensity (I), CO_2 concentration (C_{CO_2}), and water vapor concentration, or saturation, of the organism (S). Furthermore, these last three elements (I, C_{CO_2}, and S) can be thought of as limiting "substrates" to enzymatically controlled reactions (Gates, 1970). Since these reactions proceed according to Michaelis-Menton kinetics, the individual influence of each element is represented by a kinetic term of the form:

$$P = P_m / (1 + K/X) \tag{A11}$$

where P = photosynthetic rate, P_m = maximum possible photosynthetic rate, K = the "Michaelis constant" for the reaction, and $X = I, C_{CO_2}$, or a function of S ($f(S)$). Following the assumption of Gates (1970) the photosynthetic rate of the organism, as controlled by these three variables is represented as the product of the kinetic terms representing each limiting variable:

$$P = \frac{P_m}{(1 + K1/I)(1 + K2/C_{CO_2})(1 + K3/f(S))} \qquad \text{(A12)}$$

where $K1$, $K2$, and $K3$ are the constants applicable to I, C_{CO_2}, and S, respectively. Before these parameters are further evaluated, the controlling influence of the temperature (T) upon the process must first be considered.

Temperature can be thought of as influencing photosynthesis in two ways. The first is a specific effect; the maximum net photosynthetic rate is a function of temperature. Strictly speaking, this means that light compensation points change as a function of T also. A complex model would have to consider T as a variable in a set of differential equations used to describe respiration and photosynthesis. The study group's Martian models, however, have an advantage over those which might be formulated for terrestrial conditions in this respect. The temperature range over which the hypothetical organism may photosynthesize is limited to that of approximately 260–285 K. Measurements of photosynthetic rates of terrestrial organisms in this temperature range show that photosynthesis and light compensation points are relatively low, and they do not change drastically with change in temperature (Lange, 1969; Lange and Kappen, 1972; Fogg and Than-Tun, 1960; Gates, 1968). Rates and light compensation points may change by less than a factor of about 5 (and usually by only 2 or 3 times). This limited range is not significant to the model for several reasons. First, the accuracy and precision of the predictions from the model depend entirely upon the nature of the component variables, such as the actual values for temperature, resistances, thermal conductivities, and other physical factors. The cumulative error in their estimation makes it seem unlikely that variations as small as one order of magnitude are significant. Second, the biological parameters (resistances, "Michaelis" constants, and observed photosynthetic rates) vary considerably among species, and therefore a mean value, derived for a hypothetical case, will inherently possess a large standard deviation. Finally, the ultimate organism(s) used for Martian atmospheric manipulation may have very different properties due to genetic engineering. These factors, combined with the fact that the experiments which were used for the estimation of the variables rarely approached "true" Martian conditions of temperature and pressure, justifies neglecting the variation of maximum photosynthetic rates with temperature. The aim was to obtain "reasonable" (in some cases optimistic) values, and factors which would contribute only higher order effects (variations) to the models were not considered.

Temperature generally provides a controlling influence on photosynthesis in the model. Photosynthetic production, as are all cellular metabolic processes, is sensitive to freezing. This factor, therefore, can determine the cutoff points in both cases. The physical property of solute induced freezing point depression implies that cytoplasm, which may contain relatively high "solute" concentrations, will remain liquid (gel) at temperatures below 273 K. In lichens, for example, net photosynthesis has been observed as low as 262 K (Lange and Metzner, 1965). The cutoff temperatures for the models were chosen arbitrarily to be at 260 K and 273 K for lichens and algae, respectively. Given the general properties common to both cases, a discussion of some of the individual factors for each model can take place.

PARAMETERS OF CYANOPHYTE MODEL

Figure 8 shows the proposed schematic for the blue-green algal model. The organisms are envisioned as existing in a thin layer of interdigitating filaments. They may be surrounded by a gelatinous covering and can reside at or just below the surface of the planet. Since such algal mats are commonly crusty or "cuticose" in their upper segments, a desiccated layer is proposed to exist overlying the "active" cells. This desiccated layer, it is suggested, may initially result from exposure of cells to the rapid moisture loss, which would be characteristic of the Martian environment. This layer may attain a thickness equivalent to that of the active cell layer, and this desiccated matrix might provide an additional barrier to water loss by the underlying cells. The resistance property of the desiccated cell layer is an important variable in the model. The thickness of the active cells has arbitrarily been chosen at 500 μm. By terrestrial standards this is relatively thin, however, it is assumed that the severe Martian environmental conditions would not permit luxurient growth. This layer is in intimate contact with the surface or immediate subsurface of Mars and consists arbitrarily of 50% cells by volume. The remainder is proposed as being water-saturated air. In view of the extremely low atmospheric pressures on Mars, it was thought unreasonable to postulate a liquid water layer, although its presence would be of little consequence to this model. It was desired to vary the thickness and resistivity (resistance per unit thickness) to establish the influence of this property upon certain of the other variables.

Resistances to Water Transpiration

The diffusion resistance is a critical model variable since it directly influences water flux and thus indirectly affects the organism's temperature and photosynthetic rate. Figure 8 indicates that the overall resistance can be represented as the sum of several component resistances in series. This representation is similar to that employed by Nobel (1970) in his discussion of leaf transpiration. The total resistance to water vapor diffusion (R_{wv}^{tot}) is equivalent to the sum of the resistances of the cell wall covering (R_{wv}^{cw}), the intercellular air space (R_{wv}^{ias}), the desiccated cell layer (R_{wv}^{dcl}), and that due to the undisturbed boundary air layer immediately above the organism (R_{wv}^{a}). Values are estimated for these individual resistances as follows.

All water vapor diffusion occurs upwards from the saturated cell walls, through the cell wall covering, the intercellular air space and desiccated layer, to the outside atmosphere (crossing through the nonturbulent air boundary layer).

$$R^{tot}_{wv} \cong R^{cw}_{wv} + R^{ias}_{wv} + R^{dcl}_{wv} + R^{a}_{wv} \tag{A13}$$

The effective mean diffusion path from the cells through the intercellular air space is δ^{ias}; the effective mean diffusion path length through the nonturbulent air layer is δ^{a}.

R^{cw}_{wv} is dependent upon the composition of any layer (e.g., cuticle, sheath, gelatinous matrix) surrounding the cells. In plant leaves, a waxy layer may be incorporated into the cell wall (Nobel, 1970). Since this is reported to vary in resistance from 0.1 to 0.2 sec/cm for mesophytes, and up to 2 sec/cm for xerophytes, $R^{cw}_{wv} = 2$ sec/cm (assuming a high degree of drought adaptation).

R^{ias}_{wv} can be calculated from

$$R^{ias}_{wv} = \delta^{ias}/D_{H_2O} \tag{A14}$$

where D_{H_2O} is the diffusion coefficient for water vapor in Martian air. Assuming δ^{ias} is 50% of the thickness of this layer, then $\delta^{ias} = 250\ \mu m$; $R^{ias}_{wv} = 250/D_{H_2O}$.

R^{dcl}_{wv} is designated as a variable resistance, since its value is a model parameter. It may be dependent upon a number of properties; for example, age of the mat, numbers of cells dying, and the precise composition of the dead (or desiccated) cell layer matrix (desiccated cells are assumed to be physiologically inactive). Since a xerophytic adaptation of the cell wall (and/or surrounding sheaths) is assumed, it is logical that the resistance to water vapor diffusion be significantly large; perhaps equivalent to the cutinized layer in xerophytic plant leaves, which have resistances in the 200 sec/cm range. Therefore a maximum resistance of 1000 sec/cm and a maximum layer thickness of 500 μm were selected. This resistance can be represented as the product of the resistivity of the layer (r^{dcl}_{wv}) and its thickness (1^{dcl}); $R^{dcl}_{wv}) = (r^{dcl}_{wv})(1^{dcl})$, where r^{dcl}_{wv} varies from 200 to 2 E+4, and 1^{dcl} varies from 0 to 500 μm.

The diffusion pathway through the nonturbulent air layer (δ^{a}) varies with wind speed, and can be calculated from this value. Thus, R^{a}_{wv} is calculated using:

$$R^{a}_{wv} = \delta^{a}/D_{H_2O} \tag{A14a}$$

The total resistance to the diffusion of water vapor for the cyanophyte mat, as explained above, can be summarized as:

$$R^{tot}_{wv} \cong R^{cw}_{wv} + R^{ias}_{wv} + R^{dcl}_{wv} + R^{a}_{wv} = R^{cw}_{wv} + [(D_{H_2O})^{-1}(\delta^{ias} + \delta^{a})] + (r^{dcl}_{wv}\ 1^{dcl}) \tag{A15}$$

Cyanophyte Mat – Resistances to CO_2 Diffusion

The ratio of the surface area of the cells within the mat to the exposed surface area of the mat ($A^{\text{cells}}/A^{\text{mat}}$) can be used as a correction factor to compensate for the increase of surface area which is available for CO_2 diffusion. This results from the fact that the ultimate "destination" for CO_2 (a substrate for photosynthesis) lies at the chlorophyll inside the cells. Thus CO_2, in addition to the water vapor diffusion pathway, must also diffuse past the cell wall and through the cytoplasm of the cell. This necessitates the estimation of the additional resistances presented by this increased path length through such structures as the saturated cell wall, plasmalemma, and the cytoplasm. The total resistance to the diffusion of CO_2 is the sum of the following:

a. resistances also encountered by water vapor

$$(R^{cw}_{CO_2} + R^{ias}_{CO_2} + R^{dcl}_{CO_2} + R^{a}_{CO_2})$$

b. cell wall resistance ($R^{w}_{CO_2}$)

c. plasmalemma resistance ($R^{pl}_{CO_2}$)

d. cytoplasmic resistance ($R^{cp}_{CO_2}$)

Proceeding in a fashion similar to Nobel's (1970) analysis:

$$R^{j}_{CO_2} = \frac{A^{\text{mat}}}{A^{\text{cells}}} \cdot \frac{\Delta x^{j}}{D^{j}_{CO_2}\, K^{j}_{CO_2}} \qquad \text{(A16)}$$

where

$R^{j}_{CO_2}$	resistance of the jth barrier to CO_2 diffusion
Δx^{j}	thickness of the jth barrier
$D^{j}_{CO_2}$	diffusion constant of CO_2 in the jth barrier
$K^{j}_{CO_2}$	partition coefficient for the barrier

Assuming $D^{w}_{CO_2} \cong 5\ E\text{-}6\ \text{cm}^2/\text{sec}$, and $K^{w}_{CO_2} \approx 1.0$ (Nobel, 1970), and Δx^{w} (thickness of the cell wall) is 0.1 μm,

$$R^{w}_{CO_2} \approx 0.01\ \text{sec/cm}$$

(if $A^{\text{mat}}/A^{\text{cells}} = 1/200$).

Plasmalemma Resistance to CO_2 Diffusion

In a fashion which is again similar to Nobel's (1970) analysis: assuming that the permeability coefficient for CO_2 entering algal cells (P_{CO_2}) ≈ CO_2 entering plant cells, which is "at least" 0.01 cm/sec, $R^{j}_{CO_2} = (A^{mat}/A^{cells})/P_{CO_2} = 0.5$ sec/cm.

Cytoplasmic Resistance to CO_2 Diffusion

Using (A16) where $\Delta x^{cp} = 1\ E\text{-}5$, $D^{cp}_{CO_2} = 1\ E\text{-}5$ cm²/sec, $K^{cp}_{CO_2} = 1$, and $A^{mat}/A^{cell} = 5\ E\text{-}3$, then $R^{cp}_{CO_2} \approx 5\ E\text{-}3$ sec/cm.

It is therefore concluded that the additional resistances to CO_2 diffusion ($R^{w}_{CO_2} + R^{pl}_{CO_2} + R^{cp}_{CO_2}$) are negligible compared to the magnitudes of ($R^{cw}_{CO_2} + R^{ias}_{CO_2} + R^{dcl}_{CO_2} + R^{a}_{CO_2}$). It is assumed that the resistances to diffusion of water vapor and CO_2 are inversely related to the ratio of their diffusion constants (Nobel, 1970). At Martian surface pressures the diffusion constant of CO_2 in CO_2 (D_{CO_2}) is 22.3 cm²/sec, and the constant for water in CO_2 (D_{H_2O}) is 29.2 cm²/sec. The resistance of the *j*th barrier to CO_2 diffusion can be calculated from its resistance to water vapor diffusion by the equation:

$$R^{j}_{CO_2} = R^{j}_{wv}(D_{H_2O}/D_{CO_2\text{-}CO_2}) \cong 1.31\, R^{j}_{wv} \tag{A17}$$

The total resistance to CO_2 diffusion can be represented as follows:

$$R^{tot}_{CO_2} \cong R^{cw}_{CO_2} + R^{ias}_{CO_2} + R^{dcl}_{CO_2} + R^{a}_{CO_2} = 1.31(R^{cw}_{wv} + R^{ias}_{wv} + R^{dcl}_{wv} + R^{a}_{wv})$$

Estimation of Substrate Constants for Photosynthesis

The equation for net photosynthetic rate (equivalent to the net rate of CO_2 uptake) has been given previously by equation (A12). The third term of the denominator of this equation applies only to the subsequent lichen model; therefore, $K3 = 0$ for the cyanophyte model. To complete the model, three parameters (P, $K1$, and $K2$) must be estimated. Unfortunately, these parameters must be evaluated from experimental data contained in the physiological literature on blue-green algae. The experimental conditions used to derive these data did not reflect Martian surface conditions, so that the results derived from using these values must be interpreted with caution. It was desired to obtain reasonable or plausible values, and not to achieve results which would be truly indicative of an actual Mars colonization experiment. The same quantitative approach can be employed when more accurate estimates of the critical parameters become available.

Using the data of Kratz and Myers (1955), P_m was estimated from a manometric experiment to be 8 *E*-7 moles (CO_2 or O_2)/cm^2 surface coverage/hr. This relies upon the estimate of the study group that 1 g dry wt of algal culture represents 800 cm^2 coverage of a mat which is 0.05 cm thick. These same investigators gave plots of net photosynthetic rate versus light intensity and photosynthesis versus CO_2 concentration, which were used to estimate $K1$ and $K2$, respectively. If the values of these constants are taken to be numerically equivalent to the "substrate" concentrations at one-half the maximum photosynthetic rates, the values of $K1$ and $K2$ are 6 *E*-3 ly/min and 4 *E*-6 molar, respectively. It is pointed out that the predictions of this model are sensitive to these values for P_m, $K1$, and $K2$. The data used in their estimation were derived from laboratory cultures incubated under "optimal" conditions for only several species (at 298 K). In a sense, these may represent unrealistic values (i.e., maximal) for Mars. On the other hand, the actual P_m value is sensitive to the (1 g dry wt $\approx$ 800 cm^2) surface area assumption, since the rates were originally derived on a per gram dry weight basis. It should be recognized that all of these errors may interact either antagonistically or synergistically to influence the net photosynthetic production which is predicted by the model. This concludes the estimation of all variables needed to calculate the energy budget and photosynthetic production for the cyanophyte mat model.

Since it is difficult to estimate the extent of water loss under which the cells can sustain photosynthesis, an arbitrary cut-off point has been selected. The model assumes that the photosynthetic rate, calculated from equation (A12), will be sustained until 10% of the total water content of the cells has been lost by transpiration. At this point the cells are assumed to be in a quasi-dormant state of metabolic shut-down. The "active" cell layer is hypothesized to remain in this state throughout the remainder of the day, until the following sunrise. At this time, presumably, the cells can regain the water lost during the previous day and can proceed with photosynthesis at their normal rate. Parenthetically, the presence of a "subsurface water source" is required for the existence of any life, as we know it, on Mars. The cells can also be shut-down by an organism temperature of less than 273 K. By estimating the diurnal change in radiation flux on Mars, the model can be given a time dependent feature. The diurnal fluctuations will control the rate of water loss and the temperature of the organisms. The period of time during which they are physiologically capable of photosynthesis can be computed by the above criteria. The net photosynthetic production per day can then be calculated as the sum of the products of the instantaneous photosynthetic rates over short time intervals of active metabolism. This solution approaches a true net production as the limit of the time intervals approaches zero.

The authors acknowledge the fact that this approach is appropriate in view of the large errors which are inherent in the estimation of some of the critical parameters. They stress that this type of model can be improved immensely in order to make it appropriate to more accurate determinations of the physical parameters of Mars, which will result from currently planned probes. They urge that further research on the biological aspects of the model be conducted from at least two standpoints. First, there is a need for a more rigorous mathematical description of the photosynthetic and respiratory metabolic activities of the organisms to be modelled. Second, a better evaluation of the critical photosynthetic parameters (e.g., P_m, $K1$, $K2$, $K3$, etc.) should be made for those organisms which may be considered primary candidates for Martian inoculation. Experiments under simulated Mars surface conditions should be run to obtain better estimates of these variables for future models. The coordination of these two research efforts will provide future predictions pertinent to all future planetary engineering feasibility and design studies.

PARAMETERS OF LICHEN MODEL

The schematic representation of the study group's lichen model is presented in figure 7. Its structure and the representation of the variables are very similar to those employed in the algal model already discussed. As the diagram indicates, the lichen is envisioned as growing on the Martian surface, and is fully exposed to solar radiation. It could also be buried just beneath the surface, covered with sand. The segment of the lichen which is modelled is a rectangular parallelepiped of square upper surface, with an edge length of 1 cm. The thickness of this segment is T cm, including the layer of active algal and fungal symbionts in a homogeneous matrix (25% cells by volume), and a very thin "cuticose" protective layer over the top surface. Its total thickness can vary from 0.05 to 0.3 cm. A nonturbulent air layer presents an additional boundary to diffusion, and is a function of the wind speed. Inputs to and outputs from the system are the same as those in the cyanophyte model. The basic general assumptions are also the same as in the previous case, except that the minimum temperature at which the organism is photosynthetically active is set at 260 K (as opposed to 273 K). This cut-off temperature is reasonable in light of published observations (e.g., Lange and Kappen, 1972).

Resistance to Water Vapor Diffusion

Rather than calculate individual resistance components, as was done for the algal model, the total effective resistance (R^l) was estimated empirically. Stocker (1927) reported water loss and uptake rates for two lichen genera, *Usnea* and

Parmelia. These data were used to estimate a reasonable value for the overall resistance to water vapor flux. The rate (E) at which water vapor escapes from a plant leaf by diffusion is:

$$E = \frac{{}_s d_t - RH({}_s d_a)}{r_t + r_a} \tag{A18}$$

where

${}_s d_t$	water vapor density within the organism considered saturated at the organism temperature
RH	relative humidity of the surrounding atmosphere
${}_s d_a$	saturation vapor density of the surrounding air at the air temperature
r_t	resistance of the organism to water vapor diffusion
r_a	the diffusion resistance of the external pathway

Solving this equation for the total resistance ($R^{tot} = r_t + r_a$) and applying it to the data of Stocker (1927) for the lichen segment yields a total resistance to water vapor diffusion of 4.6 E-2 min/cm, under the assumption that 1 gm dry wt = 25 cm^2 surface area covered. This seems to be a reasonable empirical value for the resistance to water vapor diffusion, but the value is sensitive to the (dry weight):(surface area coverage) conversion factor. Unfortunately, the variation in this factor may span one to two orders of magnitude (Blum, 1973).

The estimate of R^l_{wv}, also allows the calculation of $R^l_{\mathrm{CO}_2}$ by equation (A17). The resistance (R^a) due to the nonturbulent air layer can be calculated from the wind speed as noted previously.

Parameters for Lichen Photosynthesis

The critical variables for equation (A12) can be estimated from data contained in the literature, as was done for the algal model. The major factors which influence the photosynthetic rate are the percentage water saturation of the lichen thalli, temperature, CO_2 concentration, and light intensity (Lange, 1969; Lange and Kappen, 1972). From the data which Lange (1969) gives for some Negev Desert lichen species, $K1$ and P_m were estimated to be 1.25 ly/min and 1.4 E-6 moles/cm^2/hr, respectively. The parameter $K2$ retains the same value which it was given previously (4 E-6 M).

The final parameters which must be evaluated are those pertaining to water saturation in equation (A12). The data of Lange (1969) showed that lichen photosynthesis, as a function of the degree of water saturation of the thallus, roughly followed first order and then zero order kinetics. This effect has been represented similarly to the way in which the influences of light intensity and CO_2 concentration were modelled. The last term in the denominator of equation (A12), $[1 + K3/f(S)]$, uses this "Michaelis-Menton" kinetic approach. The controlling influence of water content is represented by the parameters $K3$ and $f(S)$. The water saturation variable (S) is defined as the amount of water in the lichen thallus as a percentage of its dry weight. For example, $S = 100\%$ if 1 gm dry weight of lichen thallus contains 1 gm of water. Since $S = 100\%$ falls within the middle of the observed maximum water saturation range, this value was selected as the maximum possible water content. A further complication is that the minimum water saturation to permit active metabolism is 20%. Since the photosynthetic cut-off point does not occur at zero percentage water content, the expression $f(S)$ must be formulated to compensate for this. In a 0.3 cm thick lichen segment, 80% water loss (the assumed cut-off point) (Kappen, 1973) occurs at a net loss of 40 mg water/cm^2 surface area covered. Therefore,

$$f(S) = \frac{40 - (\text{mg } H_2O \text{ lost per cm}^2)}{40} \times 100 \quad \text{for} \quad S > 20 \qquad \text{(A19)}$$

This concludes the estimation of all important parameters in the lichen model.

From the standpoint of inherent error, the study group offers the same cautions as those pertaining to the cyanophyte model. It is suggested that laboratory investigations be conducted which are designed to obtain more reliable estimates of the critical parameters. It is also important, with respect to Martian planetary engineering, that further work be done concerning the viability of lichens under anaerobic conditions.

11. APPENDIX B: GREENHOUSE EFFECT

The mean global change in surface temperature which would be affected by carbon dioxide and water vapor in the atmosphere of Mars has been discussed in chapter 5; this appendix describes the methodology used for those calculations.

A mean thermal profile is assumed (Noll and McElroy, 1974) and shifted uniformly in temperature until the outgoing planetary flux at the top of the atmosphere balances the absorbed solar radiation, which is taken as 1.28×10^5 ergs/cm^2 sec. It is assumed that carbon dioxide absorbs negligible solar radiation so that the above value is fixed for all the carbon dioxide calculations. This is not true, however, for a water vapor greenhouse effect. The absorption of solar radiation by water vapor was calculated from the absorptivities for the eight water bands extending from 0.8 to 6.3 μm (Rodgers, 1967). For the assumed maximum water vapor amount of 10 mbar, the absorbed solar radiation increases to about 1.38×10^5 ergs/cm^2 sec.

The planetary flux at the top of the atmosphere, $F^{\uparrow}$, was determined from the equation,

$$F^{\uparrow} = \sum_i \pi \left[T_f^i(U) \int_{\delta_i} B_\omega^i(0) d\omega + \int_{\delta_i} B_\omega^i(u) d\omega \int_0^U dT_f^i(U-u) \right] + \Delta$$

where the mass path is referenced from the surface; T_f^i is the flux transmissivity for a spectral interval of width δ_i, where the index i runs over the six (carbon dioxide) or eight (water vapor) spectral intervals used in this study; $B_\omega(o)$ and $B_\omega(u)$ are the Planck functions for the surface and mass path u, respectively; and Δ is the contribution from the surface to the outward flux which undergoes no attenuation by the atmosphere; this flux can be represented by black body radiation. The wave-number integration was performed by a six point Gaussian quadrature, and the integration over transmission was the sum of finite differences.

The spectral data required to evaluate the transmission functions are from McClatchey *et al.* (1973). The carbon dioxide band which is of primary importance occurs near 15 μm with spectral width of 500 to 862 cm^{-1}. The water vapor absorption consists of two bands, one at 6.3 μm (1250 to 2450 cm^{-1}) and the other in the far infrared region extending out from about 13 μm. Each band was divided into several spectral intervals, and the lines in each were grouped into five line-strength decades. A random band model and Voigt profile were used. Also the dependence of line strength on the mass path weighted temperature was explicitly taken into account. The spectral intervals were chosen so as to give good agreements with laboratory measurements.

The atmosphere was divided into sixteen layers of equal pressure increments. The mean temperature for each layer was assumed to be that for the center of the layer, and the mixing ratio was assumed to be constant for each calculation.

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