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# CLOSED ECOLOGICAL SYSTEMS FOR SPACE TRAVEL AND EXTRATERRESTRIAL HABITATION

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Man's requirements for provision of oxygen, food and removal of carbon dioxide and body wastes dictate the necessity for reliable life-support systems aboard a space vehicle or in sedentary habitations on extraterrestrial bodies. That these basic needs may best be met by expendable systems for times up to 30 days has been adequately demonstrated. Extension of travel and habitation past 30 days imposes the need for nonexpendable or regenerative life-support systems. Numerous compelling reasons dictate that management of these life-support logistics can best be accomplished by biological organisms. Thus, the most rational approach appears to be synthesis of an ecological system modeled on the balance of terrestrial nature, which is biologically closed but thermodynamically open. The current status of knowledge and research in this approach is briefly reviewed. Unexpected problems are discussed and the delineation of major unsolved problems undertaken. Problems dealing with the basic biology of photosynthetic organisms, geometry of culture-vessel configurations, weightlessness, effects of space radiations, genetic stability, and illumination and intermittency effects are considered. Clear differentiation between bio-engineering and design engineering is shown and reviewed.

Man's ability to exist for extended periods of time in situations of complete isolation has been adequately proven in experiments with space-cabin simulators, lunar-base simulators, and similar devices. For short periods of time, up to 7 days, endurance and extreme serendipity have allowed human test subjects to function with considerable efficiency under very trying circumstances. Experience has shown, however, that as the test mission becomes extended in time, the human subject's efficiency declines and his endurance and serendipity decline markedly. These observations have been made in experiments where life-support systems have been somewhat crude and primitive, with little or no provision for personal comfort, psychological ease, or esthetic satisfaction. It has thus become apparent that more attention must be focused on man's comfort and psychic well-being if mission profiles are to be extended sufficiently in time for manned space missions to become practicable.

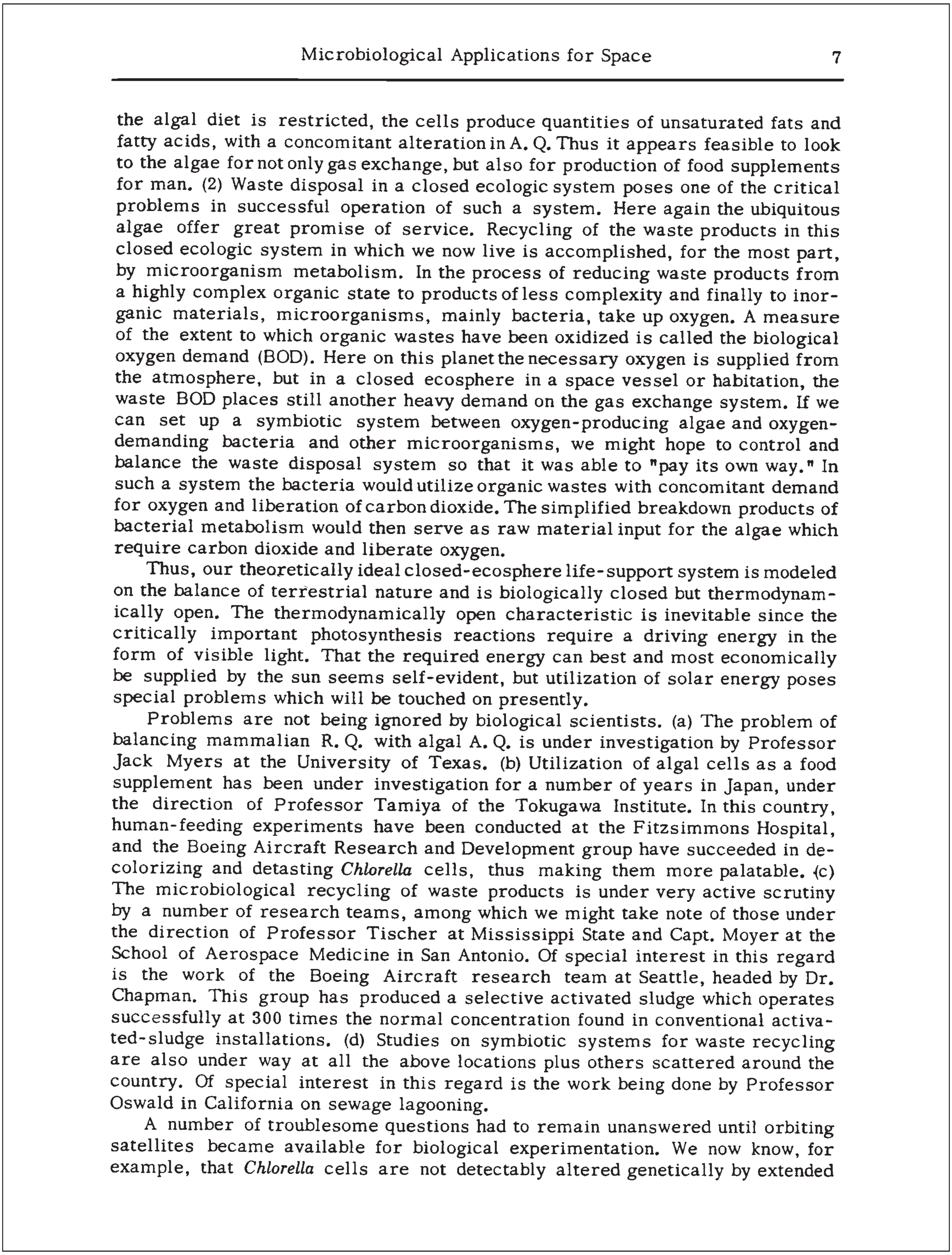
Accordingly, at the Air Force's School of Aviation Medicine (SAM) an elaborate space-cabin simulator was designed for two-man habitation for periods of up to 30 days. In designing this device, meticulous attention was paid to provision of adequate life-support systems which allow some comfort for the test subjects. With this installation, researchers at SAM have been able to conduct closed-system experiments lasting many weeks. Life support has been provided by a series of expendable systems which supply food, water, waste disposal, and a purified and partially regenerated atmosphere from fixed sources. For example, oxygen is supplied from a series of liquid-air converters, food is supplied from stored dehydrated and semisolid sources, waste is disposed of by incineration, and water is provided from stored sources placed on board at the beginning of the "flight" (Welch, 1961).

That these systems and concepts are adequate for the particular set of experimental circumstances is attested by the successful nature of the data obtained with such devices. Life support is, in some cases, so well managed that meaningful psychological data are even obtainable (Hauty, 1960). When, however, one now projects and identifies with future situations such as will be encountered in actual manned space operations, the life-support parameters and interrelated requirements change. It follows from the simplest line of logical reasoning that the total achievable mission time must be the result of the thrust or propulsion capability balanced against the weight of the payload which must be accelerated into orbit or to escape velocity. As propulsion technology and capability advance, this mission time will, of course, become extended, but achievable mission time and mission planning will always be restricted by the sharp time cutoff imposed by the propulsion vs payload compromise if life support is provided by expendable systems which must be placed aboard the vessel in toto at the start of the mission (Phillips, 1961a).

Extension of man's space tenancy time must, therefore, be sought in different technological areas. For some time past, one general approach to an alternate solution for the problem of life support has been investigation of so-called semiregenerative systems based on chemical or electrochemical reaction sequences. Greatest promise to date from such reactions seems to center on efforts at water conservation and recycling through electrolytic processes. That such processes require large amounts of energy input is self-evident, but, hopefully, we may look for some real contributions to space technology from these technological sources (Clamann, 1959, 1961). Such contributions and advances will also extend achievable mission times but, unfortunately, semi- or partial regeneration of life-support systems only moves the cutoff point in time, and does not supply a final answer. Another factor of considerable import, which must be given the most careful consideration, is that all such systems proposed to date are great energy consumers. Until such time as available energy aboard a space vehicle is not a premium item, application of such systems appears to be tenuous.

Egress from this apparent cul-de-sac is fortunately and conveniently provided if we look to means of providing regenerative life-support systems. I shall now propose that the most feasible approach is one in which biological management of life-support logistics occupies the hub position in payload calculation. This proposition may be further detailed to delineation of living-system photosynthesis as the most important key set of reactions required (Myers, 1960). In addition, there are a number of compelling reasons why green-plant photosynthesis as carried out by various microscopic unicellular algal species offers the greatest promise of success in this investigative endeavor (Phillips, 1961a). These microscopic plants have the highest intrinsic rates of photosynthesis and growth found anywhere in the plant kingdom. The photosynthetic mechanism in these species is packed into a cell unit from which all extraneous appendages are absent. The total business of an algal cell is to manufacture more algal cells and, fortunately, in the process of doing so, it takes up carbon dioxide and liberates oxygen stoichiometrically. Happily, the normal respiratory quotient (R. Q.) of man is close enough to the assimilatory quotient (A. Q.) of a number of green algal species to hope for eventual exact balancing. That this aim can be achieved is indicated by the fact that the assimilatory quotient of the algae can be altered through adjustment of the ingredients in the liquid culture medium in which the algae are suspended.

Other reasons behind choice of algae as the central organisms of a closed-ecosphere life-support system are as follows. (1) When maintained on an adequate fixed-nitrogen intake, the algae produce high-quality protein at an astonishing rate. In fact, on a protein-to-total-weight basis, production of protein by algae makes beef cattle look like amateurs. On the other hand, if the fixed nitrogen in



the algal diet is restricted, the cells produce quantities of unsaturated fats and fatty acids, with a concomitant alteration in A. Q. Thus it appears feasible to look to the algae for not only gas exchange, but also for production of food supplements for man. (2) Waste disposal in a closed ecologic system poses one of the critical problems in successful operation of such a system. Here again the ubiquitous algae offer great promise of service. Recycling of the waste products in this closed ecologic system in which we now live is accomplished, for the most part, by microorganism metabolism. In the process of reducing waste products from a highly complex organic state to products of less complexity and finally to inorganic materials, microorganisms, mainly bacteria, take up oxygen. A measure of the extent to which organic wastes have been oxidized is called the biological oxygen demand (BOD). Here on this planet the necessary oxygen is supplied from the atmosphere, but in a closed ecosphere in a space vessel or habitation, the waste BOD places still another heavy demand on the gas exchange system. If we can set up a symbiotic system between oxygen-producing algae and oxygen-demanding bacteria and other microorganisms, we might hope to control and balance the waste disposal system so that it was able to "pay its own way." In such a system the bacteria would utilize organic wastes with concomitant demand for oxygen and liberation of carbon dioxide. The simplified breakdown products of bacterial metabolism would then serve as raw material input for the algae which require carbon dioxide and liberate oxygen.

Thus, our theoretically ideal closed-ecosphere life-support system is modeled on the balance of terrestrial nature and is biologically closed but thermodynamically open. The thermodynamically open characteristic is inevitable since the critically important photosynthesis reactions require a driving energy in the form of visible light. That the required energy can best and most economically be supplied by the sun seems self-evident, but utilization of solar energy poses special problems which will be touched on presently.

Problems are not being ignored by biological scientists. (a) The problem of balancing mammalian R. Q. with algal A. Q. is under investigation by Professor Jack Myers at the University of Texas. (b) Utilization of algal cells as a food supplement has been under investigation for a number of years in Japan, under the direction of Professor Tamiya of the Tokugawa Institute. In this country, human-feeding experiments have been conducted at the Fitzsimmons Hospital, and the Boeing Aircraft Research and Development group have succeeded in decolorizing and detasting *Chlorella* cells, thus making them more palatable. (c) The microbiological recycling of waste products is under very active scrutiny by a number of research teams, among which we might take note of those under the direction of Professor Tischer at Mississippi State and Capt. Moyer at the School of Aerospace Medicine in San Antonio. Of special interest in this regard is the work of the Boeing Aircraft research team at Seattle, headed by Dr. Chapman. This group has produced a selective activated sludge which operates successfully at 300 times the normal concentration found in conventional activated-sludge installations. (d) Studies on symbiotic systems for waste recycling are also under way at all the above locations plus others scattered around the country. Of special interest in this regard is the work being done by Professor Oswald in California on sewage lagooning.

A number of troublesome questions had to remain unanswered until orbiting satellites became available for biological experimentation. We now know, for example, that *Chlorella* cells are not detectably altered genetically by extended exposure to actual space environments (Phillips, 1960). We know that algal photosynthesis will take place in the weightless state. It is known that algae as well as other microorganisms are minimally harmed, if at all, by exposure to the radiations of space, even during a large solar flare (Phillips, 1960, 1961b).

Investigations into basic biological problems have uncovered a number of unanticipated related questions. Among these should be noted problems associated with culture-vessel geometry for photosynthetic microbes (Phillips, 1961c). Technically, this difficulty is dictated by the consequence that gas exchange involves cell growth. Cell growth in turn results in less available light per cell due to mutual cell shading as cells multiply. Thus, to keep a culture operating at maximum efficiency, it is necessary to expose the cell suspension in a thin film or layer to the available light. From an engineering standpoint, exposure of a 0.5-cm layer of the algal suspension necessary to support a man would require an absurd area. Numerous approaches to the problem of miniaturizing culture equipment while maintaining the thin-film-exposure feature have been made. One such device is shown in Fig. 1 (Phillips, 1961c). This device continuously recycles the algal suspension and spreads it out in a thin film between the surfaces of inner and outer transparent cones with good efficiency.

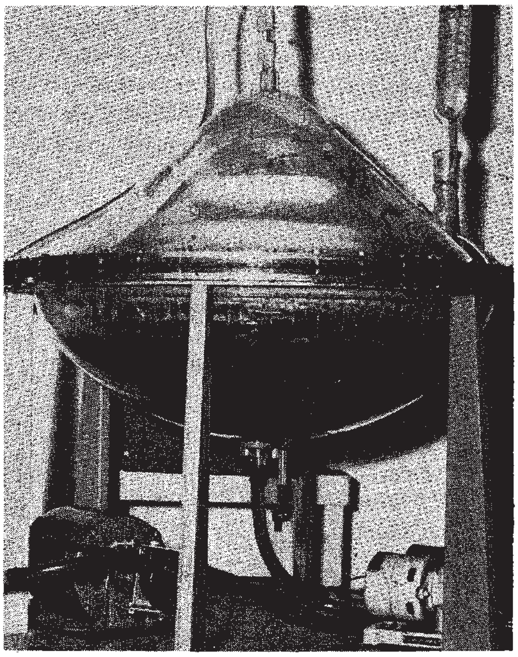


Fig. 1. The "duo-cone" algal culturing apparatus. Construction is of molded plexiglas. Illumination provided by three "circline" fluorescent lamps; total wattage rating, 94.

Another set of problems which must be dealt with involve solar intensity in our planetary system. Photosynthesis, as we know it, will be impossible outside a photic zone approximately limited by the orbit of Venus and slightly beyond the orbit of Mars (Phillips, 1961d). Of special interest is the illumination intensity on our lunar surface as shown in Fig. 2 (Phillips, 1961c). Here we see that the

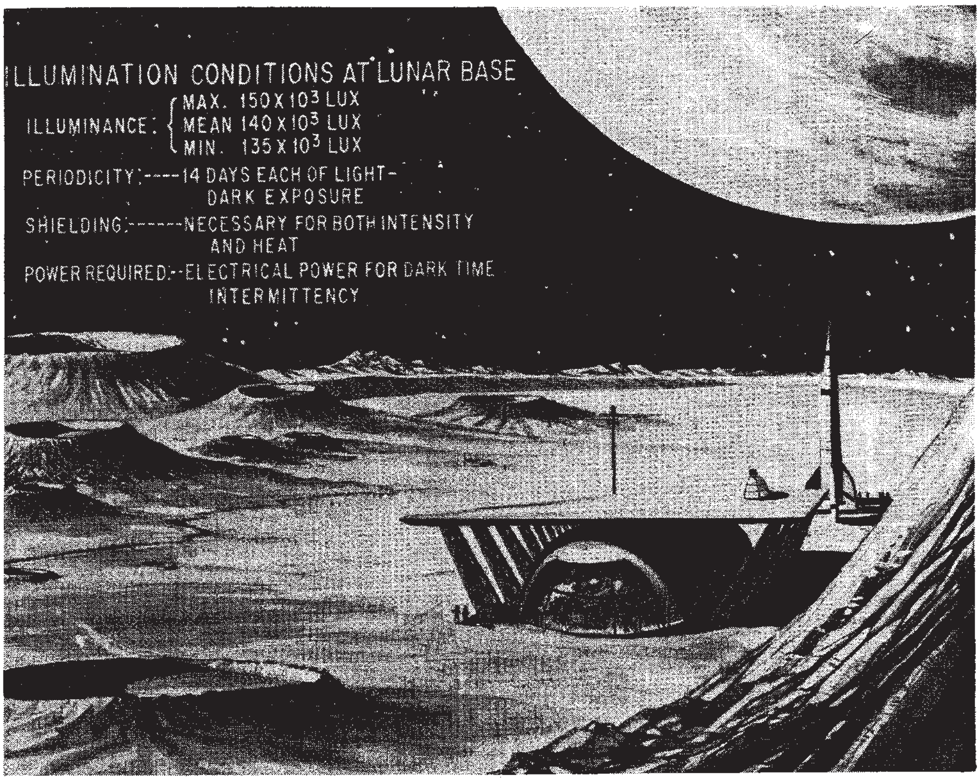


Fig. 2. Illuminance at a hypothetical equatorial lunar base.

light intensity is approximately 50% more than the maximum intensity at the earth's surface. Such high intensities will require special shielding to avoid photolysis of the photosynthetic components of a closed ecology placed on the lunar surface. Another special problem imposed by the higher solar radiation constant for the lunar surface is that of the ultraviolet portion of the spectrum, which is proportionately higher also. In contrast to the lunar situation, illumination intensity at the surface of the planet Mars, illustrated in Fig. 3 (Phillips, 1961c), frequently falls to about half the terrestrial value. Good judgment dictates most careful and astute selection of photosynthetic organisms with physiological characteristics amenable to the particular set of environmental conditions for each specific application.

A series of problems dealing with illumination intermittency effects must concern biologists. The phenomena associated with intermittency or periodicity effects are, at the present time, poorly understood and incompletely researched. Nevertheless, periodicity effects, in a gross sense, are well known in both photosynthetic and heterotrophic organisms and must eventually be coped with. To the present time biologists have been concerned with periodicity effects on photosynthetic efficiency. Here the dark times and flash times are extremely short, on the order of milliseconds. In space vessels and in sedentary space habitations, however, intermittencies of several orders of duration must be dealt with (Phillips, 1961c). Intermittencies anticipated fall into three general categories: (a) long time intervals—greater-than-1-min exposures to alternate light and dark periods;

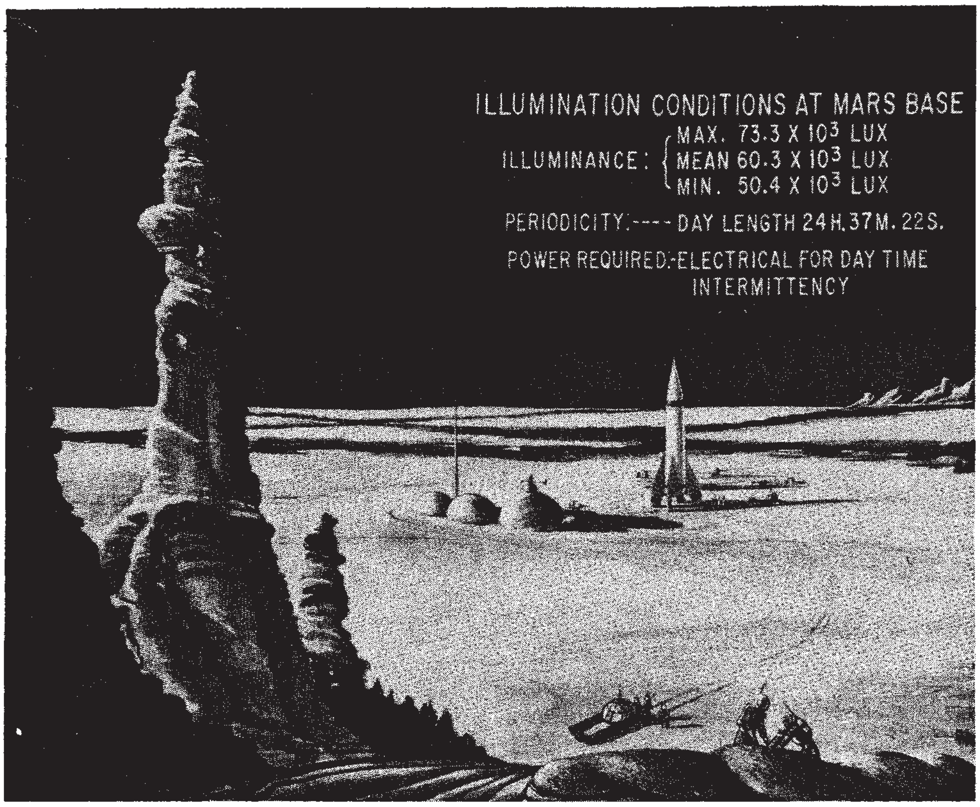


**Fig. 3. Illuminance at a hypothetical Mars base.**

(b) intermediate time intervals—1-sec-to-1-min exposures to alternate light and dark periods; and (c) short time intervals—less-than-1-sec exposures to alternate light and dark periods. Anticipated effects of all these intermittency categories have recently been listed (Phillips, 1961c). It remains to be seen if the predicted effects will be found experimentally.

Another problem intimately associated with periodicity effects has been discovered recently in dealing with photosynthetic microorganism population synchrony (Phillips, 1961c). These studies showed ultraviolet resistance of *Chlorella ellipsoidea* as illustrated in Fig. 4. Here we see that as the intermittency periods get longer, the cell survival curve becomes more nearly asymptotic. Concomitantly, as shown in Fig. 5, as the periodicity intervals get longer, the cell mutation rates increase (Phillips, 1961c). All these effects are superimposed upon an increasing degree of population synchrony as periodicity intervals get longer. One may reasonably argue that the mutants produced are not undesirable ones, but other possible physiological effects have not been explored. Thus, it is felt that this is a problem which must be explored and reliable data must be obtained to at least show that no undesirable effects are produced under these conditions.

Finally, if a closed ecology, as visualized, is to be self-perpetuating, we must address ourselves to the problem of energy to drive the system. It has been stated that a system such as is now under consideration must be biologically

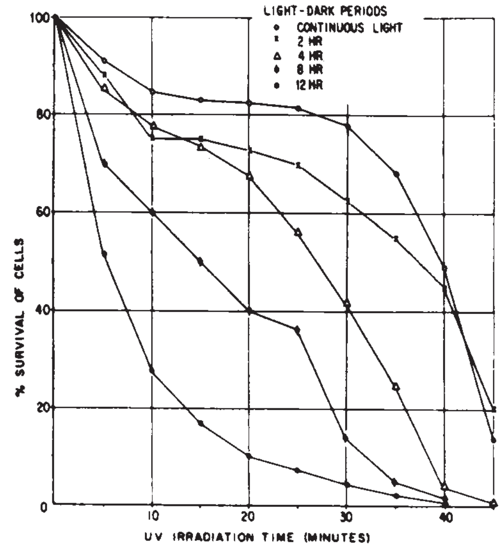


Fig. 4. Survival of *Chlorella ellipsoidea* (Tamiya strain) under ultraviolet irradiation and effects of population synchrony. Irradiation intensity was 100 ergs/mm$^2$/sec at wavelengths below 280 m$\mu$.

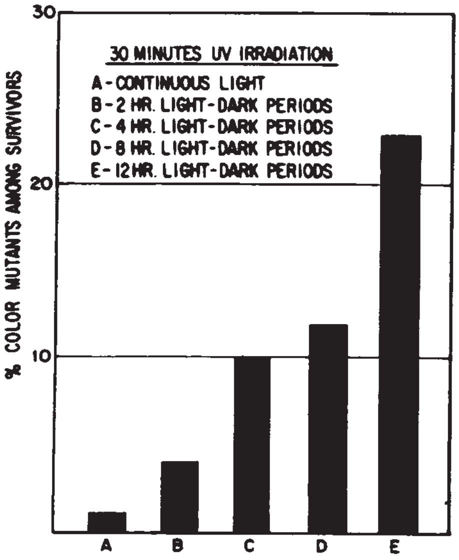


Fig. 5. Mutation rates of *Chlorella ellipsoidea* (Tamiya strain) as functions of degree of population synchrony.

closed but thermodynamically open (Phillips, 1961c). This means that the system must have a continual energy input in the form of light in the approximate spectral range of 400 m$\mu$ to 700 m$\mu$. Until the time arrives when electrical power is no longer at a premium aboard a space vessel, we must look to our own sun to supply this driving energy for our closed ecological system. Direct utilization of solar energy for photosynthesis at once poses a number of, as yet, unsolved problems. One of the most critical of these is photodestruction of photosynthetic elements, or "solarization," as it is called. One obvious answer is to reduce the solar light intensity appropriately without altering its spectral qualities. This hardly seems a satisfactory final answer and concentrated research effort is indicated and needed to discover either methods of bypassing solarization or of selecting organisms with higher resistivity to solarization than any now available.

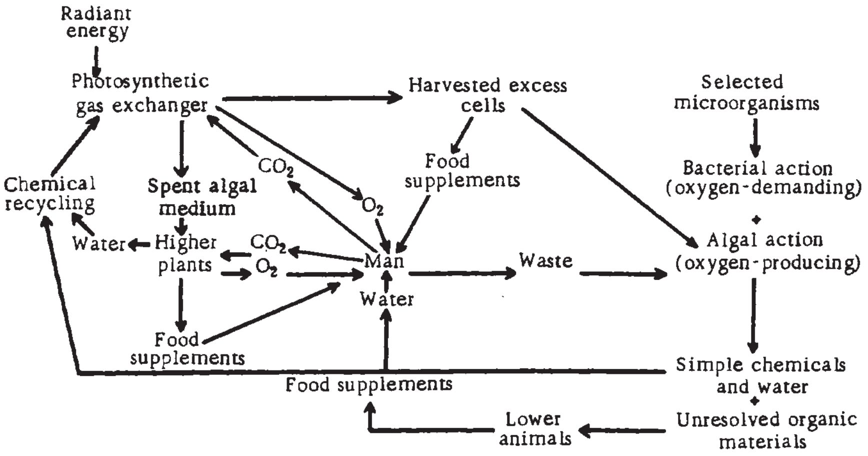


Fig. 6. Interrelations of biological systems in a closed ecological environment.

Let us now briefly recapitulate and synthesize current visualization of biological interrelations in a functional closed ecological system for space travel and habitation. Figure 6 shows such a system with its interrelations (Phillips, 1961a). Here we see the photosynthetic gas exchanger producing oxygen, algal cells, and spent culture medium. The oxygen produced is, of course, utilized by the animal component of the system. The peripheral systems involved fit into the scheme as shown. This figure is merely one representation of how a closed ecological system might be constructed, and should not be construed to represent a final answer. It does point out, however, that a system modeled on the balance of terrestrial natural processes, biologically closed and thermodynamically open, offers the greatest chance and hope of success of any concept currently available.

Finally, it should be pointed out that at this point in the basic research and development of a closed ecological system, two types of engineering are required. The first is bio-engineering, which should be defined as the process whereby one discovers the physiological capabilities of a given organism or group of organisms, and then fits this information into an over-all engineering concept such that demands of the biological components do not exceed capabilities of mechanical components. The second is design engineering of a new type which must be aware of the findings of bio-engineering in order to design equipment to take advantage of biological capabilities. The proper time for phasing in both types of engineering, if we are to achieve success in this unique task, is now.

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## DISCUSSION

HART (Grain Processing Corporation): Are you aware of the results of the feeding experiments at Fitzsimmons Hospital?

PHILLIPS (Panoramic Research, Inc.): Yes.

HART: Can you discuss those results?

PHILLIPS: I don't have the results here.

HART: I am interested in knowing because our company furnished the algae. Were they successful in some small wav? Were they satisfactory?

PHILLIPS: Yes, Mr. Zuraw points out that that paper was given in Florida. I'll wiggle out of this, I think, by turning it around and asking you and everybody else collectively a question. Have any of you people thought about the problem that a man does not have a gut like a termite; therefore, he's up against the cellulose problem? Here again is something that has to be hacked away at. I can't give you that data directly because I just don't have it.

BLOCK (University of Florida): I'm interested in knowing why a biological degradation of the waste would be preferable to simple combustion inasmuch as the oxygen utilization will be there and you don't have to go through that in many steps.

PHILLIPS: I might point out in trying to answer this question that quite a few different types of suggestions have been made as to what to do with waste that accumulates aboard a space vessel. One suggestion, for example, is that you accumulate it for a while and then just kick it overboard. You realize this makes a bunch of artificial satellites. The guy in the spaceship behind you may not have his windshield up, so you've got to be careful about that. Actually, I think the proper answer to your question is the fact that we are trying to get and utilize everything out of this pig we can, and the difference between directly incinerating waste products and using that waste material to recycle through other biological systems is the squeal. This is what we're trying to do. You see, every atom of fixed carbon there represents quite a sizable fortune in energy, and energy is ultimately the real crux of the whole problem of being able to get a functional payload that will regenerate itself. And so, at least from my standpoint, the thinking has been, you use everything, including the squeal. This business of recycling through a biological system versus incinerating is one way of getting at the squeal. At least, this is the way we feel now.

MATHERN (Quartermaster Food & Container Institute): You say that paper was given from Fitzsimmons Hospital in Florida?

PHILLIPS: I don't recall exactly when the paper was given. I think it was last year at a meeting in Florida.

MATHERN: There's another paper coming out on it and that's why I didn't want to let all the news come out before the paper was given. I can tell you that the algae they used were from Japan. They were *Scenedesmus* and *Chlorella*. It also was very highly contaminated, so that the algae had to be autoclaved before feeding. They concluded from this study that the cell wall had to be broken before it could be served as food. It was fed to humans, rats, mice, and chickens. The human feeding experiments came out rather successfully, at least I thought so. I'm familiar with yours. I had the opportunity of visiting you about a month ago, but yours are not *Chlorella* as I recall. I think they are anticipating using that for humans, but apparently they haven't as yet.