Sustaining Life in Space—A New Approach

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WITH PROGRESS in space technology, prolonged space travel and temporary habitation of extraterrestrial bodies seems inevitable. For short-term missions the provision of food and breathable air can best be met by an expendable system—that is, a life support system which provides basic needs entirely out of stored products. Missions covering extended periods of time, however, due to payload limitations, will require reutilization of waste products.

At present, it seems extremely unlikely that man's diet can be synthesized from raw waste products by other than biological means. Biosynthesis, therefore, is an important aspect of space exploration. Two of the major problems of biological regeneration are the weight required for such an integrated system and the power input needed to maintain it.

This paper discusses a closed ecological system, which differs from the photosynthetic one, in that it does not utilize light energy.This new system has shown weight advantages and has reduced power demands.

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BIOSYNTHETIC REGENERATION

Basically, biosynthetic processes which involve the conversion of carbon dioxide into cellular material are similar in all plant life. The viewpoint generally accepted is that not only is the path of carbon similar in these conversions, but that essentially the same amount of biological energy is required for the reduction process.

In essence, all living cells, human as well as plant and bacterial, use two types of energy packages. One package, with a relatively large amount of energy, is reduced pyridine nucleotide (PNH_2*). This is formed

* PN and PNH_2, oxidized and reduced pyridine nucleotide.

by the hydrogenation of its oxidized form (PN). The function of the nucleotide is that of a carrier of "cellular" hydrogen—which we shall represent by the symbol [H].

The second package, an energy-rich phosphate (ATP **), represents a relatively small amount of energy. Three of these small packages can be obtained by the oxidation of one larger unit. The process in which this occurs is common to many forms of life and is called respiration.

The function of the ATP is manifold. It mediates in cellular processes which require only a very small amount of energy per step, such as the polymerization of simple molecules into more complicated cellular constituents. It helps to maintain physiological conditions inside the cell. For example, it makes muscles contract and nerves conduct.

It is assumed that two PNH_2 and three ATP molecules represent sufficient reducing power for the conversion of one molecule of CO_2 into sugar. Additional reducing power is required to process sugar into fats and proteins, to build structures, transport materials, etc. The total amount of PNH_2 and ATP necessary for building and maintaining living matter from CO_2, SO_4, NO_3 and so on, is not known exactly.

However, there is no reason to assume that the amount differs greatly between different autotrophic organisms—organisms which are able to thrive entirely on inorganic materials and energy sources. These are quite abundant. Practically every energy source available on the earth's crust has been tapped by some form of life. Maybe it is because sunlight is the most abundant of these sources that "plants" have evolved into such a vast variety of complex multicellular organisms. All other autotrophic organisms are "primitive." Unicellular bacteria are comparable to the unicellular blue-green algae—the simplest of plants.

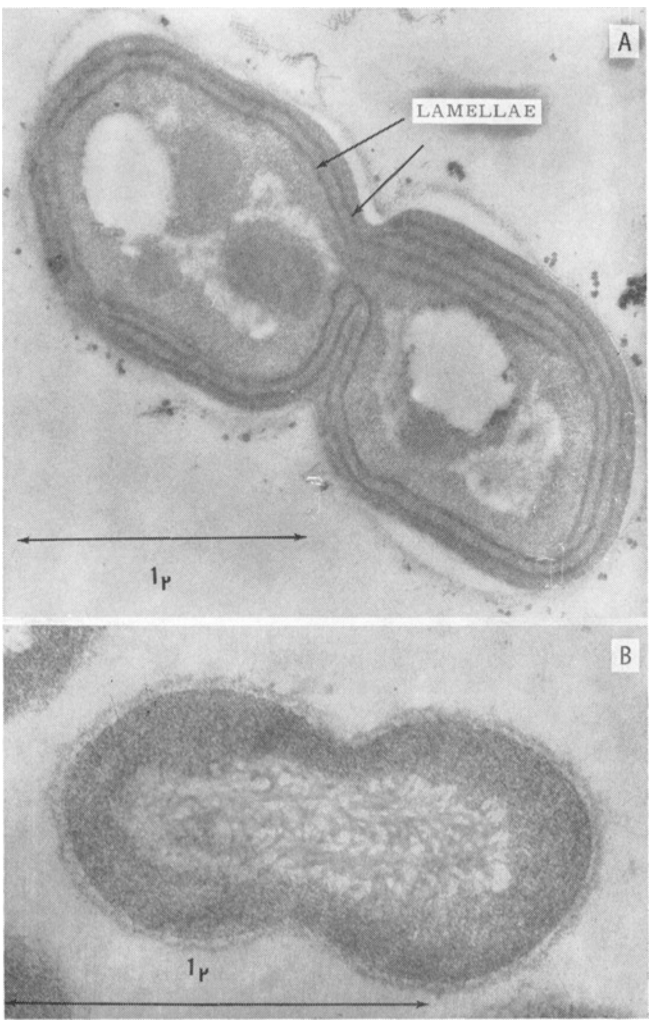

Fig. 1. Electron micrographs showing: (A) Anacystis, a photosynthetic blue-green alga; and (B) Hydrogenomonas eutropha, a chemosynthetic organism.
(A) Magnification 64,000 x
(B) Magnification 94,300 x

This is illustrated by the electron micrographs *** in Figure 1, which show: the morphology of (A) Anacystis, a photosynthetic blue-green alga; and of (B) Hydrogenomonas eutropha, a nonphotosynthetic hydrogen bacterium. Both are simple and primitive organisms. The nucleus is not segregated from the cytoplasm by a membrane. Structures such as mitochondria and endoplasmic reticulum—which are universal components of higher cells—are absent in these bacteria-like organisms. Both divide by simple fission and neither forms colonies after division. Both have a "plasma" membrane (about 75 angstroms thick) immediately beneath the cell wall, in intimate contact with the cytoplasm.

However, the photosynthetic organism does exhibit several concentric layers of "lamellae" (see Figure 1) at the periphery of the cell. Such lamellae are characteristic of all oxygen-evolving photosynthetic organisms. In higher plants and algae they are segregated from the cytoplasm by an envelope and are designated as components of a distinct cell organelle—the chloroplast. In bacteria-like cells such as Anacystis they are found free in the cytoplasm. The absence of "lamellae" in the Hydrogenomonas is the only distinguishing morphological characteristic revealed by electron microscopy.

Inorganic energy sources other than light are all chemical—and hence we speak of "chemo-autotrophic bacteria," which carry out chemosynthesis rather than photosynthesis. The energy liberated in the combustion of practically any naturally occurring chemical can be used by some microorganism to build and maintain itself with CO_2 as the sole carbon source.

One of the leanest diets used by a chemosynthetic organism is the oxidation of nitrite to nitrate. The energy liberated in this step barely suffices to generate one equivalent molecule of ATP. Probably, the other extreme on the scale of chemosynthetic conversions is the combustion of molecular hydrogen—carried out by bacteria of the genus Hydrogenomonas. A considerable amount of energy is available in this combustion.

Molecular hydrogen is a material common to many forms of life—including, for instance, green algae.[1,3] An enzyme, hydrogenase, which mediates the conversion

** ATP, adenosine triphosphate.

*** Micrographs by George Schidlovsky, RIAS, Baltimore 12, Maryland.

of this gas into PNH_2—and reversely—occurs in many organisms. However, most of these organisms use hydrogenase only to rid themselves of excess reducing power—formed, for example, under anaerobic or fermentative conditions.

Hydrogenomonas, instead, uses hydrogenase to reduce pyridine nucleotide with hydrogen. Part of this PNH_2 is used to reduce CO_2, another part is recombusted with oxygen (as in normal respiration) and the energy is retained in ATP, which assists the CO_2 reduction and cell building:

$$2\,H_2 + CO_2 \rightarrow [CH_2O] + H_2O \qquad (1)$$

$$4\,H_2 + 2\,O_2 \rightarrow n\,ATP + 2\,H_2O \qquad (2)$$

The ratio of the amounts of hydrogen involved in reactions (1) and (2) is called the "biological efficiency." Since (1) represents a very complex process, it is hard to assign a specific free energy change to it. If CH_2O were taken as sugar, ΔF would be close to zero and the thermodynamic efficiency at all times practically zero, even with a high ratio of (1)/(2). The less hydrogen combusted in (2), the more efficient is the system. It appears that, dependent upon the culture conditions,[5] this efficiency factor can vary over a wide range —indicating that the "coupling" between energy-yielding combustion and energy-consuming synthesis is not constant.

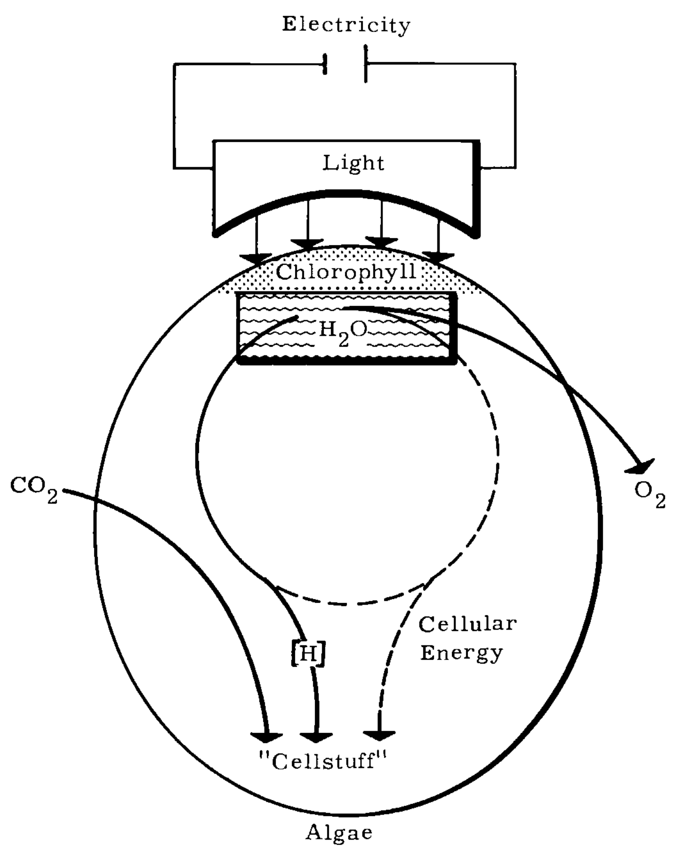

Fig. 2. An artificially illuminated photosynthetic regenerative system. The CO_2 is converted into cellstuff and oxygen is generated from water by the algae, under the input of light energy.

In the extreme, reaction (2) can run without any concomitant CO_2 uptake ("Leerlauf" or idling). The best values reported[5] show a combustion of 2 moles of hydrogen (2), for the fixation of 1 mole of CO_2 (1). Average values found[4,5,6] indicate the combustion of 4 moles of hydrogen. We have recently duplicated these data with relatively heavy suspensions.

That such a chemosynthetic process might be suitable to sustain a closed ecology in space is borne out by Figures 2 and 3. The first shows the more familiar proposi-

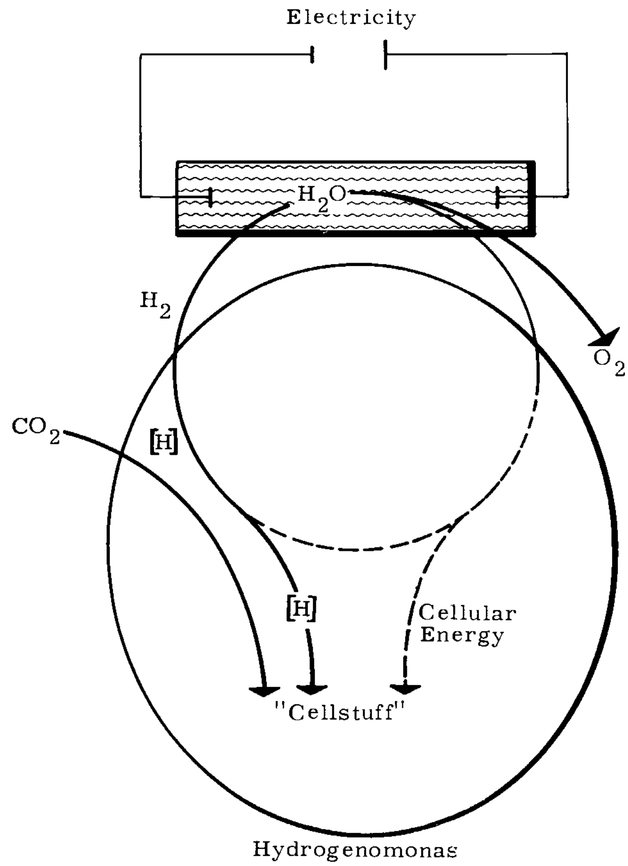

Fig. 3. A combination of electrolysis and chemosynthesis. Oxygen is generated by electrolysis, under the input of electrical energy. The biosynthetic regeneration of CO_2 and the removal of hydrogen is carried out by Hydrogenomonas.

tion of the photosynthetic regeneration: light generated electrically, or obtained from the sun, excites the chlorophyll of the algae. Water is split into oxygen and hydrogen—and the hydrogen is retained as reduced pyridine nucleotide. With the aid of ATP (cellular energy) formed directly in the light reaction and by partial recombustion of the photoproducts, CO_2 is converted into cellstuff.

Figure 3 shows the chemosynthetic gas exchange system, in which water is split directly by electrolysis—rather than by light. Again, oxygen is evolved (available for human respiration) and the hydrogen, aided by ATP formed in a partial recombustion, reduces CO_2 to cellstuff. Thus, the two processes are entirely analogous. In both, the ratio of O_2 released/CO_2 taken up is close to unity, matching human respiration. Moreover, in both cases, organic material essentially suited as human food is produced.

Our experiments have shown Hydrogenomonas to be a reliable and fast growing organism, whose culture requires no more care than does that of algae. For space missions, therefore, a further comparison between the two types of regeneration primarily concerns the crucial aspects of weight and power efficiency. The following

H_2, O_2 and CO_2), the less the volume of suspension required.

In Figure 4 and Table I the results of experiments pertaining to the conversion capacity-density relationship are summarized. The rate of CO_2 conversion obtained with suspensions up to approximately 10 grams, dry weight, per liter shows a linear relation with density would suffice for the conversion of 1 mole of CO_2—the hourly production of a man. The removal of this amount would require the cleavage of 4 moles of water on a basis of 4 H_2 combustions per mole of CO_2.

In addition, the human respiratory oxygen demand of 1 mole of O_2 per hour requires the cleavage of 2 moles of water. Therefore, the chemosynthetic regeneration and human respiration together require—on the average—the splitting of 6 moles of water per hour. The wattage required for electrolysis depends upon the efficiency of power conversion, which may range from 60% to 80%. The power required would then range from 700 to 900 watts. This means that a man can be maintained in a closed ecology at a power input of five to six times his caloric need, utilizing two efficient energy conversion processes: electrolysis and chemosynthesis.

COMPARISON OF PHOTOSYNTHESIS AND CHEMOSYNTHESIS

A photosynthetic regeneration employs green or blue-green algae, which utilize light energy to split water (photolysis) into a reduced component (hydrogen or [H]) and oxygen. Part of the light, or of the photochemical products, is used to form ATP. Together with [H], this allows the cell to generate sugar and other cellular constituents (Figure 2). In this process, the photosynthetic organism performs both the cleavage of water and the biosynthetic CO_2 conversion. Only the latter process is carried out by the organisms in a chemosynthetic conversion—the splitting of water being taken over by a highly reliable and very efficient physical process, electrolysis.

If only artificial light is available, a heavy loss has to be taken into account in the conversion of electricity into visible light. On the average, the light is generated at an efficiency of 10%, while the conversion of electrical energy by electrolysis might be well over 70%. If we assume identical biological conversion efficiencies for photosynthesis and chemosynthesis, then the difference in power consumption between these systems is obvious. The power consumption for a photosynthetic regeneration would be at least seven times the electrical input required for a chemosynthetically balanced closed ecology.

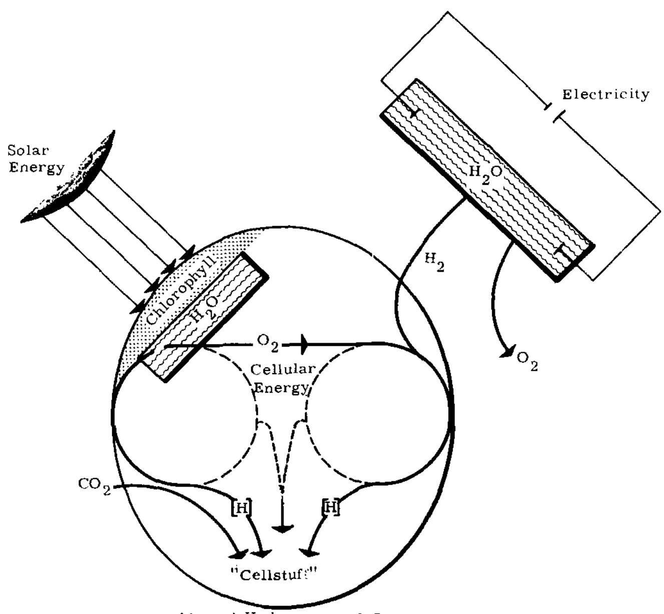

Fig. 5. Schematic representation of the regeneration of CO_2 by a mixed suspension of algae and Hydrogenomonas. Respiratory oxygen is generated by water electrolysis. The oxygen evolved by the algae is utilized in chemosynthesis.

Solar radiation can be utilized directly by a photosynthetic regenerative system. Under conditions where sunlight is abundant and constantly available, such a system may yield good service and—power-wise—would be superior to a chemosynthetic recycling system. Problems remain to be solved, however, connected with the use of large illuminated surfaces, such as the protection against harmful radiation, gas and heat exchange.

If solar radiation is not available continuously, energy storage and facilities for artificial illumination would be required to carry on photosynthesis during dark periods. This would involve additional weight penalties and the very inefficient conversion of electricity into visible light. Under these conditions, the far more efficient conversion obtainable with combinations of electrolysis and chemosynthesis would prove a great advantage. It would not exclude the possibility of utilizing natural irradiation by photosynthetic organisms for the periods where sunlight is available. Both systems could be combined into a photochemosynthetic conversion such as is schematically presented in Figure 5.

The oxygen required for human respiration would be generated by electrolysis. The hydrogen, generated simultaneously, and the oxygen, liberated by photolysis of water (photosynthesis), would be utilized by the chemosynthetic process in supporting the growth of the chemosynthetic organisms. This symbiotic community can be balanced by light input. If, however, additional hydrogen and an appropriate volume of oxygen are supplied to the mixed culture, the ratio of the two processes can be adjusted at any level, depending—for example—on the availability of sunlight. Such a mixed system would qualify as a life support system under conditions of long light-dark cycles (weeks).

The power required to maintain such a system would depend on the ratio of photosynthesis and chemosynthesis. If both processes were to proceed on an equal basis, the electrical input for electrolysis, 200 to 300 watts per man, would suffice. During dark periods, in which only the chemosynthetic conversion occurs, the electrical input would increase to approximately 1000 watts. The volume of such a mixed system would be determined by the cell concentration obtainable with algae. Therefore, it is expected that a photosynthetic system which would supply the basic needs of one man could be adapted to a photochemosynthetic system of equal size—and capable of taking care of two men.

CONCLUSIONS

As indicated by the experiments described, the utilization of a chemosynthetically closed ecology would call for a power input of about one kilowatt per man. It is expected that the power requirement could be rather independent of the suspension density. Volume-wise, 20 liters of suspension per man would be sufficient if the results can be duplicated with large exchangers. If these indications are borne out, the possibility of utilizing such a closed ecology can be considered for trips of longer than a few months. Finally, the evaluation of mixed cultures as a regenerative system for closed environments requires further investigation.

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