N.D.$ 46103

UCRL-2707
Unclassified-Health and Biology Distribution

UNIVERSITY OF CALIFORNIA

Radiation Laboratory

Contract No. W-7405-eng-48

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September 1954

Berkeley, California

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Unclassified Health and Biology

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ABSTRACT

The problem of maintaining livable oxygen and carbon dioxide pressures in a closed space in which men must live leads to consideration of the possible use of the photosynthesis of green algae. A calculation based on the known respiratory rate of man and the photosynthetic rates of Chlorella indicates that it would be feasible to use algae for this purpose.

USE OF CONTROLLED PHOTOSYNTHESIS FOR MAINTENANCE OF GASEOUS ENVIRONMENT

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In considering the problem of maintaining livable oxygen and carbon dioxide pressures in a closed space in which men must live, it is quite natural to wonder if we can reproduce the mechanism of balance that exists in the earth's atmosphere. This mechanism is simply the balance between the photosynthesis of green plants, by which carbon dioxide is absorbed and oxygen liberated, and the reverse process, respiration of all living systems, plants included, by which oxygen is absorbed and carbon dioxide liberated. If one looks at the chemical reactions which represent these two processes,

$$CO_2 + H_2O \underset{\text{respiration}}{\overset{\text{photosynthesis}}{\rightleftarrows}} O_2 + \underset{\text{organic compounds}}{\left\{CH_2O\right\}} ,$$

it is apparent there is a balance not only of the gases, CO_2 and O_2, but also of reduced organic matter, including food, and water. Therefore, in a closed, artificial system, we would be concerned not only with the immediate problem of gas exchange, but also at longer times, with the conversion of

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[*] The work described in this paper was supported in part by the Office of Naval Research, Contract NR 123-256, and the U. S. Atomic Energy Commission.

organic matter. Thus, for example, on an extended space journey of several years, it might not be possible to carry enough food and it would become necessary to process the plants to make food. We will discuss here principally the gas-exchange problem.

The reaction written above by no means represents completely the process of photosynthesis. There is, in addition to the gaseous exchange, an uptake of nitrogen (in the form of ammonium or nitrate ions), phosphate, and the ions of numerous metals, including iron, magnesium, sodium, potassium, etc. In any photosynthesizing system these elements must be supplied, just as fertilizers are required in agriculture.

In selecting a suitable plant for gas exchange, one is led to a consideration of various types of green algae by their many favorable characteristics. Suspensions of algae in nutrient solutions can be kept in tanks, which can be rather easily adapted in shape to fill available space. The suspension can be pumped and "harvesting" of the plant yield can probably be made continuous and automatic. "Planting" consists merely of inoculation of a vessel of liquid nutrient solution with a suspension of live algae. Some unicellular algae are capable of a very high rate of photosynthesis, which results in a large amount of gas exchange per unit volume of space as compared with higher plants. Absorption of light energy can be made nearly complete.

The biggest disadvantage of algae appears to be susceptibility to contamination by bacteria. In addition there is a tendency on the part of some species of algae, which might be desirable in other respects, to form spores, causing a temporary large decrease in photosynthesis rate.

Other species have complex nutrient requirements which have not been fully determined.

These problems all appear to be susceptible to solution. In regard to contamination it should be noted that in some sewage disposal research, algae are being grown very successfully in the presence of a great variety of bacteria. In this case the algae liberate oxygen which is then used by the bacteria to decompose the organic matter, supplying in turn a rich source of CO_2, minerals, and organic compounds for the algae. There are a number of algae species which do not sporulate, and nutrition requirements can be determined by patient investigation.

The space requirements of a photosynthetic-gas-exchange apparatus can be calculated from the known photosynthetic rate of one of the more active algae, Chlorella, and the respiration rate of man. A man weighing 154 pounds (70 kg.) and doing light labor would, over a 24-hour period of working, resting and sleeping, require about 600 liters of oxygen or 25 liters/hour. The very efficient unicellular green alga, Chlorella, is easily capable of rates of photosynthesis which cause the evolution of 30 liters of oxygen/hour per kilogram of fresh weight of algae, and rates as high as 45 liters/hour have been measured under laboratory conditions, though not under conditions of steady-state growth. It seems reasonable that a steady-state rate of 25 liters/hour/kilogram of algae might be achieved, and if one makes this assumption, then it is seen that the respiration of each man could be balanced by the photosynthesis of one kilogram wet weight of algae.

However, algae must be suspended in nutrient solution in order to receive adequate light and nutrient for photosynthesis. A concentration of 1% algae (wet weight) in nutrient solution is practical for maintaining growth. Therefore 100 liters of algal suspension are required for each man.

The light requirement for maintaining the necessary rate of photosynthesis can be calculated from the known light-absorption data for *Chlorella*. Such a calculation* shows that for a one percent suspension of algae 0.4 cm thick, a light intensity of about 600 foot-candles from each side would be required to supply enough light to maintain the desired rate of photosynthesis, if the light were all of the 6800 Å wave length. Since one kilogram of algae in one percent suspension occupies 100 liters, this thickness would result in a layer of algae with an area of 10^5 cm^3/0.4 cm, which is 2.5 x 10^5 cm^2 or 270 ft.^{2} One might imagine an arrangement of tanks composed of 1/4-inch-thick transparent plastic sheets about 4 ft x 4 ft in area and 0.4 cm apart, with separators to maintain the desired width. A unit layer would consist of one such tank with a thickness of about 3/4 in. and a bank of neon or fluorescent lights of perhaps 1/2 in. thickness with spaces between for air cooling. The total thickness of this unit would then be about 1-1/2 in., and, since each layer would have an area of 16 feet^2, some 17 layers would be required, making a thickness of about 27 inches. This volume would then be 4 ft x 4 ft x 2-1/4 ft, or 36 cu ft per man. If another 14 cu ft were allowed for pumping, aerating, harvesting, and control mechanisms, about 50 cu ft would be required per man. Good engineering design should result in a more compact unit. For example, the many thicknesses of plastic walls might be eliminated and the light put directly in the algae tank, with only terminals

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* We are indebted to Dr. Jack Myers, University of Texas, for a private communication concerning this and some other calculations presented here.

coming out. Cool-running lights and a good mechanism for removing heat from the rapidly circulating algae suspension would then be required.

In addition to space requirements the power requirement of an algae gas exchange system should be considered. Since respiration and photosynthesis are approximately reverse processes in energy as well as materials, we can consider the power expended by a man at 120 kcal/hr as equal to that which must be supplied to the photosynthesizing Chlorella to maintain the necessary gas exchange, and this amounts to about 0.2 hp. The maximum efficiency with which Chlorella uses light energy under laboratory conditions is still a subject of controversy, with efficiencies approaching 100% being reported by Warburg and Burke and efficiencies of about 35% reported by a number of workers. In any event, the conversion of red light energy to chemical energy by Chlorella growing on a large scale could probably not be better than about 25% even if most of the light supplied to them were of wave lengths of 6300 to 6800 Å. The wave length of the light is important in this connection since the pigment systems of the algae apparently degrade light energy of shorter wave lengths to energies equivalent to red light before converting this energy to chemical energy. Thus if blue light were used, about half the energy would be lost as heat before any conversion to chemical energy would take place.

The efficiency of the conversion of electrical energy to visible light energy is about 20% in a standard fluorescent lamp, but some further studies may be required in order to find a lamp which would produce red light with this efficiency. If we combine these efficiencies with the power requirement of 0.2 hp for one man, we obtain 0.2/(.2 x .25) = 4 hp.

If our "ship" were powered by a reactor this would require the consumption of about 10 grams of atomic fuel per year per man, if an efficiency of conversion of fuel to electrical energy of 0.02% were obtained.

The ratio of CO_2 to O_2 in the gas exchange of a respiring man is not 1.0 as would be expected if man consumed only carbohydrate but is actually about 0.8 due to the metabolic consumption of proteins and fats. Since photosynthesizing algae produce proteins and fats as well as carbohydrates the photosynthetic-gas exchange ratio or CO_2/O_2 also is different from 1.0 and can vary from 0.7 to 0.9 in the case of Chlorella, depending on whether nitrate or ammonium is used as a nitrogen source. The gas exchange ratio of Chlorella can thus be made to just compensate that of man by controlling the ratio of nitrate to ammonium in the nutrient supplied to the algae.

The nitrogen requirements of the algae can be calculated as follows: One kilogram of algae producing 25 liters of O_2 per hour at a gas exchange ratio of 0.82 would take up 20.5 liters of carbon dioxide or 0.915 moles of carbon. According to Myers, the cells produced by growth are about 50% carbon and 10% nitrogen so that 0.16 moles of nitrogen/hr would be required. This nitrogen could be supplied by the addition of 13.6 g of $NaNO_3$, 4.8 g of urea or 2.7 g NH_4 per hour. Lesser amounts of phosphate and a number of other elements would also have to be added.

Such considerations naturally lead to a desire to reclaim the nitrogen and other minerals from the harvested algae. However, processes which burn the algae harvest to inorganic minerals will consume as much oxygen and liberate as much CO_2 as was required for the algae growth.

Consequently, if we are to burn the algae we can afford to do so only by feeding it to the crew, and so we come back to the problem of converting algae to palatable food. Such conversion will probably be accomplished in the not too distant future, perhaps long before we have interplanetary travel. Algae are a potentially good food, some species containing as high as 50% protein, 7% fat, and sizeable amounts of digestible carbohydrate. Professor Tamiya and co-workers at the Tokugawa Institute in Japan have made palatable bread, cookies, and imitation "soy sauce" from algae.

If the algae harvest can be consumed as food then the human excreta would have to be processed, probably by the action of bacteria, to provide the nutrient for the algae. This processing would require some further oxygen uptake and CO_2 evolution, which would in turn bring about an increase in the volume and energy requirements of the algae cultures.

Thus there appear to be several alternate methods of using photosynthesis of algae to balance respiration of man, involving different degrees of conservation of material. We can carry along all the food required by the crew and all the nutrients required by the algae for the duration of the trip and throw away all the human excreta and the algae harvest. The other extreme is to consume all the algae harvest for food and to process all excreta and waste for feeding to the algae. Between these two extremes lie a variety of choices, such as carrying all necessary food but processing excreta for algae nutrients, etc. The method chosen will doubtless depend on the limitations of time and space imposed by the size of the space ship and the duration of the voyage.

The problems to be worked out in designing a satisfactory system are many and involve problems in microbiology, engineering, medicine, chemistry, and physics. Nonetheless, there are no theoretical reasons for believing such a system will not work. It is, after all, simply a miniature model of the biological system in which we live.